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<u>Abstract</u> : The utilization of a performant high charged ion source plays a very important role in the general economy of heavy ion accelerators. Today only two types of Ion Sources are routinely working on accelerators : the EBIS and the ECRIS. We expose their basic commun principles but also their practical differences. Some examples of ECRIS realizations are shown and recent performances are given. We also propose some ECRIS scaling laws for further research and development.

### Introduction

Several parameters enter into the quality label of heavy ion sources : Reliability, high ion charge states, good beam emittances, convenient beam currents, etc. On the graphs fig. 1 we compare particle yields vs charge states for three of the most considered highly charged ion sources - the PIGIS[1] the EBIS[2] and the ECRIS[3]. We can more or less summarize these parameters by stating that today with a same normalized emittance of ~ 0.5 mm.mrad PIGIS give high yields of ions at rather low charge states, EBIS give small yields of ions but up to high charge states and work with short duration pulses, ECRIS give enough high charged ions in continuous and pulsed regimes. Let us just recall that ECRIS means Electron Cyclotron Resonance Ion Source. EBIS, Electron Beam Ion Source and PIGIS is the classical Penning Ion Source, However until the last decade Multiply Charged Ions (MI) were mainly obtained by the foil stripper method. Today, the ECRIS, associated or not associated with foil strippers is considered as the basic ingredient of heavy ion acceleration. This breakthrough is mainly due to the fact that the ECRIS is a robust, independant, external system at high vacuum, which does not introduce neither noise nor obnoxious gaz flow into the accelerators. According to their utilizers, they contribute even to better operation of the accelerators because they allow better tunings. This is attributed to the good stability, quiescence, brightness, energy dispersion etc... of the beam, due to the absence of filaments, arcs and turbulences inside the plasma.

We should also mention that MI can be obtained with laser techniques [4]. However the results of Laser Ion Sources are not yet quite ascertained and very little is published.

### 1.1. 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-times ionized ions is by successive ionization. We are then led to increase  $\tau$  the exposure time 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<sup>9</sup> cm.s<sup>-1</sup>.

We now summarize the M.I. production criterion for three typical cases : PIGIS :  $n\tau$  <  $10^9~cm^{-3}$  s ; w <  $10^9~cm.s^{-1}$ 

M.I. with low q.

1014 P/n P/n -10<sup>10</sup> (C 10 10<sup>12</sup> 10<sup>1.3</sup> (C) (Ь 1013 ·10<sup>9</sup>  $10^{12}$ 10 10<sup>12</sup> 10<sup>8</sup> 101 10 а (a 1011 109 ·**1**0<sup>7</sup> 10<sup>10</sup> DIONE-EBIS 1010 10<sup>8</sup> 109 OXYGEN ARGON CHARGES CHARGES

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<u>Fig. 1</u>: Comparative optimum yields (pps full lines) for EBIS (a), ECRIS (b) and PIGIS (c) - ECRIS work CW or pulsed - DIONE EBIS only pulsed with several bursts  $s^{-1}$ . Yields for one burst of 300 µs duration are shown (P/ $\pi$  dashed lines). For direct synchrotron injection of extremely charged ions, when a single burst is needed, DIONE is not overpassed by MINIMAFIOS. In all other situations ECRIS are unparalleled.

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EBIS, ECRIS :  $n\tau \sim 10^{10} \text{ cm}^{-3}\text{s}$ ;  $w > 2.10^9 \text{ cm}.\text{s}^{-1}$ M.I. with totally stripped light species. Projects :  $n\tau \sim 10^{13} \text{ cm}^{-3}\text{s}$ ;  $w \sim 10^{10} \text{ cm}.\text{s}^{-1}$ M.I. with totally stripped heavy species.

