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ELECTRON CYCLOTRON RESONANCE (E.C.R.) ION SOURCES

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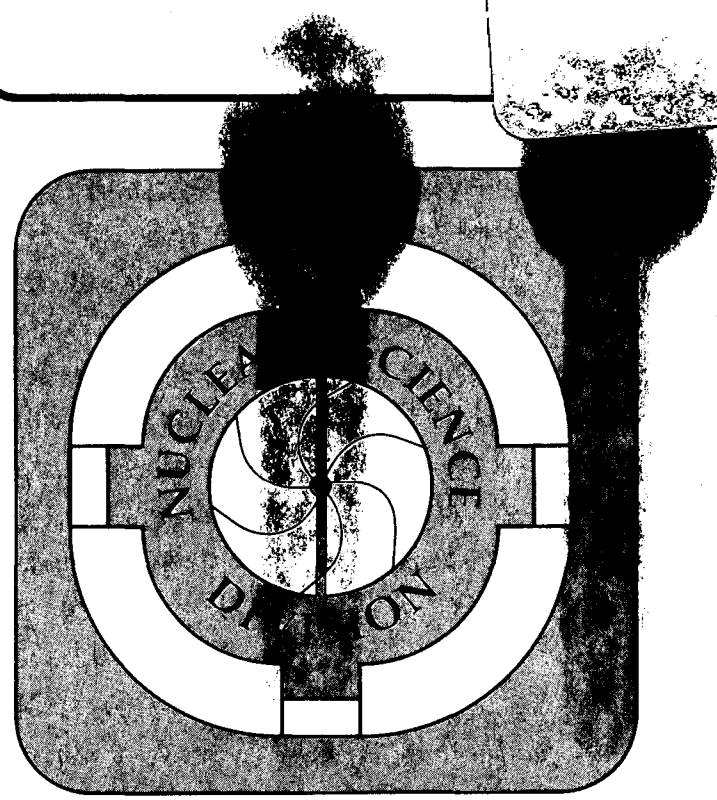
May 1984



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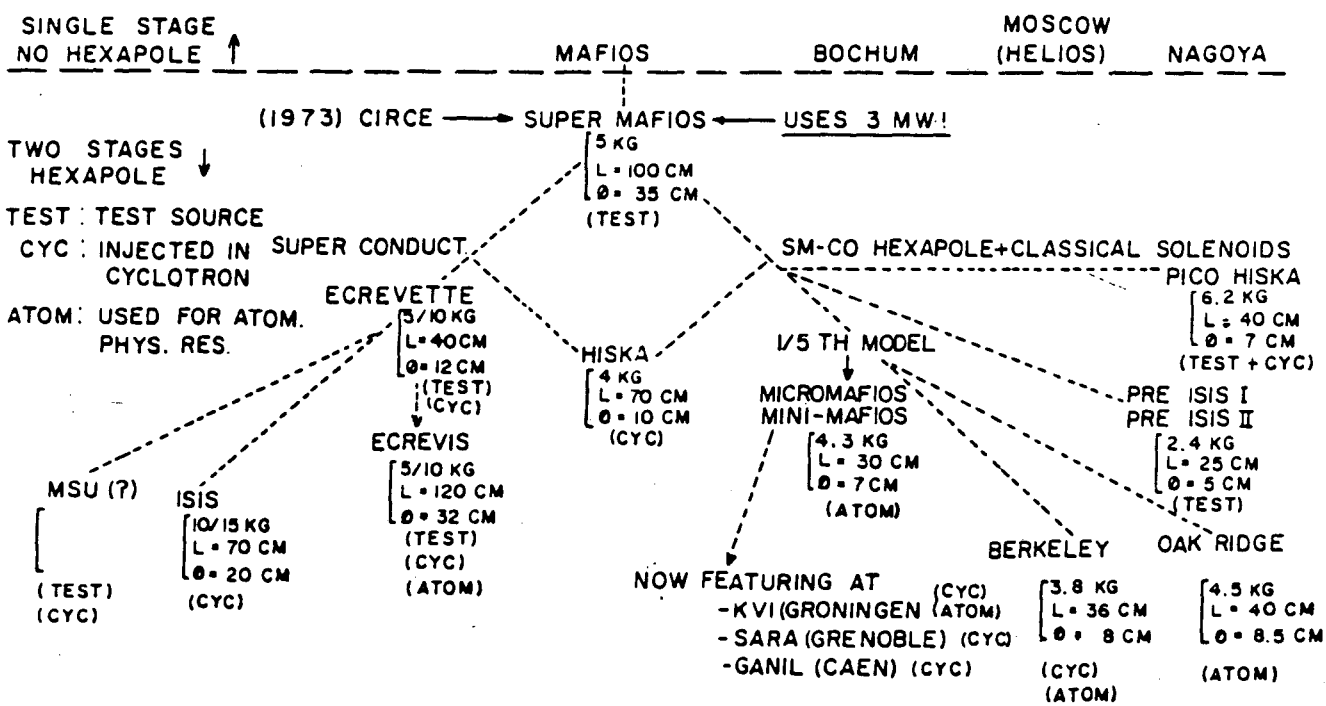
SUMMARY

Starting with the pioneering work of R.Geller and his group in Grenoble (France), at least 14 E.C.R. sources have been built and tested during the last five years. Most of those sources have been extremely successful, providing intense, stable and reliable beams of highly charged ions for cyclotron injection or atomic physics research. However, some of the operational features of those sources disagreed with commonly accepted theories on E.C.R. source operation. To explain the observed behavior of actual sources, it was found necessary to refine some of the crude ideas we had about E.C.R. sources. Some of those new propositions are explained, and used to make some extrapolations on the possible future developments in E.C.R. sources.

