SOURCES FOR HIGHLY CHARGED IONS - THE ECRIS STATUS -

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Summary

The performances of PIGIS, EBIS and ECRIS are shortly reviewed. Ion current and charge state are compared for continuous or pulsed operation. The principle of highly charged ion production inside plasmas is explained. The importance of the plasma confinement system is underlined after comparison between foil strippers and plasma strippers. Special emphasis is put on the ECR ion sources and their development for accelerators. The most recent results for gaseous and metallic ions are given. Present and future development of highly charged ECRIS are discussed.

Generalities

Heavy Ion Physics is today a major scientific aim. At low energies new types of atomic collisions open a field of interest and development in X ray spectroscopy, atomic physics, ion/surface physics and also Fusion Technology where the heavy impurities play an important role in Tokamaks. At medium and high energies, heavy ions are now a major topic for Nuclear Physics where more and more facilities are switching over from light to heavy ion acceleration. Eventually relativistic and ultrarelativistic heavy ion colliders are now under consideration. (The theoreticians of the Quantum Chronodynamics anticipate that the nuclear matter will appear in a new state : the guark gluon plasma).

But whatsoever is one's objective one has to begin with the best beginner, e.i. the most performant heavy ion source for the accelerators. Several ingredients enter into the quality label of such an ion source : Reliability, Simplicity, Versatility and Longevity are general qualities, but more decisive parameters are High Ion charge states, good beam emittances, high brightness, convenient beam currents, etc.

Therefore let us compare on the graphs Fig. 1 these decisive parameters for three of the most considered highly charged ion sources - the PIGIS, the EBIS and the ECRIS [1][2][3]. We can more or less summarize these parameters by stating that today with a normalized emittance of 0,1 to 1 mm.mrad PIGIS give high yields of ions at rather low charge states ; EBIS give smaller yields of ions but up to high charge states and work with short duration pulses adequate for synchrotrons ; ECRIS provides high charged ions in continuous and pulsed regimes and seems convenient for many accelerators. 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. In the next chapter we built the bridge between this method and the heavy M.I. sources.

1.1. Criteria for multiply charged ion production

The probability of producing M.I. (multiply charged ions) by a single electron impact falls off rapidly with increasing ion charge Z. 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 τ the exposure time of the ions to a cloud of plasma containing hot electrons. Their temperature T_e has to be in the range of keV if one wants to achieve high Z and to avoid direct electron capture processes. Another condition for multiply charged ion production is given by $n/n_0 >> 1$. The plasma density n should exceed the neutral gas density n_0 to minimize electron capture by charge exchange.

We now summarize the M.I. production criterion for three typical cases :

PIGIS	$10^8 \sim (n_e\tau)_{Te} < 100$ eV	M.I. with low Z
EBIS, ECRIS	$10^{10} \sim (n_e\tau)_{Te} < 5$ keV	M.I. with totally stripped light species
Projects	$10^{13} \sim (n_e\tau)_{Te} < 30$ keV	M.I. with totally stripped heavy species

An interesting way to look at this $(n_e\tau)_{Te}$ criterion is to compare it to the Lawson criterion for a d-t fusion which is

$$(n\tau)_T \sim 10 \text{ keV} \gtrsim 10^{14} \text{ cm}^{-3} \text{ s}$$

where n is the plasma density and τ is the plasma confinement time and $T \sim T_i \sim T_e$ is the particle temperature. Similar electron temperatures are involved in fusion and in ion stripping, but the ion stripping is much easier to satisfy than the Lawson criterion. Present day Tokamaks and mirror devices have actually reached $n\tau$ values of $> 10^{12}$ cm^{-3} s in hydrogen plasmas and with T values of some keV. Therefore if impurities are present, these devices produce M.I. with high Z.

1.2. Typical applications of the basic criterium for M.I production. The foil stripper - the ECRIS and EBIS

For multiply charged ion beam production by foil strippers, one generally injects very energetic (a few MeV/nucleon), low-charge state, ions through thin foils whose thickness is only a few micrometers.

