ECR SOURCE SCALING CONCEPTS

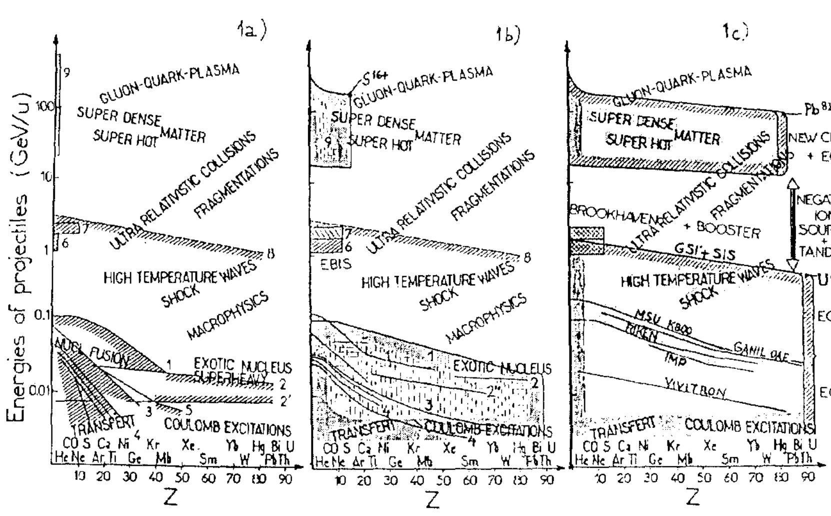
R. Geller
Centre d'Etudes Nucléaires de Grenoble
DRF.G - 85 X, 38041 Grenoble-Cedex (France)

We explicit the main criteria for multiply charged ion production. We consider only measurable parameters which are the following : ω and P the RF frequency and RF input power, B the average magnetic confinement field, q the ion charge, M the ion mass and I^q the ion currents. All the usual but not directly measurable plasma characteristics are excluded and only a few classical plasma rules about confinement and quiescence are included in the basic assumptions. They are then combined with ionization potentials and cross sections and result in the following scalings : $q \propto \log \omega^{3.5}$, $q \propto \log B^{1.5}$, $q \propto P^{1/3}$, $I^q \propto \omega^2 M^{-1}$. These relations suggest a soft upgrading by increasing ω, B and P. Experiments confirm the tendancies to a certain extent and allow further extrapolations.

1. INTRODUCTION ECRIS (Electron Cyclotron Resonance Ion Sources) were gradually improved and developped for different applications. Their high ionization efficiency and brightness are exploited for 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 evolued from a single large 3 MW power consuming prototype (SUPERMAFIOS) [1] 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 [2] [3]. In the present paper we will concentrate on the multicharged ECRIS which are of special importance in the economy of heavy ion acceleration. Such sources yield ± the same q/m particles as a K = 400 cyclotron with a strippers.

We cannot describe all the cases of upgraded linacs, cyclotrons or synchrotons but in nearly twenty different cases the utilization of an ECRIS improved dramatically the heavy ion accelerators. On the Fig. 1 we show the ECRIS impact on heavy ion physics since 1983, by illustrating the Research fields of some well know accelerators working with ARC-sources, (Fig. 1a) then with ECRIS (Fig. 1b) and eventually what should be the situation in 1992 when new heavy ion accelerators like the GSI Unilac + SIS, the Brookhaven Booster and the CERN Lead Injector will be in operation simultaneously with upgraded cyclotrons like those of MSU (East Lansing) GANIL (France), RIKEN (Japan) and IMP (China)... (Fig. 1c). Off course always more performing ECRIS are needed. The aims are to obtain higher charged ions and more beam currents. Scaling rules for ECRIS should link these aims to controlable parameters. Unfortunetely the ECRIS theory has its roots in hot plasma physics leading always to complex semantics [1], [2], [3], [4], [5]. Most of the ECR calculations involve the quantitative knowledge of RF fields in the ECR zones, particle temperature and

Fig. 1 The impact of ECRIS on Nuclear & Particle Physics :
a) 1983 without ECRIS ; b) 1987 with ECRIS ; c) 1992 anticipation.
Considered Accelerators : 1) GANIL, 1') MSU, 2) UNILAC, 2') SUPERHILAC, 2") ATLAS, 3) and 4) Various Cyclotrons : LBL, KVI, JULICH, GRENOBLE etc..., 5) DOUBNA, 6) Synchrotron SATURNE, 7) Synchrophasotron, DOUBNA, 8) BEVATRON, 9) CERN : PS + SPS.



