NEW DEVELOPMENTS ON HEAVY ION SOURCES.

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Abstract

A review is given of the new methods to produce high ionization degrees of heavy particles. There is a description of the devices with the main characteristics like ion yield, charge state distribution, emittance. The performances of these ion sources are compared with the conventional ones.

1. Introduction

In order to satisfy the growing needs of more and more energetic heavy particles with accelerators of reasonable size for nuclear chemistry, bio-medical and cosmic-ray research, new highly charged ion sources have been developed. The low charge states obtainable from classical ion sources (the most of PIG's type) don't allow to reach 10 MeV/nucleon for the very heavy elements in existing cyclotrons. The possible use of new sources able to deliver ions with charge-to-mass ratio $\zeta/A = \varepsilon$ in the range $0.25 \div 0.35$ is very attractive.

It is also clear that the majority of new proposed accelerators (BEVALAC, UNILAC, GANIL) use conventional ion sources. This fact has stimulated ideas about sources able to replace the classical ones, but with much more interesting characteristics like lifetime, yield of high charge states, emittance, energy spread.

This paper gives the performances and some recent developments of the PIG ion sources as references and a review of new ion sources with their main features. A comparison is made between new and classical sources.

2. Conventional ion sources

The basis of conventional (or classical) ion sources is an electric discharge in a magnetic field. The ions extracted from the plasma are moderately charged ($\zeta < 12$) but the ion current intensity is sufficient for accelerator applications. There is a lot of classical sources : Duoplasmatron, Duopigatron, Magnetron, Penning Ion Gauge Sources (PIGS) but for the cyclotron requirements, the PIG ion source is the most commonly used. Moreover, its performances are good references for the new concepts.

2.1 PIG ion sources - PIGS

2.1.1 Description

The PIG source consists of two cathodes placed at the end of a tubular anode, the whole immersed in an axial magnetic field. The arc discharge is striken between cathodes and anode ; the ionizing electrons coming from one cathode go through the anode and are reflected back by the opposite cathode (reflex discharge). Besides, the magnetic field constrains them so that their path length, thus their ionizing power, is strongly increased. The neutral density is $\sim 3\ 10^{13}$ at-cm^{-3} (10^{-3} Torr). The positive ions are created predominantly by a step by step collision mechanism, then an enrichment of the higher charge states needs a sufficient "lifetime" of the ions and adequate energy of the colliding electrons. The arc voltage of this source is limited by the cathode erosion due to ionic bombardment and the high neutral density does not allow long confinement times : as a result, low charge ions predominate, whereas the yield of high charge states drop precipitously. There are numerous technological variations of the PIG source7), and the most efficient to produce high values of ε is the side extraction one.

We may draw up a list of its basic properties.

- Advantages :
  - able to be set at the centre of a machine,
  - simple technology,
  - small size, inexpensive,
  - high yield for $\varepsilon \geqslant 0.05$,
  - high duty-cycle (CW possible),
  - low energy spread,
  - able to produce easily any element.
- Disadvantages :
  - charge state distribution (CSD) centred on the lower charges,
  - short lifetime,
  - poor yield in the range $\varepsilon > 0.1$, atomic number $Z_e > 40$,
  - large emittance.

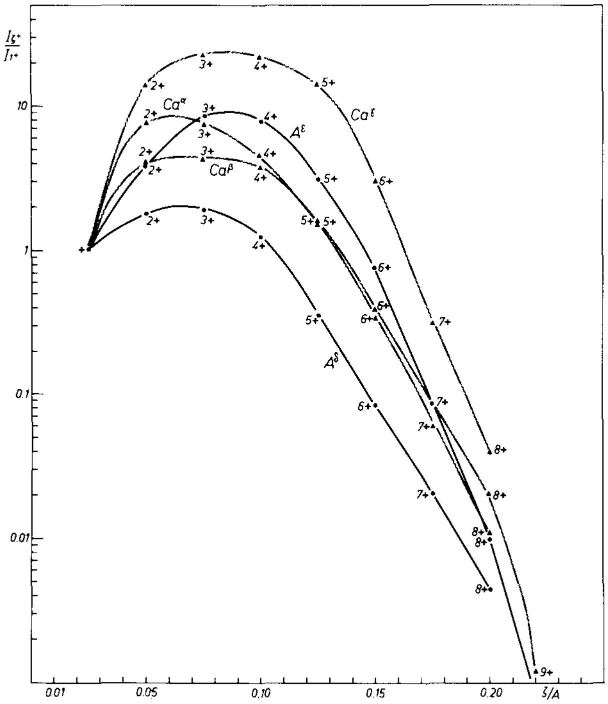

Figure 1. CSD of A and Ca obtained with PIGS. (Ref. in text.)

