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THE ADVANCED SUPERCONDUCTING ECR PROJECT AT NSCL

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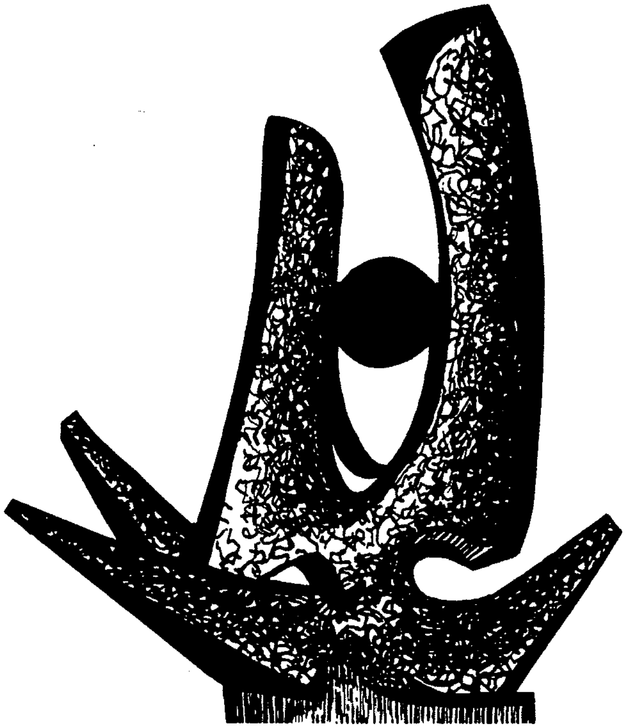

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Design studies for a high frequency ECR source were initiated at NSCL in 1986, and construction was approved by the NSF in May 1987. The design is now substantially complete, several subsystems are under construction, and hexapole coil test winding is now in progress. The motivation for this source is two-fold. First, to provide a single ECR coil set for operation over a broad range of frequencies and operating modes. Experience with the relatively wide range of field variation possible in the 6.4 GHz RT-ECR has been extremely important in the production of highly charged ions. Second, to set the upper field limit to that necessary for first harmonic operation at 30-35 GHz, in order to continue the frequency scaling studies that have reached 18 GHz operation at C.E.N. in Grenoble. The SC-ECR design follows the general principles of the RT-ECR, but the magnetic field is obtained with a full superconducting coil set (6 solenoids & hexapole), that gives the same field profile over a frequency range of 5-35 GHz. Initial operation at 6.4 GHz is expected in 1988.

MOTIVATION

The production of multiply-charged ions in an ECR source generally proceeds sequentially from a few electrons removed to many electrons removed, though the step size is not necessarily one electron. The sequential character of the ionization process can most easily be seen by pulsing the microwave feed power. Due to this sequential character, we require higher average ion lifetimes in the plasma to produce highly charged ions.

With successive electron impact ionization, the jth-electron removal rate term R_j has dependences on the electron density n_e, the electron velocity v_e, and the cross-section σ_j for the relevant ionization channel,

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$$R_j \propto n_e v_e \sigma_j \qquad (1)$$

It should be noted that the ionization cross-section is also a function of the electron velocity, so boosting the electron velocity to raise the ionization rate is not as effective as boosting the plasma density, since the cross-section declines with electron velocities that are much greater than those corresponding to the binding energy of orbital electrons. There is then strong motivation for raising the plasma density.

In any case, the acceleration of electrons to energies comparable to tightly bound orbital electrons is quite straight-forward in an ECR source. Since such energetic electrons are available, our requirements for the production of multiply-charged ions reduces to something akin to maximizing the product of the plasma density (n_e) and the ion lifetime (τ_i), $n_e\tau_i$.

