RF-PLASMA HEATING WITH L-STRUCTURES

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Abstract

RF wave-launching structures (L-coils) have been excited in a stellarator and in a magnetic mirror machine. The characteristics of the discharge are presented. They cannot be explained by known wave-plasma interactions except by RF turbulence heating.

I. Wave and Turbulence Heating

Two apparently different methods of RF-plasma-heating are at present in sharp opposition:

1) The classical conversion of vacuum waves into certain waves and their absorption by linear and nonlinear Landau-damping:

   At a low RF signal level there is good agreement between the experiments and theories dealing with wave propagation in plasma. Agreement is also obtained for the wave absorption by Landau-damping.

2) RF non-resonant or turbulence plasma heating:

   The difference between this method and classical conversion is the high RF power level used for studying the wave-plasma interaction.

   At a high RF power level most of the RF energy is converted to plasma turbulence, and so the main problem in RF heating is to maintain the confining capacity of fusion-oriented experiments.

I.1 Plasma Wave Frequency Ranges

Table 1 presents a survey of the frequency ranges of the most important RF plasma heating methods for the fusion-oriented experiments at IPP.

Allowance is made for the plasma density profile by giving the plasma resonance frequencies for density numbers from $N_e = 10^{10} cm^{-3}$ to $N_e = 10^{14} cm^{-3}$.

The lower hybrid frequency f_{LH} was calculated for a magnetic field strength B > 15 kG.

It can be seen from Table 1 that in the upper L and S bands (5×10^8 to 5×10^9 Hz) three of the most important plasma resonance frequency ranges occur: the electron plasma frequency f_{pe}, the ion plasma frequency f_{pi} and the lower hybrid plasma frequency f_{LH}. The corresponding vacuum wavelengths of this frequency range (from a few centimeters to a few decimeters) are very favourable for good conversion of vacuum waves to plasma waves.

I. 2 RF Turbulence Heating and choice of frequency

In Fig. 1 the resonance regions for a possible wave energy conversion in the middle of this frequency range are shown on a plasma density profile.

At this and higher frequencies, e.g. in the S band, the RF energy at $f < f_{pe}$ is either reflected or, at higher power levels, converted to plasma turbulence at the boundary of the plasma profile.

This wave damping, which is termed anomalous absoprtion /1/, does not depend on the presence of a certain wave plasma resonance.Even for $f < f_{pe}$ the penetration depth of the wave in the plasma allows conversion of the RF energy to plasma turbulence.

For $f < f_{pe}$ most energy is absorbed at the plasma boundary by the time the wave reaches the resonance region $f \approx f_{LH}$

inside the plasma column. It is therefore expected that only a small portion of the RF energy will be converted into plasma waves with the lower hybrid or ion plasma frequency. The same applies to the recently asserted decay of the RF energy into two or more coherent plasma waves /2/.

In general, it should be taken into account that coherent plasma wave phenomena are found only in relatively thin plasmas ($N_e \leq 10^{12} cm^{-3}$), but not in relatively dense ($N_e \geq 5 \times 10^{12} cm^{-3}$) and thermalized plasmas, as will be shown later.

For frequency independent RF turbulence heating of some fusion-oriented experiments at IPP a working frequency in the S band was choosen, viz. f = 2.4 GHz.

At this frequency there is a practically unlimited supply of RF energy commercially available in the lowest price range of the whole RF spectrum. At optimum RF absorption efficiency accompanied if possible, by maintenance of the confining capacity of experiments, the RF power shall be increased step by step from a few 10 kW to limits yet to be ascertained.

I. 3 RF structures

RF structures are used to match the RF energy to the plasma load. All known RF structures in the frequency range of the most important plasma waves were investigated to determine their suitability for fusion-oriented experiments. The knowledge gained at IPP in several years was utilized to develop some new RF plasma sources. In these plasma sources various wave delay structures, some of them new types, were used for the first time. Known as Lisitano coils they have now acquired at IPP a high efficiency and good matching over a wide range of plasma parameters and frequencies from 10^8 to 10^{10} Hz. Some examples of these structures are shown in

Figs. 3, 5 and 10. As they are intended for fusion-oriented experiments, these RF structures are made, where possible, without insulating material.

The main property of these "L" structures is that they largely maintain the confining capacity of fusion-oriented experiments.

This is made possible by the symmetric distribution of the RF energy about the plasma column.

In addition, the minimum RF field configuration of the RF energy inside the "L" structures apparently has a stabilizing effect on the confined RF-heated plasma.

