DESIGN OF THE INJECTION SYSTEM FOR THE CHALK RIVER SUPERCONDUCTING CYCLOTRON PROJECT

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Abstract

The Chalk River superconducting cyclotron will employ radial injection with stripping at the inner equilibrium orbit. Methods of matching the very tight and variable acceptance requirements of such a cyclotron are discussed along with the methods used for buncher phase control and Tandem injector control. Emphasis is given to the use of symmetry and modularity in the design.

Introduction

The Chalk River heavy ion superconducting cyclotron project will consist of a 13 MV MP Tandem accelerator injecting into a K = 520 (ME/Q^2) superconducting cyclotron. The mass-energy range extends from 7 to 50 MeV/u carbon to 3 to 10 MeV/u uranium.

The complete injection system consists of: (See Fig. 1)

i) 250 keV low energy negative ion injector
ii) Double cavity first and second harmonic low energy buncher
iii) MP Tandem
iv) Tandem analyser and control achromat
v) Second harmonic high energy buncher
vi) Buncher phase control achromat
vii) Cyclotron matching system

This paper will deal mainly with items iv to vii and in particular with the problem of matching the properties of the beam to the continuously variable optical properties of the cyclotron in order to meet its rather stringent and variable acceptance phase space.

Cyclotron Injection

The Chalk River cyclotron employs charge-exchange injection using a 20 $\mu g/cm^2$ C foil stripper at the inner equilibrium orbit[1)]. The stripping foil C (see Fig. 2) is placed such that the injection orbit of mean radius Ri is tangential to the inner equilibrium orbit of radius Ro. Thus

$$\frac{Ro}{Ri} = \frac{Qi}{Qo}$$ where Qo is the ion charge after stripping.

The ratio Qi/Qo ∿ 1/3 for all ions but because Qi and Qo are integers, the ratio and hence Ro cannot be constant and some radial motion of the stripper is required. A small ±1° steering magnet is also needed to ensure that the injection orbit is always tangent to the inner orbit at the stripper position.

Although the injection trajectories lie mainly in a valley and cross the hill at nearly normal angles, the optical properties of the cyclotron vary widely as a function of Bo and ion species. For example the axial focal length varies from 6.9 cm to 77.1 cm for carbon ions with energies between 50 MeV/u and 15 MeV/u denoted C-50 and C-15 respectively. By way of illustration, the first order transfer matrices for U-3 from the 1.24 m radius to the cyclotron center are given below. For the radial plane the matrix is

$$\begin{bmatrix} 1.00 & .105 & 0 & .706 \\ -36.82 & -2.881 & 0 & 5.972 \\ -3.20 & -.267 & 1 & 1.110 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ \theta \\ \ell \\ \delta \end{bmatrix}$$

and for the axial plane it is

$$\begin{bmatrix} -4.74 & -.162 \\ -67.67 & -2.532 \end{bmatrix} \begin{bmatrix} y \\ \phi \end{bmatrix}$$

The units[2)] are cm, mrad, and %$\Delta p/p$.

Table 1 gives the injection parameters for the extremum cases, U-10, U-3, C-50 and C-15.

The cyclotron will accept beams somewhat larger than the 2σ or 95% contour of the 6 dimensional phase space. It is seen that the acceptance is very tight as is expected for a compact cyclotron. Furthermore the optical properties are a strong function of Bo the mean field because the hill to valley field is not a ratio as in a conventional cyclotron but is approximately a constant difference. $B_H = B_V + B_D$.

The charge Qo is chosen to be at the peak of the charge state distribution for the injection energy Ei which fixes Qi. The production of ions with charge Qi is maximized by adjusting the pressure of the N_2 gas stripper in the MP Tandem terminal.