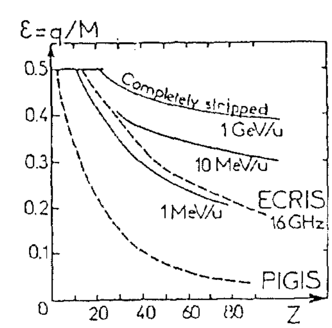


Fig. 2 Comparative results for conventional sources, ECRIS and Accelerators with strippers.

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density gradients, velocity distributions, ES plasma potentials, diffusion times and lengths etc. But all these parameters cannot be easily evaluated (neither theoretically nor experimentally). In addition, many turbulence – thresholds hinder simple extrapolations. We avoided this difficulty by assuming that the ECR plasma is always "mildly turbulent", because we consider that the experimental tunings for optimization involve already the elimination of violent instabilities (thus we can ignore them). Then the scalings should link the aims through some driving ECRIS factors only to those parameters which are directly measurable and monitored. These parameters are the magnetic field B, microwave frequency ω, microwave power P, and gas pressure. Then remained the hardest task : Cognize the driving factors of high charged ion production in an ECR plasma. In order to choose what is important let us review the basic features of an ECRIS.

2. ECR plasmas - Basic Aspects

An ECR zone is created whenever magnetic fields B and RF fields $\bar{E}$ are superimposed and the electron gyrofrequency ω_B equals the frequency ω_{RF} of the applied RF fields. In this ECR zone, a component of the electrical RF fields is perpendicular to the B field, and electrons crossing the zone are accelerated (in the same way as ions inside the dees of a cyclotron). The energy gain W_e of the electrons depends on the value of $\bar{E}/\omega$, their phase with respect to $\bar{E}$, and the time they stay inside the ECR zone, assuming that collisions on the gas do not damp out the resonance effect. If these collisions allow the electrons to reach energies above the Ionization potential of the gas, an ECR plasma is ignited. In general this happens below 1 torr gas pressure and the plasma can then be maintained without any electrodes or arcs down to 10^{-9} torr, provided that two cascading plasma stages (the 1rst at > 10^{-5} torr and the 2nd at lower pressure with a good magnetic confinement) exist. The absence of electrodes makes the ECRIS very robust, but the most out standing feature is its flexibility which allows large variations of those plasma parameters which enable high charged ion formation. Thus it becomes possible to adjust the following characteristics : T_e the electron temperature (from some eV to some KeV), n_0 the neutral gas density (from ~ 10^7 to ~ 10^{16} cm^{-3}), n the plasma density (from 10^9 to $10^{13} cm^{-3}$), τ the confinement (from < 10^{-6} sec to > 10^{-2} sec). These characteristics surely are among the driving factors mentionned earlier and they are connected to supervized parameters due to the following circumstances : T_e is strongly related to the microwave power density P/Vol ; n depends on the gas pressure but is also limited by the cut-off frequency ω_{co} for wave penetration, above which turbulence generally grows : $\left(n_{co} \sim 1,2\ 10^{-8} (\omega/2\pi)^2\right)$. As for q, it increases with n, τ and T_e ; τ the exposure time of the ions to electron bombardment (i.e. the ion confinement time) depends not only on