Compared with other known RF structures (e.g. disc loaded waveguide, Stix coils, etc.) these structures only slightly reduce (in the shadow of a normal limiter) the inner wall diameter of a discharge tube.

The RF structures were provided with vacuum plug connectors for quick replacement. This is of great advantage, particularly in complicated, expensive experiments such as Tokamaks and Stellarators. Any damage to the RF connectors in these machines can be readily repaired without wasting valuable time.

II. RF Plasma Heating Systems

In large machines that can only be operated by RF experts there is a risk of obtaining only one-sided information remote from the fundamental aspects of fusion-oriented experiments.

In the devices described below the properties of the RF heated plasma are therefore mainly studied by the experimental group concerned with the particular fusion-oriented experiment, just as in the case of, for example, ohmic heating.

This applies particularly to the RF plasma heating systems in the "Wendelstein W II b"-Stellarator and the "Pulsator I"-Tokamak.

Only the relevance of these systems to RF heating will be reported in the following.

II. 1 Stellarator W II b+)

As shown in Fig. 2 three Lisitano coils were incorporated in the W II b. The internal diameter of this coil, Fig. 3, is 14 cm; the length is 7 cm. The coils are made of pure stainless steel, i.e. they include no ceramic components and can thus be subjected to RF, ohmic heating (OH) or any other discharges. So far only two coils have been put into operation and each of these is fed with a pulsed power of 400 W in the S band (Δt = 2 ms; f = 2.4 GHz). With this total RF power of 800 W it was possible to produce an hydrogen plasma with a high degree of ionization. Typical discharge parameters are: $p_{OH_2} \approx 5 \times 10^{-5}$ torr, $B \approx 10$ kG, $N_e \approx 5 \times 10^{12} cm^{-3}$, $T_e \approx 10$ eV, $T_i \approx 5$ eV.

The following are some features of this RF discharge in the Stellarator W II b:

1) Reproducibility of the OH discharge

By simultaneous input of the RF power and the OH pulse voltage it was possible to obtain completely reproducible OH discharges down to a neutral gas pressure of 3×10^{-5} torr. Without induced OH voltage, an ignition plasma of a few times $10^{11} cm^{-3}$ is required to initiate the RF discharge. This is probably due to the relatively low RF power ($p_{RF} \approx 800$ W) in a 100 liter vacuum vessel. The RF power density of 8 mW/cm^3 is not sufficient for a self-starting discharge. Experience with a linear machine of same i.d.

+) This work has been done in collaboration with G. Pacher, H. Renner, H. Ringler and E. Würsching

(LISA), has shown that preionization is unnecessary at higher RF power ($\approx$ 2 kW).

2) Possible improvement in efficiency of the OH discharge

With the OH main discharge (OH II), plasma density numbers of $N_e \approx 5 \times 10^{12} cm^{-3}$ and electron temperatures of $T_e \approx 100$ eV were obtained in the W II b. The OH input power in the plasma is 5 to 15 kW. Air-cored transformers (like that of OH II) usually have a low efficiency, and so with these discharge parameters a primary pulse power of approx. 10 MW at a pulse length of 5 ms is required. Owing to the enhanced conductivity of the RF-preionized plasma it is very probable that the efficiency of the OH air cored transformer could be improved by increasing the applied RF power to the L coils. The three L coils in the W II b can be loaded with a total pulse power of $P_{RF} \approx 3 \times 5$ kW which may be sufficient for a measurable improvement of the efficiency of the main OH discharge which is now $\eta \approx 1.5 \times 10^{-3}$.

3) Maintenance of the plasma confinement times

At a high RF power level most of the RF energy is converted into plasma turbulence, and the design of the L coil is such as to maintain plasma confinement in fusion-oriented experiments. The RF power used hitherto in the W II b is perhaps too small to allow a final pronouncement on this property of the L coil. The influence of RF heating on the plasma confinement time in the W II b may be better studied by increasing the RF power to a few times 10 kW.

From available data on RF heating in the W II b (RF discharges in the low gas pressure range $p_{OH_2} \approx 2 \times 10^{-5}$ torr) it can be concluded qualitatively that the plasma confinement times are maintained. Elsewhere, with other heating systems (such as microwave horn antennas, ohmic heating, Stix coils etc.), the plasma has been lost in this low-pressure region because of pump-out effects.