INTRODUCTION

Single stage sources using the E.C.R. to heat a plasma confined in a simple magnetic mirror have been developed in the late sixties in France: Geller et al. (1) and in Germany: Wieseman et al. (2). Such sources have also been developed in Japan and Soviet-Union: Golovanivsky et al. (3). A major step was made when Geller transformed a large mirror device used for fusion plasma research (CIRCE, 1973) into an extremely successful ion source: SUPERMAFIOS. The basic design features of this source: two stage configuration with the second stage stabilised by a hexapole, have been used in all subsequent sources designed for high charge state production. The main drawback of SUPERMAFIOS was the large energy consumption of the hexapole. Two technical solutions were developed to solve this problem. Some sources have used superconducting coils. Some other sources have used hexapoles made of rare earth permanent magnets. During the last five years, at least 12 E.C.R. sources for high charge state production have been built and tested. Essentially all those sources have been successful in producing stable and reliable beams of high charge state ions. E.C.R. source beams have been successfully injected in cyclotrons in Karlsruhe, Louvain-la-neuve, Groningen and Grenoble, and are now extensively used, suppressing completely the use of P.I.G. sources for high charge state beams. In addition to cyclotron injection, some sources are used for atomic physics research.

THE E.C.R. SOURCES SAGA !



Although generally successful, the sources tested did show some unexpected characteristics, making it necessary to reconsider some of the simple ideas generally accepted about E.C.R. sources. It is probably useful to review briefly some of those surprising findings.

-After SUPERMAFIOS, it was generally accepted that E.C.R. sources should be large to achieve a long plasma confinement. It came as a surprise that the four times smaller MICROMAFIOS produced charge state distributions (c.s.d.) quite comparable to those of SUPERMAFIOS.

-It was also accepted that the pressure in the source should be in the 10^{-7} Torr range to keep charge exchange within acceptable limits. It was found on MICROMAFIOS that the lowest possible pressure was not the best one. Actually MICROMAFIOS worked best at a pressure close to 10^{-5} Torr, sometimes with the vacuum pump partly or fully closed.

-It was accepted that, in order to maximize the $n\tau$ product, the highest possible plasma density was necessary. The microwave frequency was considered to be the limiting factor for the plasma density. For this reason, sources were built using superconducting coils, to allow the use of higher magnetic fields and, correspondingly, higher E.C.R. frequencies. However, it was found on ECREVETTE and ECREVIS that the highest possible plasma density was not the one giving the best c.s.d.. On ECREVETTE, a test made at higher field and correspondingly higher frequency gave totally identical c.s.d. and plasma parameters. It was found experimentally that larger sources were ideally operated at lower pressure, with lower plasma density and higher electron energy.

-It was considered necessary to provide a smooth magnetic field gradient to transport the plasma from the first to the second stage. Experience with MICROMAFIOS, ECREVETTE and ECREVIS did show that a correct diffusion could be obtained without any magnetic field gradient at all, or even with a gradient in the wrong direction.

-It was found that some gas mixing could significantly improve the c.s.d.. Charge exchange cross-sections would suggest that helium would be the best possible gas to mix. Actual tests in Berkeley did show that oxygen or nitrogen were better than helium when mixed with argon.

-It was always found that a careful plasma tuning was always essential to get a good c.s.d.. The extreme possible value of a parameter was almost never the best one. Optimum values were found to be reproducible from run to run and relatively uncritical.

To explain those surprising findings, it was necessary to refine the simple ideas we had

about the mechanisms governing E.C.R. source operation. Some present ideas are presented in the subsequent paragraphs. It is however likely that new experimental facts will oblige us to revise some of those ideas in the future.

SOME IDEAS ON E.C.R. SOURCES THEORY

Computer simulations of an E.C.R. plasma

One possible way to try to explain experimental observations in an E.C.R. source is to design a computer code simulating the equilibrium in the plasma. Starting with a preliminary attempt of Chan-Tung (4), such a code has been developed by Jongen (5) and later improved by West (6). Such codes are extremely useful to understand the influence of various parameters on the c.s.d., and allow a set of plasma parameters to be found, accurately fitting the observed c.s.d.. However, all those simulations have a common weakness: such models are quite insensitive to the hypotheses made on the confinement mechanisms, as long as the confinement times are within the right range. Therefore they are useless for proving the validity of confinement models.

Ionization cross-section and production rate

It is sometimes said that in E.C.R. sources the ideal electron energy should be the one giving the maximum cross section for the ions of interest. We show here that the production rate is much less sensitive to the electron energy than the cross-section is. Most of the smaller sources built to date probably suffer from too low electron energies.

In E.C.R. sources, high charge states are produced mainly by step-by-step ionizations. Experimental ionization cross-section data are still scarce and incomplete. Formulas fitting the existing data have been proposed by Salzborn et al. (7) and Lotz (8). An excellent compilation has been made by Crandall (9). The formula of Lotz is more involved, including ionizations in different sub-shells, and is generally considered more accurate. However, actual c.s.d. of E.C.R. sources agree much better with the Salzborn formula.

