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ABSTRACT

Electron Cyclotron Resonance Ion Sources (ECRIS) using RF between 5 and 16 GHz have been developed into stable, reliable sources of highly charged ions produced from a wide range of elements. These devices are currently used as ion sources for cyclotrons, synchrotrons, and heavy-ion linacs for nuclear and relativistic heavy-ion physics. They also serve the atomic physics community as a source of low energy multiply-charged ions. In order to improve their performance both with respect to maximum charge state and beam intensity, ECRIS builders are now designing and constructing sources which will operate at frequencies up to 30 GHz. In this paper we review the present status of operating ECRIS, review recent experimental measurements on plasma parameters, and look at the technology and potential of sources operating at frequencies up to 30 GHz.

INTRODUCTION

Electron Cyclotron Resonance ion source (ECRIS) are now widely used for the production of high charge state ions. They are stand-alone ion sources with their own power supplies, vacuum systems and control systems. ECRIS produce multiply-charged ions via electron impact ionization in a plasma with hot electrons and cold ions. The electrons are heated by electron cyclotron resonance heating and the plasma is confined in a magnetic mirror. Both the electron heating and ion confinement couple strongly to the magnetic field. This makes ECRIS both simple to build and at the same time difficult to analyze quantitatively. In 1989, 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.

Development of ECRIS began in the 1960's as a spin off of plasma fusion efforts. The early history and the basic operating principles are reviewed in a paper by Jongen and

Lyneis.[1] The 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. ECRIS have now largely replaced arc discharge ion sources for this purpose in most cyclotron facilities, where gains are made in both intensity and energy, and maintenance 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. In 1985 modifications began at CERN, to accommodate beams from an ECRIS-RFQ injector. Oxygen ions were accelerated to 200 GeV/u in the SPS in 1986 and sulfur in 1987. 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. The first beam from an ECRIS based positive ion injector was recently accelerated in the superconducting heavy-ion linac at the ATLAS facility at ANL. This injector is scheduled to replace the tandem injector at ATLAS later this year.

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, and ECRIS have been built in Oak Ridge and Giessen specifically for atomic measurements, while other facilities such as the LBL 88 Cyclotron, KVI Groningen, Louvain-la-Neuve, and ATLAS allow atomic studies on a time shared basis.

PERFORMANCE OF ECRIS

The performance of ECRIS has steadily improved over the last decade. In general terms, the intensities for intermediate charge states have increased by an order of magnitude and much larger gains have been made for the highest charge states. In Table 1 some currents are listed that are indicative of the present best performance levels for gases. Fully stripped ions up to mass 20 can now be delivered at currents greater than 1 eμA and fully stripped argon has been produced at the 1 enA level. For heavier gases the 1 eμA level is Kr^{25+} and Xe^{32+}. The data in Table 1 are taken from the performance of three sources, CAPRICE-$2\omega_{ce}$ which operates at 10 GHz[2], ISIS which operates at 14.5 GHz[3], and Minimafios-16GHz[4]. CAPRICE is the least conventional of the three. Its magnetic structure produces sufficiently strong fields so that a closed surface with $|B|$ equal to twice the ECR field is produced. A second unusual feature is the use of an iron puller to modify the magnetic field the the extraction region. This source produces exceptionally high intensities of intermediate charge state ions. ISIS is the only superconducting ECRIS now in operation and is much larger than either CAPRICE or Minimafios-16GHz. It produces excellent results for fully stripped ions such as O^{8+} and Ne^{10+}. Minimafios-16GHz is the highest frequency ECRIS. It holds the record for highly stripped heavy-ions[4,5] such as Ar^{18+} and Xe^{32+}.