4) X-ray yield

As already mentioned above, this RF heating system cannot be explained by any known method of wave-plasma interaction, except by that of RF turbulence heating. The electron and ion energy distribution can therefore be expected to contain high-energy electrons and ions. This may probably explain the yield of X-ray by the RF heating. This X-ray-yield is however controllable by reducing the duration of the RF pulse /4/ and in some discharge conditions is less than that with the OH discharge alone. A more exact analysis of the energy distribution would clarify the question of RF turbulence heating or coherent electron energy growth rate. Unfortunately, the method of X-ray measurements used up to date in W II b cannot yield sufficient informations on the distribution of the electron energy.

5) Preionization in Tokamaks

Another property of the RF plasma produced with the L coils was the maintainance of a RF discharge, even at $\iota = 0$, i.e. the Stellarator W II b was operated without exciting the helical windings. This proves the possibility of RF preionization in Tokamak operation which is equivalent to the condition $\iota = 0$ in the Stellarator W II b. No X-ray yield was observed with $\iota = 0$. No OH discharge at $\iota = 0$ is possible without the use of the RF power. Figure 4 shows the electron density and temperature radial profiles at $\iota = 0$ and $\iota = 0.1$. At $\iota = 0$ the RF discharge fills the vacuum tube with hydrogen plasma of $N_e \approx 3 \times 10^{12} cm^{-3}$ and $T_e \approx 10$ eV, which is quite sufficient for initiating a Tokamak discharge at $p_{OH_2} \approx 10^{-5}$ to 10^{-4} torr.

6) RF ion heating

Finally, the problem of RF turbulence ion heating should be mentioned. In the W II b an ion temperature of about 4 eV was measured at the plasma boundary. The size of the ion probe did not allow the ion temperature further inside the plasma core to be measured. At the site of the ion temperature measurements, i.e. at the plasma boundary, an electron temperature of 7 eV was measured. As can be seen from Fig. 1 b, the electron temperature rises to $T_e \approx 10$ eV in the center of the plasma core. If the same temperature profile is assumed for electrons and ions, an ion temperature of $T_i \approx 6$ eV can be expected in the center of the plasma.

II. 2 "Pulsator I" Tokamak

The Pulsator-Tokamak has a large radius of 70 cm and a minor radius of 14 cm. In the design phase no provision was made for high frequency heating. Only a weak preionization was programmed and for this purpose a L coil was incorporated in the discharge vessel.

During the construction of the vaccum vessel, the enhanced interest in RF preionization led to the second L coil shown in Fig. 5.

The two L coils can be fed with 10 kW pulse RF power at any frequency between 100 MHz and 10 GHz.

A distinct possibility of RF heating in Pulsator was offered by the special construction of a retraceable limiter. We are now working on a combination limiter-L-coil to be fed in a frequency band around 600 MHz and at a pulse power level from 100 kW up to 1/2 MW.

II. 3 "Dinnammare"-Toroidal Machine

The measurements on the Stellarator W II b have shown that it is possible to maintain a RF discharge at $\iota = 0$. A toroidal machine without helical magnetic field windings were built from an old toroidal vacuum vessel having the same major and minor radii (R = 55 cm and r = 10 cm) as the Stellarator W II b.

As shown in Fig. 6 eight L coils of the same type as used in W II b are installed in this machine. Each of these eight L coils is fed with RF pulse power of 5 kW in the S band The attainable magnetic field strength on the minor torus axis is limited to B = 10 kG in keeping with the loading capacity of the magnetic field coils. When this machine is put into service in summer 1973, a RF plasma with the following parameters is expected: $N_e \approx 10^{13} cm^{-3}$, $T_e \approx 80$ eV, $T_i \approx 30$ eV, B = 10 kG, $p_{H2} \approx 3 \times 10^{-5}$ torr. Owing to magneto-electric confinement effects (see IPP Annual Report 1970, p. 64 et seq.) a plasma confinement time of approx. 1/4 ms is expected. These plasma parameters are relevant to RF heating studies for their application in larger fusion-oriented machines such as Pulsator and W VII. As already described, the wide frequency bandwidth of the eight installed L coils allows various RF high power experiments in the most important RF heating frequency ranges such as the electron plasma frequency, ion plasma frequency and lower hybrid frequency. With a pulse power limit of 10 to 20 kW for each RF connector it should be possible to conduct RF plasma heating experiments with a total pulse power of 100 kW to 200 kW.

Besides being used for RF heating experiments, the DINNAMMARE machine serves for developing various diagnostic methods for the Pulsator-Tokamak.