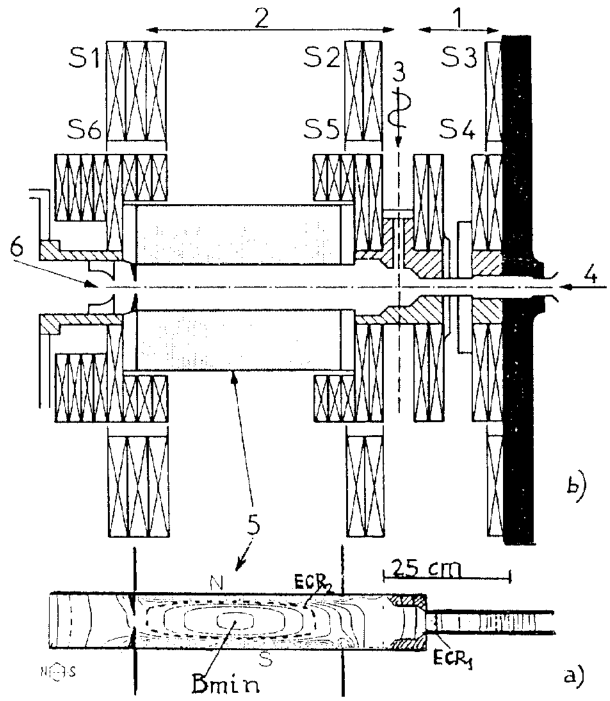

Fig. 3b) ECRIS prototype MINIMAFIOS 16 GHz
1. First stage plasma ; 2. Second stage plasma ; 3. RF injection ; 4. Gas inlet ; 5. Permanent magnet Hexapole ; 6. Extraction electrodes ; S. Solenoidal coils.
The novel MINIMAFIOS can operate at 10, 14 and 16 GHz. The radial field Br is obtained with a $SmCo_5$ 0.8 Ts Hexapole. The solenoidal field Bz is variable

Fig. 3a) MINIMAFIOS 16 GHz magnetic equipotentials with B_{min} and ECR surface B = 0.44 to 1.04 Ts. B_{ECR} = 0.58 Ts.

the value of the magnetic field but also on the kind of magnetic field configuration, which determines the particle losses towards the walls and thus the RF power one has to couple to the plasma. The better the confinement, the higher are the efficiencies of ionization and highly charged ion production. For these reasons, multimirrors (radial mirrors in addition to axial mirrors) are of great help. Such confinement structures are obtained by superposing solenoidal and hexapolar (or multipolar) fields. They are called "B_{min} structures" because they exhibit a surface of minimum magnetic field in their center (with a concentric egg – shaped ECR surface) (Fig. 3a). They are utilized in all high performance ECRIS ; their confinement time τ generally exceed 10^{-3} second whereas for only axial mirrors, τ is at least 50 times smaller (The ECR surface should not intercept the walls if not the confinement collapses). (Fig. 3b) shows the main components of a modern ECRIS and also its axial and radial magnetic fields. For feeding RF power into the first and the second stage, microwaves are injected through a tight window. Ion extraction is beyond the axial magnetic mirror.

3. GENERAL PRINCIPLES OF HIGH CHARGED ION PRODUCTION

The probability of producting high charged ions by a single electron impact is poor. Therefore the only efficient way is by successive ionizations. 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 energy should be in the KeV range and exceed the relevant Ionization Potential I.P.). Fig. 4a) shows typical mean charges q for carbon ions versus $nw\tau$ [6]. They are obtained through "batch model" calculations which are based on the knowledge of ionization cross sections and assume that only the confinement time τ limits the achievable charge [7]. No other loss mechanisms are considered. Note the very slow quasilogarithmic increase of q vs $nw\tau$, which is due to the quasilogarithmic decrease of the step by step ionization cross sections versus q (we will take it into account in our scaling rules). Only when $nw\tau$ exceeds 10^{19}, do highly charged ions appear and this remains true for all elements.

