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VERSATILE SOURCE FOR INTENSE MULTIPLY-CHARGED ION BEAMS

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Measurements of yield and charge state distribution of ions extracted from a DUOPIGATRON multiply-charged ion source are reported. Two different modes can be distinguished: the first one is characterised by low discharge voltage and high discharge current, the other one by low discharge current and high discharge voltage. With the first mode high shares of moderately charged ions are extracted and also the generation of multiply-charged ions of solids via sputtering is possible. The second discharge mode shows similar results to low-power PIG ion sources.

Due to its versatility and comparatively long lifetime this ion source seems to be appropriate for many applications such as in heavy-ion accelerators, for ion implantation, and for surface investigation methods.

1 INTRODUCTION

Sources of intense beams ($\gtrsim 10^{13}$ particles/second) of multiply-charged ions are of considerable interest for applications in high-energy heavy-ion accelerators, ion implantation, and surface and solid studies with fast ions (Rutherford backscattering, channeling etc.). For a given experimental setup, use of multiply-charged ions offers convenient means for increasing the available energy range.

For generation of multiply-charged ion beams, DUOPLASMATRON ion sources [1–5] as well as PIG ion sources[6–8] have been employed. The charge state distributions (CSD) of ions extracted from plasmas of such sources can be estimated if values for the "principal" parameters of the ion source plasma, i.e., energy distribution and density of ionising electrons as well as the mean confinement time of ions are known.[9] For sufficiently long ion-source lifetimes ($\gtrsim$20h), these ion sources have to be run at limited mean discharge power ($\lesssim$ some killowatts), whereby dc operation is desirable for the majority of applications.

For dc-operated DUOPLASMATRON ion sources the available ion charge states are severely limited[2,3]; however, for pulsed operation with noble gases recently ion charge states comparable to those available from side extracted PIG sources have been obtained.[5]

For operation at discharge power below 1 kW the lifetime of DUOPLASMATRON-ion sources is conveniently high ($\gtrsim$50h).

For PIG ion sources generally greater expenditure for the source magnetic field is needed; at low discharge current urged by the need for longer source lifetime the available CSD are characterised by a steep decrease for ion intensities towards higher charge states.[7,10]

In view of the different applications mentioned above it seems desirable to use one single ion source being able to supply moderately charged ions with high intensity as well as ions not limited to low charge states.

In this paper we show that, to a certain extent, this goal can be achieved by use of the DUOPIGATRON source configuration.[11,12]

We have investigated such an ion source with regard to yields and CSD for singly- and multiply-charged ions and can state the following points:

Two different discharge modes can be run; these modes can be converted into each other by passing over a very unstable range.

In the first mode (DUOPIGATRON-I mode), low discharge voltages ($\lesssim$100 V) with discharge currents $\lesssim$ 10 A are applied; the total ion current reaches values up to 10 mA and the CSD of ions is similar to that of DUOPLASMATRON sources. In this mode also singly- and multiply-charged ions of solids can be efficiently generated via sputtering. In the second mode (DUOPIGATRON-II mode), at lower discharge currents ($\lesssim$1 A) the discharge voltage can be varied over a wide range

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(500 V ≤ U_D ≤ 2000 V) and thus the CSD characteristics of axially extracted PIG sources can be reached.

2 ION SOURCE CONSTRUCTION AND MEASUREMENTS

In the DUOPLASMATRON discharge a considerable fraction of fast primary electrons from the cathodic space impinges on the anode without making inelastic collisions in the anodic part of the discharge. The probability for inelastic collisions can be considerably enhanced by posing a reflector electrode (RE) behind the anode; thus the fast electrons after passing the anode aperture are reflected back into the discharge. This process is repeated till electrons will either diffuse out of the ionisation space or undergo an inelastic collision.

In that way, the discharge can be run stably at much lower neutral gas pressure as compared with a DUOPLASMATRON ion source. Furthermore, it has been shown[12] that the use of a RE permits much greater emission apertures and thus leads to considerable improvement of ion beam quality. However, in this so-called DUOPIGATRON discharge usually the voltage is chosen in the same range as for DUOPLASMATRON discharges, i.e., most fast electrons with energies of about 100 eV and below can cause not more than one inelastic collision.

