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ECR ION SOURCE STATUS 1988

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INTRODUCTION

Electron Cyclotron Resonance ion sources (ECRIS), like Electron Beam Ion Sources (EBIS), produce multiply-charged ions via electron impact ionization. As with EBIS, they are stand- alone ion sources with their own power supplies, vacuum systems and control systems--they can be as complex as small accelerators. In contrast to EBIS, the electron acceleration process and the ion confinement strongly couples through the magnet field, and this makes ECRIS both simple to build and at the same time difficult to understand quantitatively.

In 1988, ECRIS find important application in nuclear, atomic, and high energy physics. Also there is an emerging new application--efficient bulk ionization, which will extend the application of ECRIS to ionizers for isotope separation and polarized beams.[1-3] The initial driving force in the development of ECRIS was the need for more highly charged ions. The first ECRIS injection into a cyclotron occurred in Karlsruhe in 1981, and was quickly followed by Cyclone in Belgium, SARA in France, KVI- Groningen in the Netherlands, and Berkeley.[4-8] ECRIS have now largely replaced arc discharge ion sources for this purpose in most cyclotron facilities,[9] where gains are made in both intensity and energy, and maintainence costs are substantially reduced. ECRIS have made the stand-alone cyclotrons so competitive that the coupled operation of the two cyclotrons at MSU has been bi-passed in favor of operation of the K=1200 booster cyclotron stand-alone with ECRIS injection.[10] In 1985 modifications began at CERN, to accomodate beams from an ECRIS-RFQ injector.[11] Oxygen ions were accelerated to 200 GeV/u in the SPS in 1986 and sulfur in 1987.[12] Further increases in mass at CERN probably require reconstruction of Linac 1, and it has been estimated that lead beams would require 30 eμA of 25-30+ ions.[13] In 1989, an ECRIS-based positive ion injector will replace the tandem injector at the ATLAS facility at ANL.[14]

The potential for atomic physics measurements in new regimes using ECRIS ion beams was also recognized early. Experiments were begun in 1979 at LaGRIPPA in Grenoble,[15] and ECRIS have been built in Oak Ridge and Giessen specifically for atomic measurements,[16,17] while

other facilities such as the LBL 88 Cyclotron, KVI Gronnigen and Louvain-la-Neuve allow atomic studies on a time shared basis.[18-20]

ECRIS DEVELOPMENT FOR HIGHLY CHARGED IONS

Approximately 30 ECRIS have been built for the production of highly charged ions. By and large these sources are two stage devices. In a two stage ECRIS, low charge ions generated in the first stage diffuse across a pressure gradient to the main stage where they are further ionized. The output of two stage ECRIS is generally peaked at high charge states. Fig. 1 show a nitrogen charge state distribution obtained from the RTECR at MSU.[21] The charge state distribution is peaked at 5+, with approximately equal currents of 6+ and 1+. Fully stripped nitrogen is obscured by the helium 2+ peak. The helium in the spectrum is deliberate, enhancing the currents of highly charged nitrogen ions. This so called "gas mixing effect" is discussed below.

