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

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TABLE

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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 accelerator 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.

(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)
<table>
<thead>
<tr>
<th>Ref.</th>
<th>Plasma source</th>
<th>Freq. source</th>
<th>$\phi_{\text{plasma}}$ cm</th>
<th>$n_e$ max cm$^{-3}$</th>
<th>$T_e$ range (eV)</th>
<th>$T_i$ range (eV)</th>
<th>$\delta n/n$ %</th>
<th>neutral p. Torr</th>
<th>B-field k Gauss</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>open waveguide ECR</td>
<td>2.35GHz 2kW</td>
<td>9</td>
<td>$10^{12}$</td>
<td>9</td>
<td>?</td>
<td>3·10^{-3}</td>
<td>$\equiv .9$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2)</td>
<td>open waveguide ECR</td>
<td>2.45GHz 1.7kW</td>
<td>8</td>
<td>$10^{12}$</td>
<td>20</td>
<td>?</td>
<td>5·10^{-4}</td>
<td>$\equiv .9$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3)</td>
<td>open waveguide ECR</td>
<td>1.7GHz 5.8kW</td>
<td>8</td>
<td>$10^{12}$</td>
<td>?</td>
<td>$10^{-3} + 10^{-2}$</td>
<td>$= .6$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4)</td>
<td>on conical vessel open waveguide ECR</td>
<td>10GHz 150W</td>
<td>2.5</td>
<td>$10^{-12}$</td>
<td>?</td>
<td>$10^{-3} + 10^{-1}$</td>
<td>4000 Oe</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(5)</td>
<td>open waveguide on conical vessel ECR</td>
<td>9.375gW</td>
<td>2.5</td>
<td>3 + 5</td>
<td>0.1 + 0.2</td>
<td>?</td>
<td>$10^{-4} + 10^{-1}$</td>
<td>6000 Oe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(6)</td>
<td>Pyramidal horn</td>
<td>10.3GHz</td>
<td>$10^{13}$</td>
<td>5 + 30</td>
<td>?</td>
<td>$10^{-5} + 10^{-2}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(7)</td>
<td>RF</td>
<td>155MHz</td>
<td>9.5</td>
<td>$10^{12}$</td>
<td>15</td>
<td>up to 15</td>
<td>$10^{-3}$</td>
<td>16 k Gauss</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

résumé: open waveguide ECR ($\omega_0 = \omega_{ci}$) | 1.7 + 10 GHz 30W + 5.8kW | max. 10 cm | max. $10^{13}$ over crit. density ($\omega_0 = \omega_{pe}$) | $3 + 30eV$ | $T_e \bot T_i$ up to $1 + 2eV$ | $T_i$ max. | no answer found | $10^{-5} + 10^{-1}$ | at res. with $\omega_0$ | $\equiv 1kGauss$ |

