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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Notes of the "Workshop on ECR source problems"

held on

Thursday, April 30, 1992

at

CERN,
Geneva, Switzerland

edited by
K. Langbein

Contents

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Note by the editor

The the following notes of the discussion were taken by hand and edited at a later stage. Large parts of the discussion had to be omitted. Most sentences have been shortened and changed grammatically. Great care was however taken to avoid any alterations to the contents of the contributions. The text was verified by all participants quoted.

Introduction by H. Haseroth

After welcoming the participants from the outside institutions, H. Haseroth explained that there is a great interest at CERN to find ways and means to increase the output of highly charged ions from ECR ion sources. This is important not only for the heavy ion injector for fixed target experiments, which will be installed in the near future, but also for the LHC project, where even higher intensities are required. H. Haseroth stated that, provided there is interest, CERN would encourage collaboration between JINR, CEN, GANIL, FZ-Jülich, possibly other institutes and CERN to work on this topic.

H. Haseroth remarked that, as a result of CERN's interest in the matter, G.D. Shirkov from JINR, Dubna, a theoretical physicist working on the theory of ECR ion sources, had been invited to CERN and that G. Brianti and G. Plass (CERN) had proposed to arrange this meeting together with the other ECR experts.

Talk by G.D. Shirkov:

"Highly charged ion production in ECR ion sources"

Discussion

Baskaran: Radiative recombination is not included in your theory. This does however become important for the recombination of low energy thermal electrons with ions of charge states >20.

Shirkov: The simulation presented here was made for Krypton. (ed.: A=84, Z=36 for Kr.) Radiative recombination has not yet been taken into account in my theory. We must include this at a later stage simultaneously with thermal electrons.

Beuscher: How much evidence is there for ion cooling. Is there experimental proof ?

Shirkov: The experimentalists should answer this question.

Beuscher: (Displays a charge/mass spectrum measured at Jülich.)
In the (^{40}Ar+^{16}O)-plasma optimized on high charge states of ^{40}Ar, the ^{16}O charge states showed much more instabilities than the ^{40}Ar charge states. Could that be "heating" of ^{16}O and "cooling" of ^{40}Ar ions ?

Shirkov: Yes, ions with a low charge may be heated and therefore lost. If you have a cup of water and give it a shock, the water at the top will be spilled. The high charge states ions, which are at the bottom of the cup, are kept and only the upper part, where the low charges are, is pushed out. You can compare the different ion species with liquids of different densities, where liquids with the higher densities sink to the bottom.

Sortais: There is some evidence for ion cooling by Antaya (ed.: Michigan State University). He made measurements of the ion energy with and without a cooling gas. However, in my opinion, these are not safe measurements, as the total output current from the source is modified, which means that the beam optics is also modified.

Geller: It is very important for experimentalists working on ECRIS, that theoreticians ponder all aspects of this device. We have many questionmarks. For the ECR you can predict a lot of things and thereby find new results. There are many problems and it is very good that theoreticians work on these. Maybe this will give us clearer ideas and a better understanding of our results.

Speaking of simulation programs there are no "good" codes or "bad" codes. Also in plasma physics the arguments are never black or white, they are always grey. You always have to make a compromise.

Shirkov uses the Pastukhov postulate in his work; this applies for the magnetic bottle in an open configuration. However the ECR is, in my opinion, different from an open configuration. The difference is the ECR mirror plug. Every time electrons of a given category enter the ECR surface, they receive a kick, gain energy and are trapped in the magnetic field. This may not be a correct description; however in the usual magnetic bottle there are no spots where the electrons acquire an energetic component.

Thus there is a sudden difference in temperature on an ECR surface. This surface is a discontinuity !

I don't know something better than the Pastukhov postulate. However, in this postulate, turbulence is ignored. In an ECR you have noise. This is no ordinary noise. You have instabilities, they are not strong, they are however instabilities.

In the Pastukhov theory the magnetic field has no large influence. However experimentally (ed.: in the ECR) we find a large influence. I have nothing better than Pastukhov, but the theory must be improved.

Turbulence is a collective phenomenon. Turbulence in a plasma will give the same results as collisions. It is possible to calm down turbulences. Calming down turbulences is also cooling. Thus turbulences are very important in our case.

Beuscher: An ECR plasma for the production of highly charged ions is not a very quiet plasma. It is much noisier than, for example, an ECR heated plasma for H^+ production at a high gas pressure of about 10^{-3} mbar and bad confinement.

Geller: It is quieter than some other plasmas! But nevertheless an ECRIS is not an open configuration. Pastukhov's theory is more than 10 years old - you should now take the mirror plug into account. You should also take into account, that the ECR has no loss cone but rather a loss hyperboloid.

Geller addressing Shirkov:

You assume in your theory that ions are confined by the negative potential produced by a surplus of electrons in the plasma. You say that the low charge state ions are not confined as well as the ions with a higher charge state and you assume an average temperature for all ions. How do you manage that?

Shirkov: By binary collisions. The frequency of binary collisions is very high. The mixing of ions of different temperatures is comparable to the mixing of hot and cold water.

Geller: Is cooling a binary process?

Shirkov: Yes.

Geller: The frequency of binary collisions must be larger than the frequency of turbulences.

Shirkov: I neglect turbulence in my theory.

Beuscher: Gas mixing in an ion source does a lot of other things in addition to ion cooling.

Geller: The emittance of the ion beam is a function of the ion temperature. Binary collisions may give us a lower temperature and thus reduce the emittance.

Beuscher: Can you make the destruction of the potential well faster?

Shirkov: Yes, as already mentioned in my talk, by the injection of ions.

Beuscher: What is the beam quality in pulsed mode (ed.: i.e. afterglow mode)?

Comments were made by Geller, Sortais and Langbein. It was agreed that this question is not yet fully understood.

It was stated by Sortais that the beam diameter increases during the afterglow compared to the beam diameter in the main pulse. Furthermore the position of the beam on a profile monitor (after a spectrometer magnet) changed during the afterglow, which indicates either a change of energy and/or a change in the output angle at extraction.

Langbein stated, that similar observations were made at CERN, i.e. the optics of the low energy beam transport and the steering need to be adapted to the afterglow. Generally the strength of focusing elements needs to be increased (e.g. the current in the solenoid which focuses the ion beam into the RFQ had to be increased from 330 to 370 A, i.e. by 12%), which indicates a larger beam diameter and/or a higher beam energy. It was however found that these changes of the beam parameters during the afterglow have no negative effect on the transmission through the accelerators and that the accelerated ion intensity in the PS was increased by a factor of five using the afterglow.

Sortais: I have a remark concerning the injection of ions into the ECR plasma: The largest part of the ions is expelled from the source during the afterglow. It is probably not very interesting to improve this. It may be possible to optimize the afterglow, but I expect the increase will not be very large.

Haseroth: If there is radiative recombination of the ions, it is necessary to get the ions out of the source as fast as possible.

Shirkov: 10 µs is the time scale for the ion expulsion without a negative potential. The limit given by the TOF of the ions through the source chamber is 10-20 µs but the time scale of electron cooling and loss in RF pulse mode is much more and this time determines the duration of the ion pulse in the afterglow.

Geller: The potential in the source plasma is electrostatic. This means you have a capacity. So maybe you can use an ion beam to change this potential.

Beuscher: It may be very difficult to inject ions into an ECRIS.

Geller: The cutoff of the rf is probably much faster.

Shirkov: The cutoff of the confinement is very fast. However the building up of a positive potential is much slower.

Beuscher: What is the risetime of the afterglow?

Shirkov: I assume something in the order of 0.5 ms, but this depends on the plasma parameters.

Langbein: The rise time is much shorter in our case. We observe rise times of approximately 200 µs. However the decline is much slower than in your theoretical results.

The discussion was followed by a comparison of the theoretical and experimental results. Sortais and Langbein displayed plots of the afterglow obtained from the CAPRICE and MINIMAFIOS sources. The rise time of the afterglow of the CAPRICE source is found to be much longer than that of the MINIMAFIOS.

Talk by K. Langbein:

"Upgrading of the 'Sulphur'-ECRIS at CERN"

Discussion

It was stated by Geller that the results obtained at CERN are outstanding and that this was the first time the afterglow of the ECR discharge was utilized for the injection into an accelerator.

There were further questions concerning the position, the geometry and the operating voltage of the cold cathode. Langbein explained, that the cathode consists of a tantalum tube of 10 mm diameter made from a foil, positioned at the entrance of the discharge chamber. It is operated at -300 V with respect to the source body.

The question arose how the cathode in the ECR can enhance the afterglow. Langbein suggested that, assuming the existence of the negative potential postulated by Shirkov, the cathode would increase this potential during the main pulse by providing additional electrons. In the afterglow the cathode would serve as an additional loss region for electrons, as fast electrons can overcome the applied negative potential.

Beuscher asked for a further explanation of the separation of oxygen and sulphur ions after acceleration in the LINAC (ed.: O^{8+} and S^{16+} have the same charge to mass ratio). The method utilizing the difference in the energy degradation in a thin foil was explained.

Furthermore an estimate of the S^{16+} intensities at various points of the accelerator chain was given: 20 eμA of S^{16+} are measured using the secondary emission monitor (SEM) grids at the exit of the LINAC assuming a calibration factor of 4. Using 0.5 as the ratio of the total current (O^{8+} and S^{16+})

at the exit of the LINAC to the total current at the entrance of the LINAC (note the current increase of 33% by stripping after the LINAC) the S^{16+} current at the entrance of the LINAC can be assumed to be 40 eμA. The RFQ transmits and accelerates aprox. 50% of the current measured at the entrance . Thus the S^{16+} current at the entrance of the RFQ amounts to 80 eμA and to about 130 eμA at the exit of the source. The total current (O^{8+} and S^{16+}) at the entrance of the RFQ is approximately 350 eμA.

Lunch

Talk by P. Sortais:

"Proposal for the upgrading of pulsed currents of highly charged heavy ions"

Discussion

Beuscher: How fast can the magnetic compression be made? (Ed.: referring to the suggestion by Sortais to compress the ECR plasma after its production in a normal mode of operation.)

Geller: We have achived 5 Tesla in 5 ms (i.e. 1T/msec). This can be improved with a certain amount of effort.

Sortais: Is the shortening of the afterglow pulse useful?

Haseroth: Only if the total number of charges in the pulse can be maintained. The pulse length should be about 10 μs.

Haseroth explained the method of multiturn injection into the PS Booster, which is currently employed and the advantage of single turn injection, i.e. the reduction in emittance with the consequence of the desired higher luminosity. He stated that this would mainly be useful for the planned LHC.

With the system now under construction, i.e. the Pb-injector for SPS fixed target physics, a luminosity of 10^{24}-10^{25} may be obtained. The aim for LHC is a luminosity of $2 \cdot 10^{27}$ or more.

Geller: Did you ever try to use monoturn injection with a 10 μs pulse?

Haseroth: Only with protons, not with ions.

Geller: Does the short pulse cause any additional problems?

Haseroth: There is only the problem of the increase in space charge.

Hill: It is also possible to use less than a full turn in the Booster.

Haseroth: It may be better to use only one of the four rings of the PSB.

Haseroth addressing Shirkov:

If a collaboration between CERN and JINR and other institutes were established with the aim to do further ECR studies, what would you like to do in this context?

Shirkov: I would like to simulate the ECR plasma numerically in pulsed regime including ion cooling. Also recombination should be included. A model for ion heating by electrons should be established.

Geller: Do you have any ideas how to include heating in this model.

Shirkov: In the Kurtschakov Institute a theory for cyclotron resonance heating for nuclear fusion plasmas, which also includes heating by electrons, was established by Timofeev. Maybe this can also be applied to ECR ion sources.

To create a uniform computer program one would have to solve the kinetic equation. But I do not know if we could profit from a global simulation program. Maybe it is better to study the different problems separately.

Haseroth addressing Beuscher:

Would you be able to make experimental investigations at Jülich to verify theoretical results?

Beuscher: Yes, we are however restricted in the time we could use for this. Furthermore experiments at the Jülich ECR, which require changes in the mechanical set up, are difficult because of the radially closed cryostat and the far reaching magnetic field of the large superconducting coils.

Sortais: It would be very interesting to study a large source (ed.: referring to the Jülich ECRIS) in the afterglow mode.

Geller: If, for a single stage source, it could be shown, that, by operating with a very low pressure, you starve the plasma, this would be an explanation for the improved performance with a cathode. Thus we need to study starving plasmas and also the injection of electrons. It would be very interesting to add electron injection in Shirkov's theory (and this seems possible). Results could be compared to experiments...

Baskaran: In starvation mode there are probably not enough thermal electrons which are essential for the production of low charge state ions. Since the highly charged ions are produced by a step by step ionization, a sufficient thermal electron density is necessary to obtain a high flux of highly charged ions. Thermal electrons are supplied by various mechanisms and it is difficult to estimate the electron density at different points of the source.

Beuscher: If you add electrons, the plasma will not be neutral any more.

Langbein: This helps to build up the negative potential, which is assumed in Shirkovs theory.

Sellmair: Where are the loss regions for the electrons?

Shirkov: In the theory I assume losses only along the axis through the loss cones.

Sellmair: Are there no radial losses?

Geller explained the triangular cross section of the plasma in the radial plane, which is produced by the combination of the longitudinal solenoidal and the radial hexaplole field. He stated that there are in fact radial loss regions.

Sellmair: Is there cooling of electrons by electrons?

Shirkov: No, the rate for this is too low.

In the final discussion various ideas (including exotic ideas) to enhance the output from ECR ion sources were exchanged. Different ways to inject an ion beam into an ECRIS were suggested and the problem of the increased space charge in the extraction system caused by additional ions was discussed. It was also suggested to change the polarity of a cathode from a negative polarity in the main pulse to a positive polarity during the afterglow.

H. Haseroth closed the meeting thanking especially the visitors from the outside institutions for their participation.

Appendix A

Highly Charged Ion Production in ECR Ion Sources

G. D. Shirkov

Joint Institute for Nuclear Research,
Dubna, Russia

ERIS Project in JINR.

(Electron Ring Ion Source)

Project leaders: G. Musiol (TU Dresde
A. Sumbaev (JINR)
G. Shirkov (JINR)

The ionization processes of neutral atoms and charge changing trasitions can be described by a set of nonlinear balance equations in differential form:

$$\frac{dn_0}{dt} = \frac{S}{V} v_0 (n - n_0) - n_0 \Big(\sum_i \sigma_i^{ex} n_i v_i + \sum_i \sigma_i^{2ex} n_i v_i + (\sigma_i^{i} + \sigma_i^{2i}) n_e v_e \Big) = 0 \quad \text{in static case}$$

$$\frac{dn_1}{dt} = \ldots\ldots \qquad = 0 \quad \text{in st. case}$$

– – – – –

$$\frac{dn_i}{dt} = \sigma_i^{i} v_e n_e n_{i-1} + \sigma_{i-1}^{2i} v_e n_e n_{i-2} + (\sigma_{i+1}^{ex} n_{i+1} v_{i+1} + \sigma_{i+2}^{2ex} n_{i+2} v_{i+2}) n_0 -$$

$$- n_i \Big((\sigma_{i+1}^{i} + \sigma_{i+1}^{2i}) v_e n_e + (\sigma_i^{ex} + \sigma_i^{2ex}) v_i n_0 \Big) - n_i/\tau_i$$

$$= 0 \quad \text{in st. case}$$

– – – –

$$\frac{dn_z}{dt} = (\sigma_z^{i} n_{z-1} + \sigma_{z-1}^{2i} n_{z-2}) v_e n_e - n_z \Big((\sigma_z^{ex} + \sigma_z^{2ex}) v_z n_0 \Big) - n_z/\tau_z$$

$$= 0 \quad \text{in st. case.}$$

Here:

n — densities of ions and neutrals

σ - cross sections of electron impact ionization "i" and charge exanche "ex"

τ - lifetimes of ions

Cross sections:

Ionization W. Lotz (1967)

$$\sigma_i^{1} = \frac{4.5 \cdot 10^{-14}}{T_e} \sum_k \frac{n_k}{I_k} \log \frac{T_e}{I_k} \quad \langle cm^2 \rangle$$

Double ionization A. Müller (1980)

$$\sigma_i^{2i} = \frac{2.6 \cdot 10^{-14}}{T_e (I_i + I_{i+1})} \ln \frac{T_e}{I_i + I_{i+1}} \quad \langle cm^2 \rangle$$

Charge exange A. Müller and E. Salzborn (1976)

$$\sigma_i^{ex} = 1.43 \times 10^{-12} \, i^{1.17} \, I_0^{-2.76} \quad \langle cm^2 \rangle$$

$$\sigma_i^{2ex} = 1.08 \times 10^{-12} \, i^{0.71} \, I_0^{-2.8} \quad \langle cm^2 \rangle$$

This set of equations is used usually for study any kind of plasma with multicharged ions and ion sources. For ECRIS it was used only in static case as a set of algebraic equations.

Jongen Y. (1980)

Bliman S., Chan-Tung N. (1981)

West, H. I., Jr. (1982)

new investigations was began in 1989 in Dubna:

Kutner V. and Shirkov G. (1989 ÷

in TU Dresden (Germany) in 1989

Shirkov G. and Zschornack and C°

The ionization degree of ions depends on n_e and τ_i.

The definition of the life time of ions or ion confinement time is one of the main problems.

ECRIS is plasma in open magnetic trap.

The theory of plasma in the open magnetic trap was studied carefully in connection with investigations for thermonuclear fusion. Pastukhov V. (1984)

Two main types of ion losses:

1. Classial losses according to classical theory;
2. Instabilities and turbulences.

1. The classical losses always presence.
2. Instabilities and turbulences
   - may be yes, or may be no.

The problem of instability and turbulence appearance in plasma is difficalt promlems. But the opinion of the specialists in the physics of open magnetic traps from Moscow Institute of Atomic Energy is that there processes have a small probability due to a strong axial magnetic field and variations of azimutal field.

As the result of elastic collisions the ions have the Maxwell energy distribution with equal temperature for all ion species.

Ion Con-finement

The strong axial magnetic field with magnetic mirrors confines the electrons The ions have high mass and low energy and the confinement condition for them in magnetic trap are worse. The negative plasma pottential appears when ions leave the trap and its value regulates the rate of ion losses.

So, the magnetic field keeps the electrons, the electrons keep the ions.

The ions with energy

$$E_i > ieU$$

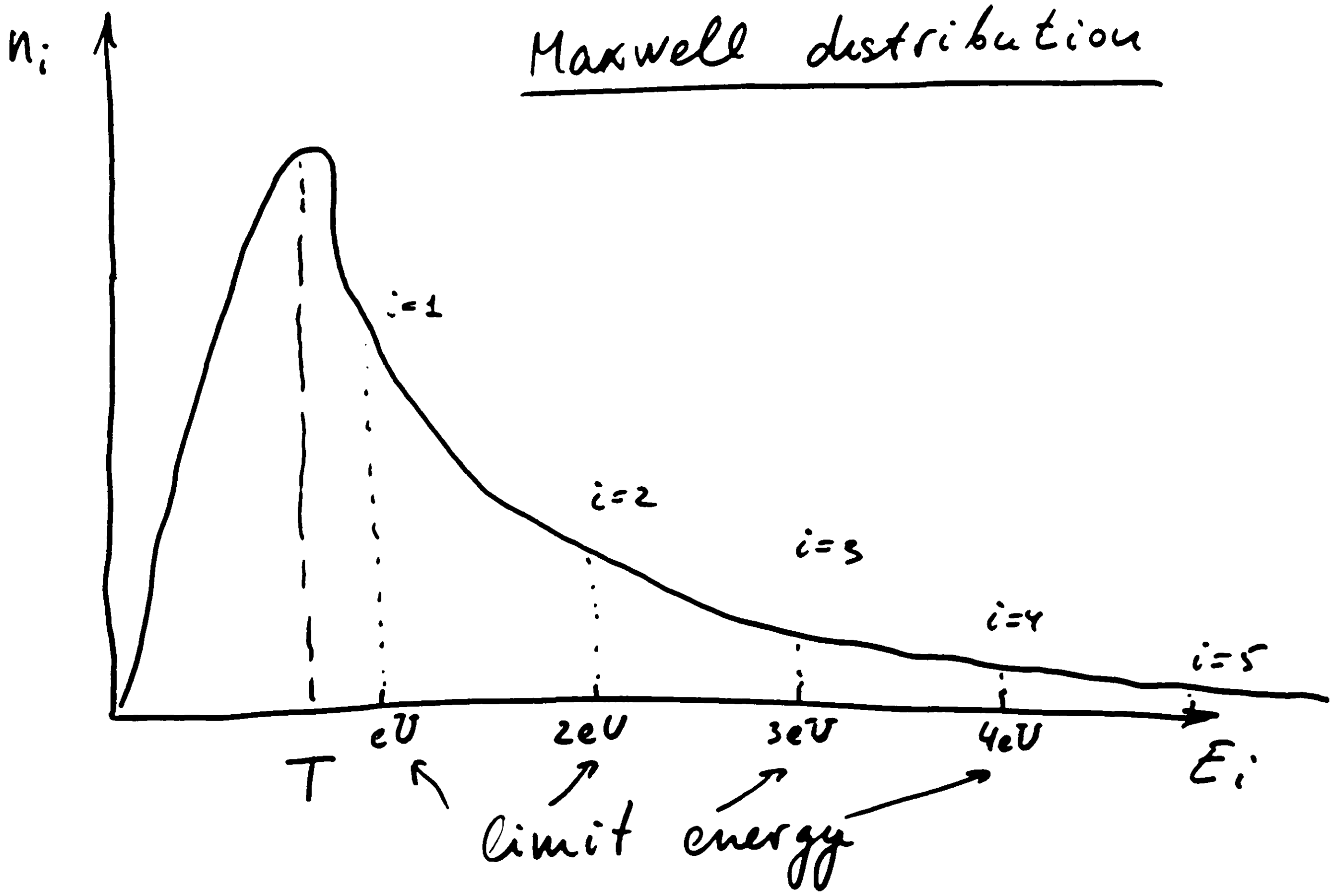
loss. from the trap, where

U - potential of plasma,

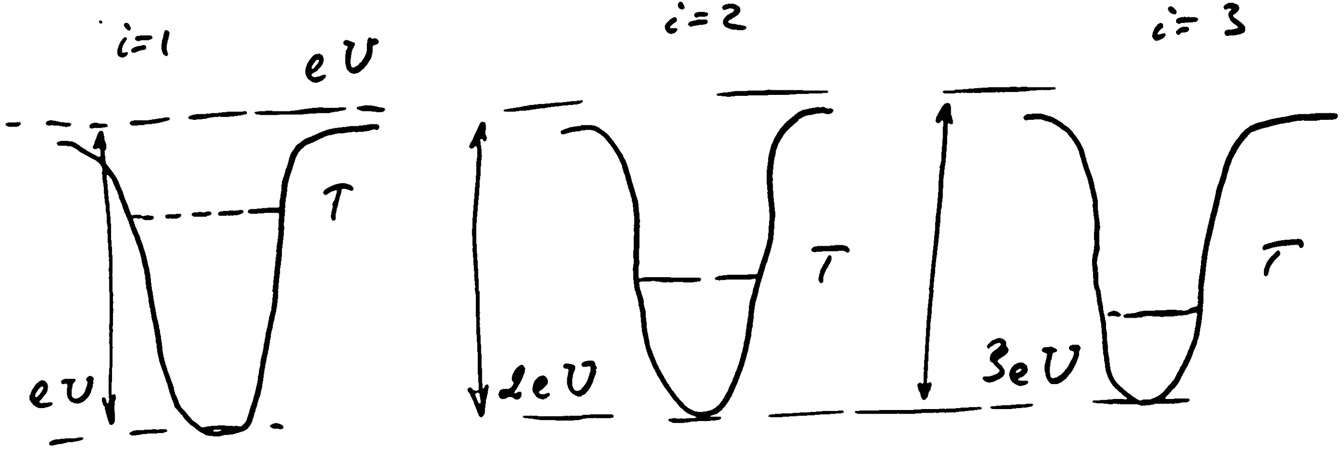
i - ion charge state.

