AD-A244 290

2

REPORT DOCUMENTATION PAGE

E

JAN 1 4 1992

S D

D

1a. Unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Distribution unlimited
Approved for public release

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)
5

6a. NAME OF PERFORMING ORGANIZATION
Texas Tech University

6b. OFFICE SYMBOL *(If applicable)*

7a. NAME OF MONITORING ORGANIZATION
Air Force Office of Scientific Researc

6c. ADDRESS *(City, State, and ZIP Code)*
P. O. Box 43102
Lubbock, TX 79409

7b. ADDRESS *(City, State, and ZIP Code)*
Building 410
Bolling AFB, D.C. 20332-6448

8a. NAME OF FUNDING / SPONSORING ORGANIZATION
Same as 7A

8b. OFFICE SYMBOL *(If applicable)*

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
AFOSR-87-0154

8c. ADDRESS *(City, State, and ZIP Code)*
Same as 7B

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
61102F	2301	A8	

11. TITLE *(Include Security Classification)*
Investigation of a Plasma Edge Cathode Under High Current Density Electron Extraction

12. PERSONAL AUTHOR(S)
Klaus W. Zieher

13a. TYPE OF REPORT
Final Technical

13b. TIME COVERED
FROM 04/01/87 TO 09/30/91

14. DATE OF REPORT *(Year, Month, Day)*
1991, December, 05

15. PAGE COUNT
37

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
Electron Source, Plasma Cathode, Plasma Source

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

A scheme with the potential for generation of an electron beam with high brightness and several usec pulse duration for microwave generation, electron accelerators or free electron lasers has been investigated experimentally. An electron beam was extracted transversely to the flow of a plasma jet. The transverse boundary of the plasma allowed extraction of a space charge limited electron current for 7 microsec at a current density of a8 A/cm^2. A normalized microscopic brightness of 8X10^8 A/m^2/rad^2 was achieved. Closure of the extraction gap by invasion of plasma has been observed with a velocity as low as 0.1 cm/microsec. Higher current density and higher brightness is expected for higher plasma densities and larger extraction fields. Numerical simulation using the MAGIC code confirmed the expected features of the scheme.

92-01112

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL
Dr. Robert J. Barker

22b. TELEPHONE *(Include Area Code)*
(202)767-4904

22c. OFFICE SYMBOL
NP

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted
All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE

92 1 13 020

INVESTIGATION OF A PLASMA EDGE CATHODE UNDER HIGH CURRENT DENSITY ELECTRON EXTRACTION

Klaus W. Zieher
Texas Tech University
Department of Electrical Engineering
P.O. Box 43102
Lubbock, TX 79409

05 December 1991

Final Technical Report for Period 01 April 1987 - 30 September 1991

Prepared for

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
Building 410/NP
Bolling AFB, D.C. 20332-6448

Abstract:

A scheme with the potential for generation of an electron beam with high brightness and several µsec pulse duration for microwave generation, electron accelerators or free electron lasers has been investigated experimentally. An electron beam was extracted transversely to the flow of a plasma jet. The transverse boundary of the plasma allowed extraction of a space charge limited electron current for 7 µsec at a current density of 18 A/cm^2. A normalized microscopic brightness of 8×10^8 $Am^{-2}rad^{-2}$ was achieved. Closure of the extraction gap by invasion of plasma has been observed with a velocity as low as 0.1 cm/µsec. Higher current density and higher brightness is expected for higher plasma densities and larger extraction fields. Numerical simulation using the MAGIC code confirmed the expected features of the scheme.

SUMMARY 1

I. INTRODUCTION: 3

II. PRINCIPLE OF THE PLASMA EDGE CATHODE SCHEME: ..5

III. RESEARCH OBJECTIVES: 8
  Experimental tasks 8
  Theoretical tasks 9

IV. RESEARCH ACTIVITIES: 9
  Experiments 9
  Theoretical work 24

V. RESULTS: 31
  Experimental results 31
  Theoretical results 32

VI. PRESENTATION OF THE RESULTS: 32

VII. PARTICIPATING PROFESSIONAL PERSONNEL AND
  STUDENTS:...................................34

REFERENCES 35

SUMMARY

The investigation of the Plasma Edge Cathode Scheme has yielded significant results. It was found that the concept of transverse extraction of an electron beam from a plasma jet allows long pulse extraction of electrons with significantly reduced gap closure velocities of order 0.1 cm/µsec compared to cold field enhanced emitters which close at a velocity of typically 5 cm/µsec. The measurements indicate that at current densities up to 18 A/cm^2 and total currents up to 240 A no detrimental instabilities occur. In the present arrangement, conditioning shots are essential for the operation of the diode at about 1x10^{-6} Torr. The measurements at a current density of 5.7 A/cm^2 yield a normalized microscopic brightness of 8x10^8 Am^{-2}rad^{-2}.

Measurement of the extracted electron beam showed that the plasma boundary is only slightly curved as expected from a simple one fluid description. An electron temperature of 1 eV was measured in the extraction region without extraction turned on. The plasma from the plasma gun was analyzed using a time-off-flight method. Highly ionized oxygen was found at the time of extraction in the extraction region. The hydrogen in the plasma jet is reduced if the time between shots is reduced to below 1 min.

The numerical simulation with MAGIC gave confirming results. The simulated current density agrees with the theoretical space charge limit. The temperature of the plasma after a few nsec extraction has risen from cold to the necessary temperature to satisfy the Bohm criterion. The penetration of the current into the cold plasma can be observed. The maximum plasma density that can be simulated with MAGIC is much lower than the experimental values. This is compensated by a larger plasma temperature.

The brightness of the beam from the plasma edge cathode is presently inferior to the values achieved with other emitters. Still the plasma edge cathode is resilient to a moderate background pressure of order 10^{-6} Torr in contrast to most thermionic emitters and ion bombardment should not degrade its operation.

The prospects of increasing the brightness of this cathode scheme are quite promising. It should be feasible to increase the current density extracted from such a cathode to a few 100 A/cm^2, possibly to 1 kA/cm^2 for larger plasma densities and appropriate extraction drivers. This would make the plasma edge cathode superior to the thermionic emitters and the cold field enhanced emitters, provided the transverse temperature of the extracted electrons can be maintained at the higher extraction current density.

I. INTRODUCTION:

Electron beams allow a high power density which can be converted into electromagnetic radiation by interaction with resonant or travelling wave structures. The efficiency and the performance of these generators depend on the beam quality mainly characterized by the normalized brightness of the electron beam.[1] For a free electron laser the upper frequency limit for a given driving current is proportional to the square root of the normalized brightness of the electron beam.[2]

The generation of high current density electron beams relies on a sufficient supply of free electrons at some real or virtual cathode. There are various methods of producing free electrons. Some of these methods are limited to low current densities or short pulse duration, while others produce a rather unordered electron beam.

Thermionic emitters are limited in the production of free electrons by the maximum temperature which can be tolerated by the cathode material and cathode structure. A very good beam quality can be achieved at electron current densities up to 100 A/cm^2.[3] The high temperature limits the lifetime of these cathodes and some of them require a clean vacuum.[4] In addition some of the thermionic cathodes are sensitive to ion bombardment.[5]

Cold field enhanced emitters can deliver a nearly unlimited number of free electrons but also generate a rapidly expanding plasma which tends to invade any extraction gap within about a microsecond depending on the gap width. Typical closure velocities are 5 - 10 cm/μsec. The extracted electron beam is quite unordered and severely limits the achievable beam brightness.[6]

Photo emission of electrons by laser irradiation can produce large numbers of free electrons with low initial transverse velocity but is limited to submicrosecond operation due to heating of the cathode surface.[7,8]

Operation of a grid controlled plasma cathode[9] will depend on a delicate balance of plasma generation and electron extraction. Unbalanced operation will either lead to erosion of the plasma or to closure of the extraction gap.

An alternative scheme which avoids the above mentioned limitations of the cold field enhanced emitters and the grid controlled plasma cathode has been suggested and initially tested in a very preliminary way.[10] This new plasma cathode is investigated in detail in this paper. It has the advantages of a cold field enhanced emitter and a plasma cathode which is a nearly unlimited supply of electrons while it avoids the fast gap closure and to a large extend the uneveness of the plasma surface. The electrons in the plasma are free and therefore have practically a zero workfunction. The supply of free electrons is nearly unlimited as long as the plasma generating arc is not extinguished. The potential of this cathode scheme lies in the production of large current densities of 100 - 200 A/cm^2 at low transverse temperature of order 1 eV over long pulses of several microseconds in a modest vacuum of typically 10^{-5} to 10^{-6} Torr.

This would result in an ideal normalized brightness of $B_n = 0.8$ to 1.6×10^{11} $Am^{-2}rad^{-2}$. There is no significant thermal heat load on the surrounding structure. Ion bombardment of the cathode should not have any adverse effect.

II. PRINCIPLE OF THE PLASMA EDGE CATHODE SCHEME

The basic concept is shown in Fig. 1. A plasma jet originating from a small surface flashover plasma gun is intercepted partially by a straight material edge thus forming a transverse plasma boundary with a steep density gradient. The boundary will be nearly stationary in space if the temperature and the velocity of the jet is not changing significantly and if no electric field is applied. In addition, it can be shown from the fluid equations for such a plasma that the transverse dynamics are, to first order, independent of the plasma density in the jet.

An extraction grid is set up parallel to the plasma boundary at a distance d from the plane defined by the gun axis and the straight material edge. An extraction potential is applied to the grid thus extracting electrons perpendicularly from the plasma. The electrons fill the gap with a space charge distribution which will settle to the space charge limited steady flow if a sufficient supply of electrons is available from the plasma source.