Bunching

The d.c. beam will be bunched initially by a two-cavity first and second harmonic buncher (see Fig. 1) that captures about 50% of the d.c. beam into ±1.5° of R.F. phase for all ion species. The phase difference between a particle following an arbitrary trajectory and one following the central trajectory is

$$\Delta\phi = \omega\left[\frac{L_o}{v_o} - \frac{L}{v}\right]$$ where v_o, L_o and v,L are the velocity

and effective path lengths of the central trajectory and arbitrary trajectory; ω is the angular R.F. of the cyclotron. In terms of the usual paraxial optical coordinates[2)] this becomes

Table 1

	Qi	Qo	Ri (cm)	Ro (cm)	Ei (MeV)	x† (cm)	θ (mrad)	y (cm)	φ (mrad)	ℓ (cm)	δ (%)
U-10††	10	33	65	16	138.9	.04	1.5	.14	.50	.10	.018
U-3	7	21	65	17.6	51.6	.05	2.1	.20	.50	.075	.025
C-50	2	6	62.7	17	38.9	.03	.9	.05	.50	.22	.011
C-15	2	6	61.0	20	14.0	.035	1.2	.05	.80	.12	.014

†The acceptance phase space at the stripper is for a waist at the one σ contour and includes 68% of the beam intensity.

††U-10 etc means 10 MeV/u ^{238}U extracted from the cyclotron.

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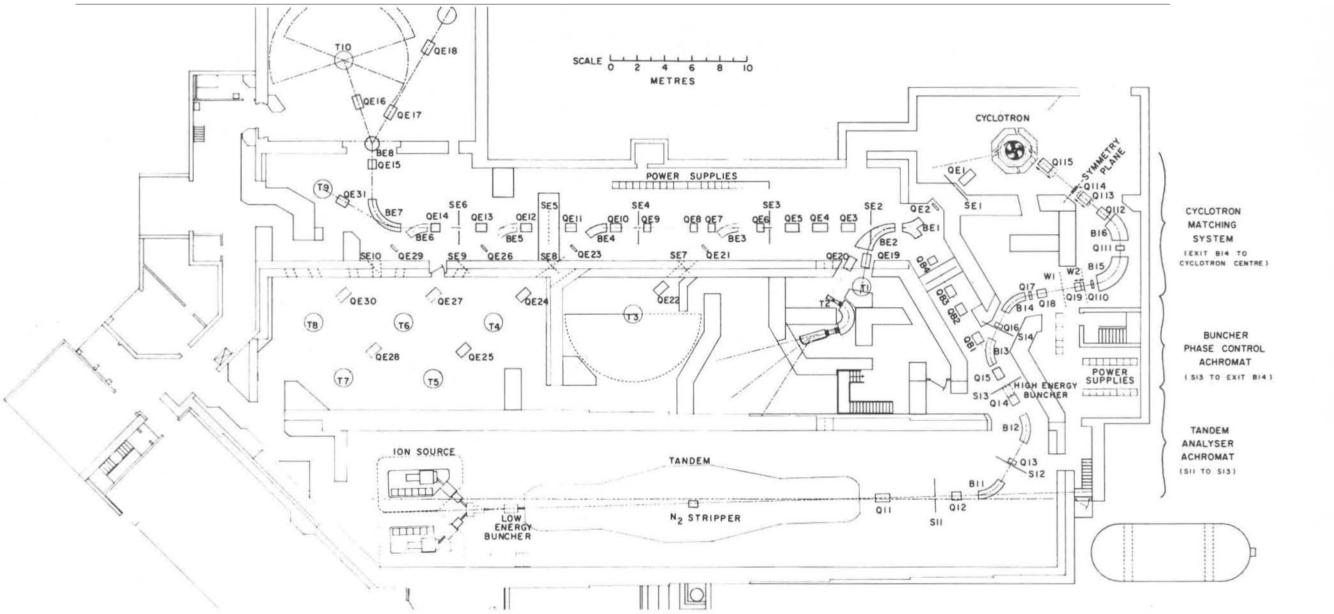

Fig. 1 Schematic layout diagram of the Chalk River superconducting cyclotron laboratory

$$\Delta\phi = \omega \left[\frac{L_o\delta + \ell_o - (\ell|x)x_o - (\ell|\theta)\theta_o - (\ell|\delta)\delta_o}{v_o(1+\delta_o)} \right].$$

For a single ray $\delta_o = \delta_n + \delta_B$, the sum of the ion source noise and the coherent buncher component.

