A HIGH RESOLUTION SPATIAL-TEMPORAL IMAGING DIAGNOSTIC FOR HIGH ENERGY DENSITY PHYSICS EXPERIMENTS

Y. T. Zhao, Z. M. Zhang, H. S. Xu, W. L. Zhan
Institute of Modern Physics, Chinese Academy of Science, Lanzhou, China
W. Gai, J. Q. Qiu, S. C. Cao, Argonne National Lab., Argonne, IL 60439 USA
C. X. Tang, Department of Engineering Physics, Tsinghua University, Beijing, China

Abstract

We present a scheme that uses a high energy electron beam as a probe for time resolved (~ pico – nano seconds) imaging measurements of high energy density processes in materials with spatial resolution of < 1 μm. The device uses an electron bunch train with a flexible time structure penetrating a time varying high density target. By imaging the scattered electron beam, the detailed target profile and its density evolution can be accurately determined. In this paper, we discuss the viability of the concept and show that for densities in the range up to 400 gram/cm3, an electron beam consisting of a train of ~800 MeV bunchlets, each a few ps long and with charges ~nC is suitable. Successful demonstration of this concept will have a major impact for both future fusion science and HEDP physics research.

High Energy Density Physics aims to study the properties of matter under extreme states of temperature and pressure. Recent work on high intensity ion- and laser beams and advanced pulse power techniques have been used to reach regions of the phase diagram of matter under controlled conditions for fusion research that were not accessible before in laboratory experiments [1]. In general, high energy density matter can only be transiently produced in the laboratory on a time scale of 10 ns to 1 μs. In addition, the pressure in a high energy density sample exceeds 1 Mbar (100 GPa), thus the hydrodynamic response of the sample is a high expansion velocity in the range of km/s (μm/ns). Therefore diagnostics which are capable of high time resolution (< ns) and space resolution (10 μm) are needed. For example, the proposed Heavy Ion Accelerator Facility at the Lanzhou Institute of Modern Physics [2] requires advanced imaging diagnostics to understand the details of the fuel compression process in inertial fusion ignition experiments, and provide feedback. The imaging system must have a large dynamic range and must be sensitive to a mixture of high and low Z (atomic number) elements. It is essential to measure the moving boundary as well as the proportions of different materials in order to understand the hydrodynamic processes of the HED/ICF sample. We must point out that the compression of the target material is from many directions, thus a time dependent imaging system in three spatial dimensions is desirable.

Many diagnostic tools are based on the use of hard X-rays from a high intensity laser striking an X-ray generator [3]. However, it is challenging to focus and transport x-rays with lenses or mirrors and to achieve the necessary contrast if high and low Z target materials are simultaneously involved. Moreover, it is technically arduous to tune the X-ray wavelength to the specific needs of the experiment. Other diagnostics methods, such as shadowgraphs using laser produced proton, electron, or even neutron beams constitute significant progress, but these techniques are restricted to geometrical imaging due to the large momentum spread of the laser generated particle beam. High energy proton radiography developed at Los Alamos National Laboratory has shown excellent results with respect to space and time resolution in high energy density matter diagnostics [4]. This technique is also proposed at the FAIR facility with 4.5 GeV protons [5]. Although it is arguable whether use of a proton beam is superior to an electron beam in penetrating the target, a high energy proton accelerator is costly. Also, a picosecond bunch length proton beam is not yet available in the lab. Here we propose a practical method that uses a high energy electron beam as a probe beam for high energy density matter studies. The principle is similar to that of the TEM (Transmission Electron Microscope). A relatively high energy electron beam (~ GeV) passing through a high density material, say an imploding ICF fuel pellet, would sample the structure of the target plasma over the duration of the pulse. The electron beam can then be imaged onto a fluorescent screen sothe material distribution can be inferred. Multiple electron bunches at intervals of ns to μs can then be used to measure the density change as a function of time. Electron beams consisting of bunch trains can be easily generated with present day RF photocathode technology. A typical target can be compressed from mm to 100 μm, thus resolution of < 10 μm is desired. In principle, such a resolution requirement can be easily met with a high energy electron beam with an appropriate optical system. A resolution of ~ 100 μm has been demonstrated with 30MeV electron radiography at LANL [6].