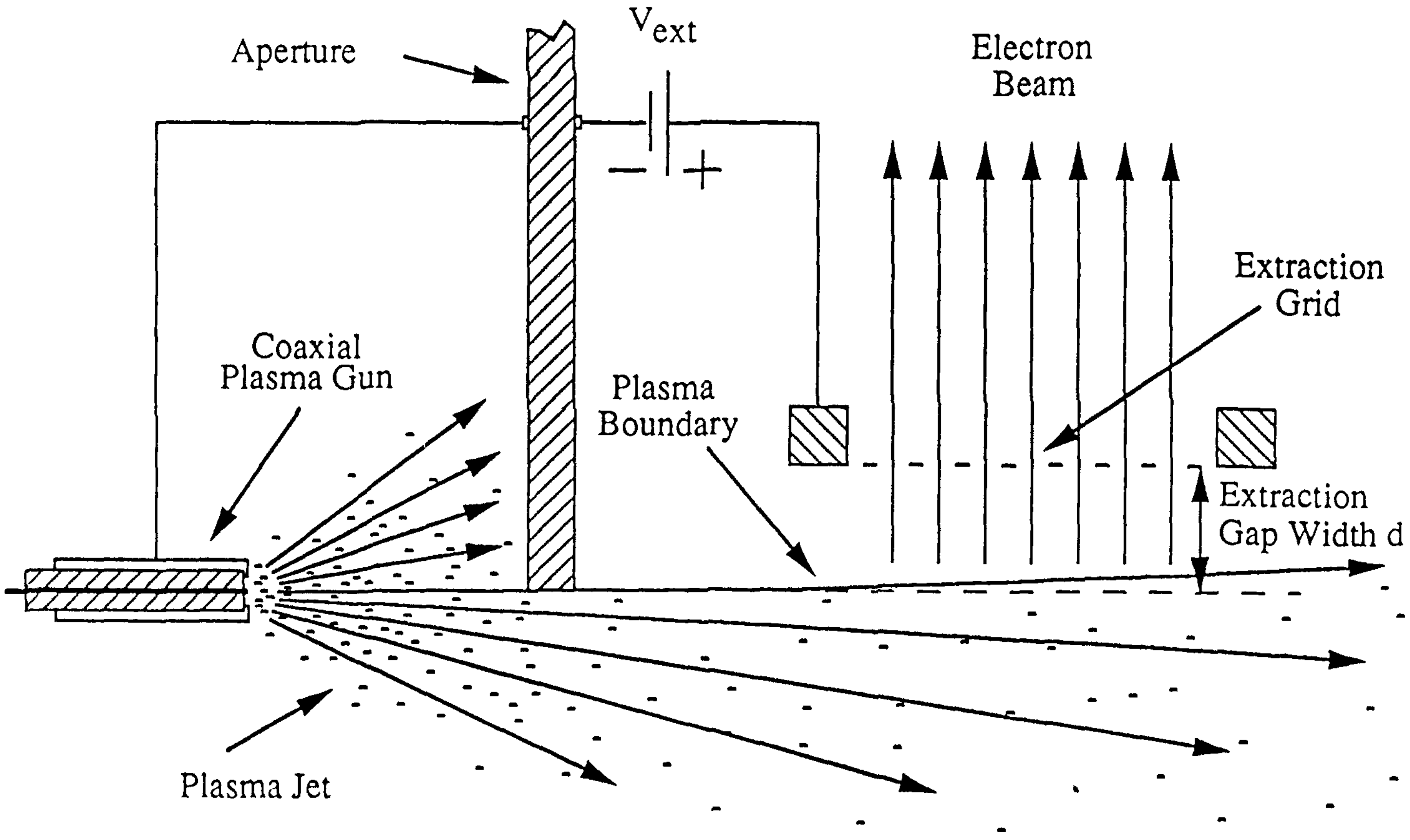


FIG. 1. Principle of the plasma edge cathode.

The supply of free electrons is sufficient if the electron plasma temperature is at least of order

$$kT_e = 2\pi m_e \left(\frac{j_e}{e_0 n_e} \right)^2$$

where j_e is the extracted electron beam current density, m_e is the electron mass and n_e is the electron plasma density. The electric field intensity at the effective boundary of the plasma jet is nearly zero for space charge limited flow and therefore does not influence the flow of the plasma significantly. If no instabilities develop, then the electron beam quality will be determined essentially by the electron plasma temperature. Especially the normalized beam brightness is given for a circular and uniform current density electron beam by[1]

$$B_n = \alpha_0 I_b / \pi^2 \epsilon_n^2$$

where α_0 is a geometrical factor of order unity. For a four-dimensional hyper-ellipsoidal distribution this factor is 2. I_b is the electron beam current. e_n is the normalized emittance. The brightness[1,11] in terms of the transverse temperature T with which the beam is generated is

$$B_n \approx \frac{j}{2\pi \left(\frac{kT}{mc^2} \right)}$$

Ideally the beam temperature would be as low as the electron plasma temperature and the current density equal to the maximum current density. Under these ideal circumstances the normalized brightness would be

$$B_n = \left(\frac{e_0 n_e c}{2\pi}\right)^2 \cdot \frac{1}{j_e} \quad .$$

For example a plasma density of $n = 7 \times 10^{14}$ cm^{-3} and an electron plasma temperature of $kT_e = 1$ eV will theoretically allow an extraction current of about $j_e = 100$ A/cm^3 and a brightness $B_n = 8 \times 10^{10}$ $Am^{-2}rad^{-2}$. These data have not been achieved yet.

III. RESEARCH OBJECTIVES:

The research objective of the investigation was to study the behavior of the plasma edge cathode scheme both experimentally and by numerical simulation.

Experimental tasks:

1. Set up an experiment consisting of a vacuum system housing a plasma gun, an extraction electrode with a fluorescent screen, and diagnostic probes.

2. Develop drive circuits for the plasma gun and the extraction electrode.

3. Analyze the intrinsic beam emittance and brightness of the extracted electron beam.

4. Analyze the composition and velocity distribution of the ions in the plasma jet.

Theoretical tasks:

1. Simulate the dynamics of the plasma flow without and with extraction of electrons numerically.

IV. RESEARCH ACTIVITIES:

Experiments:

Description of the extraction experiment:

The experimental apparatus[12] for transverse extraction of electrons from a plasma jet is shown in Fig. 2. The vacuum vessel housed the plasma jet source, an extraction structure, and several flux probes. The vacuum pressure was maintained at about 1×10^{-6} Torr.

The plasma source consisted of a marine spark plug driven from a 0.3 μF capacitor bank through a triggered spark gap. The energy stored in the capacitor bank was typically 94 J. The ringing frequency of the discharge current was 725 kHz and the initial current amplitude of 32 kA was damped with a time constant of 4.8 μsec. The plasma jet passed through a sequence of aligned horizontal slit apertures which were 1 cm high and 5 cm wide. A flat plasma jet emerged into the extraction region with the upper boundary facing the extraction anode.

Biased flux probes allowed the measurement of the density distribution across the transverse boundary of the plasma jet as shown in Fig. 3. The origin for the distance coordinate for this

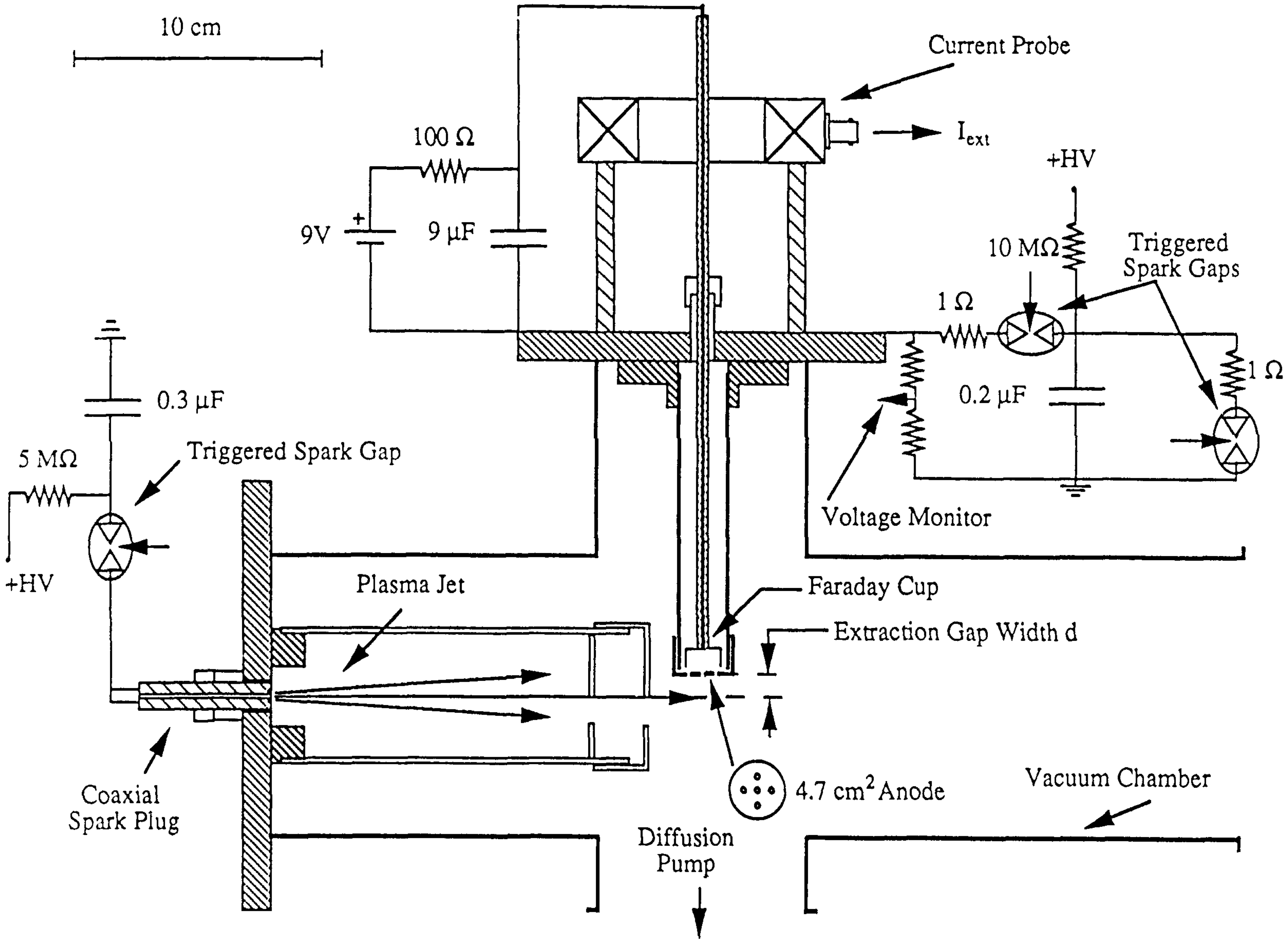


FIG. 2. Experimental apparatus with small anode.

measurement was the plane defined by the axis of the spark plug and the upper edges of the slit apertures. Two biased flux probes separated by a drift space indicated a fast ion component moving at a velocity of 5.5 cm/µsec and a slow one at 1.2 cm/µsec. The temperature of the plasma jet was measured with a double Langmuir probe. At a distance D = 18 cm downstream of the spark source an electron plasma temperature of $kT_e = 1.2$ eV was found. The temperature determined at a distance of 54 cm was $kT_e = 0.3$ eV. The measured plasma density fell off like $1/D^2$. This gave an expansion of the plasma jet with an apparent ratio of the specific heats $C_p/C_v = 1.6$ which indicated adiabatic expansion of the plasma jet.

