ION CYCLOTRON RESONANCE ACCELERATOR

T.L. Grimm, C.T. Ramsell, and R.C. York
National Superconducting Cyclotron Laboratory
Michigan State University
East Lansing, MI 48824

Abstract

The Ion Cyclotron Resonance Accelerator (ICRA) is ideally suited for the production of radioisotopes or neutrons. The general theory of the ICRA and the designs of and simulation results for a proof-of-principle, one MeV ICRA and a 10 MeV ICRA for isotope or neutron production are presented.

1. INTRODUCTION

The Ion Cyclotron Resonance Accelerator (ICRA), based on the operating principles of cyclotrons and gyrotrons, should provide beam suitable for the production of radioisotopes for positron emission tomography (PET) or neutrons for material research at a fraction of the cost of the cyclotrons or linacs presently used in these applications. In addition, the ICRA technique holds the potential for higher intensities and energies, as well as for the acceleration of heavier ions.

In a cyclotron, the accelerated particles are axially confined in a solenoidal magnetic field and accelerated azimuthally. In a gyrotron, the energy of a dc electron beam is converted into microwaves in a resonant cavity within a solenoidal magnetic field. The inverse process of electron acceleration by an rf-driven gyrotron structure has also been demonstrated [1].

The ICRA extends cyclotron resonance acceleration to ions by using a magnetron rf structure operating at a harmonic of the cyclotron frequency and a superconducting solenoid. Gyrotron structures use waveguide modes on the order of a wavelength, and hence would be too large at the low frequencies required for ions. However, since a magnetron rf structure is basically a lumped circuit, it can be much smaller than a wavelength [2]. The combination of a magnetron rf structure and the high magnetic fields (>5T) of a superconducting magnet, provide an rf structure which can be placed in a solenoid of reasonable diameter.

Unlike many accelerators, the beams produced in an ICRA will range in energy from that injected to the peak accelerated energy (E_p). However, for the applications discussed, all energies above $E_p/2$ will be productive. Beam extraction is inherently simple in the ICRA since all beam drifts axially through the solenoid to the target position where it can be isolated from the accelerator mitigating maintenance and radiation shielding issues.

Because a compact, superconducting solenoid does not require any steel, the ICRA could be light (<2 tons) and hence portable making it possible for the radioisotope or neutron source to be shared by several institutions or used in the field.
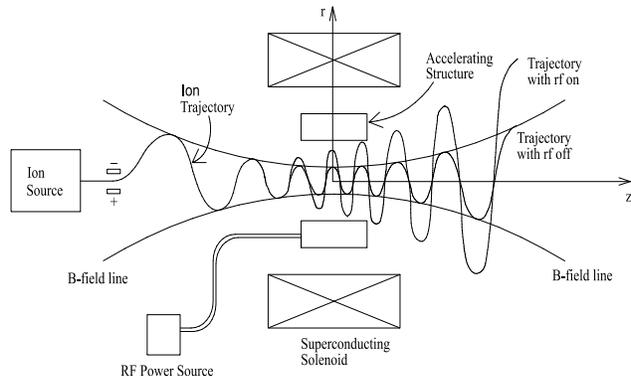
Figure 1 Components of an ICRA.

2. GENERAL THEORY

The main elements of an ICRA, shown schematically in Figure 1, are an ion source, superconducting solenoid, accelerating structure, microwave source, and target system. The beam is extracted from the ion source along a magnetic field line and then electrostatically deflected onto the injection orbit such that most of the beam's velocity is perpendicular to the magnetic field ($v_\perp$). A comparatively small velocity component parallel to the solenoidal magnetic field ($v_\parallel$) causes the beam to drift through the accelerating structure. Within the solenoid, the beam gyrates at the cyclotron frequency, $\omega_c = qB/\gamma m$, where B is the local magnetic field, γ is the relativistic mass factor, q is the ion charge and m is the ion rest mass. The velocity perpendicular to the magnetic field can be written, $v_\perp = r\omega_c$, where r is the beam's radius of curvature.