A typical RF photocathode based linac system is shown schematically in Figure 1. Beams ranging from a few pC to 100 nC/bunch and energy in the range of a few MeV to 1000 MeV can be generated, operating at RF frequencies in the 1 – 12 GHz range. The beam energy can be increased easily by adding more accelerating sections without any impact on the other beam parameters. State of the art technology allows the electron beam timing to be locked to a master clock with a timing jitter less than 1 ps. Details can be found in [7]. For our requirements, one can easily generate a small group of 3 electron bunches separated by one RF period. When the beam exits the accelerator, it can be passed through a 1/3 harmonic deflecting cavity that separates the beam into three directions, deliv-

ISBN 978-3-95450-132-8

ered to a target with timing adjustment for a 3-D measurement of the target. In addition, a second and third bunch group can be generated at arbitrary time delays and used for a time evolution study of the HEDP target to ps accuracy. Normalized emittances from RF guns are typically 1 mm-mR/nC with about 1 % energy spread, so that the beam can be easily focused down to micro-spot sizes for high spatial resolution studies. We will discuss the details of this proposed technique in the rest of this paper.

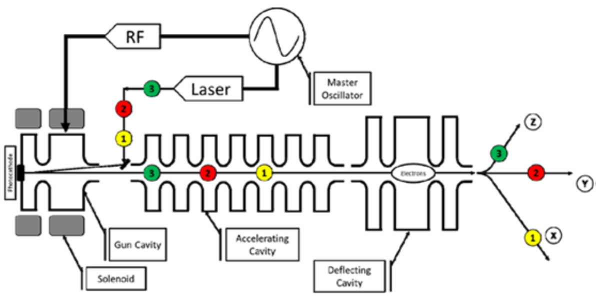

Figure 1: A typical RF photocathode electron injector system. A mode locked laser is used to produce a train of several electron bunches. Three bunches at a time can then be delivered to target with proper timing adjustment to achieve synchronization in three directions. Multiple bunch trains can be used to study the time evolution of the target density distribution.

Electron scattering processes in a dense material are complicated, but in general just two cases need to be considered: 1) multiple elastic scattering, where particles lose almost no energy. Electrons are scattered primarily in the forward direction. The number of particles transmitted is strongly dependent on the thickness and density of the target. It is because of these dependences that the proposed scheme would work. 2) Inelastic scattering (bremsstrahlung) where particles lose some large fraction of their energy. One of the major characteristics of this scattering process is that the electron is deflected at large angles with respect to the beam axis and thus can be filtered out. For the proposed diagnostic we are only interested in electrons with energy close to the incident value (see next section). A well tested particle transport simulation code, such as EGS4nrc or Geant4, is suitable for this study. Figures 2 and 3 show a scattering diagram of deuterium, with a density ranging from 0.02 g/cm^3 to 400 g/cm3, during a compression process. As shown in the Figure, for a given energy, the scattering angle and energy loss depend strongly on the material density. There is also a strong dependence on the radiation length which is an issue for multi-component inhomogeneous plasma, so technically we are not probing the density but density times the radiation length. On the other hand, for a given density, due to the flexible input energy, one could find a suitable beam energy that will be able to pass through the target and can be transported to the imaging plane no matter what the density is. This flexibility gives us some confidence in the effectiveness of the technique.

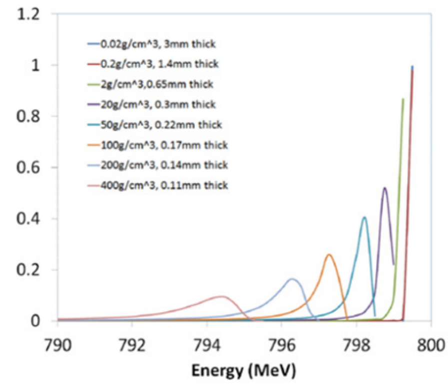

Figure 2: Energy distribution of the forward scattered 800MeV electron beam passing through a compressed target.

The initial target is 3 mm in diameter and compressed in all the directions, and finally compressed to 400 g/cm^3, which is near the critical density for fusion. Most of the transmitted electrons are still near the input energy (< 1%), with the general scattering characteristics as shown in Figures 2 and 3.

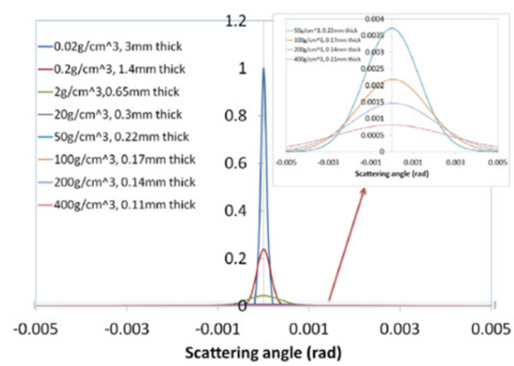

Figure 3: A figure showing the angular distribution vs. density as in Figure 2.

One can see that forward scattered electrons at very high target density are transmitted only at ~ 10^{-4} fraction of the incoming beam intensity, but using a high charge beam (> 10^{10} electrons), there are still more than enough electrons for imaging.