comments:
- 10+50% ionization is reached but bad radial density profile
- high B-field at the source
- noisy
- high frequency noise to plasma .....
<table>
<thead>
<tr>
<th>Ref.</th>
<th>Plasma source</th>
<th>Freq. source</th>
<th>s plasma cm</th>
<th>n_e,max (cm^-3)</th>
<th>T_e range (eV)</th>
<th>T_i range (eV)</th>
<th>δn/n (%)</th>
<th>neutral p. (Torr)</th>
<th>B-field (k Gauss)</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>(8)</td>
<td>interdigital Lisitano coil ECR</td>
<td>8.45GHz</td>
<td>3.5</td>
<td>2.5 × 10^10</td>
<td></td>
<td></td>
<td></td>
<td>10^-4+10^-2</td>
<td>1.3</td>
<td>1+50% ionization</td>
</tr>
<tr>
<td>(9)</td>
<td>Lisitano coil ECR</td>
<td>10GHz 100W</td>
<td>5</td>
<td>5 × 10^11</td>
<td>20</td>
<td>5+1</td>
<td></td>
<td>5.1 × 10^-6+</td>
<td>10</td>
<td>50% ionization max.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.35GHz 5kW</td>
<td></td>
<td>1.5 × 10^12</td>
<td></td>
<td></td>
<td></td>
<td>10^-4+10^-3</td>
<td>13</td>
<td>10% ionization</td>
</tr>
<tr>
<td>(11)</td>
<td>SWS</td>
<td>3GHz 70W</td>
<td>3</td>
<td>10^12</td>
<td>10</td>
<td>5</td>
<td></td>
<td>10^-3</td>
<td>1.8</td>
<td>30%</td>
</tr>
<tr>
<td>(12)</td>
<td>SWS ECR</td>
<td>2.45GHz 1kW</td>
<td>16</td>
<td>4 × 10^11</td>
<td>8</td>
<td>10^-3</td>
<td></td>
<td>.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(13)</td>
<td>SWS</td>
<td>2.45GHz 1kW</td>
<td>5</td>
<td>2 × 10^12</td>
<td></td>
<td>5</td>
<td></td>
<td>10^-3</td>
<td>2 max</td>
<td></td>
</tr>
<tr>
<td>(14)</td>
<td>helical coil</td>
<td>5</td>
<td>10^12</td>
<td>3+6</td>
<td></td>
<td></td>
<td></td>
<td>1 × 10^-4+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(15)</td>
<td>helical coil</td>
<td>15</td>
<td>10^11</td>
<td>5</td>
<td>1</td>
<td>10^-4-</td>
<td></td>
<td>10^-5</td>
<td></td>
<td>.9</td>
</tr>
<tr>
<td>(16)</td>
<td>SWS ECR</td>
<td>2.45GHz 5kW</td>
<td>8</td>
<td>2 × 10^12</td>
<td>5</td>
<td>2 × 10^-4</td>
<td></td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(17)</td>
<td>helical coil ECR</td>
<td>4+5</td>
<td>10^11</td>
<td>15</td>
<td>0.2+2</td>
<td>1+5</td>
<td></td>
<td>10^-5+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(18)</td>
<td>helical coil</td>
<td>2.45GHz 1.5kW</td>
<td>10</td>
<td>10^13</td>
<td>7.5</td>
<td>10^-3+</td>
<td></td>
<td>10^-2</td>
<td></td>
<td>1+10% H</td>
</tr>
<tr>
<td></td>
<td>Résumé mainly SWS</td>
<td>2.45GHz</td>
<td>3+16</td>
<td>10^-13</td>
<td>3+20</td>
<td>.2+2</td>
<td>1+10</td>
<td>5 × 10^-6+</td>
<td>mainly 1</td>
<td>-max. 50% ionization - high B-field</td>
</tr>
<tr>
<td>Ref.</td>
<td>Plasma source</td>
<td>Freq. source</td>
<td>( \phi ) plasma (cm)</td>
<td>density (cm(^{-3}))</td>
<td>( T_e ) range (eV)</td>
<td>( T_i ) range (eV)</td>
<td>( \delta n/n ) (%)</td>
<td>neutral p. (Torr)</td>
<td>B-field (k Gauss)</td>
<td>comments</td>
</tr>
<tr>
<td>------</td>
<td>---------------</td>
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<td>------------------------</td>
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<td>----------------</td>
<td>----------------</td>
<td>----------------</td>
<td>----------</td>
</tr>
<tr>
<td>(19)</td>
<td>hollow cathode</td>
<td>7kV</td>
<td>1.4</td>
<td>( 10^9+10^{11} )</td>
<td>.3+12</td>
<td>3</td>
<td>10(^{-2} )</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(20)</td>
<td>washer gun</td>
<td>10kV</td>
<td>1.4</td>
<td>( 10^{16} )</td>
<td>300+500</td>
<td>50+150 (impurities)</td>
<td>?</td>
<td>3</td>
<td></td>
<td>70% ionization</td>
</tr>
<tr>
<td>(21)</td>
<td>hollow cathode</td>
<td>1kW/100A</td>
<td>.64</td>
<td>( 10^{-13} )</td>
<td>5</td>
<td>5</td>
<td>?</td>
<td>3 ( 10^{-4} )</td>
<td>(chamber)</td>
<td></td>
</tr>
<tr>
<td>(22)</td>
<td>washer gun</td>
<td>1+15kV</td>
<td>( \tau=15+600\mu s )</td>
<td>( 3 \times 10^{14} )</td>
<td>3</td>
<td>3</td>
<td>?</td>
<td>10(^{-2}-10^{-4} )</td>
<td></td>
<td>90% ionized</td>
</tr>
<tr>
<td>(23)</td>
<td>filamentary hot cathode</td>
<td>.6</td>
<td>( 10^{15} ) source (source) ( 10^{12} ) chamber (chamber)</td>
<td>( 30+300 )</td>
<td>( 3+500 )</td>
<td>3+150</td>
<td>?</td>
<td>10(^{-4} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>résumé</td>
<td>washer gun</td>
<td>10+100\mu s</td>
<td>2</td>
<td>( 10^{14}+10^{15} )</td>
<td>3+500</td>
<td>3+150</td>
<td>?</td>
<td>10(^{-4} )</td>
<td></td>
<td>70+90% ionization</td>
</tr>
<tr>
<td>Ref.</td>
<td>Plasma source</td>
<td>Freq. source</td>
<td>ø plasma (cm)</td>
<td>density (cm⁻³)</td>
<td>Tₑ range (eV)</td>
<td>Tᵢ range (eV)</td>
<td>δn/n (%)</td>
<td>neutral p. (Torr)</td>
<td>B-field (k Gauss)</td>
<td>comments</td>
</tr>
<tr>
<td>------</td>
<td>---------------</td>
<td>--------------</td>
<td>---------------</td>
<td>----------------</td>
<td>---------------</td>
<td>---------------</td>
<td>-----------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>----------</td>
</tr>
<tr>
<td>(23)</td>
<td>filamentary cathode (very large source)</td>
<td>Ip=15A heating 4kW</td>
<td>8</td>
<td>10¹¹</td>
<td>2.5</td>
<td>.2</td>
<td>1</td>
<td>3·10⁻⁴</td>
<td>1</td>
<td>1% ionization</td>
</tr>
<tr>
<td>(24)</td>
<td>large size cathode ø 50cm</td>
<td>heating 9 kW</td>
<td>45</td>
<td>10¹²</td>
<td>2</td>
<td>.2</td>
<td>?</td>
<td>2·10⁻⁴</td>
<td>.15</td>
<td>νcoil/ωce=5·10⁻³ 10% ionization</td>
</tr>
<tr>
<td>(25)</td>
<td>large size cathode ø 60cm</td>
<td>Ip=200A/40V heating 20kW</td>
<td>60</td>
<td>10¹²</td>
<td>2</td>
<td>2</td>
<td>?</td>
<td>?</td>
<td>2</td>
<td>no much output work to my knowledge probable: ~ 10% ionization</td>
</tr>
<tr>
<td>résumé</td>
<td>cathode ø 50 cm ø 60 cm</td>
<td>heating 9+20kW Ip=150+200A</td>
<td>ø 40+60</td>
<td>10¹²</td>
<td>2</td>
<td>.2 to 2</td>
<td>.5+2%</td>
<td>10⁻⁴</td>
<td>.15+2</td>
<td>- 10% ionization - low B-field - low νcoil/ωce</td>
</tr>
</tbody>
</table>
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
<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil inner diameter</td>
<td>0.522 m</td>
</tr>
<tr>
<td>Coil outer diameter</td>
<td>0.830 m</td>
</tr>
<tr>
<td>Coil thickness</td>
<td>0.092 m</td>
</tr>
<tr>
<td>Number of turns</td>
<td>4</td>
</tr>
<tr>
<td>Number of layers</td>
<td>9</td>
</tr>
<tr>
<td>Conductor type</td>
<td>copper OF</td>
</tr>
<tr>
<td>Conductor size</td>
<td>$20.83 \times 15.75 \text{ mm}^2$</td>
</tr>
<tr>
<td>Cooling</td>
<td>water flow through a circular hole of diameter 6.35 mm</td>
</tr>
<tr>
<td>Typical coil electrical resistance at $20^\circ\text{C}$</td>
<td>4.58 mΩ</td>
</tr>
<tr>
<td>Total inductance of the solenoid</td>
<td>$5 \cdot 10^{-2} \text{ H}$</td>
</tr>
<tr>
<td>Max. input water temperature</td>
<td>$60^\circ\text{C}$</td>
</tr>
<tr>
<td>Max. output water temperature</td>
<td>$75^\circ\text{C}$</td>
</tr>
<tr>
<td>Water flow rate</td>
<td>120 l/min at 8.6 bars</td>
</tr>
</tbody>
</table>

