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REVIEW OF PLASMA SOURCES IN THE VIEW OF A BEAT-WAVE ACCELERATOR EXPERIMENT

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TABLE

I Introduction

II Review of low and medium density plasma sources

III Expertise of CRPP in low and medium density plasma sources and experiment construction

IV Possible design of the Beat wave Accelerator Experiment

A-HF cavity at the plasma extremities
- High Frequency type source:
  - Interdigital Source (Lisitano coil Type I)
  - Slow Wave Structure (Lisitano coil Type II)
  - Horn antenna
  - Turnstile source

B-HF cavity placed around drifting plasma
- Small plasma type sources:
  - Washer gun
  - Marshall gun
  - High Frequency source

- Hot cathode type sources
  - Large filamentary source
  - small cathode
  - Large cathode; oxide (Ba O, Sr O, Ca O....) cathode Lanthanum hexaboride

V Review of instrumentation for test of cavity (at CRPP) in french *By S. Alberti*

VI Annexes

1) Compilation of plasma sources from publications
   Open waveguide sources, turnstile, horn antenna
   Capacitive antenna at low RF (155MHz)
   Interdigital structure (Lisitano Coil Type I)
   Slow Wave Structure (Lisitano Coil Type II)
   Hollow cathode and Washer gun
   Hot Cathode and filamentary assembly
2) Plasma diagnostics *By F. Skiff*
3) Plasma parameters tables

I INTRODUCTION

The beat wave accelerater concept is described in (1) where it is shown that large amplitude (10^4 V/cm) plasma waves can be resonantly excited by beating microwave pumps in an open resonator (2) filled with plasma of subcritical density.

The longitudinal component of the E field is used for accelerating particles, where as the radial component which is decoupled from the longitudinal field, could be at the origine of defocusing the microwave beam.

There are two ways in performing the experiment : one is the use of laser beams (Chen, Josky, Dangor, ...), the second way is the use of high frequency microwave generated by gyrotrons, CARM ... in the regime of 100÷150GHz.

The use of lasers makes it difficult in focusing the beams because of their small size, and also because of the short pulse length which renders difficult detection of the high E-field generated.

The proposed Plasma source, with differential pumping, large La B6 cathode for long life time, low magnetic field , plasma could be produced continuously for adjustment of HF cavity in order to avoid high reflection due to plasma and so improve Q value during high density phase.

Problems :

- Near to 100% ionized Hydrogen plasma.
- Low noise dn/n less than or in order of 1%, at low and high frequency compare with ion plasma frequency and total pulse length. See pulses sequences.
- Should have low collision frequency and low level of turbulence. See plasma parameters table.

(1) U. de Angelis et al. IEEE Transactions on plasma Science, Vol PS-15, 2, april 1987, pp 179-185

(2) See for example the presentation of J. Lawson and G. di Massa at the first meeting at Rutherford Appleton Lab.

II
REVIEW OF LOW AND MEDIUM DENSITY PLASMA SOURCES

The reference numbers correspond to annexe VI a)

Ref.	Plasma source	Freq. source	ø plasma cm	n_e max cm^{-3}	T_e range (eV)	T_i range (eV)	$\delta n/n$ %	neutral p. Torr	B-field k Gauss	comments
(1)	open waveguide ECR	2.35GHz 2kW	9	10^{12}	9		?	$3 \cdot 10^{-3}$	$\cong .9$	
(2)	open waveguide ECR	2.45GHz 1.7kW	8	10^{12}	20		?	$5 \cdot 10^{-4}$	$\cong .9$	
(3)	open waveguide ECR	1.7GHz 5.8kW	8	10^{12}			?	$10^{-3} + 10^{-2}$	$= .6$	
(4)	on conical vessel open waveguide ECR	10GHz 150W	2.5	10^{-12}			?	$10^{-3} + 10^{-1}$	4000 Oe	
(5)	open waveguide on conical vessel ECR	9.375gW	2.5		3 + 5	0.1 + 0.2	?	$10^{-4} + 10^{-1}$	6000 Oe	
(6)	Pyramidal horn	10.3GHz		10^{13}	5 + 30		?	$10^{-5} + 10^{-2}$		
(7)	RF	155MHz	9.5	10^{12}	15	up to 15	?	10^{-3}	16 k Gauss	
résumé	open waveguide ECR ($\omega_0=\omega_{ci}$)	1.7 + 10 GHz 30W + 5.8kW	max. 10 cm	max. 10^{13} over crit. density ($\omega_0=\omega_{pe}$)	3 + 30eV $T_{e\perp} \neq T_{e\parallel}$	low T_i up to 1 + 2eV max.	no answer found	$10^{-5} + 10^{-1}$	at res. with with ω_0 $\cong$ 1kGauss	comments : - 10+50% ionization is reached but bad radial density profile - high B-field at the source - noisy - high frequency noise to plasma .....

Ref.	Plasma source	Freq. source	ø plasma cm	$n_e$max (cm^{-3})	T_e range (eV)	T_i range (eV)	$\delta n/n$ (%)	neutral p. (Torr)	B-field (k Gauss)	comments
(8)	interdigital Lisitano coil ECR	8.45GHz	3.5	2.5 10^{10}				$10^{-4}+10^{-2}$	1.3	1+50% ionization
(9)	Lisitano coil ECR	10GHz 100W	5	5 10^{11}	20		5+1	$5.10^{-6}+$ 5.10^{-4}	10	50% ionization max.
(10)	helical microwave gun $\omega_{ce} \gg \omega_0$	2.35GHz 5kW		$1.5.10^{12}$				$10^{-4}+10^{-3}$	13	10% ionization
(11)	SWS	3GHz 70W	3	10^{12}	10		5	10^{-3}	1.8	30%
(12)	SWS ECR	2.45GHz 1kW	16	4 10^{11}	8			10^{-3}	.9	
(13)	SWS	2.45GHz 1kW	5	2 10^{12}				10-3	2 max	
(14)	helical coil		5	10^{12}	3+6			1 $10^{-4}+$ 2 10^{-3}		
(15)	helical coil		15	10^{11}	5	1		10^{-4} - 10^{-5}	.9	
(16)	SWS ECR	2.45GHz 5kW	8	2 10^{12}	5			2 10^{-4}	.9	
(17)	helical coil ECR		4+5	10^{11}	15	0.2+2	1+5	$10^{-5}+$ 10^{-3}		
(18)	helical coil	2.45GHz 1.5kW	10	10^{13}	7.5			$10^{-3}+$ 10^{-2}	4+20	1+10% H 5+30% Ar
Résumé	mainly SWS	2.45GHz	3+16	10^{-13}	3+20	.2+2	1+10	5 $10^{-6}+$ 10^{-2}	mainly 1	-max. 50% ionization - high B-field

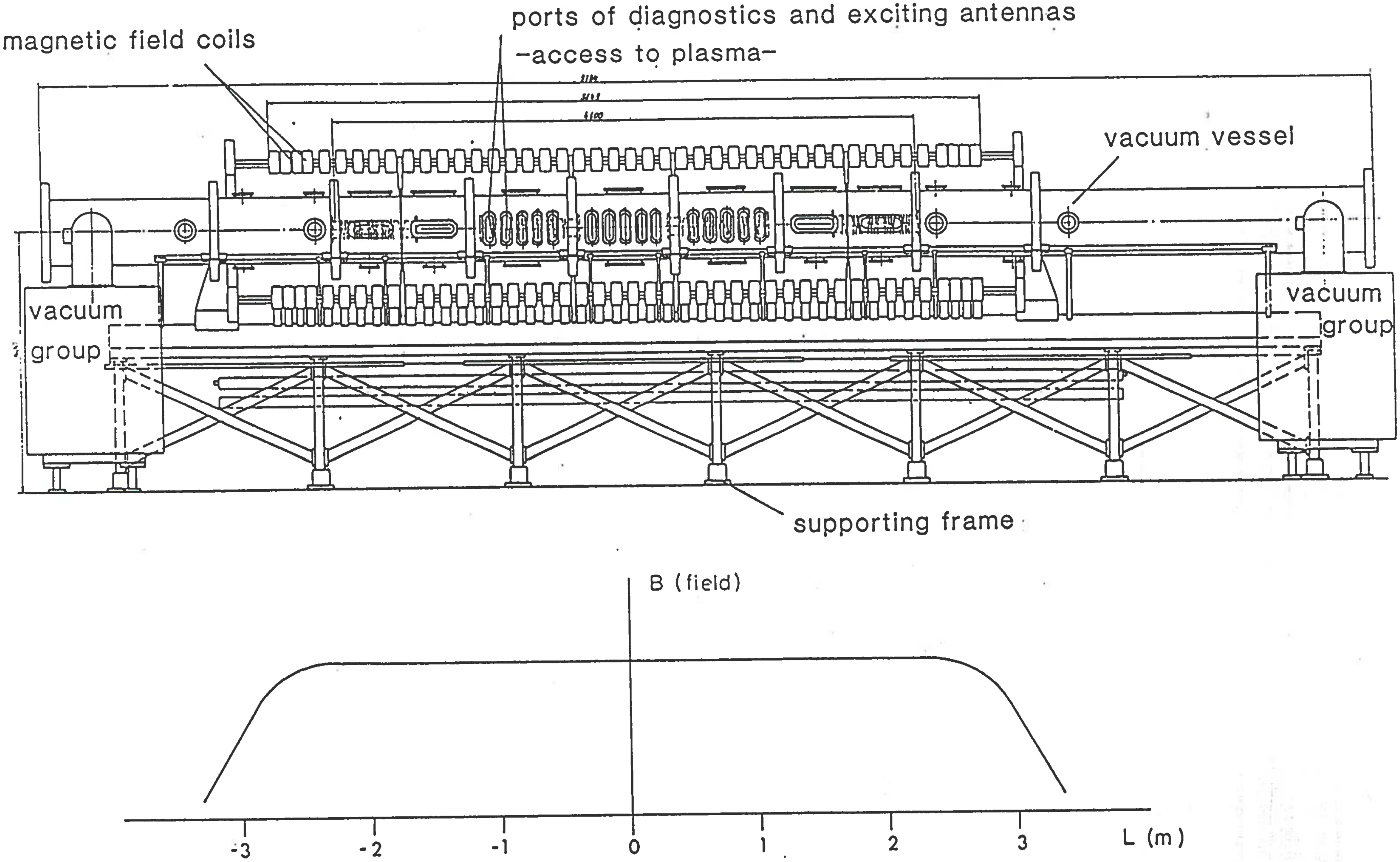
Ref.	Plasma source	Freq. source	ø plasma (cm)	density (cm^{-3})	T_e range (eV)	T_i range (eV)	$\delta n/n$ (%)	neutral p. (Torr)	B-field (k Gauss)	comments
(19)	hollow cathode	7kV	1.4	10^9+10^{11}	.3+12		3	10^{-2}	3	
(20)	washer gun	10kV $\tau \simeq 8\mu s$	1.4	10^{16}	300+500	50+150 (impurities)	?			70% ionization
(21)	hollow cathode	1kW/100A I_{max} 800A τ=	.64	5 10^{13}	5		?	3 10^{-4} (chamber)		
(22)	washer gun	1+15kV τ=15+600μs 200A+3kA		3 10^{14}	3	3	?	10^{-2}-10^{-4}		90% ionized
(23)	filamentary hot cathode		.6	10^{15}source 10^{12}chamber	30+300					
résumé	washer gun	10+100μs	2	10^{14}+10^{15}	3+500	3+150	?	10^{-4}		70+90% ionization

Ref.	Plasma source	Freq. source	ø plasma (cm)	density (cm^{-3})	T_e range (eV)	T_i range (eV)	$\delta n/n$ (%)	neutral p. (Torr)	B-field (k Gauss)	comments
(23)	filamentary cathode (very large source)	I_p=15A heating 4kW	8	10^{11}	2.5	.2	1	3 10^{-4}	1	1% ionization
(24)	large size cathode ø 50cm	heating 9kW	45	10^{12}	2	.2	?	2 10^{-4}	.15	$\nu_{coll}/\omega_{ce} \approx 5\ 10^{-3}$ 10% ionization
(25)	large size cathode ø 60cm	I_p=200A/40V heating 20kW	60	10^{12}	2	2	?	?	2	no much output work to my knowledge probable : ~ 10% ionization
résumé	cathode ø 50 cm ø 60 cm	heating 9+20kW I_p=150+200A	ø 40+60	10^{12}	2	.2 to 2	.5+2%	10^{-4}	.15+2	- 10% ionization - low B-field - low ν_{coll}/ω_{ce}

III

EXPERTISE AT THE CENTRE DE RECHERCHES EN PHYSIQUE DES PLASMAS (CRPP), IN LOW AND MEDIUM DENSITY PLASMA SOURCES DEVELOPMENT AND EXPERIMENTAL CONSTRUCTION

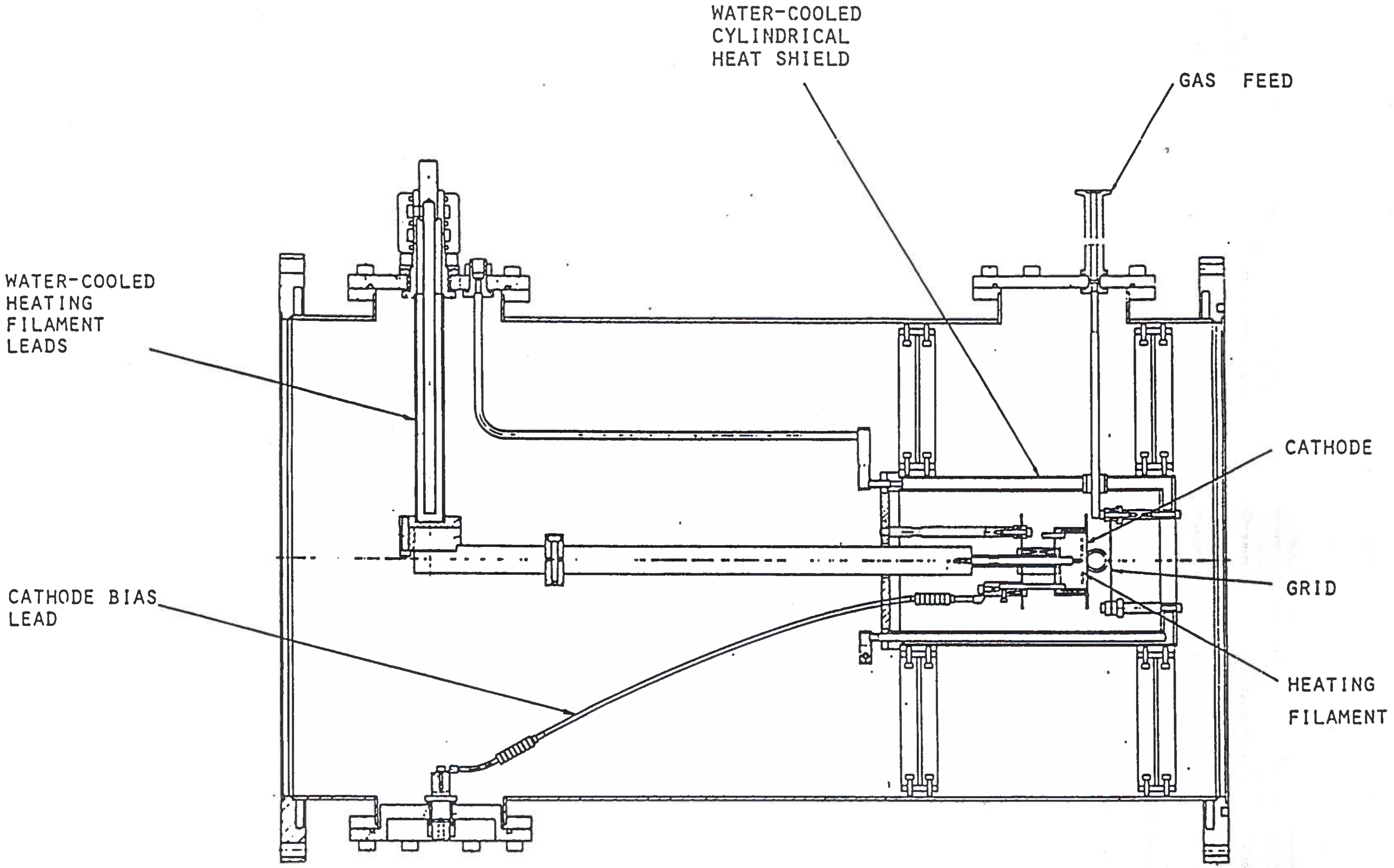
Some experiments constructed at CRPP are shown. The plasma sources are different from each other and the characteristics of each are presented. Not all of them are still in operation.



LMP – general view and B field graph –
Fig. 1

Coil inner diameter	.522 m
Coil outer diameter	.830 m
Coil thickness	.092 m
Number of turns	4
Number of layers	9
Conductor type	copper OF
Conductor size	20.83 × 15.75 mm^2
Cooling	water flow through a circular hole of diameter 6.35 mm
Typical coil electrical resistance at 20° C	4.58 mΩ
Total inductance of the solenoid	$5 \cdot 10^{-2}$ H
Max. input water temperature	60° C
Max. output water temperature	75° C
Water flow rate	120 l/min at 8.6 bars

TABLE I : Coil characteristics



Oxide cathode source

Fig. II

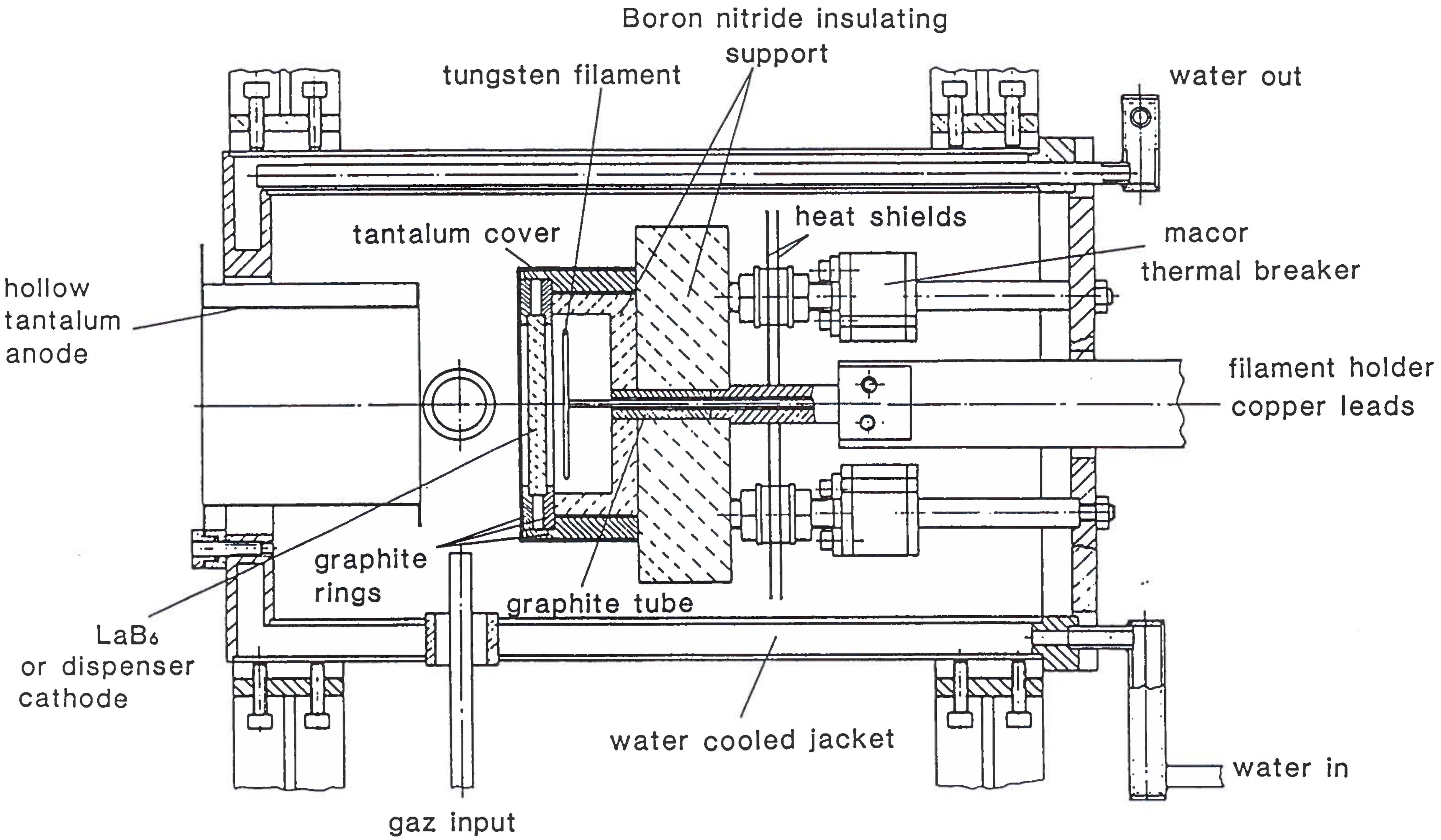
Plasma source :

Hot cathode (BaO)	
Cathode diameter	5 cm
Cathode current	~ 1 - 15 A continuous regime < 50 A pulse regime

Plasma :