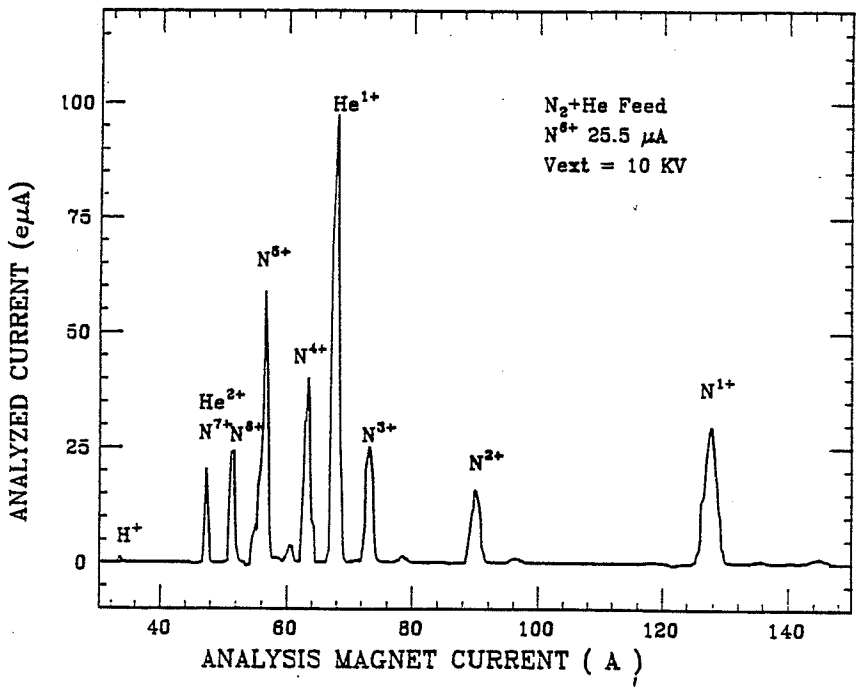

Fig.1. The production of highly charged nitrogen ions in the two stage RTECR at MSU is shown for the feeding of a nitrogen plus helium gas mixture into the first stage.

Most ECRIS accelerator applications use intensities of the order of 10^{12} pps. Therefore most ECRIS development occurs at the eμA level or higher, and little account is taken of more highly charged ions of significantly lower intensity. It is then difficult to

establish the maximum charges obtainable from the present two stage ECRIS; in Table I selected performance data are summarized. Table I is intended to be representative rather than exhaustive. The ECRIS development effort in Grenoble under R. Geller still comprises a large fraction of the total ECRIS development effort, and this is reflected in Table I.

Table I. Some Benchmarks for Two Stage ECRIS Performance

SPECIES	CHARGE	INTENSITY (pps)	SOURCE
^{20}Ne	10+	$7.5\ 10^{11}$	Juelich 14 GHz (22)
^{40}Ar	16+	$2.0\ 10^{11}$	Juelich 14 GHz (22)
^{40}Ar	18+	$3.5\ 10^{8}$	Grenoble 18GHz (23)
^{86}Kr	20+	$3.0\ 10^{11}$	MSU 6.4 GHz (21)
^{129}Xe	29+	$2.2\ 10^{11}$	Grenoble 10GHz (24)
^{181}Ta	29+	$6.5\ 10^{11}$	Grenoble 18GHz (25)
^{209}Bi	34+	$1.0\ 10^{10}$	LBL 6.4 GHz (26)
^{238}U	36+	$1.7\ 10^{11}$	Grenoble 18GHz (25)

BEAMS FROM SOLIDS

The development of techniques which allow the production of high charge state ions from solid materials has been of great importance. Since a very high percentage of the elements more massive than argon are solids at room temperature, the ability to use solid materials as source feeds is vital for ion sources used with heavy-ion accelerators. The two main methods are direct insertion of solids into the plasma and use of ovens to vaporize solids.

Direct insertion has been studied in detail in Grenoble with the CAPRICE source for a wide variety of materials ranging from aluminum to gold.[27] In CAPRICE, a solid rod is positioned close to the ECR surface where it is vaporized by hot electrons in the plasma. The plasma is maintained by adding a support gas such as oxygen or nitrogen. To maintain a stable plasma the rod's position is automatically controlled with a feedback loop. In a one week run using tantalum in CAPRICE, the average consumption was approximately 1.0 mg/hr.[28] Direct insertion has been used in the ORNL-ECR to produce iron, nickel, and chromium beams,[29] in the LBL-ECR to produce niobium

beams for atomic physics,[30] and in the MSU RTECR to produce flourine, magnesium, silicone, vanadium, iron and tantalum beams.[31] Even without feedback, the stable beams can be produced for periods of several hours.[32]

A variety of metallic ion beams have been produced from the LBL ECR using a resistance heated ovens.[33] A low temperature oven which operates up to 700 deg. C is used for a variety of elements such as Li, Mg, K, Ca, and Bi. A high temperature oven which can operate up to 2000 deg C is used for higher temperature elements such as Sc, Fe, Ni,Cu, Ag, La, and Tb. Because the oven temperatures are regulated externally, stable oven operation and efficient material usage are possible. The ovens are inserted radially into the second stage so that vaporized metal atoms stream through the ECR plasma and are ionized by electron impact. Typically, the plasma is maintained by running either oxygen or nitrogen as a support gas in the first stage. This is similar to the use of a mixing gas when operating the source with gases heavier than oxygen. The amount of metal in the plasma is adjusted by varying the oven temperature.
As can be seen in Fig. 2, the performance of the LBL ECRIS for oven feed is really equivalent to gaseous feed operation.