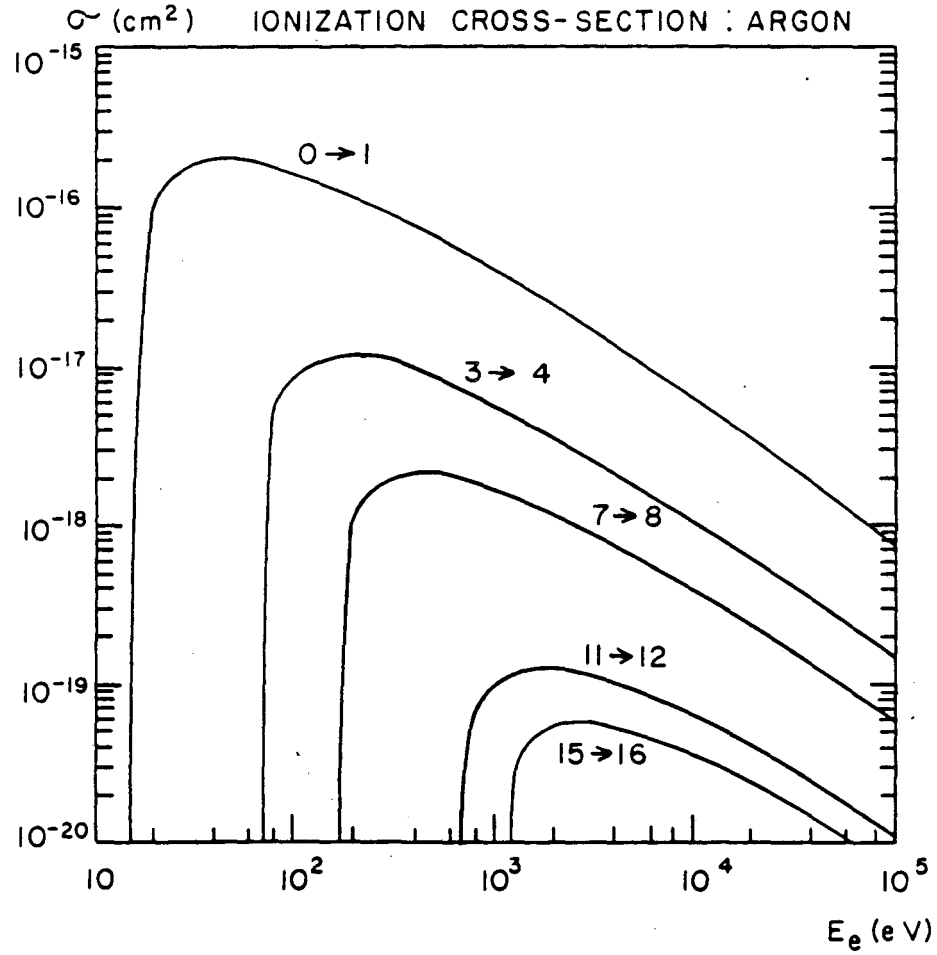


Fig.1 :Computer calculation of some Argon ionization cross-sections using the Salzborn formula.

The rate of ionization of an ion from charge state i to i+1, by electrons of energy E is:

$$\nu_{ION\ i \to i+1} = \sigma_{ION\ i \to i+1}(E)\ v(E)\ n(E)$$

Where :

- σ is the cross-section
- v is the electron speed
- n is the electron density

As the electrons are not monoenergetic, but have some energy distribution, an integration must be performed on all possible energies. For simplicity a Maxwell-Boltzmann distribution is generally assumed. However we show later that this hypothesis is hardly valid. It is important to note that, although the cross-section decreases with energy, the product of the cross section by the electron velocity is quite constant for energies above the ionization threshold.

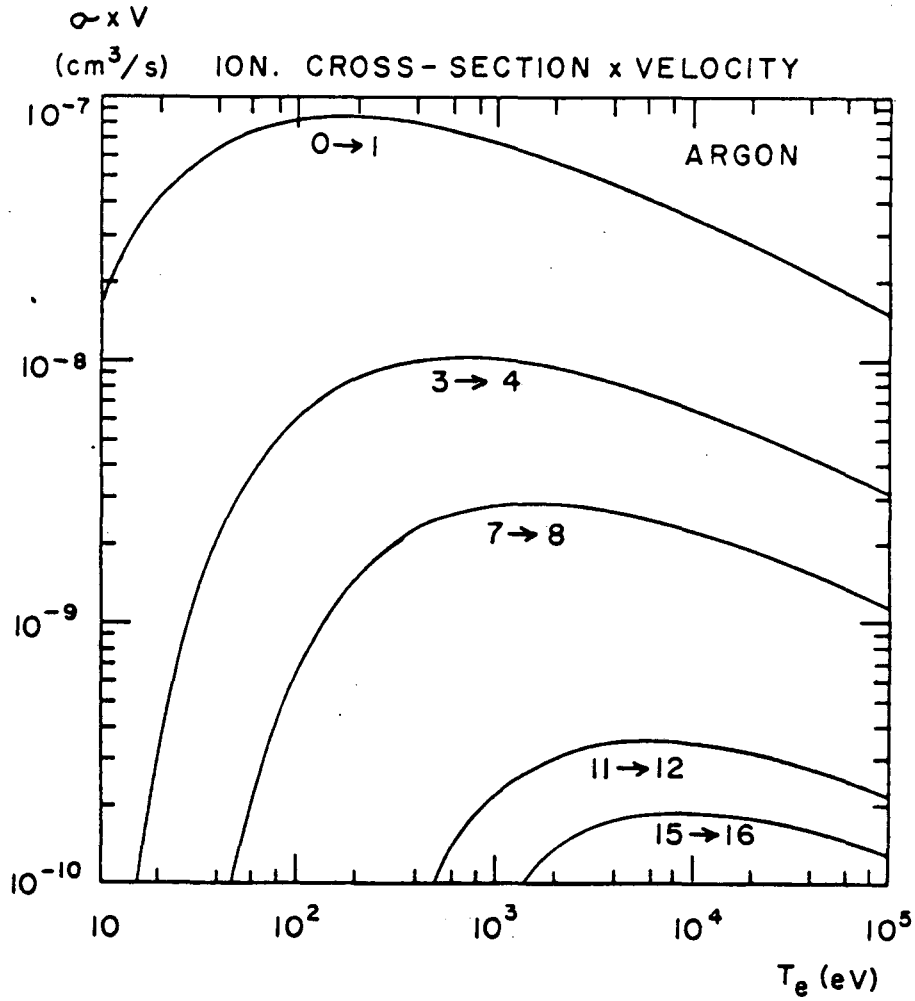


Fig.2 Ionization rates for various Argon ions versus electron temperature.