The ion components with different charge states have different part of ions with energy more then potential barrier

Maxwell distribution



Potential well



The ions with the high charge states have low probability to be lost, they are on the bottom of potential well.

According to the Pastukhov theory the ion confinement time is:

$$\tau_i = kl \sqrt{\frac{\pi A M}{2 T_i}}\, e^{ieU/T_i}$$

According to West, the outgoing ion current from plasma:

$$J = \frac{i n_i l}{\tau_i}.$$

So, the main results of this model of ion confinement and loss:

1. The charge state distribution of output current differ from charge state distr. of ions inside plasma
2. The ions with high charge states have the high life-times and it is difficult to extract them from the source.
3. The decreasing of ion temperature increases the ion confinement time.

The real examples.

Ion cooling (gaz mixing)

The first idea of ion cooling in the ion sources appeared ~ 10 years ago

Soviet patent E. Donets, G. Shirkov (1984)

There are a lot of experiments from 1986 in the wourld.

The first calculations to ion coaling in ECRIS:

T. Antaya (1989)

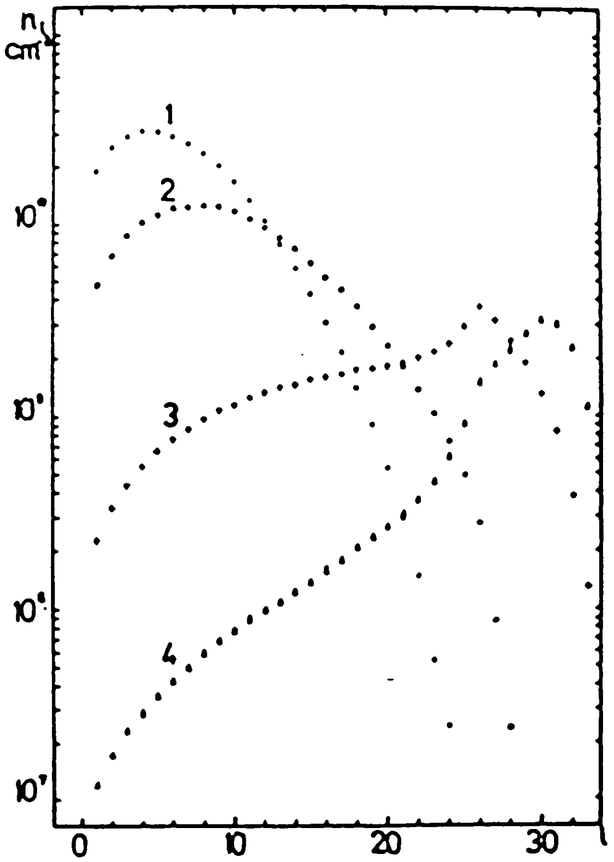
G. Shirkov (1990)

The main idea:

The addition into the plasma the light ions with low charges and energies is a cause of heavy ion temperature decrease as the result of elastic scattering. The light ions take the heavy ion energy, loss from the source and take away the energy. The life-time and the charge state of heavy ions increase.

Kr

$T_e = 5000 eV$ $n_e = 2 \cdot 10^{12} cm^{-3}$



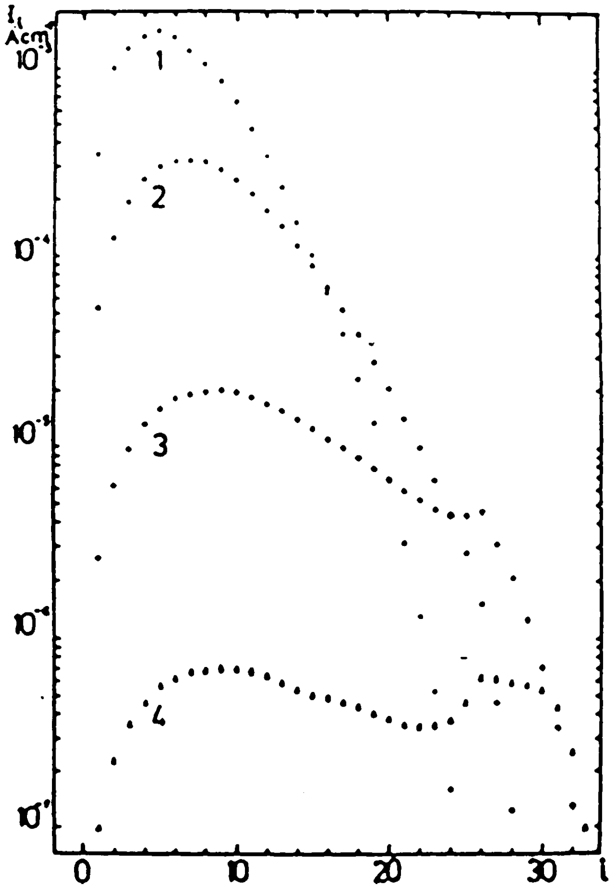
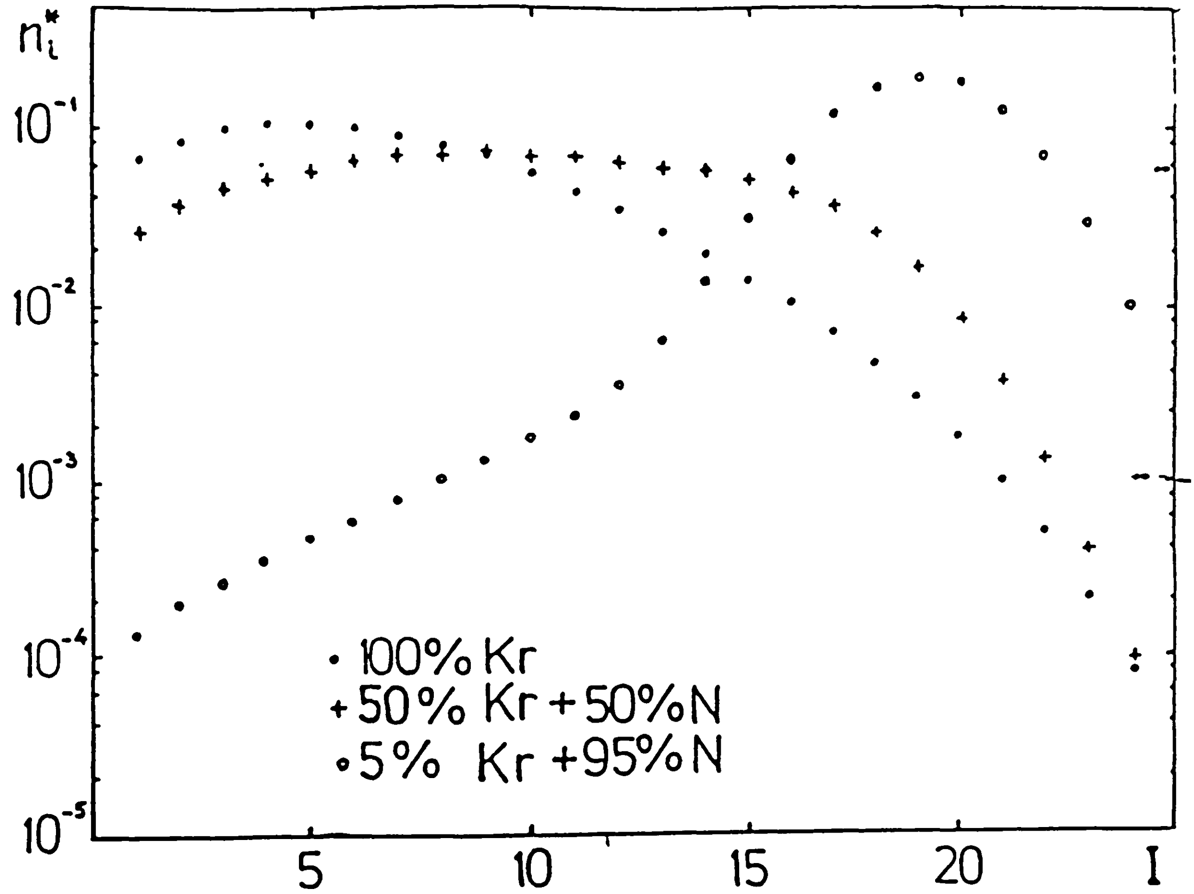


Fig.1. Ion densities n_i for krypton charge states i in ECR plasma for various mixture of krypton and nitrogen ions.

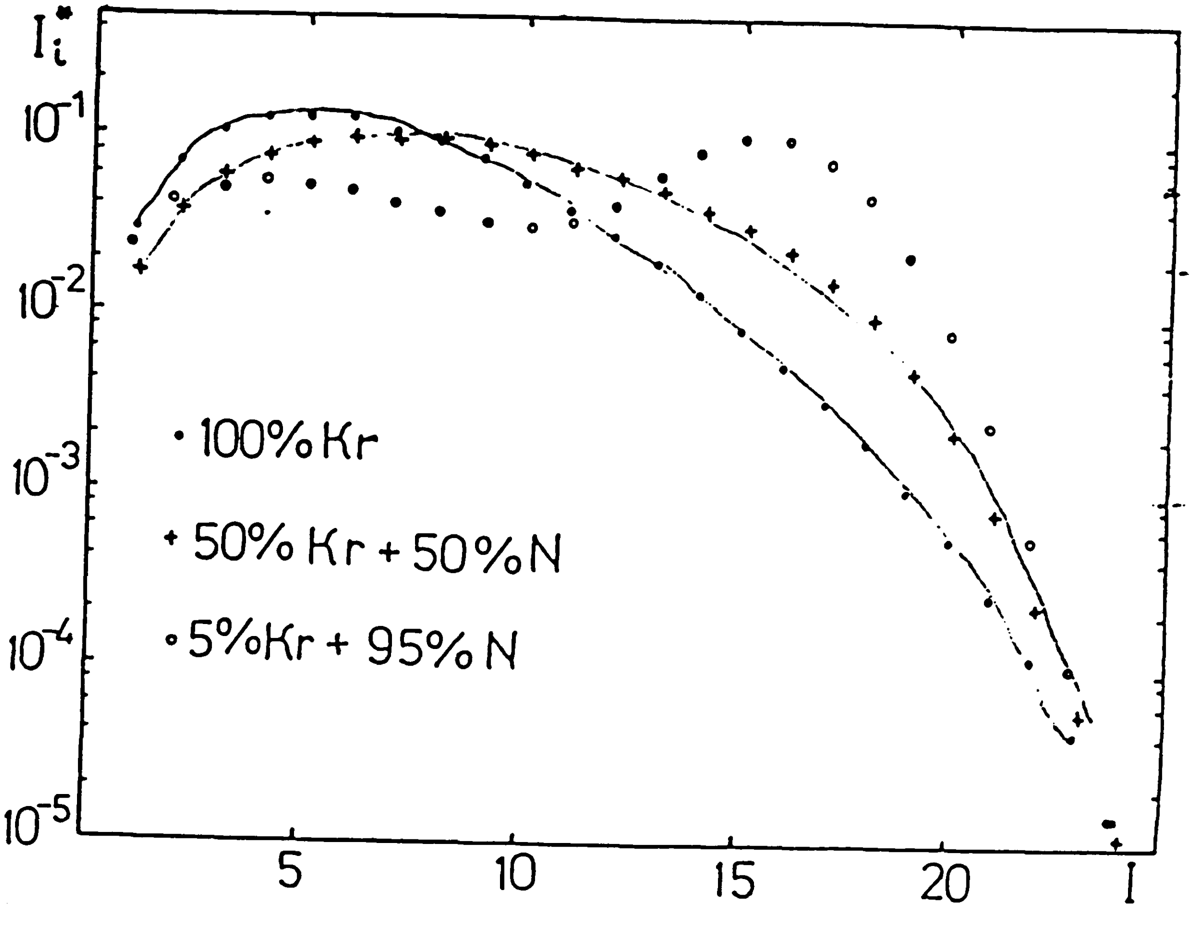
Fig.2. Ion currents I_i for krypton charge states i from ECRIS for various mixture of krypton and nitrogen ions.

In Fig.1 and Fig.2 the designations are: "1" - pure krypton; "2" - 75% ion charge is Kr and 25% ion charge is N; "3" - 50% - Kr and 50% - N; "4" - 33% - Kr and 67% - N;

Kr



$T_e = 5000 eV \quad n_e = 2 \cdot 10^{12} cm^{-3}$



Pulse mode

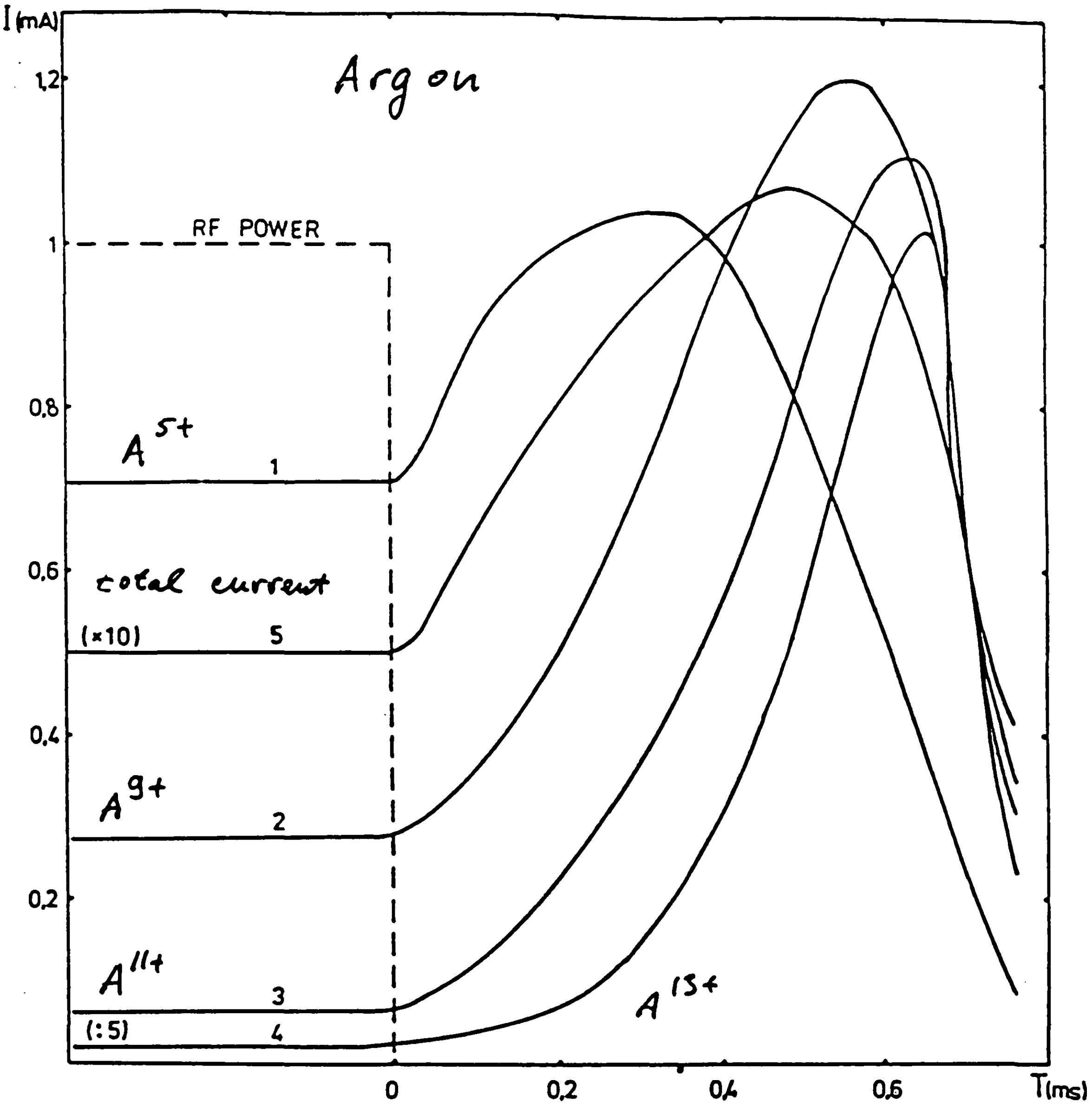
The first observation of afterglow effect in pulse regime mode was 3-4 years ago.

The first calculations and numerical simulations was last year.

G. Shirkov (1991)

According to our results, The highly charged ions accumulate in the source and it is very difficalt to obtain them from the source trap.

If the potential well will taken off, the all stored ions will "pour out" from the trap and one can obtain the current pulse with the charge state distribution like the distribution of accumulated ions.



$T_e = 5000\,eV$ $n_e = 10^{12}\,cm^{-3}$

Kr $T_e = 5 \cdot 10^3$ eV $n_e = 2 \cdot 10^{12}$ cm^{-3}

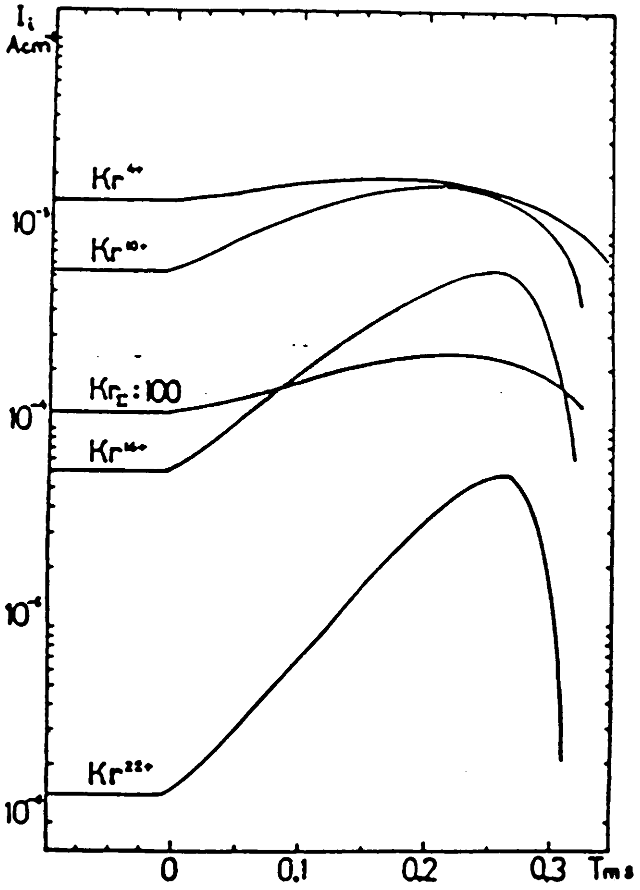


Fig.3. Time dependence of ion output currents I from ECRIS in RF pulsed operation mode for Kr^{4+}, Kr^{10+}, Kr^{16+}, Kr^{22+} ions and total ion current.

