DESIGN STUDY OF A HIGH INTENSITY TEST CYCLOTRON

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1. Introduction

The design of a high intensity, low energy cyclotron has been studied. The design goal for this cyclotron was a 10-milliamp beam of 5 MeV protons. The current of 10-milliamps was chosen because it represents a significant milestone in cyclotron intensity. There are at least two industrial applications for such a 10-milliamp cyclotron. The first is boron neutron capture therapy (BNCT). BNCT is a treatment modality for cancer using a source of thermal neutrons. It is believed that a 2.5 MeV, 10-milliamp proton accelerator with a lithium target could produce an appropriate flux of thermal neutrons (1). The second industrial use for a 10-milliamp cyclotron is as a source of supplemental high-energy neutrons for a sub-critical nuclear reactor (2). The planned High Intensity Test Cyclotron (HITC) would provide evidence that a cyclotron with an internal ion source can reliably produce a 10-milliamp beam of protons.

The HITC was designed to operate near its theoretical space charge limit. This makes it a useful tool for measuring the effects of space charge on beam dynamics. An approximate formula for the axial space charge limit of a cyclotron is given (3):

$$I_{lim} = A\varepsilon_0\omega_0\nu_z^2(\Delta\phi/2\pi)(\Delta E/e)$$

Where A is the full axial height of the beam, ε_0 is the permittivity of free space, ω_0 is the angular velocity of the ions, ΔE the energy gain per turn and $\Delta\phi$ the phase width of the beam. The operating parameters for the HITC are listed in Table 1.

Energy	4.8 MeV
Number of Sectors	4
Number of Turns	13.5
Axial Beam Height (A)	0.8 cm
Cyclotron Frequency (ω_0)	9.6×10^7
Axial Tune (ν_z)	0.25
Phase Width ($\Delta\phi$_)	36^0
Energy Gain per Turn ($\Delta E/e$)	360 keV
Axial Space Charge Limit (I_{lim})	15 mA

Table 1. Design parameters of the HITC

We have investigated the primary components of the cyclotron: the magnetic field, the central region and the RF system.

2. Magnet

The design of the high intensity test cyclotron was based around the so called airport magnet, which started its life in the 1960 s as the NSCL steering dipole magnet M3. In the early 1990 s this magnet was modified for possible use as a cyclotron for contraband detection (the airport cyclotron.) It was also the starting point for the design of an Accelerator Mass Spectrometry cyclotron (4).

The first step in designing the HITC was to design modifications to the existing pole tips that would produce an isochronous magnetic field suitable for 4.8 MeV protons. Magnetic field calculations were done with a commercially available three dimensional magnetic field program called TOSCA (5). Before any modifications to the magnet were made, the magnetic field was mapped and modeled in TOSCA in its current configuration. The TOSCA calculations proved to be within a 2% of the mapped fields for most of the magnet.

Once computational capability was confirmed, changes were made in the shape of the pole tip in the model to produce the desired field shape. Figure 1 shows the final mesh used to calculate the magnetic fields for the HITC.

