ECR ION SOURCES FOR ACCELERATORS

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The basic principles of Electron Cyclotron Resonance Ion Sources are recalled. The properties of single, double and multimirror plasmas are reviewed. We insist on the difference between low charged and high charged heavy ion production on which we mainly concentrate. The present state performances and the upgrading schemes are shown. A few prototypes are described.

1. Introduction : The field of Electron Cyclotron Resonance Ion Sources (ECRIS) has its roots in the plasma fusion developments of our group and our first source worked as early as 1965. Since then our sources were gradually improved and developped for different applications. Today, single and multimirror ECRIS are utilized as well for ion implantation, deposition and etching as for surface physics and all kinds of atomic physics. But ECRIS had also immediate application in particle accelerators. Their high ionization efficiency and brightness are exploited for H^- beams, polarized ions and on line radioactive particles. However their most dramatic break-through happened in the field of multiply-charged ions where the performances of multimirror ECRIS are absolutely unparalleled. Since 1975 in our laboratory this type of ECRIS has evolved from a single large 3MW power consuming prototype (SUPERMAFIOS) into a variety of compact high performance sources (some of them built in small series) and among them our last prototype NEOMAFIOS entirely made of permanent magnets. In the present paper we will shortly recall the principle of single and double mirror ECRIS, and then mainly concentrate on the multicharged Ion Sources which are of special importance in the economy of heavy ion acceleration. Presently some 20 ECRIS are working in association with such accelerators.

2. Specific features of ECRIS for Single or Multiply Charged Ions : The bestknown advantage of an ECR ion source is to be cathodeless and subsequently very robust and longliving. But in addition, ECRIS enable to adjust some capital parameters like T_e the electron temperature, n_e the plasma density and q the ion charge state. This flexibility is certainly its most important and original feature and makes a big difference with other plasmas /1/. For instance Te is strongly related to the microwave power density P_{RF}/vol, n depends on the gas pressure but is generally limited by the cut off frequency p_{RF}, whereas q increases with n, τ and Te (τ being the exposure time of the ions to electron bombardement ie the plasma confinement time :

2.1 Plasma Density, Ion Current Density, Ion current and Emittance : The extracted ion current density must be at least balanced by the ion flow $n_+ v_+ \propto n\sqrt{Te}$ arriving on the extraction meniscus, so that inside the plasma, the density $n^+ = n^- = n$ must be fitted for this purpose. We generally propose that $\omega_p = |ne^2/m\,\varepsilon_o|^{1/2} = \omega_{RF}$, gives the upper limit of plasma density without instabilities. (e and m are the charge and mass of the electron and ε_o the vacuum dielectric constant) Note that quiescence is capital for good emittances. Thus, the extracted ion current density being limited by the resonance conditions, in order to increase the total ion current, one can to a certain extend enlarge the extraction area (multigrids). Though the extraction optics is beyond the scope of this paper we insist on the feasibility of building large and dense illumination plasmas.

2.2 ECRIS Plasma Containers and Plasma Profiling: ECR plasmas can be generated inside waveguides, high Q resonators or multimode resonators. In all these containers at least one resonance surface must be present and the gas pressure must be such that the collisions are not out-damping the resonance effects.Fig. 1, 2 and 3 illustrate prototypes of ECRIS built by our group since 1965 and yielding currents from a few mA up to tens of amperes of single or low charged particles. In all these sources, in spite of turbulent particle diffusion, the plasma follows more or less the magnetic field lines and occupies a volume shaped by the profile of the magnetic structure (obtained with coils or permanent magnets). This plasma profiling enables to achieve spatial expansions or compressions. The figures 1, 2 and 3 are the basic schemes of all ECRIS for low charged ions.