The beam is accelerated in the magnetron structure by the rf electric field transverse to the constant magnetic field. A four gap magnetron structure is shown in Figure 2. A first-order estimate of the accelerating voltage is obtained by assuming a magnetron cavity consisting of a

hyperbolic fin structure with 2n vanes. In this case, the potential, V, for $r<r_0$ can be written as:

$$V = V_t \left(\frac{r}{r_0} \right)^n \cos(n\theta) e^{i\omega_{rf} t}$$

where V_t is the peak rf voltage at the cavity wall, r_0 is the cavity wall's inner radius, n is the azimuthal mode number of the cavity and ω_{rf} is the rf frequency.
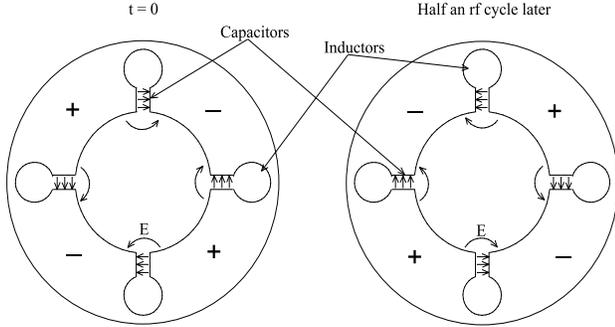
Figure 2 ICRA Magnetron Accelerating Structure.

The resonance condition requires a harmonic relationship between the ion's gyration and the rf frequency ($\omega_{rf} = n\omega_c$). With this condition, the kinetic energy gain across a single gap is given by:

$$K_{gap} = \frac{\pi}{4} e V_0 \left(\frac{r}{r_0} \right)^n$$

where $V_0 = 2V_t$ is the total rf voltage swing in the cavity. The number of turns, N_t, through which the ion is accelerated as it drifts through the cavity depends on the drift velocity, the active cavity length, l, and the cyclotron frequency by:

$$N_t = \frac{l}{v_{\parallel}} \frac{\omega_c}{2\pi}$$

Since the largest energy gains result from maintaining the beam as close to the cavity wall as possible, $K_{gap} \sim (r/r_o)^n$, it is desirable that the cavity radius increase with the beam's orbit radius.

3. DESIGN

A one MeV ICRA was designed as a proposed prototype to provide the basis for concept demonstration, experimental verification of the three-dimensional simulation code, and determination of critical design parameters such as rf voltage, perpendicular and parallel injection velocities, and magnetic field requirements. The prototype would provide a sound basis for the development of a design for a 10 MeV, 50 µA proton ICRA suitable for PET isotope production or neutron source for material research.

Detailed simulations, which tracked particles from the ion source to the target position, were done using the computer codes RELAX3D developed at TRIUMF [3] and a modified version of Z3CYCLONE developed at the NSCL [4]. These codes are well-tested and have been used successfully to design the central regions of the superconducting cyclotrons in operation at the NSCL [5,6].

3.1 One MeV ICRA

Detailed simulations of injection, acceleration, and extraction of a finite emittance beam in a realistic magnetic field were done for the one MeV ICRA. Table 1 provides a synopsis of the parameters chosen.

A significant design parameter is the choice of the solenoidal magnetic field value. In general, the accelerating structure dimensions scale as $1/\omega_{rf}$, and hence, the required magnet bore is inversely related to both the magnetic field and the rf harmonic number. Therefore, a higher magnetic field requires a smaller magnetic field volume reducing the solenoid cost. Existing NbTi superconducting solenoids have peak field values of 8 T and warm bores of 20 cm. Larger magnetic fields and warm bores would require substantially more expensive technology. (For a solenoidal field of 8 T, proton beams of 1 and 10 MeV have radii of 1.8 cm and 5.7 cm respectively.) Simulations predict acceptable performance with a magnetic field variation of 0.5% (B_z/B_{z0}=0.995) over the length of the accelerating structure.

The injection geometry simulated placed the ion source in a region of low magnetic field (B_z=0.6 T) where the turn spacing and orbit diameter are relatively large. The ion source was aligned with the magnetic field and placed at a potential of 51 kV. The electrostatic bend was modeled as two flat plates 0.8 cm wide, spaced 1.2 cm apart, and operating at ±11 kV. A 4th harmonic rf frequency ($\omega_{rf} = n\omega_c$) was chosen since rf sources for 488 MHz are readily available, and the cavity size is compatible with manufacturing techniques and a 20 cm warm bore. The active cavity length was 10 cm and would be made of OFHC copper by an EDM process. The estimated power required to drive the cavity at the specified voltage is about 430 watts with an additional 380 watts of rf power required to accelerate the beam.