The thin foil contains in its crystalline structure atoms together with cold electrons with density $n_e \sim 10^{24}$ cm^{-3}. The relative interaction velocity ω between the energetic ions and the cold electrons is, 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 $n_e\tau$ 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 ω, 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. Thus one would have to create a hot electron target plasma that present a value of $(n_e\tau) \approx 10^{10}$ cm^{-3} s similar to that of the solid stripper.

In Fig. 2 we emphasize the symmetry between ECRIS and foil strippers. For foil strippers, ions are extracted from an ion source and accelerated through an ion cyclotron resonance, whereas for ECRIS the cold electrons are accelerated through an electron cyclotron resonance (ECR). In the latter case, for identical relative collision velocities, the technology is much simpler and the equipment much cheaper. However, one has to consider that if the value of the hot electron density is only $\sim 10^{12}\ cm^{-3}$, one needs an ionic lifetime of $\sim 10^{-2}$s. Such ion lifetimes can only be obtained in sophisticated systems involving magnetic wells.

However in EBIS instead of magnetic ion confinement and instead of bulk electron resonance heating, the electrons are concentrated in a beam and accelerated by potential differences. The main EBIS parameter is $I\tau \equiv n_e \omega \tau \propto (n_e \tau)_{T_e}$ where ω is again the relative interaction velocity between fast electrons and slow ions but the same basic criterium is valid for our three examples illustrated in Fig.2.

2. The ECRIS principles

When we built our first ECRIS in 1964 the idea was not only to construct a robust ion-source without cathodes and useless heat production but also to realize a versatile low pressure source where density n, electron temperature T, plasma volume V and ion charge Z could be easily changed [4][5]. These ambitious objectives came from our earlier experience with ECR plasmas [6][7].

A) For instance, we knew that 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. Ions are generally not energized. If in addition the electron atom collision frequency ν is of the same order or smaller than the ECR frequency, breakdown occurs always and an ECR plasma is ignited.

B) The maximum ion current density one can extract from such a plasma is linked to n_{max} the maximum density of the plasma and n_{max} is more or less self regulated by the wave penetration into the plasma which is limited by the plasma frequency ωp. The wave penetrates if:

ω_{RF} is larger than $\omega p = \sqrt{\frac{n_e}{m\varepsilon_0}}$ (ωp varies like the square root of the density n_e). If ωp equals ω_{RF} instabilities often appear. Therefore we consider that ωp gives an upper limit for quiescent plasma density.

C) But ECR is not always a pure resonance. For instance if the electrons pass several times through the ECR surface according to their phases they can be accelerated or decelerated. Globally they are heated up to a certain limit and this heating is called ECR Stochastic heating which was already mentionned in 1972 [8] but no reliable theories are available. Experimentally we found that the electron temperature increases quasi linearly with the microwave power [9].

However there exists also a plasma density effect which shifts the resonance frequency ω_{ECR} from Electron Cyclotron Resonance towards the Upper Hybride Resonance ω_{UH} [10]. This new resonance occurs at weaker magnetic fields and its frequency is given by this formula:

$$\omega^2_{UH} = \omega^2_{ECR} - \omega^2_p$$

D) Finally we also knew that the ion charge Z strongly depends on the particle lifetime which depends on the magnetic confinement system [11]. But in addition if this system is good, the plasma losses become small and therefore both the electrical and gaseous efficiencies of the source improve. For high Z production, as mentionned in many previous articles only step-by-step ionization is very efficient and therefore we need long lifetimes τ for the ions which are exposed to the electron bombardment. Evidently to minimize charge exchange recombination we need a good vacuum. In other words the plasma density must be greater than the neutral density.

In addition we have seen that the electron energy must exceed the ionization potentials. We need keV electrons. Let us take a modern ECRIS where $n\ \tau$ equals $10^{10}\ cm^{-3}$; with 10 GHz microwave frequency the cut off density is about $10^{12}\ cm^{-3}$. To achieve 10^{10} τ must be of the order of 10^{-2} sec. This is not trivial. In an ordinary plasma mirror device one achieves only 10 to 100 microseconds.