The experimental data strongly support the concept that ECRIS operating at higher frequencies produce both higher intensities and higher average charge state distributions. Geller has developed a set of scaling laws based on measurable plasma parameters.[6] He found that the peak of the charge state distribution, q_{opt}, scales approximately as $\log\omega^{3.5}$ where ω is the RF frequency. Since there are many design factors which influence ECRIS performance, the comparison of any two sources may not follow this scaling. However, the comparison of the performance of a number of well characterized ECRIS operating at different frequencies support frequency scaling.[6]

A wide range of ions can also be produced using solid feed material. 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[7] and use of ovens to vaporize solids.[8] Direct insertion works for both low and high temperature solids as long as sufficient vapor pressure can be attained before the solid melts. Although direct insertion is both simple and effective, it has two operational disadvantages. First, the source tuning becomes quite critical due to the strong coupling between the plasma and sample heating. Second, the high charge state performance for high melting point materials is not as good as for similar mass gases.[9] This is probably due to the loss of hot electrons from the plasma that scatter from the sample being heated. Using an oven overcomes these two disadvantages, but at the cost of a more complex system. The advantage of oven feed is the independent control of the material feed rate. Recent development of oven technology has raised the maximum operating point to about 2000 °C making all but the most refractory materials accessible.[8] Figure 1 shows that the performance of the LBL ECR with oven feed is comparable to its performance with gas feed.

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 designed 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. The corresponding resonance field range is 0.18-1.25 T. This source, the SCECR, is shown in Fig. 2. 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 K1200 cyclotron at MSU. 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 Fall 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 with first operation scheduled for the fall of 1989. The design of the AECR is illustrated in Fig. 3. The axial magnetic field is produced by three groups of copper coils. These groups are sub-divided into three independently adjustable elements, for fine adjustment of the magnetic field. The iron plates between coils 2 and 3 serve to increase the mirror ratio. The magnetic field profile is similar to that used currently in the LBL ECR, which was optimized experimentally. 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. The main feature of this source are slots in the sextupole that allow radial access in the plasma chamber for pumping and ovens.

ECR4 at GANIL is a compact 14.5 GHz ECRIS[10] similar in general design to the lower frequency CAPRICE developed in Grenoble.[9] Its design is shown in Fig. 4. It uses a Nd-Fe sextupole, copper coils, and an optimized iron yoke and requires only 40 kW of magnet power. for 14.5 GHz operation. Unlike the AECR, it has no radial access, but has a stronger sextupole and is designed to operate with higher axial mirror ratios.

PROGRESS IN THE UNDERSTANDING OF ECRIS

Although there has been remarkable progress in the performance of ECRIS in the last decade, progress toward understanding their operation has been slower. One reason for this has been the lack of measurements to determine the actual plasma parameters in ECRIS. However, this situation is changing as more groups focus on measurement of the plasma properties. Below we will summarize the results of some of these recent measurements many of which are reported on in this conference.

In Grenoble plasma diagnostics have been used both on CAPRICE and Minimafios-16GHz.[4] They have measured the plasma diamagnetism on CAPRICE and found a value of n_eE of 25 x 10^{12} keV/cm^3. This is surprisingly large since the source presumably operates below the critical plasma density which is 1.24 x10^{12} /cm^3 at 10 GHz. This suggest a population of very hot perhaps relativistic electrons in the plasma. Another interesting observation is that at very low RF power levels (~2 W) the K_α and K_β lines are observed indicating the presence on 12 keV electrons.

At MIT the Constance-B fusion research machine has been used as a test bed for the measurement of plasma parameters related to ECRIS.[11] This device differs from conventional ECRIS in three significant aspects. First, in the axial direction the walls are located far from the ECR region in a region of low magnetic field. This was intended to reduce plasma-wall interactions, but it allows relatively large plasma potentials to develop. Second, the radial confinement field is a quadrupole rather than sextupole or octupole. Third, the ions can not be extracted at high voltage and are therefore measured by looking at the end loss with a TOF analyzer. However, its basic operating parameters such as plasma volume, RF power, neutral pressure are similar to conventional ECRIS. In this source the plasma parameters such as the cold and hot electron densities and temperatures, plasma potential, plasma diamagnetism, radial confinement time, and ion temperature have been measured or extrapolated. The results have been used in an ion production model for the plasma, which has been used to model the charge state distribution.