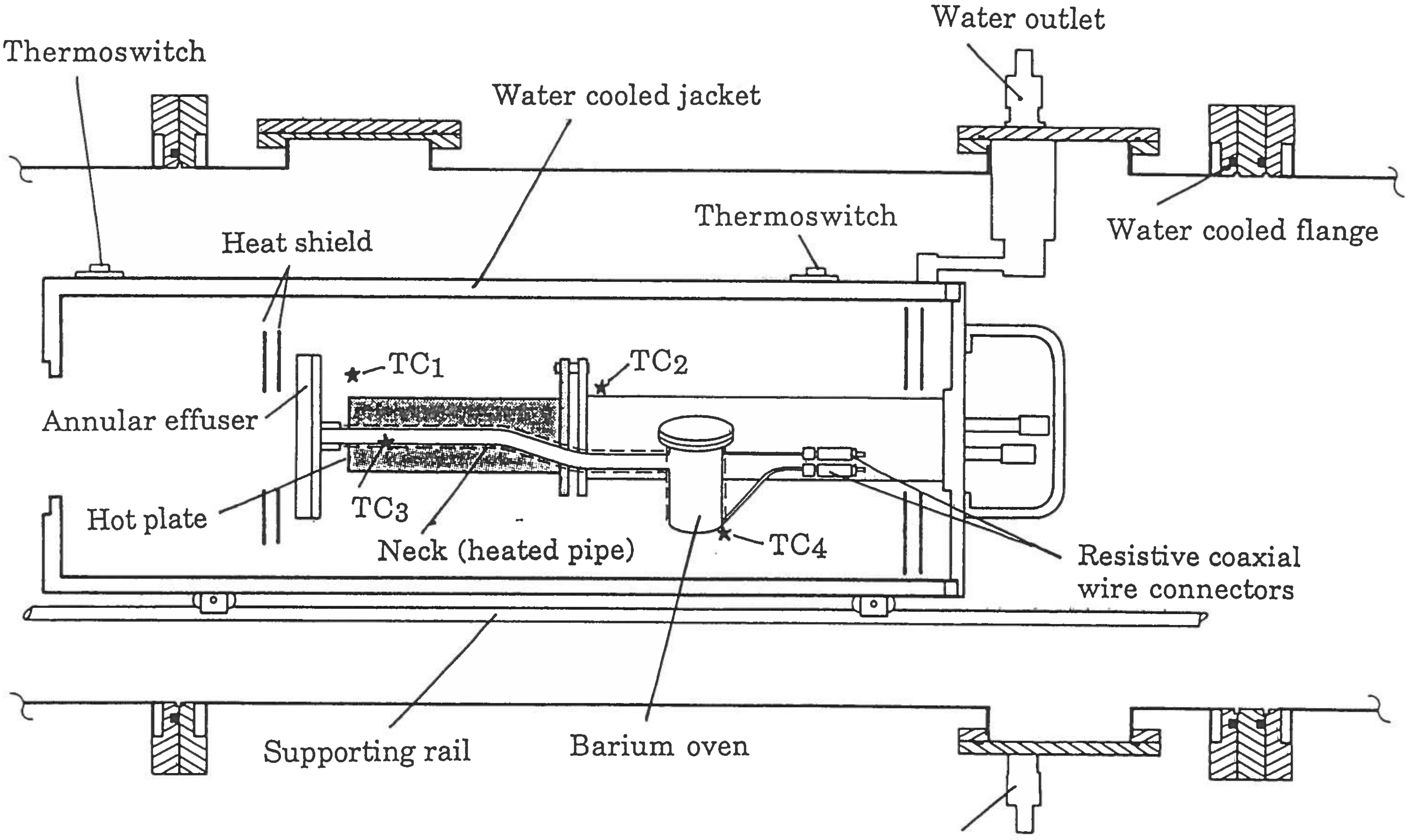
Plasma diameter	5 cm
Plasma length	4.75 m
Plasma density	$\sim 10^{10} - 10^{12}$ cm^{-3}
Ratio of plasma density to discharge current (Ne plasma)	6×10^{10} cm^{-3} A^{-1}
Neutral density	$\sim 10^{12} - 10^{13}$ cm^{-3}
Electron temperature	~ 6 - 15 eV
Ion temperature	~ 0.15 - 10. eV
Electron Larmor radius (T_e = 9 eV, B = 0.3 T)	2.38×10^{-3} cm
Ion Larmor radius (for a Ne_{20} ion T_i = 0.2 eV, B = 0.3T)	6.8×10^{-2} cm
Ion Larmor radius (for Ar_{40} ion T_i = 0.2 eV, B = 0.3 T)	9.6×10^{-2} cm

TABLE II : Design and plasma parameters of the LMP
(with BaO cathode)



Lanthanum hexaboride cathode arrangement

Fig. III



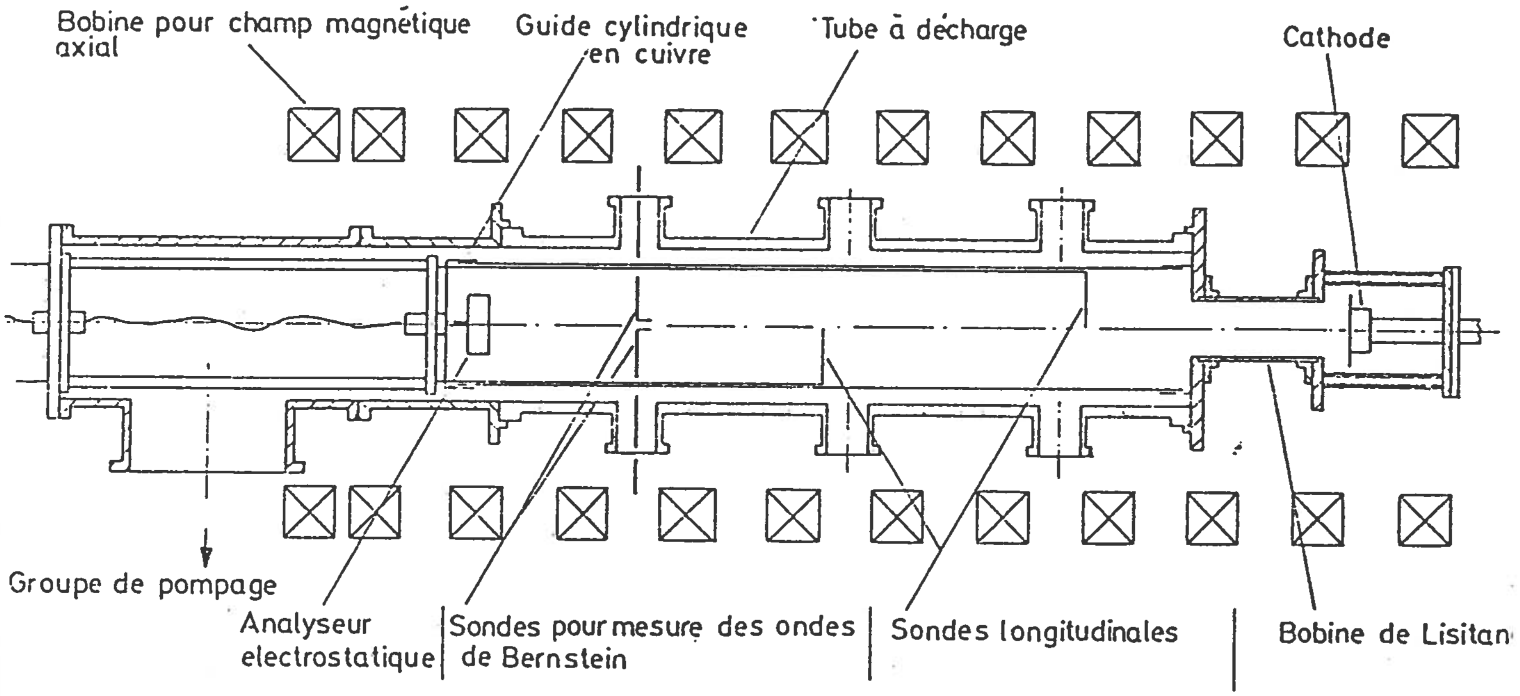
TC_1 ... TC_4 are thermocouples

Fig. 4

Barium	M = 138 a.m.v.	$M/m_e = 2.5 \times 10^5$
n_i	$10^8 < n_i < 10^{11}$ part/cm^3	
T_i=T_e	$T \approx 0.2$eV	
B field		$1<B<3$kGauss
Ion gyroradius	r_{gi}=0.18cm	for B=3KG and T_i=0.2eV
Electron gyroradius	r_{ge}=3.67×10^{-4}cm	for B=3KG
Ion thermal velocity	$V_{thi} \approx 5.3\times10^4$cm/s	
Ion drift velocity	$V_{di} \approx 1.2\times10^5$cm/s	
Ion thermal energy	T_i = 0.2 eV	
Ion drift energy	$E_{D\parallel} \approx$ 1.0 eV	
Ion plasma freq	$f_{pi} \approx$ 565 KHz	for $n=10^9$cm^{-3}
Electron plasma freq	$f_{pe} \approx$ 284 MHz	for $n=10^9$cm^{-3}
Ion collision rate	ν_{ii} = 4.8KHz	for $n=10^9$cm^{-3}
Electron collision rate	ν_{ee} = 0.29MHz	for $n=10^9$cm^{-3}

TABLE IV : LMP Q parameters

ESRIN Plasma Wave



Plasma parameters (two possible plasma sources) : - in cathode

- RF

RF discharge :

$n_e \sim 10^9 - 10^{11}$ el cm^{-3}

$T_e \sim 2 - 5$ eV

$T_i \sim .1 - .2$ eV

Pressure $\sim 5\cdot10^{-5} - 4\cdot10^{-3}$ (Argon)

Collisional frequencies :

$7\cdot10 < \nu_{en} < 3\cdot10^6$ Hz $(1\cdot10^{-3} < p < 4\cdot10^{-3}$ Torr)

$3\cdot10 < \nu_{ei} < 3\cdot10^6$ Hz $10^{10} < n < 10^{11}$ el.cm^{-3}, $T_e \sim 2$eV

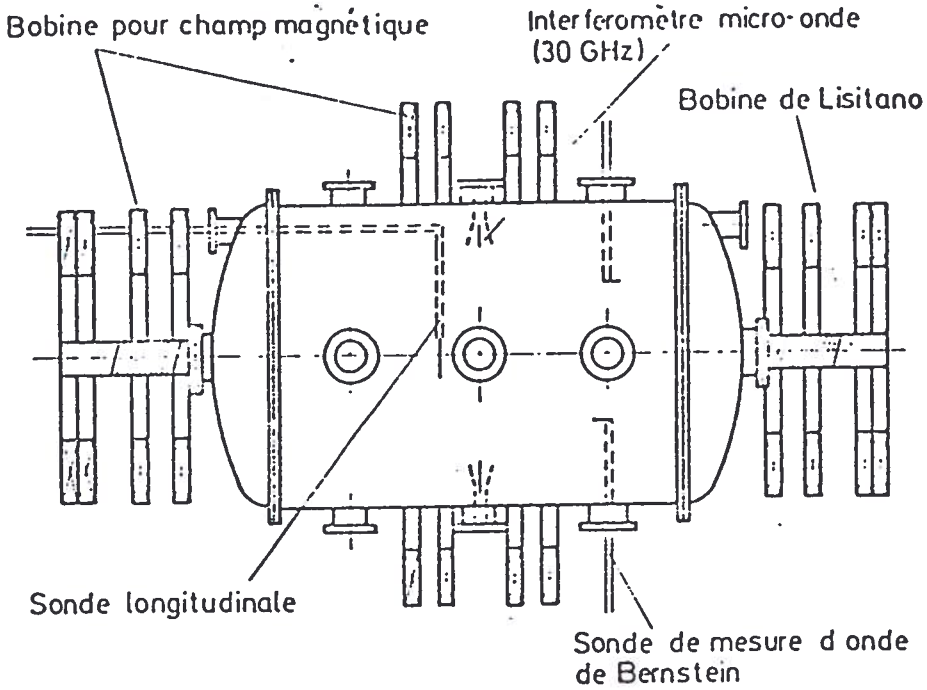
$\lambda_D \sim .5$mm

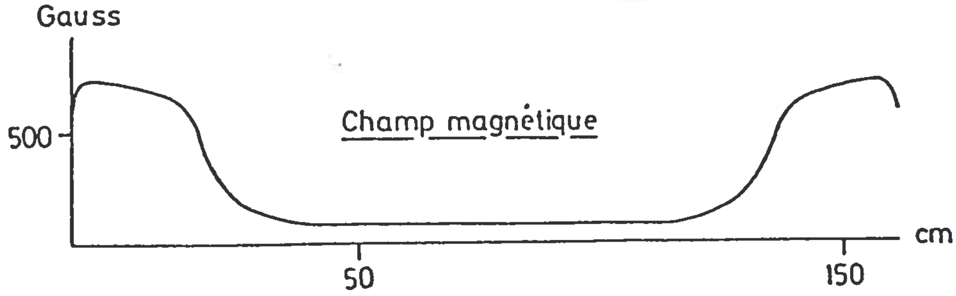
$5\cdot10^{-3} < \frac{\delta n}{n} < 5\cdot10^{-2}$

Magnetic field (0 - 2 KGauss) is used for RF discharge from $\nu_{ce} = .9 - 3$ GHz

Diagnostics.

MIROX





A. First results and possibilities

Plasma source : 2 Helical Lisitano coils (Øint ∿ 5.3 cm)

Slow wave structure

with Ail RF Power Generator :

- frequency .9 GHz
- power ∿ 20 - 40 Watts CW
- n_e ∿ 10^9 el cm^{-3}
- T_e ∿ 3 - 6 eV
- T_i ∿ .1 - .3 eV (probable)
- pressure ∿ 10^{-4} - 10^{-3} Torr
- fluctuation level $\delta n/n$ ∿ 1 - 10%

Mirror ratio : B_m/B_o 3 to 10

Maximum B main 400 Gauss

Maximum $B_L$coil 4 KGauss

ν_{en} and ν_{ei} (see ESRIN device)

B. Possibilities

Power sources for Lisitano coils :

Magnetron	2.45 GHz	100 watts
Microtron	2.45 GHz	1 Kwatt
Magnetron	2.45 GHz	6 Kwatts

With the 6 KW source, one should expect maximum densities of the order of 10^{12} - 10^{13} el cm^3.

PLASMA BOX Ø2m

Plasma parameters : Plasma sources : Hot filaments

$n_e \sim 10^8 - 2\cdot10^{11}$ el cm^{-3}

$T_e \sim 2$ eV

$T_i \sim .1$ eV

Pressure $\sim 5\cdot10^{-5} - 2\cdot10^{-3}$ Torr

Collision frequencies :

$\nu_{en} \sim$ 18 KHz - 740 KHz
$\nu_{ei} \sim$ 1.6 KHz - 2.4 MHz

$\lambda_D \sim 7.5\cdot10^{-2}$ cm - $2.4\cdot10^{-3}$ cm

fluctuations $\sim 10^{-3} - 10^{-2}$

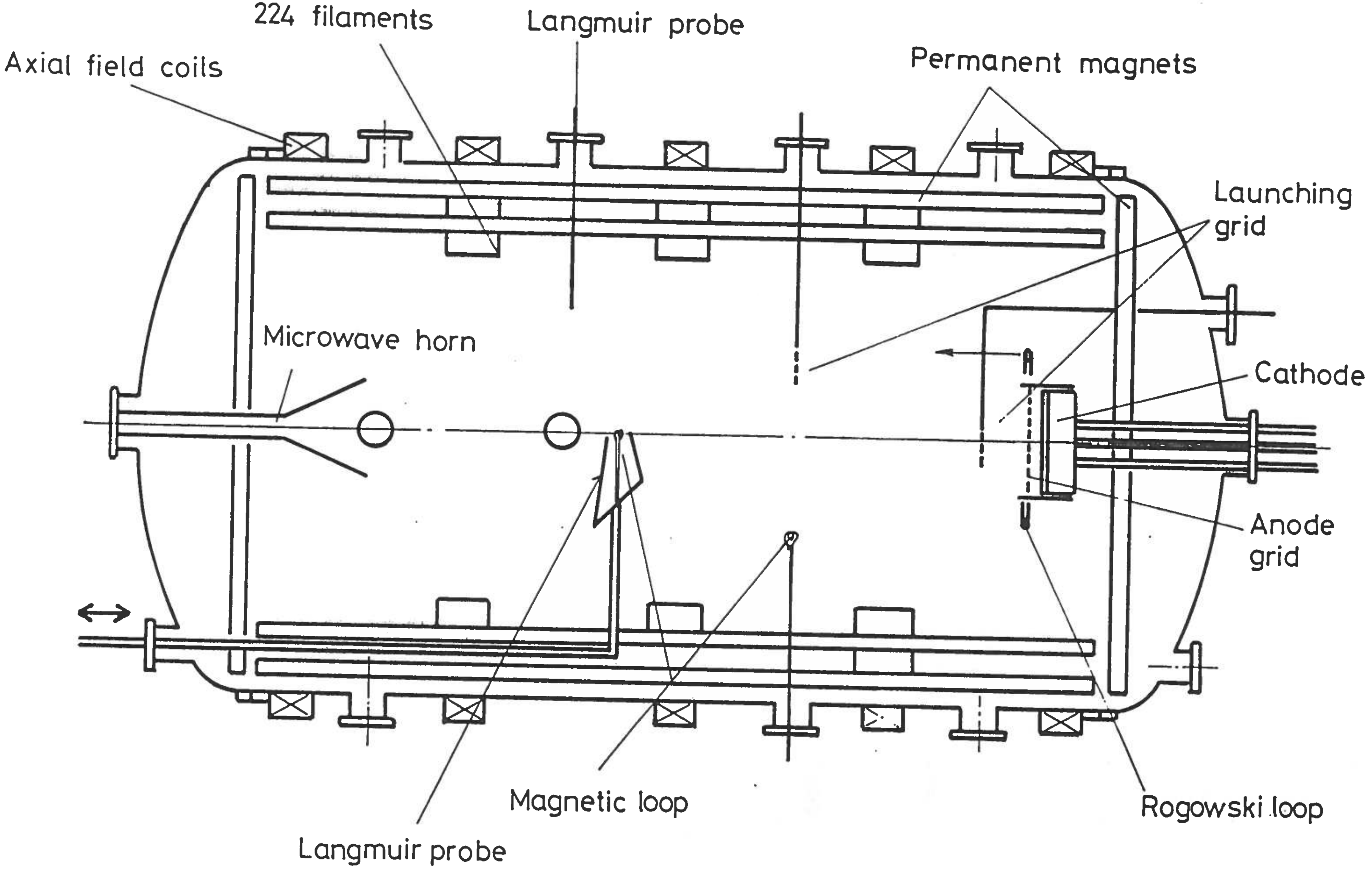
Work done :

Microwave - plasma interactions

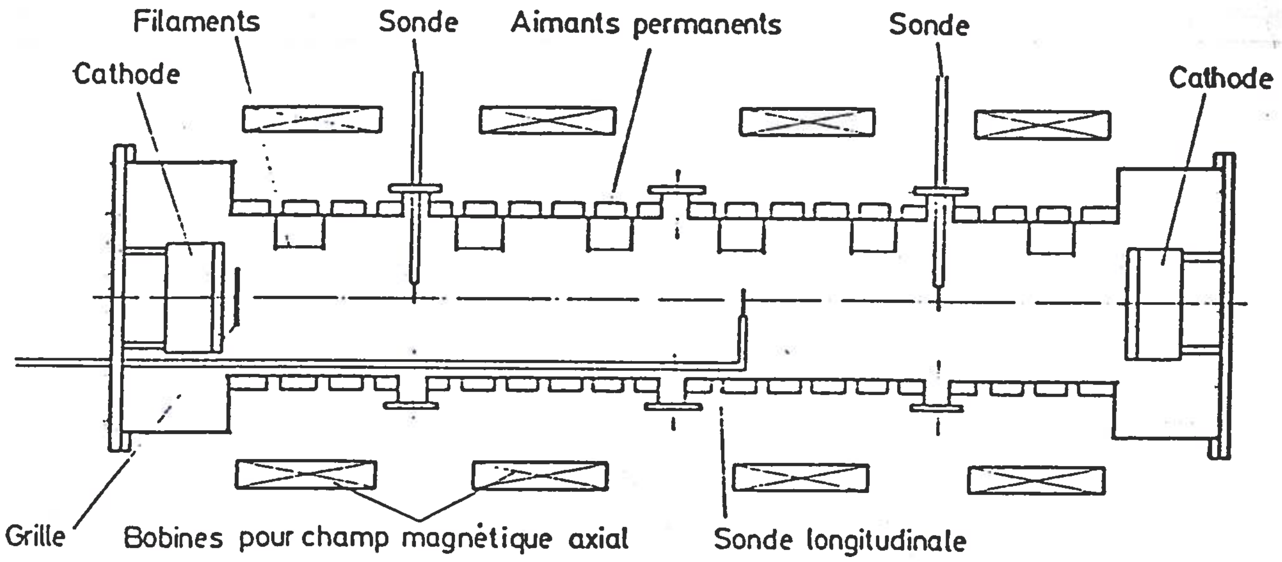
Current work :

Microwave - plasma interactions

Experimental set-up



NESSIE



Plasma box : Plasma source : Hot filaments

$n_e \sim 10^8 - 10^{10}$ el.cm^{-3}

$T_e \sim 1. - 3$ eV

$T_i \sim .1 - .2$ eV

Pressure $10^{-4} - 10^{-3}$ Torr

Collision frequencies:

$\nu_{en} \sim 30$ kHz

$\nu_{ei} \sim 40$ kHz

fluctuations $\delta n/n \sim 1\%$ (without $\vec{B}$ field)

possible $\vec{B}$ field $\sim$ 100 Gauss

Current work :

A current is drawn between 2 cathodes; this experiment is mounted in order to excite turbulent spectra.

