Cyclotrons for Radioactive Beams

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Abstract

This paper discusses the magnet design of a cyclotron to be used as a primary accelerator in a radioactive beam facility of the ISOL type. The assumed specifications are a proton energy of 600 MeV with 100 μA current. It has a single stage, a normal conducting magnet coil and a 9.8 m outside yoke diameter. 8 sector and 4 sector designs are studied. The magnetic field was calculated with the 3D magnet code TOSCA, and orbit stability was checked with an equilibrium orbit code and phase plots. Some post-accelerator cyclotron options are also discussed.

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. In this paper the primary cyclotron is assumed to have a single stage and a normal conducting coil, as discussed previously [2], [3]. The linacs discussed as post-accelerator options in Ref. [1] can be replaced by cyclotrons.

2. THE 8 SECTOR MAGNET

The 8 sector design of this paper completes the previous work with a final magnet iron design which gives orbit stability with a magnetic field close enough to isochronism that it can easily be trimmed by trim coils. The required increasing field with radius is obtained by increasing the fractional hill width with radius. The magnetic field of this magnet was calculated with the 3D code TOSCA. The 3D grid used by TOSCA is shown in Fig. 1.

The rf system is similar to that of Ref. [3]. It has 2 dees in opposite valleys supported on axial dee stems and run at the 4th harmonic. Auxiliary dees or cavities near the edge increase the turn separation there to give single turn extraction.

The magnetic field from TOSCA was used in the equilibrium orbit code (E.O.C.) GENSPEO to find the axial and radial frequencies. The field was also Fourier analyzed to find average field and its gradient, the flutter and the spiral angle of the lowest harmonic of the field. These were used in $Nuz^2 = FSQ\ (1 + 2\tan^2 Eps) - \mu'$, a simple approximation formula, where Nuz is the axial frequency, FSQ the field flutter, Eps the spiral angle and μ' the average field gradient. The radial frequency Nur is given by the approximation: $Nur^2 = 1+\mu'$. A sample spread sheet calculation of Nuz and Nur, using this approximation, is given in Table 1.

It is interesting to compare the simple approximations with the E.O.C. results. This is done in Fig. 2, showing that the simple formula gives a good approximation to the more accurate E.O.C. The oscillations at 3 m radius in the E.O.C. Nuz are believed to be due to the grid size used in the the hill specification or in TOSCA. Without further shimming phase slip would limit the energy to about 580 MeV for 2000 kV/turn energy gain.

3. THE 4 SECTOR MAGNET

The 8 sector magnet has low flutter focusing in the center region and poor transit time in the first turns for a dee-in-valley design like this one. The design chosen previously [3] makes a transition to 4 sectors at small radius to solve these problems. While this appears to work, a simpler solution is to use 4 sectors for the whole magnet, unless resonances are a problem. A 4 sector magnet having the same spiral and fractional hill width as the 8 sector design was tried in TOSCA.

Equilibrium orbits were found with the E.O.C. up to 600 MeV. The resulting focusing is shown in Fig. 3. The Nur of E.O.C. is higher than that of the formula due to the larger flutter of the 4 sector design. The Nur of the E.O.C. reaches almost 1.8 at 3 m, but does not cross the resonance at 4/2 = 2.0. A phase plot where Nur = 1.8 shows good stability. Phase plots where Nur = 4/3 show slow instability for a few MeV, but this should be crossed safely with 2 MeV/turn energy gain. The resonance at Nur = 3/2 was not investigated, but may be crossed with some correction coils in that region. More careful study is necessary to study the effects of these resonances.

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4. POST-ACCELERATORS

In the BenchMark design [1] it is assumed that the secondary accelerator is a linac. Linacs have high transmission and can have excellent beam quality. Cyclotrons can go to higher energy more economically and can also have excellent beam quality with single turn extraction. The challenge is to get both good transmission and high beam quality with cyclotrons. Some illustrations are given here of cyclotrons to meet the recent goal of 25 MeV/u uranium beams.

Fig. 4 shows that 3 K=1200 cyclotrons are needed if we start with 1^+ ions from the source. This is an expensive system. Since linacs are more efficient at low energies, the first stage could be a linac, as in Fig. 5. This is a cheaper system and also gives higher final energy of 70 MeV/u. The most attractive solution is to replace the first two cyclotrons in Fig. 4 by a high charge state ECR source. A charge state of U^{34+} has been demonstrated by existing ECR sources. GANIL is planning this type of system. Development is necessary to produce high charge states in an ECR at high efficiency in spite of possible high gas flow from the target.

5. REFERENCES

[1] The IsoSpin Laboratory (ISL), LALP 91-51, North American Steering Committee of the ISL, 1991.

[2] D. J. Clark, "A conceptual design for a primary cyclotron for the ISL radioactive beam project", Proc. 13th Int'l Conf. on Cyclotrons and Their Applications, Vancouver, B.C., Canada, July 1992, pp. 721-723.