2.1.2 Recent developments

A lot of developments have been carried out recently in order to minimize these disadvantages and to extend the possibilities, for instance : extension of the ability to produce non gaseous materials by using sputtering with dynode1,2), plasma heating3), ion return4) increasing by a

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factor of 3 of the lifetime with multibody ion source$^{5)}$ or rotatable cathode$^{6)}$. The main problem remains the charge state distribution (CSD), in spite of considerable spread in performances due to variations either in the neutral production, (sputtering Ca^{β} $^{2)}$ or furnace Ca^{α} $^{2)}$ Ca^{γ} $^{9)}$, figure 1) or discharge parameters (self heated or cold cathodes Xe^{α} $^{11)}$, Xe^{β} $^{12)}$ or hot cathode Xe^{γ} $^{10)}$, figure 2), recent works seem to show that there are others unexplored ways of improvement : on Fig. 1 is drawn the Argon CSD (A^{ε}) obtained by Bennett and Gavin$^{8)}$ in a cold cathode PIG source by lowering the pumping speed of the arc and uniformizing the magnetic field, compared with the best previous data (A^{δ} $^{10)}$) ; anode heating$^{9)}$ (to ∿1100°C) in a suitable geometry experimented by Malard gives a similar effect : Kr^{ε} compared so with the best previous data Kr^{δ} $^{10)}$, figure 2.

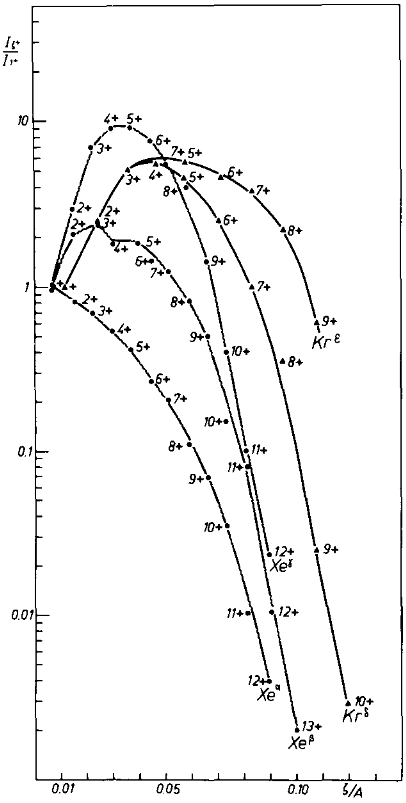

Figure 2. CSD of Kr and Xe obtained with PIGS. (Ref. in text.)

The great deal of studies devoted to a best understanding of the complex mechanisms occurring within the discharge during these last years may issue on a substantial gain of highly charged ions yield. For the different elements, we can plot the average yield of this source for low values of ε, figure 11, (values calculated from the ref. 2) and the maximum charge-to-mass ratio attainable with an acceptable yield, figure 10. For the heaviest element ζ/A∿0.05 can be considered as an upper limit.

Few authors have measured emittances of side extraction PIG sources ; the values we give in Table 1 are normalized according to the relation$^{13)}$

$$E_N \sim \frac{V_z}{C} E \sim \beta E$$

	$E_{N_{x'x}}$ (mrad)	$E_{N_{y'y}}$ (mrad)	% of total current
N^{+} $^{15)}$	2.8 10^{-7}		50%
N^{2+} $^{15)}$	2.3 10^{-7}		50%
A^{2+} $^{14)}$	2.46 10^{-7}		95%
Xe^{7+} $^{14)}$	5.4 10^{-7}		95%
Kr^{8+} $^{5)}$	11.6 10^{-7}	4.6 10^{-7}	100%

Table 1.

As found Bennett$^{7)}$, there is not obvious dependence on charge state, an average value seems to be $E_N \sim 5\ 10^{-7}$ mrad. An upper limit for the energy spread is ∿ 100 . ζ (eV) $^{16)}$.

3. Plasma electron heating ion sources - PEHIS

This first group of new ion sources uses the possibility of energy transfer to the plasma electrons by either electron cyclotron resonance heating or beam-plasma interaction within a radial magnetic trap. The basic pressure is 10^{-3} Torr, and they can practically run with 100% duty cycle. The conditions are such that single impact is the dominant process, but methods are developed to achieve a certain containment in order to add stepwise ionization processes.

