ECR Sources for Multiply Charged Ions at Michigan State University

T.A. Antaya
National Superconducting Cyclotron Laboratory
Michigan State University

Invited Talk Presented at the Vth International Symposium on Electron Beam Ion Sources and Their Applications, Dubna, Russia, 26 September 1991.

MSUCP–68

ECR Sources for Multiply Charged Ions at Michigan State University

T.A. Antaya
National Superconducting Cyclotron Laboratory
Michigan State University

1. Introduction

In this paper we will review the design and operating characteristics of the ECR ion sources at the National Superconducting Cyclotron Laboratory. As you may recall, NSCL has two compact superconducting cyclotrons.[1] In the original facility concept, the low charge beam accelerated in the first cyclotron (K500) would be stripped on injection to a higher charge state in the second cyclotron (K1200), and then reaccelerated to higher final energy. With this facility, it was envisioned that heavy ion beams from Q/M=1/2 at 200MeV/n down to uranium at 20MeV/n would be produced. The initial beam would be produced by an internal cold-cathode PIG ion source.[2] The K500 was actually commissioned with this internal ion source in 1981-82, and operated 'stand alone' through early 1986 as a primary beam accelerator for the nuclear physics program at NSCL.

By 1984 it was clear that the booster K1200, operating *by itself* with external ECR source injection, could perhaps be competitive with the coupled cyclotron operation described above; with the added benefit of operating only a single accelerator to achieve the facility energy and intensity goals. It was at this time that the ECR ion source effort at NSCL was started. Therefore the goal of the ECR development program at NSCL from the outset has been to create primary ion beams from ECR sources that would allow stand-alone operation of the K1200 cyclotron, while meeting or exceeding the coupled cyclotron design goals for energy and intensity. Additionally, this permits independent operation of the K500 cyclotron with internal or external ion sources. The K500 cyclotron began operation with the "room temperature" RTECR primary beam injection in March 1986. The "compact" CPECR was added to produce lithium beams in 1987, and was also used in the commissioning of the K1200 cyclotron in 1988. The variable frequency "superconducting" SCECR became operational in Fall of 1990. The design and performance goals of these three ion sources illustrate many of the main themes of the world-wide ECR effort, that has resulted in the development of about 40 ECR sources for accelerator and atomic physics laboratories over the past decade.

2. The Room Temperature RTECR

The RTECR has been the primary cyclotron injection ECR source at NSCL. It has on average operated about 6000 hours every year since 1986. It has a very low equipment failure rate—about 1 failure every two years, and those failures have primarily been associated with wear on pumps in the vacuum subsystem. Starting as an ECR with two independently tunable stages,[3] it has undergone a continuous evolution. Like the

CPECR, the operating frequency is 6.4 GHz. In contrast to the CPECR, it is mainly used for highly charged ions from either gaseous or solid feed materials.

The present 2B operating configuration is shown in Figure 1. The '2B' label is in reference to the axial solenoid field on the microwave injection end (the upper end in Fig. 1), that peaks at more than twice the 6.4 GHz ECRH resonance field of 2.29kG. Originally, the middle solenoid group allowed the division of the RTECR into 2 Minimum $\vec{B}$ Stages. Since 1988, the upper solenoid group has operated at twice the original design excitation, adding to the field from the middle group to produce this high mirror field.[4] The effect of the large mirror field on the injection side of the main stage is to reduce axial ion losses in that direction, which is functionally equivalent to having a strong first stage on that side that injects plasma into the main stage.[5] In this geometry, feed gases are mixed in a small microwave resonant structure on the upper end and pre-ionized, and a single off-axis waveguide is used to introduce 6.4 GHz microwaves into the main stage.

With high magnetic confinement, and a large plasma vessel (l=70cm, ϕ=15cm), the RTECR is able to operate at a very low pressure, about 7×10^{-8}Torr. With such low pressure, recombination losses are reduced and charge state distributions are observed to peak at highly charged ions, as shown for argon in Figure 2. The charge state distribution is seen to be narrow and peaked at about Ar^{10+}. The high charge state argon ion intensities are enhanced by the presence of the oxygen in the plasma. This is evidently an ion cooling effect.[6]

This sharp charge state distribution is a function of the source *operating mode*, not the origin of the feed materials. Figure 3 shows a calcium charge state distribution in an oxygen plasma. The charge state distribution is similar to argon in Fig. 2, however, the calcium is being introduced from a small high temperature oven attached to a main stage port, while the argon was fed along with the oxygen into the pre-ionizer at the injection end of the RTECR.

Part of the low pressure operation of the RTECR comes from the presence of a SiO_2 layer deposited on the copper plasma chamber by an *in situ* deposition process. As Figure 4 shows, the high charge state argon ions are sharply enhanced by the presence of the SiO_2 layer. Operationally, one observes that the total extracted current is higher, but at lower operating pressure, implying that the neutral density-plasma density coupling is reduced. The result is a kind of quadrature: the ionization rate increases while simultaneously the recombination losses decrease, and highly charged ions are produced.

While the SiO_2 coating improves the 2B geometry performance, it is not significantly better than the earlier 2 minimum $\vec{B}$ mode of operation, as shown for krypton in Figure 5. In the earlier 2 stage geometry, a strong tunable first stage injected plasma into the main stage for further ionization. As can be seen, the 2B geometry + SiO_2 wall coating performance is only slightly better than 2 stage operation for krypton. The wall coating effect is like having a strong first stage. However, with the wall coating, the ion source operation is simple—only one stage must be optimized, and no 1st stage-to- 2nd stage coupling problems are observed. And only one microwave transmitter is needed!

Just what is the origin of this SiO_2 wall coating effect? The layer is grown by feeding silane (SiH_4) into an oxygen plasma for 2-3 days, and this results in a glassy translucent coating on the copper plasma chamber, which is thought to be SiO_2. But one is not really sure what the composition of the coating is. If it is SiO_2, then it is speculated that wall secondary electron emission (from energetic electron impact)

is enhanced, because SiO_2 has a much higher secondary electron coefficient than bare copper. In order to test this theory, we made a MgO layer on a copper liner and placed that in the plasma chamber of the RTECR. MgO is also a substantially better secondary electron emitter than copper, and if that is the effect, an MgO coating should also result in the performance enhancement like that observed in Figure 4. Figure 6 shows a comparison of RTECR neon and argon performance for the *in situ* SiO_2 layer versus the manufactured MgO layer. As can be seen, the source performance is about the same—giving further support to the enhanced secondary electron emission argument.