RF pulse mode.

When RF power is switched of the electrons become cool, the electron confinement conditions become worse and them begin to loss. The potential well disappears and all stored ions are escaping outside.

The moment of ion appearing and ion pulse duration are determined by the electron confinement time $\tau_e \sim 0.3 \div 1.10^{-3}$ s.

The total current density of ion pulse can be valued as

$$j_{tot} = \frac{V e n_e}{2 S \tau_e} \longrightarrow j\,\tau_{pulse} = const$$

V - plasma volume

S - square of butt-end

If we can destroy the potential well in a short time (~ 10μs) the pulse duration will determined by ~~the~~ time of ion flight pass through the source ~ 0.1 ÷ 0.01 m with accordingly higher current.

Total ion charge in the potential well:

$$Q = V e n_e = 10^3 cm^3 \cdot 1.6 \cdot 10^{-19} C \cdot 2 \cdot 10^{12} cm^{-3}$$
$$= 3 \cdot 10^{-4} C$$

Total ion current in pulse regime:

$$I = \frac{Q}{\tau}$$

Current density throught the butt-ends:

$$j = \frac{I}{2S} = \frac{V e n_e}{2S\tau} = \frac{l S e n_e}{2 \cancel{S} \tau} = \frac{l e n_e}{2\tau}$$

for $\tau = \tau_e \sim 10^{-3} s$:

$$j = \frac{30 cm \cdot 1.6 \cdot 10^{-19} C \cdot 2 \cdot 10^{12} cm^{-3}}{2 \cdot 10^{-3} s} = 5 \cdot 10^{-3} \frac{A}{cm^2}$$

for one charge state:

$$j_i = j/20 \approx 0{,}2 \div 0{,}3 \ mA/cm^2$$

If $\tau = 0{,}1$ ms :

$$j_i \gtrsim 1 \ mA/cm^2$$

The ion cooling can shift the distributio of ion charge states (if the charge exchange processes are negligible) to the region of $Pb^{35+} \div Pb$

There are different ways to destroy the potential well, probably. One of the possible methods is to inject a beam of positive ions into the working region of the source.

The pulse regime, especially with light ion cooling, is a very promising way to obtain a short intensive pulse of highly charged ions for heavy ion accelerators and storage rings. The valuetions can show, that we can hope to obtain the pulses of $Pb^{35+} \div Pb^{40+}$ with current $0.1 \div 0.3$ mA or maybe more. if the duration of ion pulse will be ~ 100 µs or lower.

We have now:

1. The physical model of Ion confinement and loss with a good agrement with experiments.

2. The computer codes for numerical simulations of differ regimes of ECRIS operation:
   a) in static regimes for gaz mixture (ion cooling);
   b) in dynamic regimes (pulse mode).

We have *a plan* to create in future a self consistent model of physical processes in ECR plasma and software for numerical simulation.

The plan may consists of the (next first steps:

1. The compute package for numerical simulations of pulse regime with ion cooling.
2. The compute code for two stages ECRIS.
3 The compute code for two different energy electron components in ECRIS.
4. The investigations of the microwave electron heating and determination of the distribution function and temperatur of electrons.

Appendix B

Upgrading of the 'Sulphur'-ECRIS at CERN

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Upgrading of the "Sulphur"-ECRIS at CERN

Talk presented on the

Workshop on ECR source problems

CERN

Thursday, April 30, 1992

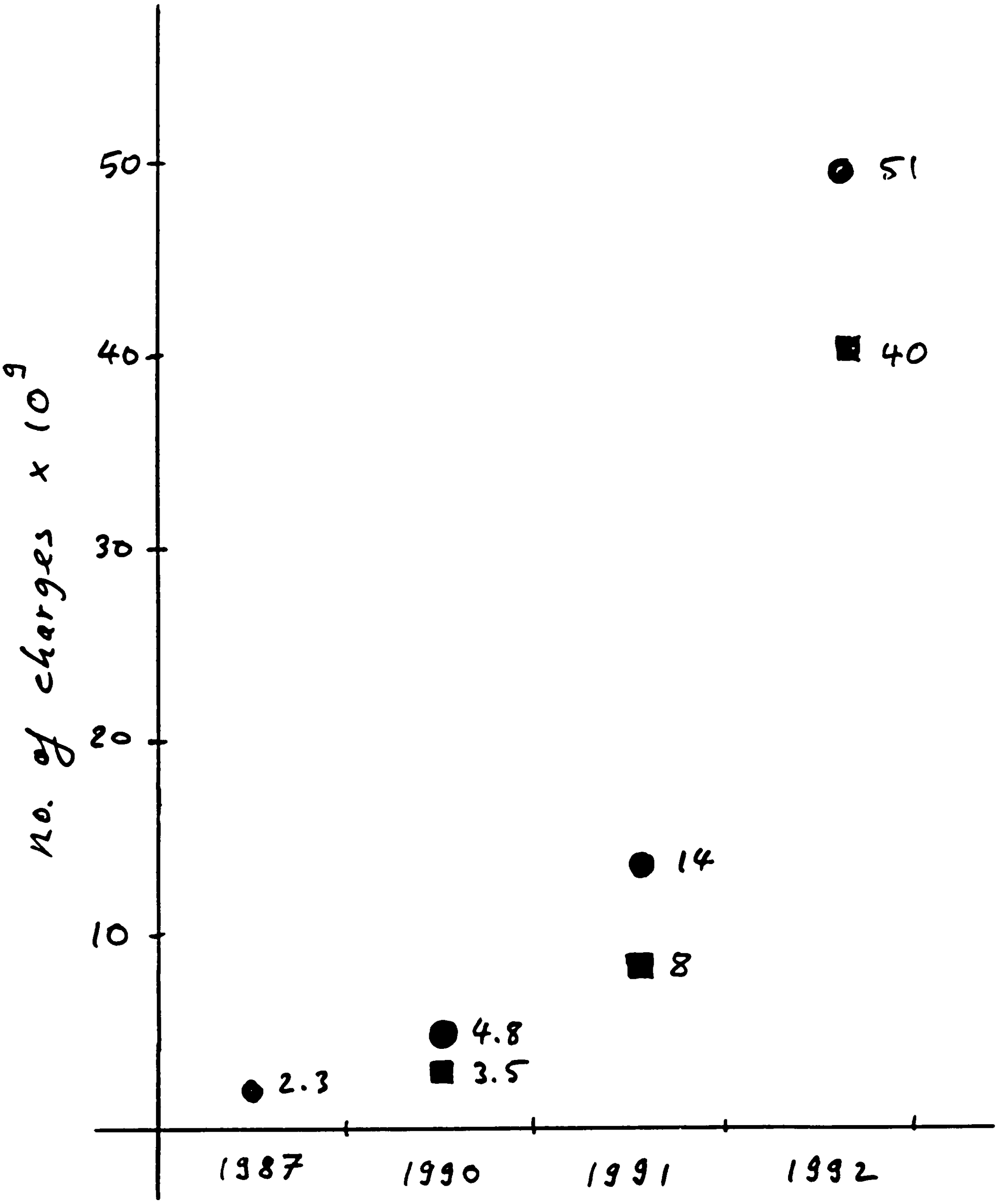
by

K. Langbein

- Performance during the 1992 sulphur run
- Characteristics of secondary electron emitter in ECRIS
- Investigation of afterglow

Development of sulphur intensity in PS (1987-1992)

Number of sulphur charges in the sum of four pulses after separation from oxygen at transition



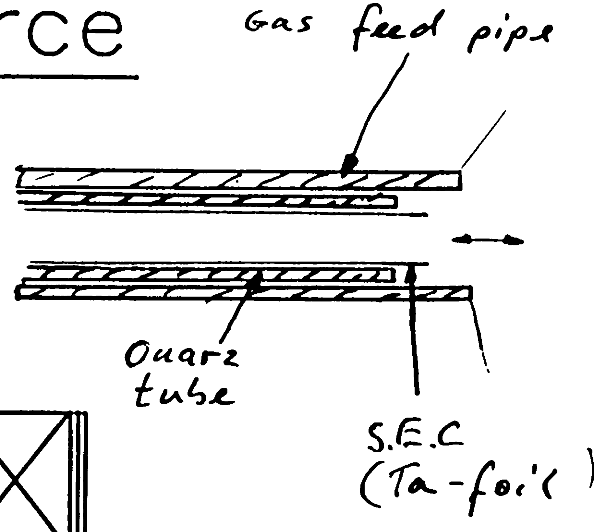
● record intensity

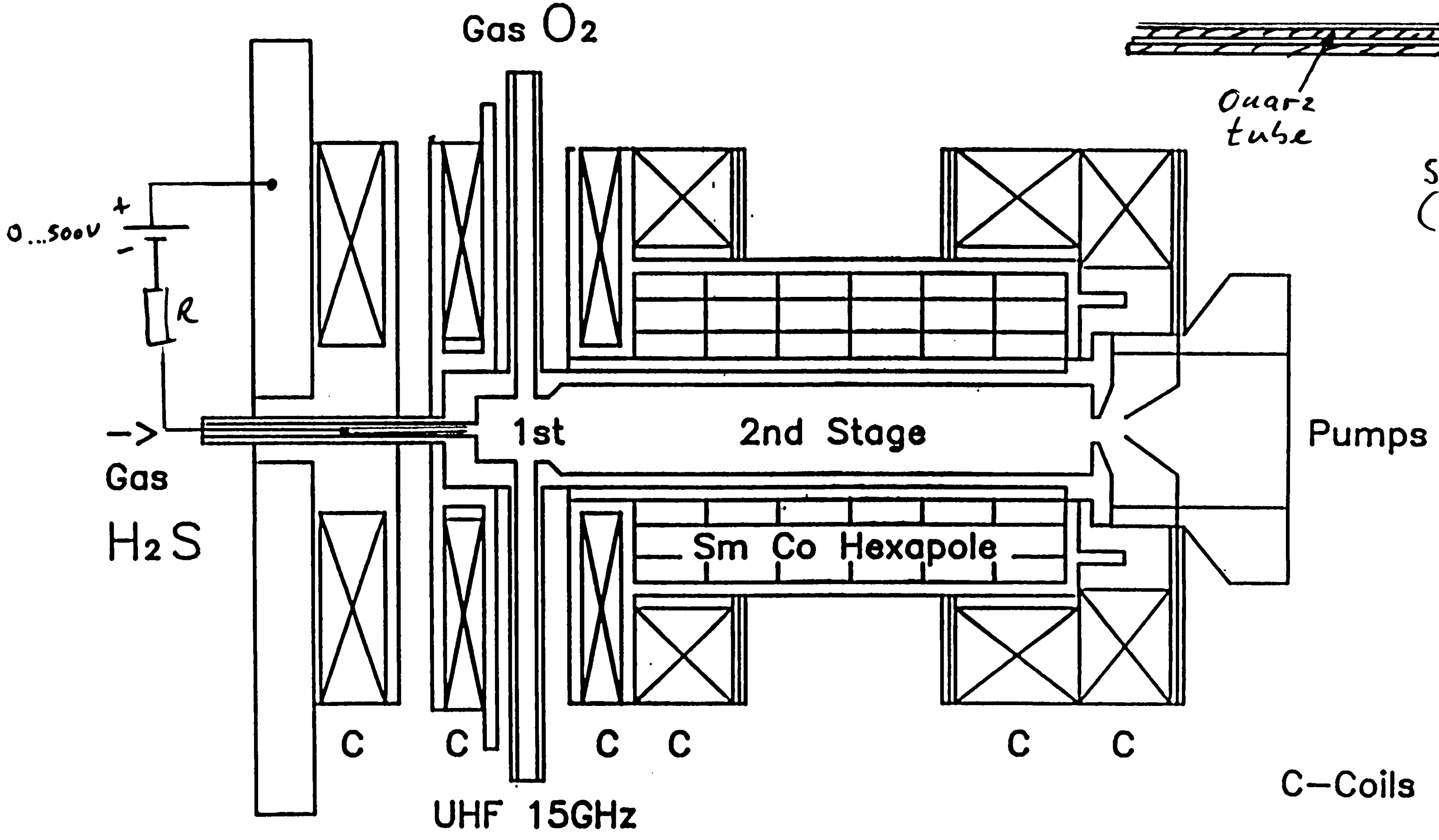
■ av. int. which can be maintained for > 1h

by K. Langbein, PS-HI

The ECR SULPHUR Source

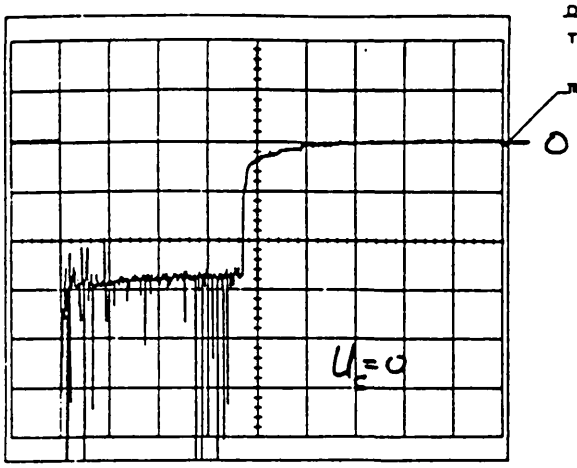
Plasma volume at extraction potential

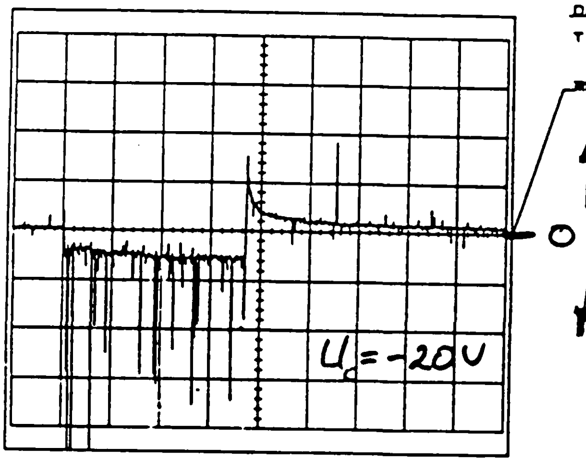




HEC 22/9/87

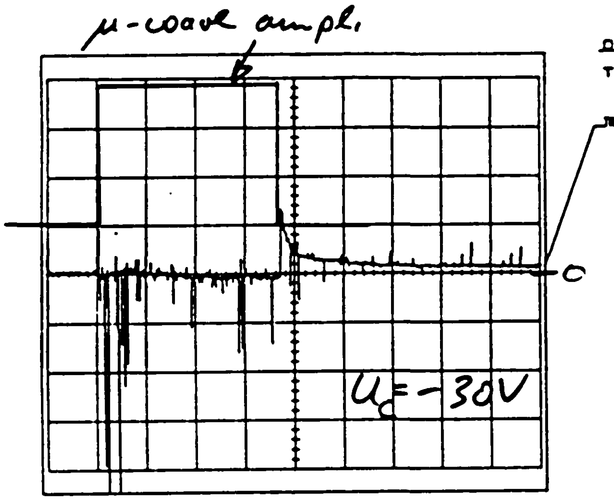
Characteristics of sec. el. emission cathode in ECR





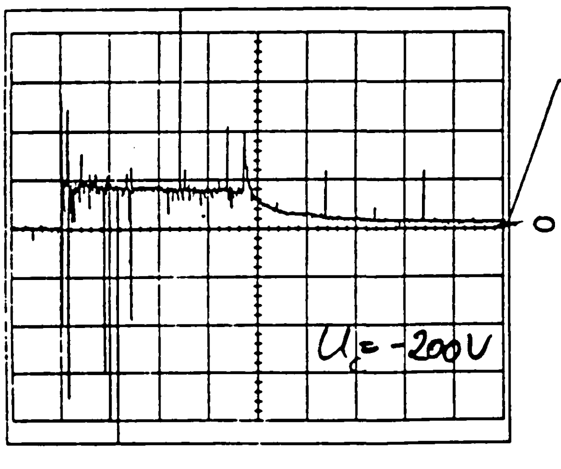
↑ electrons leave cathode + ions towards C