**TABLE I : Coil characteristics**
**Plasma source:**

Hot cathode (BaO)

Cathode diameter

Cathode current

5 cm

\( \sim 1 - 15 \ \text{A continuous regime} \)

\( < 50 \ \text{A pulse regime} \)

**Plasma:**

Plasma diameter

Plasma length

Plasma density

Ratio of plasma density to discharge current (Ne plasma)

Neutral density

Electron temperature

Ion temperature

Electron Larmor radius

\((T_e = 9 \ \text{eV}, B = 0.3 \ \text{T})\)

Ion Larmor radius (for a Ne\(_{29}\) ion

\(T_i = 0.2 \ \text{eV}, B = 0.3 \ \text{T}\))

Ion Larmor radius (for Ar\(_{40}\) ion

\(T_i = 0.2 \ \text{eV}, B = 0.3 \ \text{T}\))

5 cm

4.75 m

\(~10^{10} - 10^{12} \ \text{cm}^{-3}~\)

\(~6 \times 10^{10} \ \text{cm}^{-3} \ \text{A}^{-1}~\)

\(~10^{12} - 10^{13} \ \text{cm}^{-3}~\)

\(~6 \times 10^{-2} \ \text{cm}~\)

\(~6.8 \times 10^{-2} \ \text{cm}~\)

\(~9.6 \times 10^{-2} \ \text{cm}~\)

**TABLE II:** Design and plasma parameters of the IMP

(with BaO cathode)
Lanthanum hexaboride cathode arrangement

Fig. III
Fig. 4

TC₁ ... TC₄ are thermocouples
Barium  \[ M = 138 \text{ a.m.v.} \quad \frac{M}{m_e} = 2.5 \times 10^5 \]

\[ n_i \]

\[ 10^8 < n_i < 10^{11} \text{ part/cm}^3 \]

\[ T_i = T_e \]

\[ T = 0.2 \text{eV} \]

B field \[ 1 < B < 3 \text{kGauss} \]

Ion gyroradius \[ r_{gi} = 0.18 \text{cm} \]

Electron gyroradius \[ r_{ge} = 3.67 \times 10^{-4} \text{cm} \]

for \[ B=3\text{KG} \] and \[ T_i = 0.2 \text{eV} \]

Ion thermal velocity \[ V_{thi} = 5.3 \times 10^4 \text{cm/s} \]

Ion drift velocity \[ V_{di} = 1.2 \times 10^5 \text{cm/s} \]

Ion thermal energy \[ T_i = 0.2 \text{ eV} \]

Ion drift energy \[ E_{DI} = 1.0 \text{ eV} \]

Ion plasma freq \[ f_{pi} = 565 \text{ KHz} \]

for \[ n = 10^9 \text{cm}^{-3} \]

Electron plasma freq \[ f_{pe} = 284 \text{ MHz} \]

for \[ n = 10^9 \text{cm}^{-3} \]

Ion collision rate \[ v_{ii} = 4.8 \text{KHz} \]

for \[ n = 10^9 \text{cm}^{-3} \]

Electron collision rate \[ v_{ee} = 0.29 \text{MHz} \]

for \[ n = 10^9 \text{cm}^{-3} \]

\[ \text{TABLE IV : IMP Q parameters} \]
ESRIN Plasma Wave

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

- RF

RF discharge:

\[ n_e \sim 10^9 - 10^{11} \text{ el cm}^{-3} \]
\[ T_e \sim 2 - 5 \text{ eV} \]
\[ T_i \sim 0.1 - 0.2 \text{ eV} \]

Pressure \( \sim 5 \cdot 10^{-5} - 4 \cdot 10^{-3} \) (Argon)

Collisional frequencies:

\[ 7 \cdot 10 < \nu_{en} < 3 \cdot 10^6 \text{ Hz} \quad (1 \cdot 10^{-3} < p < 4 \cdot 10^{-3} \text{ Torr}) \]
\[ 3 \cdot 10 < \nu_{ei} < 3 \cdot 10^6 \text{ Hz} \quad 10^{10} < n < 10^{11} \text{ el.cm}^{-3}, T_e \sim 2 \text{ eV} \]

\[ \lambda_D \sim 0.5 \text{ mm} \]
\[ 5 \cdot 10^{-3} < \frac{\delta n}{n} < 5 \cdot 10^{-2} \]

Magnetic field \((0 - 2 \text{ K Gauss})\) is used for RF discharge from

\[ \nu_{ce} = 0.9 - 3 \text{ GHz} \]

Diagnostics.
A. First results and possibilities

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

Slow wave structure

with AIL RF Power Generator:

- frequency ~ 0.9 GHz
- power ~ 20 - 40 Watts CW
- \( n_e \) ~ \( 10^9 \) el cm\(^{-3} \)
- \( T_e \) ~ 3 - 6 eV
- \( T_i \) ~ 0.1 - 3 eV (probable)
- pressure ~ 10\(^{-4} \) - 10\(^{-3} \) Torr
- fluctuation level \( \delta n/n \sim 1 - 10\% \)

Mirror ratio: \( B_m/B_o \) ~ 3 to 10

Maximum B main ~ 400 Gauss

Maximum \( B_L \) coil ~ 4 KGAuss

\( v_{en} \) and \( v_{ei} \) (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 parameters : Plasma sources : Hot filaments

\[ n_e \sim 10^8 - 7 \cdot 10^{11} \text{ cm}^{-3} \]
\[ T_e \sim 2 \text{ eV} \]
\[ T_i \sim 0.1 \text{ eV} \]

