DEVELOPMENT OF HIGH-CURRENT RF-PLASMA SOURCES FOR NEUTRAL PARTICLE INJECTORS

J. Freisinger, H. Hellmann, M. Kaufmann, H.W. Loeb, and A. Scharmann
1st Institute of Physics
Giessen University
Heinrich-Buff-Ring 16, D-6300 Giessen, FRG

and

W. Kraus
Max-Planck-Institute of Plasma Physics
Boltzmannstrasse 2, D-8046 Garching, FRG

ABSTRACT

One important spin-off of the rf-electric propulsion systems is the neutral particle injector for heating fusion plasmas to the temperature of thermonuclear burn.
For the neutral beam injection heating system of the ASDEX Upgrade Tokamak (AUG) at Garchng/Munich, the use of an rf-plasma source is envisaged. As part of a development programme

- o a circular rf-plasma source RIG 20 had been put onto a standard ASDEX extraction system and operated
- o a prototype of a PINI-compatible rf-source RIG-HEX had been designed, built, and tested.

The rf-discharge power of RIG 20 is 20 kW. For 8 sec up to 18 A hydrogen ions had been extracted at 40 kV. The beam quality is similar to the standard one, when a periplasmatron or Kaufman-type ion source is used. The atomic species fraction is much higher (80%).

For the actual injection heating of AUG, which is presently under construction, a neutral power of 6 MW (H^0) is needed. This power will be delivered by one injector box, equipped with four ion sources; each of them has to produce 85 A at 55 kV. The design of these rf-plasma sources, called RIG-HEX, is based on the JET PINI-structure. RIG-HEX had been operated up to a maximum rf-discharge power of 140 kW at 1 MHz. The duty cycle is 10 sec pulse/5 min pause. Inside the discharge volume the local distribution of the plasma current density had been measured. Compared to dc-ion sources, twice as high ion beam densities (800 mA/cm^2) had been observed.
The research and development work on RIG-HEX has been terminated at Giessen. In September 1988 the complete unit (rf-plasma source and 140 kW rf-generator) was transferred to Garching to test RIG-HEX with a full size PINI grid system.

1. INTRODUCTION

It is well known that fusion reactors, now under development, could solve the energy problem of the future. Remarkable progress has been made, especially in magnetic confinement machines.

One of the major problems in Tokamaks and Stellerators is the heating of the fusion plasma to the temperature of thermonuclear burn (10^8 K).

The injection of intense high-energy neutral hydrogen beams into the torus of a fusion reactor (neutral injection) seems to be an effective method of additional plasma heating (1) (2) (3).

Compared to dc-injector sources (periplasmatron, magnetic multipole source, JET-PINI-source, etc.), the inductive rf-plasma source shows several advantages (2):

- simplicity of the mechanical construction and of the power supply
- by omitting discharge electrodes, filaments, etc. a high reliability and lifetime is achieved
- higher atomic species fraction (4) (5)
- low impurity fraction (4) (6)

These were the reasons for initiating a national research programme in 1977.

2. PRINCIPLE OF THE NEUTRAL INJECTION LINE

The scheme of a neutral injection line is shown in Fig. 1. The main components are:

- hydrogen ion source
- ion beam accelerator
- neutralizing gas cell
- bending magnet and ion dump
- high speed pumping regions
- duct and port to the fusion torus

From Fig. 1 the operation of the neutral injector beam line is evident. The ion source produces an intense hydrogen ion beam which is accelerated in the direction to the torus entrance port.

As charged particles are not able to penetrate the magnetic confinement field of the torus, the ion beam must be neutralized by charge exchange in the gas cell. The neutralization efficiency drops rapidly with increasing ion energy (7). That implies high currents at relative low voltages.

The unneutralized ionic component is removed from the beam by a bending magnet. When the fast neutrals enter the torus plasma, they transfer their energy by Coulomb-collision to the torus plasma.

3. REQUIREMENTS TO THE INJECTOR ION SOURCE

To meet the requirements of an injection system, the following conditions must be fulfilled by the ion source (2) (16):

- o High ion beam density ($\geq$ 200 mA/cm^2) in order to reach high beam power at modest beam voltages.
- o Ion optics and collimation of the neutral beam demand a high uniformity of the ion current density over the extraction area (maximum deviation from the mean value $\leq$ 8%).
- o Beam divergence must be small ($\leq$ 1 deg), as the particle cannot be focussed after neutralization.
- o The fraction of atomic hydrogen ions (H^+ or D^+) in the beam should be in the order of 80%. The molecule ions H_2^+ and H_3^+ must be kept within 20%, because they dissociate during the charge exchange process in the gas cell mostly into H^0, carrying one half or one third of the initial energy.

- The impurities, transported by the beam into the fusion plasma, should be less than 3%, because they cool the plasma by radiation and diffusion (7).
- Pulsed operation of the source is necessary (pulse duration: some seconds; repetition rate: some minutes).

Beside these demands the simplicity and the relability of the ion source is also of essential interest.

4. RESEARCH PROGRAMME

From 1977 till 1986, 5 different-sized radio frequency ion generators RIG for fusion-plasma heating have been developed, optimized and,tested at Giessen University (2) (3) (6). Under sponsorship of the German Research Society DFG (by total funds of about 1.7 Mio DM), cylindrical engines with 10 cm, 15 cm and 20 cm ionizer diameters as well as 10 cm x 20 cm and 10 cm x 30 cm rectangular sources (8) were investigated, both experimentally and theoretically. Based on the excellent performance data of these RIG plasma sources, the Max-Planck-Institute IPP at Garching/Munich financed (0.7 Mio DM) the 1st Institute of Physics, and from 1986 till August 1988, a 25 cm x 50 cm hexagonal rf-plasma source RIG-HEX has been developed successfully (9). This injector source is now in a Garching test-bed for full-beam investigation. The future application on the large Tokamak-machine ASDEX-UPGRADE is envisaged.

5. THE RF PLASMA SOURCE RIG 10

The rf plasma sources RIG 10 and RIG 20 are described in detail in (2), demonstrating their potentiality by showing that the injector requirements (see chapter 3) could be satisfied. To bring the information up to date we have to add some recent findings on beam impurities and beam divergence.

5.1. Impurities

Under optimum operational conditions the beam of RIM 10 carries the principal components H^+, H_2^+, H_3^+ (Fig. 2; typical values 85:9:5) and about 1% impurities.

Besides the principal constituents more than 40 masses and about 60 different ion species have been identified by mass-spectroscopic means (Table 1) (10). After the baking phase of the discharge chamber many initially observed species have vanished (in Table 1 marked by "X" in the second column).

