International conference on heavy ion sources.
Gatlinburg, USA, 27-30 October 1975
CEA-CONF--3385
FR7601383

ELECTRON CYCLOTRON RESONANCE MULTIPLY CHARGED ION SOURCES

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ABSTRACT : We describe three ion sources working in our laboratory, that deliver multiply charged ion beams. All of them are E.C.R. ion sources and are characterized by the fact that, the electrons are emitted by the plasma itself and are accelerated to the adequate energy through electron cyclotron resonance (E.C.R.). They can work without interruption during several months in a quasi-continuous regime. (Duty cycle : <.5). Their charge state distributions (C.S.D.) depend on the size and the characteristics of the plasma. For the smallest source the performances are comparable to those of P.I.G. sources. For the biggest source, the C.S.D. tend towards those obtained by EBIS type sources. Experimental results and guiding ideas concerning these three ion sources are reviewed.

The first E.C.R. ion source was built in our laboratory 10 years ago and the advantages of this type of source have been underlined in several of our previous papers.[1,2,3]. No need for electrical power supplies on the high voltage plateform, no electrode corrosion due to arcs. There are neither cathodes nor anodes in the discharges. The E.C.R. sources can work at low gas pressure, in continuous or pulsed regime, and are end-extraction sources. When heavy atoms are used in the source, highly stripped ions are produced through energetic electron impact on atoms and ions. Single collision processes such as Auger cascades and Shake off effects [5,6] but also step by step (i.e. multiple collision ionization requiring long ion lifetimes) are involved in the ion stripping.

1 - MAFIOS[7-13]

MAFIOS (Fig. 1.1) the smallest and simplest of our sources is a one stage ion source where E.C.R. is produced on one side of a magnetic bottle and ions are extracted on the other side. The source can deliver a total beam of tens of mA. The emittance of a total Nitrogen ion beam of 23 mA at an extraction voltage of 12 kV was measured and found to be 290 mm/mrad[13] (Fig. 1.2 and 1.3). The source body is made of a quartz tube situated in a magnetic bottle. The quartz tube is placed on the axis of an electromagnetic resonant cavity. Electromagnetic energy leaking out of the cavity creates in the capillary tube a cold plasma. There the local pressure is of the order of 10^{-3}Torr. This cold plasma diffuses along a magnetic field gradient and a pressure gradient and the electrons penetrate in a region where locally E.C.R. occurs ($\omega_{RF} = \omega_c^- = 2\pi 10$GHz ; $P_{RF} \sim 2$kW). Here the electrons are heated up to kilovolt energies (Appendix 1) and are therefore able to ionize and create highly charged ions. In addition the electrons are more or less accumulated in the magnetic bottle, their average perpendicular energy $W_\perp$ being greater than their parallel one. Local pressure inside the magnetic bottle is of the order of 10^{-5}Torr, gas consumption is very small (~ 1cm^{3}Torr/sec.) and the source is at a high positive potencial with respect to the grounded extractor. The power supplies for the magnetic field are grounded. The extraction hole in the source has a diameter of 4 mm. The pressure in the extraction region is of the order of 5.10^{-6}Torr. In normal use, the source is pulsed : pulse width may be adjusted, H.F. pulses last from .1 to 10 ms. Repetition rate can be adjusted so that the duty cycle is varied between 10^{-2} and .5. The cavity resonnates, when empty, on a TE_{321} mode at 10 GHz. A diamagnetic loop passed around the quartz tube gives, under working conditions, values of n k T^- up to 6.10^{12} eV/cm^3. The electron density n is measured with an 8 mm wavelength interferometer. The electron mean number density is $5.10^{11} < n < 3.10^{12}$ depending both on neutral gas pressure in the source and R.F. power incident on the cavity. The electron life time τ^- can be evaluated by n k T^-x vol./P_{RF} absorbed $\simeq 10^{-5}$sec. If $\tau^+ \simeq \tau^-$, then the product $n\tau^+$ never exceeds some 10^7.

The most significant result of this simple E.C.R. ion sources is to give currents and charge state distributions comparable to those of radial P.I.G. sources without short lived cathodes and tortured emittance diagrams. This is already an encouraging result. However, important quantities of very highly charged ions are not produced in MAFIOS. Their production rate is balanced by recombination and charge exchange due to the relatively high gas pressure, and also limited by the short particle life time due to some turbulence inside the plasma.[8-11]

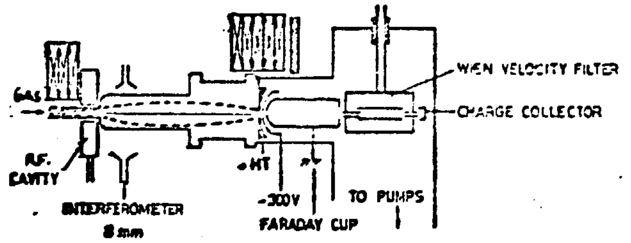
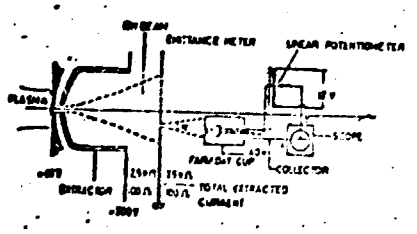


fig.1.1. Experimental device. MAFIOS



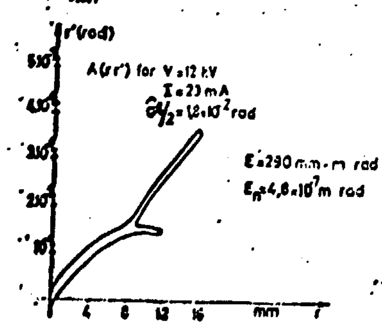


fig.12. Emittance diagram at V = 12 KV, MAFIOS

2 - SUPERMAFIOS

2.1. GENERALITIES. In order to improve the results of MAFIOS and reach better C.S.D. is was necessary[15,16]

a) to decrease de gas pressure in the source,
b) to maintain the hot electron density n,
c) to increase the ion life time τ^+ as much as possible (i.e. to obtain $n\ \tau^+ max$).

