A COMPACT SUPERCONDUCTING CYCLOTRON FOR THE PRODUCTION OF HIGH INTENSITY PROTONS*

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Abstract

This paper reviews a study of a compact superconducting cyclotron to accelerate 200 microamps of protons to 250 MeV. The basic cyclotron structure is the same as that developed in a previous study of a 250 MeV cancer therapy cyclotron, the chief difference in the study reported here being much higher beam current (x10,000) than in the therapy cyclotron to meet desired specifications for the 'Driver' accelerator of an ISOL type radioactive beam facility. The increase in current is far below (x1/50) the axial space charge limit of the proposed cyclotron, but longitudinal space charge requires changing the extraction system from a single turn to a multi-turn system thereby increasing beam losses. Leading design uncertainties, namely the overall efficiency of the multi-turn extraction system and the distribution of radioactivity generated by lost beam are addressed herein; results indicate reasonable residual activity in the cyclotron from the perspective of customary 'hands-on' maintenance operations.

1 INTRODUCTION

Oak Ridge National Laboratory is reviewing accelerator systems appropriate for use as an upgraded primary production (or 'Driver') accelerator in their Holifield Radioactive Ion Beam Facility. Tentative beam specifications for this new Driver accelerator are 100 to 200 microamps of protons at 250 MeV.

Many accelerator systems are intrinsically capable of providing the desired beams i.e. linac, separated sector cyclotron, compact cyclotron, negative ion cyclotron, etc. and with either superconducting or room temperature as a design option for most of the above. The study discussed in this paper selects one of the above options, namely the compact superconducting cyclotron for more detailed review, this option offering advantages in size and cost relative to other systems, but with added innovation in that beam power considerably exceeds levels which have thus far been achieved in cyclotrons of this type. (A second paper describes features of a room temperature separated sector cyclotron to achieve the same goals.)

2 K250 CYCLOTRON STRUCTURE

Basic features of the K250 cyclotron are shown schematically in Figure 1 and have been described in a previous NSCL report [1]. The basic structure is a four sector dee-in-valley design with spiral hills to provide adequate axial focusing. The superconducting coil is mounted in an annular cryostat as is typical in compact superconducting cyclotrons.

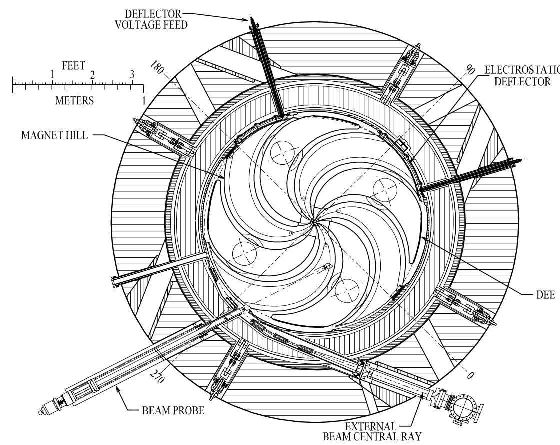

Figure 1: Median plane section of the K250 proton cyclotron: Note azimuthal coordinate labels at 0, 90, 180, 270 deg: Extraction system entry /exit at 60/340.

The 4 dee radio-frequency system operates on the 2nd harmonic of the orbital frequency so that the total in-out energy gain from each of the 45 degree dees is approximately 1.4 times the peak voltage to ground of the dee. Two opposite dees in the four dee system are galvanically coupled by the central region electrode system; the intervening dees at +/- 90 degrees are driven capacitively from the primary pair by the central region coupling and tuned individually to the push-pull mode relative to the primary pair by servo adjustment of 'fine' tuning elements.

Beam extraction uses two 45 degree electrostatic deflectors followed by a line of five inert magnetic quadrupole elements which guide the beam through the edge field of the magnet and compensate the strong radial defocusing of the edge field so as to maintain a nearly uniform beam profile through the complete extraction trajectory.

The ion source will follow the design used in the Harper Hospital neutron therapy cyclotron; this simple cold cathode system routinely produces 200 microamp beams from a 1.4 mm dia. exit hole in a 6.4 mm dia. molybdenum chimney. The vacuum system design separates beam chamber and coil cryostat vacuums into two separate systems so that the beam chamber can be opened as desired without disturbing the superconducting coil. Other cyclotron subsystems are routine in character and well described in the previous report [1] and are therefore not reviewed here.

3 SPACE CHARGE EFFECTS

The beam in the proposed cyclotron is accurately described by the 'uniform charge' approximation and, using 500 keV for the expected energy gain-per-turn from the 8 gap accelerating system, 5 mm for the full beam height, +/- 10 rf degrees for the beam phase width, 36 Mhz for the orbital frequency, and 0.2 for the minimum NuZ, the usual formula [2] gives 11 milliamps for the limiting current. The x50 factor between the axial limit and the desired beam current then implies no significant space charge effects in the axial behaviour of the beam.