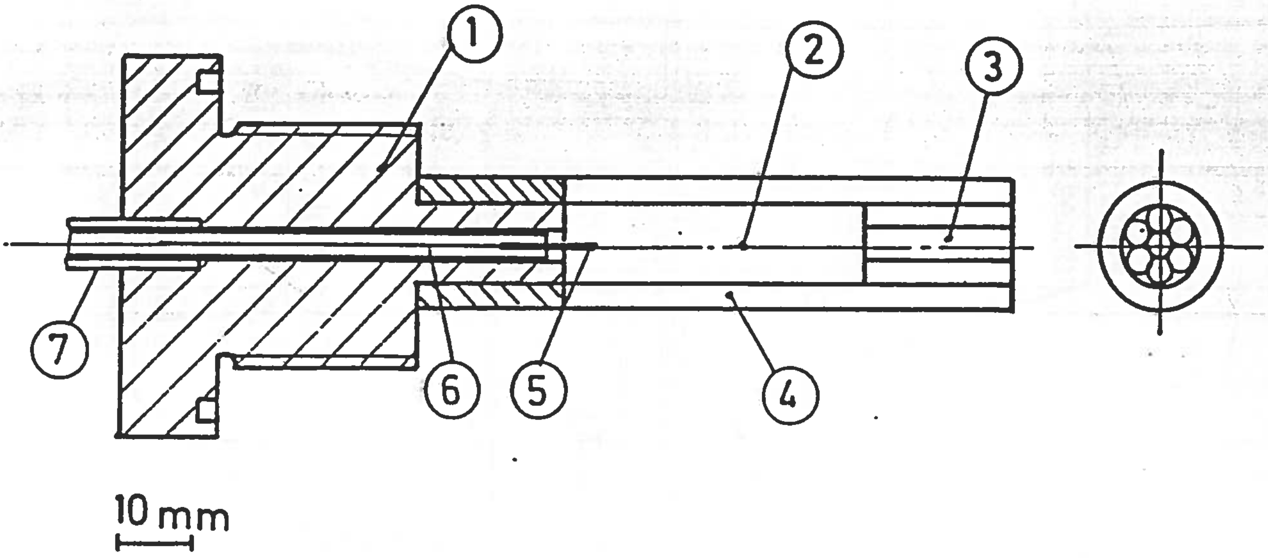


Fig. A.18 Multichannel Hollow Cathode

1) Copper Support
2) Tantalum tube setted on the copper support
3) Multichannel cathode made of 7 tantalum tubes of 3 mm i.d.
4) Tantalum tube (heat shield)
5) Starter electrode
6) Ceramic insulator
7) Copper tube and gas inlet.

electron density	n_e	10^{12} - 10^{13} cm^{-3}
electron temperature	T_e	1 - 10 eV
plasma current	I_p	20 - 120 A
axial field	B_z	0.1 - 0.2 T
plasma diameter	d	~1.5 cm
neutral gas pressure	p	$< 5 \cdot 10^{-4}$ Torr

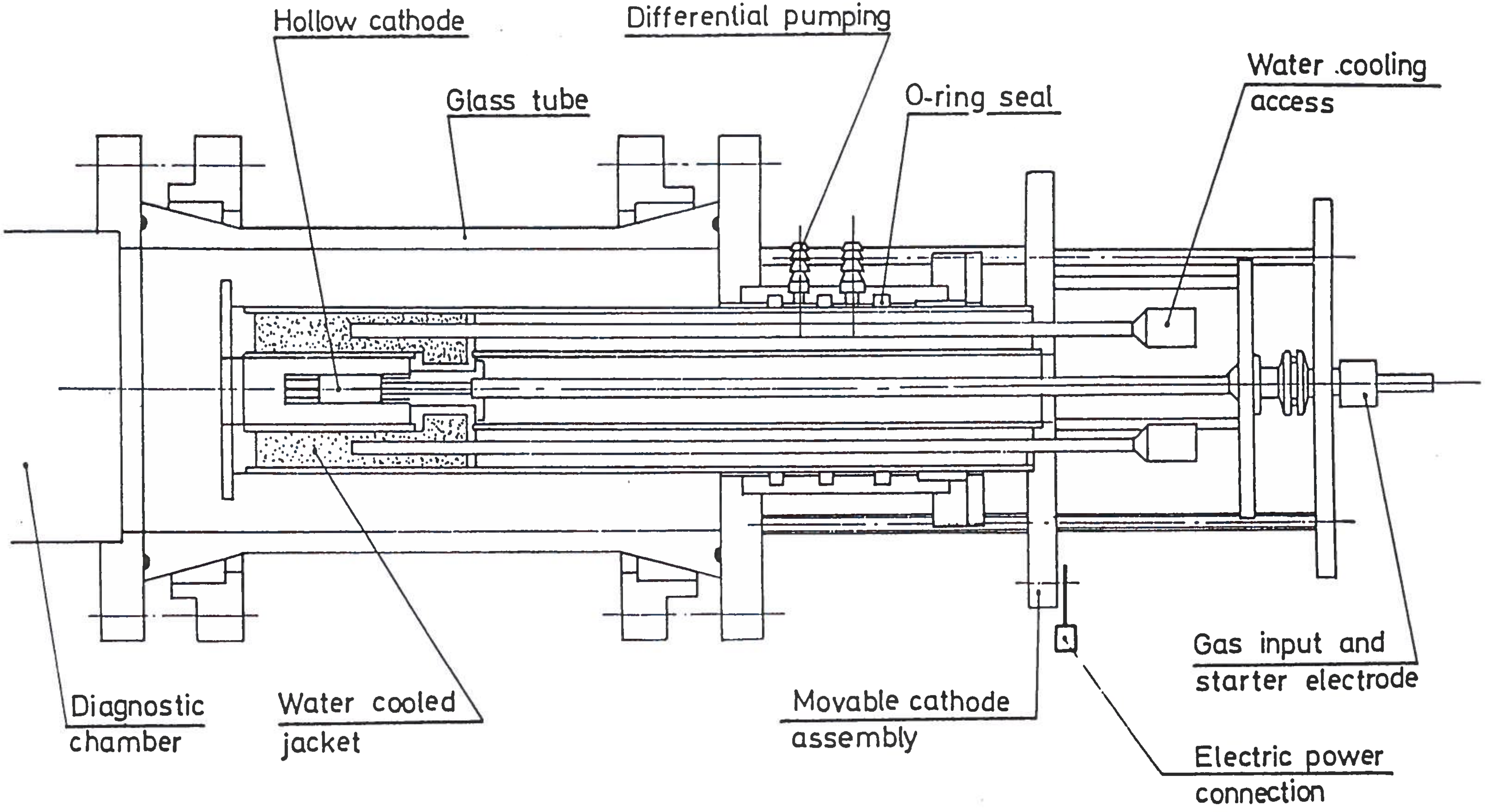
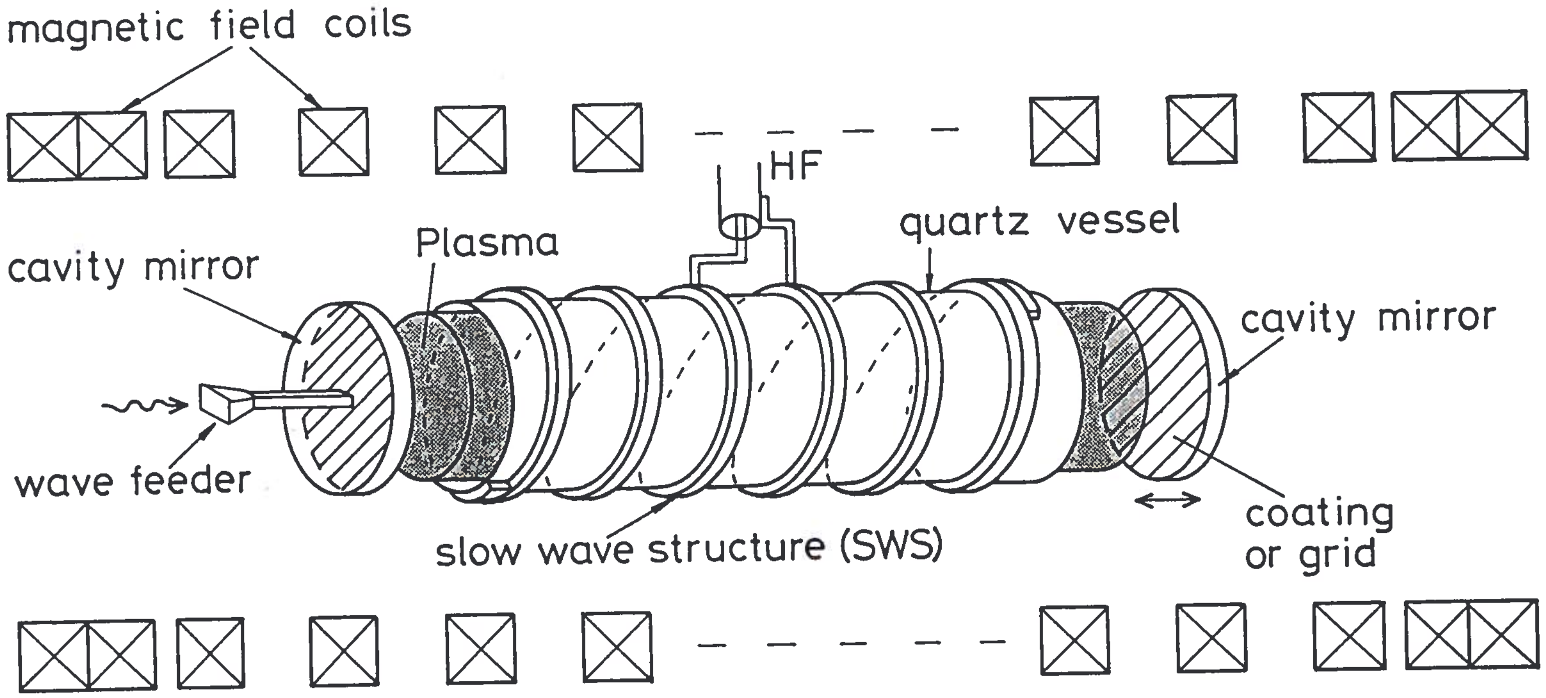


Fig. A.16 Diagram of the cathode

IV

POSSIBLE DESIGN OF THE BEAT WAVE ACCELERATOR EXPERIMENT SHOWING MAINLY PLASMA PRODUCTION

The design of the experiment will depends on the restricted parameters for feasability. The induced electric field in the plasma is depending mainly on the level of turbulence and on the collision frequencies.Efforts should be made for focusing on these problems, so experimental arrangement will be a function of desired density, low magnetic field used for plasma confinement if needed, also atom species should be totally ionized or ionizing frequency much lower than 1/100 plasma periods.



Coaxial plasma - cavity configuration
- SWS - CPC -

Coaxial plasma cavity configuration

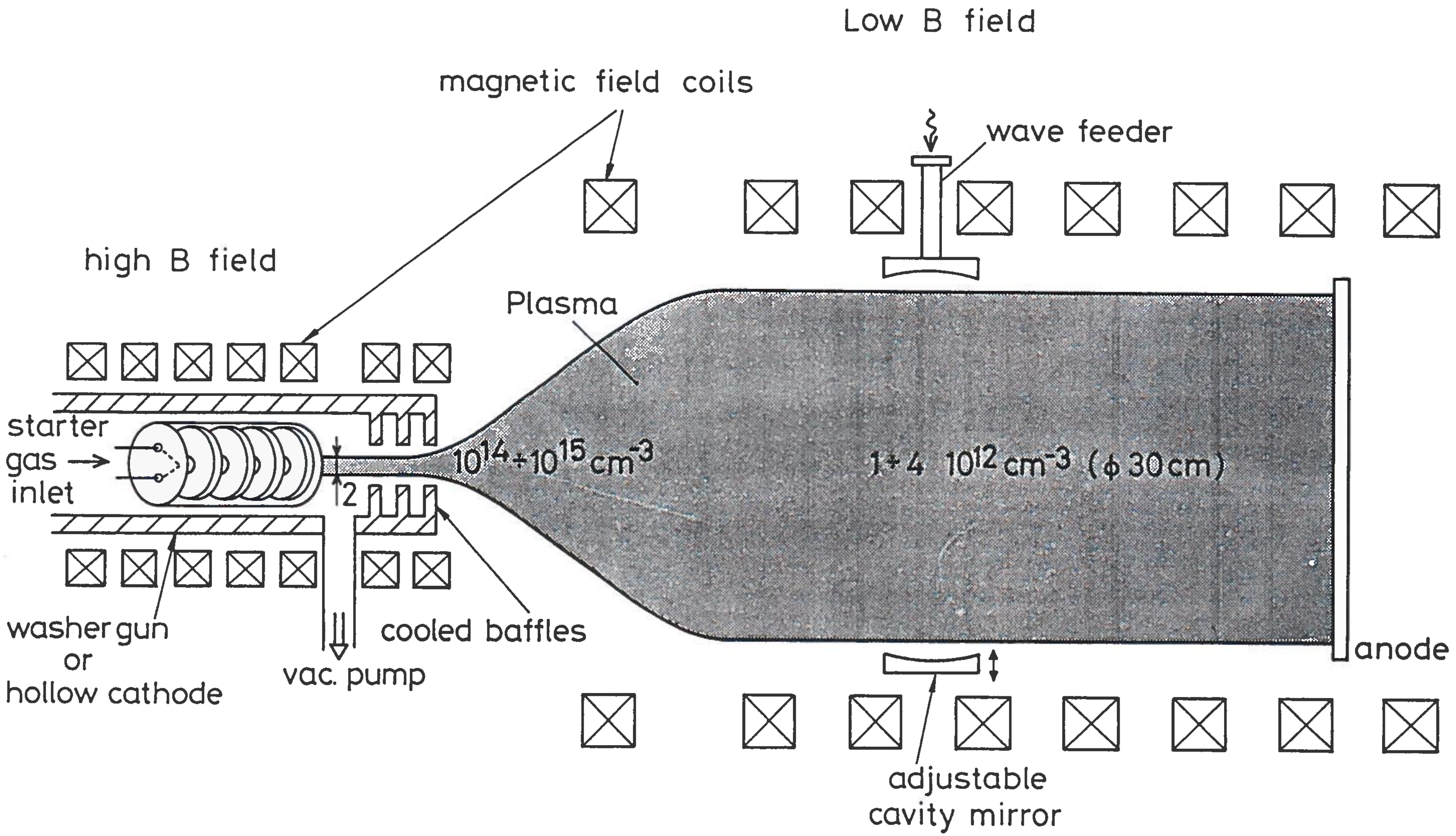
- CPC -

Advantages

- simplicity
- large size plasma
- diagnostics through quartz vessel
- plasma production off ω_{ce} resonance homogeneous B-field in the interaction region and all over plasma and cavity length

Disadvantages

- generally low degree of ionization
- density gradients at cavity mirror surface
- HF noise, turbulence
- very often hollow density radial profile
- B-field along cavity and plasma axis
- poor access for diagnostics (in between the windings of RF coil)



High density sources (PTC configuration)

-HDS-

Plasma axis to cavity axis configuration

- PTC -

Advantages

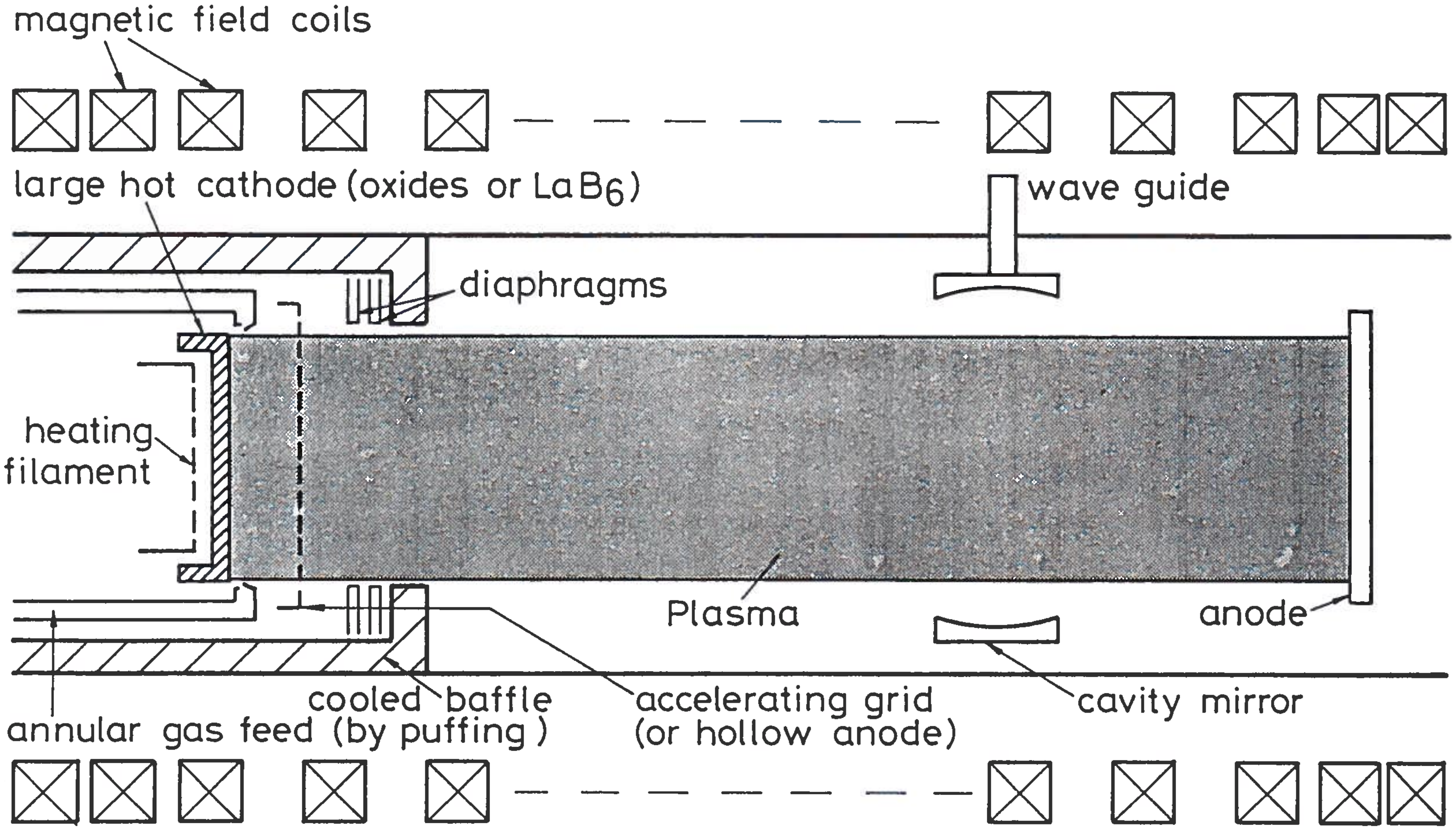
- good degree of ionization
- very high density in source region
- low neutral pressure in plasma-cavity region due to differential pumping
- good access for diagnostics i.e. :
  - interferometry
  - laser light scattering
  - etc.
- low B field perp. to cavity axis
- large plasma volume
- cavity mirrors distached from the plasma

Disadvantages

- impurities from gun
- noisy plasma
- B-field perpendicular to cavity axis, generation of hybrid modes
- high electric field at the source

Large rectangular magnetized plasma (TPC conf.)

-LRMP-



Large rectangular magnetized plasma (TPC conf.)

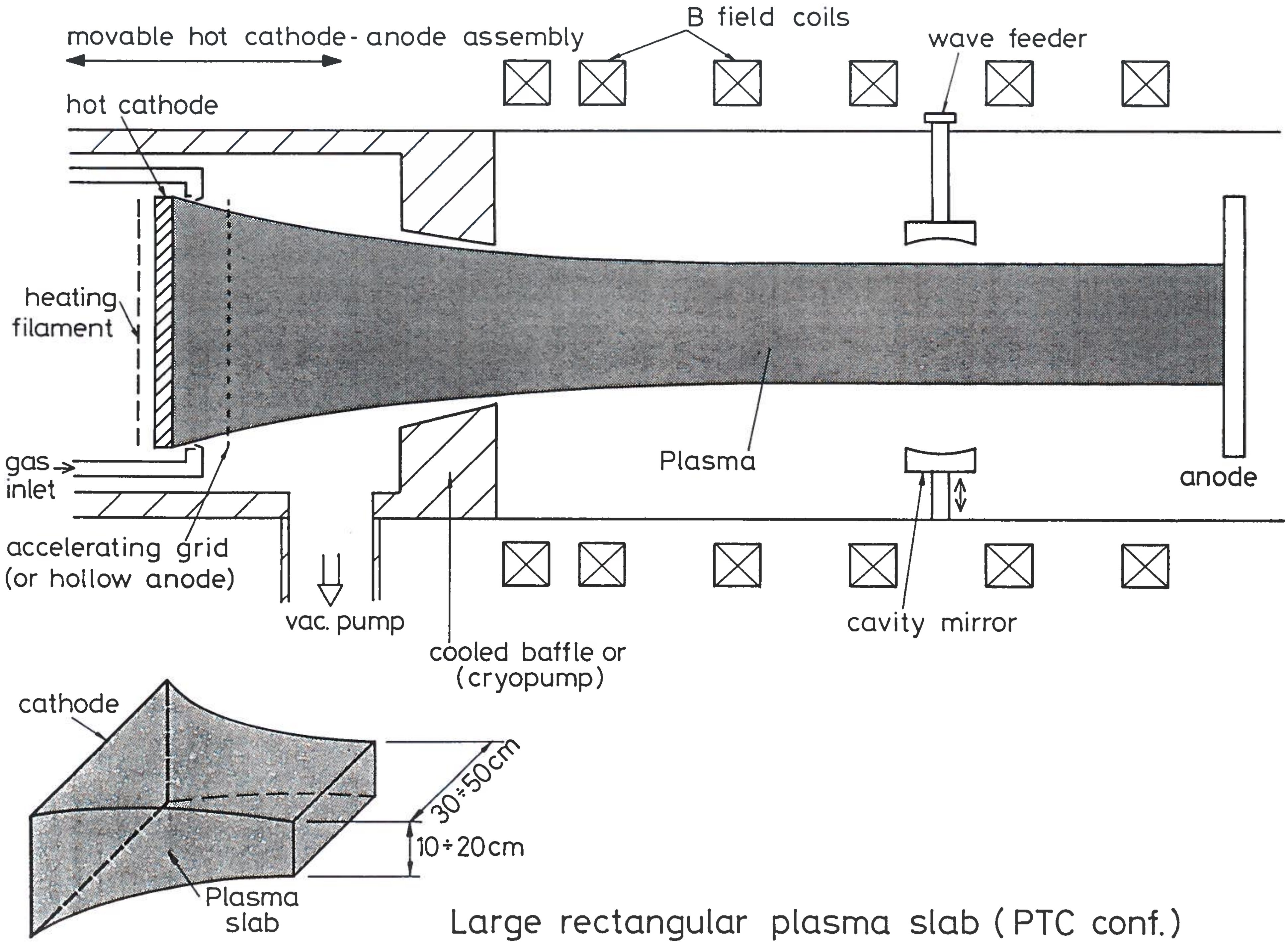
- LRMP -

Advantages

- low noise level
- homogeneous B-field
- cavity hot in contact with plasma
- good density homogeneity along radius
- small continuous density, which allows for high density plasma production H_2 gas puffing (on pulse regime)
- large cathode size increases life time of cathode layer
- cathode could be rectangular to decrease heating power
- good access for diagnostics

Disadvantages

- impurities from plasma source or accel. grid
- high neutral pressure
- usual operation allows only low degree of ionization
- B-field transverse to cavity axis



Large rectangular plasma slab (PTC conf.)