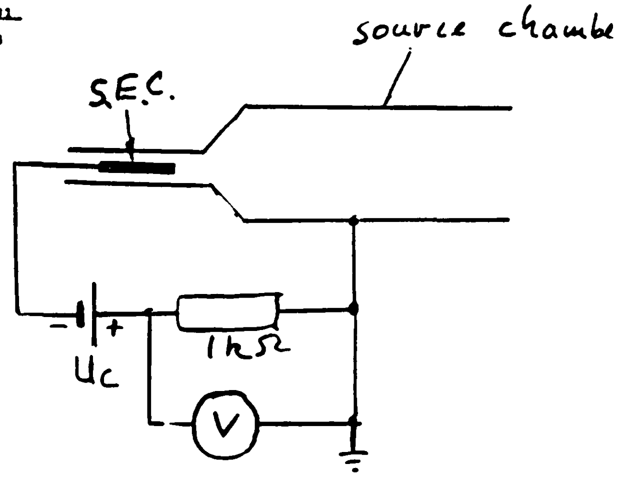
↓ electrons towards C



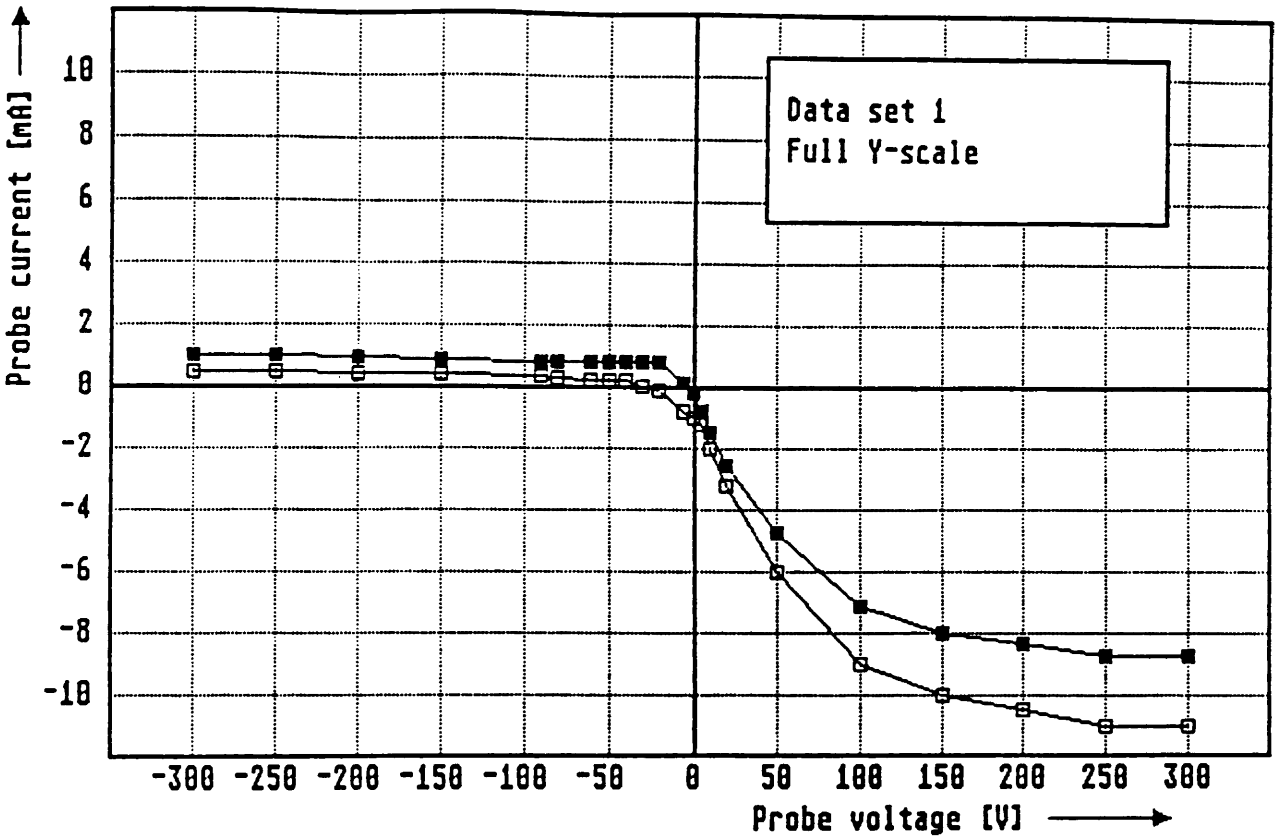
x: 20 ms / div

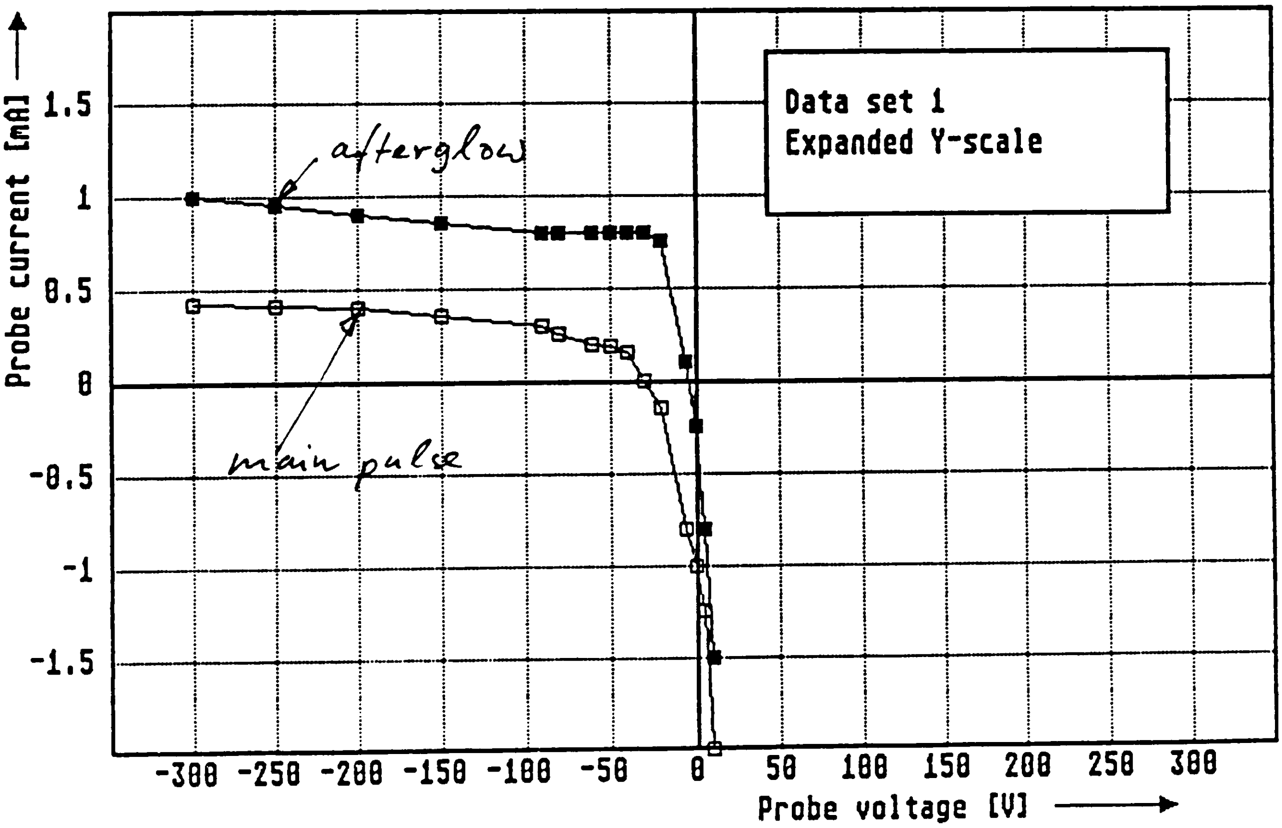
y: 0.5 V/div → 0.5 mA/div



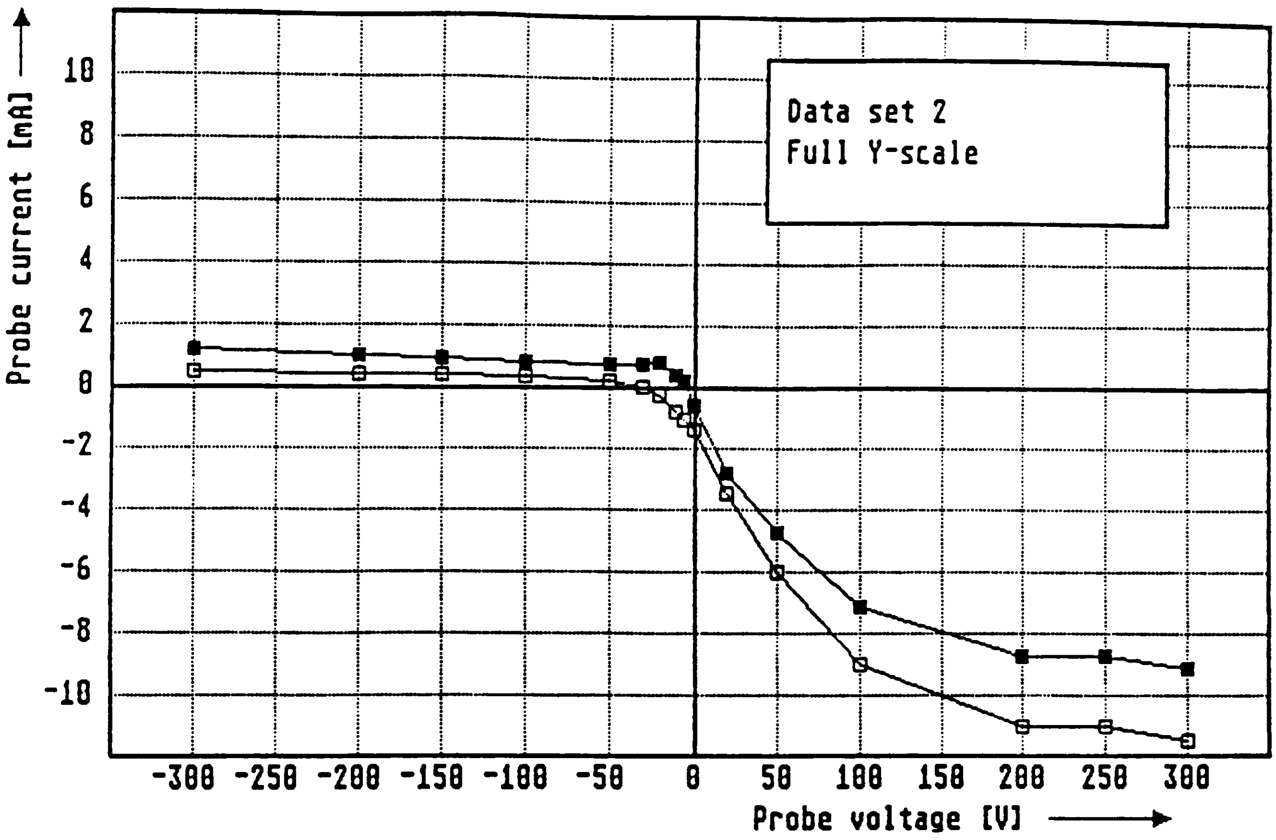


Current/voltage characteristic of S.E.C.

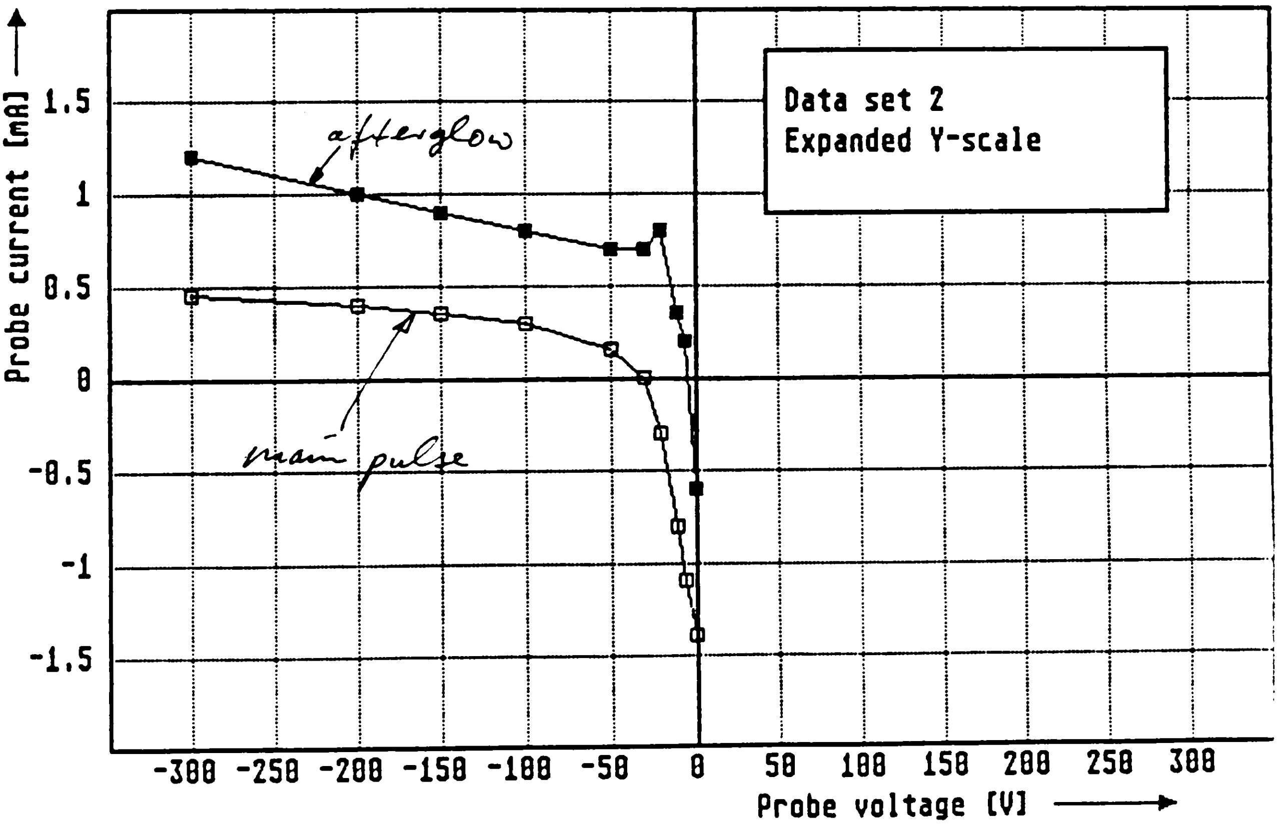




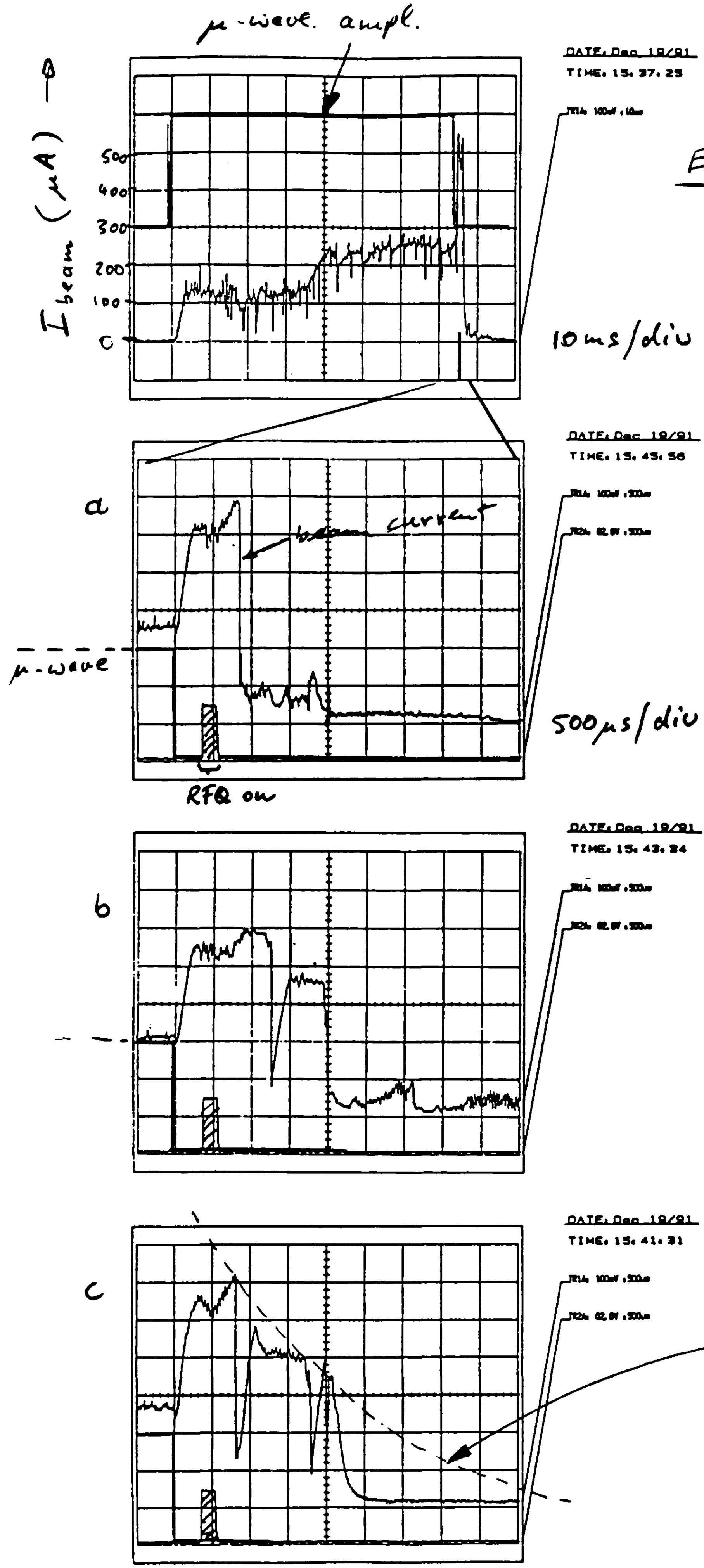
Current/voltage characteristic of S.E.C.



optim. for min. noise or discharge



Examples of "afterglow"



O^{6+} beam current at entrance RFQ

y: 100 μA/div

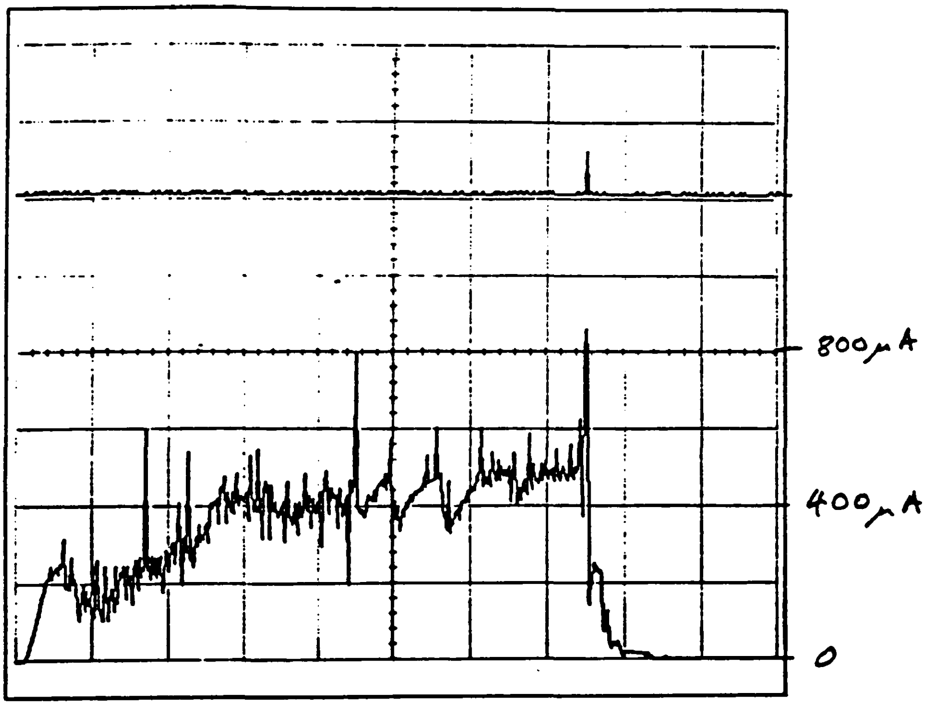
I_{max} = 500 μA

a, b, c:

variation of afterglow from pulse to pulse (no change of source parameters)

complete afterglow probably decays like this

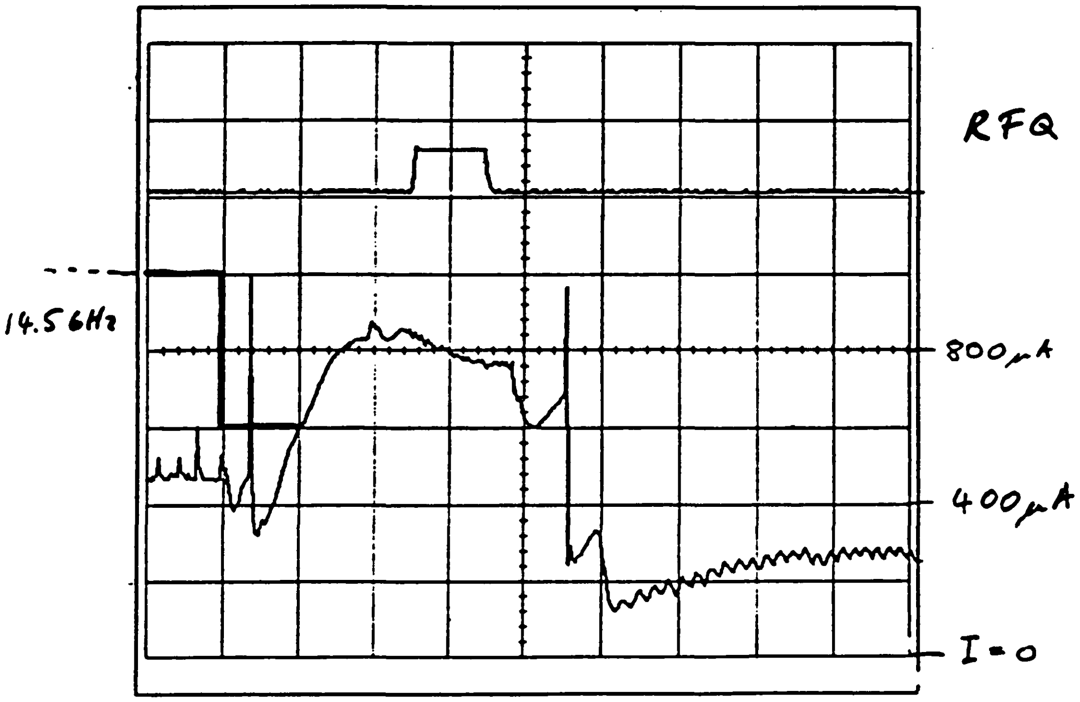
O^{6+} current at entrance of RFQ



O^{6+} current at entr. of RFQ

main pulse

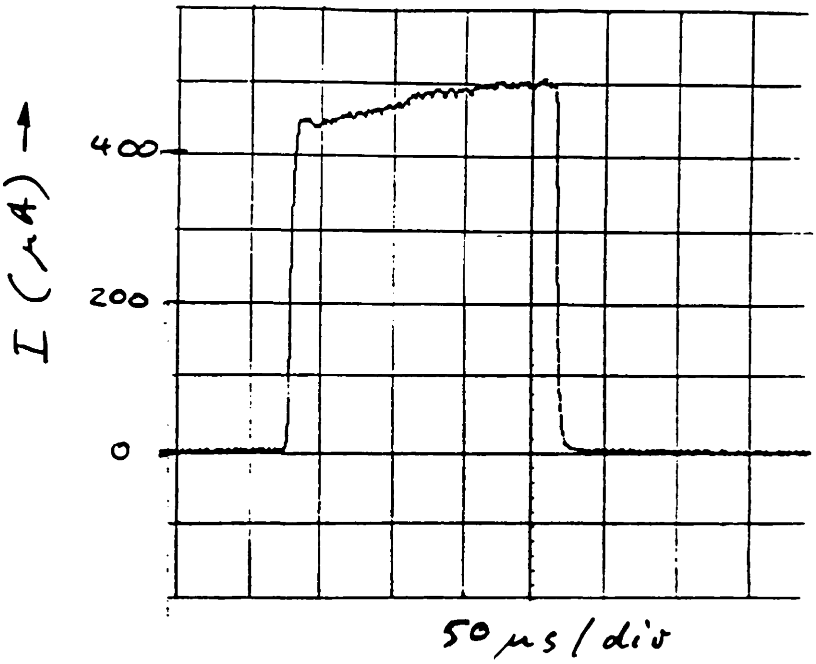
20 ms/div



afterglow

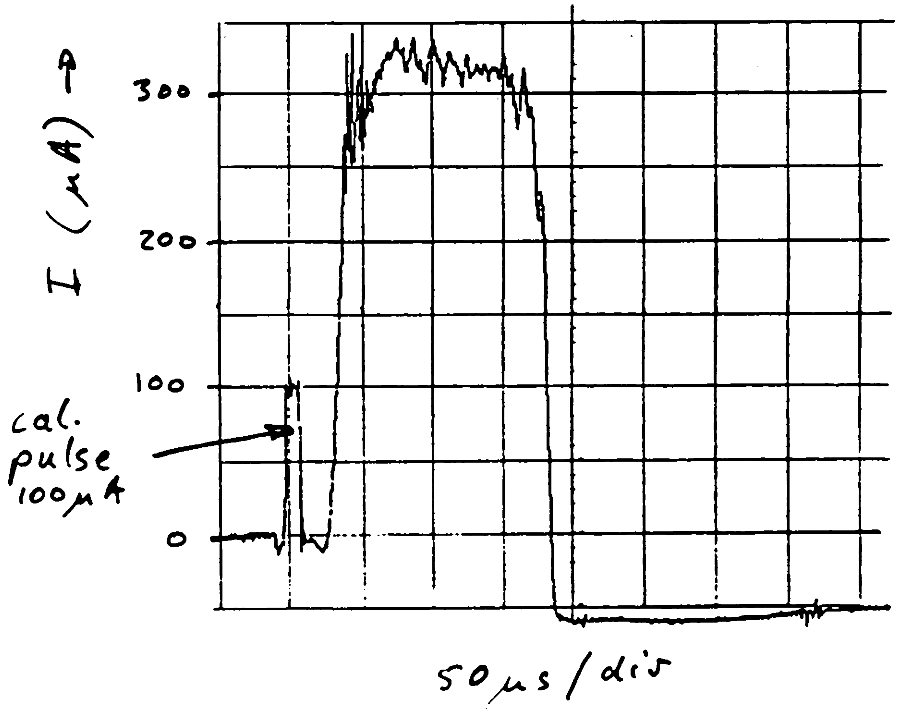
200 μs/div

O^{6+} currents up to 1 emA have been observed in the afterglow oxygen ion currents in RFQ and LINAC using S.E.C. and afterglow



O^{6+} current at exit of RFQ measured by Faraday-cup (with sec. el. suppr.)

