Intense ion beam generation in " RPI " and " SOWA " ion-implosion facilities

E. Skladnik-Sadowska, J. Baranowski, M. Gryzinski, J. Langner, M. Sadowski

J. Physique **43** (1982) 715-721 MAI **1982,** PAGE 715

Classification
Physics Abstracts
29.25 — 52.75

Intense ion beam generation in « RPI » and « SOWA » ion-implosion facilities

E. Składnik-Sadowska, J. Baranowski, M. Gryziński, J. Langner and M. Sadowski

Institute of Nuclear Research, Otwock-Świerk, Poland

(*Reçu le 1er juin 1981, révisé le 26 novembre, accepté le 20 janvier 1982*)

Résumé. — On présente les résultats de mesures sur les spectres de masse et d'énergie des ions produits dans les dispositifs d'implosion ionique RPI-5, RPI-15 et SOWA-150A.
On a produit des ions par décharges à basse pression entre électrodes coaxiales transparentes pour les particules. Des électrodes en forme de tiges métalliques minces ont été reliées à la batterie des condensateurs de capacité de 6,5 à 55 μF, alimentée de 30 à 35 kV. On a mesuré les spectres de masse et d'énergie des ions avec le spectromètre de Thomson. Dans les conditions gazeuses appropriées on a observé des faisceaux de deuterons d'énergie moyenne de quelques dizaines de keV, l'énergie maximale dépassant 200 keV, et l'intensité totale quelques dizaines à cent kiloampères. On a effectué aussi des études sur la direction du faisceau ionique.

Abstract. — The results of measurements of mass- and energy-spectra of ions from the RPI-5, RPI-15, and SOWA-150A ion-implosion devices, are presented. The ions were produced by low pressure discharges between coaxial transparent-for-particles electrodes consisting of thin metal rods, supplied from 6.5-55 μF condenser banks charged up to 30-35 kV. The measurements of mass- and energy-spectra of ions were performed by means of a Thomson spectrometer. Under appropriate gas conditions it was possible to observe the beams of deuterons of the average energy of several dozen keV, of the maximum energy over 200 keV, and of total intensity of several tens up to one hundred kA. Some preliminary studies on the direction of the ion beam emission were also performed.

1. **Introduction.** — The studies on the generation of convergent intense ion beams for the purposes of nuclear fusion were initiated in the early sixties [1, 2]. Recently the concepts of using high-energy ion beams for heating the pellets to fusion temperatures, as well as similar concepts based on the application of intense laser pulses or relativistic electron beams, attract great attention [3-5].

Since very intense ion pulses have been generated with various high-voltage diodes and reflex triodes [6-8], as well as large ion beams have been discovered in high-current plasma focus experiments [9-12], these developments have improved the prospects for the ion beam fusion. One of the most promising ways toward this goal seems to be the cylindrical ion implosion [13], studied extensively at the Institute of Nuclear Research in Świerk, Poland.

The concept of the application of high-current electrical discharges between cylindrical electrodes of a penetrable (multirod) structure, was in fact proposed about 15 years ago [1, 2].

The main idea of this concept was to realize a magnetic containment (insulation) of electrons within the interelectrode region by means of a magnetic field generated by currents flowing through the electrode rods, and to produce radially imploding beams of ions. A series of later studies [14-20], performed with so called RPI devices, demonstrated that under appropriate experimental conditions it is possible to concentrate ions in a small volume inside the penetrable cylindrical cathode, i.e., at the axis of symmetry of the system.

Recently measurements in the SOWA device with a cylindrical discharge of mirror symmetry have been started. Some preliminary results obtained with that device working under the RPI conditions, i.e., with electrodes supplied from one side only — at the lack of mirror symmetry, were briefly reported at the Innsbruck Conference [13]. Since the generation of ions is of primary importance for the realization of the ion beam fusion, a wide program of mass- and energy-measurements was undertaken. The first results of those are given in this paper.