When the neutral gas feed rate is increased in a single cell ECR, like that shown in Fig. 1, the total extracted current, as read off the source bias supply, increases as the cell pressure increases. The total extracted current should be proportional to the confined plasma density, so we infer that raising the pressure in the cell raises the plasma density. The currents of ions also seems to depend directly on the pressure in a single cell ECR.[1] While the neutral pressure sets a range of possible plasma densities, the ionization process, driven by microwave heating, sets the ratio of plasma density to neutral density. This ratio may be as high as one hundred.[2] (This means that the measured pressure is lower with microwave heating than without microwave heating.) However, as the pressure is raised, the charge state distribution shifts towards higher currents of low charge ions, a process that can be realistically modeled. Fig. 2 shows argon charge state distributions for an ECR source computed with a modification of the West Code[3] by J. Booske at Maryland[4]. This calculation shows that overall densities are higher at higher pressure, due to the greater contribution from low charge ions, but the high charge state densities decline due to increased charge exchange. In a single cell ECR, increasing the plasma density decreases the ion lifetime in the plasma, and $n_e\tau_i$ remains about the same.

This difficulty has been overcome somewhat in two cell ECR sources, in which a high pressure, low average charge plasma, from the first cell,

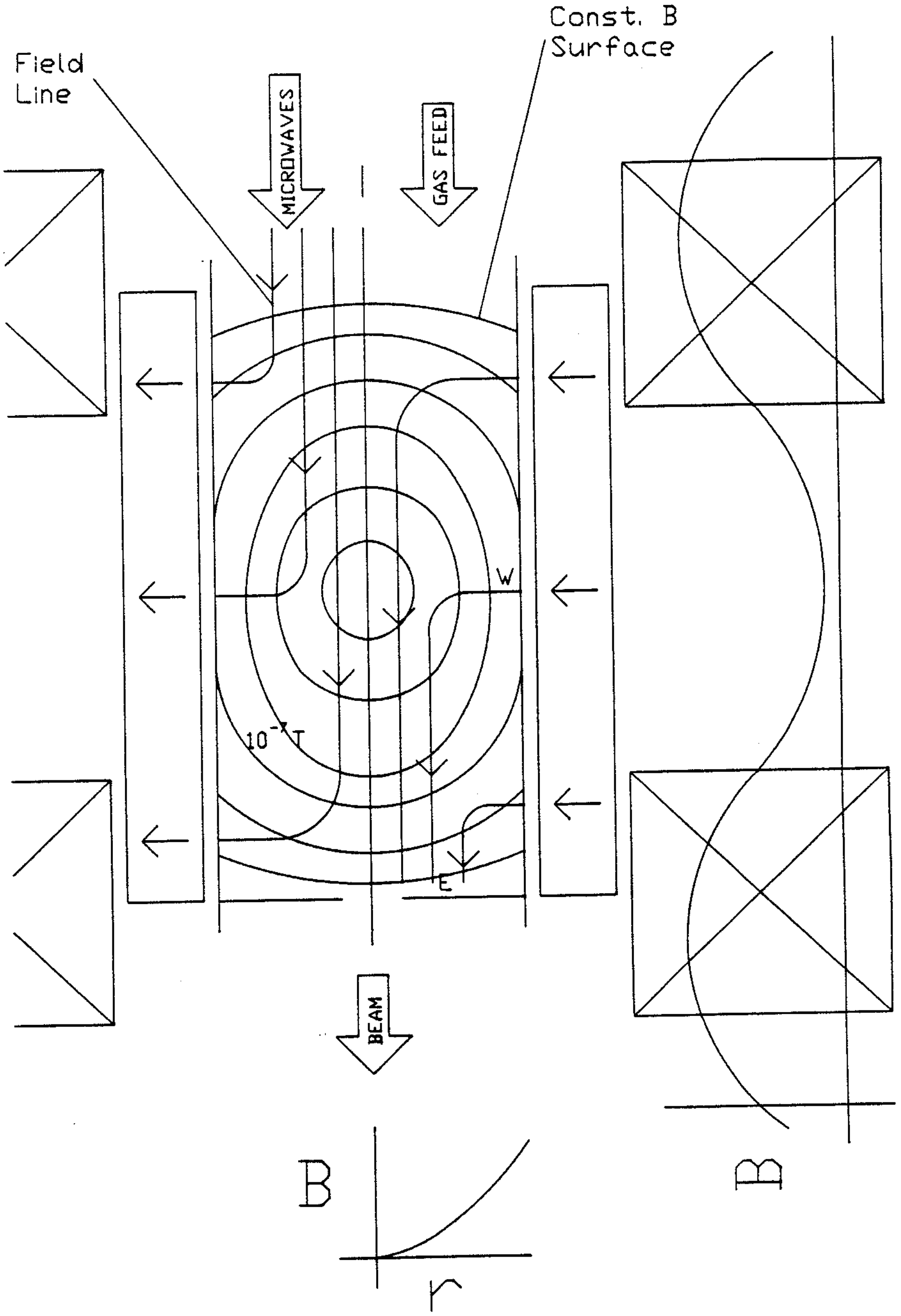

Fig. 1 -- For discussions in the text, an ECR cell consists of a minimum B magnetic geometry in a vacuum vessel that has microwave and gas feeds. In this case the minimum B field is obtained from a superposition of two mirror coils and a permanent magnet hexapole.

diffuses into a second cell across a pressure gradient. A high plasma density is then maintained in the second cell, at a much lower neutral pressure than in a single cell ECR, so that both the plasma density and