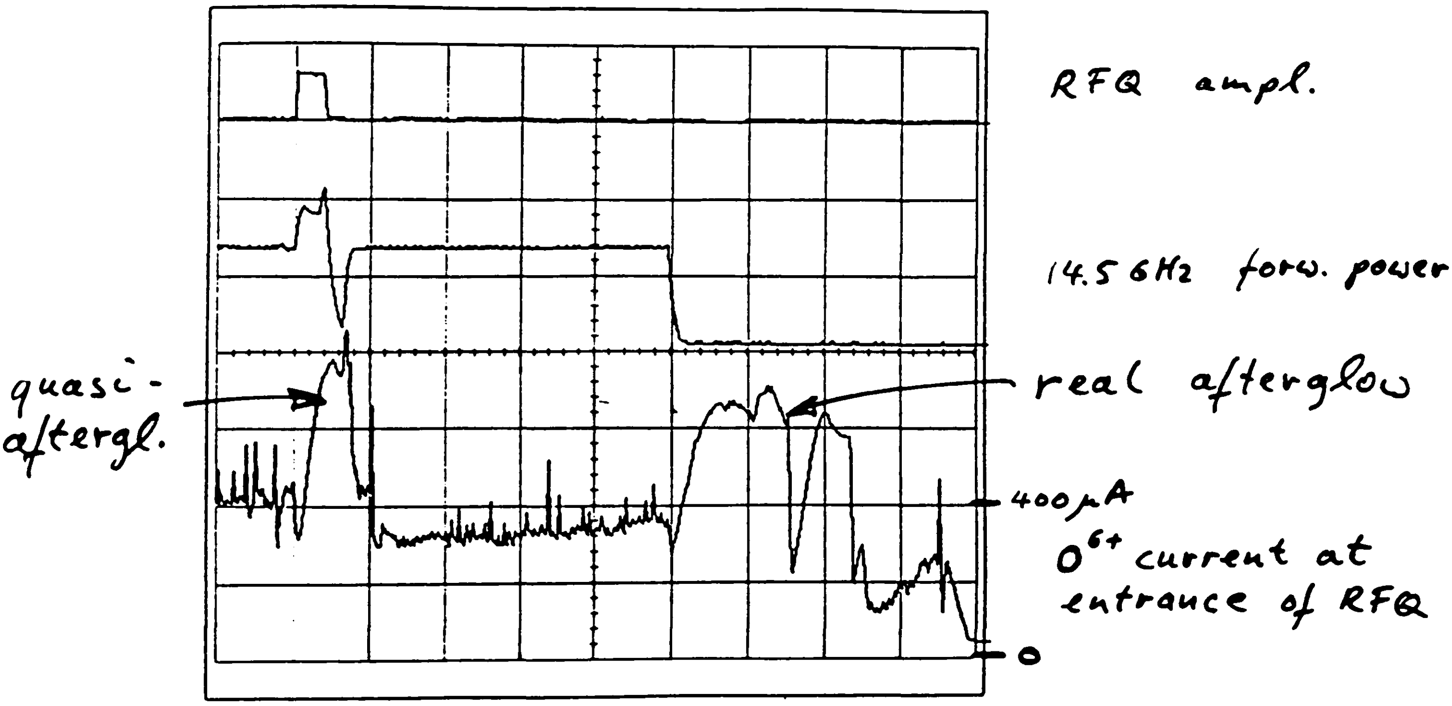
$\boxed{500\mu A\ O^{6+}}$



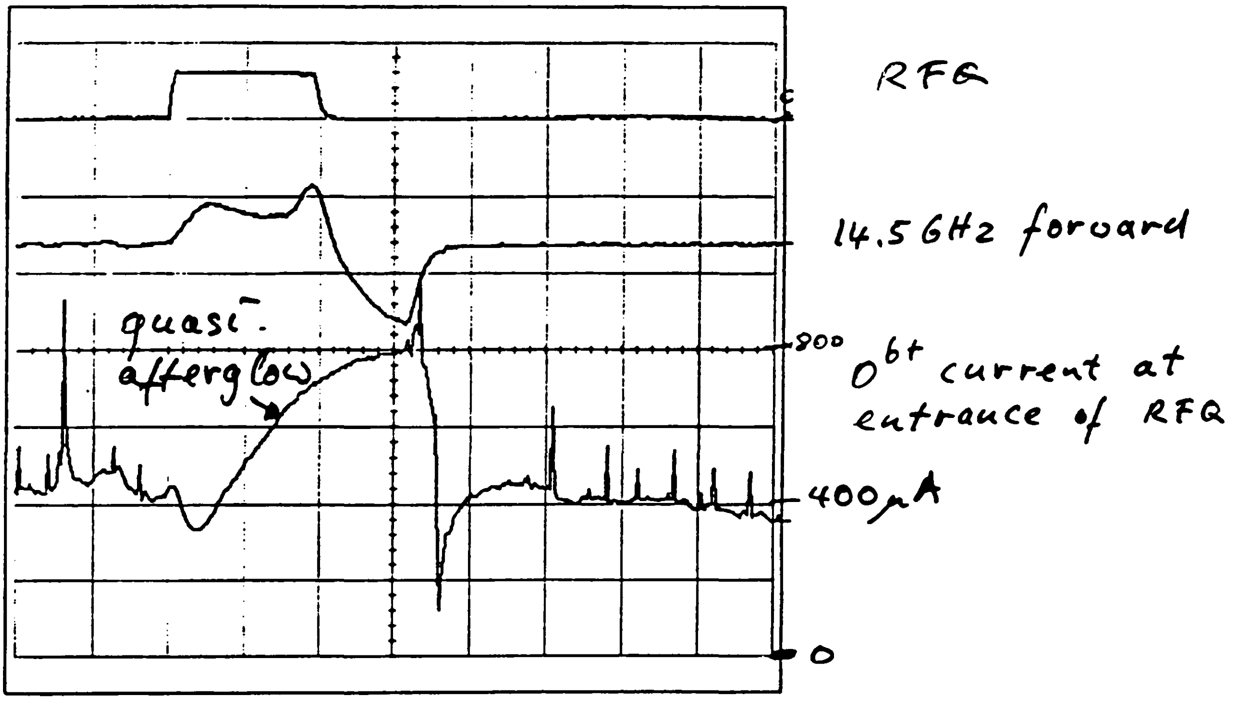
O^{8+} current at exit of LINAC measured by beam transformer "TRA44".

$\boxed{350\mu A\ O^{8+}}$

Quasi afterglow prod. by perturbation of discharge and/or source rf (14GHz) by noise from LINAC (200MHz)



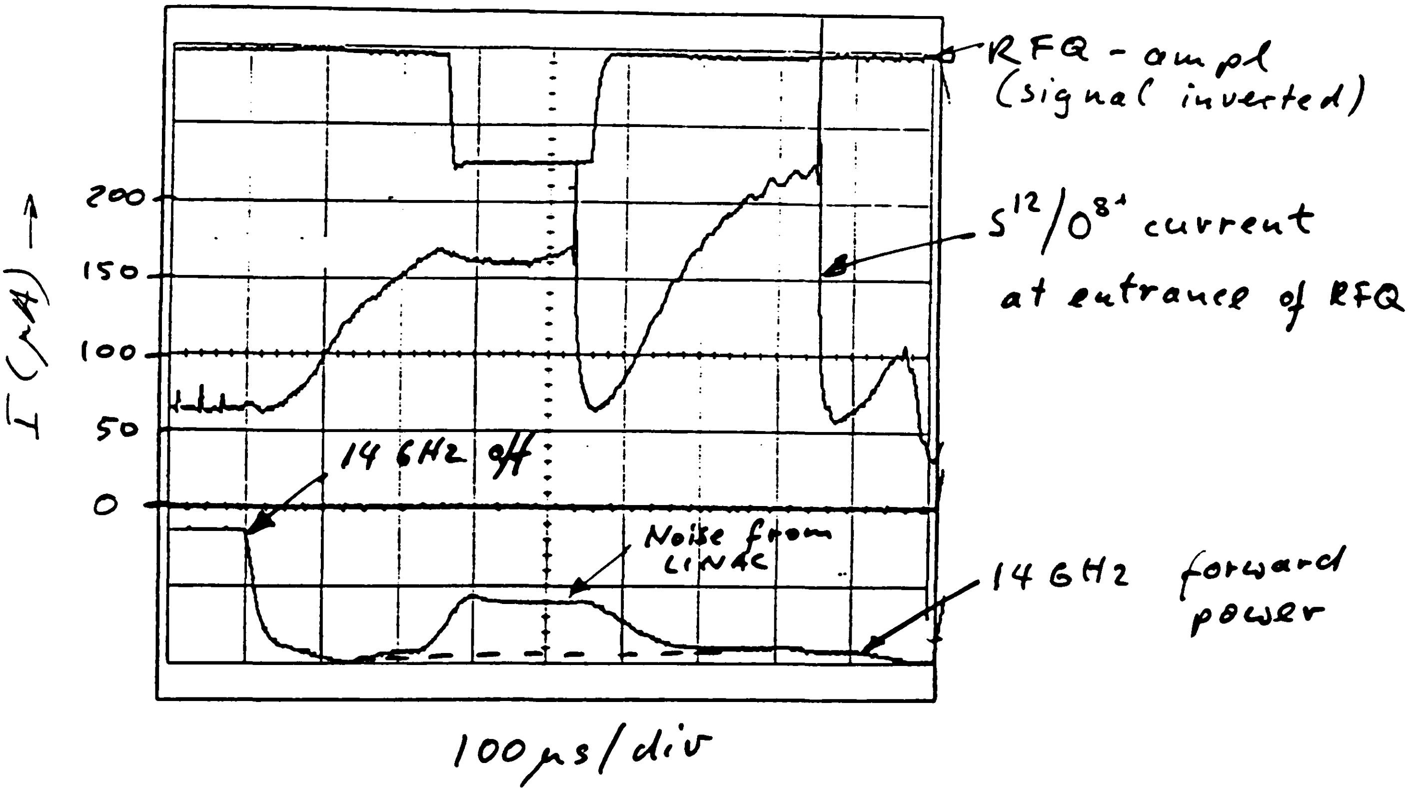
500µs / div

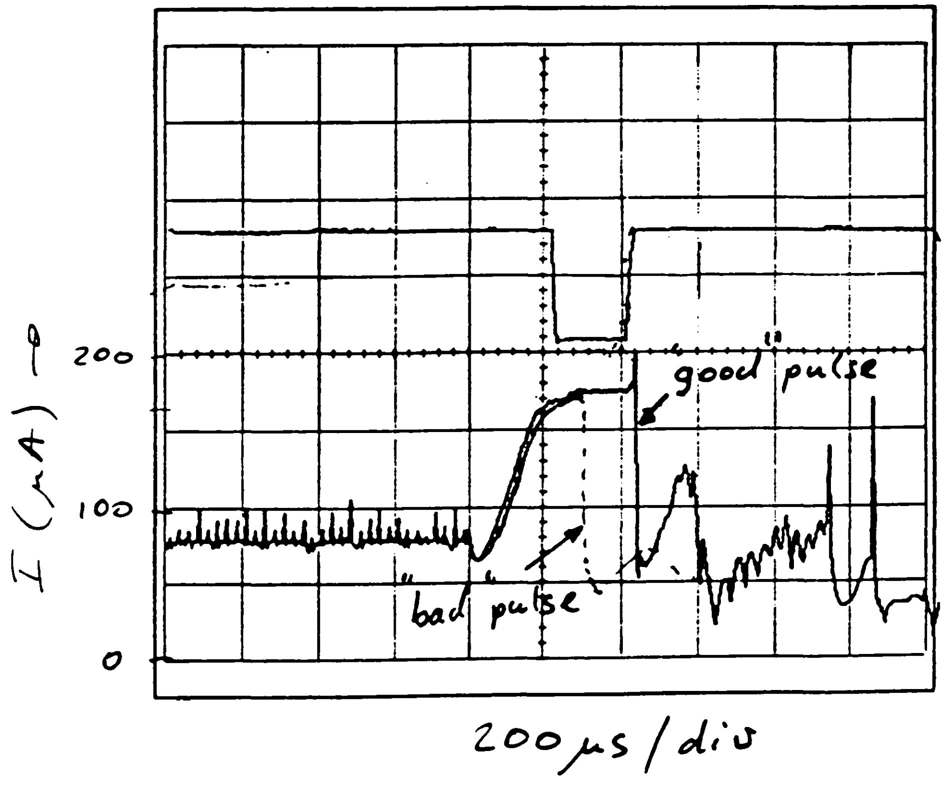


100µs / div

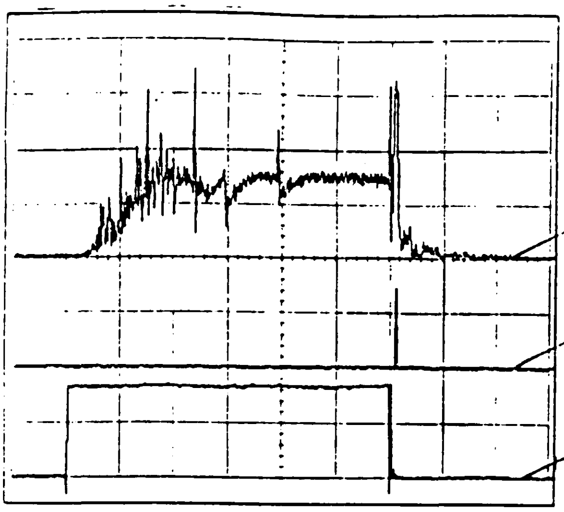
Afterglow with Oxygen/sulphur operation

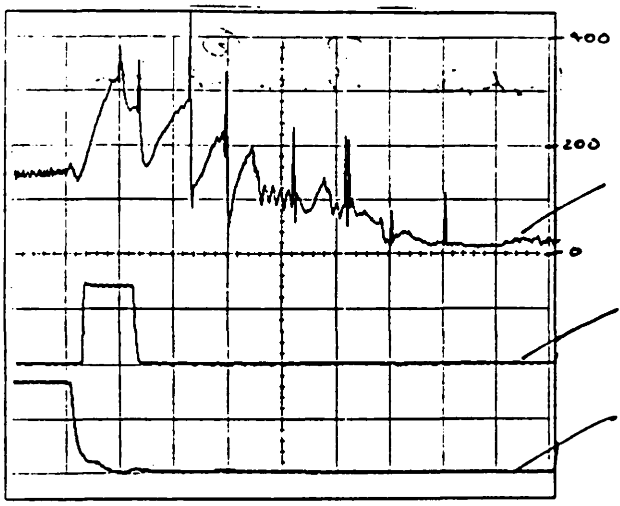
(after 2 weeks of operation)





Enhancement of afterglow by post pulsing of the ECR



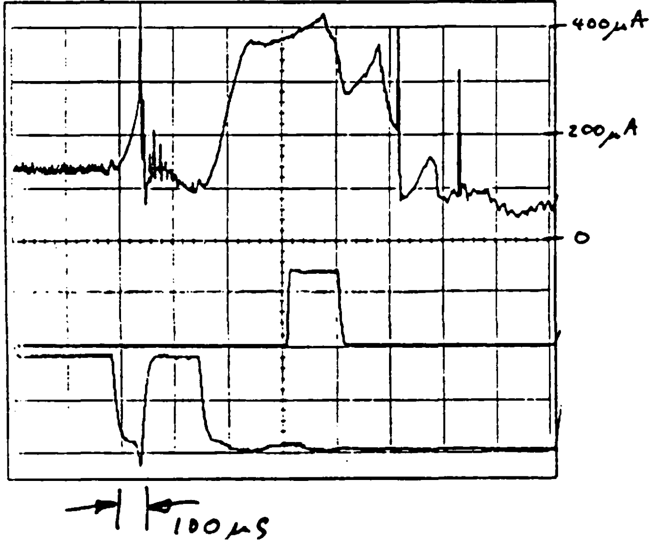


"Afterglow" of ECR discharge in normal operation

2nd afterglow by double pulsing

2nd rf pulse after 1st afterglow peak.

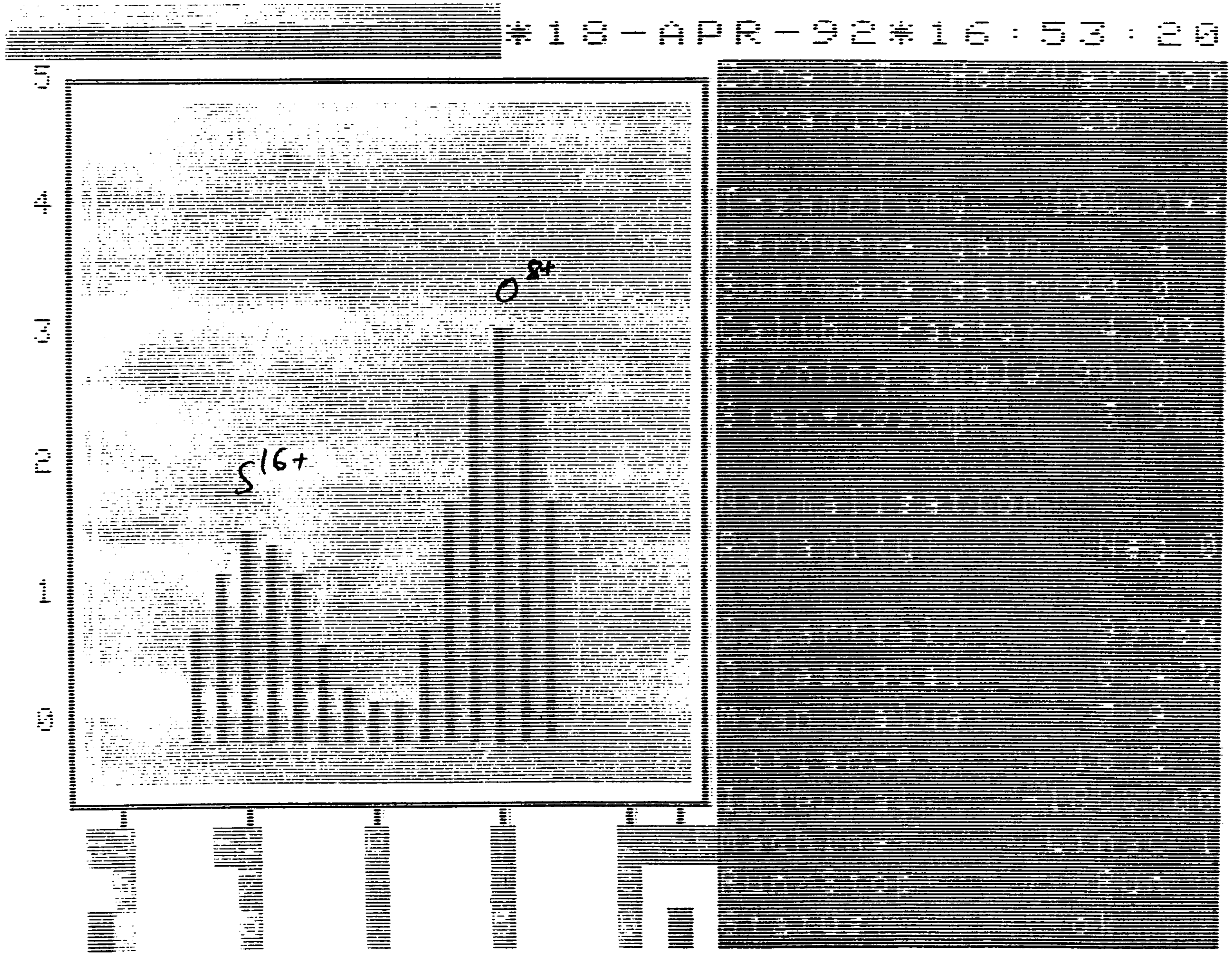
→ 2nd afterg. is broad and stable



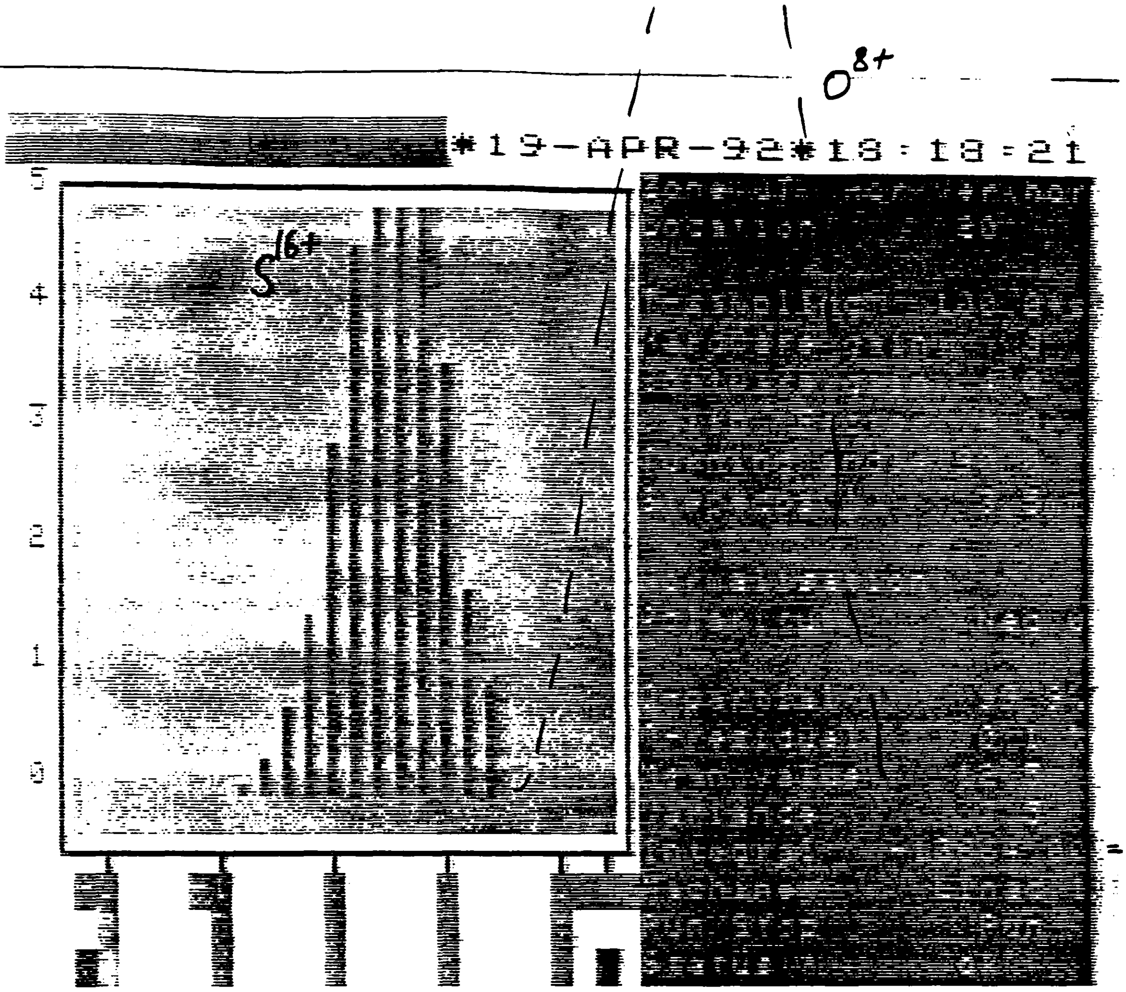
Pos. and length of 2nd pulse optimized for max. intensity

