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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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Introduction

The interaction of energetic electrons with highly charged ions is of great importance to several research fields such as astrophysics, laser fusion and magnetic fusion. In spite of this importance there are almost no measurements of electron interaction cross sections for ions more than a few times ionized.[1] To address this problem an electron beam ion trap (EBIT) is being developed at LLNL. The device is essentially an EBIS except that it is not intended as a source of extracted ions. Instead the (variable energy) electron beam interacting with the confined ions will be used to obtain measurements of ionization cross sections, dielectronic recombination cross sections, radiative recombination cross sections, energy levels and oscillator strengths. Charge-exchange recombination cross sections with neutral gasses could also be measured. The goal is to produce and study elements in many different charge states up to He-like xenon and Ne-like uranium.

Preliminary Design

Compared to previous EBIS devices, our approach is somewhat different. Fig. 1 shows a schematic of our preliminary design and an enlargement of the critical drift tube region. The design is optimized for x-ray spectroscopy of the trapped ions, with the central drift tube split into four quadrants for radial access. The length of the trap will be only 1 cm as this is a sufficient x-ray source length, and longer plasmas are more likely to develop instabilities.[2]

The device is intended to be iron-free to facilitate diagnostic access and eliminate the need to align massive iron flux return parts. (The only exception is an iron magnetic shield for the extracted ion channel.) A peak field of 3 T will be produced by a pair of superconducting Helmholtz coils whose cold bore also serves to cool the drift tube assembly. We have designed the drift tube assembly to support a bias of up to 50 kV above the grounded magnet spool. Thermal contact is made through sapphire insulators under compression.

In order to achieve the highest ionization stages a vacuum approaching 10^{-12} Torr is required. Hence our design attempts to minimize the conductance between the drift tubes and the warm walls and also between the drift tubes and the collector, where gas may be desorbed by the electron beam. Note that the electron beam is oriented vertically.

Electron Beam Launching and Compression

Taking 20 keV as a typical electron beam energy in the ion trap, the Brillouin current density corresponding to our 3 T magnetic field would be $J_B = 6 \times 10^4$ A/cm^2. This is unobtainable for any realistic electron gun because of the finite electron temperature at the cathode and the lack of perfect laminarity of the beam as it is launched from the gun. We have taken 5×10^3 A/cm^2 as a goal for EBIT. At this current density Ne-like uranium would be reached in approximately 1/2 sec.

Because of the Helmholtz coil geometry (as opposed to a long solenoid with an iron end plate) the peak magnetic field will extend for only a few centimeters. The fringing field at the position of the electron gun ($\sim$ 15 cm from the trap) will be about 0.2 T, and will be zeroed at the cathode position by a room temperature bucking coil. The bucking coil supplies the appropriate magnetic field gradient to match the optics of the electron gun; and the compression to peak current density will be done adiabatically in the rising field of the Helmholtz coils.

Studies of electron guns indicate that the transverse velocity content (i.e. nonlaminarity) of the beam from an electron gun is roughly proportional to the spherical half angle of the cathode.[3] Because of this we have aimed our design toward lower perveance (< 1 μperv) guns. However, the final electron gun design has not yet been selected. For proper alignment of the electron gun its axis should coincide with the axis of the magnetic field. In our design this will be achieved by x-y position adjustments at the top and bottom of the cryostat. A split suppressor electrode in front of the electron collector will be used to detect the beam displacement by capacitive pickup. A total current of ∿ 150 mA appears to be large enough for our proposed cross section measurements and small enough to avoid microwave oscillations.

Electron Collector

A diagram of the electron collector design is shown in Fig. 2. The collector is intended to satisfy five requirements: (1) no reflection or loss of the beam electrons, (2) suppression of secondary electron emission, (3) a minimal source of desorbed gas for the drift tube vacuum, (4) dissipation of the beam power ($\leq$ 300 W), and (5) efficient extraction of ions. A solenoid coil around the collector reduces the fringing field of the main magnet to the point where the electron motion is no longer dominated by the magnetic field. We have used the SLAC electron trajectory program[4] to show that a 150 mA beam entering the collector with $1 \leq E_e \leq 2$ keV spreads out satisfactorily over the inside wall of the collector.

Secondary electrons will be suppressed by a separate electrode just upstream of the collector entrance. The entrance of the collector is long and narrow to reduce gas flow back toward the drift tubes, and the collector is open at the back for pumping. Our design calls for cooling the collector and its surrounding solenoid coil with a forced flow of liquid nitrogen in order to dissipate the primary beam power and reduce the evolution of gas. There is an electron-repeller/ion-extractor electrode on the collector axis. However, since its voltage with respect to the collector is only ∿ 10% of the ion kinetic energy, this electrode does not have a major effect on the ion trajectories and serves mainly as a defining aperture for ion extraction.

