EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-PPE/91-182
17.10.1991

STATUS AND FUTURE DEVELOPMENT OF ION-SOURCES FOR ON-LINE MASS-SEPARATORS

H. L. Ravn

CERN-ISOLDE, CH-1211 Geneva 23, Switzerland

ABSTRACT

The status is given of ion sources for on-line mass separators with examples of recent developments on element availability, ionization efficiency, speed and selectivity. Since the target and the ion-source most often are integrated a discussion is included of the progress in the important methods used to bring the nuclear reaction products out of the target and into the active region of the source. A number of novel more advanced target and ion source systems have recently emerged and may in the future offer new possibilities for existing machines.Selected examples will be given for:
1) new release and delay studies
2) selective resonant laser ionization
3) electron cyclotron resonance (ECR) ion sources
4) chemical reactions inside the ion source
5) ion sources with bunched beam release
In view of the planned new facilities with post acceleration of radioactive ion beams or on-line to high intensity low repetition rate accelerators a number of future requirements to the ion-sources are discussed.

Invited talk at the Twelfth International Conference on Electromagnetic
Isotope Separators and Techniques Related to their Applications (EMIS12)
Sendai, Japan, 2-6 September 1991
To be published in Nucl. Instrum. & Methods B

1. INTRODUCTORY REMARKS

I was asked to give a talk on the status of Ion sources for on-line mass separators and point out some future directions. Since the mass transfer from the target or in some cases the catcher to the vapour phase of the ion source often is the performance limiting factor of the integrated ion-source and target system a discussion of these have been included. I immediately realized that this is a pleasant but also a somewhat difficult task. Pleasant because extensive reviews of this nature have been given by others at the previous EMIS conferences [1,2,3] and elsewhere [4] so that for a number of definitions and explanations of general problems in the field I now can assume that they are common knowledge and refer to the earlier papers. Difficult because of the large volume of interesting reports on progress of these systems. In fact after a number of years during which about 25 on-line mass separators in the world have been operating at a steady level a change towards a considerable expansion both in number and quality seems to be immediate. Not only have new or improved facilities started up but the interest in using the on-line mass separator as injector to radioactive nuclear beam accelerators has greatly increased. The about 10 such new facilities presently under consideration [5] have already started a development programme which greatly stimulates the field.

The major areas of progress include the successful introduction of advanced ion-source technology which make use of lasers and electron cyclotron resonance (ECR). Significant progress can be reported on the understanding of the diffusion and desorption processes and the chemical reactions in the target and ion source. This has opened up for more elements shorter delays and higher selectivity. Ion sources with improved emittance have allowed experiments with isobaric mass separation and sources with bunched release have improved selectivity and signal to noise ratios. In order to keep my presentation brief and not repeat the information in the some 27 papers to be presented on the subject at this conference I will restrict myself to assess the different systems on which progress has been reported by means of selected examples often from the work which I am most familiar with. I want to address these issues today under the following headings: 2. General criteria and status of beams. 3. Vapour transfer and chemical reactions. 4. Ion sources.

2. THE GENERAL PROBLEM

The techniques which rapidly separate thermalized nuclear reaction products from the irradiated target material and continuously converts them into an intense radioactive ion beam distinguish themselves in a number of ways from the ionization techniques used elsewhere mainly because of the scarcity and rapid decay of the radioactive ion-source feed material. Although the development of these techniques generally has followed the trend in ion source development in other fields a number of additional requirements have to be fulfilled for on-line use as discussed in detail in ref. [1, 2, 3 and 4]. These depend strongly on the chemical properties of the elements so that they have to be developed specifically for each element or group thereof. Today techniques have been developed which in principle allow on-line to produce radioactive ion-beams of about 80 of the 92 naturally occuring elements [2]. However, a number of these beams need further improvement before they fulfill the requirements of all types of experiments. In fact since my last status report [2] beams of more elements have only been added at a rate of one every 2 years and as we will see in the following the bulk of the progress has been on improvement of existing beams mainly in terms of purity, emittance, delay or intensity. The elements that remain to be brought on-line and those that require improvement can be divided roughly in two groups, one that belongs to transition metals from the group 4b, 5b, 6b, 7b, and 8 and one that belongs to the lightest elements of group 3a, 4a, 5a, and 6a of the periodical system. The problem with them is not the ionization itself. As pointed out already 10 years ago by Kirchner, [1] there already exists ion sources that will ionize these elements reasonably efficiently. It is their refractory character or their formation of stable refractory compounds that causes their release and transport from the target or catcher to be inefficient and slow so that the microscopic amounts of source feed material will spend most of the time attached to the walls of the target or the ion-source. Development of beams of these elements seems to be dependent on techniques which employ formation of chemical compounds in the target or ion source or laser desorption and ionization of the product possibly transported and deposited by He-jet technique.

2.1 New requirements

The increased interest in using on-line mass separators as injectors for radioactive-ion post-accelerators raises the question on how to do this in the most efficient way in order to obtain the required intensity and energy. This may introduce some new general requirements to the ion sources. Since energy is the product of charge and total voltage gain, there is a high premium on producing beams with the highest possible charge state because the higher charge state allows a lower voltage dc accelerator or shorter linac to provide a given energy. For cyclotrons the incentive is even higher since the energy is proportional to the square of the charge. Traditionally the present target and ion source technique produces only singly charged ions. It is therefore interesting to discuss if the introduction of ion sources that allow production of the high charge states directly out of the ISOL may become a more efficient method than the pre-acceleration, bunching and stripping scheme, which presently is favoured. The bunching of the radioactive ions directly at the ISOL ion source is also required by experiments making use of Penning traps and lasers. The interesting possibility to inject ISOL beams into a tandem as suggested by the Oak Ridge group [6] has renewed the discussion of direct production of negative ion beams.

3. VAPOR TRANSPORT AND CHEMICAL REACTIONS

The transfer of the radioactive nuclei into the active volume of the ion source was in the past mainly studied by means of simple radiotracer technique where prospective target or catcher materials were activated and the release of the radioactivity as function of temperature or addition of reactive gases were determined by gamma ray spectrometry. This method has a number of shortcomings especially for light elements where often no suitable gamma ray emitter exists or those produced disappear in the gamma background often dominated by other more abundant reaction products. Also the time resolution of this method is in most cases too slow.

Today, new more precise on-line methods are taken in use for the study of the release properties of target and catcher materials. The material to be studied may be doped with energetic heavy ions of the element to be studied. If the sample is situate inside the ion source the release efficiency and time structure can be studied directly on-line under conditions which are identical to the final running conditions. Since in this case ion counting is used as detection technique a very fast time response is achieved.

The successful application of laser spectroscopy to the study of unstable nuclei has led to a new technique for desorption studies. In order to do laser spectroscopy on refractive elements which are not available as ion-beams on-line, several groups have developed efficient techniques for laser desorption and subsequent resonant laser ionization of refractory elements formed by the decay of available ions. A technique that holds promise for application directly on the catcher or in the ion source in order to make beams of these elements on line. The widespread industrial use of ion beam and plasma assisted techniques in coating and thin film production has justified to use advanced techniques like Secondary Ion Mass Spectrometry (SIMS), Bombardment Induced Light Emission (BLE) and Ion Scattering Spectroscopy (ISS). In recent years this field has produced a wealth of publications on the surface chemistry involved in Reactive Ion Beam Etching (RIBE) which is a mass transfer operation identical to what happens on the walls of ion sources and where inspiration to solve release problems in our field may be found. New developments in high temperature gas phase chemistry studied by means of Knudsen effusion mass spectrometry describe the formation of negative ions of platinum and other refractory metals.

3.1 Release and delay studies

At the last EMIS conference Kirchner [7] outlined the importance and the status of the knowledge of the surface-controlled delays in ion sources and related the observed release time distributions to the known or calculated enthalpies of desorption of the individual elements. Since then his group has introduced the above mentioned method of simulating the release and ionization process by means of energetic heavy ions from the UNILAC accelerator. From the observed release profiles a typical example of which is seen in fig. 1 they demonstrate that due to the long attachment time on surfaces the refractive elements have a tendency [8,9,10] to rediffuse into the construction details of the ion source resulting in 80-90% losses.

Beams of the isotopes of Oxygen, Carbon and Nitrogen have actively been investigated since they are of great interest for physics. The neutron rich ones are required for the study of phenomena near the neutron drip line and the neutron deficient ones as post-accelerated beams are important for studies of nuclear reactions of astrophysical interest. They are unfortunately difficult to separate efficiently from the target. The losses caused by adsorption on hot metal surfaces where these elements readily form refractory compounds result in overall efficiencies [11,12] of typically 0.01% for N^+ and C^+ and 0.1% for N_2^+ and CO^+. The release of N_2 from graphite targets was studied very exhaustively by the Louvain group [13,14]. By means of the ^{13}N-radioassay method they showed (fig. 2) that the release yield from the target is about 100%. Gas chromatographic measurements proved that the reactive ^{13}N atoms quickly were incorporated into a $^{13}N^{14}N$ molecule and that a partial pressure of $^{14}N_2$ was necessary in order to assure an efficient transport. A study at ISOLDE [15] of the production of neutron rich Nitrogen and Oxygen from a Pt-graphite target combined with a conventional plasma discharge source made out of graphite, shows that the intensity of a $^{16}N^{14}N^+$ beam is a strong function of the $^{14}N_2$ partial pressure in the ion source as seen in fig. 3. In off-line studies of the same system where enriched $^{15}N_2$ was used, the overall delay time distribution of the $^{15}N^{15}N^+$,$^{15}N^{14}N^+$ and the $^{15}N^+$ beams were studied in detail. As seen in fig. 4 the delay of the ions increases in the order mentioned indicating that they are formed by dissociation including an surface-adsorption step of the ^{15}N. The elements Carbon and Oxygen behaves in a similar way where the molecule formed is the highly stable CO and future studies of the thermochemistry of this compound in ion-sources holds the key to efficient production of C^+ and O^+ beams. In fact ion sources which avoid the gettering effect of the hot cathode or metal layers evaporated from it are being developed as discussed in section 3.2.