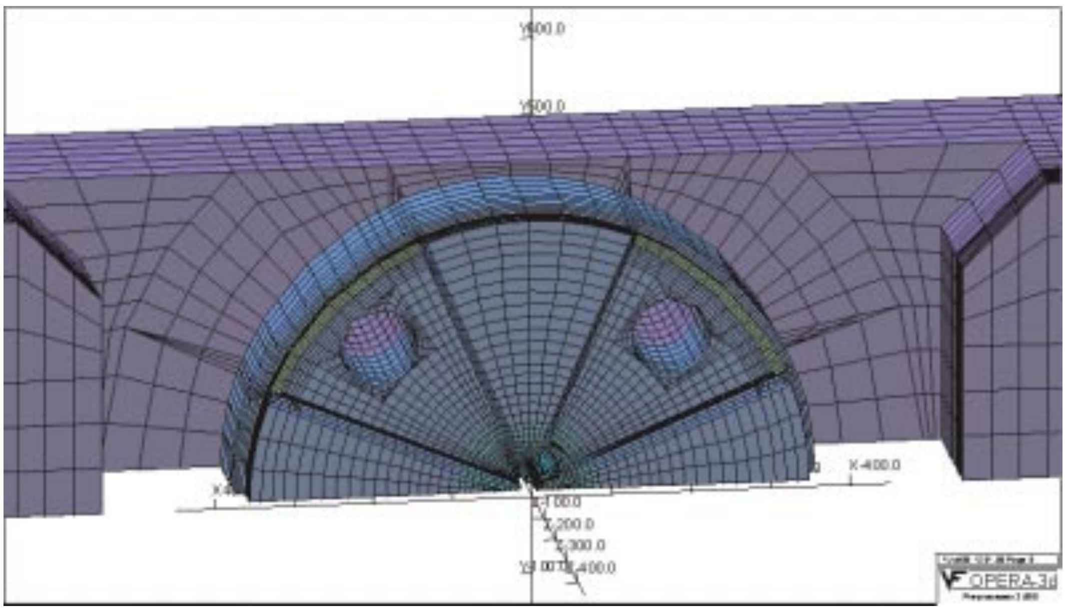

Figure 1. TOSCA mesh.

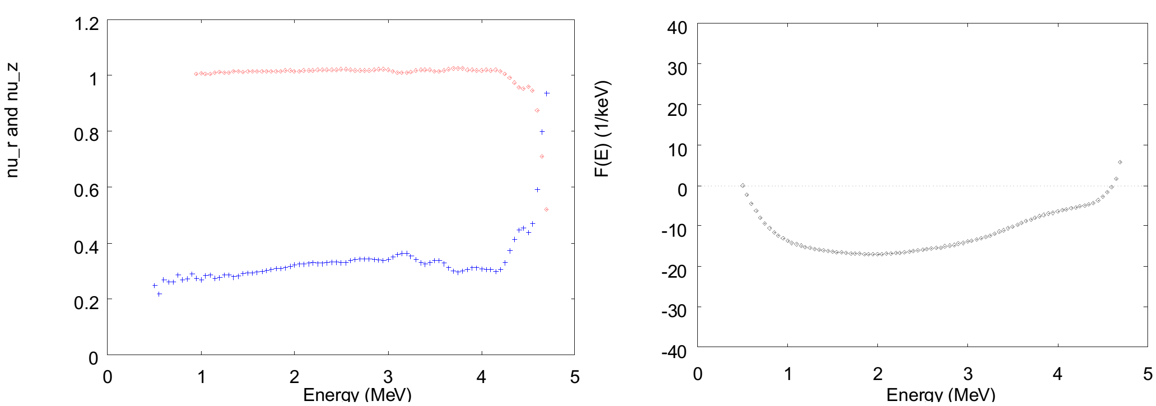

Figure 2. Results from GENSPE1. ν_r (red), ν_z (blue) do not show any difficult resonances. ν_r is imaginary below 1 MeV. F(E), a measure of isochronism, has a minimum of —17.1, which gives a maximum $\Delta\sin(\phi)$ of 0.18.

The criteria used for a good magnetic field came from the equilibrium orbit data provided by the GENSPE1, general spiral equilibrium orbit code. The magnetic field needed to be isochronous, provide good axial focusing, and be free of any dangerous resonances. Figure 2 shows the degree to which these criteria were met.

3. Central Region

The central region of a cyclotron is responsible for extracting the beam from the ion source and making sure the beam is centered as it leaves the center of the cyclotron. It also needs to provide electric focusing to supplement weak magnetic focusing in the center due to flat field shape.

