A REPORT ON THE DESIGN AND PERFORMANCE OF A VERTICAL, 2 X 6.4 GHZ, FULL IRON YOKE ECR ION SOURCE FOR THE NSCL SUPERCONDUCTING CYCLOTRONS*

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Summary

At the time of the last cyclotron conference, design studies were underway for a large superconducting ECR ion source to provide beams for acceleration in the K500 cyclotron.[1] Later, these studies were expanded to include a room temperature ECR ion source with a smaller confined plasma volume, but sharing main design considerations with the superconducting source. After a design review meeting in East Lansing in November 1984,[2] a decision was made to proceed with the construction of the room temperature source first. At the same time a joint study with LBL found that same bore hexapoles and octupoles in the LBL source have equivalent performance; the fact that this performance is higher than that of the original hexapole was due to other factors, including better microwave coupling and/or increased plasma volume.[3] On the basis of this study the plasma volume of the room temperature ECR was pushed a new intermediate size region, between the existing small sources such as MINIMAFIOS,[4] and large sources, such a ECREVIS in Louvain.[5] These concepts were combined in one design in December 1984. Construction began in January 1985, with first plasma produced in July 1985 and first analyzed beam in August 1985. In the fall of 1985 the initial operation and development of the source proceeded in parallel with the assembly of the beam transport line to the K500 cyclotron. Initially, nitrogen, oxygen and argon were studied. The most extensive development work however was done for krypton ion production. A series of studies of the coupling between the two stages led to a relatively high pressure mode with Kr^{19+} above the 1 eμA level. First beam was injected into the K500 cyclotron in March 1986, with the commencement of nuclear physics experiments shortly thereafter. Subsequently it was found that high charge state light ions require a different tune than krypton; instead a very low pressure plasma is required. Recently both fully stripped nitrogen and oxygen have been accelerated and extracted from the K500 cyclotron.

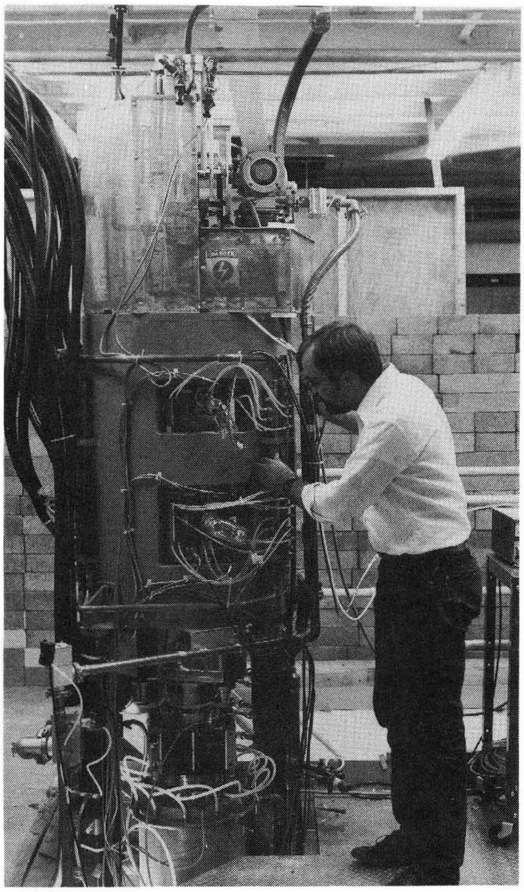

Fig. 1--The NSCL room temperature ECR ion source.