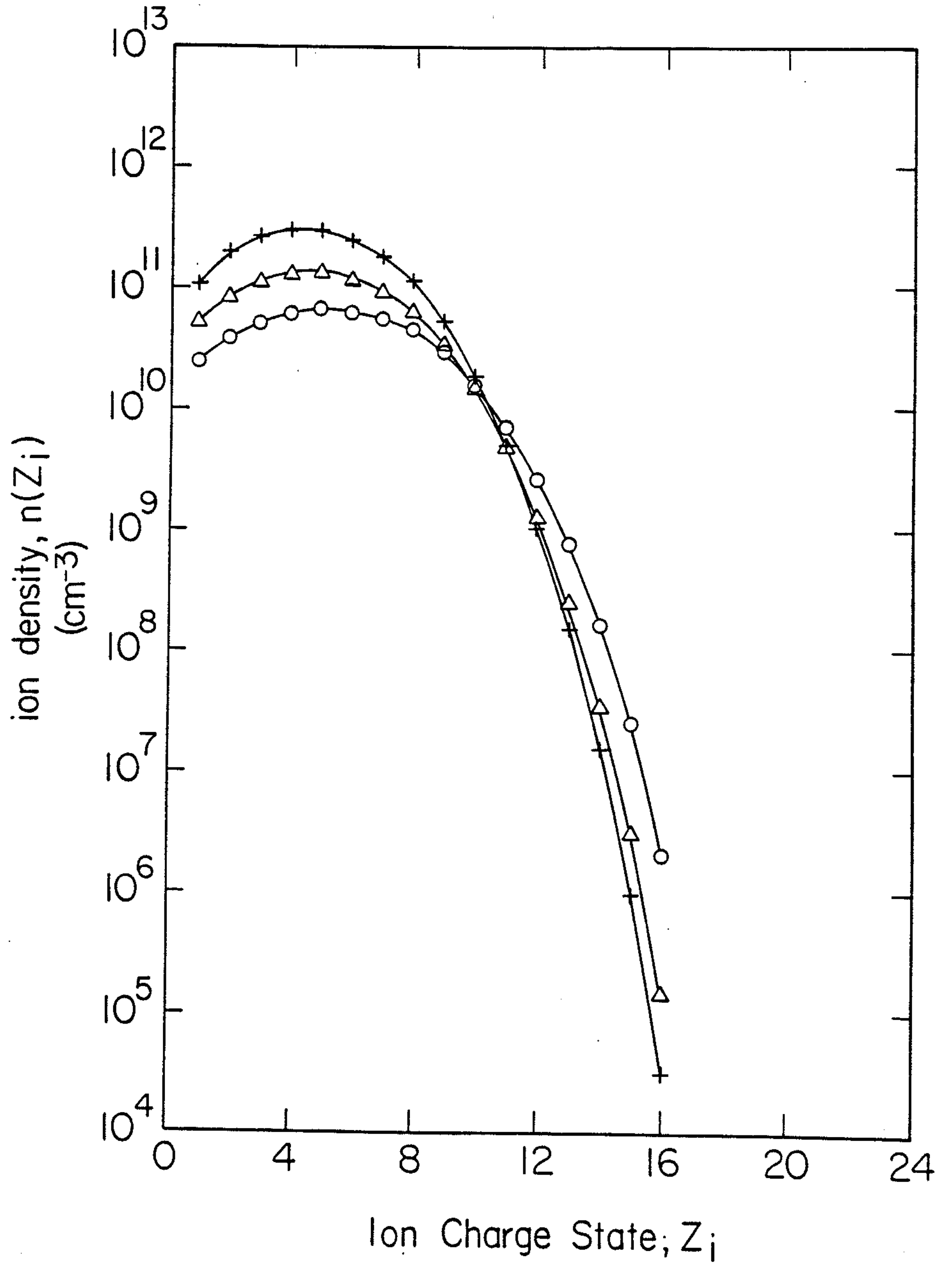

Fig. 2 -- A prediction for the equilibrium Argon charge state distribution in a single cell ECR source for pressures of 0.5×10^{-6} torr (circles), 1.0×10^{-6} torr (triangles), and 2.0×10^{-6} torr (crosses), taken from Ref. 4. In this calculation the plasma density was 10^{12} cm^{-3} and the not electron temperature was 10 keV.

average ion lifetime are higher. Since both the plasma density and ion lifetimes have been increased, the percentage of highly charge ions should also increase, and that is exactly what is observed.

At present, all ECR sources that produce very highly charged ions are two cell devices.[5-10] Since all of these sources have similar performance, the detailed nature of the first cell, which varies greatly, is probably not as important as simply having one. That these sources are all 2 cell ECRs does not preclude the possibility of finding a way to obtain similar performance in a single cell ECR source. For example, improved magnetic confinement at low pressure in a single cell ECR should have the same effect.

The development of two cell ECR sources, which has been extensive, has not lead to unlimited gains in intensity with charge. The optimum multipole order has been studied, with some subtleties, but no strong multipole order effects observed.[11-13] In ECR sources having a tunable multipole magnet, wall mirror strengths of the order of the axial mirror strengths are found to be optimal.[14-16] The surprising results in the small Caprice source suggests that more work should be done in the areas of microwave coupling and magnetic confinement.[17]