There are four groups of impurities:

- Mass number 12 to 23: hydrocarbons C^+ to CH_3^+, nitrogen and its compounds N^+ to NH_3^+, oxygen and its compounds O^+ to OH_3^+.
- Mass number 24 to 35: mainly hydrocarbons containing two C-atoms C_2^+ to $C_2H_6^+$, carbon monoxide CO^+, oxygen and nitrogen molecules O_2^+ and N_2^+, as well as silicon and silane ions Si^+ to SiH_4^+ originating from the quartz walls of the discharge chamber.
- Mass number 36 to 45: mainly C_3-compounds and CO_2^+.
- Mass number 46 to 68: metal ions which are in total less than 10^{-3}%.
- Mass numbers greater than 68: not observed in the beam.

The total amount of impurities in Table 1 is 1.5% by a factor of two better han demanded (chapter 3).

5.2. Beam Divergence

To determine the minimum beam divergence, beam profiles (Fig. 3) at different operation conditions had been measured 70 cm downstream of RIG 10 (11). From these beam profiles the divergence angle of Fig. 4 is computed. The minimum divergence angle amounts to 1.1 deg.

6. THE RF-PLASMA SOURCE RIM 20

As a part of the development programme the prototype of RIG 20 (Fig. 5) (2) had been redesigned (Fig. 6) and tested at the IPP Garching/Munich (Fig. 7) (12) using the full scale standard ASDEX extraction system (14).

The beam quality was similar to standard, e.g. when a periplasmatron is used. The atomic species fraction was much higher. Problems occured with the optimization of the rf-coil geometry and with the power in the backstreaming electrons which led to a partial melting of the alumina coating of the backplate.

6.1. Experimental Arrangement

As mentioned the tests of RIG 20 have been carried out on the test stand at the IPP in Garching (12). This test stand is a full size beam line, as it will be used on the ASDEX/Wendelstein VII-AS experiments, but equipped with one ion source only. The beam line is connected to a target tank with a beam and a magnetic species analyzer. The beam profile can be measured with thermocouples on a calorimeter. With water flow calorimetry it is possible to determine the total amount of power to the calorimeter and the beam stop.

The technical drawing of the modified RIG 20 with its electrical elements is shown in Fig. 6:

The quartz discharge vessel of 20 cm in diameter is surrounded by the induction coil of the rf-generator which couples the rf-power up to 20 kW to the discharge plasma. The backplate is now made of copper and coated with a layer of Al_2O_3 (alumina). Integrated into the backplate is the cooling loop (H_2O) and the gas feeding (H_2).

The rf-power supply is connected to the secondary of an 80 kV isolation transformer which normally is used for the supply of the filaments of the periplasmatron plasma generator. The power cable runs through an air coil snubber to reduce the electrical noise problems during HV-breakdowns.

Fig. 7 is a photo of the beam line. RIG 20 can be seen in the middle.

6.2. Aims of the Experiments

The objective of these exeriments was to get answers to four problem areas:

- Operation of the ion source in the presence of many extraction holes (transparency of the extraction system $\tilde{=}$ 38%) which may influence the distribution and the containment time of the neutral gas in the source.
- Influence of the metallic plasma grid surface on the species fraction.
- Relation between the rf-power, the current density of the extracted beam, and beam quality.
- Thermal behaviour of the source; especially of the coating of the backplate.

6.3. Results

6.3.1. Starting of the Discharge

Starting of the discharge turned out to be very easy. A 200 msec long pressure pulse with a gas flow of approximately 3 times the standard flow rate together with the rf-power on was used to initiate the discharge. After approximately 500 msec the discharge

parameters had obtained stable values. Normally extraction started after this phase. - Restarting of the discharge or arc notching has not been tried.

6.3.2. Beam Current
The beam current depends almost linearly on the rf-power (Fig. 8). For a rf-power input of 20 kW the beam current amounts to 15 A.

Above a gas flow limit of about 4 Torr·ℓ/sec (315 sccm), no significant dependence on the extraction current was observed (Fig. 9).

6.3.3. Induction Coil
The coil geometry turned out to be an imporant parameter. In the frequency range of 4 ÷ 4.5 MHz and with a coil of 7 windings (Fig. 10), the highest currents and simultaneously the best matching were reached with small coil diameters (the coil diameter of 222 mm corresponds to an interspace of 11 mm between the coil and the rf-plasma).

6.3.4. Perveance, Beam Divergence
A comparison of the beam divergence as a funciton of perveance with the rf-source RIG 20 and a standard periplasmatron source is shown in Fig. 11. For both sources, the optimum beam divergence is similar, whereas for the rf-source the optimum is at a much higher perveance value. This can partially be explained by the higher atomic species fraction in the beam (H^+:H_2^+:H_3^+ equal to 0.7:0.15:0.15 or 0.4:0.4:0.2, respectively) which would account for a 20% higher perveance optimum. The total amount of power (carried by ions and neutrons) to the beam stop is also comparable to the standard source.

6.3.5. Hydrogen Ion Species
In these tests proton fractions of about 70% (nearly of factor of 2 better than with the standard periplasmatron) were reached. In former experiments, which were carried out with RIG 10 at an open area of 1 cm^2 in a plasma grid (completely alumina covered), we had found proton fractions of 85 ÷ 95% in the beam (see Fig. 2 and (13)).

The difference can be explained by the high recombination for atomic hydrogen on the now used metallic plasma grid. The ratios of the hydrogen species as a function of the extraction current or of the gas flow showed the expected behaviour (Figs. 12 and 13).

6.3.6. Pulsed Operation
A significant change of the species ratio was observed with increasing pulse length (Fig. 14). The proton fraction is for a 1 sec-pulse 65%; it increases to 80% for a 8 sec-pulse.

6.3.7. Damage by Backstreaming Electrons
A series of pulses at 40 kV and 15 A with a pulse length of 8 sec was performed near the end of the test period. During this series of pulses, no problems occured concerning the operation of RIG 20. However, after opening and inspecting the source, severe melting of the alumina coating of the backplate, exactly opposite to the individual extraction holes, could be seen. The backstreaming electrons are following apparently straight trajectories which concentrate the power to areas with the size of an extraction hole, each. This may have led in this special case to the deposition of power densities up to 4 MW/cm^2 at the backplate.

6.3.8. Recapitulation of the RIG 20 Full Power Experiments
The circular rf source RIG 20 had been tested on a large scale extraction system. Up to 18 A at 40 kV had been extracted for 8 sec. Perveance and atomic species fraction are higher than those of a periplasmatron source. Coil geometry and coupling of the rf-generator to the plasma source are very important for good efficiency. Better methods for coating the backplate and the plasma grid and the problem of a proper starting of the discharge will be investigated.

7. THE RF-PLASMA SOURCE RIG-HEX

For the neutral beam injection of the ASDEX-Upgrade (AUG) Tokamak, a neutral power of 6 MW (H^0) is needed, which will be delivered by one injector box equipped with four ion sources operating simultaneously. Each of these has to produce a beam of 85 A at 55 kV (beam power 4.7 MW).

