

AN ELECTRON CYCLOTRON RESONANCE SOURCE FOR CYCLONE†

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Summary

An E.C.R. source is under construction at the cyclotron laboratory. Design goals of this heavy ion source include fully stripped ions up to oxygen, with intensities of several microamperes. Basic parameters of this two stage device are discussed, design characteristics are explained and the present status of the project is reported.

1. Introduction

The project of upgrading the heavy-ion performance of CYCLONE (the isochronous CYCLOTRON of the catholic university of LOUVAIN-la-NEUVE) started six years ago.

At that time, it was found that the best solution was to add to CYCLONE a $K = 70$ injector cyclotron.(1,2,3)

However, a long time was required to get the funding and when in 1977 the funding was obtained, it was no longer certain that the original technical solution was still the best one.

A new and careful comparison led to the conclusion that the Electron Cyclotron Resonance type of source, as developed by Geller et al. in Grenoble,(4,5,6,7) which had been originally disregarded because of its poor intensity, had meanwhile made substantial progress. As a matter of fact, beam performance of such a device, combined with an axial injection system, is comparable with that of the injector cyclotron. The operation is easier, the investment and operating costs are smaller.

It was finally decided, during 1977, to start the construction of such a device.

Table 1 summarizes the design goals of the source.

| Table 1 | | | | | | | | | |
|--|-------------------|-------------------|--------------------|--------------------|--|--|--|--|--|
| E.C.R. source design goals | | | | | | | | | |
| Conditions: Extraction Voltage: 20 kV | | | | | | | | | |
| Extraction Diameter: 14 mm | | | | | | | | | |
| Emittance: < 480 (π .mm.mrad) | | | | | | | | | |
| all intensities in electrical microamperes | | | | | | | | | |
| Carbon | Nitrogen | Oxygen | Neon | Argon | | | | | |
| 4 ⁺ 45 | 5 ⁺ 45 | 5 ⁺ 50 | 6 ⁺ 50 | 7 ⁺ 45 | | | | | |
| 5 ⁺ 12 | 6 ⁺ 10 | 6 ⁺ 25 | 7 ⁺ 25 | 8 ⁺ 45 | | | | | |
| 6 ⁺ 4 | 7 ⁺ 2 | 7 ⁺ 5 | 8 ⁺ 6 | 9 ⁺ 30 | | | | | |
| | | 8 ⁺ 1 | 9 ⁺ 0.5 | 10 ⁺ 15 | | | | | |
| | | | | 11 ⁺ 4 | | | | | |
| extracted currents from CYCLONE should be approx. 5% of those values | | | | | | | | | |

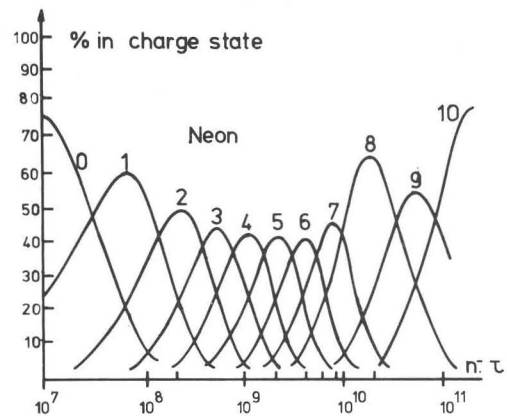
2. Principles of operation

The usual way to get high charge states in an ion source is to subject an atom to a flow of energetic electrons, causing successive ionizations.

In order to get the highest ionization cross section for a given charge state, the electron energy should be substantially (3 or 4 times) higher than the ionization threshold of this charge state. This is one of the factors limiting the classical P.I.G. source to quite low charge states. Ideally, to get very high charge states, the electron energy should lie in the tens of kilovolts region.

For high energy electrons, the ion charge state distribution in a plasma becomes only a function of the product of the electron density (n^-) times the time of interaction (τ).

Fig. 1 shows the charge state distribution in neon subjected to a flow of 10 kV e⁻, as a function of the $n^- \tau$ product.(7)



- Figure 1 -

It is evident from this figure that a $n^- \tau$ product of at least 10^{10} is required to reach the highest charge states.