The desorption of the refractory elements Gold and Platinum implanted as their Hg precursors has been extensively studied by means of the pulsed-laser induced desorption

(PLID) [16] method mentioned in section 3 as outlined in fig. 5. The efficiency in the desorption step reached 60% independently of the implantation energy between 6 keV and 60 keV.
The chemical evaporation method where volatile compounds of otherwise refractory elements are synthesized in the target or ion source in order to enhance the desorption has since last reviewed [1] made considerable progress also for a number of other elements than the C, N and O discussed above and is now successfully used as a standard method by several groups [17,18,19,20] as we shall hear at this conference. The detailed mechanism of these chemical reactions are not well understood and they often give fluctuating results. The ISOL use of the method is almost identical to the method of RIBE [21] mentioned above where the ion surface interactions are used to dry-etch materials by bombardment with ions of 10 eV to 1000 eV energy in the presence of a CF_4 partial pressure of 0.1 mtorr. In an interesting study of the evaporation of Si and W in a rather elaborate RIBE apparatus, Cox et al. [21] show a strong dependence of the desorption of fluoride molecules both as function of the presence of excess Carbon and as a function of ion energy. Similar threshold effects have been observed by Eder et al [17] in the formation of Lu fluoride sidebands as function of ion-source anode potential. Another aspect of the release of refractory elements as chemical compounds is the possibility to avoid dissociation of the compounds and to ionize them as such. This effect is often observed in mass separators mostly as an disturbing contamination of the wanted beams. Since the isobaric mass elements have different chemical properties and often do not form a similar compound these molecular ions may be used to achieve a very high chemical selectivity as discussed in the next section.

3.2 Molecular beams

By proper control of the ion source parameters like source construction materials, temperature, reactant-gas pressure and anode voltage it is possible to favour the formation of molecular ions or sidebands often with overall efficiencies of 10%. In fact, as will be see below, we seem only to be discovering the many chemical species which can be produced. The well known addition of the mono-isotopic stable fluorine in the form of CF_4 continues to bring new interesting beams. The conditions for formation of a number of pure beams of fluoride molecular ions have been studied at ISOLDE [17]. For group 2a and group 3b elements overall efficiencies of 10% were found in the sidebands resulting in the intense and pure beams of Sr and Y shown in fig. 6 which allowed the study of the new isotopes ^{76}Sr and ^{79}Y. The refractory compound Silicon carbide has been tested by several groups as target material and found only slowly to release the interesting products. In a test at ISOLDE [22] with a strongly Al contaminated SiC target not only interesting yields of the light mass Ne, Na and Mg nuclei were found but also intense beams of the otherwise difficult to produce element. Fluorine was found in the in the AlF^+ sideband as shown in fig. 7. The well known Zeolites compounds which may contain a variety of metallic elements have been successfully applied as targets at TISOL [23]. These compounds release rare gases at room temperature like the emanating stearate and hydrous oxide targets used at an early stage at ISOLDE [24] but without being decomposed by the beam. In an unsuccessful attempt to find the homologous element Se as SeO^+ beams produced by O_2 addition to a ZrO_2 fiber target the CO_2 analogous carbonyl molecule $COSe^+$ was found in the high yields shown in fig. 8. This allowed us to identify the two new light Se isotopes ^{67,68}Se under isotopically pure conditions [22]. The formation and ionization characteristics of the Lanthanide oxide beams MeO^+ in connection with O_2 addition to hot-cavity sources have been carefully studied by the Osaka and Tokai groups [25,26]. The high overall efficiencies shown in fig. 9 were exploited to identify the new isotopes ^{121}La and ^{154}Pr.

4. ION SOURCES

4.1 Conventional ion sources

The displacements of the insulators of the hot-cathode plasma-discharge ion-sources to colder regions of the source and reduction of the product flow towards the cold insulator by means of 'molecular flow restrictions' [27] allowed raising the temperature of plasma sources to the level of thermal and surface ion-sources. A similar design allowed the GSI group [28] to achieve ionization efficiencies of the order of 3 to 11 % for a number of light transition metals. The efficiency and thermodynamics of the thermal ion source have been studied by Kirchner [29] in a very thorough and conclusive manner by means of the energetic heavy ions from the UNILAC discussed in section 3.1. He found that thermal equilibrium is generally not attained in this kind of ion source since much lower ionization efficiency was obtained than is expected for a thermalized system as shown in fig. 10. For both types of ion source this seems to have marked the end of their development in the direction of higher efficiencies by means of temperature and geometrical changes. For some elements further improvements in efficiency may be done by means of the chemical effects or by careful choice of target and source construction materials with low desorption enthalpies for the element in question as discussed in section 3.1. Only few such cases have been found, one being the case of graphite source material for the elements C, O and N. Molecular beams of the Carbon isotopes as CO^+ ions have been used in experiments for some time at ISOLDE [30] in the low yields discussed in section 3.1. In a test at ISOLDE of a target ion-source system made out of a graphite and platinum target [31] combined with an all graphite FEBIAD type ion-source [32] interesting beams of CO^+ containing the heavy Oxygen isotopes were found [15] for the first time. Also the production of heavy nitrogen nuclei were studied on-line by means of this system. Off-line tests rapidly showed that the electron emission from the all-graphite cathode was insufficient to assure standard source efficiency so that a 0.5 cm^2 tungsten cathode kept at about 2400°C was used. A similar observation was made with the the graphite target and source system of Louvain group [33]. At ISOLDE the 630 ms ^{18}N intensity raised by a factor of 20 compared to the earlier investigated CaO-target Ta ion-source combination [30]. For the first time at ISOLDE beams of oxygen were observed all the way out to the very heavy isotopes. The intensity of the $^{15}O^+$ beam of interest for post-acceleration was $1*10^3$ atoms/s μA compared to $1.5*10^4$ atoms/s μA for the Louvain system. At both places roughly 10 times more intensity was found in the $^{12}C^{15}O^+$ beam. Production rates of both systems may be improved: at Louvain by applying their ECR ion source, at ISOLDE by a factor of 10^6 using a 3 μA 1 GeV proton beam, a thicker, lower Z target and an ECR source. The overall efficiency of the ISOLDE system is still below 1 %. This may be due to the fact that a W cathode was still used which probably caused a gettering effect.

4.2 Electron cyclotron resonance ion sources

The direction further development may take in order to resolve the problems of losses to the walls of the source was already indicated by Schubaly [3] at the last conference. He suggested to use hot cathode plasma sources with multipole cusp type confinement. By applying the "minimum B" magnetic field configuration where the field is strongest outside the plasma the long confinement times of the ions provides efficiencies of up to 70% for Ar. A very similar confinement is found in the Electron Cyclotron Resonance (ECR) ion-sources where the gettering effects and lifetime problem of the hot cathode are avoided by sustaining the plasma by means of a 5 to 14 GHz radiofrequency field. Ionization efficiencies for singly charged ions of a number of light gaseous elements or compounds exceed by orders of magnitude those of the presently used plasma-discharge ion-sources. For N^+, O^+, Ne^+ and Ar^+ ionization efficiencies of 26%, 54%, 34% and 24% respectively have been measured [34]. A number of such ECR type sources now go into operation at on-line mass separators where these gaseous element efficiencies have been confirmed [35,36,37,38]. The connection to the target is seen from the typical layout of the TISOL [35] version in fig. 11. Another advantage of these ion sources is their capability of producing high charge states in a pulsed mode if required. Efficiencies integrating all charge states approach 100% for the rare gases with about 20% in the most probable charge state. The ionization efficiencies for metallic ions of these devices are, as for conventional ion sources, mainly determined by the condensation or adsorption losses to the walls of the cavity. Due to their high plasma density and long confinement times there are indications that high efficiency also for multi-charged metallic ions may be achieved without heating the walls of the cavity. Such a single stage ECR ion source in a compact version with permanent magnet containment is now under development at GANIL for ionization of radioactive ions [39].

4.3 Laser ion sources

The development of laser techniques for detection or study of radioactive atoms has after years of discussion [40] now led to their use also in the ion source region of the on-line mass separators where several such laser ionization schemes are in use.

The focusing of light issued from powerful Nd glass or CO_2 excimer lasers onto a solid target or a deposit is at low laser power (10^6-10^8 W/cm^2 in 10 ns pulses) dominated by pulsed desorption of the atoms present at the surface as discussed in section 3.1. Ionization of the desorbed atoms may now follow by means of three-colour three-step resonant excitation to an autoionizing stage or two-colour two-step excitation to Rydberg states followed by field ionization. Two groups [16,41] have recently studied the isobar separation of Au and Pt nuclei with an resonance ionization efficiency of 5 10^{-3}. It should be noted that the efficiency of this method like the other techniques for on-line mass separators depends strongly on the chemistry or atomic levels of the individual elements. The major problem is to find the most efficient excitation scheme and sufficient laser intensity to drive each step into saturation. When this is done not only a chemically selective ionization is achieved but ionization efficiencies of up to 20 % may be reached often exceeding those of conventional sources. The application of this method to the flow of atoms which effuse out of the on-line target has been studied by the IRIS-Moscow [42,43] and the ISOLDE-Mainz-Moscow [44] groups. They have chosen their starting point in their high-temperature tubular ionizer used for efficient (10-60 %) but unselective ionization of the rare earths shown in fig.12. The advantage of this tubular source compared to the insulated cavity originally used by Letokhov [45], to obtain 17 % Sr ionization efficiency, is that it is free of insulators which would adsorb the rare earths and may be kept at higher temperature. Surface-ionization to laser-ionization ratios of up to 10^5 and ionization efficiencies of 15% were achieved generally for the rare earths. Recent work by the ISOLDE-Mainz-Moscow Group [46] has identified an efficient excitation scheme for the ionization of the element tin. The wavelengths λ_1=317 nm, λ_2=812 nm, λ_3=824 nm leads to an auto ionization state in the third transition. The excitation steps can easily be saturated with the following laser powers: I_1=0.6 mW/mm^2, I_2=10 mW/mm^2 and I_3=100 mW/mm^2 leading to an ionization efficiency of 10 %. Interesting information on the production of element Li was obtained by the same group from a study of its laser ionization. The low 5 % overall Li efficiency obtained with surface ionizers combined with high-temperature Ta-targets at ISOLDE compared to the expected 90 % was somewhat in contrast to the other alkalies where the theoretical ionization efficiencies were readily obtained. By tuning the lasers to the photo ionization of the nuclear reaction produced ^{7}Li it could be shown that the laser ionization effect vanished when the surface ionizer reached its operating temperature indicating that about 90 % surface-ionization efficiency indeed was achieved. The fast diffusing Li seems therefore to be lost by diffusion out through the wall of the Ta target container leading to the conclusion that the 20 cm long 122 g/cm^2 thick Ta target may be made considerable smaller without reduction of Li production.

4.4 Ion sources with pulsed and bunched beams

A bunched beam release of the ions from the ISOL target and ion source is of great interest for a number of experiments with radioactive beams. The time scale of interest ranges from times comparable to the half-lives of the nuclei of interest i. e. 10^{-1} s - 1000 s for spectroscopic studies to megaherz in connection with post-acceleration of the ions to higher energies. The bunching effect may start already in the solid target where clear evidence of radiation enhanced diffusion have been observed. In the operation of the ISOLDE targets it has been noted that a number impurity atoms present in the target material, even after outgassing at higher temperature than the in beam operating temperature, are released much faster when the beam hits the target.This is pariticularly the case when the 910 MeV ^{3}He beam is used which deposits a very high power density in the target. With the future move to the 1 GeV proton beam from the PS-BOOSTER the protons will be concentrated a factor of 1000 in time due to the structure of this synchrotron beam. In fact this effect may explain the 10-100 times shorter delay times observed for the alkalies by the ORSAY group [47], in their experiments on-line to the 20 GeV PS beam, as compared to the delay observed for the same target materials used at the SC-ISOLDE. One could therefore in the future hope for bunched beams in the region of 100 ms length at a 1 s repetition rate.