The plasma density in the extraction region derived from the Langmuir probe measurements was $n = 10^{13}$ cm^{-3} while ion flux probes indicated a density of $2x10^{12}$ cm^{-3}. A pulse with a voltage up to 25 kV and a duration up to 10 µs was applied to the anode structure. The driver consisted of a charged capacitor bank which was connected to the anode through a triggered spark gap. The extraction pulse was terminated by a second triggered spark gap which shorted out the extraction potential between the anode and cathode arrangements. The extraction voltage was monitored by a resistive voltage divider.

The electron beam current density could be measured inside the anode structure by a biased Faraday cup behind a series ofsmall holes with known area. An integrating inductive probe was used to measure the collected current. The measurements of the

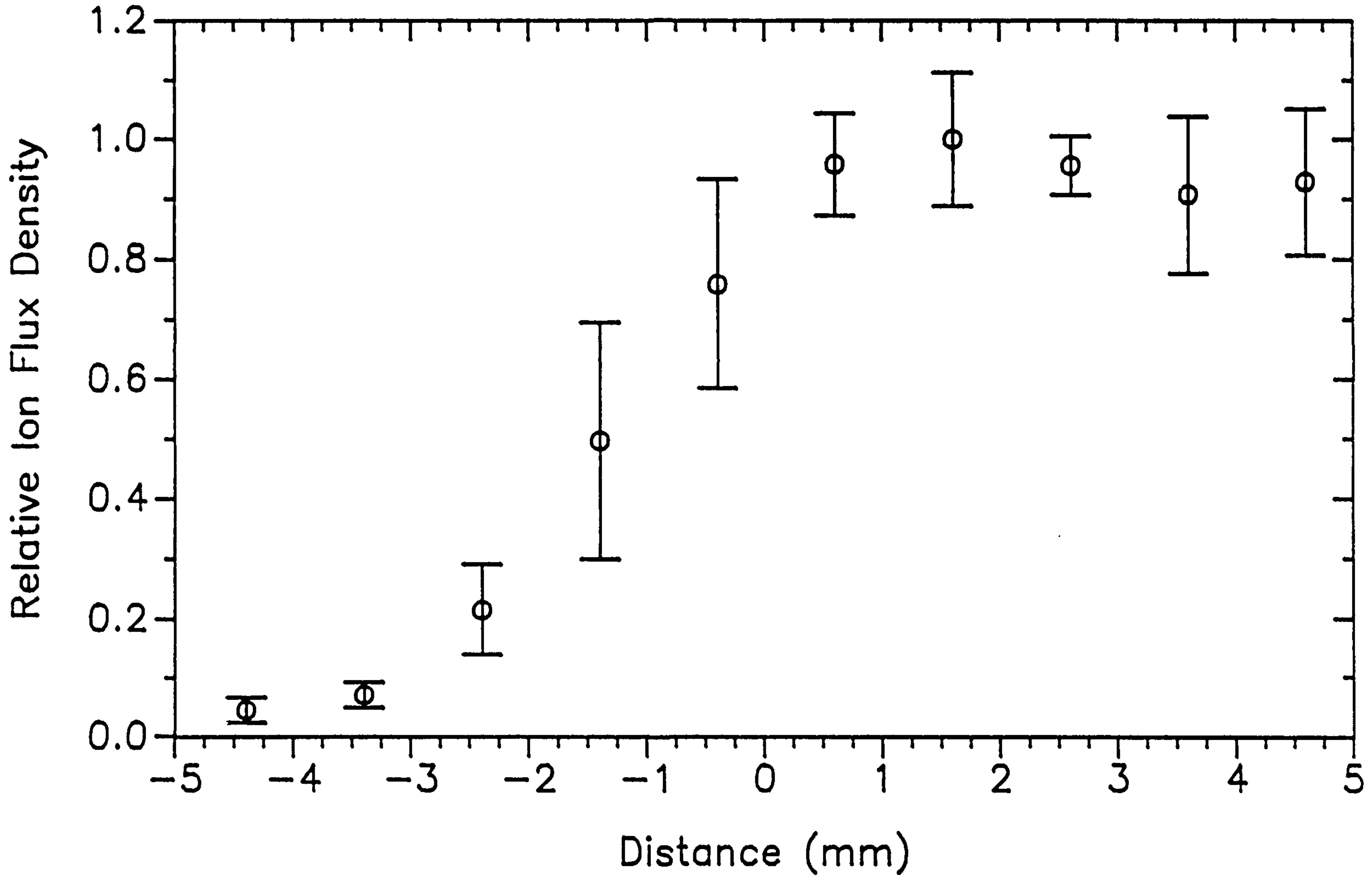
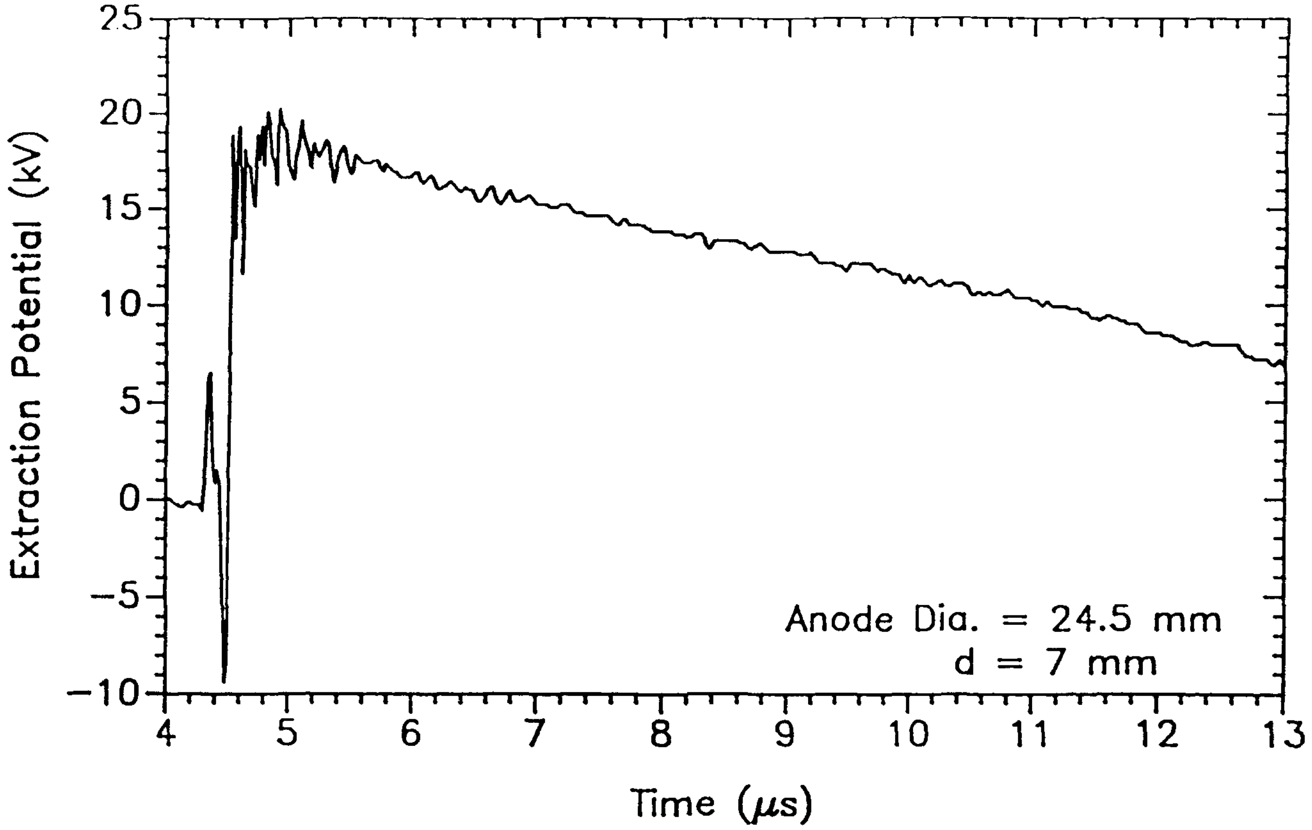


FIG. 3. Relative ion flux density at the transverse plasma boundary.

electron current density and the extraction voltage as a function of time showed that the effective extraction gap width decreased with a velocity of typically 0.1 cm/μsec, in some shots as low as 0.07 cm/μsec. The effective gap width was substituted for the geometrical gap width d to match the measured current density. It practically contained the deviation from planar geometry which was significant for the small anode but expected to be time independent together with the closure of the gap by plasma invasion into the gap region part of which was given by the transverse fluid dynamic expansion of the cathode plasma. The low expansion velocity allowed the extraction of an electron current density of 18 A/cm^2 for a duration of 7 μsec at a geometrical gap width of 7 mm measured from the plane through the upper edge of the slit apertures and an anode diameter of 24.5 mm (Fig. 4). Conditioning shots were necessary for long pulse operation after interruptions.