Pressure \sim 5 \cdot 10^{-5} - 2 \cdot 10^{-3} \text{ Torr}

Collision frequencies :
\[ \nu_{en} \sim 18 \text{ KHz} - 740 \text{ KHz} \]
\[ \nu_{ei} \sim 1.6 \text{ KHz} - 2.4 \text{ MHz} \]
\[ \lambda_d \sim 7.5 \cdot 10^{-2} \text{ cm} - 2.4 \cdot 10^{-3} \text{ cm} \]

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

Work done :

Microwave - plasma interactions

Current work :

Microwave - plasma interactions
Experimental set-up

Axial field coils

224 filaments

Langmuir probe

Permanent magnets

Launching grid

Cathode

Anode grid

Magnetic loop

Rogowski loop
Plasma box: Plasma source: Hot filaments

\[ n_e \sim 10^8 - 10^{10} \text{ el.cm}^{-3} \]
\[ T_e \sim 1 - 3 \text{ eV} \]
\[ T_i \sim 0.1 - 0.2 \text{ eV} \]
Pressure \( 10^{-4} - 10^{-3} \text{ Torr} \)
Collision frequencies:
\[ \nu_{en} \sim 30 \text{ kHz} \]
\[ \nu_{ei} \sim 40 \text{ kHz} \]
fluctuations \( \delta n/n \sim 1\% \) (without \( B \) field)
possible \( B \) field \( \sim 100 \text{ Gauss} \)

Current work:

A current is drawn between 2 cathodes; this experiment is mounted in order to excite turbulent spectra.
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 $n_e \quad 10^{12} - 10^{13} \text{ cm}^{-3}$
- electron temperature $T_e \quad 1 - 10 \text{ eV}$
- plasma current $I_p \quad 20 - 120 \text{ A}$
- axial field $B_z \quad 0.1 - 0.2 \text{ T}$
- plasma diameter $d \quad \sim 1.5 \text{ cm}$
- neutral gas pressure $p \quad < 5 \cdot 10^{-4} \text{ Torr}$
Fig. A16 Diagram of the cathode

- Differential pumping
- Glass tube
- O-ring seal
- Hollow cathode
- Water-cooled jacket
- Diagnostic chamber
- Water cooling access
- Gas input and starter electrode
- Movable cathode assembly
- Electric power connection
IV
POSSIBLE DESIGN OF THE BEAT WAVE ACCELERATOR EXPERIMENT SHOWING MAINLY PLASMA PRODUCTION

The design of the experiment will depend on the restricted parameters for feasibility. 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 $\omega_{ce}$ 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 distanced 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 cont.)

magnetic field coils

large hot cathode (oxides or LaB₆)

wave guide

diaphragms

heating filament

Plasma

annular gas feed (by puffing)

cooled baffle

accelerating grid (or hollow anode)

cavity mirror

anode

- 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. H₂ gas puffing (on pulse regime)
- large cathode size increases lifetime 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, LaB₆,......
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 homogeneous 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.
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 experimental sequences show continuous production of plasma to a level of $10^{11}$ cm$^{-3}$. Then the gas puffing is operated at $t_0$ 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

- Microwave pulses
  $\delta t = 100 \div 1000$ plasma periods
  $\delta t = 10 \div 100$ ns

- Plasma current $I_p$
  $I_p \propto n_e$
  Afterglow

- Gas flow
  Gas puffing

Timeline:
- $t_4$ to $t_5$
- $t_0$ to $t_2$ with $1 \div 5$ ms
- $t_0$ to $50 \div 100$ ms
V

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

S. Alberti
MATERIEL A DISPOSITION POUR LES TESTS MICROONDES AU GYROTRON

♦ Carcinotrons (BWO)  
  1) $f = 115 + 150$ GHz  
      $f \leq 500$ mW  
  2) $f = 90 + 103$ GHz  
      $f \leq 300$ mW

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

♦ Guides d’onde (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

♦ Détecteurs

- Diodes  
  5 diodes (sensibilité - 50 dBm)
  3 diodes (sensibilité - 50 dBm)

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

Rem 1) Des mixers "fondamentaux" ($n = 1$) ont comme oscillateur, local, soit le carcinotron, soit une diode Gunn acceptable.

2) Pour amplifier le signal LO $8 + 12$ 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 $8 + 12$ GHz (Weinschel).

♦ Power meter HP, $f = 110 + 130$ GHz
  sensibilité = - 30 dBm

♦ Analyseur de spectre HP 70000

- 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
Tableau $XY$ pour la mesure de profils de champ EM dans les guides d'ondes
- Haute précision mécanique (moteur pas à pas)
- commandée par ordinateur

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

Liste établie par Stefano Alberti                               CRFP - Octobre 1989
VI
ANNEXES

VI-1 COMPILATION OF LOW DENSITY PLASMA SOURCES FROM PUBLICATIONS

VI-2 PLASMA DIAGNOSTICS

VI-3 PLASMA PARAMETERS TABLE
Argon: $p = 3 \times 10^{-3}$ torr

$\omega_e/\omega = 2,3$

$P_{\text{obs}} \sim E^4$

Anomalous absorption

$N_e \sim E^2$

Density of the plasma produced by the cylindrical microwave gun ($C$ band)
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
\( P_0 = 3. \, 10^{-3} \, \text{Torr} \)
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 uninhomogeneous 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

\( T_e \geq 9 \text{eV} \)

\( \frac{dn}{n} ? \)

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_{\text{abs}} = E^2 in 10^{11} to 10^{12} cm^{-3} range, and P_{\text{abs}}=E^4 over 10^{12} cm^{-3}

J. Musil, F. Zacek and P. Schmiedberger, Prague
Plasma Physics, 1974, Vol. 16, p. 735
(2) **Open waveguide**

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

M.A.G. Calderón and J.M. Perez
*Uni of Santander, Spain*

(3) **Open Waveguide Source with Turnstile Junction**

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

$P_{inc} =$

<table>
<thead>
<tr>
<th>Power (kW)</th>
<th>Density (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>low density</td>
</tr>
<tr>
<td>3.4</td>
<td>$6 \times 10^{11}$</td>
</tr>
<tr>
<td>4.9</td>
<td>$0.9 \times 10^{12}$</td>
</tr>
<tr>
<td>5.8</td>
<td>$1 \times 10^{12}$</td>
</tr>
</tbody>
</table>