Figure 7 illustrates the overall performance of the RTECR when tuned to optimize the highest charge states. The absolute intensity decreases with increasing Z, while the charge state distribution spreads out. With this performance, the RTECR injecting the K1200 cyclotron already meets most of the design goals for the original coupled cyclotron proposal!

3. The Compact Single Stage CPECR

The CPECR is primarily a single stage ionizer for lithium and other light ion beams.[7] (Lithium ion beams were an important part of the NSCL nuclear science program before ECR sources.) Initial attempts to produce lithium in the RTECR were not very successful—neutral lithium vapor injected from a hot oven into the RTECR main stage mostly condensed on the water cooled copper plasma chamber walls, rather than ionizing in the plasma. Further, this lithium contamination complicated heavy ion tuning of the RTECR. In addition, the RTECR, once coupled to the K500, was fully utilized—and therefore difficult to free for further development, including improving the lithium performance!

We needed a source designed for the chemistry of lithium, but also capable of producing other beams so as to reduce the demand on the RTECR. The primary CPECR configuration is shown in Figure 8. It consists of a hexapole stabilized tandem mirror cell, mounted below a large volume metal vapor oven. Lithium vapor from the oven is injected into a helium plasma and ionized. The resulting charge state distribution is shown in Figure 9. This charge state distribution is typical of single stage ECR sources: the intensity peaks at 1+ ions and drops monotonically as the number of electrons removed increases. In single stage ECR sources, the plasma density is strongly coupled to the neutral density. To raise extracted intensities, the neutral density must be raised, and the resulting charge state distribution is dominated by charge recombination. In producing lithium beams, and reducing material consumption, the heated liner in the CPECR plasma chamber is absolutely critical. Little lithium is extracted from the source if the liner temperature is less than 400°C. (At low liner temperature, the lithium is observed to condense out in droplets on the liner and at the bottom of the plasma chamber.) The CPECR has radial off-axis 6.4 GHz microwave injection into the main stage, through a port located between two poles of the hexapole magnet. For lithium, the CPECR main stage operating pressure is about 5×10^{6} Torr.

We used the CPECR for other ions as well. Figure 10 shows the gaseous ion operating geometry of the CPECR. The oven hardware and the main stage heated liner are removed. A small cylindrical alumina tube is installed coaxially at the entrance of the plasma chamber and gas is fed into this tube. This tube crosses the falling axial field

6.4 GHz ECRH resonance (at 2.29kG) at roughly the position of the upper iron yoke cap. This resonance is excited by microwaves coupling through the baffle that separates the main stage from the oven chamber, and some pre-ionization of the gas occurs before it enters the main stage. With this modification, the operating pressure of the CPECR drops to about 1×10^{-6}Torr, and the multiply charged ion performance is enhanced.

In this geometry, the 1 eμA performance of the CPECR is obtained for C^{5+}, N^{6+}, O^{7+} and Ar^{9+}. Then when these ions are needed by the cyclotrons, the CPECR can be used, freeing the RTECR for further beam development work. The most unusual beam produced by the CPECR, HeH^+, is shown in Figure 11. At high pressures, ECR sources can produce significant quantities of molecular ions. Normally, this operation is avoided though because high pressure operation results in gas absorption that hinders subsequent high charge state tuning, and also possibly complicates the operation of the microwave vacuum feed through. However, the CPECR vacuum design for oven operation permits gaseous operation at 10^{-5} to 10^{-4} Torr with no difficulty, permitting the development of molecular beams like HeH^+ that require higher pressure operation (to suppress ionization.) This particular beam allows the production of low energy hydrogen beams from the NSCL cyclotrons—the helium 'ballast' being stripped after acceleration.

4. The Superconducting SCECR

In 1986, the first operation of a Grenoble 16.6 GHz ECR source were announced.[8] This source had two remarkable features: (1) the charge state distribution could be peaked at much higher charge states than other existing ECR sources, and (2) the total extracted current was significantly higher than other ECR sources. Both features imply a higher plasma density is present, and this higher plasma density was interpreted as being the result of raising the plasma density cutoff limit (by raising the frequency).[9] However, the high axial field Caprice 2B ECR source announced in 1986 by the same group, also had higher currents of highly charged ions, but it was only a 10 GHz source.[10] Additionally, the Jülich ISIS ECR source, first operated at 14.5 GHz in the late 1986, produced very highly charged ions, but very low total ion currents.[11] What is going on here?

It is important to note that for first harmonic ECRH, the operating magnetic field and frequency are linearly related.

$$\nu_{ECR} = \frac{e}{2\pi M_e} B = 28 GHz/Tesla \qquad (1)$$

so that raising the frequency necessarily implies raising the magnetic field. But raising the magnetic field improves the confinement of a magnetized plasma .[12] So when enhanced production of highly charged ions is observed at higher frequency, is it due to higher plasma density or improved confinement, or both?

In order to answer these questions, we have built a new superconducting ECR source at NSCL, the SCECR, and will use it to study both magnetic confinement and frequency scaling.[13] The SCECR is shown schematically in Figure 12. At its heart is a full superconducting coil set for the Minimum $\vec{B}$ structure. Also, the coils are not operated in persistent mode. Instead, gas cooled leads allow real-time magnetic field tuning during source optimization. Peak design axial and radial field strengths are 2.2

Tesla and 1.7 Tesla respectively. The operating frequency is variable—from 5 to 35 GHz, and at a given frequency, the magnetic topology has a large dynamic range. Otherwise, the plasma chamber dimensions, microwave and gas injection, and ion extraction are very close to the RTECR design.