[3] D.J. Clark, "A 600 MeV Cyclotron for Radioactive Beam Production", Proc. 1993 Part. Accel. Conf., Washington D.C., U.S.A., May 1993, pp. 1724-1726.

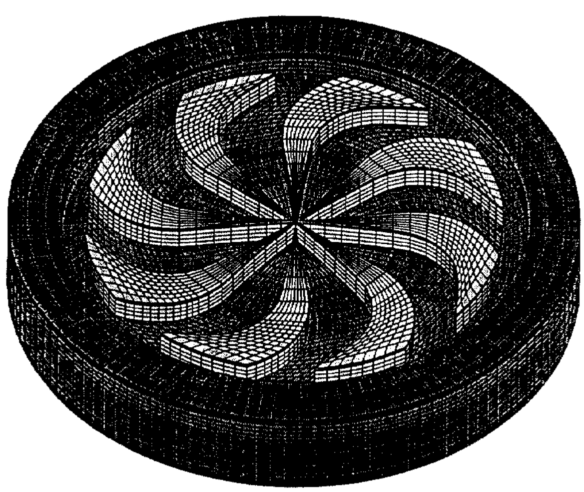

Figure 1. TOSCA grid for 8 sector magnet calculation.

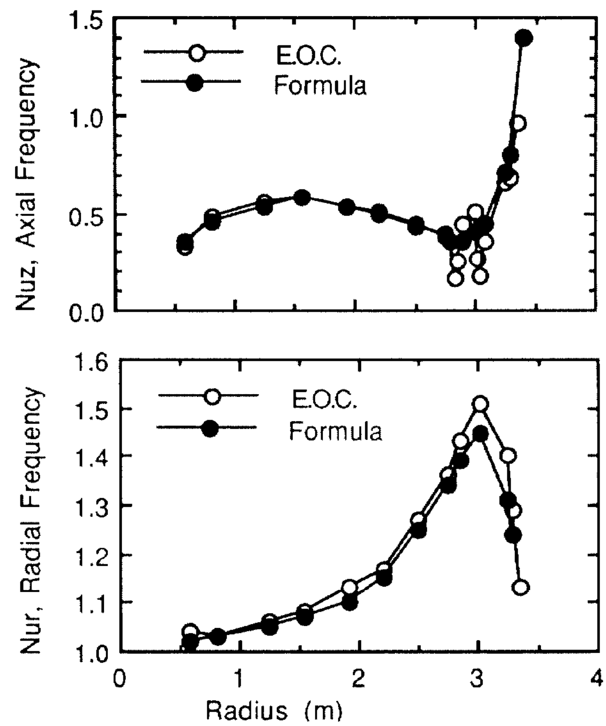

Figure 2. Nuz, Nur for 8 sectors.

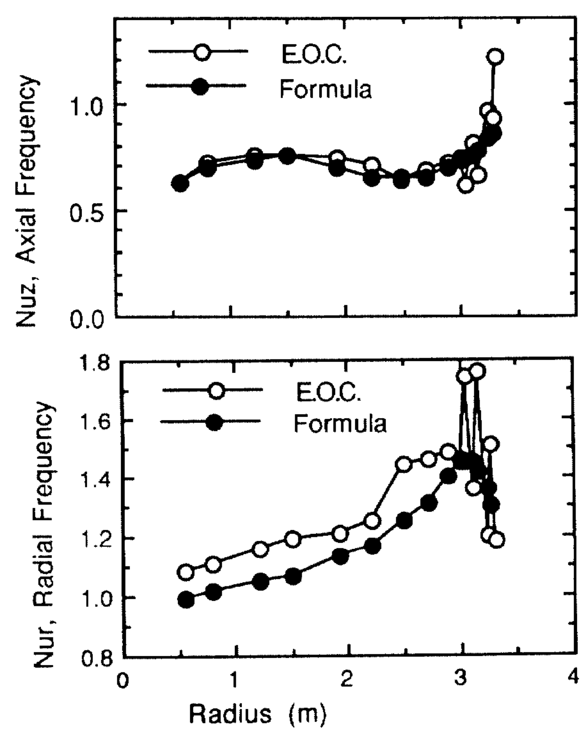

Figure 3. Nuz, Nur for 4 sectors.

Table 1. Spreadsheet calculation of Nuz and Nur.

