Electron cyclotron resonance ion trap: A hybrid magnetic system with very high mirror ratio for highly charged ion production and trapping

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In the Paul Scherrer Institute [PSI Switzerland] an experimental program was started to measure the ground state shift and width of pionic hydrogen. To calibrate the crystal spectrometer x-ray transitions in hydrogen-like heavy ions (e.g., Ar^{17+}), produced by electron cyclotron resonance (ECR) ion sources, are necessary. In PSI a superconducting cyclotron trap magnet, originally developed for particle physics experiments, will be transformed into an ECR ion trap (ECRIT). The SC magnet can deliver more than 4 T magnetic fields with a mirror ratio of 2. A careful calculation showed this mirror ratio can be increased upto 10 and the trap can operate with frequencies between 5 and 20 GHz. To form a closed resonance zone an open structure NdFeB hexapole will be applied. The first tests will be performed at 6.4 GHz. Later higher frequencies and the two-frequency heating (6.4+10, 6.4+14.5, or 10+14.5 GHz) are planned to be applied to get enough quantity of H-like heavy ions. The ECRIT will operate at ground potential while a simple 90° beamline (at negative potential) will help the fine tuning of the plasma for very high charge states. © *2000 American Institute of Physics.* [S0034-6748(00)66502-4]

I. INTRODUCTION

At the Paul Scherrer Institute (Switzerland) an experiment is presently being setup,[1] which intends to determine the strong interaction shift and width of the pionic hydrogen atom ground state by measuring Lyman x rays with a high resolution Bragg crystal spectrometer. The experiment combines the use of the most intensive pion beam (more than 10^8 pions/s at a momentum of 100 MeV/c) produced by a proton beam of 1.5 mA current with a magnetic device (cyclotron trap) to stop pions in dilute matter. For the analysis and the detection of the x rays spherically bent quartz crystals (diameter 100 mm with a curvature radius of 3000 mm) will be used together with state of the art charge-coupled device (CCD) detectors (Fig. 1).

The binding energy of the p-π^- ground state is about 3228 eV and the expected strong interaction shift and width are about 7 and 1 eV, respectively. They both should be determined with a relative accuracy of about one percent, which certainly represents a challenge to present experimental techniques. It is therefore intended to tune and measure the resolution and the response function of the crystal off-beam with x-rays of single electron ions, e.g., Ar^{17+}.

The most promising candidate for this purpose is an ECR ion source. In contrast to the EBITs in an ECRIS the ion motion is decoupled from the electron motion to a high degree. The ions have kinetic energies of only some eV and therefore a Doppler broadening of the x rays is expected, which is negligible compared to the instrumental width of about 200 meV. This is in contrast to the width of fluorescence x rays in the region of 3000 eV which are of the order of eV and in addition are distorted by satellite transitions.

Therefore it was decided[2] to build an electron cyclotron resonance ion trap (ECRIT) to produce x rays coming from H-like heavy ions. The superconducting cyclotron trap magnet originally developed in PSI for high energy experiments will be transformed into an ECRIT. The details of the calculations of the magnetic system are presented here.

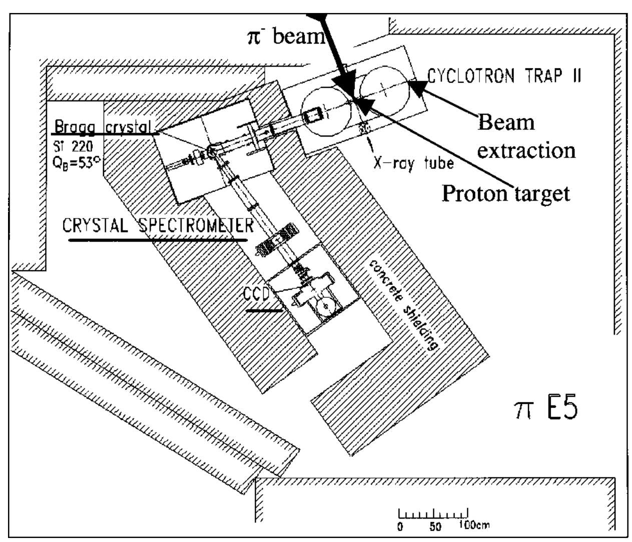

FIG. 1. The original cyclotron magnet and beam line. A very similar arrangement will be used for the proposed experiment.