The current density of the extracted electron beam was measured for various extraction potentials and geometric gap widths. The current densities were slightly higher than the expected space charge limit. This could be partially attributed to an effective gap width which was smaller than the geometric gap width caused by the plasma jet curving into the extraction gap. Fig. 5 shows the measured and calculated electron current density for varying extraction potential and different geometrical extraction gap widths. The theoretical curves were fitted to the experimental data by adjusting the effective gap width. Two



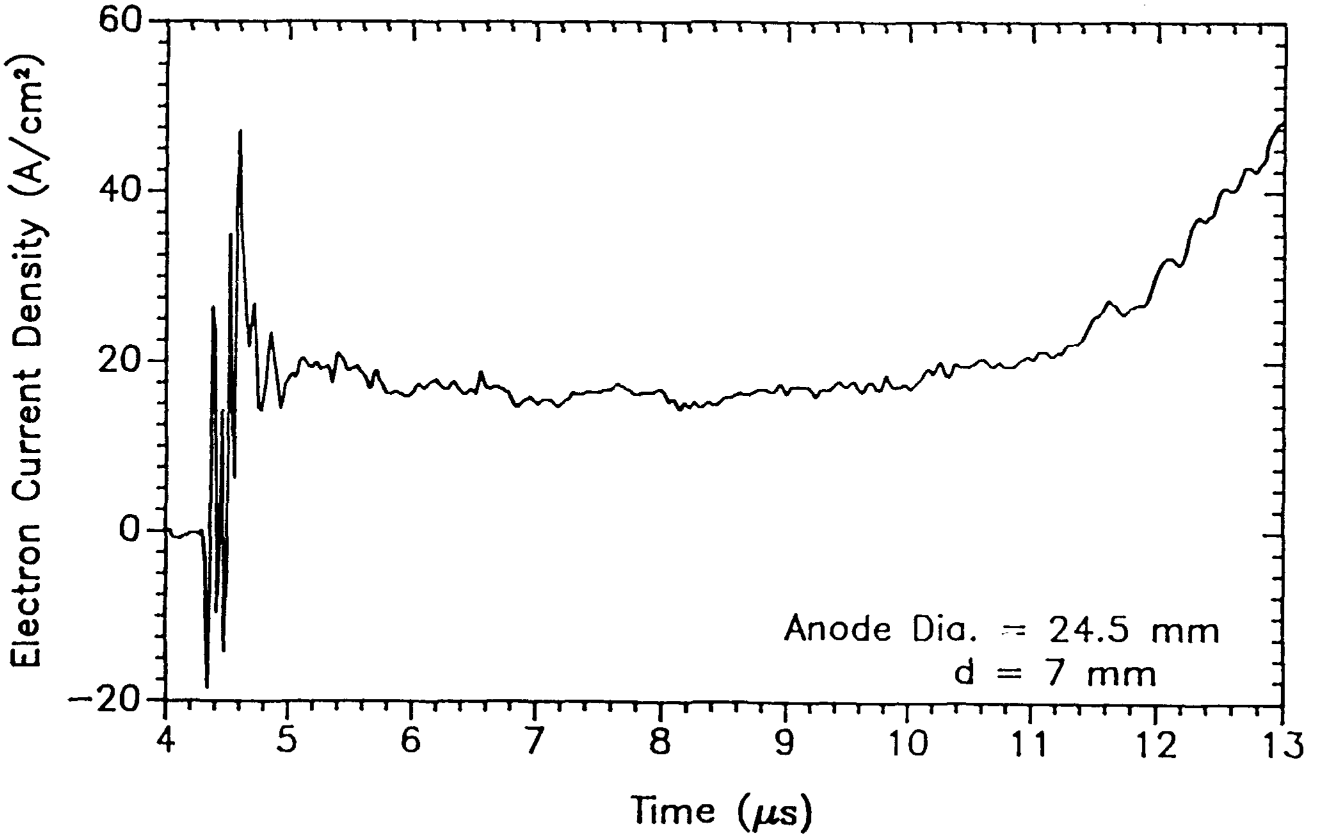
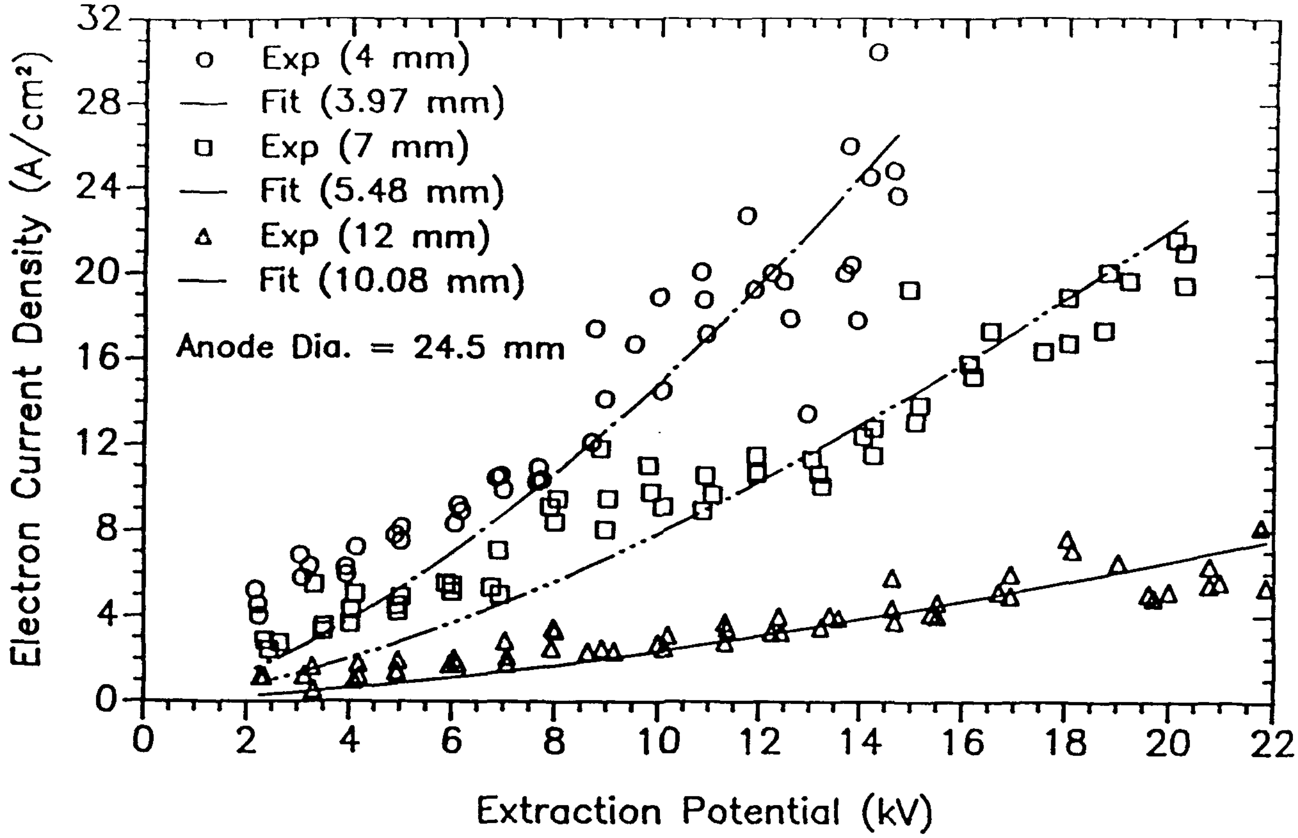


FIG. 4. Electron beam extraction with small anode and 7 mm extraction gap spacing.



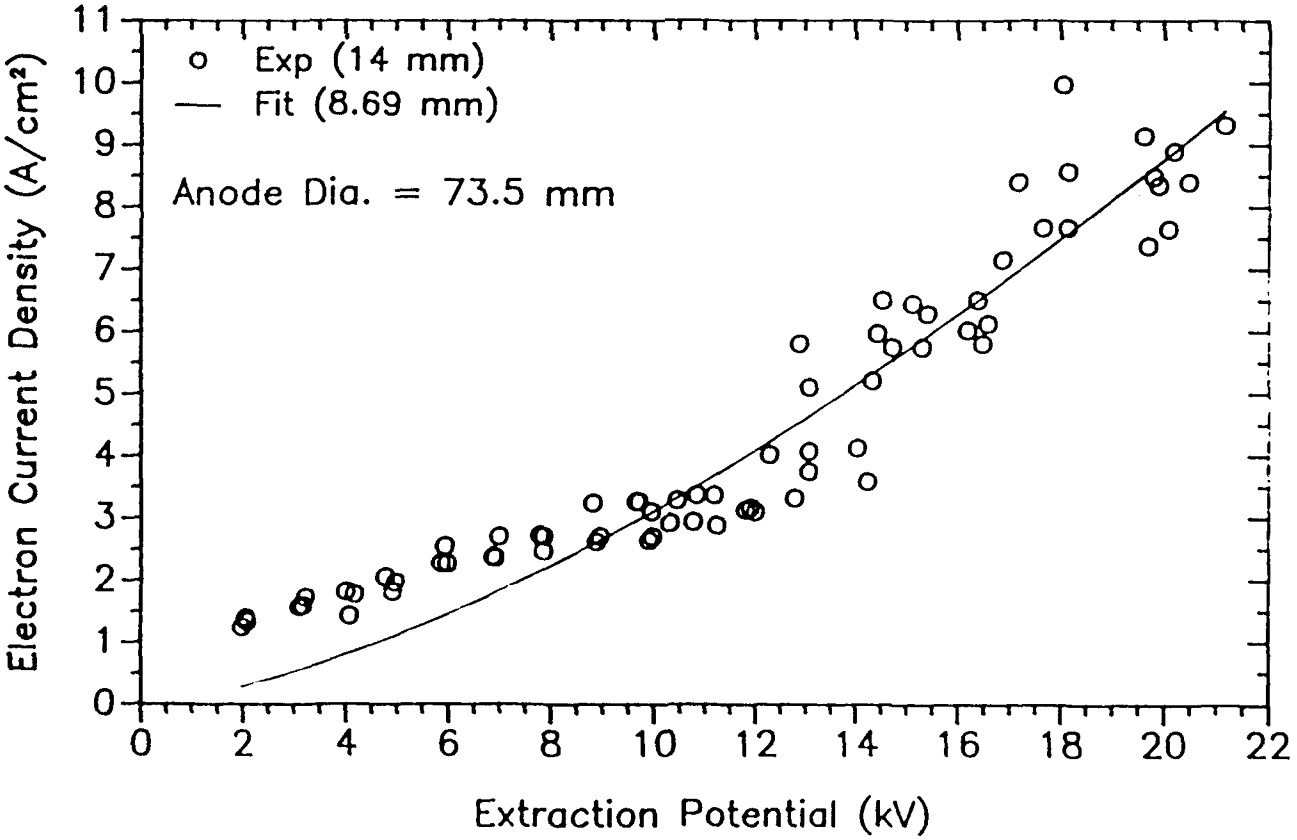


FIG. 5. Electron current density measured (Exp) and calculated (Fit) for an effective gap width and space charge limited monopolar flow.

anodes were used, a small area anode with a diameter of 24.5 mm and a larger one with a diameter of 74 mm. The experimental data appeared to follow the Child-Langmuir relation.

The geometry of the extracted electron beam was analyzed by a multiple pinhole plate serving as the anode with a plastic scintillator screen at some distance behind it. The image on the screen was recorded by an open shutter camera. From the size of the spots an average transverse electron energy of about 5 eV was determined at a current density of 5.7 A/cm^2 and an extraction potential of 15 kV after correction for space charge expansion of the beamlets and the finite resolution of the densitometer. This corresponds to a normalized microscopic brightness of $8\text{x}10^{8}$ Am^{-2}rad^{-2}.