The next step in the mass transfer process which allows a accumulation of the atoms is the surface adsorption effect discussed in section 3.1. In fact Kirchner [7] has used this effect for bunching and a very elegant type of thermo-chromatographic chemical separation in a FEBIAD source. By means of a mechanically operated cooling pocket repetition rates and pulse widths of the order of seconds were achieved. By replacing the mechanical plunger with a permanently cooled spot inside the ion source from where the atoms are desorbed by means of the pulsed laser technique, as discussed in section 3.1 and sketched in fig. 13, longer lifetime and a much wider time range may be achieved. The same technique may be used in conjunction with the tubular source shown in fig.12 where laser desorbed ion bunches have been observed [44]. Due to the interaction between the tube heating potential and the pulsed laser the ion beam was pulsed with the 10 kHz laser frequency. The pulse width was 20 μs determined by the heating potential of 0.6 V across the the tube. Shorter pulse widths may be obtained if thinner walled tubes can be used. In case of elements with no affinity to insulators potentials of the order of 100 V may be applied as shown in tests [46] with ceramic tubes. At higher laser power a high density energetic plasma is produced at the impact surface from which ions of a wide charge distribution may be extracted. This method which may be of particular interest for ion beams to be post-accelerated if sufficient efficiency can be achieved. The IRIS group has produced bunched beams as we will hear at this conference [48] by inserting an electrode in front of a hot cavity source like the one in fig. 12 onto which a pulsed gating potential is applied.

4.5 Negative Ions

A few of the proposed schemes for post-acceleration of radioactive ions involve the use of tandem accelerators [5,6] which require that negative ions are injected. An interesting possibility to produce negative ions of elements with high electron affinity like the halogens, C, O, S, Se, and Te by means of the laser method is described in the previous chapter. Several groups [49,50] have extracted intense beams of these elements from relatively cool plasmas induced by 10^7-10^8 W/cm^2 laser pulses. Negative surface ionization of transition metal fluorides lead also to interesting negative ion intensities. Recently the thermodynamic equilibria of a number of transition metals compounds which form negatively charged fluoride ions have been determined [51]. This indicates a further chemical technique to make negative ion beams of these difficult elements.

5. CONCLUSION

The ion source and target techniques used for on-line production of radioactive ion beams have since long lost their character of "witchcraft and sorcery" and been replaced by a thorough understanding of the physics laws by which it is governed. We have seen that for the production of an intense radioactive ion beam no single solution is the best possible choice in all situations. Each element presents an individual case which most often can be solved with a determined effort and many interesting problems are still awaiting their solution. Nowhere is the progress more evident than in the use of chemical reactions in the target and ion source which now allow routine beam production of elements until now difficult to produce. The first generation of novel sources based on laser and ECR techniques has demonstrated a satisfactory level of reliability and performance. These innovations and new developments will open up new domains of energies and radioactive ion beams both in the existing and in the number of planned future accelerators.

REFERENCES

[1] R. Kirchner, Nucl. Instr. and Meth. 186 (1981) 275.

[2] H. L. Ravn, Nucl. Instr. and Meth. B 26 (1987) 72.

[3] M. R. Shubaly, Nucl. Instr. and Meth. B 26 (1987) 195.

[4] H. L. Ravn and B. W. Allardyce, Treatise on Heavy-Ion Science Ed. D. Allan Bromley Vol. 8 (Plenum Press New York 1989) p 363.

[5] H. L. Ravn, Radioactive Nuclear Beam Facilities Based On ISOL-Postaccelerator Schemes. To be published in Proc. 2nd. Int Conf on Radioactive Nuclear Beams Louvain La Neuve, Belgium August 19, 1991.

[6] G. D. Alton, H. K. Carter , C. M. Jones and D. K. Olsen Design Considerations For Target And Sources For The Proposed Oak Ridge Exotic Beam Facility, To be published in Proc. 2nd. Int Conf on Radioactive Nuclear Beams Louvain La Neuve, Belgium August 19,1991.

[7] R. Kirchner, Nucl. Instr and Meth. B26 (1987) 204.

[8] R. Kirchner, C. Bruske K. Burkhard and W. Hüller, GSI Scientific Report No.88-1 Sect. 5.5,1988.

[9] R. Kirchner et. al. Ion source development for the on-line isotope separator at GSI, This volume.

[10] R. Kirchner, On the release and ionization efficiency of catcher-ion-source systems in isotope separation on-line, This volume.

[11] R. Kirchner, Nucl. Instr. and Meth. 234 (1985) 226.

[12] H.L. Ravn, J.M. D'Auria, M.J.G. Borge, Y. Huang, O.C. Jonsson, L. Nikkinen and S Sundell, Proc. Accelerated Beams Workshop, Parksville B.C.1985, Eds. L. Buchmann and J.M.D'Auria Triumf Report TRI-85-1, p 94.

[13] D. Darquenne, Th. Delbar and P. Lipnik, Nucl. Instr. and Meth. B 47 (1990) 311.

[14] P. Van Duppen et al, Extraction efficiency of ^{13}N from a graphite target, This volume.

[15] K. Elsener and The ISOLDE Collaboration work in progress.

[16] U. Krönert, St. Becker, G. Bollen, M. Gerber, Th. Hilberath, H.-J. Kluge and G. Passler, Nucl. Instr. and Meth A 300 (1991) 522.

[17] R. Eder H. Grawe, E. Hagebø, P. Hoff, E. Kugler, H. L. Ravn and K. Steffensen, The production Yields Of Radioactive Ion-Beams From Fluorinated Targets At The ISOLDE On-Line Mass Separator. Submitted to Nucl. Instr. Meth. B.

[18] B. Fogelberg, Efficiency and delay of the integrated target and bi-mode ion source of OSIRIS, This volume.

[19] E. Yabe, Oxygen ion source with plasma cathode, This volume.

[20] Y. Kawase, Fluorination method for the surface ionization of Sr and Ba with a He-Jet type ISOL, This volume.

[21] T. I. Cox and D. G. Armour, Proc. It. Conf. Ion & Plasma assisted Techniques Geneva May 1989, CEP Consultants Edinburgh 1989 p 42.

[22] E. Hagebø, P. Hoff, O. C. Jonsson, E. Kugler, J. P. Omtvedt, H. L. Ravn and K. Steffensen, New Production Systems At ISOLDE. This volume.

[23] M. Dombsky et. al.,Targets and ion sources for the TISOL facility. This volume.

[24] P. Patzelt, Proc. Int. Conf. on Electromagnetic Isotope Separators and the Techniques of their Application, Marburg (Bundesministerium für Technologie und Wissenschaft), Rept. K70-28 (1970), p. 158.

[25] S. Ichikawa, T. Sekine, H. Iimura and M. Oshima, Nucl. Instr and Meth. A274 (1989) 259.

[26] Y. Kawase and K. Okano Nucl. Instr and Meth. B37/38 (1989) 116.

[27] J. M. Nitchke, Nucl. Instr and Meth. A236 (1985) 1.

[28] R. Kirchner, O. Klepper, D. Schardt and T. Sekine, Nucl. Instr and Meth. B26 (1987) 235.

[29] R. Kirchner, Nucl.Instr. and Meth A 292 (1990) 203.

[30] H. L. Ravn, ISOLDE User's Guide, Ed. H. -J. Kluge, CERN 86-05 (1986).

[31]Andreasen, H. R. Eder, H. Haas, E. Hagebø, P. Hoff, H. L. Ravn, K. Steffensen, and S. Sundell, Mixtures of Molten Metals and Graphite as Targets For On-Line Mass-Separators To be published in Nucl. Instr. and Meth. B

[32] S. Sundell, Ion source with combined cathode and transfer-line heating, This volume.

[33] J. Deutch, F. Gimeno-Nogues, R. Prieels, N. Severijns, J. Wouters, P. De Moor, J. Gentens, M. Huyse, P. Schuurmans, L. Vanneste, W. Vanderpoorten, J. Vanderhaverbeke, D. Wouters and T. Vanderlinden, Rapport Scientifique De L'Utilisation Du Cyclotron Et Des Activities De L'Unite De Physique Nucleaire. Institut Interuniversitaire Des Sciences Nucleaires University Catholique De Louvain

[34] V. Bachtold and S. A. Shiekh, Proc of the Accelerated Radioactive Beams Workshop Parksville BC, Canada Sept. 1985, Eds. L. Buchmann and J. D'Auria TRIUMF Rep. TRI-85-1, p 110.

[35] Buchmann, L. J. Vincent, H. Sprenger, M. Dombsky J. M. D'Auria, P. McNeely and G. Roy, The ECR Ion Source At The TRIUMF Isotope Separator, TISOL, Submitted to Nucl.Instr. and Meth. B

[36] Decrock, P. M. Huyse P. Van Duppen, F. Baeten, C. Dom and Y Jongen, Nucl.Instr. and Meth. B 58 (1991) 252.

[37] P.Van Duppen, An ECR ion-source for the LISOL facility, This volume.

[38] A. Gizon, Present status of single charged ion ECR source at the SARA on-line separator, This volume.

[39] P. Sortais, P. Attal, M. Bisch, M. P. Bourgarel, P. Lehérissier and J. Y. Pacquet, Rev. Sci. Instrum. 61 (1990) 288.

[40] W. M. Fairbank and H. K. Carter, Nucl.Instr. and Meth. B26 (1987) 357.

[41] J. K. P. Lee, G. Savard, J. E. Crawford, G. Thekkadath, H. T. Duong, J. Pinard, S. Liberman, F. Le Blanc, P. Kilcher, J. Obert, J. C. Putaux, B. Roussière and J. Sauvage, Nucl.Instr. and Meth. B34 (1988) 252.

[42] G. D. E. Alkhazov, Ye Berlovich, and V. N. Panteleyev, Nucl.Instr. and Meth. A 280 (1989) 141.

[43] V. Panteleyev et. al., Selective laser ion-source at the IRIS facility, This volume.

[44] V. Mishin et. al.,Chemically selective Ion Source for the CERN ISOLDE on-line mass-separator facility, This volume.

[45] S. V. Andreev, V. I. Mishin and V. S. Letokhov, Opt. Comm.57 (1986) 317.

[46] F. Sherer et. al. To be published in the proceedings of the 4th Int. Conf. on Ion Sources Bensheim-Germany Sept 1991. Rev. Sci. Instrum.

[47] F. Touchard, J. Biederman, M. de Saint Simon, C. Thibault, G. Huber, M. Epherre and R. Klapisch, Nucl. Instr. and Meth. 186 (1981) 329.