Since resonant microwave heating of electrons is the "plasma drive" in these devices, microwave injection into the plasma is of course essential under all operating conditions. Elementary theory predicts that an injected plane wave incident on a plasma, will be attenuated when the frequency (ω_{ecr}) of this wave becomes less than the plasma frequency (ω_p):

$$\omega_{ecr} < \omega_p \tag{3}$$

where, assuming a non-dielectric, non-magnetic and collisionless plasma,

$$\omega_p^2 = 4\pi e^2 n_e / m_e \tag{4}$$

The cut off plasma density, for microwave heated plasma, occurs when

$$\omega_{ecr} = \omega_p \tag{5}$$

for which we obtain

$$n_{e,max} = (m_e / 4\pi e^2)\omega_{ecr}^2 \qquad (6)$$

If this limit on the density is valid, then of course $n_e\tau_i$ is also limited, and there is here, a very rare instance of the prediction of limiting phenomena in a positive ion source.

By 1984, two stage ECR sources had been built over the frequency range of 5-10 GHz, which would give a factor of four difference in the maximum allowed plasma density. However, the maximum charges and intensities obtained in the existing sources over this range of frequencies were not significantly different, suggesting perhaps that the plasma cut off frequency was not an important design criteria. There were several possible explanations for this lack of a frequency dependence on ionization process. First, the simplifying assumptions in this rather elementary derivation may not be appropriate for an ECR ion source. Second, if the theory did in fact apply, perhaps a factor of four difference in the maximum density was not a large enough change to see a qualitative effect on ionization. Third, if the theory did apply, and a factor of four difference was significant, it would be of no use if the operating sources were not operating at the plasma density limit.