Ion Injection

Recently a metal-vapor vacuum-arc (MEVVA) ion source has been developed at LBL.[5] It appears to be an ideal source for injecting into EBIS devices: It is high vacuum compatible, produces up to one amp of output current for several different elements, and is capable of pulsed repetative operation. In our case we will mount a miniature MEVVA on the axis of EBIT and inject ions downward through the collector. The ion source must ride at the same potential as the drift tubes, and the ion trapping voltage must be pulsed in order to capture ions transiting the drift tubes.

Ion Charge State Measurement

Time of flight has been the most common method of measuring charge state distributions in EBIS sources. However, the charge state resolution has been marginal for the most highly charged ions, and we plan to use two other methods. The first method is magnetic analysis of the extracted ions, which offers high resolving power. We will probably use a photodiode array as the focal plane detector.

The second method is ion cyclotron resonance (ICR) spectroscopy of the confined ions. This can be done by applying a transverse rf electric field across the split central drift tube and measuring the characteristic resonance frequencies of the ions in the 3 T magnetic field. In this method the electron beam would be turned off briefly for the ICR measurement then turned on again, allowing the sequential ionization process to continue with the same ions whose charge state distribution had just been measured.

X-Ray Measurements

Three different x-ray detection instruments are proposed for EBIT, all of which will view the ions from the radial direction. First, a Si(Li) counter will provide a high efficiency measurement of the absolute x-ray yield. Second, the best spectral resolution will be obtained from a crystal spectrometer with a position sensitive proportional counter. And third, an imaging slit will cast a radial image of the x-ray emitting region onto another position sensitive proportional counter. This provides a measure of the ion radial distribution, which should be less than the electron beam radius in the absence of anomolous heating.

Summary

Our plans for an EBIT at Lawrence Livermore National Laboratory have been briefly described above, with emphasis on those features which are different from previous EBIS devices. At present (May,1985) most of the design decisions have been made and fabrication will begin in a few months.

RM:mpd:0974A

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3. R. True, IEEE Trans. on Electron Devices 31, 353 (1984).

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Figure Captions

Fig. 1. (a) Scale diagram of EBIT. Ions are injected from the top and extracted to the side using an electrostatic deflector just above the electron collector. (b) Enlargement of the drift tube region. The drift tube shield, which is flared at top and bottom, is designed to operate at up to +50 kV.

Fig. 2 Diagram of the EBIT electron collector. Top: Plot of the residual magnetic field along the collector axis on the same length scale as the diagram below.