Figure 13 shows some of the first results obtained at 6.4 GHz and 14.5 GHz in the SCECR. At the 'Nominal $\vec{B}$' 6.4 GHz magnet setting, the SCECR has the same magnetic field as the RTECR and other similar conventional ECR sources. At the 'High $\vec{B}$' setting at 6.4 GHz, the peak magnetic mirror fields are almost as high as for 14.5 GHz operation. Finally, the 'Nominal 14.5 GHz' setting is a straight frequency ratio scaling of the nominal 6.4 GHz field. Comparing the charge state distributions, one sees that both high field cases result in increased high charge oxygen ion production over the 'Nominal $\vec{B}$' 6.4 GHz low field results. However, the high field 6.4 GHz and 14.5 GHz results are quite close. To first order then, the frequency scaling effect in ECR sources appears to be simply a magnetic confinement scaling effect, otherwise the 14.5 GHz results would be substantially higher. It is predicted that the optimum extracted charge state, Q_{opt}, should depend on the magnetic field as

$$Q_{opt} \propto K \log B \tag{2}$$

in ECR sources, where K is a constant, when only the magnetic field B is varied.[14] Figure 14 shows the ratio of Xe^{10+}/Xe^{6+} extracted from the SCECR as the maximum radial magnetic field is increased (by ramping the hexapole), with all other parameters held constant. The best fit to the experimental data does in fact show this log B_{max} dependence. Hence, the charge state distribution shifts towards more highly charged ions as the magnetic field is raised. Therefore, we may conclude perhaps that one should design an ECR source for the highest affordable magnetic field at a given frequency. Certainly the very good results with the various high field 10 GHz Caprice sources would corroborate this.[15]

5. Summary and Conclusions

Perhaps the best way to conclude this paper would be to put all this together in the form of what we envision to be the present 'state-of-the-art' for a general purpose ECR source. Figure 15 shows one possibility for such a source. We show a compact, high field ECR source operating at 14.5 GHz. One chooses 14.5 GHz to raise the maximum magnetic field (to enhance confinement) while still using first harmonic ECRH. (14.5 GHz microwave power is still relatively inexpensive, when compared to 16.6 GHz or higher.) The geometry is simple, and probably one would mostly tune highly charged ions of high Z materials in an oxygen plasma in the presence of a SiO_2 or some other wall coating. Such a source should be capable of intense fully stripped ions up to neon, as well as useful Ar^{16+}, Kr^{28+}, Xe^{36+} and U^{44+}. Finally, most physics laboratories should be capable of building such a source.

6. References

1. H.G. Blosser, IEEE Trans. Nucl. Sci, NS-26, 2040 (1978).
2. T.A. Antaya and P.S. Miller, IEEE 84CH 1996-3, 341 (1984).
3. T.A. Antaya, et.al., 6th Int. Workshop on ECR Ion Sources, LBL -5143, 126 (1985).
4. T.A. Antaya, Int. Conf. on the Physics of Multiply Charged Ions, Les Editions de Physique 50, 707 (1988).
5. T.A. Antaya and Z.Q. Xie, 7th Workshop on ECR Ion Sources, Kernforschunsanlae Jülich Jülich–Conf-57, 72 (1986).
6. T.A. Antaya, *op. cit.* 4.
7. D.P. Sanderson, et.al., Int. Conf. on ECR Sources and Their Applications, MSUCP-47, 300 (1987).
8. R. Geller, *loc. cit.* 3, p.1.
9. P. Sortais, Doctoral Tesis, Universite Scientifique et Medicale De Grenoble, (1985).
10. F. Bourg, et.al., *loc. cit.* 3, p.174.
11. H. Beuscher, *loc. cit.* 6, p.58.
12. D.R. Nicholson, Introduction to Plasma Theory, John Wiley and Sons, New York, 189 (1983).
13. T.A. Antaya, et.al., *loc. cit.* 7, p.312.
14. R. Geller, et.al., *loc. cit.* 7, p.1.
15. G. Melin, *loc. cit.* 4, p.673.

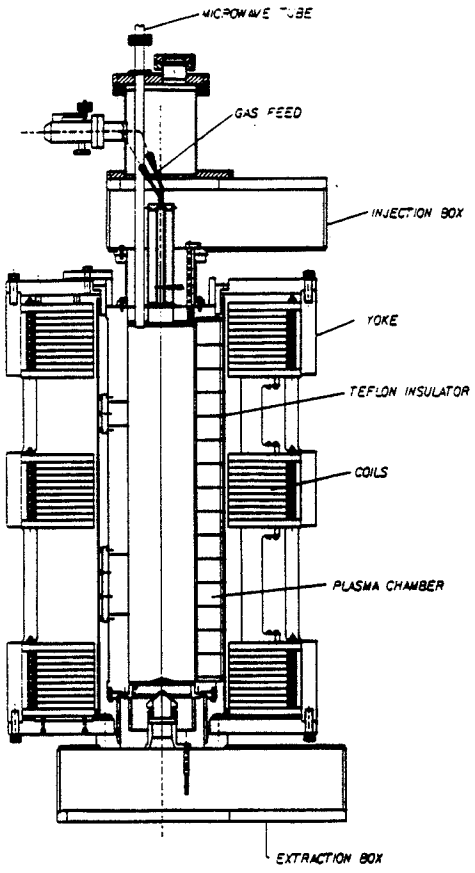

Figure 1. The present 2B configuration of the RTECR is shown.

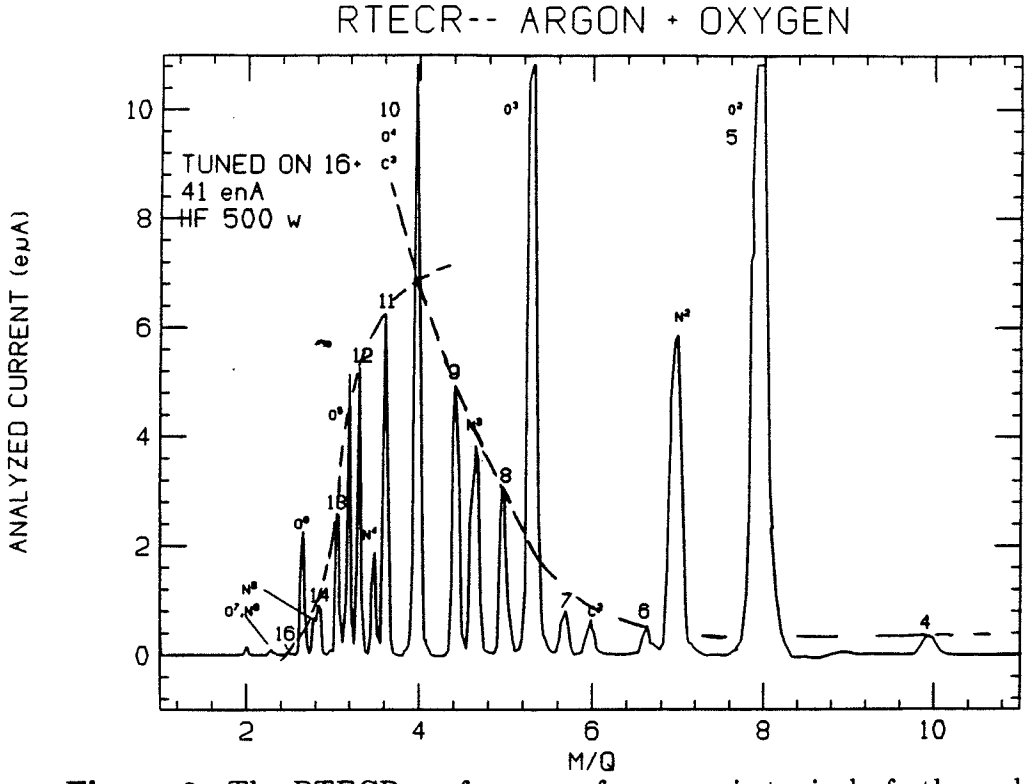

Figure 2. The RTECR performance for argon is typical of other advanced ECR sources. The charge state distribution peaks at a highly charged ion, in this case Ar^{10+}, in an O_2+ Ar plasma.