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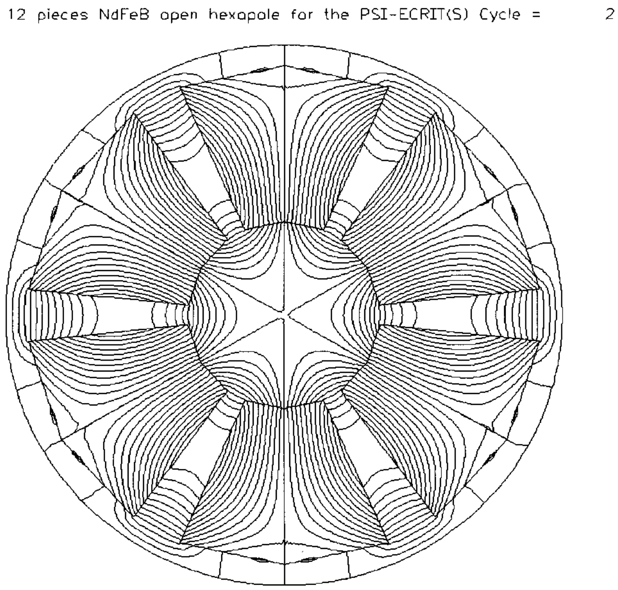

FIG. 2. Cross-sectional view of the open hexapole. i.d.=90 mm, o.d.=240 mm, length=300 mm, $B_r=1.28$ T, $H_{cj}=21$ kOe.

II. CALCULATION OF THE RADIAL FIELD

As it is showed in the next section a relatively large distance between the two SC coils is necessary in order to reach a very high mirror ratio. Estimates showed that a usual two-side axial pumping would not be enough to produce low basic pressure and high pumping speed which are necessary to get very high charge states in the plasma. Therefore an open structure NdFeB hexapole was chosen. At the calculations the LBL AECR-U[3] design was considered as a starting point, however, all the geometrical and magnetic parameters were optimized for the current conditions and requirements. For the calculations the SUPERFISH/POISSON/PANDIRA group of codes[4] was used.

A relatively large internal diameter was chosen to increase the plasma volume. The open structure and the large diameter resulted in a magnetic field of about 1 T only at the chamber walls, however, this still allows safe resonance frequencies up to 20 GHz. Figures 2 and 3 show the resulted structure and magnetic fields. The radial pumping windows

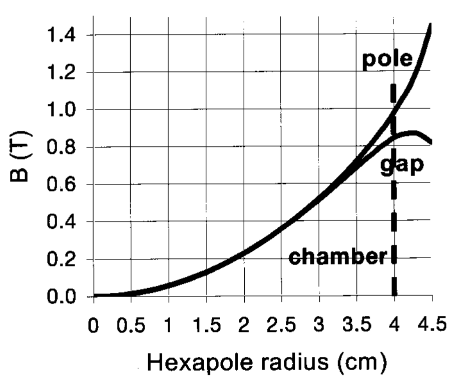

FIG. 3. The radial magnetic induction at the poles and at the gaps inside the open hexapole.

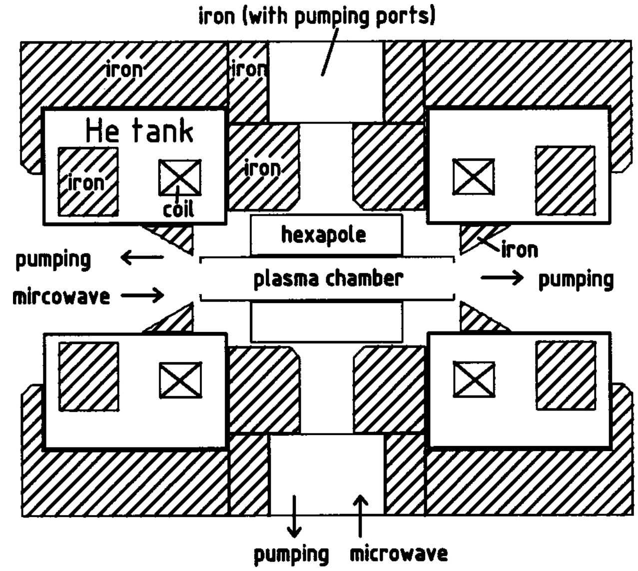

FIG. 4. The modified arrangement of the PSI SC cyclotron trap.

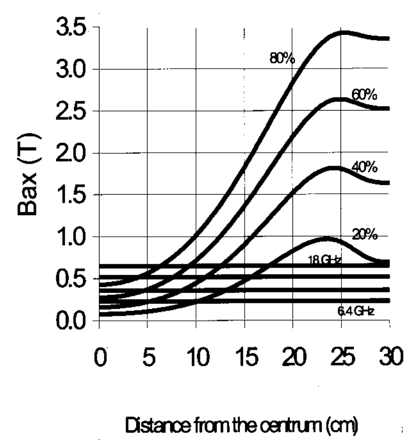

FIG. 5. Axial distributions at different coils currents (20%–40%–60%–80%). The horizontal lines represent resonance values for 6.4, 10, 14.5, and 18 GHz.