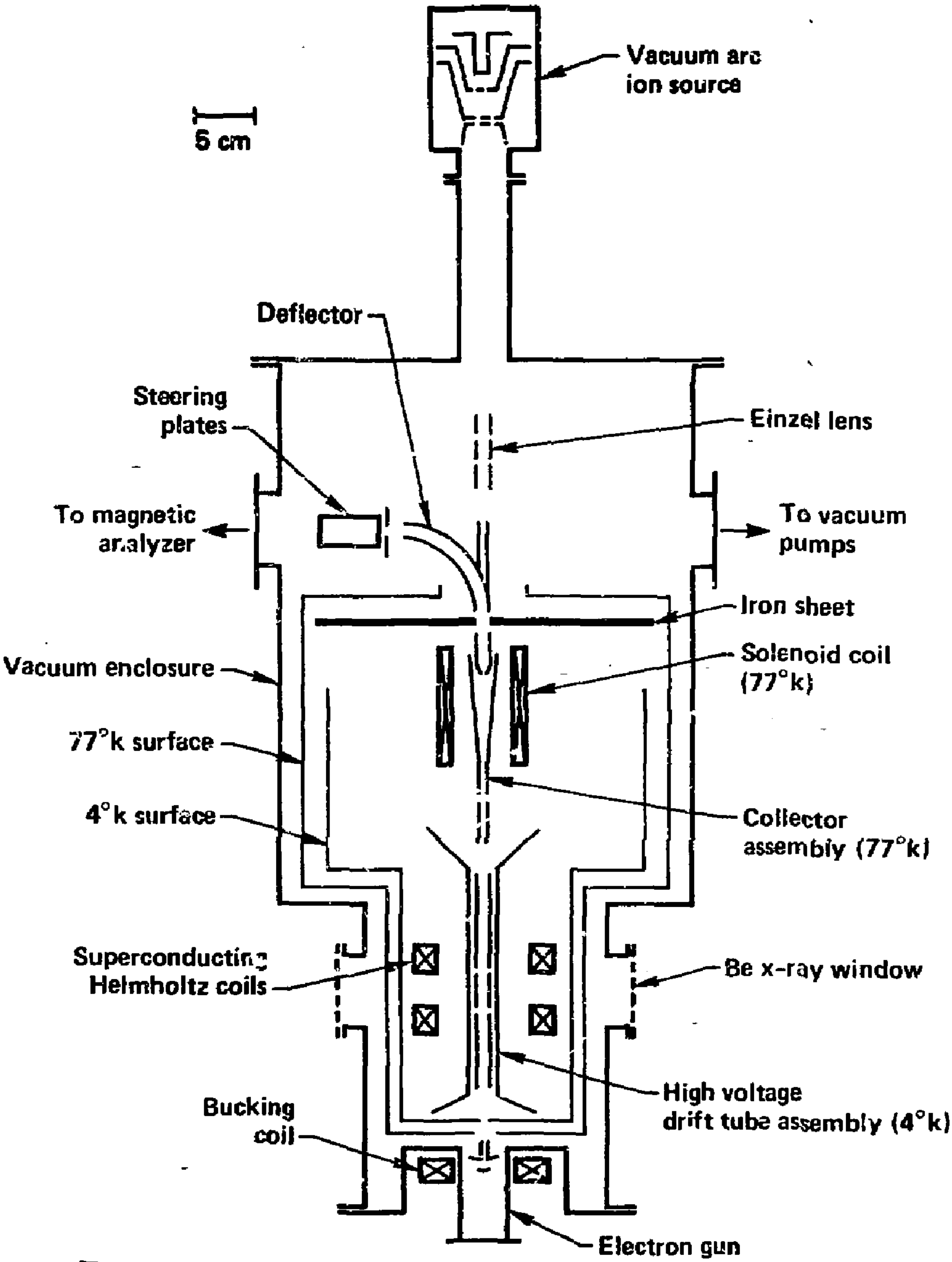

Vacuum arc
ion source
5 cm
Deflector
Steering
plates
Einzel lens
To magnetic
analyzer
To vacuum
pumps
Iron sheet
Solenoid coil
(77°k)
Vacuum enclosure
77°k surface
4°k surface
Collector
assembly (77°k)
Superconducting
Helmholtz coils
Be x-ray window
High voltage
drift tube assembly (4°k)
Bucking
coil
Electron gun

