### A Laser-Based Beam Profile Monitor for the RAL Front End Test Stand

David Alexander Lee Imperial College London

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#### For Dad

-who introduced me to the joy of physics-

#### and Mum

-who has had to endure the many hours of dinnertime conversation that follow from having three male scientists in the family...

## Declaration

Throughout this thesis, references are provided where collaborative work or the work of others is presented. The remainder is either my understanding of the material being presented or the result of my own work.

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## Abstract

The development of high-power proton accelerators requires a simultaneous effort to develop non-invasive beam diagnostics. Laser-based instruments are an excellent candidate for non-invasive beam diagnostics; an example of one such device—a laser-based beam profile monitor—is the subject of this thesis. This instrument forms part of the Front End Test Stand, an  $H^-$  accelerator that is being constructed to demonstrate many of the key technologies required in the low-energy section of high-power proton accelerators.

Laser-based  $H^-$  beam profile monitors measure the distribution of the ions within the beam by photo-detaching the outer electron from a small proportion of the ions and measuring the corresponding charge. By stepping the laser beam across the ion beam and measuring the number of electrons detached at each position of the laser beam, a projection of the ion beam onto a plane can be built up. The instrument presented in this thesis is designed to measure a series of projections at different angles, which could then be computationally recombined to give the underlying 2D transverse distribution of the  $H^-$  ions. This is the first time that an instrument has been designed to be able to do this.

In this thesis, the principle behind laser-based beam diagnostics for  $H^-$  ions is described in detail before the design of and results from the initial commissioning of the Front End Test Stand's laser-based beam profile monitor are presented. Two algorithms, capable of reconstructing the 2D distribution of the ions from a series of projection measurements, are also discussed.

Simulations performed during the design phase of the instrument showed that all of the photo-detached electrons should be captured by the detector. However, to date, the background signal has proved to be larger than the expected photo-detached electron signal and so the photo-detached electron signal was not able to be measured. Consequently, an experimental study of the background signal and recommendations to improve the signal-to-noise ratio are also presented.

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## Preface

The body of work which this thesis describes is the design and commissioning of a laser-based instrument designed to measure the correlated 2D transverse density distribution of the Front End Test Stand's  $H^-$  ion beam. The Front End Test Stand is under construction at the Rutherford Appleton Laboratory to demonstrate many of the key technologies that would be required for future high-power, pulsed proton accelerators.

This thesis begins by motivating the construction of high-power, pulsed proton accelerators by considering some of their applications. The possible approaches to their construction are then described, all of which would require the technology being developed for the Front End Test Stand. The constituent parts of the Front End Test Stand are described, alongside their status at the time of writing, in Chapter 2.

In Chapter 3, the requirement for beam diagnostics to successfully commission and operate accelerators is outlined. Some beam parameters that are useful to know are introduced, as well as the instruments that can be used to measure them. Particular focus is given to the beam parameters of interest at the Front End Test Stand, the instruments that will be used to measure them and to devices capable of measuring the transverse distribution of the beam. The benefits of non-invasive instruments, such as laser-based beam diagnostics, are introduced before the principles behind laser-based beam diagnostics for  $H^$ beams are described in Chapter 4.

The design of the Front End Test Stand laser-based beam profile monitor is described in detail in Chapter 5. Two algorithms that could be used to computationally reconstruct the correlated 2D profile from a series of projections measured by the device are then described and compared in Chapter 6.

Commissioning results from the Front End Test Stand ion source and laserbased beam profile monitor are presented, alongside recommendations for further development, in Chapter 7. Finally, conclusions are made in Chapter 8.

### Chapter 1

# High-Power Proton Accelerators

High-power proton accelerators (HPPAs) are broadly defined as proton accelerators with average beam powers in the megawatt range and typically have beam energies of several giga-electron-volts (GeV). They are now becoming technologically feasible and there are many applications foreseen (see, for example, those listed in [1, 2]). In this chapter, two potential applications—neutrino sources and neutron sources—and two different implementations—the full-energy linear accelerator (linac) and an accelerating ring to take the beam to its final energy—of high-power proton accelerators are discussed. Facilities that require the beam to have a high repetition rate (of order kHz), such as an acceleratordriven sub-critical reactor, are not considered here.

#### 1.1 Applications of HPPAs

#### 1.1.1 Neutrino Physics

Neutrino flavour changes have been observed by the Super-Kamiokande [3], Sudbury Neutrino Observatory [4] and KamLAND [5] experiments, amongst others. These observations are best explained by a mixing between the neutrino flavour eigenstates ( $\nu_e$ ,  $\nu_\mu \& \nu_\tau$ ) and the mass eigenstates ( $\nu_1$ ,  $\nu_2 \& \nu_3$ ), which leads to the possibility of oscillations between the flavour eigenstates. This mixing can be parameterised by the Maki-Nakagawa-Sakata matrix,  $\mathrm{U}_{\mathrm{MNS}}$ :

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{U_{\rm MNS}} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{U_{\rm MNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$(1.1)$$

where  $s_{ij} = \sin \theta_{ij}$ ,  $c_{ij} = \cos \theta_{ij}$  and  $\delta$  is a CP-violating phase. The mass differences between the mass eigenstates are  $\Delta m_{21}$  and  $\Delta m_{31}$ . The current best fit values of the mixing parameters are summarised in Table 1.1.

Parameter	Value
$\Delta m_{21}^2$	$8.1^{+1.0}_{-0.8}\times 10^{-5}~{\rm eV^2}$
$\Delta m^2_{31}$	$2.2^{+1.1}_{-0.8} \times 10^{-3} \text{ eV}^2$
$\sin^2 \theta_{12}$	$0.3\substack{+0.08\\-0.07}$
$\sin^2 \theta_{23}$	$0.5_{-0.16}^{+0.18}$
$\sin^2 \theta_{13}$	$0^{+0.47}_{-0}$
δ	$0^{+\pi}_{-\pi}$

TABLE 1.1: The current best fit to the neutrino mixing parameters [6].

There is a desire in the neutrino physics community to further study the mixing parameters. Of particular interest is the currently unmeasured mixing parameter  $\theta_{13}$ . If this is non-zero, it is possible that there is CP violation in the neutrino sector (parameterised by  $\delta$  in the mixing matrix) that may contribute to the observed matter-antimatter asymmetry in the universe. Currently there are two reactor-based experiments, Double Chooz [7] and Daya Bay [8], being constructed and the accelerator-based T2K experiment [9] being commissioned that hope to measure  $\theta_{13}$ .

To date, the majority of neutrino experiments have relied upon incidental sources of neutrinos (for example, neutrinos produced in the sun; in the atmosphere by cosmic rays; or as a by-product of nuclear fission in nuclear power stations) but the next generation of high-precision neutrino experiments will be acceleratorbased. This is because an accelerator-based source allows the production parameters to be controlled, unlike incidental sources, which helps to reduce the uncertainties in the measurement of neutrino mixing parameters. The goals of a next generation neutrino experiment are the first measurements of  $\delta$  and  $\theta_{13}$ , if they have not already been measured, along with precision measurements of the currently known parameters. In the remainder of this section, three possible approaches to an accelerator capable of producing the required neutrino beam are discussed, all of which would require a high-power proton accelerator (also know as a *proton driver*) as the first part of the accelerator complex.

#### 1.1.1.1 Neutrino Superbeams

The current generation of accelerator-based neutrino sources, such as the T2K neutrino beamline at J-PARC or the NuMI beamline at FNAL (which is shown schematically in Figure 1.1), produce a tertiary neutrino beam from the decay of pions that are produced by a proton beam hitting a target:

 $p + A \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$  (+ charge conjugate process)

The pions produced have a large divergence and so have to be captured by a magnetic horn before entering the decay volume. The magnetic horn only captures one pion charge and so also defines whether the subsequent beam is a neutrino or anti-neutrino beam.

If evidence for  $\theta_{13}$  is observed by the current generation of neutrino oscillation experiments then an upgrade of a current accelerator-based neutrino experiment (such as T2K) or the construction of a new conventional neutrino source (such as the Super Proton Linac—SPL—superbeam project at CERN) would prove the most cost-effective way of making precision measurements of the neutrino parameters.

For a superbeam, the number of neutrinos produced is proportional to the proton beam power. This means there are less constraints on the proton beam energy provided that enough beam current can be delivered to produce the beam power required [11]. Additionally, the only requirement on the time structure of the proton beam is the ability to suitably reject the background signal from atmospheric neutrinos [11, 12]. Consequently there is a variety of solutions that could satisfy the proton driver requirements. As an example of a superbeam proton driver, a summary of the SPL parameters is presented in Table 1.2.



FIGURE 1.1: The NuMI beamline [10].

Parameter	Value
Average beam power	$5 \mathrm{MW}$
Beam energy	$3.5~{\rm GeV}$
Pulse duration	$0.72~\mathrm{ms}$
Protons per pulse	$1.78\times 10^{15}$
Repetition rate	$50~\mathrm{Hz}$

TABLE 1.2: A summary of the Super Proton Linac parameters [13].

Measurements of the neutrino oscillation parameters at a superbeam would be performed by counting the number of  $\nu_{\mu}$  that disappear from or the number of  $\nu_e$  or  $\nu_{\tau}$  that appear in the neutrino beam. For example, the appearance of  $\nu_e$  in the  $\nu_{\mu}$  beam would be used to measure  $\theta_{13}$  and is the most important channel for a superbeam. A measurement of a second channel—the  $\nu_{\mu}$  disappearance channel—would help resolve some of the degeneracies present in the measurement of  $\theta_{13}$  using the  $\nu_{\mu} \rightarrow \nu_e$  channel [14]. When performing these measurements, contamination of the neutrino beam from  $\pi \rightarrow e + \nu_e$  and kaon decays has to be considered.

#### 1.1.1.2 The Beta-Beam

The beta-beam concept [15] is based on the production of a tertiary beam of electron-type neutrinos from the beta decay of radioactive ions that have been accelerated to a high energy. The beta-beam is under development as part of the EUROnu Design Study [16], which is investigating using <sup>6</sup>He and <sup>18</sup>Ne ions to produce  $\bar{\nu}_e$  and  $\nu_e$  respectively<sup>\*</sup>:

$$p + A \to {}^{6}\text{He}^{2+} \to {}^{6}\text{Li}^{3+} + e^{-} + \bar{\nu}_{e}$$
  
 $p + A \to {}^{18}\text{Ne}^{10+} \to {}^{18}\text{F}^{9+} + e^{+} + \nu_{e}.$ 

The current proposal for the accelerator complex would make use of as many existing and planned facilities at CERN as possible (see Figure 1.2). The SPL would be used to drive an Isotope Separator On-Line (ISOL) target to produce the radioactive atoms required. The atoms would then enter an electron cyclotron resonance ion source, where they would be ionised [18]. From here, the isotopes produced would be accelerated to the energy required by a new linac, a new rapid-cycling synchrotron (RCS), the proton synchrotron (PS) and super proton synchrotron (SPS), before injection into a decay ring.

<sup>\*</sup>Recently, the possibility of using <sup>8</sup>B and <sup>8</sup>Li has begun to be investigated [17].



FIGURE 1.2: A schematic illustration of a beta-beam at CERN [19].

As with the superbeam and the neutrino factory, the target is one of the most challenging areas of development for the beta-beam. The current favoured solution for the <sup>6</sup>He is production from a BeO ISOL target: a 200 kW proton beam would produce neutrons from a spallation target which would then hit the BeO ISOL target, located concentrically around the spallation target, to produce the <sup>6</sup>He. This arrangement should be able to produce the  $2 \times 10^{13}$  <sup>6</sup>He per second required [17]. The ISOL method of radioactive ion beam production is favoured to the alternative in-flight method because the quality of the beam produced (in terms of energy spread and emittance) is significantly better [20]. For the <sup>14</sup>Ne, the technology currently under development is a direct production on a thin MgO target mounted on a water-cooled beam dump. It will be challenging to produce the  $2 \times 10^{13}$  <sup>14</sup>Ne per second required with this technology. Alternative target technologies, based on a production ring, are under development [17, 19].

One advantage of a beta-beam is that a mono-flavour beam of neutrinos is produced, which reduces the background when searching for flavour-changing processes. The channels of interest for the beta-beam are the  $\nu_e \rightarrow \nu_{\mu}$  appearance measurement and the  $\nu_e$  disappearance measurement. For the beta-beam configurations currently under consideration, the  $\nu_{\tau}$  appearance channel is not accessible [14].

Additionally, as the CERN beta-beam proposal would not require all of the protons delivered by the SPL, there is an interesting possibility of combining a beta-beam and superbeam experiment [14, 21] which would give an improved physics performance, compared to just having the beta-beam or a superbeam.



FIGURE 1.3: The baseline neutrino factory design [23].

#### 1.1.1.3 The Neutrino Factory

The neutrino factory (shown schematically in Figure 1.3) is the most competitive proposed future neutrino facility over a large range of the parameter space [14] and is under active development [22]. In contrast to the current generation of accelerator-based neutrino sources, the neutrino factory would utilise the decay of muons produced from pion decay as its source of neutrinos (making the neutrino beam a quaternary beam):

$$p + A \to \pi^+ \to \mu^+ + \nu_\mu$$
  
 $\downarrow e^+ + \nu_e + \bar{\nu}_\mu$  (+ charge conjugate process)

To be able to perform the desired physics measurements at the neutrino factory,  $\mathcal{O}(10^{21})$  muon decays are required per year [14]. This requires a high-power proton accelerator to produce a large number of pions that will subsequently decay into muons. The proton driver design depends on where the neutrino factory would be sited but the requirements for it, as laid down by the 2006 "International Scoping Study of a future Neutrino Factory and super-beam facility" (ISS) [11, 14], are common. They are outlined in Table 1.3.

Following the proton driver, the baseline target is a liquid mercury one, after the success of the proof-of-principle MERIT experiment at CERN [24]. Solid targets [25] and powder-jet targets [26] are under investigation as possible alternatives. The target will be in a high-field solenoid to capture the pions

Parameter	Value
Average beam power	$4 \mathrm{MW}$
Beam energy	$10{\pm}5~{\rm GeV}$
Number of bunches per pulse	$2\pm1$
Bunch duration	$2\pm1$ ns
Repetition rate	$50~\mathrm{Hz}$

TABLE 1.3: The neutrino factory proton driver requirements [11].

produced. A 100 m decay section then allows the pions to decay to muons<sup>†</sup>, which are then bunched and phase-rotated to match their longitudinal phase space distribution to the longitudinal acceptance of the subsequent accelerating structures. A ionisation cooling channel will then be used to reduce the transverse emittance of the muon beam to reduce the number of muons lost downstream. The muons would then be rapidly accelerated by a series of recirculating linacs and fixed-field alternating gradient (FFAG) rings to an energy of 25 GeV<sup>‡</sup>. The muons will then be transferred to two decay rings, one directed at a detector at a baseline of ~4,000 km and the other at a detector at a baseline of ~7,500 km. Two detectors are required as the optimal baseline is different for different physics (the shorter baseline is more sensitive to measurements of  $\delta$  and the longer baseline is more sensitive to measurements of the mixing parameters to be removed, although this can also be done by considering different oscillation channels [14].

There are many oscillation channels that could be explored with the neutrino factory (see Table 1.4). The focus, however, would be on the so-called 'golden' channel,  $\nu_e \rightarrow \nu_{\mu}$  (and the charge-conjugate oscillation,  $\bar{\nu}_e \rightarrow \bar{\nu}_{\mu}$ ) which provides excellent sensitivity to  $\theta_{13}$  and  $\delta$  [14]. This channel's signal would be a muon with the opposite charge to it's parent muon which, with a magnetised detector capable of identifying the charge of a particle, gives a good background rejection of the large same-sign background.

In addition to being an excellent source of neutrinos, the neutrino factory requires similar components to the muon collider [28]: a proposed, compact, multi-TeV lepton collider which is an alternative to an  $e^+e^-$  linear collider. Although a muon collider would require considerably more cooling than the

<sup>&</sup>lt;sup>†</sup>The mean energy of the pions that come from the target is 130 MeV [24], which corresponds to  $\gamma = 1.93$ . The pion's mean decay length is  $c\tau = 7.80$  m [27] so all the pions should have decayed in a 100 m channel ( $c\gamma\tau = 15.6$  m).

<sup>&</sup>lt;sup>‡</sup>Ionisation cooling (as opposed to more conventional methods of cooling) and rapid acceleration are required because of the muon's short lifetime of  $2.2\mu$ s.

Channel	Type of measurement
$\nu_e \rightarrow \nu_e$	disappearance
$\nu_e  ightarrow  u_\mu$	appearance
$\nu_e \rightarrow \nu_\tau$	appearance
$\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$	appearance
$\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{\mu}$	disappearance
$\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{\tau}$	appearance

TABLE 1.4: The oscillation channels at the neutrino factory. The channels listed here are for the positive muon decay; for all cases, the charge conjugate process would also be considered [14].

neutrino factory and would have a different acceleration scheme for the muons, the neutrino factory can be seen as a stepping stone towards a muon collider.

#### 1.1.1.4 Comparison of Proposed Facilities

One of the purposes of the ISS was to compare the performance of the different proposed facilities with regard to their potential to measure the currently unmeasured neutrino mixing parameters. Broadly speaking, the neutrino factory has sensitivity to the largest area of parameter space, with the superbeam and beta-beam being preferred for certain regions of parameter space. The sensitivities to  $\theta_{13}$  and  $\delta$  for the different facilities are shown in Figure 1.4.

From Figure 1.4a, it can be seen that the three types of facility—superbeam, beta-beam and neutrino factory—have comparable sensitivities to  $\theta_{13}$  for large values of  $\theta_{13}$  (sin<sup>2</sup>  $2\theta_{13} \gtrsim 10^{-3}$ ); for intermediate values of  $\theta_{13}$  ( $10^{-4} \lesssim \sin^2 2\theta_{13} \lesssim 10^{-3}$ ) the beta-beam and neutrino factory outperform the superbeam; and for small values of  $\theta_{13}$  (sin<sup>2</sup>  $\theta_{13} \lesssim 10^{-4}$ ) the neutrino factory is the only facility with sensitivity. From Figure 1.4b it can be seen that, for the values of  $\sin^2 2\theta_{13}$ considered, no facility is able to cover all of the possible values of  $\delta$ . The superbeam proposals have some discovery reach for  $\delta$  down to  $\sin^2 2\theta_{13} \sim 10^{-3}$ ; the beta-beam has reach down to  $\sin^2 2\theta_{13} \sim 4 \times 10^{-4}$ ; and the neutrino factory to  $\sin^2 2\theta_{13} \sim 1.5 \times 10^{-5}$ . For large  $\theta_{13}$  (sin<sup>2</sup>  $2\theta_{13} \gtrsim 4 \times 10^{-3}$ ), the beta-beam has a better coverage of the possible values of  $\delta$  than the neutrino factory.



FIGURE 1.4: A comparison of the performance of proposed future neutrino facilities: SPL is the CERN Super Proton Linac superbeam; T2HK is an upgrade of the T2K facility; WBB is a Wide Band Beam, an on-axis superbeam with a large neutrino energy spread; NF is the Neutrino Factory and BB is the Beta-Beam. The area to the right of the coloured bands is the parameter space where (a)  $\sin^2 2\theta_{13} = 0$  and (b)  $\delta = 0, \pi$  can be excluded at a  $3\sigma$  level, as a function of the true values of  $\sin^2 2\theta_{13}$  and  $\delta$ ; the right-hand edges of the coloured bands correspond to conservative setups and the left-hand edges correspond to optimised setups [14].

#### 1.1.2 Neutron Scattering

Neutrons are used to study a vast array of scientific phenomena and to address a wide range of challenges in engineering and material science (see, for example, [29]). As neutrons are not charged, they mainly interact with the nuclei of the sample under consideration<sup>§</sup>. This makes neutron sources a complementary tool to synchrotron light sources, where the photons interact with the electrons in the sample.

Neutrons are an excellent probe of crystalline materials, where the interatomic distances are comparable with the wavelength of a thermal neutron. This can be seen from the following: the de Broglie wavelength of a neutron,  $\lambda$ , is given by

$$\lambda = \frac{h}{m_n v},$$

where h is Plank's constant,  $m_n$  is the mass of the neutron and v is the neutron's velocity. A neutron with a thermal energy of  $k_B T$ , where  $k_B$  is Boltzmann's constant and T is the temperature, will have a velocity of

$$v_T = \sqrt{\frac{2k_BT}{m_n}}$$

and so if T = 300 K, the neutron's wavelength is  $\lambda_T = 3.6 \times 10^{-10}$  m.

Neutrons for scattering experiments are typically produced either as a byproduct of nuclear fission reactions—such as those produced at the Institut Laue-Langevin (ILL) [31]—or from spallation neutron sources—such as those produced at ISIS [32]. Neutrons from reactors are produced in a continuous flux whereas those from spallation sources are typically pulsed. In both cases, the neutrons are produced at an energy that is too high for them to be directly used in experiments (the initial neutron energy is of order MeV, compared to the meV required for scattering experiments [33]). The neutrons are therefore passed through a moderator, from which they emerge in thermal equilibrium with, such that their wavelengths are useful for experimenters.