The other primary space charge consideration in an isochronous cyclotron is the longitudinal effect [3] which acts to enhance the energy gain of the leading particles in the beam phase wedge and decrease the energy on the trailing edge of the wedge. If 'single-turn' (i.e. no-loss) extraction is the goal, this effect sets a lower limit on the energy-gain-per-turn and on the beam phase width and these limits are incompatible with a compact cyclotron structure such as envisaged here. This cyclotron must therefore operate in a broad phase, multi-turn extraction mode with the extraction trajectories separated from the internal circulating beam by the thin septum of the first electrostatic deflector. The main goal of the studies summarized herein is then to realistically assess the efficiency which can be achieved in such an extraction system, and secondarily to estimate the distribution and intensity of the radioactivity induced in the cyclotron due to particles lost in the extraction process.

4 ORBIT COMPUTATIONS

Our study of deflector efficiency uses an extensively tested set of cyclotron computer programs which track orbits from ion source to extraction in a highly realistic fashion. In the central region the codes include detailed maps of the electric field derived from 3D relaxation calculations of the central region electrode structure. Away from the central region, orbits are transferred to a faster 'Z4' code which includes non-linear terms in the axial motion through fourth order; for added speed the Z4 code represents acceleration gaps by delta functions (in the correct spiral location and with the radial impulse of the spiral gaps included). Finally a special 'Septum Penetration' code is used to track orbits which hit the (Copper) septum, with energy loss introduced via a table derived from detailed Monte Carlo calculations (the effect of multiple scattering in the septum is not yet included in the calculation).

A massive initial condition ensemble is used to represent the extensive phase space volume of the multi-turn beam. Specifically this volume 1) uses 41 rf times (220, 220.5, ..., 240 degrees) to span the 'phase width' of the 10 eV beam leaving the source, 2) at each of these rf times 16 radially displaced rays are added at the entry point of the Z4 code (distribution: 1+8+8 on eigenellipses with average radial amplitudes of 0, 0.44, & 0.88 mm respectively), and 3) finally, for each radial ray at each rf time an eight point axial eigenellipse of 1.6 mm average amplitude is added. The total ensemble of tracked orbits is then 41x17x5 = 3485 (the last factor being 5 rather than 9 due to the median plane symmetry of the fields). Figure 2 gives a histogram plot (at the azimuth of the deflector entrance) of number of orbits vs. radius with the 'toward-the-cyclotron-center' corner of the deflector septum indicated by the light vertical line.

At the deflector entry the 3485 rays from the acceleration family transfer to the Septum Penetration program which tracks the rays until they they arrive at a beam stop at the exit of the deflector or, in the case of rays penetrating the septum, until they hit the vacuum tank wall at some azimuth (no rays actually stop in the septum due to the range of the 250 MeV beam). With the deflector entrance radius positioned as shown in Figure 2 and with a 0.25 mm septum thickness, 3309 of the 3485 rays (95.0%) pass cleanly through the deflector -- if the septum thickness is reduced to 0.13 mm the transmitted group increases to 3401 (97.6%).

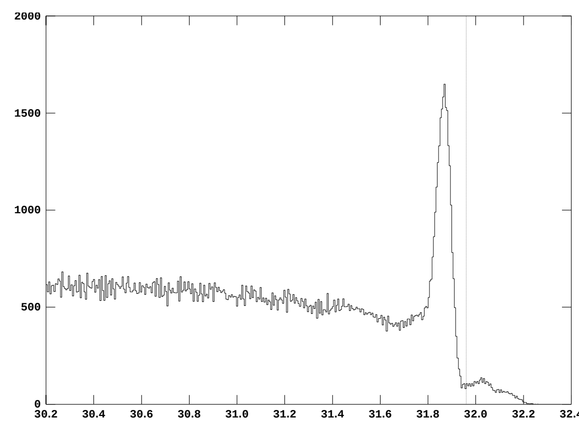

Figure 2: Radius histogram of 3485 ray family at azimuth 60 deg (radius in inches): Tracking ends where the azimuth 60 radius first exceeds 31.96 inches.

Fig. 3 shows a sample of trajectories of rays which hit the septum; the outer circle in this Figure is the 33 inch radius inner wall of the beam chamber vacuum tank with the inset double line in the 45 degree upper arc showing the aperature of the first electrostic deflector. Almost all of the rays which penetrate the septum hit the vacuum tank wall in the azimuthal region at the right (around 60 degrees upstream from the deflector entrance) with a few rays being as much as 120 degrees upstream. The most upstream cluster of rays (those which experience the largest energy loss in the septum) show substantial axial defocusing coming from alignment of the trajectories with a defocusing edge of one of the magnet sectors; higher energy rays hit the wall further upstream and show reasonable axial focusing.