At the "time focus" of the low energy buncher, which occurs at the tandem stripper, the bunch will have an approximately Gaussian spacial distribution with a variance $(L_o\delta_n)^2$ where now x_o, θ_o, ℓ_o, δ_o represent the standard deviations of the appropriate particle distributions; $\delta_o^2 = \delta_n^2 + \delta_B^2$. The probability of finding a particle at a distance s from the stripper is:

$$P(s) = \frac{1}{\sqrt{2\pi}\, L_o\delta_n} \exp\left[-\frac{1}{2}\left(\frac{s-L_o}{L_o\delta_n}\right)^2 \right].$$

The term involving δ_B drops out because one chooses δ_B such that $L_o\delta_B + \ell_o = 0$.

Although the stripper gas is adjusted to maximize the injection charge state probability, which implies sub-equilibrium stripping for all light ions, the stripper straggling adds a significant noise component to the bunch, especially for the heavier ions. For example, without rebunching, the minimum RMS bunch lengths attainable at the cyclotron would be .14 cm, .27 cm, .18 cm and .33 cm for U-10, U-3, C-50 and C-15 respectively.

It is easily shown that the growth in longitudinal phase space is minimized by minimizing the bunch length at the noise source, in this case the terminal stripper. Since position and velocity must be highly correlated (r > .97) for the high energy buncher to be effective, it is important not only to minimize the longitudinal phase space but also to ensure that the system is achromatic between the stripper and the high energy buncher and the buncher and the cyclotron stripper. With proper design one can decouple the longitudinal phase space from the transverse phase space which greatly simplifies the design calculations but more importantly the operation of the injection system.

Cyclotron Matching

For optimum operation, the cyclotron requires a waist at the stripper (C in Fig. 2) in each plane of the 6 dimensional phase space volume. Furthermore the x and y magnifications must be adjustable over a 2:1 range. As stated in the previous section, the matching philosophy is to produce an achromatic solution at the cyclotron stripper such that the transverse phase space can be adjusted independently of the longitudinal phase space. To ensure the above, the phase space matching system must be diagonal in the x and y planes. For convenience we will choose it to be the unit matrix.

In order to produce achromatism, the dispersion of the cyclotron, but of more immediate importance to us, the path length matrix elements $\ell x = (\ell|x)$ and $\ell\theta = (\ell|\theta)$ must be exactly cancelled by terms generated by dispersive elements external to the cyclotron. Note that a relationship exists between the dispersive matrix elements $dx, d\theta$ and the path length matrix elements $\ell x, \ell\theta$ given by [3]

$$\begin{bmatrix} \ell x \\ \ell\theta \end{bmatrix} = \begin{bmatrix} R_{21} & -R_{11} \\ R_{22} & -R_{12} \end{bmatrix} \begin{bmatrix} dx \\ d\theta \end{bmatrix}$$

so that if $\ell x = \ell\theta = 0$ then $dx = d\theta = 0$.

To achieve this cancellation one must have a high degree of symmetry[4]. Three possible schemes were investigated: a) Reflection symmetry with the matching lens in the reflection plane, denoted $M\,M_{Ref}$ and two variants of M^2, denoted MFM AND $(MF)^2$. It was found that MFM where F is a thin matching lens in the symmetry plane was the easiest to manage. It turns out to be advantageous to maximize the symmetry by requiring unity magnification in the x plane. The principal symmetry plane passes through QI14 so that QI15 and the cyclotron are identified with M, QI14 with F and the elements QI10 through QI13 inclusive are adjusted such that in all important respects the transformation matrix is identical with M.

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The matching procedure is as follows:

i) The quadrupole triplet QI15 is used to produce an exact focus in both the x and y planes with magnification $m_x = -1$ for the region from QI14 to the cyclotron stripper. If QI15 is allowed to move then its x and y focal lengths are nearly constant for all ion-energy combinations; the maximum motion required is 50 cm. The x and y transforms become

$$M_x = \begin{bmatrix} -1 & 0 & 0 & dx \\ 1/F_x & -1 & 0 & d\theta \\ \ell x & \ell\theta & 1 & \ell\delta \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{and } M_y = \begin{bmatrix} p & 0 \\ 1/F_y & 1/p \end{bmatrix}$$

The y magnification p varies from 2.8 to 6.3.

ii) The path length matrix elements ℓx and $\ell\theta$ determined in i) are duplicated exactly by adjusting the quadrupole singlets QI10 and QI11.