The $n\tau$ product

If we try to compute the c.s.d. from the ionization cross-section and production rates described above, we find that an essential parameter describing the system is the product $n\tau$, where n is the electron density in the plasma and τ is the time during which the ions are exposed to the ionizing electrons. If there is no loss mechanism, τ will be the confinement time. In the general case τ will be a life time, resulting from the combination of all loss mechanisms. There is some similarity between the $n\tau$ product described here and the well known $n\tau$ product of the Lawson criterion for nuclear fusion. Actually reactors designed for nuclear fusion are excellent, although somewhat unpractical, sources of highly stripped heavy ions. In simple cases, where all ions have the same confinement time and there is no other loss mechanism, the $n\tau$ product is all that is needed to compute the c.s.d.. Fig. 3 shows such a calculation for Argon. Fortunately, the $n\tau$ products needed to get an acceptable c.s.d. are a few orders of magnitude lower than the Lawson criterion (10^{14} $cm^{-3}.s$). Typical plasma densities in E.C.R. sources range from 2. to 5. 10^{11} cm^{-3}, with confinement times

from 10^{-3} to 10^{-2} s, resulting in $n\tau$ products around 10^{9} $cm^{-3}.s$.

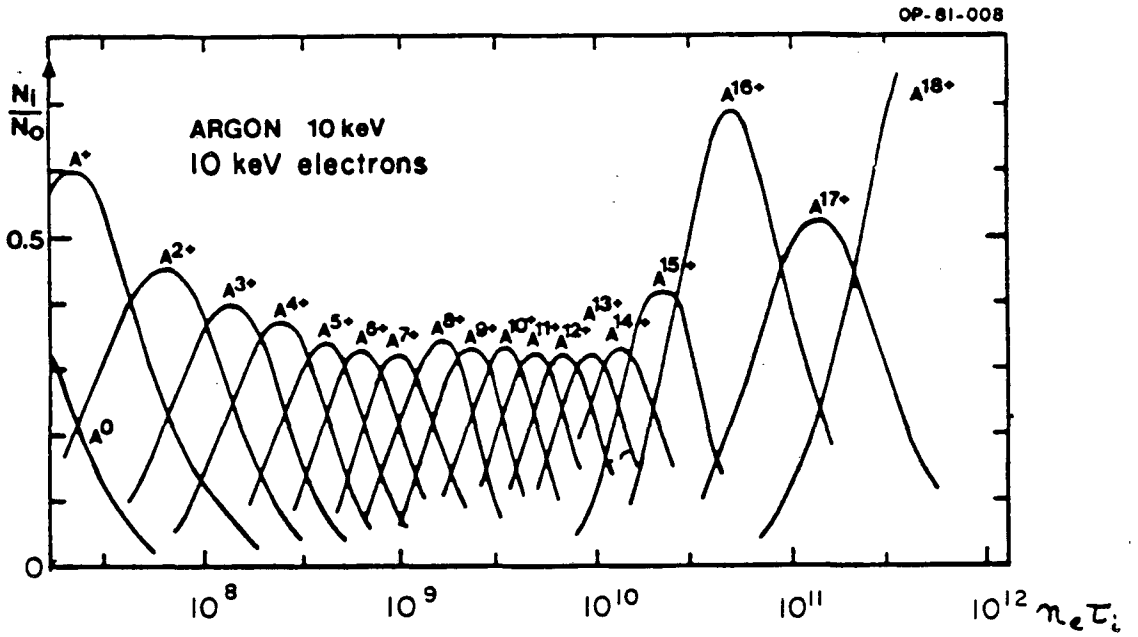


Fig.3 Computed c.s.d. versus $n\tau$ product for Argon.

It should however be noted that such a simple representation is not appropriate for an E.C.R. source, and the c.s.d. represented on fig.3 are never observed in actual E.C.R. sources. The first reason is that the confinement time is not an arbitrary parameter like in EBIS sources: in an E.C.R. source the confinement time is a function of the charge state. In an E.C.R. source, the extracted ions are a fraction of the plasma leaking out of the main confinement region. The leaking flux is the ratio of the number of confined ions divided by the confinement time of those ions. Ions which are too well confined scarcely appear in the extracted beam, although they may be present in significant proportion inside the plasma. Generally, in E.C.R. sources, the c.s.d. in the extracted beam is very different from the c.s.d. in the plasma. Other reasons that make the simple $n\tau$ description inaccurate is the existence of charge exchange losses and the fact that the electrons are not monoenergetic but have a quite broad energy distribution. However, the general philosophy of the $n\tau$ product remains valid: in a source, to improve the c.s.d., one should increase the electron density and the life-time of the ions.

Charge exchange

The cross-sections for charge exchange between highly stripped ions and neutrals are extremely large. An empirical formula has been proposed by Muller and Salzborn to

compute charge exchange cross sections between ions and neutrals.

$$\sigma_{exch\ I \to I-1} = 1.5\ 10^{-12}\ I^{1.17}\ P_{0\to1}^{-2.36}\ cm^2$$

Where :

-I is the ionisation state

-P is the ionisation potential of the +1 ion

Typical charge exchange cross sections are three to four orders of magnitude larger than ionization cross sections. Fortunately, the rate is proportional to the product of the cross-section times the velocity and cold ions are much slower than electrons . Even so, the rates are such that all existing E.C.R. sources are charge exchange dominated.

Injector stages

To keep the charge exchange rate at a reasonably low value, it is necessary to keep a very low neutral pressure in the plasma ($5x\ 10^{-7}$ to $5x\ 10^{-6}$ Torr). However it is quite difficult to start a plasma at those low pressures. For this reason, most E.C.R.sources are built as two stages devices. The first stage is a cold plasma generator, operating at higher pressure. The plasma produced in the first stage diffuses into the second stage, following the magnetic field lines. This diffusion is essentially governed by the gradient of density between first and second stage. Magnetic fields gradients were found to have little influence on this diffusion, because the cold plasma is highly collisional. It is generally observed that the first stage operates at plasma densities close to the maximum density allowed by the microwave frequency. For this reason, the first stages are often operated at an higher E.C.R. frequency than the second stage, to allow a large density gradient between the two stages. The gradient is also increased by locating the first stage as close as possible to the second stage.