3.1 Electron cyclotron resonance ion sources-ECRIS

3.1.1 Description

In these devices, the microwave heating energizes the electrons . The plasma is confined within a magnetic mirror configuration.

Device	Elmo 17,18)	Mafios 19,20,21,22)	Supermafios 23,24)	
			1st stage	2nd stage
Volume (cm^3)	2000	160	1000	
Electron density ($el\text{-}cm^{-3}$)	3 10^{12}	6 10^{11}÷9 10^{12}	3 10^{13}	5 10^{11}
Electron Temperature (keV)	10÷500	1÷20	< 1	20÷100
Neutral density ($at\text{-}cm^{-3}$)	3 10^{12}	6 10^{11}÷9 10^{12}	3 10^{13}	10^{10}
Heating power (kW)	9	2	0.5÷10	3÷20
Extraction diameter (cm)	0.1	0.2	0.3	

Table 2.

The electron cyclotron resonance condition may be fullfilled in several places by magnetic adjustment. To inhibit plasma instabilities, other electro-magnetic configurations may be superposed to the magnetic bottle. Table 2 gives the main parameters of ECRIS. The basic vacuum (10^{-6} Torr) is provided by classical systems.

3.1.2 Main characteristics

On figure 3 are drawn the Argon and Xenon CSD obtained with the Mafios and Supermafios devices (Fig. 4): increasing of heating power with a lower neutral density in the second stage of Supermafios has a clear effect : higher charge states are attainable with a better yield. On the figures 11, 12 is plotted the yield of the Supermafios ECRIS assuming a total extracted current of 50 μA[23]. The emittance would not be different from the Mafios one : $E_N \sim 4.5\ 10^{-7}$ mrad. The measured energy spread is lower than 60.ζ (eV).

As for PIGS, we may draw a list of basic features.

- Advantages :
  - electrodeless (long lifetime),
  - CW possible,
  - low energy spread,
  - easy vacuum technology,
  - high ε possible for light elements (below Argon).
- Disadvantages :
  - emittance comparable with the PIGS one,
  - drop of the ε_{max} for the heaviest element, (figure 10),
  - high power consumption (actually),
  - large size.

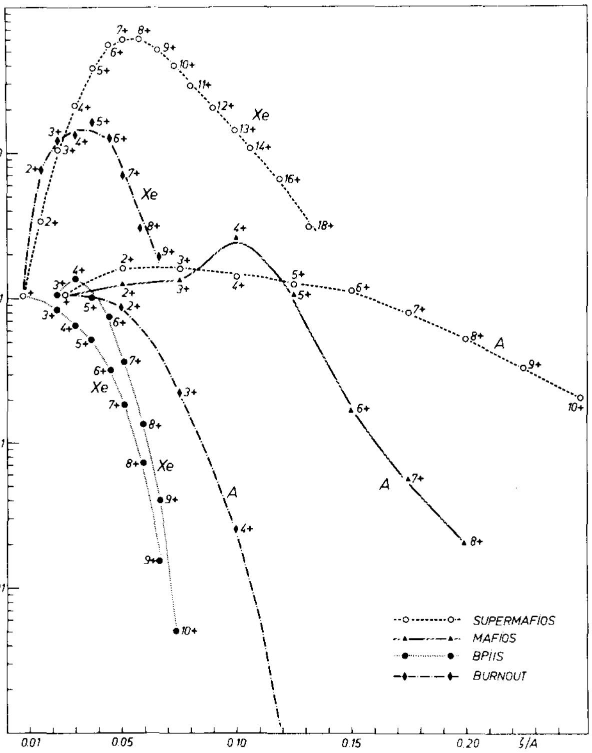

Figure 3. CSD obtained with PEHIS (Ref. in text).