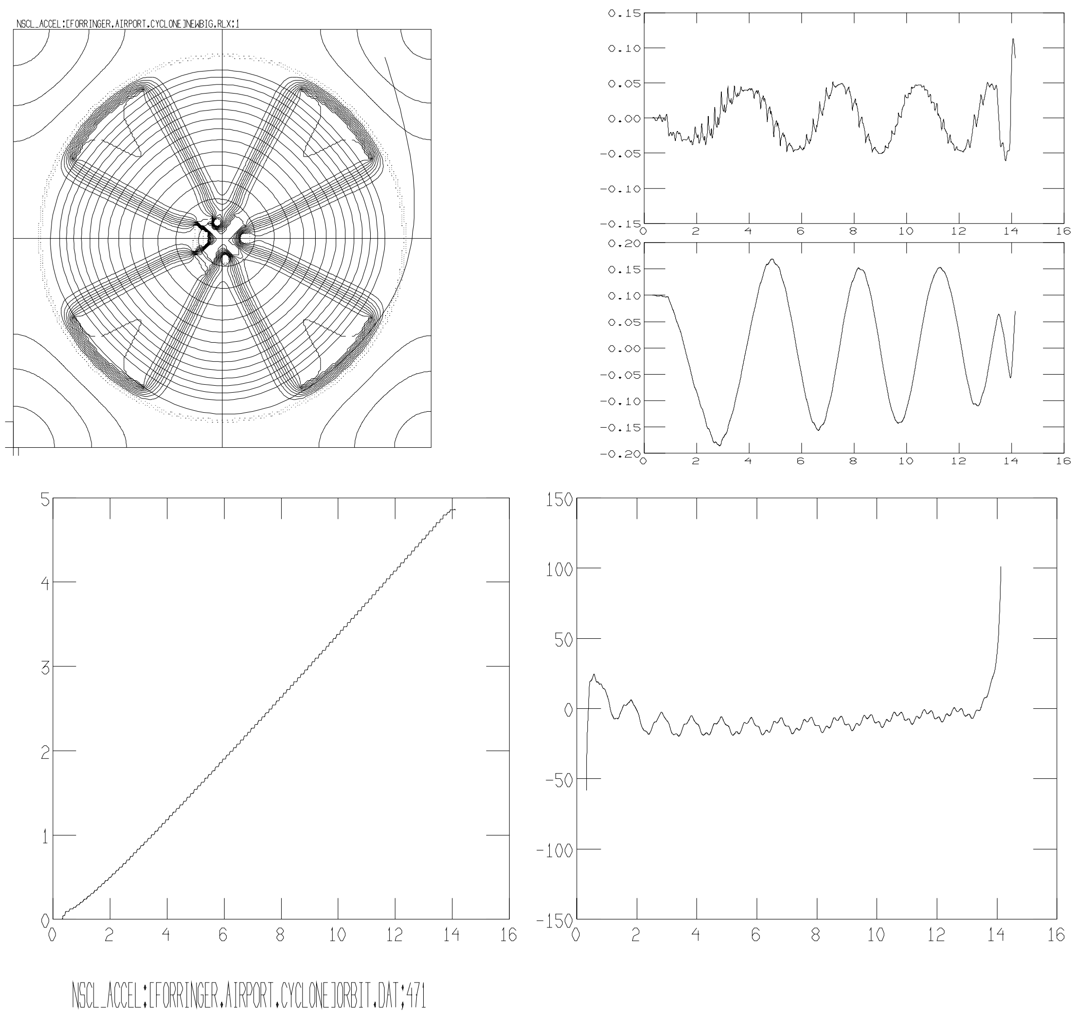

Figure 3. The top left graph shows the path of an accelerated ion. 13.5 turns can be seen. The top right graph shows the z-motion of an accelerated proton. The sinusoidal shape of z and p_z indicate good focusing. The bottom left graph shows energy as a function of turn number. The bottom right graph shows phase as a function of turn number. The small oscillations indicate a small centering error. The near flatness of the curve indicates good isochronism.

The HITC central region was derived from the central region of the Cyclone 235 cancer therapy proton cyclotron manufactured by Ion Beam Applications (IBA) of Louvain-la-Neuve Belgium. The IBA central region was scaled for the magnetic field and dee voltage of the HITC and was modified to match its four-dee configuration as opposed to IBA s two-dee configuration. The resulting shape was entered into Relax3D. The electric fields calculated by Relax3d, combined with the magnetic fields calculated from TOSCA were used with Cyclone, an orbit tracking code developed here at the NSCL. Figure 3 shows the output from a cyclone run.

4. Radio Frequency

The HITC design is based on 4 dees operating at the fourth harmonic of the cyclotron s orbital frequency, which results in an RF frequency of 61.1 MHz. The four dees, the dee stems and the liner make a resonant cavity, which must be tuned to the RF frequency of the cyclotron. The power required for the RF amplifier is the beam power plus the power required to excite the dees to 50 Kilovolts.

We used the method detailed in John Vincent s Doctoral Thesis (6) to optimize the shape of the resonant cavity in order to minimize resistive losses in the cavity. This method also provided an estimate on how much power would be dissipated in the RF cavity.