The emittance and the energy spread of an ion source is proportional to the average energy of the positive ions in the plasma. Thus we need a way to heat the electrons of the plasma to energies of tens of kV, keeping the positive ions as cool as possible.

In this source, the selective heating of the electrons is done by feeding radiofrequency power at the Electron Cyclotron Resonance in a magnetic field.

Experiments show that, at the ECR frequency, feeding the microwave power into the plasma is quite easily done without special electrodes and a zero-reflected-power condition can be found in various geometries. However, a plasma acts as a high-pass filter for microwaves, with a cut-off frequency related to the electron density by the following equation:

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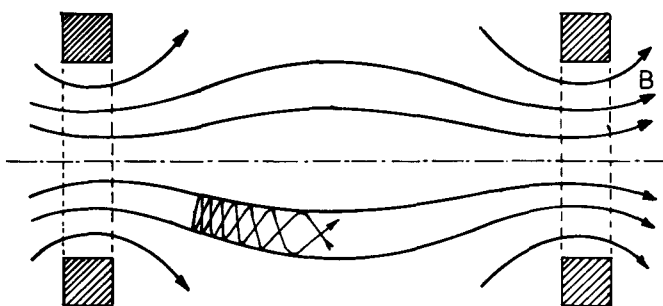
$$\omega_p = \sqrt{\frac{n^- e^2}{\epsilon_0 m}}$$

where

ω_p is $2 \times \pi$ x the microwave frequency, n^- the electron density, e and m respectively the electron charge and mass and ϵ_0 the dielectric constant of vacuum.

This gives a minimum frequency to heat a plasma of given density and, in turn, the ECR relation defines the corresponding magnetic field at the resonance place.

Plasma confinement is realized by a magnetic mirror configuration. Such a configuration can be easily realized with two solenoids (Fig. 2).



- Figure 2 -

However, such a simple geometry rapidly develops different kinds of plasma instabilities and to get the long containment times required for our application, the superposition of a hexapolar field is necessary. In such a mirror plus hexapole geometry, the absolute value of the magnetic field is always increasing from the center of the device toward the outside, whichever direction is considered (it is a so-called "minimum B" geometry).

To get a long ion lifetime in the plasma, it is not sufficient to reach a long magnetic confinement time. It is also necessary to keep the other losses at a low level.

Losses due to electron recapture may be neglected, the cross sections for electrons in the tens of kilovolts region being relatively small.

Charge exchange with neutrals, however, has very large cross sections, and to keep the losses down requires a very good vacuum in the source. To keep those losses at a negligible level the neutral density has to be in the region of 10^{-2} times the electron density, which is a condition difficult to meet in practice.

The unavoidable plasma losses mean that a permanent neutral gas generation will occur in the source. This together with the necessity for a high vacuum means that high pumping speeds and high conductances are required. Such a device has thus to be large in size.

Finally, initiating a plasma in a high vacuum region is extremely difficult. The easiest vacuum region to ionize a gas is 10^{-2} to 10^{-4} torr.

It is thus necessary to generate the plasma outside the high vacuum region of the source, in a first stage operating at 10^{-3} torr. The plasma is then brought to the confinement region by diffusion along a gradient of magnetic field. In the first stage, too, ionization is produced by microwave electron acceleration at the ECR. (In this stage, any other method could be considered; but, here again, ECR has the advantage of being electrodeless and therefore able to keep the positive ions as cold as possible.)

3. Description of the device

In the original prototype of Geller et al.⁽⁷⁾ the main confinement tank was 1 m long by 35 cm in diameter. The axial and hexapolar fields were realized by classical watercooled copper coils, which led to a power dissipation of 3 MW.