2.3 The RF power Coupling to the Plasma : The EM power can be introduced into the plasma container by coaxial lines, antennas, loops or tight dielectric windows, the choice depending mainly on the wavelength of the RF and the desired EM field pattern. The coupling of the RF power to the electrons through ECR has been studied theoretically for a single electron passage through the resonance zone. But no reliable theory exists for the realistic case where dense swarms of electrons pass several times through the ECR zones and a stochastic ECR heating prevails. Nevertheless in this case, ECRIS plasmas are obtained with an excellent coupling efficiency (RF power coupling $>$ 50%) and without conspicous experimental difficulties. It is also important to emphasize that the resonance does not necessarily happen at $\omega_{RF} = \omega_{ce}$ but also around the upper hybrid resonance $\omega_{UH} = \sqrt{\omega_{ce}^2 - \omega_p^2}$ which occurs at lower magnetic fields. This resonance becomes the main RF power absorption processus when the plasma density approaches the cut-off density . All together, ECRIS reach high ionization efficiencies and therefore are well fitted for radioactive on line ion injectors or rare isotope ionizers.

2.4 The plasma confinement in ECRIS : The magnetic field configuration plays a capital role because it influences the ECR plasma diffusion rate and accordingly the particle losses towards the walls. Therefore, the B structure has not only an effect on the ionization efficiency and subsequently on the gas consumption, but also on the particle lifetime which in turn acts strongly on the necessary RF power one has to couple to the plasma. As better is the confinement as higher are the efficiencies of ionization, and highly charged ion production etc... For these reasons, radial mirrors in addition to axial mirrors are of great help. Such confinements structures are obtained with coils, permanent magnets or a mixture of both.

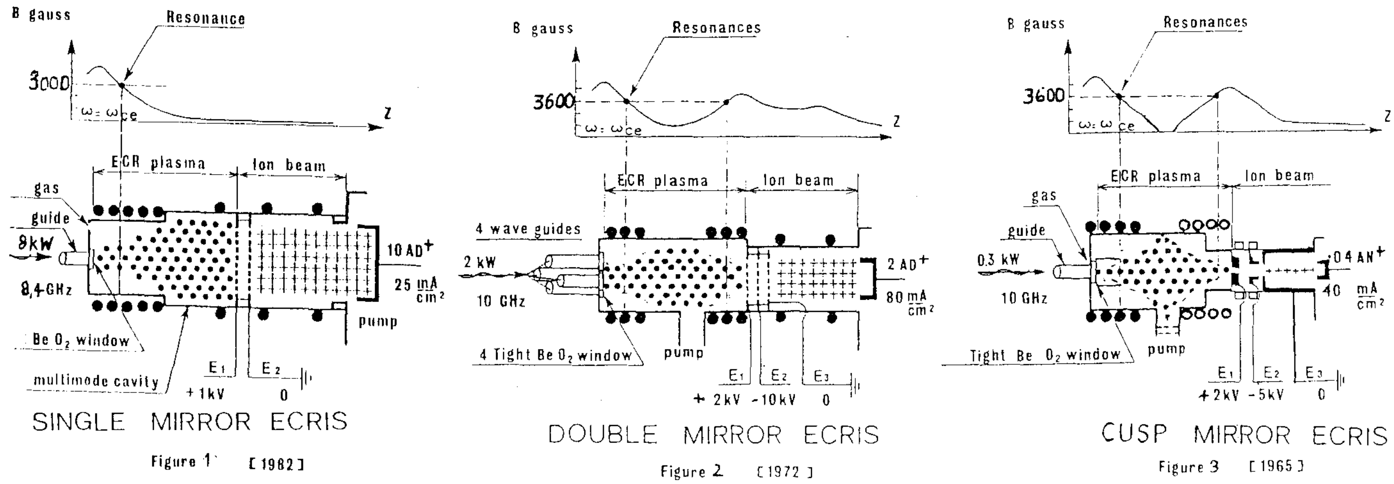

Fig. 1, Fig. 2 and Fig. 3 : Typical ECR plasma shaping by respectively single double and cusped axial magnetic mirrors (obtained with EM coils or permanent magnetrings). Large plasma extraction areas are achievable, but only low charged ions are obtained.