Gas recirculation

Due to the imperfect nature of the plasma confinement, ions escape from the plasma and get neutralized when they hit the wall. A small fraction (5 to 10%) ends up in the extraction system and gets accelerated. The neutrals generated at the wall are reionized by the plasma or are pumped by the system vacuum pumps.

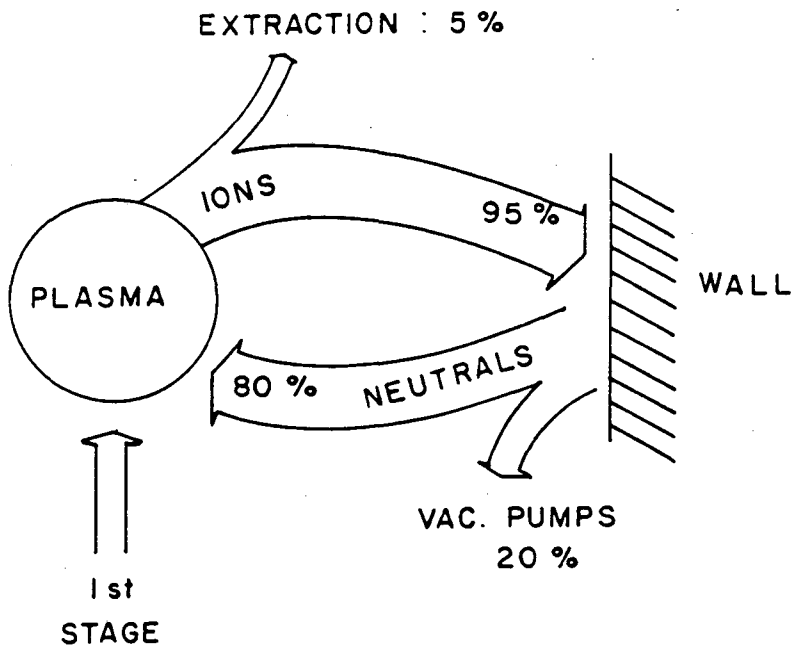


Fig.4 Gas recirculation in an E.C.R. source.

In all the existing sources,the pumping speed of the plasma is much larger than the pumping speed of the vacuum pumps. This means that each ion undergoes several plasma-wall cycles before escaping the system through the extraction or into the vacuum pumps. The role of the first stage is to provide a flow of ions equal to the flow lost through the extraction and the vacuum pumps: the higher the external pumping speed is, the larger the flux needed from the first stage. This recirculation of gas is the origin of the relation observed in E.C.R. sources between plasma density and neutral pressure: it was found experimentally impossible to raise the plasma density without raising the neutral pressure at the same time, or to lower the neutral pressure without starving the plasma. Therefore, the best n product was not obtained at the highest possible plasma density. This optimum plasma density corresponds to a neutral pressure such that the life-time of the ions for charge exchange is approximately equal to their confinement time. If a source is operated at a plasma density higher than this optimum, the charge exchange losses cause the ion lifetime to decrease faster than the

density increases. Because the external pumping speed adds to the plasma pumping speed, the external pumping speed value becomes irrelevant when it is very small compared to the plasma pumping speed. Actually, when the first stage is performing marginally, an improvement of the c.s.d. may be obtained by partially closing the pumps. However, increasing the plasma density by increasing the first stage flux remains preferable.

Magnetic confinement and electrons motion

E.C.R. sources uses an magnetic mirror geometry to trap charged particles. The motion of a charged particle in a simple mirror can be decomposed in three parts:

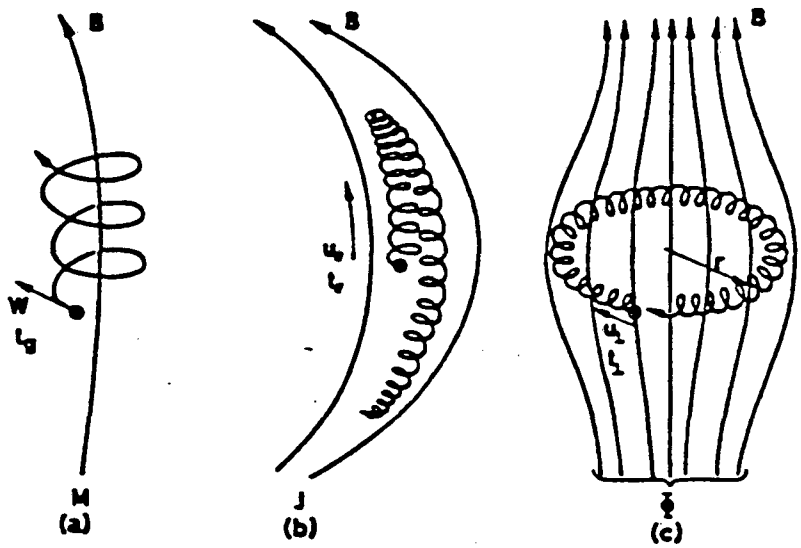


Fig.4 Motion in a simple mirror geometry (repr. from (10))

a) the cyclotron or Larmor rotation around a field line. The associated period τ_1 is independent of energy for non relativistic particles.

b) an oscillation along a field line, by reflection between field maximums. The associated period τ_2 is inversely proportional to the particle speed.

c) an azimuthal drift caused by the radial gradient of the field. The associated period τ_3 is inversely proportional to the particle energy.

$$\tau_1 < \tau_2 < \tau_3$$

A particle may escape the magnetic confinement when it undergoes a large angle scattering. The scattering time scales as

$$\tau_{COLL} = k E^{-1.5}$$

For hot electrons

$$\tau_1 < \tau_2 < \tau_3 < \tau_{COLL}$$

in a simple mirror geometry. Energetic electrons are very well confined magnetically and the confinement time scales as

$$\tau_{CONF} \approx \tau_{COLL} = k E^{-1.5}$$

For low energy ions, on the other hand

$$\tau_{COLL} \approx \tau_1 \ll \tau_2 \ll \tau_3$$

Therefore, low energy ions do follow the magnetic field lines, but are not confined magnetically.