The velocities of thermalised neutrons are distributed according to the Maxwell-Boltzmann distribution. The flux as a function of wavelength,  $\phi(\lambda)$ , can be derived from this  $\P$  and is proportional to

$$\phi(\lambda) \propto \frac{4n_0}{\sqrt{\pi}} \frac{1}{v_T^3} \left(\frac{h}{m_n}\right)^4 \frac{1}{\lambda^5} \exp\left(-\frac{h^2}{2m_n \lambda^2 k_B T}\right),$$

<sup>&</sup>lt;sup>§</sup>Neutrons can interact with the electrons of a magnetic material; in this case, the interaction is between the electrons and the neutron's magnetic dipole moment [30].

<sup>&</sup>lt;sup>¶</sup>See, for example, [33].



FIGURE 1.5: Thermal neutron flux as a function of neutron wavelength.

where  $n_0$  is the total number of neutrons. (A plot of this distribution is shown in Figure 1.5.) The peak flux is at a wavelength of

$$\lambda_m = \frac{h}{(5m_n k_B T)^{1/2}}$$

An increase in the neutron flux available would enable measurements to be carried out with a better spatial (or temporal) resolution and so is highly desirable [34]. Reactor-based sources are reaching the limit of the fluxes they can provide because of the level of cooling required in the reactor core [34]; the ILL reactor is close to the cooling limit and provides a flux of order 10<sup>15</sup> neutrons/cm<sup>2</sup>/s [33]. The current generation of spallation neutron sources have a similar average flux to reactor-based sources but a higher peak flux, due to their pulsed nature. Spallation sources with peak fluxes a couple of orders of magnitude higher than those currently in operation are technically feasible [34] and are discussed in the next section.

#### 1.1.2.1 Spallation Neutron Sources

Spallation neutron sources operate by accelerating a proton beam to a high energy (typically of order 1 GeV) and impinging the beam onto a high-Z target.

A proton which hits a nucleus will excite it, causing an internal nucleon cascade. High-energy nucleons are then ejected from the nucleus, exciting other nuclei within the target. The excited nuclei then de-excite, with the emission of many lower-energy neutrons (amongst other particles) [33].

ISIS, the UK's Spallation Neutron Source, produces a comparable neutron flux to the ILL reactor with a proton beam power of 160 kW. To produce higher flux accelerator-based sources, accelerators with greater beam powers are required. In the U.S.A., the Spallation Neutron Source (SNS) has been constructed with a design proton beam power of 1.4 MW and is currently operating at 0.52 MW [35]. In Japan, the Japanese Spallation Neutron Source (J-SNS) at J-PARC has also recently been commissioned. It has a design proton beam power of 1 MW [36] and is currently operating with beam powers of  $\sim 20$  kW [37].

ISIS, SNS and J-SNS are 'short-pulse' facilities, where the proton beam's pulse length is compressed in a synchrotron before being directed to the target. In this mode of operation the peak neutron flux is maximised. This time structure also allows time-of-flight techniques to be used to analyse the sample under testing.

Other accelerator-based facilities, such as SINQ at the Paul Scherrer Institute in Switzerland operate in CW mode and produce a constant beam of neutrons. CW sources generally have a larger mean neutron flux than short-pulse facilities but increasing the power of CW accelerator-based sources is challenging as they are based on cyclotrons, for which it is non-trivial to increase the beam current transmitted (and therefore the beam power). Facilities operating in a 'long-pulse' configuration, like the proposed European Spallation Source (ESS), where there is no compressor ring and the protons go directly from a linac to the target, are a way to maximise the total neutron flux to produce a higher power, CW-like source. The ESS has been identified by the European Strategy Forum on Research Infrastructures as a high priority [38]. If constructed, the ESS will be built at Lund in Sweden; it is currently under development [39].

Having described how neutrons can be produced for neutron scattering, some of the techniques that can be used to perform experiments with neutrons are briefly described in the next two sections. A more detailed description can be found in [33].

#### 1.1.2.2 Elastic Neutron Scattering

Elastic neutron scattering occurs when the energy of the incident and scattered neutron are the same; the only change is in the direction of the neutron's wave vector. Elastic neutron scattering experiments measure the differential scattering cross-section,  $d\sigma/d\Omega$ , by counting the number of neutrons (of a given wavelength) that are scattered into the solid angle element  $d\Omega$ . These measurements provide information about the crystal structure of the sample. An alternative way of measuring the diffraction pattern is to vary the wavelength of the neutrons and look at a limited range of the total solid angle. For a pulsed source, the natural spread in the wavelengths of the neutrons can be used with a time-of-flight measurement to make a diffraction measurement.

#### 1.1.2.3 Inelastic Neutron Scattering

Situations where there is energy transferred between the neutron and the sample under test are described as inelastic neutron scattering. Within inelastic neutron scattering, two further classifications can be made: coherent inelastic scattering and incoherent inelastic scattering. Coherent inelastic scattering provides information about the bulk lattice dynamics, whilst incoherent inelastic scattering provides information about the dynamics on an atomic level. Inelastic scattering experiments measure the double differential cross-section,  $d^2\sigma/d\Omega dE_f$ , where  $E_f$  is the final energy of the neutron. To perform this measurement at a pulsed source, a time-of-flight spectrometer is used with either the incident energy,  $E_i$ , or final energy,  $E_f$ , fixed and the other being measured with a segmented detector that can also provide information about the solid angle into which the scattering has taken place.

#### **1.2** Approaches to the construction of HPPAs

Having discussed two applications of high power proton accelerators, the two main approaches to their construction will now be considered. Either a linac or a ring (typically a synchrotron) is used to take the beam to its full energy. For the full-energy linac case, an accumulator ring can be used to compress and intensify the beam. The linac (and accumulator ring) approach is discussed, along with its advantages and disadvantages, in §1.2.1 and the accelerating ring, in §1.2.2. The accumulating and accelerating ring share many of the same advantages and disadvantages. All cases have a requirement for a low-energy front end; this common requirement is described in §1.2.3.

#### 1.2.1 A Full-Energy Linac

Using a linac to take the beam to the full energy is generally a simpler approach than using an accelerating ring as collective effects in the ring, as well as injection in to and extraction from the ring do not need to be considered. Additionally, a proton source instead of an  $H^-$  source can be used. This is

advantageous as proton sources can provide higher currents at higher duty cycles than  $H^-$  sources. Using a proton source is also beneficial as the stripping of an  $H^-$  beam does not need to be considered. Consequently, for facilities that require a long pulse of protons (such as a long-pulse neutron source) the full-energy linac approach is ideal.

However, the amount of longitudinal phase space manipulation that can be performed is limited and consequently the pulse duration, as well as the temporal beam intensity, is largely defined by the ion source performance. If a short pulse or temporally intense beam is required from a full-energy linac pulses with durations of order  $\mu$ s are required for short-pulse neutron sources an accumulator ring is needed (discussed in §1.2.1.1). However, the amount of compression that can be achieved with an accumulator ring is limited by the amount of RF power available; to achieve the ns pulse durations required for the neutrino factory would require an additional compressor ring [14].

#### 1.2.1.1 An Accumulator Ring

Using an accumulator ring requires an  $H^-$  beam to be accelerated so that an intense beam can be accumulated over multiple (up to several hundred) turns by multi-turn charge-exchange injection (illustrated in Figure 1.6). The ring can then be used to compress the beam to deliver a short pulse.

In terms of ring design, this approach is simpler than using an accelerating ring as it only needs to operate at a single energy. Also, for a given final beam energy, the space-charge intensity limit in an accumulator ring will be higher



FIGURE 1.6: An illustration of charge-exchange injection. The circulating protons (shown in black) and  $H^-$  ions (in blue) are bent in opposite directions by a dipole field to occupy the same phase space. The  $H^-$  ions then loose their electrons when they pass through the stripping foil to become protons and join the circulating beam. Any unstripped  $H^-$  ions are deflected by the dipole field after the stripping foil into a beam dump. Partially neutralised  $H^0$  atoms are not deflected by the dipole field and also go into a beam dump. than that in an accelerating ring because of the higher injection energy. This means more beam can be accumulated.

However, any losses that occur at injection are at a higher energy than in the accelerating ring case and so are more likely to lead to component activation. For both the accumulator ring and accelerating ring the lifetime of the stripping foil must be considered, as failure of this during a high power machine cycle could lead to significant activation and delays in the restarting of the machine. Recently, the development of systems to strip the  $H^-$  ions using a laser beam has begun and is a promising avenue of exploration [40, 41].

#### 1.2.2 An Accelerating Ring

This approach consists of a linac that accelerates the  $H^-$  beam to a few hundred MeV before charge-exchange injection into a ring (typically an RCS although FFAGs are popular in some proposed designs). The ring accumulates, bunches and accelerates the beam before it is extracted to the target.

There are some advantages in using an accelerating ring over the linac and accumulator ring. The losses at injection to the ring should be reduced due to the larger cross-section for electron stripping at lower energies and any losses that occur will lead to less activation, because of the lower beam energy. Additionally, if the ring is used to accelerate the beam rather than just accumulate it, the same final beam power can be achieved for a lower beam current. Shorter duration bunches can also be produced. However, because of the lower energy at injection, the beam intensity is more likely to be space-charged limited. There may also be losses as the beam is bunched for acceleration. However, this is also true for a compressed beam in an accumulator ring.

#### **1.2.3** Common Requirements for the Front End

Whichever scheme is used to get the beam to its final energy, a high-quality front end for the accelerator is required. To maximise the beam power on target, the front end should produce a high *brightness*<sup> $\parallel$ </sup> H<sup>-</sup> beam that has low losses. Low losses are required both to increase the amount of beam to target and to reduce the activation of the accelerator (to enable hands-on maintenance, losses need to be below 1 W of beam power per metre [1]). A low *emittance*<sup>\*\*</sup> beam will reduce losses along the linac and in any ring that follows. It is also preferable to bunch the beam longitudinally to minimise losses that occur if the beam is not completely captured in the linac's RF bucket. This bunching is typically

<sup>&</sup>lt;sup>||</sup>Where brightness is defined as current per unit area per unit solid angle [42].

<sup>\*\*</sup>Emittance is a measure of the phase space the beam occupies; see  $\S3.1.2.1$  for a fuller discussion of emittance.

done by an Radio Frequency Quadrupole, which adiabatically bunches the beam before accelerating it.

If an accumulator or accelerating ring is part of the high-power proton accelerator complex, a beam chopper is required. This is because the revolution frequency of the ring will (typically) be lower than the RF frequency of the linac and so some bunches of the macropulse may need to be removed to minimise losses at injection to the ring (again, so that hands-on maintenance can be carried out). This is done with a beam chopper, that uses electric fields to provide a transverse deflection of some bunches onto a beam dump. Beam chopping is done at low energy to reduce the activation of beamline components. The pulse generator used to provide these electric fields need to have a fast rise time such that the field can come on between bunches.

The Front End Test Stand (FETS), under construction at the Rutherford Appleton Laboratory (RAL), aims to demonstrate the key technologies that are required for such HPPA front ends. It is described in detail in the next chapter.

### Chapter 2

### The Front End Test Stand

The Front End Test Stand is under construction at the Rutherford Appleton Laboratory to demonstrate two key components for the front end of the next generation of high-power proton accelerators: a high brightness, high dutycycle H<sup>-</sup> ion source and a 'perfect' beam chopper. In addition to the ion source and chopper it will consist of a three solenoid Low-Energy Beam Transport (LEBT); a 324 MHz Radio Frequency Quadrupole (RFQ); a Medium Energy Beam Transport (MEBT), which will house the chopper; and a comprehensive set of beam diagnostics. The FETS is intended to be flexible enough to operate in a variety of regimes that would meet the requirements of different HPPAs. A schematic of the FETS is shown in Figure 2.1.

In this chapter, the accelerator components that will make up the FETS are described, alongside their statuses at the time of writing.



FIGURE 2.1: A CAD model of the Front End Test Stand [43].

#### 2.1 Ion Source

The Front End Test Stand uses a modified version of the ISIS Penning surface plasma ion source. On ISIS, the ion source regularly delivers a 35 keV, 35 mA, 200  $\mu$ s H<sup>-</sup> beam at a 50 Hz repetition rate for periods of up to 50 days [44].

The desired performance for the FETS is a 65 keV, 60 mA, 2 ms beam at 50 Hz with a reduced emittance of  $0.25\pi$  mmmrad. The FETS ion source is installed and operational. Beam currents of over 60 mA and pulse durations of 1.6 ms at a 3.125 Hz repetition rate have been achieved, with development work ongoing [45]. Some of the results from the commissioning of the FETS ion source are presented in §7.1.

#### 2.1.1 Ion Source Operation

The ion source is shown schematically in Figure 2.2. The timing of the different processes required to produce a plasma and extract an ion beam from the plasma is shown in Figure 2.3.

Elemental caesium, heated in an oven, provides a constant flow of caesium vapour into the ion source through a hole in the anode. To operate the ion source, a burst of hydrogen gas is fed into the discharge region through a peizoelectric valve and an 80 V, 50 A pulse (the *discharge current*) is passed between the anode and the cathode to form a plasma. The Penning field is used to confine the electrons that sustain the discharge pulse. Although the mechanism for the production of the H<sup>-</sup> ions is not completely understood, it is thought that production occurs on the surfaces of the (molybdenum) anode and the cathode, with the caesium serving to lower the work function of the molybdenum and so increase the production rate of H<sup>-</sup> ions [46, 47].

To maximise the amount of beam that can be extracted, the discharge region is extended in the direction perpendicular to the Penning field. As extraction is most efficient when the extraction geometry matches the plasma shape, a slit extraction system is used (the slit is  $10 \times 0.6$  mm). A +17 kV potential is applied to the extract electrode to extract a beam. (Eventually, a 25 kV extract pulse will be used for the FETS to extract a larger current.)

After extraction, a 90° analysing dipole magnet separates the H<sup>-</sup> ions from the other species that are extracted from the plasma. The analysing magnet sits in a cold box, which is held at  $-5^{\circ}$ C and is used to condense any excess caesium from the ion source. After the analysing magnet, a design post-extraction acceleration voltage of 48 kV boosts the energy of the ion beam to 65 keV<sup>\*</sup>.

<sup>\*</sup>At the time of writing, problems with the platform voltage power supply, which provides the post-acceleration voltage, are limiting the final ion beam energy to 40 keV.



(b) The ion source installation, showing the analysing magnet, coldbox and post-acceleration gap.

FIGURE 2.2: The FETS ion source [47].



FIGURE 2.3: The FETS ion source timing.

#### 2.2 LEBT

A three solenoid magnetic LEBT has been developed to match the divergent beam from the ion source into the RFQ. The total length of the LEBT, including drift spaces, is 178 cm. A magnetic LEBT was chosen over an electrostatic one because of concerns that sparking may be induced by the caesiated ion source. Magnetic LEBTs generally also introduce fewer aberrations than electrostatic ones [48]. A three solenoid configuration provides a good level of flexibility in the variety of beams that can be matched from the ion source to the RFQ; this has been demonstrated by simulations [49]. The LEBT solenoids have 320 normally-conducting turns with a maximum field of 0.4 T and incorporate Lambertson dipoles for beam steering. A Faraday cup is incorporated in the large drift vessel between the second and third solenoids. A linear translator, driven by compressed air, is used to withdraw the Faraday cup from the path of the beam to allow the beam to continue down the beamline. If the compressed air supply is cut off, the Faraday cup moves into the beampath. A toroid is also mounted in this vessel to measure the beam current when the Faraday cup is in its withdrawn position.

The LEBT components are complete and the LEBT is currently being installed; a photograph of it is shown in Figure 2.4.


FIGURE 2.4: The FETS LEBT, during installation. The first two solenoids and the drift vessel can be seen; the final solenoid had not been installed when this picture was taken.

## 2.3 RFQ

A four metre, four-vane RFQ that will operate at 324 MHz is being developed for the FETS [50]. This will adiabatically bunch the ion beam into a series of micropulses within the continuous 2 ms macropulse and then accelerate it from 65 keV to 3 MeV, whilst keeping the beam focussed. The focussing is done by the electric quadrupole field that is set up between the vanes (see Figure 2.5). The polarity of the electric quadrupole changes with the polarity of the RF so that the beam is focussed in both x and y. The bunching and acceleration is done by modulations on the vanes, which introduce a longitudinal component to the field (see Figure 2.6).

An RFQ was chosen to be the accelerating structure for the FETS because, for low beam energies, it is a very efficient transport channel as it can both focus and accelerate the beam. For higher energies, it is not so effective as the electric field required to keep the beam focussed becomes impractically large, whereas magnetic quadrupoles benefit from an enhancement in the focussing force they produce from the velocity component of the  $\mathbf{v} \times \mathbf{B}$  term in the Lorentz force law. Additionally, the period of the modulations required on the vanes to continue to accelerate the beam becomes so long that it is no longer a cost effective way of accelerating the beam.



FIGURE 2.5: A transverse cross-section through four RFQ vanes, showing the electric field lines between vanes. As shown, the electric field generated by the RF would focus a negatively charged beam in the x-direction, whist defocussing it in the y-direction. As the polarity of the RF changes, the polarity of the vanes changes, to give focussing in y and defocussing in x. Overall focussing is achieved as the magnitude of the electric field is linearly dependent on  $r = \sqrt{x^2 + y^2}$ .



FIGURE 2.6: A longitudinal cross-section between two adjacent RFQ vanes, showing how the longitudinal component of the electric field is introduced by the vane modulations. As the polarity of the vanes changes, the direction of the z-component of the electric field changes. This means that the period of the vane modulations has to be altered, depending on the RF frequency of the RFQ and the speed of the ion beam, to continually accelerate the beam.



FIGURE 2.7: The FETS RFQ cold model.

#### 2.3.1 RFQ Cold Model

Due to the size and cost of the RFQ, extensive computational simulations have been undertaken to assess its performance before construction begins. To verify the simulations, a 40 cm prototype (known as a cold model, due to the low levels of RF that are used to power it) has been constructed and characterised. A photograph of the cold model is shown in Figure 2.7.

The resonant frequency and Q-value of the cavity were measured and compared to the simulated values. A reasonable agreement was found between the simulated and measured resonant frequencies (319.2  $\pm$  0.1 MHz measured compared to 319.7 MHz simulated) but the measured Q-value was considerably lower than the simulated one (7770  $\pm$  30 measured compared to 9300 simulated) [51]. However, given that experience suggests that the measured Q-value will be at best 80% of the simulated Q-value [52], this is a good result. The electric field flatness along the length of the RFQ was also measured, using a bead-pull system, and is slightly better than simulated flatness (see Figure 2.8); the discrepancy is thought to be due to the simulated RFQ end flanges not completely matching those that were manufactured.

Some tuning mechanisms have also been tested. The trend of the change of resonant frequency with the position of conventional plug tuners agreed with the



FIGURE 2.8: The FETS RFQ cold model's field flatness. The datum at each position is an average of four measurements. The sinusoidal variation in the data is thought to be due to the bead vibrating.

simulations, although there was a discrepancy in the absolute values of about 8 MHz [53]. An alternative type of tuner, which operates by introducing copper in the region near the end of the vane-tips, was also tested. It has been shown that it can be used to reduce the resonant frequency of the cavity [51].

The results from the cold model tests show that the simulation results are in sufficient agreement with the measurements such that the simulation can be trusted. An integrated design method, incorporating design, CAD and electromagnetic modelling is underway for the final design of the FETS RFQ [54].

## 2.4 MEBT

If the FETS were to be incorporated into a larger linac, the Medium Energy Beam Transport line would be used to match the beam from the RFQ into the next accelerating structure (typically, this would be a drift-tube linac). The MEBT consists of quadrupole magnets, re-bunching cavities and the beam chopper (discussed in §2.4.1). The quadrupole magnets are used to keep the beam focussed within the beampipe and to match it to the acceptance of the next component of the linac. The re-bunching cavities maintain the bunches that



FIGURE 2.9: A illustration of one of the options for the FETS MEBT [55].

were formed in the RFQ and prevent them from slowly joining up to reform a continuous macropulse. This re-bunching enables the beam chopper to function and also allows for further acceleration with low losses.

The MEBT optics design is currently being finalised, with three possible schemes being considered [56], one of which is shown in Figure 2.9. When a decision is made on which scheme to use, a full engineering design incorporating vacuum pumps, flanges, diagnostics and other required features will be produced. The construction of a cold model for the re-bunching cavities is also under consideration.

#### 2.4.1 Beam Chopper

One of the goals of the FETS project is to test a beam chopper, which is used to remove a series of micropulses from within the macropulse. This reduces losses at injection into a circular accelerator, which enables hands-on maintenance.

For the FETS, this will be achieved by applying a transverse electric field to deflect some of the micropulses onto a beam dump. To prevent partially chopped micropulses that would be lost on injection, the electric field must rise between two micropulses. As it would be technically very challenging to have a pulse generator with a sub-3 ns switch-on time (the micropulse separation is approximately 3 ns) and a flat-top long enough to remove the number of micropulses required for clean injection (the flat-top would need to be of order  $\mu$ s), a fast-slow two-stage chopping process has been devised. It is illustrated in Figure 2.10.



FIGURE 2.10: An illustration of the two-stage, fast-slow chopping scheme that will be implemented for the FETS [57]. Note that this illustration assumes 200 MHz, rather than 324 MHz, RF.