7.1. Specification

Considering the excellent performance data of RIG 20, it was decided to develop, as a last step in this research programme, an rf-plasma source, which will meet the requirements of an AUG-injector:

- o Compatibility with the AUG extraction system basing on the JET-PINI structure
- o Beam current density of 230 mA/cm^2
- o Uniformity of 8% over the whole extraction area of 850 cm^2
- o Pulsed operation

The compatibility with PINI (15) implies the hexagonal shape of the rf-source. Therefore, we called the prototype of the rf-plasma sources RIG-HEX.

7.2. Experimental Arrangement

Fig. 15 gives an impression of the computerized test facility. Fig. 16 shows the RIG-HEX plasma source. Fig. 17 is a drawing of the base-plate.

The side-walls of the hexagonal discharge chamber are made of quartz. It has a maximum length of 60 cm, a width of 30 cm, and an optimized height of 18 cm. As the side-walls would not stand atmospheric pressure, the source is mounted in a vacuum chamber. Base- and back-plate are water-cooled and covered with a layer of alumina to get a low recombination coefficient for the recombination of atomic to molecular hydrogen, which is a necessary condition for a high proton fraction in the plasma. In the final experiments Co-Sm-magnets were mounted at the back-plate in a line cusped arrangement.

The discharge vessel is surrounded by a water-cooled coil of 8 windings. The rf generator has a maximal power of 140 kW at the working frequency of 1 MHz.

In one quadrant of the base-plate 61 probes are arranged in three rows (Fig. 17), which are switched as double probes and enable the measurement of current density profiles in three directions (vertical, horizontal, and diagonal) within 1.2 seconds.

The JET-PINI-extraction area is indicated in Fig. 17 by the broken lines.

7.3. Results (9)

7.3.1. Starting of the Discharge
In the pressure range of more than 1 Pa switching on only of the rf generator was sufficient to initiate the discharge. At lower discharge pressures a pressure pulse or a heated electrons-emitting filament in the back-plate was used for starting.

In the center of the base area stable values of the current densities were reached after approximately 130 ms at 0.75 Pa. With increasing pressure this time extended to 200 ms at 1.25 Pa (Fig. 18).

The measurements near the coil showed shorter rais-

ing times of about 20 msec and 100 ms, respectively (Fig. 18). There the induced rf-field is more intense (17).

7.3.2. Restart Capability of the Discharge

After interruptions of 1 ms up to 100 ms (arc notching) the discharge started immediately. Typical oscillations over 20 ms are observed. Fig. 19 shows examples for notching times of 15 ms and 40 ms. In the case of application in neutral injectors arc notching is used during operation, which may distinguish flash-overs, which may cause breakdowns.

7.3.3. Thermal Behaviour

Although the discharge vessel is only cooled by radiation, it was possible to work at discharge powers up to 100 kW in a duty cycle of 10 sec pulse/5 min repetition rate. The limiting factor has been the temperature of the organic sealings of the discharge vessel, which should not surpass 200°C.

7.3.4. Current Density

The current density depends, like in the case of RIG 20, almost linearly on the rf power (Fig. 20). At the maximum power of 140 kW more than 770 mA/cm^2 were observed.

Considering that a fraction of about 80% of the probe current density can be extracted, the required (specified) beam current density of 230 mA/cm^2 will be achieved at a discharge power of approximately 70 kW.

In the pressure range from 0.3 Pa to 1 Pa the source is working with the highest efficiency (Fig. 21). Variations of the working frequency to 0.5 MHz and to 2 MHz did not improve the quality of the source.

7.3.5. Current Density Profiles

Plasma current density profiles had been measured by double probes (see also chapter 7.2.). Without magnets at the back-plate of RIG-HEX the plasma current density shows a falling-off near the center of the discharge (Fig. 22, right). The profiles are not very uniform. We find two usable areas of extraction (Fig. 22, left). But his configuration leads to no practical application.

By mounting Co-Sm-magnets in a line-cusp arrangement at the back-plate, the efficiency of the rf-plasma source and the uniformity of the density profiles (Fig. 23, right) could be improved significantly. With regard to the 8% uniformity criterion (chapter 7.1.) an extraction area of about 850 cm^2 is usable. The usable extraction area harmonizes very well with the PINI grid system.

7.3.6. Recapitulation of the RIG-HEX Experimental Results

As a final step of a ten years research program the hexagonal rf plasma source RIG-HEX has been developed and tested. It is scheduled for the application in the neutral beam injection system of the ASDEX Upgrade Tokamak. This 1 MHz source works in a duty cycle of 10 s pulse/5 min interruption without thermal problems up to an rf power of 100 kW. Double probe measurements have shown a linear dependance of the ion current density on the rf power. Current densities of more than 770 mA/cm^2 have been reached at an rf-discharge power of 140 kW. The uniformity of the density profiles was improved by Co-Sm-magnets on the back-plate. Considering the 8% uniformity criterion an extraction area is usable, which is compatible with the JET-PINI extraction system.

8. CONCLUSION

In September 1988 the prototype of the rf-plasma source RIG-HEX and the 140 kW rf-generator had been transported to Garching/Munich. Beam extraction with a full size PINI grid system will be started at IPP within the next months.

9. ACKNOWLEDGEMENTS

The authors thank J.H. Feist and E. Speth of the IPP/Garching for long and inspiring discussions.

The authors acknowledge the financal supports by DFG (Deutsche Forschungsgemeinschaft) and by the Max-Planck-Institut für Plasmaphysik IPP/Garching.

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Table 1: Distribution list of the impurities in the hydrogen rf-discharge of RIG 10 (X: observed only during the baking phase).

MASS No.	INTENSITY, %	IDENTIFIED ION MASSES (singly charged)				GROUP
12	0.027			C		
13	0.004			CH		
14	0.048		N	CH_2		
15	0.037		NH	CH_3		
16	0.268	O	NH_2	CH_4		I
17	0.364	OH	NH_3	CH_5		
18	0.552	OH_2				
19	0.086	OH_3				
20	0.001				Ne	
21	X					
23	0.0016				Na	
24	X			C_2		
25	X			C_2H		
26	0.0005			C_2H_2		
27	0.0016			C_2H_3	Al	
28	0.07	CO	N_2	C_2H_4	Si	
29	0.022	COH	N_2H	C_2H_5	SiH	
30	0.011	COH_2, NO		C_2H_6	SiH_2	II
31	0.002				SiH_3	
32	0.002	O_2			SiH_4	
33	X					
34	X					
35	X					
36	X			C_3H		
37	X			C_3H_2		
38	X			C_3H_3		
39	X			C_3H_4	SiC, K	
40	0.002			C_3H_5	Ca, Ar	III
41	0.001			C_3H_6		
42	X			C_3H_7		
43	X			C_3H_8		
44	0.001	CO_2, SiO, N_2O				
45	0.0002	SiOH				
46	X	NO_2				
56	X				Fe	
63	0.0001				Cu	
64	0.0001				Zn	IV
65	X				Cu	
66	X				Zn	
68	X				Zn	
12-68	1.5	impurities (total)				I-IV

