A CONCEPTUAL DESIGN FOR A PRIMARY CYCLOTRON FOR THE ISL RADIOACTIVE BEAM PROJECT*

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ABSTRACT

A design for a 600 MeV proton cyclotron is described. Features include a single stage with external ion source, a normal conducting magnet coil with 2 T peak field in the hills, and dees in valleys. The design can be extended to 800 and 1000 MeV.

1. INTRODUCTION

The report on the IsoSpin Laboratory (ISL)[1] describes a "benchmark" reference design for a facility for the production of radioactive nuclear beams in North America. The primary accelerator is required to produce protons at an energy of .5-1.0 GeV and an intensity of 100 μA, while a secondary accelerator will accelerate radioactive beams from the target up to 10 MeV/u. The primary accelerator can be a cyclotron such as the PSI ring or TRIUMF. Because of the high beam power an essential requirement for this cyclotron is that of minimizing the beam lost at high energy inside the cyclotron, to prevent component damage and reduce radiation exposures during maintenance. This in turn requires very high extraction efficiency either by good turn separation at extraction or by use of negative ions. This paper presents a primary cyclotron design which minimizes cost while maintaining high extraction efficiency.

2. DESIGN CHOICES

A principal design choice is that between positive and negative ion acceleration. The negative ion choice (TRIUMF) is attractive because of easy beam extraction. However it requires low field to prevent electromagnetic stripping, and thus a large radius magnet. Also some beam is lost during acceleration, causing component activation. The positive ion choice (PSI ring) is attractive because of the very low beam losses and the smaller diameter magnet, but very careful beam handling and good turn separation are necessary. The large turn separation requires large energy gain per turn. The PSI design uses separate sectors, allowing space for 4-550 kV cavities giving over 2 MV/turn. The separate sector design requires an injector cyclotron. This paper combines features of both these cyclotrons. A positive ion design is chosen because of its smaller magnet and low beam losses. A compact magnet, rather than separated sectors, is used because it requires only one main coil, and eliminates the injector stage.

The requirement of good turn separation implies a large radius at full energy, since the turn separation at extraction is proportional to this radius for a given maximum energy. Large radius also means higher cost, since all the components are larger, and more magnet steel is required. So a compromise must be used to optimize cost and turn separation.

The magnet and rf design are closely related. Two styles of rf design are the "dees over hills and valleys" used at TRIUMF, and "dees or cavities in valleys" used at PSI. The dees in valleys design is chosen here because the hill gaps can be made small, just larger than the beam size, giving acceleration out to near the edge of the magnet, and easier extraction. Also the magnet power is lower with a small gap. These factors reduce the cost for a given energy. Dees in the valleys at this energy require the resonators to be in the valleys also, since the radial length of the dees is the order of 1/4 wavelength. The highest acceleration is required near extraction, so additional dees can be added there.

The number of sectors should be large enough to avoid the essential radial resonance at Nur=2 for small sector number. This requires at least 6 sectors for an energy of 600 MeV. A review of resonances is given by Richardson[2]. A sector number of 8 gives the possibility of accelerating through Nur=2, as demonstrated in an electron model at ORNL, Analogue II[3].

The sector number of 8, with dees in valleys, would cause problems of low axial focusing and large rf transit time near the center of the cyclotron. One solution is to start with 4 sectors near the center and have a transition to 8 sectors part way out in radius. Examples of this design are shown in Figs. 1 and 2. These are for illustration only, and use no spiral. They represent a region near the center, and spiral could be added if necessary. The flutter has not been evaluated. The design of 4 straight valleys, Fig. 1, would be simpler for the dee system. The design of 4 straight hills, Fig. 2, would be simpler for the magnet structure, but the dees would be rather complicated. The 4 sector, dee-in-valley design has been used very successfully by IBA in their 30 MeV proton cyclotron[4]. It uses axial injection at 30 kV with H^- ions, accelerates on harmonic 4 and produces 500 μA of external beam.

The ion source is assumed to be external, with an injection energy of about 50 kV. An external source allows bunching into the required phase width for turn separation at extraction. The energy and particle would be fixed. In a special design one might also accelerate other light ions by changing magnet level and harmonic number of the rf.

3. PRESENT DESIGN

The present design for 600 MeV protons is shown in Fig. 3. As mentioned above it is a compact design using a single main coil. The maximum radius is about 3/4 of that of the PSI ring design. 8 sectors are used to avoid the Nur=2 resonance of 3 or 4 sectors and to allow valleys for small dees near extraction. This figure doesn't show the N=4 center region of Fig. 1, but that design is an option. The ion source is mounted below. Extraction is shown schematically, since no calculations have been done. It will use electrostatic and magnetic channels.

The hill field is assumed maximum at 2 T at maximum radius, and made proportional to gamma at smaller radius by varying the gap. The hill gap is .1 meter at the edge, and the beam accelerates to within .1 meter of the pole edge in the hill. The return yoke is assumed cylindrical outside the pole edge. The magnet yoke is split at the midplane, and the upper half can be lifted for maintenance.

