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A CYCLOTRON BASED ACCELERATION CHAIN FOR A 400 MeV/u DRIVER FOR A RADIOACTIVE BEAM FACILITY

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ABSTRACT

The creation of intense radioactive beams requires intense and energetic primary beams. A task force analysis of this subject recommended an acceleration system capable of 400 MeV/u uranium at 1 particle μA (6.2 x 10^{12} particles/s) as an appropriate driver for such a facility. This document proposes for the driver acceleration system an ion source, radio frequency quadrupole (RFQ), and linac chain capable of producing a final energy of 20 MeV/u and a charge (Q) to mass (A) of Q/A ≅1/3. This acceleration system would be followed by a Separated Sector Cyclotron with a final output energy of 400 MeV/u to provide a more cost effective solution than a fully linac system.

INTRODUCTION

The acceleration scheme presented is intended for the creation of the high intensity beams necessary for the production of rare isotopes by projectile fragmentation. Linacs when compared to cyclotrons provide the widest range of possible operational characteristics, but at a substantial cost penalty. As a consequence, this paper proposes a hybrid system in which the linac is used to accelerate ions to a fixed final energy of 20 MeV/u at a charge state to mass ratio (Q/A) of approximately 1/3. The final acceleration to 400 MeV/u is accomplished by a Separated Sector Cyclotron. This acceleration chain provides a more cost-effective solution than a fully linac system with the same primary beam output parameters.

DESIGN CONCEPT

Separated Sector Cyclotron

The general design philosophy of the proposed Separated Sector Cyclotron is to take benefit of the highly successful design of the Paul Scherrer Institute's (PSI) 590 MeV/u Ring Cyclotron (RC) and to keep the system as simple as possible to enhance operational efficiencies and performance, and to minimize initial capital investment.

To minimize the requirements for the trim coils used to achieve a radial magnetic field profile compatible with isochronicity, a fixed charge (Q) to mass (A) ratio was chosen. As shown in Figure 1, a Q/A band of 0.333 ± 0.003 provides nearly complete coverage of the periodic table and will likely yield relatively modest trim coil requirements. Proton and deuteron like beams would be achieved by using the molecules H_3^{1+} and DH^{1+}. Other beam examples would be $^{18}O^{6+}$ and $^{48}Ca^{16+}$.

To allow a fixed frequency rf system, the injection and extraction energies are fixed at specific values. Given the Q/A = 1/3 choice, the minimum injection energy is set by the energy required for the heaviest ion (^{238}U) to achieve the appropriate equilibrium charge state after stripping. The empirical formula of Baron et al.[1] was used to evaluate the energy necessary to achieve the Q/A condition. From Figure 2, a value of 20 MeV/u was chosen for a Separated Sector Cyclotron injection energy.

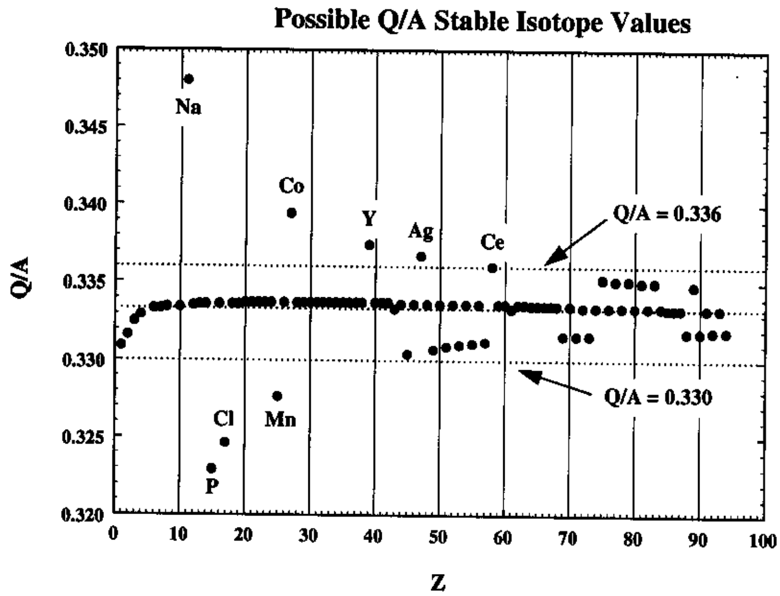

Figure 1. Possible primary beams with a charge (Q) to mass (A) ratio near 1/3.