- low ionisation
- noise? seems noisy at high power

$(P_{inc} = 5.8$ kW $\Rightarrow$ power flux $115$ W/cm$^2$)

*C. Jansen and E. Räuchle*
*Physics Letters 1981, 83A, p. 15*
Fig. 1. Experimental arrangement. 1) Coll; 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%
p₀ = 10⁻³ + 10⁻¹ Torr
ω₀ = 10 GHz  200 ms  150 watts pulse
nₑ = 10¹² cm⁻³ at ECR condition
ω = 3 GHz, 100 watts CCW
Ioffē Institut.
V.N. Budnīkov, V.E. Goland and A.A. Obolekov

(5) Microwave Gun

cn0 = 9.375 GHz
p₀ = 10⁻⁴ + 10⁻¹ Torr
nₑ = 10¹⁰ cm⁻³ to 10¹¹ cm⁻³
B₀ = 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, v < 100kHz

but \( \frac{\partial nₑ}{nₑ} \) ??
nₑ = 4 + 5 \( 10¹¹ \) Q cm⁻³ where Q is in W/cm⁻³
Tₑ = 3 + 5 eV
Tᵢ = 0.1 + 0.2 eV
V.N. Budnīkov et al
FIG. 1. A 155-MHz plasma source.
(6) High Frequency Plasma source = pyramidal horn

10.3 GHz  30 Watts
Ar, P₀ = 10⁻⁵ + 3  10⁻² Torr
10¹⁰ < n < 10¹³ cm⁻³
5 < Tₑ < 30 eV
δn
n ??
P.A. Tulle
Plasma Physics Vol. 15, p. 971-976, 1973

B- Capacitive antenna at low RF (155MHz)

(7) RF Plasma Source

ωₚₑ * ω ~ ωₚᵢ = 155MHz, 8 kW
but B = 16kG (1.4m)
Plasma is generated at RF near to and above ion plasma freq. or lower
hybrid freq.

nₑ = 10¹² cm⁻³, n₀ = 1.5 10¹³ cm⁻³, Tᵢ = 15 eV max heating, Tₑ up
to 15 eV.
In argon, heating efficiency is higher with low neutral pressure, 10⁻⁴torr, heating eff. is 50%.

R.W. Motley et al.
J. Appl. Phys. Vol. 46(8), 1975, p. 3286
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, Ne
3 \(10^{-4} + 9 \cdot 10^{-3}\) Torr
\(B_{\text{max}} = 1.3\) kG
\(n_e \leq 2.5 \cdot 10^{10} \text{ cm}^{-3}\)
1 \(\div\) 50\% ionisation

P.L. Colestock and W.D. Getty
Uni. of Michigan, Ann Arbor

(9) Lisitano Coil
Complex Device

Gas: H, He, N\(_2\), A, Kr
5 \(10^{-6} + 5 \cdot 10^{-4}\) Torr
base \(10^{-7}\) torr
\(B_{\text{max}} = 10\) kG
- work mainly at ECR (3.7 kG)
- with 100 watts
  \(n_e = 1 \cdot 10^{11} \text{cm}^{-3}\) with 1 \(10^{-4}\) Torr
  \(n_e = 1.5 \cdot 10^{11} (2.5 \cdot 10^{-4}\) Torr)
  \(n_e = 7.5 \cdot 10^{10} (1.25 \cdot 10^{-3}\) Torr)
2 \(< T_e < 20 \text{ eV}\)
max ionization 50 \%
\(\frac{\delta n_e}{n_e} \sim 5 + 10\%\)

I.G. Brown et al.
Fig. 1.—Schematic diagram of the experimental device ER-2.
D- Slow Wave Structure (Lisitano coil type II)

(10) Helical Microwave Gun

Gas: H
\( p_0 = 10^{-4} + 10^{-3} \text{ Torr} \)
\( \frac{\Delta B_0}{B_0} = \pm 0.1 \)
\( B_{0\text{ max}} = 1.3 \text{T} \)
\( f_0 = 2.35 \text{ GHz} \)
\( p_{\text{max}} 5 \text{ kW, but > .2kW for density start.} \)
\( n_e = 5 \times 10^{11} + 1.5 \times 10^{12} \text{ cm}^{-3} \)
\( \tau = 0.5 \text{ to } 1 \text{ ms (for hot cathode coaxial gun)} \)
1% ionised initial density \( 10^{10} \text{ cm}^{-3} \).
V. Kopecky, J. Musil and F. Záček,
*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
\( p_0 = 10^{-3} \text{ Torr} \)
\( B_{0\text{ max}} = 1.8 \text{ kG} \)
SWS in mirror 25:1
RF; \( f_0 = 3 \text{ GHz} \)
70W
\( n_e > 10^{12}\text{cm}^{-3} \)
\( \omega_{\text{rf}} < \omega_b < \omega_p < 10\omega_{\text{rf}} \)
\( \frac{\Delta n_e}{n_e} \leq 5\%, \ T_e = 10\text{eV} \)
ionization 30%
G.Lisitano, M. Fontanesi and E. Sindoni
L-3 DEVICE
(12) Helical L. coil (SWS)

12 cm - 1 kW cw power source - ECR conditions
neutral gas $P_0 = 5 \times 10^{-7}$ to $5 \times 10^{-6}$ Torr
noise level, $(\Delta I/I_{sat} \propto 5\%)$
$n_e \text{ max} = 4 \times 10^{11} \text{ cm}^{-3}$
$T_e \text{ max} = 8 \text{ eV}$
R. de Dionigi, M. Fontanesti and E. Sindoni
Milano

(13) Slow Wave Structure (SWS)

L-3 Device

Gas: He
$P_0 < 10^{-3}$ Torr
$n_0 \leq 2 \times 10^{12} \text{ cm}^{-3}$
$\lambda || \approx 3 + 10 \text{ cm}$
$\lambda \perp = 5 \text{ cm}$
Studies : Parametric instabilities
Plasma production, $\phi \text{ plasma} = 5 \text{ cm}$
P=1kW, $\nu = 2.45 \text{ GHz}$
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 + 20 10^{-4} Torr
n_e = 10^{11} + 10^{12} cm^{-3}
T_e = 3 + 6 eV
P_0 base 2 \times 10^{-3} Torr