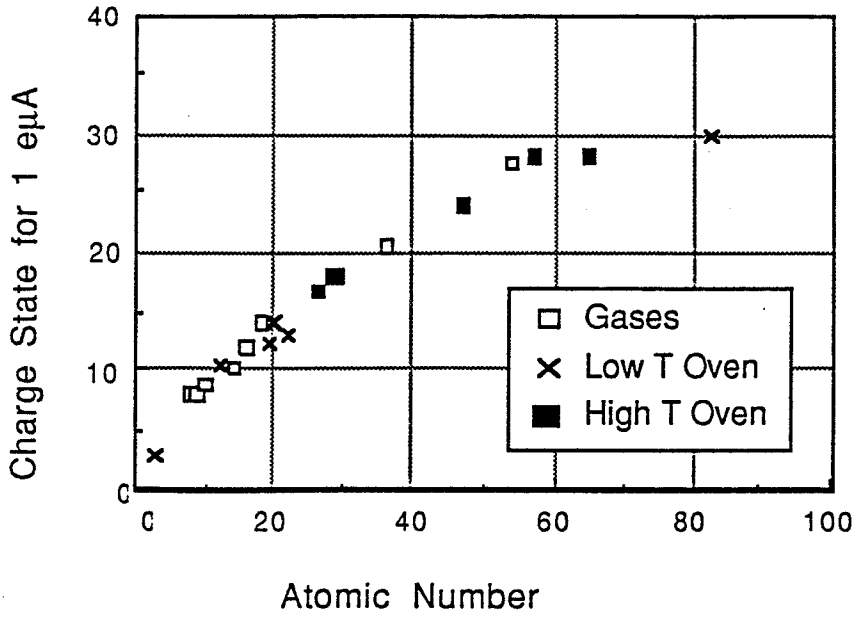

Fig. 2. Charge states for the 1 eμA level for elements run from gas feed and from the low and high temperature ovens at LBL.

THE GAS MIXING EFFECT

ECR builders meeting at the Kyoto ISIAT Symposium in 1983 and the Oxford Conference on Highly Charged Atoms in 1984 reported observing that the addition of a lighter gas to the plasma significantly increased the currents of highly charged ions of a heavier species. One rather surprizing finding at KVI-Groningen was discussed- that the installation of a dirty extraction end plate to the source there significantly increased the current of Ne^{9+} ions.[34] While the reasons for studying dirty electrodes remains obscure, the effect could also be obtained by directly mixing oxygen with neon, suggesting that the normal outgassing of the electrode, when exposed to plasma, was the cause. Gradually the systematics of the effect have become established, and all sources use gas mixing to some degree to inprove currents of highly charged ions. Fig. 3 shows the direct dependence of gas mixing effectiveness on mass for He, N_2 and O_2 mixing with argon in the MSU RT-ECR, for the production of argon ions. All three mixing gases improve the charge state distribution over pure argon feed, with oxygen slightly better than nitrogen, and both significantly better than helium.