2.5 Multistage ECRIS Sometimes one associates ECR plasmas in cascade. Each ECR stage can fullfill separated practical functions. For instance fig(4) shows a typical multiply charged ion source where the first stage is a single mirror ECR plasma at relatively high gas pressure, playing the role of an injector for the second ECR stage at very low gas pressure, where the plasma is confined and heated in a magnetic multimirror well obtained by superimposing a hexapolar and a solenoidal field.

2.6 Location and features of the extraction system: Like other ion sources, ECRIS are working with different extractor electrodes which can comprise holes, grids, single, double or multielectrodes with or without accel/decel systems. These electrodes can be located after a magnetic expansion cup inside zero B field or inside the main magnetic field of the source. For multiply charged ECRIS the extractor must be inside the main magnetic field beyond an axial mirror point in order not to disturb the particle confinement between the mirror points. Eventually for each case, an optimum compromise must be searched.

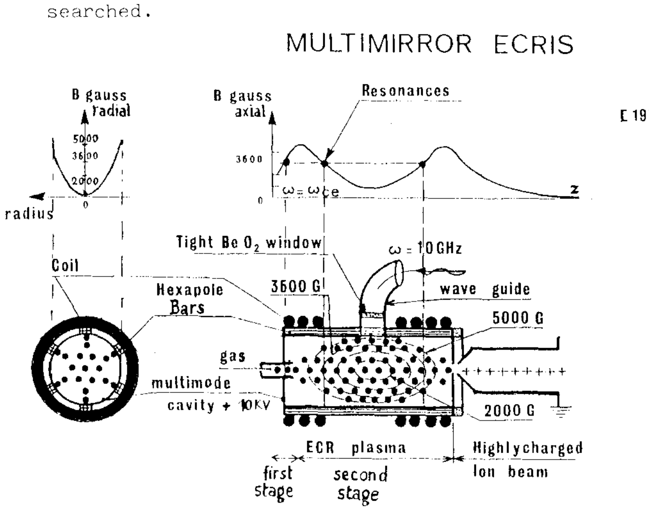

Fig. 4 : Ingredients for a highly charged ECRIS. Multimirrors obtained by superimposition of a double axial mirror and a hexapolar field. In addition two ECR plasmas in cascade are provided.

3. The multiply charged ECRIS /1,2,3,4,5,6,7,8/

3.1 Criteria for multiply charged ion production : The probability of producing M.I. by a single electron impact falls off rapidly with increasing ion charge q. Therefore the only efficient way for obtaining a reasonable yield of many-time ionized ions is by successive ionization. We are then led to increase the exposure time τ of the ions to a cloud of electrons of density n and velocity w. The parameter $nw\tau$ determines the achievable q. But the electron impact velocity w should exceed 2.10^9 cm s^{-1} (i,e the electron temperature should be in the KeVrange). Fig.5) shows typical mean charges q for Nitrogen ion versus $n\tau w$. They are obtained through "batch calculations" which are based on the knowledge of ionization cross sections and assume that only the confinement time τ limits the achievable charge. No other loss mechanisms are considered. This type of calculations is an acceptable approach for ECRIS if one looks for the charge optimum q_{opt} which gives the maximum ion current in a peaked charge state distribution. Note the very slow increase of q vs $nw\tau$. Only when $nw\tau$ exceeds 10^{19} highly charged ions appear. We can summarize the M.I. production criterion for three typical cases:

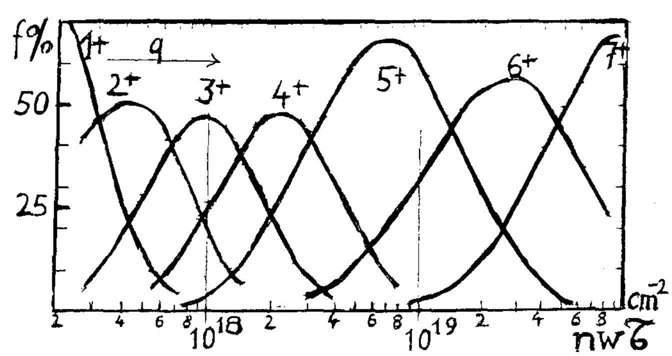

Fig. 5 Batch results for Nitrogen mean charges q vs $n\tau w$ for electrons of 5,4 KeV ($w \sim 4.4\ 10^9$ cm s^{-1}

a. Single or double mirror ECRIS : $n \sim 10^{12}$ cm^{-3} : $\tau \sim 10^{-5}$ s : $w \sim 10^{9}$ $cm.s^{-1}$. In this case one only obtains M.I. with low q.

b. Multimirror ECRIS (today) : $n \lesssim 10^{12}$ cm^{-3} ; $\tau \sim 10^{-2}$ s ; $w \geq 2\ 10^{9}$ cms^{-1}. In this case, M.I. of light species up to totally stripped particles are observed and utilizable for particle acceleration.

c. Multimirror ECRIS (nextfuture) : $n \sim 10^{13}$ cm^{-3}; $\tau \sim 10^{-1}$ s ; $w > 6\ 10^{9}$ cms^{-1}. M.I. upto totally stripped Xe are expected to be utilizable

3.2 Basic applications : the foil stripper and the ECRIS : The foil stripping is based on the same criteria but in this case (fig. 6a) one injects energetic (a few MeV/nucleon), low-charge state ions through a thin foil. This foil contains in its crystalline structure atoms together with cold electrons with density $n \sim 10^{24}$ cm^{-3} The relative interaction velocity w under these conditions, approximately equals to the transit velocity of the accelerated ions (a few 10^{9} cm/sec). The interaction time will be that during which the ions passes through the foil ($\tau \sim 10^{-14}$s)and ($n\tau$) will thus be about 10^{10} cm^{-3}s. During the interaction, two types of collisions are in competition : the step by step ionization of the incident ion and the recombination of the multiply charged ion through electron capture. At high speed the ionization process predominates and the ion beam that emerges from the thin foil is very highly charged. The ECRIS idea consists in inversing the process through ECRIS cascades. A first-stage ECR plasma of cold ions diffuses slowly through an ECR plasma of hot electrons. One would obtain the same relative interaction speed if this second ECR stage yielded electrons of a few KeV. Then one would have to create a hot electron target plasma that present a value of ($n\tau$) $\sim 10^{10}$ cm^{-3}s, similar to that of the solid stripper. In fig. (6b) we emphasize the symmetry between ECRIS and foil strippers. For foil strippers, ions are strongly accelerated (through a cyclotron or a linac) prior to the electron-ion collision, whereas for ECRIS the electron are accelerated (through an electron cyclotron resonance). In the latter case, for identical relative collision velocities, the technology is much simpler and the equipment must cheaper. However, in the usual ECR plasmas the values of the hot electron density is only $\sim 10^{12}$ cm^{3}. Thus one needs ionic lifetimes of 10^{-2}s. Such ion lifetimes can only be obtained in sophisticated magnetic wells...

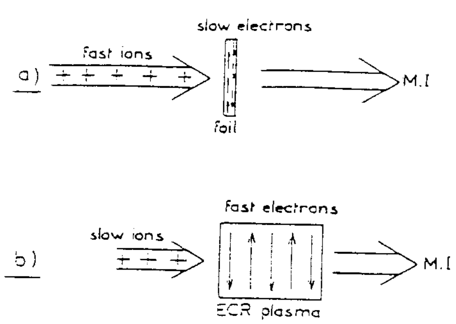

Fig. 6 : In foil strippers (a) and ECRIS (b) the same relative collision velocity between the electron and ions with the same ($n\tau$) values give a similar charge states of the multicharged ions (M.I.) But the short and intense interaction in (a) provides excited levels and additional ionization and (a) is more efficient but also more expensive.