On the contrary, in high-voltage PIG discharges ($U_D \gtrsim 500$ V) the fast electrons can each cause a series of ionising events, thus losing energy in a stepwise manner; they may either leave the plasma still with considerable energy or will be thermalised into the bulk of slow secondary electrons.

If one tries to increase the voltage of a DUOPIGATRON discharge by reducing the gas flow, beyond a certain limit usually strong oscillations appear; they are mainly caused by instabilities of the cathode fall region due to starvation effects ("hash"). However, if the dimensions of the Zwischenelectrode (ZE) channel are carefully chosen in relation to the imposed discharge currents, a considerable pressure difference between cathodic and anodic parts can exist even at low discharge currents, due to ion pumping. Thereby the pressure in the anodic space can be lowered effectively while the pressure in the cathodic space remains still high enough to permit stable operation. Thus the discharge voltage can be increased up to more than 500 V and some fast electrons with correspondingly high energy will be present.

Figure 1 shows the DUOPIGATRON discharge configuration as deduced from DUOPLASMATRON and PIG discharge geometries. In Figure 2 a drawing of the ion source for high voltage operation is given; Figure 3 depicts the course of axial magnetic flux density along the anodic discharge space. The electric circuit is shown in Figure 4.

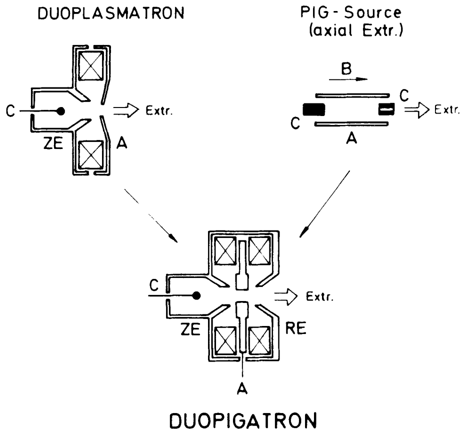

FIGURE 1 DUOPIGATRON configuration as deduced from both DUOPLASMATRON and axially extracted PIG ion source
C—cathode; A—anode; ZE—Zwischenelectrode; RE—reflector electrode.

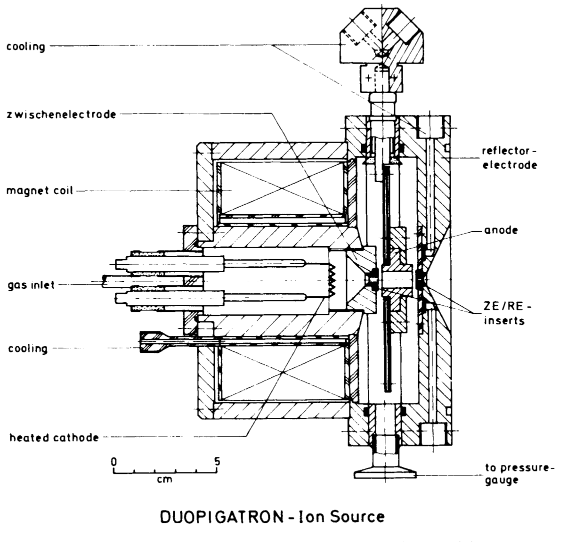

FIGURE 2 DUOPIGATRON multiply-charged ion source.

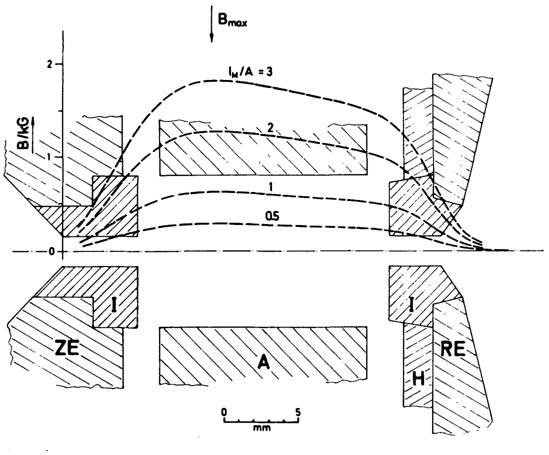

FIGURE 3 Distribution of axial magnetic flux density in the anodic discharge region.
ZE, RE, H (insert holder): magnetic material
A—Ta; I (inserts)—Ti or material to be sputtered.