In addition we looked for the following conditions :

d) High duty cycle (quasi continuous regime suitable for cyclotrons),
e) no electrodes or short lived cathodes,
f) no advanced technology.

To fullfill the pressure requirements, the new device called SUPERMAFIOS is divised into two stages separated by an efficient differential pumping. This device is of large size in order provide considerable gas conductance for high speed pumps. It permits the plasma to be created in a high pressure region, to be heated and accumulated in a low pressure region. The main equipment and structure for the new device was furnished by the CIRCE experiment which was formerly a mirror machine for fusion research[17,18]

2.2. DESCRIPTION. A sketch of the experimental apparatus and magnetic field profiles are shown in Fig. 2.1. The first stage is a plasma injector. A plasma having already some multiply charged ions is created from a ~ 10^{-3}Torr background gas in a U.H.F. cavity by a first electron cyclotron resonance. (Available R.F.$_1$ power < 15 kWatts, $\omega_{RF_1} = \omega^-_{c1} = 2\pi 16$GHz, $B_1 \sim .6$ Tesla).
There are no filaments or limited lifetime electrodes in the injector. As in MAFIOS, the electrons are emitted by the plasma itself and accelerated by the R.F. electric fields. The plasma's electron energy can be experimentally controlled and theoretically evaluated. (Appendix 1 and 2).

The injector plasma diffuses along a decreasing magnetic field toward the machine second stage which consists of a prapagating electromagnetic wave inside a magnetic bottle. The magnetic bottle is superimposed with a large diameter magnetic hexapole field to create a minimum B configuration (its purpose is to damp out some strong turbulence).

Inside this field configuration the right hand polarized propagating wave is absorbed by the plasma as the electrons pass one or several times through resonances (RF$_2$ power < 20 kW, $\omega_{RF} = \omega^-_{c2} = 2\pi 8$Ghz). As the E.C.R. resonances increase the electron's perpendicular energy, (Appendix 2) the electrons increase their lifetime τ^- and become confined to the magnetic field structure. In turn, the ions, bound to the electrons by an ambipolar force also increase their lifetime τ^+ inside the dense hot electron plasma. They suffer now further hot electron-ion impacts ; and whatever is the nature of the collision (step by step, Auger or Shake off ionization)[24,25,26,48,49] the ions increase their charge Z. The cold electrons generated inside the second stage (which are obnoxious because they promote the ion recombination) are either expelled through the loss cone and the magnetic leaks of the hexapolar field or heated up by E.C.R. and confined.

2.3. EXPERIMENTAL RESULTS WITH SUPERMAFIOS.[15,16,17,20]

Plasma characteristics. Different gases such as N^2, CO^2, He, A, Kr and Xe have been tested in the device. For instance Fig. 2.2 gives some interesting Xenon plasma characteristics in the second stage versus RF$_2$ power P$_2$ when RF$_1$ power P$_1$ in the first stage is kept constant (100 Watt) and pressure is 10^{-7}Torr

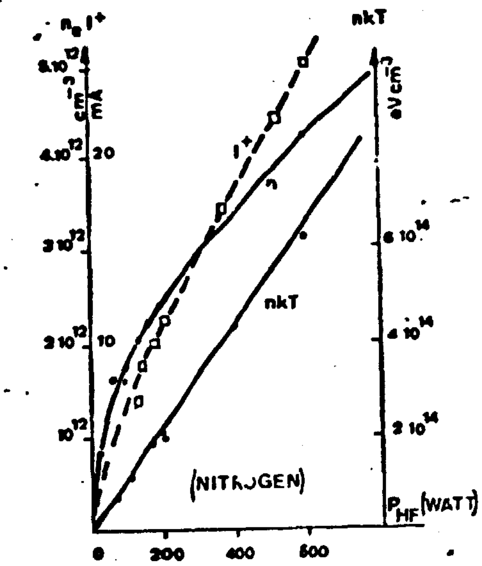


Fig 1.3.

MAFIOS DIAMAGNETISM ION CURRENT & DENSITY f (ABSORBED RF POWER)

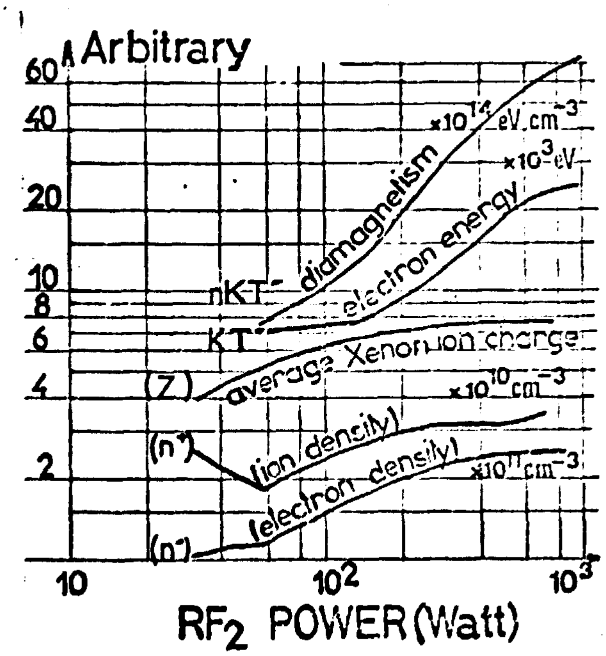


fig 2.2.

Plasma characteristics versus RF$_2$ power when RF$_1$ power (~100 W) and Xenon pressure in the second stage (~10^{-7} torr) are kept constant.