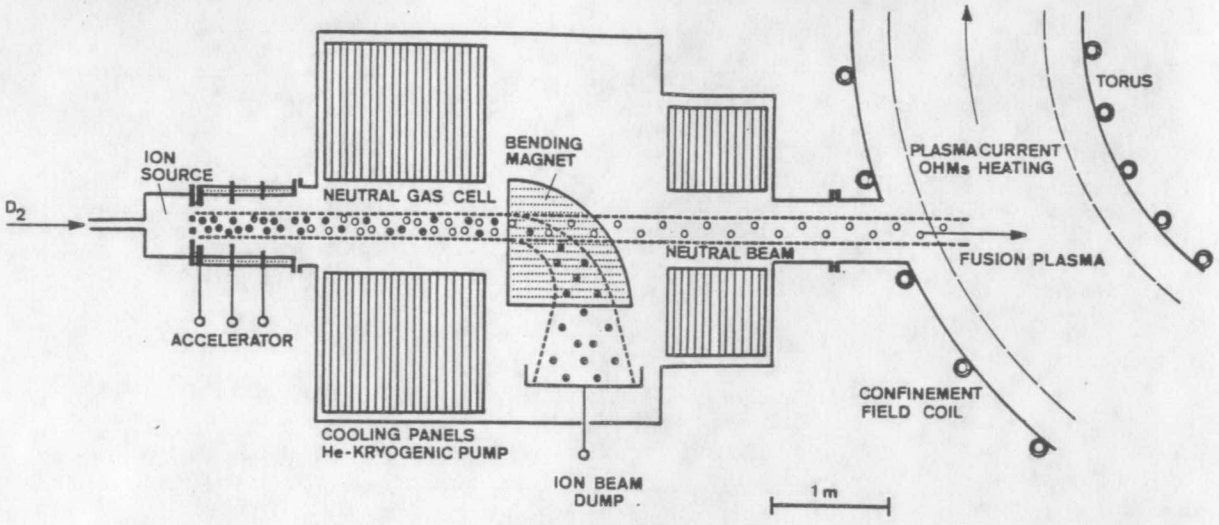


Fig. 1: Principle of a neutral beam injection line.

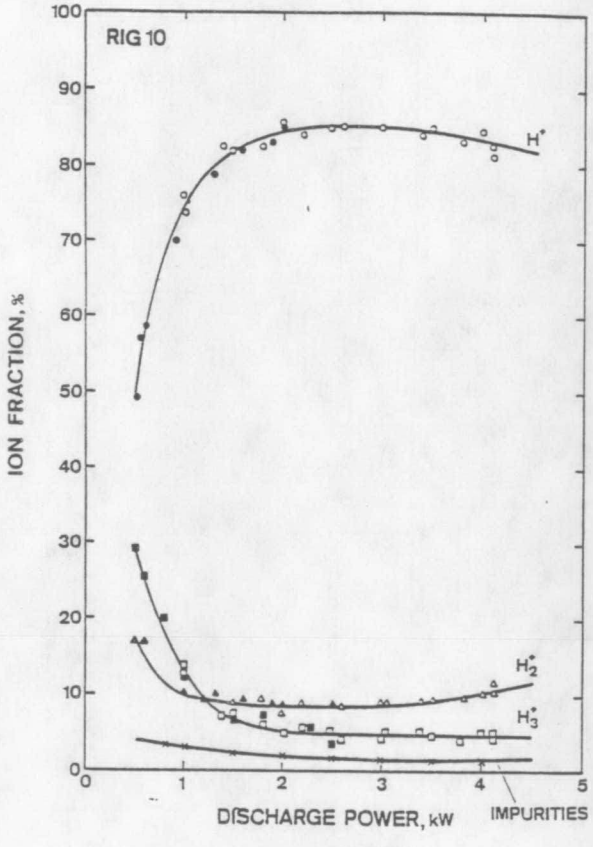


Fig. 2: Hydrogen ion species and impurities in the beam of RIG 10 for different rf-discharge powers.

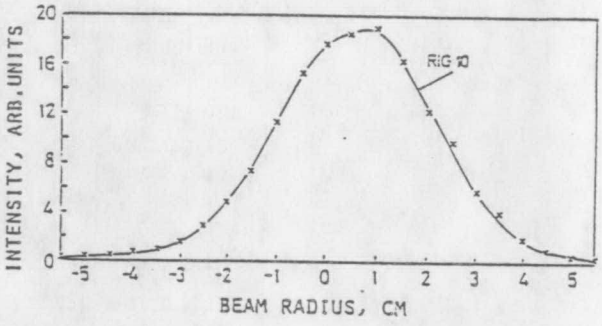


Fig. 3: Beam profile of RIG 10.

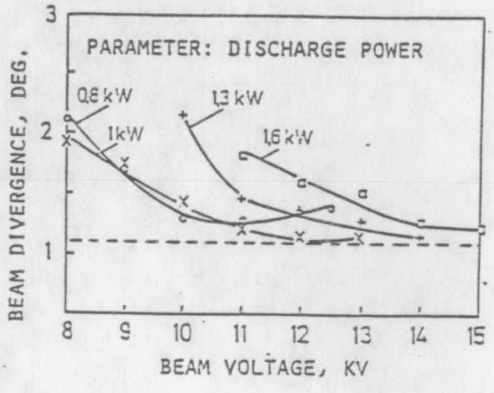


Fig. 4: The minimum divergence angle is 1.1 deg.

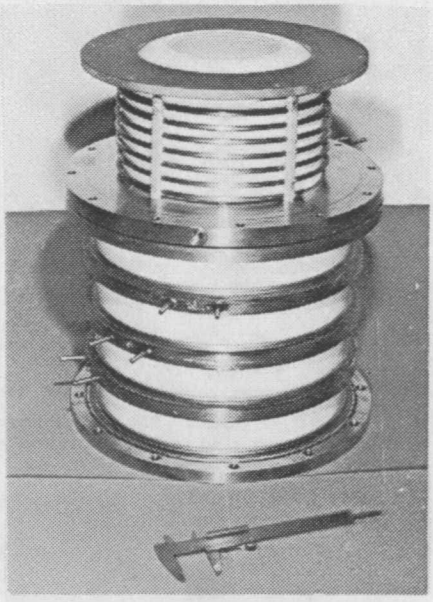


Fig. 5: Prototype of RIG 20 mounted at the accelerator tube.

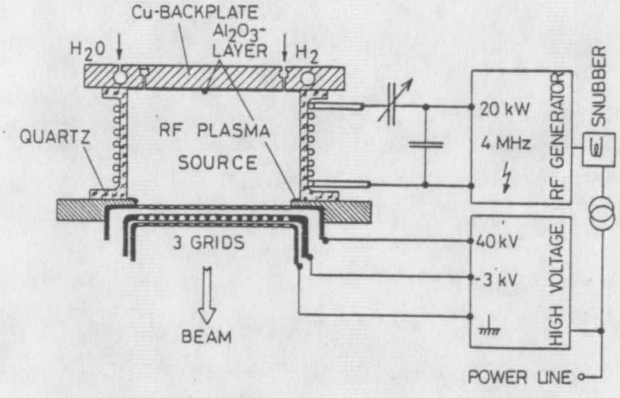


Fig. 6: Drawing of the modified RIG 20 for full power operation at IPP/Garching.