J.E. Schaefer and J.E. Mitzlaff

(15) Helical coil

B_0 = 1 kGauss
10^{10} < n < 10^{11} cm^{-3}
P_0 = 10^{-4} + 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.
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$_e = 1 + 2.10^{12}$ cm$^{-3}$
T$_e = 5$ eV

G. Müller, E. Räuchle and W. Staib

(17) Helical Coil  Coaxial in Housing cylinder

- ECRH condition $T_1 = 0.2 + 2$ eV
- Gas: Ar
- 2 $10^{-5} + 2$ $10^{-3}$ Torr
- $\frac{\delta n}{n} = 1 + 5\%$

D.P. Grubb and T. Lovell
Madison
Fig. 1.—(a) Experimental apparatus. (b) Details of the helical coil.
(18) Helical Coll

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} \text{ cm}^{-3}
ionisation degree 1 + 10% H
5 + 30% Ar

R. Cano, B. Zanfagna, G. Lisitano

---

![Graph](image)

**Fig. 4.**—(a) Average density and temperature vs magnetic field Bz. (b) Average energy density $\bar{\epsilon}K+T$ vs magnetic field Bz. Gas pressure (Hydrogen): 1. $p = 1\cdot10^{-8}$ torr; 2. $p = 2\cdot10^{-7}$ torr; 3. $p = 6.5\cdot10^{-7}$ torr; 4. $p = 1\cdot10^{-6}$ torr.
Fig. 1. Experimental plasma source and power supply.
E- Hollow cathode and Washer gun

(19) Hollow-cathode discharge

Argon $p_0 = 10^{-2}$ Torr
$\phi$ 14mm, $L = 80$ cm
$T_c = 0.3 + 1.2$ eV
$n_e = 10^9 + 10^{11}$ cm$^{-3}$
$\frac{\delta n_e}{n_e} \sim 3\%$ start voltage $\sim 7$ kV
B field max 3 kG homogenity 2%
M. Subasi and G. Taxcan
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
$\to$ C$^+$, C$^{++}$ Ti$^{++}$ 50 $\div$ 150 eV
$n_e > 10^{16}$
$\frac{\delta n}{n}$ ?
- pulse length $\tau = 9$ $\mu$sec
- experiment in $L \sim 1$m
- ionization rate $\sim 70\%$ max.
E.D. Andrukhina and I.S. Spighel
Soviet Physics Vol. 10(7), 1966, p. 962
**Fig. 1.** Occluded gas, cold plasma source.
Hollow Cathode with Starter

<table>
<thead>
<tr>
<th>Lanthanum hexaboride (LaB$_6$)</th>
<th>Tungsten (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>temp. J(A/cm$^2$)</td>
<td>temp. J(A/cm$^2$)</td>
</tr>
<tr>
<td>1500°C 2.5</td>
<td>2400°C 1.6</td>
</tr>
<tr>
<td>1600 7</td>
<td>2500 3.5</td>
</tr>
<tr>
<td>1700 18</td>
<td>2700 14.5</td>
</tr>
<tr>
<td>1800 42</td>
<td>2900 47</td>
</tr>
</tbody>
</table>

1) Large current is extracted from cathode up to 800A  
   ⇒ streaming out  \( n_e \sim 5.4 \times 10^{13} \text{ cm}^{-3} \)  
   \( T_e \sim 5 \text{ eV} \)

2) low voltage  
   - 50V (Ar)  
   - 80V (H)

3) different vacuum  
   - gun \( 5.6 \times 10^{-2} \text{ Torr} \)  
   - chamber \( 3 \times 10^{-4} \text{ Torr} \)

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 et al.  

Washer Gun

Starter  \( 1 \div 15 \text{ kV} \)  
       \( 15 \div 650 \text{ μs} \)
arc  \( 90\text{V} \)  
     \( 200\text{A} \div 3\text{kA} \)
\( B_0=30\text{kG} \)  
   \( n_e = 3 \times 10^{14} \text{ cm}^{-3} \)  
   \( T_e \sim 3 \text{ eV} \)  
   \( T_i = T_e \)  
   \( P_0 = 1.5 \times 10^{-4} \text{ Torr} \)  
   90 % ionized

J.F. Steinhaus et al.  
Phys. Fluids Vol. 8(9), 1965, p. 1720
Fig. 2. Cathode assembly.
(23) Filamentary hollow cathode source

$\text{H}_2$

$T_e = 30 \div 300 \text{ eV}$

$n_e = 10^{12}\text{cm}^{-3}$

$n_e = 10^{15}\text{cm}^{-3}$ at source

*H.H. Fleishmann and R. Aribel*

Fig. 3. Schematic of multifilament cathode (left) and its location (right) on the isomagnetic surface $B \approx 10 \text{ G} \approx \text{const.}$ 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
B₀ uniform φ 8 cm
B₀ = 1 kG
δn
n ≤ 1%
nₑ > 10¹¹ cm⁻³
p₀ = 3 × 10⁻⁴ Torr
νₑn ≈ 10⁵ Hz
Tₑ ~ 2.5 eV
T₁ ~ .2 eV
discharge current max 15A
Power requirement for filament 4kW
W. Gekelman and R.L. Stenzel
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/cm², 50eV electrons
collisionless mean free path > 10 m

\[ p_0 = 2 \times 10^{-4} \text{ Torr, } \frac{\delta B}{B_0} \leq 0.5\%, B_{\text{axial}} < 150 \text{ Gauss} \]

Axial magnetic field by multimirror permanent magnets walls (Sanarium) \( B_{\text{max}} = 4 \text{ kG} \)
\( n_e = 10^{12} \text{ cm}^{-3} \)

\[ \frac{\nu}{\omega_c} = 5 \times 10^{-3} \text{, collisionless} \]

\( kT_e = 2 \text{ eV} = 10kT_1 \text{ in discharge} \quad \text{Pulse operation} \)
\( kT_e = 0.2 \text{ eV} = kT_1 \text{ in afterglow} \quad \text{2kJ capacitor bank} \)
cathode lifetime 2 months
Pulse = 4 + 10 msec.