It should also be mentioned that the possibility of rapid assembly and dismantling of this machine allows further development of high-power RF connectors and RF structures for application in fusion-oriented experiments at IPP.

II. 4 LISA Machine

The LISA machine, schematically represented in Fig. 7, is a linear mirror machine with a total length of 2.5 m and uniform component of the magnetic field strength in the center of the machine extending 1 m. The maximum field strength of the uniform component can be operated in c. w. up to 10.5 kG, the mirror field up to 13 kG.

The main purpose of the LISA machine is to develop new plasma sources for direct use in fusion-oriented experiments at IPP.

At present the development of these plasma sources is intended for three possible applications: a) plasma filling of large machines by means of microwave guns, b) plasma source for fast neutral injection heating and c) RF structures for plasma heating. This development work is as follows:

a) Plasma filling with microwave guns

Owing to the low efficiency of the ohmic heating system with air-cored transformer and to the slow build-up of the plasma density with neutral injection systems it is essential to fill large fusion-oriented experiments (such as W VII, Pulsator II and the Belt Pinch) with a high-density target plasma with the lowest possible neutral residual gas pressure.

A microwave gun system developed for filling large machines has already been decribed in the IPP Annual Report 1970 on pp. 66-68.

This system has been largely improved. At present hydrogen discharges in the following parameter range are being obtained: $P_{RF} \approx 1$ kW, B = 12 kG, $N_e \approx 5 \times 10^{12} cm^{-3}$, $T_e \approx 20$ eV, $p_{H2} \approx 5 \times 10^{-5}$ torr. Compared with the conventional helical L coils in Fig. 3 and 5 it is possible with this new source to work in a low (a factor of 2 - 3 less) neutral gas pressure range. Fast pulse gas valves and a volume getter system are beeing used at present in an attempt to reduce further the residual neutral gas pressure during filling of the machine. Experience with conventional L coils in the W II b has shown that the working gas pressure in toroidal vacuum systems is much lower than in linear machines, and so this new microwave gun system may possibly allow an acceptable target plasma for Stellarators and Tokamaks to be obtained.

Extensive profile measurements made in several radial directions to determine the electron density number, the electron temperature and the plasma and floating potentials indicate a laminar plasma flow about the plasma core. This flow is controlled by the RF field strength, forms eddies at the plasma boundary as a result of viscosity and disintegrates there into turbulence at elevated RF power. Figure 8 gives a qualitative representation of the flow lines around the plasma core.

The RF turbulence does not constitute any recognizable limit to further RF heating of the plasma. As shown in Fig. 9, a ring-shaped plasma potential well and a positive plasma potential ring concentric with it are formed closely around the plasma core.

From this plasma potential well and ring-shaped source it can be seen that there is magnetoelectric confinement of the ions and electrons near the plasma axis. If this sharp radial plasma confinement can be maintained at low neutral gas residual pressure as well, this microwave gun system could replace the present material limiter in toroidal machines. The absence of neutral residual gas and the very low plasma density at the outer plasma boundary would then cause much less power loss of ohmic heating at the site of the present plasma limiter owing to the reduced conductivity of the residual gas and low density plasma at the outer plasma boundary.

b) Plasma source for fast neutral injection heating

To get an idea of the power level required for fast neutral injection heating, it should be borne in mind that for a Tokamak of the size of Cleo, Pulsator or Petula ($R \approx 70 - 90$ cm, $r \approx 10 - 20$ cm) a jet power of approx. 100 kW is needed to increase the initial temperature of the ions 10 % (e.g. from 300 eV at $N_e \approx 10^{13} cm^{-3}$) /3/.

Efforts are therefore being made to develop stable ion sources of higher power j e t density with small residual neutral gas and impurity components.

At IPP an experimental study is being made with the LISA machine to determine whether it is of advantage for neutral injection to replace the usual plasma source of the DuoPIGatron type in an ion accelerator with an L source. The source should produce a hydrogen plasma of high density number ($N \approx 10^{13} cm^{-3}$) with a fairly uniform density distribution ($\pm$ 10 %) over a large plasma cross section ($s > 100 \ cm^2$).

For this purpose the microwave gun system, shown in Fig. 10, is fitted with another ten guns (i.e. 16 altogether). The source is fed with a total pulse power of 5 x 16 kW to 10 x 16 kW in the S band. This plasma source will be used for supplying an optimum plasma to the usual multi-grid accelerating gap. This expected to afford the following advantages:

1) a flat plasma density profile over the first extraction grid, i.e. improved illumination of the accelerating gap;

2) no modulation of the ion beam due to plasma density fluctuations, such as are caused by instabilities in the DuoPIGatron;

3) a reduction of the neutral gas streaming from the plasma source in the direction of the injection experiment by several orders of magnitude, which allows the use of cross beam neutralization, thus appreciably decreasing the quantity of gas injected.