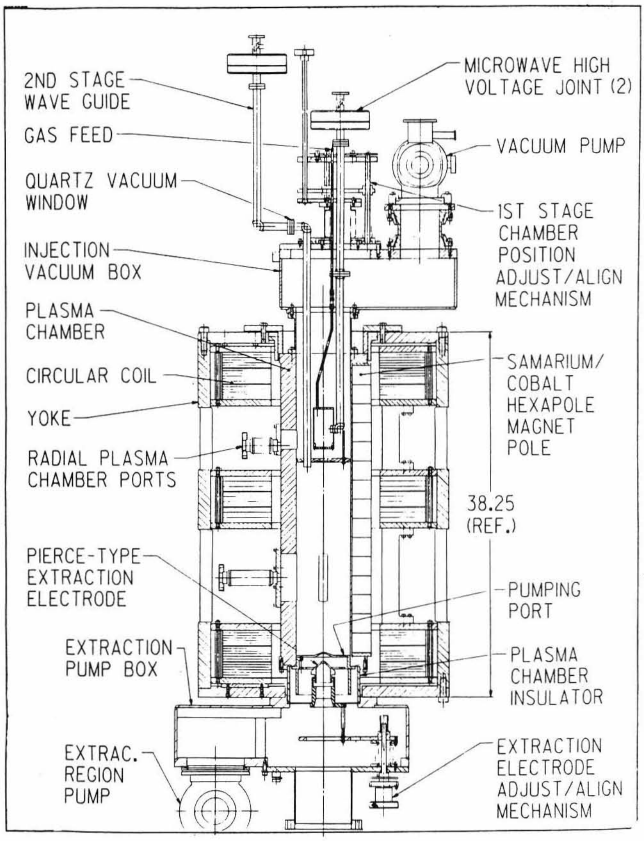

Fig. 2.--A schematic diagram showing the main features of the RT-ECR ion source.

In this report, the design and present performance of the RT-ECR will be presented. (A report on the initial development and performance was made at the Julich ECR Workshop in May, 1986.[6]) In addition, two new sources are under development at NSCL, and brief reports will be made here on each of these. A compact single stage source for light ions and metals, CP-ECR, is now under construction. The second, a superconducting source having a magnet capable of ECR operation a high as 30GHz, the SC-ECR project, is now in the design phase.

RT-ECR SOURCE DESIGN

Figures 1 and 2 show the main features of the ion source. The operating microwave frequency of both stages is 6.4 GHz. This was chosen on the basis of there being no large difference in the performances of the source operating in the range of 5 - 10 GHz,[7-10] so that the low cost, high output power Varian transmitter at 6.4 GHz could then be chosen on the basis of economy. The first stage is a small chamber, situated inside the main plasma chamber, into which microwave power and gas is fed. The second stage microwave power can be fed either axially from the source top, as shown in Figure 2, or through a radial second stage port (not shown).

The ion source is intermediate is size, having a plasma chamber bore of 14 cm and a main stage length of 41 cm. Yet overall the ion source is very compact. This is due to the fact that the ion source design includes a cylindrical iron return yoke, which simplifies the design in many respects. One third of the axial magnetic field comes from the return yoke. This reduces the operating requirements of the circular coils substantially over air-core designs. There are nine circular coils in three groups of three. The coils can be operated as high as 350 A, but the nominal current for 6.4 GHz operation is only 190 A in each coil. (This wide range gives a very good capability for tailoring the shape of the magnetic field which was found to be very useful in the initial source tuning.) The nominal power consumption in the circular coils is only 24 kW. The machined inner surface of the yoke provides the coil alignment and the basic mechanical support for the ion source structure. This simple mechanical design allowed for the relatively fast assembly of the source and significantly lowered the source cost. The RT-ECR was built for 140 k$ in purchases and 7900 hours of design, fabrication and assembly man-power.

A samarium cobalt hexapole magnet provides the radial component of the magnetic bottle. The hexapole magnet has been extended axially to cover the first stage region in addition to the normal second stage application. This means also that the first stage has the same magnetic topology as the second: the first stage ECR zone is closed and the plasma has a triangular fluted structure. The resulting hexapole magnet is large, given the diameter of the plasma chamber and the length required to span both stages. The hexapole was constructed from 360 individually magnetized pieces, that were mixed according to strength on order to obtain a hexapole with azimuthal and axial strength variations of only a few tenths of a percent.

RT-ECR Operation and Performance

The ion source performance to date for gases is summarized in Table 1, while the performance for solid feed materials is summarized in Table 2.