With a flexible beam from a LINAC as shown in Figure 1, an electron beam based imaging system in principle can be made to exactly correspond to a conventional geometric light optics imaging system. A possible imaging system is shown in Figure 4, which requires a lens for object imaging. In electron optics, one can use a quadrupole triplet to act as a single thin lens in both the horizontal and vertical planes as for a single focusing lens in light optics. However, use of additional quadrupole lenses (5 in the example discussed here) provides additional flexibility for adjustment of the image, as in Figure 5. The quad fields can be adjusted to track the beam energy as determined by the expected target thickness. Also, a small aperture is used to collimate the scattered electron beam for both off axis and off energy particles [8]; with an appropriate size and location of the aperture, a high contrast image can be obtained.

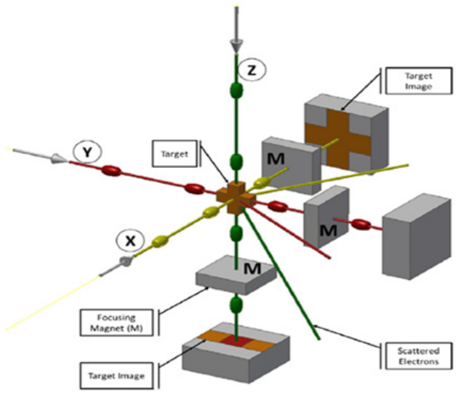

Figure 4: A proposed time dependent and three spatial dimension electron imaging system for a high density target. A bunch train with three beamlets 1, 2, 3 is generated via photocathode gun as in Figure 1. The beamlets are then delivered to the target in three orthogonal directions with precision timing adjustments. In this way, three dimensional target density/distribution information can be extracted.

To illustrate the system concept design and to guide a system test experiment, we have made a numerical design which can be easily implemented in a typical laboratory setting as illustrated in Figure 5. The system resolution may be limited by a number of factors, like imaging detector thicknesses and chromatic aberrations. However, these factors are always inversely proportional to the incident electron beam motion; thus by increasing the electron beam energy, a very high resolution can be achieved. A typical of submicron resolution can be achieved from the simulation.

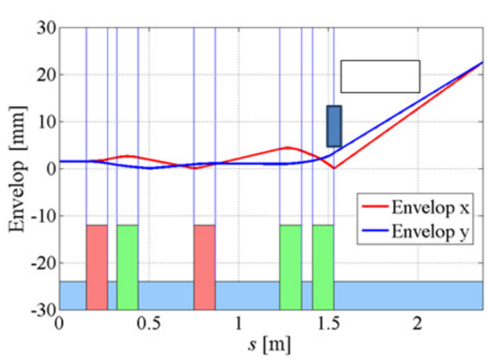

Figure 5: A layout of a prototype imaging system with 5 magnetic quadrupoles. Quads are arranged in a DFDFF pattern in the horizontal plane.

We have presented a conceptual design of an electron radiograph system for materials at high energy density. Verified by numerical simulations, we found that this device has distinct advantages over a traditional X-ray imaging system: 1) The electron beam can be easily focused to micron spot sizes and transported; 2) With mature RF photocathode based electron beam technology, high electron intensities (10^{11} per pulse) are available at reasonable cost; 3) Unprecedented resolution can be achieved with very high energy electron beams; 4) 3D imaging with high precision time resolution can be achieved. A successful implementation of this scheme may have impact on implications for heavy ion driven high energy density physics research. This technique can provide ultimate real time feedback on the target information, thus the drive beam can be adjusted to compensate for any non-uniform target compression. An engineering design of this system is being developed.

This work is partially supported by the U.S. Department of Energy under contract No. DE-AC02-06CH11357

REFERENCES

[1] S. Atzeni and J. Meyer-ter-Vehn, The Physics of Inertia lFusion : Beam Plasma Interaction, Hot Dense Matter (Oxford University Press, 2004).

[2] Z. Wang, Y. He, H. Jia, S. Liu, C. Li, X. Xu, B. Zhang, W. Wu, and H. Z. IMP, in Proceedings of LINAC-2012 (Jacow, Tel-Aviv, Israel, 2012).

[3] S. H. Glenzer and R. Redmer, Reviews of Modern Physics 81, 1625 (2009).

[4] N. S. P. King et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 424, 84 (1999).

[5] M. Durante and H. Stöcker, Journal of Physics: Conference Series 373, 012016 (2012).

[6] F. E. Merrill, A. A. Golubev, F. G. Mariam, V. I. Turtikov, and D. V. H. Collaboration, AIP Conference Proceedings 1195, 667 (2009).

[7] J. G. Power, AIP Conference Proceedings 1299, 20 (2010).

[8] F. E. Merrill, C. Morris, K. Folkman, F. Harmon, A. Hunt, and B. King, in Proceedings of PAC 2005 (IEEE, Knoxville, Tennessee, USA, 2005).

ISBN 978-3-95450-132-8