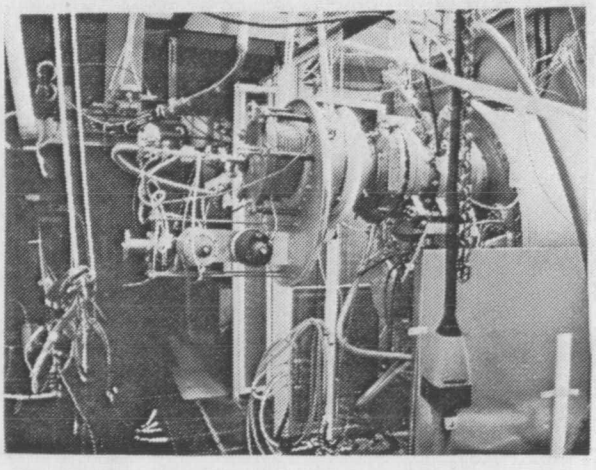


Fig. 7: Modified RIG 20 mounted to the full size beam line at IPP/Garching (rf-screen removed).

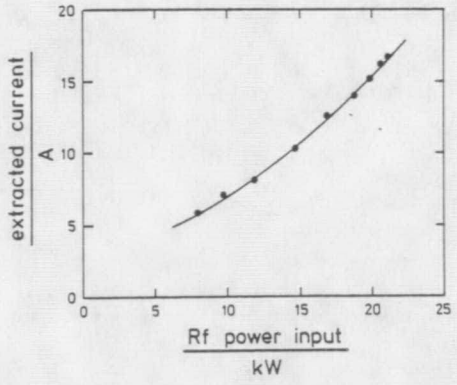


Fig. 8: The extraction current of RIG 20 increases almost linearly with the rf-discharge power.

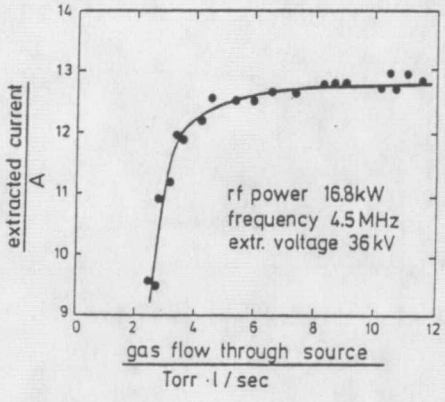


Fig. 9: Extraction current vs. gas flow through RIG 20 source (1 Torr·ℓ/s = 79 sccm).

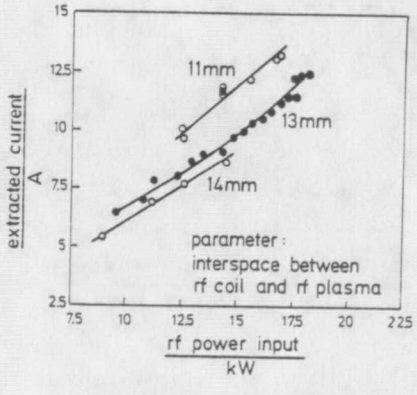


Fig. 10: Influence of the distance between the induction coil and the plasma.

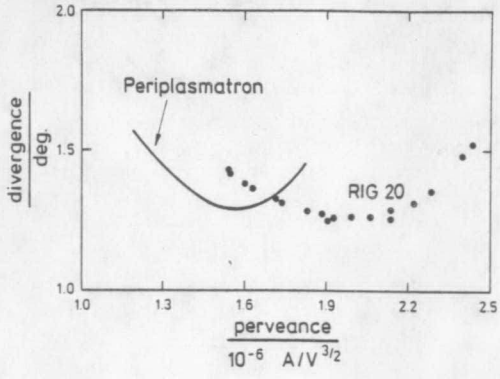


Fig. 11: Perveance and beam divergence of the periplasmatron and the RIG 20.

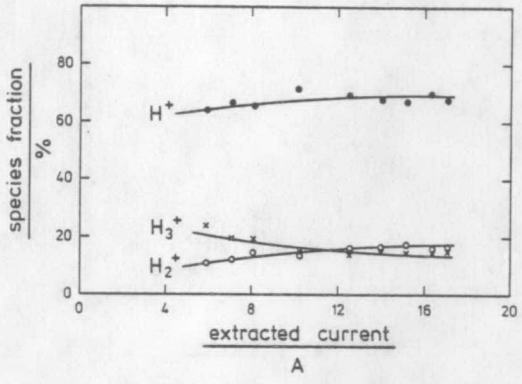


Fig. 12: Hydrogen ion species within the RIG 20 beam vs. the extracted current.

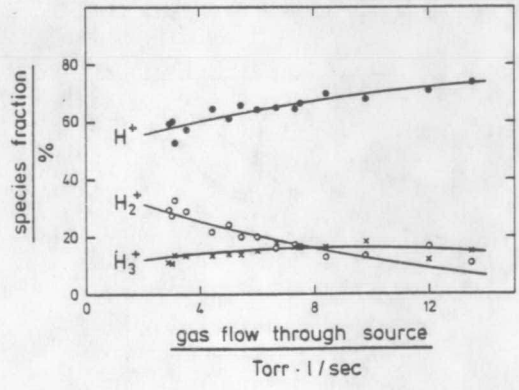


Fig. 13: Dependance of the atomic species fractions on the gas flow through the source RIG 20 (1 Torr·ℓ/s = 79 sccm).

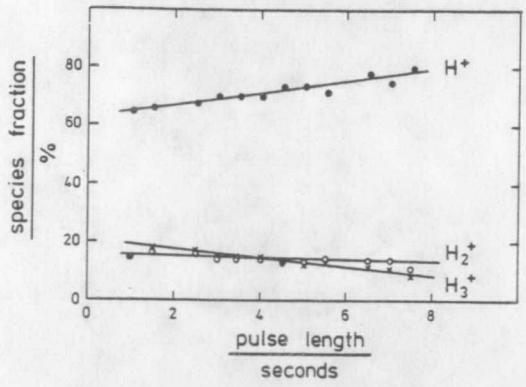


Fig. 14: The relative ratios of the ion species in the beam of RIG 20 for pulses up to 8 sec.