In order to reduce this dissipation, two alternative methods have been considered:

- 1) the use of the superconductivity: a preliminary design of the system including a cost evaluation, has been made by the C.E.A. in France, as well as by some private companies. The cost (approx. 0.55 M\$) is comparable to the cost of the normally-conducting system but has the advantage of being able, in a further step, to go to twice the original magnetic field. This would allow a 4-fold increase in n^- the electron density and, probably, a still larger improvement of the $n^- \tau$ product.
- 2) another way to realize the hexapolar field could be the use of Sm-Co permanent magnets, if some reduction of the performance is allowed: diameter reduced to 25 cm, hexapolar field at the tank reduced from 4.6 to 4.3 kG. With this method, the axial field is still realized by normal watercooled coils, but a careful design of the solenoids leads to a power dissipation of only 120 kW. This method is much cheaper, the total cost being almost one-half of the superconducting system. To check the validity of this method, a scale model, 25 cm long by 7 cm in diameter, is now under construction. Magnetic field mapping will take place end of October 1978 and plasma tests will be conducted, in cooperation with Geller et al., at the end of the year.

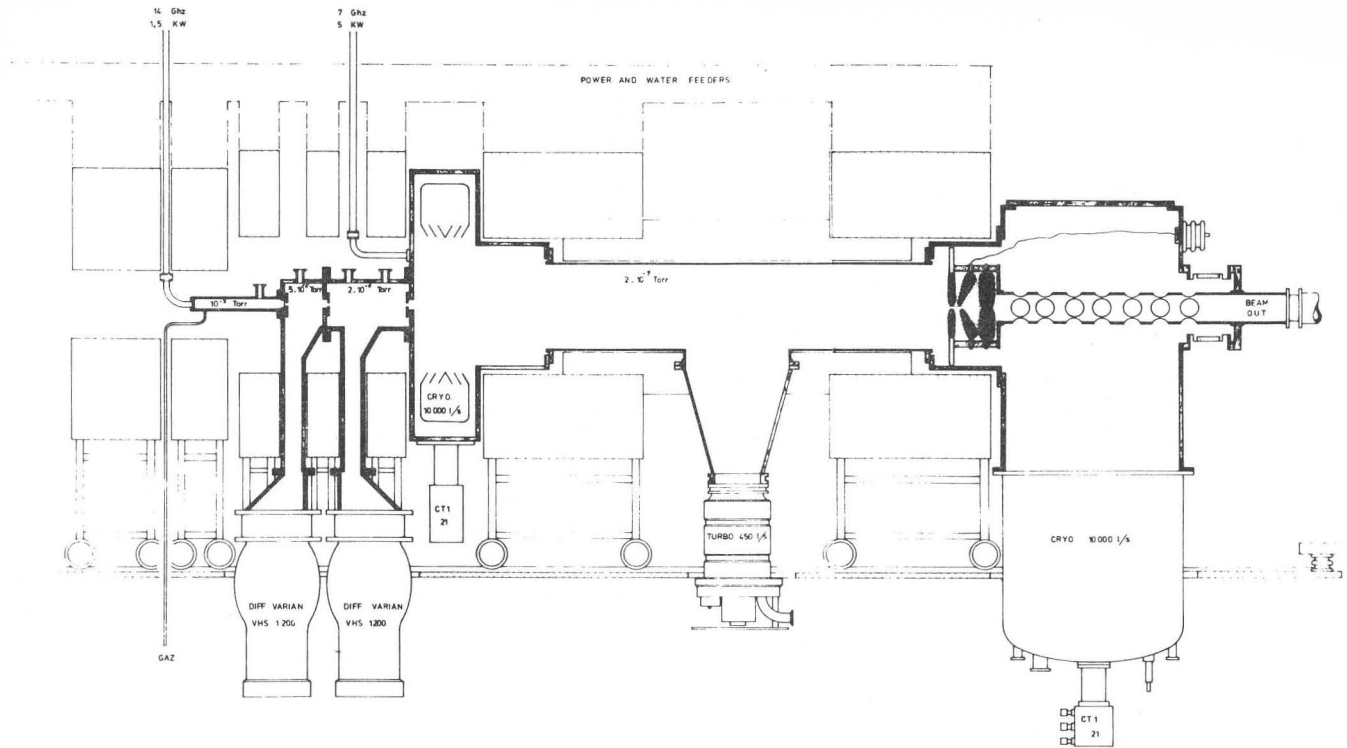
The final choice between those two solutions has not yet been made. The decision will be taken following the results of the measurements of the permanent-magnet model hexapole and the last industry proposals for the superconducting system.