One interesting result of this work at MIT is a clearer picture of the gas mixing effect.[12] In this effect,which is observed in all ECRIS, the addition of a light gas to the plasma enhances the high charge state ion currents of the heavier element. A comparison of a 100% oxygen plasma with a 55% oxygen 45% helium mixture in Constance-B showed several differences. With gas mixing the ion temperature, the hot and cold electron temperatures, and the radial transport all decreased. Their conclusion is that the enhancement of the O^{6+} observed in the end loss (gas mixing effect) was due to an increase in the perpendicular confinement time. While this conclusion may be specific to Constance-B since they found it had anomalously high radial transport, the decrease in ion temperature is consistent with other measurements. In an ion cooling model proposed by Antaya for gas mixing a reduced ion temperature results in improved confinement, and the energy spread in an analyzed argon beams was shown to be smaller with gas mixing.[13] In any case as Meyer points out, the energy spread in an extracted beam is a function of both ion temperature and the plasma potential.[14] Since the MIT results showed both lower plasma potential and ion temperature, the question of which is more important remains open. What is needed to resolve this question are measurements of the plasma potential with and without gas mixing for a working ECRIS.

While making definitive judgements on the mechanisms of ECRIS remain difficult, the new information coming from detailed measurements is beginning to shed light on the problem.

ACKNOWLEDGEMENT

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References

1) Y. Jongen and C. Lyneis, in *The Physics and Technology of Ion Sources*, edited by Ian G. Brown (Wiley, New York, 1989)
2) B. Jacquot and M. Pontonnier, Scientific Note 189, DRF-G/SPhAT/PSI, Grenoble(June 1989).
3) H. Beuscher, "The Superconducting 14 GHz ECRIS at Jülich," this conference, to be published in Rev. Sci. Instrum.
4) G. Melin, G. Bourg, P. Briand, J. Debernardi, M. Delaunay, R. Geller, B. Jacquot, P. Ludwig, T.K. N'guyen, L. Pin, M. Pontonnier, "Some Particular Aspects of the Physics of the ECR Sources for Multicharged Ions," this conference, to be published in Rev. Sci. Instrum.
5) R. Geller, et.al., Proc. Int. Conf. ECRIS MSUCP 47, 1 (1987).
6) R. Geller, Proceeding of the 1989 Particle Accelerator Conf.(to be published).
7) F. Bourg, et.al., NIM A254, 13 (1987).
8) D.J. Clark and C.M. Lyneis, Journal de Physique, Colloque C1, number 1, 759 (1989).
9) B. Jacquot and R. Geller, Proc. Int. Conf. ECRIS MSUCP 47, 254 (1987).
10) P. Sortais, P. Attal, M. Bisch, M.P. Bourgarel, P. Leherissier, J.Y. Pacquet, "ECRIS Development at GANIL," this conference, to be published in Rev. Sci. Instrum.

11) C.C. Petty, D.K. Smith, D.L. Smatlak, D.L. Goodman, Proc.Int.Conf.ECRIS MSU-CP 47, 151(1987).

12) C.C. Petty, MIT Report PFC/RR-89-9 (1989)

13) T.A. Antaya, Journal de Physique, Colloque C1, number 1, 707 (1989).

14) F.W. Meyer and J.W. Hale, "Ion source studies at the ORNL ECR source facility," this conference, to be published in Rev. Sci. Instrum.

Table 1

Representative Ion Currents for ECRIS in eμA for selected ECRIS

Ion	*5+*	*6+*	*7+*	*8+*	*9+*	*10+*	*11+*	*12+*	*13+*	*14+*	*17+*	*18+*
N	382[a]	141[a]	6[b]									
O		383[a]	46[a]	6[b]								
Ne		192[a]	120[a]	104[a]	11[b]	1.2[b]						
Ar				560[a]	260[a]	*	100[b]	80[c]	30[c]	20[c]	.02[c]	1nA[c]
Ion	*13+*	*15+*	*17+*	*18+*	*19+*	*20+*	*22+*	*23+*	*25+*			
Kr	34[b]	25[b]	21[b]	19[b]	15[b]	11[b]	4.5[b]	2.6[b]	0.8[b]			

a) Data for the new 10 GHz CAPRICE -2ω_{ce}.[2]

b) Data for ISIS at Jülich.[3]

c) Data from MINIMAFIOS-16 GHz, [4]