The main mode of operation has a strong coupling of the two stages. The source tuning for heavier ions, say argon and higher, is different than for neon and lighter elements. For example, for krypton, the ion source is operated on oxygen at relatively high pressure in both the first and second stages, with only enough krypton fed into the first stage to optimize the high charge states. The high pressure in the second stage is obtained from the use of a 2 cm aperture in the baffle between the two stages. The first stage O^{1+} ion output was often nearly 100 microamperes under these conditions. High charge state argon tuning is similar, though we have not had much experience with argon in this source. This mode also worked well for iodine, where a mixture of 90% oxygen and 10% hydrogen iodine was fed into the first stage--though the feeding of hydrogen iodine into the first stage resulted in substantial corrosion to the first stage chamber walls.

Table 1. DC ECR Performance for gaseous feed materials, Sept 1986.

	^{12}C	^{14}N	^{16}O	^{20}Ne	^{40}Ar	^{86}Kr	^{127}I†
4	25.5	>100	87.	67.	19.		
5	5.6	68.	61.	50.5	*		
6	*	25.5	52.	41.1	42.		
7		*	12.2	16.5	55.		
8			*	5.0	94.		
9				1.0	44.		
10				*	*	23.	
11					7.0	*	
12					1.6	23.3	
13					0.10†	29.0	1.7
14					0.10†	29.0	2.3
15						23.2	3.0
16						*	*
17						6.8	2.7
18						3.2	*
19						1.4†	2.5
20						0.4†	2.3
21							2.1
22							1.8
23							1.0
24							*
25							.035††

Conditions: 10 kV ext. voltage; 8 mm ext. aperture.
† Vertical emittance decreased by 2.0 to increase resolution.
†† Vertical emittance decreased by 6.0 to increase resolution.
* Mixed M/Q

This high pressure mode does not work well for highly charged light ion production. While oxygen was used as a support gas for heavy ions, helium was preferred for light ions, but never more than 50 % of the total gas feed was helium. In addition, the second stage must be operated at a half-order of magnitude lower pressure. This was obtained by reducing the gas feed and also going to a 0.6 cm aperture in the baffle plate. With these conditions, the analysed output of

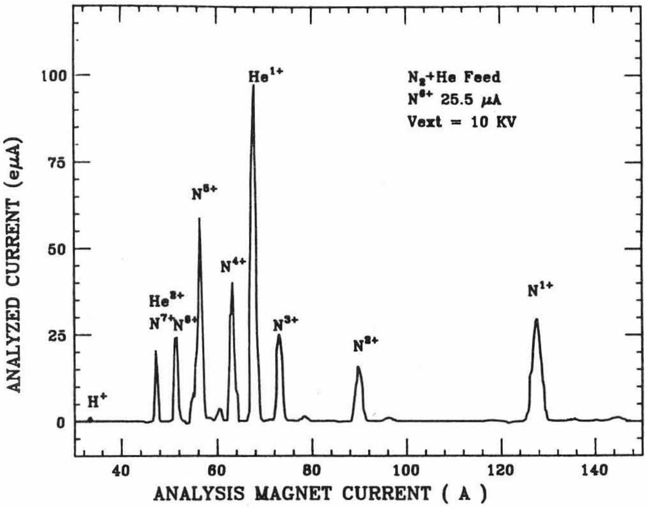

Fig. 3.--High charge state nitrogen ion production in the RT-ECR.

light ions is sharply peaked at high charge states. For example, the spectrum corresponding to the 25.5 eμA N^{6+} entry in Table 1 is shown in Figure 3.

Solid Feed Ion Production

We are just beginning to develop beams of ions from solids. The first solid material used to form a beam in the RT-ECR was produced by a high pressure nitrogen plasma removing copper from the baffle plate surfaces. Charge states up to 17+ of both copper isotopes were identified in the source output. The conditions for this effect were reproducible.