3.3 ECRIS techniques for multicharged ion production : Whenever in a vacuum containing microwaves and magnetic fields, an ECR surface exists, an electron cannot cross this surface without being energized : after one passage the energy of the electron depends on the component of the electric field of the wave which is perpendicular to the magnetic field and on the sharpness of the magnetic gradient. If in addition the electron/atom collision frequency is of the same order or smaller than the ECR frequency, breakdown occurs and an ECR plasma is ignited. In ECRIS the electrons are delivered by such a plasma and not by a cathode and owing to the absence of filaments and arcs, the reliability becomes excellent. The ECR heating mechanism of the electrons can be briefly summarized as follows. Consider an empty metallic box of undetermined shape, filled with microwave power (for instance f = 10 GHz, λ = 3 cm). If the dimensions of the box are large with respect to the wavelength λ , the box can be considered as a multimode cavity. If the box is now immersed in a magnetic well (minimum B structure) where the magnetic field strength is between for exemple, 0.2 and 0.5 T, then there must exist a magnetic surface where the field strength is B_o = 0.36 T (fig. 4). On this surface, the gyrofrequency of the electron is 10 GHz and thus equals the frequency of the microwaves. The ECR resonance necessarily occurs because in a multimode cavity there is a component E of the electrical field of the waves that is perpendicular to the magnetic field lines. In the magnetic well the electrons pass many times through the ECR surface. They can sometimes be decelerated (according to their phase). However, after many passages, they acquire a global heating called stochastic ECR heating and reach rapidly the keV energy-range. The plasma density (i.e. the ion current) is limited by the wave penetration. The cutoff density is given by $n_{co} \sim 1.2\ 10^{-8}$ f^{2} f in Hz, n in cm^{-3}. Generally the source has two stages in cascade. In the first, which is at $\lesssim 10^{-3}$ torr pressure, a cold plasma is ignited which then diffuses towards the second stage with the hot electrons in the min B confinement system ; The neutral gas pressure in the second stage must be as low as possible in order to avoid charge exchange recombination losses. As long as the ECR surface does not intercept a solid obstacle,the confinement remains good. If not, the confinement is destroyed and now the power is dissipated in the solid which is vaporized or molten. This property is utilized for direct, in situ metal ion production. The metallic sample is on a movable piston and can more or less approach the ECR surface. In the second stage, the ion pumping due to ECR and the effects of wall recycling play also a certain role in the source behaviour.

Fig. (7) shows the main components of a typical MINIMAFIOS source and also its axial and radial magnetic field. For feeding RF power into the first and the second stage, micro-waves are injected through a tight BeO window. Generally 70 to 90 % of the power is absorbed in the plasmas. Ionic extraction is beyond the axial magnetic mirror. The whole ion source is isolated up to 25 kV and connected to the high voltage except the solenoïds which are grounded. All the Grenoble built ECRIS utilize only one microwave generator for the two stages and three remote controls for the adjustable parameters which are : the gas flux handled by a needle valve, microwave power and extraction voltage. The magnetic well is obtained by adding solenoidal and hexapolar fields.