For 10 m sec one needs a multi-mirror system or also called minimum B magnetic configuration. On the figure 3 we see a multimode cavity for 10 GHz inside such a B minimum structure obtained by superimposing an hexapolar field and a solenoidal field. If for instance the minimum field in the center is 0.2 Tesla and the maximum near the wall reaches 0.5 Tesla then there exists necessarily a magnetic surface where the field strength is 0.36 T where Elect. Cyclotron Resonance occurs.

The confined electrons now pass many times through the ECR surface and endure stochastic heating, rising their temperature towards KeVs.

Generally the source has two stages:

In the first which is at 10^{-3} torr pressure a cold pressure is ignited by ECR which then diffuses towards the second stage at low gas pressure with the hot electrons and min B confinement.

In the second stage as long as the ECR surface does not intercept a solid obstacle, the confinement remains good. But if some obstacle intercepts the ECR surface 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.

On Fig. 4 for instance we show two different charge state distributions for a movable Calcium sample. In the first case the Calcium gets very hot and its vapor pressure is high leading to excessive charge exchange. The most populated charge state is then Calcium 4^+. Whereas in the second case the position of the piston is optimized for Calcium 10^+ production.

3. Description of ECRIS

Let us now describe our normal ECR sources called Minimafios N. The figure 5 shows the axial and radial B field. In the first stage ECR creates a plasma at 10^{-4} torr pressure. Ionic and turbomolecular pumping provide 10^{-7} torr in the second stage where 10 GHz microwave power is injected. The aperture O provides microwave power for the first stage ECR. The multimode cavity C is made of a box of stainless steel. The hexapole is made of $SmCo^5$ permanent magnets, 4000 Gauss on the poles. Ionic extraction is beyond the axial mirror. The whole system is isolated up to 25 KV and connected to the high voltage except the solenoids which are grounded.

The only adjustable parameters are the gas flux handled by a needle value – microwave power – pulsed or continuous, and extraction voltage. This source is now working for four years without any internal failure. For gaseous ions it can work for weeks without interruption ; stability and reproducibity are complete. The Fig. 6 shows the hexapole alone. The Fig. 7 is a picture of Minimafios on its teststand. The electrical power consumption of this source is roughly 100 KW mainly spent for the solenoids. This is sometimes excessive for a high voltage plateform for instance utilized for Linac injection.

In order to decrease this power, very recently, we built a smaller source where Iron masses help to build up a similar solenoidal field with only 20 KW. This new source called Minimafios C (Caprice) is shown on the picture (Fig. 7). It is a compact source without auxiliary pumping. The ECR *in situ* pumping is sufficient.

The microwave generator is directly mounted on the top of the microwave window. The principle is strictly the same and the performances very similar – to those of the normal Minimafios version – The construction of a still smaller source needing only 10 KW of electrical power is planned.

4. Some experimental performances of Minimafios N

On Fig. 9 we show the method of recording ion yields versus RF power and on Fig. 10 we see that for charged ions Minimafios needs between 200 and 700 Watts. Minimafios can also work with low repetition rates in pulsed regimes provided that the RF pulses are longer than the needed ionization times (ie. > 10 ms.) (Fig. 11) By pulsing the RF power only we obtain higher instantaneous ion yields. For instance 1 μ A N^{7+} in routine operation. To be sure that this peak is really N^{7+} we check its Lyman α radiation. Fig. 12 shows a pulse of O^{6+}. Its current reaches 80 μ A during 50 m sec. Its emittance is about 7 π mm rad at 15 KV extraction. This performance is aimed for the CERN to inject into the old Linac preceding P.S. Table 1 gives some typical currents in quasi continuous regime. The results for C^{6+} O^{8+} N^{7+} and Ne^{10+} are obtained with gas isotopes. This allows to separate them from the Molecular Hydrogen ions which are always present. On Fig. 13 we see the spectrum of a mixture of normal and isotope oxygene – in continuous regime. The maximum current $\sim$ 40 μ A is around O^{4+}. The completely stripped O^{8+} is about 100 nA (by optimizing individually the peaks one can improve by a factor of 3).