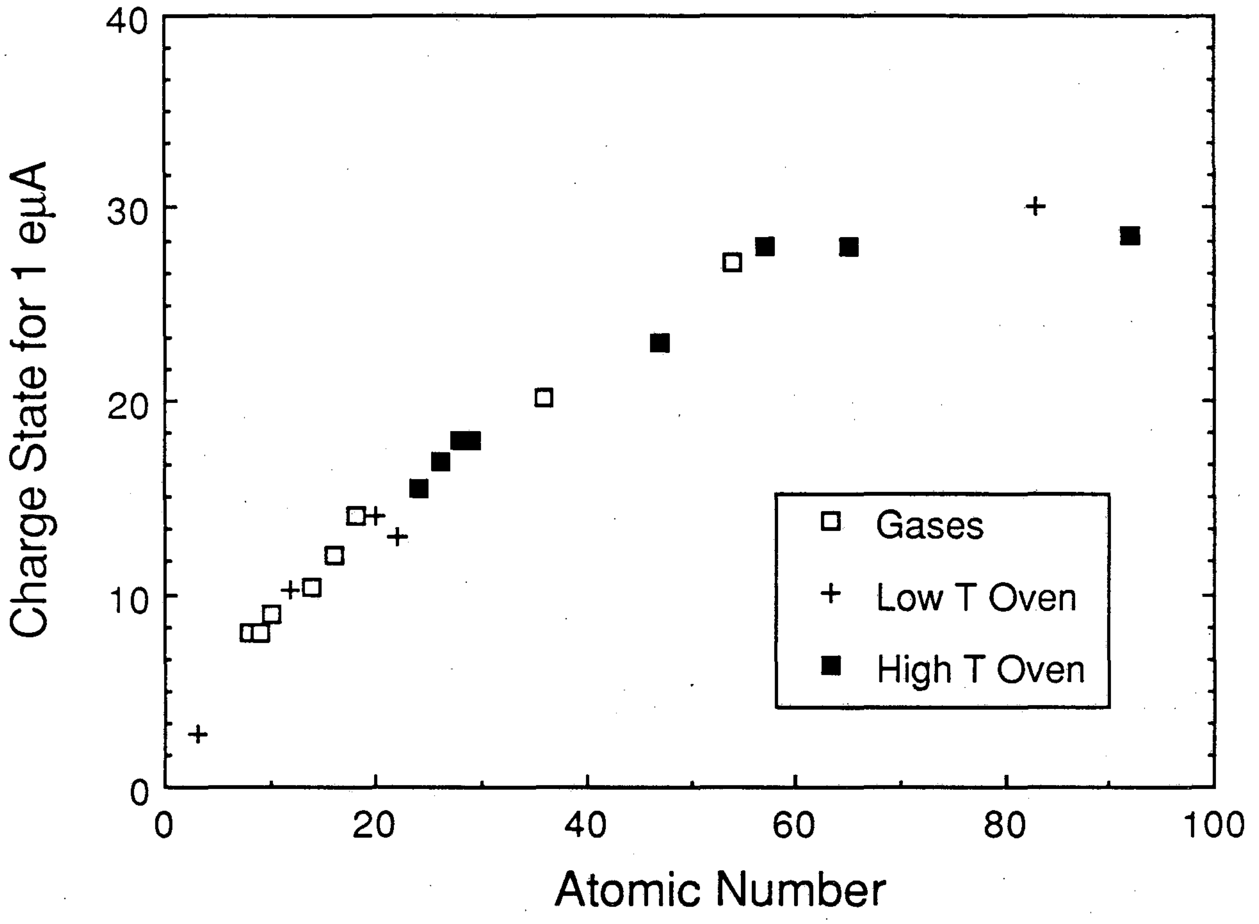

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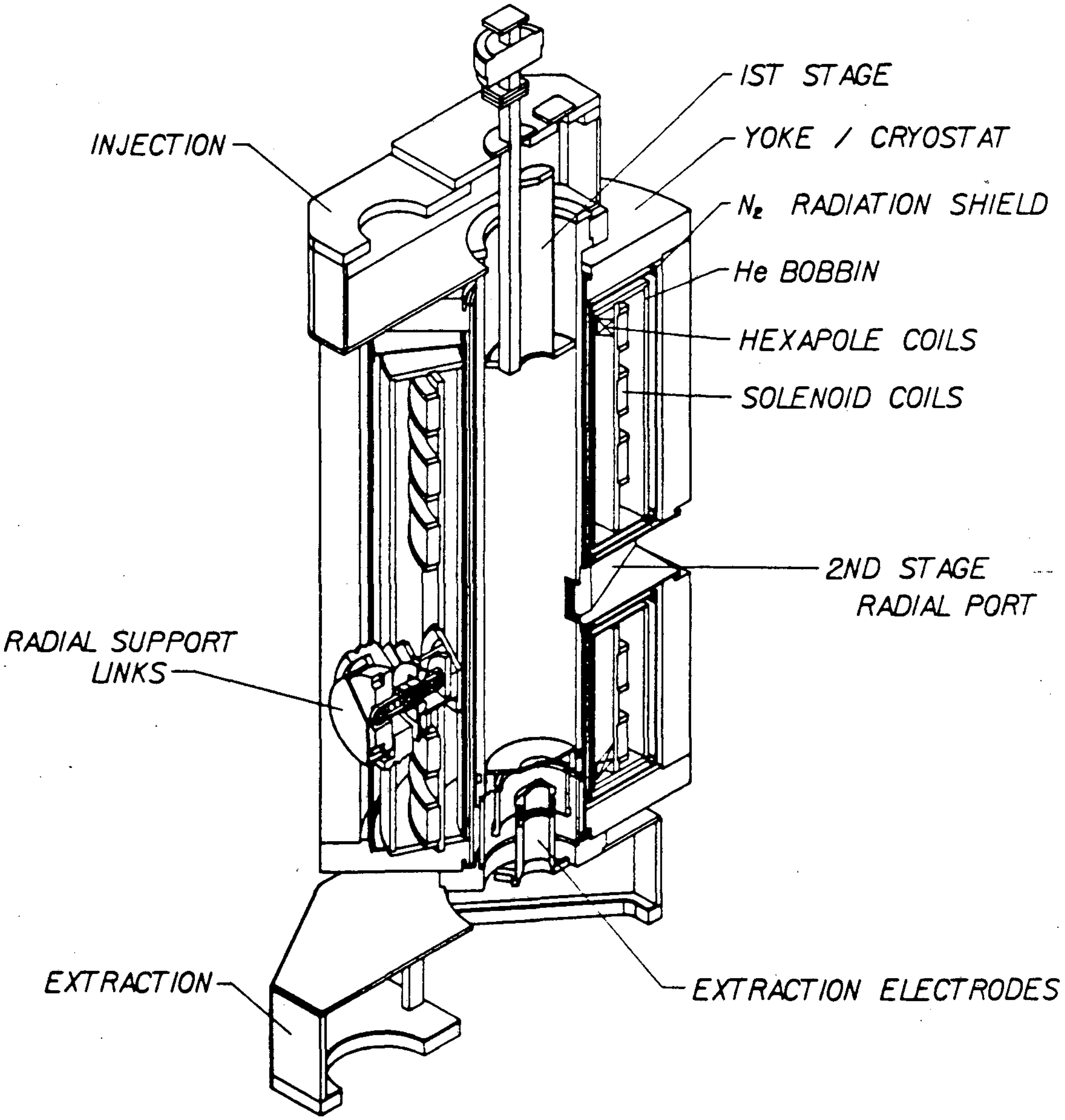
Fig. 1. The charges states achieved at the 1 eμA level for the LBL ECR as a function of atomic number for gases and solids. The open squares indicate gas feed, + indicates solid feed in the low temperature oven, and the closed squares indicate solid feed in the high temperature oven.