3.4 ECRIS prototypes : Among our models the 10 GHz MINIMAFIOS (1979) is still the most popular because such sources now work for years without any internal failure. The hexapole is made of $SmCo_5$ permanents magnets with 4000 Gauss on the poles. Some ion current are shown in fig. 11. Typical emittances at 15 KV are $\sim\pi$ 50 mm mrad. Let us recall that the Groningen KVI facility, GANIL, NAC, CERN and SARA work with MINIMAFIOS sources. In the last years, the SARA source was operating 100% of the demanded time. Its reliability is legendary and no maintenance problem exists. However its high power consumption (100 kW) is sometimes an inconvenient. Therefore we launched more compact sources like FERROMAFIOS and CAPRICE. The 10 GHz CAPRICE source (fig.8) has in addition to its compact structure completely enclosed by a return yoke, a coaxial wave plasma coupling, which allows an entirely removable vacuum chamber without any microwave window in contact with the metallic-vapor. The metal evaporator is constituted as usually in our other ECRIS by a metal sample approaching more or less the ECR surface. CAPRICE with 50 KW in the coils can operate with average magnetic fields twice their usual value. This improves the yields of highly charged gaseous ions . Fig. 12 shows metallic ion currents for different elements. Let us emphasize that the nature of the mixing gases and the wall layers plays also an important role/8/. Another interesting prototype is NEOMAFIOS 8 GHz (fig.9) whose magnetic structure is entierely made of (NeFeB) permanent magnets so that the power consumption for the magnetic structure drops to zero. This system simplifies enormously the setup and the tunings specially for high voltage operation and under these condition ~ 5 KW electrical power on the HV plateform are sufficient. Many other prototypes were built all over the world. In contrast to the Grenoble Sources, all of them until now, have two separated irst stage and 2nd stage microwave generators. Among the best, let us quote the LBL source,(fig.10) the JULICH source(with a superconduction magnetic structure enabling 14 GHz operation) and the iron yoke ECRIS with minimum B in the 1st and 2nd stage working at 6.4 GHz built by MSU. Other ECRIS are being built in the USA, JAPAN and FRG. In short all of them behave more or less satisfactory with comparable performances in spite of some technical differences. In all cases they over-top by far the now obsolete PIG sources. Most of these ECRIS are described in ref./3,4,5,6,7,8,9/.

3.5 ECRIS upgrading : All ECRIS utilizers now know that gas mixings and specific wall coating push the charge state distribution towards higher charges. However we proposed recently some more general scaling laws for ECRIS upgradings /8/. In summary we find the following relations where B is the average magnetic trap field, ω the incident RF frequency, q_{opt} the charge state giving the maximum ion current, I^q the value of this current and M the ions mass.

$n\tau_w \propto B^{1.5}$	$q_{opt} \propto \log B^{1.5}$	$n\tau_w \propto \omega^{3.5}$
$q_{opt} \propto \log \omega^{3.5}$	$I^q \propto \omega^2 M^{-1}$	

These relations indicate a "soft" tendancy of upgrading by increasing ω and B . Experiments done by varying ω from 6.4 to 16.6 GHz confirm this tendancy (Fig.11) whereas the experimental dependance of I vs M^{-1} and ω^2 are shown fig.13 to 14. A superconducting ECRIS at 30 Ghz is now developped in a joint MSU-Grenoble effort/9/. Let

Fig. 7 to Fig. 10 : ECRIS PROTOTYPES first stage (1) Second stage (2), RF injection (3), Gas inlet (4), Hexapole (5) Extraction electrode (6). S are coils, R Permanent magnet rings, P pumps, F coaxial RF.

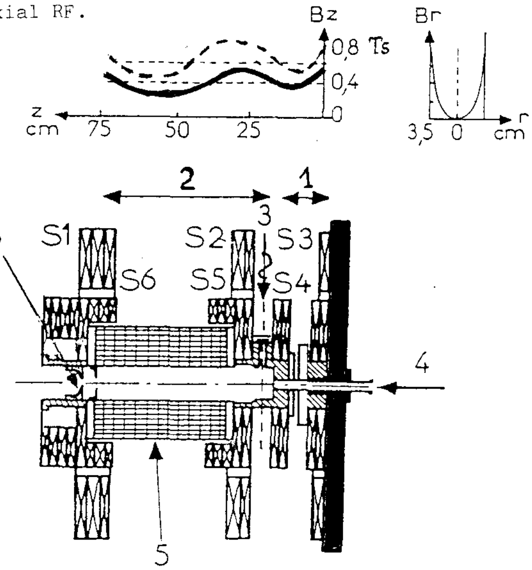

Fig. 7 : The novel MINIMAFIOS presently the most performant ECRIS Note that it can operate at 10, 14 and 16 GHz. The radial field Br is obtained with a $SmCo_5$ 0,8 Ts Hexapole. The solenoidal field Bz is variable (full line for 10 GHz, dashed line for 16,6GHz.