Table 2 gives some metallic ion yields. Each material needs a different specific power absorbtion for convenient vapor production. Therefore the samples are fixed on a movable piston and its position must be carefully adjusted. Tantalum ions up to 40 times ionized are observed. These results were obtained during short runs (typically 4 hours). However one week runs could already be obtained for Aluminium after a careful experimental approach. Other studies will be undertaken and we hope to obtain in the next years similar longetivities for other metals. Anyhow the results of Table II are improvable.

TABLE I

MINIMAFIOS YIELDS (IN ELECTRIC MICROAMPERES) AT 10 KV EXTRACTION FOR GASEOUS IONS

Z	1	2	3	4	5	6	7	8	9	10	11	12	13	16
$^{6}_{12}C$	>30	>30	>30	>30	5	0.2								
$^{7}_{15}N$	>30	>30	>30	>30	20	3	0.2							
$^{8}_{16}O$	>30	>30	>30	>30	25	15	3	0.1						
$^{10}_{20}Ne$	>30	>30	>30	>30	>30	20	10	2	0.3	0.001				
$^{18}_{40}A$	>30	>30	>30	>30	>30	>30	>30	>30	10	3	1	0.3	0.1	0.002
$^{36}_{84}Kr$	>20	>20	>20	20	18	16	14	14	11	10	8	6	4	3

TABLE II

MINIMAFIOS YIELDS (IN ELECTRIC MICROAMPERES) AT 10 KV EXTRACTION FOR SOME METALLIC IONS

Z	2	4	6	8	10	12	13	16	18	20	22	24	26
Al	>5	>5	3	1	0.1	10^{-3}	10^{-4}						
Ca	10	10	>10	10		5	1	0.03	0.002				
Cu	>2	>2	> 2	> 2	> 2	1	0.2						
Mb				> 1	> 1	> 1	>1	2	1.8	1	0.2		
Ta				> 3	> 3	> 3		>3	>3	3	1.5	0.5	0.1
Au			> 2	> 2	> 2	> 2	>2	1.8	1	0.4	0.2	0.1	
W								>2	>2	3	3	2	1

Fig.14 shows the Ly α and Ly β lines identifying the bare Aluminium nucleus obtained in a one electron capture collision.

5. Upgraded ECRIS

To improve the values of Z and beam current one should increase $n\tau$ and Te. However the extrapolation for the confinement time τ are only theoretical [12] and not yet checked over an appreciable range. What one strongly believes is that the density n is linked to the square of the RF frequency. That ω_{RF} should be > ωp for the sake of stability and wave penetration. Therefore if one wants to increase n one has to increase ω_{RF} and if one wants to maintain ECR one has to increase proportionally the magnetic field B.

As $SmCo_5$ hexapoles are limited to $\sim$ 1 Tesla our next Minimafios will only be capable to work with a frequency of $\sim$ 20 GHz given by Klystrons. With Neomax hexapoles up to 30 GHz will be tried.

To utilize the possibilities of the coming power gyrotrons (30 – 112 GHz) one needs superconducting magnetic structures to reach 4 Tesla. Our first superconducting project was worked out in 1976 [12]. However it was not realized by us but in an improved version by the Louvain-La-Neuve University in Belgium [13]. The source called ECREVIS is now running fine for roughly two years and their results are comparable to Minimafios. But for practical reasons they did not yet work with RF frequencies above 8 GHz. Therefore we cannot yet check the scaling laws. Another big superconducting ECRIS is ready to start: ISIS at Jülich. But once more no experimental data were available at the time being [14].