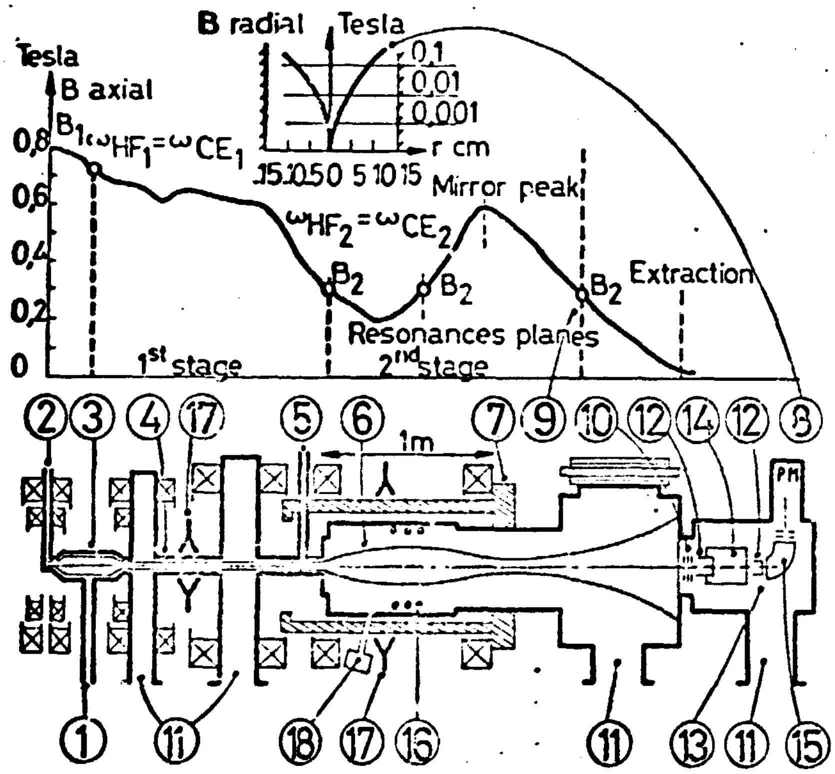
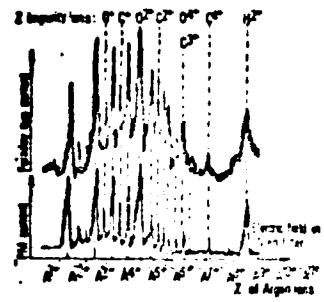


fig. 2.1.

1) Gas injection; 2) Wave guide for RF_1 (16 GHz); 3) UHF cavity – source of plasma to be injected; 4) Diffusion zone; 5) Wave guide for RF_2 (8 GHz); 6) Accumulation zone for hot plasma; 7) Hexapole field coils; 8) Radial magnetic field; 9) Axial magnetic field; 10) Ion extraction; 11) Vacuum pumping; 12) Retractable faraday cup; 13) Ion abundace measurement; 14) Wien filter; 15) Energy analyzer; 16) Diamagnetic loop; 17) Microwave 8 mm interferometer for density measurements; 18) Beryllium window for X ray measurements.



Argon C.S.D.
fig 2.6. & 2.7.

fig 2.3. Expanded by 4

Xenon ions spectrum with some impurity ions

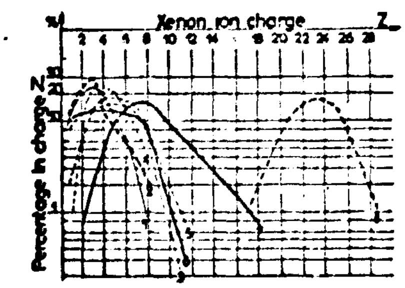


fig. 2.5. Xenon abundances for different ion sources.

Orgl.	Source type	Observation	∅ dutycycle
1	Duoplasmatron	End extraction	1
2	PIG	End extraction. Cold cathode	$<3.10^{-3}$
3	PIG	Side extraction. Indirect cathode	$<10^{-1}$
4	PIG	Side extraction. Self heated cathode	1
5	PIG	Side extraction. Cold cathode	<0.74
6	E.C.R. "MAFIOS"	Electrodeless, one resonance. End extraction	<0.3
7	E.C.R. "SUPERMAFIOS"	Electrodeless, multiple resonance. End extraction	<0.3
8	Electrostatic well "CRYON"	Batchtype. Electron gun. End extraction	$\sim 10^{-4}$

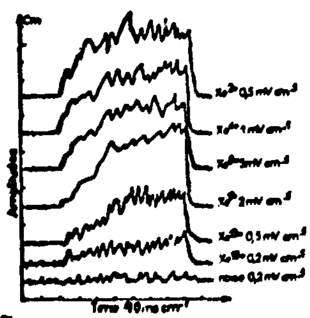


fig. 2.4.

typical Xenon ion currents given by the multiplier versus time.

$(N_o = 3 10^9 cm^{-3})$. In this particular case we notice that it is useless to increase P_2 above 1 kWatt because all the power is tranferred to the diamagnetism whereas the average Xenon ion charge does no longer increase. Let us emphasize that the ratio n^-/No reaches ~ 80 and n^+/No ~ 10.

The hot electron density is found from the perpendicular energy which is measured with a diamagnetic loop, and the total electron density from a U.H.F. interferometer. The ion analysis showed ion energy spreads ΔW that varied proportionally with the charge Z. For the single charged ions, the FWHM energy spread varied between 30-70 eV depending on plasma condition.

Charge state distributions. To make C.S.D. measurements, the plasma which leaves the bottle is allowed to diffuse towards an extraction electrode having a 6,5 mm diameter orifice. In this region B ~ 0,01 Tesla and the plasma density is less than 10^{10}/cc. By using a system of 3 electrodes, ion beams of some 10^{-5} Amps. can be formed, accelerated to some KV, and passed into a Faraday cup. Part of the current entering the cup is then passed into a Wien type velocity filter having crossed electric and magnetic fields. For a given acceleration voltage V, Wien filters only pass particles having a given Z/M. To better appreciate the different ion currents, the Faraday cup behind the filter could be replaced by an electrostatic analyzer and a high gain photomultiplier tube. The system then permits measuring the energy spread of an ion species, and provides more resolution for separating the charge states Z. Also, by making measurements through a time "window" at various time positions, the evolution of the ion abundances during the plasma pulse could be studied. The plasma studied is formed by a synchronous pulsing of the two R.F. frequencies for 0,05 - 0,3 sec at a 0,05 - 1 Hz repetition rate. The ion analyzer system has been described in great detail in[22,23]. Fig 3.7 & Fig 3.8. The Fig. 2.3, shows the abundance spectrum of the different Xenon ions using the photomultiplier.

