EXPERIMENTAL STUDY OF AN ION CYCLOTRON RESONANCE ACCELERATOR

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Abstract

The Ion Cyclotron Resonance Accelerator (ICRA) uses a novel geometry which combines the radial confinement and azimuthal acceleration of cyclotrons together with the axial drift used in gyrotrons. Use of a common NbTi superconducting solenoid and an rf driven magnetron structure lead to a simple, lightweight, and compact machine that could be designed for portability. An ICRA designed to accelerate protons to 10 MeV would be ideal for production of PET isotopes or as an accelerator based neutron source. As a demonstration of the concept, an ICRA has been built that accelerates a proton beam to 50 keV. This paper presents the 50 keV design and gives experimental results.

1 INTRODUCTION

The Ion Cyclotron Resonance Accelerator (ICRA), 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 for these applications.

In a cyclotron, the magnetic field confines ions radially and focuses them axially, while the beam is accelerated in the azimuthal direction. In a gyrotron a dc electron beam is radially confined around magnetic field lines but is allowed to drift axially while the energy of the beam is converted into microwaves within a resonant structure. The ICRA is similar to the cyclotron in that ions orbit around magnetic field lines while being accelerated azimuthally. However, the beam is allowed to drift axially, as in a gyrotron. The ICRA differs from the cyclotron primarily in this lack of axial focusing and in the type of rf accelerating structure.

Jory and Trivelpiece demonstrated electron cyclotron resonance acceleration in 1968 [1]. However, until now, this method of acceleration has not been demonstrated for ions. The ICRA extends cyclotron resonance acceleration to ions by using a high field superconducting solenoid together with an rf driven magnetron structure operating at a harmonic of the cyclotron frequency. The resulting high rf frequency together with the fact that the magnetron structure is basically a lumped circuit means that the accelerating structure can be small enough to fit into a solenoid of reasonable diameter [2].

Unlike many accelerators, the beam produced in an ICRA will have a full energy spread ranging from the injected energy to the peak accelerated energy (E_{design}). However, for the applications discussed here a mono-energetic beam is not required, in fact generally all energies above $\frac{1}{2}E_{design}$ will be useful for these applications.

Beam extraction in the ICRA is inherently simple 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 the 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.

The main components of an ICRA, shown in figure 1, are the superconducting magnet, ion source, electrostatic bend, accelerating structure, and the target. The ion beam is extracted from the source directly along a field line so that the $\vec{v} \times \vec{B}$ force on the beam is zero. At the electrostatic bend, the dc beam is deflected (into the page in figure 1) so that its momentum perpendicular to the B-field ($p_\perp$) causes ions of charge q to orbit around field lines at radius $r = p_\perp/qB$. The remaining parallel momentum ($p_\parallel$) causes the beam to spiral axially into the high field region. At the acceleration region the B-field is relatively flat and the beam drifts axially through the magnetron structure. While inside the magnetron, the beam is accelerated by rf electric fields which are transverse to the axial B-field. Upon exit from the magnetron, the beam spirals into the lower field of the extraction region until striking a target downstream [3].

Our initial design for a 10 MeV proton model would use an 8 Tesla superconducting magnet and a 488 MHz magnetron. A computer code developed for modeling the ICRA uses many single particle trajectories to model the beam phase space. Modeling of the 10 MeV design predicted that a 2 mA injected beam of 2π mm mrad (unnormalized), would produce 13 μA of beam accelerated to an energy range of 5 to 10 MeV [3]. This current level would be useful for PET isotope or neutron production.