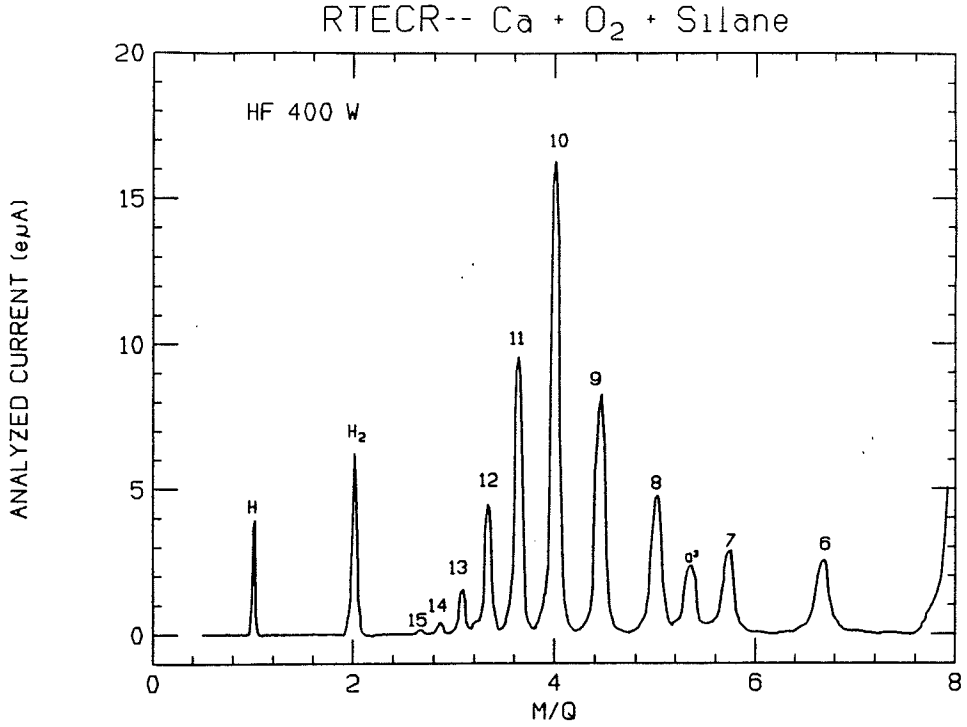

Figure 3. The same charge state distributions can be achieved in the RTECR for metallic species. Here ^{40}Ca is injected into a O_2 plasma from a small oven that has been connected directly to a main stage port.

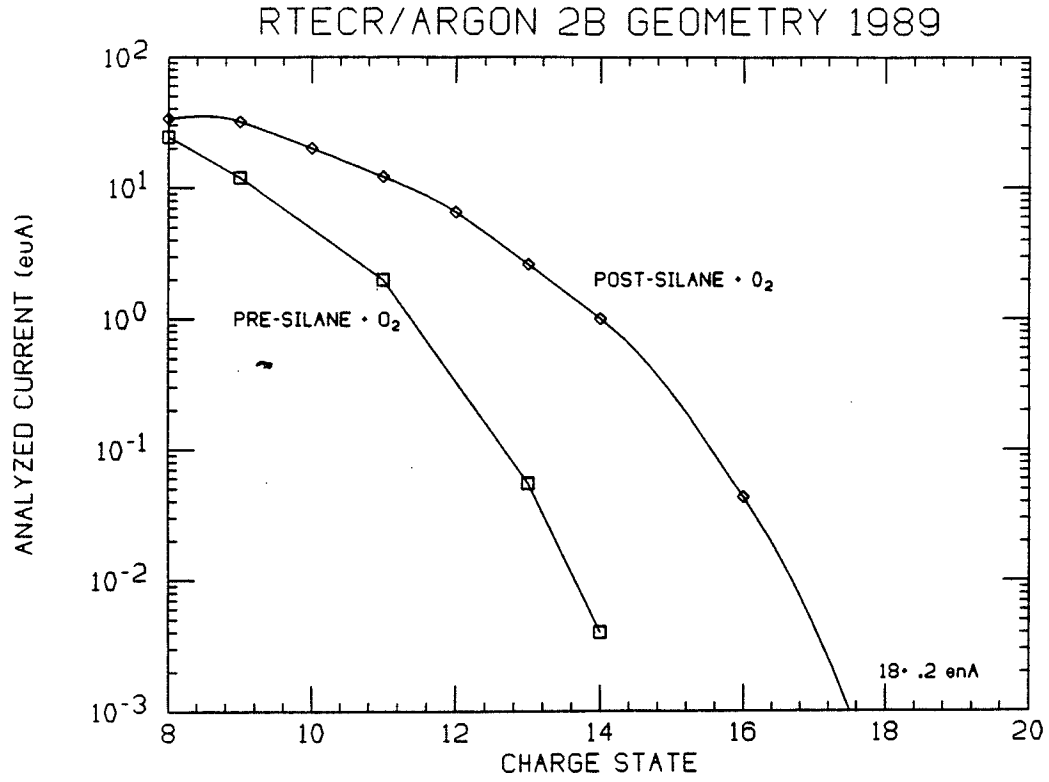

Figure 4. The RTECR performance is achieved in part by growing *in situ* a S_iO_2 layer on the main stage chamber walls. The affect of this layer on source performance is dramatic.