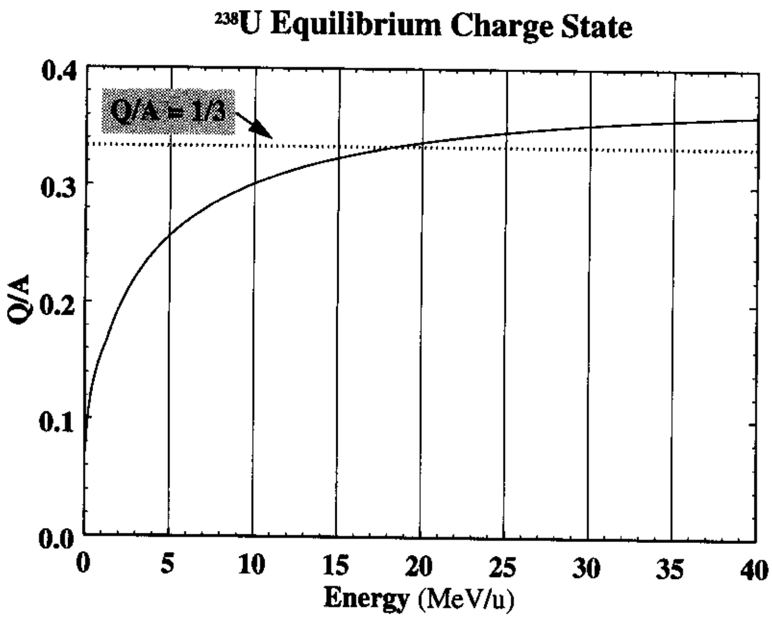

Figure 2. Equilibrium charge (Q) to mass (A) ratio for ^{238}U as a function of energy.

A preliminary analysis of a Separated Sector Cyclotron has been done. Listed in Table 1 are some of the basic parameters of the Separated Sector Cyclotron, and for comparison, those of the PSI 590 MeV/u Ring Cyclotron (RC). A magnetic field analysis has been done using TOSCA, a three dimensional magnetic field code. Two views of the Separated Sector Cyclotron are given in Figure 3 and Figure 4.

	PSI RC	**SSC**
BEAM		
A	1	238
Charge State	1	79
Q/A	1	1/3
Injection Energy (MeV/u)	73.5	20
Extraction Energy (MeV/u)	590	400
Current (p μA)	1,500	1
Beam Power (kW)	885	95
MAGNET		
Bρ (Tm)	4.01	9.52
Orbital Frequency (MHz)	8.49	4.05
Number of Sectors	8	6
Hill Gap (Max/Min) (cm)	9/5	9/5
Hill B (Max/Min) (T)	2.1/1.5	2.1/1.5
R (Injection/Extraction) (m)	1.95/4.45	2.4/8.43
Steel Weight (10^3 kg)	1960	16,500
Conductor Weight (10^3 kg)	28	53
Main Coil Power (kW)	650	1231
PRIMARY RF		
Harmonic	6	6
Frequency	50.92	24.29
Gaps/Turn	4	4
Effective Volts/Gap (kV)	730	730
Number of Turns	210	390
RF Power (MW)	0.3	0.36
HARMONIC RF		
Frequency	152.76	72.87
Gaps/Turn	1	1
Effective Volts/Gap (kV)	325	325

Table 1. Some parameters of the proposed Separated Sector Cyclotron (SSC) and for comparison those of the PSI Ring Cyclotron (PSI RC).

Given the PSI experience, a final turn separation of ~1 cm and the inclusion of a 3rd harmonic "flat-topping" rf system should provide a very high extraction efficiency. The Separated Sector Cyclotron design closely follows that of the PSI 590 MeV/u Ring Cyclotron (RC) that routinely and reliably extracts beams with nearly ten times the power proposed for this application. Thus, the Separated Sector Cyclotron will not be the source of any beam current limitations. Excepting minor variations of the trim coil setting, the fixed nature of the cyclotron operating parameters should yield an operationally reliable and robust system.