2. **Experimental systems.** — Investigations of ions were performed with three experimental facilities :

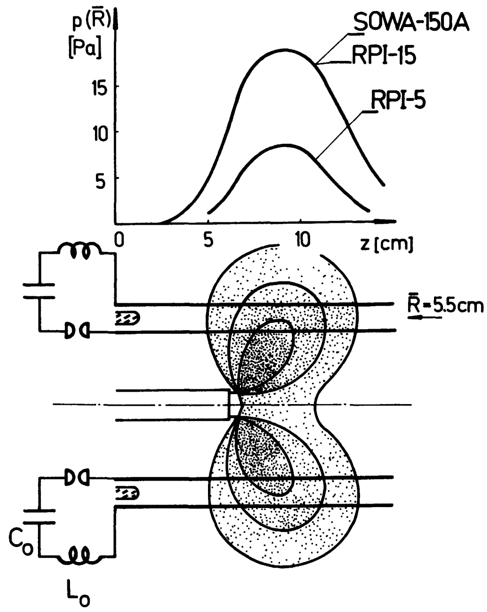

Fig. 1. — Geometry of transparent-for-particles electrodes and characteristics of gas conditions in the RPI and SOWA facilities of one-hand symmetry.

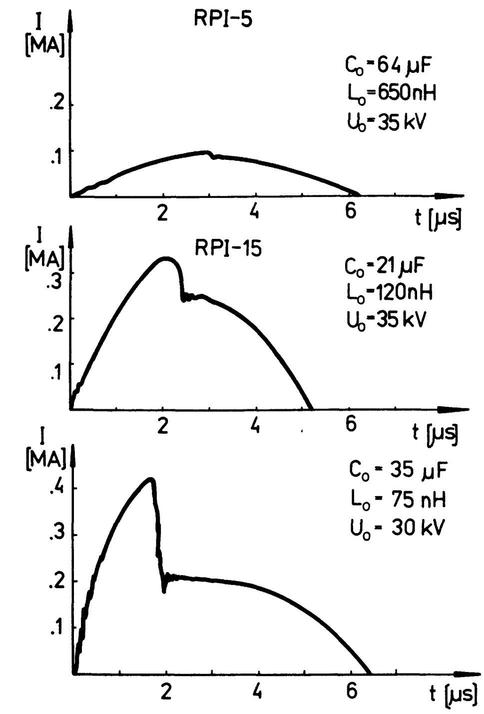

Fig. 2. — Characteristics of electrical circuits of various experimental facilities and appropriate discharge current traces.

the RPI-5, RPI-15, and SOWA-150A (operated at 20 kJ). All the devices were equipped with two coaxial cylindrical electrodes, each of them consisted of 32 molybdenum rods of 2 mm in diameter and approximately 200 mm in length. Those rods were spaced symmetrically around the electrode peripheries and directed parallel to the symmetry axis of the system. The diameter of the outer multirod electrode of each device was equal to 130 mm, and that of the inner electrode was 90 mm. The systems of the multirod electrodes were supplied nonsymmetrically (from one side only) through the sets of coaxial cables.

In order to feed working gas (deuterium) each experimental facility was equipped with an electromagnetic fast gas valve, insulated from the main discharge circuit. The valve was placed at the symmetry axis in such a way that the gas inlet was at the distance of 120 mm from the free ends of the electrodes. Some information on gas condition is given in figure 1.

Preliminary studies were performed with the RPI-5 facility supplied from a 6.4 μF condenser bank charged up to 35 kV, and with the RPI-15 device supplied by the 21 μF current pulse generator charged up to 35 kV. Some measurements were carried out with the SOWA-150A machine supplied by a part of the GI-150 generator [21] containing 55 μF capacity charged to 35 kV, but most measurements were made with $C_0 = 35$ μF and $U_0 = 30$ kV. The basic characteristics of the electrical circuits and typical current traces are presented in figure 2.

In the analysis of the voltage traces it was necessary to take into account the fact that voltages were measured at the collector plates, the inductance of which was approximately 20 nH. Considering the current traces one can estimate the value of the term $L_c\, dI/dt$ and assess the values of voltages between the electrodes. Making use of the relation $U_{el} = U_c - L_c\, dI/dt$ one obtains the voltages over 80-120 kV which can occur between the electrodes under the experimental conditions investigated.

In order to perform mass- and energy-analysis of the ions produced in the devices investigated, use was made of a Thomson parabola spectrometer similar to those described in references [22-24]. The detailed description of the construction of the spectrometer used in the experiment was given in reference [25]. The results of calibration measurements which were carried out with that spectrometer, are presented in reference [26]. A block diagram of the measuring system is given in figure 3, and a general view of the