Fig. 2 shows typical mean charges <q> for Nitrogen ions versus nTw. They are obtained through "batch calculations" which are based on the knowledge of Ionization cross sections and assume that only the confinement time  $\tau$  limits the achievable charge[2]. No other loss mechanisms are considered. This method is not only suitable for EBIS but also for ECRIS if one looks for the charge optimum  $q_{opt}$  (which gives the maximum ion current in a peaked charge state distribution [14]). Note the very slow increase of q vs nwT.

# 1.2. <u>Basic</u> applications : the foil stripper - the ECRIS and EBIS

The foil stripping is based on the same criteria but in this case (fig 3a) 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  $n \sim 10^{24} \text{ cm}^{-1}$ . The relative interaction velocity w under these conditions, approximately equal to the transit velocity of the accelerated ions (a few  $10^9$  cm/sec). The interaction time will be that during which the ion passes through the foil ( $\tau \approx 10^{-14}$ s) and (nT) will thus be about  $10^{10}$  cm<sup>-3</sup>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. For this, it is necessary to have a plasma of cold ions that diffuses slowly through a plasma of hot electrons. One would obtain the same relative interaction speed if the cyclotron resonance yielded electrons of a few keV. Then one would have to create a hot electron target plasma that present a value of (n  $\tau$ )  $\approx 10^{10}$  cm<sup>-3</sup>s, similar to that of the solid stripper. In Fig. 3b we emphasize the symmetry between ECRIS and foil strippers. For foil strippers, ions are strongly accele-rated (through a cyclotron) prior to the electron-ion collision whereas for ECRIS the electrons are accelerated (through an electron cyclotron resonance). In the latter case, for identical relative collision velocities, the technology is much simpler and the equipment much cheaper. However, in the usual ECR plasmas the value of the hot electron density is only  $\sim 10^{12} \mbox{ cm}^{-3}.$  Thus one needs ionic lifetimes of ~  $10^{-2}$ s. Such ion lifetimes can only be obtained in sophisticated systems involving magnetic wells. Fig. 3c shows also the symmetry between ECRIS and EBIS where instead of magnetic ion confinement and instead of bulk electron resonance heating, the electrons are electrostatically confined and accelerated by potential differences. The main EBIS parameter is  $nw\tau$  where w is again the relative interaction velocity between fast electrons and slow ions.

# 1.3. The power flux limitations and the importance of the lifetime of energy in ECRIS and EBIS

In addition to long ion lifetimes for practical reasons it is also advantageous to have long lifetimes for the hot electrons. To explain that let us consider the flux of electron energy that is required to satisfy the stripped ion production. Writing  $\boldsymbol{\vartheta}_e$  for RMS electron velocity, this flux equals (assuming  $\tau \equiv \tau_{e1} \equiv \tau_{EN}$ , i.e., electron, ion and energy lifetimes identical):  $\boldsymbol{\vartheta}_e = 1/2 \ n_e \ \boldsymbol{\vartheta}_e \ kT_e \tau_{EN}$  where  $kT_e$  is the electron energy.



<u>Fig. 3</u>: In the foil stripper (a) the ECRIS (b) and the EBIS (c) the same relative collision velocity between the electron and ions with the same  $(n\tau)$  values give similar charge states of the multicharged ions (M.I.) But the short and intense interaction in (a) provides excited levels and additional ionization. (a) is the most efficient way but by far the most expensive one.

For  $% \left( {{{\rm{totally}}} \left( {{{\rm{stripped}}} \left( {{{\rm{argon}}} \right)} \right)} \right)$  we need as previously written

$$n_{\mu} \tau \approx 10^{10}$$
  $T_{\mu} \approx 5 \text{ keV}$   $\vartheta_{\mu} \approx 4 \times 10^9 \text{ cm s}^{-1}$ 