- LRPS -

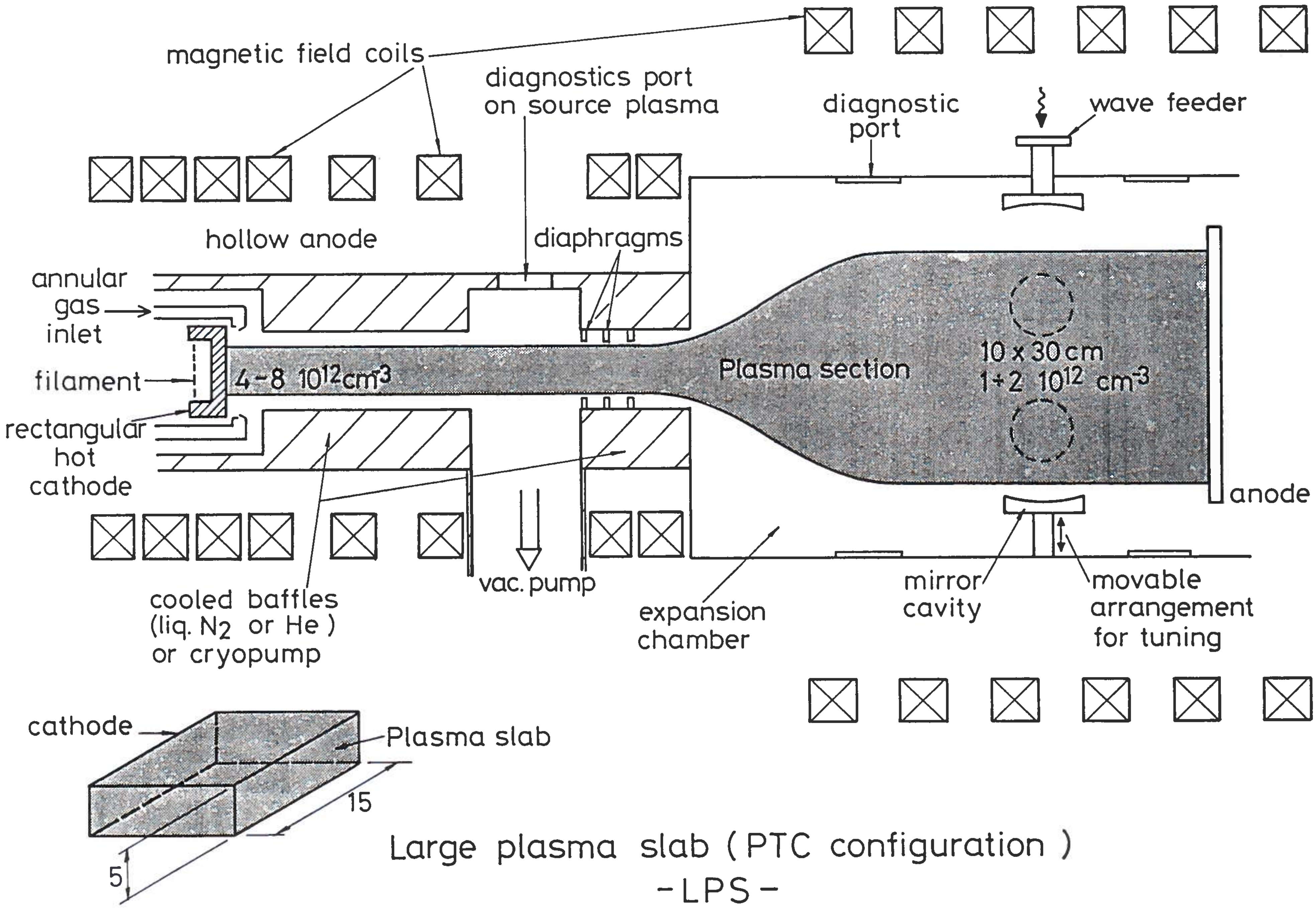
Earlier proposed plasma source LRPS (Large Rectangular Plasma Slab)

Filaments heater W, Ta (radiational heating or e^- bombardment)
Cathode : BaO, LaB_6,......
Dimensions of the cathode : L= 100 ÷ 150 cm , l= 30 ÷ 50 cm
Plasma source located in the natural B gradient (20 Gauss) of the field created by large diameter coils.

B field homongeneous over ϕ =50 cm

100 Gauss ÷ 300 Gauss
The plasma in drifting in the high field will have a rectangular section of : ---- L= 20 to 30 cm and l= 6 to 10 cm

This source was thought to be attractive because of low naturel level of noise, but it appears that high power is required to heat the cathode (over 200 kWatts). Also the differential pumping is difficult to realize, so low level of ionization will occur.



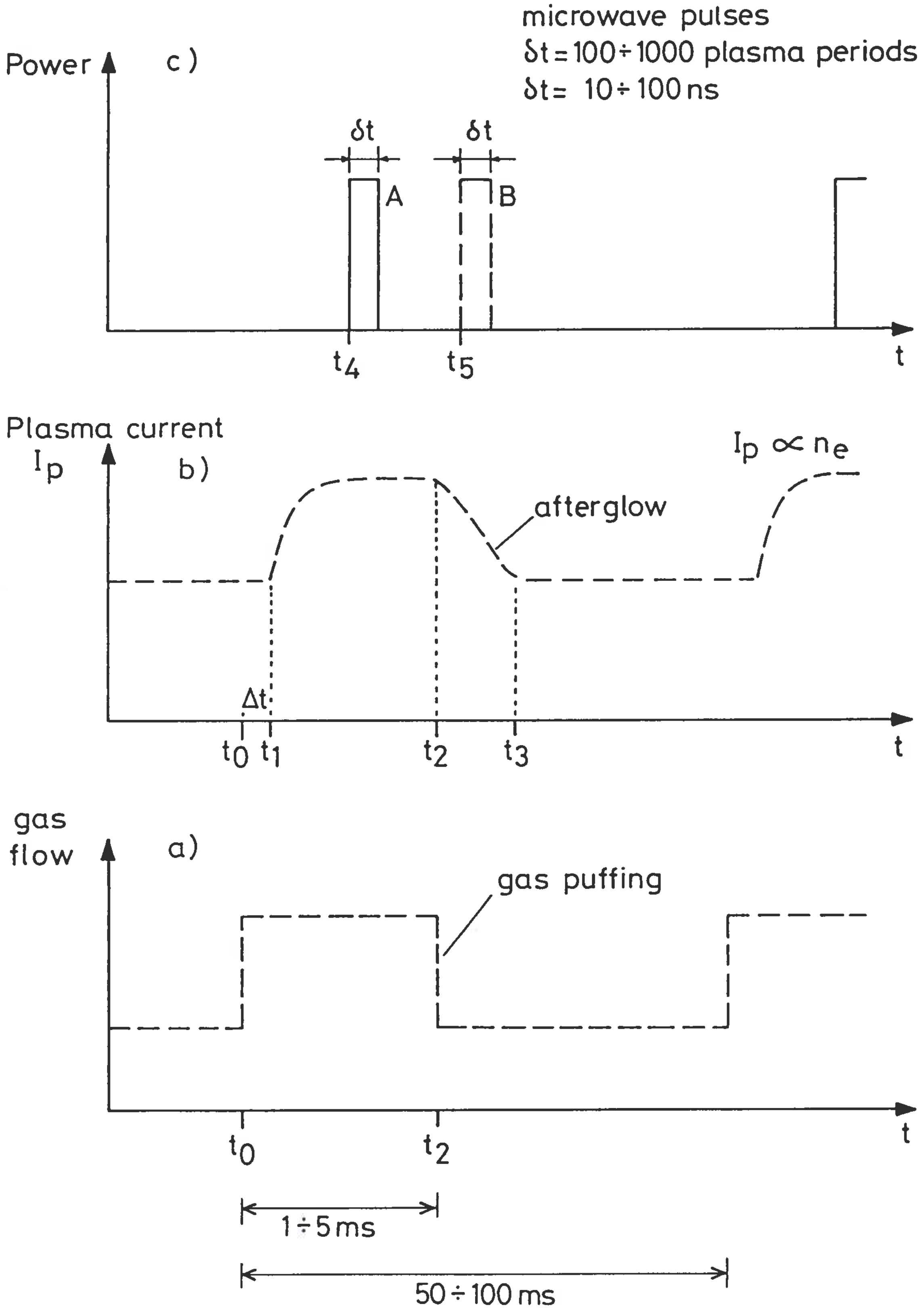
Large plasma slab (PTC configuration)

-LPS-

Recently proposed plasma source (Large Plasma Slab, PTC conf.)

The plasma is created by a hot cathode and placed in high magnetic field in which it streams along the lines before penetrating in the expansion chamber where it takes the design dimensions.
This configuration allows good differential cryo-pumping in the creation section. Baffles help in that pumping as well as in defining the section before entrance in the expansion volume.
Low magnetic field is necessary in plasma volume in order to define dimensions. The anode is placed far from interaction volume of microwaves with plasma, define by the cavity, this in order to avoid bad reflection and mismatch.
The exparimental sequences show continuous production of plasma to a level of 10^{11} cm^{-3}. Then the gas puffing is operated at to for a time 1 to 5 ms. The plasma current is increased at t_1 by a factor 10, to bring up density to 10^{12} cm^{-3}. this till time t_2. The microwaves pulses would be operated at t_4, if plasma is quiet enough, or at t_5 during the afterglow for quiescence purposes, if the drop in density is slow enough to keep resonance conditions.
With this scheme, one would expect good plasma density and perhaps low level of noise = 1 to 3 %. The advantages are with the level of ionization and a reasonable level of heating power. The possible use of the afterglow period is encouraging.

Experimental sequences



V

REVIEW OF MICROWAVE INSTRUMENTATION FOR TEST OF THE CAVITY (AT CRPP)

S. Alberti

MATERIEL A DISPOSITION POUR LES TESTS MICROONDES AU GYROTRON

- <u>Carcinotrons</u> (BWO)
  1) $f = 115 \div 150$ GHz
     $f \cong 500$ mW
  2) $f = 90 \div 103$ GHz
     $f \cong 300$ mW

  - Peuvent être "lockés" en fréquence
  - Sweep possible $f_{modulation} \cong 500$ Hz
    Excurrian de la fréquence maxi : $\Delta f = 3 - 4$ GHz

- <u>Guides d'onde</u> (guides, atténuateurs, T hybrides, atténuateurs variables, coupleurs cornets, twists, bends, E - H tuner, dephaseurs, etc.)

- D-band	WR-7	110 - 170 GHz
- W-band	W-10	75 - 110 GHz

- <u>Détecteurs</u>

- Diodes	W-band	5 diodes (sensitivité - 50 dBm)
	D-band	3 diodes (sensitivité - 50 dBm)

  - Mixers
    1 W-band (harmonique $n \cong B$) $f_{LO} = 8 \div 12$ GHz
    1 W-band (fondamental $n \cong 1$) $f_{LO} = 8 \div 12$ GHz
    1 W-band (harmonique $n = 18$) à utiliser avec un analyseur de spectre HP
    1 D-band (fondamental $n \cong 1$) $f_{LO} = 8 \div 12$ GHz

  <u>Rem</u>
  1) Des mixers "fondamentaux" ($n = 1$) ont comme oscillateur, local, soit le carcinotron, soit une diode Gunn accordable.
  2) Pour amplifier le signal LO $8 \div 12$ GHz toute une série d'amplificateurs RF (+ 20 dB + 30 dB) est disponible.
  3) Le mixer "harmonique" ($n = 9$) a comme oscillateur local un générateur dans la bande $8 \div 12$ GHz (Weinschel).

- <u>Power meter</u> HP, $f = 110 \div 130$ GHz
  sensibilité = - 30 dBm

- <u>Analyseur de spectre HP 70000</u>
  - Pour mesurer des fréquences en bande W il faut utiliser un mixer externe (harmonique $n = 18$)
  - Sensibilité - 70 dBm (bruit de fond)
  - Sweep maximal 5 GHz en 5ms

- <u>Table XY</u> pour la mesure de profils de champ EM dans les guides d'ondes
  - Haute précision mécanique (moteur pas à pas)
  - commandée par ordinateur

- <u>Support pour résonateurs</u> (optiques ou quasi-optiques)
  - Déplacement des miroirs par moteurs pas à pas

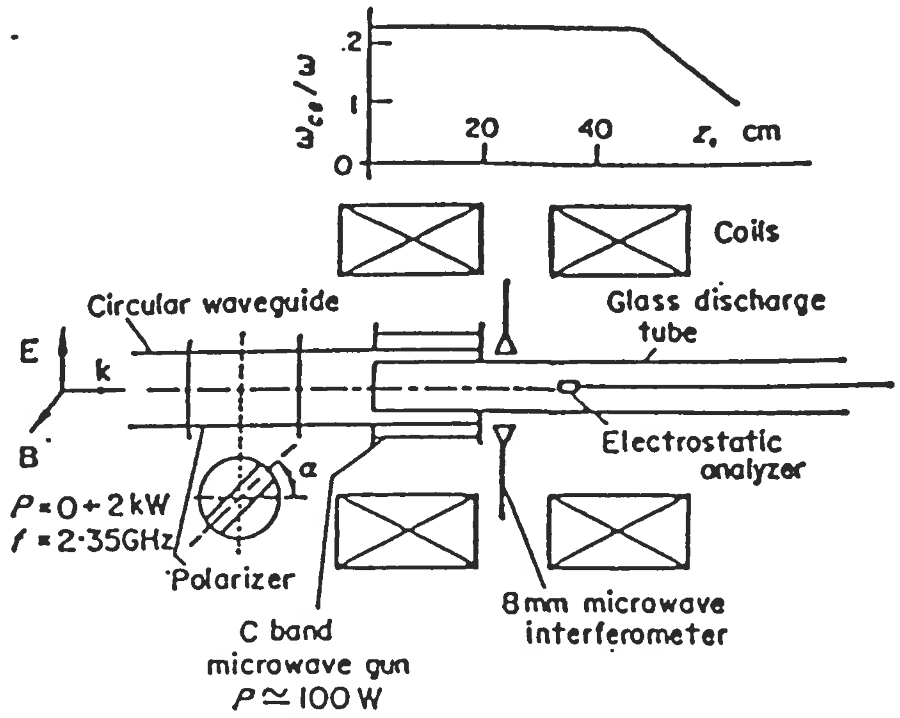
Liste établie par Stefano Alberti CRPP - Octobre 1989

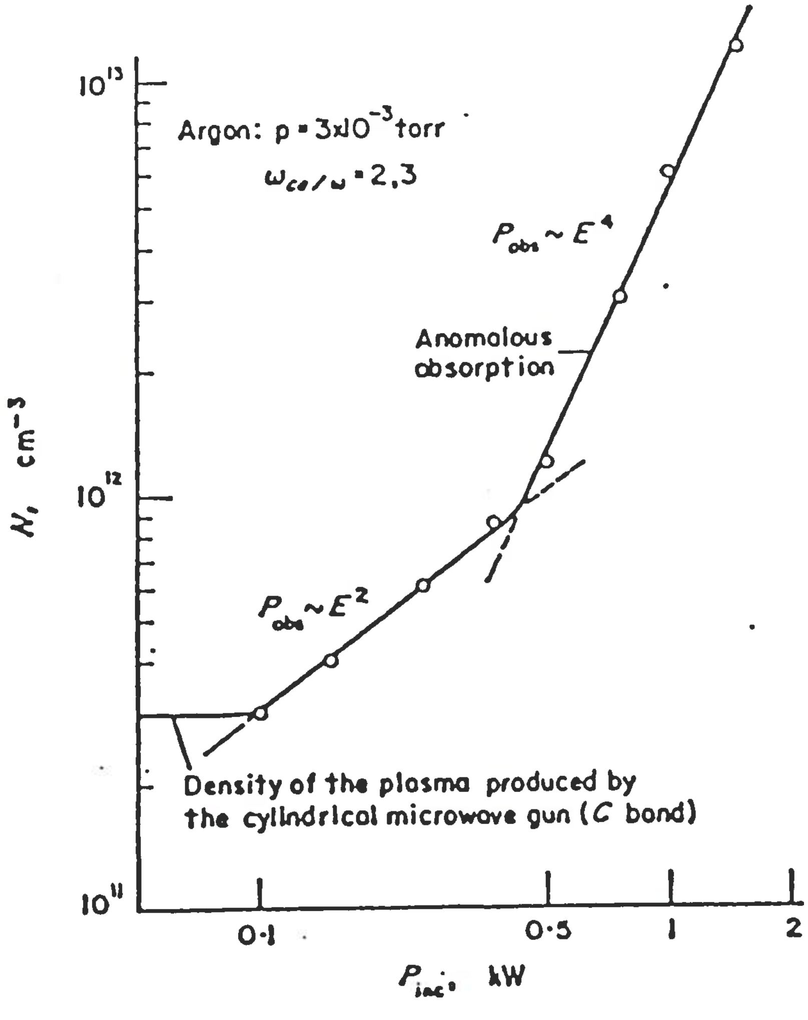
VI
ANNEXES

VI-1 COMPILATION OF LOW DENSITY PLASMA SOURCES FROM PUBLICATIONS

VI-2 PLASMA DIAGNOSTICS

VI-3 PLASMA PARAMETERS TABLE


ω_{ce}/ω
2
1
0
20
40
z, cm
Coils
Circular waveguide
Glass discharge tube
E
k
B
Electrostatic analyzer
α
P = 0 ÷ 2 kW
f = 2·35GHz
Polarizer
C band microwave gun
P ≃ 100 W
8 mm microwave interferometer


10^{13}
10^{12}
10^{11}
Argon: p = 3x10^{-3} torr
ω_{ce}/ω = 2,3
$P_{abs} \sim E^4$
Anomalous absorption
$P_{abs} \sim E^2$
n, cm^{-3}
Density of the plasma produced by the cylindrical microwave gun (C band)
0·1
0·5
1
2
P_{inc}, kW

ANNEXE VI-1

COMPILATION OF LOW DENSITY PLASMA SOURCES FROM PUBLICATIONS

A - Open waveguide sources, turnstile, horn antenna

(1) Open waveguide with polarizer Source

Study : Anomalous absorption of intense EM waves.
Gas: A.
f = 2.35GHz
P = 0-2kW

$\tau_{\text{Pulse}} = 200 \div 500\ \mu s$ rep rate 50 Hz
$P_0 = 3.\ 10^{-3}$ Torr
Wave coupling, by glass discharge tube filling the circular waveguide (i.d. 92 mm). Turnstile coupling, with polariser.
Two regions of resonance condition, for EM waves propagating obliquely in an unhomogeneous plasma :

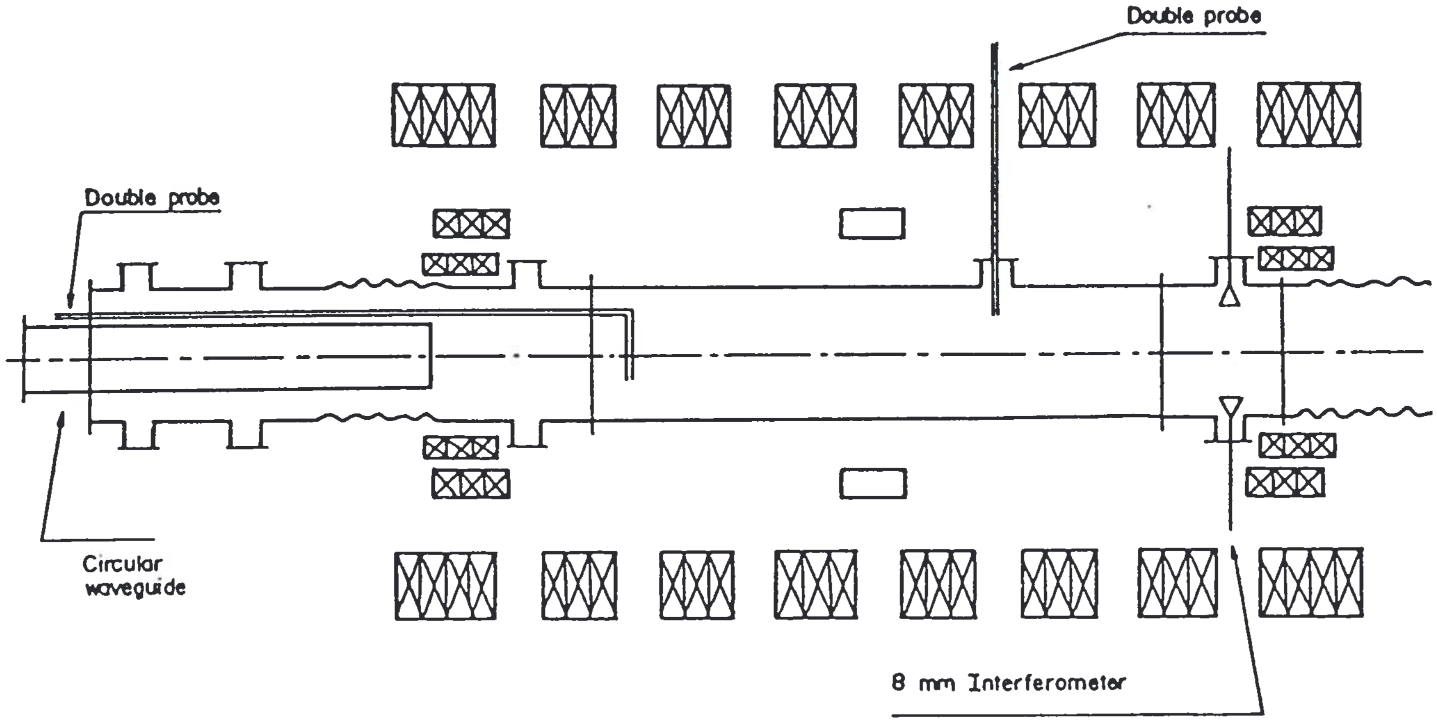
a) $\left(\frac{\omega_p}{\omega}\right)^2 = \frac{1-\omega_{ce}^2/\omega^2}{1-\omega_{ce}^2/\omega^2\cos^2\alpha}$ at $\omega_{ce}/\omega<1$ extraordinary wave RHCP

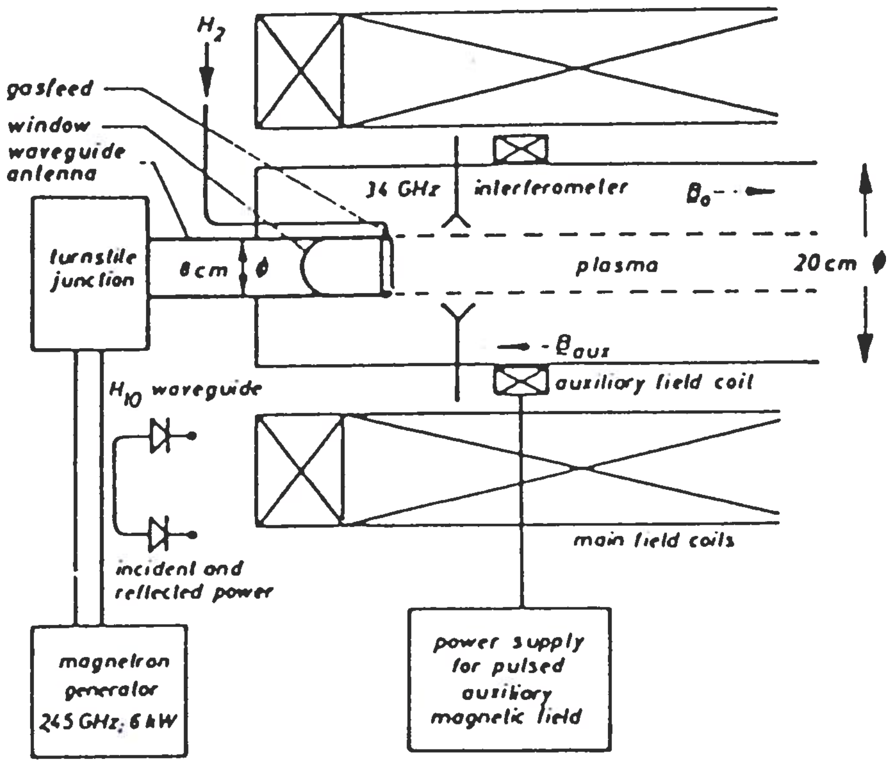
b) $\left(\frac{\omega_p}{\omega}\right)^2 = \frac{\omega_{ce}^2/\omega^2-1}{\omega_{ce}^2/\omega^2\cos^2\alpha-1}$ at $\omega_{ce}/\omega \cos \alpha >1$ ordinary wave LHCP

$Te \geq 9eV$

$\frac{\delta n}{n}$?