Since then, the existence of a frequency dependence on the maximum density, and the importance of raising the frequency to raise the density and ionization rates, have been confirmed in a set of studies at 10, 16.6 and 18 GHz in Grenoble.[18-20] To summarize those results, the total extracted current increased by the ratio of the square of the ECR frequency, and the average charge state also increased. The scaling of the total extracted current with frequency indirectly confirms the plasma density scaling with frequency. The increase in the average charge, due to large increases in intensity with increasing charge, indirectly confirms that the ionization rate increased with the increasing density.

These experiments were not without some difficulties. First, the same strength hexapole was used for operation at all three frequencies, and this may not have been optimal. Second, the source operation was pulsed, to minimize the stress on the high frequency klystron amplifiers. While there is no guarantee that similar results will hold in cw frequency scaling tests, there is the suggestion in long pulse operation (0.5 sce/sec) of the

Grenoble source at 18 GHz, in which 70 eμA of S^{2+} has been obtained, that cw operation at high frequency will be similar. Certainly the results suggest that both cw scaling studies in this frequency regime, as well as further studies at higher frequency, are warranted.

THE SC-ECR DESIGN CONCEPT

NSCL has undertaken to design and build the magnet for variable frequency ECR ion source. The first harmonic frequency range will be 5-35 GHz. The source design includes a tunable hexapole magnet. With such a field range, this magnet can be used at fixed frequency for novel microwave coupling and magnetic confinement studies. It will also be possible to study frequency scaling in a single geometry, in which the magnetic topology can be optimized at each frequency. The upper limit for first harmonic operation was set to reach existing gyrotron microwave generators at 28-35 GHz. In order to reach this regime, a full superconducting coil set has been chosen. The magnet will not operate in persistent mode. The coils will be "live" for dynamical tuning of the magnetic field during source operation. It may be possible to operate the cyrogenics system in a batch feed mode, to allow operation in a site where a helium refrigerator is not available.

In order to minimize the development time the design parameters of the NSCL RT-ECR has been adopted. The SC-ECR will have a two minimum B topology, with a main stage length and bore of 50 cm and 14 cm respectively. The overall source configuration is shown in Fig. 3. The source orientation is vertical, with an integral iron return yoke as the outside wall of the cryostat and also the main structural support. The vacuum design is the same as the RT-ECR, where the low actual pumping speeds to the two stages minimizes mass consumption. The large bore will allow an independently tunable first stage (as shown), or alternatively a single feed with internal coupling, which would be more appropriate at higher frequencies where single transmitter operation is likely.

The magnetic field needs be adjustable over a wide range. Figs. 4-5 show the axial and radial field profiles for operation from 6-30 GHz. The yoke does not saturate at the 30 GHz operating level, so that the field