[48] V. Panteleyev et. al.,Ion source of a mass separator with accumulation and bunching of ions, This volume.

[49] D. Berkovits, E. Boaretto, G. Hollos, W, Kutschera, R. Naaman, M. Paul and Z. Vager, Nucl. Instr. and Meth. A302 (1991) 379.

[50] G. Korschinek and T. Henkelmann Nucl. Instr. and Meth. A302 (1991) 376.

[51] S. V. Kuznetsov, M. V. Korobov, and L. N. Sidorov, Int. J. Mass Spectrom. Ion Processes. 91 (1989) 283.

FIGURE CAPTIONS

Figure 1
Release profiles of "refractory" elements implanted by means of UNILAC into a tantalum catcher at 2400 K inside a FEBIAD ion source [8].

Figure 2
Release yield of ^{13}N from a graphite target as function of proton beam power [13].

Figure 3
Release of $^{16}N^{14}N^{+}$ from a mixed Platinum-graphite target as function of $^{14}N_2$ partial pressure in arbitrary units [15].

Figure 4
Delay time distribution of various Nitrogen beams in a graphite ion-source [15].

Figure 5
Layout of the experiment in which Pulsed-Laser Induced Desorption is used (PLID) [16].

Figure 6
Beam intensities of Sr and Y ions obtained by irradiating a Ti foil target combined with a W-surface ionizer to which CF_4 gas was added [17].

Figure 7
Beam intensities of F and AlF ions obtained by irradiating a SiC target combined with a high temperature plasma discharge source in the presence of Al-vapor [17].

Figure 8
Beam intensities of Se as COSe ions obtained by irradiating a ZrO_2 fiber target combined with a high temperature plasma discharge source to which O_2 gas was added [27].

Figure 9
Ionization efficiency of Rare earth elements as oxide sidebands obtained by O_2 gas addition to a He-Jet combined with a surface ionizer [26].

Figure 10
Ionization efficiency of various elements versus ionization potential. The curves are calculated assuming N=1 (surface ionization efficiency), N=7500 (thermoequilibrium) and N=150, respectively. The latter results from a fit to the experimental data [29].

Figure 11
Layout of the TISOL target and ECR ion-source [35].

Figure 12
Layout of the ISOLDE laser ion source [44].

Figure 13
Sketch of a bunched beam source using pulsed laser desorption.

FIGURE CAPTIONS

Figure 1
Release profiles of "refractory" elements implanted by means of UNILAC into a tantalum catcher at 2400 K inside a FEBIAD ion source [8].

Figure 2
Release yield of ^{13}N from a graphite target as function of proton beam power [13].

Figure 3
Release of $^{16}N^{14}N^+$ from a mixed Platinum-graphite target as function of $^{14}N_2$ partial pressure in arbitrary units [15].

Figure 4
Delay time distribution of various Nitrogen beams in a graphite ion-source [15].

Figure 5
Layout of the experiment in which Pulsed-Laser Induced Desorption is used (PLID) [16].

Figure 6
Beam intensities of Sr and Y ions obtained by irradiating a Ti foil target combined with a W-surface ionizer to which CF_4 gas was added [17].

Figure 7
Beam intensities of F and AlF ions obtained by irradiating a SiC target combined with a high temperature plasma discharge source in the presence of Al-vapor [17].

Figure 8
Beam intensities of Se as COSe ions obtained by irradiating a ZrO_2 fiber target combined with a high temperature plasma discharge source to which O_2 gas was added [27].

Figure 9
Ionization efficiency of Rare earth elements as oxide sidebands obtained by O_2 gas addition to a He-Jet combined with a surface ionizer [26].

Figure 10
Ionization efficiency of various elements versus ionization potential. The curves are calculated assuming N=1 (surface ionization efficiency), N=7500 (thermoequilibrium) and N=150, respectively. The latter results from a fit to the experimental data [29].

Figure 11
Layout of the TISOL target and ECR ion-source [35].

Figure 12
Layout of the ISOLDE laser ion source [44].

Figure 13
Sketch of a bunched beam source using pulsed laser desorption.

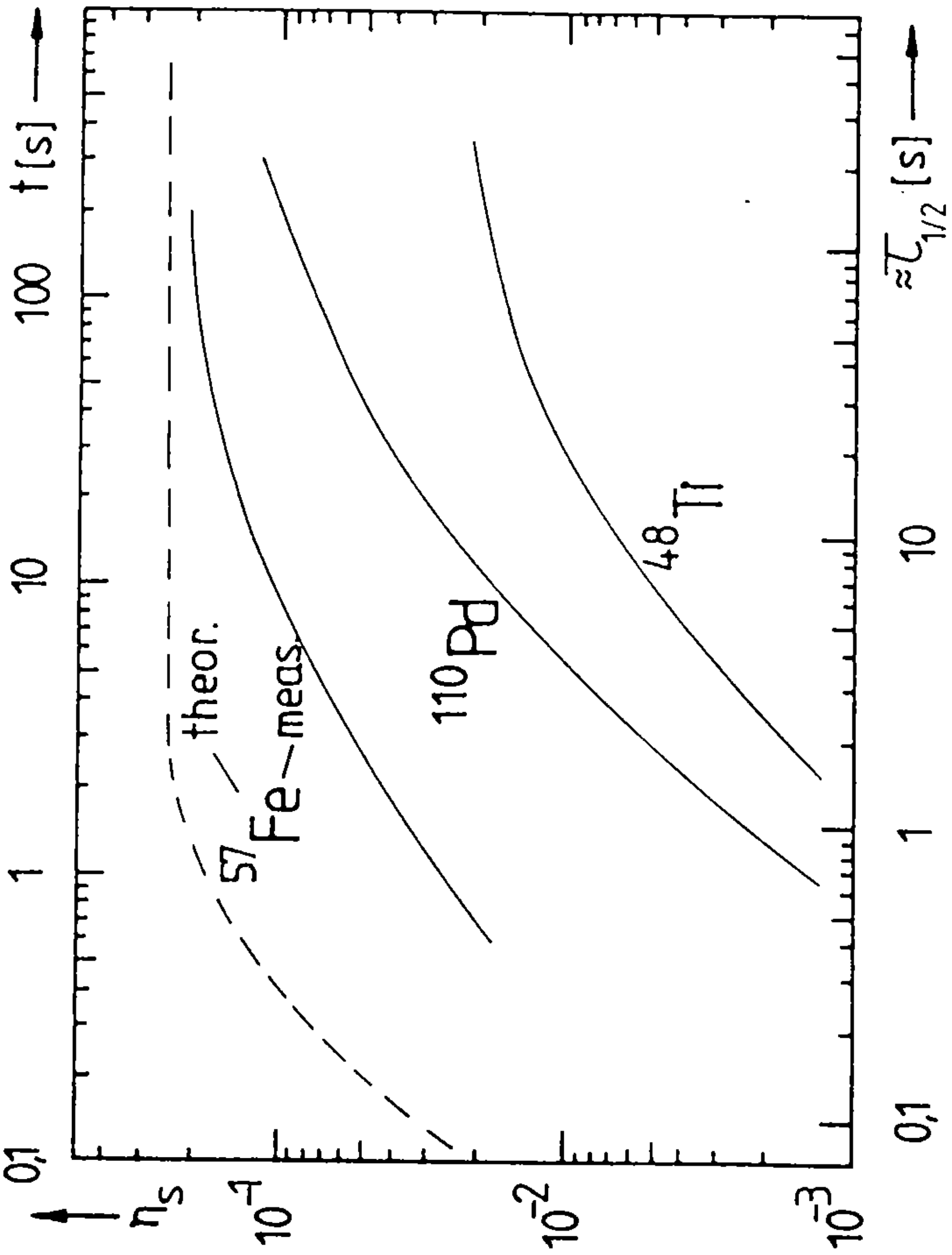
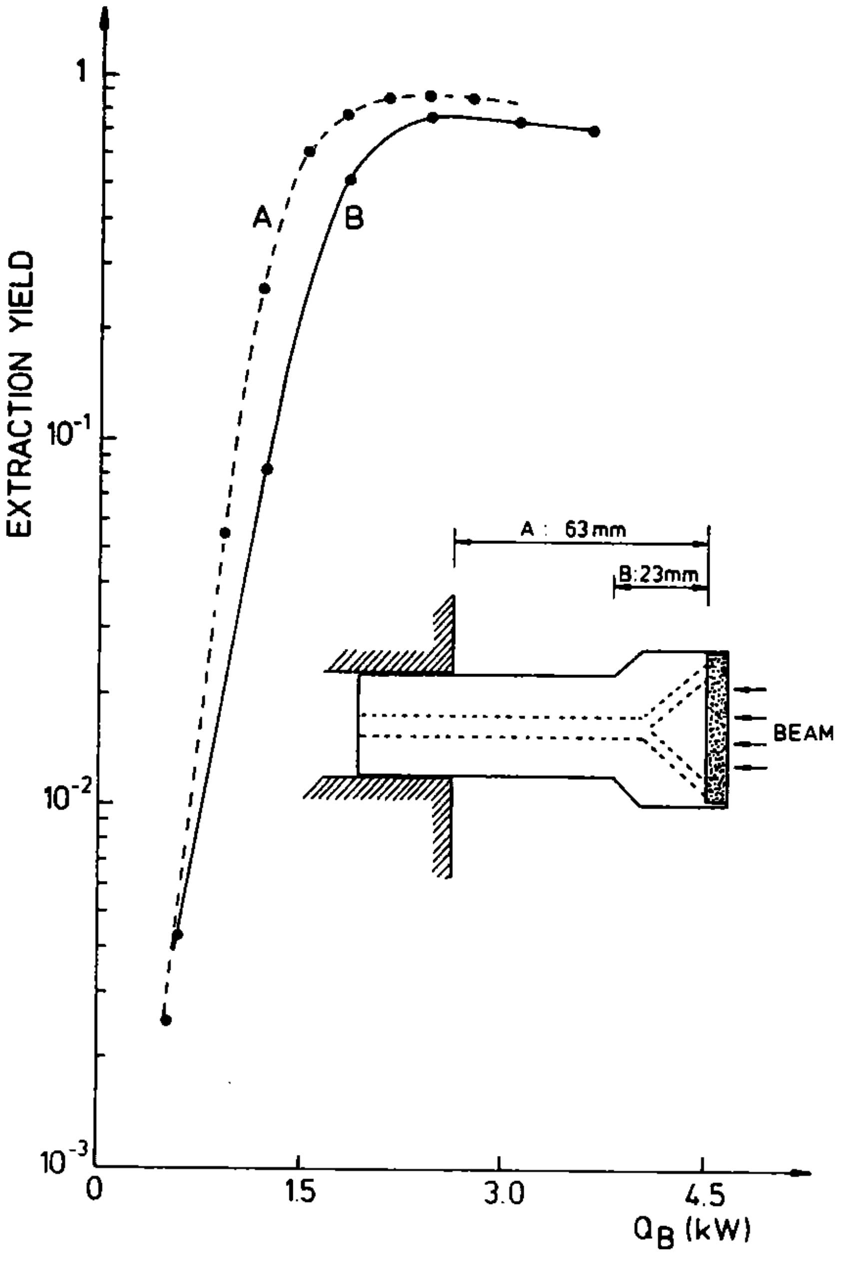

n_s
10^-1
10^-2
10^-3
0,1
1
10
100
t [s]
0,1
1
10
≈τ_1/2 [s]
theor.
57Fe
meas.
110Pd
48Ti