The displacement of the beamlet images appearing on the scintillator screen in relation to the corresponding holes in the anode was used to reconstruct the shape of the effective plasma boundary during extraction (Fig. 6). The electrons were assumed to leave the plasma perpendicular to the surface. It was found that the effective transverse plasma boundary deviated from a plane by less than ±0.5 mm over an area of about 55 mm diameter. This indicated that the planar approximation for the large area anode was reasonable.

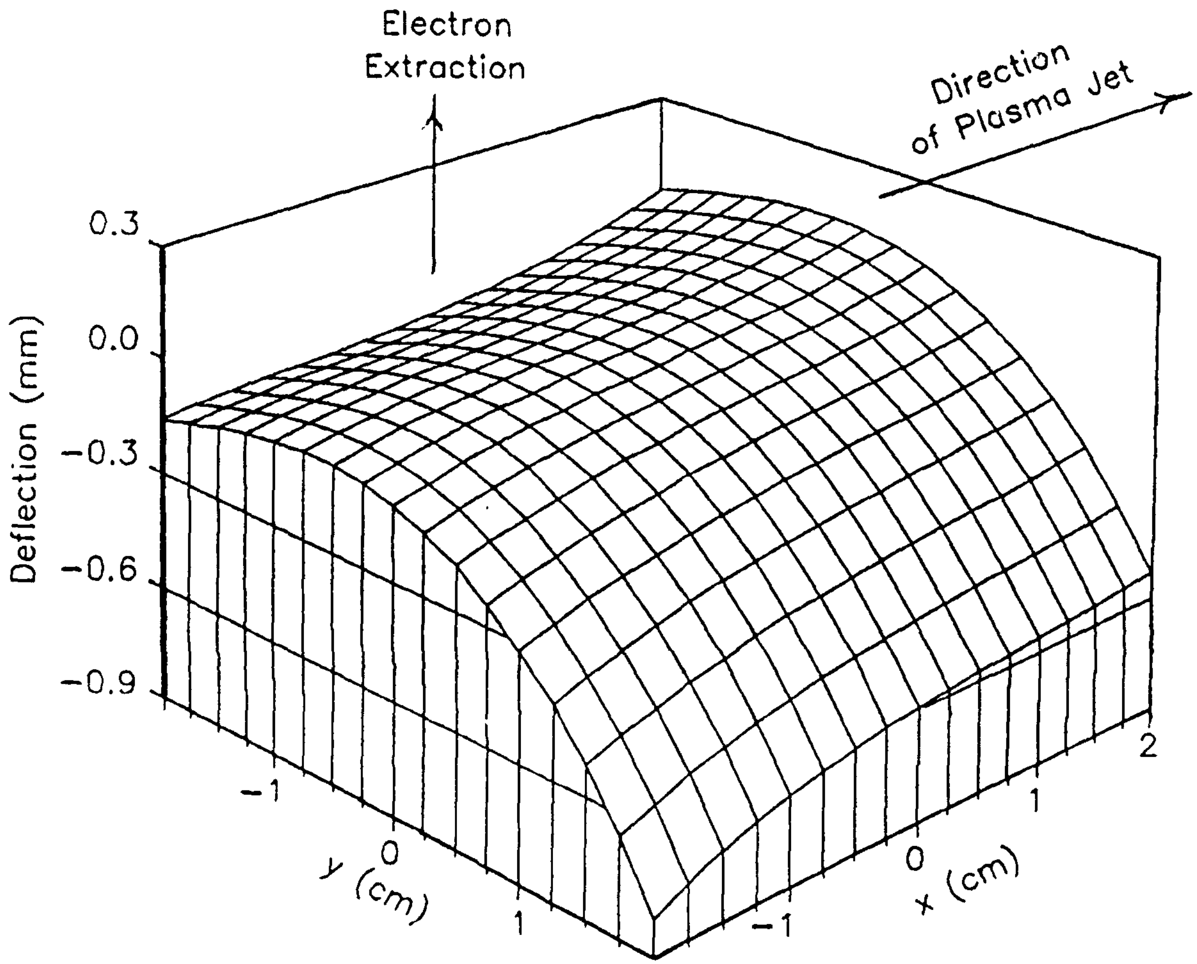


FIG. 6. Distortion of the effective plasma boundary derived from the measured electron trajectories.

Description of the time of flight experiment:

A time-of-flight experiment[13,14] was set up to analyze the composition and velocity of the various ions in the plasma jet. Figure 7 shows the experimental arrangement of the time-of-flight spectrometer. The plasma jet was created in the same way as in the extraction experiment. The plasma gun consisted of a capacitor bank, a spark gap and a spark plug. The plasma propagated down a vacuum chamber to an accelerating gap which was pulsed negative to U = -3 kV for a pulse duration of τ = 110 nsec. A drift tube was hiding the ions after they were accelerated for a time longer than the duration τ of the accelerating pulse. The time t_1 between firing of the spark plug and the acceleration pulse, together with the distance L_1 = 181 cm from the spark plug to the acceleration gap, yielded an approximate value of the initial velocity $v_1 = t_1/L_1$ of the ion species. After the accelerating gap the ions have an energy of

$$E_2 = \frac{1}{2} M_i v_i^2 + ZeU$$

where M_i and v_i are the ion mass and the ion velocity respectively. Z is the charge state of the ion.

The time for the drift from the acceleration gap to a particle detector at a distance L_2 = 194 cm is given by

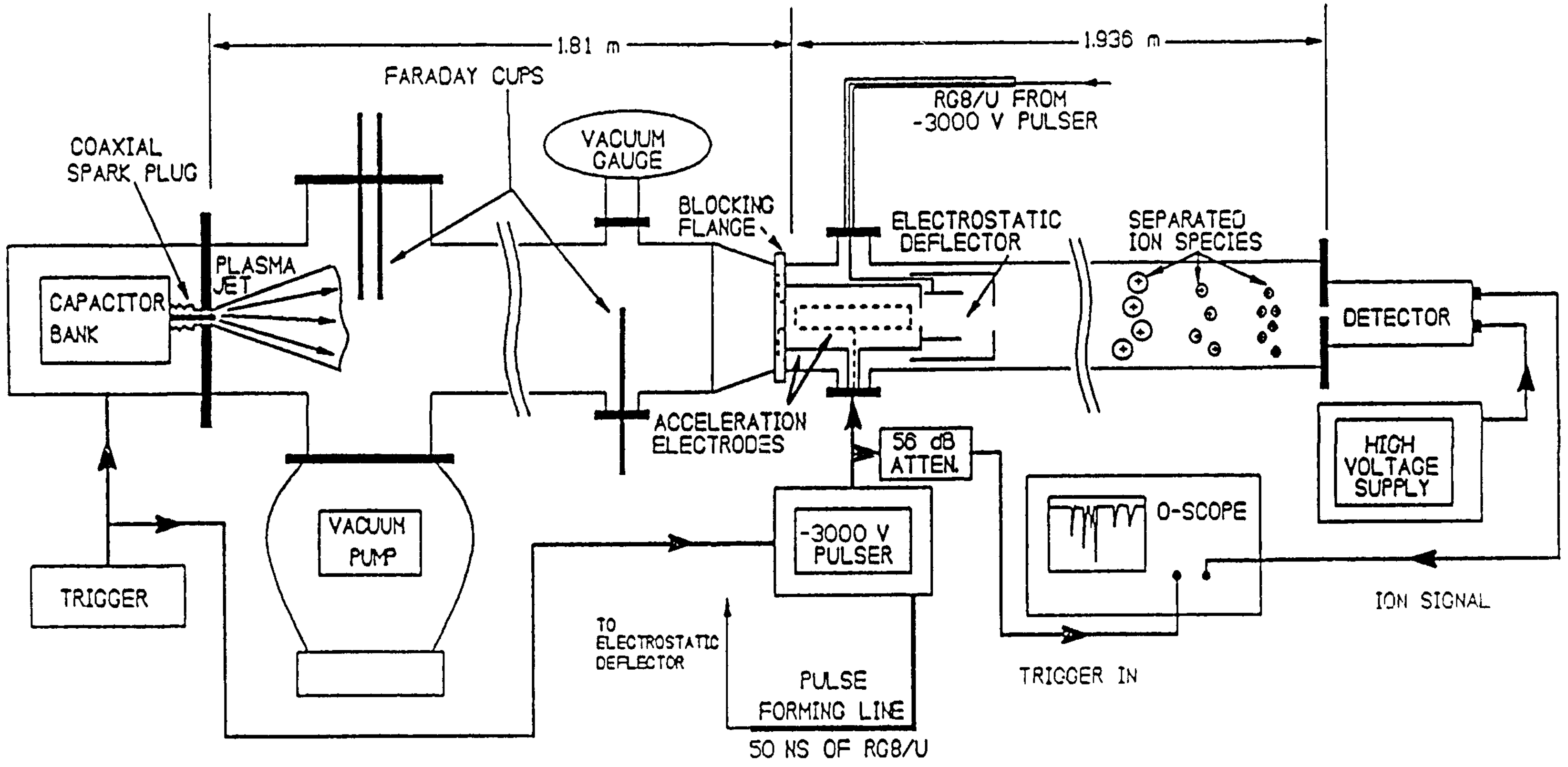


FIG. 7. Time-of-Flight Mass Spectrometer

$$t_2 = L_2\sqrt{\frac{M_i}{2ZeU + M_i v_i^2}}$$

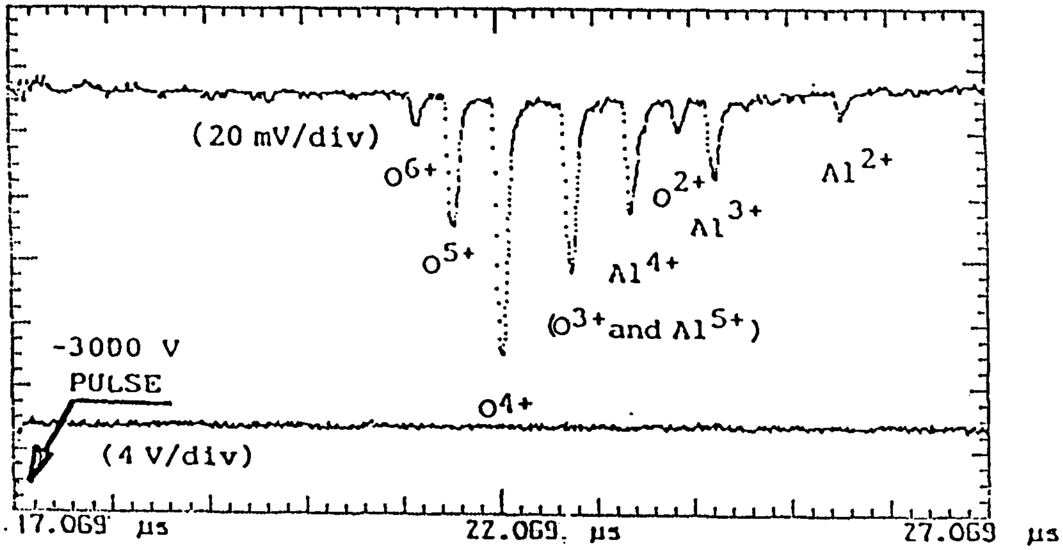
From the measurement of t_1 and t_2 one can derive the ratio of the mass to the charge:

$$\frac{M_i}{Ze} = 2\frac{U}{(L_2/t_2)^2 - v_i^2}$$

The relative resolution $\delta M_i/M_i$ in our experiment was between 2% and 4% for the observed mass range.