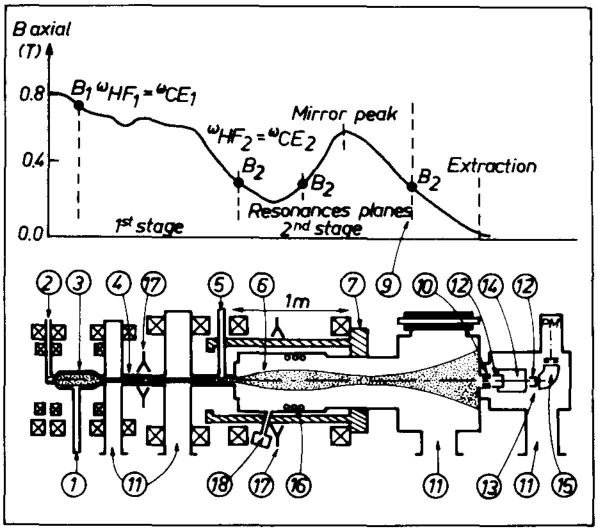

Figure 4. Scheme of the Supermafios device.

Legend for figure 4 :
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.
9) Axial magnetic field.
10) Ion extraction.
11) Vacuum pumping.
12) Retractable Faraday cup.
13) Ion abundance measurement.
14) Wien filter.
15) Energy analyzer.
16) Diamagnetic loop.
17) Microwave 8 mm interferometer for density measurements.
18) Beryllium window for X rays measurements.

3.2 Beam plasma interaction ion sources - BPIIS.

3.2.1 Description

The plasma electrons are heated by beam-plasma interaction. An electron beam is fired in a magnetically confined[25,26] or mirror contained plasma[27,28,29]. Depending on temperature mode, energies of the plasma electrons vary in the range of $10^2 \div 10^5$ eV[30], other characteristics are similar to those of ECRIS. Xenon CSD of the Burnout device (ORNL mode II) and Vladimirov's BPIIS are drawn on figure 3.

4. Pulsed plasma ion sources[31]- PPIS.

High energy concentrated into a small volume of gas or solid may produce high temperature-high density plasmas ($n_e \sim 10^{16} \div 10^{20}$ el-cm^{-3}, $T_e \sim 10 \div 10^3$ eV). The energy is supplied by a capacitor bank (spark source and pinch discharge), or a laser beam.

4.1 Spark sources, pinch discharges as ion sources.

The vacuum spark was, during a long time, the most widely used source of highly ionized atoms for spectroscopic studies. Zwally32) has analyzed the beam from such a source, C^{4+} and Cu^{14+} (and probably even higher charge states) were obtained. It has been supplemented in recent years by plasma devices used in controlled fusion research : the pinch sources. Almost fully stripped ions are attainable (A^{17+} 33), Fe^{25+} 34)) but the very short duration of the ion pulses, the low repetition rate and the uncertainty about the extraction system make them less attractive for cyclotron application notwithstanding the extremely simple technology, and the high yield of very highly charged ions.

4.2 Laser ion sources - LIS.

4.2.1 Description

The interaction between a powerful laser beam and a solid target in vacuum, produces an energy and momentum transfer from light to matter which is, consequently, heated and set into motion. This motion is an expansion wave able to provide very highly charged ions. As for spark and pinch sources, the electron density is extremely high (up to 10^{21} el-cm^{-3}) then the interaction time of some nsec is sufficient to reach high ionization degree. The kinetic energy of ions increases with their own charges (for instance, 6 keV for Al^{6+} and 32 keV for Al^{13+} 35) and the higher the charge states, the smaller the emission angle of the ions. The ion pulse is very brief but magnetic mirror containment can be used to lengthen it36).

Tonon et al.37,38) have observed Al^{11+} and Fe^{16+} with a 3 J, 100 MW, 30 nsec Neodynium laser (2 10^{12} W-cm^{-2}). More recently, with a most powerfull laser (30 J, 3.5 nsec, 2 10^{13} W-cm^{-2}), they have detected Al^{13+} and Fe^{24+} 39).

4.2.2 Main characteristics

Figure 5 shows a plot of Al and Co CSD, in terms of number of ions, registered within a solid angle of ∿5 10^{-7}rad40). This experimental yield is reported on figure 11 ; assuming that ∿10^{14} ions are emitted by the plasma, recalculations in terms of total emission angle show a theoretical yield of $10^{9} \div 10^{10}$ Al^{13+} per pulse35). We may estimate the theoretical LIS yield per pulse (figures 11,12) by using the Tonon's compilation $n\zeta$ / $n_{total} = f(\zeta)$ (figure 15, ref. 38)). The question of repetition rate may be overcome with the CO_2 laser which does provide ∿10^{3} pulses per second, but with low powers41), in the actual state of the art. On figure 10 , we have drawn the ε_{max} obtained with a 2 10^{12} W-cm^{-2}LIS37) (higher values seem possible with greater fluxes). The energy spread is nearly equal to the average kinetic energy of the considered ions39), and proportional to ζ. The estimation of emittance according C. Faure38) gives a value $E_N \approx$ 1 10^{-7} mrad, (interesting value bound to the emission directivity of the higher charge states). The basic features can be summarized :