2nd rf pulse during rise of 1st afterglow.

→ 2nd afterglow is higher and slightly less stable.

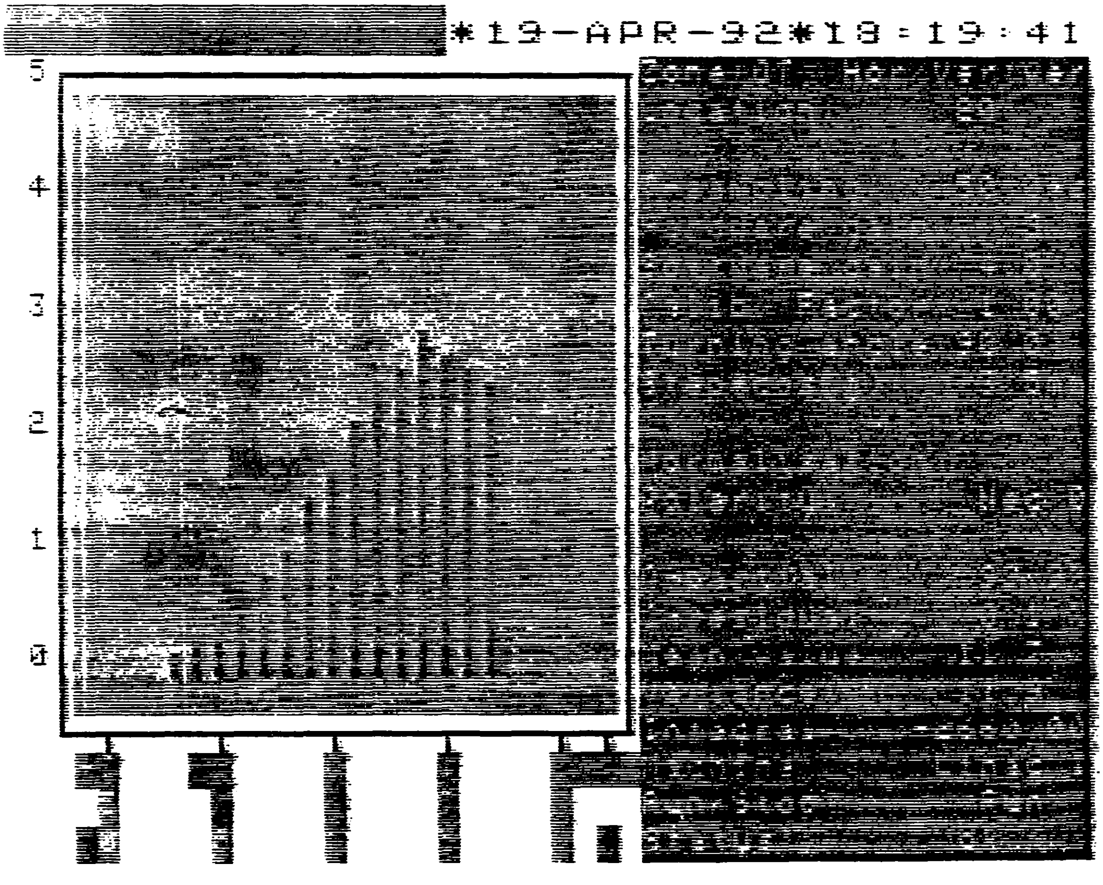


Separation of O^{8+} and S^{16+} by degrader

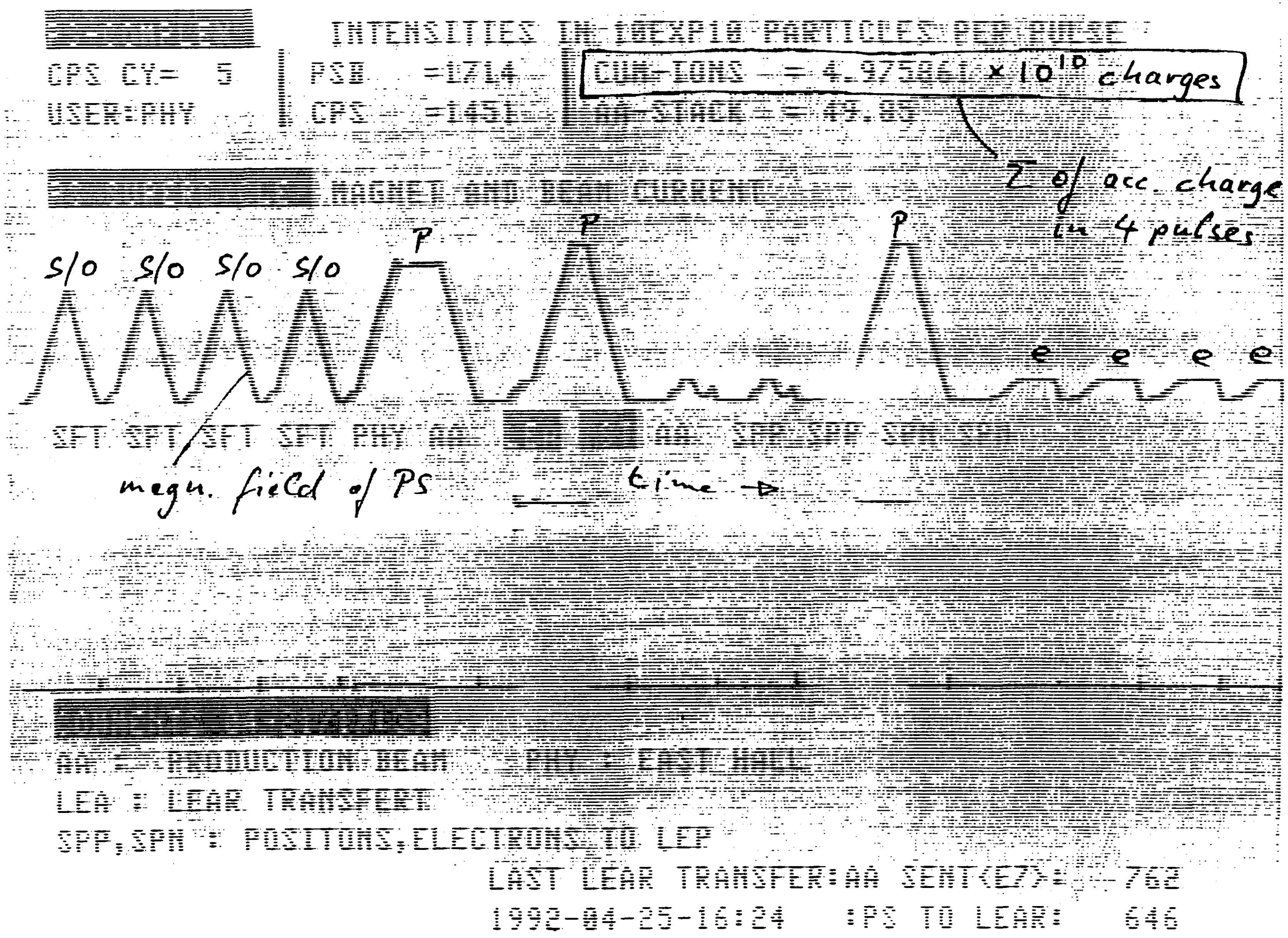


2/3 of beam on SEM in vertical direction

→ estimated S^{16+} current after LINAC ≈ 20 eμA



24 Apr. '92
≈ 16:20



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INTENSITIES IN 10EXP10 PARTICLES PER PULSE
CPS CY=  5  | PSB  =1714 | CUM-IONS  = 4.975861
USER:PHY    | CPS  =1451 | AA-STACK  = 49.85

MAGNET AND BEAM CURRENT

SFT SFT SFT SFT PHY AA        AA  SPP SPP SPN SPN

AA : PRODUCTION BEAM    PHY : EAST HALL
LEA : LEAR TRANSFERT
SPP,SPN : POSITONS,ELECTRONS TO LEP
                        LAST LEAR TRANSFER:AA SENT(E7)=   762
                        1992-04-25-16:24   :PS TO LEAR:   646
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Record sulphur intensity in PS using the 2nd afterglow produced by post pulsing of the ECRIS

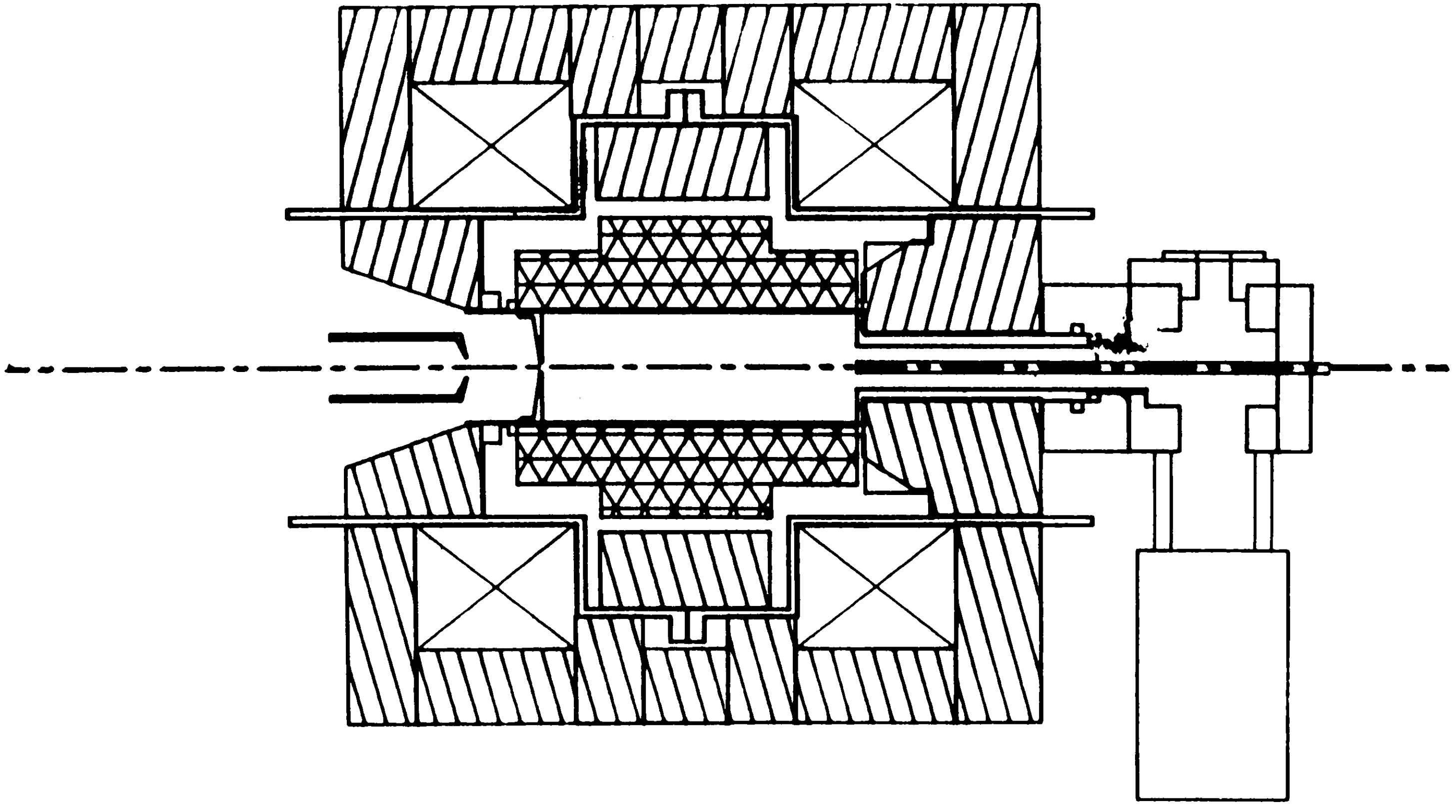
Appendix C

Proposal for the Upgrading of Pulsed Currents of Highly Charged Heavy Ions

P. Sortais

GANIL,
Caen, France

GANIL source ECR4 14.5 GHz

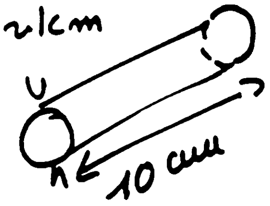


extraction, plasma, uhf, gaz, cooling and pumping system

hexapolar magnetic system

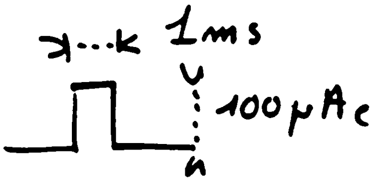
axial magnetic system

PLASMA AND NUMBER OF IONS (ECR4)



$\rightarrow \boxed{\text{Volume} \sim 10\ \text{cm}^3}$ ($7.5\ \text{cm}^3$)

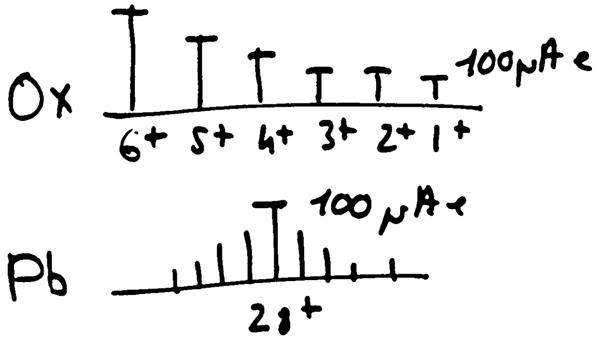
with $n_e \approx 0.3 - 1\ 10^{12}\ e/\text{cm}^3$(?)



Afterglow pulse $q = 28^+$

$\longrightarrow \boxed{\sim 3\,10^{10}\ \text{Pb}^{28+}/\text{pulse}}$

Spectrum



$\langle Z_{ox} \rangle \sim 3$

$\boxed{{}^{ox} I_{tot} \sim 2\,\text{mA}}$

$\langle Z_{Pb} \rangle \sim 28$

$\boxed{{}^{Pb} I_{tot} \sim 1\,\text{mA}}$

with ~15% of n_i for 28^+

$$I_{ox} = 2 I_{Pb} \implies \frac{n_{ox} Z_{ox}}{\tau_{ox}} \simeq 2 \frac{n_{Pb} Z_{Pb}}{\tau_{Pb}}$$

$$\text{and} \sim 3 n_{ox} + 28\, n_{Pb} = n_e$$

if $\tau_{ox} = \tau_{Pb} \longrightarrow \underline{n_{Pb} \sim 5\ 10^9\ \text{Pb}/\text{cm}^3}$

if $\tau_{ox} = \frac{\tau_{Pb}}{10} \longrightarrow \underline{n_{Pb} \sim 5\ 10^{10}\ \text{Pb}/\text{cm}^3}$

$$\implies \boxed{N_{Pb\,28+}^{\text{afterglow}} \approx N_{Pb\,28+}^{\text{plasma}}}$$

CHARGE DEPENDENCE OF THE AFTERGLOW PEAK CURRENT

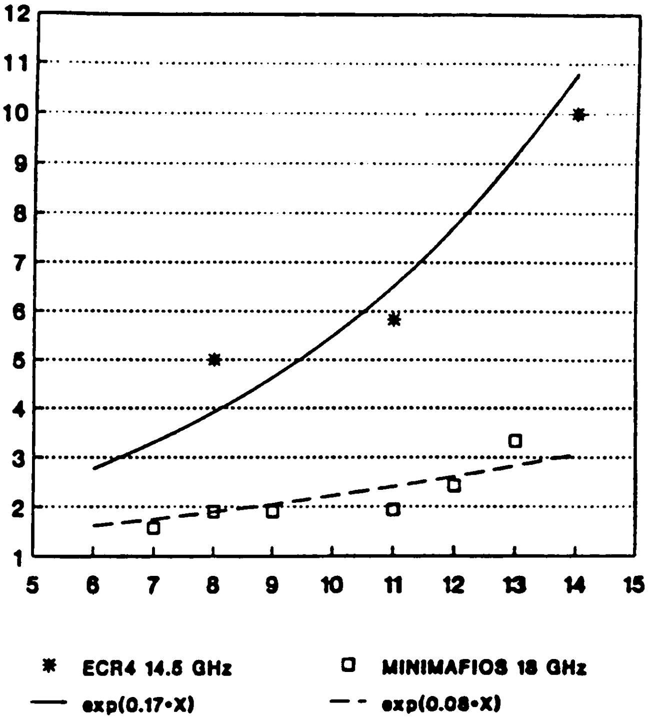
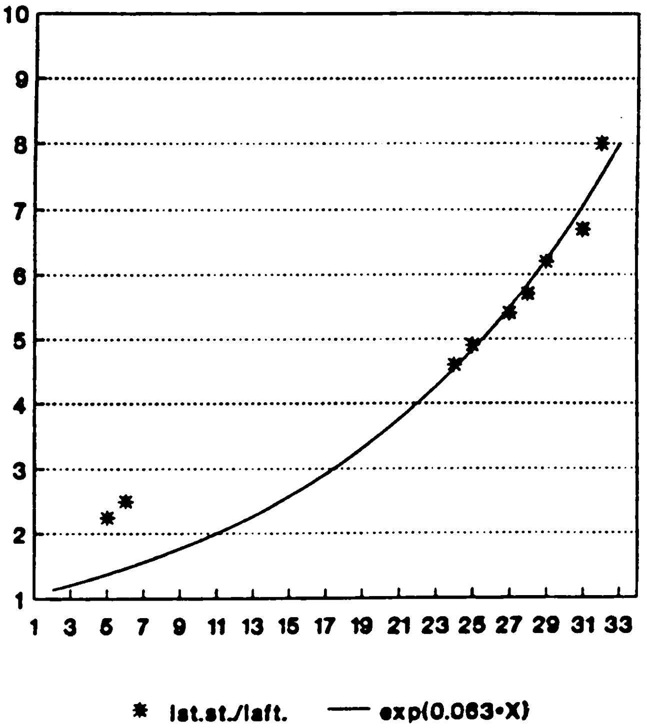