The accelerated ions were detected with an open electron multiplier. Two deflector electrodes followed the drift tube to block the plasma flow to the detector until the accelerating pulse was applied. The deflector and the cable pulser for the acceleration pulse were charged from the same voltage supply. Fig. 8 shows a typical response of the ion detector.

In the same experiment the temperature of the plasma T_e was measured using a triple Langmuir probe as shown in Fig. 9. This probe allowed to measure the plasma temperature in a single shot as a function of time. Fig. 10 shows four temperature measurements of four independent shots. An electron temperature in the range of 0.8 to 1.4 eV was found in good agreement with measurements in the jet of the extraction experiment.



INITIAL ION VELOCITY = 10.05 cm/µs
ACCELERATING VOLTAGE = 2970 volts
++

TIME OF SPIKE	CALCULATED M/Z RATIO	ION	THEORETICAL M/Z RATIO	ERROR
4.136	2.652	O6+	2.665	-.47%
4.504	3.182	O5+	3.198	-.51%
4.995	3.977	O4+	3.998	-.48%
5.707	5.324	O3+	5.331	+.13%
6.342	6.740	Al4+	6.745	-.06%
6.841	8.012	O2+	7.997	+.18%
7.197	9.013	Al3+	8.993	+.22%
8.516	13.52	Al2+	13.490	+.25%

FIG. 8. Typical spectrum at a delay of 17 µs

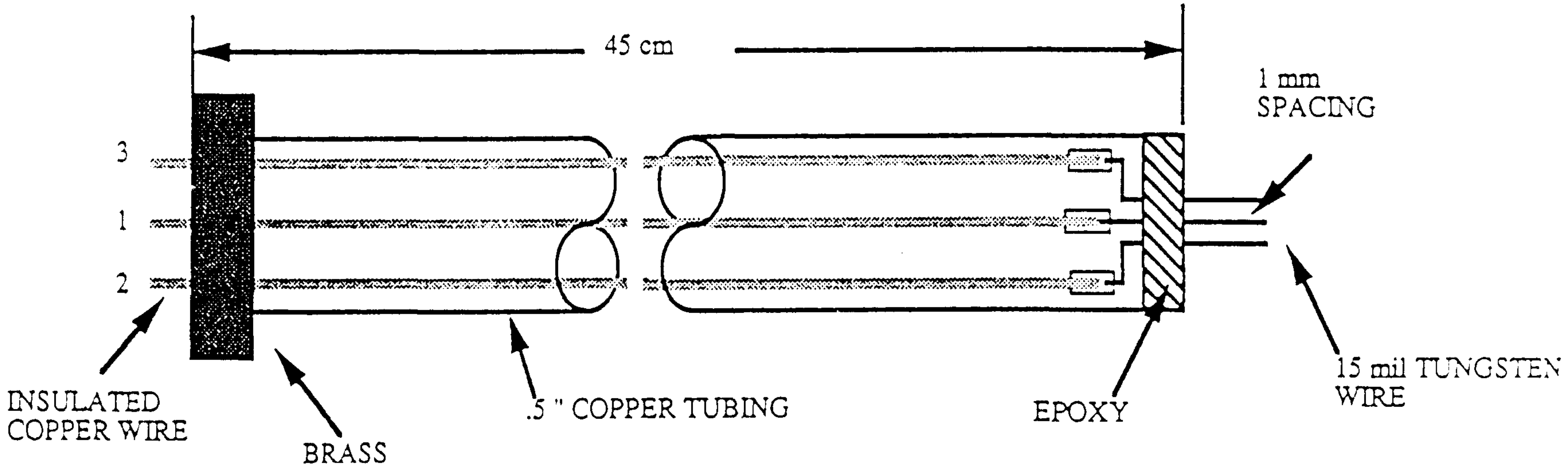


FIG. 9. Triple Langmuir probe

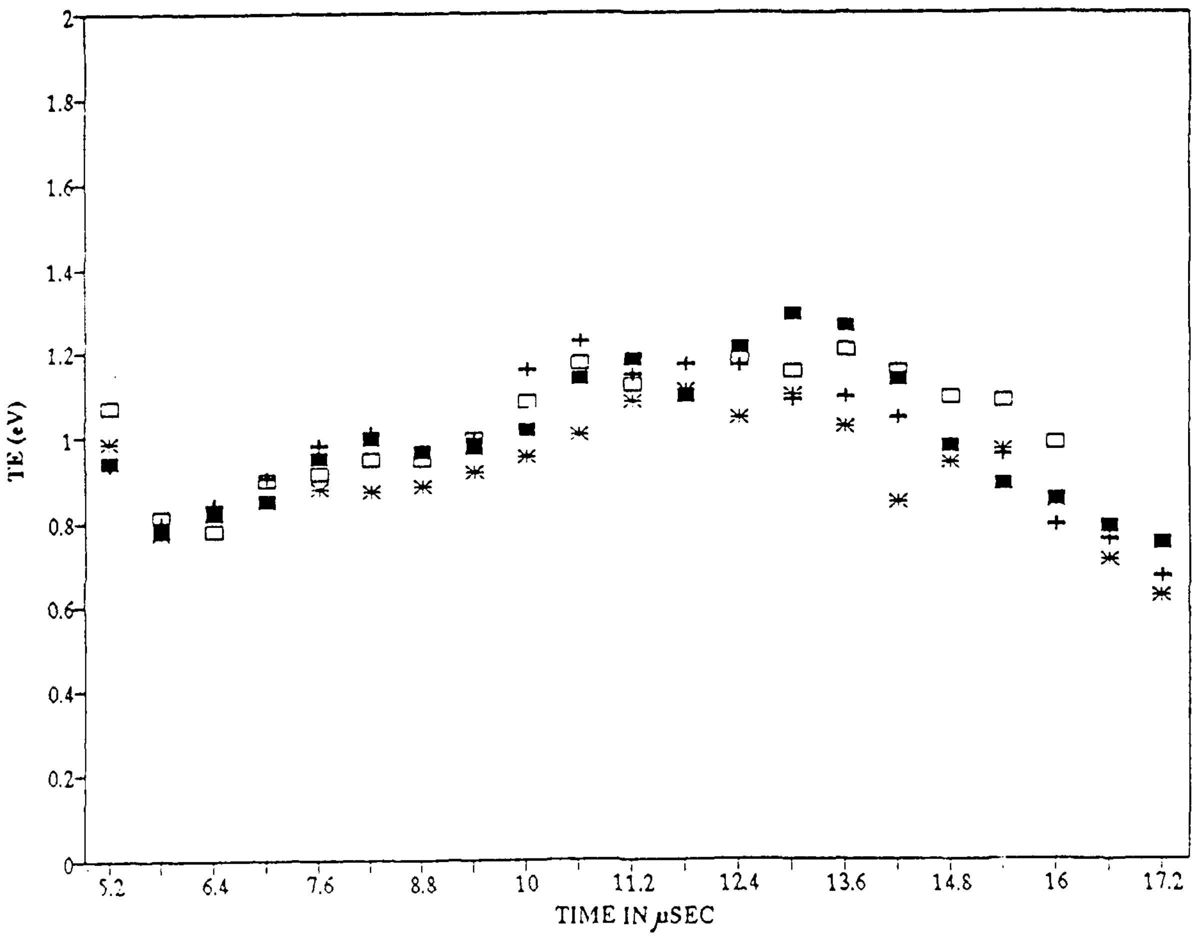


FIG. 10. Electron temperature for four independent shots

Theoretical work:

Simulation using the one-fluid model:

A one-dimensional and a two-dimensional one-fluid model was used to describe the expansion of the plasma jet. A rough picture of the expansion of the plasma jet was obtained from a one-fluid description of the plasma flowing past an edge. The plasma pressure is related to the plasma density by

$$p = n_e k T_e + n_i k T_i = nkT\left(1 + \frac{1}{Z}\right)$$

where Z is the charge state of the ions and $T_e = T_i = T$ is assumed.

The differential equations governing the motion are the one-fluid force equation and the continuity equation:

$$\rho \frac{d\vec{v}}{dt} = -\nabla p$$

$$\frac{\partial n}{\partial t} = -\nabla(n\vec{v})$$

The two equations can be written in two dimensions as

$$\frac{\partial v_x}{\partial t} = -\gamma \frac{(1+Z)kT}{M_i}\left(\frac{n}{n_0}\right)^{(\gamma-2)} \frac{\partial \frac{n}{n_0}}{\partial x} - v_x \frac{\partial v_x}{\partial x}$$

$$\frac{\partial v_y}{\partial t} = -\gamma \frac{(1+Z)kT}{M_i}\left(\frac{n}{n_0}\right)^{(\gamma-2)} \frac{\partial \frac{n}{n_0}}{\partial y} - v_y \frac{\partial v_y}{\partial y}$$

$$\frac{\partial n}{\partial t} = -v_x \frac{\partial n}{\partial x} - v_y \frac{\partial n}{\partial y} - n \frac{\partial v_x}{\partial x} - n \frac{\partial v_y}{\partial y}$$

M_i is the ion mass and $\gamma = (2 + f)/f$ for adiabatic expansion, where f is the number of degrees of freedom of the plasma particles.

The differential equations were solved numerically using a two-step Lax-Wendroff method with a near-step function with a width of 0.1 cm as the initial distribution. The ion velocity and the bulk plasma temperature were set at 7 cm/µs and 1 eV respectively. The ion species was taken as O^{3+}. The calculation showed the development of a steep front which causes a reduction of the extraction gap width of approximately 0.5 cm for adiabatic expansion (Fig. 11).