In this chopping scheme, an AC-coupled, short duration (15 ns) beam chopper with a fast transition time—a few ns—first removes 5 micropulses from the beam, producing a small gap. This then allows a DC-coupled, long duration (0.17–100  $\mu$ s) beam chopper with a slow transition time—about 10 ns—to come on in the gap and remove the remaining micropulses. The fast chopper is then used a second time, to provide a gap for the slower transition time chopper to switch off [58]. In this way, the beam is chopped cleanly (there are no partially chopped micropulses) and there is sufficient separation between micropulses to allow clean injection into a circular accelerator. Transverse electric fields in the fast and slow choppers are generated by a slow-wave transmission line and a set of discrete, lumped-element electrodes, respectively. These structures are designed to match the propagation velocity of the electric field to that of the beam micropulses to minimise partial chopping of the micropulses.

Currently, two possible transmission line schemes are being prototyped to enable a decision to be made on which technology performs best [59]. This scheme will then be developed into a full engineering design for the FETS chopper. The fast- and slow-pulse generators broadly meet the requirements of the FETS chopper [58]. The final development work is dependent on which of the transmission line schemes is adopted and will be carried out once a decision has been made on which transmission line to use [59].

In this chapter, the various accelerator components that make up the Front End Test Stand have been described. In the next chapter, the beam diagnostics that will be installed as part of the Front End Test Stand (amongst other accelerators) are discussed, starting with an introduction to the beam parameters that are useful to measure.

# Chapter 3

# **Beam Diagnostics**

Beam diagnostics are essential for the successful operation of a particle accelerator; without them, it would be impossible to commission the machine to maximise the transmission of the beam. In this chapter, some beam parameters that are useful to measure are introduced. A classification scheme that can be used in assessing beam diagnostics is described before instruments that can measure the beam parameters described are discussed. Particular focus is given to the diagnostics that will be used on the FETS and to those capable of determining the transverse motion of the beam.

# 3.1 Beam Parameters

#### 3.1.1 Beam Current

The beam current is a very important parameter as it defines, in part, luminosity for collider experiments or production rates for fixed-target experiments. It is also important to monitor as an indicator of beam loss. For example, if the beam current is monitored before and after an accelerator component, losses within that component can be measured and, with the help of other diagnostic measurements, the accelerator can be reconfigured to minimise these losses.

### 3.1.2 Beam Coordinates

The distribution of particles in a beam can be specified by a ensemble of coordinates in a six-dimensional phase space,  $\Gamma(x, x', y, y', s, p)$  where x and y are the horizontal and vertical displacements of a given particle from the path of the *reference particle*<sup>\*</sup> in the plane perpendicular to the direction of travel of

<sup>\*</sup>The reference particle is the particle that travels along the ideal path through the accelerator



FIGURE 3.1: A diagram illustrating the transverse coordinates used to define the distribution of particles within a beam. The gradient of the arrow in the x-s plane is x'; the gradient of the arrow in the y-s plane is y'.

the beam; x' and y' are the divergences of the beam in x and y, given by

$$x' = \frac{dx}{ds} \quad \& \quad y' = \frac{dy}{ds},$$

where s is the position along the accelerator (see Figure 3.1 for a diagram showing these parameters); and p is the momentum of the particle. An alternative convention for describing the longitudinal coordinates of the beam is to use the pair of coordinates ( $\phi$ ,  $\delta p$ ), where  $\phi$  is the phase of the particle relative to the RF that is being used to accelerate the particle and  $\delta p$  is the difference between the momentum of the particle in question and that of the reference particle.

#### 3.1.2.1 Phase Space and Emittance

The distribution of the particles within the full six-dimensional phase space, along with the beamline components, fully define the beam transport (if collective effects are not considered). As such, measurements of the phase space occupied by the beam allow the acceptance required by new beamline components to be defined or can predict the transmission of the beam through existing components.

Although the six-dimensional phase space needs to be considered for a full understanding of the beam dynamics, in many cases the subset of coordinates (x, y, x', y') is sufficient to describe the transverse dynamics of the beam. As such, an understanding of the beam's distribution in real (x-y) and phase (x-x') and y-y' space can provide a large amount of useful information about the beam.

#### Transverse Emittance

The emittance is a way of quantifying the amount of phase space occupied by a beam. Typically, the transverse (in x-x' and y-y' space) and longitudinal (in s-p or  $\phi$ - $\delta p$  space) emittances are considered separately. Here, just the transverse emittance will be discussed.

There are many ways to measure the transverse emittance; the normalised root mean square (rms) emittance is one that is often used. The rms emittance in the *x*-plane is defined as

$$\varepsilon_{rms,x} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2},$$

with a similar definition in the y-plane and the normalised rms emittance is given by

$$\varepsilon_{Nrms} = \beta \gamma \varepsilon_{rms}$$

where  $\beta$  is the reference particle's speed divided by the speed of light,

$$\beta = \frac{v}{c}$$

and  $\gamma$  is

$$\gamma = \frac{1}{\sqrt{1 - \beta^2}}.$$

The normalised rms emittance is used to ensure that the emittance is constant as the beam is accelerated. If the unnormalized rms emittance is used, the divergence angle goes down as the beam is accelerated and consequently the emittance measured decreases.

Typically, a region in phase space (a *phase space cell*) is considered instead of individual particles as it is not possible to measure each particle's position and divergence. Consequently,  $\langle x^2 \rangle$ ,  $\langle x'^2 \rangle$  and  $\langle xx' \rangle$  are defined as

$$\langle x^2 \rangle = \frac{\sum_i \rho_i x_i^2}{\sum_i \rho_i} \quad \langle x'^2 \rangle = \frac{\sum_i \rho_i x_i'^2}{\sum_i \rho_i} \quad \langle xx' \rangle = \frac{\sum_i \rho_i x_i x_i'}{\sum_i \rho_i}$$

where  $x_i$  is the central position of the *i*th phase space cell,  $x'_i$  is the central angle of the *i*th phase space cell and  $\rho_i$  is the particle density in the *i*th phase space cell.

#### 3.1.2.2 Real Space

The particles' distribution in real (x-y) space can provide information about the charge density of the beam which, in turn, can give insights into space charge effects and the beam's self-field. This information is particularly useful in low energy regimes, such as those encountered at the Front End Test Stand, as it is here that the influence of these effects is largest. Knowledge of the beam halo can also be gained from the beam profile, which is useful because it will give an estimate of the beam losses—as most losses come from the halo—and also help to identify operating conditions in which halo formation is minimal. Additionally, and very simply, the beam profile provides information about how much, if any, of the beam will collimate on an aperture. Finally, if the beamline is well understood, a series of profiles, measured at locations along the beamline, can be used to reconstruct the phase space occupied by the beam (see, for example, [60]).

#### Profiles and Projections of a Beam

For the purposes of this thesis, a *profile* of a beam is the correlated 2D distribution of the beam in x and y. A *projection* of a beam is the 1D projection of the 2D profile onto a plane. A diagram comparing the two measurements is shown in Figure 3.2.

Whilst more information about the beam can be gained from a profile measurement, it is typically experimentally simpler to measure a projection.



FIGURE 3.2: A profile and a projection of the FETS ion source beam. The data in both these plots has been normalised such that the maximum value is 1.

# 3.2 Classification of Beam Diagnostics

When assessing the performance of different beam diagnostics, it is useful to consider how they interact with the beam to give an indication of instrument lifetime and the effect that they will have on the beam dynamics. In this section, four different classifications of beam diagnostics are introduced; they are summarised in Table 3.1.

Category	Effect on beam	Potential for damage
Destructive	Destroyed	High
Invasive	Medium	Medium
Minimally Invasive	Negligible	None
Non-Invasive	None	None

TABLE 3.1: The different categories of diagnostics.

## 3.2.1 Destructive Diagnostics

Destructive diagnostics are those which destroy the beam in the act of measuring it such that it is no longer able to be further accelerated or used. Whilst this is obviously disadvantageous, this type of instrument typically benefits from being simple to operate with a high data rate, a good signal-to-noise ratio and data that is easy to interpret. The lifetime of destructive diagnostics is often shorter than those in the other classifications, particularly for high-power beams, because of their direct exposure to the beam. Examples of destructive diagnostics include the Faraday cup (see §3.3.1.2) and, for low energy beams, scintillator screens (see §3.3.3.1).

#### 3.2.2 Invasive Diagnostics

Invasive diagnostics are ones which, whilst not fully intercepting the beam, do have some material passing through it. Although the beam can be further accelerated and used, the instrument does influence the beam dynamics. For example, some particles could be lost or could have their paths' altered by multiple scattering within the material. It is also possible that the instrument could be damaged by the beam. Wire scanners (see §3.4.1) are an example of an invasive diagnostic.

#### 3.2.3 Minimally Invasive Diagnostics

Minimally invasive diagnostics are those which do not pass any material through the beam. The laser-based diagnostics described in Chapter 4 are an example of minimally invasive diagnostics. As no part of the instrument is passed through the beam, the instrument can not be damaged by the beam. However, there will still be a small residual effect on the beam dynamics due to, for example, the laser interacting with the beam and photo-detaching electrons from it.

#### 3.2.4 Non-Invasive Diagnostics

Non-invasive diagnostics are those which have no macroscopic effect<sup> $\dagger$ </sup> on the beam and so are highly desirable. Beam current transformers (see §3.3.1.1) and beam position monitors are examples of this class of diagnostic device.

## 3.3 Conventional Beam Diagnostics for the FETS

The beam diagnostics that will be installed in the FETS beamline before the MEBT are shown schematically in Figure 3.3; the MEBT design is still under review and so the diagnostics that will sit in it have not been finalised.



FIGURE 3.3: The diagnostics that will be installed in the FETS beamline. "T" indicates a toroid and "FC" a Faraday cup. The Faraday cup between Solenoid 2 and Solenoid 3 can be moved out of the way of the beam.

In addition to these fixed diagnostics, a movable diagnostics vessel containing a beam toroid, a pepperpot emittance measuring device (which can be used without the pepperpot head to measure the beam's profile) and a pair of slitslit emittance scanners will be used for beam commissioning as the FETS is built up. (It, along with the beamline that was used to obtain the results presented in Chapter 7, is illustrated in Figure 7.1.)

In the remainder of this section the various diagnostic devices that will be used along the FETS beamline are described.

 $<sup>^\</sup>dagger {\rm On}$  a quantum mechanical level, there will always be some effect on the beam when a measurement is made of it.

#### 3.3.1 Current Measurements

Two types of devices will be used to measure the beam current along the FETS beamline: beam current transformers and Faraday cups. Their functionality is described in this section.

#### 3.3.1.1 Beam Current Transformer

A beam current transformer (or beam toroid) consists of a coil of wire wrapped around a high permeability core which, with the beam as a single turn primary winding, acts as a transformer (illustrated in Figure 3.4). The beam current is measured by the signal induced on the coil. The cores used in beam toroids often saturate at relatively low external magnetic fields and so additional shielding can be required. Typically, the signal is connected to a current-to-voltage amplifier and then observed on an oscilloscope. The amplifier will introduce additional features to the pulse shape. For example, if a fast rise time is desirable then the signal will inevitably have some droop to it.



FIGURE 3.4: An illustration of a beam current transformer.

Figure 3.5 shows the response of the toroid mounted after the FETS ion source to a 50 Hz, 100 mA, 1 ms, current pulse through a test wire. The measured signal droop of 1.5% is within the manufacturer's stated droop of 2%.

#### 3.3.1.2 Faraday Cup

The Faraday cup, shown schematically in Figure 3.6, directly measures the beam current by having the beam impinge upon it. To prevent electrons that may be liberated from the surface of the cup when the beam hits it from escaping, which would give an false current reading, a suppression electrode, placed in front of the Faraday cup and held at a negative potential, is incorporated into the cup design. For the FETS, the signal from the Faraday cup is passed through a resistor and the voltage drop across the resistor is observed on an oscilloscope. Platinum resistance thermometers are embedded into the FETS Faraday cups to monitor their temperatures.



FIGURE 3.5: An oscilloscope trace showing the response of the toroid installed after the ion source in the FETS beamline to a test signal. The offset between the two signals was introduced so that they could be distinguished from one another.



FIGURE 3.6: A diagram showing a cut-through of half of the FETS Faraday cup, showing the potential inside the assembly volume due to the bias on the suppression ring, as a percentage of the suppression ring bias. The on-axis potential is approximately 60% of the suppression ring bias.

#### 3.3.2 Transverse Phase Space Measurements

The two instruments that are used as part of the FETS to directly measure the transverse phase space occupied by the beam are discussed in this section.

#### 3.3.2.1 Pepperpot

To complete the simulations of the beam transport through the FETS LEBT, a measurement of the correlated 4D transverse emittance of the ion source beam was required. A pepperpot emittance measurement device was constructed to do this.

The pepperpot head consists of a 100  $\mu$ m sheet of tungsten with a 41 × 41 array of 50  $\mu$ m holes on a 3 mm pitch drilled through it. The tungsten sheet is sandwiched between a 2 mm thick copper block (upstream) and 10 mm thick copper block (downstream) which have the same hole pattern as the tungsten, except that the holes are 2 mm in diameter. Behind the downstream copper block is a quartz scintillator, imaged by a CCD camera. (A detailed description of the FETS pepperpot is given in [61].) The tungsten grid defines the sampling of the ion beam (the x- and y-positions) and the distance drifted away from the position of the holes in the tungsten grid defines the angular offsets (x' and y'). The resolution of the pepperpot is less than can be achieved with the slit-slit emittance scanners but it has the advantage of measuring the correlated 4D transverse emittance.

A schematic of the pepperpot is shown in Figure 3.7 and an example measurement taken with it is shown in Figure 3.8.

#### 3.3.2.2 Slit-Slit Scanners

A pair of slit-slit emittance scanners that are capable of performing high resolution measurements of the uncorrelated x- and y-emittances of the FETS beam are mounted on the movable diagnostics vessel. The first slit, which defines the position component of the measurement, is 250  $\mu$ m wide. This, along with the 1.25  $\mu$ m step-size of the stepper motor, defines the position resolution. The second slit, which defines the angular component of the measurement, is 20 mm downstream of the first slit and 80  $\mu$ m wide. The beamlet that passes through both the slits is captured by a Faraday cup. This signal is then digitised by a computer and read into the emittance scanner software, which is described in detail in [62]. This software is able to show the phase space distributions, calculate the emittances by a variety of methods and display x- and y-projections of the beam (by integrating measurements over x' and y', respectively). An example emittance scan is shown in Figure 3.9.



FIGURE 3.7: A CAD model of the FETS pepperpot. The pepperpot head can be seen at the left-hand-side of the figure (the scintillator is not shown) and the CCD camera, to the right-hand-side. Near the centre of the figure is the mounting flange. The yellow component is a light-tight bellows that reduces the background light observed by the CCD camera. The silver bellows in the foreground is a linear drive mechanism that enables the head to be moved along the beam axis within the vacuum vessel. The pepperpot head can be removed and replaced with an open frame to enable profile measurements to be made [61].



FIGURE 3.8: A measurement from the FETS pepperpot for a 13 kV extract voltage, 35 keV platform voltage beam on the ISIS ion source development rig [61].



FIGURE 3.9: Example slit-slit emittance scans of the FETS beam for 14.5 kV extract voltage and 40 kV platform voltage [63].

#### 3.3.3 Profile Measurements

In addition to the laser profile monitor described in detail later in this thesis, the pepperpot head can be removed from the pepperpot device and the scintillator screen can be used to measure the beam profile. The relative merits of using a scintillator screen for measuring a beam profile are discussed in this section.

#### 3.3.3.1 Scintillator Screens

A scintillator screen, monitored by a CCD camera, is a very simple way of measuring the x-y distribution of any beam that impinges upon it. An example of a measurement made with a scintillator screen is the profile shown in Figure 3.2.

However, the use of scintillators is not ideal for all situations. At low energies particles are stopped in the scintillator, making it a destructive diagnostic technique. Additionally, particles with enough energy to pass through the scintillator may be affected by multiple scattering within the material. Furthermore, for high intensity beams many scintillators are quickly damaged such that the light yield drops below usable levels (see, for example, Figure 3.10) [64].



(a) A ruby scintillator with burnmarks on the pitch of the pepperpot grid.



(b) The aluminium backing of a P46 scintillator that has burnt through.

FIGURE 3.10: FETS pepperpot scintillators that the beam has damaged.

# 3.4 Other Transverse Beam Distribution Diagnostics

Before describing the laser-based profile monitor that is the focus of this thesis, other diagnostics that can measure profiles and projections of an ion beam are considered. How they work, their advantages and their disadvantages are discussed.

#### 3.4.1 Wire Scanners

Wire scanners measure beam projections by passing a thin wire through the beam and measuring the beam intensity at each position of the wire. There are two ways the beam intensity can be measured: either the secondary emission current induced in the wire is measured or a detector is placed downstream of the wire scanner to detect the secondary particles produced. In both cases the signal size is proportional to the density of the beam at the position the wire was in when the signal was produced. By stepping the wire through the beam a projection of the beam can be built up. If a time-resolved measurement of the current induced in the wire or of the secondaries can be made, the longitudinal distribution of the particles within the beam can also be measured.

Wire scanners can be used to make high resolution measurements of beam projections (measurements of  $\mu$ m-sized electron beams have been made; see, for example, [65, 66]) but they do have some limitations: they can only measure projections of the beam (typically just the x- and y-projections are measured, although several projections can be made in one device by using several wires; see, for example [67]); multiple scattering within the wire can affect the beam dynamics; the secondary particles produced can activate accelerator components around the wire scanners (as well as the possibility that the wires themselves become activated); and high intensity beams often damage the wires [68].

#### 3.4.1.1 Wire Grids

Wire grids (also known as harps) are effectively several wire scanners joined together in a single unit and contain an array of wires that allow a projection measurement to be performed on a single bunch. These devices can also contain wires in both the x and y directions to enable both projections to be measured simultaneously. However, these devices suffer from the disadvantage that the resolution is determined by the wire spacing and so is significantly less than that of a wire scanner. The electronics used to measure the secondary emission current also needs to be duplicated for each wire.

#### 3.4.2 Optical Transition Radiation Monitors

Optical Transition Radiation (OTR) is emitted when a charged particle crosses the boundary between two media of different dielectric constants. The light is emitted in a cone of half-angle  $\theta = 1/\gamma$  (see Figure 3.11). To utilise this phenomenon for beam diagnostics, the radiation is imaged by a CCD camera in a similar way to a scintillator screen. However, because of the dependence on  $\gamma$ , it is realistically only useful for relativistic particles. For protons, this means an energy of greater than ~20 GeV [69].



FIGURE 3.11: An illustration of optical transition radiation, with the OTR being emitted from the upstream side of a foil (so-called backwards OTR light). The light is emitted in a cone of opening-angle  $2\theta$ , where  $\theta = 1/\gamma$ .

#### 3.4.3 Ionisation Profile Monitors

Ionisation profile monitors (or residual gas profile monitors) utilise the interaction between the beam and the residual gas in the vacuum vessel to measure a projection of a beam. The beam ionises the residual gas to produce ions and electrons. The ionised particles are then accelerated towards the edge of the vacuum vessel using an electric field and detected using a segmented detector. To obtain a reasonable signal size in a linac, a pressure bump typically needs to be introduced; this is obviously not desirable if it can be avoided [39].

#### 3.4.4 Beam-Induced Fluorescence Monitors

Beam-induced fluorescence occurs when the residual gas molecules (the majority of which are N<sub>2</sub>) are excited by the passing beam. There is a strong fluorescence from nitrogen in the wavelength range 390 nm  $< \lambda < 470$  nm [70], which can be imaged by an image-intensifying CCD camera. An observation of the fluorescence can then be used to measure a projection of the beam, as the amount of fluorescence is proportional to the beam density. For low-energy ion beams in the region immediately after the ion source, care must be taken in interpreting the data as processes that produce photons other than the fluorescence excitation can take place (for example, recombinations or excitations of the ion beam) [70].

## 3.5 Laser-Based Beam Diagnostics

As an alternative to the instruments presented in the previous sections, laserbased beam diagnostics offer an elegant solution to diagnosing beams in a minimally invasive manner. Typically, the laser beam only interacts with a small proportion of the beam and so the vast majority of the ion beam can be used further down the accelerator chain. Additionally, because it is the laser beam that interacts with the ion beam the mechanics of the instrument can not be damaged by the ion beam.

The basic principle behind laser-based beam diagnostics for  $H^-$  beams is described in the next chapter before the design of the FETS laser-based beam profile monitor is discussed in more detail in Chapter 5.

# Chapter 4

# Laser-Based H<sup>-</sup> Beam Diagnostics

In this chapter, laser-based diagnostics for  $H^-$  beams are introduced. In §4.1, the basic principle underpinning the technique is described, along with some of the measurements that can be performed on  $H^-$  beams using laser beams. In §4.2, the formula for the number of electrons that are photo-detached from their parent  $H^-$  ions is derived and discussed.

# 4.1 Laser-Based Beam Diagnostics for H<sup>-</sup> Ions

Laser-based diagnostics for  $H^-$  beams were first used at Los Alamos National Laboratory [71] before being developed by Brookhaven National Laboratory and SNS [72, 73]. They work by using a laser beam to photo-detach the outer electrons from some of the ions in the ion beam. The secondary particles produced (electrons and  $H^0$  atoms) are separated from the remaining  $H^-$  ions using a dipole magnet<sup>\*</sup> and are then used to diagnose the ion beam. To use the electrons for beam diagnosis, a Faraday Cup is used to measure the amount of charge that has been detached<sup>†</sup>; to use the neutrals, a scintillator and a CCD camera are used to image their spatial distribution [74]. The two schemes are shown in Figure 4.1.