then  $\tau_{\rm EN}$  equals 1 s,  $\Phi_{\rm e}$  becomes ~ 16 kJ cm<sup>-2</sup>. But If in small plasma confinement devices,  $\boldsymbol{\tau}_{\text{EN}}$  the lifetime the energy hardly reaches  $10^{-3}$  s. Under these conof ditions, one has to create inside the plasma an electron power flux of ~ 16 MW cm<sup>-2</sup>. This is the typical case of an ECRIS. But if the lifetime of energy is  $<10^{-3}~{\rm s}$  the necessary power flux is  $>16~{\rm MW}~{\rm cm}^{-2}$  . This is typical for EBIS sources where the beam electrons are not confined but essentially passing through the plasma which explains the short lifetime of energy. For even shorter energy lifetime (~ 10<sup>-9</sup> s),M.I. production is still possible with laser impact but it requires now tens of millions of MW  $\rm cm^{-2}$ . With a microwave power of a few kW inside an ECRIS a way for achieving a continuous flux of 16 MW  ${\rm cm}^{-2}$  consists in creating an electron flow of, let us say, 1.6 kW cm<sup>-2</sup>  $(kT_{a} \approx 5 \text{ keV}, 0.32 \text{ A cm}^{-2})$  and forcing this flow to pass  $\sim 10\ 000$  times through the ion plasma (and the same 1 cm<sup>2</sup> plane). This is possible because in the ECRIS one traps the hot electrons and the ions (i.e., the plasma) in a efficient magnetic confinement system such as, for example, a high performance mirror. In an EBIS the electrons are concentrated in a unidirectional high density beam. To achieve an electron power flux of  $\ge$  16 MW cm<sup>-2</sup> another technique is utilized. For instance a beam of 1.6 A accelerated to 10 kV is magneto-focussed in such a way that its section in the plasma region is only  $10^{-3}$  cm<sup>2</sup>. The above mentioned power flux can then be achieved, but eventually the Brillouin flow limits such compressions. In addition it seems that EBIS are also limited by the power dissipation on the electrodes and by different hardly controlable wall effets (outgassing - secondary emis-sion, etc.). It is important to recall that in EBIS big amounts of power must be dissipated on small and fragile electrodes whereas in ECRIS less power is dissipated on large and rugged walls.

#### 2. EBIS techniques

Invented by D. Donets [2] the electron beam ion source is a linear containment device using an ultrahigh vacuum vessel (P  $\approx 10^{-9}$  to  $10^{-10}$  torr) and superconducting magnets. The basic configuration is shown in Figure 4. An electron beam is generated from a "gun" and magnetic focusing is provided by a solenoidal magnetic field. The beam goes through a series of cylindrical electrodes, while keeping a constant diameter. The geometric and magnetic axes are strictly colinear. This electron beam is energetic, intense, and dense. Its space charge radially traps ions, while successive potential distributions are applied on the electrodes -called drift tubes- either to avoid axial losses of ions (PD2) or to expel them toward the accelerator (PD3). The primary beam travels only once and blows up in the fringe field of the solenoid where it is collected on a water-cooled electrode. An electron repeller is biased below the cathode voltage to prevent electrons from entering the ionic line. In general EBIS work in pulsed regimes with a very strict duty cycle and most of its limitations look mainly technological. Achieving highly charged heavy ions needs highly focussed electron beams up to > 50 kV with beam densities of extreme values and then a very high beam power to dissipate on the electron collector without disturbing the ultrahigh vacuum. So the technology becomes very difficult. But in addition, it seems that the interaction time is somehow limited. This is perhaps occasioned only by thermal effects, unless the electrostatic well, due to negative space charge, is just filled up by the ions or/and beam plasma instabilities perturb the behaviour. Nevertheless beams containing ~  $5.10^9$  ions per second of  $C^{6+}N^{7+}$  and  $10^8$  ions of  $A^{18}$  could be achieved with several extraction bursts per second. But after a long world wide effort of R & D (different EBIS work for atomic physics) only one EBIS works presently for ion acceleration. It is the DIONE-EBIS at Saclay which is connected through MIMAS to the SATURNE Synchrotron [5]. To our knowledge, today, no other examples can be quoted.