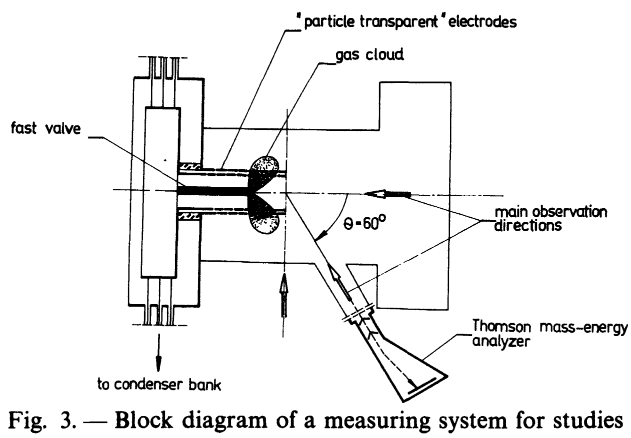

Fig. 3. — Block diagram of a measuring system for studies of ion beam generation in the SOWA-150A facility. The Thomson analyser was placed at the distance of 1.5 m from the ends of the electrodes.

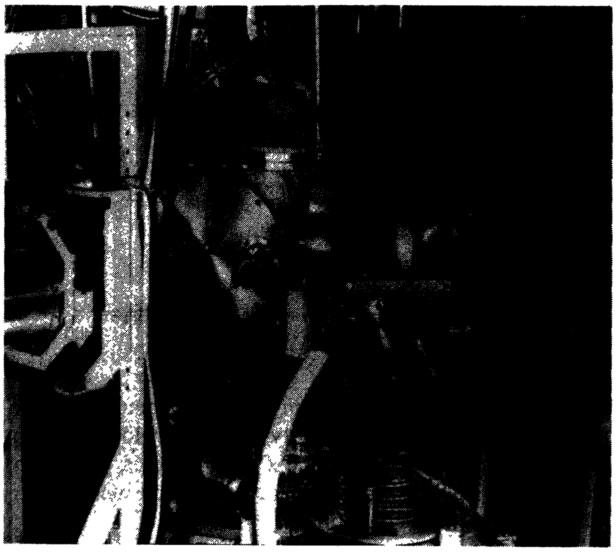

Fig. 4. — General view of the Thomson spectrometer at the SOWA-150A ion-implosion facility.

spectrometer during the measurements in the SOWA-150A device is shown in figure 4.

The studies in question were performed for different initial gas conditions by varying the time delay τ between the moment when the voltage was applied to the fast gas valve and that when the voltage was switched to the main electrodes.

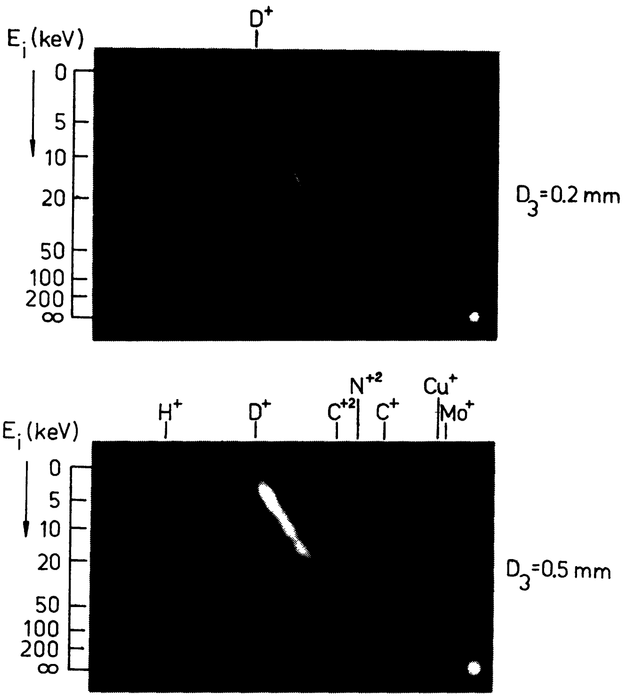

Fig. 5. — Mass-spectrograms obtained for the SOWA-150A device. The upper spectrogram was taken with $C_0 = 55\ \mu F$, $U_0 = 35$ kV, and $\tau = 350\ \mu s$, using an input diaphragm of 0.2 mm in diameter. The lower spectrogram was obtained with $C_0 = 35\ \mu F$, $U_0 = 30$ kV, and $\tau = 300\ \mu s$. To demonstrate heavy impurities, use was made of the diaphragm of 0.5 mm in diameter, and the number of discharges was increased to 10 shots.

3. **Experimental results.** — The measurements carried out with the different facilities described above were aimed to determine the basic parameters of the generated ion beams, i.e., the composition of the beams, energy spectra of ions, absolute intensities and directional properties of the ion generation under various gas conditions and for different energetics.