Conclusion

Due to their fundamental simplicity ECRIS become fashionable and replace more and more traditional ion sources. A Minimafios type ECRIS working with pulses of > 50 ms up to CW can produce 10^{11} fully stripped light ions per second and much higher amounts of less stripped ions. These can be obtained in continuous or pulsedmode of operation. The reliability of the source and reproducibility of the results are complete. The emittance and energy dispersion are good. The manner of operation and adjustment of the source is very simple since it depends only on the two parameters: gas feed and RF power injected. In addition metallic ions can be produced directly. In general ECRIS are well fitted for heavy ion accelerators. Its high ion fluxes in quasi continuous regime enable numerous original applications and open new fields for LINACS.

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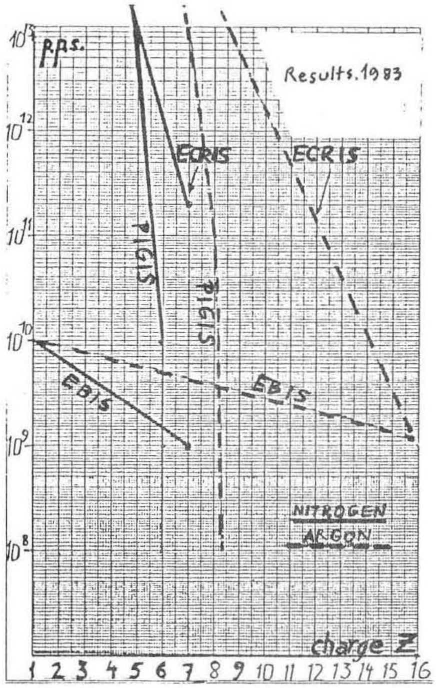


fig.1 Comparative ion yields for Argon and Nitrogen vs charge states (experimental)

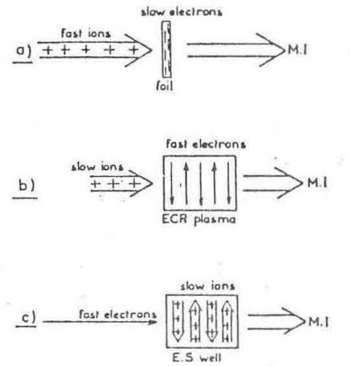


Fig. 2. In the foil stripper (a) the ECRIS (b) and the EBIS (c) the same relative collision velocity between the electron and ions with the same ($n\tau$) values give the same charge states of the multicharged ions (M.I.).

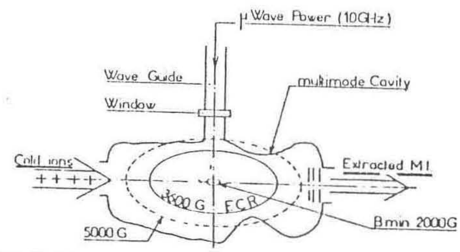


Fig. 3. Main ingredients of an ECRIS-ECR surface in a magnetic well associated with a multimode microwave cavity;

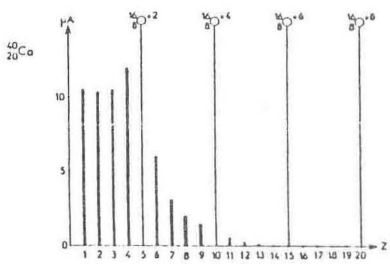
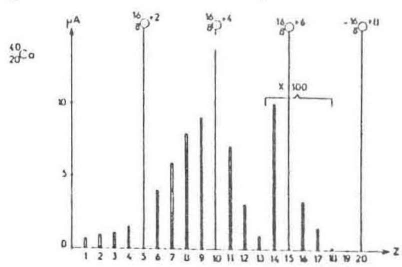