Unfortunately, plasma confinement in a simple mirror geometry is unstable. It can be shown (10) that the plasma boundary is stable if the magnetic field is convex toward the plasma. It becomes unstable if the opposite is true, as in a mirror geometry.

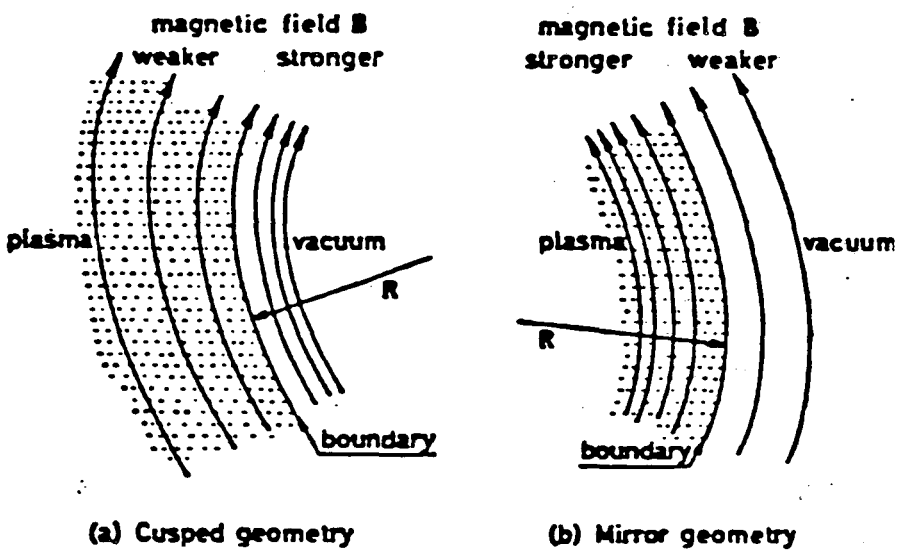


Fig.5 Stability of a plasma boundary (repr. from (10))

To improve the stability of open mirrors, Ioffe (11) has introduced the use conductors,located around the circumference, parallel to the axis and carrying current in alternating directions.

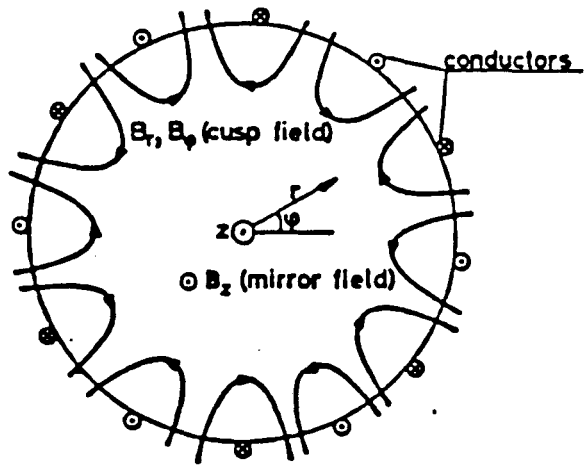


Fig.6 Ioffe bars (repr. from (10))

The same multipole field can be generated by rare earth permanent magnets, as originally proposed by Geller and Pauthenet. In such a geometry, the magnetic field increases when going from the center to the wall in any direction. It is therefore called a "minimum B" geometry. It is worth noting that the stability is obtained with any order of multiple, although all E.C.R. sources built up to now (1984), have used hexapoles. The threedimensional field pattern resulting from the combination of the mirror field and the hexapole is somewhat difficult to visualize. However, it is possible (5) to compute the shape of the plasma in the source. Such calculations agree very well with the axial aspect of the plasma and with the traces left by the plasma on the walls. The multipole field allows a stable plasma confinement,but has also some negative features :

- radial plasma losses are introduced. A smaller proportion of the highly stripped ions escapes on the axis, where the extraction device is located

-a new loss mechanism is introduced for energetic electrons. An azimuthal drift caused by the radial gradient of the field is still present. In this case the field increases radially, so the direction of the drift is reversed. Energetic electrons drift azimuthally out of the plasma, on field lines where the magnetic confinement is impossible and are lost. The loss rate is proportional to the electron energy and to the field line curvature. The field line curvature increases with radius: for this reason, one expects to find very few high energy high electrons at large radii. It is also

obvious that for similar designs, the radius increases with the size of the source. This explains the observed scaling of electron energy with the source size. A reduction of the field line curvature close to the axis could also be obtained by the use of a higher order multipole such as an octupole. This configuration would give higher electron energies,and therefore better c.s.d.for the same R.F. power. Such an octupole geometry is under construction at Berkeley

R.F. power and electron energy

We have seen that low energy electrons are lost by large angle scattering, while high energy electrons are lost by azimuthal drift into regions where the confinement is impossible. The first loss rate scales as $E^{-3/2}$, the second scales as E.