The three shapes that were considered for the resonant cavity are shown in Figure 4. The first shape is similar to the resonant cavity used in Superconducting cyclotrons such as the K-500 and K-1200, with a dee stem attached to top and bottom of each dee and exiting the magnet vertically through dee stem holes in the magnet yoke. The second design uses four dee stems attached to the outer edge of each dee and exiting the magnet horizontally. The final design uses only two dee stems attached to the outer edge of opposite dees and exiting the magnet horizontally. The criterion for each design was that the dee voltage at the center of the cyclotron was 50 kilovolts.

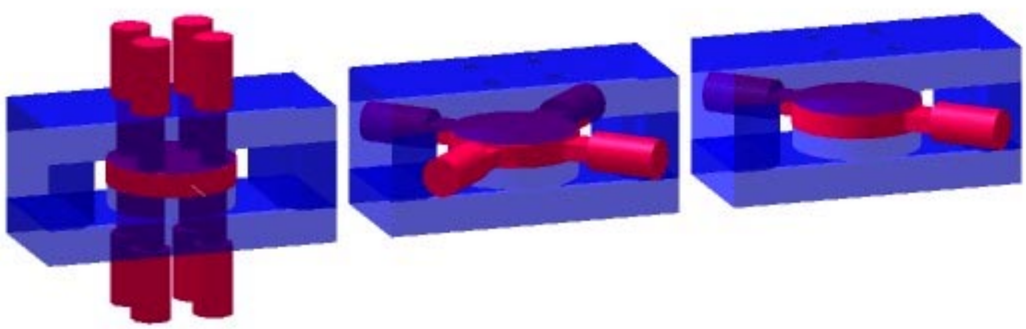

Figure 4. The three RF cavity designs tested for the HITC.

	8 dee stems	4 dee stems	2 dee stems
Beam Power	50 kW	50 kW	50 kW
Resistive Losses	32 kW	21 kW	20 kW
Total Required Power	82 kW	71 kW	72 kW

Table 2. The power requirements for each design.

The results show that for the HITC using eight vertical dee stems is not efficient. The small dee stem holes in the magnet would have required using small outer diameter dee stems which have a large capacitance. This extra capacitance added to the power required to drive the resonator. Using either 2 or 4 horizontal dee stems produced less power requirements. The 4 dee stem configuration is the preferred choice because it produced a more uniform dee voltage than the 2 stem configuration.

It was estimated that a 100KW RF amplifier would be needed to power the HITC. This estimate includes the beam power plus the resistive losses in the RF cavity plus a safety margin.

5. Conclusions

The proposed modifications of the airport magnet into an HITC would give an interesting cyclotron that could be used to measure the effect of space charge on an accelerated beam and test results of computer codes designed to calculate space charge effects. It would also serve as a proof of concept for other cyclotron applications.

Unfortunately, the 100 kW RF amplifier needed to power the dees is expensive. Price estimates for these amplifiers ranged from $250,000 (Energy-Onix Broadcast Equipment Co.) to $360,000 (Harris Corp.).

Additionally, it is yet to be determined if the proposed ion source which is similar to the source in the Harper Medical cyclotron (7) could produce the required 10 milliamp beam of protons. Development of a DC ion source test stand that should help answer this question is ongoing and should be completed in the spring of 2001.

References

1. Sasaki M. and T Yamanaka. Conceptual Design Study on an Accelerator Based BNCT Facility Applications of Acceleratory in Research and Industry p1029 1999.
2. Carelli, M. D., L Green and D. V. Paramonov. A Subcritical Reactor Design for the Accelerator Transmutation of Waste. Third International Topical Meeting on Nuclear Applications of Accelerator Technology, 1999.
3. Blosser, H. G. and M. M. Gordon. Performance Estimates for Injector Cyclotrons Nuclear Instruments and Methods 1961
4. Schubert, J. R. Extending the Feasibility Boundary of the Isochronous Cyclotron Doctoral Thesis, Michigan State University 1997.
5. http://www.vectorfields.com/tosca.htm
6. Vincent, J. J. Modeling and Analysis of Radio Frequency Structures using an Equivalent Circuit Methodology with Application to Charged Particle Accelerators RF Resonators Doctoral Thesis, Michigan State University 1996.
7. "Proposal for a Manufacturing Prototype Superconducting Cyclotron for Advanced Cancer Therapy", Michigan State University Report MSUCL-874, February 1993.