In the theoretical batch model the ion production is governed by the following equation : $dn_q/dI = n_{q-1}\,\sigma_{q-1,q} - n_q\,\sigma_{q,\,q+1}$ where n_q is the ion density with charge (q), $\sigma_{q,\,q+1}$ is the ionization cross section from charge q to (q+1) by electron impact and I is the ionization factor which is equal to a product of electron current density (enw) and confinement time (τ). The above equation can be solved under such conditions that the neutral gas atoms are continuously supplied or the gas is injected under a pulsed mode. For ECRIS in cw mode, i.e. for continuous gas injection, the production of ions becomes equilibrated ($dn_q/dI = 0$) at large values of the ionization factor and their intensity ratios are given by $n_q/n_{q-1} = \sigma_{q-1,\,q}/\sigma_{q,\,q+1}$ (Fig. 4b) at equilibrium. The normalized total ion density $Q = \Sigma q \cdot n_q/n_0$ where n_0 is the density of neutral atoms injected, becomes saturated for the pulsed gas injection, meanwhile this increase with I for the continuous gas injection. In the latter theoretical case the ion fluxes for q = 1, 2, 3, 4, and 5 reach a saturation whereas q = 6 increases always. The same thing would happen to the extractable ion beams whose currents are obtained by multiplying the previous ion fluxes by their respective charge q (Fig. 4c). If one plots now the ion beam I^q vs q one sees that the batch model leads to a spectrum where the currents always grow with q (Fig. 4d). This is obviously unreal. Experimentally one obtains spectra where I^q grows vs q up to q_{opt} and then decreases (Fig. 4d). We have to conclude that the batch model becomes irrelevant beyond q_{opt}. This happens when particle losses perturb the model, for instance when the confinement is just long enough to reach q_{opt} without losses or if recombinaisons balance ionizations. However when one considerers the spectrum only from q = 1 to q_{opt} one can accept the batch model. It can help to evaluate q_{opt} in ECRIS scalings [2].

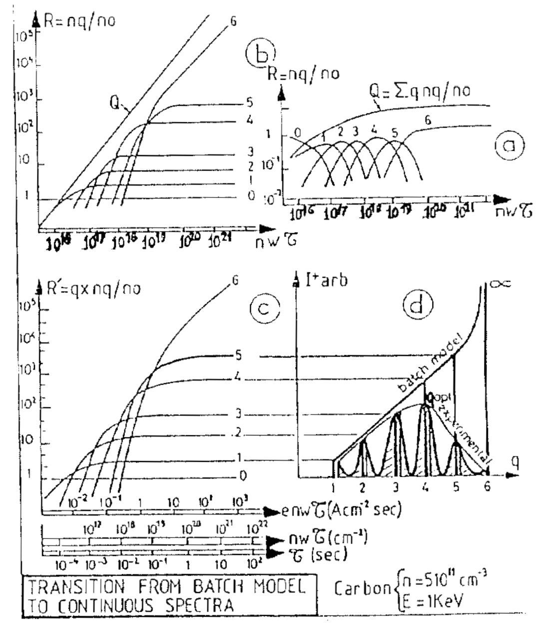

Fig. 4 gives the fractions of charge distributions calculated for a carbon plasma of $n = 510^{11}$ cm^{-3}, $W_e = 1$ KeV ($w \sim 2\ 10^9$ cm/s) as a function of ($en\tau w$) under a) the pulsed gas mode (batch).
b) the continuous mode. At equilibrium the intensities are saturated. Only the highest charge C^{6+} increases always. c) exhibits quantities proportionnal to the ion currents one can extract from the continuous plasma. They are represented in fig. 4d) giving I^+ (vs) q compared to a real carbon charge spectrum obtained which an ECRIS.