Figure 1



EXTRACTION YIELD
1
10^-1
10^-2
10^-3
0
1.5
3.0
4.5
Q_B (kW)
A
B
A : 63 mm
B: 23mm
BEAM

Figure 2

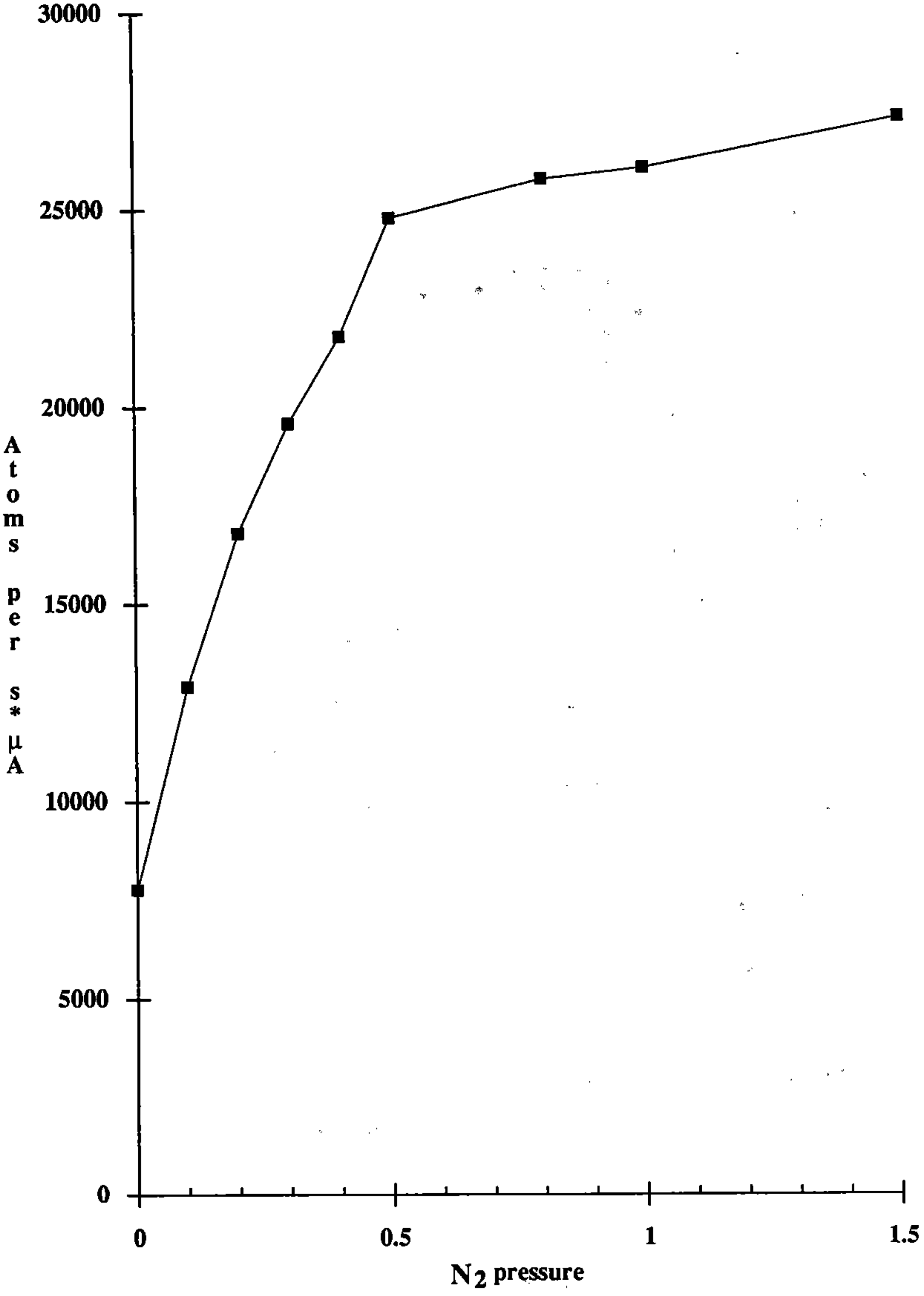

30000
25000
20000
15000
10000
5000
0
Atoms per s*µA
0
0.5
1
1.5
N_2 pressure

Figure 3

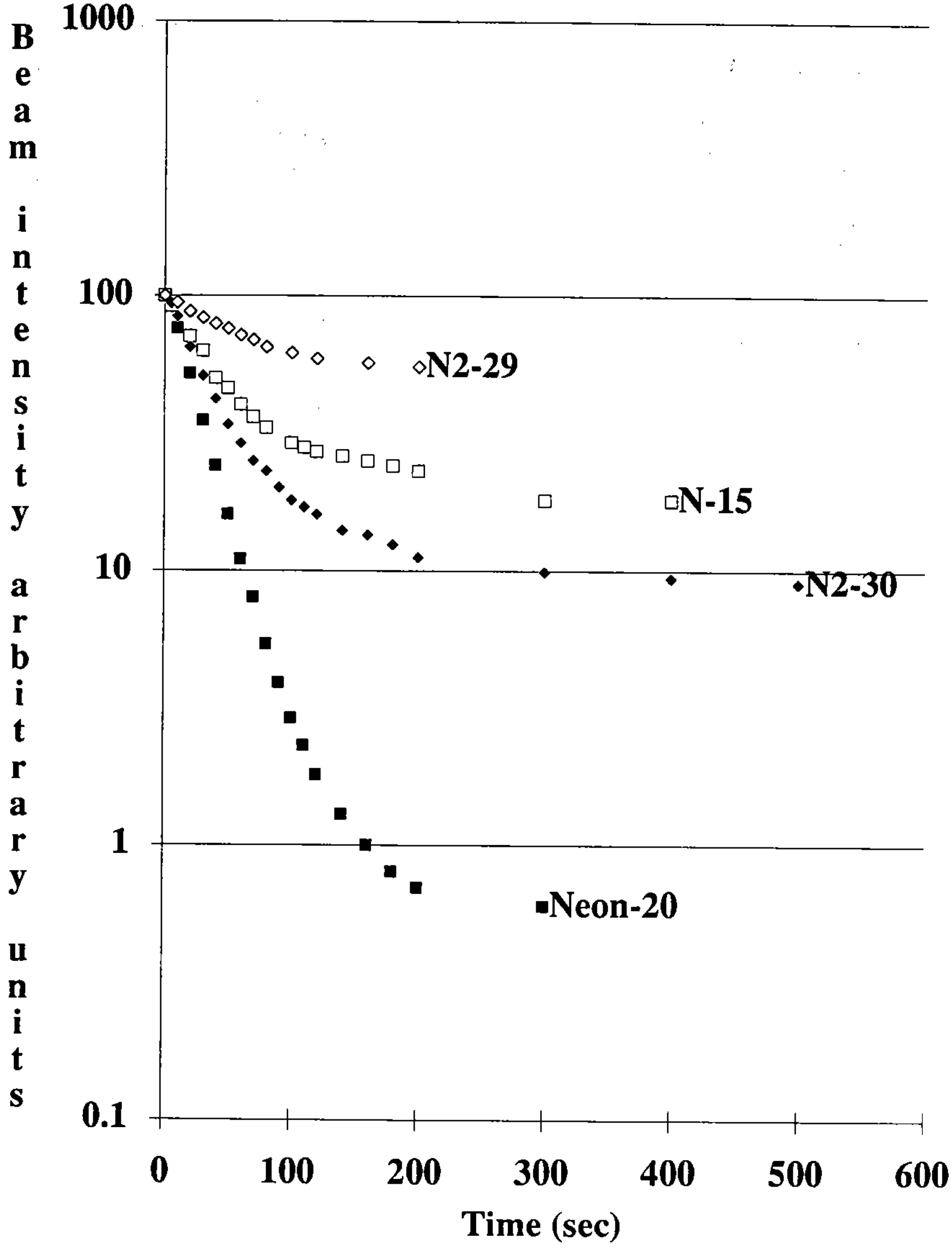

Beam intensity arbitrary units
1000
100
10
1
0.1
0
100
200
300
400
500
600
Time (sec)
◇N2-29
□N-15
◆N2-30
■Neon-20