- Advantages :
  - the LIS is able to be set easily in a high voltage terminal,
  - good emittance,
  - high yield theoretically possible,
  - able to produce very high charge states.
- Disadvantages :
  - short lifetime of the lasers,
  - large target size for numerous successive shots,
  - large energy spread,
  - large pumping speed required to avoid strong rise of pressure at the shot time,
  - unable to easily produce non solid materials.

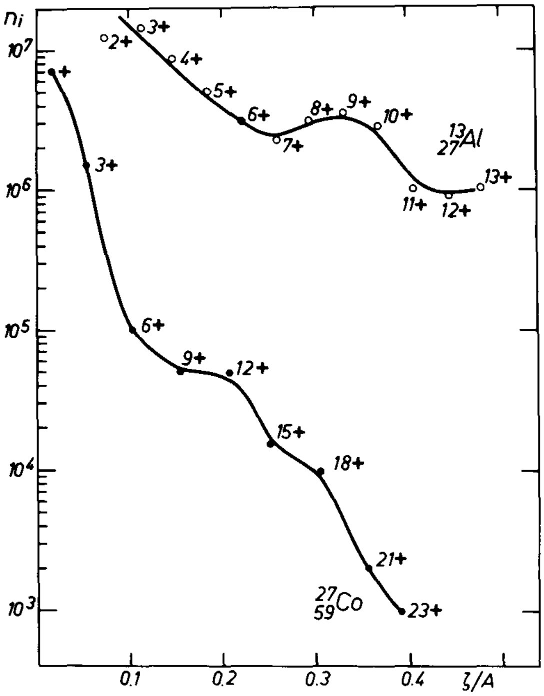

Figure 5. CSD obtained with LIS40).

As a conclusion, the LIS (and PPIS in general) seems to be more suitable for synchrotron applications as sources of nuclei, waiting for the developments of high power molecular lasers with high repetition rates 42).

5. Electron cloud ion sources - ECIS.

These devices use closed or open energetic electron clouds to ionize and to trap the created ions in their own potential well. The high ionization degrees are attained mainly by a step by step ionization process. The beam output is inherently pulsed (except with TOFEBIS). The maximum number of ions per pulse is proportional to the electron volumic density and to the cloud volume. The most important feature is a narrow CSD exactly comparable with the stripping foil one. The basic vacuum is such that the potential well is not levelled by ions issued from the background gas (P < 10^{-8} Torr).

5.1. Closed electron cloud ion sources - CECIS.

5.1.1 The HIPAC ion source.

The closed cloud is contained by an azimuthal magnetic field into a toroidal ultrahigh vacuum vessel43,44). With the following characteristics45) the calculated yield is, for instance, 10^{12} ions-sec^{-} U^{40+} or 10^{11} ions-sec^{-1} U^{60+} (figure 12) :

Basic vacuum : $\sim 5\ 10^{-10}$ Torr.
Electron energy : ~ 10 keV.
Electron volumic density : $\sim 10^{11}$ el-cm^{-3}.
Major radius of the torus : 20 cm.
Minor radius : 3 cm.
Volume : 3.6 10^{3} cm^{3}.
Potential well depth : 400 kV.
Magnetic field : 0.45 T.
Emittance U^{40+} : $\approx$ 3 10^{-7} mrad.

In spite of considerable promises notwithstanding technological problems (particularly the extraction) this work has been discontinued.

5.1.2 Electron ring ion trap.

An electron ring ion trap[46) may be used as an ion source of very highly charged ions, but this application does not look promising. This device needs an electron injector (linear accelerator), and the extraction seems a tremendous problem.

5.2 Open electron cloud ion sources - OECIS.

In these devices a very dense energetic electron beam travels along the axis of a solenoid which confines it. The ions are trapped into the radial potential well due to the electron beam.

5.2.1 Electron beam ion sources - EBIS.

Along the solenoid axis, the electron beam goes through a succession of insulated tubes allowing to apply a potential distribution which prevents an axial escape of the ions during the containment time[47) - figure 6.