Fig. 2.4, shows the current for different Xenon species versus time. Let us notice that Xe^{13+} and Xe^{18+} ions are already produced at the very beginning of the RF_2 pulse. This is probably due to Auger processes and shake off collisions. However their current increases with time due to step by step ionization whereas the weakly charged Xe ion current reaches its equilibrium much earlier[26].

Fig. 2.5, exhibits optimum Xenon abundance obtained in Duoplasmatrons[27] PIG discharges.[28,29,30,31] Electrostatic confinement ion sources[32] and E.C.R. ion sources (θ is the utilisation time par second, i.e. current duration x repetition rate).

Fig. 2.6, shows the abundance of Argon currents collected by the Faraday cup. Fig. 2.7, gives the same case with the complete analyzer system ; it shows that the secondary emission of the photomultiplier tube varies with the incident ion's charge in a complex manner and that the addition of the electrostatic analyser increases the resolving power of the detection system.[22] Fig. 2.8, shows typical abundances obtained with SUPERMAFIOS for different gases.[21]

Let us now summarize some outstanding characteristics of SUPERMAFIOS. The product $n^-\tau$ is ~ 10^5 :

- The average charge of the ion beam is substantially higher than that of PIG discharge and there is a smooth tail towards the highest charges whereas in PIGS there is an abrupt cutoff.
- The highly charged quasi continuous ion flux is about 10^{11} to 10^{12} p/p/s. which is better than the equivalent charged ion flux of the Donets source.
- However the Donets source can give higher ions in batch type operation with 10^{-4} duty cycle.[12]

Anyhow future nuclear accelerators need still higher ion fluxes and higher charge states. Therefore the performances of SUPERMAFIOS ought to be still improved.

3 - TRIPLEMAFIOS

3.1. GENERALITIES. In order to increase $(n^-\tau^+)$ two possibilities were envisaged : either to raise the electron density n^- or to extend τ^+ the exposure time of the ions to the hot electron plasma. It is technically easy to raise n^- by increasing the microwave frequency ω_{RF}. This allows to raise the plasma frequency ω_p in a E.C.R. plasma the following relation is generally fullfilled :

$$\omega_{RF} \sim \omega_c^- = \frac{Be}{m} > \omega p = \left(\frac{n^- e^2}{\varepsilon_o m}\right)^{1/2}$$

and the increase of $n^- \alpha\ (\omega_{RF})^2$ has been verified in several E.C.R. experiments.[44,45] Unfortunately each variation of ω_{RF} necessitates a subsequent variation of the B field in order to satisfy the E.C.R. condition $\omega_{RF} \sim \omega_c^-$. An increase of ω_{RF} means in other words to rebuild entirely the magnetic structure of SUPERMAFIOS. In addition it was not sure that such an alteration would not damage the value of τ^+. Therefore we prefered the cheaper way which consisted to extend the exposure time τ^+, as much as possible.

However if τ^+ is the most crucial parameter for stripped ion production, it is also the least foreseeable and plasma theoreticians are aware of this. When clear mathematics fail, hazy semantic helps..... So let us call τ^+ : << The average ambipolar diffusion time along the z axis from the entrance A to the exit B of the hot electron plasma >>. Fig. 3.1 and 3.2. It is a rule in Plasma Physics to teach that ambipolar diffusion is controlled by the slowest particle (Perpendicular to B : $\mathcal{D}_{\perp amb} \simeq \mathcal{D}_\perp^-$; parallel to B : $\mathcal{D}_{//amb} \simeq \mathcal{D}^+_{//}$). If along the z axis the magnetic field is corrugated, the parallel ambipolar diffusion is such that near the mirrors the electrons slow down the ions and inside the bottle the ions are slowing down the electrons. If we also assume that the overall perpendicular losses are smaller than the parallel end losses, one can propose an average diffusion time $\langle\tau_{dif}\rangle$ along z given roughly by :

$$\langle\tau_{dif}\rangle \ \alpha\ \Sigma \left(\frac{L_1^2}{\mathcal{D}_\perp^-} + \frac{L_2^2}{\mathcal{D}_\perp^-} + \ldots \frac{l_1^2}{\mathcal{D}^+_{//}} + \frac{l_2^2}{\mathcal{D}^+_{//}} \ldots\right)$$

$$\simeq \Sigma \frac{L_1 + L_2 + \ldots l_1 + l_2 \ldots}{\langle v\rangle} \simeq \frac{Ltotal}{\langle v\rangle}$$

In this heuristic formula : L_1 L_2... are mirror lengths ; l_1 l_2 intermirror lengths, $\mathcal{D}_\perp^-$ and $\mathcal{D}^+_{//}$ are respectively the electronic and ionic diffusion coefficients and <v> the average axial ambipolar diffusion velocity for random steps due to Coulomb collisions. The ionicself collision time in a plasma as given by Spitzer is :

$$t_{ii} \sim \frac{11,4\ A^{1/2}\ T^{3/2}}{n\ Z^4\ \log \Lambda}$$

where Log Λ ~ 10, the Atomic weight A = 1 for a proton, $n(cm^{-3})$, $T(°K)$, and Z being respectively the ionic density, temperature and charge. Due to the relatively high values of n and Z our plasma is collision dominated (i.e. $t_{ii} \ll \tau$) which makes sense when one considers a normal diffusion regime. (Turbulent Bohm diffusion is supposed to be damped out by the hexapolar field). Under this