Figure 4

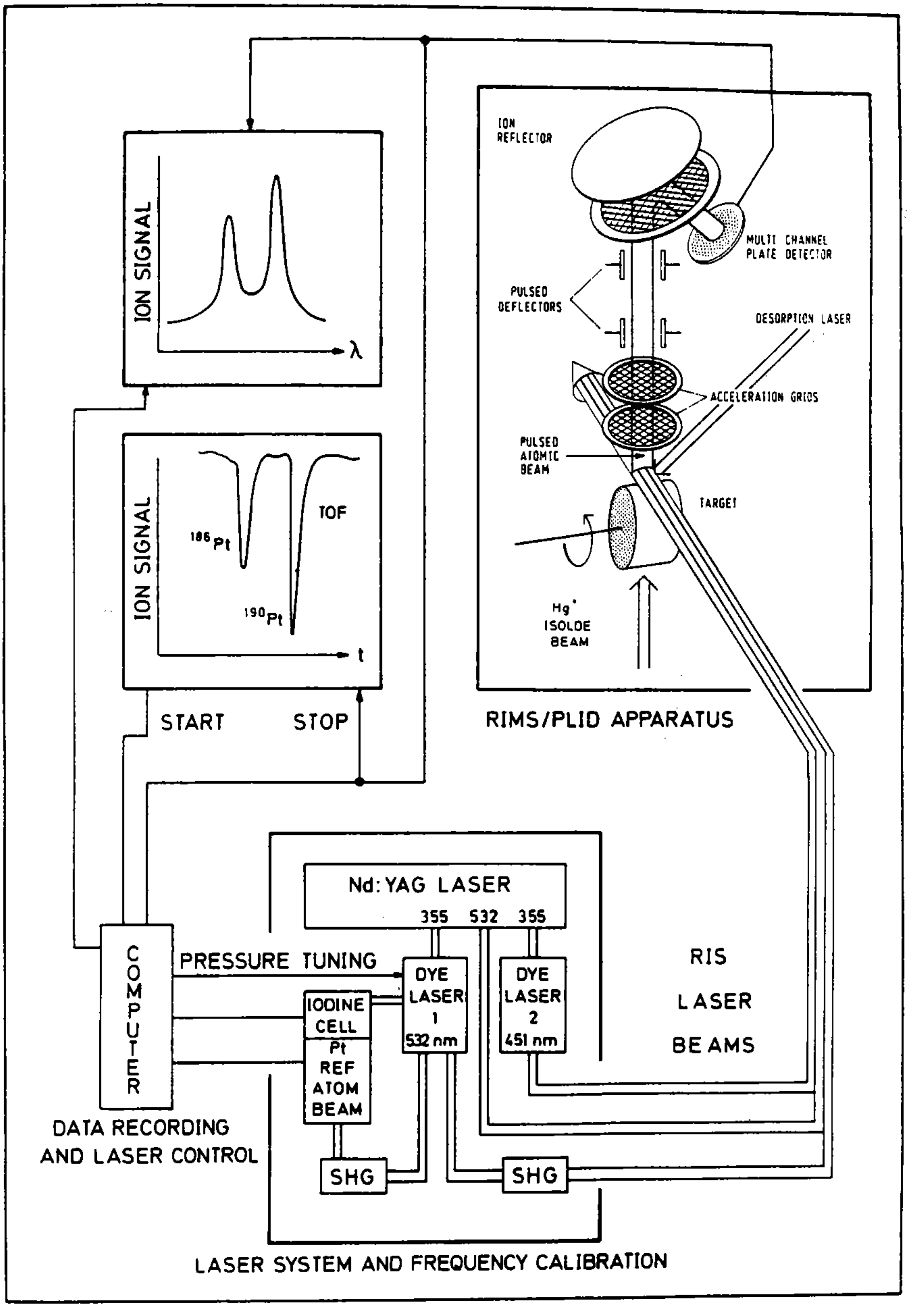

ION SIGNAL
λ
ION SIGNAL
^{186}Pt
^{190}Pt
TOF
t
START
STOP
ION REFLECTOR
MULTI CHANNEL PLATE DETECTOR
PULSED DEFLECTORS
DESORPTION LASER
ACCELERATION GRIDS
PULSED ATOMIC BEAM
TARGET
Hg$^+$ ISOLDE BEAM
RIMS/PLID APPARATUS
Nd:YAG LASER
355
532
355
PRESSURE TUNING
COMPUTER
DYE LASER 1 532 nm
DYE LASER 2 451 nm
IODINE CELL
Pt REF ATOM BEAM
SHG
SHG
RIS LASER BEAMS
DATA RECORDING AND LASER CONTROL
LASER SYSTEM AND FREQUENCY CALIBRATION

Figure 5

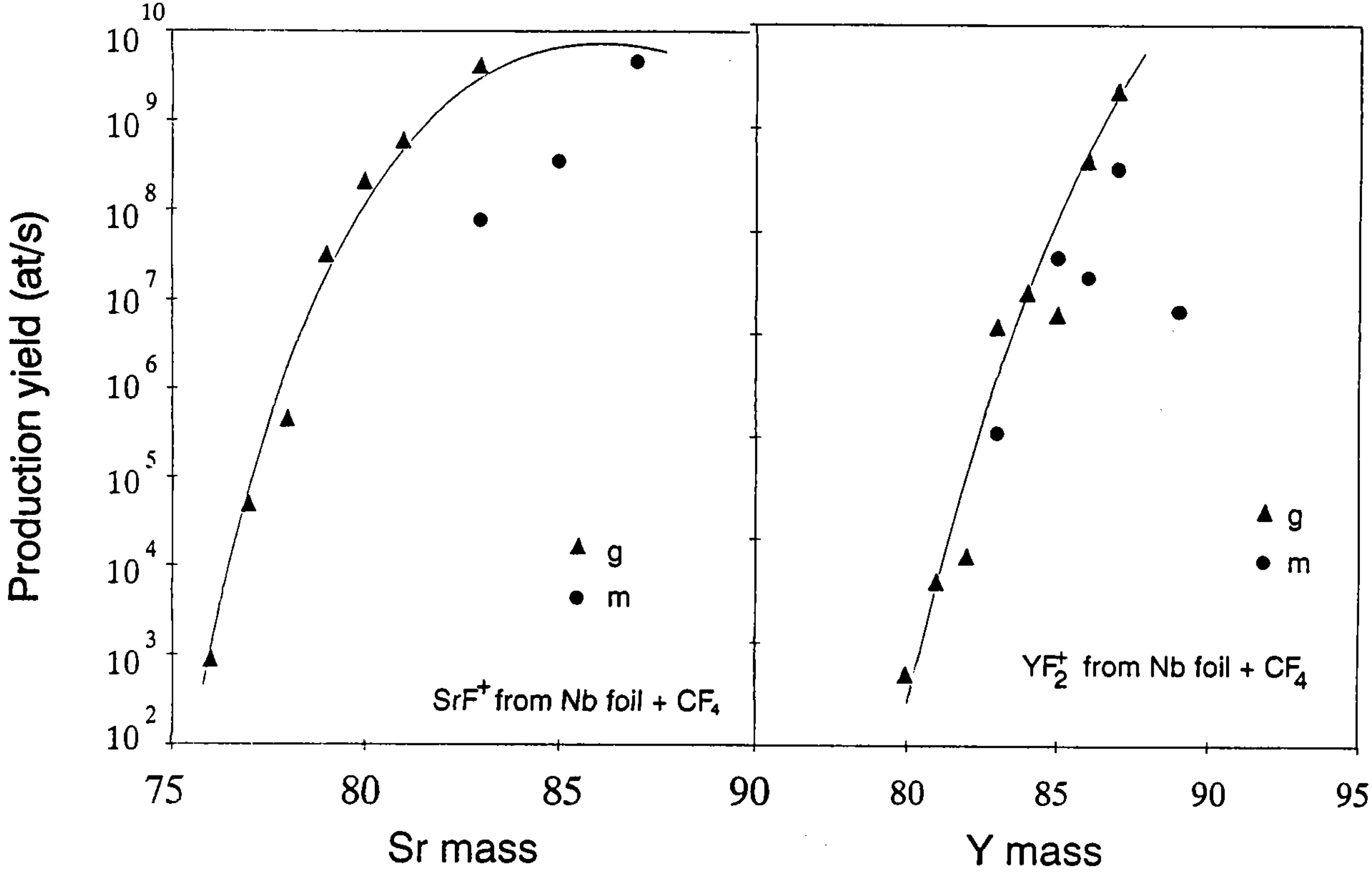

Production yield (at/s)
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
75
80
85
90
Sr mass
g
m
SrF^+ from Nb foil + CF_4
80
85
90
95
Y mass
g
m
YF_2^+ from Nb foil + CF_4

Figure 6

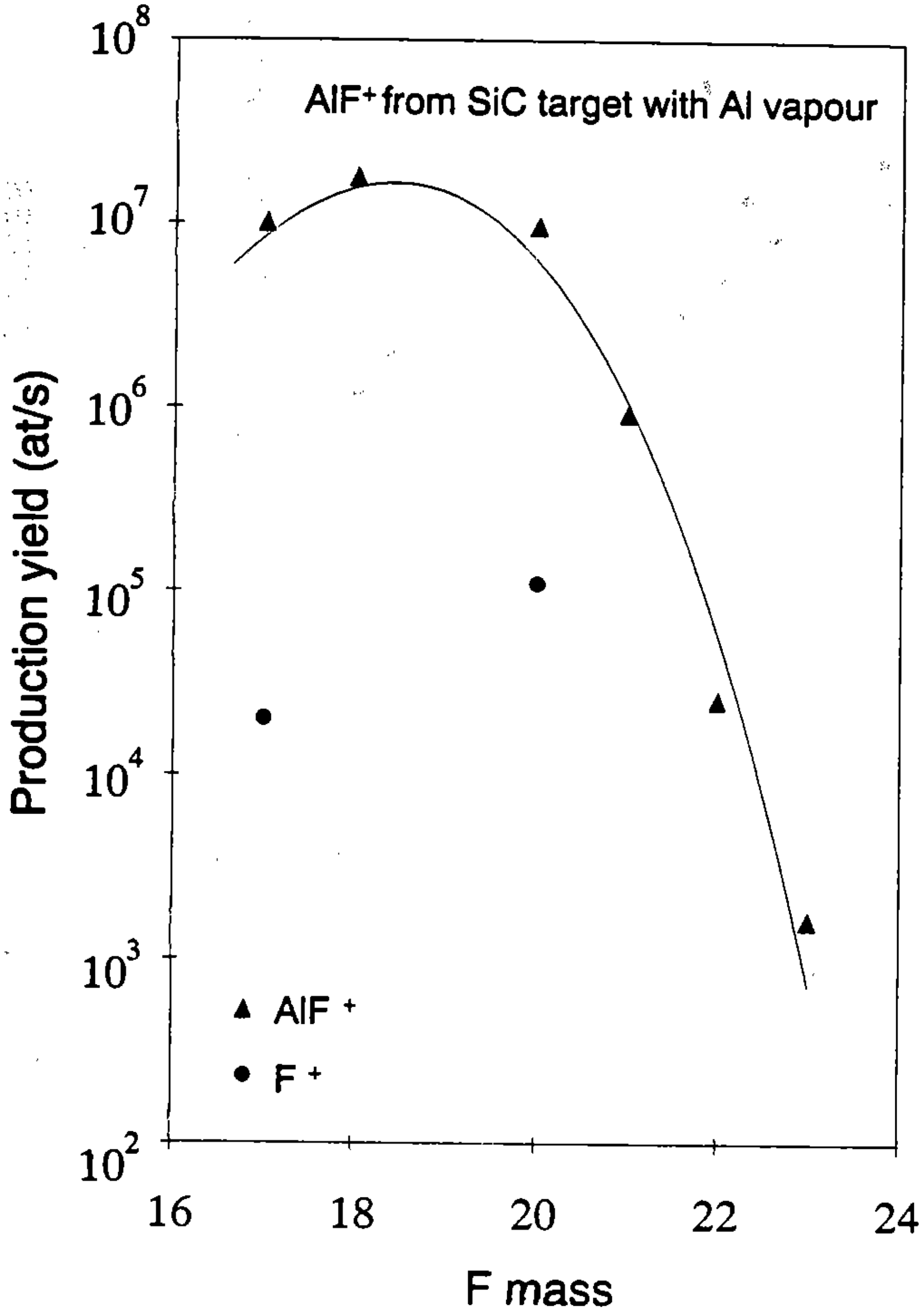

AlF⁺ from SiC target with Al vapour
Production yield (at/s)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
16
18
20
22
24
F mass
▲ AlF +
● F +