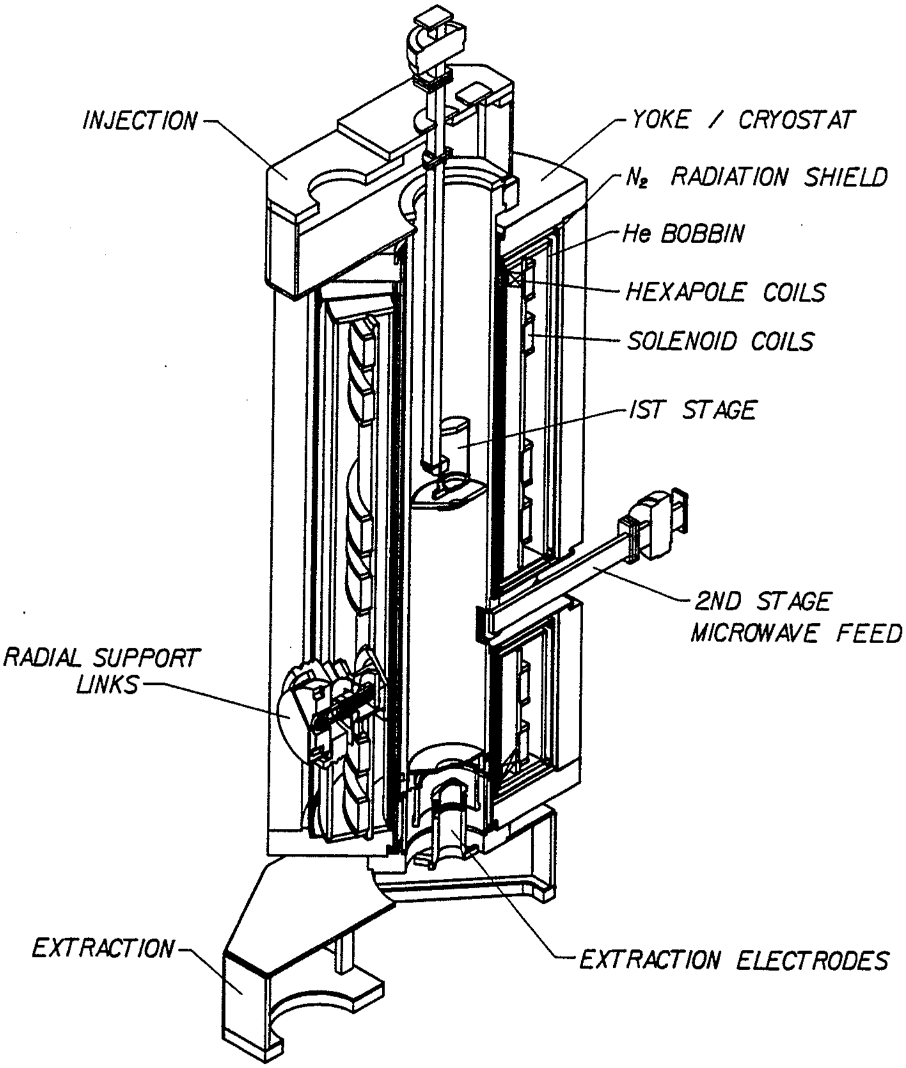

Fig. 3 -- The SC-ECR ion source design concept is shown.

profile scales linearly with coil excitation over the entire operating range.

PRESENT STATUS OF THE SC-ECR PROJECT

At the present time the main elements of the magnet design are complete, and we have begun to wind prototype superconducting coils for the hexapole magnet. Correct single coil testing, followed by test operation of the 6-coil hexapole, first without, and then with the solenoid coils, will be performed in a test dewar before the magnet design is finalized. The components necessary to complete the magnet as an ion source will be fabricated in parallel with the magnet testing, so that source operation should follow shortly after full operation of the magnet. Initial