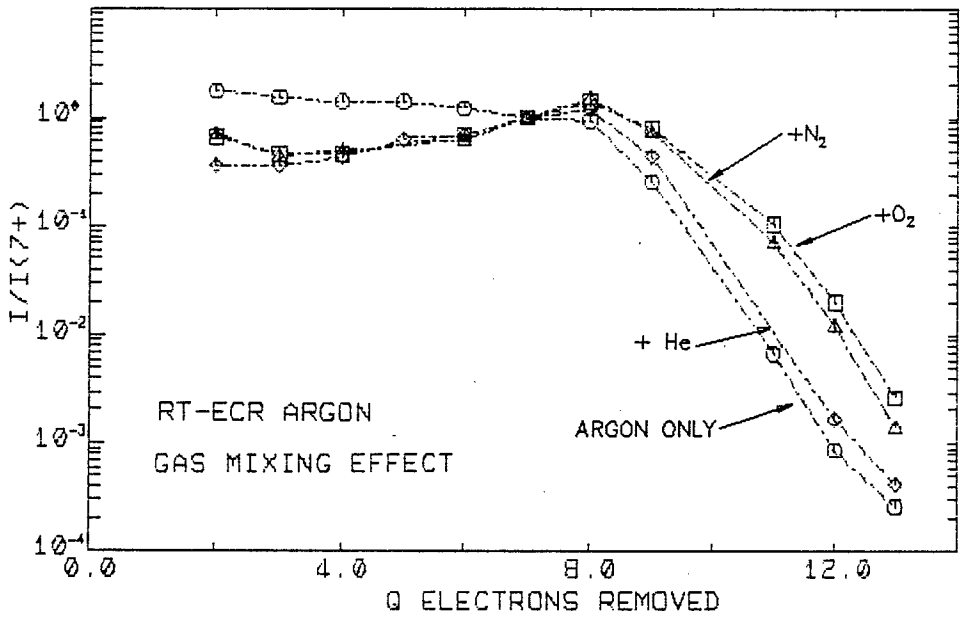

Fig. 3. The effect of the addition of light gases to an argon plasma in the RTECR at MSU is shown.

Several models have been proposed for the gas mixing effect,[35,23] but the most likely explanation was recently reported By Antaya at the Grenoble ECR Workshop in 1988, on the basis of argon

energy spread measurements made on the RTECR at MSU.[36] It was found that the argon ion thermal energy in the RTECR increases with the degree of ionization, with the linear rate of 6.5*Q eV for Q>5+. Further, the thermal energy of argon 9+ ions was observed to decrease by 1/3 when oxygen was added to the argon plasma. Such cooling, the result of ion-ion collisions in the plasma, would be expected to significantly alter ion confinement times (longer for argon, shorter for oxygen), since the confinement times are set by ion-ion collision rates.

WALL COATING EFFECTS

At the ECR Conference at MSU in 1987, the LBL and Grenoble groups made first reports on the beneficial effect of wall coatings on the production of highly charged ions in ECRIS. The origin of this effect may be related to the emission of electrons from the walls of the plasma chamber when bombarded by energetic electrons from the plasma.

The day to day performance of the LBL ECR ion source is strongly influenced by the conditions of its walls. In particular, the addition of SiO_2 coating to the walls significantly enhances its performance for high charge state ions such as N^{6+}, O^{7+}, and Ar^{14+}.[26] Fig. 4 clearly demonstrates the basic effect of coating the walls with SiO_2. Most surprising was the discovery that under certain conditions the LBL ECR could produce more intense high charge state currents operating without the first stage than has ever been done operating it as two stage source. This single stage operating mode offers the possibility of building high performance single stage ECR ion sources without the added cost and complexity associated with a first stage.

The enhanced performance in single stage operation after coating the walls with SiO_2 appears to result from an increase in the production of cold electrons at the wall of the plasma chamber. As pointed out previously, the coefficient for secondary emission for electron impact on SiO_2 is between 2 and 4-- considerably above 1.3 for bare copper.[26] Geller et al found that coating the walls of Ferromafios with good electron donor materials with low work functions resulted in improved performance.[23] In equilibrium the production of cold electrons in the plasma must equal the losses to maintain plasma neutrality. In the second stage of an ECR source, cold electrons are injected from the first stage, produced by electron impact ionization of neutral atoms and ions, and produced by secondary emission at the walls. The losses of cold electrons come from loss of confinement, recombination, and ECR heating. The optimum plasma density in an ECR source seems to be set by stability requirements related to the critical density.[23] If the walls serve as a sufficient source of cold electrons to achieve the optimum