Figure 7

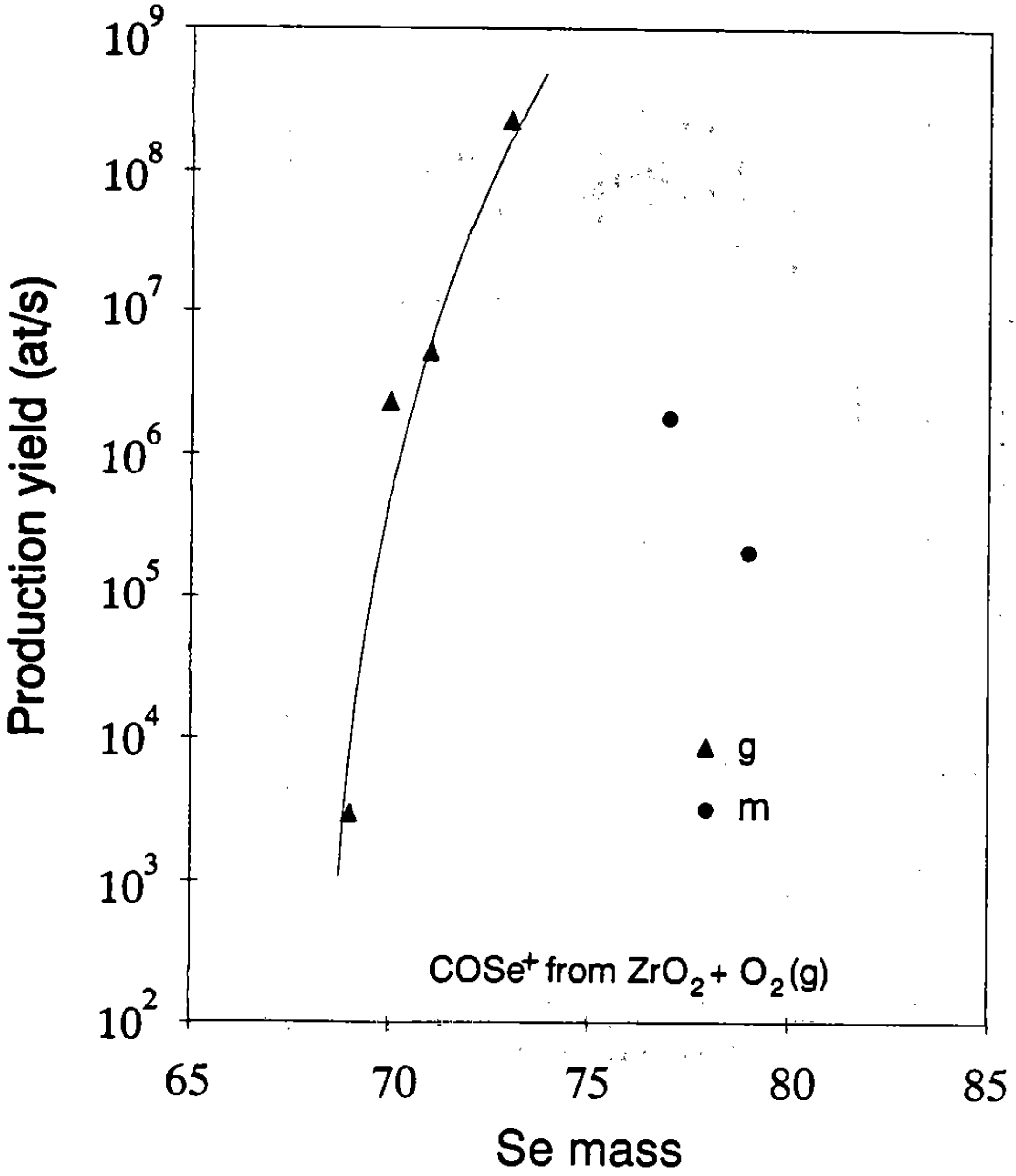
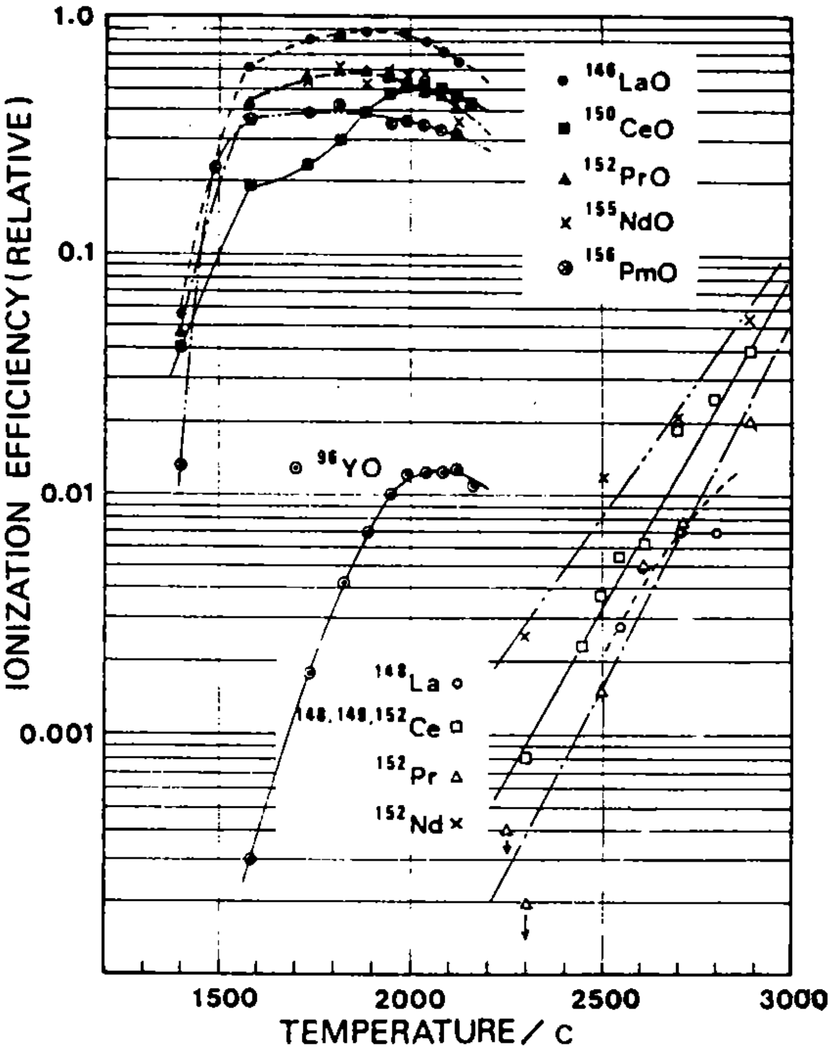

Production yield (at/s)
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
▲ g
● m
COSe$^+$ from ZrO$_2$ + O$_2$(g)
65
70
75
80
85
Se mass

Figure 8



1.0
0.1
0.01
0.001
IONIZATION EFFICIENCY (RELATIVE)
1500
2000
2500
3000
TEMPERATURE / C
● ^{146}LaO
■ ^{150}CeO
▲ ^{152}PrO
× ^{155}NdO
⊗ ^{156}PmO
⊙ ^{96}YO
^{148}La ○
^{148,149,152}Ce □
^{152}Pr △
^{152}Nd ×

Figure 9

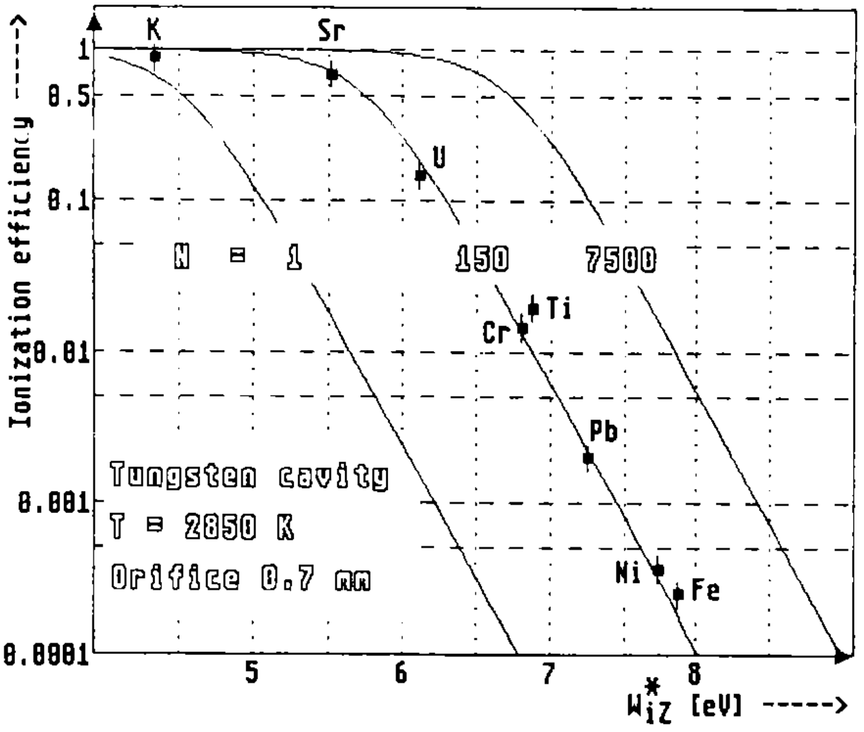

K
Sr
U
Ti
Cr
Pb
Ni
Fe
N = 1
150
7500
Tungsten cavity
T = 2850 K
Orifice 0.7 mm
Ionization efficiency ----->
1
0.5
0.1
0.01
0.001
0.0001
5
6
7
8
W_{iZ}^* [eV] ----->