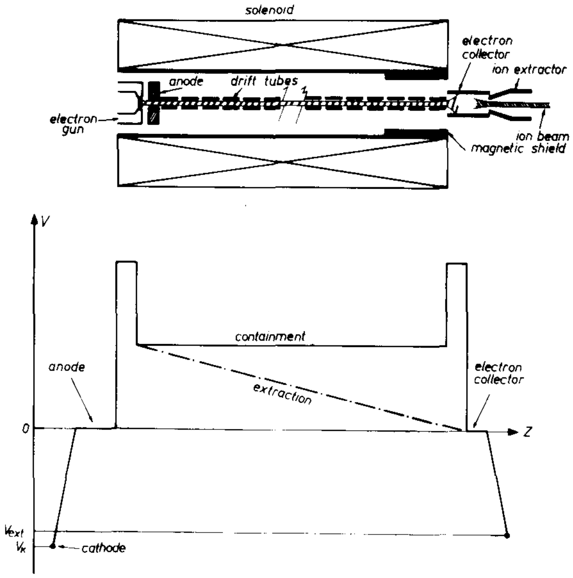

Figure 6. Scheme and potential distribution of EBIS.

At the end of the "batch", the ions are expelled from the ionization region by lowering the positive electrode potential on the output end of the source. Three EBIS are working whose characteristics are summarized in Table 3.

	Texas A&M[48)	Dubna[50) CRYON	Orsay[49) SILFEC
Vacuum inside the tubes (Torr)	$\sim 10^{-10}$	$\sim 10^{-11}$	$\sim 10^{-8}$
Magnetic field (T)	0.88	1.5	0.8
Solenoid	classical	cryogenic	classical
Electron energy (keV)	1 ÷ 10	1 ÷ 2.3	1 ÷ 5
Electron density (A-cm^{-2})	>100	~ 30	~ 30
Beam diameter (mm)	1	~ 3	~ 1

Table 3.

Figure 7 shows the spectra of Argon obtained with CRYON and SILFEC ; we can see a narrower CSD in the case of the pulsed neutral injection of CRYON.

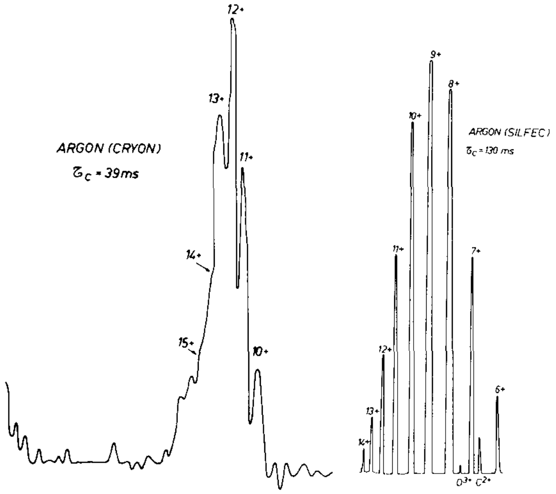

Figure 7. Spectra of Argon obtained with EBIS.
(CRYON : pulsed neutral injection
SILFEC : continuous injection).

On figure 8 are plotted typical CSD. The yield of this kind of ion sources is proportional to the density, on figures 11,12 the EBIS yield has been calculated[51) assuming a density of 100 A-cm^{-2}, recent experiments have shown that 1000 A-cm^{-2} are easily attainable with external guns and double magnetic compression[51), then this yield may be improved. We have plotted also the experimental yields of CRYON (assuming a containment time of 39 msec, there are 20 pulses per second in a cyclotron mode), and SILFEC. On figure 10 is drawn the ε_{max} possible with CRYON. The calculated emittance[52) is $E_N \sim 6\ 10^{-8}$ mrad for Kr^{8+}, a rough estimation by Donetz[53) gives a value which is greater by a factor of 3. The energy spread is $\approx 150\zeta$ (eV) in the case of SILFEC.