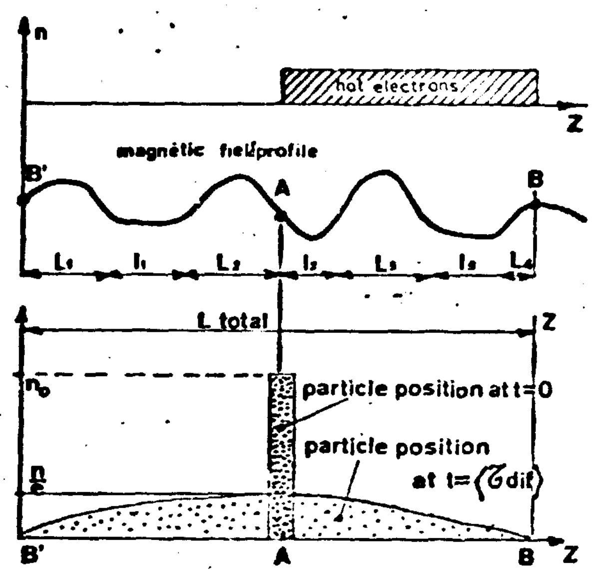


Fig 3.1 et 3.2

Ambipolar Particle diffusion from A to B, $\langle \tau_{dif} \rangle$ is the decrease time of the density from n_0^+ (at point A) to $\frac{n_0}{2.71}$ corresponding roughly to the arrival time of the particles to points B and B'

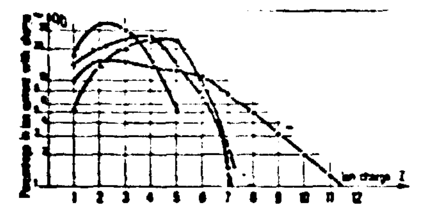


fig.2.8:
C.S.D. various gases in Supermafios

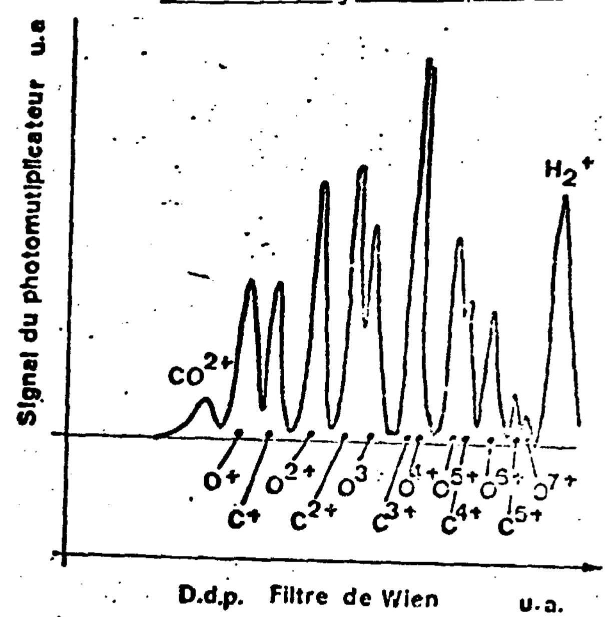


Fig 3.4 Carbon & Oxygen C.S.D. in Triplemafios

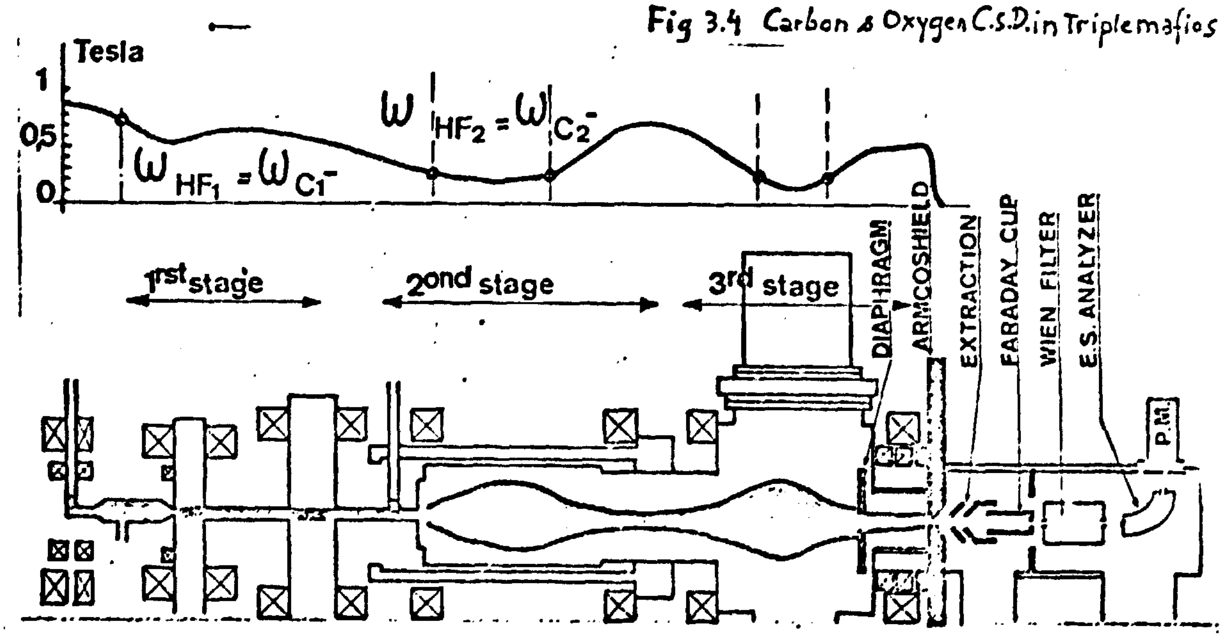


fig. 3.3.

condition, and this condition only, it seems advantageous to increase the number of magnetic hurdles and to enlarge the electron ion interaction zone along the z axis. According to this over-simplified model we lengthened the hot electron plasma, by adding a third stage and SUPERMAFIOS became TRIPLEMAFIOS.