Figure 10

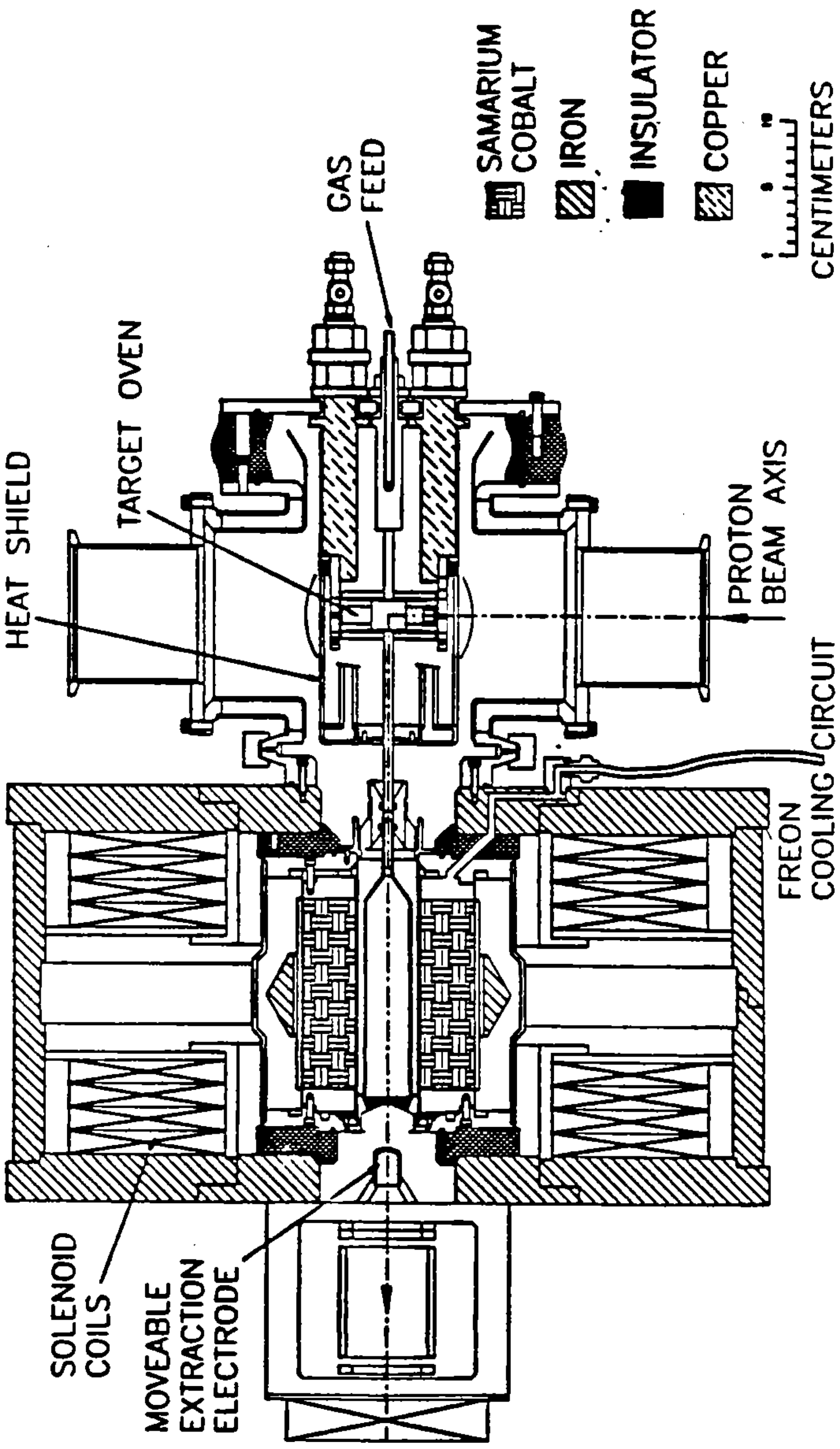

HEAT SHIELD
TARGET OVEN
GAS FEED
SAMARIUM COBALT
IRON
INSULATOR
COPPER
CENTIMETERS
PROTON BEAM AXIS
FREON COOLING CIRCUIT
SOLENOID COILS
MOVEABLE EXTRACTION ELECTRODE

Figure 11

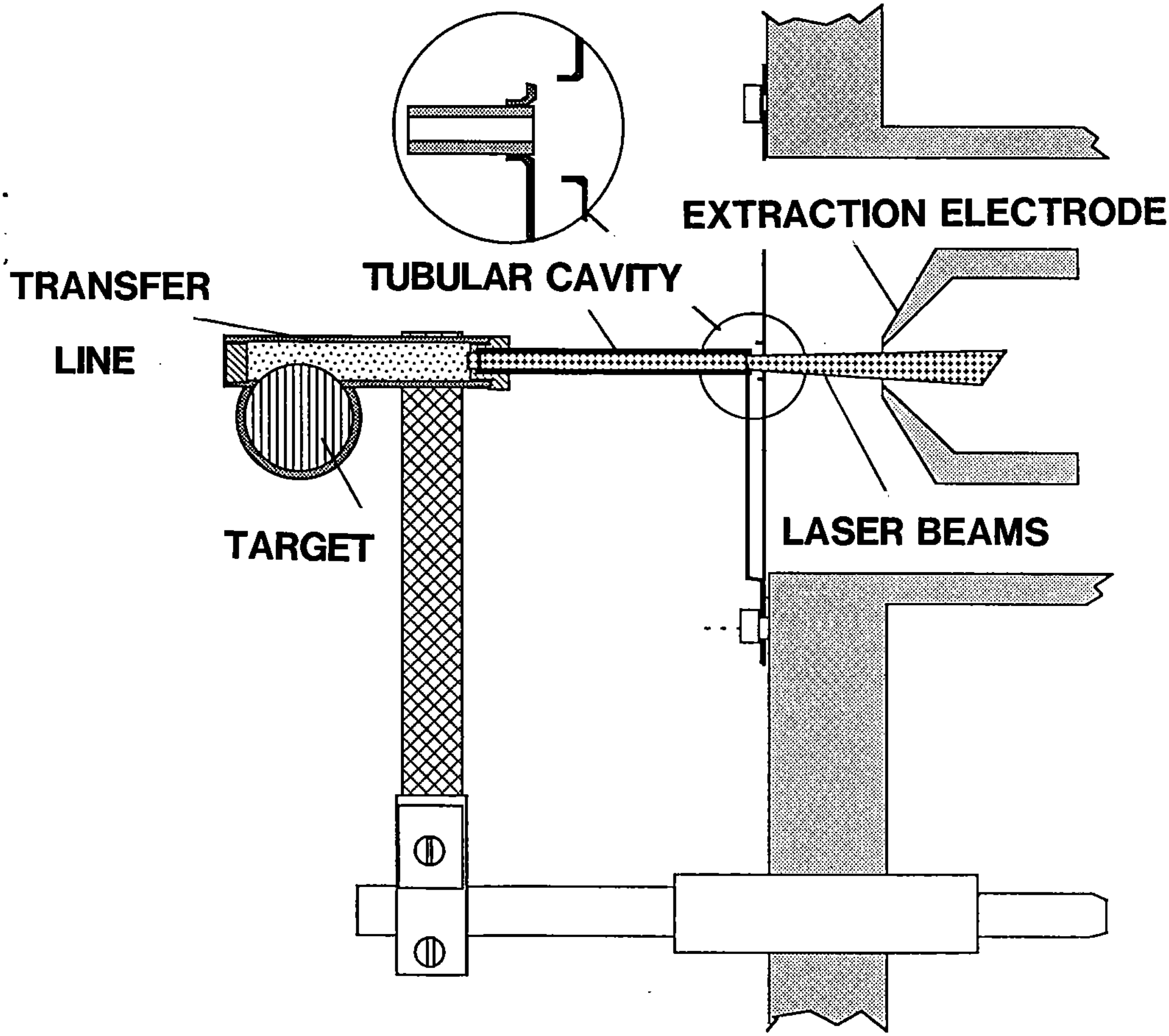

EXTRACTION ELECTRODE
TRANSFER LINE
TUBULAR CAVITY
TARGET
LASER BEAMS

Figure 12

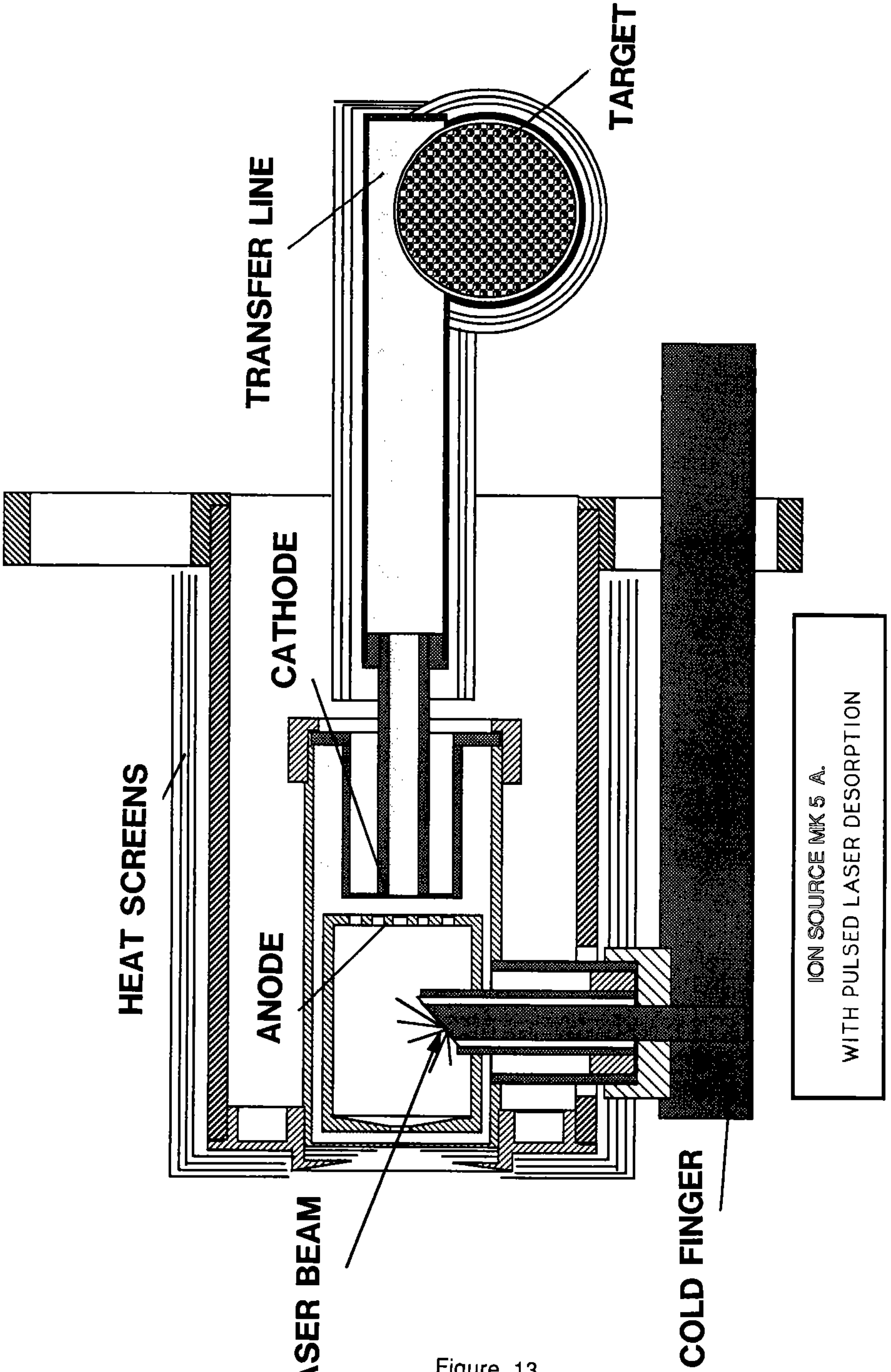


Figure 13

Imprimé au CERN. Prix : 0.90 Fr.