The detached electrons are typically used to measure transverse projections of the ion beam. This is done by focussing the laser beam into a narrow beam so that it is smaller than the ion beam and stepping the laser beam across the

<sup>\*</sup>Although sometimes electrostatic deflectors are used; see, for example, [73].

<sup>&</sup>lt;sup>†</sup>If a significant fraction of the beam is neutralised with a short-pulse laser, the electrons can be swept away by a dipole magnet and a notch in the ion beam current can be observed by a toroid; see, for example, [72].



(a) Configuration to detect electrons. The deflection of the  $H^-$  ions by the dipole is negligible.

(b) Configuration to detect the neutralised  $H^0$  atoms. The path of the detached electrons is not shown

ion beam. The number of electrons detached at each position is proportional to the ion beam density integrated along the path of the laser. This allows a projection of the ion beam (onto a plane perpendicular to the path of the laser) to be measured. This is illustrated in Figure 4.2. A profile of a beam can then be reconstructed from several projections computationally. (A description of some of the algorithms that can in principle be used to do this is given in Chapter 6.)

For bunched beams, the detached electrons can also be used to measure the longitudinal emittance (in p- $\delta\phi$  space) by using a fast Faraday Cup and a laser pulse that is shorter than the ion pulse, synchronised to the RF (see [75] for further details). However, this technique has not yet been demonstrated.



FIGURE 4.2: An illustration of how a projection of the beam is built up over several measurements. The ion beam is represented by the circles and the laser by a red arrow. The blue bar represent the measurement made in the current step; the grey bars represent the measurements made in previous steps.

FIGURE 4.1: The principle of laser-based beam diagnostics for  $H^-$  ions. The paths of the different species are indicated by the arrows, with the species that is being used to diagnose the ion beam shown in blue. The dipole magnet is shown in grey.

Whilst the neutralised  $H^0$  atoms could be used to measure the transverse profile, a large magnet capable of deflecting the  $H^-$  ions would need to be incorporated into the beamline. This would have the disadvantage of unnecessarily increasing the beamline length when just a small magnet capable of deflecting the detached electrons is required. Additionally, further magnets would be required to restore the ions to their original path, increasing the cost of the instrument. Consequently, the use of the detached electrons is favoured for measuring the transverse profile.

However, the neutralised  $H^0$  atoms are useful in the measurement of the transverse emittance of the beam [74]. Again, the laser beam is focussed into a narrow beam such that it is smaller than the ion beam. The neutrals produced by the interaction of the laser beam and the ion beam are then imaged by a scintillator screen and a CCD camera. This produces a slit-to-point measurement of the emittance (compared to a slit-to-slit measurement, as obtained by a slit-slit emittance scanner or a point-to-point measurement, as obtained by a pepperpot system). The emittance in the plane perpendicular to the direction of the laser beam can then be measured by using the position of the laser beam to define the position (x or y) and the deviation of the particles from position of the laser beam, as observed on the scintillator screen, to define the divergences (x' or y'). To obtain the other emittance plane, the laser beam can be rotated through 90° and the process repeated. However, this can prove difficult due to the need to manipulate the laser beam's path between the pole pieces of the dipole magnet. An alternative solution is to use the extra information that comes from the slit-to-point nature of the measurement: by moving the scintillator screen in the z-direction, the emittance in the other plane can be reconstructed using this additional information [76].

# 4.2 Photo-Detached Electron Production Rates

There are three factors that need to be considered when estimating the number of electrons produced from photo-detachment: the number of particles within the ion beam pulse; the fraction of the ion beam that the laser passes through; and the number of electrons that will be photo-detached within that volume. These three aspects are considered in turn in this section before being combined to give a formula for the electron yield in §4.2.4. Factors that need to be taken into consideration for relativistic ion beams are discussed in §4.2.5. The parameters that are introduced in this section are to calculate the photo-detached electron production rate are illustrated in Figure 4.3.



FIGURE 4.3: The parameters used to calculate the electron yield in §4.2. The blue cylinder represents the ion beam; the red cuboid, the interaction volume.

#### 4.2.1 The Number of Ions per Pulse

The initial number of H<sup>-</sup> ions per pulse,  $N_0$ , is simply a function of the beam current, I, and the duration of the ion pulse,  $\tau_{\text{ion}}$ ,

$$N_0 = \frac{I\tau_{\rm ion}}{e}.\tag{4.1}$$

## 4.2.2 The Interaction Volume

There are two components of the interaction volume that need to be considered: the longitudinal fraction of the ion beam that the laser beam intercepts,  $f_{\text{long}}$ , and the transverse fraction of the ion beam that the laser intercepts,  $f_{\text{trans}}$ .

#### 4.2.2.1 The Longitudinal Fraction

For a pulsed laser, where the laser's pulse duration,  $\tau_{\text{laser}}$ , is shorter than that of the ion pulse,  $\tau_{\text{ion}}$ ,  $f_{\text{long}}$  is given by the ratio of the two durations,

$$f_{\rm long} = \frac{\tau_{\rm laser}}{\tau_{\rm ion}}.$$
 (4.2)

Note that this assumes that the longitudinal ion beam density is homogeneous. For a laser that has a pulse duration longer than that of the ion beam,  $f_{\text{long}} = 1$ .

#### 4.2.2.2 The Transverse Fraction

To estimate the transverse fraction of the ion beam that the laser beam intercepts, the ion beam is assumed to be homogeneous and circular. In practice, these assumptions may not be true but they are valid in making an estimate the electron yield. Given them, the transverse fraction of the ion beam that the laser beam intercepts is

$$f_{\rm trans} = \frac{4 \, r_{\rm laser} \, r_{\rm ion}}{\pi r_{\rm ion}^2},\tag{4.3}$$

where  $r_{\text{laser}}$  is the radius of the laser beam and  $r_{\text{ion}}$  is the radius of the ion beam. For a laser beam that has a Gaussian beam profile, the  $1/e^2$  radius is often chosen for  $r_{\text{laser}}$ , as 95% of the beam power is contained within this radius.

#### 4.2.3 The Photo-Detachment Neutralisation Fraction

The rate of loss of H<sup>-</sup> ions due to photo-neutralisation, in the volume in which the laser intercepts the ion beam, is given by

$$\frac{\mathrm{d}n}{\mathrm{d}t} = -\sigma(\lambda)\phi n,\tag{4.4}$$

where n is the number of H<sup>-</sup> ions, t is time,  $\sigma(\lambda)$  is the photo-detachment cross-section (which is a function of the photon's wavelength,  $\lambda$ , and is shown in Figure 4.4) and  $\phi$  is the photon flux. Equation 4.4 can be integrated to give

=

$$\int_{N_0}^{N} \frac{\mathrm{d}n}{n} = \int_{0}^{t_{\mathrm{int}}} -\sigma(\lambda)\phi \,\mathrm{d}t$$
  

$$\Rightarrow \left[\ln(n)\right]_{N_0}^{N} = \left[-\sigma(\lambda)\phi t\right]_{0}^{t_{\mathrm{int}}}$$
  

$$\Rightarrow \ln \frac{N}{N_0} = -\sigma(\lambda)\phi \,t_{\mathrm{int}}$$
  

$$\Rightarrow \frac{N}{N_0} = \exp\left(-\sigma(\lambda)\phi \,t_{\mathrm{int}}\right), \qquad (4.5)$$

where N is the number of  $H^-$  ions after the interaction of the ion beam with the laser and  $t_{int}$  is the interaction time of the laser and the ion beam.

Equation 4.5 can be used to write  $f_{\text{neut}}$ , the fraction of the H<sup>-</sup> ions that are neutralised in the volume where the laser intercepts the ion beam,

$$f_{\text{neut}} = \frac{N_0 - N}{N_0}$$
$$= 1 - \exp\left(-\sigma(\lambda)\phi t_{\text{int}}\right).$$



FIGURE 4.4: The cross section for the process  $H^- + \gamma \rightarrow H^0 + e^-$ , as calculated by Broad & Reinhardt [77] and Ajmera & Chung [78]. There are some resonances at higher photon energies (~ 12 eV) that are not shown.

The photon flux,  $\phi$ , can be written as a function of the laser's parameters,

$$\phi = \frac{\lambda}{hc} \frac{E_{\text{laser}}}{\tau_{\text{laser}} \pi r_{\text{laser}}^2},\tag{4.6}$$

where h is Planck's constant, c is the speed of light,  $E_{\text{laser}}$  is the energy in the laser pulse and  $\tau_{\text{laser}}$  is the duration of the laser pulse. For a CW laser,  $E/\tau_{\text{laser}}$  can be replaced by the laser's power, P. Using Equation 4.6, the neutralisation fraction can be written as

$$f_{\rm neut} = 1 - \exp\left[-\sigma(\lambda)\frac{\lambda}{hc}\frac{E_{\rm laser}}{\tau_{\rm laser}\pi r_{\rm laser}^2}t_{\rm int}\right].$$
(4.7)

For a non-relativistic beam, the interaction time is defined by the ion's velocity,  $v_{ion}$ , and the diameter of the laser beam,

$$t_{\rm int} = \frac{2r_{\rm laser}}{v_{\rm ion}}$$
$$= 2r_{\rm laser} \sqrt{\frac{m_{\rm ion}}{2E_{\rm ion}}},$$
(4.8)

where  $E_{ion}$  is the ions' kinetic energy.

Combining Equations 4.7 and 4.8 gives

$$f_{\rm neut} = 1 - \exp\left[-\sigma(\lambda)\frac{\lambda}{hc}\frac{E_{\rm laser}}{\tau_{\rm laser}\pi r_{\rm laser}^2} 2r_{\rm laser}\sqrt{\frac{m_{\rm ion}}{2E_{\rm ion}}}\right].$$
 (4.9)

#### 4.2.4 Electron Yield

Combining Equations 4.1, 4.2, 4.3, 4.9, gives an estimate of the number of electrons that will be produced,  $N_e$ ,

$$N_{e} = N_{0} f_{\text{long}} f_{\text{trans}} f_{\text{neut}}$$

$$= \frac{I\tau_{\text{ion}}}{e} \frac{\tau_{\text{laser}} f_{\text{ron}}}{\tau_{\text{ion}}} \frac{4r_{\text{laser}} r_{\text{ion}}}{\pi r_{\text{ion}}^{2}} \left[ 1 - \exp\left(-\sigma(\lambda) \frac{\lambda}{hc} \frac{E_{\text{laser}}}{\tau_{\text{laser}} \pi r_{\text{laser}}^{2}} 2r_{\text{laser}} \sqrt{\frac{m_{\text{ion}}}{2E_{\text{ion}}}} \right) \right]$$

$$= \frac{I\tau_{\text{ion}}}{e} \frac{\tau_{\text{laser}}}{\tau_{\text{ion}}} \frac{4r_{\text{laser}}}{\pi r_{\text{ion}}} \left[ 1 - \exp\left(-\sigma(\lambda) \frac{\lambda}{hc} \frac{E_{\text{laser}}}{\tau_{\text{laser}} \pi r_{\text{laser}}} \sqrt{\frac{2m_{\text{ion}}}{E_{\text{ion}}}} \right) \right]. \quad (4.10)$$

This equation is used in §5.1.1 to estimate the electron yield for the FETS laser-based beam profile monitor.

With a relatively long ion beam pulse, as is the case for the FETS laserbased beam profile monitor, it is not necessarily beneficial to have a pulsed laser with a short laser pulse delivering a large peak power, as this does not necessarily maximise the signal size. There are two reasons for this. First, as a large fraction of the beam within the interaction volume is neutralised, there is a diminishing return on the number of electrons that can be photo-detached from the H<sup>-</sup> ions as the energy of the laser pulse increases. Secondly, unless the laser has a high repetition rate, such that it can fire multiple times within one beam pulse, only a small longitudinal fraction of the ion beam is sampled<sup>‡</sup>.

When the ion beam has a micropulse structure (as it would after the RFQ on the FETS, for instance), either a short-pulse, high peak-power laser that can measure individual micropulses or a longer-pulse, lower peak-power laser that would require several micropulses to make a measurement can be used. To be able to measure individual micropulses, a large fraction of the micropulse being measured would have to be neutralised to get a good signal-to-noise ratio. The benefits of being able to measure individual micropulses therefore needs to be weighed against the instrument no longer being minimally invasive.

It can also be seen that for small neutralisation fractions, in the linear regime (where the number of  $H^-$  ions that are neutralised does not significantly reduce the number of  $H^-$  ions that are available to be neutralised),  $N_e$  is independent

 $<sup>^{\</sup>ddagger}$ If the detector and the detector electronics have a sufficiently high time resolution such that the electrons detached by individual laser pulses can be measured separately, these problems can be overcome.

of the laser's radius,

$$\begin{split} N_e &= \frac{I\tau_{\rm ion}}{e} \frac{\tau_{\rm laser}}{\tau_{\rm ion}} \frac{4r_{\rm laser}}{\pi r_{\rm ion}} \left[ 1 - \exp\left(-\sigma(\lambda)\frac{\lambda}{hc}\frac{E_{\rm laser}}{\tau_{\rm laser}\pi r_{\rm laser}}\sqrt{\frac{2m_{\rm ion}}{E_{\rm ion}}}\right) \right] \\ &\approx \frac{I\tau_{\rm ion}}{e} \frac{\tau_{\rm laser}}{\tau_{\rm ion}} \frac{4r_{\rm laser}}{\pi r_{\rm ion}} \times \\ & \left[ 1 - \left(1 - \sigma(\lambda)\frac{\lambda}{hc}\frac{E_{\rm laser}}{\tau_{\rm laser}\pi r_{\rm laser}}\sqrt{\frac{2m_{\rm ion}}{E_{\rm ion}}} + \text{higher order terms} \right) \right] \\ &= \frac{I\tau_{\rm ion}}{e} \frac{\tau_{\rm laser}}{\tau_{\rm ion}} \frac{4r_{\rm laser}}{\pi r_{\rm ion}} \sigma(\lambda)\frac{\lambda}{hc}\frac{E_{\rm laser}}{\tau_{\rm laser}\pi r_{\rm laser}}\sqrt{\frac{2m_{\rm ion}}{E_{\rm ion}}} \\ &= \frac{I\tau_{\rm ion}}{e} \frac{\tau_{\rm laser}}{\tau_{\rm ion}} \frac{4}{\pi r_{\rm ion}} \sigma(\lambda)\frac{\lambda}{hc}\frac{E_{\rm laser}}{\tau_{\rm laser}\pi r_{\rm laser}}\sqrt{\frac{2m_{\rm ion}}{E_{\rm ion}}}, \end{split}$$

as would be expected if the number of  $H^-$  ions that are available to neutralise is not significantly decreased over the course of the ion pulse.

#### 4.2.5 Relativistic Considerations

So far, it has been assumed that the ion beam is a low-energy beam (that is, non-relativistic), as it will be for the FETS laser-based beam profile monitor. For relativistic ion beams, extra factors have to be taken into account in the calculation of the neutralisation fraction.

#### 4.2.5.1 Relativistic Correction to the Photon Energy

For relativistic ion beams, the rest frame of the ions and the laboratory are different. Consequently, photons produced at a given energy by a laser in the laboratory rest frame appear at a higher energy in the rest frame of the  $H^-$  ions. If the ions are travelling at a velocity

$$\beta = \frac{v_{\rm ion}}{c},$$

then the energy of a photon in the ions' rest frame is

$$E'_{\gamma} = \gamma E_{\gamma} (1 + \beta \cos \theta_{\text{laser}}) \ [79],$$

where  $\gamma$  is the relativistic  $\gamma$ ,  $E_{\gamma}$  is the energy of the photon in the laboratory rest frame and  $\theta_{\text{laser}}$  is the angle at which the laser intercepts the ion beam (with  $\theta_{\text{laser}} = 0$  corresponds to a head-on collision between the laser beam and the ion beam). The first term corresponds to the increased photon energy due to the increased frequency of the laser light in the ions' rest frame. The second term corresponds to the Doppler shift of the photon's wavelength. The consequence of this increase in photon energy is a change in the effective photo-



FIGURE 4.5: The effective wavelength of a Nd:YAG laser and the corresponding photo-detachment cross sections (shown by the crosses) for a variety of  $H^-$  ion energies.

detachment cross section. Figure 4.5 shows how the wavelength the ions see varies as the energy of the ions increases, for a Nd:YAG laser (which has a fundamental wavelength of 1064 nm) intercepting the ion beam at an angle of  $\theta_{\text{laser}} = 90^{\circ}$ . For laser-based H<sup>-</sup> beam diagnostics for high energy H<sup>-</sup> beams, using an infrared laser is beneficial as, compared to a visible laser, it maintains a larger effective cross section over a wider range of energies.

#### 4.2.5.2 Relativistic Correction to the Interaction Time

In addition to the change in the energy of the photons for relativistic ion beams, which leads to a change in the photo-detachment cross section, corrections to the Newtonian velocity of the ions need to be made in the calculations of the interaction time. Figure 4.6 shows the neutralisation fraction for a variety of ion beam energies, calculated using the Newtonian and relativistic velocities. Because of the asymptotic behaviour of relativistic velocities, the interaction time,  $t_{int}$ , decreases less quickly when calculated relativistically than if calculated classically. This provides an enhancement in the neutralisation fraction for high ion beam energies.

The interaction time is also affected by a contraction in the spatial length



FIGURE 4.6: The variation in the neutralisation fraction as the ion beam energy increases, calculated using both the Newtonian and relativistic ion velocities, with and without the effect of the changing photo-detachment cross sections. The laser parameters used in the making of this figure were a 1 mm wide, 20 ns, 50 mJ pulse, after [72].

of the laser beam; however, the photon flux is increased by the same factor and so compensates for this in the calculation of the neutralisation fraction.

#### 4.2.5.3 Relativistic Correction to the Interception Angle

If the duration of the laser pulse is less than that of the ion beam (as it would have to be, for example, to make longitudinal emittance measurements using photo-detachment techniques), the angle at which the laser passes through the ion beam also has to have relativistic corrections applied to it. (This is necessary as, to continue with the example of the longitudinal emittance measurement, if this angle is incorrect the boundaries of the slice of the beam that the laser neutralises will not be at constant times into the ion beam and so the data will be difficult to interpret). For a given angle  $\theta'_{\text{laser}}$  in the ion rest frame, the angle in the laboratory rest frame is given by

$$\theta_{\text{laser}} = \cos^{-1} \left( \frac{-\beta \gamma + \gamma \cos \theta'_{\text{laser}}}{\gamma - \beta \gamma \cos \theta'_{\text{laser}}} \right)$$
[79].

If the duration of the laser pulse is longer than that of the ion beam, this does not need to be taken into consideration as  $f_{\text{long}} = 1$  in this case.

In this chapter, the basic principles behind laser-based beam diagnostics for  $H^-$  ions have been introduced and some design considerations for any instrument built to exploit this diagnostic technique have been given. In the next chapter, the design and implementation of the FETS laserwire system are described in detail.

# Chapter 5

# Laser-based Beam Profile Monitor Design

This chapter describes the design of the Front End Test Stand's laser-based beam profile monitor (which will also be referred to as the FETS *laserwire*). The instrument is built in and around the differential pumping vessel located between the ion source and the LEBT. Although this is not the ideal location to build a laserwire instrument—as this location places some constraints on its design because the vessel has a limited beamline length and there is also a high residual gas pressure because of the proximity to the ion source—it was the only one available, given the timescales of the FETS and laserwire projects.

The design and characterisation of the optical scheme used to detach the electrons from the H<sup>-</sup> ions is described in §5.1. The design of the detector is presented in §5.2. In this section there are also a selection of the results from the extensive simulation work that was done during the detector's design phase, a verification of the magnetostatic simulations performed and details of the efforts made to minimise the background signal from the interaction of the H<sup>-</sup> ions with the residual gas. Finally, the electronics designed to integrate and digitise the photo-detached electron signal are described in §5.3.

# 5.1 The Optical Scheme

#### 5.1.1 The Laser

A diode-pumped, solid state laser built around a Nd:YVO<sub>4</sub> crystal is the basis of the optical system for the FETS laserwire. The laser's output is frequencydoubled from the crystal's fundamental wavelength such that the laser operates at 671 nm (the measured spectrum of the laser is shown in Figure 5.1). At this



FIGURE 5.1: The spectrum of the FETS laserwire laser. The photodetachment cross section and Nd:YAG wavelength are shown for reference.

wavelength the cross section for the photo-detachment process  $H^- + \gamma \rightarrow H^0 + e^$ is  $3.7 \times 10^{-21} \text{ m}^2$ . The laser operates near to the fundamental TEM<sub>00</sub> mode (which means it has a Gaussian beam profile) and has a nominal beam power of 500 mW. For the nominal FETS beam parameters (a 65 keV, 60 mA, 2 ms pulse with  $r_{\text{ion}} = 25$  mm), this laser should photo-detach  $4.3 \times 10^7$  electrons (6.9 pC); for the initial FETS beam parameters (a 40 keV, 35 mA, 200  $\mu$ s pulse with  $r_{\text{ion}} = 25$  mm), it should photo-detach  $3.2 \times 10^6$  electrons (0.5 pC).

#### 5.1.2 The Optical Beamline

Before the design of the optical beamline is discussed in  $\S5.1.2.3$ , the mathematics that describes the optical propagation of Gaussian laser beams is introduced in  $\S5.1.2.1$  and the results of the characterisation of the FETS laserwire laser are presented in  $\S5.1.2.2$ . The alignment of the system is discussed in  $\S5.1.2.4$ .