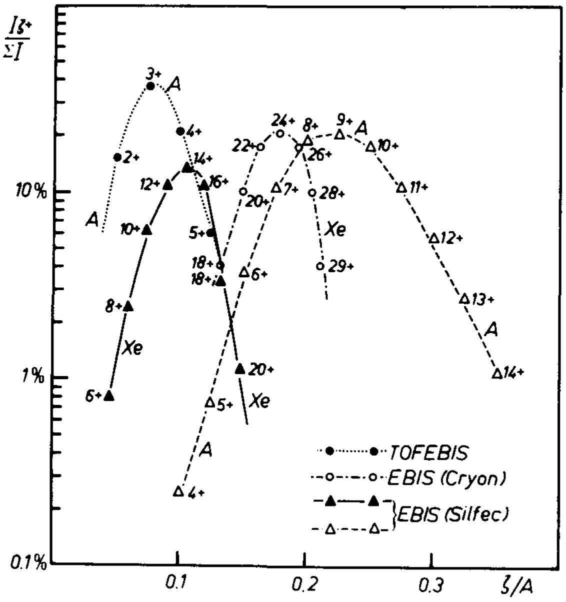

Figure 8. CSD obtained with OECIS

The basic features of this source are :

- Advantages :
  - good emittance,
  - narrow CSD with possibility of adjustment of the most probable charge state,
  - $\varepsilon \gtrsim 0.2$ possible for all elements,
  - long lifetime ($\sim$100 h for the actual electron gun, $\sim$3000 h with an external gun).
- Disadvantages :
  - "batch" operation with low duty cycle,
  - avanced technology (electron gun with high density, ultrahigh vacuum $\sim 10^{-10}$ Torr, cryogenic solenoid),
  - yield depending on the electron gun design,
  - large size.

5.2.2 Time of flight electron beam ion sources - TOFEBIS.

Another mode of operation of the EBIS has been proposed by Becker et al.[54].

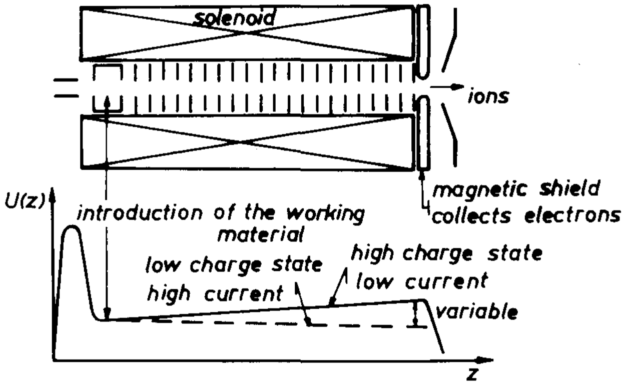

Figure 9. Scheme of TOFEBIS.

If the time of flight of ions along the electron beam is regarded as the ionization time, a TOFEBIS can produce highly charged ions without any kind of axial containment and in DC mode of operation. Figure 9 is a scheme of TOFEBIS, the ions are heated by Coulomb collisions, but reflected back by the potential hill, until they have reached sufficient energy to get out. Experimental Argon CSD[55] is drawn on figure 8. Obviously, for a same electron density, the TOF mode reaches charge states lower than the containment mode but the output intensity is greater. On figure 11 is plotted the estimation of the TOFEBIS yield for a 10 keV - 10^4 A-cm^{-2} electron gun and for $\zeta/A = 0.05$. Achievement of such densities is not at all utopic, it remains the problem of the injected power (which can be recuperated[56]) therefore TOFEBIS would provide at least charge states and currents comparable to PIG's ones without their shortcomings.

6. Comparisons between sources. Conclusions.

There are no sufficient experimental data to do accurate comparisons between ion sources of novel design, technological progresses and further investigations remain to be done, nevertheless we can make some general considerations. On figure 10, we have drawn ε_{max} $((\zeta/A)_{max})$ attainable with the different ion sources for all elements (with the actual apparatus) : the EBIS and the LIS appear to be able to produce high charge-to-mass ratio even for the heaviest element, but with "batch" output and low duty cycle, while the ECRIS provide lower ε_{max} but with high duty cycle (100% possible). We have drawn for comparison the ion source yields (experimental and theoretical).

For $\varepsilon \leqslant 0.1$ on the figure 11.
For $\varepsilon > 0.1$ on the figure 12.

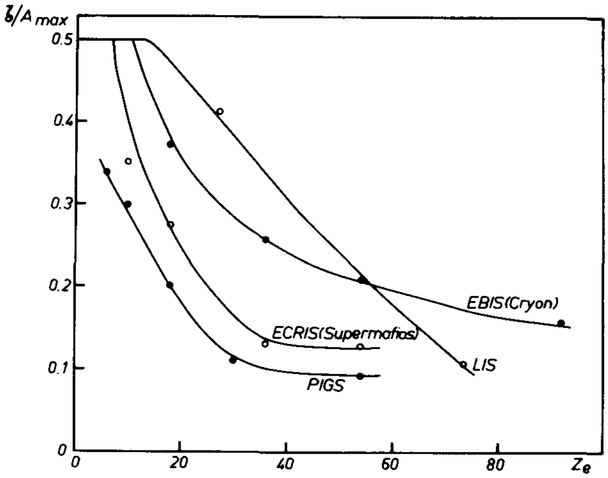

Figure 10. Maximum charge-to-mass ratio attainable with the different ion sources.