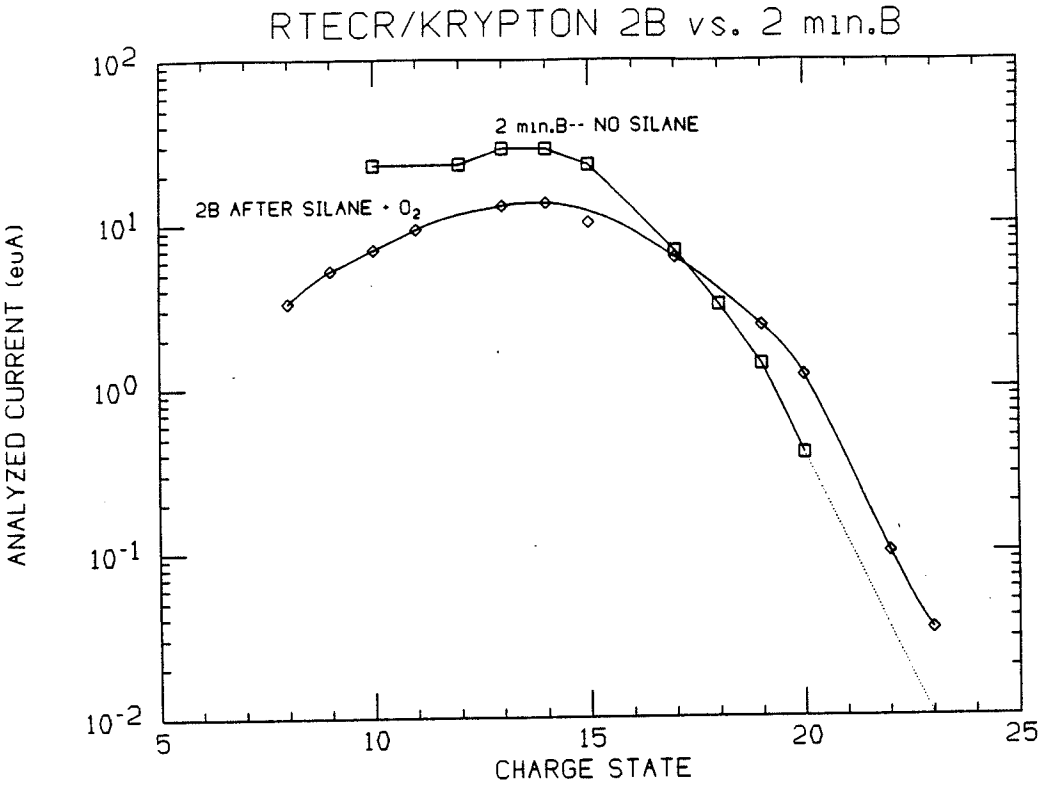

Figure 5. If we compare the 2B geometry performance of the RTECR (see Fig. 5) with a SiO_2 layer, to an earlier 2 stage, 2 minimum B geometry, this wall coating effect is less dramatic, implying that a SiO_2 wall coating effect is similar to having a strong first stage.

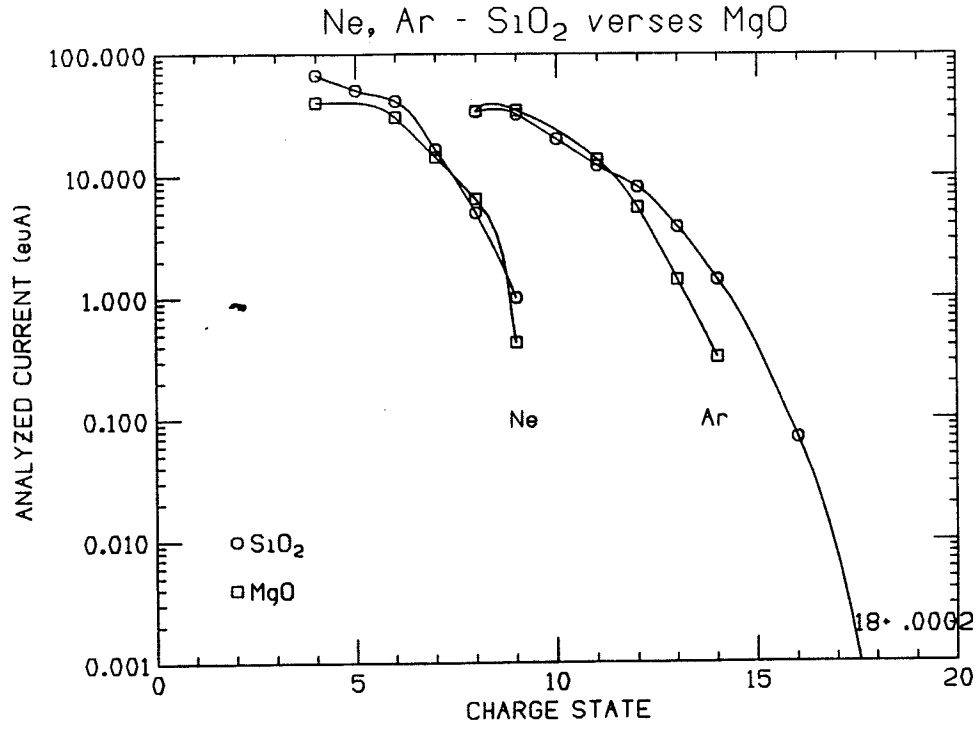

Figure 6. SiO_2 and MgO coatings of the RTECR plasma chamber result in equivalent performance as shown here for neon and argon.