The results of these simulations, given in Figure 3, show that 10% of an initial 2 π mm-mrad (unnormalized) beam will be accelerated to >0.5 MeV with about 12% of the particles lost on the inner surface of the accelerating structure. The remaining beam with <0.5 MeV is delivered to the target system. A high current density proton source such as a duoplasmatron with a current of ~2 mA would produce 200 µA of accelerated beam (>0.5 MeV) [7]. Further optimization is possible since it was found that the simulated acceptance of the one MeV ICRA was substantially larger than 2 π mm-mrad. The

capture efficiency could be increased, for example, by making the injected beam radial dimensions 2-3 times larger than simulated.
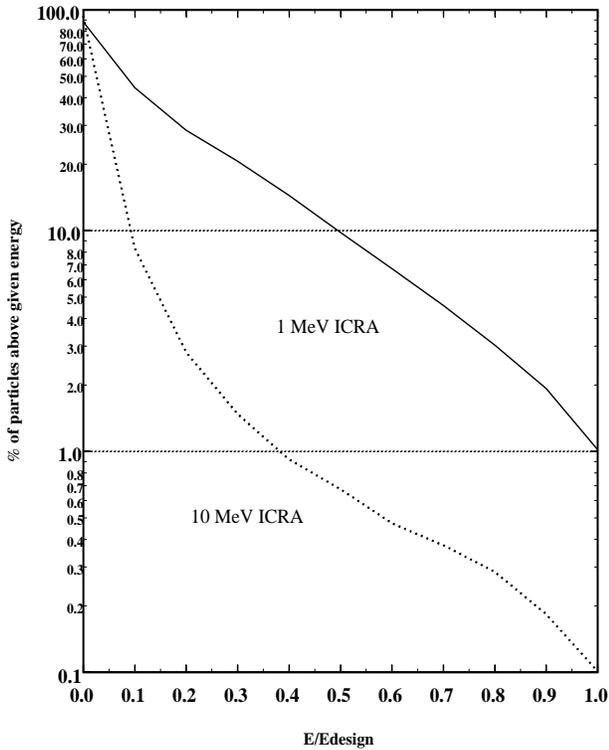
Figure 3 Output beam intensity vs. energy for a one MeV ICRA (solid line) and a ten MeV ICRA (dashed line).

3.2 Ten MeV ICRA

A preliminary, 10 MeV ICRA design was developed in large part by scaling the one MeV ICRA parameters as shown in Table 1. The peak accelerating voltage of 70 kV resulted in an electric field of 190 kV/cm in the gaps. A worst-case field enhancement leads to a peak field of <380 kV/cm, which is well below the Kilpatrick criterion for this frequency regime [8].

Gun-to-target particle tracking was performed as explained for the one MeV ICRA. Assuming an initial phase space of 2π mm-mrad and beam current of 2 mA, simulations predict that 13 μA of beam would be accelerated to 5-10 MeV as shown in Figure 3. Though less than the design goal of 50 μA, this intensity is encouraging since even at the 13 μA level such a device would be appropriate for the production of PET radioisotopes or neutrons for material research. Design optimization strategies which will be explored include, among others, optimizing and/or increasing the injected phase space, increasing the injection energy to increase the beam brightness, reducing the number of turns, increasing the interaction length, and reducing the solenoidal magnetic field.

Design Energy	1 MeV	10 MeV
Magnetic Field	8 T	8 T
Cavity Length	10 cm	25 cm
RF Frequency	488 MHz	488 MHz
RF Power	<1 kW	8 kW
Cavity Voltage	16 kV	70 kV
Source Current	2 mA	2 mA
Source Voltage	51 kV	54 kV
Beam Perpendicular Energy at Cavity Entrance	44 keV	46 keV
Cavity ID at Entrance	1.1 cm	1.2 cm
Cavity ID at Exit	4 cm	12.2 cm
Number of Acceleration Turns	11	40
Accelerated Current	200 μA	13 μA
Beam area on Target	2.3 cm^2	16 cm^2

Table 1 Design parameters and simulation results for one and ten MeV ICRAs.

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