4. ECRIS - THEIR SCALINGS AND PERFORMANCES

In 1987 we proposed some plain (i.e. oversimplified) scaling laws for ECRIS upgrading [2]. They only deal with controlable parameters and a few reasonable assumptions. Let us list them :

a) In steady state ECR plasmas, electrical neutrality is preserved $n_e = \langle q\rangle\, n_i$. $\langle q\rangle$ is the average ion charge inside the plasma. In addition we assume that the equation of continuity is respected i.e. the sum of particle creations and destructions is zero per time unit. At equilibrium one looses $\langle q\rangle$ times more electrons than ions, so one has to create $\langle q\rangle$ times more electrons.

b) The upper electron density is limited by the cut off frequency of wave penetration : $n \propto \omega_{co}^2$.

c) In order to maintain electron cyclotron resonance inside the plasma the average magnetic trap field B must vary proportionnally to the frequency : $B \propto \omega$.

d) τ_i : the ion lifetime in the B_{min} trap increases according to ambipolar diffusion laws : $\tau_i \propto B^{1.5}$. (We consider that the plasma is mildly turbulent and discard the turbulent Bohm diffusion as well as the classical diffusion).

e) The energy lifetime θ inside the plasma is limited by the electron losses, because due to ECR heating the energy is contained essentially in the electrons. But we also know that for every q charged ion arriving at the wall, q plasma electrons disappear in order to maintain the electrical neutrality inside the plasma ; so we assume that $\theta \propto \tau_i/\langle q\rangle$.

f) The needed electron energy W_e for reaching a given q is proportionnal to IP, the ionization potential, and IP increases like q^2 inside a given shell of the atom. We assume that : $W_e \propto q^2$ is roughly true for all the ion.

g) In stochastic ECR heating the electron energy W_e increases more or less linearly with the RF power up to a certain limit. We assume that $\langle W_e\rangle$ is proportionnal to P up to $P/n\ Vol \sim 10^{-12}$ Watt. Beyond one considers the non linear behaviour where $\langle W_e\rangle$ becomes rather proportional to $P^{1/2}$.

h) For simplification we write that $\langle q\rangle \sim q$ and $\frac{1}{2}mv^2 \sim \langle W_e\rangle$ and that the necessary RF power for achieving $\langle q\rangle$ depends on $P \propto n\langle W_e\rangle V_{ol}\ \theta^{-1}$, in the linear case and $P^{1/2} \propto n\langle W_e\rangle V_{ol}\ \theta^{-1}$ in the non linear case.

Combining the above assumptions b) c) d) e) f) and h) one obtains $P \propto \omega^2 q^3 V_{ol} B^{-1.5}$ and $P \propto \omega^{1/2} q^3\ V_{ol}$ when only P is varied (i.e. ω, B, V_{ol} are fixed). Then in the linear case one obtains $\boxed{q \propto P^{1/3}}$ and $q \propto P^{1/6}$ in the non linear case.

If we consider that the parameters n, W_e, P, V_{ol} and ω are fixed but only B is varied then according to d) $\boxed{n\omega\tau \propto B^{1.5}}$ and as we have observed that in may cases q_{opt} is varying roughly with log $n\omega\tau$, then $\boxed{q_{opt} \propto \log B^{1.5}}$. The same rational is employed when only ω and B are changed together according to b) and c). One then obtains $\boxed{n\omega\tau \propto \omega^{3.5}}$ and $\boxed{q_{opt} \propto \log \omega^{3.5}}$.

Independantly we write that the extractable ion current is balanced by the plasma ion flux arriving on the meniscus giving :

$$I^q \propto qn_i\ v_i \simeq q\ \frac{n_e}{\langle q\rangle}\sqrt{\frac{W_i}{M}} \simeq n_e\sqrt{\frac{W_e}{M}\left(\frac{m}{M}\right)} \quad \text{and} \quad \boxed{I^q \propto \omega^2\ M^{-1}}$$

where we assumed that the ion energy W_i is $\sim W_e\left(\frac{m}{M}\right)$. This involves that the elastic electron/ion collisions are too rare to allow substantial ion heating. Otherwise one would rather obtain $I^q \propto \omega^2\ M^{-1/2}$.