3.2. ION EXTRACTION AND ANALYSIS. To achieve higher ion beam currents we located the first extraction electrode close to the mirror zone where the plasma density is supposed to be concentrated. However in order to obtain a good emittance for the ion beam, an Armco Shield cancels abruptely the B field before the ions enter into the acceleration gap. The plasma expansion cup is carved directly in the magnetic shielding plate. The extraction holes are Ø ~ 15 mm and the new extraction electrodes are shown (Fig. 3.3). A 15 cm long, 3 cm diameter, Faraday cup measures the total ion current. On the bottom of this Faraday cup we pierced a thin slot and the few particles which pass through this slot can reach the Wien Filter and their C.S.D. can be monitored. Unfortunately the present vacuum pumping in the extraction box is insufficient ; when an ion beam of more than 1 mA is captured in the Faraday cage the subsequent outgassing leads to charge exchange inside the cage which deteriorates the C.S.D. Therefore the best abundances are obtained when we extract only a fraction of the available ion current by inserting a diaphragm in the plasma mirror zone. Thus the system is far from optimisation.

3.3. PRELIMINARY PERFORMANCES OF TRIPLEMAFIOS. TRIPLEMAFIOS is presently working for one month and the results must be considered as preliminary. On Fig. 3.4 we show the C.S.D. when CO^2 is used as test gas[14]. Table 1 compares the results of SUPERMAFIOS and TRIPLEMAFIOS for roughly the same R.F. powers, gas pressure and B field configuration in the first and second stage. The plasma diamagnetism and density are also very similar in both cases, but the total extracted current from TRIPLEMAFIOS was 300 μA, and from SUPERMAFIOS 30 μA.

Thus not only the ion beam current is increased but also the average charge <Z> which indicates that $n\tau^+$ has substantially increased. If we assume that the analyzed sample is representative of the captured ion current in the Faraday cage, then TRIPLEMAFIOS is presently capable of delivering in quasi continuous operation ~ 10^{14} particles/sec. of C^{5+} and O^{6+}. This very important assumption has to be verified carefully. So our next task will be to measure the emittance per specie, in order to check if the C.S.D. is homogenous throughout the radius of the ion beam. We also introduced some Krypton gas into the CO^2, just enough to monitor a Krypton C.S.D. spectrum. Fig. 3.5. shows the results. The average <Z> of the Krypton ion beam is higher than 7. 5% of Krypton 15^+ particles were clearly measured.

Fig. 3.6., shows the C.S.D. spectrum for Neon with a 200 μA beam in the Faraday cup. On the same figure we give the best results obtained for Neon in a PIG[17]

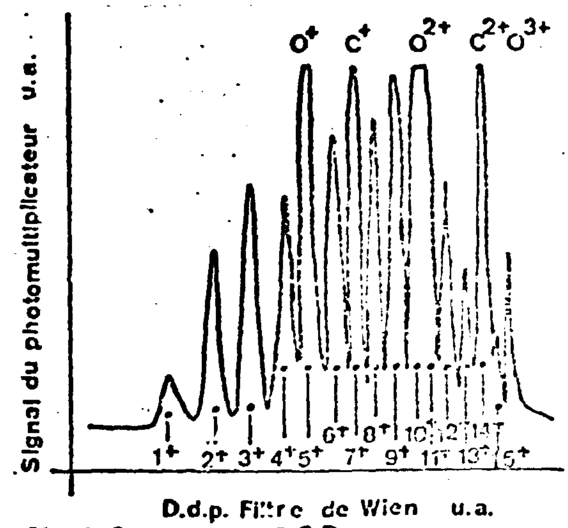


Fig. 3.5 krypton C.S.D.

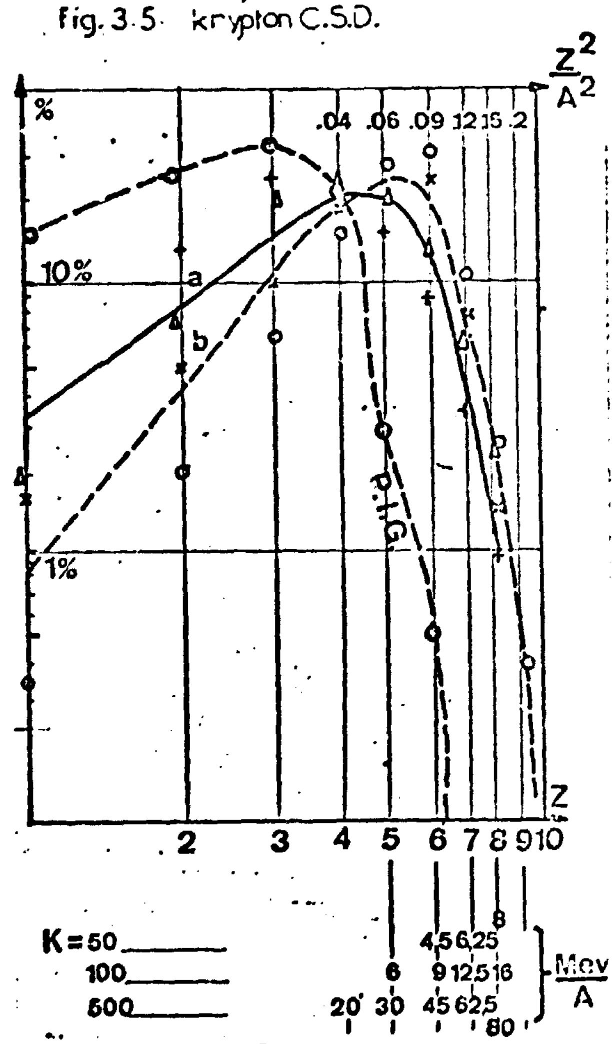


FIG. 3.6.

NEON C.S.D.

a) particle abundance $\frac{+}{x}$

b) abundance in electr. current

4 - COMPARISIONS AND EXTRAPOLATIONS

4.1. Numerous theoretical studies and previsions were devoted to stripped ion sources, and we will not rewrite equations which have been derived and well derived by different authors.[48-55] Our question is : Is it possible to apply these studies to TRIPLEMAFIOS ? The answer is yes if one handles the same parameters and speaks the same language.