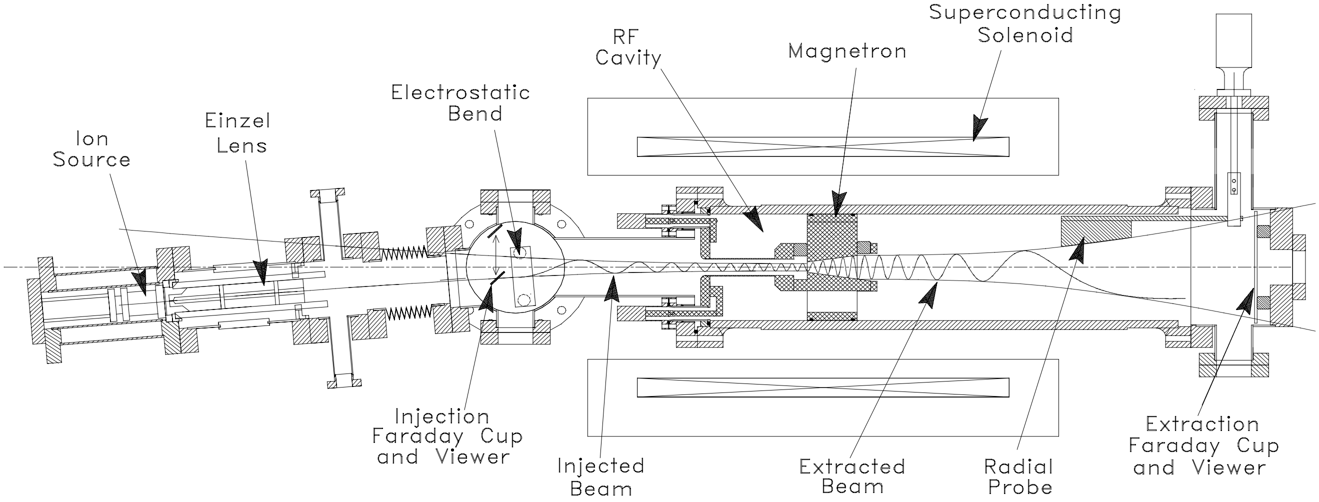

Figure 1: Cutaway view of the 50 keV ICRA experiment

In order to demonstrate the ICRA and benchmark the computer code in a relatively short time and with limited funds, a low energy 50 keV proton ICRA has been designed, built, and tested. The design and experimental results of this proof-of-principle device are presented in the following sections.

2 DESIGN

2.1 Superconducting Magnet

The superconducting solenoid provides a 2.5 Tesla magnetic field in a 20.3 cm warm bore. At this field, the cyclotron frequency for protons is 38 MHz. The resonance requirement over the acceleration region (for about 10 turns), leads to a field flatness criterion of $\Delta B/B_o<0.5\%$. The solenoid used has a field flatness suitable for an acceleration region of 5 cm in axial length.

2.2 Ion Source and Injection

The ion source is a simple electron filament source with a 0.51 mm aperture. H_2 gas is fed into the source along with Argon as a support gas. A 6.4 keV dc beam is extracted along a field line. An Einzel lens provides a wide range of focusing before the beam enters the electrostatic bend. The electrostatic bend consists of two copper plates with an axial length of 2 cm and a gap of 0.8 cm.

2.3 Accelerating Cavity

A classic magnetron structure operating at the 4th harmonic ($\omega_{rf} = 4\omega_c$) would not fit into the 20.3 cm warm bore of the 2.5 Tesla superconducting magnet. The solution was to build a hybrid quarter wave / magnetron cavity. This allowed the inductive component of the resonant structure to be extended in the axial direction rather than radially as in a pure magnetron. The result is a shortened $\lambda/4$ coaxial cavity with magnetron vanes mounted across its open end [4]. Our design operates at the 4th harmonic, thus there are a total of 2n=8 vanes. Of the 8 vanes, every other vane is electrically connected to the outer conductor of the $\lambda/4$ cavity, and the remaining 4 vanes are connected to the inner conductor and interleaved between the first 4 vanes.

The finished rf cavity operates at 152 MHz and generates a gap voltage of 3 kV at 100 watts input power. The inner diameter of the magnetron is tapered for improved acceleration as the beam radius increases. The acceleration region has an entrance diameter of 1.1 cm, an exit diameter of 2.5 cm, and an axial length of 5 cm.

2.4 Beam Diagnostics

The 50 keV ICRA is equipped with three diagnostics for measuring the beam. On the injection side, a Faraday cup with phosphor coating can be moved into the beam at a point immediately upstream from the electrostatic bend. This Faraday cup is used for aligning the ion source on a magnetic field line and for measuring the total injected beam current.

On the extraction end there are two beam diagnostics. The first is a Faraday cup mounted on a motion feedthrough that can be moved radially to intercept the beam. This radial probe is used to measure the beam radius and to obtain the current vs. energy distribution of the accelerated beam. The radial probe has an electron blocker mounted on the upstream edge which prevents secondary electrons from the cavity from reaching the radial probe. The second beam diagnostic on the extraction end is a large Faraday cup with phosphor coating and a glass viewport so that the image of the accelerated and unaccelerated beams can be viewed.