XBL 897-2887

Fig. 2. The present design of the SCECR ECRIS now under construction at MSU.

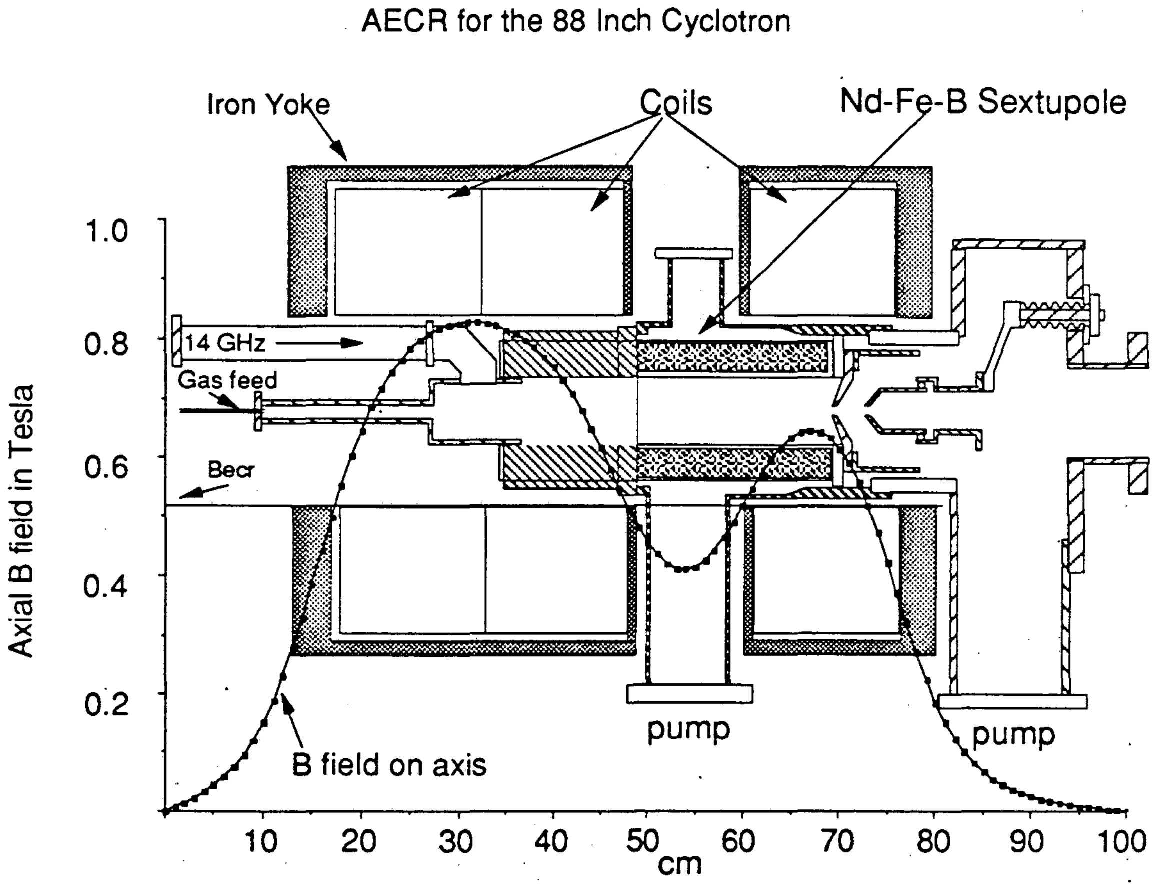


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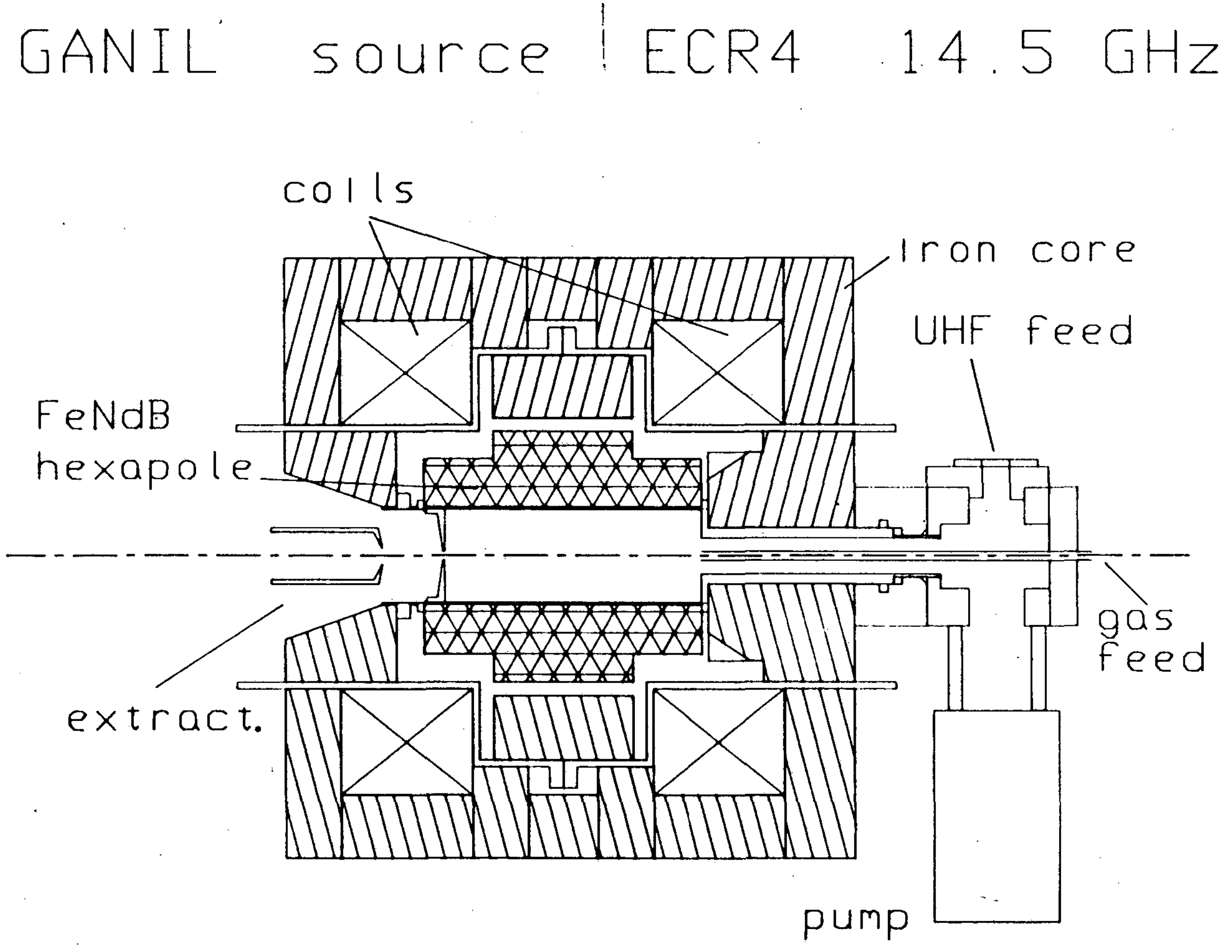
Fig. 3. Elevation view of the AECR source now under construction at LBL. The axial magnetic field corresponding to 250 Amp current in the coils is superimposed on the drawing.



XBL 898-2923

Fig. 4. Elevation view of the new 14 GHz source, ECR4, under construction at GANIL. The iron yoke
that an axial magnetic field of 1.1 T on axis can be produced with only 40 kW of electrical power.

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