Fig. 4.1., for instance gives the probability for charge states of Neon versus τ in a batch type source (losses are neglected) when Neon atomes are exposed to a cloud of 13 keV electrons with 2.10^{10} cm^{-3} density. (Computed by Sargent James quoted in ref.[47] We can compare these previsions with our results of Fig. 3.6, provided that we forget about the Neon abundance data (which are the balance of creation and destruction) and consider only the presence of a given charge state. For instance we obtain clearly Ne^{3+} particles. (~ 3% of the total current). Accordigg to Fig. 4.1 such particles need $4.10^9 < n^-\tau < 10^{10}$; n being measured in TRIPLEMAFIOS ($n \sim 2.10^{11}$) we can deduce that τ must be comprised between 20 and 50 m/sec.

One can argue that Fig. 4.1. was obtained on the basis of Bethe's ionization cross sections. If one takes into account Auger cascades τ would propably decrease by a factor of two.[53] Considering $\tau \equiv \langle\tau_{dif}\rangle$ we can under these conditions approximate experimentally the value of $\langle v\rangle$ for Neon in TRIPLEMAFIOS.

$$\langle v\rangle = \frac{L_{total}}{\langle\tau_{dif}\rangle} \sim 2.10^{4} cm/s^{-1}$$

It is important to notice that this experimental value of $\langle v\rangle$ is at least 20 times smaller than v^+ the velocity of a 1 eV Neon ion. A ratio of $v^+/\langle v\rangle = 20$ involves strong ambipolar retention along the z axis. In fact we find that $\langle v\rangle \sim v_{thermal}$ of the gas atom ; this is a curious result.[56] Taking again data from[47] and considering Uranium one can also speculate on Uranium ion yields in TRIPLEMAFIOS, and one would expect comparable yields of U^{25+} and Ne^{3+}. The same conclusion can be drawn if we compare TRIPLEMAFIOS with MEBIS previsions![50-52] If we assume again that $\langle v\rangle \sim v^+/20$, and that U ions have an energy of a couple of eV, we can directly use the MEBIS diagram of Fig. 4.2 and locate TRIPLEMAFIOS on the diagram. We see again that U^{+25} ions should be available in TRIPLEMAFIOS (After all if Kr^{15+} ions are created, such a performance looks feasible).

4.2. On the same Fig. 4.2 we propose also a bolder extrapolation. Let us consider the Uranium characteristics of TRIPLEMAFIOS unchanged except for ω_{RF} and subsequently B. (i.e. considering that $\langle v\rangle$ remains what it is presently). On the abscissa we plot ω_{RF} ($\sim \omega_c^- > \omega_p$) for commercially available microwave equipments. With a 56 GHz generator TRIPLEMAFIOS should furnish up to U^{50+} ions !

4.3. Let us come back to our oresent experimental results and consider what kind of energy per Nucleon one would expect if TRIPLEMAFIOS ions were injected into cyclotrons with multiplication factors k equal to 50, 100 and 500. Considering for instance Neon ions we see that energies up to 80 MeV/A should be reached with one big separated sector cyclotron. Fig. 3.6.

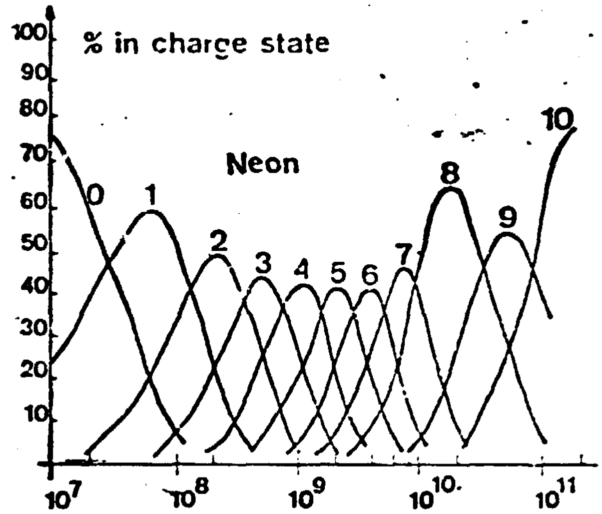


FIG. 4.1.

Neon C.S.D. vs $(n\tau)$ W^- = 13 KeV

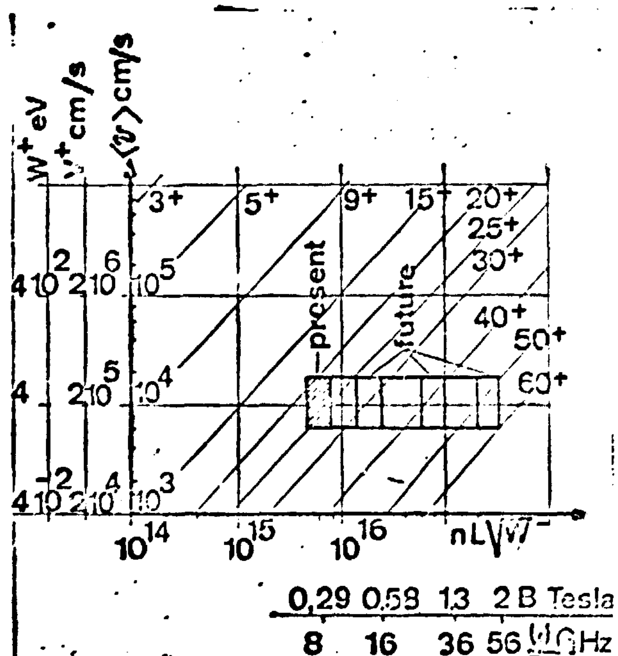


FIG. 4.2.