iii) The two quadrupole doublets QI12, QI13 are used to obtain an exact focus in both x and y with $m_x = -1$ and $m_y = 1/p$. These lenses do not modify ℓx and $\ell\theta$ obtained in step ii). As in step i), it turns out to be convenient to allow QI13 to be moveable. In fact it would be quite difficult and expensive to match the large variation in cyclotron optical properties without using moveable elements.

iv) The results of steps i, ii, and iii are combined with QI14 to produce an achromatic transformation

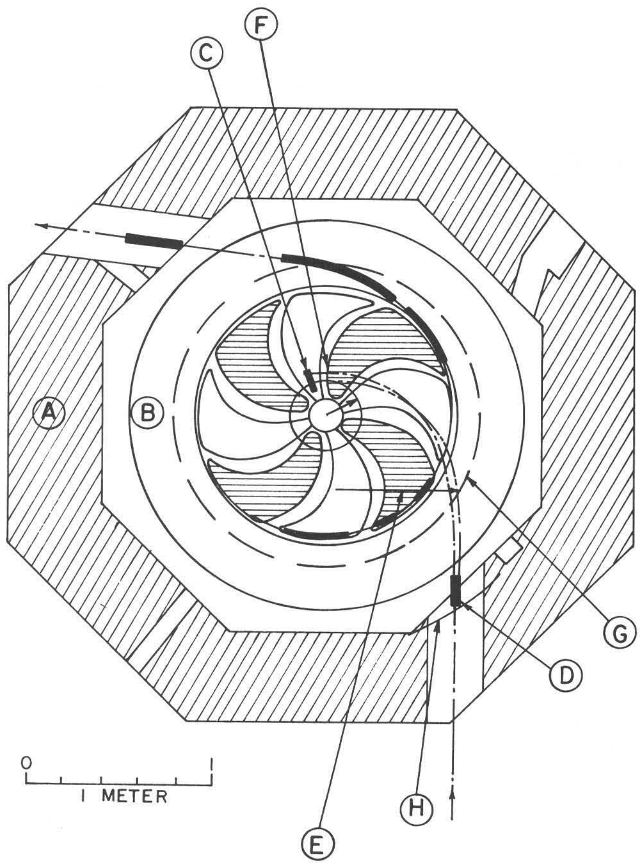

Fig. 2

Midplane plan of the cyclotron; A - yoke, B - cryostat, C - carbon stripper foil, D - injection steering magnet, E - injection radius Ri, F - inner equilibrium radius Ro, G - effective field boundary, H - 1.24 m matching radius.

(i.e. $\ell x = \ell\theta = 0$) with a point focus at the cyclotron stripper and $m_x = m_y = 1$. The longitudinal and transverse phase spaces are now decoupled resulting in the three independent transport matrices

$$M_x = \begin{bmatrix} 1 & 0 \\ -1/F_x & 1 \end{bmatrix} \quad M_y = \begin{bmatrix} 1 & 0 \\ +1/F_y & 1 \end{bmatrix} \quad M_\ell = \begin{bmatrix} 1 & L_{eff} \\ 0 & 1 \end{bmatrix}.$$

The signs of F_x and F_y are shown explicitly since this choice of sign is crucial to achieving telescopic matching.

v) The transformation of M_x and M_y into the unit matrix or telescopic condition is achieved by using the quadrupole doublet QI9. Here advantage is taken of the fact that the principal planes of a doublet are separated in the x and y planes. So in the x plane we can have

$$\begin{bmatrix} 1 & 0 \\ -1/F_x & 1 \end{bmatrix}\begin{bmatrix} 1 & 2F_x \\ 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & \\ -1/F_x & 1 \end{bmatrix}\begin{bmatrix} 1 & 2F_x \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}$$

and in the y plane

$$\begin{bmatrix} 1 & 0 \\ 1/F_y & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ -1/F_y & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}.$$

These conditions can only be met in general if QI9 is also a moveable lens system. Also the position of the x and y waists are now separated, with the x waist in the vicinity of W1 and the y waist in the vicinity of W2 in Fig. 1. The separation of the waists, essential to the formation of the telescopic condition, also helps achieve the astigmatism required at the image.

vi) The transverse phase space is matched by adjusting the lenses QI7 and QI8 to produce the appropriate waists at the matching points W1 and W2 and is independent of the buncher.

vii) The longitudinal waist is now easily achieved by adjusting the high energy buncher such that $\delta_{B2} = \ell/L_{eff}$ where ℓ is the path length difference at the buncher and L_{eff} the effective distance from the buncher to the center of the cyclotron.