#### 3.1. ECRIS techniques

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 always and an ECR plasma is ignited.

In ECRIS the electrons are delivered by such a plasma and not by a cathode ; they are accelerated by an oscillating electromagnetic wave at the frequency of the electronic cyclotron resonance  $\boldsymbol{\omega}_{\text{ECR}}$  and not by a potential difference. 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,  $\lambda$  = 3 cm). If the dimensions of the box are large with respect to the wavelength  $\lambda$ , 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 example, 0.2 and 0.5 T, then there must exist a magnetic surface where the field strength is  $B_0 = 0.36 \text{ T}$  (Fig. 5). On this surface the gyrofrequency of the electron is  $\sim$  10 GHz and thus equals the frequency of the microwaves. The ECR resonance necessarily occurs because in a multimode cavity there is always a component E of the electrical field of the waves that is perpendicular to the magnetic field



Fig. 4: General arrangement of an EBIS with pulsed successive potential distributions and its continuous magneto-focussed electron beam.

lines. In a 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 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  $n_{co} \sim 1.2 \ 10^{-8} \ (\omega/2\pi)^2$  in cm  $^{-3}$ .

Generally the source has two stages :

In the first which is at  $\leq 10^{-3}$  torr pressure a cold plasma is ignited by ECR 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.



<u>Fig. 5</u>: Main ingredients of an ECRIS-ECR surface in a magnetic well associated with a multimode microwave cavity.

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. Figure 6 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, microwaves are injected through a tight BeO window. Gene-rally 70 to 90 % of the power is absorbed in the plasma. The multimode cavity C is made of a box of stainless steel. 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 solenoids which are grounded. All the Grenoble built ECRIS utilize only one microwave generator for the two stages and three remote control buttons 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.

# 3.2. ECRIS prototypes

Among our ECRIS models [6] 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<sub>5</sub> permanent magnets with 4000 Gauss on the poles. Some Ion Currents are shown in Fig. 8. Typically emittances at 15 kV are  $\leq \pi$  50 mm.mrad. When a minimum energy dispersion is needed, small apertures in the extraction system help and energy dispersion of < 1 eV/charge have been measured with 0<sup>8+</sup> ion beams.

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. Ten MINIMAFIOS were built by our group for accelerators. However its power consumption (100 kW) is sometimes an inconvenient. Therefore we launched more compact sources.

Among them let us quote the 10 GHz CAPRICE source [7] elaborated by B. JACQUOT (Fig. 7). In this ECRIS in addition to its compact structure completely enclosed by a return yoke, the wave plasma coupling system differs from all others. It is achieved with a coaxial 10 GHz microwave accessibility. This allows a very compact two stages source in an entirely removable vacuum chamber without any microwave window in contact with the vapor. Thus CAPRICE is well fitted to produce metallic ions in long runs. The metal evaporator is constituted as usually in our other ECRIS by a metal sample approaching more or less the ECR surface.

In CAPRICE two different working modes are possible :

- A classical mode : with in average ~ 300 W RF power and 30 kW electrical power for the coils gives performances similar to MINIMAFIOS 10 GHz.
- 2. A high B field mode : with in average ~ 600 W RF power and  $\langle 50 \rangle$  kW power in the coils. In this mode the ion currents on high charge states are clearly increased. The reasons for that are not yet ascertained. On can suppose a) an additionnal resonance surface at  $2\omega_{\rm RF}$  [7] or b) simply assume a better magnetic confinement due to a higher average B field associated with more favorable B gradients. In Fig. 8 we see this effect for some gases. In Fig. 9 we see available ion currents for different metals. Let us emphasize that the natures of the mixing gases and the wall layers (coating) play an important role [14].

Another interesting prototype is NEOMAFIOS 10 GHz (1987) whose magnetic structure is entirely 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. Now its ion performances are nearly as good as our other ECRIS at 10 GHz [8] but further development is needed.