In the experiment $(\omega_{ce}/\omega) > 1$ for RHCP(right hand circularly polarised wave, or extraordinary wave), use equ.b.???
Diagnostics: Langmuir probe, electrostatic multigrid analyser, 8mm interferometer.
$P_{abs} = E^2$ in 10^{11} to $10^{12} cm^{-3}$ range, and $P_{abs} = E^4$ over 10^{12} cm^{-3}
J. Musil, F. Zacèk and P. Schmiedberger, Prague
Plasma Physics, 1974, Vol. 16, p. 735


Double probe
Double probe
Circular waveguide
8 mm Interferometer


H_2
gasfeed
window
waveguide antenna
turnstile junction
8 cm ϕ
34 GHz interferometer
B_0
plasma
20 cm ϕ
B_{aux}
auxiliary field coil
H_{10} waveguide
incident and reflected power
main field coils
magnetron generator 2.45 GHz; 6 kW
power supply for pulsed auxiliary magnetic field

(2) Open waveguide

Study : absorption of EM waves by a magnetoplasma.
Gas: H
$p_0 = 4.8\ 10^{-4}$ Torr
$f_0 = 2.45$ GHz, Magnetron pulse (rep. rate ≈ 20ms)
pulsed B field, ECR condition
ϕ plasma 8 ÷ 10 cm ??
$T_e \approx 20$ eV
$P_{inc} \sim n_e$ for power lower than 1.7kW.
$P^2{}_{inc} \sim n_e$ for power higher than 1.7 kW.
highly overdense plasma ....n_e/n_e crit. = up to 40

Plasma Physics *<u>23</u>, pp203-210, 1981*
M.A.G. Calderòn and J.M. Perez
Uni of Santander, Spain

(3) Open Waveguide Source with Turnstile Junction

Gas: H
$P_0 = 1 \div 10$ mTorr
plasma dimension: ϕ 8 cm L = 2.5 m
$B_0 = 0.6$ T
auxiliary coil is needed to start the plasma
⇒ ECR condition $\omega_0 = \omega_{ce}$ is locally fulfilled for a short time

$P_{inc} =$	2.2. kW	low density	
	3.4 kW	$6\ 10^{11}$cm^{-3}	over dense regime
	4.9 kW	$0.9\ 10^{12}$cm^{-3}	$\omega_0 < \omega_{pe}$
	5.8 kW	$1\ 10^{12}$cm^{-3}	

- low ionisation
- noise? seems noisy at high power
  ($P_{inc} = 5.8$ kW ⇒ power flux 115W/cm^2)

C. Jansen and E. Ränchle
Physics Letters 1981, 83A, p. 15

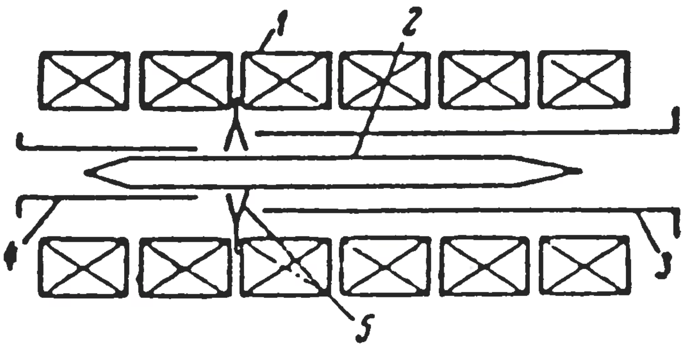


Fig. 1. Experimental arrangement. 1) Coil; 2) container with plasma; 3) rectangular waveguide for 10-cm wavelength range; 4) circular waveguide for 3-cm wavelength range; 5) horns of the 8-mm interferometer.

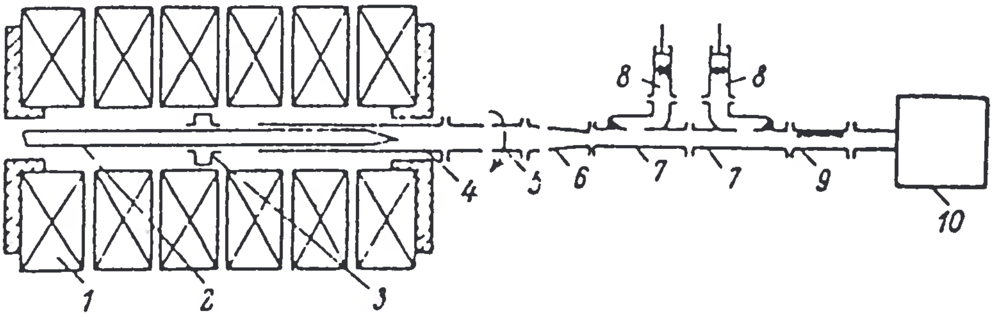


Fig. 1. Schematic diagram of experimental arrangement. 1) Electromagnet; 2) discharge vessel; 3) resonator; 4) cylindrical waveguide; 5) rotatable joint; 6) smooth transition section joining circular and rectangular waveguides; 7) directional couplers; 8) detector sections; 9) ferrite isolator; 10) microwave generator.

(4) Microwave Gun

B field homogeneous
4000 Oe, 5%
$p_0 = 10^{-3} \div 10^{-1}$ Torr
$\omega_0 = 10$ GHz 200 ms 150 watts pulse
$n_e \approx 10^{12} \text{cm}^{-3}$ at ECR condition
$\omega = 3$ GHz , 100 watts CCW
Ioffé Institut.
V.N. Budnikov, V.E. Goland and A.A. Obolekov
Soviet Physics Tech. Phys., Vol. 15(1), 1970, p. 97 - 100

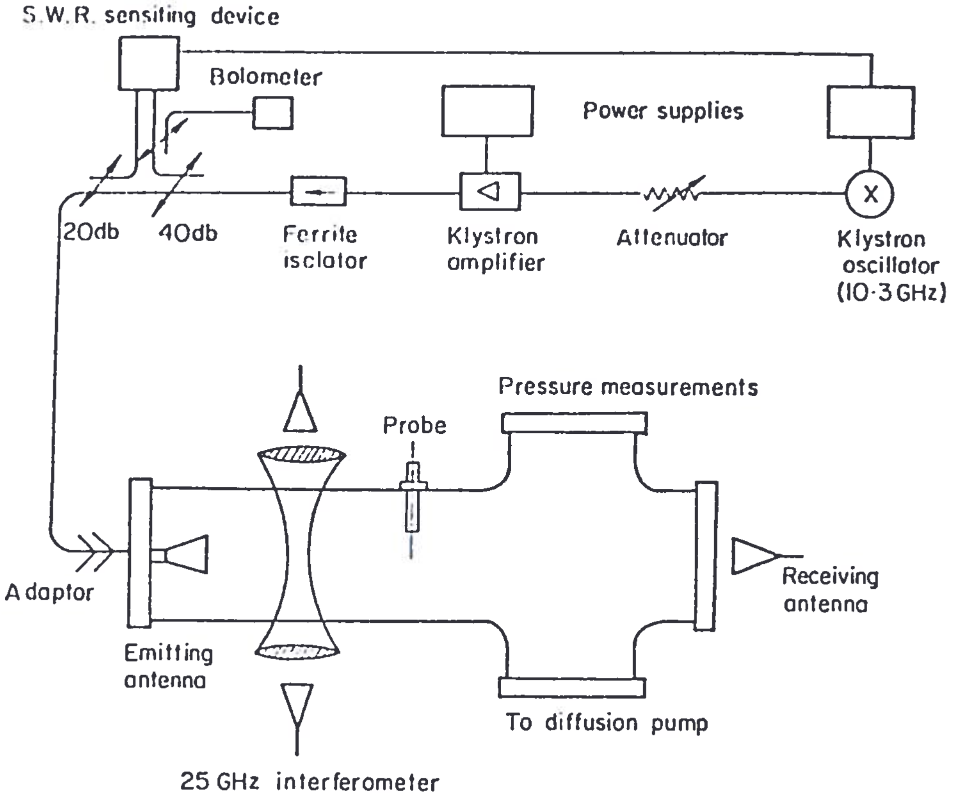
(5) Microwave Gun

frequency = 9.375 GHz
$p_0 = 10^{-4} \div 10^{-1}$ Torr
$n_e \approx 10^{10}$ cm^{-3} to 10^{11} cm^{-3}
$B_0 = 6000$ Oe

- variation B field - 1% (time) non flux form 1%
- conical vessel to promote matching of the wave guide channel (over 6cm long).
- noise oscillation, $\nu < 100$kHz

  but $\frac{\partial n_e}{n_e}$??

$n_e = 4 \div 5 \; 10^{11}$ Q cm^{-3} where Q is in W/cm^{-3}
$T_e \approx 3 \div 5$ eV
$T_i \approx 0.1 \div 0.2$ eV
V.N. Budnikov et al
S. Phys. Tech. Phys.<u>12</u>, 5,1967, p610



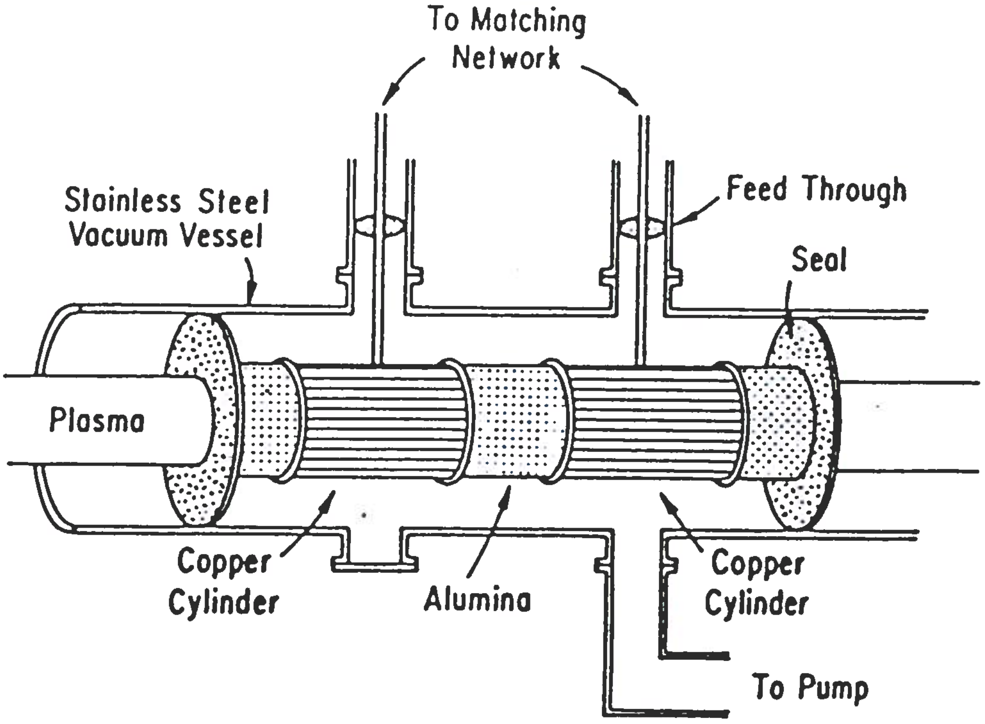


FIG. 1. A 155-MHz plasma source.

(6) High Frequency Plasma source = pyramidal horn

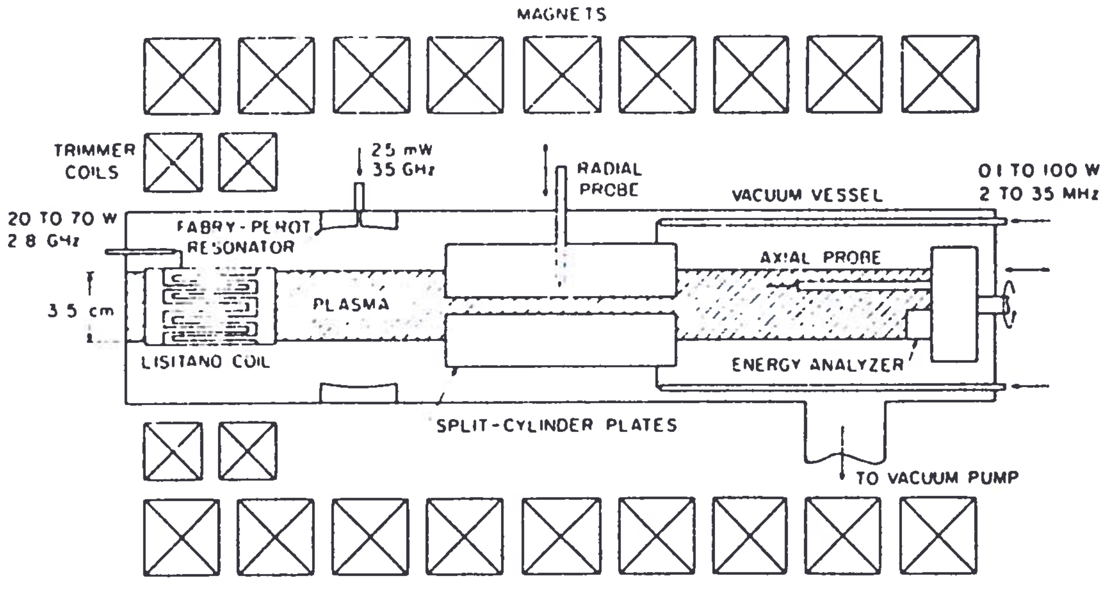
10.3 GHz 30 Watts
Ar, $P_o \approx 10^{-5} \div 3\ 10^{-2}$ Torr
$10^{10} < n < 10^{13}$ cm^{-3}
$5 < T_e < 30$ eV
$\frac{\delta n}{n}$??
P.A. Tulle
Plasma Physics Vol. 15, p. 971-976, 1973

B- Capacitive antenna at low RF (155MHz)

(7) RF Plasma Source

$\omega_{pe} \gg \omega \sim \omega_{pi}$ = 155MHz, 8 kW
but B = 16kG (1.4m)
Plasma is generated at RF near to and above ion plasma freq. or lower hybrid freq.
$n_e = 10^{12}$ cm^{-3}, $n_o = 1.5\ 10^{13}$ cm^{-3}, Ti = 15 eV max heating, Te up to 15 eV.
In argon, heating efficiency is higher with low neutral pressure, 10^{-4}torr, heating eff. is 50%.

R.W. Motley et al.
J. Appl. Phys. Vol. 46(8), 1975, p. 3286



NOT TO SCALE

FIG. 1.—Experimental system. The total plasma length is 1.42 m.

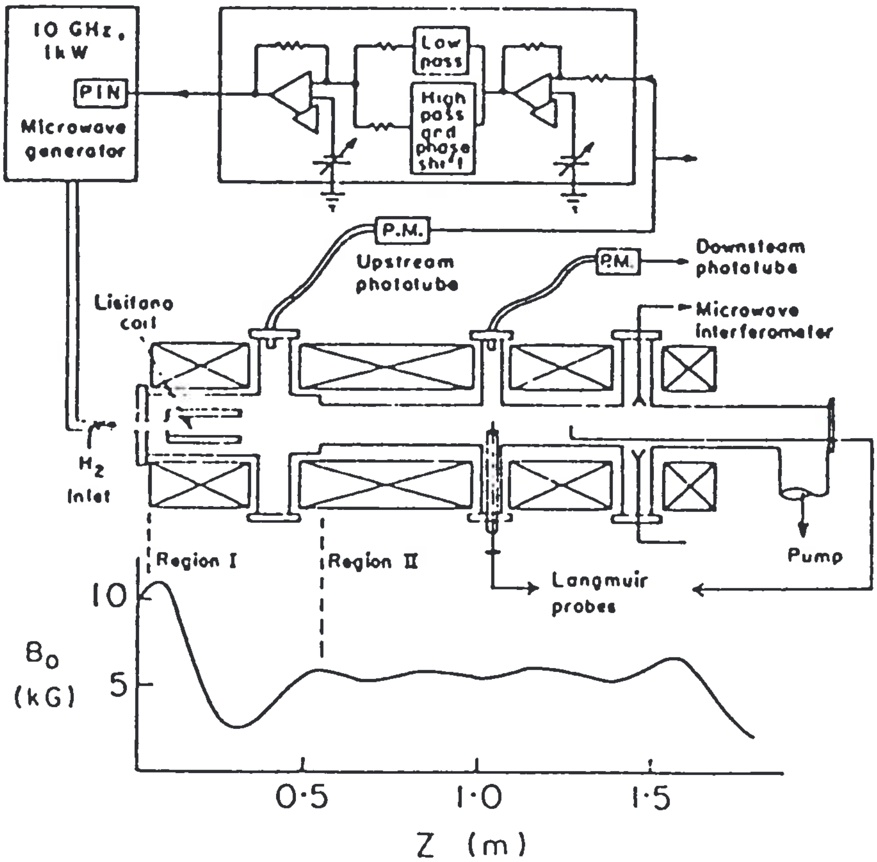


FIG. 1.—The COMPLEX device, including schematic for the feedback control and a typical plot of magnetic field strength on the axis.

C- Interdigital structure (Lisitano coil type I)

(8) Interdigital Lisitano Coil

Gas: A, He, H, D, N_e
3 $10^{-4} \div 9\ 10^{-3}$ Torr
$B_{max} = 1.3$ kG
$n_e \leq 2.5\ \ 10^{10}$ cm^{-3}
1 ÷ 50% ionisation
P.L. Colestock and W.D. Getty
Plasma Physics Vol. 19, 1976, p. 455 - 465
Uni. of Michigan, Ann Arbor

(9) Lisitano Coil
Complex Device

Gas: H, He, N_2, A, Kr
5 $10^{-6} \div 5\ \ 10^{-4}$ Torr
base 10^{-7} torr
$B_{max} \approx 10$kG
- work mainly at ECR (3.7kG)
- with 100 watts
  $n_e = 1\ \ 10^{11} cm^{-3}$ with 1 10^{-4} Torr
  $n_e = 1.5\ \ 10^{11}$ (2.5 10^{-4} Torr)
  $n_e = 7.5\ \ 10^{10}$ (1.25 10^{-3} Torr)
  $2 < T_e < 20$ eV
  max ionization 50 %
  $$\frac{\delta n_e}{n_e} \sim 5 \div 10\ \%$$

I.G. Brown et al.
Plasma Physics Vol. 13, 1971, p. 47 - 61, Berkeley

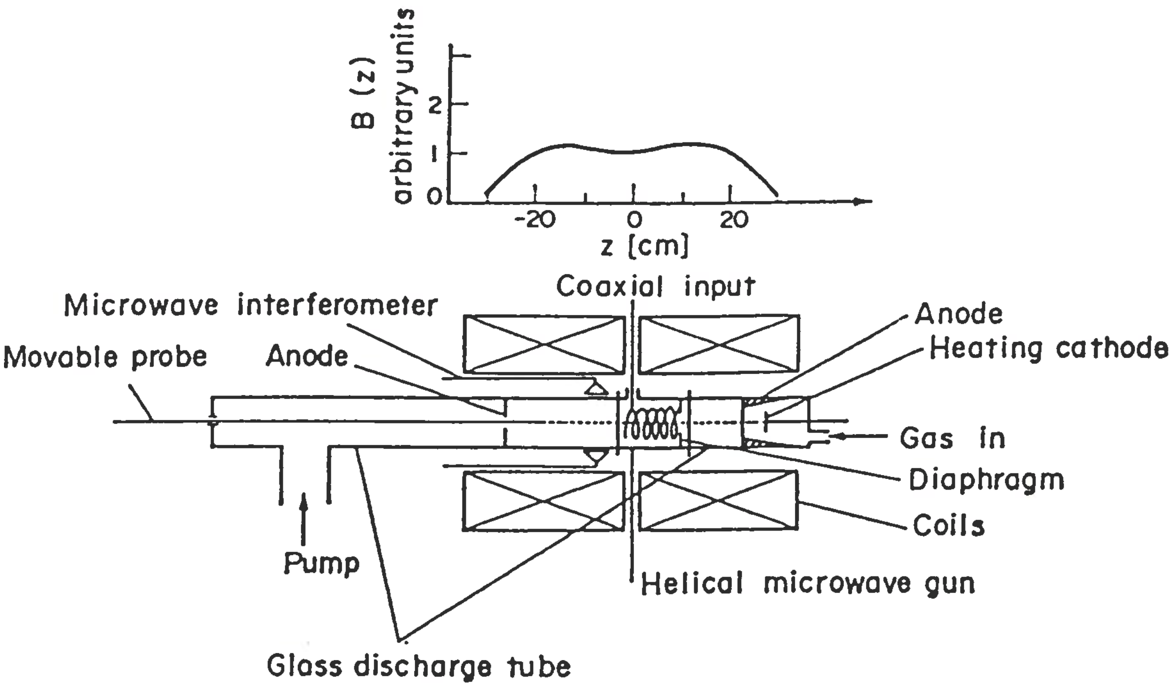


FIG. 1.—Schematic diagram of the experimental device ER-2.