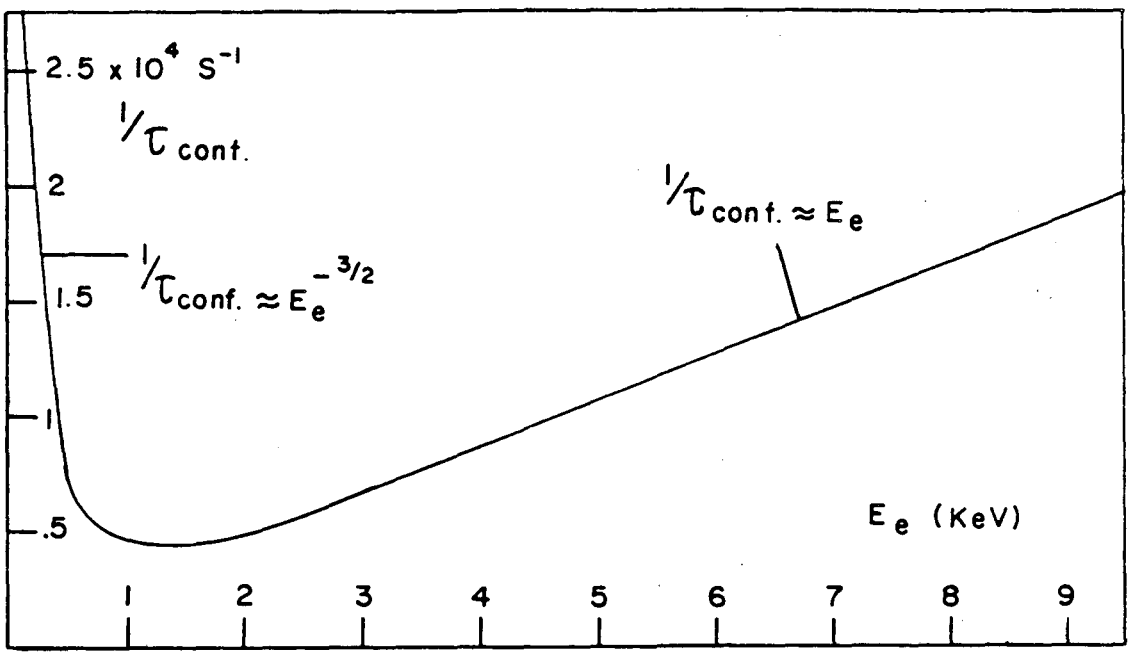
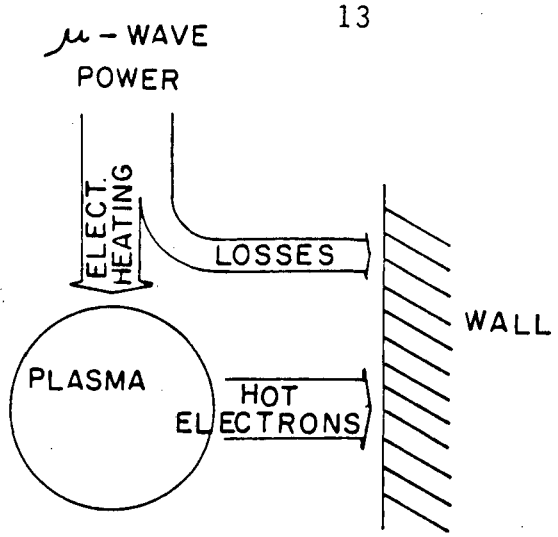


Fig.7 Electron loss rate versus energy

In E.C.R. sources,it is generally accepted that a large part of the incoming microwave power is actually coupled to the energetic electrons. In a system in equilibrium, this power is equal to the power drained out of the system by energetic electrons escaping the confinement



$$P_{R.F.} = \eta V \int_{E=0}^{\infty} n(E) \times E \times \frac{1}{\tau(E)} \, dE$$

where :

η is the heating efficiency
V is the plasma volume
E is the electron energy
n is the electron density
τ is the electron confinement time

Introducing the computed confinement time of the electron, we can compute the power needed to keep the system in equilibrium as a function of the electron temperature.