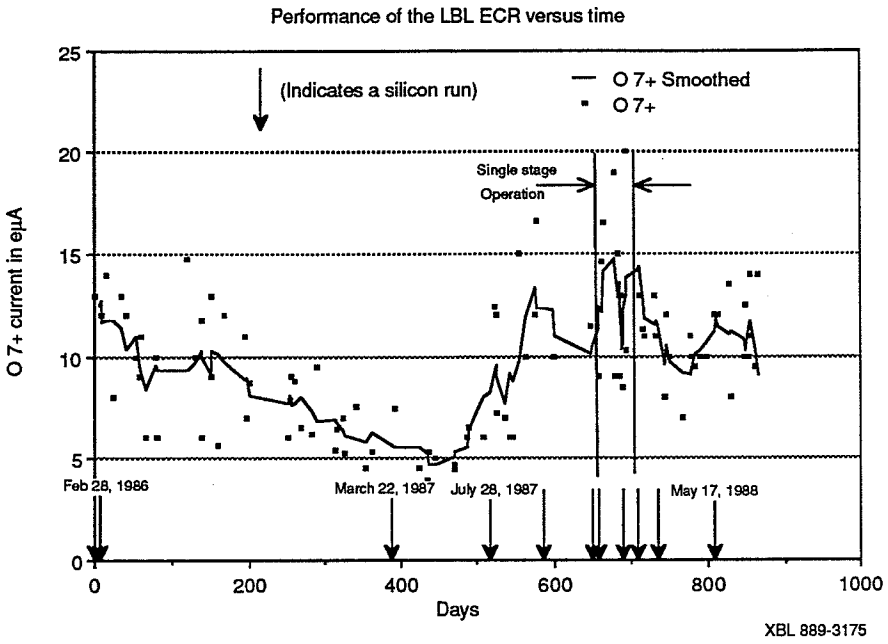

Fig. 4. The O^{7+} performance of the LBL ECR is plotted versus time. The slow decline in average performance from February 1986 to March 1987 coincides with a period in which silicone was not run. In December 1987 and January 1988 heavy usage of silicone made it possible to produce up to 20 eμA of 7+ with single stage operation.

plasma density, then it is no longer necessary to supply cold electrons form the first stage.

ECRIS FREQUENCY SCALING

The existence of a frequency dependence on the maximum plasma density in ECRIS, arising from the plasma cutoff limit, and the value to ion production of raising the plasma density, have been confirmed in a set of studies at 10, 16.6 and 18 GHz in Grenoble.[37-39] In these studies, it was found that the total extracted current increased by the ratio of the square of the resonance frequency, and that the average charge state extracted increased with frequency. The scaling of the the total extracted current with square frequency indirectly confirms the plasma density scaling with frequency. The increase in the average charge of the total extracted current with frequency indirectly confirms that the ionization rate scales with increasing density. In fact the best ECRIS performance to date for several species have been obtained at 18 GHz (see Table I).

Clearly, further work in this area is warranted. A further frequency step increase to 30 GHz would result in an equivalent increase in the cuttoff density over that at 18 GHz. Making this large qualitative step would be important for additional studies of

ion production scaling with density in ECRIS.

NEW ECRIS DESIGNS UNDER CONSTRUCTION

Present trends in ECRIS design can be illustrated by looking at three new source designs: the SCECR at MSU, the AECR at LBL, and ECR4 at GANIL. All three have been design to operate at 14 GHz or higher, all have simplified vacuum vessels and two mirror (dominantly main stage) magnetic fields. All three are presently under construction, with first operation expected during 1989. Nevertheless, these three source have substantial design differences, and it is expected that the operation of these new sources will affect the designs of future ECRIS for highly charged ion production.

MSU has undertaken to build an ECRIS with a resonance frequency range of 5-35 GHz, for further study of frequency scaling.[40] The corresponding resonance field range is 0.18-1.25 Tesla. This source, the SCECR, is shown in Fig. 5. A full superconducting coil set is used to produce the required radial and axial field profiles. It will then be possible in a single geometry to study scaling at and beyond existing levels with a magnetic field that can be fully optimized at each frequency. The upper limit for first harmonic operation is set to reach existing gyrotron tubes at 28-35 GHz. The SCECR will become the primary ion source for the K800 cyclotron at