FIGURE 5.2: The parameters of a Gaussian laser beam around it's focal point.

#### 5.1.2.1 Gaussian Beam Optics\*

For laser beams with a Gaussian beam profile the beam's radius, w, traces out a parabola as the position at which it is measured is varied. At a position z the radius is

$$w(z) = w_0 \sqrt{1 + \left(\frac{z - z_0}{z_R}\right)^2},$$
(5.1)

where  $w_0$  is the laser beam's radius at the focus (or *waist*),  $z_0$  is the position of the waist, and  $z_R$  is the Rayleigh length,

$$z_R = \frac{1}{M^2} \frac{\pi w_0^2}{\lambda},$$

where  $M^2$  is a laser-specific parameter that indicates how far from the ideal Gaussian beam propagation the beam propagation of the laser in question is. In the ideal case,  $M^2 = 1$  but for real lasers,  $M^2 > 1$ . The Rayleigh length is a measure of the depth of focus of the laser beam. (The area of the laser beam one Rayleigh length away from the position of the waist is twice that of what it is at the waist.) These parameters are illustrated in Figure 5.2.

The radius of curvature of the wavefronts (subsequently referred to as just the radius of curvature), R(z), is given by

$$R(z) = (z - z_0) \left[ 1 + \left( \frac{z_R}{z - z_0} \right)^2 \right],$$

where if R(z) < 0 the laser beam is converging towards a waist and if R(z) > 0 the laser beam is diverging away from a waist.

If a thin lens of focal length f is introduced at a point where the radius of

<sup>\*</sup>A fuller discussion of the optics of Gaussian beams, including a derivation of the formulae presented in this section, can be found in [80].

curvature is  $R_1$ , the radius of curvature after the lens,  $R_2$  is given by

$$\frac{1}{R_2} = \frac{1}{R_1} - \frac{1}{f}$$

The distance to the new waist, d, is given by

$$d = \frac{R_1}{1 + \left(\frac{M^2 \lambda R_2}{\pi w_1^2}\right)^2},$$

where  $w_1$  is the size of the laser beam at the lens, and the new waist size is

$$w_0' = \frac{w_1}{\sqrt{1 + \left(\frac{\pi w_1^2}{M^2 \lambda R_2}\right)}}$$

With a knowledge of the initial laser parameters (the measurement of which is discussed in the next section), these equations can be used to predict the laser beam's envelope at any position along the beamline.

#### 5.1.2.2 Laser Characterisation

Before designing the optical beamline, it was necessary to characterise the laser. This was done (using the setup shown in Figure 5.3) by measuring the beam's radius at a variety of positions, fitting Equation 5.1 to that data, and obtaining  $w_0$  and  $M^2$  from the fit. (These values were then used in the design of the optical beamline, discussed in §5.1.2.3). The laser's  $M^2$  was measured to be  $1.72 \pm 0.1$ . The laser's output power stability over time was also measured which, whilst not necessary to know for the positioning of the optical components within the beamline, is useful to understand when measuring the photo-detached electron production rate as the production rate is dependent on the laser power.

To measure the laser power stability, a LabVIEW interface to a laser power meter was written to record the laser power measured over time. To measure the beam's radius, a series of *knife-edge* measurements were performed<sup>†</sup>. An expanded version of the LabVIEW power meter interface was used to perform the control and data acquisition required for the knife-edge measurement. The integral of a Gaussian distribution was fitted to the measurement of the integrated beam profile and the beam's radius was determined from the fit parameters. An example knife-edge measurement is shown in Figure 5.4.

<sup>&</sup>lt;sup>†</sup>A knife-edge measurement is one where a well-defined edge is positioned in the laser beam and the power of the beam that makes it past the edge is measured. By stepping the edge through the laser beam and measuring the power at each position of the edge, an integral of the laser beam's profile is obtained.


FIGURE 5.3: The setup used to measure the laser beam parameters, here configured to measure the laser's spot size on a mock-up of the final optical beamline. At the bottom of the picture, the laser can be seen; to the left is the power meter head; at the top centre is the movable stage with the edge attached. Also visible are the mirrors and lens that make up the beamline.



FIGURE 5.4: An example knife-edge measurement. The fit to the data is the (a-)cumulative distribution function of a Gaussian distribution.

The laser's output power stability is quoted by the manufacturer as 1% over two hours, 3% over four hours and 5% over eight hours. However, the laser's output power persisted to vary significantly, despite repeated attempts to resolve the problem. (The laser was replaced by the manufacturer and the replacement exhibited the same problems. It was also shown, for example, that the fluctuations in laser power were not caused by problems with the temperature stability of the laser; see Figure 5.5.) Even in regions of comparative stability, the stated performance was not achievable. (For example, for the hour between 120 and 180 minutes in Figure 5.5 the output power stability was 3.9%). To compensate for this variability, a laser power meter was incorporated into the beamline design as a beam dump to monitor the laser power.



FIGURE 5.5: The FETS laserwire laser's output power and temperature over a period of five hours. The dotted lines show the minimum (563 mW) and maximum power (746 mW) measured.

#### 5.1.2.3 Optical Beamline Design

To be able to have a well-defined projection of the ion beam, it is desirable to have a laser beam that remains (broadly) parallel through the ion beam. This limits the amount that the laser beam can be focussed as the more tightly focussed it is, the more rapidly it diverges after the waist. This can be seen from the Rayleigh length, which is proportional to the square of the laser beam's radius at the waist.

For this reason and because the centre of the laser beam-ion beam interaction region is 510 mm from the entrance window of the vacuum vessel, a single f = 500 mm convex lens was used as the focussing component in the FETS laserwire optical beamline. The long focal length provides a gentle focussing with a waist located in the centre of the interaction region. The equations in §5.1.2.1 were implemented in a spreadsheet and used to optimise the positioning of the lens, relative to both the laser and the laser beam-ion beam interaction region. The optimised design produces a laser beam radius that is only 0.25% larger at the edge of the ion beam as it is in the ion beam centre. Good agreement was seen between the expected and measured laser beam radius in the interaction region, as can be seen from Figure 5.6.



FIGURE 5.6: The predicted and measured (using the knife-edge technique) laser beam radius in the laser beam-ion beam interaction region. The dotted line shows the maximum size of the ion beam.  $z_R = 620$  mm for this optical configuration.

Because of the relatively high power of the laser, the breadboard on which it is mounted sits in an interlocked enclosure (such that when the enclosure is open the laser can not be turned on). The enclosure is linked to the differential pumping vessel via a stainless steal beamtube and the optical interface with the vessel is a laser window mounted on a CF40 port.

To be able to measure several projections of the ion beam (and so reconstruct the correlated 2D beam profile), it is necessary to be able to direct the laser through the ion beam at an arbitrary angle and position. To be able do this, a series of four mirrors mounted on four pairs of piezo-electric stages (each pair consisting of one linear and one rotary stage), will be installed inside the laserwire vacuum vessel (initially, just two pairs have been installed). The linear stages allow the laser to be stepped through the beam to measure a projection whilst the rotary ones enable this to be done at an arbitrary angle. The stages are controlled by a LabVIEW interface.

The layout of the optical components outside the vacuum vessel is shown in Figure 5.7; those inside the vacuum vessel are shown in Figure 5.8. The chassis on which the components internal to the vacuum vessel are mounted is shown in Figure 5.9. Figure 5.10 schematically shows how the laser beam can be scanned through the ion beam at an arbitrary angle.



FIGURE 5.7: The optical components that are located outside of the vacuum vessel. A, B and D are mirrors; C is the f = 500 mm lens; E is the beamtube going between the breadboard and the vacuum vessel; and F is the laser window.



FIGURE 5.8: The optical components inside and connected to the vacuum vessel. E is the beam tube from the breadboard enclosure; F and J are the laser windows; G and I are the mirrors; H represents is the ion beam; and K is the power meter.



(b) The chassis is mounted to a door in the differential pumping vessel that can be opened to allow easy access to the components. The path of the laser is illustrated by the red line.



(a) Here, the two horizontal pairs of stages can be seen above and below the second differential pumping volume, which is anodised.

FIGURE 5.9: The chassis on which the components that sit inside the vacuum vessel are mounted.



(a) The configuration to measure a projection onto the *x*-plane.



(b) The configuration to measure a projection onto the plane y = x.





(c) The configuration to measure a projection onto the plane y = -x.

(d) The configuration to measure a projection onto the y plane.

FIGURE 5.10: An illustration of how a laser beam can be passed through an ion beam at a variety of angles. The ion beam is shown in yellow, the laser beam's path in red and the mirrors in grey. The mirrors can rotate about their centre-line and move linearly. To measure a projection of the beam the mirrors are stepped such that the laser beam translates through the ion beam at a constant angle.

#### 5.1.2.4 Alignment of the Optical System

To align the optical components, a low-power alignment laser was used (shown in Figure 5.11). First, the components located inside the vacuum vessel were aligned. To quantify the mis-alignment, the rotary stages were configured to send the laser beam vertically down and a paper target was used to measure how far the laser beam's spot moved as the linear stages were moved over their full travel (corresponding to a change in the path length of 400 mm). The output position of the laser was found to vary by 7 mm (see Figure 5.11), which corresponds to a mis-alignment of 0.0175 radians. This level of mis-alignment was tolerable, as the beam was coupled out from the vessel, but has since been improved by placing shims between the mirror mounts and the stages.

The optical components in the breadboard enclosure were then aligned. To do this, the alignment laser jig was attached to the output window of the vacuum vessel and the laser beam was then directed back through the vessel into the breadboard enclosure. The mirrors in the enclosure were then used to steer the alignment laser beam to the location of the output aperture of the Nd:YVO<sub>4</sub> laser. Some fine-tuning was required to maximise the Nd:VO<sub>4</sub> laser power transmitted through the vacuum vessel because there was a slight angular offset between the Nd:VO<sub>4</sub> laser's optical axis and its expected optical axis.



(a) The alignment laser mounted in its jig, attached to the input window of the vacuum vessel.



(b) The shortest path length configuration.



(c) The longest path length configuration.

FIGURE 5.11: The setup results of the initial optical alignment tests. The radii of the target's circles are 5 mm, 7.5 mm, 10 mm and so on.

Despite the efforts made to maximise the laser power transmitted through the vessel, not all of the power present at the vessel's input window could be coupled out of the vessel again (a transmission of 50% was the best that was achieved). The source of these losses has yet to be finally determined but there are several possibilities as to what may be causing them. After the problem was first observed, the vessel was opened and one of the mirrors mounted inside it was found to have a damaged reflective coating (see Figure 5.12). The damage to the coating was thought to have been caused either by heat not being able to be dissipated away from the mirror (possibly exasperated by caesium from the ion source contaminating the mirror's surface) or by a severely mis-steered ion beam. To protect the replacement (and remaining) mirror from this, shields that block the line of sight between each mirror and the ion source have been installed. When the vessel was opened after the problem had been observed for the second time, a residue was seen on the inside face of the input window, which may have limited the laser power coupled into the vessel. It is also not known whether some of the laser beam is missing one of the mirrors inside the vessel. This is because it is currently not possible to operate the  $Nd:YVO_4$  laser with the differential pumping vessel open, such that the mirrors mounted on the movable stages are accessible. The design of the optical enclosure is currently being altered to allow this to be done, which should give a better understanding of the losses and so increase the amount of laser power that is able to be coupled in and out of the vessel.



FIGURE 5.12: The damaged mirror, shown in its mount. The reflective coating can be seen to be peeling off where it is damaged.

## 5.2 Detector Design

The detector used to collect the photo-detached electrons had to be compact so that it could fit in the downstream volume of the differential pumping vessel. (To minimise the losses from the divergent ion beam between the ion source and the LEBT, the beamline length of the entire vessel is only 200 mm; the downstream volume of the differential pumping vessel, where the detector is located, only has an internal beamline length of 90 mm.)

The basic components of the detector are shown in Figure 5.13. They are a 100 amp-turn, soft iron core dipole magnet, a Faraday cup and an accelerating sheath (the *copper jacket*). The Faraday cup can be biased to prevent secondaries produced on its surface from escaping. There is also a suppression electrode (the *suppression ring*), to reduce the background from residual gas neutralisation (see §5.2.2 for more details of this), and a wire grid (that can also be biased) between the copper jacket and the Faraday cup.



(a) A schematic of the detector. The magnet is shown in red, the accelerating sheath in yellow and the Faraday cup in blue.



(b) A cut-through of the detector, showing the path of the electrons in tan and of that the  $H^-$  and  $H^0$  particles in black.



(c) A photograph of the detector, shown in it's mechanical assembly. The magnet is not shown in this picture.

FIGURE 5.13: The electron detector, viewed from upstream. The suppression electrode and the wire grid are not shown. The electrons are deflected up into the Faraday Cup whilst the  $H^-$  ions pass straight through. The height of the detector is 16 cm.

Because the momentum transfer between the photon and the photo-detached electron is negligible, the photo-detached electrons continue with the same velocity as their parent  $H^-$  ions. This means that an electron detached from a 65 keV parent ion only has an energy of 35 eV, and so needs to be accelerated to prevent it from being deflected by stray magnetic fields. The copper jacket, which sits between the pole pieces of the dipole magnet at a design potential of 2 kV, accelerates the photo-detached electrons such that they have a large enough magnetic rigidity to no longer be deflected by stray fields. The dipole magnet separates the electrons from the unneutralized  $H^-$  ions and deflects them into the Faraday cup. The  $H^-$  ions are unaffected by the dipole magnet because of the large mass difference between  $H^-$  ions and electrons.

The suppression ring, accelerating sheath, and wire grid are connected to their bias power supplies in parallel to a 10 M $\Omega$  resistor to ground. This resistor is used to drain any charge that builds up from stray H<sup>-</sup> ions and electrons hitting the electrodes, that would otherwise, over time, cause breakdowns.

The detector Faraday cup is biased through a 10 M $\Omega$  bias resistor, with its readout channel capacitively coupled via a 10 nF ceramic capacitor to the Faraday cup (so that the readout electronics are not exposed to the bias voltage). A ceramic capacitor was used because of its low leakage currents. To minimise the signal lost through the bias resistor, a large time constant for the filter was required; hence the large bias resistor value used. A large bias resistor will also increase the beam-induced voltage drop on the Faraday cup, compared to a smaller bias resistor, but, as the anticipated FETS laserwire signal current is several orders of magnitude lower than the current through the bias resistor, the voltage on the Faraday cup will not be significantly reduced by this effect. A diagram of the bias connections is shown in Figure 5.14.

## 5.2.1 Detector Simulations

Extensive electrostatic, magnetostatic and particle-tracking simulations were performed to optimise the detector's design. The electrostatic and magnetostatic simulations were performed in CST EM Studio [81], a finite element electromagnetic simulation program. From these simulations, maps of the magnetic and electric field were produced. These maps were then imported into the General Particle Tracer package [82] for the particle-tracking simulations. The expected particle distribution at the plane of the laser neutralisation, produced from pepperpot measurements of the ISIS ion source [83], was tracked through the field maps to assess the various detector designs. The results of the particle tracking through the (simulated) final detector design are shown in Figure 5.15.



FIGURE 5.14: The bias connections to the laserwire detector. The suppression ring is shown in green. The nominal biases for the different components are also shown.



FIGURE 5.15: The results of the simulations of the finalised detector design. Particle tracks are shown in black, with the starting point of the tracks corresponding to the location where the laser will intercept the beam. A cross section of the detector can be seen, with the iso-potential lines shown in colour and going from -500 V (dark blue) to 2000 V (red).

#### 5.2.1.1 Verification of the Magnetic Field Simulations

The bending component of the dipole field (the *y*-component in the coordinate system used for these measurements) was measured<sup>‡</sup> on a 5 mm grid in the region that the photo-detached electrons pass through. (The grid on which the magnetic field was measured is illustrated in Figure 5.16 [84].) The measured field map was compared to the simulated field map to verify the magnetostatic simulations performed.

When the effects of hysteresis are taken into account, there is a good agreement between the measured field and the simulated field (Figure 5.17 shows a comparison between the simulated and measured fields). To quantitatively compare the two fields, the percentage difference between them at each measurement point was calculated. The discrepancy between the measured and the simulated magnetic field, averaged across all measurement points, is 0.23%. Additionally, the percentage differences for each y-plane were averaged and compared. This is shown in Figure 5.18. From this, it can be observed that the largest discrepancies are seen in the region nearest to the pole pieces. The discrepancies are expected to be largest in this region due to problems meshing the surface of the



FIGURE 5.16: The coordinate system used for the measurement of the detector's dipole magnet's field. The blue dots mark the points where a measurement was made; the black quarter circle, the pole pieces of the magnet. The notched edge of the pole pieces is located at the entrance to the dipole. Measurements were made in the planes y = -25, -20, -15, -10, -5, 0, 5, 10, 15, 20, 25 mm. (The spacing between the pole pieces is 60 mm.)

<sup>&</sup>lt;sup>‡</sup>This was performed by Ben Shepherd, of the Magnetics and Radiation Sources Group of the Accelerator Science and Technology Centre (http://www.astec.ac.uk), using the Insertions Devices Laboratory at Daresbury Laboratory.



FIGURE 5.17: A comparison of the y-component of the simulated detector's and constructed detector's magnetic fields in the plane y = 0 mm.



FIGURE 5.18: The percentage difference between the simulated and measured values of the bending component of the dipole's magnetic field. The crosses (+) show the average percentage difference for each plane. The ticks  $(\neg, \vdash)$  show  $\pm 1\sigma$  from the average point. The ends of the lines show the maximum and minimum discrepancies. The dashed line shows the discrepancy, averaged over all points.

pole pieces in the simulation. Additionally, as most of the beam is transported through the middle of the dipole, the discrepancies near the pole pieces do not affect the beam transport significantly. Consequently, the measured dipole field is sufficiently close to the simulated field that no discrepancy between the simulated and actual performance is expected.

## 5.2.2 Background Estimation and Reduction

Any electrons in the vacuum vessel that are not produced by neutralisation of an  $H^-$  ion by the laser beam are a potential background for the measurement. It was anticipated that the major source of these background electrons would be interactions of the  $H^-$  ions with the residual gas in the vessel<sup>§</sup> (*residual gas electrons*). The main processes that contribute to this are

$$\begin{split} \mathrm{H}^- + \mathrm{H}_2 &\rightarrow \mathrm{H}^0 + \mathrm{e}^- + \mathrm{H}_2 \\ \mathrm{H}^- + \mathrm{N}_2 &\rightarrow \mathrm{H}^0 + \mathrm{e}^- + \mathrm{N}_2. \end{split}$$

The cross-sections for these processes are  $\sigma_{\rm H_2} = 1.5 \times 10^{-16} \,\mathrm{cm^2}$  and  $\sigma_{\rm N_2} = 5.0 \times 10^{-16} \,\mathrm{cm^2}$  [85]. For the FETS laserwire, the interaction with molecular hydrogen dominates, as the partial pressure of the hydrogen is much larger that that of the nitrogen because of the proximity to the ion source. The sub-dominant processes

$$\begin{split} H^- + H_2 &\rightarrow H^+ + 2e^- + H_2 \\ H^- + N_2 &\rightarrow H^+ + 2e^- + N_2 \end{split}$$

also contribute. The smaller cross-sections of  $\sigma_{\rm H_2} = 2 \times 10^{-17} \rm cm^2$  and  $\sigma_{\rm N_2} = 1 \times 10^{-16} \rm cm^2$  [85] is enhanced by the detachment of two electrons. The partial pressure of the molecular hydrogen is estimated to be  $5 \times 10^{-5}$  hPa and the partial pressure of nitrogen is estimated to be  $5 \times 10^{-7}$  hPa.

The rate of loss of H<sup>-</sup> ions is given by

$$\frac{dN_{\rm H^-}}{dz} = \sum_{\rm RG \ species} -\sigma \rho_{\rm RG} N_{\rm H^-}$$
(5.2)

where  $N_{\rm H^-}$  is the number of H<sup>-</sup> ions; z, the distance along the beamline;  $\sigma$ , the detachment cross section and  $\rho_{\rm RG}$ , the density of the residual gas particles. The ideal gas law,

$$pV = nRT$$

 $<sup>^{\$}</sup>$ Positive ions will also be produced by the interaction of the H<sup>-</sup> ions with the residual gas and are also potentially a background; however, they are not considered in this section.

(where p is the pressure; V, the volume; n, the number of moles; R, the ideal gas constant and T, the temperature) can be used to simplify Equation 5.2. By rewriting it as

$$\rho = \frac{pM}{RT},$$

where M is the molar mass and  $\rho$  is the mass density of the gas,

$$\rho = \frac{n}{V}M,$$

Equation 5.2 can be written as

$$\frac{dN_{\rm H^-}}{dz} = \sum_{\rm RG \ species} -\sigma \left[ \frac{p_{\rm RG}M}{RT} \right] N_{\rm H^-}$$

With the four processes listed above and a temperature of 298 K, the rate of production of electrons is  $1.8 \times 10^{13} \text{ m}^{-1} (2.87 \mu \text{Cm}^{-1})$  for the nominal FETS beam. Assuming that all the residual gas electrons produced in the 200 mm long laserwire vacuum vessel are collected by the laserwire detector implies a background signal of  $3.6 \times 10^{12}$  electrons (575 nC) per pulse. However, this does not take into account the transport of the residual gas electrons from where they are produced to the detector Faraday cup and so is an over-estimate. To determine the longitudinal acceptance of the detector, the transport of the residual gas electrons to the Faraday cup from various positions within the laserwire vacuum vessel was simulated. To perform these simulations, it was assumed that the residual gas electrons would have the same velocity distribution as their parent H<sup>-</sup> ions (as is the case for photo-detached electrons).