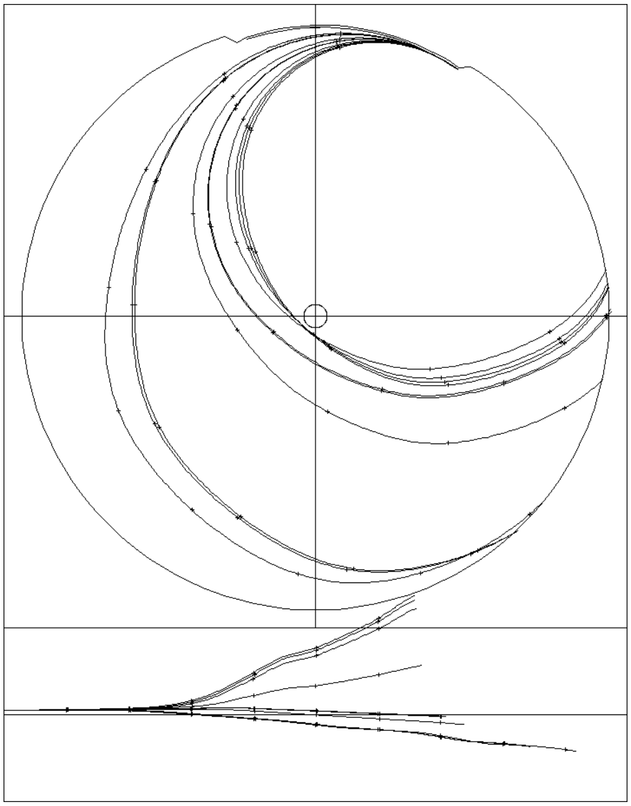

Figure 3: Top - Polar plot of selected orbits (rf times 200, 205, ..., 220 deg) which penetrate deflector septum: Bottom - Z vs path length for these orbits.

5 INDUCED RADIOACTIVITY ESTIMATES

Estimates of radioactivity induced in the cyclotron by the lost beam depend on many factors and are accordingly difficult to make in an accurate way. A previous lower energy cyclotron, the 72 MeV 'Phillips Injector' at the Paul Scherrer Institute operated for a number of years with a 200 microamp external beam and with with 93% extraction efficiency in the multi-turn mode [4]; this group moreover maintained careful records of integrated beam current and of radiation dose received by maintenance personnel (the latter being of course the final most important factor in judging the viability of a high-current accelerator based on multi-turn extraction).

The orbit computations from the previous section indicate that careful attention to fabrication details and tolerances, in conjuction with a septum of 0.13 mm (or smaller) thickness, can reduce extraction losses to the 2.5% range, i.e. lower than the PSI Phillips Injector by a factor of 3. The thick-target neutron yield at 250 MeV on Copper (the stopping material for most protons in the Phillips Injector) is higher by a factor of 12.5 than at 72 MeV [5], but, if Carbon is used for the septum and for the lost beam collectors on the vacuum tank wall, the 250 MeV yield is reduced by a factor of 3.3 relative to Cu, so that total neutron production in the K250 will be nearly the same (i.e. 12.5/3/3.3=1.3) as in the Phillips Injector.

Neutron yield is moreover far from being the only important factor in estimating residual radiation hazards. The increased range at 250 MeV (63 vs 7.4 mm in Cu) relative to 72 MeV tends to bury, disperse, and self shield induced activity. Cossairt [6] plots the 'Danger Parameter' representing radiation level in 4pi cavities in various materials uniformly irradiated by protons of various energies. For Cu the danger parameter (24 hours after a 365 day irradiation) increases by x3.7 in going from 50 to 500 MeV (the nearest energies at which results are quoted) whereas in C the parameter decreases by 1/2.1 for the same energy change. Interpolating, 250 MeV stopping in C is inferred to be only about 1/8 as dangerous as 72 MeV stopping in Cu [7].

Finally we note that actual radiation records [4] for the Phillips Injector group at PSI for the three years 1982-84 (years where the integrated extracted beam exceeded 500 milliamp-hours/year) averaged 103 mSv/year total for the group. If this work is shared by four people the annual dose is at 1/2 of allowable tolerance, and as noted in the previous paragraph there is good reason to expect radiation levels in a graphite stopping environment to be lower by x1/24 compared to the PSI Phillips injector. Relatively simple remote handling systems could easily lower this dose level by additional significant factors.

6 CONCLUSIONS

With a graphite septum, and graphite outer wall liners at beam loss points, maintenance radiation levels should be reduced by more than an order of magnitude relative to the level of the PSI facility, and since maintenance exposures at that facility were well below present tolerance levels, it is reasonable to project a comfortable margin for 'hands-on' maintenance of a 250 MeV, 200 microamp cyclotron of the type suggested herein.

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[7] Beam tests at NSCL show Pyrolytic graphite to be an excellant septum material.

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