It would be worthwhile to investigate experimentally the possible influence of RF fields and a small axial magnetic field on the high-voltage stability of the accelerating gap.

c) RF structures for plasma heating

Extensive wave measurements made for developing RF structures lead to the already mentioned RF turbulence heating as a working bases for the L plasma sources. After it was found that only a tiny component of the RF energy is converted to whistler modes (see IPP Annual Report 1970, p 68), an attempt was made to gain a better insight into the wave absorption mechanisms. Figure 11 shows the radial profiles of the electron temperature, plasma density and RF power for a hydrogen pulse discharge in the LISA machine. The minimum RF field distribution of the RF power inside the L coils can be seen from the radial RF profile in Fig. 11. The time development of this radial RF profile indicates damping of the

RF power when the electron temperature and plasma density reach saturation value at t = 2 ms, as compared with the RF radial profile at t = 0 ms, e.g. at the beginning of the discharge.

Also observed at the same time as the decrease of the RF signal in the plasma was a broad spectrum of low-frequency plasma density fluctuations, which indicate the turbulent character of this non-resonant RF discharge. All these measuremnts together with various electron and ion energy distribution measurements, are to be presented shortly in an IPP Report.

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/3/ Report CLM-P 314 (1972)

/4/ S. Corti, G. Lisitano, G. Pacher, H. Renner, H. Ringler, E. Würsching, Bull. of the American Phys. Soc., 17, 1038 (1972)

FIGURE CAPTIONS:

Table 1 - Plasma wave frequency ranges

Fig. 1 - Resonance regions for wave-energy conversion

Fig. 2 - Sketch of Stellarator W II b

Fig. 3 - Helical Lisitano coil

Fig. 4 - Plasma density and electron temperature profiles for a) = 0 and b) = 0.1

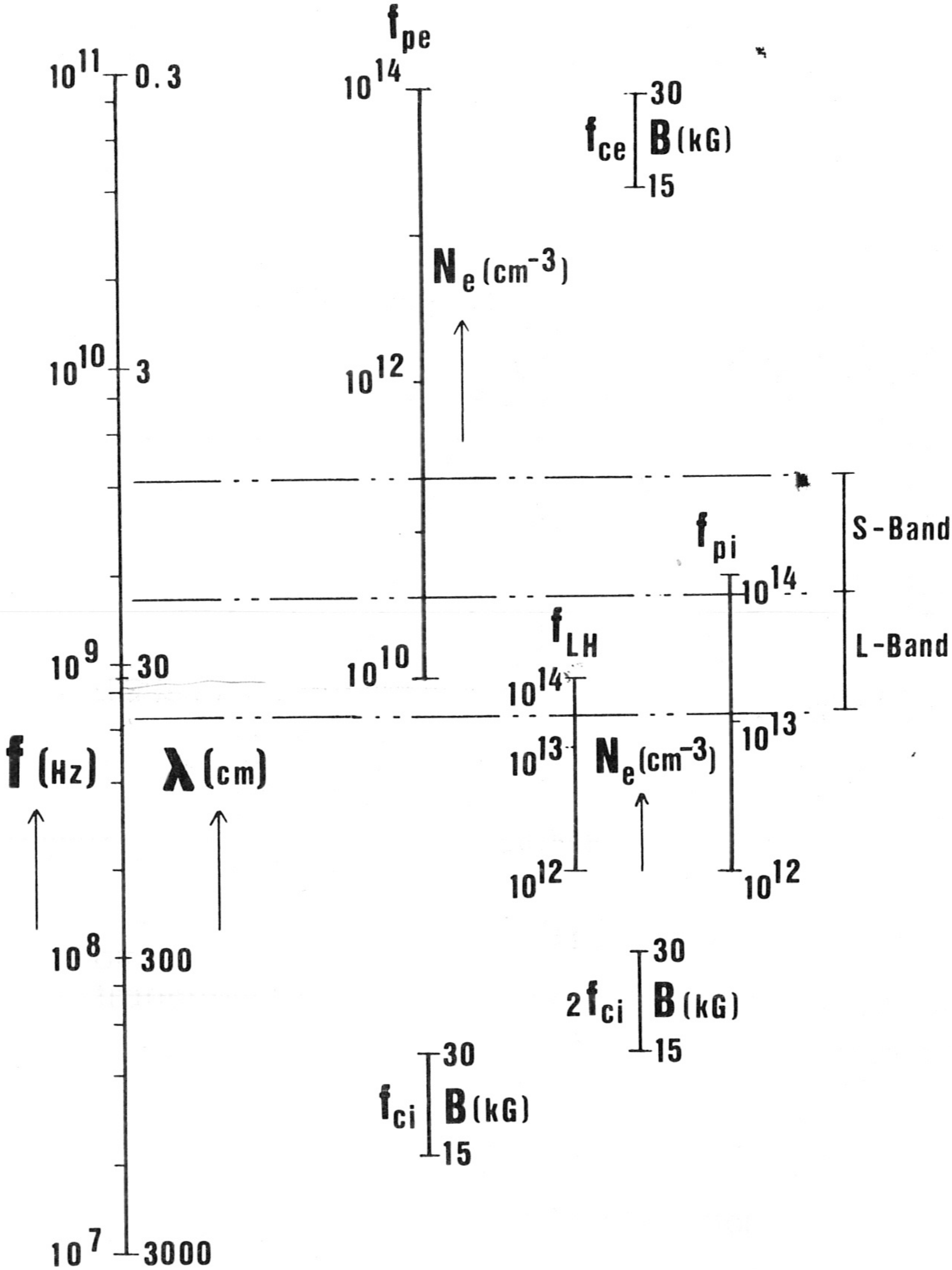
Fig. 5 - One of the L coils for Pulsator-Tokamak, i.d. = 24 cm