Some examples of mass spectrograms obtained for different experimental conditions are presented in figure 5. Other examples are given in figure 6. The spectrograms presented show that the variation in the energetics and in the operating parameters causes a remarkable change in mass- and energy-spectra of ions. If supplying energy is increased the fast regime of the operation (when the energy of the ions is comparable with the initial supplying voltage) is shifted to larger values of τ. Under appropriate experimental conditions, the energy of the deuterons exceeds the value of 200 keV. The spectrograms presented demonstrate also that the generated beams of deuterons contain relatively small amount of heavy impurities.

Energy spectra of deuterons emitted along the symmetry axis of the different devices, as determined on the basis of the whole series of measurements, are shown in figure 7. It can easily be seen that there are remarkable differences in the mean energy of ions produced by the RPI-5, RPI-15, and SOWA-150A facilities. Since the electrode configurations and gas conditions are very similar, the main difference between these devices relates to the features of the supplying systems. That induces considerable differences in the values of the discharge current, which together

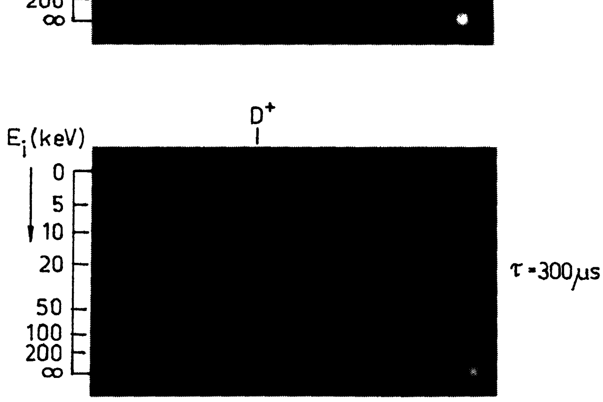

Fig. 6. — The ion mass-spectrograms corresponding to various operating conditions of the SOWA-150A ion-implosion facility, as measured along the symmetry axis of the system (at $\theta = 0°$).

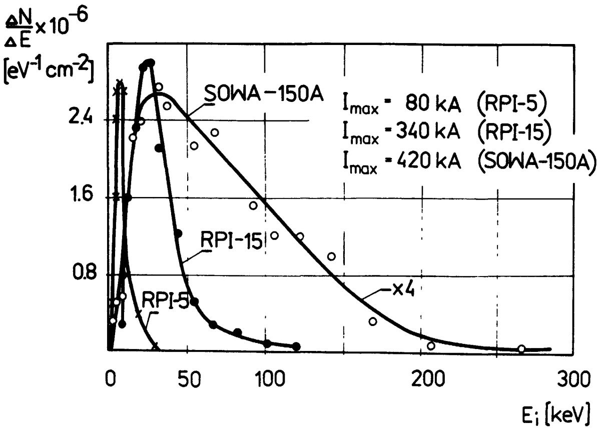

Fig. 7. — Comparison of energy spectra of deuteron beams produced by different RPI and SOWA facilities supplied from one side only. The measurements were performed at different operating pressures : for the RPI-5 device — at $\bar{p}$ = 8 Pa, for the RPI-15 device — at $\bar{p}$ = 10 Pa, and for the SOWA-150A facility — at $\bar{p}$ = 6 Pa. The diagram shows the dependence of the average ion energy on the amplitude of the discharge current ($\bar{E}_i \sim I^2_{max}$).

with the dimensions of the electrodes constitute the basic parameters describing the considered experimental systems.

The ions emitted along the symmetry axis of the device are those which come to the passive region of the electrode system, i.e., those penetrating through the cathode almost parallel to its internal surface [1, 27]. According to the considerations presented in reference [1] the energy of ions emitted in this direction can be expressed by the following formula

$$\bar{E}_i \sim I_0^2 \left(\frac{x}{d}\right)^2 \frac{Z_i}{A_i} \qquad (1)$$

where I_0 is the discharge current, d is the distance between the electrodes, and x determines the place of the ion generation in the active region, i.e., within the interelectrode gap. If the ions accelerated start from the surface of the external electrode (anode) then $x \simeq d$. If the ions are generated in a plasma within the active region then, for a rough analysis, one can assume $x \simeq d/2$. In order to assess the discharge current value that should be substituted to equation (1), one can take an average value of the current intensity during the acceleration phase.