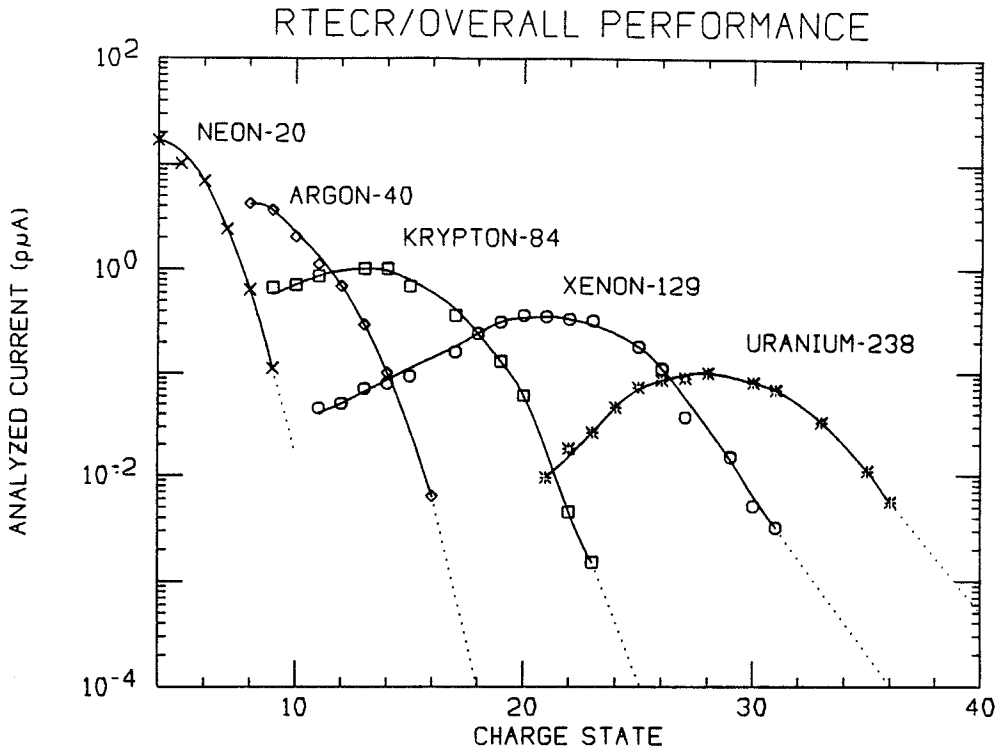

Figure 7. The overall performance of the RTECR for noble gases and uranium is shown. (Ne^{9+}, Ar^{14+}, Kr^{22+}, Xe^{30+}, U^{34+}). In each case the RTECR has been optimized on a highly charged ion.

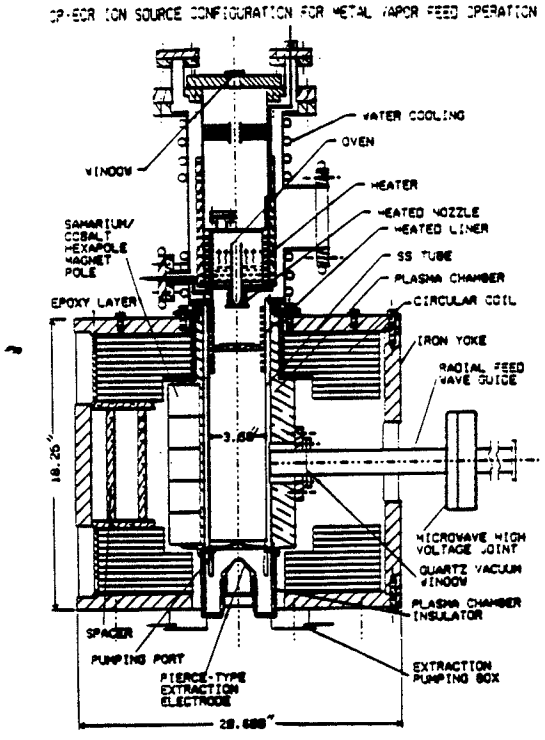

Figure 8. The CPECR has a vapor oven stage and heated plasma chamber liner when configured to produced Lithium and other alkali metal beams.

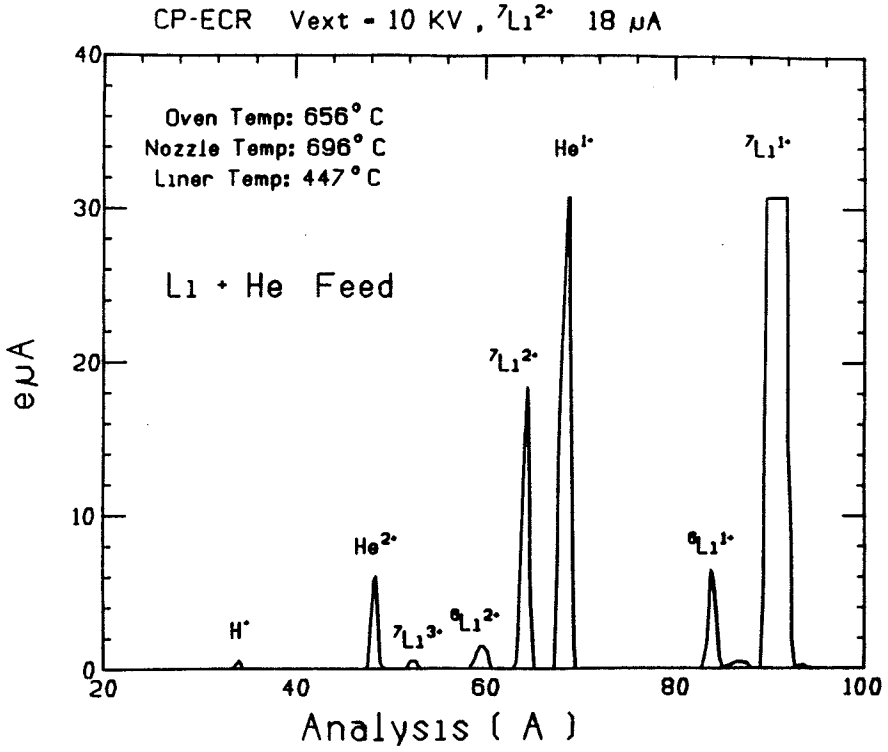

Figure 9. A natural lithium (plus helium support gas) spectrum from the CPECR operated in the configuration of Fig. 1 is shown. The $^7Li^{1+}$ peak is off scale on this plot, and the $^6Li^{3+}$ is hidden by the $^4He^{2+}$ peak.

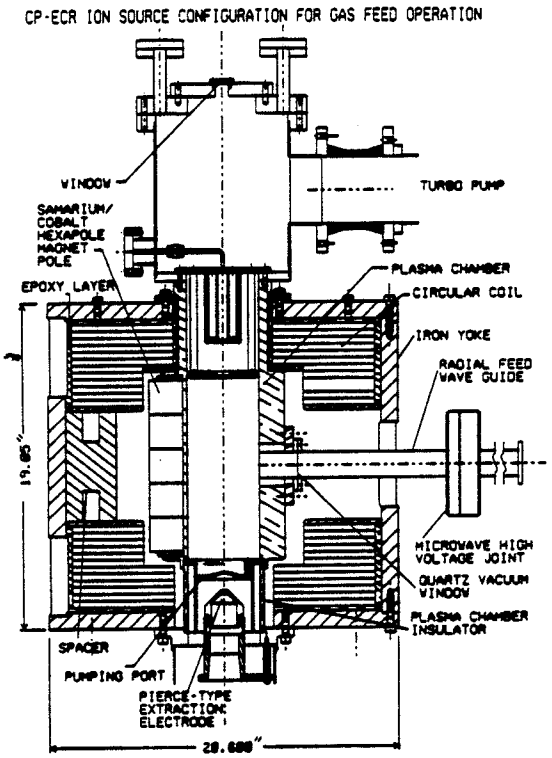

Figure 10. The CPECR can be used for gaseous ions as well. The oven hardware is replaced by a first stage that uses the ECR resonance in the falling axial solenoid field to pre-ionize the gas before it enters the main stage.