Fig. 4 Calcium CSD for 2 piston locations



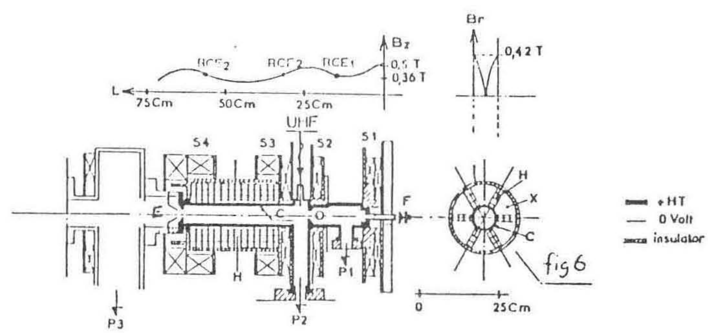


Fig. 5. MINIMAFIOS: F = iron shield; $S_1S_2S_3S_4$ = solenoids; O = diaphragm; H = SmCo$_5$ hexapole; I = insulators; E extraction electrode; $P_1P_2P_3$ = pumpings ports; C = multimode cavity; X shield; B_z = solenoidal magnetic field.

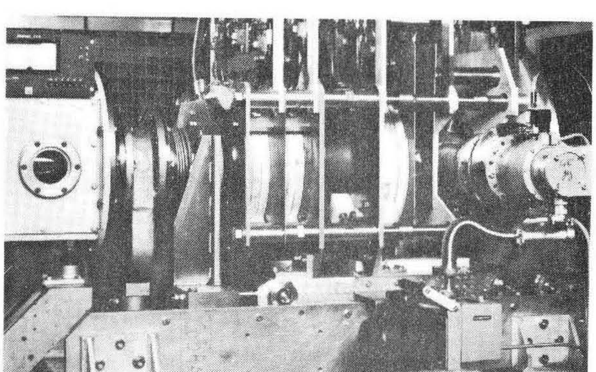


Fig7 *The Multiply Charged Ion Source MINIMAFIOS* "N"

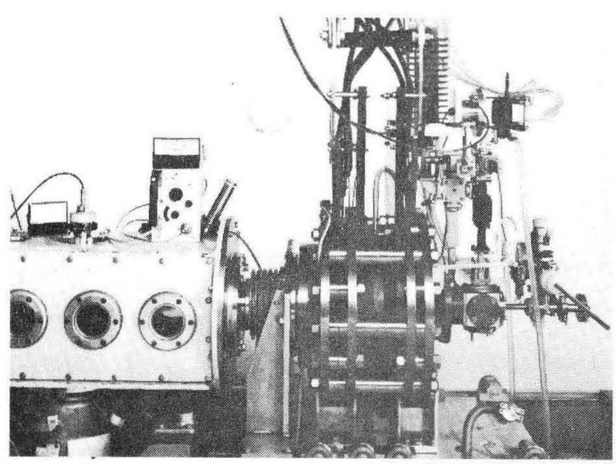


Fig 8 *The Multiply Charged Ion Source MINIMAFIOS* "Caprice"

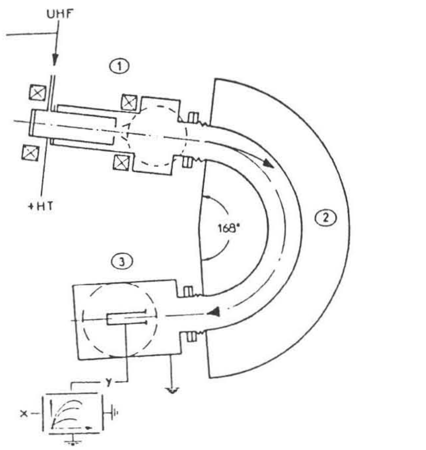


Fig. 9 Ion selection and recording system (1) MINIMAFIOS. (2) Magnetic selector. (3) Collector.

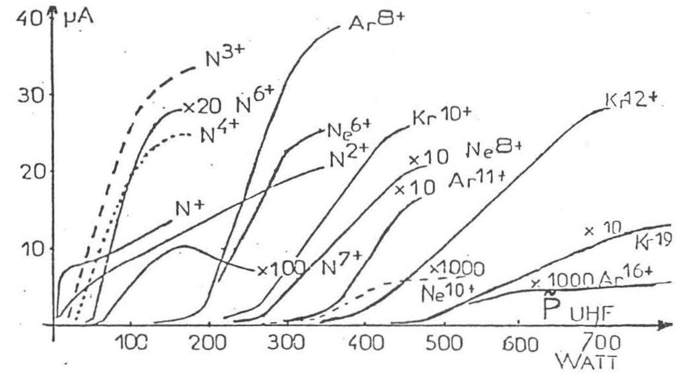


Fig. 10 Ion currents vs. microwave power.