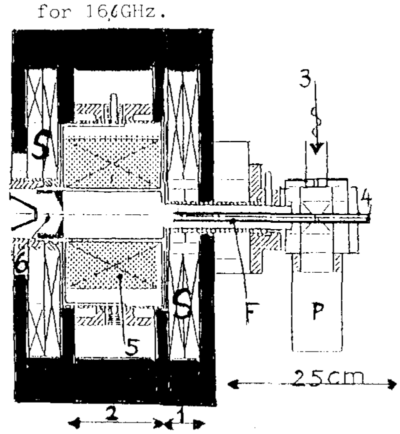

Fig.8 : CAPRICE
Note the compact ironyoke and the coaxial microwave feeder F

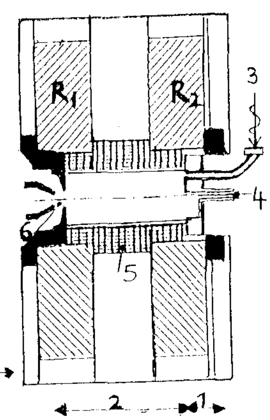

Fig.9 : NEOMAFIOS
Note the absence of coils and pumps

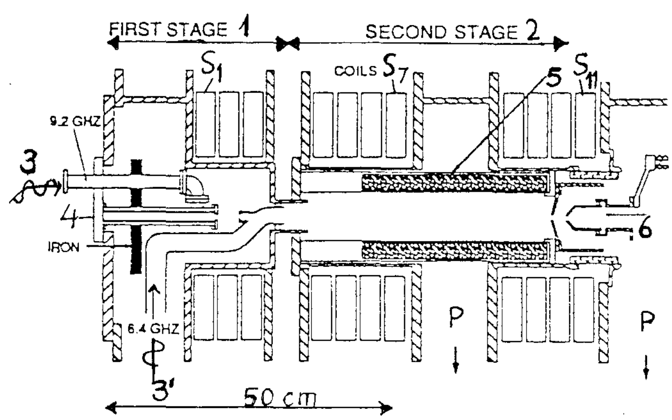

Fig. 10 : The LBL ECRIS : Note the two separated RF supplies 3 , and 3'.

us remind that in 1987 a 14 GHz MINIMAFIOS providing S^{12+} beams allowed to reach 6.4 TeV projectiles with the CERN S.P.S. complex and a 20 GHz source is presently proposed for the future CERN lead injector.

Conclusion : ECRIS are often conditionning the heavy ion physics and play an important role in its economy. They enable considerable reductions in size and cost of the new accelerator projects or considerable energy upgrade of present existing machines. ECRIS beams are today injected into all kinds of accelerators (RFQ, Linacs, Cyclotron, Synchrotrons). Today more than 20 ECRIS are operating with accelerators and in the next decade their number will increase considerably. The race for higher performances passes through higher ECR frequencies and superconducting magnets.

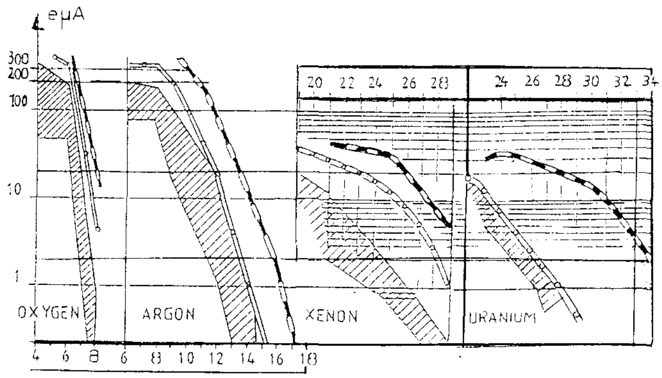

Fig.11 : Optimized ion currents vs q for O Ar Xe and U. The hachured zone contains data from various ECRIS ; double line Caprice high B, dashed line Minimafios 16 GHz - pulsed 1 HZ.