R.L. Stenzel
Phys. Fluids Vol 19(6), 19??, p. 857

(26) Large size cathode

\( B_0 = 2 \text{ kG} \)
\( B_{\text{30}} \text{ cathode, } \Phi = 60 \text{ cm} \)
20kW heating power
\( \tau = 4 \text{ msec, 40V, 200 A discharge} \)
\( n_e = 10^{12} \text{ cm}^{-3} \)
\( kT_e = 2 \text{ eV} = kT_1 \)
\( \delta n \quad n \quad ? \)

H. Sugni, S. Kishimoto
Nagoya, annual report 1983
# ANNEXE VI-2

## DIAGNOSTICS FOR LOW DENSITY PLASMA

*F. Skiff*

<table>
<thead>
<tr>
<th>QUANTITY</th>
<th>METHOD</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_e \cdot \sqrt{T_e}$</td>
<td>ion saturation current</td>
<td>Swift + Schwar, Electrical Probes for Plasma Diagnostics (New York Elsevier). See also Gen. ref. 1. below</td>
</tr>
<tr>
<td>$T_e$</td>
<td>i-V characteristic</td>
<td></td>
</tr>
<tr>
<td>$\phi_{rf}$</td>
<td>Radio frequency (rf) capacitive probe</td>
<td>Rev. Sci. Instr. <strong>42</strong>, 589 (1971)</td>
</tr>
<tr>
<td>$E_x \text{ rf}$</td>
<td>- double tip</td>
<td></td>
</tr>
</tbody>
</table>

## B) Energy Analysers

| $f(v_{||})_e$ | Multigrid analyser | see Gen. ref. 1 |
| $f(v_{||})_l$ | ion analyser | Phys. Rev. **28**, 104 (1926) |

## II. ELECTROMAGNETIC PROBES

| $B_{n\perp}$ | Magnetic probe (Mironov) | Nucl. Fus. **19**, 115 (1979) |


\[ n_e T_e + n_i T_i \quad \text{Rogowski loop} \quad \text{see gen. ref. 1} \]

-III. WAVE DIAGNOSTICS-

A) Dispersion relations

\[ T_e T_e / T_i \quad \text{ion acoustic wave} \quad \text{see gen. ref. 2} \]

\[ n_e \left( \frac{T_e}{T_i} \right) \quad \text{Lower hybrid wave} \quad \text{Phys. Fluids 14, 857 (1971)} \]

Species concentrations

\[ \text{Low frequency resonance cone} \quad \text{PRL 42, 1267 (1979)} \]

\[ T_{i\perp} \quad \text{Ion Bernstein wave} \quad \text{Phys. Rev. A. 26, 2297 (1982)} \]

B) Scattering, frequency shift (see also laser)

\[ \int n_e dx \quad \text{ordinary mode} \quad \text{M.A. Heald, C.B. Wharton, Plasma Diagnostics with microwaves (John Wiley, 1965)} \]

\[ n_e \text{ rf}(\omega, k) \quad \text{microwave scattering} \]

\[ \int dz n_e(x,y,z) \quad \text{Phase contrast} \quad \text{Infrared Phys. 25, 543 (1985)} \]

\[ \int n_e d^2 x \quad \text{Cavity frequency shift} \quad \text{J. Appl. Phys. 36, 3642 (1965)} \]

-IV LASER DIAGNOSTICS-

A) Laser induced fluorescence

\[ f(v_{\perp}, v_{\parallel}) \quad \text{ion or atomic line shape} \quad \text{Rev. Sci. Instr. 56, 1006 (1985)} \]

\[ V_{D \rightarrow E} \quad \text{line shift} \quad \text{PRL 34, 1548 (1975)} \]

trajectory of tagging ions in phase two photon space species doppler free concentration excitation

\[ \text{Thèse No. 626, P. Kohler, EPFL (1986)} \]

\[ \text{PRL 32, 643 (1974)} \]
B) Small angle scattering
\[ \tilde{n}(\omega, k) \]
homodyne mixing
\[ \text{CO}_2 \text{ laser} \]

V. PASSIVE SPECTROSCOPY
\begin{align*}
T_l & \quad \text{Line width} \\
T_e & \quad \text{Line intensity}
\end{align*}
see gen. ref. 1

GENERAL REFERENCES

2. Introduction to Plasma Physics, F. Chen (Plenum 1976)
**ANNEXE VI-3**

**PLASMA PARAMETERS FOR HYDROGEN**

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

*Te in eV

\( n \) in cm\(^{-3}\)

<table>
<thead>
<tr>
<th>( \bar{n}(\text{cm}^{-3}) )</th>
<th>( \text{Te} = 1\text{eV} )</th>
<th>( \text{Te} = 5\text{eV} )</th>
<th>( \text{Te} = 10\text{eV} )</th>
<th>( \text{Te} = 20\text{eV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 10^{11} )</td>
<td>10.80</td>
<td>13.92</td>
<td>14.25</td>
<td>15.13</td>
</tr>
<tr>
<td>( 10^{-12} )</td>
<td>9.65</td>
<td>12.77</td>
<td>13.10</td>
<td>14.14</td>
</tr>
<tr>
<td>( 10^{13} )</td>
<td>8.50</td>
<td>11.62</td>
<td>11.95</td>
<td>12.99</td>
</tr>
</tbody>
</table>

\[ \nu_{ee} = 2.90 \cdot 10^{-6} \frac{n \ln \Lambda}{\text{Te}^{3/2}} \]

*\( n \) in cm\(^{-3}\)

*Te in cm\(^{-3}\)

\[ \lambda_{\text{mp}'} = \frac{V_{\text{the}}}{\nu_{ee}} = 1.4 \cdot 10^{13} \frac{\text{Te}^2}{n \ln \Lambda} \]