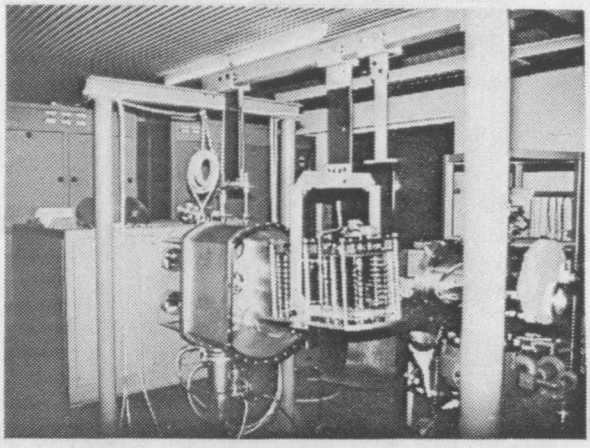


Fig. 15: Teststand for the development of RIG-HEX (Giessen University). In the middle: RIG-HEX and its vacuum housing; in the background: 140 kW rf-generator.

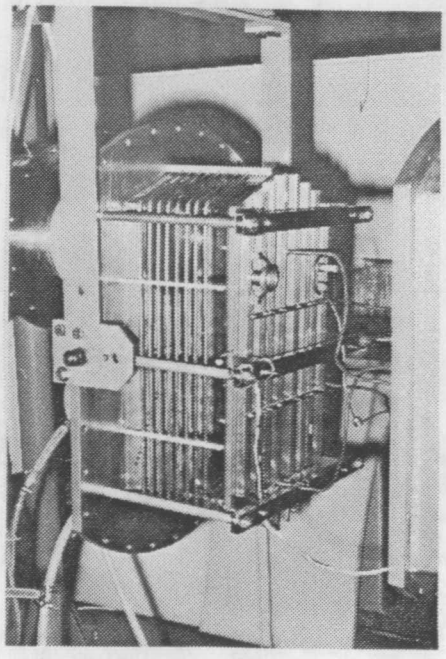


Fig. 16: RIG-HEX plasma source: The discharge chamber is surrounded by the water cooled rf-induction coil (8 turns). At the back-plate Co-Sm-magnets are mounted in a line cusped arrangement.

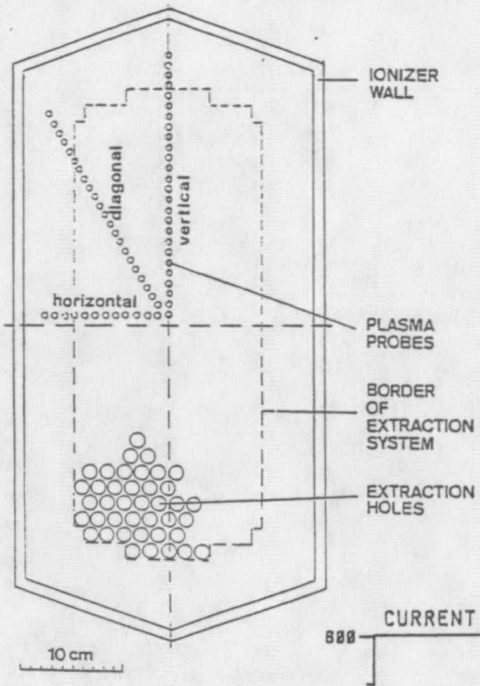


Fig. 17: Drawing true to scale of the RIG HEX baseplate with 61 plasma probes. The border of the PINI-extraction area is indicated (broken lines).

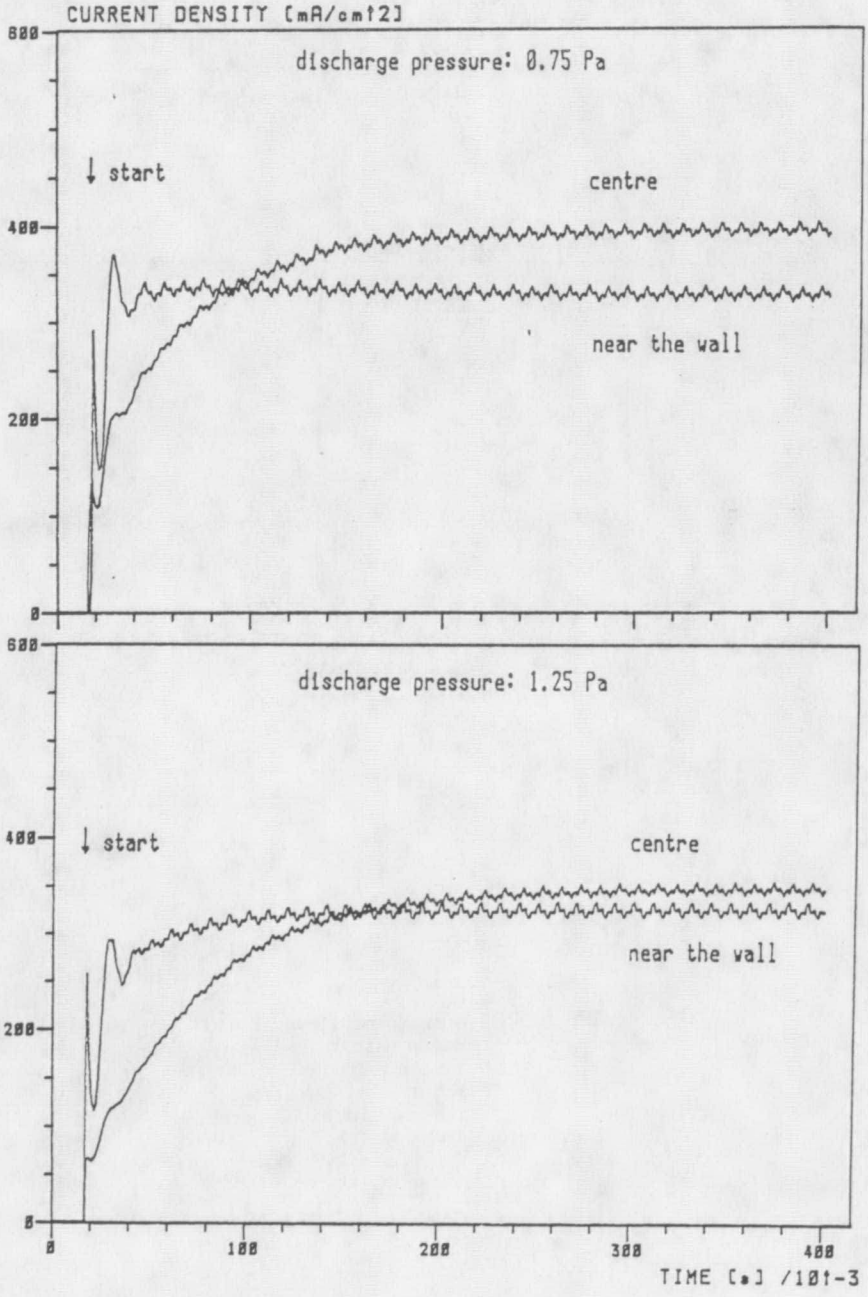
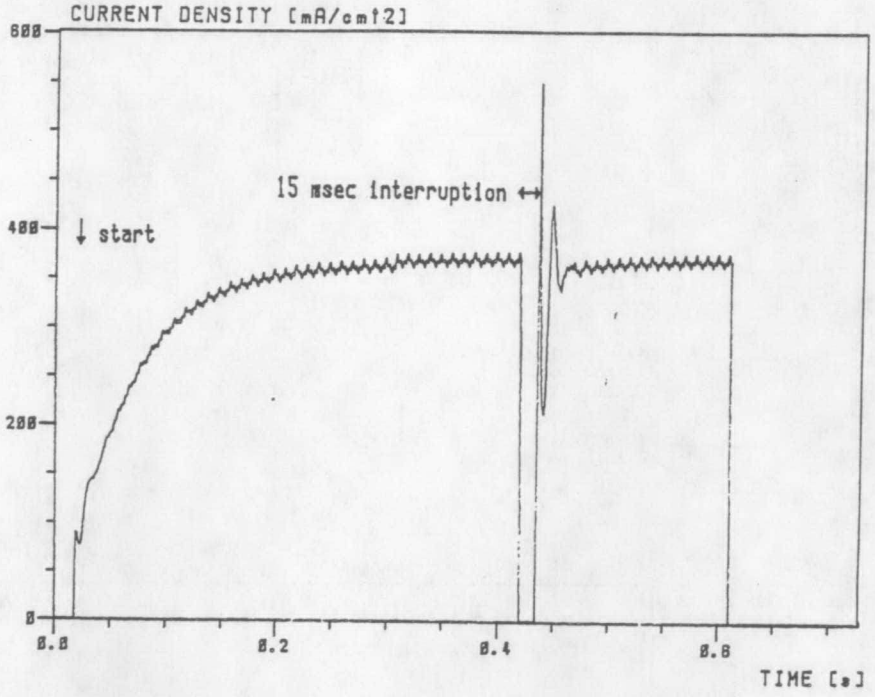