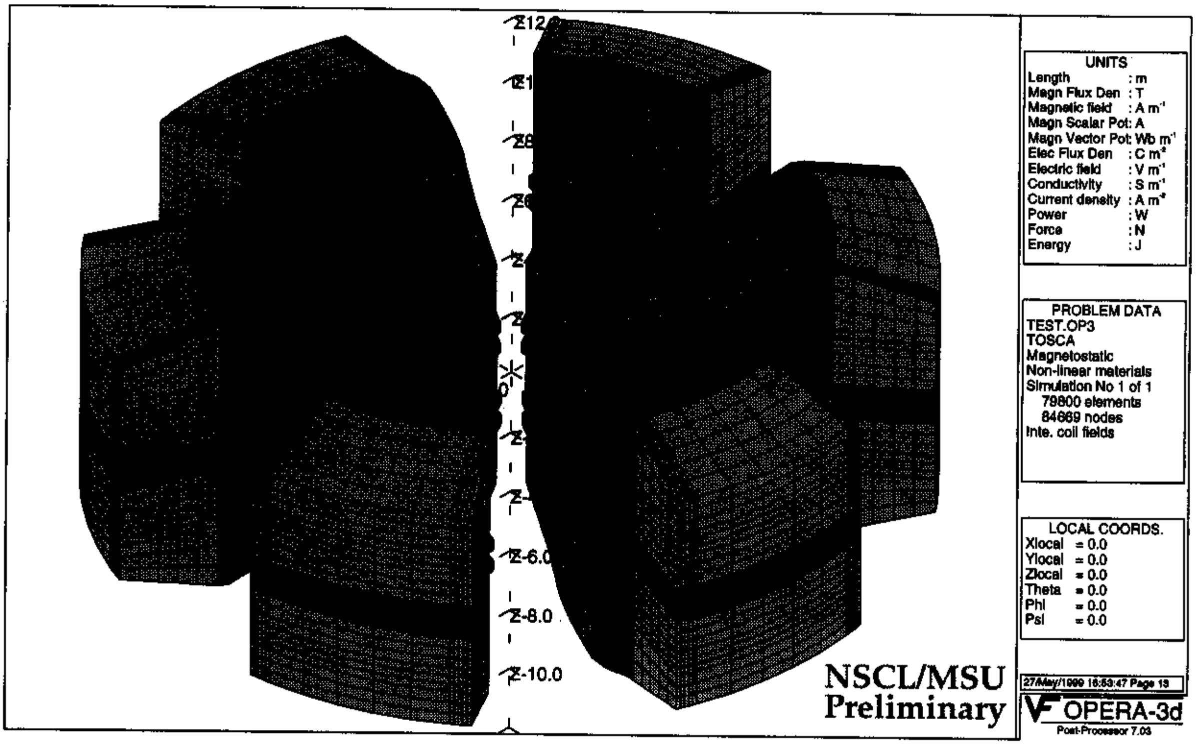

Figure 3. Three dimensional view of the Separated Sector Cyclotron magnet system.