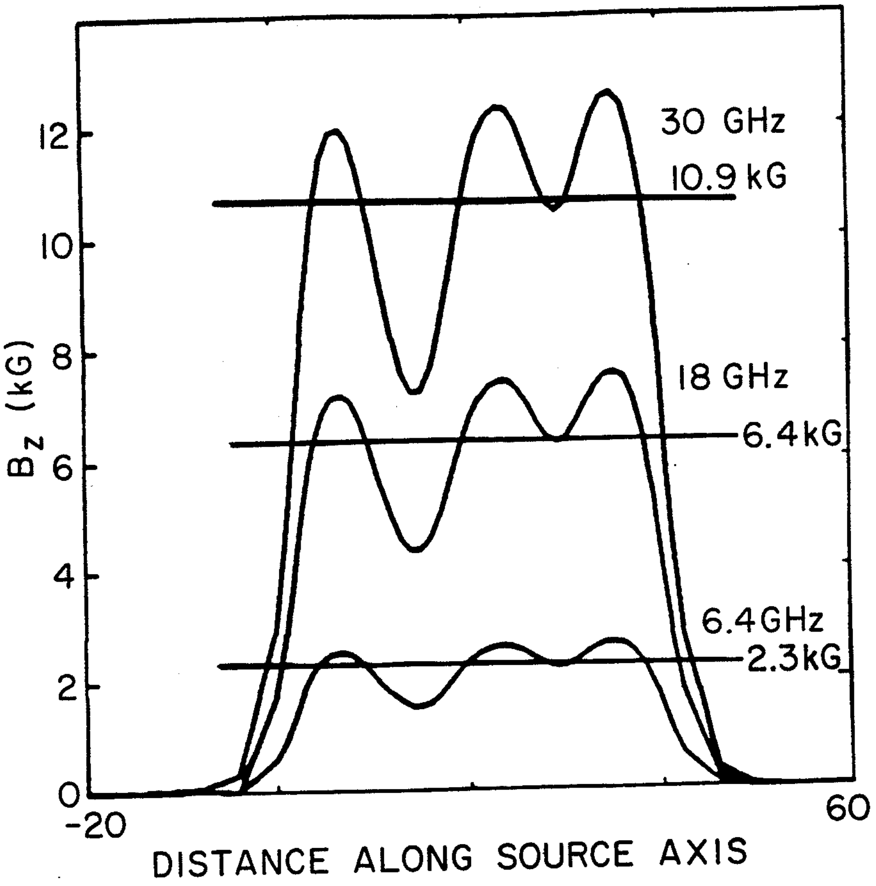

Fig. 4 -- The axial field profile of the SC-ECR is shown for resonance frequencies of 6.4, 18 and 30 GHz.

operation will occur at 6.4 GHz, using existing transmitters. At 6.4 GHz the operation and performance should be equivalent to the RT-ECR. At this frequency, it will also be possible to substantially alter the magnetic field, make qualitative changes in the magnetic confinement and microwave coupling over a broad range. The next step in frequency is likely to be to 14 GHz, by conversion of a 6.4 GHz transmitter. This converted transmitter may be available early in the operation of the SC-ECR.

Beyond 14 GHz, a specific frequency has not been selected, but it is likely that the step will be directly to the gyrotron oscillator band at 28-35 GHz, where high power may be available for not much more cost than high power klystrons at 16-18 GHz. There is some uncertainty with respect to the microwave power level at higher frequency. One analysis has suggested that the required cw power for optimum performance may be as high as 70 kW at 15 GHz,[21] but the experience with ISIS, operating at 14 GHz,

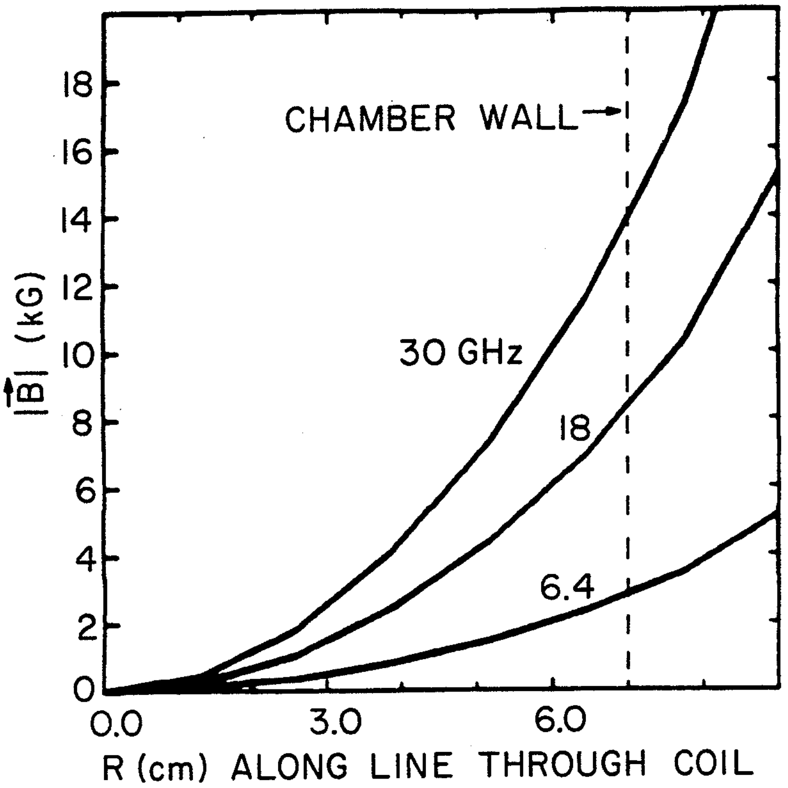

Fig. 5 -- The radial field profile of the SC-ECR is shown for resonance frequencies of 6.4, 18 and 30 GHz.