Fig. 18: Starting of the RIG-HEX discharge at two different discharge pressures. The rise-time to constant operation is faster near the induction coil than in the center of the discharge.



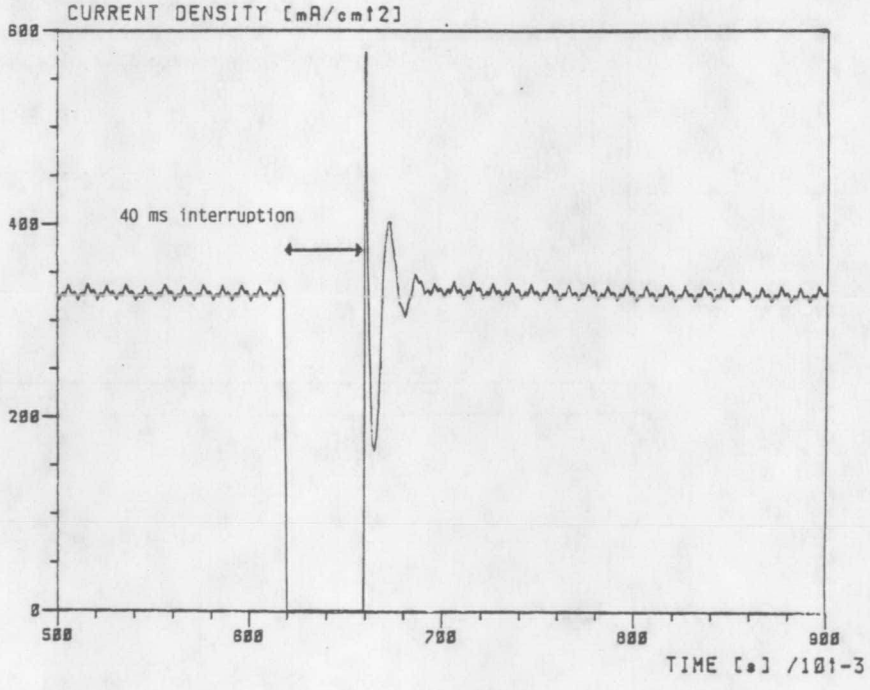


Fig. 19: Restart capability of RIG-HEX: The notching time is 15 s and 40 ms (discharge pressure 0.8 Pa). Oscillations lasting 20 ms after restart are typical. Notice the different time scales in the two diagrammes.

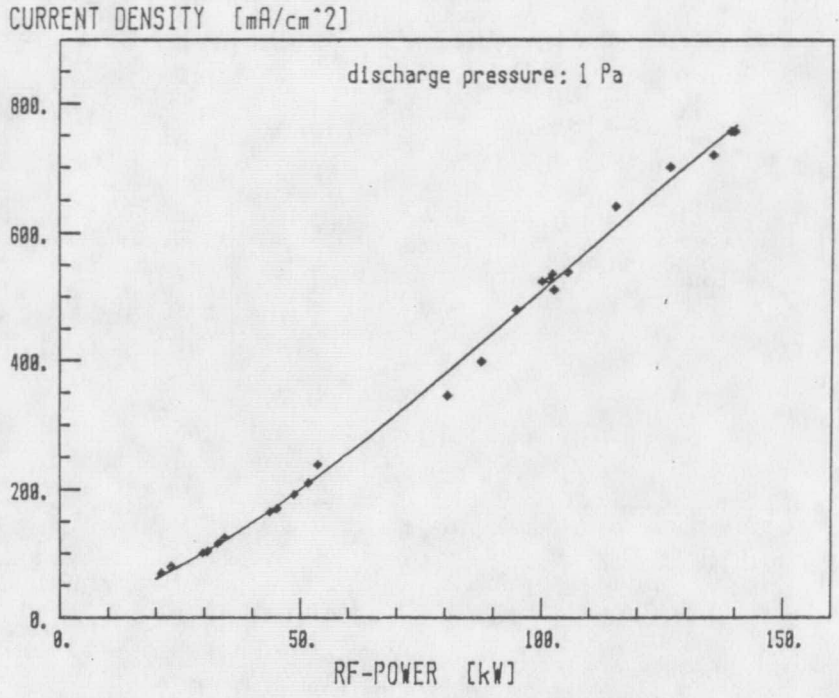


Fig. 20: The plasma current density increases linearly with the discharge power of RIG-HEX.