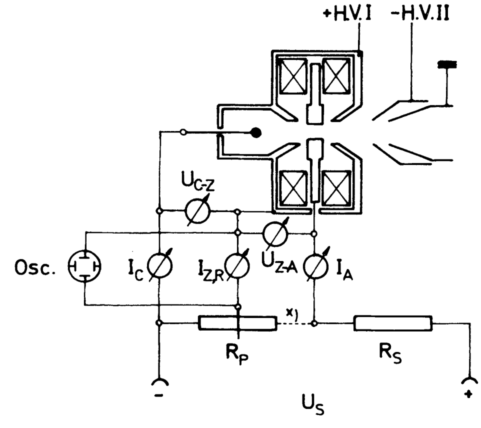

FIGURE 4 Electric circuit of DUOPIGATRON discharge. (×)—connection only for low voltage mode.

The state of stability of the discharge can be investigated by observing the current flowing commonly to ZE and RE.

The ions are extracted from the discharge plasma and accelerated to usually $30 \cdot \zeta$ keV (ζ—ion charge state) energy. The total ion beam current is measured, summing over all isotopes and charge states. Simultaneously the CSD is determined by analysing a small central beam fraction. Although this procedure might prefer higher charge states to a certain (however unknown) extent, it gives conveniently information about the dependence of CSD on the discharge parameters. For all measurements the heated cathode has been operated in such a manner that the common floating potential of ZE and RE reached the cathode potential.

3 RESULTS FOR DUOPIGATRON-I MODE

Measurements of CSD and total current of extracted ions have been made by using stabilised power supplies and imposing different magnetic field strengths; the discharge voltage has been varied at constant discharge current by adjusting the gas flow.

The first measurements were made with a source not suitable for high voltage operation.[13,14] Later, the source construction was improved for high voltage operation (cf. Figure 2); both source types yielded similar results at low discharge voltages.

The generation of multiply-charged ions is strongly influenced by stepwise ionisation processes similar to the DUOPLASMATRON discharge.[2,3,9] CSD of ions of various noble gases as well as of solids (by use of corresponding inserts in ZE and RE, cf. Figure 2) have been investigated. Typical results are shown in Tables I and II. The

TABLE I

Typical CSD measurements for noble gas ions in DUOPIGATRON-I mode;[13,14]
$U_D = 100$ V; $I_D = 5$ A; $B_{\max} = 2.1$ kG;
material of ZE and RE inserts: tungsten I_i^ζ—current of ions in charge state

	CSD $-\dfrac{I_i^\zeta/\zeta}{\sum_\zeta I_i^\zeta/\zeta}$ (‰)					Fraction of total ion current, sum of all isotopes (%)	Total ion current (mA)
ζ	1	2	3	4	5		
Ar	769	218	13.2	—	—	69	7
Kr	788	198	13.1	0.24	—	85	3.5
Xe	757	216	25.3	1.62	0.1	90	3

TABLE II

Typical CSD measurements for ions of solids in DUOPIGATRON-I mode;[13,14]
$U_D = 100$ V; $I_D = 5$ A; $B_{\max} = 2.1$ kG;
auxiliary gas: argon (?)—ion charge state obscured by auxiliary gas ions with similar e/m

	CSD (‰)					Fraction of total ion current, sum of all isotopes (%)	Total ion current (mA)
ζ	1	2	3	4	5		
C	980	20	—	—	—	1.0	5.0
Ti	886	110	3.37	0.18	—	16.3	5.5
Fe	848	149	2.49	—	—	31.0	7.0
Ni	910	90	?	—	—	29.6	3.0
Cu	941	58.4	0.6	—	—	25.8	11.0
Zr	808	173.5	17.2	1.3	?	22.4	3.0
Mo	752	211	33.3	3.61	?	21.3	9.5
W	558	342	83.5	16.9	?	30.7	7.0

most convenient results for ions of solids have been obtained by using Ar as auxiliary gas; further details of these measurements are given elsewhere.[13,14] The total ion currents depend on the plasma composition as well as the size of emission aperture; for an aperture diameter of 2 mm they typically amount to values between 2 and 10 mA.