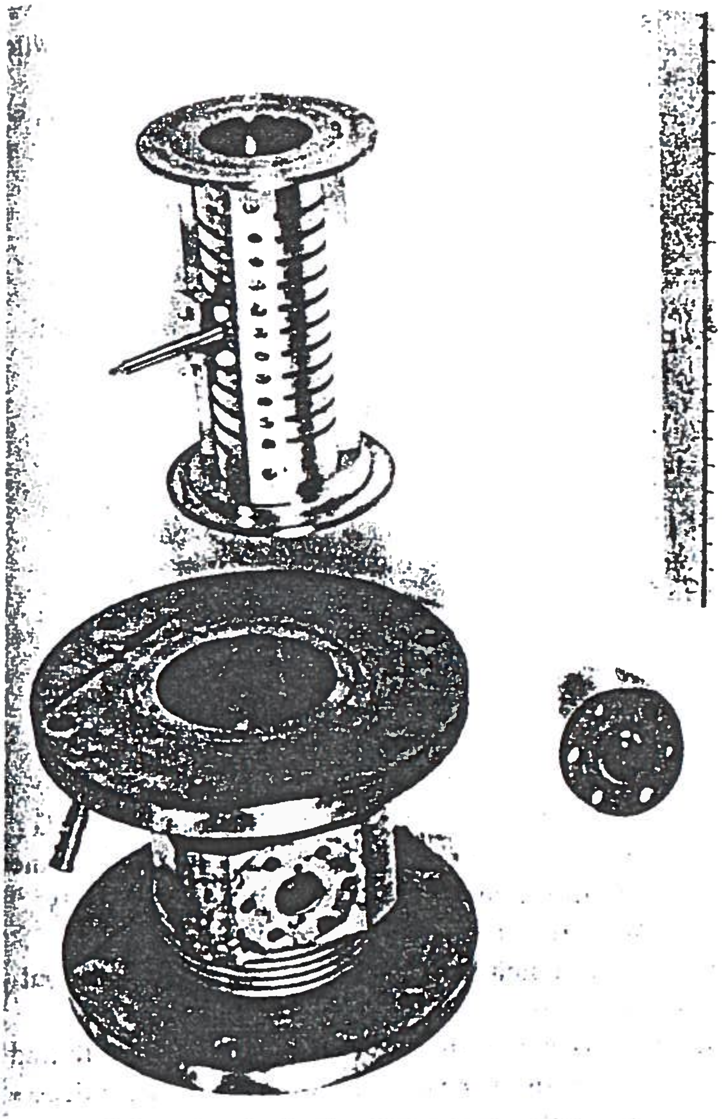


FIG. 1. Slow wave structure.

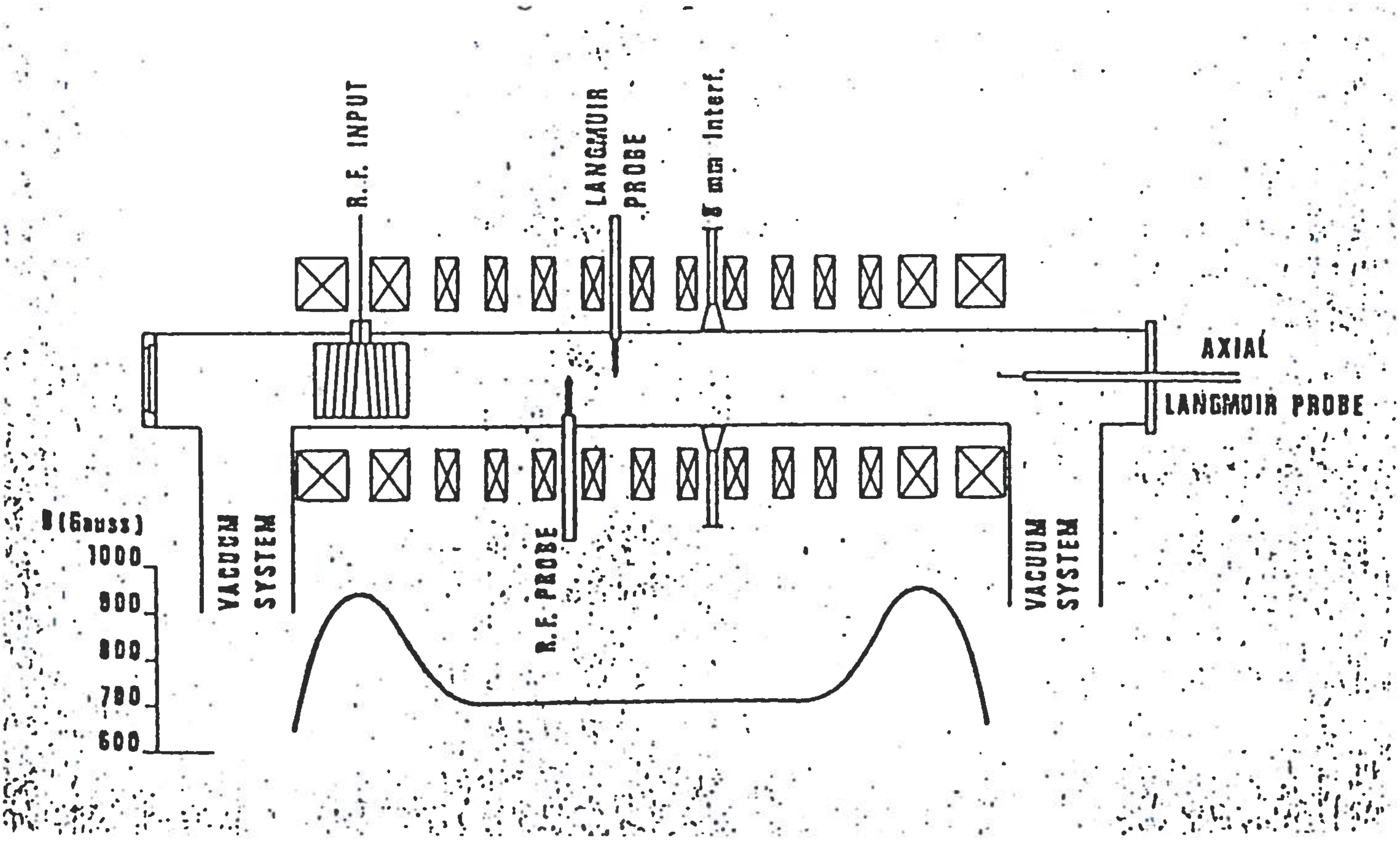
D- Slow Wave Structure (Lisitano coil type II)

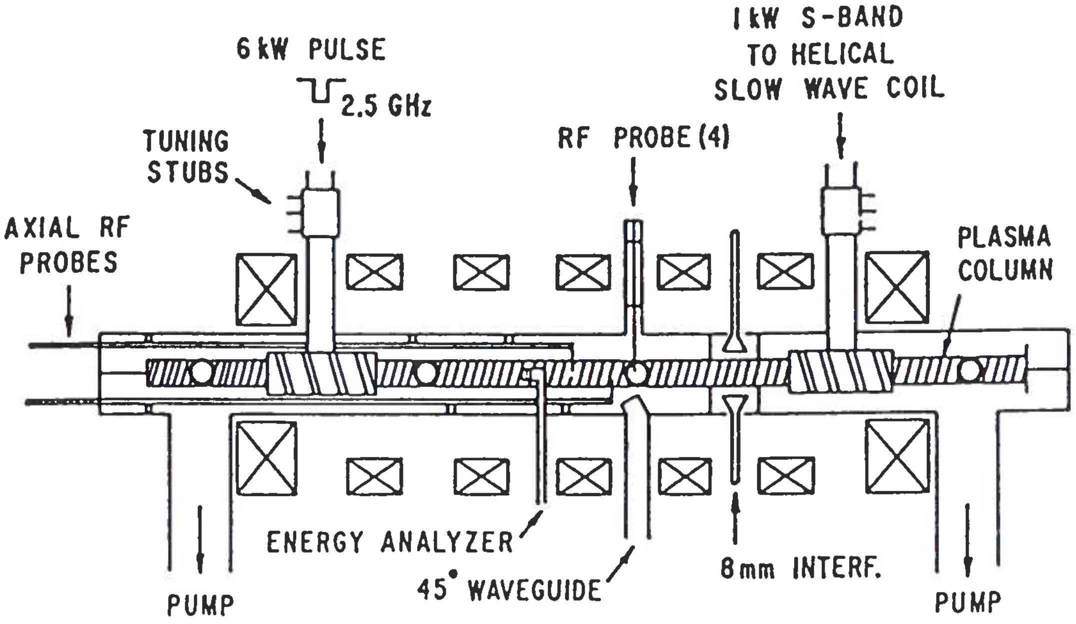
(10) Helical Microwave Gun

Gas: H
$P_0 = 10^{-4} \div 10^{-3}$ Torr
$\frac{\Delta B_0}{B_0} = \pm 0.1$
$B_{0\,max} = 1.3$T
$f_0 = 2.35$ GHz
p_{max} 5 kW, but > .2kW for density start.
$n_e \approx 5\ \ 10^{11} \div 1.5\ \ 10^{12}\ cm^{-3}$
$\tau = 0.5$ to 1 ms (for hot cathode coaxial gun)
1% ionised initial density $10^{10}\ cm^{-3}$.
V. Kopecky, J. Musil and F. Zàcèk,
Plasma Physics Vol. 17, 1975, p. 1147 - 1153

(11) Non resonant absorption of EM waves in a high density plasma (Slow Wave Structure)

Gas : A
$p_0 = 10^{-3}$ Torr
$B_{0\,max} = 1.8$ kG
SWS in mirror 25:1
RF; $f_0 = 3$ GHz
70W
$n_e > 10^{12} cm^{-3}$
$\omega_{rf} < \omega_b < \omega_p < 10\omega_{rf}$
$\frac{\Delta n_e}{n_e} \leq 5\%$, $T_e = 10eV$
ionization 30%
G.Lisitano, M. Fontanesi and E. Sindoni
Appl. Phys. Lett. Vol. 16, 1970, p. 122


R.F. INPUT
LANGMUIR PROBE
8 mm Interf.
AXIAL LANGMUIR PROBE
VACUUM SYSTEM
R.F. PROBE
VACUUM SYSTEM
B(Gauss)
1000
900
800
700
600


6 kW PULSE
2.5 GHz
TUNING STUBS
AXIAL RF PROBES
RF PROBE (4)
1 kW S-BAND TO HELICAL SLOW WAVE COIL
PLASMA COLUMN
ENERGY ANALYZER
45° WAVEGUIDE
8 mm INTERF.
PUMP
PUMP

L-3 DEVICE

(12) Helical L. coil (SWS)

12 cm - 1 kW cw power source - ECR conditions
neutral gas $P_0 = 5\ 10^{-7}$ to $5\ \ 10^{-6}$ Torr
noise level, $(\Delta I_i/I_{isat}\ \alpha\ \ 5\%)$
$n_{e\ max} = 4\ \ 10^{11} cm^{-3}$
$T_{e\ max} = 8$ eV
R. de Dionigi, M. Fontanesi and E. Sindoni
Appl. Physics Letter Vol. 19(1), p 19 - 21, 1971
Milano

(13) Slow Wave Structure (SWS)
L-3 Device

Gas: He
$P_0 < 10^{-3}$ Torr
$n_0 \leq 2\ \ 10^{12} cm^{-3}$
$\lambda_{\|} \approx 3 \div 10$ cm
$\lambda_{\perp} \approx 5$ cm
Studies : Parametric instabilities
Plasma production, Φ plasma= 5 cm
P=1kW, ν=2.45GHz
B field up to 2 kG
3 m long device

M. Porkolab, V. Arumsalam and N.C. Luhmann
Plasma Physics Vol. 17, 1971, p. 405 - 419

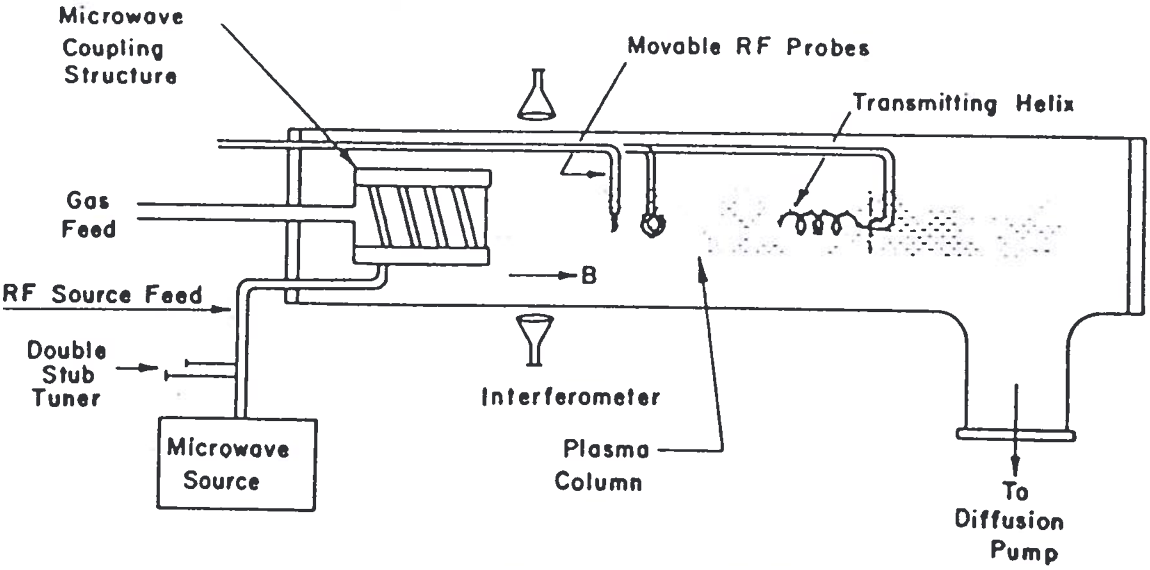


FIG. 1.—Cyclotron wave plasma facility.

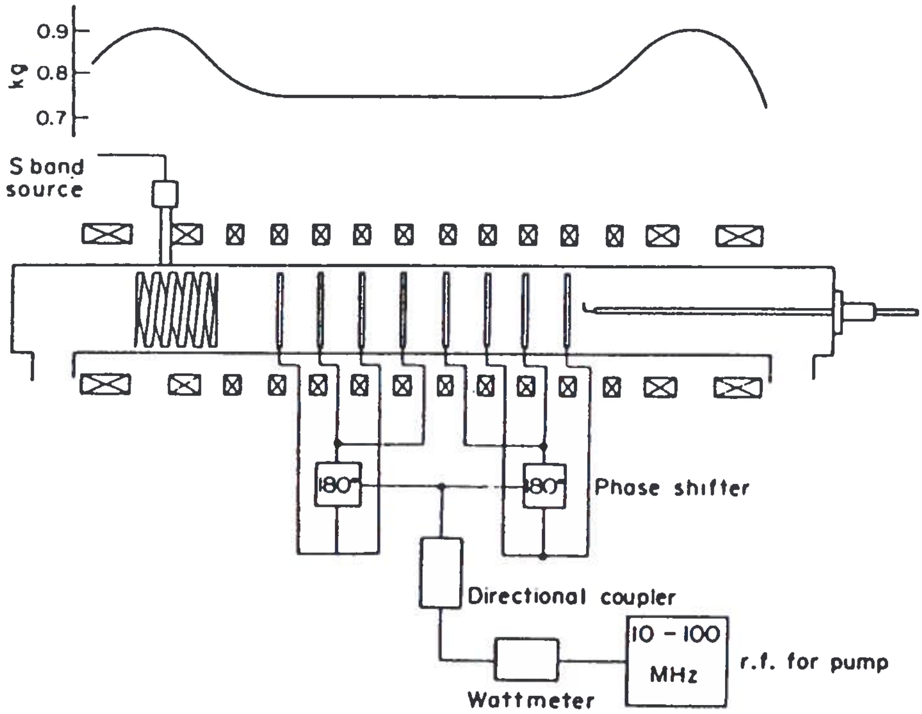


FIG. 1.—Experimental set up and magnetic field profile.

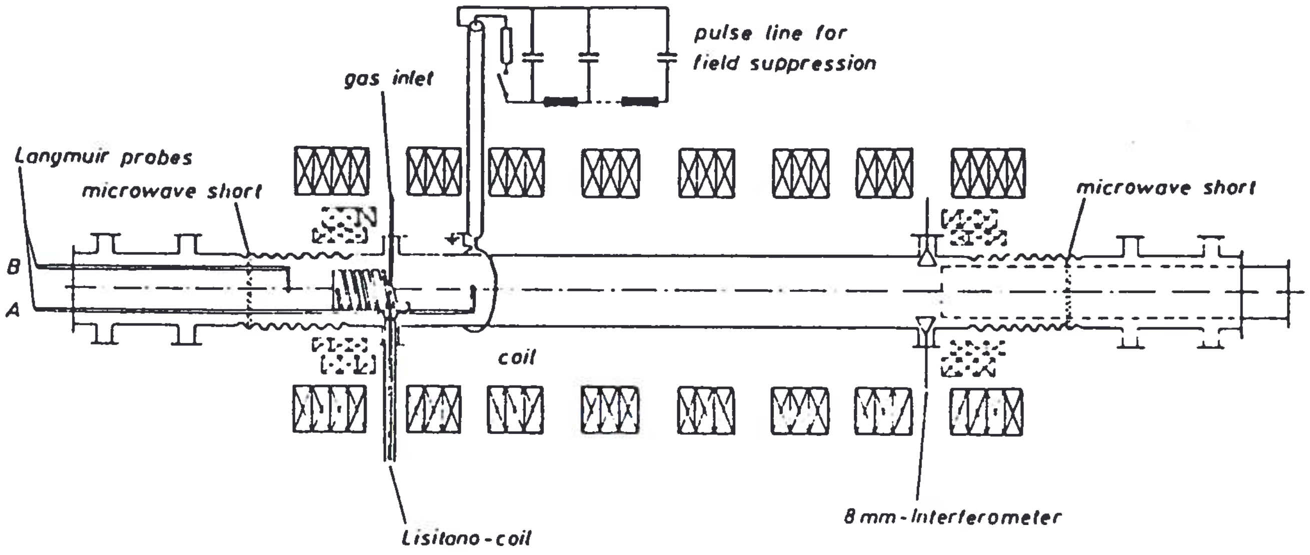
(14) Helical Coil with Central Gas Feeding

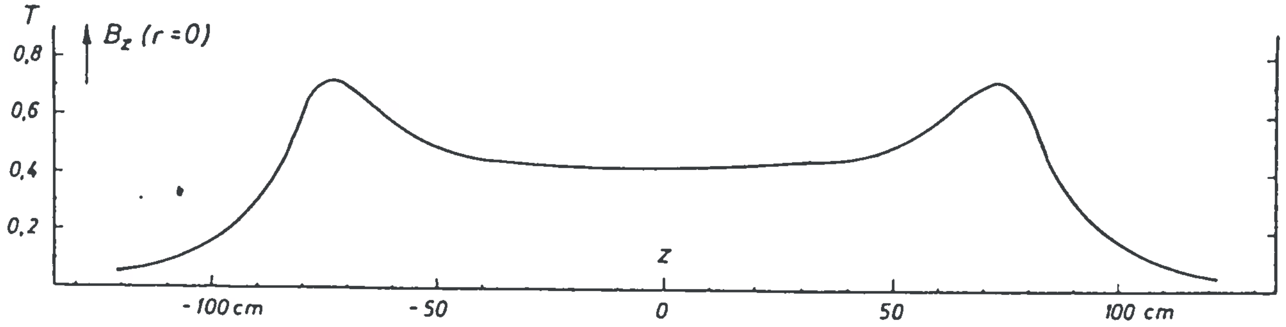
Gas : Ar
$2 \div 20 \ 10^{-4}$ Torr
$n_e = 10^{11} \div 10^{12} \mathrm{cm}^{-3}$
$T_e = 3 \div 6$ eV
P_0 base 2 10^{-3} Torr
J.E. Schaerer and J.E. Mitzlaff
Plasma Phys. Vol. 19, 1977, p. 413 - 422

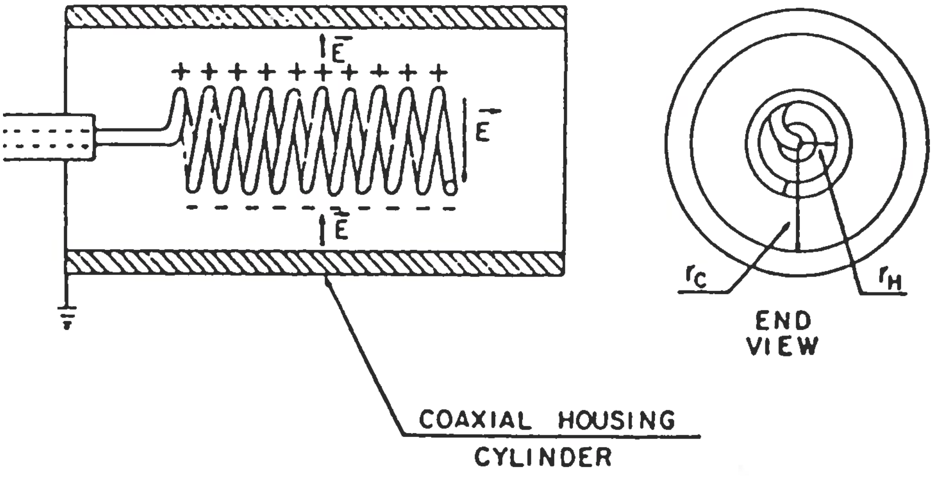
(15) Helical coil

$B_0 = 1$ kGauss
$10^{10} < n < 10^{11}$ cm^{-3}
$P_0 = 10^{-4} \div 10^{-5}$ Torr
$T_e = 5$ eV
$T_i = 1$ eV
Power efficient coupling to plasma 70%
(Parametric decay instability near the lower hybrid resonance.)