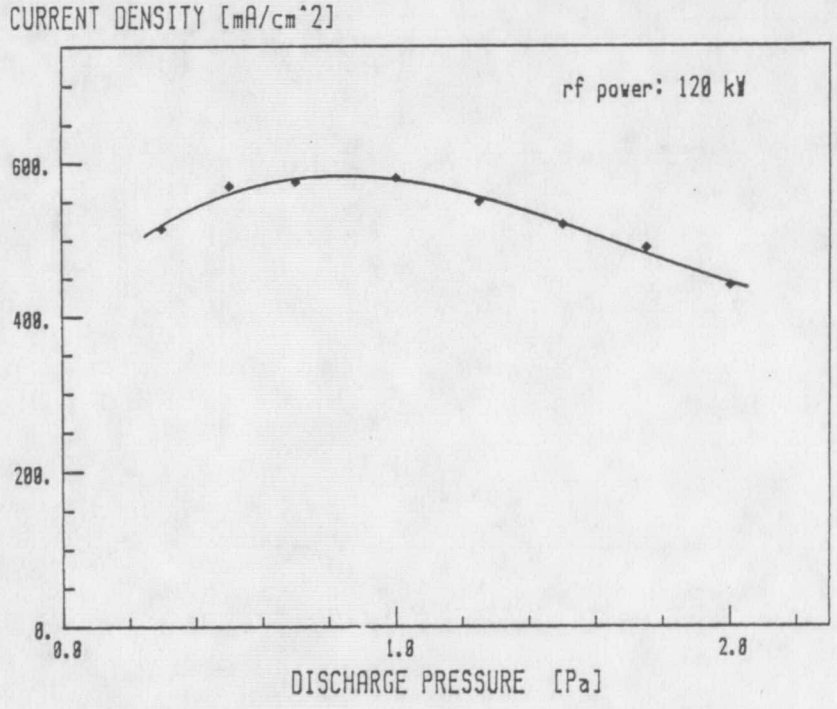


Fig. 21: Depedence of the plasma current density on the discharge pressure of HIG-HEX.

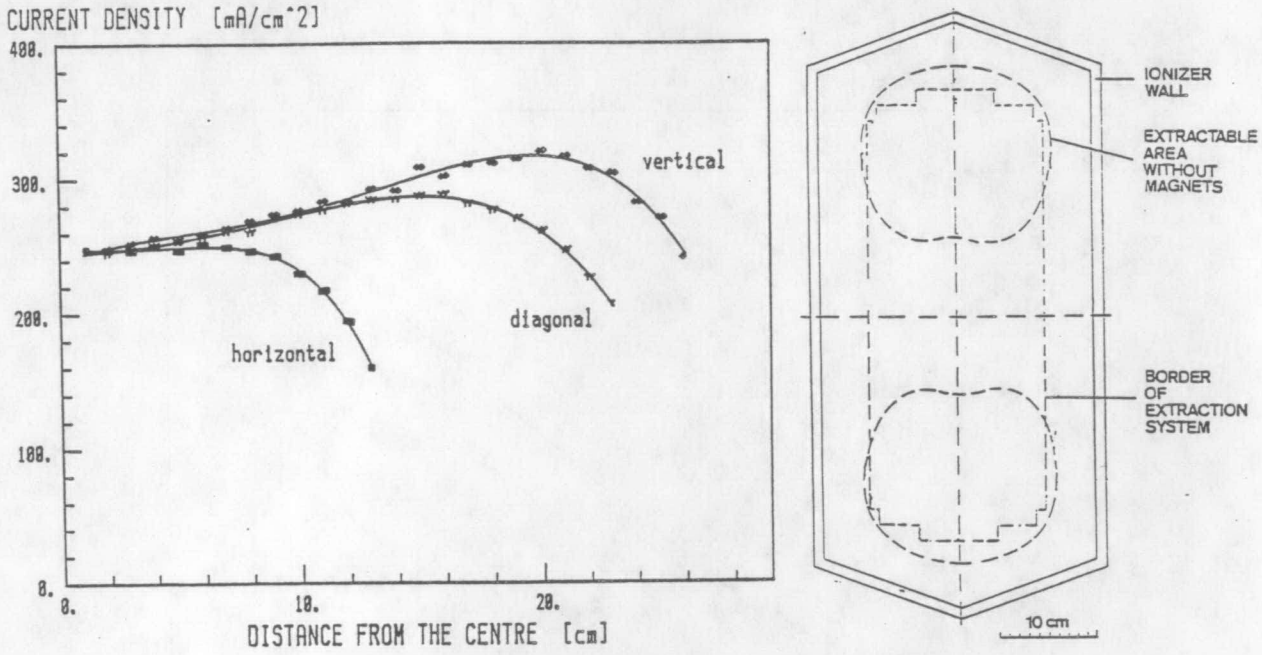


Fig. 22: Plasma current density profiles measured by double probes (without magnets at the back-plate) and usable extraction area (right). For probe position (vertical, horizontal, diagnoal) compare Fig. 7.

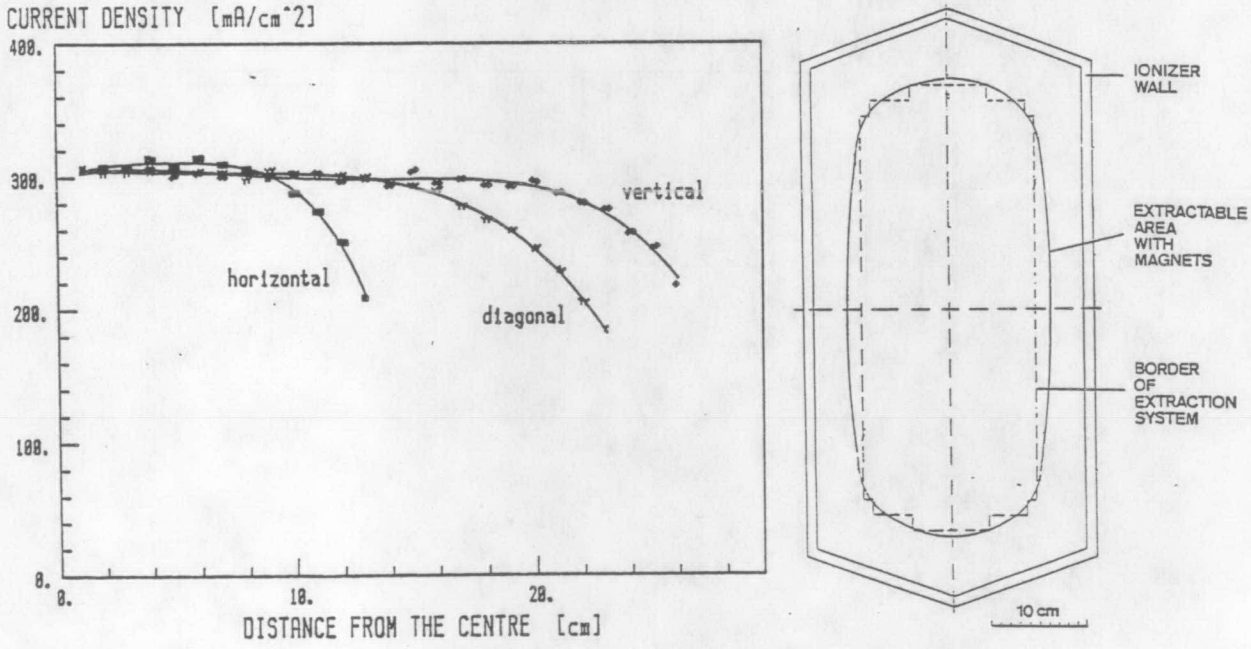


Fig. 23: Plasma current density profiles with Co-Sm-magnets mounted in a line cusped field arrangement at the back-plate. The usable extraction area fits very well the PINI-extraction system (right).