The lower abundance of multiply-charged ions as compared with the DUOPLASMATRON discharge can be explained in the following way: In contrast to DUOPLASMATRON discharges with similar discharge parameters these discharges exhibit much more instability near and above 100 kHz. Thus the mean ion confinement time might effectively be lowered by anomalous fast diffusion; on the other hand also higher loss rates of fast electrons might affect the production of multiply-charged ions.

4 RESULTS FOR DUOPIGATRON-II MODE

Since for reasonably high ion source lifetime at high discharge voltage only low discharge currents ($\lesssim 1$ A) can be permitted, one expects then the creation of multiply-charged ions to be caused mainly by single impact ionisation processes.[9]

For these measurements an unstabilised power supply unit with high internal impedance has been used. Titanium served as insert material in the ZE and RE of the source (cf. Figure 2).

Once again the CSD and total currents of extracted ions have been measured by running the discharge at several currents and magnetic flux densities and varying the voltage via variation of neutral gas flow. The fraction of Ti ions at discharge currents below 1 A always remained below 5%.

On the contrary to the low-voltage mode, here the following points are remarkable.

The discharge was considerably more "hashy." With the same emission apertures, the total ion current was smaller by a factor of about 10. This is mainly caused by the correspondingly lowered plasma density. At discharge currents below 0.2 A and high discharge voltage (>1 kV) pure cold cathode PIG discharges could be run, while at higher discharge currents the discharge ceased when the cathode emission was shut off. Thus it is shown that at higher discharge currents the fraction of primary electrons coming from ZE and RE is of minor importance as compared with electrons delivered by the cathodic plasma. This has also been supported by analysis of the various discharge currents (cf. Figure 4).

The discharge could only be run down to a limiting magnetic flux density of about 600 G. This proves the necessity of electron oscillation in the anodic space. The CSD for multiply-charged ions was best when the discharge was least hashy.

In Table III the CSD of extracted ions of Ar, Kr and Xe are given together with corresponding discharge parameters. Further details may be found elsewhere.[15] Figure 5 shows a comparison between the measured CSD's and those estimated assuming single impact ionisation causing generation of multiply-charged ions exclusively; data have been deduced from[16] and also from,[17] although therein only electron energies at and above 2 keV have been treated. However, it is shown in[16] that the ratios of different cross sections do not vary

TABLE III

Typical CSD measurements for noble gas ions in DUOPIGATRON-II mode; material of ZE and RE inserts: titanium

CSD-$\frac{I_i^\zeta/\zeta}{\sum_\zeta I_i^\zeta/\zeta}$ (‰)						Total ion current, all isotopes			
ζ	1	2	3	4	5	(mA)	U_D/kV	I_D/A	$B_{\max}$/kG
Ar	753	223	23.3	0.86	—	0.5	1.5	0.5	1.8
Kr	800	170	26.6	3.2	—	0.25	1.0	0.5	1.25
Xe	687	237	59.2	13.0	3.3	0.15	1.2	0.4	1.8

considerably between 1 and 2 keV; thus an extrapolation of the data from[17] down to electron energies below 2 keV seems to be justified. The following facts may be deduced from Figure 5:

In the high-voltage mode some contribution of stepwise ionisation for creation of doubly-charged ions must exist as the measured CSD indicate. The abundance of higher ion charge states, however, remains more and more below the rates predicted if only single impact ionisation processes at electron energies corresponding to the applied discharge voltages are assumed.

Therefore, we conclude that the fast primary electrons entering the source plasma are lost faster the less stable is the discharge. A further discussion on the development of the energy distribution of primary electrons in PIG discharge configurations is given in.[18] The influence of fast electrons on the creation of multiply-charged ions is thus gradually reduced.