G. Bonizzoni et al.
Plasma Physics Vol. 19, 1977, p. 1163 - 1175







1. Charge distribution and electric fields for a helix with ≈ 1.

(16) Lisitano Slow Wave Structure (SWS)

2.45 GHz source 5kW
ECR condition.
H_2 $P_0 = 2.10^{-4}$ Torr
$n_e = 1 \div 2.10^{12}$ cm^{-3}
$T_e = 5$ eV
G. Müller, E. Räuchle and W. Staib
Physics Letters Vol. 54A, 1975, p. 261 - 262

(17) Helical Coil Coaxial in Housing cylinder

- ECRH condition $T_i \approx 0.2 \div 2$ eV
- Gas: Ar
- 2 $10^{-5} \div 2$ 10^{-3} Torr
- $\frac{\delta n}{n} = 1 \div 5$ %

D.P. Grubb and T. Lovell
Rev. Sci. Instr. Vol. 49, 1978, p. 77
Madison

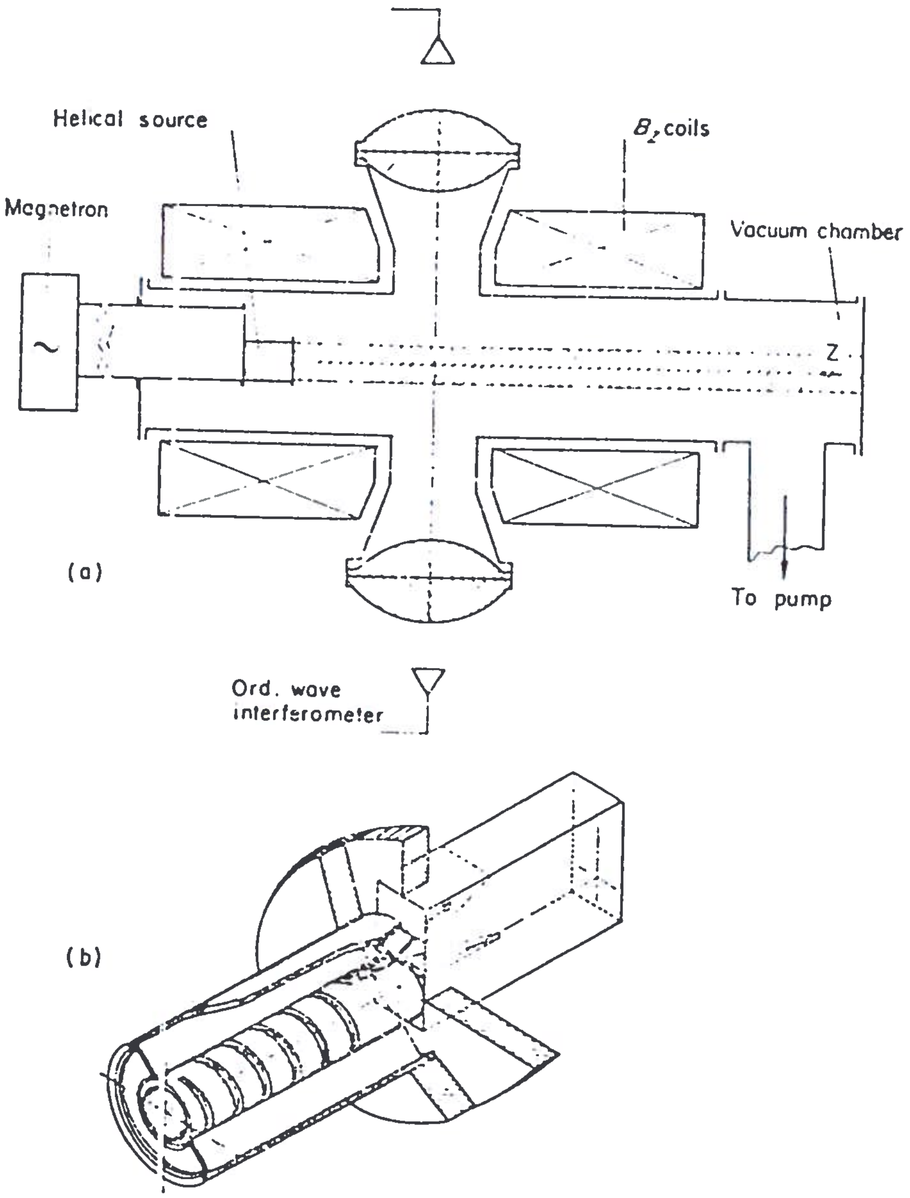


FIG. 1.—(a) Experimental apparatus. (b) Details of the helical coil.

(18) Helical Coil

Gas. A,H
f = 2.45 GHz
P = 1.5 kW
in mirror field (2.17:1)
$1 < f_{ce}/f < 30$
$10^{11} < n < 10^{13}$ cm^{-3}
ionisation degree 1 ÷ 10% H
5 ÷ 30% Ar
R. Cano, B. Zanfagna, G. Lisitano
Plasma Physics Vol. 15, 1973, p. 457 - 460

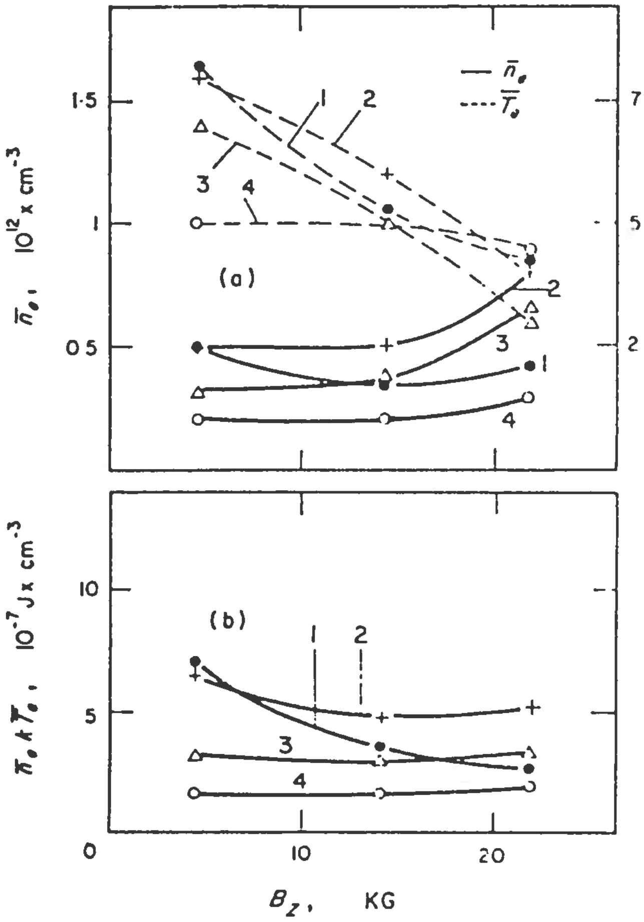
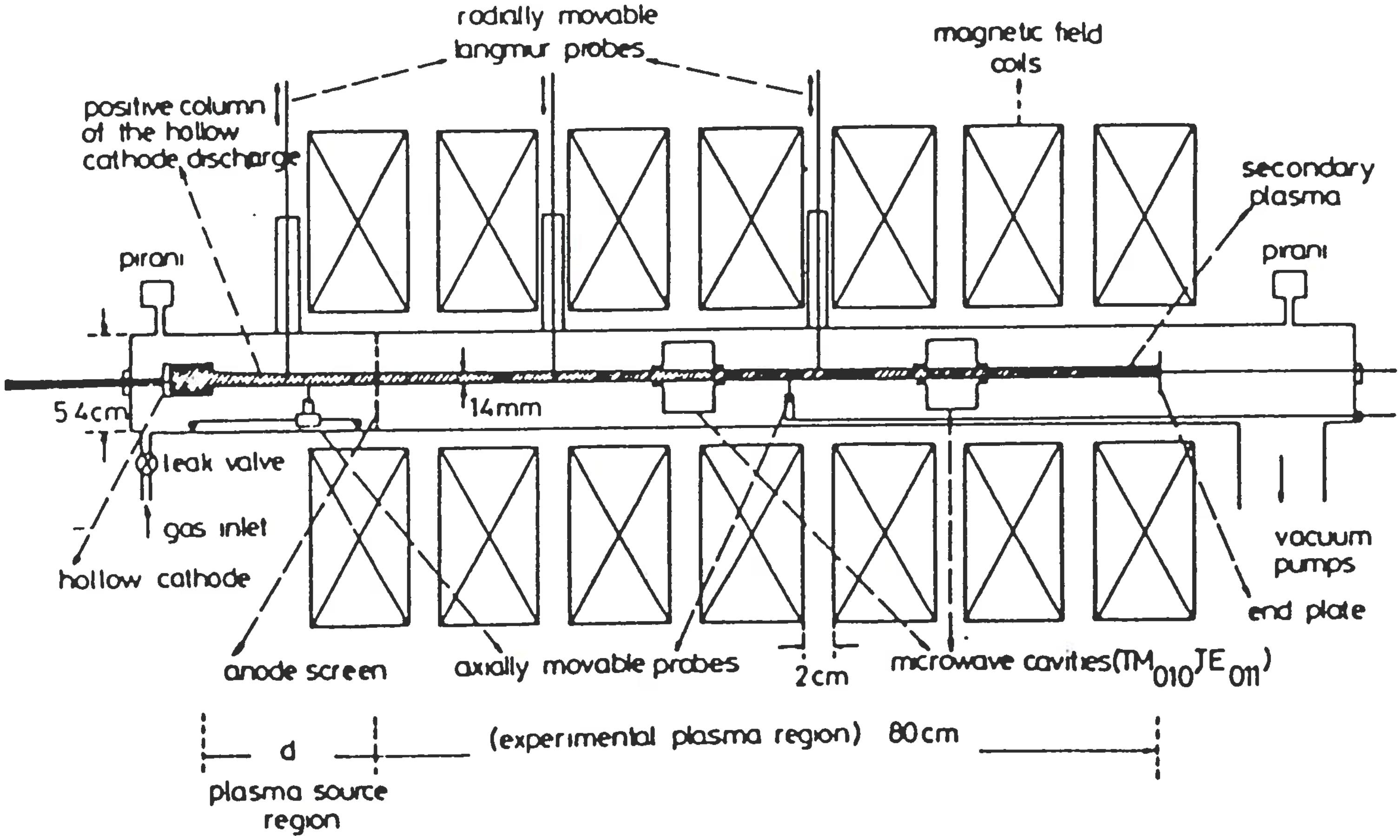


FIG. 4.—(a) Average density and temperature vs magnetic field B_z. (b) Average energy density $\bar{n}K\bar{T}$ vs magnetic field B_z. Gas pressure (Hydrogen): 1. $p = 1{\cdot}1{\cdot}10^{-3}$ torr; 2. $p = 2{\cdot}10^{-3}$ torr; 3. $p = 6{\cdot}5{\cdot}10^{-3}$ torr; 4. $p = 1{\cdot}1{\cdot}10^{-2}$ torr.



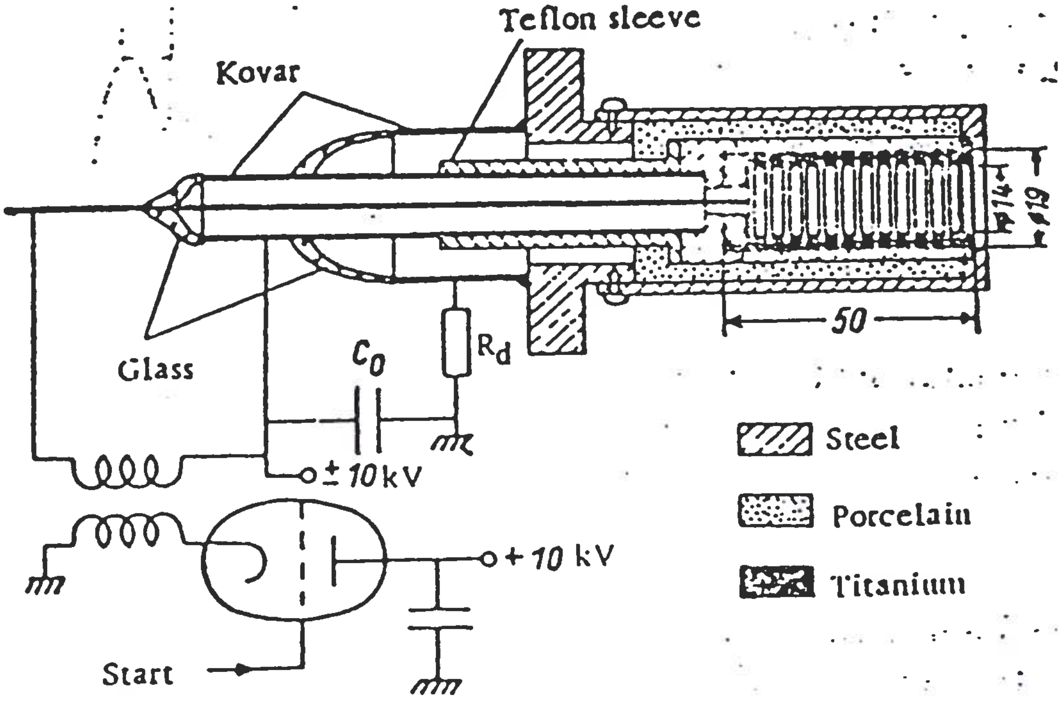


Fig. 1. Experimental plasma source and power supply.

E- Hollow cathode and Washer gun

(19)Hollow-cathode discharge

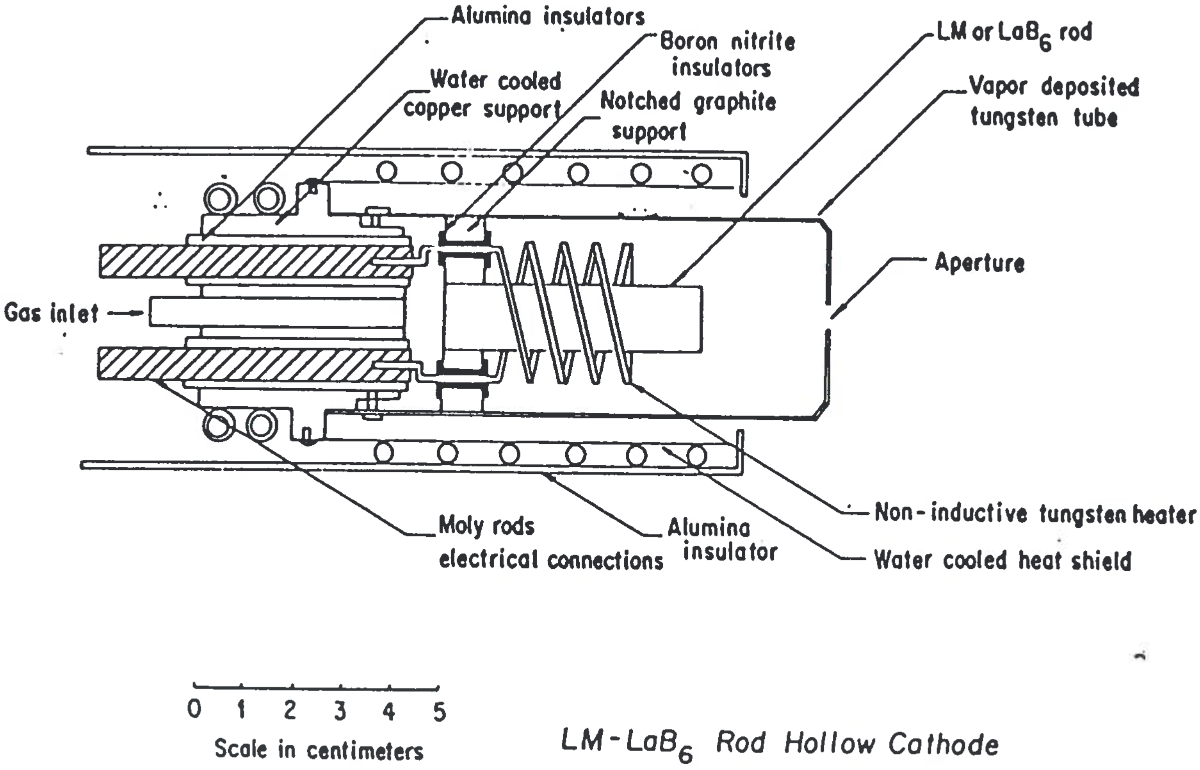
Argon $p_o \approx 10^{-2}$ Torr
ϕ 14mm, L = 80 cm
$T_e = 0.3 \div 1.2$ eV
$n_e = 10^9 \div 10^{11}$ cm^{-3}
$\frac{\delta n_e}{n_e} \sim 3\%$ start voltage ~ 7 kV
B field max 3 kG homogenity 2%
M. Subasi and G. Taxcan
Rev. Sci. Inst. Vol. 55, 1984, p. 12
Nuclear Res. Center, Instanbul

(20) Titanium plasma source (Washer gun)

Gas: H, D
20 titanium washers saturated to 1:1 atoms H
H^+ and H_2^+ $300 \div 500$ eV
$\rightarrow C^+, C^{++}\ T_i^{++}$ $50 \div 150$ eV
$n_e > 10^{16}$
$\frac{\delta n}{n}$?

- pulse length $\tau \approx 9\ \mu$sec
- experiment in L ~ 1m
- ionization rate ~ 70% max.

E.D. Andrvukhina and I.S. Spighel
Soviet Physics Vol. 10(7), 1966, p. 962



LM-LaB_6 Rod Hollow Cathode

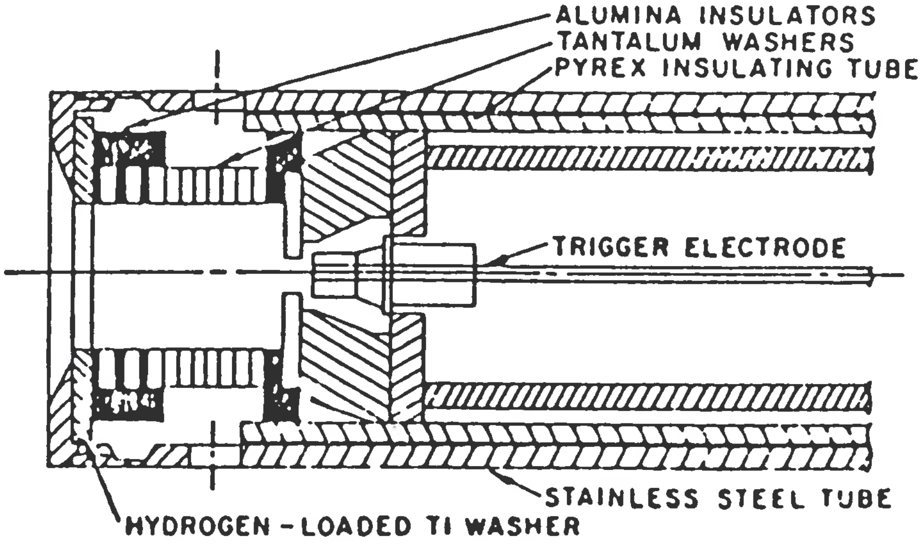


FIG. 1. Occluded gas, cold plasma source

(21) Hollow cathode with starter

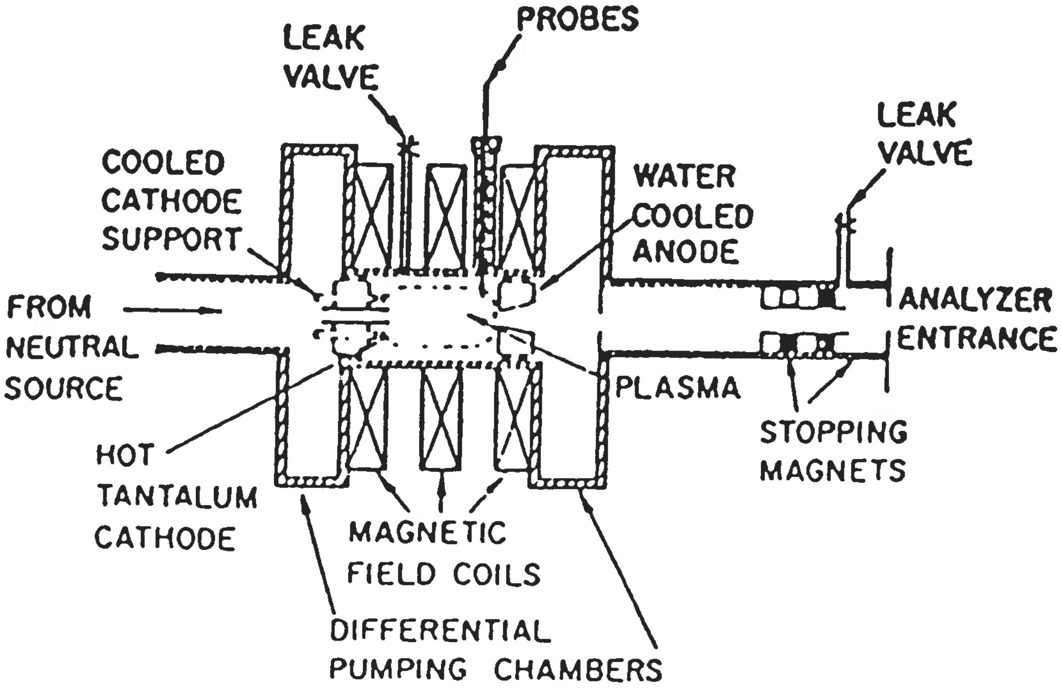
Lanthanum hexaboride La B_6		**Tungsten** W	
temp.	$J(A/cm^2)$	temp.	$J(A/cm^2)$
1500^oC	2.5	2400^oC	1.6
1600	7	2500	3.5
1700	18	2700	14.5
1800	42	2900	47

1) large current is extracted from cathode up to 800A
$\Rightarrow$ streaming out $n_e \sim 5.4\ 10^{13}\ cm^{-3}$
$T_e \sim 5$ eV
2) low voltage 50V (Ar)
80V (H)
3) different vacuum gun $5.6\ 10^{-2}$ Torr
chamber $3\ 10^{-4}$ Torr
4) cathode life time 300 hours, even up to air 100h, expected 3500h
5) to initiate discharge apply 1 kW which corresponds to 100A
(for W-heater)

D.M. Goebel at al.
Rev. Sci. Instr. Vol. 49(4), 1978, p. 469

(22) Washer Gun

Starter $1 \div 15$ kV
$15 \div 650\ \mu s$
arc 90V
$200A \div 3kA$
B_0=30kG $n_e = 3\ 10^{14} cm^{-3}$
$T_e \sim 3$ eV
$T_i \approx T_e$
$P_0 = 1.5\ 10^{-4}$ Torr
90 % ionized
J.F. Steinhaus et al.
Phys. Fluids Vol. 8(9), 1965, p. 1720



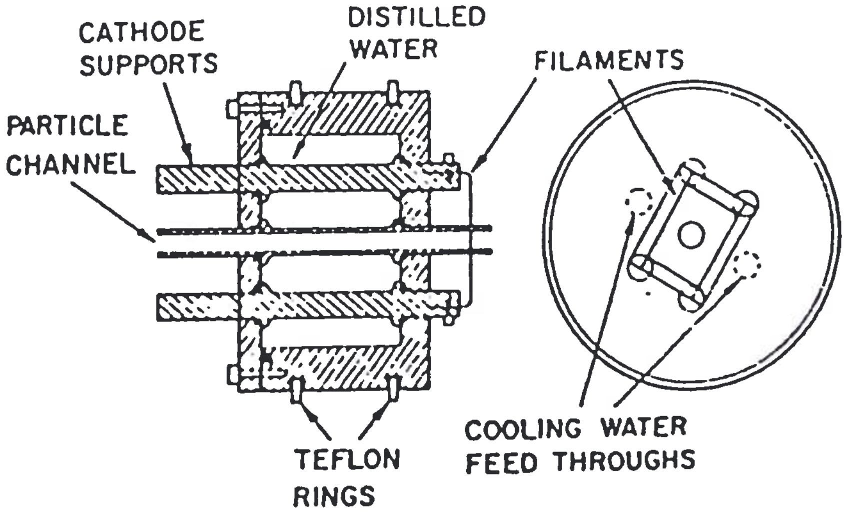
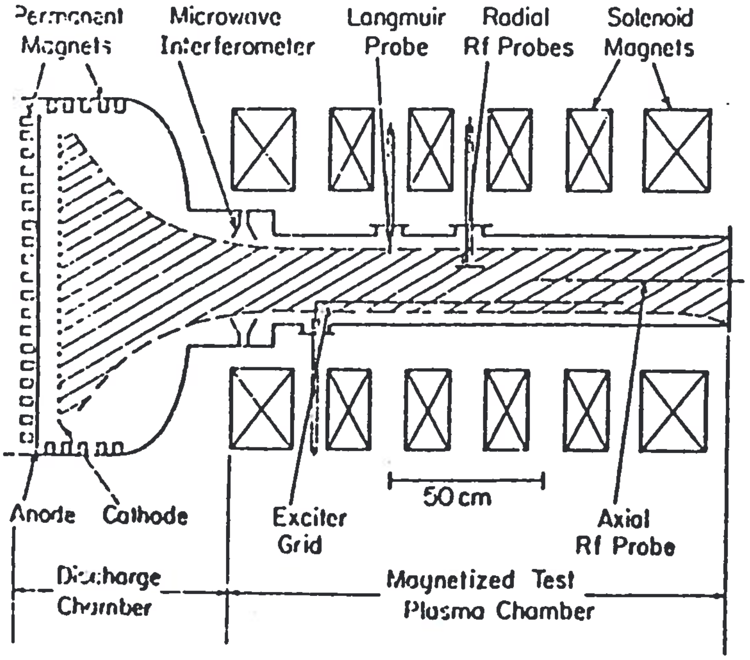


FIG. 2. Cathode assembly.