<table>
<thead>
<tr>
<th>( n(\text{cm}^{-3}) )</th>
<th>( \nu_{\text{pe}}(\text{Hz}) )</th>
<th>( \text{Te}=1\text{eV} )</th>
<th>( \text{Te}=5\text{eV} )</th>
<th>( \text{Te}=10\text{eV} )</th>
<th>( \text{Te}=20\text{eV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 10^{11} )</td>
<td>3.10(^9)</td>
<td>3.24 (10^6)</td>
<td>3.61 (10^5)</td>
<td>1.31 (10^5)</td>
<td>4.91 (10^4)</td>
</tr>
<tr>
<td></td>
<td>( \nu_{ee}(\text{Hz}) )</td>
<td>12.9</td>
<td>2.51 (10^2)</td>
<td>9.82 (10^2)</td>
<td>3.7 (10^3)</td>
</tr>
<tr>
<td></td>
<td>( \lambda_{\text{mpf}}(\text{cm}) )</td>
<td>1.45</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( 10^{12} )</td>
<td>8.9 (10^9)</td>
<td>2.9 (10^7)</td>
<td>3.32 (10^6)</td>
<td>1.2 (10^6)</td>
<td>4.59 (10^5)</td>
</tr>
<tr>
<td></td>
<td>( \nu_{ee}(\text{Hz}) )</td>
<td>1.45</td>
<td>27.4</td>
<td>1.06 (10^2)</td>
<td>3.96 (10^2)</td>
</tr>
<tr>
<td></td>
<td>( \lambda_{\text{mpf}}(\text{cm}) )</td>
<td>0.164</td>
<td></td>
<td>1.09 (10^6)</td>
<td></td>
</tr>
<tr>
<td>( 10^{13} )</td>
<td>3 (10^{10})</td>
<td>2.55 (10^8)</td>
<td>3.02 (10^7)</td>
<td>11.71</td>
<td>43.11</td>
</tr>
<tr>
<td></td>
<td>( \nu_{ee}(\text{Hz}) )</td>
<td>0.164</td>
<td>3.012</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \lambda_{\text{mpf}}(\text{cm}) )</td>
<td>0.164</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ \nu_{el} = 2 \frac{m_e}{m_i} \nu_{ee} = 1.089 \cdot 10^{-3} \nu_{ee} \]

\[ \nu_{II} = 2.316 \cdot 10^{-2} \left( \frac{T_i}{\text{Te}} \right)^{3/2} \nu_{cc} \]
(1) $v_{ll} = 6.76 \times 10^{-8} \frac{n \ln \Lambda}{T_{l3/2}}$

also one can find (2) $v_{ll} = 4.8 \times 10^{-8} \frac{n \ln \Lambda}{T_{l3/2}}$

$\lambda_{mpf} = 2.03 \times 10^{13} \frac{T_{l}}{n \ln \Lambda}$

<table>
<thead>
<tr>
<th>$n(cm^{-3})$</th>
<th>$v_{pf}(Hz)$</th>
<th>$\nu_{ll}(Hz)$</th>
<th>$\lambda_{mpf}$ cm (2)</th>
<th>$\nu_{th}(Hz)$</th>
<th>$\lambda_{mpf}$ cm (2)</th>
<th>$\nu_{th}(Hz)$</th>
<th>$\lambda_{mpf}$ cm (2)</th>
<th>$\nu_{th}(Hz)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{11}$</td>
<td>6.64 $10^{7}$</td>
<td>3.04 $10^{6}$</td>
<td>2.15 $10^{6}$</td>
<td>0.143</td>
<td>2.8 $10^{7}$</td>
<td>1.98 $10^{7}$</td>
<td>1.55 $10^{-2}$</td>
<td>2.55 $10^{8}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(1)</td>
<td></td>
<td></td>
<td>(2)</td>
<td>1.81 $10^{8}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.7 $10^{-3}$</td>
</tr>
<tr>
<td>$10^{12}$</td>
<td>2.1 $10^{8}$</td>
<td>3.04 $10^{6}$</td>
<td>2.15 $10^{6}$</td>
<td>0.143</td>
<td>2.8 $10^{7}$</td>
<td>1.98 $10^{7}$</td>
<td>1.55 $10^{-2}$</td>
<td>2.28 $10^{7}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(1)</td>
<td></td>
<td></td>
<td>(2)</td>
<td>1.61 $10^{7}$</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.26 $10^{-2}$</td>
</tr>
<tr>
<td>$10^{13}$</td>
<td>6.64 $10^{8}$</td>
<td>3.04 $10^{6}$</td>
<td>2.15 $10^{6}$</td>
<td>0.143</td>
<td>2.8 $10^{7}$</td>
<td>1.98 $10^{7}$</td>
<td>1.55 $10^{-2}$</td>
<td>8.07 $10^{6}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(1)</td>
<td></td>
<td></td>
<td>(2)</td>
<td>5.73 $10^{6}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.26 $10^{-2}$</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>$Te(\text{eV})$</th>
<th>$V_{th}(\text{cm/s})$</th>
<th>$\sigma_0(\text{cm}^2)$</th>
<th>$\lambda_{mpf}(\text{cm})$</th>
<th>$\nu_{en}(\text{Hz})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.19 $10^{7}$</td>
<td>49 $10^{-16}$</td>
<td>2.04 $10^{2}$</td>
<td>2.05 $10^{5}$</td>
</tr>
<tr>
<td>5</td>
<td>9.36 $10^{7}$</td>
<td>62 $10^{-16}$</td>
<td>1.61 $10^{2}$</td>
<td>5.78 $10^{5}$</td>
</tr>
<tr>
<td>10</td>
<td>1.32 $10^{8}$</td>
<td>40 $10^{-16}$</td>
<td>2.5 $10^{2}$</td>
<td>5.28 $10^{5}$</td>
</tr>
<tr>
<td>20</td>
<td>1.87 $10^{8}$</td>
<td>20 $10^{-16}$</td>
<td>5 $10^{2}$</td>
<td>3.74 $10^{5}$</td>
</tr>
<tr>
<td>100</td>
<td>4.19 $10^{8}$</td>
<td>~ 1 $10^{-16}$</td>
<td>1.25 $10^{4}$</td>
<td>3.35 $10^{4}$</td>
</tr>
</tbody>
</table>

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

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