The measurements which were made over wide ranges of discharge parameters ($500 < U_D < 2000$ V; $0.1 < I_D < 1$ A; $0.5 < B_{\max} < 2$ kG) generally show the following tendencies:

With increasing discharge voltage and all other parameters held constant the CSD for multiply-charged ions improve according to the single impact ionisation cross sections till hashy conditions are set up.

With increasing magnetic flux density or discharge current and all other parameters held constant the CSD for multiply-charged ions is

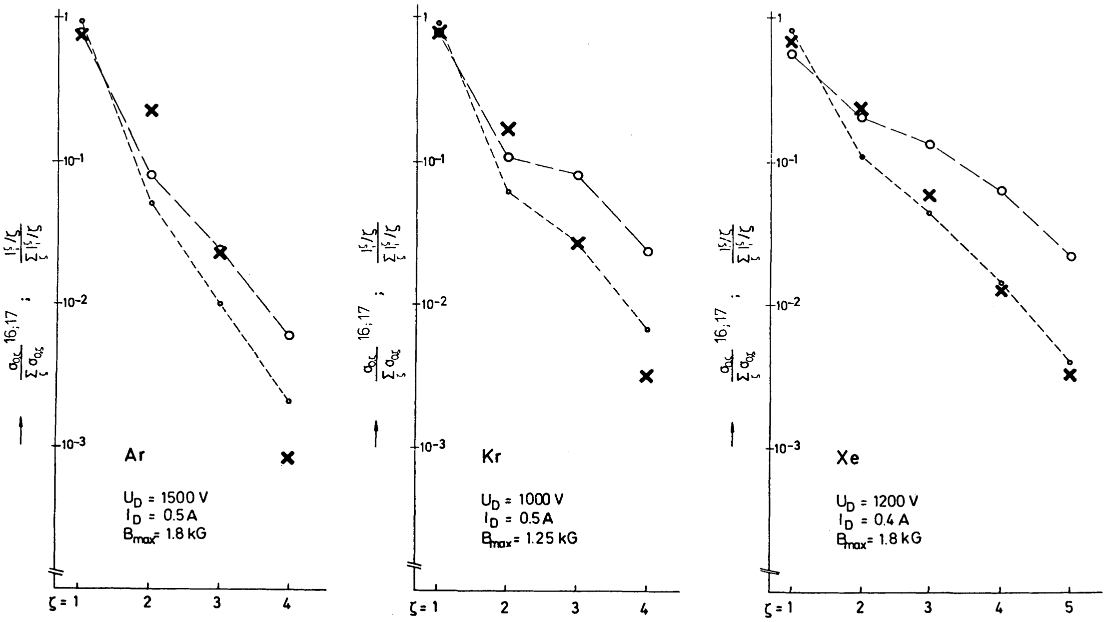

FIGURE 5 Comparison of measured CSD $[(I_i^\zeta/\zeta)/(\sum_\zeta I_i^\zeta/\zeta)]$ for different noble gases with single-step ionisation cross-section data $(\sigma_{0,\zeta}/\sum_\zeta \sigma_{0,\zeta})$ according to[16] (small circles) and extrapolated data[17] (large circles).

improved up to a point where the increasing rate of hash causes a drop of the CSD with further increase of magnetic flux density or discharge current.

5 SUMMARY

In the discharge mode with low voltage and high current strong influence of stepwise ionisation can be found. Thereby the CSD of extracted ions is comparable with those found for DUOPLASMATRON ion sources. In this discharge mode also multiply-charged ions of solids can be obtained with high efficiency.

In a second discharge mode when applying high voltage and low current the corresponding CSD of extracted ions mainly results from single step ionisation. Due to considerable discharge modulation, fast loss of primary electrons occurs causing a poorer CSD for multiply-charged ions.

This ion source in some way shows combined properties of DUOPLASMATRON and PIG ion sources; in the DUOPIGATRON-II mode its lifetime exceeds that of conventional PIG sources operated at similar discharge conditions. Because of its considerable versatility the source may be of advantage for many applications.

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