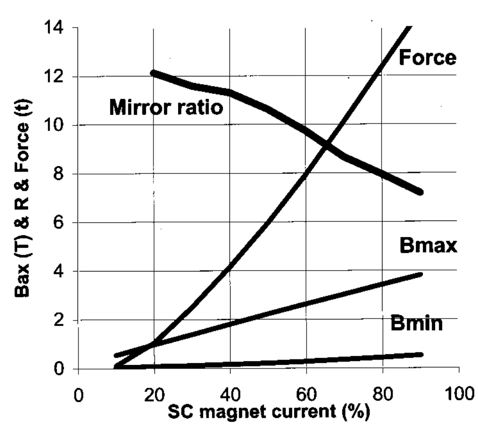

FIG. 6. The peak and minimum fields on the axes together with their (mirror) ratio and with the force effects to one of the SC coils.

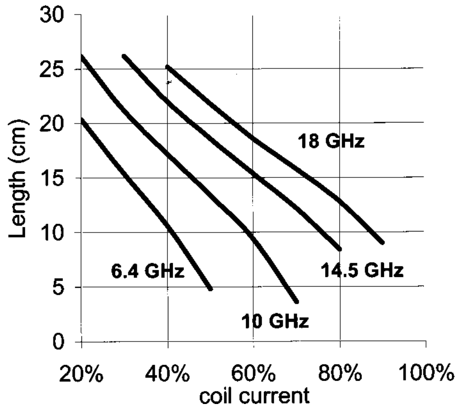

FIG. 7. The length of the resonance zone at different frequencies.

are usable for other purposes (gas inlet, microwave coupling, plasma diagnostics etc.).

III. CALCULATION OF THE SC AXIAL FIELD

The original mirror ratio of the SC cyclotron magnet was only 2. The peak field could be 4.5 T with a minimum of higher than 2 T. POISSON calculations showed this mirror ratio can be increased upto 8–12 on the axes (depending on the coils current) by putting special iron plugs between the coils and smaller tips near the hexapole edges. An average axial mirror ratio ($R = B_{max}/B_{min}$) of 10 can be considered. The optimized geometry can be seen in Fig. 4. Figures 5 and 6 show the resulted magnetic field distributions and mirror ratios.

IV. THE COMPLETE MAGNETIC SYSTEM

Figure 7 shows the lengths of the resonance zones for four different frequencies. These frequencies (6.4, 10.0, 14.5, and 18.0 GHz) are considered to be tested at the PSI-ECRIT. First a 6.4 GHz transmitter available at PSI will be used for tests. Then a 10.0 GHz transmitter will be borrowed from inside PSI. If none of these two or even their simultaneous coupling will give satisfactory results (enough quantity of Ar^{17+} ions) a 14.5 GHz generator must be bought or lent. This solution will also give the opportunity to try the two-frequencies coupling (6.4+14.5 or 10+14.5 GHz).

We note that the so called effective axial mirror ratio ($R = B_{max}/B_{min}$ inside the volume of the hexapole) is less than 10, it is about 4–6 depending on the coils current.

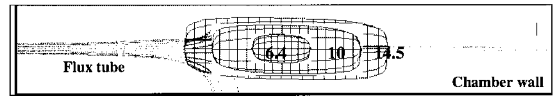

FIG. 8. TrapCAD[5] simulations of three resonance zones (6.4+10.0+14.5 GHz) with a flux tube. In the experiment one or two frequencies will be coupled.

Figure 8 shows the resonance zones for the three most probable frequencies to be applied (50% magnet current).

V. ECRIT OR ECRIS?

The main goal of this machine is to be a trap and no extraction is necessary. However, the fine tuning of the plasma for very high charge states might require the ion charge spectrum to be analyzed. In this case a simple beamline at negative potential will be built and the ECRIT becomes temorarily ECRIS by the extraction. The ECRIT(S) will still work at ground potential which keeps the mechanical design (especially the insulation) simpler.

VI. CONCLUSION

In PSI a superconducting cyclotron trap will be transformed into an ECR ion trap (ECRIT) by placing a room-temperature, open structure NdFeB hexapole between the SC coils. The resulted hybrid system has a very high mirror ratio in order to produce H-like heavy ions. The designing of the mechanics and ordering of the absent elements (hexapole, gas feeding, microwave, beamline) is in progress. The assembly of the ECRIT is expected in 2000. The first plasma and x-ray tests are planned to be performed in 2001.

ACKNOWLEDGMENT

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