Fig. 1a

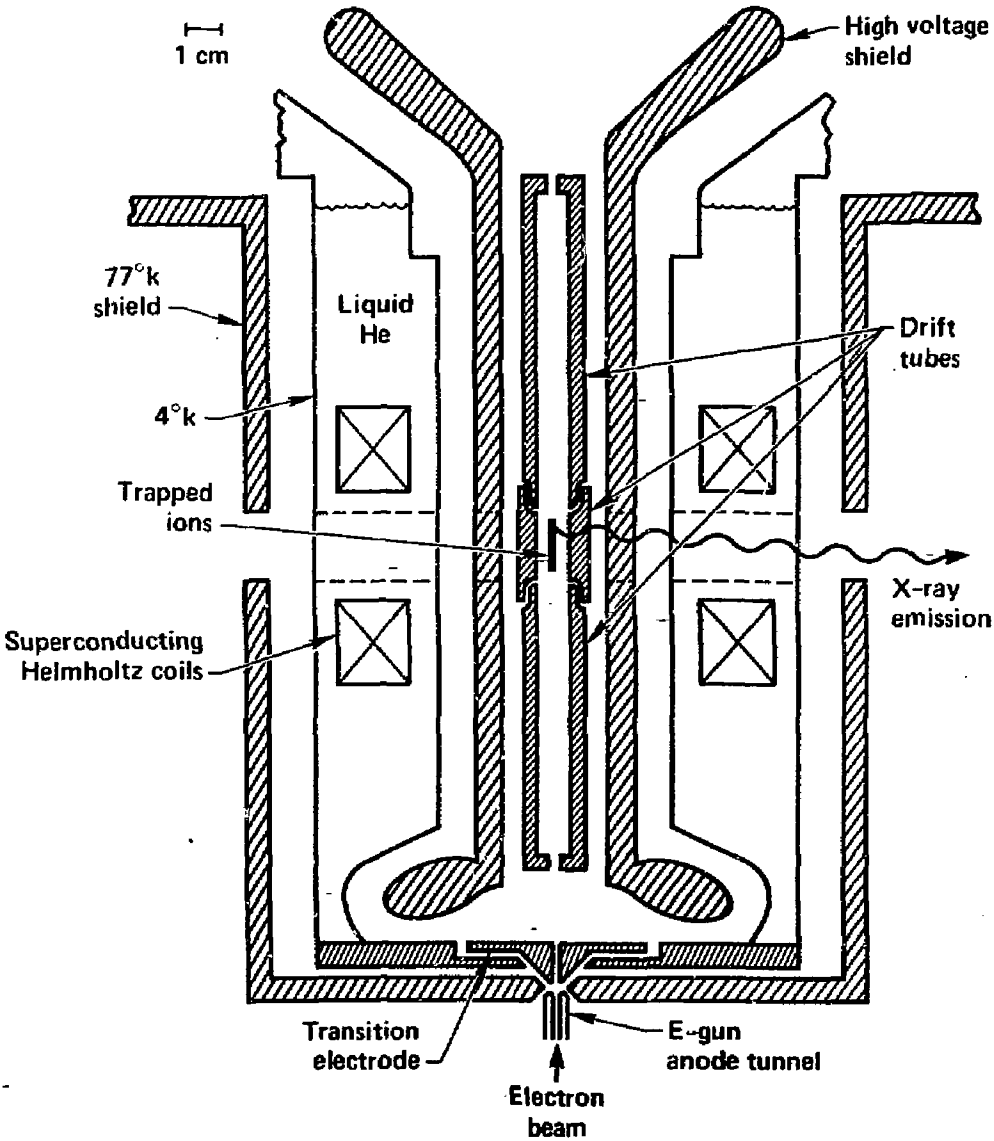
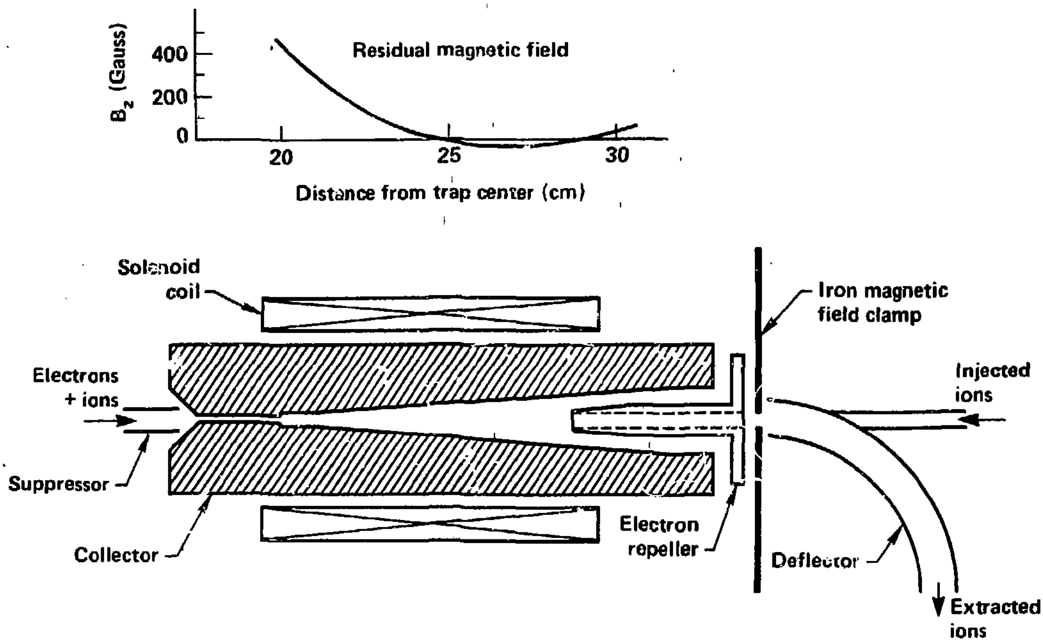

1 cm
High voltage shield
77°k shield
Liquid He
Drift tubes
4°k
Trapped ions
X-ray emission
Superconducting Helmholtz coils
Transition electrode
E-gun anode tunnel
Electron beam

Fig. 1b



Residual magnetic field
B_z (Gauss)
400
200
0
20
25
30
Distance from trap center (cm)
Solenoid coil
Iron magnetic field clamp
Electrons + ions
Injected ions
Suppressor
Collector
Electron repeller
Deflector
Extracted ions

Fig. 2