Tandem Analyser Achromat

Control of the Tandem terminal voltage is achieved in the usual way by the use of an analysing magnet BI1. An image of SI1 is produced at SI2 with a magnification of .8 and a dispersion dx of 320 cm giving a first order dx/m of 400. If logarithmic slit amplifiers are used to collect say 1% of the beam on each of the left (I_L) and right (I_R) slits then

$$\varepsilon = \log (I_R) - \log (I_L) = \log\left[\frac{\operatorname{erfc}(U(1+\lambda))}{\operatorname{erfc}(U(1-\lambda))}\right]$$

where $U = \eta/\sqrt{2}$; η is associated with a given percentage of beam intercepted by the slits. Hence

$\lambda = d_x\delta_T/\eta S$ where δ_T is the momentum spread resulting from changes in the tandem terminal voltage and

$S = \sqrt{(mx_o)^2 + (d_x\delta_o)^2}$. If we assume that it is sensible to control the tandem voltage such that $\delta_T \sim \frac{1}{2}\delta_o$, where δ_o is the noise in the beam, then λ varies from .055 for U-10 to .15 for C-15 leading to error signals from .30 to .81 respectively, well within the capabilities of present stabilizing technology. These values correspond to an energy resolving power of 46,000 for U-10 and 18,000 for C-15. Clearly, resolving powers of about 50,000 are possible if necessary.

The achromatic condition required at the high energy buncher is achieved by making BI2 a reflection

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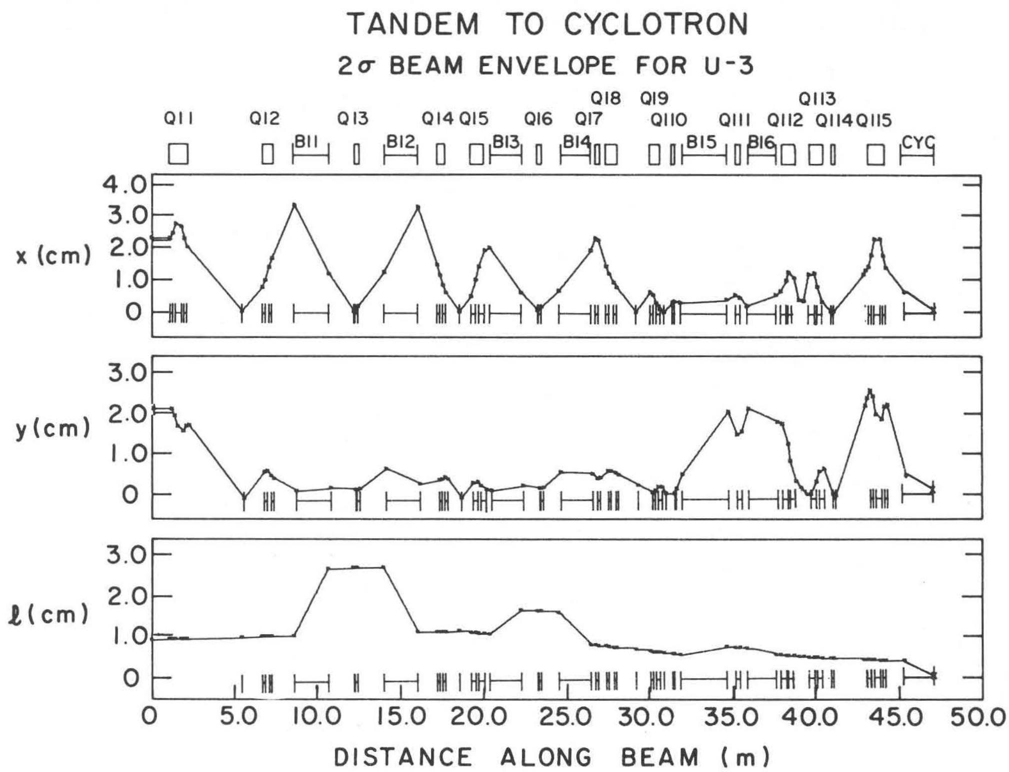