Fig. 6 - Schematic sketch of the "DINNAMMARE"-machine

Fig. 7 - Schematic sketch of the "LISA"-machine

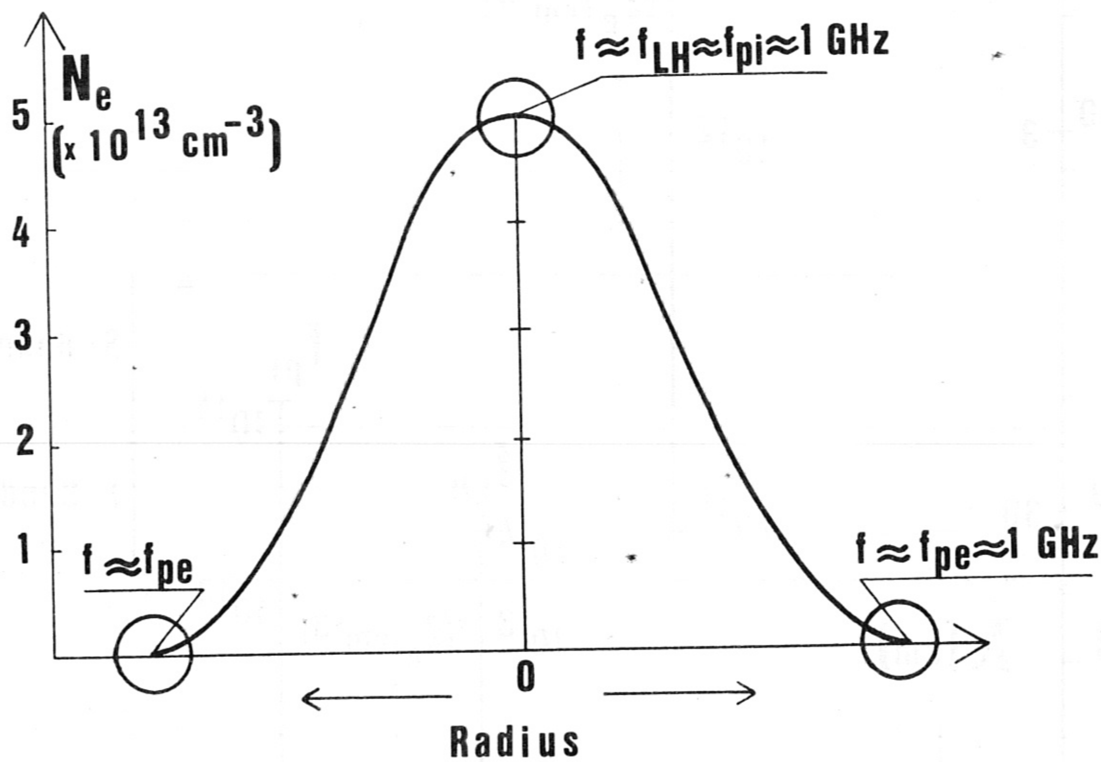
Fig. 8 - Qualitative representation of the plasma flow lines around the plasma core