Taking into account that the average current values in the investigated RPI-5, RPI-15, and SOWA-150A facilities were, respectively, equal to approximately 80 kA, 270 kA, and 320 kA, on the basis of equation (1) one can easily find that the mean energy of the ions emitted along the symmetry axis of the system should preserve the proportion 0.1 : 1 : 1.4. This assessment remains in a rough qualitative agreement with the results of the measurements shown in figure 7. (For the mean values of deuteron energy equal to approximately 5 keV, 40 keV, and 77 keV, respectively, the proportion in question is 0.12 : 1 : 1.9.)

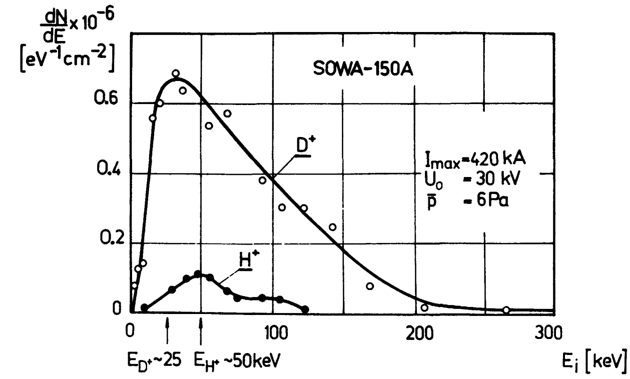

Fig. 8. — Energy spectra of protons and deuterons produced by the SOWA-150A facility at relatively low operating pressure (C_0 = 35 μF, U_0 = 30 kV, τ = 280 μs, $\bar{p}$ = 6 Pa). The diagram shows the dependence of the ion mean energy on the atomic number of ions ($\bar{E}_i \sim 1/A_i$).

The other experimental results presented in figure 8, which were obtained with the SOWA-150A device at lower gas pressure, are also in a sufficient agreement with equation (1). Absolute values of energy corresponding to the maximum of deuteron and proton spectra are almost the same as those found from equation (1) under the assumption that the ions are generated at the anode surface ($x = d$). The ratio of the deuteron and proton energy is exactly such as determined by the formula in question. Simultaneously, this is also an evidence that deuterons and protons are generated in the same places.

Energy spectra obtained at higher gas pressures, as shown in figure 9, demonstrate a small decrease in the mean energy of deuterons while the mean energy of protons remains almost the same as in the case considered above (see Fig. 8). This seems to show that the anode surface is still the origin of protons, while most of the deuterons are now generated somewhere within the interelectrode region.

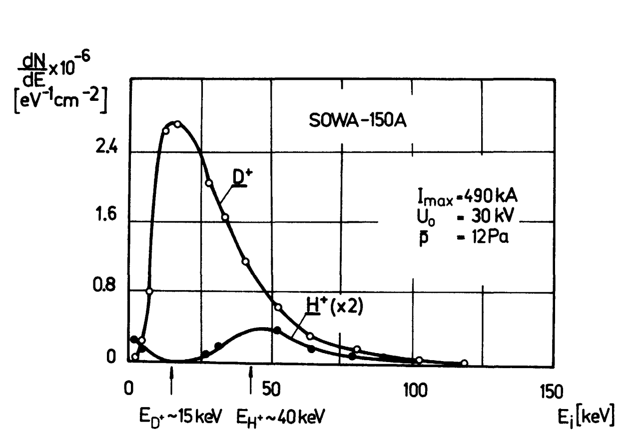

Fig. 9. — Deuteron and proton energy spectra obtained with the SOWA-150A facility at a higher operating pressure (C_0 = 35 μF, U_0 = 30 kV, τ = 300 μs, $\bar{p}$ = 12 Pa). A shift of the deuteron spectrum, as compared with that presented in figure 8, shows that the protons and deuterons are generated in different regions of the interelectrode gap.

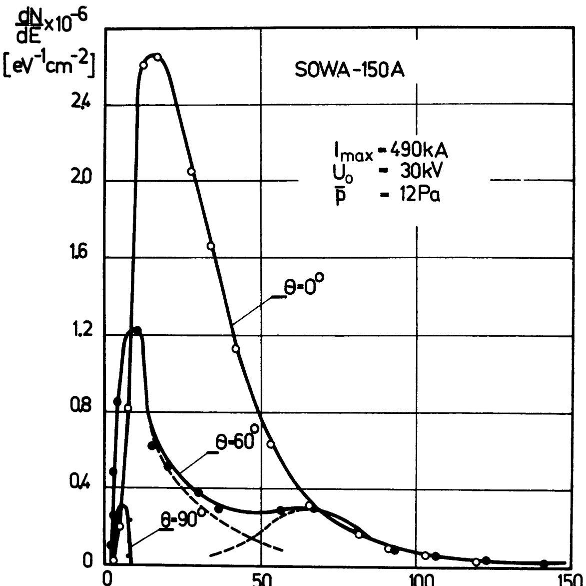

Fig. 10. — Deuteron energy spectra measured for various angles with respect to the symmetry axis of the SOWA-150A ion-implosion machine at the higher operating pressure ($\bar{p}$ = 12 Pa).