Simulation by the one-dimensional electrostatic particle in cell code ESI V2.01 (modified):

The code ES1 V2.01 was modified to allow the simulation of the extraction of electrons from the plasma boundary in the moving frame of the jet. There was an indication of a slight heating of the plasma when electrons were extracted. This program allowed also to observe the expansion of the plasma (Fig. 12).

Simulation using the MAGIC code:

The simulation shifted to the use of the 2 1/2 - dimensional fully electromagnetic PIC code as soon as is got available on our local network. The transverse extraction of electrons from a

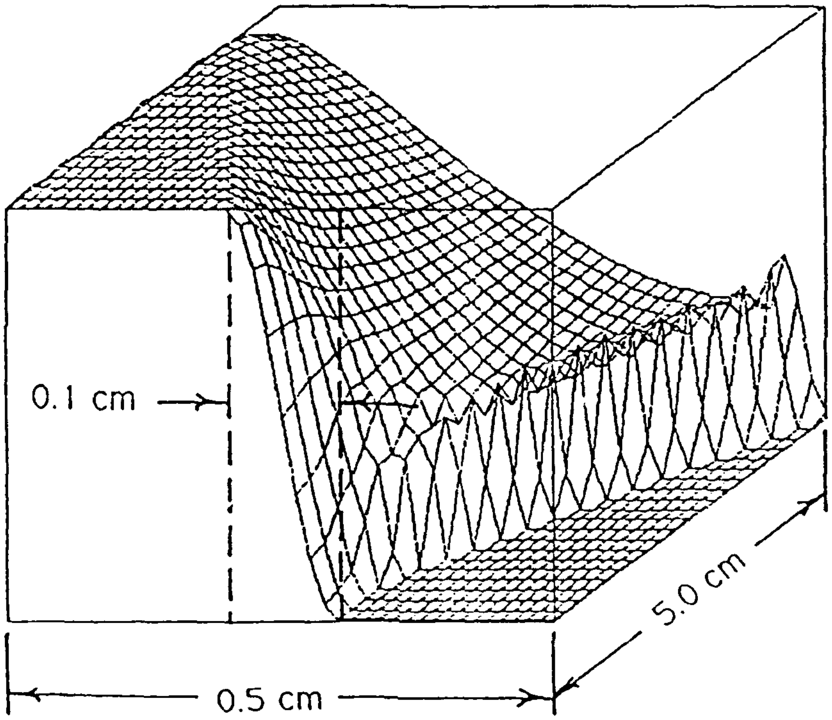


FIG. 11. Density distribution of a plasma jet behind a straight edge.

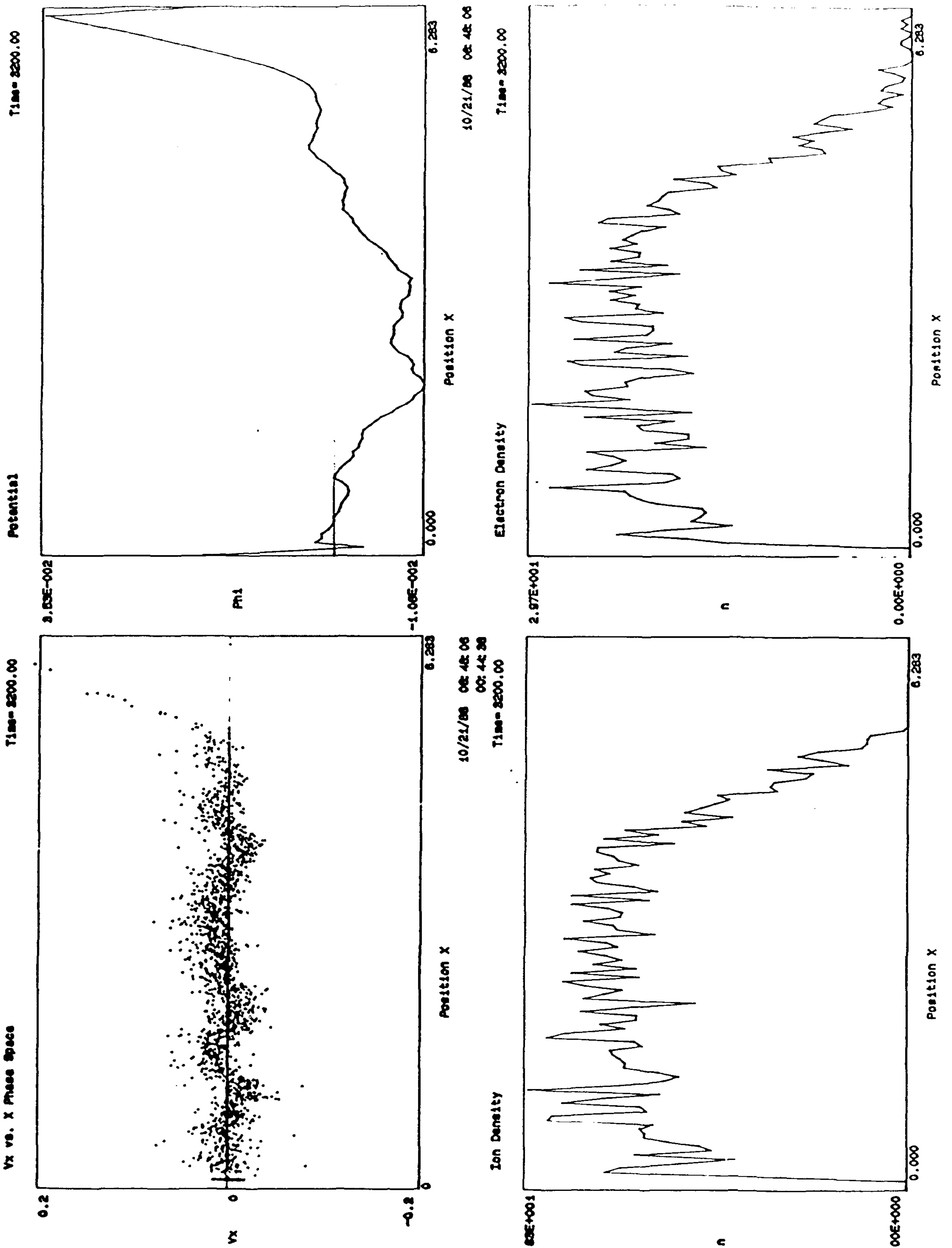


FIG. 12. Simulation of the plasma boundary with ESI V2.1 (modified); t=509 electron plasma periods.

plasma jet has been simulated with this code. The chosen geometry corresponded directly to the experimental dimensions. The plasma jet was initially populated with a uniform plasma density of 9×10^{10} cm^{-3}. The ions and the electrons in the simulation were represented by macroparticles with a mass and charge of 1.3×10^{9} real particles. The applied extraction potential was 25 keV and the extraction gap was chosen to be 1 cm. An electron current density of 9 A/cm^{2} was found which agrees within about 10% with the space charge limited flow density according to the Child-Langmuir relation (Fig. 13). The initial energy of the electrons was taken to be 260 eV to give an appropriate Debye length comparable to the cell size. It was observed that the extraction of electrons from the hot plasma initially decreases the electron temperature. Later the plasma is heated up by a two stream instability. This mechanism had been predicted when this investigation was initiated. It is essential for meeting the requirements of the Bohm criterion. The expansion of the plasma boundary into the extraction region occurs on a time scale which is much longer than the plasma period and could not be investigated with real mass ratios with the available computer resources.

Figure 14 shows the electrons in the plasma and in the extraction region after 10 ns. It shows a region were the plasma electron temperature has decreased due to the extraction of electrons. The left side has already heated up again due to the two stream instability.

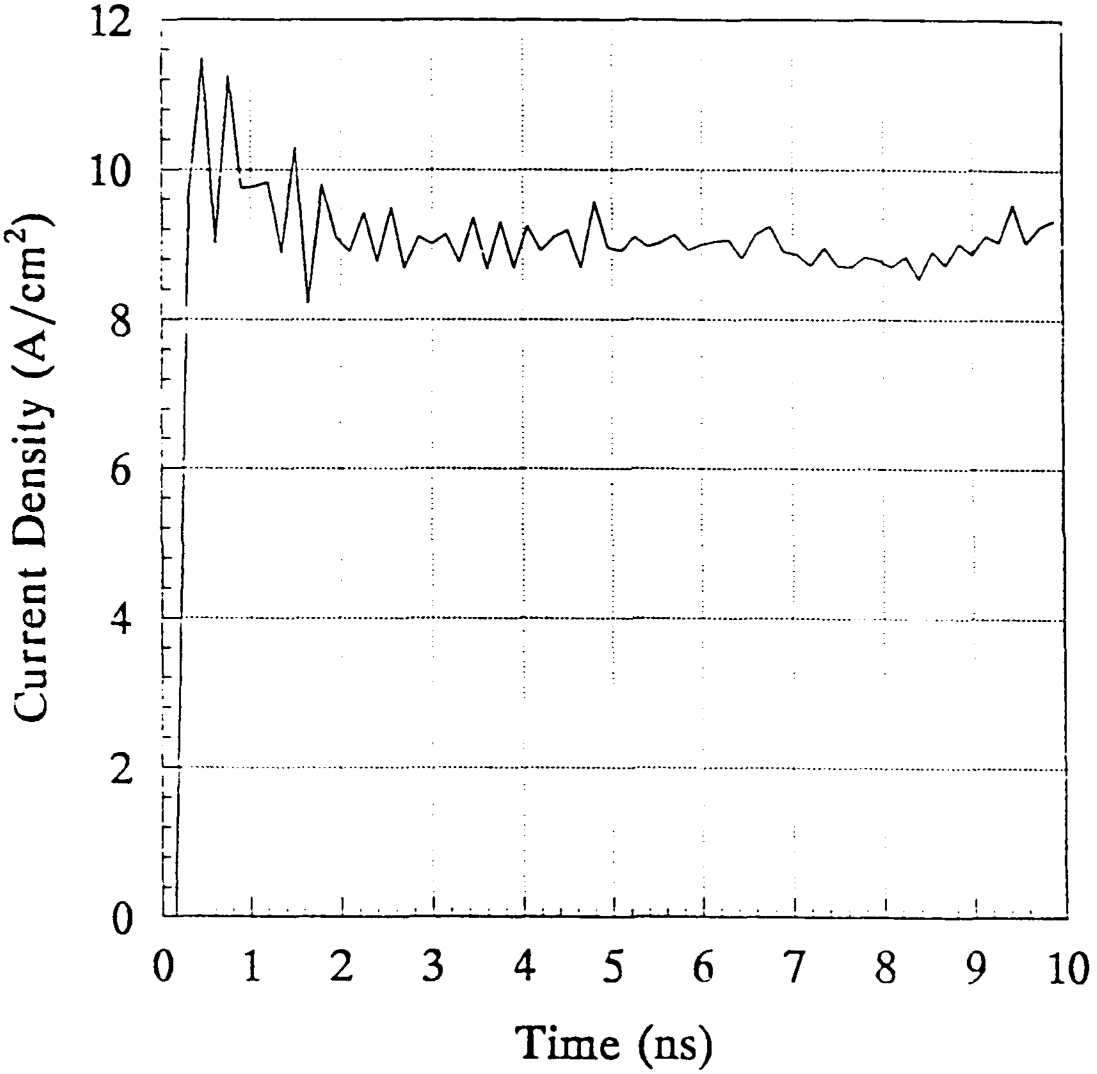


FIG. 13. Electron current density (MAGIC simulation)