The framed relations indicate for q_{opt} a "soft" upgrade by increasing ω and B. Experiments done by varying ω from 6.4 to 16.6 GHz confirm this tendancy (Fig. 5). The experimental results are coherent for different sources as well as for a single MINIMAFIOS source capable of working at different ω. The dependances of I vs M^{-1} and ω^2 and q vs $P^{1/3}$ were

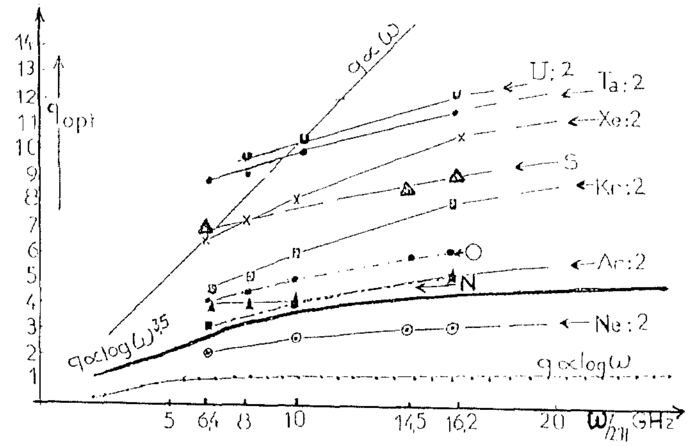

Fig. 5 Experimental variations of q_{opt} vsω for different elements and obtained with different ECRIS : 6,4 GHz LBL and MSU [10][9] 8GHz,10GHz, 14.5 GHz and 16 GHz Grenoble compared to log $\omega^{3.5}$

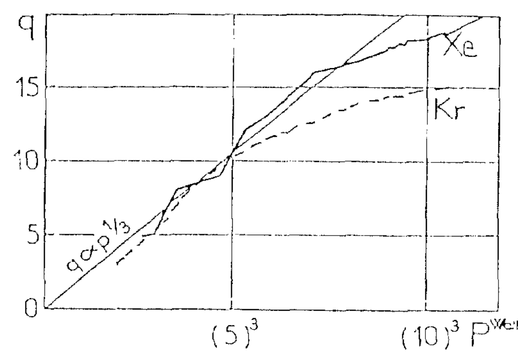

Fig. 6 q vs $P^{1/3}$ experimental results, MINIMAFIOS 16 GHz, full line Xenon dashed line Krypton.

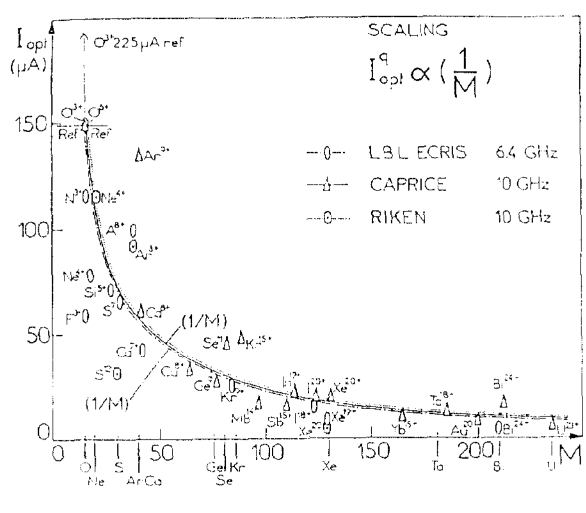

Fig. 7 CW optimum Ion currents I^q vs M for 3 different sources compared to $I^q \propto M^{-1}$

also reasonably verified (figs 6, 7, 8). Thus the scalings, though inaccurate, look relevant to a certain extent and allow further extrapolations, for instance up to 30 GHz. Such a project is now launched in a joint MSU-Grenoble effort. Many ECRIS prototypes were built all the world over with frequencies comprised between 2.45 and 16.6 GHz and as predicted by the scalings the 16.6 GHz MINIMAFIOS Source is by far the most performing. Low frequency ECRIS involve easier technology and therefore the ratio of "performance over cost" is maybe in their favor, but the available currents and charges are clearly lower. On the other hand it is not yet clear whether large or small ECRIS are better. In the first case the confinement τ should be longer, in the second case the power needs should be smaller and considering $q \propto P^{1/3}$ this is important.