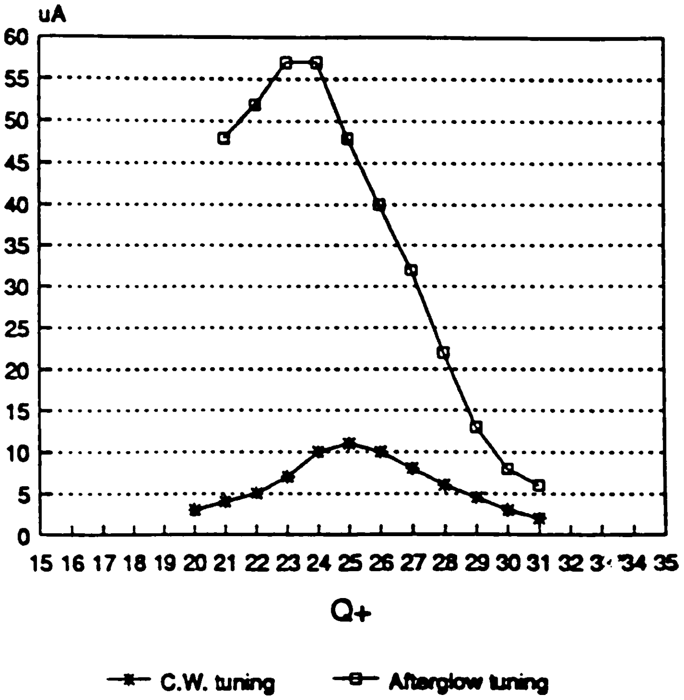
fig. 7: Charge dependence of the ratio of the afterglow current to the steady state current for Argon ions



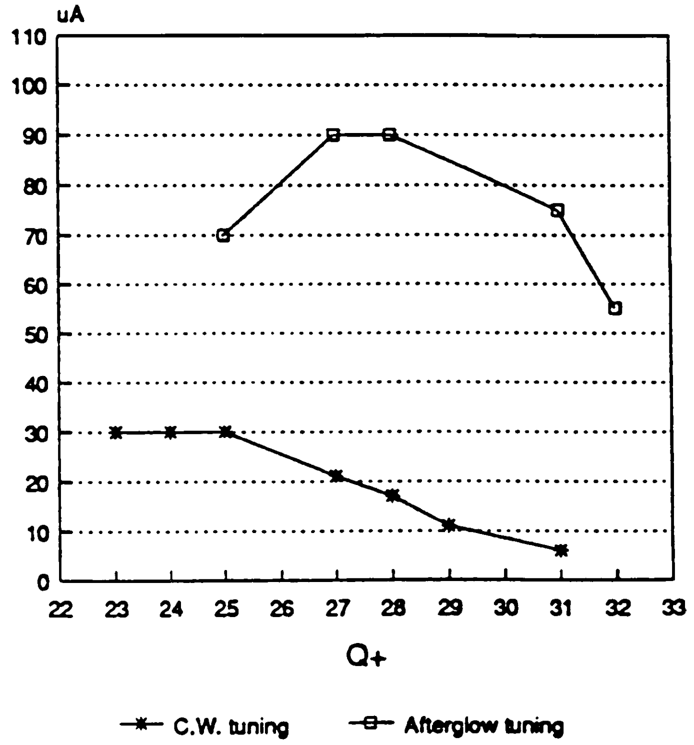
$$\frac{e\Delta\phi}{kT_i} \sim 0.1$$

fig. 8: Charge dependence of the ratio of the afterglow current for lead ion (charge: 5 and 6 correspond to O ions)

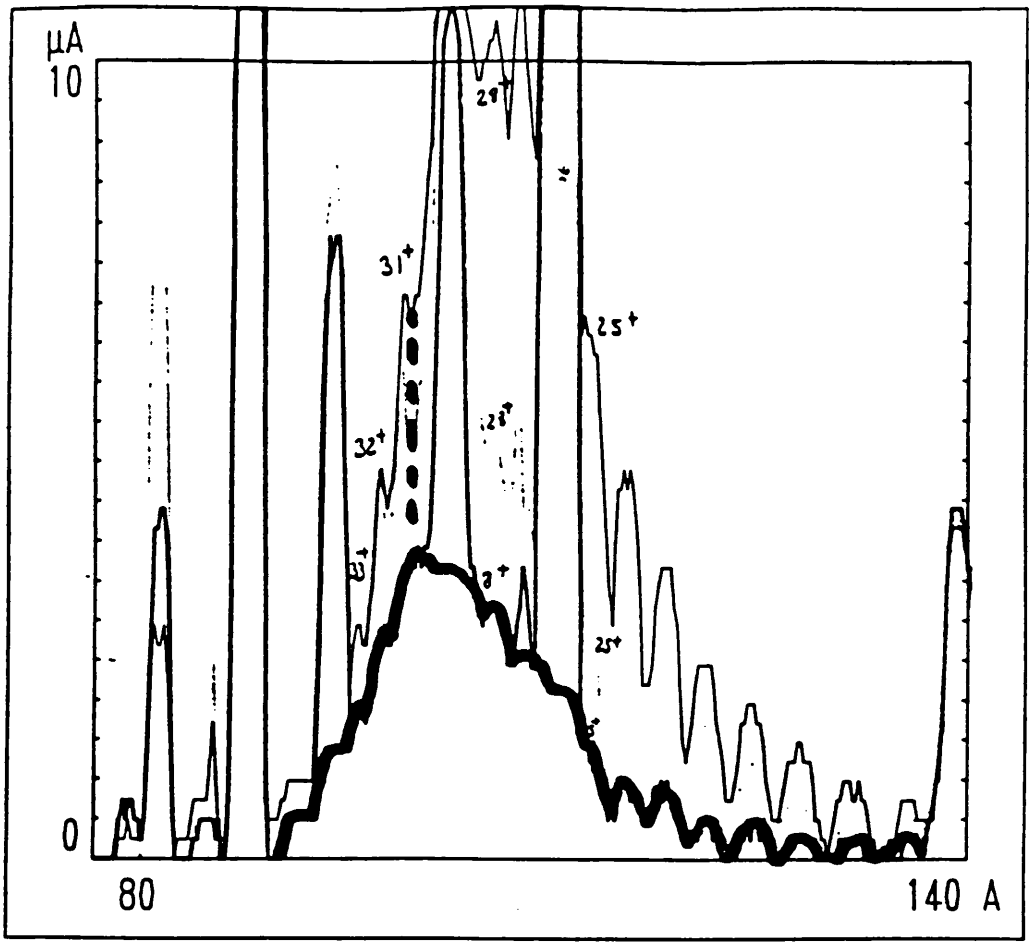
ENHANCEMENT OF THE CHARGE STATE DISTRIBUTION DURING THE AFTERGLOW



Enhancement of the charge state
distribution of U ions during
the afterglow (MINIMAFIOS 16.6 GHz)



Enhancement of the charge state
distribution of Pb ions during
the afterglow (ECR4 14.5 GHz)

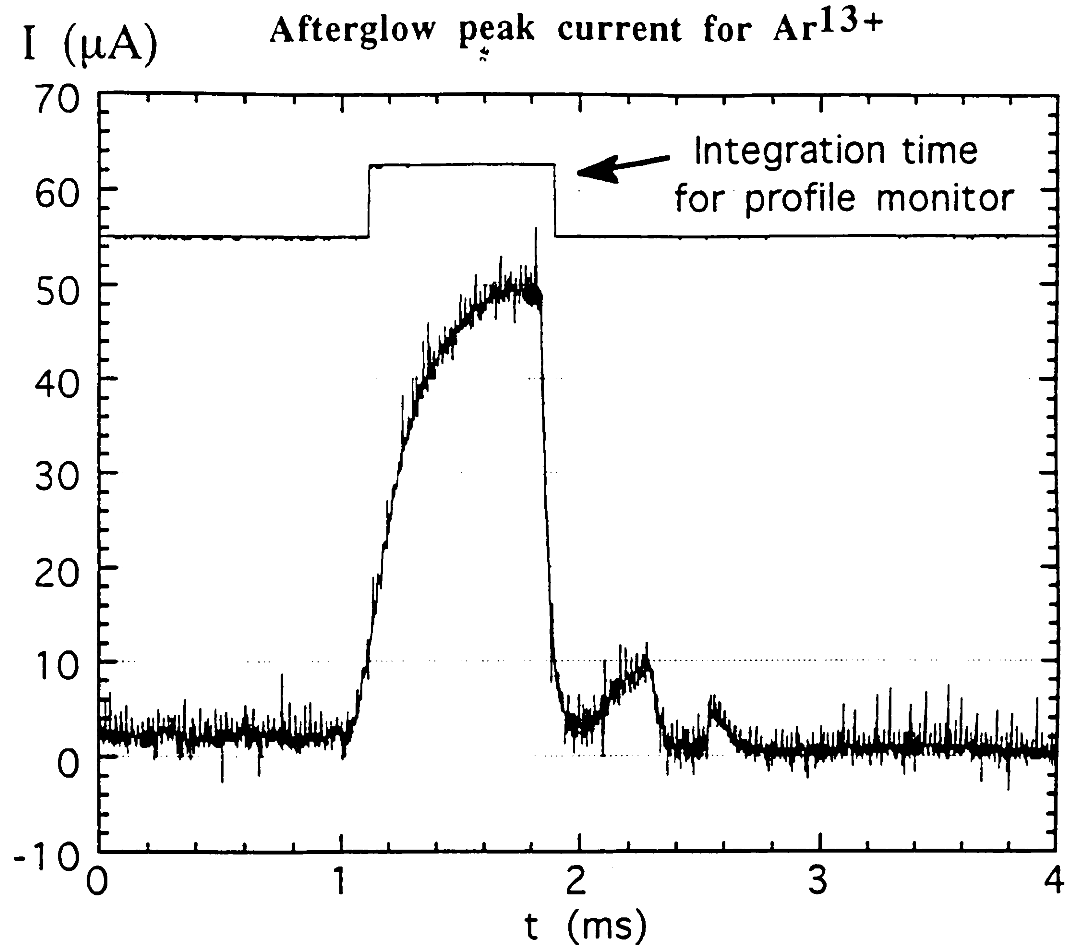


phf (W)	591
bp1 (A)	1033
bp2 (A)	1100
ssg (V)	4.94
sss (V)	0.14
ssl (V)	0.01
tg1 (V)	0.0
tg2 (V)	5.6
ht1 (kV)	15.0
ht2 (kV)	0.0
it1 (mA)	0.59
it2 (mA)	0.49
date	0514
heure	1432
metal	1000
accord	5070
ion	Pb
support	0

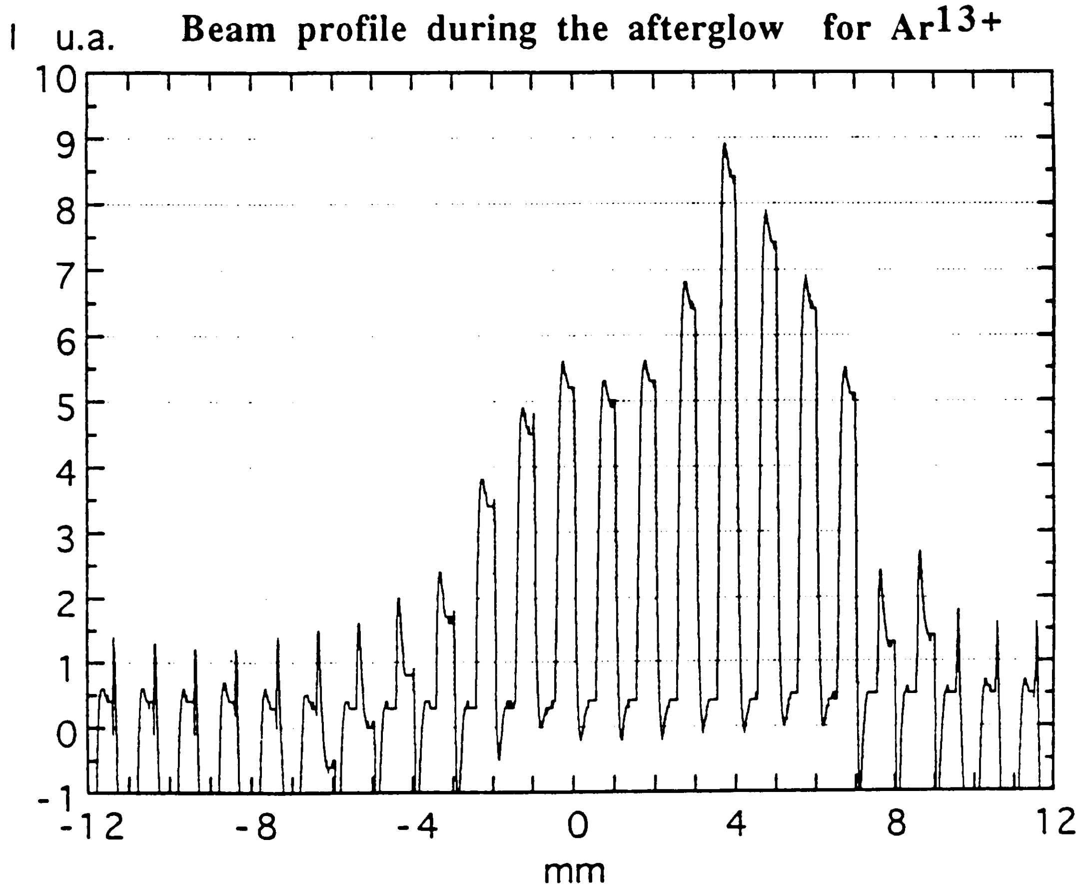
$^{82}_{208}Pb^{31+}$ optimal.

(0,872)

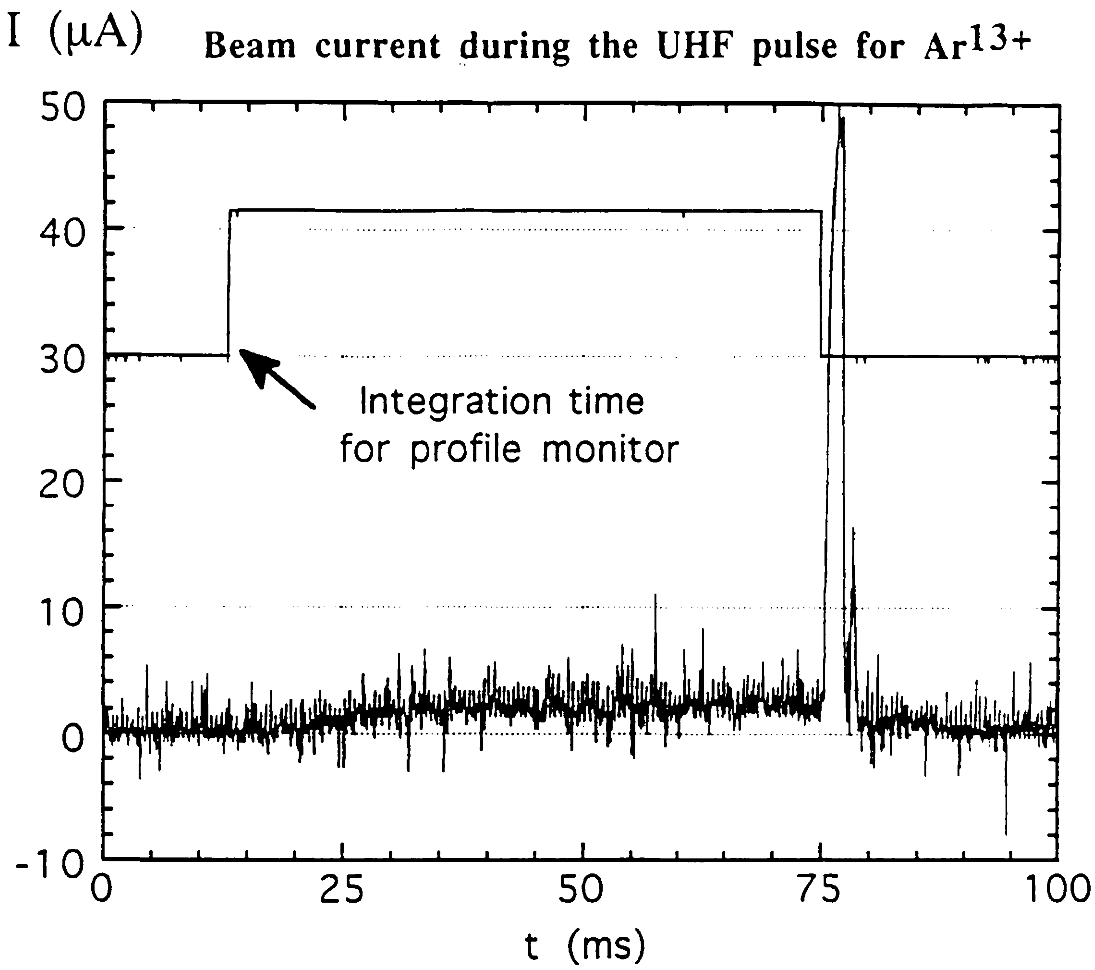
q+	µAe	µAp	% des ions extraits
25	1,5	0,060	
26	2,5	0,096	
27	2,7	0,100	
28	3,0	0,107	
29	3,2	0,110	
30	3,4	0,113	
31	3,5	0,113	13%
32	3,5	0,078	8,9%
33	1,7	0,052	6%
34	1,0	0,029	3,3%
35	0,5	0,014	1,6%



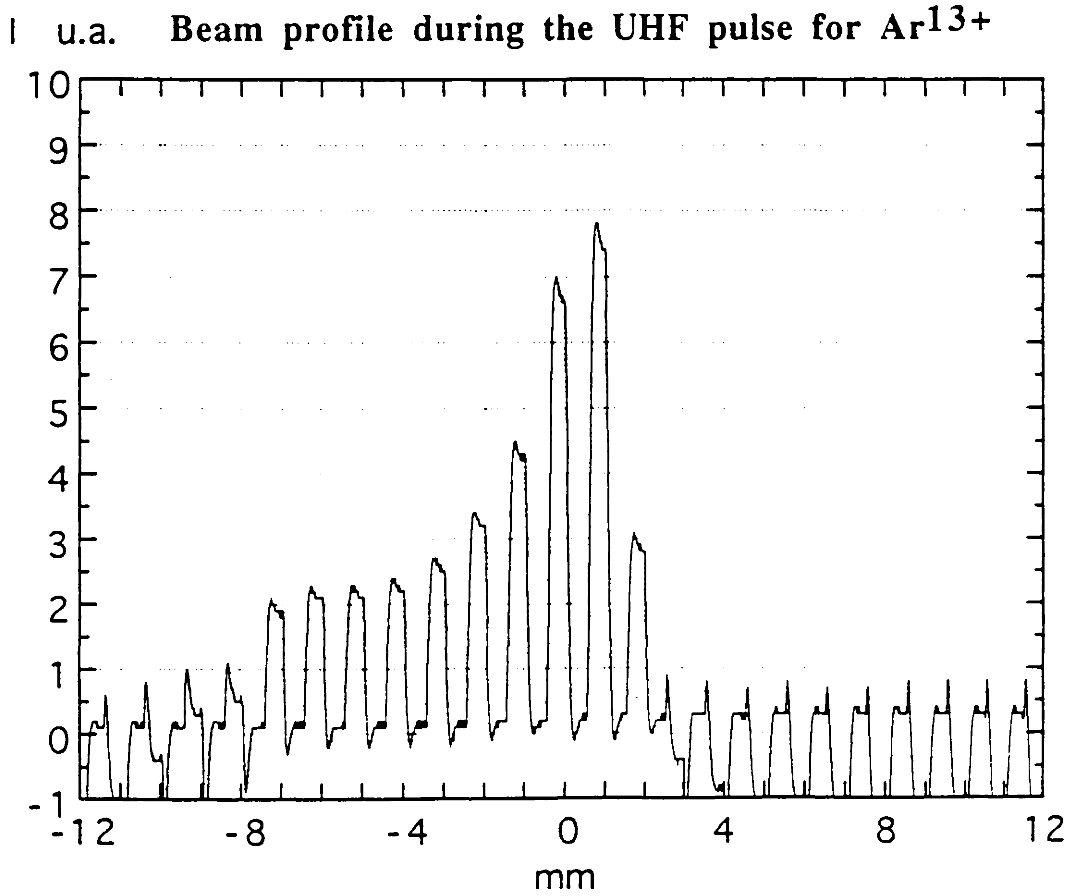
Afterglow peak current for Ar^{13+}



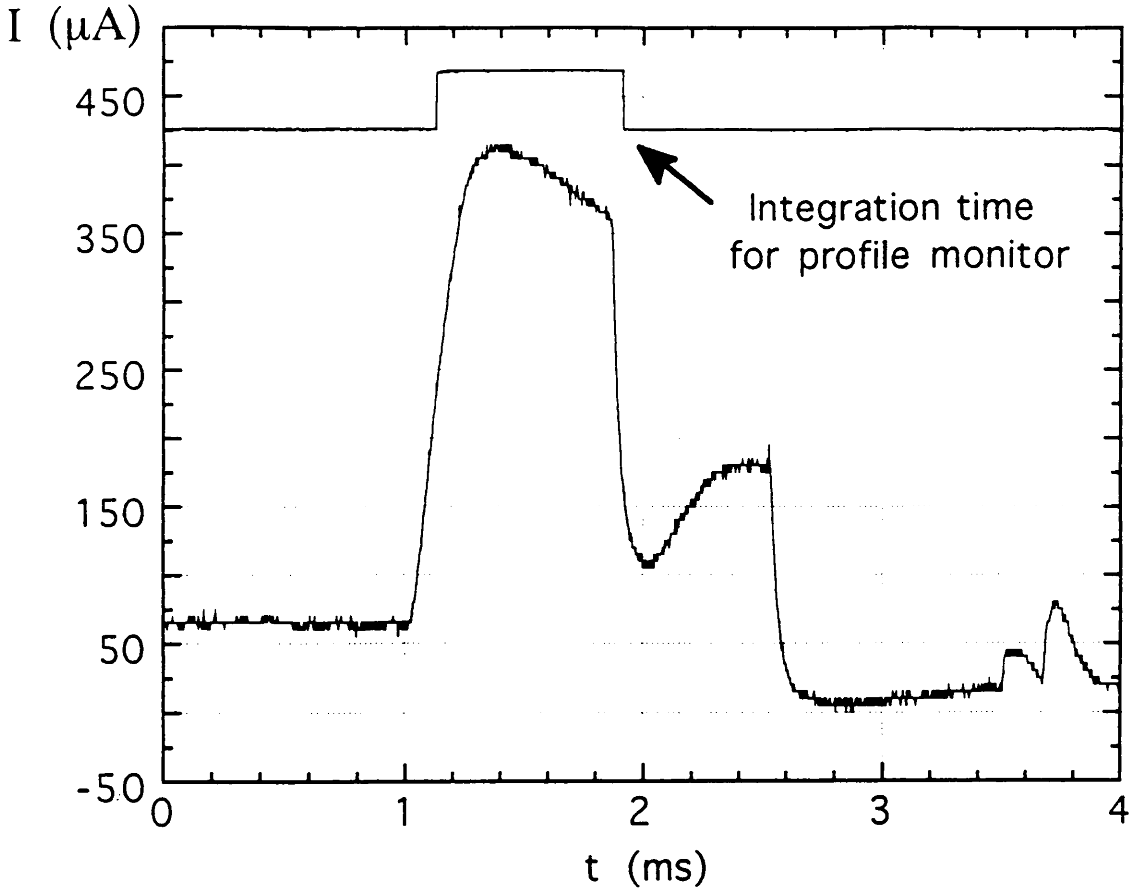
Beam profile during the afterglow for Ar^{13+}