The main dees operate at harmonic 4, 44 MHz, and extend in to the center. 1/4 wavelength of rf is 1.7 m, only about 1/2 the extraction radius, so the resonators must be in the valleys, with vertical dee stems. The rf amplifiers can feed from the side. Small dees, ED, indicated near extraction radius in Fig. 3, increase the energy gain/turn there and give the option of flat-topping for better turn separation. For acceleration they can operate at harmonic 8. For example, 4 dees at 250 kV, harmonic 8 would give about 2 MV/turn.

The orbit calculations used the simple formula for the axial focusing[5]:

$$Nuz^2 = F^2 (1 + 2 \tan^2 Eps) - \mu'$$

where Nuz is axial frequency, F^2 is flutter, Eps is spiral angle and μ' is the gradient term. A hard edge hill and valley boundary is assumed, and the valley field is assumed zero because of the large valley depth. In this case $F^2 = (1/f_h) - 1$. The hill fraction, f_h, is set equal to .6 and is assumed constant vs. radius. This gives $F^2 = .67$ at all radii. The spiral tan Eps is assumed proportional to radius squared to give a Nuz of about .8 at all radii. The actual soft edge F^2 will be smaller than assumed, but can be compensated with an increase in spiral angle. For example the PSI ring F^2 is about 20% less than the hard edge value. This would require a 3 degree increase in spiral angle in the present design. Nur is approximately equal to gamma: 1-1.6 for 0-600 MeV. Small trim coils on the hills can be used to produce the isochronous field.

Extraction will require some increase in turn separation beyond the natural value for an isochronous field. Since turn separation at extraction is proportional to radius, for fixed maximum energy, both the radius and the turn separation are 3/4 of the PSI ring values. It is assumed that the turn separation can be sufficiently increased to give nearly 100% extraction, by using high energy gain/turn, precession, letting the field fall below isochronism at extraction, and using the Nur=1.5 resonance. PSI uses these techniques to get a turn separation of 9 mm at extraction[6].

Table 1 gives some of the parameters of the present design. The maximum values of gamma, and spiral angle are given. The total angle of turning of the hills, theta, is shown and the weight is given. Also shown in Table 1 are higher energy designs at 800 and 1000 MeV, using the same assumptions of hill fraction of .6, maximum hill field of 2 T and valley field of zero. The 1000 MeV design would require accelerating through Nur=2, which appears possible, as mentioned earlier.

4. ACKNOWLEDGMENTS

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5. REFERENCES

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Table 1.

E(MeV)	B-Rho (Txm)	Gamma	R_{pole} (m)	Spiral (deg)	Nuz	Theta (deg)	Magnet Wgt. (Met.T)
600	4.06	1.64	3.49	48	.8	36	1200
800	4.88	1.85	4.17	53	.8	41	1700
1000	5.65	2.07	4.81	57	.7	54	2300

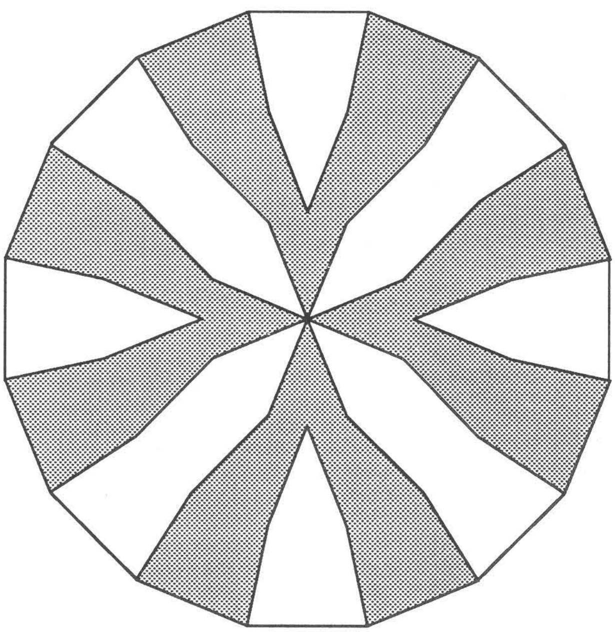

Fig. 1. N=4 center, N=8 edge. 4 valleys straight.