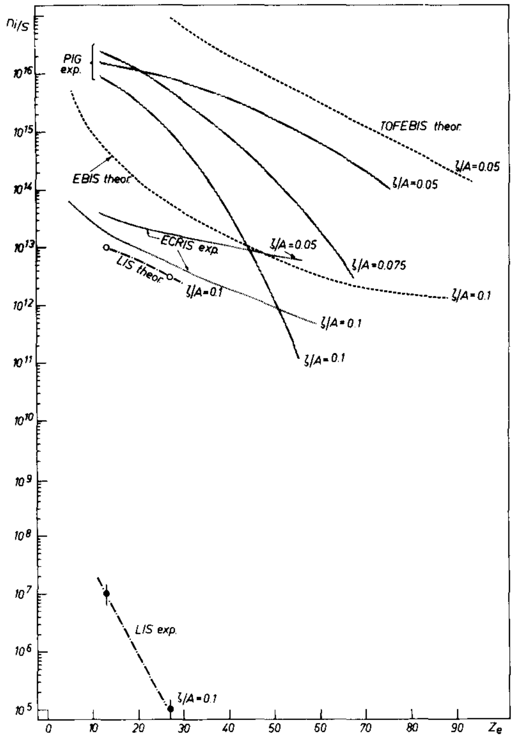

Figure 11. Ion yields for $\varepsilon \leqslant 0.1$.

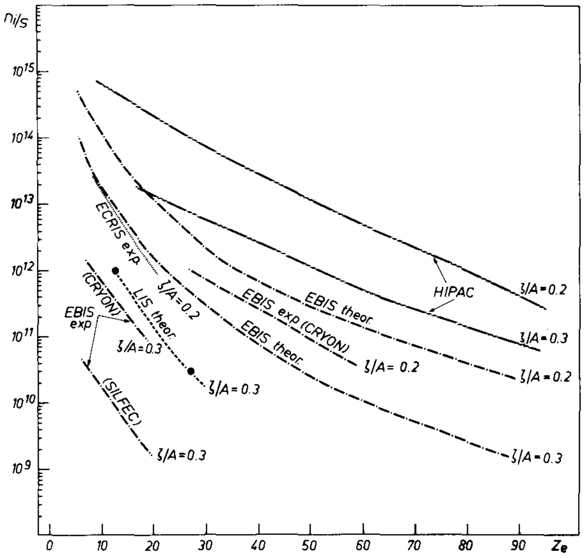

Figure 12. Ion yields for $\varepsilon > 0.1$.

Primarily built as tools of understanding, the actual devices have not yields matching with cyclotron requirements, but the ways to improve them are well known.

- In ECRIS, by increasing the plasma density near the extraction hole,
- in EBIS, by using a $10^2 \div 10^3$ A-cm^{-2}electron gun,
- in TOFEBIS, by using 10^4 A-cm^{-2} electron gun,
- in LIS, by increasing the laser fluxes and the repetition rate.

Let us mention that some of these new devices are going to be set on a machine or provided for (EBIS on the Texas A&M cyclotron[48]), EBIS on the Dubna synchrophasotron[50]) : CRYON, which is already working).

As a conclusion, important progresses have been obtained these last years by few groups, but more extensive research in this field may have spectacular results in a very near future.

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DISCUSSION

J.S.C. MCKEE: Is the laser a component of the ion source, or does it illuminate the target through a window into the ion source itself?

J. ARIANER: The laser is external and it illuminates the target through an additional window.

J.S.C. MCKEE: Are they generally pulsed?

J. ARIANER: No.

J. CLARK: Could you comment on plans for installing the electron-beam type ion sources in accelerators at your laboratory and in the USSR?

J. ARIANER: There are problems connected with the cooling of the solenoid. At Dubna, for instance, they have chosen superconducting solenoids: one for injecting very high electron densities; the other is a cryogenic solenoid, 1.5 m long and 30 cm in radius. Concerning the power, there are experiments showing that it is possible to recuperate the energy of the electron beam.