Step by step ionisation of uranium

in triple mafios (L=200cm)

V^+ ion velocity $(cm\,s^{-1})$

n electron density (cm^{-3})

$\langle v\rangle$ ambipolar diffusion velocity along Z

W^+ ion energy W^- electron energy $(10^4 eV)$

APPENDIX 1

(Single passage through the resonance)

Several theoretical models have been proposed[33-39] in order to relate the electron energy W^- (or velocity v^-) to the E.C.R. conditions (i.e. to the magnetic field parameters B_o and dB/dz) and the microwave power P and the electromagnetic field E. It was found by[33,34] that the magnetic moment μ of the thermal electron after one passage through the resonance becomes :

$$\mu = \frac{W_\perp^-}{B_o} \sim \left(\frac{5,8\ g^3}{\frac{m^-}{m^+}\ \delta^2}\right)^{2/5}$$

where $g = \frac{eE}{m^- C}$ is relative to the microwave characteristics and

$\delta = dB/dz/B_o$ is relative to the B gradient around the resonant field B in the E.C.R. region. ($C = 3\,10^{10}$)

The final perpendicular velocity of the electron leaving the E.C.R. zone is then proportional to

$$v_\perp^- \sim E^{6/5}\ \delta^{-4/5} \sim P^{3/5}\ \delta^{-4/5}$$

Assuming that the initial parallel velocity is small with respect to the initial perpendicular velocity, a slightly different scaling law was found by[38,39]

$$v_\perp^- \sim E\delta^{-2/3} \sim P^{1/2}\delta^{-2/3}$$

APPENDIX 2

(Many passages through the resonance)

The energy gained at the resonance is strongly dependent upon the electron wave phase. During the successive passages through the resonance, (i.e. in the case of mirror reflections) the electron can be either accelerated or decelerated. In[38,39] it is shown that the wave electron interaction can be considered pratically as a stochastic process. This stochastic heating is limited by adiabatic invariants depending on the electric field. With our experimental parameters, the energy may take an upper stochastic limit W_s and an ultimate adiabatic value W_B given by :

$$W_{s\,(keV)} = 7,2\ E^{3/4}_{(V/m)}\ ;\ W_{B\,(keV)} = 36\ E^{3/4}_{(V/m)} \sim P^{3/8}_{(W)}$$

these energies can be reached in some microseconds. A numerical simulation has been done using ref /34/'s model for the electron movement.[2] The results are in agreement with those of[38,39]

The plasma life time has also been calculated[42] in the case of hot electron Hydrogen plasma ($T^- \gg T^+$) :

$$n\tau_{(cm^{-3}s)} = 1.63\,10^{10}\ \left(\frac{m^-}{mp}\right)^{1/2}\ (T^-)^{3/2}_{(keV)}\ Log_{10}R$$

mp being the proton mass and R the mirror ratio.

The dependence of $n^-\tau$ with $\langle Z \rangle$ and $m^+ > m_p$ is not clear as yet. Anyhow the previous calculations lead to a negative potential of some 10^2 eV in the magnetic trap. Such a negative potential has never been experimentally evidenced in SUPERMAFIOS.

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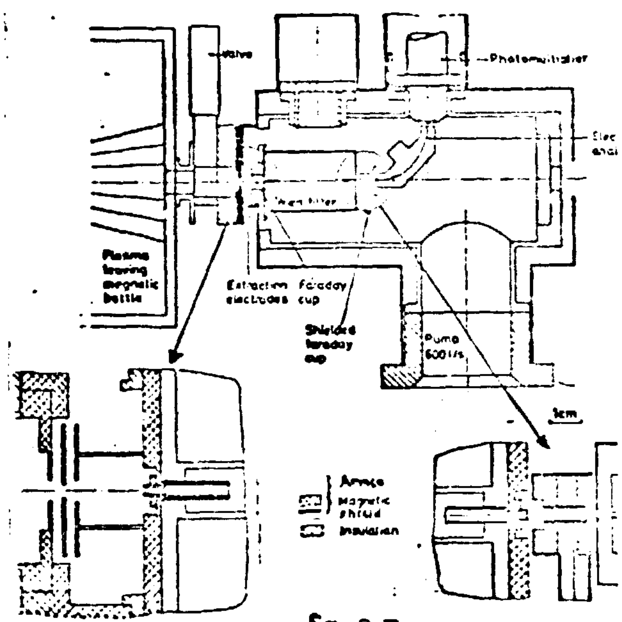

fig. 3.7. Schematic of apparatus used for measuring abundances of heavy stripped ions.

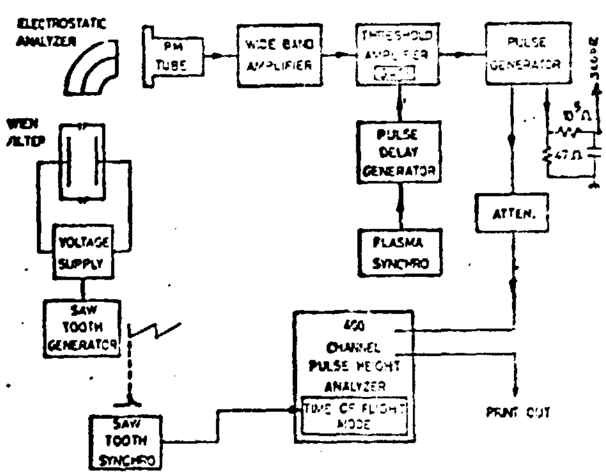

fig. 3.8. Pulse counting detection system used for measuring ion abundance.

CARBON	1+	2+	3+	4+	5+	6+		
SUPERMAFIOS	35%	35%	20%	8%	2%	?		
TRIPLEMAFIOS	18%	36,5%	23%	17,5%	5%	?		
OXYGEN	1+	2+	3+	4+	5+	6+	7+	8+
SUPERMAFIOS	27%	26%	20%	16,5%	7%	3%	0,5%	?
TRIPLEMAFIOS	12,5%	22,5%	18%	17,5%	16,5%	11%	2%	?

TABLE 1

TABLE 1 - Particle abundance of Carbon and Oxygen. Comparison between Supermafios and Triplemafios working with the same plasma characteristics except for the length.