From the "No suppression electrode" trace in Figure 5.19, it can be seen that only the residual gas electrons produced before the detector volume will be transported into the Faraday cup. Although this limited transmission reduces the expected background to  $2.2 \times 10^{12}$  electrons (351 nC) per pulse, this is still a high level of background and so an additional suppression electrode was incorporated into the entrance to the detector. By holding this electrode at a negative potential a smaller longitudinal acceptance is created, where the electrons produced by photo-detachment are transported to the Faraday cup but fewer of the background electrons are.

Several suppression ring designs were considered; two—the *collar electrode* (the collar electrode is a ring that sits inside of the entrance aperture to the detector volume) and the *nose electrode* (the nose electrode is the same as the collar electrode but has a nose that extends over part of the outer volume of the second differential pumping volume)—are illustrated in Figure 5.20. Their effect on acceptance of the residual gas electrons is shown in Figure 5.19. The nose



FIGURE 5.19: The reduction in the longitudinal acceptance of the detector by the introduction of an additional background suppression electrode.



FIGURE 5.20: The different suppression electrode designs. The top half of the figure shows the positive (0-2000 V) lines of equipotential for the different electrode designs (from right to left, no electrode, collar electrode, nose electrode), giving a qualitative indication of the reduction in acceptance. The position of the laser beam indicated by a red arrow. The bottom half of the figure shows the details of the electrode designs, with the electrodes shown in red and the insulators in blue.

Detector configuration	Longitudinal	Expected Charge	
	Acceptance	Initial beam	Nominal beam
	(Fractional)	[nC]	[nC]
Full acceptance	1	34	575
No suppression electrode	0.610	21	351
Collar suppression electrode	0.296	10	170
Nose suppression electrode	0.245	8	141

TABLE 5.1: A comparison of the various background levels for the different suppression electrode designs. The 'Initial beam' is a 40 keV, 200  $\mu$ s, 35 mA beam that was available when the FETS ion source was commissioned; the 'Nominal beam' is the nominal FETS beam.

electrode was incorporated into the final design as it gave the best background suppression—reducing the level of background by 60%, compared to the case without a suppression electrode—to  $8.8 \times 10^{11}$  electrons (141 nC) per pulse. A comparison of the expected background levels for the various suppression electrode designs is given in Table 5.1.

Although the expected background signal is larger than the expected photodetached electron signal, the Poissonian width of the background is smaller than the expected photo-detached electron signal and so the signal should be able to be observed above the background.

## 5.3 Detector Electronics

A readout electronics board has been designed and constructed to integrate, hold and digitise the photo-detached electron signal. It is built around a Texas Instruments DDC112 [86], which is a current input analogue-to-digital converter (ADC), controlled and read out<sup>¶</sup> by Atmel ATMega128 microprocessor. The ADC is able to integrate over a variety of ranges by switching between integrating capacitors; the smallest (highest resolution) range can measure from -0.2-50 pC and the largest (lowest resolution) range is from -4-1000 pC<sup>||</sup>. The ADC is 20-bit, with a maximum resolution of 48 aC/bit<sup>\*\*</sup>.

The DDC112 (shown schematically in Figure 5.21) has two inputs, with each input connected to a switched (two-sided) integrator. The benefit of this design is that when the signal is being digitised on one side of the integrator, it can continue to be integrated on the other. The ADC is of the delta-sigma type,

 $<sup>\</sup>P Both$  from the ADC to the microprocessor and from the microprocessor to a PC, via a serial link

 $<sup>\</sup>parallel$  The readout electronics were designed to measure the photo-detached electron signal, before the size of the background signal was fully appreciated.

<sup>\*\*</sup>The highest resolution can only be achieved in conjunction with the smallest range.



FIGURE 5.21: A schematic of the DDC112 current input ADC [86].

with a 479.4  $\mu$ s measure-reset-zero cycle [86]. Including the time it takes to get the data from the DDC112 to the microprocessor (with a small amount of overhead), the shortest integration period possible operating in this continuous mode is  $600\mu$ s<sup>††</sup>. The integrators are switched using the DDC112's CONV line. The CONV line is controlled by two outputs ("Gate Open" and "Gate Closed") from the microprocessor that are triggered by two signals from the FETS timing control system. Data is ready to be read out 421.2  $\mu$ s after the measure-reset-zero cycle starts [86]; this is indicated by the DDC112's **#DVALID** output going low. When the DDC112's **#DXMIT** line is taken low, the data can be clocked out (using the data clock, DCLK, provided by the microprocessor) over the DDC112's **#DUUT** output. A timing diagram of the processes that occur in this 600  $\mu$ s window is shown in Figure 5.22.

The DDC112 has a test mode, in which a test charge is injected internally onto the integrating capacitor. This feature was used to test the noise performance of the DDC112. A histogram of a series of measurements of this test charge is shown in Figure 5.23. It shows that the inherent noise of the readout electronics is sufficiently small (< 1 fC) to allow an accurate measurement of the expected photo-detached electron signal (which is of order pC).

<sup>&</sup>lt;sup>††</sup>The DDC112 also has a non-continuous mode which would allow the integration period to be shorter. However, this mode is not able to continuously measure the signal on the input and so was not used in the work presented in this thesis. See [86] for more information on this mode.







FIGURE 5.23: A histogram of 57485 measurements of the DDC112's test charge.

Having described the various components that make up the FETS laserbased beam profile monitor, the various reconstruction algorithms that could be used to reconstruct the 2D profile of a beam from the 1D projections measured by the instrument are presented in the next chapter.

## Chapter 6

# **Reconstruction Algorithms**

The laser-based beam profile monitor described in the previous chapter is designed to measure a series of projections of the FETS ion beam. As it is preferable to know the correlated 2D profile, rather than just a series of projections, a reconstruction of the 2D profile from the 1D projections is required.

In this chapter, two algorithms that are capable of reconstructing a beam profile from a series of projections—the Filtered Back-Projection algorithm and the Algebraic Reconstruction Technique —are described and their performances are compared. A third algorithm that has been used to reconstruct emittance measurements from a series of profile measurements (see, for example, [60, 87, 88, 89])—the Maximum Entropy Algorithm—could be used to reconstruct a beam profile from a series of projections but it is not considered here.

## 6.1 Filtered Back-Projection<sup>\*</sup>

Filtered Back-Projection (FBP) and developments of it are typically used for medical Computed Tomography (CT) applications [90]. Before the Filtered Back-Projection algorithm is introduced (§6.1.3), the Radon Transformation (§6.1.1) and the Fourier Slice Theorem (§6.1.2) are described.

## 6.1.1 The Radon Transformation

The Radon Transformation,  $P_{\theta}(t)$ , of a two-dimensional distribution,  $f(x, y)^{\dagger}$ , is the integral of the distribution along the line

$$x\cos\theta + y\sin\theta - t = 0 \tag{6.1}$$

<sup>\*</sup>The derivations presented in this section follow those in [90].

 $<sup>^{\</sup>dagger}f(x,y)$  will also be referred to as an *image* in this chapter.



FIGURE 6.1: A series of Radon Transformations of a profile of the FETS ion beam.

and can be written as

$$P_{\theta}(t) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) \,\delta(x \cos \theta + y \sin \theta - t) \,\mathrm{d}x \,\mathrm{d}y.$$

A projection of the distribution is then just the collection of all (non-zero)  $P_{\theta}(t)$ , for a given angle  $\theta$ . A Radon Transformation of a profile of the FETS ion beam is shown in Figure 6.1.

The Radon Transformation can be used for image reconstruction in conjunction with the Fourier Slice Theorem, which states that a Fourier Transform of a given  $P_{\theta}(t)$  is equal to a slice of the two-dimensional Fourier Transform of the original distribution, f(x, y) [90]. The derivation of the Fourier Slice Theorem is given in the next section.

## 6.1.2 The Fourier Slice Theorem

To derive the Fourier Slice Theorem, it is necessary to consider a coordinate system rotated by an arbitrary angle,  $\theta$ :

$$\begin{bmatrix} t \\ u \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

For constant t,  $P_{\theta}(t)$  in the rotated co-ordinate system is given by

$$P_{\theta}(t) = \int_{-\infty}^{\infty} f(t\cos\theta - u\sin\theta, t\sin\theta + u\cos\theta) \,\mathrm{d}u.$$

The Fourier Transform of  $P_{\theta}(t)$  in the rotated coordinate system is

$$S_{\theta}(w) = \int_{-\infty}^{\infty} P_{\theta}(t) e^{-2\pi i w t} dt$$
$$= \int_{-\infty}^{\infty} \left[ \int_{-\infty}^{\infty} f(t \cos \theta - u \sin \theta, t \sin \theta + u \cos \theta) du \right] e^{-2\pi i w t} dt$$
$$= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(t \cos \theta - u \sin \theta, t \sin \theta + u \cos \theta) e^{-2\pi i w t} dt du.$$

Transforming this back to the original coordinate system gives

$$S_{\theta}(w) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) e^{-2\pi i w (x \cos \theta + y \sin \theta)} dx dy$$
$$= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) e^{-2\pi i [(w \cos \theta) x + (w \sin \theta) y]} dx dy,$$

which can be recognised as the two-dimensional Fourier Transform of the original distribution, f(x, y),

$$F(u,v) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x,y) e^{-2\pi i (ux+vy)} \,\mathrm{d}x \,\mathrm{d}y, \tag{6.2}$$

with  $u = w \cos \theta$  and  $v = w \sin \theta$ . So,

$$S_{\theta}(w) = F(w\cos\theta, w\sin\theta). \tag{6.3}$$

The fact that the Fourier Transform of a series of projections is equal to the Fourier Transform of the original distribution can be used to reconstruct the original distribution from a series of projections of it. One way by which this can be done is the Filtered Back-Projection algorithm, which is described in the next section.

## 6.1.3 Filtered Back-Projection

The inverse Fourier Transform of F(u, v) can be expressed in polar coordinates with the coordinate transformations  $u = w \cos \theta$  and  $v = w \sin \theta$ ,

$$f(x,y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(u,v) e^{2\pi i (ux+vy)} du dv$$
  
= 
$$\int_{0}^{2\pi} \int_{0}^{\infty} F(w\cos\theta, w\sin\theta) e^{2\pi i w (x\cos\theta+y\sin\theta)} w dw d\theta, \qquad (6.4)$$

where the Jacobian is w. By considering the ranges  $0 \le \theta < \pi$  and  $\pi \le \theta < 2\pi$  separately, Equation 6.4 can be written as

$$f(x,y) = \int_0^{\pi} \int_0^{\infty} F(w\cos\theta, w\sin\theta) e^{2\pi i w (x\cos\theta + y\sin\theta)} w \, \mathrm{d}w \, \mathrm{d}\theta + \int_0^{\pi} \int_0^{\infty} F(w\cos(\theta + \pi), w\sin(\theta + \pi)) e^{2\pi i w (x\cos(\theta + \pi) + y\sin(\theta + \pi))} w \, \mathrm{d}w \, \mathrm{d}\theta.$$
(6.5)

Noting that

$$\cos(\theta + \pi) = -\cos\theta$$
 and  $\sin(\theta + \pi) = -\sin\theta$ ,

the second term of Equation 6.5 can be rewritten as

$$\int_0^{\pi} \int_{-\infty}^0 F(w\cos\theta, w\sin\theta) e^{2\pi i w (x\cos\theta + y\sin\theta)} |w| \, \mathrm{d}w \, \mathrm{d}\theta,$$

where the variable substitution w = -w has been made to change the direction of integration over w. Equation 6.5 then becomes

$$f(x,y) = \int_0^{\pi} \int_{-\infty}^{\infty} F(w\cos\theta, w\sin\theta) e^{2\pi i w (x\cos\theta + y\sin\theta)} |w| \, \mathrm{d}w \, \mathrm{d}\theta.$$

Substituting the equation of the line (Equation 6.1) and the Fourier Transform of a projection (Equation 6.3) gives

$$f(x,y) = \int_0^{\pi} \int_{-\infty}^{\infty} S_{\theta}(w) e^{2\pi i w t} |w| \, \mathrm{d}w \, \mathrm{d}\theta.$$

This is commonly expressed as

$$f(x,y) = \int_0^{\pi} Q_{\theta}(t) \,\mathrm{d}\theta, \qquad (6.6)$$

where

$$Q_{\theta}(t) = \int_{-\infty}^{\infty} S_{\theta}(w) e^{2\pi i w t} |w| \,\mathrm{d}w.$$
(6.7)

 $Q_{\theta}(t)$  is known as a *filtered projection*, where the factor of |w| accounts for the increasing sparsity of data in the high-frequency regions of the (u, v) space. This is illustrated in Figure 6.2, which shows six equally-spaced projections in (u, v) space. Note that even for an infinite number of projections, |w| is still required—this is most easily seen by observing that it enters the equation as the Jacobian when the coordinate system is changed. Figure 6.3 shows images reconstructed from sets of unfiltered and filtered projections.



FIGURE 6.2: The population of the (u, v) space for six projections.



FIGURE 6.3: Reconstructed images from (computationally-calculated) unfiltered projections and filtered projections (i.e. without and with the factor of |w| in Equation 6.7).

To reconstruct an image, the filtered projections of it are *back-projected* over the (x, y) space. In practice, as there will not be an infinite number of projections from which to reconstruct the image and because the Fourier Transform is bandwidth-limited (due to the limited amount of information present in the higher frequency components), a discretized version of Equation 6.6 is used. This limited bandwidth defines the angular sampling interval required to give a reasonable reconstruction of the original distribution.

Further details of the algorithm, the discretization process, how the discretization process is implemented computationally, and additional filters that can be applied to improve the noise performance of the algorithm can be found in [90].

## 6.2 The Algebraic Reconstruction Technique<sup>‡</sup>

The Algebraic Reconstruction Technique (ART) was first introduced for the reconstruction of objects from electron micrographs where only a few projections of the object were available [91]. It is an iterative process that modifies an array of pixels until the projections of the reconstructed density distribution are the same as the projections of the original density distribution to within some discrepancy.

The notation used to describe the projections is introduced in 6.2.1 and the ART algorithm is described in 6.2.2.

## 6.2.1 Projection Notation

The number of projections of the original distribution is denoted by  $n_{\text{proj}}$ , with each projection made up of  $n_{\text{steps}}$  steps (or *bins*). The integral of the original distribution in each bin of a projection (for the laserwire, this corresponds to the number of electrons detached by the laser passing through the ion beam at a given position and angle) is denoted  $R_j$ , where j = 1, 2, 3..., m and m = $n_{\text{proj}} \times n_{\text{steps}}$ . An illustration of two 15-bin projections is given in Figure 6.4.

## 6.2.2 A Description of the Algorithm

A description of the Algebraic Reconstruction Technique algorithm follows, along with some details about how it has been implemented for the FETS laserwire. A graphical description is shown by Figures 6.5, 6.6 and 6.7.

#### 6.2.2.1 Variable Initialisation and Construction

Before reconstruction can begin, several variables need to be initialised. A  $n \times n$  array of pixels over which the image is to be reconstructed is made, with the value of each pixel being denoted  $\rho_i$ , where  $i = 1, 2, 3, ..., n^2$ . The  $\rho_i$  are constrained to be between 0 and 1, inclusive, and are initialised to 0. Within the  $m R_j$  measurements, the different bins are grouped together by their projections (*i.e.*  $R_1...R_{n_{\text{proj}}}$  correspond to the first projection,  $R_{n_{\text{proj}}+1}...R_{2\times n_{\text{proj}}}$  to the second, and so on). An array of  $n \times n$  pixel masks,  $P_{ji}$ , is also constructed, with each mask corresponding to a particular step of a particular projection. These masks can either be binary or can have smoothed edges, which is useful when they represent something which itself has a profile (for example, the FETS laserwire's laser beam's Gaussian profile).

<sup>&</sup>lt;sup>‡</sup>The description presented in this section follows that of [67].



FIGURE 6.4: A profile of the FETS ion beam alongside 15-bin, computationally-calculated projections of it onto the x- and y-planes.

#### 6.2.2.2 The Reconstruction Algorithm

Once all the necessary variables have been constructed and initialised, the algorithm considers each  $R_j$  value in turn, by setting

$$j = \begin{cases} m & \text{if } q+1 \text{ is divisible by } m \\ \text{the remainder of } (q+1)/m & \text{otherwise,} \end{cases}$$

where q is the iteration number. The mask corresponding to the  $R_j$  in question is cast across the array of pixels over which the image is being reconstructed (see Figures 6.5 and 6.6). The sum of the values of all the pixels that fall within the mask after q iterations is calculated by

$$R_j^q = \sum_i P_{ji} \rho_i^q,$$

where  $\rho_i^q$  is the value of the *i*th pixel after *q* iterations.  $R_j^q$  is then compared to the measured value of  $R_j$  and the difference between the two values is then spread across the pixels in question in the reconstruction array,

$$\rho_i'^{q+1} = \rho_i^q + P_{ji} \times \frac{(R_j - R_j^q)}{N_j},$$

where  $N_j$  is number of pixels contained within each step  $R_j$ ,

$$N_j = \sum_i P_{ji}.$$

The pixel values are then confined to be between 0 and 1, inclusive,

$$\rho_i^{q+1} = \begin{cases} 0 & \text{if } \rho_i'^{q+1} < 0\\ \rho_i'^{q+1} & \text{if } 0 \le 0\rho_i'^{q+1} \le 1\\ 1 & \text{if } \rho_i'^{q+1} > 1 \end{cases}$$

and the process is iterated over until an exit condition is met. For the data presented in this chapter, the discrepancy between  $R_j$  and  $R_j^q$ , defined as

$$D^{q} = \sqrt{\frac{1}{m} \sum_{j=1}^{m} \frac{\left(R_{j} - R_{j}^{q}\right)^{2}}{N_{i}}},$$
(6.8)

was used to form the exit condition. If the ART was used to reconstruct experimentally-measured projections, a  $\chi^2$  test based on the discrepancy between  $R_j$  and  $R_j^q$  and the measurement error would be a suitable exit condition.



FIGURE 6.5: The reconstruction of the ion beam profile shown in Figure 6.4 using the projection onto the x-plane. The masks corresponding to the first and second steps in this projection are shown on the top row. The grid on which the profile is being reconstructed is shown below the masks, where the corresponding strips have been reconstructed. These images have been scaled to give a range of 0 (black) to 0.1 (white) to show the detail in them. The image in the bottom right (whose scale goes from 0 to 1) shows the reconstruction grid after the reconstruction of the projection onto the x-plane has been completed for the first time.



FIGURE 6.6: The reconstruction of the ion beam profile using the projection onto the y-plane, after a single iteration over the x-plane on which the profile is being reconstructed is shown below the masks, where the corresponding strips have been reconstructed. The image in the bottom right shows the reconstruction grid after the reconstruction of the projections onto the x- and y-planes have has been completed. The masks corresponding to the first and second steps in this projection are shown on the top row. The grid been completed for the first time.



10 passes over each projection



100 passes over each projection











FIGURE 6.7: The reconstructed profile after 1, 10, 100 and 1000 iterations over both the x- and y- projections. A version of the original image, re-sampled to the same resolution as the reconstructions, is included for comparison. The reconstructed images do not show all the information in the rescaled image because only two projections were used to perform the reconstruction.

## 6.3 Implementation of the Algorithms

## 6.3.1 Filtered Back-Projection

The radon and iradon functions of the MATLAB Image Processing Toolbox [92] were used to perform the Radon Transformations and Filtered Back-Projections presented in this thesis. The radon function uses sub-pixel smoothing to produce a quasi-continuous Radon Transformation of a pixelated image. The iradon function filters and back-projects the data passed to it to reconstruct the original image. To simulate the projection data being binned, the Radon Transformation was split into bins and the data in each bin was averaged.

## 6.3.2 The Algebraic Reconstruction Technique

The ART algorithm was also implemented in MATLAB, using some routines from the Image Processing Toolbox. The code can be found in Appendix A.

## 6.4 Assessment of the Algorithms

In this section, the performance of the algorithms are assessed individually, before being compared. To assess the algorithms, various computationally-constructed projections of a  $256 \times 256$  pixel version of the scintillator profile of the FETS beam shown in Figure 6.1 were reconstructed and compared<sup>§</sup>.

## 6.4.1 Filtered Back-Projection

The Filtered Back-Projection algorithm requires the data to be finely binned over a large number of projections to give a reasonable reconstruction of the original image (see Figures 6.8 and 6.9 for illustrations of what happens with too few projections and steps per projection, respectively). A large number of projections are required (to faithfully reconstruct the original distribution) to minimise the amount of interpolation performed in (u, v)-space. A large number of steps per projection are required because the algorithm is based upon an integral (Fourier) transform of a projection of a continuous distribution. The result of the discontinuities in the binned projections lead to artifacts being introduced in the reconstructed image (like the rings that can be seen in Figure 6.9). The maximum number of steps per projection achievable with the FETS laserwire system is of order 50 (without over-sampling). At this level of binning, the number of artifacts in the Filtered Back-Projection image is significant (as can be seen from the 41 steps per projections image in Figure 6.9).

 $<sup>^{\</sup>text{S}}$ The original version of the scintillator profile was 2000 × 2000 pixels. This was scaled to a 256 × 256 image to reduce the computational time required to perform the assessment.