(23) Filamentary hollow cathode source

H_2
$T_e = 30 \div 300$ eV
$n_e \approx 10^{12} \mathrm{cm}^{-3}$
$n_e \approx 10^{15} \mathrm{cm}^{-3}$ at source
H.H. Fleishmann and R. Aribel
Rev. Sci. Instr. Vol. 39(2), 1968, p. 233 - 238



chematic of the SCAMP device. The magnetized plasma electrically insulated from the source chamber.

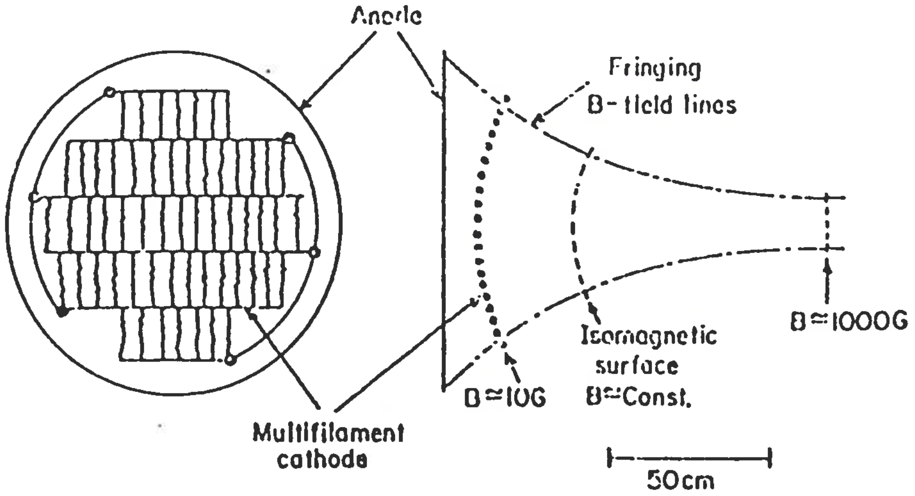
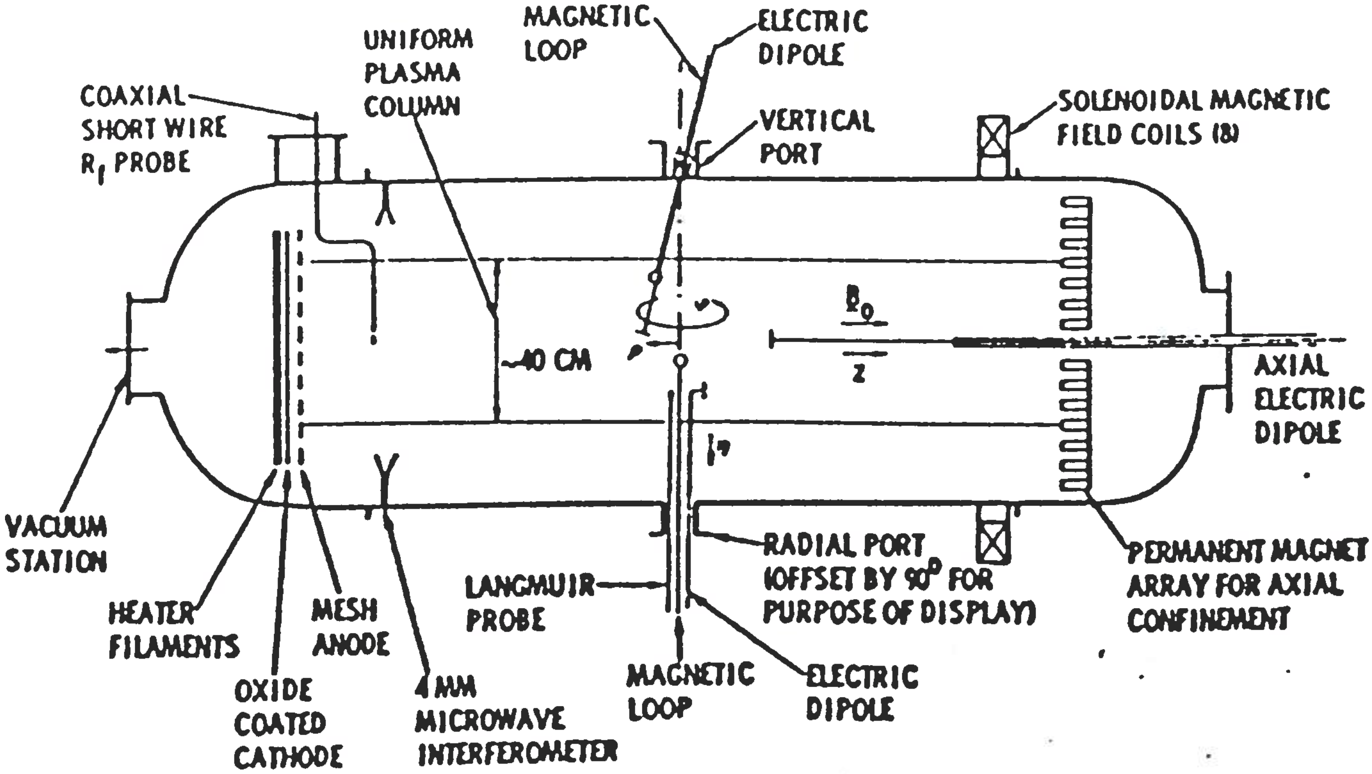


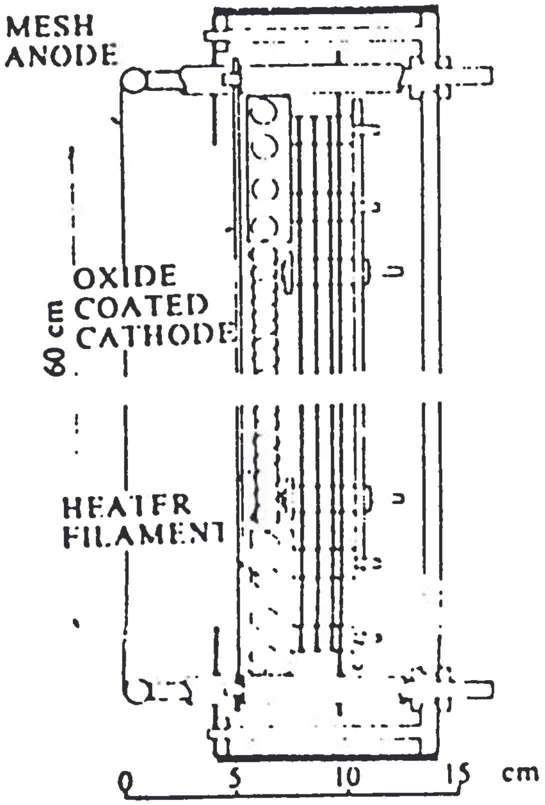
FIG. 3. Schematic of multifilament cathode (left) and its location (right) on the isomagnetic surface $B \simeq 10$ G=const. of the fringing field of the solenoid magnet.

F- Large size hot cathode and filamentary assembly

(24) Filamentary cathode in B field gradient

Gas: A
B_0 uniform ϕ 8 cm
$B_0 = 1$ kG
$\frac{\delta n}{n} \leq 1\%$
$n_e > 10^{11} cm^{-3}$
$p_0 = 3 \ \ 10^{-4}$ Torr
$\nu_{en} \approx 10^5$ Hz
$T_e \sim 2.5$ eV
$T_i \sim .2$ eV
discharge current max 15A
Power requirement for filament 4kW
W. Gekelman and R.L. Stenzel
Rev. Sci. Instr. Vol. 46(10), 1975, p. 1386





End view of the TPL device.

(25) Large size cathode

ϕ vacuum chamber 1 m
L vacuum chamber 3.5 m

magnetized plasma (± 10%) ϕ=45cm, L = 300 cm

Large cathode BaO,SrO,CaO... ϕ=50cm, indirectly heated (9 kW heating power)
Current density 1A/cm^2, 50eV electrons
collisionless mean free path > 10 m

$p_0 = 2 \ \ 10^{-4}$ Torr, $\frac{\delta B}{B_0} \leq 0.5\%$, $B_{axial} < 150$ Gauss
Axial magnetic field by multimirror permanent magnets walls (Sanarium) $B_{max} \approx 4$ kG
$n_e \approx 10^{12}$ cm^{-3}

$\frac{\nu}{\omega_c} \approx 5 \ \ 10^{-3}$, collisionless

$kT_e = 2$ eV $\approx 10kT_i$	in discharge	Pulse operation
$kT_e = 0.2$ eV $\approx kT_i$	in afterglow	2kJ capacitor bank

cathode lifetime 2 months
Pulse ≈ 4 ÷ 10 msec.
R.L. Stenzel
Phys. Fluids Vol 19(6), 19??, p. 857

(26) Large size cathode

B_0 2 kG

B_a0 cathode, Φ= 60 cm
20kW heating power
τ = 4 msec, 40V, 200 A discharge
$n_e = 10^{12}$cm^{-3}
$kT_e = 2$ eV $= kT_i$
$\frac{\delta n}{n}$?
H. Sugni, S. Kishimoto
Nagoya, annual report1983

ANNEXE VI-2

DIAGNOSTICS FOR LOW DENSITY PLASMA

F.Skiff

QUANTITY	METHOD	REFERENCE
I. ELECTROSTATIC PARTICLE-COLLECTING PROBES		
A) Langmuir Probes		
$n_e \cdot \sqrt{T_e}$	ion saturation current	Swift + Schwar, Electrical Probes for Plasma Diagnostics (New York Elsevier). See also Gen. ref. 1. below
T_e	i-V characteristic	
ϕ_p	Emissive probe	Rev. Sci. Instr. 36, 316 (1965), Phys. Fluids 14, 1120 (1971)
ϕ_{rf}	Radio frequency (rf) capacitive probe	Rev. Sci. Instr. 42, 589 (1971)
E_x rf	- double tip	
B) Energy Analysers		
$f(v_{\parallel})_e$	Multigrid analyser	see Gen. ref. 1
$f(v_{\perp})_i$	Katsumata probe	Japan J. Appl. Phys. 6, 123 (1976). Phys. Lett. 70A, 413 (1979)
$f(v_{\parallel})_i$	ion analyser	Phys. Rev. 28, 104 (1926)
II. ELECTROMAGNETIC PROBES		
$B_{\tilde{n}}$ rf	Magnetic probe (Mirnov)	Nucl. Fus. 19, 115 (1979)

$n_eT_e + n_iT_i$ I_p	Rogowski loop	see gen. ref. 1

III. WAVE DIAGNOSTICS

A) Dispersion relations

$T_e, T_e/T_i$	ion acoustic wave	see gen. ref. 2
$n_e, \{{T_e \atop T_i}\}$	Lower hybrid wave	Phys. Fluids 14, 857 (1971)
Species concentrations	Low frequency resonance cone	PRL 42, 1267 (1979)
$T_{i\perp}$	Ion Bernstein wave	Phys. Rev. A. 26, 2297 (1982)

B) Scattering, frequency shift (see also laser)

$\int n_e dx$	ordinary mode	M.A. Heald, C.B. Wharton, Plasma Diagnostics with microwaves (John Wiley, 1965)
n_e $_{rf}(\omega, k)$	microwave scattering	
$\int dz n_e(x,y,z)$	Phase contrast	Infrared Phys. 25, 543 (1985)
$\int n_e d^2x$	Cavity frequency shift	J. Appl. Phys. 36, 3642 (1965)

IV LASER DIAGNOSTICS

A) Laser induced fluorescence

	ion or atomic	
$f(v_\perp, v_\parallel)_i$	- line shape	Rev. Sci. Instr. 56, 1006 (1985)
$V_D \rightarrow E$	- line shift	PRL 34, 1548 (1975)
trajectory of ions in phase space	- tagging	Thèse No. 626, P. Kohler, EPFL (1986)
species concentration	- two photon doppler free excitation	PRL 32, 643 (1974)

B) Small angle scattering

$\tilde{n}(\omega,k)$	homodyne mixing CO_2 laser	Phys. Fluids 23, 472 (1980)

V. PASSIVE SPECTROSCOPY

T_i	Line width	see gen. ref. 1
T_e	Line intensity	

GENERAL REFERENCES

1 Plasma Diagnostic Techniques, Huddlestone and Leonard, (Academic Press, 1965)
2 Introduction to Plasma Physics, F. Chen (Plenum 1976)
3 Plasma Diagnostic, W. Lochte-Holtgreven (North-Holland, 1968)
4 Plasma Physics for Nuclear Fusion, K. Miyamoto, (MIT Press, 1976)

ANNEXE VI-3
PLASMA PARAMETERS
FOR HYDROGEN

$$\Lambda = 1.55 \cdot 10^{10} \frac{Te^{3/2}}{n^{1/2}}$$

Te in eV

n in cm^{-3}

ln Λ

$\tilde{n}$(cm^{-3})	Te = 1eV	Te = 5eV	Te = 10 eV	Te = 20 eV
10^{11}	10.80	13.92	14.25	15.13
10^{-12}	9.65	12.77	13.10	14.14
10^{13}	8.50	11.62	11.95	12.99

$$\nu_{ee} = 2.90\ 10^{-6} \frac{n \ln\Lambda}{Te^{3/2}}$$

n in cm^{-3}

Te in cm^{-3}

$$\lambda_{mpf} = \frac{V_{the}}{\nu_{ee}} = 1.4\ 10^{13} \frac{Te^2}{n \cdot \ln\Lambda}$$

n(cm^{-3})	ν_{pe}(Hz)		Te=1eV	Te=5eV	Te=10eV	Te=20eV
10^{11}	3.10^9	ν_{ee}(Hz)	$3.24\ 10^6$	$3.61\ 10^5$	$1.31\ 10^5$	$4.91\ 10^4$
		λ_{mpf}(cm)	12.9	$2.51\ 10^2$	$9.82\ 10^2$	$3.7\ 10^3$
10^{12}	$8.9\ 10^9$	ν_{ee}(Hz)	$2.9\ 10^7$	$3.32\ 10^6$	$1.2\ 10^6$	$4.59\ 10^5$
		λ_{mpf}(cm)	1.45	27.4	$1.06\ 10^2$	$3.96\ 10^2$
10^{13}	$3\ 10^{10}$	ν_{ee}(Hz)	$2.55\ 10^8$	$3.02\ 10^7$	$1.09\ 10^6$	$4.22\ 10^6$
		λ_{mpf}(cm)	0.164	3.012	11.71	43.11

$$\nu_{ei} = 2\frac{m_e}{m_i}\nu_{ee} = 1.089\ 10^{-3}\ \nu_{ee}$$

$$\nu_{ii} = 2.316\ 10^{-2} \left(\frac{Ti}{Te}\right)^{-3/2} \nu_{ee}$$

(1) $\nu_{ii} = 6.76\ 10^{-8} \frac{n \ln \Lambda}{Ti^{3/2}}$ Ti in eV

also one can find (2) $\nu_{ii} = 4.8\ 10^{-8} \frac{n \ln \Lambda}{Ti^{3/2}}$

$\lambda_{mpf} = 2.03\ 10^{13} \frac{Ti^2}{n \ln \Lambda}$

$n(cm^{-3})$	$\nu_{pi}(Hz)$		Ti=0.1eV	Ti=0.5eV	Ti=1eV	Te=5eV
10^{11}	$6.64\ 10^{7}$	$\nu_{ii}(Hz)$ (1)	$3.04\ 10^{6}$	$2.72\ 10^{5}$	$9.633\ 10^{4}$	$8.61\ 10^{3}$
		(2)	$2.15\ 10^{6}$	$1.93\ 10^{5}$	$6.84\ 10^{4}$	$6.11\ 10^{3}$
		λ_{mpf} cm (2)	0.143	3.57	14.3	$3.58\ 10^{2}$
10^{12}	$2.1\ 10^{8}$	$\nu_{ii}(Hz)$ (1)	$2.8\ 10^{7}$	$2.5\ 10^{6}$	$8.85\ 10^{6}$	$7.99\ 10^{4}$
		(2)	$1.98\ 10^{7}$	$1.77\ 10^{6}$	$6.28\ 10^{5}$	$5.61\ 10^{4}$
		λ_{mpf} cm (2)	$1.55\ 10^{-2}$	$3.9\ 10^{-1}$	1.55	$3.9\ 10^{2}$
10^{13}	$6.64\ 10^{8}$	$\nu_{ii}(Hz)$ (1)	$2.55\ 10^{8}$	$2.28\ 10^{7}$	$8.07\ 10^{6}$	$7.2\ 10^{5}$
		(2)	$1.81\ 10^{8}$	$1.61\ 10^{7}$	$5.73\ 10^{6}$	$5.13\ 10^{5}$
		λ_{mpf} cm (2)	$1.7\ 10^{-3}$	$4.26\ 10^{-2}$	$1.7\ 10^{-1}$	4.26

In the case of hydrogen gas, totally ionized, we must have a base pressure in the plasma source region of $P_0 = 2.83\ 10^{-5}$ Torr, for $n_0 = 10^{12} cm^{-3}$ (Loschmidt's number $n_0 = 3.53\ 10^{13} cm^{-3}$ at $P_0 = 10^{-3}$ Torr, standard temperature).

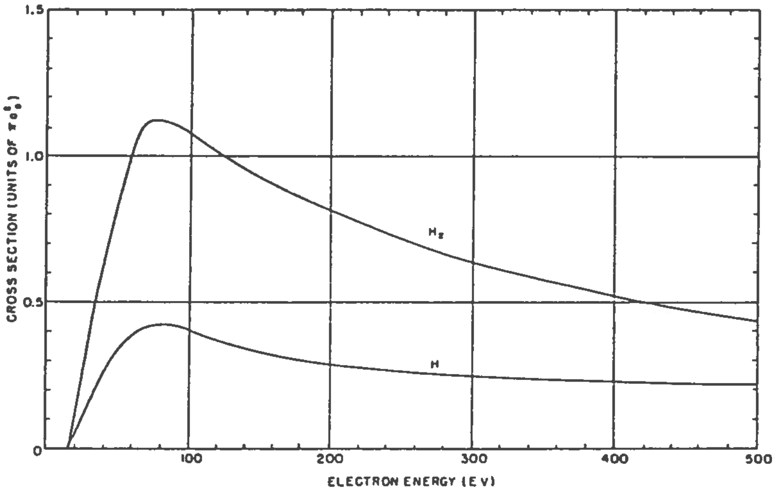
One should notice that P_0 is the pressure of H_2 in the vessel (correction should be made in case of absolute pressure is measured).

Electron neutral momentum transfer (at $P_0 = 2.83\ 10^{-5}$ Torr) in molecular hydrogen

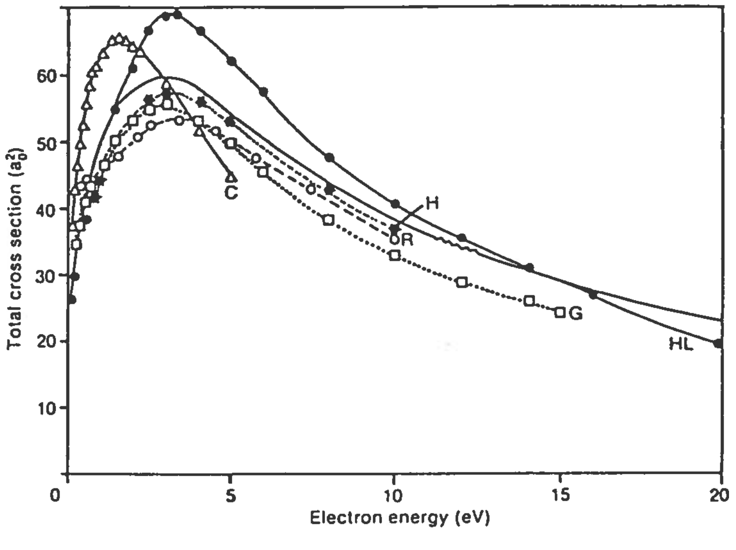
Te(eV)	V_{the} (cm/s)	σ_0 (cm^2)	λ_{mpf} (cm)	ν_{en} (Hz)
1	$4.19\ 10^{7}$	$49\ 10^{-16}$	$2.04\ 10^{2}$	$2.05\ 10^{5}$
5	$9.36\ 10^{7}$	$62\ 10^{-16}$	$1.61\ 10^{2}$	$5.78\ 10^{5}$
10	$1.32\ 10^{8}$	$40\ 10^{-16}$	$2.5\ 10^{2}$	$5.28\ 10^{5}$
20	$1.87\ 10^{8}$	$20\ 10^{-16}$	$5.\ 10^{2}$	$3.74\ 10^{5}$
100	$4.19\ 10^{8}$	$\sim 1\ 10^{-16}$	$1.25\ 10^{4}$	$3.35\ 10^{4}$

$v_{the} = 4.19\ 10^{7}\ Te^{1/2}\ (cm\ s^{-1})$

$\lambda_{mpf} = \frac{1}{\sigma_0 n_0}$ (cm) $\nu_{en} = \sigma_0 n_0 v_{the}$ (Hz)



Ionization cross sections of hydrogen on electron impact
From "In elastic collisions of electrons" by S.C. Brown, Basic
Data of Plasma Physics, MIT, 1959



Total cross sections for molecular hydrogen
From "Basic processes of electrical discharges" from different
authors, J.A. Rees in Electrical Breakdown and Discharges in
Gases, Nato, Ed. Plenum Press, 1983