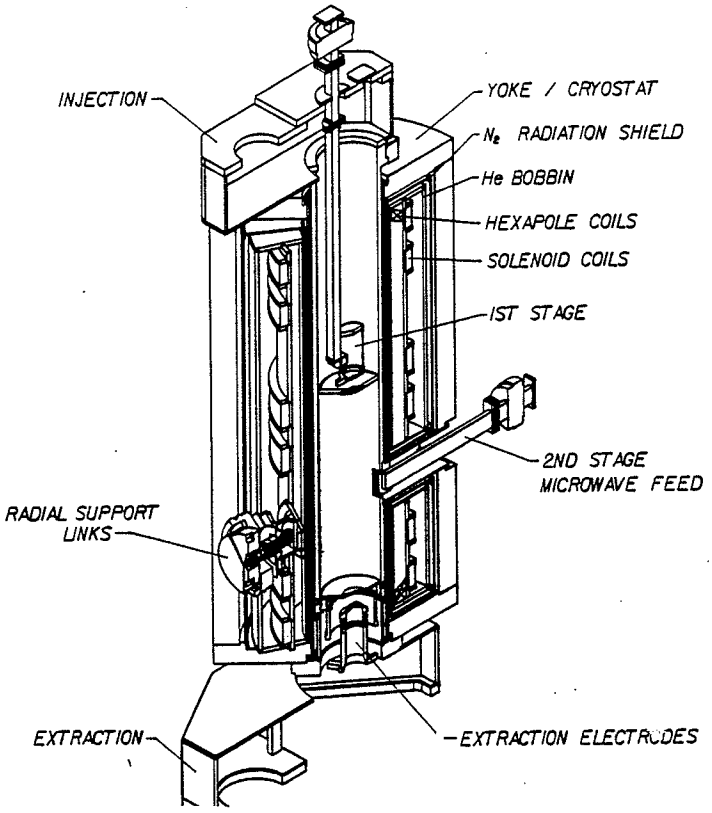

Fig. 5. The present design of the SCECR ECRIS now under construction at MSU.

MSU.[10] The main design parameters of the SCECR are taken from the Fall 1988 operating configuration of the RTECR. Initial operation of the SCECR at 6.4 GHz is expected in Spring 1989, with increases in frequency made subsequently as transmitters become available.

The project to build the AECR at LBL and couple it the 88 Inch Cyclotron began in 1988 and should be completed in two years.[41] The design of the AECR is illustrated in Fig. 6. The axial magnetic field is produced by three groups of copper coils. These groups are sub-divided into three independently adjustible elements, for fine adjustment of the magnetic field. The iron plates between coils 2 and 3 serve to increase the mirror ratio. In Fig. 6, the axial magnetic field is plotted assuming 250 Amps in all coils. This field profile is similar to that used currently in the LBL ECR, which was optimized experimentally. The first stage will operate on the "uphill" gradient of the axial magnetic field, as is the case in the LBL ECR. During the first year of operation, both stages will be driven by a single 14.5 GHz 2.5 kW klystron. The choice of 14.5 GHz was made because commercial klystron amplifier systems are available at this frequency. Even thought it may not be optimal to divide the power bewteen the first and second stage, by coating the wall with SiO_2, it is expected that excellent results for gases such as N_2, O_2 and Ar will be obtained in single stage operation.