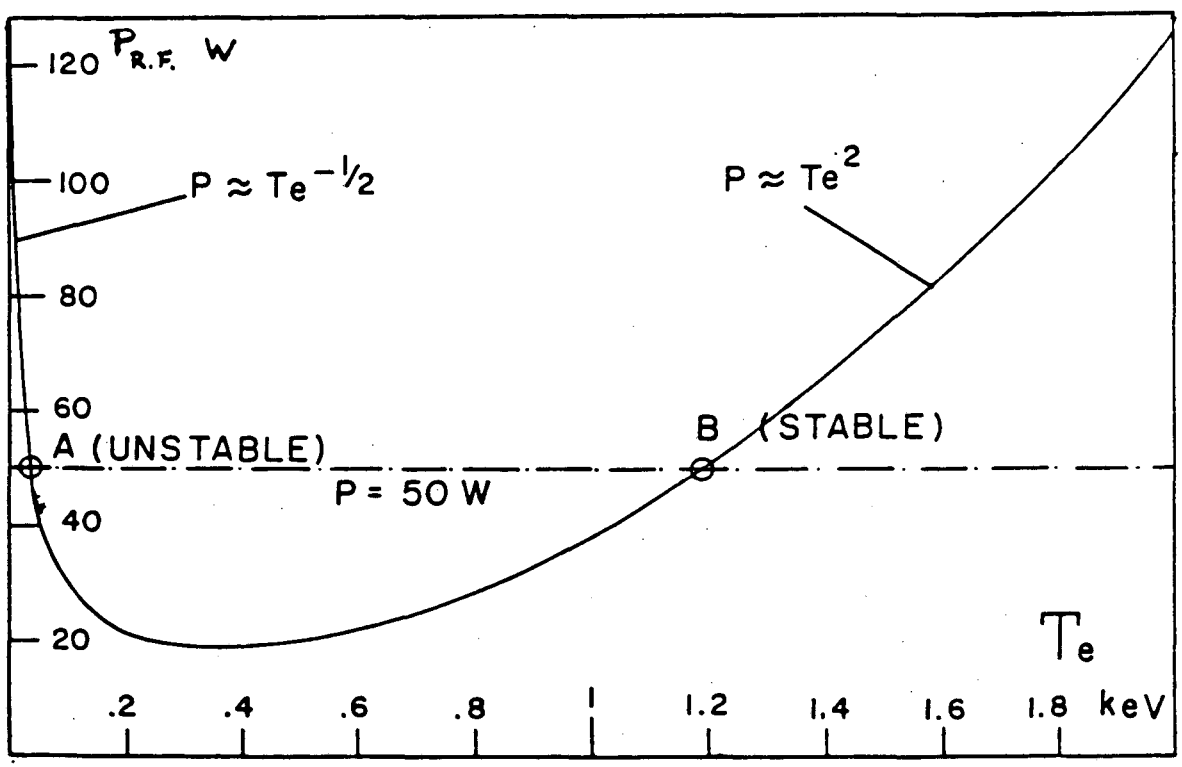


Fig.8 R.F. power needed versus electron energy

We see that for any R.F. power fed to the system, there are two possible electron temperatures. It is however evident that the first intersection (A) represent an unstable solution. The point (B) is stable and is the actual operating point. As was experimentally observed in the ECREVIS source, there is a minimum power to keep the system in equilibrium. This power is a function of the plasma density. If we increase the power level above this minimum level, we increase the electron energy but we also increase the flux of electrons escaping from the plasma. The plasma neutrality forces out an equal flux of ions, decreasing the ion confinement time. When the R.F. heating is abruptly stopped, the flux of electrons leaving the plasma falls immediatly. The electrons still confined in the system are lost by scattering, with very long time constants (several seconds in ECREVIS). Because the average collision time for electrons is much longer than their life-time, the electrons are not thermalized and there is no reason to expect a Maxwell-Boltzmann energy distribution. Instead the energy distribution is shaped by the loss rate shown in Fig.7 and the stochastic acceleration. Preliminary calculations indicate that the distribution obtained is much broader than a Maxwell-Boltzmann. This explains why attempts to determine the electron temperature from the high energy tail of the X-ray spectrum led to an overestimate of the temperature by one order of magnitude or more.

Plasma potential and source tuning

It is well known that the flux of ions and electrons leaving a plasma must be equal, to maintain the plasma neutrality. If one of the species has a tendency to escape faster, a plasma potential will appear, which will attract the escaping species and expel the others. In the E.C.R. sources the ions are

extremely collisional and therefore are not confined by the magnetic field. But because they are so collisional, the ions take a long time to diffuse through the plasma. Also, due to their low energy, the ions will be very sensitive to any plasma potential. Data from beam bunching on ECREVIS have shown that the source energy dispersion was less than 5 eV. Obviously, this puts an upper limit of 5 eV on the ion energy. A plasma potential will be added to or substracted from the extraction voltage, and could be detected by a careful measurement of the energy of the beam. Such measurements have been made on ECREVIS and on the E.C.R. source in Berkeley. In the latter case, the resolution obtained was +-10 eV. No evidence of plasma potential of that size was found on well tuned beams, although plasma potential variations were unambiguously seen during beam tuning and during beam turn-on period with pulsed R.F. . Computer simulations of the plasma show clearly that any plasma potential comparable with the

ion energy would have a very detrimental effect on the higher charge states. It is obvious that positive potentials would rapidly expel high charge states ions, drastically reducing the n product. But negative plasma potentials are detrimental as well. It takes a very small negative potential to almost stop the flux of higher charge state ions. The ions are still produced, and are present in large amount in the plasma, but are trapped by a potential well proportional to their charge state and are mostly lost by charge exchange. This explains why E.C.R. sources must be tuned: when optimizing for the best beam, the operator actualy tunes the plasma potential, equalizing the ion and electron fluxes. The physical parameters that tune the plasma are: the first stage tuning (determining the cold plasma flux and, consequently, the plasma density), the microwave power (changing simultaneously the electron temperature and lifetime), and the magnetic field (changing the electron confinement and the E.C.R. zone positions).

EXTRAPOLATIONS TO FUTURE SOURCES

After the successful SUPERMAFIOS experience, the directions to improve E.C.R. sources seemed clear. Higher plasma densities would result from higher frequencies and fields. A better pumping could reduce charge exchange losses. Large sources would give long confinement times. Unfortunately, the tests made on 12 more sources show the situation is not so simple. We have shown above that the plasma parameters are not independent, but are inter-related by a series of equilibrium conditions. In the initial extrapolations, one was clearly shown to be false: it is not sufficient to just raise the E.C.R. frequency to raise the plasma density and to enhance the c.s.d.. Another extrapolation seems to be valid: larger sources seem to give better c.s.d.. The reason is more probably to be found in a higher electron energy than in a longer confinement time for the ions. A large size is probably not the only way to raise the electron energy. An alternative method, used on MINIMAFIOS is simply to force the electrons into a higher energy, higher losses region by increasing the R.F. power. The price paid is a shorter confinement time. An alternative way to modify the energy/lifetime relationship for the electrons would be the use of higher order multipoles. The last of the original directions of improvement (large pumping speeds) has never been significantly tested. All sources built to date had an external pumping speed small compared to the plasma pumping speed. However, the physical equilibrium conditions we have found could indicate the way for less obvious, more subtle improvements. A better control of the plasma potential could be obtained by the injection of charged beams (electrons or ions) in the plasma. It is quite clear that existing sources are still very far from having reached their ultimate performances. On the technological side,

one can expect that future E.C.R. sources will use a magnetic steel yoke to improve the magnetic efficiency, reduce the stray field and make the plasma less sensitive to external magnetic perturbations. Lower energy consumption is possible and will be achieved. To obtain the large heating powers needed in larger sources, multiple Klystron generators with multiple feeds will probably be used.

CONCLUSIONS

E.C.R. sources are uncritical, stable and reproducible devices, extremely successful in producing intense beams of highly charged ions. However, the physics underlying their operation is more involved than originally thought. For this reason, we expect future improvements to come more from a better understanding of the source, resulting in better operating conditions, than from the construction from larger, higher field sources.

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