The results of angular measurements are presented in figure 10. In the energy spectrum of deuterons emitted at the angle $\theta = 60°$ two marked maxima can be distinguished. This fact can be explained in the following way. The first (low energy) maximum is probably related with the ions produced in the region between the electrodes, and the second (high energy) maximum originates from the ions generated in the close proximity of the anode surface. A direct support for this hypothesis can be found in a theoretical consideration that takes into account the angle at which the ions accelerated come to the passive region of the device. According to the formula derived in reference [1], the mean energy of ions depends on the emission angle θ in the following way :

$$E(\theta) \simeq E(0)/\cos^2 \theta \,. \tag{2}$$

The mean energy value, as computed on the basis of the relation given above, is in a satisfactory agreement with the energy corresponding to the second maximum in figure 10.

The measurements performed perpendicular to the symmetry axis of the system (see also Fig. 10), show a complete lack of high energy ions, what can be interpreted as follows. The ion implosion device, in which high axial currents flow in the rod electrodes, forms an open magnetic trap that makes it difficult for the charged particles to escape in the perpendicular direction. A small amount of low-energy ions observed experimentally is probably descended from the ions leaving the passive region of the system at zero discharge current or from those generated during later

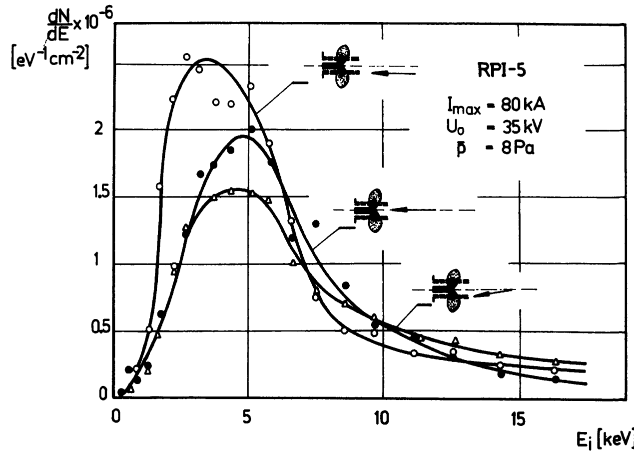

Fig. 11. — Ion flux intensity *versus* the ion energy for different angles of observation. The diagram shows some results of measurements performed with the RPI-5 device under normal operating conditions (C_0 = 6.4 μF, U_0 = 35 kV, τ = 315 μs, $\bar{p}$ = 8 Pa).

phases of the discharge, when the electrode polarization is opposite to that during the first phase.

The system of the multirod electrodes, under the experimental conditions investigated, did not constitute a point source of ions. Therefore, in order to determine the total flux of ions generated by the devices considered, it was necessary to scan over the whole surface of the injector (in practice, it has been done by performing the measurements at small angles with respect to the symmetry axis of the system). Such measurements have been performed within the scope of the studies realized with the RPI-5 facility [28]. The results of the measurements, which are presented in figure 11, demonstrate that the total ion beam intensity in the given direction can approximately be expressed by the formula

$$I = \frac{S_{RPI}}{S} I_{meas} \tag{3}$$

where S_{RPI} is the cross-section of the electrode system, taken perpendicular to the direction considered, S is the surface seen by the mass-analyser in the plane of the free ends of the electrodes, and I_{meas} is the ion-beam intensity estimated on the basis of appropriate calibration tests of the photographic plates used for the ion detection.

Estimates performed so far show that the total energy carried by high-energy ions ranges from two hundred joules (in the case of the RPI-5 device) up to one kilojoule (in the case of the RPI-15 and SOWA-150A facilities).

Taking into account the fact that the high-energy ions are produced during a short pulse of the order of 200 ns, which corresponds to the high-voltage peak, one can conclude that a considerable fraction (approximately 50 %) of the discharge current flowing between the electrodes (during the time interval considered) constitutes the ion current.