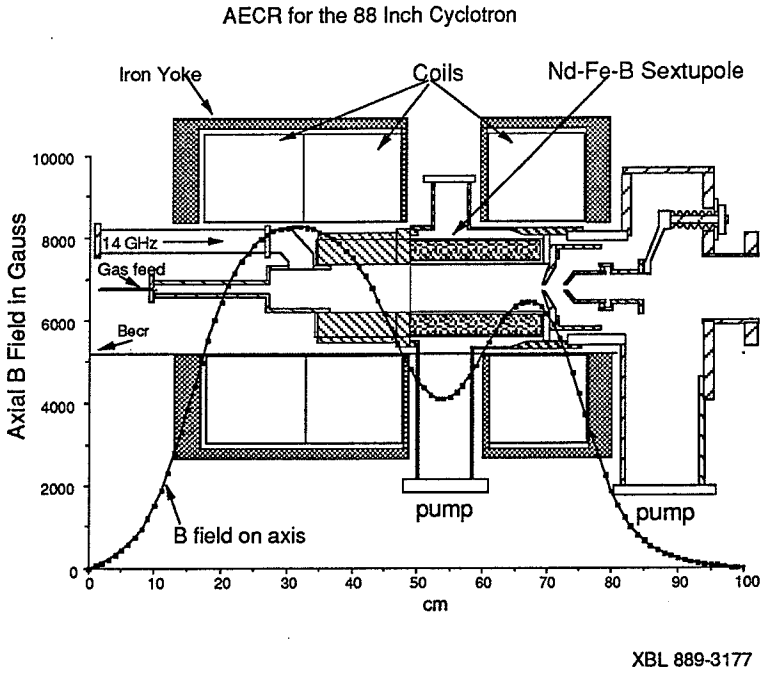

Fig. 6. Elevation view of the AECR source now under construction at LBL. THe axial magnetic field corresponding to 250 Amp current in the coils is superimposed on the drawing.

ECR4 at Ganil, is a 14.5 GHz ECRIS designed to operate with low power consumption on a high voltage platform.[42] This ECRIS is shown

in Fig. 7. In order to minimize coil power consumption and work with a small plasma chamber for low microwave power levels, the axial magnetic field of ECR4 is partially made of FeNdB permanent magnets in a structure similar to the Neomafios 10 GHz ECRIS of Grenoble.[43] The axial structure is obtained with an uniformly magnetized ring, divided into 6 blocks, like the Grenoble source. A small magnet ring in the source midplane is used to shape the mirror ratio, and radially magnetized magnets placed at the ends increase the maximum mirror strength. While Neomafios 10 at Grenoble is entirely a permanent magnet structure, the ECR4 design includes coils, to allow tuning of the mirror field between .65 Tesla and 1.05 Tesla, and this should aid source optimization. The source assembly is expected to be complete by the middle of 1989.

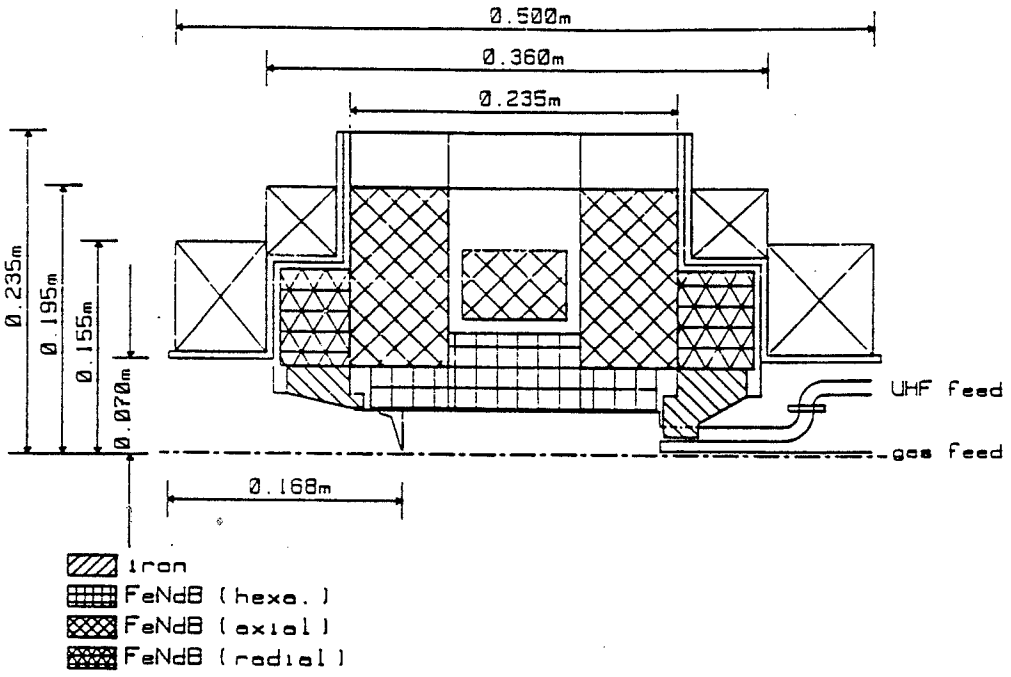

Fig. 7. Schematic diagram of the GANIL ECR4 ion source.

In summary, the trend in ECRIS design for highly charged ions is moving toward simple tandem mirror geometries with gradient first stages, operating at higher frequencies. The 10^{11} pps level may be pushed beyond 40+ for heavy mass beams produced in these sources.

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