5. ECRIS PRESENT STATUS AND FUTURE PROJECTS

On Fig. 10 we review the presently achieved q with 6.4, 10 and 16 GHz ECRIS for two typical currents I_1 = 1 eμA and I_2 = 10 eμA. Note that the yields are linked to the boiling temperature of the elements [8]. Laser evaporation or ovens should mitigate the effect. The future of the ECRIS will once more be determined by its capability of increasing q and I^q for heavy solid elements. Some specific needs are already requested for the next future. a) Maximum charged heavy ions for single accelerators in the range of I ~ 1 eμA. b) Highly charged, very heavy ions (q ~ 30) in the range of tens of eμA for cascading machines. c) Medium charged, medium heavy ions (q < 12) in the milliamp range. d) Low current but extremely charged ions, for atomic physics. On the Fig. 10 we also plotted with the help of our scaling rules the extrapolated q and I for the 30 GHz ECRIS, the operation of which is predicted before 1992 [9].

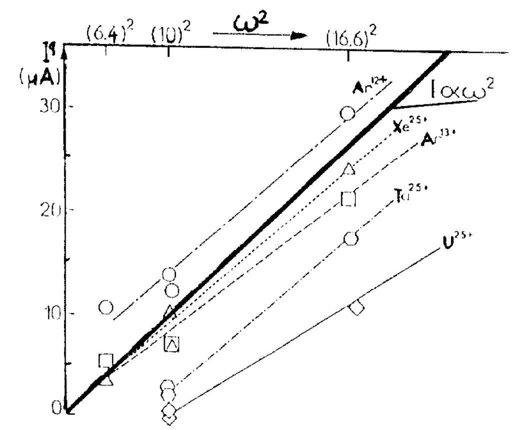

Fig. 8 CW high q Ion currents vs ω^2 for 6.4 GHz 10 GHz and 16 GHz.

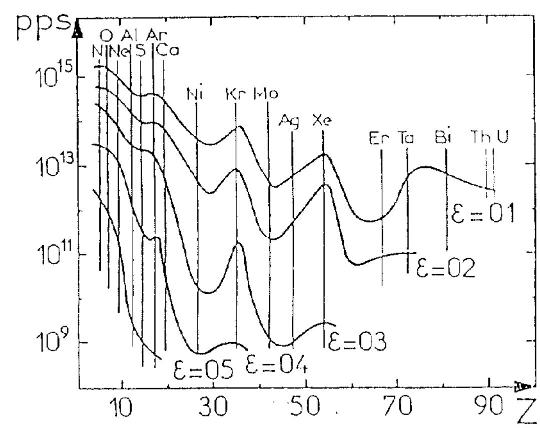

Fig. 9 Summary of the output intensities and the available $\epsilon = q/m$. The emittance is < 5 10^{-7} m.rad and the energy spread < 20 qeV. $V_{extraction}$ = 20 KV. MINIMAFIOS 16 GHz.

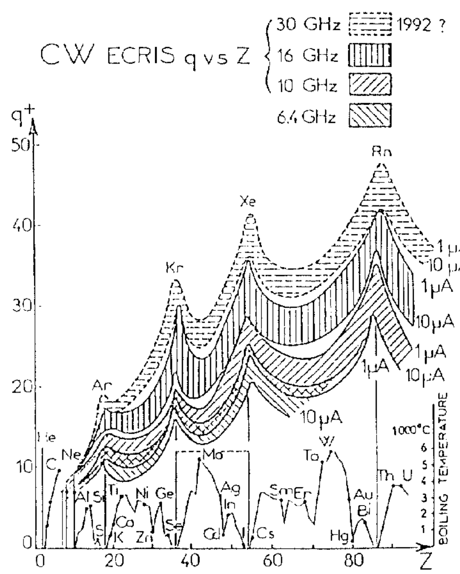

Fig. 10 Summary of the achieved q of different elements for two Ion currents : 10 eμA and 1 eμA in CW. Are considered ECRIS operating at 6.4, 10 and 16 GHz. Extrapolated results for the 30 GHz ECRIS are proposed.

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