Fig. 3

Horizontal, vertical and longitudinal beam envelopes of the 2σ(95%) emittance contour for ^{238}U accelerated to 3 MeV/u. This is the upper extremum.

of BI1 in a plane passing through the center of QI3[4]. Under these conditions QI3 can be adjusted to make $dx = d\theta = \ell x = \ell\theta = 0$. The lenses QI2 and QI4 are adjusted such that at SI3 $M_x = \begin{bmatrix} .8 & 0 \\ .01 & 1.25 \end{bmatrix}$ and $M_y = \begin{bmatrix} .86 & 0 \\ 0 & 1.16 \end{bmatrix}$.

Hence the y solution is telescopic and the x solution is approximately telescopic which results in optical properties that are nearly independent of the phase space.

The Buncher Phase Control Achromat

Instead of the more conventional R.F. chopper, magnetic analysis[3] will be used as the means for controlling the buncher phase and removing the "dark" current. Signals proportional to the mean phase error will be picked up on the slits SI4 and fed to the phase control amplifier in an analogous manner to the tandem voltage control system. The mean momentum spread δ_ψ caused by a small phase error ψ is:

$$\delta_\psi = \tfrac{1}{2}\frac{\Delta E}{E} = \frac{QiVo}{2E}\int_{\phi+\psi}^{\phi+\psi} \sin(\theta)\,d\theta$$

$$= \frac{QiVo}{2E}\left[\cos(\phi+\psi) - \cos(\phi-\psi)\right] \simeq \frac{\ell\psi}{L_{eff}}$$

where Vo is the peak voltage of the buncher, $\phi = 2\omega\ell o/v_o$, and $\ell\psi = \psi v_o/2\omega$, ω being the cyclotron R.F. frequency.

In a manner similar to the tandem analyser, about 2% of the beam would be intercepted by the slits. If we assume $\varepsilon = .01$ is a reasonable sensitivity then $\lambda = .0019$ for a dx/m of 180, leading to a value of $\delta\psi$ of 1×10^{-4}% which corresponds to a ψ of .6 mrad or $.04^o$ for U-10. Since the acceptance of the cyclotron is $\pm 1.5^o$ of R.F. phase this system should give a high degree of phase stability. The above assumes beam currents in excess of 100 na. For smaller currents a larger fraction of the beam would have to be intercepted by the slits, reducing the sensitivity. However a factor of two or three reduction in phase control is perfectly acceptable.

In an exactly analogous manner, BI3, QI6 and BI4 are made achromatic by using reflection symmetry with QI6 the adjustable parameter. Hence the optical system is achromatic from the low energy buncher to the entrance of the cyclotron matching system, guaranteeing the orthogonality of the longitudinal and transverse phase spaces. The x, y and ℓ plane beam envelopes are shown in Fig. 3.

Conclusions

Although matching the acceptance phase space of a compact, radially injected superconducting cyclotron is difficult because its acceptance requirements are very tight and the optical properties are a function of B and Ri, solutions have been obtained at representative points in the energy-ion space. The design is highly modular, separating the various functions into distinct areas, none of which influence earlier steps. This modularity is important in achieving acceptable solutions in theory but will be even more important in realizing the solutions in practice. As well as the modularity, two other points of design philosophy are worth noting. These are: firstly the decoupling of the longitudinal and transverse phase spaces and secondly the use of telescopic imaging to reduce the dependence of the solutions on the emittance of the beam.

References

1) J.H. Ormrod, C.B. Bigham, J.S. Fraser, E.A. Heighway, C.R. Hoffmann, J.A. Hulbert, H.R. Schneider and Q.A. Walker, 7th Int. Conf. on Cycl., Zürich 11975, Biskhauser and J.S. Fraser and P.R. Tunnicliffe (Eds) AECL-4913 (1973).

2) K.L. Brown, SLAC Report #75, 1967 and #91, 1970.

3) G. Hinderer and K.H. Maier, IEEE Trans. on Nucl. Sci. 22 (1975) 1722.

4) J.C. Herera and E.E.Bliamptis, Rev. Sci. Instr. 37 (1966) 183.