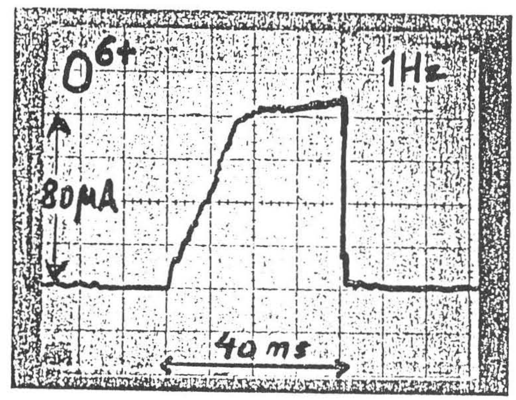


fig.12 Pulsed O^{6+} beam for CERN LINAC + PS.
Vextr. 15 KV, emittance : < 200 mm mrad.

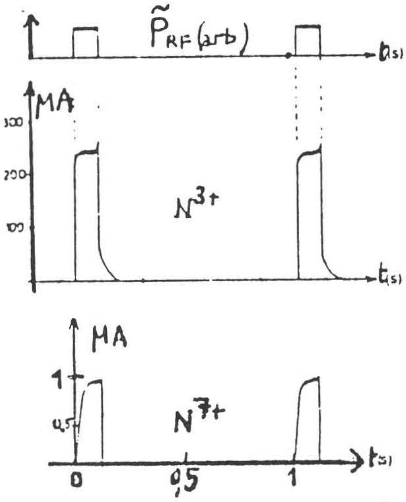


Fig. 11 Nitrogen beam pulses against time.

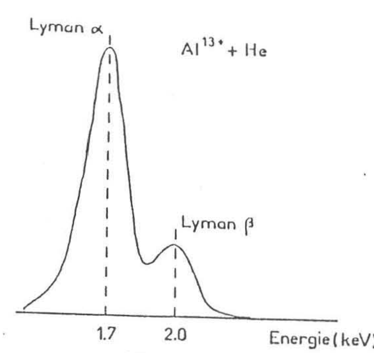


fig.14 Al^{13+} ion beam identified through radiative charge exchange in a Helium target

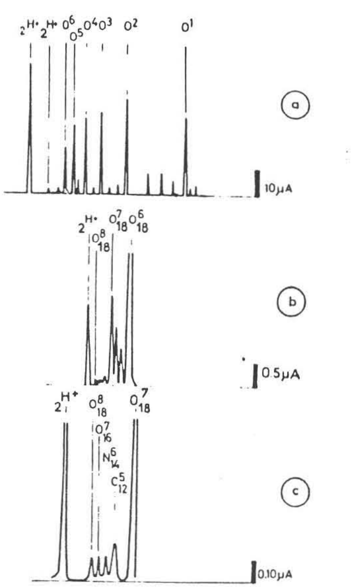


Fig 13. Charge state spectrum for oxygen: (a) Total spectrum. (b) Enlarged spectrum for highly charged ions. (c) Enlarged spectrum of particles ionized in their K-shell.

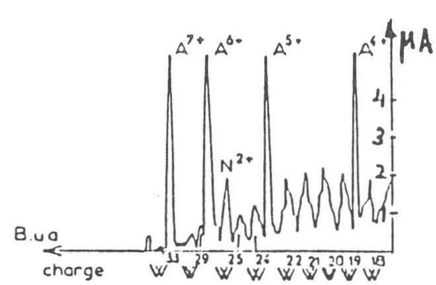


Fig. 15 Typical tungsten ion spectrum P = 2 KW. Duty cycle ρ = 02.