Finally, it should be noted that a remarkable number of ions possessing energies much higher than those corresponding to the initial charging voltage of the supplying system, has been observed and even the ions of energy above 200 keV have been detected.

It should also be noted that the amount of impurity ions, observed in the experiments described, was negligibly small and, under appropriate experimental conditions, it can be lower than 1 %.

The main experimental data for deuteron beams, as obtained with the different devices investigated, can be gathered in the following table :

	$\bar{p}$ (Pa)	$\bar{E}_i$ (keV)	$E_{i\,max}$ (keV)	E_{tot} (J)	I_i^{est} (kA)
RPI-5 (80 kA)	8	5	30	200	30
RPI-15 (340 kA)	10	40	200	1 000	100
SOWA-150 A (420 kA) (operated at 20 kJ)	6	77	250	1 000	150

It should be noted that the operating pressures of the investigated facilities, which characterize the devices from the point of view of the ion-beam generation, were different. Generally, for a given facility, the value of the optimal pressure can be found empirically (see for instance Figs. 8 and 9). Studies on the influence of gas conditions on ion emission characteristics are being continued.

4. **Conclusions.** — The main results of the studies described in this paper can be summarized as follows.

The ion measurements performed so far demonstrate that the effective generation of high-energy ions takes place in the high current, low-pressure discharges, realized between the transparent-for-particle (multirod) electrodes of the RPI and SOWA devices.

The analysis of the experimental results presented

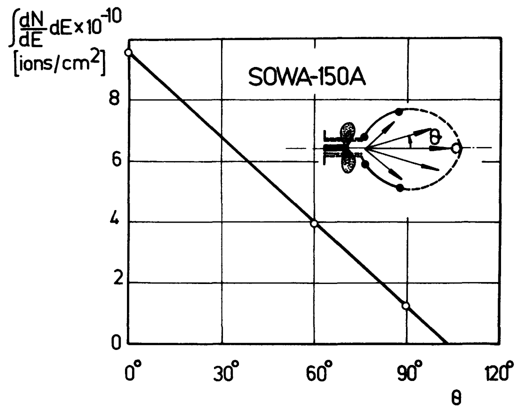

Fig. 12. — Ion flux density $n(\theta)$ at the input diaphragme of the mass-spectrometer, given as a function of the observation angle θ.

in the paper shows that they are in a good agreement with the theoretical predictions.

The main parameters of the ion beams produced by the systems considered, i.e., ion energies and ion beam intensity can be sufficiently high for performing the ion-implosion breakeven experiments, provided that the spatial- and time-focussing of the beams will also be realized successfully.

At the moment, the optimization of the ion-implosion facilities requires further detailed studies, and in particular time-resolved analysis and more precise spatial-measurements are necessary.

Acknowledgments. — The authors of this paper would like to thank their colleagues of the High-Temperature Plasma Physics Department at Świerk, who were helpful in the course of the studies described, and in particular Mr. K. Zdanowski — for his valuable help during some experimental tests with the RPI-5 machine. The authors wish also to thank Dr. A. Jerzykiewicz and his group — for continuous support in the exploitation of the experimental facilities.

References

[1] Gryziński, M., IBJ Report INR No. 711/XVIII/PP, Warsaw (1966); *Nukleonika* **14** (1969) 679.

[2] Gryziński, M., Nowikowski, J., Sadowski, M., Składnik-Sadowska, E., Suckewer, S., in *Controlled Fusion and Plasma Physics* (Proc. 2nd Europ. Conf. Stockholm) 1967; *Plasma Phys.* **10** (1968) 450.

[3] Winterberg, F., *Nature* **251** (1974) 44.

[4] Shearer, J. W., *Nucl. Fusion* **15** (1975) 952.

[5] Clauser, M. J., *Phys. Rev. Lett.* **35** (1975) 848.

[6] Humphries, S., Jr., Sudan, R. N., Wiley, L., *Appl. Phys.* **47** (1976) 2382.

[7] Olson, K. L., *Plasma Phys.* **3** (1977) 465.

[8] Yonas, G. and Sandia Lab. Particle Beam Fusion Group, in *Plasma Physics and Controlled Nuclear Fusion Research* (Proc. 7th Int. Conf. Innsbruck) 1978; Vol. III, IAEA, Vienna (1979) 125.

[9] Gullickson, R. L., Sahlin, H. L., *J. Appl. Phys.* **49** (1978) 1099.