A system for more accurately introducing solid feed materials into the second stage has now been built. The device consists of a linear motion feed-thru attached to a high vacuum airlock. The material is fed through a radial port at the middle of the second stage between hex poles. Using tantalum wire with this system, a spectrum of charge states from 5+ to 29+ with the peak charge state 3.6 eμA of Ta^{18+} was easily produced.

Lithium and fluorine atoms were produced by this same method by hanging a LiF crystal from a tantalum wire and allowing the second stage to slowly evaporate the material. Beam currents of 10 eμA of $^{7}Li^{1+}$ and 0.5 eμA of $^{7}Li^{2+}$ were produced at low microwave feed power over a 50 hour run using a small crystal, while the higher currents shown in Table 2 were obtained at higher microwave power over a shorter interval. As a by-product of lithium ion production, beams of fluorine ions were also produced.

Evolution of the First Stage Design

The RT-ECR source, as mentioned previously, has a minimum B magnetic field in the first stage region which results in a closed ECR zone inside the first stage chamber approximately the size of an index finger. At low feed pressure, high charge states up to a few nanoamperes of Ar^{8+} have been observed from the first stage. Since it does work a low pressures, it is a good match to a source with a pumping scheme like the RT-ECR.

The original first stage chamber, shown in Figure 2, in not now in use. Instead, a larger chamber has been installed to increase the microwave coupling efficiency and move the ECR zone away from the inside chamber walls. The disadvantage of going to the larger first stage chamber is that it requires a radial second stage microwave feed, the larger chamber taking space originally occupied by the axial second stage microwave feed. The successful operation with radial second stage feel required two iterations-- microwave power traveling towards the second stage must in the radial direction pass through an ECR zone on the back side of the hexapole magnet without a plasma forming inside the waveguide. The initial configuration did allow a plasma in the waveguide, it was found to be intrinsically unstable; in the second configuration the external ECR zone was crossed at atmospheric pressure by putting the window inside the radius if the external zone, no plasma forms and the radial feed works.

Table 2. DC ECR Performance for solid feed materials, Sept. 1986.

	^{7}Li	^{19}F	^{63}Cu†	^{65}Cu†	^{181}Ta
1	14.5	5.0			
2	14.5	5.0			
3		8.0			
4		14.0			
5		12.0			
6		7.0			
7		2.0			
8		0.1			
9			*	0.07	0.4
10					*
11			0.47	0.17	0.5
12			0.46	0.20	1.0
13			0.37	0.24	*
14			0.20	*	1.6
15			0.12	0.05	*
16			0.06	0.03	3.1
17			0.02	0.01	3.6
18					3.6
19					3.1
20					2.7
21					2.0
24					0.6
27					0.11
29					0.08

Conditions: 10 kV ext. voltage; 8 mm ext. aperture.

† Analysis slits set to 5 mm x 5 mm to resolve peaks -this typically results in a factor of 5 reduction in current.

It appears that the larger first stage chamber, with improved microwave coupling (the reflected power is near zero), and reduced sensitivity to magnetic field adjustments changing the ECR surface, allows stable operation at lower pressure, and that high charge state light ions greatly benefit from this lower pressure. The present overall configuration of the ion source has the larger first stage chamber and radial second stage microwave feed--coupled with lower overall operating pressures in the two stages. With this configuration, significant increases in all highly charged light ions have been observed during the past three months leading up to this conference. As time and the K500 operating schedule permits, these results are being extended to other species.

The CP-ECR Project

The construction of a compact single stage ECR ion source, CP-ECR, is now underway. This device, shown in Figure 4, is designed to complement the other ECR sources at NSCL by providing beams of materials that would contaminate the other sources and by freeing the other sources for development when the cyclotrons only need low and intermediate charge state beams. The primary goals of this project are to build a compact, low cost, highly reliable alternate ECR source that could easily be cleaned and maintained.