E (MeV)	B-Rho (T-m)	Gamma	Bave (T)	Rave (m)	Mu' (TOSCA)	Eps Iron (deg)	Tan Eps (TOSCA)	1+2 x Tansq Eps (P)	FSQ (TOSCA)	FSQxP (F)	Nuz-sq F-Mu'	Nuz	Nur Sqrt. (1+Mu')
730	4.598	1.778	1.351	3.402	-.96	55.0	1.163	3.71	.273	1.01	1.97	1.40	.200
555	3.872	1.592	1.210	3.201	.93	54.0	1.252	4.14	.318	1.31	.38	.62	1.389
435	3.342	1.464	1.112	3.004	1.11	47.7	1.071	3.29	.388	1.28	.17	.41	1.453
342	2.903	1.365	1.037	2.799	.87	37.0	.771	2.19	.453	0.99	.12	.35	1.367
272	2.548	1.290	.980	2.599	.62	29.6	.577	1.67	.495	0.82	.20	.45	1.273
217	2.246	1.231	.936	2.400	.50	22.6	.417	1.35	.522	0.70	.20	.45	1.225
172	1.978	1.183	.899	2.200	.33	14.7	.229	1.10	.532	0.59	.26	.51	1.153
135	1.737	1.144	.869	1.998	.27	6.6	.148	1.04	.528	0.55	.28	.53	1.127
105	1.520	1.112	.845	1.799	.20	.0	.037	1.00	.511	0.51	.31	.56	1.095
80	1.319	1.085	.825	1.599	.15	.0	.004	1.00	.483	0.48	.33	.58	1.072
60	1.136	1.064	.809	1.405	.13	.0	.001	1.00	.443	0.44	.31	.56	1.063
43	0.958	1.046	.795	1.205	.10	.0	.000	1.00	.391	0.39	.29	.54	1.049
29	0.783	1.031	.783	1.000	.06	.0	.000	1.00	.330	0.33	.27	.52	1.030
18.3	0.621	1.020	.775	0.801	.05	.0	.000	1.00	.258	0.26	.21	.46	1.025
10.1	0.460	1.011	.768	0.599	.04	.0	.000	1.00	.172	0.17	.13	.36	1.020
4.46	0.305	1.005	.764	0.400	-.06	.0	.000	1.00	.076	0.08	.14	.37	.970
1.11	0.152	1.001	.761	0.200	-.01	.0	.000	1.00	.012	0.01	.02	.15	.995
.00	0.000	1.000	.760	0.000	#REF!	.0	.000	1.00	.000	0.00	#REF!	#REF!	#REF!

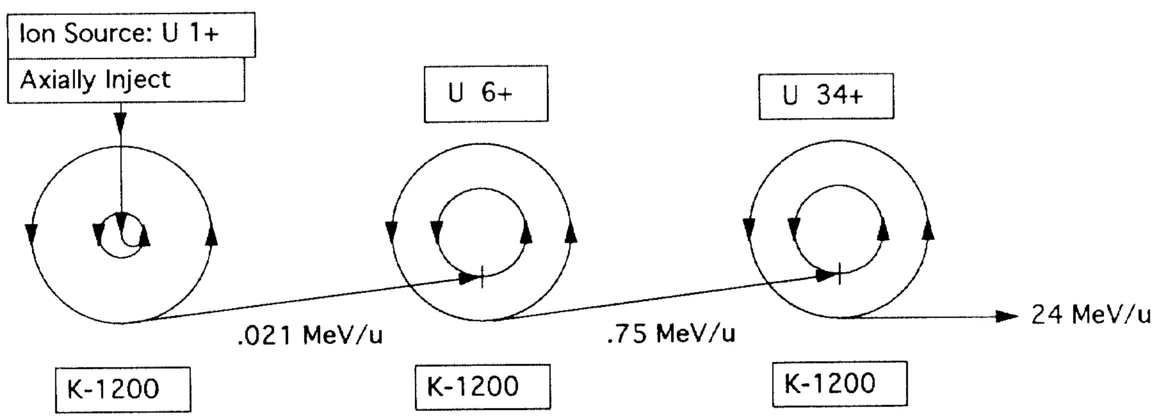

Figure 4. Post-accelerator using 3 cyclotrons.

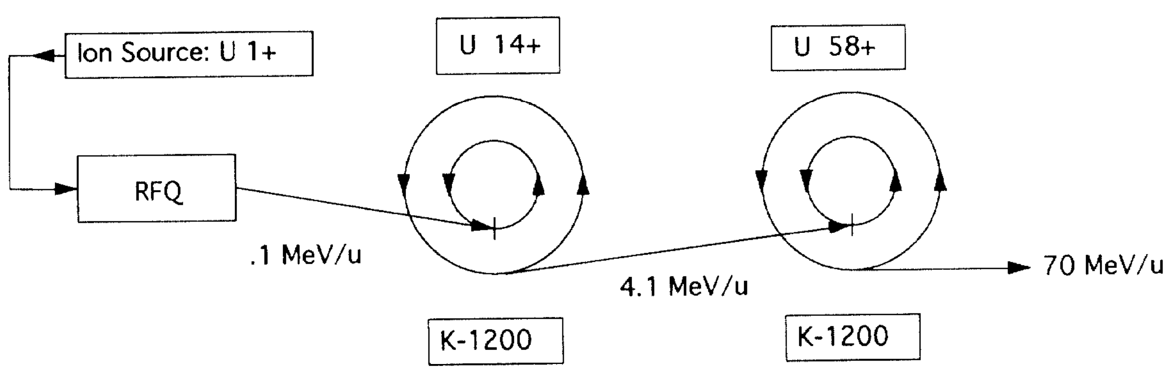

Figure 5. Post-accelerator using a linac and 2 cyclotrons.