FIGURE 6.9: Images reconstructed from 80 projections, with a variety of number of steps per projection, using the Filtered Back-Projection algorithm.

## 6.4.2 The Algebraic Reconstruction Technique

For the data presented in this chapter, a discrepancy (as defined by Equation 6.8) of 0.1 was used as the exit condition for the algorithm.

The ART struggles to reconstruct the original image from a very small number of steps per projection, even with a large number of projections (48, in the case of Figure 6.10). However, this is not unreasonable as in these cases the beam occupies a small number of the steps in each projection (as few as three for the case of eight steps per projection) and so expecting a good reconstruction in these cases is unrealistic.

For the case of 48 steps per projection, comparable to the nominal case of 50 steps per projection for the FETS laserwire, the ART offers a reasonable reconstruction right down to as few projections as 16 (spread over  $180^{\circ}$ ), with increasing faithfulness in reconstruction as the number of projections increases (see Figure 6.11).








#### 6.4.3 A Qualitative Comparison of the Algorithms

Having considered the performance of the algorithms individually, it is beneficial to compare them.

A qualitative comparison of the algorithms can be made by comparing the reconstructed images from the two algorithms This has been done for the nominal FETS laserwire operating conditions of about 50 steps per projection and is shown in Figure 6.12. As can be seen from this figure, the artifacts present in the FBP reconstruction partially mask the reconstructed distribution in a way that is not seen in the ART reconstruction. Even in the case of 16 projections over 180°, where the shape of the beam can be made out in the FBP reconstruction, the artifacts hide some of the details that can be seen in the ART reconstruction. As will be discussed in the next section, these qualitative observations are backed up by a quantitative assessment of the data.



ART; 48 steps per projection

 $\operatorname{FBP};$  53 steps per projection

#### 6.4.4 A Quantitative Comparison of the Algorithms

To quantitatively compare the performance of the algorithms, a measure of the discrepancy between the reconstructed and original images was used,

$$D = \sum_{\text{all pixels}} \frac{|\varrho_i - \rho_i|}{N}$$

where  $\rho_i$  and  $\rho_i$  are the values of the *i*th pixel in the reconstructed and original image respectively and  $N = 256 \times 256 = 65536$ , the total number of pixels.

Figure 6.13 shows the discrepancy between the original and reconstructed distributions for a varying number of projections for the different algorithms. Quasi-continuous projections for the FBP algorithm are considered, as well as (close to) the nominal number of steps per projection for the FETS laserwire (53 steps per projection). For the ART, reconstructions from (close to) the nominal number of steps per projection (48) are considered, as well as those from half (24) and twice (96) this value.

When quasi-continuous projections are considered for the FBP algorithm, the ART outperforms it for up to 25 projections over 180° (the expected operational maximum number of projections for the FETS laserwire); for between 25



FIGURE 6.13: The discrepancy between the original and reconstructed distributions for a varying number of projections for the different algorithms.

and 50 projections over  $180^{\circ}$ , the performance of the two algorithms is approximately equal (depending on the number of steps per projection considered for the ART algorithm); for more than 50 projections, the FBP algorithm outperforms ART. Indeed, whilst the performance of the ART is seen to level off above 50 projections over  $180^{\circ}$ , the performance of the FBP algorithm continues to improve up to about 120 projections over  $180^{\circ}$ . When binned projections are reconstructed using the FBP algorithm, it is significantly outperformed by the ART.

Figure 6.14 shows the discrepancy between the original and reconstructed distributions for a varying number of steps per projections for the two algorithms. When the nominal number of steps per projection is considered for the FBP algorithm its performance, as measured by the discrepancy between the original and reconstructed images, is approximately an order of magnitude worse than that of the ART for any number of projections. Indeed, the ART can be seen to outperform the FBP algorithm for any number of steps per projection for significantly fewer projections.



FIGURE 6.14: The discrepancy between the original and reconstructed distributions for a varying number of steps per projection for the different algorithms.

#### 6.4.5 A Comparison of the Speeds of the Algorithms

Although the ART algorithm performs better than the FBP algorithm in terms of the quality of the reconstructed image, the FBP algorithm is considerably faster than the ART. This is because the ART is an iterative process, whereas the projections are just calculated, filtered and back-projected once for the FBP algorithm. For example, for the case of 32 projections over 180°, where the ART and quasi-continuous FBP reconstructions have similar discrepancies, the FBP computation took 0.131 seconds to complete the reconstruction whereas the ART took 148 seconds, making it three orders of magnitude slower. However, even the time taken to perform the ART reconstruction is less than the time required to acquire the data.

The time taken to complete the FBP algorithm is only weakly dependent on the number of projections (rising by approximately an order of magnitude for each increase in the order of the number of projections) and is broadly independent of the number of steps per projection. For the ART, however, the number of iterations taken to reach convergence (and consequently, the time taken to complete the algorithm) is more strongly dependent on both the number of projections and the number of steps per projection increases (rising by approximately two orders of magnitude for every factor of 10 increase in the number of projections and by one order of magnitude for every factor of 10 increase in the number of steps per projection).

#### 6.4.6 Other Uses of the Reconstruction Algorithms

The algorithms described in this chapter have applications beyond the reconstruction of beam profiles from a series of projections. In this section, a brief discussion of some of these other uses is given, alongside observations of the effectiveness of the different algorithms in these situations.

In medical imaging, for example, the FBP algorithm is used to reconstruct data in x-ray computed tomography (CT). Because of the abundance of data acquired during a CT scan (where a large number of finely-binned projections can be easily measured), the FBP algorithm is able to satisfactorily reconstruct the image. This large amount of data also makes iterative methods (like the ART) prohibitively slow, and so they tend not to be used [93]. However, for nuclear medical imaging (like positron emission tomography and single photon emission computed tomography), the data sets are smaller and iterative methods provide better reconstruction, particularly the Maximum Entropy algorithm [93]. Comparisons of the different algorithms for medical applications (see, for example, [94]) have, like the study presented in this chapter, observed that FBP is fast and efficient with large numbers of projections whilst iterative reconstruction methods, like ART and the Maximum Entropy algorithm, require more time but are accurate with only a few projections. The study presented in [94] found that the Maximum Entropy algorithm was superior to ART, although [60] found that the performance of the Maximum Entropy and the ART algorithms was equal when reconstructing an emittance test figure from a series of beam projections, measured along an accelerator beamline. Following these observations, it would be interesting to investigate the use of the Maximum Entropy algorithm to reconstruct beam profiles from a series of projections of the beam.

#### 6.4.7 Conclusions

In this chapter, two algorithms that are capable of reconstructing a 2D, correlated profile from a series of projections have been described and assessed. Whilst the FBP algorithm is significantly faster than the ART algorithm, the faithfulness of reconstruction was considerably better for the ART algorithm over a wide range of projection parameters, particularly for those at which the FETS laserwire is anticipated to operate. Other studies support the findings presented in this chapter.

# Chapter 7

# Results

In this chapter, the results from the initial commissioning of the FETS ion source  $(\S7.1)$  and laserwire  $(\S7.2)$  are presented. The commissioning process is on-going and so the following describes the status at the time of writing. The beamline and diagnostic instruments used to obtain the results presented in this chapter are shown in Figure 7.1.



FIGURE 7.1: The beamline and diagnostics used to obtain the results presented in Chapter 7; "DV" is the diagnostics vessel. "T1" indicates toroid 1; "T2", toroid 2; "S", the vertical slit-slit scanner (the horizontal one is not shown); "P", the pepperpot head/scintillator; "C", the pepperpot camera. The slit-slit scanners can be fully retracted out of the path of the beam.

### 7.1 Ion Source Commissioning

The performance goals for the FETS ion source are a 65 keV, 60 mA, 2 ms  $\rm H^-$  pulse at 50 Hz with an emittance of 0.25  $\pi$ mmmrad. The FETS ion source is a development of the ISIS ion source, which routinely delivers a 35 mA, 200 $\mu$ s H<sup>-</sup> pulse at 50 Hz. Several design improvements have been made to the ISIS ion source so that it can meet the FETS specifications; they are described in [45] and will be introduced in this chapter, where relevant.

#### 7.1.1 Ion Source Commissioning Summary

Pulses with durations of 1.6 ms and ones with over 60 mA of beam current have been produced, although not yet simultaneously. Reductions in emittance have also been made and work is underway to further understand and reduce the amount of phase space occupied by the beam. Design problems with the ion source platform power supply, which defines the ion source beam energy, are currently limiting the beam energy to 40 keV. However, when these have been resolved, increasing the beam energy to 65 keV will be fairly straight-forward, at which point the geometry of the post-extraction acceleration will be optimized.

#### 7.1.2 Peak Beam Current

On the FETS, currents in excess of 60 mA have been extracted from the ion source; Figure 7.2 shows oscilloscope traces for a 65 mA beam. Since this data was taken the beam transport has been improved and now 60 mA of beam current can be transported to the second toroid [95] (rather than just 50 mA, as shown in Figure 7.2). Further improvements in transmission are expected when the misalignment of the ion source assembly, shown in Figure 7.3 and currently causing the beam to be mis-steered horizontally by  $\sim 10$  mrad, is corrected.



FIGURE 7.2: A 65 mA beam extracted from the FETS ion source [45]. Toroid 1 is located between the ion source and the differential pumping vessel and toroid 2 is located after the differential pumping vessel.



FIGURE 7.3: A scintillator image of the beam shown in Figure 7.2 [45], taken  $\sim 1$  m downstream of the ion source.

Figure 7.3 also shows that the ion beam is collimating on a circular aperture, which will contribute to losses. Efforts are being made to further improve the beam transport for a wide range of ion source operating conditions.

Previous studies on the ISIS ion source development rig have demonstrated that increasing the extraction voltage increases the beam current extracted from the ion source [96]. Therefore, in addition to increasing the amount of beam transported by reducing the losses, a new extract power supply is being designed that will provide a 25 kV extraction voltage, which should further increase the beam current available from the ion source.

#### 7.1.3 Long Pulse Length

A 1.6 ms beam has been extracted from the FETS ion source, with 40 mA making it through the first toroid and 30 mA through the second (see Figure 7.4).

To enable the ion source to run at long pulse lengths, modifications, based on thermal modelling [97], were made to allow the ion source to dissipate the extra heat generated. However, the extract power supply is not capable of running with long pulse lengths at 50 Hz so, to test the ion source with long pulses, the extract power supply repetition rate was reduced to 3.125 Hz. The discharge power supply, which can produce 2 ms pulses at 50 Hz, was left operating at



FIGURE 7.4: A 1.6 ms beam extracted from the FETS ion source [45]. The droop and undershoot on the toroid 1 trace are due to temporary electronics having to be used to measure the current through this toroid.

50 Hz to maintain the plasma formation in the ion source. Efforts are underway to enable higher currents to be extracted over longer pulse lengths.

#### 7.1.4 Post-Extraction Acceleration Studies

The focussing performed by the post-extraction acceleration in the ion source is dependent on the gradient of the post-extraction potential. It can therefore be altered by either changing the post-extraction acceleration gap or the potential across this gap. It is envisaged that this will be optimised to maximise transmission into the LEBT. A preliminary experimental study has been undertaken to study the effect of varying the post-extraction acceleration gradient by varying the platform voltage (= extract voltage + post-extraction acceleration voltage), the results from which are shown in Figure 7.5. From this figure it can be seen that the ion beam goes through a focal point at a platform voltage of 37.5 kV, illustrating that the transmission can be optimised by altering the post-extraction acceleration gradient. For a further discussion of these results, see [98].



FIGURE 7.5: The beam profile, measured  $\sim 1$  m downstream of the ion source, for a variety of post-extraction acceleration voltages. The white text is the platform voltage (= extract voltage + post-extraction acceleration voltage), the black text is the currents measured through the second toroid. The pseudo-colour scale is the same for each picture [98].

#### 7.1.5 Emittance Reduction

#### 7.1.5.1 Ion Source Dipole Field Gradient

Recent studies have shown that the field gradient, n, of the standard ISIS analysing dipole in the ion source is too large (n = 1.4) for the level of space charge present and overcompensates the defocussing effect of the space charge. A new, optimised n = 1.2 dipole is being used for the FETS [99].

#### 7.1.5.2 Plasma Meniscus Studies

To minimise the emittance of the ion source, optimisation studies of extraction from the ion source have recently begun, as the initial divergence of the ion beam is defined by the extraction electrode geometry and the curvature of the plasma meniscus<sup>\*</sup>. It has been shown [100] that an optimised extraction geometry can be designed for any meniscus curvature or, conversely, for a given extraction geometry, the conditions for optimum beam transport can be achieved by varying the curvature of the plasma meniscus.

The curvature of the plasma meniscus is influenced by the extraction voltage and the plasma density. Given that it is preferable to have the extraction voltage as large as possible to maximise the beam current extracted, the plasma density needs to be varied to optimise the curvature of the plasma meniscus. This can be varied by either varying the gas pressure in the ion source or the discharge current.

An experimental study [100] has been performed using the FETS ion source to optimise the curvature of the plasma meniscus by varying the discharge current. The aim of this study was to find the discharge current that gave the minimum divergence angle. A extraction voltage of 14 kV was used, with the

<sup>\*</sup>The plasma meniscus is effectively the surface from which the H<sup>-</sup> ions are emitted.



FIGURE 7.6: The measured variation of the horizontal emittance and divergence angle as a function of discharge current for a 14 kV extraction voltage [100].

ion source temperature being kept constant by varying the flow of cooling air. The results are shown in Figure 7.6.

The optimal divergence angle is found at a discharge current of 55 A (there is also a local minimum in the emittance at this point). The smaller emittances for lower discharge currents are thought to be due to less beam being extracted for these conditions. The effect in the vertical divergence angle was significantly less because of the FETS ion source slit extraction: the curvature of the plasma meniscus is a lot less over the 10 mm length of the slit than over its 0.6 mm width.

Additional optimisation work on the extraction of the FETS ion source is ongoing, with further improvements anticipated.

### 7.2 Laserwire Commissioning

#### A Note on Errors

Many of the graphs in this chapter are presented without error bars because of the difficulty in quantifying the errors present in many of the measurements. For example, whenever the ion source dropped out and needed to be restarted, the results of any repeated experiments were the same as the original ones in terms of the trends observed but not in terms of the absolute changes. In addition, the absolute precision of the pressure measurements is  $\sim 50\%$ , although the precision of measurements relative to one another is much better than this. As such, primary consideration should be given to the trends shown rather than to the absolute changes.

#### 7.2.1 Suppression Electrode Function

The suppression ring, the design of which is described in §5.2.2, was shown to be effective in suppressing some of the background electrons produced from interactions of the ion beam with the residual gas. This is demonstrated by the data presented in Figures 7.7 and 7.8. The ion source and detector settings that were used in the production of these data are given in Table 7.1.

Parameter	Value	
$H_2$ valve voltage	4 V	
Pressure (ion source)	$9.6 \times 10^{-5}$ mbar	
Discharge current	55 A	
Magnet current	11.2 A	
Extract voltage	14  kV	
Caesium oven temperature	$168^{\circ}\mathrm{C}$	
Detector Settings <sup>†</sup>	<u> </u>	
Parameter	Value	
Jacket potential	$1800 V^{\ddagger}$	
Faraday cup bias	500 V	
Suppression ring bias	Varied	
Grid potential	0 V	
Magnet current	1 A	

Ion Source Settings

TABLE 7.1: The ion source and detector settings for the results presented in  $\S7.2.1$ .

 $<sup>^{\</sup>dagger}A$  description of the detector components is given in §5.2.

<sup>&</sup>lt;sup> $\ddagger$ </sup>High-voltage breakdowns between the jacket and the suppression ring prevented the jacket being held at it's nominal potential of 2 kV for most of the results presented in this chapter.



FIGURE 7.7: Oscilloscope traces of the signal measured on the Faraday cup for suppression ring biases of 0 V and -500 V.



FIGURE 7.8: The total charge collected per pulse and the average current in the last  $100\mu$ s of the pulse, as a function of the suppression ring bias.

#### A Note on Analysis

In assessing these and many of the other data sets presented in this chapter, two methods of quantifying the signal size were used: the total charge within the pulse (where the extent of the pulse is defined as the 300  $\mu$ s window indicated by the two solid lines in Figure 7.7) and the average current within a 100  $\mu$ s window at the end of the pulse (indicated by the dotted lines in Figure 7.7). Over all the experiments performed, the trends in the two measures were found to agree with one another (see, for example, Figure 7.8) and so, for clarity, only the total charge measured will be considered for the remainder of this chapter.

The suppression ring reduces the total charge collected by approximately a third, compared to an simulated reduction of 60%. However, the measured charge was larger than the charge expected from the simulation both with (24 nC measured versus 8 nC<sup>§</sup> expected for a bias of -500 V) and without (34 nC measured versus 21 nC expected) a bias on the suppression electrode. If the offset between the measured and expected charge is removed, the suppression electrode performs as expected (this can be seen graphically by comparing the gradient of the measured and expected charge, as a function of the suppression ring bias, in Figure 7.8).

This offset between the measured and expected charge is thought to be due to the collection of some of the secondary electrons produced by the 10 mA of  $H^-$  ions lost in the laserwire vacuum vessel. There could also be an additional contribution if the assumption made in the simulations—that the residual gas electrons have the same velocity as their parent  $H^-$  ions—is not completely valid and (for example) residual gas electrons produced inside the detector volume are collected.

#### 7.2.1.1 The Unsuppressed Background

In this section, the background that is not suppressed by the suppression electrode is considered. The ion source and detector settings for the results presented in this section are given in Table 7.2.

Some unsuppressed background signal is to be expected as there will be residual gas electrons produced in the region where the suppression ring allows transmission. To investigate this remaining background, the potential on the grid (which sits between the copper jacket and the Faraday cup) was varied and the charge on the Faraday cup was measured (see Figure 7.9).

 $<sup>^{\</sup>S}$ Where comparisons with simulated data are made in this chapter, it is to the simulations of the initial, rather than nominal, FETS beam as defined in §5.2.2.

Ion Source Settings

Parameter	Value	
$H_2$ valve voltage	4 V	
Pressure (ion source)	$9.6 \times 10^{-5}$ mbar	
Discharge current	55 A	
Magnet current	11.2 A	
Extract voltage	14 kV	
Caesium oven temperature	$168^{\circ}\mathrm{C}$	
Detector Settings		
Parameter	Value	
Jacket potential	1800 V	
Faraday cup bias	500 V	
Suppression ring bias	$-400 { m V}$	
Grid potential	Varied	
Magnet current	1 A	

TABLE 7.2: The ion source and detector settings for the results presented in  $\S7.2.1.1.$ 



FIGURE 7.9: The total charge collected per pulse as a function of the grid bias, for a suppression ring bias of -400 V.

As Figure 7.9 shows, the functional form observed as the potential on the grid is increased is similar to that of the suppression electrode case (see Figure 7.8), which supports the hypothesis that the electrons being stopped are residual gas electrons produced in the region where the suppression electrode allows transmission. However, there are some electrons that are not stopped by the grid, suggesting that part of the background is not related to interactions with the residual gas. This part of the background signal remains for grid biases of up to 2 kV and is thought to be related to the secondary particles produced from the 10 mA of losses produced from collimation of the H<sup>-</sup> beam in the laserwire vessel. If this hypothesis is correct then this background should reduce as the ion beam reduces in size.

#### 7.2.1.2 Varying the Residual Gas Pressure

To further investigate the hypothesis that some of the background signal measured is due to residual gas electrons, the pressure in the vacuum system was varied by altering the hydrogen gas flow rate into the ion source. (The ion source and detector parameters for the results presented in this section are given in Table 7.3.) Whilst this is not the ideal way to alter the residual gas pressure, as the plasma dynamics in the ion source (and consequently the beam dynamics) are also altered, it was the only way available. That the ion source performance also changes in these measurements is most obviously illustrated by the change

Ion Source Settings			
Parameter	Value		
$H_2$ valve voltage	Varied		
Pressure (ion source)	Varied		
Discharge current	55 A		
Magnet current	14 A		
Extract voltage	11.2  kV		
Caesium oven temperature	$170^{\circ}\mathrm{C}$		
Detector Settings			
Parameter	Value		
Jacket potential	0 V		
Faraday cup bias	500 V		
Suppression ring bias	0 V		
Grid potential	0 V		
Magnet current	0 A		

|--|

TABLE 7.3: The ion source and detector settings for the results presented in §7.2.1.2.



FIGURE 7.10: The total charge measured and expected  $\P$  per pulse per unit ion beam current, as a function of residual gas pressure. The ion beam current measured through the second toroid is also shown.

in beam currents for different gas flow rates, as shown in Figure 7.10.

Figure 7.10 also shows that there is a decrease in the charge measured on the Faraday cup as the amount of hydrogen injected into the ion source (and consequently the residual gas pressure) decreases. This can be partially ascribed to the reduction in the number of residual gas interactions, although not completely as the gradient of the decrease is less than -1, the gradient that would be expected if the decrease was solely attributable to the reduction in the residual gas pressure. The additional decrease is thought to be due to the change in ion source performance as the gas flow changes.

<sup>&</sup>lt;sup>¶</sup>The detector settings used to produce the measured data presented in this graph were not simulated and so the expected charge shown is for the nominal detector settings (without a suppression electrode). As such, a direct comparison between the measured and expected charge can not be made.