The plasma injector (first stage) magnetic system will in any case be classical, using watercooled copper solenoids. Here again, a total power dissipation of approx. 120 kW is foreseen.

Vacuum pumping of the main tank will be made mainly by large cryogenic pumps, combined with a turbomolecular or a diffusion pump to evacuate the tank and to pump the light gases.

Special care shall be taken during the design to reach a base pressure of 2×10^{-8} torr, giving $2 - 5 \times 10^{-7}$ torr under normal load.

Differential pumping between the 10^{-3} torr plasma injector and the 10^{-7} torr high vacuum tank is done by conventional oil diffusion pumps.



- Figure 3 -

Table 2

| | Stage 1 | Stage 2 |
|--|---------------------------|-------------------------------------|
| | Plasma injector | Main confinement |
| f_{RF} | 14.3 GHz | 7.15 GHz |
| $P_{RF} (max)$ | 1.4 kW | 5 kW |
| B_{reson} | 5.20 kG | 2.60 kG |
| n^- | 10^{12} cm^{-3} | $2 \times 10^{11} \text{ cm}^{-3}$ |
| $\langle E^- \rangle$ | 50 - 100 eV | 10 - 40 keV |
| P | 10^{-3} Torr | $2 - 5 \times 10^{-7} \text{ Torr}$ |
| $\frac{n^-}{n_0}$ | 0.03 | 30 |
| $\langle \tau^+ (\% < \tau^-) \rangle$ | 10^{-5} sec | $1 - 5 \times 10^{-2} \text{ sec}$ |

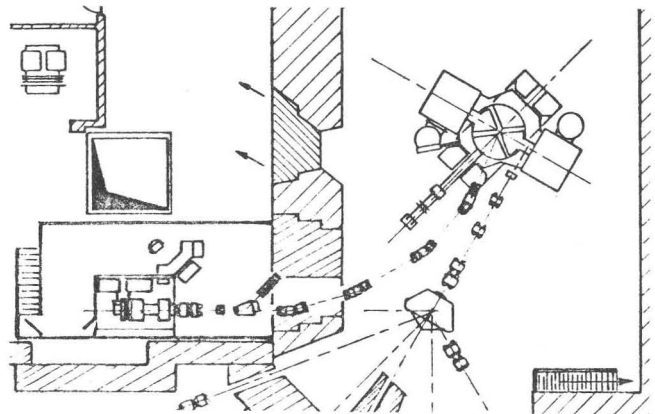
4. Injection into the cyclotron

The ECR source will be placed on a high voltage platform, located outside the cyclotron vault.

Injection voltage will be between 10 and 20 kV depending on cyclotron conditions. An accel.-decel. configuration is foreseen at the extraction of the source to get the best possible matching between source perveance and injection requirements. Maximum extraction voltage will be 40 kV.

The beam will be injected vertically along the axis of the cyclotron, coming from the top, and then deflected into the median plane by a pseudo-cylindrical deflector. The axial injection system will be a close copy of the one developed in Grenoble by Belmont et al. (8)

The horizontal beam line between the source and the top of the cyclotron will be approx. 15 m long. A good vacuum ($1 \times 10^{-7} \text{ Torr}$) together with large-aperture, low-aberration and quasi-achromatic optics will be required to keep a good transport efficiency. The optics of this line are under calculation now and Fig. 4 shows a possible solution.



- Figure 4 -

5. Status report

All components of the first stage (plasma injector) have been ordered and are under construction. The 5 x 10 meters supporting platform is being mounted at the time of this meeting and should be completed by October 1st, 1978. A 1.5 kW 14.3 GHz transmitter has been ordered from Varian and will be delivered in November 1978. Assembling and wiring of the first stage will take place early 1979, and the first plasma should be obtained around March 1979.

During the same period the hexapole scale model will be investigated.

It was decided to wait for the results of those investigations and the first results of the injector stage before placing the orders for the second stage.

Following schedule, the first ions from the two stage device should be obtained in 1980 and injected beam accelerated by the cyclotron in 1981.

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