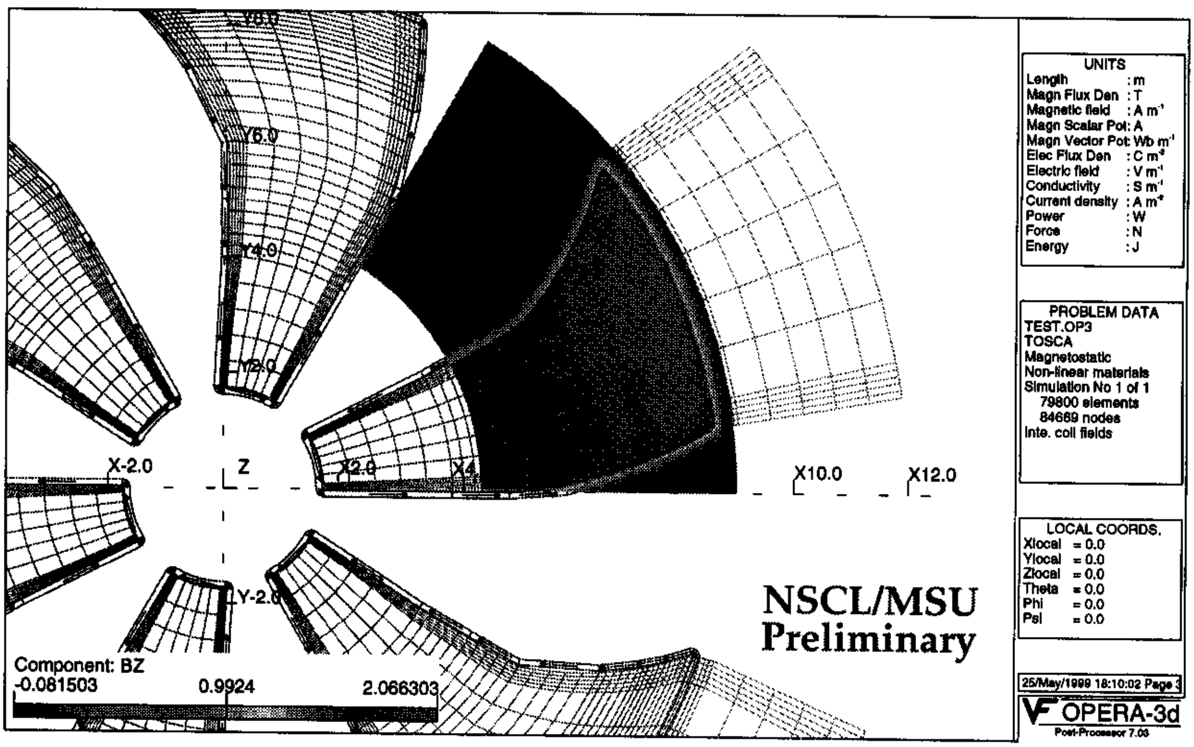

Figure 4. Top view of the Separated Sector Cyclotron magnet system.

A preliminary evaluation of major cost elements for the Separated Sector Cyclotron has been done. It is estimated that the magnet materials will cost about 70 M$ derived from estimates for the steel ($4/kg) and coil ($50/kg) costs. Based upon PSI experience, the RF system is estimated to cost about 30 M$ giving a total cost of 100 M$ for these major subsystems. Other cost elements including engineering design, assembly, commissioning, and control, vacuum, injection, and extraction systems will be the subject of future evaluations. It seems likely that the total Separated Sector Cyclotron cost will be <150 M$.

20 MeV/u Acceleration System Issues

Many issues such as ion source performance, stripper foil technology and RFQ and linac system design choices do not depend on whether or not a Separated Sector Cyclotron is used as the last element of the acceleration chain. These common issues are not discussed here; only those items specific to the Separated Sector Cyclotron concept are considered.

The Separated Sector Cyclotron sensitivity to field errors scales like the product of the turn number and the rf harmonic number. Then, increasing the rf harmonic number increases the rf frequency while increasing sensitivity to field errors. It is this consideration that led to the proposed Separated Sector Cyclotron rf frequency of 25 MHz. As a consequence, the 20 MeV/u acceleration chain requires a linac operating either at 25 MHz or a subharmonic bunching scheme. It seems likely that a linac frequency near 75 MHz would be technically advantageous, and therefore, a third subharmonic bunching scheme would be required. It is anticipated that such a system would not entail significant technical challenges nor have any deleterious effect on the beam quality.

The preliminary specification for the allowable momentum spread of the Separated Sector Cyclotron injected beam is $\Delta p/p < 10^{-3}$. This should be easily achievable by a phase rotation system particularly for the case where the linac beam is accelerated with 75 MHz structures.

SUMMARY

The application of a Separated Sector Cyclotron as the last element (20 – 400 MeV/u) of a 400 MeV/u acceleration chain for radioactive beam production is likely to provide significant cost advantages with no significant concomitant performance limitations when compared to a linac system.

REFERENCES

1 E. Baron, M. Bajard and Ch. Ricaud, "Charge exchange of very heavy ions in carbon foils and in the residual gas of GANIL cyclotrons", NIM, **A328** (1993), 177-182.