#### 7.2.2 Negating the Unsuppressed Background Signal

The effect of varying the grid potential over a range of positive and negative biases was studied, with the other detector parameters fixed at  $zero^{\parallel}$ . It was observed (see Figure 7.11) that the total charge collected goes through zero and becomes positive for voltages above approximately 250 V. This is because the signal measured on the Faraday cup becomes bipolar as the grid voltage increases and the magnitude of the positive and negative components vary at different rates as the grid potential varies (an example of a bipolar signal is shown in Figure 7.12). The positive component of the signal is thought to be due to secondary electrons (produced on the surface of the Faraday cup by the incident electrons) being attracted out of the cup towards the grid. If the number of secondary electrons produced and attracted out of the cup towards the grid is greater than the number of incident electrons, a net positive charge will be measured on the Faraday cup. There may also be a contribution from the positive residual gas ions produced by interactions of the ion beam with the residual gas, although these would first need to overcome the potential barrier introduced by the grid.

This feature was also observed with nominal detector settings (albeit at a different grid potential) and, by partially negating the background signal in this way, the high-resolution electronics (described in §5.3) could be be used to measure the signal (instead of a digital oscilloscope). To use these electronics, the grid voltage was varied until the total charge accumulated on the Faraday cup over the duration of a pulse was less than 1 nC (the largest signal that can be measured using these electronics) and then the measurement was made. A measurement made of the background signal (with the laser turned off) is shown in Figure 7.13.

This measurement illustrates one of the problems encountered in measuring a signal from the photo-detached electrons: even when the offset introduced by the background is partially removed, the width of the distribution<sup>\*\*</sup>—4.9 pC is significantly larger than the photo-detached electron signal expected from the initial FETS beam parameters—512 fC. Indeed, the bin width of 335 fC is comparable to that the photo-detached electron signal. (For comparison, the expected photo-detached electron signal from the nominal FETS beam parameters, 6.9 pC, is comparable with the width of the distribution.)

 $<sup>\</sup>parallel$ That a signal was measured on the Faraday cup with the all the detector components off apart from the grid bias indicates that the residual gas electrons have a larger transverse velocity than assumed in the simulations in §5.2.2, as hypothesised in §7.2.1.

<sup>\*\*</sup>Caused by the pulse-to-pulse variation of the ion source.

Ion Source Settings			
Parameter	Value		
$H_2$ valve voltage	3.8 V		
Pressure (ion source)	$9.0 \times 10^{-5}$ mbar		
Discharge current	55 A		
Magnet current	14 A		
Extract voltage	15.5  kV		
Caesium oven temperature	$165^{\circ}\mathrm{C}$		
Detector Settings			
Parameter	Value		
Jacket potential	0 V		
Faraday cup bias	0 V		
Suppression ring bias	0 V		
Grid potential	Varied		
Magnet current	0 A		

TABLE 7.4: The ion source and detector settings for the data presented in Figure 7.11.



FIGURE 7.11: The total charge collected per pulse, as a function of the grid bias. The ion source and detector settings used to produce the data presented in this graph are given in Table 7.4.

Ion Source Settings

Parameter	Value	
$H_2$ valve voltage	3.8 V	
Pressure (ion source)	$9.0 \times 10^{-5}$ mbar	
Discharge current	53.8 A	
Magnet current	12 A	
Extract voltage	14.6 kV	
Caesium oven temperature	$180^{\circ}\mathrm{C}$	
Detector Settings		
Parameter	Value	
Jacket potential	1800 V	
Faraday cup bias	500 V	
Suppression ring bias	0 V	
Grid potential	677 V	
Magnet current	1 A	

TABLE 7.5: The ion source and detector settings for the data presented in Figure 7.12.



FIGURE 7.12: A oscilloscope trace of a bipolar current measurement, where the sum of the positive-going signal is 57.9 nC and the of the negative-going signal is -62.2 nC, giving a total charge of -4.3 nC. The ion source and detector settings used to produce the data presented in this graph are given in Table 7.5.

Ion Source Settings		
Parameter	Value	
$H_2$ valve voltage	$3.8 \mathrm{V}$	
Pressure (ion source)	$9.0 \times 10^{-5}$ mbar	
Discharge current	50 A	
Magnet current	12.2 A	
Extract voltage	14.6  kV	
Caesium oven temperature	$175^{\circ}\mathrm{C}$	
Detector Settings		
Parameter	Value	
Jacket potential	1800 V	
Faraday cup bias	500 V	
Suppression ring bias	0 V	
Grid potential	$747 \mathrm{V}$	
Magnet current	1 A	

TABLE 7.6: The ion source and detector settings for the data presented in Figure 7.13.



FIGURE 7.13: The background signal with the laser turned off, measured by the laserwire electronics. The histogram contains a total of 10,000 entries. The ion source and detector settings used to produce the data in this graph are given in Table 7.6.



FIGURE 7.14: The variation of the signal measured on the Faraday cup for two sets of data, as a function of time. Each point corresponds the average of 500 measurements (10 seconds-worth), with the error bars giving the standard deviation of the data in each time bin. The red (top) signal is the same data that was used to produce Figure 7.13.

Another factor that contributed to the difficulty in measuring the signal from photo-detached electrons was the longer-term ion source stability. Sometimes, small fluctuations in the source output—so small that they were not observed on the beam current transformers—could be observed as a change over time in the current measured on the Faraday cup (see, for example, Figure 7.14). These fluctuations make it impossible to use the FETS laserwire electronics to measure the signal on the Faraday cup over a prolonged period of time to accumulate large sets of data with good statistics.

Attempts were made to measure the photo-detached electron signal but proved unsuccessful due to the high background level. Recommendations for improving the signal-to-noise ratio are given in §7.2.5. In the next section, a study of the background signal is presented.

### 7.2.3 The Spectrum of the Background

Having been unable to reduce the background enough to measure the photodetached electron signal, the spectrum of the background was studied. This was done by turning off the magnet, suppression ring and copper jacket and measuring the signal on the Faraday cup with an oscilloscope for various potentials on the grid between the jacket and the Faraday cup. From this data, the variation in the spectrum of the residual gas electrons with time could be retrieved.

Figure 7.15 shows the spectrum of the signal measured on the Faraday cup, integrated between the energy defined by the grid bias, E, and infinity,

$$I_{total} = \int_{E}^{\infty} I(E) dE,$$

for various different times into the beam pulse.

It is more instructive to consider the discrete differential of this data,

$$\frac{\delta I}{\delta E} = \frac{I(E_i) - I(E_{i-1})}{E_i - E_{i-1}},$$

where  $I(E_i)$  and  $E_i$  are the current measured for the *i*th grid bias and the



FIGURE 7.15: The integrated spectrum  $(I_{total} = \int_{E}^{\infty} I(E)dE)$  of the signal measured on the Faraday cup for different times into the pulse.

energy defined by the *i*th grid bias, respectively. This allows the spectrum of the particles collected by the Faraday cup at different times into the beam pulse to be calculated.

These spectra are shown in Figure 7.16. From this figure it can be seen that the spectrum changes up to 80  $\mu$ s into the beam, after which time it stabilises. (The spectra for times after 100  $\mu$ s did not vary significantly from those at 80  $\mu$ s and 100  $\mu$ s and so are not shown for clarity.) The changes in the first 20  $\mu$ s can be attributed in part to the rise-time of the ion source extract pulse. (Figure 7.17 shows oscilloscope traces of the ion source extract pulse, the ion beam current and the signal measured on the Faraday cup. From this figure it can be seen that all of these traces have reached their maximum values after 20  $\mu$ s.) The changes in the spectrum that happen in the 60  $\mu$ s between 20  $\mu$ s and 80  $\mu$ s into the beam pulse are thought to be due to space-charge: as the degree of space-charge compensation builds up, the beam potential decreases and so the energy of the electrons produced in the beam by the interactions with the residual gas decreases. When an equilibrium is reached, no further changes are seen.



FIGURE 7.16: The spectrum  $(\delta I/\delta E = [I(E_{i+1}) - I(E_i)]/[E_{i+1} - E_i])$  of the signal measured on the Faraday cup for different times into the pulse.



FIGURE 7.17: Oscilloscope traces of the ion source extract pulse, the ion beam current and the signal on the Faraday cup. All signals have been normalised such that their maximum value is +1.

### 7.2.4 The Effect of the Laserwire Detector on the Ion Beam

During the commissioning of the FETS laserwire it was observed that the potential on the copper jacket had an influence on the profile of the transmitted ion beam (see Figure 7.18). This was unexpected from the simulations of the transmission of the ion beam through the detector. It is thought that the change in profile is due to the space-charge compensating particles being affected by the potential (a mechanism that was not accounted for in the simulation work): for a positive voltage on the jacket, the compensation particles are expelled from the detector volume by the potential; for a negative voltage on the jacket, the compensating particles are attracted to the jacket. In both instances, space-charge compensating particles are removed from the beam, allowing space-charge to act. This increases the size of the beam. These results are discussed in more detail in [98] but are not yet completely understood; further experiments are required to fully explain the mechanism for what is occurring.



FIGURE 7.18: Scintillator images of the ion beam for different potentials on the copper jacket. The pseudo-colour scale is the same for each picture but the intensities have been scaled according to the beam current transmitted through the second toroid. The white text is the potential that was on the copper jacket when the corresponding image was acquired [98].

### 7.2.5 Comparison of the FETS laserwire to the SNS laserwire

In this section a comparison between the FETS laserwire and the (successful) SNS laserwire is made, to help understand why the FETS laserwire has been, to date, unable to detect photo-detached electrons.

The SNS laserwire is used to measure projections of the SNS beam onto the xand y-planes at several positions in the SNS's 186–1000 MeV superconducting linac. To photo-detach the electrons, it uses a Q-switched, Nd:YAG laser that operates at 1064 nm and can deliver between 50 and 200 mJ in 7 ns [101].

There are two features of the SNS laserwire that mean it has a significantly better signal-to-noise ratio than the FETS laserwire. First, its background is lower. This is because the measurements are performed further downstream than the FETS laserwire, where the pressure is significantly lower than just after the ion source (the pressure in the SNS superconducting linac is specified as  $1.3 \times 10^{-9}$  hPa [102], four orders of magnitude lower than the pressure just after the FETS ion source). This means that the SNS laserwire has a significantly smaller residual gas electron background, compared to the FETS laserwire, and so a better signal-to-noise ratio. Secondly, the SNS laserwire operates with a laser that routinely delivers 100 mJ in a 7 ns pulse. Because of the higher laser power, the neutralisation fraction is significantly larger for the SNS laserwire (7.5% at 200 MeV and 5% at 1 GeV [101]), than that of the FETS laserwire (1.13  $\times 10^{-4}$ %). This also improves the signal-to-noise ratio.

#### 7.2.6 Possible Improvements to the FETS laserwire

To detect the photo-detached electrons with the FETS laserwire, the signal-tonoise ratio needs to be improved. This can be done by either reducing the noise level or increasing the signal size. Some ways in which this could be done are outlined in this section.

If the residual gas pressure was reduced, the background signal from the interaction of the H<sup>-</sup> beam with the residual gas would be reduced. However, given the location of the FETS laser-based beam profile monitor (just after the ion source, where 20 ml/min of H<sub>2</sub> gas has to be pumped in to operate the ion source), extra pumping is unlikely to significantly reduce this. An alternative is to move the instrument further down the beamline, where the pressure would be considerably less. (The instrument was placed in this particular location as it was the only part of the beamline that was going to be completed on time.)

However, the most significant reduction of the background is likely to come

as a by-product of the continuing improvement of the ion source, when of the ion beam is reduced in size such that it does not collimate in the laserwire's vacuum vessel. This would remove the high-energy component of the background, which would be a significant development as, not only is it a large background, it also, unlike the residual gas background, can not be suppressed.

To increase the photo-detached electron signal size, the laser power could be increased. An increase by a factor of 10 to 5 W would give a photo-detached electron signal equivalent to the width of the background signal, if the size of the background signal was not reduced. Further increases would make it easier still to differentiate between the signal and the background. However, the cost associated with a more powerful laser is not negligible (and prevented a more powerful laser being used for the work presented in this thesis). Additionally, electronics that could measure a larger range at high resolution would remove the need to negate the unsuppressed background signal, which may make it easier to measure the photo-detached electron signal (as the effect on the transport of the photo-detached electrons that follows from having a potential on the grid between the copper jacket and the Faraday cup is currently not completely understood).

It is also possible that a pulsed laser with the same average power and a high repetition rate (such that there are multiple laser pulses within one ion pulse) could be used, in conjunction with fast electronics, to overcome the size of the background. This last avenue is currently being explored in collaboration with Royal Holloway, University of London.

In this chapter, the results of the initial commissioning of the FETS ion source and laserwire have been presented. At the time of writing, the ion source performance goals have not been met and the detection of photo-detached electrons has not been observed in the laserwire detector. However, the commissioning process is on-going and it is expected that the ion source performance goals and the operation of the laserwire instrument (having implemented some of the improvements discussed above) will be demonstrated soon.

# Chapter 8

# Conclusions

#### 8.1 Summary

The design and results from the initial commissioning of a laser-based beam profile monitor, the basis of which is the photo-detachment and collection of the outer electrons from a small proportion of the FETS  $H^-$  beam just after the ion source, have been described.

The formula for the expected number of photo-detached electrons was derived in §4.2.4. The expected number of photo-detached electrons was calculated (in §5.1.1) to be  $3.2 \times 10^6$  electrons for the beam that was available during the initial FETS laser-based beam profile monitor commissioning<sup>\*</sup> and  $4.3 \times 10^7$  electrons for the nominal FETS beam<sup>†</sup>, for the 500 mW, 671 nm CW laser used in the beam profile monitor. The simulations of the detector (see §5.2.1) indicated that it should be capable of capturing all of the photo-detached electrons produced. Additionally, the readout electronics have the necessary sensitivity to measure the expected signal accurately and precisely (see §5.3). However, the background to the measurement of the photo-detached electrons, consisting of electrons produced from the interaction of the H<sup>-</sup> ions and the residual gas and secondaries produced from the 10 mA of the beam that was lost in the instrument's vacuum vessel, proved to be larger than the expected photo-detached electron signal. Consequently, the photo-detached electron signal was unable to be measured separately from the background.

Recommendations for developments of the instrument to improve the signalto-noise ratio were made in §7.2.5. The main reduction in the background level will come when the ion beam is reduced in size such that 10 mA of beam current is not lost in the laserwire vacuum vessel. The signal size could be increased

<sup>\*</sup>A 40 keV, 35 mA, 200  $\mu \mathrm{s}$  pulse of H  $^-$  ions.

 $<sup>^{\</sup>dagger}\mathrm{A}$  65 keV, 60 mA, 2 ms pulse of H  $^{-}$  ions.

by simply increasing the power of the laser used to photo-detach the electrons from the  $H^-$  ions. Other methods of improving the signal-to-noise ratio, such as using a pulsed laser with a high repetition rate, in conjunction with fast electronics, are also being explored.

An experimental study of the background signal (see §7.2) showed that, whilst it comprised largely of residual gas electrons, it had a sizable component that was not produced by interactions with the residual gas and had a high energy (E > 2 keV). The source of this part of the background is unconfirmed but it is thought that these electrons were produced by the ion beam collimating on the apertures near the detector. Whilst the residual gas electrons could be partially suppressed (demonstrated in §7.2.1), this high-energy background could not and so formed a part of the irreducible background to the measurement of the photo-detached electrons. The time-resolved spectrum of the background electrons was measured and used to show that the space-charge compensating particles are built up in the first 80  $\mu$ s of the initial FETS ion beam.

Two algorithms that are capable of reconstructing the beam profile from a series of beam projections—the filtered back-projection algorithm and the algebraic reconstruction technique—were introduced and compared in Chapter 6. The filtered back-projection algorithm was shown to be computationally faster than the algebraic reconstruction technique but the reconstruction performed by the algebraic reconstruction technique more faithfully reproduces the initial distribution, especially from the number and type of projections that would be measured by the FETS laser-based beam profile monitor.

The development of the FETS laser-based beam profile monitor is ongoing. Increased international interest in laser-based beam diagnostics for  $H^-$  beams (from, for example, SNS, who wish to further develop the systems they have, and CERN) mean that the development of this elegant technique will continue and that it will be added to the suite of tools that will be used to ensure the successful operation of the next generation of high-power proton accelerators.

# Appendix A

# Algebraic Reconstruction Technique: Implementation

## A.1 Code

In this section, the code used to implement the algebraic reconstruction technique in Matlab is presented. The **parse\_inputs** sub-function, which parses the inputs to the function to ensure they are correctly formatted and initialises some of the optional inputs, is not included as its inclusion would not add to the description of how the ART algorithm was implemented.

Note that, in Matlab, '...' indicates that the next line is a continuation of the current line. It is used to split long lines of code over several lines. Also, % is the Matlab comment indicator.

```
function [recon_image, D, it_no_write] = ...
ART_recon(n,R_averages,p,varargin)
%%%%%%%%%
% FUNCTION SYNTAX:
% [recon_image,D,it_no_write] = ART_recon(n,R_averages,p,no_it,N)
%
% INPUTS:
% 'n' n^2 is the number of pixels in the reconstructed
% image.
% 'R_averages' is the the measured data.
% 'p' is an array containing the masks.
```

%	OPTIONAL INPUTS:			
%	'no_it'	This variable can be one of two things. It is		
%		either the number of interations over which to		
%		run the main loop, if it is greater than or equal		
%		to 1. The default value is 10000.		
%		Alternatively if it is less than 1, this is the		
%		value of the discrepancy at which the program		
%		will break out of the main loop.		
%	'N'	is an array containing the number of pixels		
%		covered by a ray. If it is not provided here it		
%		is calculated in the code.		
%				
%	OUTPUTS:			
%	'recon_image'	is the final reconstructed image. It corresponds		
%		to the image that has the smallest descrepancy.		
%	ʻD'	is a vector containing values of the discrepancy		
%		between the reconstructed and original		
%		projections.		
%	'it_no_write'	is the iteration number that recon_image was		
%		recorded.		
%				
%	Written by Day	vid Lee (david.a.lee@imperial.ac.uk).		
%	Last modified	: 01.08.2008.		
%%				
%1	°%			
% Error messages for if the number of outputs requested is not				
% compatible with the function.				
$\%$ Input variables are dealt with by the parse_inputs subfunction.				
%%	· · ·			
if	nargout>3			
	error('A maximum of three output variables can be'			
	' specified	<pre>l: [recon_image,D, it_no_write] ='</pre>		
	' ART_recor	<pre>n(n,R_averages,p,varargin)');</pre>		
el	seif nargout<	L		
	error('A minimum of one output variable must be'			
	<pre>' specified: [recon_image,D, it_no_write] ='</pre>			
	' ART_recor	<pre>n(n,R_averages,p,varargin)');</pre>		
er	nd			

```
%%%
% Initialising variables
%%%
rho_tilde=zeros(n.*n,1);
rho=zeros(n.*n,1);
rho_add=zeros(n.*n,1);
rho_final=zeros(n.*n,1);
no_proj=size(R_averages,2);
no_rays=size(R_averages,1);
m=no_rays.*no_proj;
Rq=zeros(m,1);
% Initialising R_i
R=zeros(m,1);
j=1:no_rays;
for i=1:no_proj
    index=(i-1).*no_rays+j;
    R(index,1)=R_averages(j,i);
end
[P, no_it, N, D_limit] = ...
 parse_inputs(no_proj, no_rays, n, m, p, varargin{:});
P=sparse(P);
                \% Reduces the time the matrix multiplication at
                % the beginning of the main loop takes.
Dsum=zeros(m,1);
D=zeros(no_it,1);
D_min=10;
disp_check=floor(no_it./10);
%%%
% Main Loop
%%%
for q=0:no_it
    % Calculating Rq
    Rq=P*rho; % The bottle-neck w.r.t. the computational speed.
```
```
% Cycling over projections
    if rem(q,m) == 0
        ind=m;
    else
        ind=rem(q,m);
    end
    % Updating the density grid
    rho_tilde = rho + P(ind,:)'*((R(ind,1)-Rq(ind,1))./N(ind,1));
    rho(:,1) = ( ( ( rho_tilde(:,1) > 0 ) & ...
     ( rho_tilde(:,1) < 1 ) ).*rho_tilde(:,1) ) ...</pre>
     + ( rho_tilde(:,1) >= 1 ) ;
    if q~=0 \% Don't do for first iteration
        summ = sum(((R(:,1)-Rq(:,1)).*(R(:,1)-Rq(:,1)))./N(:,1));
        D(q,1)=sqrt(summ./m);
    end
    % Updating 'best' (lowest discrepancy) rho
    if q>1
        if D(q,1)<D_min
            rho_final=rho;
            it_no_write=q;
            D_{\min}=D(q,1);
        end
    end
    if D_limit<1&&D_min<D_limit</pre>
        break
    end
end
\% Reshaping rho to be read as the reconstructed image
for i=1:n
    for j=1:n
        index=(i-1).*n+j;
        recon_image(i,j)=rho_final(index);
    end
end
return
```

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All things were created by Christ and for him. He is before all things, and in him all things hold together.

Colossians 1:16–17

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Yn olaf, mae fy ngwraig hyfryd Catrin wedi bod mor gefnogol ac mor amyneddgar yn ystod cyfnod gwneud fy noethuriaeth, yn enwedig pan oedd y gwaith yn mynd yn drwm iawn. Rwyt ti'n wych; diolch yn fawr.

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