3 EXPERIMENTAL RESULTS

The ion source produces H^+, H_2^+ and Ar^+. However, immediately downstream of the electrostatic bend, ions with greater mass will orbit in the magnetic field with larger radii. Since the size of each gyro radius increases with the bending voltage, each constituent in the beam can be clipped on the aperture at the entrance to the acceleration region until only the innermost ion beam remains. This technique is used to insure that only the H^+ beam is injection into the acceleration region. It can also be used to obtain a mass spectrum of the ion beam and allow measurement of the total H^+ beam current.

Several techniques have been developed for measurement of injected beam parameters such as r, Δr, p_z and Δp_z. These measurements are important for comparison with the full computer model.

Acceleration of the H^+ beam was first obtained in January 1999. The beam orbit was shown to have a large diameter by observing the image of the accelerated beam on the extraction viewer, then moving the radial probe into the beam and observing the shape and location of the shadow cast into the beam image.

Since beam energy is proportional to the square of the radius, a radial scan can be plotted as an energy distribution. Figure 2 shows what fraction of the proton beam is accelerated to above a given energy (rf on) and the 6.4 keV injected beam (rf off). Total beam current was 9.2 nA. Notice that the graph shown is an integrated distribution.

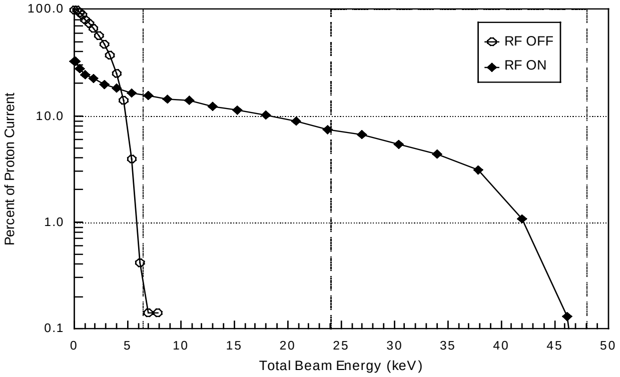

Figure 2: Measured Energy Distribution
for the 50 keV ICRA

The measured current requires three corrections due to the geometry of the radial probe. Data in figure 2 has been corrected for beam lost on the electron blocker, and for the fact that the axial length of the probe is insufficient to intercept all of the beam. An additional correction that has not yet been applied to the data is to account for a range of energies included at each data point. This effect is caused by the slope on the radial probe and leads to the roll off seen on the unaccelerated beam in figure 2. However, the magnitude of this correction is small for energies above $\frac{1}{2}E_{design}$ and will only shift current from low energy toward higher energies.

The three vertical dotted lines in figure 2 mark the injected beam energy, $\frac{1}{2}E_{design}$, and E_{design} limited by the exit diameter of the magnetron cavity (E_{design}= 48keV). The figure shows that beam is accelerated up to 46 keV and that more than 7% of the total beam current is above ½ of the design energy.

4 DISCUSSION

The 50 keV ICRA was designed primarily based on analytical calculations, together with experience from previous computer modeling results. Analytical calculations have been shown to be accurate for calculating most aspects of the central ray through the system. However, the computer code is necessary when using many rays to model a finite phase space volume for determination of the accelerated beam current and for calculating the range of magnetic detuning.

Computer modeling is currently underway with the goal of comparing experimental results with the computational predictions and to benchmark the code. Injection beam parameters such as r, Δr, p_z, Δp_z have been measured and should provide the information needed to model the injected beam phase space.

5 CONCLUSION

The 50 keV ICRA experiment has successfully demonstrated ion acceleration using the same axial drift geometry that is characteristic of gyrotrons. A proton beam has been accelerated to the design energy with over 7% of the beam current above ½ of the peak energy. Computer modeling and comparison to measured data is currently underway with the goal being to benchmark the ICRA code. With this tool in hand, it will be possible to design a 10 MeV proton machine that should offer a new low-cost alternative to machines currently being used for applications such as production of medical radioisotopes, accelerator based neutron sources, and for some materials science applications.

6 REFERENCES

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