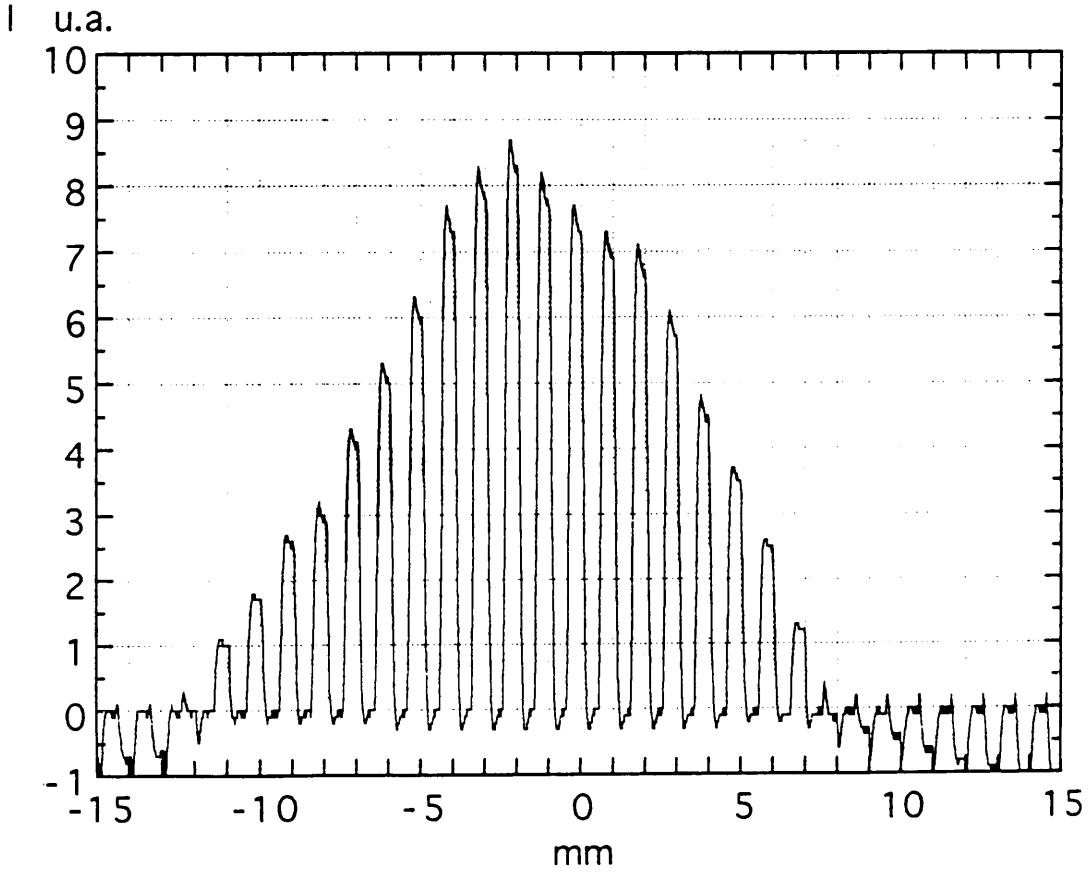


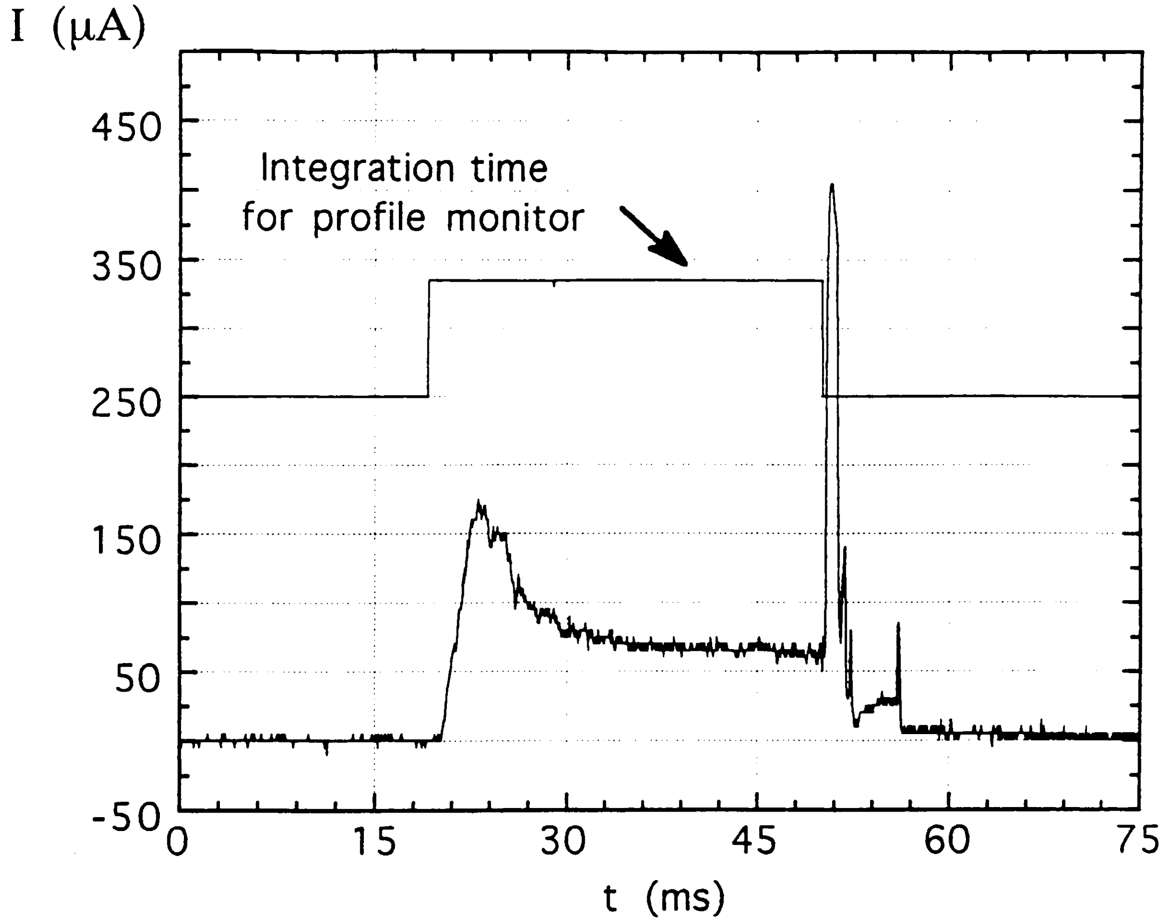
Beam current during the UHF pulse for Ar^{13+}

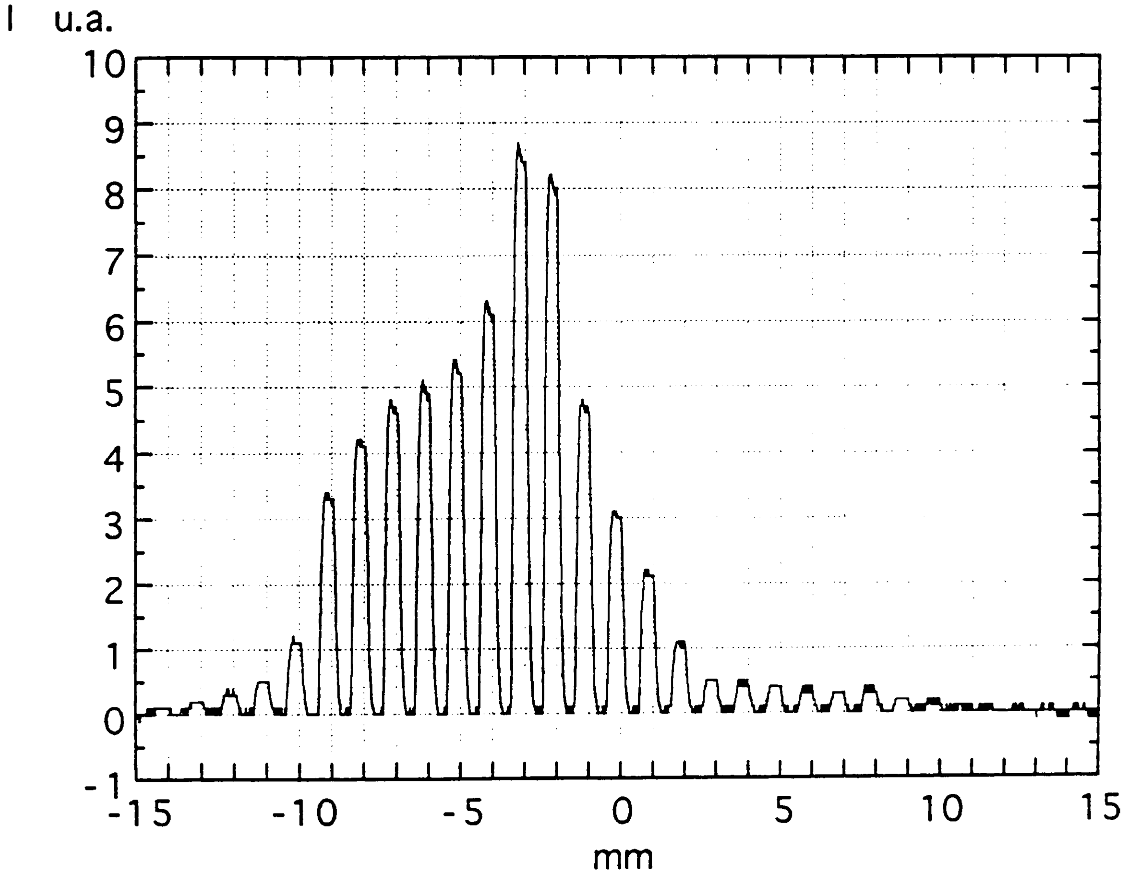


Beam profile during the UHF pulse for Ar^{13+}

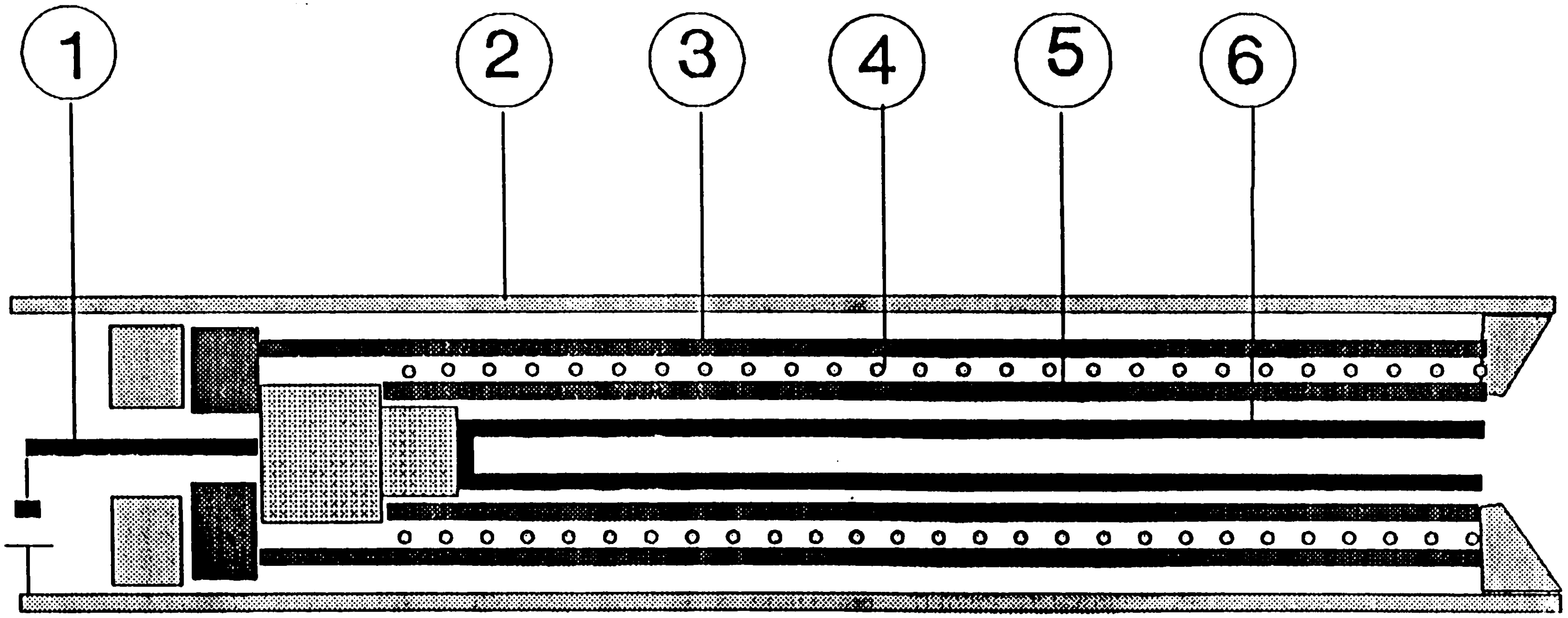

I (μA)
450
350
250
150
50
-50
0
1
2
3
4
t (ms)
Integration time
for profile monitor


I u.a.
10
9
8
7
6
5
4
3
2
1
0
-1
-15
-10
-5
0
5
10
15
mm


I (μA)
450
350
250
150
50
-50
Integration time for profile monitor
0
15
30
45
60
75
t (ms)


I u.a.
10
9
8
7
6
5
4
3
2
1
0
-1
-15
-10
-5
0
5
10
15
mm

MICRO-OVEN



1-Power supply
2-Reflector tube
3-Insulator
4-Heating system
5-Insulator
6-Evaporator tube

SIZES

Φ 5mm Lenght 50mm

Proposal for the upgrading of pulsed currents of highly charged heavy ions

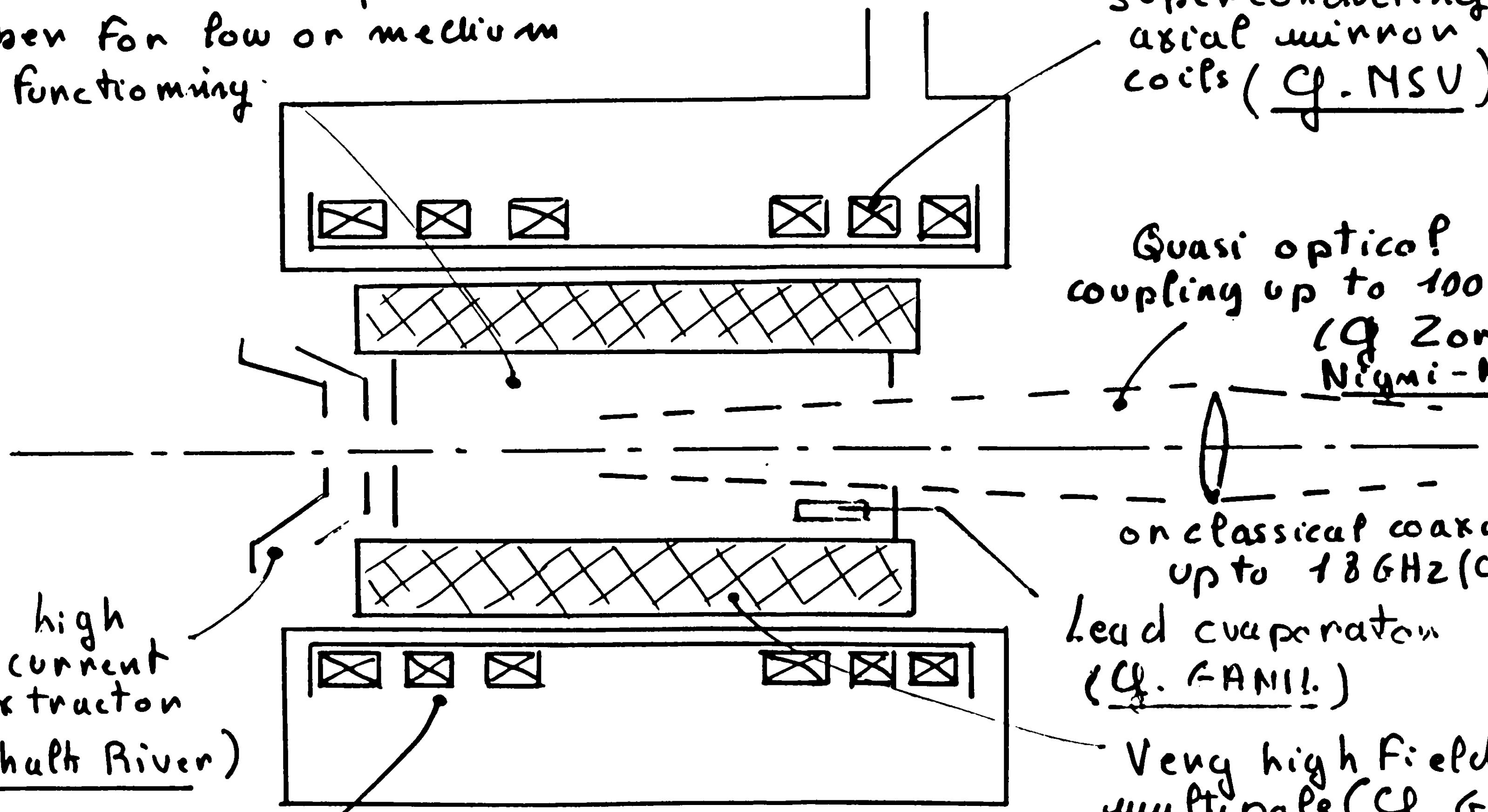
① - Upgrading of ECR4 GANIL at 18 GHz with 1300 A alimentations and 1.5 kW of UHF power → reach the range of 200 µAe or more for $Pb^{27 \rightarrow 29+}$

② - Next step of magnetic field / frequency scaling up to 100 GHz in a Minimafios-like device with hybrid : permanent magnets / superconducting coils for C.W. or lang pulses up to 18 GHz or pulsed gyrotron between 18 GHz and 100 GHz

$I \uparrow \propto n_i \uparrow$ (up to x 100 possible)

③ - Development of a purely pulsed ECR device (ECR4-like) with classical C.W and pulsed coils for radial magnetic compression and axial release of the plasma.

COMPACT HYBRID HIGH FREQUENCIES ECR DEVICE



MinimaFios-like plasma chamber for low or medium power functioning

superconducting axial mirror coils (Cf. MSU)

Quasi optical coupling up to 100 GHz (Cf Zorin/Golubev Nigni-Novgorod)

on classical coaxial coupling up to 18 GHz (Cf. GANIL)

Lead evaporator (Cf. GANIL)

Very high field FeNdB multipole (Cf GANIL or Phys. Atom.) using anisotropy of Rare Earth permanent magnets

high current extractor (Cf. Chalk River)

Multi-coils for multi-gradient/multi-module of minimum $|B|$ magnetic structure with $1\ T < |B| < 5\ T$

PULSED ECR DEVICE USING A PULSED COIL FOR RADIAL COMPRESSIION AND COLLAPSE OF THE MIMIMUM |B| MAGNETIC STRUCTURE INDUCING THE AXIAL RELEASE OF THE PLASMA.