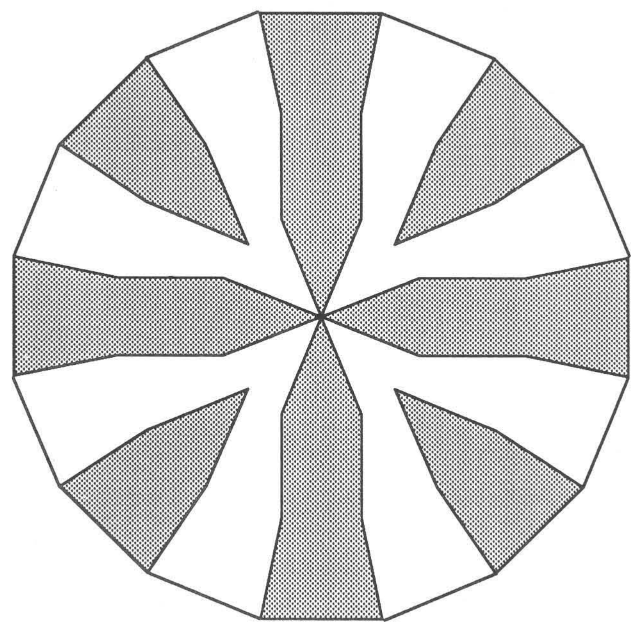

Fig. 2. N=4 center, N=8 edge. 4 hills straight.

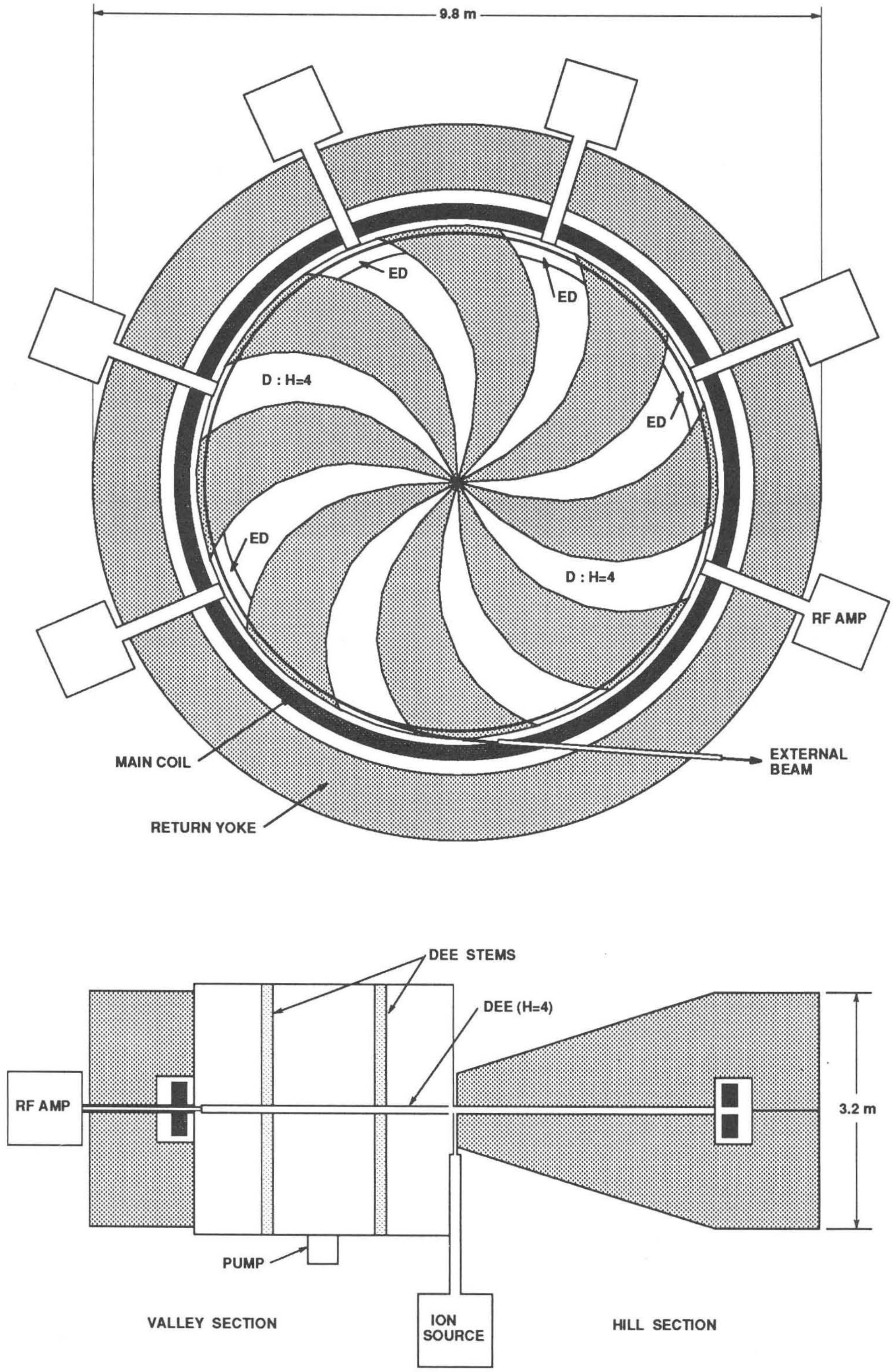

Fig. 3. 600 MeV proton cyclotron, plan and elevation views.