[10] Bernard, A., Garçonnet, J. P., Jolas, A., Le Breton, J. P., De Mascureau, J., in *Plasma Physics and Controlled Nuclear Fusion Research* (Proc. 7th Int. Conf. Innsbruck) 1978; Vol. II, IAEA, Vienna (1979) 159.

[11] Nardi, V., Bostick, W. H., Feuqeas, J., Prior, W., Cortese, C., in *Plasma Physics and Controlled Nuclear Fusion Research* (Proc. 7th Int. Conf. Innsbruck) 1978; Vol. II, IAEA, Vienna (1979) 143.

[12] Maisonnier, Ch., Rager, J. P., in *High Power Electron and Ion Beam Research and Technology* (Proc. 3rd Int. Topical Conf. Novosibirsk) 1979; Invited Paper, C.N.E.N.-Ed. Sci., Rome (1979).

[13] GRYZIŃSKI, M., APPELT, J., BARANOWSKI, J., BIELIK, M., GÓRSKI, E., HORODEŃSKI, A., JAKUBOWSKI, L., JERZYKIEWICZ, K., KURZYNA, J., LANGNER, J., LIPIŃSKI, B., MELZACKI, K., NAWROCKI, Z., NOWIKOWSKI, J., SADOWSKI, M., SKŁADNIK-SADOWSKA, E., STANISŁAWSKI, J., SUDLITZ, K., in *Plasma Physics and Controlled Nuclear Fusion Research* (Proc. 7th Int. Conf. Innsbruck) 1978; Vol. III, IAEA, Vienna (1979) 225.

[14] SADOWSKI, M., SKŁADNIK-SADOWSKA, E., in *Controlled Fusion and Plasma Physics* (Proc. 2nd Europ. Conf. Stockholm) 1967; *Plasma Phys.* **10** (1968) 470.

[15] GRYZIŃSKI, M., NOWIKOWSKI, J., SUCKEWER, S., in *Plasma Physics and Controlled Nuclear Fusion Research* (Proc. 3rd Int. Conf. Novosibirsk) 1968; Vol. II, IAEA, Vienna (1969) 87.

[16] GRYZIŃSKI, M., NOWIKOWSKI, J., SADOWSKI, M., SKŁADNIK-SADOWSKA, E., *Nukleonika* **14** (1969) 885.

[17] SADOWSKI, M., SKŁADNIK-SADOWSKA, E., *Nukleonika* **15** (1970) 145.

[18] GRYZIŃSKI, M., NOWIKOWSKI, J., JAKUBOWSKI, L., *Nukleonika* **21** (1976) 1225.

[19] SKŁADNIK-SADOWSKA, E., Directional properties of plasma produced by a multirod injector, Ph. D. Thesis, IBJ Świerk (1975).

[20] SKŁADNIK-SADOWSKA, E., GRYZIŃSKI, M., KURZYNA, J., SADOWSKI, M., in *Plasma Accelerators* (Proc. 3rd All-Union Conf. Minsk) 1976; AN USSR, Minsk (1976) 299.

[21] GRYZIŃSKI, M., JERZYKIEWICZ, A., NOWIKOWSKI, J., *Bull. Acad. Polon. Sci., Ser. Sci. Techn.* **20** (1974) 135.

[22] KRUPNIK, L. I., DEMCHENKO, P. A., SCHULIKA, N. G., in *Diagnostika Plazmy* Vol. 3, Atomozdat, Moskva (1973) 240.

[23] OLSEN, J. N., KUSWA, G. W., JONES, E. D., *J. Appl. Phys.* **44** (1973) 2275.

[24] ZOLOTOTRUBOV, L. M., NOVIKOV, JU. M., SKOBLIK, I. P., SKOBLIK, M. N., TOLSTOLUTSKIJ, A. G., Preprint Kh. Ph. T. I. Acad. Sci. Ukr. SSR No. 77-1, Kharkov (1977).

[25] BARANOWSKI, J., SKŁADNIK-SADOWSKA, E., IBJ Report INR No. 1683/XXIV/PP/B, Warsaw (1977).

[26] ZDANOWSKI, K., *J. Techn. Phys.* **21** (1980) 135.

[27] BELIKOV, A. G., GONCHARENKO, V. P., *Zh. Techn. Fiz.* **40** (1970) 764.

[28] SADOWSKI, M., SKŁADNIK-SADOWSKA, E., ZDANOWSKI, K., to be published.