shows that very good performance was obtained at less that 4 kW of cw power.[22] A new power scaling law, presented by Geller,[23] has only a root dependence on the microwave frequency, and this law seems to give correct scaling for the frequency range from 10-18 GHz. We can use this law to estimate the power required for 30 GHz operation in the SC-ECR, assuming that the volume is the same as the RT-ECR, and that the average and peak charges go up a factor of two at 30 GHz over operation at 6.4 GHz. With these assumptions, the ratio of the power required at 30 GHz, to that of 6.4 GHz, would be,

$$\frac{P_{30}}{P_6} = \frac{\omega_{30}^{1/2}}{\omega_6^{1/2}} \; \frac{Q_{30}^2}{Q_6^2} \; \frac{\langle Q_{30}\rangle}{\langle Q_6\rangle} \; \frac{V_{30}}{V_6} \approx 2.5 \cdot 4 \cdot 2 \cdot 1 = 20 \qquad (6)$$

Assuming the present best performance of the RT-ECR at 6.4 GHz requires approximately 0.6 kW of microwave power, we obtain

$$P_{30} \approx (0.6\ \text{kW}) \cdot 20 = 12\ \text{kW} \qquad (7)$$

If this scaling is valid, then a generator with an output power level 20-30 kW at 30 GHz would provide sufficient margin.

REFERENCES

1. D.K. Bose and T.A. Antaya, Paper G.6 this conf.
2. R. Bardet, et. al., Nuclear Fusion 15(1975)865.
3. H.I. West, Calculation of Ion Charge-State Distribution in ECR Ion Sources, LLNL Report UCRL-53391 (1982).
4. J.H. Booske, et. al., to be submitted to J. Appl. Physics.
5. C.M. Lyneis, 7th Int. Workshop on ECR Sources, Julich, FRG (1986)1.
6. F.W. Meyer, 7th Int. Workshop on ECR Sources, Julich, FRG (1986)10.
7. R. Geller and B. Jacquot, 7th Int. Workshop on ECR Sources, Julich, FRG (1986)31.
8. H. Beuscher, 7th Int. Workshop on ECR Sources, Julich, FRG (1986)58.
9. T. Antaya and Z.Q. Xie, 7th Int. Workshop on ECR Sources, Julich, FRG (1986)72.
10. A. Chevalier and Y. Jongen, 7th Int. Workshop on ECR Sources, Julich, FRG (1986)266.
11. C.M. Lyneis and T.A. Antaya, 6th Int. Workshop on ECR Ion Sources, Berkeley, CA (1985)63.
12. F. Boug, et. al., 6th Int. Workshop on ECR Ion Sources, Berkeley, CA (1985)174.
13. E. Conard, et.. al., Paper B.1 this conf.
14. R. Geller, private comm.
15. H. Beuscher, private comm.
16. Y. Jongen, private comm.
17. B. Jacquot and R. Geller, paper F.1 this conf.
18. R. Geller, et. al., 6th Int. Workshop on ECR Ion Sources, Berkeley, CA (1985)1.
19. R. Geller, B. Jacquot and P. Sortais, NIM A243(1986)244.
20. R. Geller, et. al., 7th Int. Workshop on ECR Sources, Julich, FRG (1986)187.
21. V. Bechtold, L. Friedrich and F. Schulz, 10th Int. Conf. on Cyclotrons and Their Applications, IEEE 84CH1996-3 (1984)118.
22. H. Beuscher, Paper A.2 this conf.
23. R. Geller, et. al., Paper A.1 this conf.