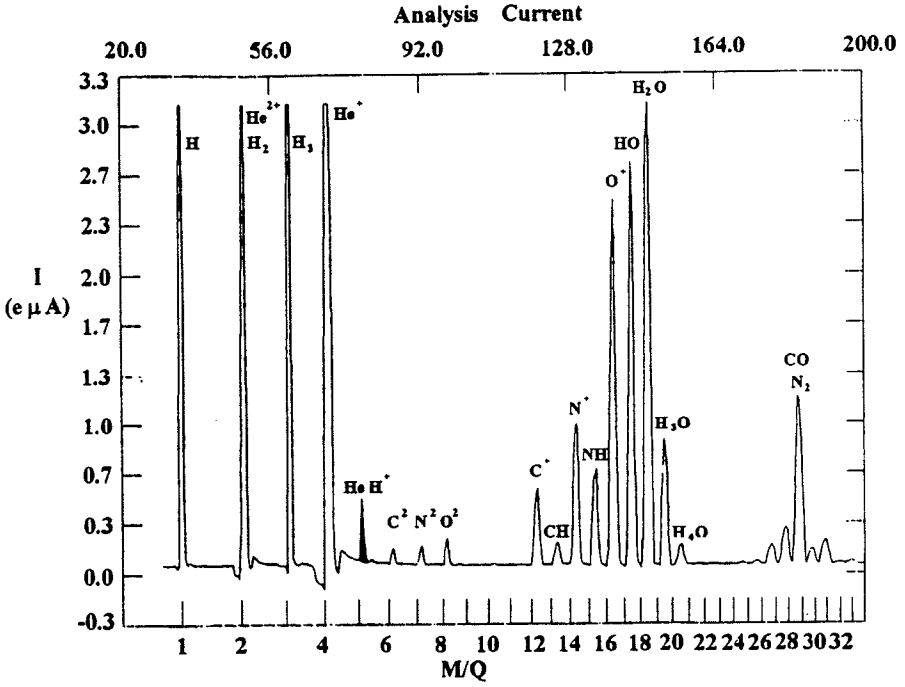

Figure 11. The CPECR is capable of operating at high pressures ($\approx 10^{-4}T$), a consequence of designing the source for high temperature oven operation. At high pressure, a feed mixture of $H_2 + He$ can be used to produce HeH^+, a molecule we used to generate low energy H beams in the superconducting cyclotrons.

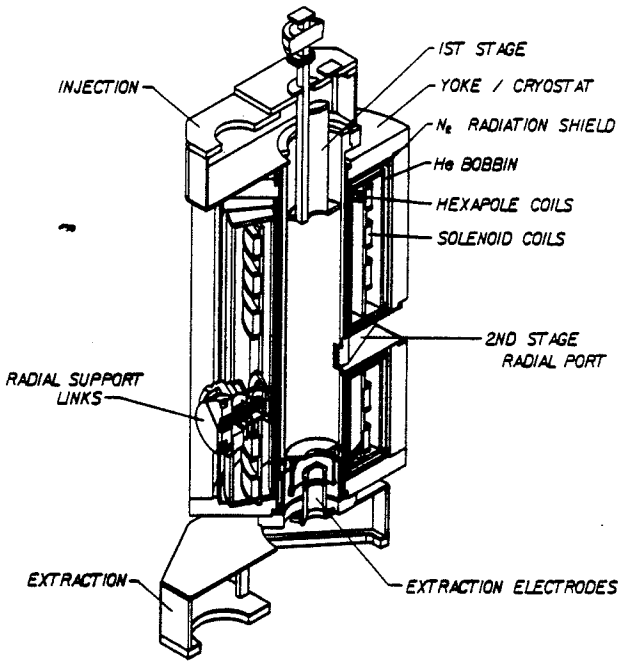

Figure 12. The design configuration for the superconducting SCECR is shown.

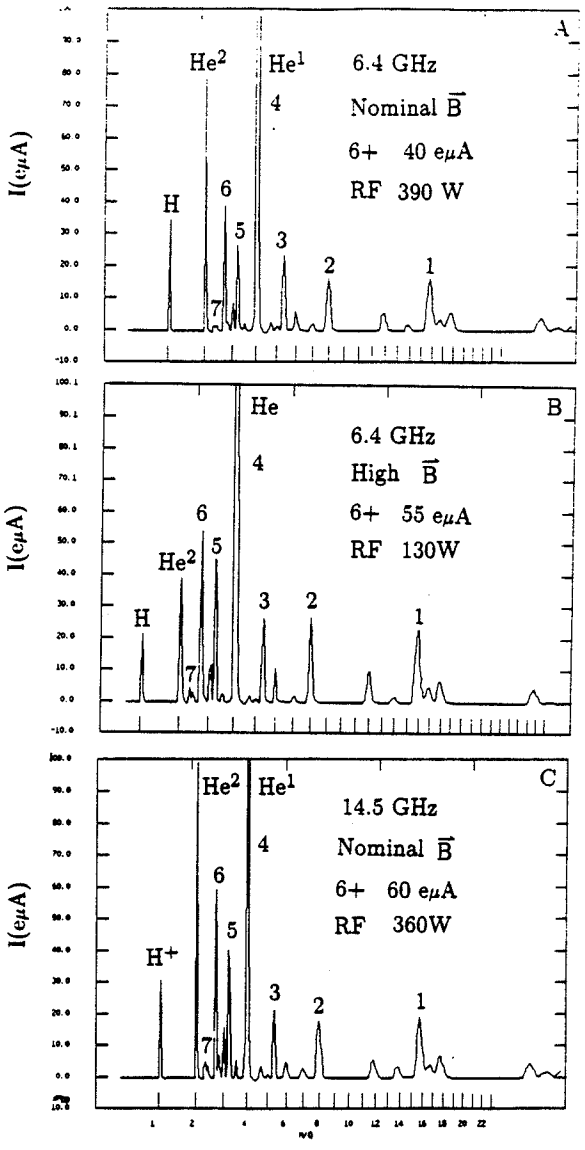

Figure 13. This figure shows ions extracted from an O_2 + He plasma in the SCECR, for a) 6.4 GHz operation at nominal magnetic field levels, b) 6.4 Hz operation at high magnetic fields, and c) 14.5 GHz operation at nominal magnetic field levels. In each case, O^{6+} was optimized. (Slight amounts of hydrocarbon based ions and nitrogen ions may also be observed.)