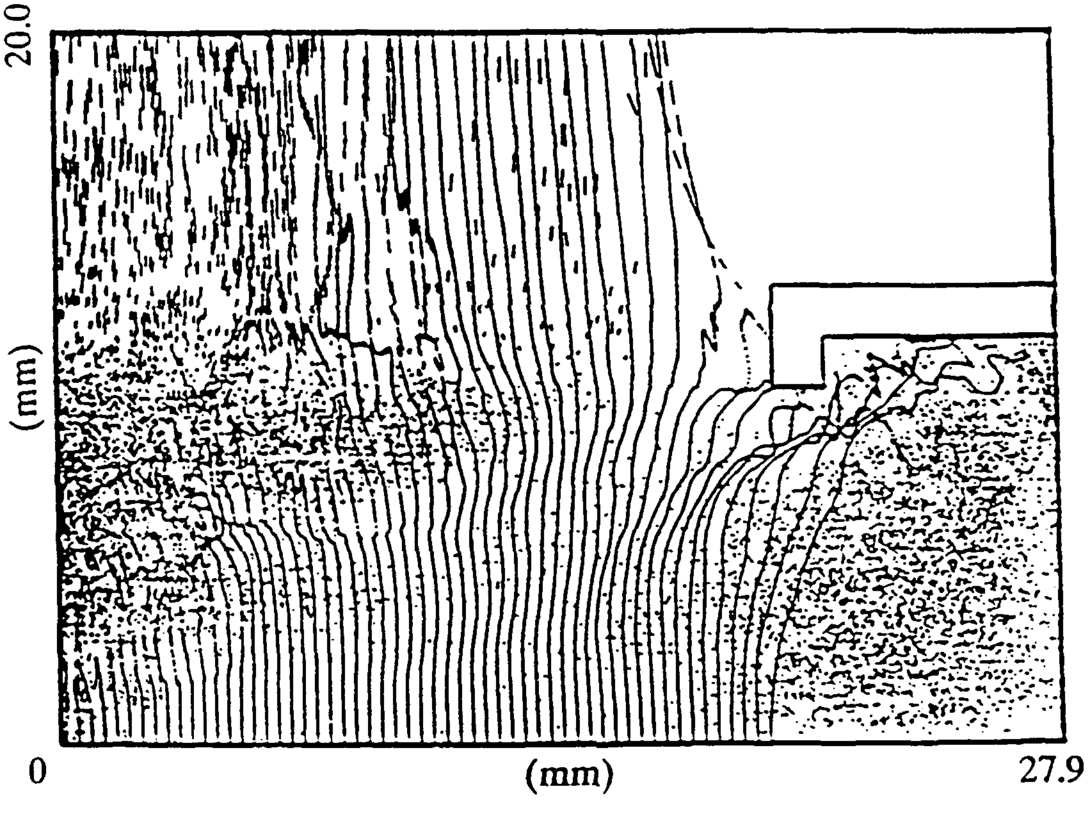


FIG. 14. Electron extraction at 10 ns (MAGIC simulation)

V. RESULTS:

Experimental results:

* An extracted current density of 18 A/cm^2 for an extraction time of 7 μsec has been achieved.

* The analysis of the extracted electron beam has been extended to the large area anode with a diameter of 74 mm. The intrinsic divergence has been determined for this anode to be about 38 mrad FWHM at a gap width of 15 mm, an extraction potential of 15 kV, and a current density of 5.7 A/cm^2. This gives a normalized microscopic brightness of 8×10^8 $Am^{-2}rad^{-2}$.

* The total current for the large area anode was 240 A.

* The shape of the plasma surface has been derived from a "pepper pot" plate imaging arrangement. The evaluation indicates a relatively small curvature of the plasma surface.

* The electron temperature of the plasma was measured with a double Langmuir probe at different locations. In the extraction region the temperature is 1 eV while further downstream the temperature is about 0.5 eV.

* The analysis of the plasma jet was achieved with a time of flight scheme. The content of highly ionized ions up to O^{6+} was surprising. The observed relative flow of different ionization states of the same ion species does not reflect a thermal equilibrium. There are very few hydrogen ions in the jet if the time between shots is reduced below about a minute. This agrees with the observation of good diode operation after conditioning shots.

*   The flow collimator was varied but, if in place at all, was not a critical item.

Theoretical Results:

*   The extraction of electrons from the plasma jet has been simulated using the code MAGIC. The extracted electron current agrees with the theory.

*   The temperature of a cold plasma rises to the theoretically needed temperature for supporting the extracted current density in approximate agreement with the Bohm criterion.

*   The magnetic field and the current density penetrate into the cold plasma within a very short time of a few nsec. This result would be hard to derive theoretically since it involves turbulent heating of the plasma.

VI. PRESENTATION OF THE RESULTS:

The results of the research were presented at the following seminars and conferences:

Seminars:

Kernforschungszentrum Karlsruhe GmbH, Karlsruhe, W-Germany (FRG) (1987)

Department of Physics, Texas Tech University, Lubbock, TX (1987)

Continuous Electron Beam Accelerator Facility, Newport News, VA (1987)

Conferences with proceedings:

29th Annual Meeting of the Division of Plasma Physics of the American Physical Society, San Diego, CA , 2-6 Nov. 1987.
[Bull. Am. Phys. Soc., 32, 1867 (1987)]

1988 IEEE International Conference on Plasma Science, June 6-8, 1988 Seattle, Wash.
[IEEE Cat. No. 88CH2559-3, 53 (1988)]

7th International Conference on High-Power Particle Beams, Karlsruhe, Germany, July 4-8, 1988
[Proc. 7th Intl. Conf. High-Power Particle Beams, 1031 (1988)]

7th IEEE Pulsed Power Conference, June 11-14, 1989 at Monterey, California
[Proc. 7th Pulsed Power Conf., Monterey, Cal., 941 (1989)]

International Conference on Phenomena in Ionized Gases, 10-14 July 1989 in Belgrade, Yugoslavia
[Proc. XIX Intl. Conf. on Phenomena in Ionized Gases, Belgrade, Yugoslavia, 238 (1989)]

1990 IEEE International Conference on Plasma Science, May 21-23, 1990 in Oakland, Cal.
[IEEE Cat. No. 90CH2857-1, 158 and 159, (1990)]

8th International Conference on High-Power Particle Beams, July 2-5, 1990, Novosibirsk, USSR
[Proc. 8th Intl. Conf. on High-power Particle Beams, Vol. 2, 946 (1990)]

Journal Publication:

J. Appl. Phys. 70, 15 Dec. 1991 (to be published)

Theses and Dissertations:

Master theses:

David E. Buraczyk, "Mass Spectrometry of a Fast Plasma Jet" (1990)

Gretchen E. Graham Edelmon, "Influence of Source Parameters on the Properties of a Plasma Jet" (1991)

Robert R. Burton, "Numerical Simulation of Electron Extraction from a Plasma" (1991)

Ph.D. Dissertation:

Michael G. Grothaus, "Experimental Investigation of a Plasma Edge Cathode Scheme for High Current Density, Long Pulse Electron Extraction"

VII. PARTICIPATING PROFESSIONAL PERSONNEL AND STUDENTS:

Klaus W. Zieher (Associate Professor) was participating in the research and supervising the students working on the plasma edge cathode investigation.

The participation of graduate students in the research lead to one Ph.D. dissertation and three M.Sc. theses.

At various times undergraduate students were involved in the investigation.

REFERENCES

[1] C. LeJeune and J. Aubert, Advances in Electronics and Electron Physics, Suppl. **13A**, Applied Charge Optics, A. Septier, Ed. New York: Academic, 159 (1980)

[2] C. W. Roberson and P. Sprangle, Phys. Fluids B 1, 3 (1989).

[3] P. Loschialpo and C. Kapetanakos, J. Appl. Phys. 63, 2552 (1988).

[4] C. R. K. Marrian and A. Shih, IEEE Trans. Electron Dev. 36, 173 (1989).

[5] J. Hasker, J. E. Crombeen, and P. A. M. van Dorst, IEEE Trans. Electron Dev. 36, 215 (1989).

[6] G. Bekefi, R. Shefer, and S. Tasker, Nucl. Instr. and Meth. in Phys. Res. A 250, 91 (1986).

[7] C. H. Lee, P. E. Oettinger, E. R. Pugh, R. Klinkowstein, J. H. Jacob, J. S. Fraser, and R. L. Sheffield, IEEE Trans. Nucl. Sci. **NS-32**, 3045 (1985).

[8] J. S. Fraser and R. L. Sheffield, IEEE J. Quant. Electronics **QE-23**, 1489 (1987).

[9] S. Humphries, Jr., S. Coffey, M. Savage, L. K. Len, G. W. Cooper, and D. Woodall, J. Appl. Phys. 57, 709 (1985).

[10] K. W. Zieher, 1986 IEEE International Conference on Plasma Science (Saskatoon, Canada, May 19-21, 1986), Conf. Record Cat. No. 86CH2317-6, p. 12.

[11] J. D. Lawson, The Physics of Charged-Particle Beams (Clarendon, 2nd edition, 1988), p. 210.

[12] M. G. Grothaus and K. W. Zieher, Proceedings of the 7th IEEE Pulsed Power Conference, Monterey, June 11-14, 1989, p. 941.

[13] I. G. Brown, J. E. Galvin, R. A. MacGill, and R. T. Wright, Rev. Sci. Instr., 58, 1589 (1987)

[14] L. K. Len, C. Burkhart, G. W. Cooper, S. Humphries, Jr., M. Savage, and D. M. Woodall, IEEE Trans. on Plasma Science, **PS-14**, 256 (1986)