<u>Fig. 6</u>: The novel MINIMAFIOS can operate at 10, 14 and 16 GHz. The radial field Br is obtained with a fixed 0.8 Ts Hexapole. The solenoidal field Bz is variable (full line for 10 GHz, dashed line for 16 GHz. Note the small first stage (1) compared to second stage (2), the radial RF injection (3), gas inlet (4) Hexapole (5) extraction electrode (6). S<sub>1</sub> to S<sub>6</sub> are coils consuming ~ 130 kW power.



Fig. 7: CAPRICE Source : (1) Hexapole - (2) coils - (3) Closed ECR surface - (4) Water cooling inlet - (5) Water cooling outlet - (6) R.F. power inlet - (7) Gas inlet - (8) Turbo molecular pump (9) Ions extraction - (10) Gas inlet tube - (11) RF window - (12) Removable vacuum chamber.

Many other sources were built all the world over. Among the best let us quote the ORLN source (similar to MINIMAFIOS) [9], the LBL [10], LOUVAIN la NEUVE [11] and JULICH sources with separated 1st and 2nd stage RF supplies and in the last case a superconducting magnetic structure enabling 14 GHz operation[12]. Finally, let us mention the efficient iron yoke ECRIS with minimum B in the 1st and 2nd stage, working at 6,4 GHz and build by MSU [13]. Other ECRIS are being built in the USA, JAPAN and FRG. In short all of them behave more or less similarly and satisfactory with comparable performances in spite of some technical differences. In all cases they over-top by far the PIGIS as seen in fig. 8.

#### 3.3. ECRIS upgradings

All ECRIS utilizers now know that gas mixings and specific wall coating push the charge state distribution towards higher charges [14]. However we proposed recently some more general scaling laws for ECRIS upgradings [14]. In summary we find the following relations where B is the average magnetic trap field,  $\omega$  the incident RF frequency,  $q_{opt}$  the charge stage giving the maximum Ion current, I<sup>q+</sup> the value of this current and M the ion mass.

$$\begin{array}{ll} {\bf ntw} \propto {\bf B}^{1.5} & {\bf q}_{\rm opt} \propto \log {\bf B}^{1.5} & {\bf ntw} \propto \omega^{3.5} \\ \\ {\bf q}_{\rm opt} \propto \log \omega^{3.5} & {\bf I}^{q_{\rm opt}} \propto \omega^2 \ {\bf M}^{-1} \end{array}$$

These relations indicate a "soft" tendancy of upgrading by increasing  $\omega$  and B ; operating MINIMAFIOS sources at 14 and 16 GHz we could evidence the improvements in acceptable agreement with the above scalings (Fig. 8). A superconducting ECRIS at 30 Ghz is now developped in a joint MSU-Grenoble effort. Let us remind that in 1987 a 14 GHz MINIMAFIOS providing S<sup>12</sup>. beams allowed to reach 6.4 TeV projectiles with the CERN S.P.S. complex and a  $\sim$  20 GHz source is presently considered for the future CERN Lead injector.

#### Conclusion

Though work on LASER sources and EBIS is still continuing, ECRIS are today considered as the most suitable for accelerators. They 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). More than 20 ECRIS are presently operating with accelerators and in the next decade their number will increase considerably. Presently the race for higher performances passes through higher ECR frequencies. Soon we will learn if there are other limitations.

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Fig. 8 : Optimized Ion currents vs q for Oxygen, Argon and Xenon. The hachured zone contains various data from LBL, MSU and MINIMAFIOS for comparable ECRIS conditions. The double line is for CAPRICE high B mode, the dashed line for the novel 16 GHz MINIMAFIOS.



Pig.9 : Typical metallic-ion yields for TO GHz ECRIS-CW Dashed lines : MINIMAFIOS Full lines : CAPRICE high B mode

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