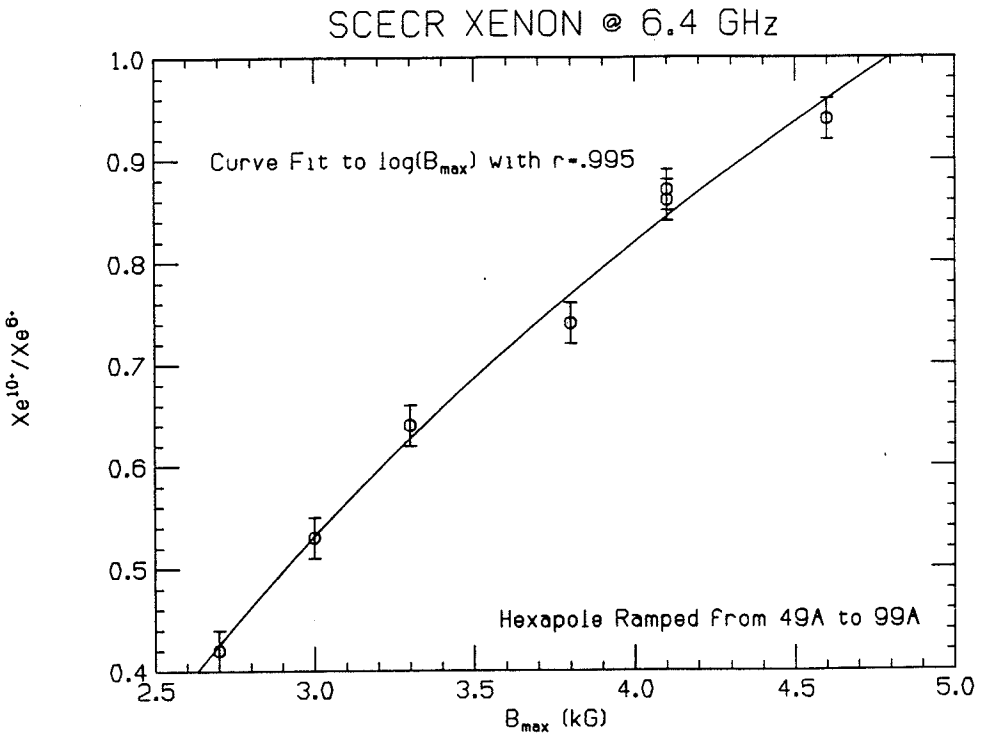

Figure 14. Holding the axial field of the SCECR constant, and ramping the hexapole 50A from 49A to 99A, causes a shift in the charge state distribution towards higher charge ions, as shown here for Xenon, implying increased confinement.

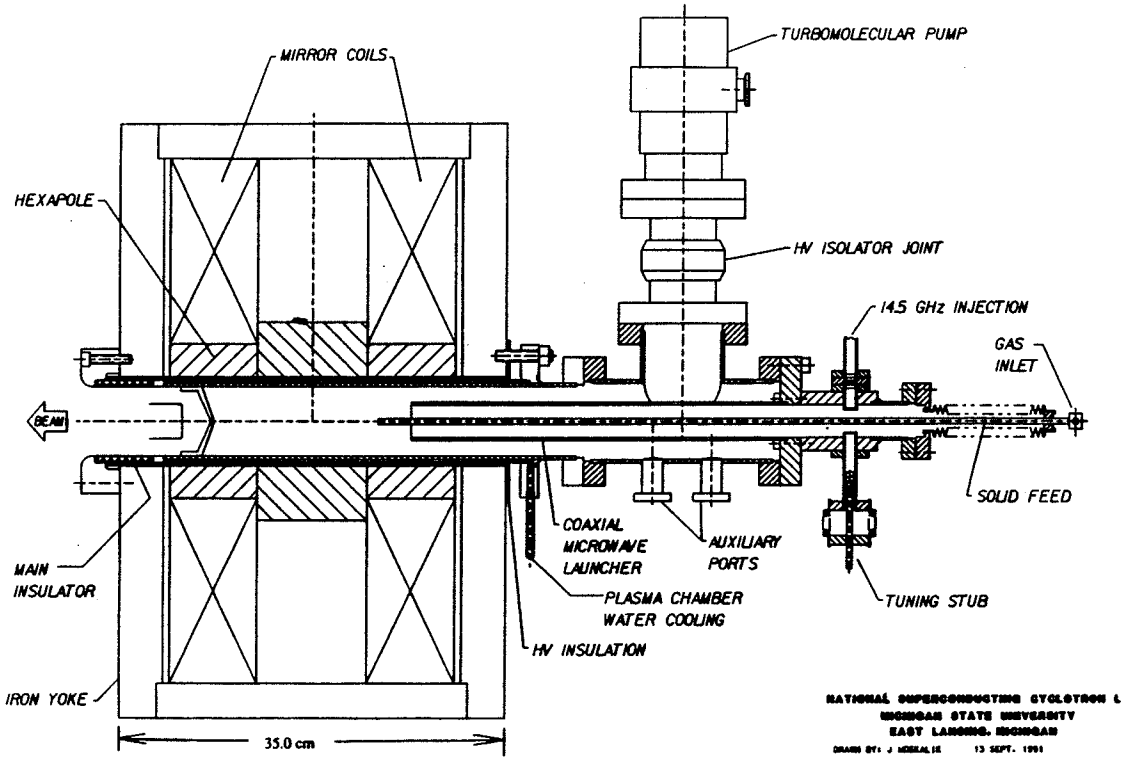

Figure 15. Perhaps the present 'state of the art' would be a compact high field 14.5 GHz ECR source. We show here a 14.5 GHz RTECR design for metallic species. It should easily achieve performance in the 1pμA range for species like $^{40}Ca^{14+}$.