Since the research program at NSCL will require metallic beams which could result in high contamination, particularly if supplied to the ECR by a metal vapor oven, it was decided to instead design a source for production of metallic beams such as lithium and calcium. Further motivation for the compact source concept is derived from a single stage mode or operation found for the source RT-ECR during early operation.[11] In this mode, the first stage field is well above the level required for an ECR resonance there. This high field inhibits first stage operation but seems to improve second stage confinement. As a result, low currents of high charge state nitrogen, oxygen and argon ions could be tuned from the source with only one stage operation. Very high currents of low and intermediate charge states were also obtained. The CP-ECR field design and operating plan are based on this one stage mode of operation of the RT-ECR. By using proven designs and a simplified mode of operation,the whole source, including an integral metal vapor oven and the analysis magnets, will cost less than 60 k$. This source should begin operation at NSCL at the beginning of 1987.

The SC-ECR Project

The improvements in performance of the existing ECR sources have come from patient optimization of the source design and operation. The only design philosophy that has resulted in significant increases in intensity with charge stage over and above the usual

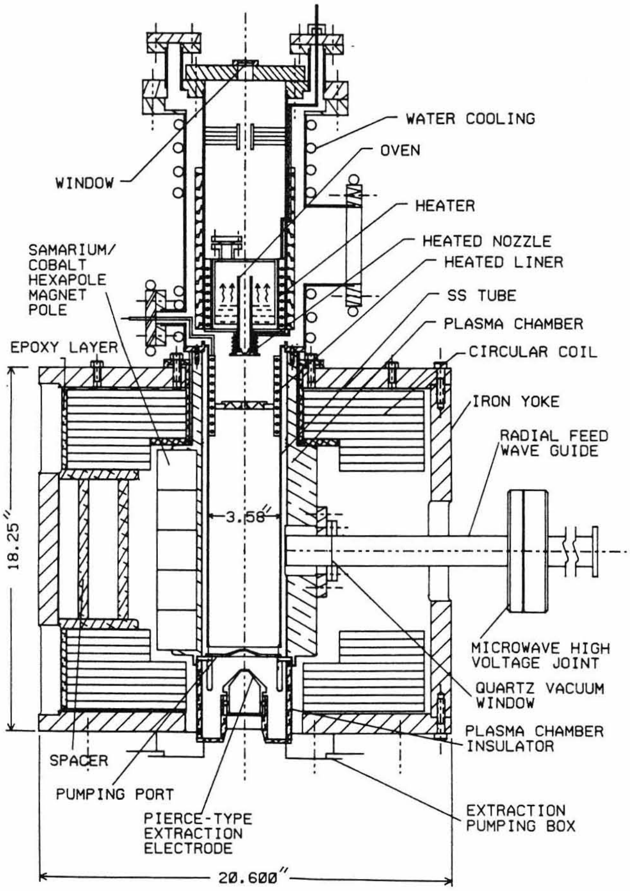

Fig. 4.--The compact CP-ECR ion source.

optimization has been the recent successes with the high frequency ECR sources in Grenoble.[12,13] The performance of these sources has scaled with the increase in the allowed cut-off frequency at the higher operating frequency. There is a need to extend these results to the continuous output regime (the Grenoble sources were pulsed to avoid microwave transmission and plasma coupling difficulties), and to extend these results to higher frequencies. The microwave component of source project appears to be the main difficulty, but a test magnet capable of operating at high magnetic fields could be built now and would be useful in the mean time for microwave heating and confinement studies at lower frequencies.

Figure 5 shows the design of a superconducting ECR ion source with a continuously adjustable operating range of al least 5-30 GHz. This design follows the general features of the RT-ECR ion source. The main difference is that the radial magnetic field in this case is provided by an independently tunable superconducting hexapole coil instead of the permanent magnet hexapole of the RT-ECR. The design is also consistent with the experience gained in the Laboratory with the development of superconducting magnet systems of similar design.[14,15] The coils will be composed of random-wound, epoxy-impregnated, NbTi wires. Quench characteristics and coil forces have been studied and indicate that this is sufficiently rugged coil design.