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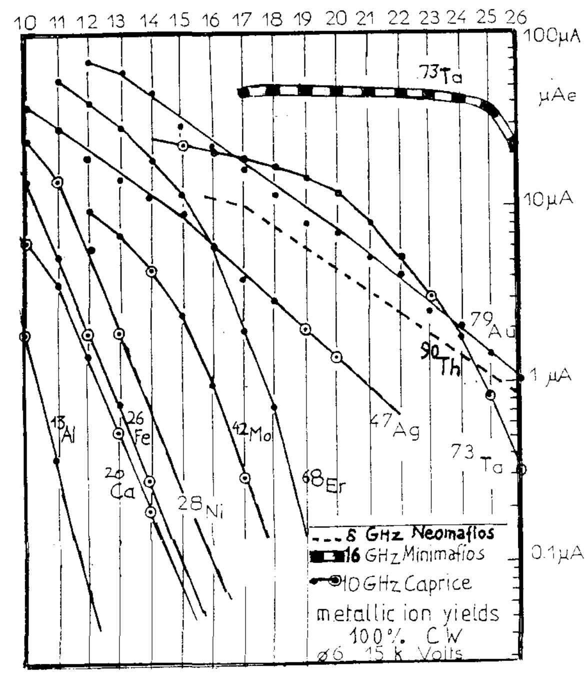

Fig.12 : Metallic ion yields CW vs (q)

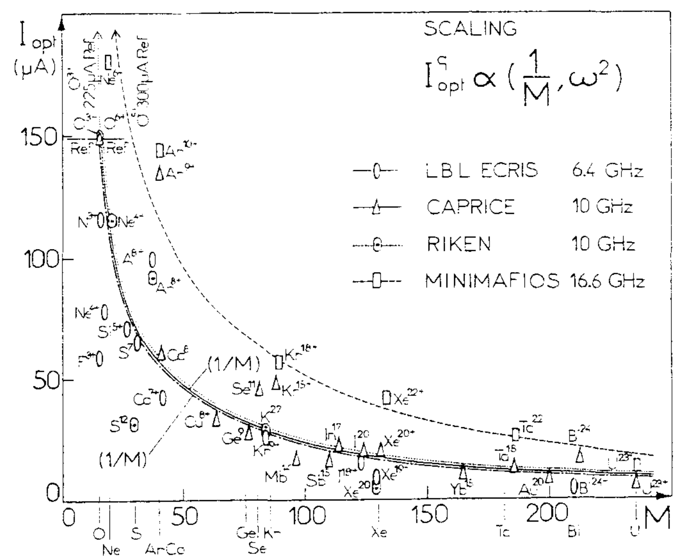

Fig.13 : CW Optimum Ion currents vs ion mass for four different ECRIS.

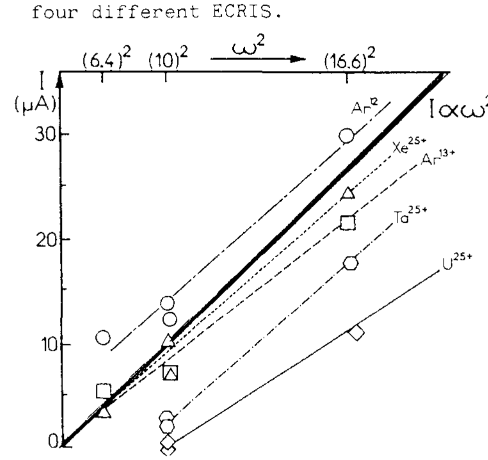

Fig.14 : CW high q currents vs (ω^2)for LBL 6,4 GHz, Caprice and Minimafios 10 Ghz and Minimafios 16,6 GHz.