We propose to build the superconducting magnet and assemble a configuration that will operate at 6.4 GHz (there exists spare microwave capacity to operate three sources at this frequency with the existing NSCL transmitters). A second ion source at 6.4 GHZ would greatly speed the development of new beams in parallel with the execution of the nuclear physics program. At the same time the magnet will be tested at field levels required for 30 GHz operation.

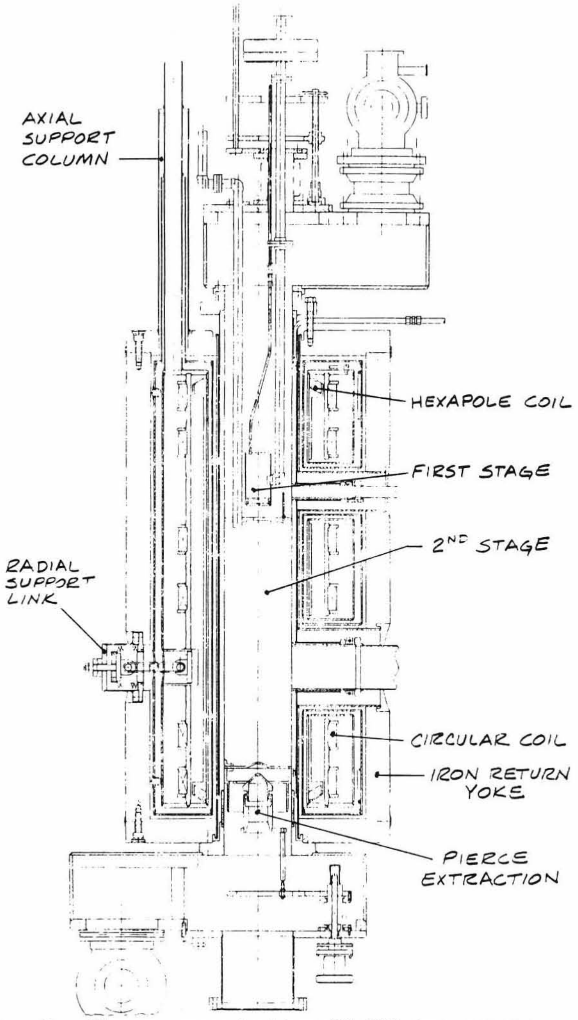

Fig. 5.--The superconducting SC-ECR ion source.

As higher frequency transmitters become available, it will be possible to push the operating frequency of this source higher.

References

1. T.A. Antaya, H.G. Blosser and R.J. Burleigh, Proc. 10th Int. Conf. on Cyclotrons and their Appli., East Lansing, (1984) 184.
2. T.A. Antaya, unpublished (1984).
3. T.A. Antaya and C.M. Lyneis, Proc. 6th Int. Workshop on the ECR Ion Source, Berkeley (1985) 63.
4. R. Geller, et. al., Proc. 6th Int. Workshop on the ECR Ion Source, Berkeley (1985) 1.
5. Y. Jongen, et.al., Proc. 6th Int. Workshop on the ECR Ion Source, Berkeley (1985) 28.
6. T.A. Antaya and Z.Q. Xie, Proc. 7th Int Workshop on ECR Ion Sources, Julich (1986) to be published.
7. C.M. Lyneis, Proc. 7th Int Workshop on ECR Ion Sources, Julich (1986) to be published.
8. A. Chevalier and Y. Jongen, Proc. 7th Int Workshop on ECR Ion Sources, Julich (1986) to be published.
9. F. Meyer, Proc. 7th Int Workshop on ECR Ion Sources, Julich (1986) to be published.
10. R. Geller and B. Jacquot, Proc. 7th Int Workshop on ECR Ion Sources, Julich (1986) to be published.
11. ibid., ref 6.
12. ibid., ref. 4.
13. ibid., ref. 10.
14. J.C. DeKamp, et.al., IEEE Trans. Mag. Mag 21 (1896) 990.
15. A.F. Zeller, et.al., Proc. 9th Int. Conf. Magnet Tech., Zurich, Switz. (1985) 167.