Fig. 9 - Plasma potential well concentric with the plasma core



f (Hz)
λ (cm)
10^11 0.3
10^10 3
10^9 30
10^8 300
10^7 3000
f_pe
10^14
10^12
10^10
N_e (cm^-3)
f_ce
B (kG)
30
15
S-Band
L-Band
f_pi
f_LH
10^14
10^13
10^12
N_e (cm^-3)
2 f_ci
B (kG)
30
15
f_ci
B (kG)
30
15

TABLE 1



N_e
$(\times 10^{13}\ cm^{-3})$
5
4
3
2
1
$f \approx f_{LH} \approx f_{pi} \approx 1$ GHz
$f \approx f_{pe}$
$f \approx f_{pe} \approx 1$ GHz
0
Radius

FIG. 1

WIIb WENDELSTEIN STELLARATOR

l=2 m=5

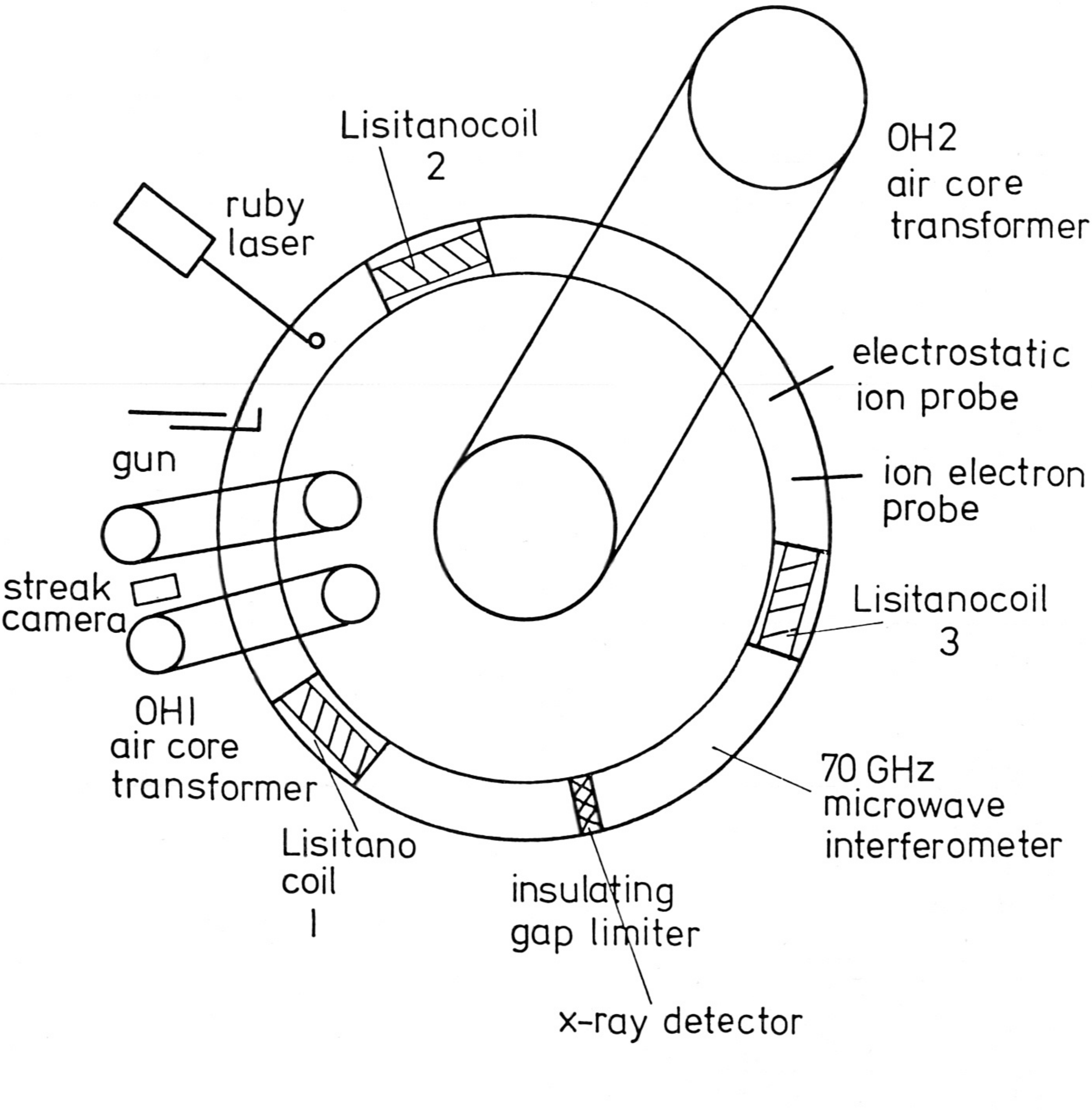
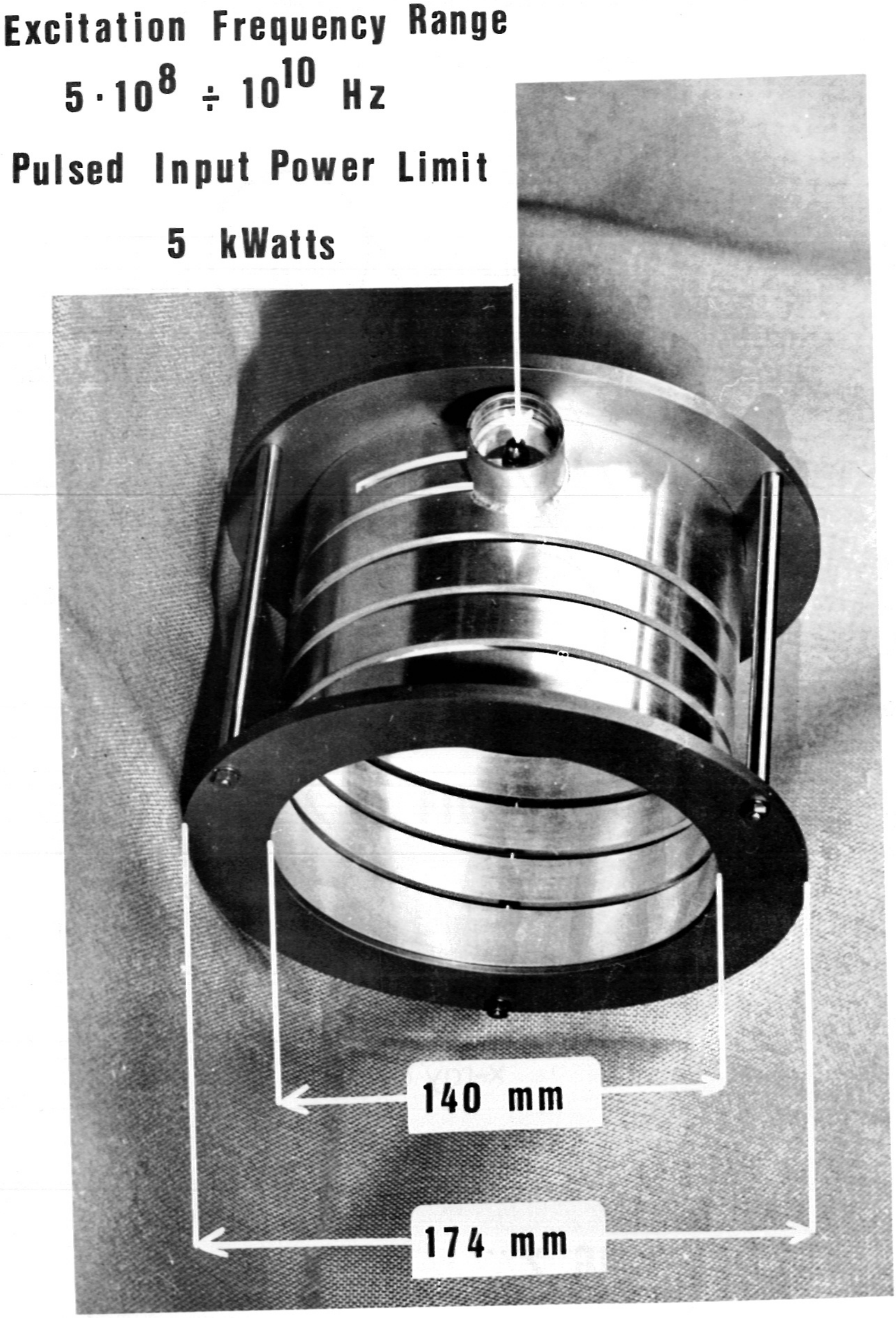
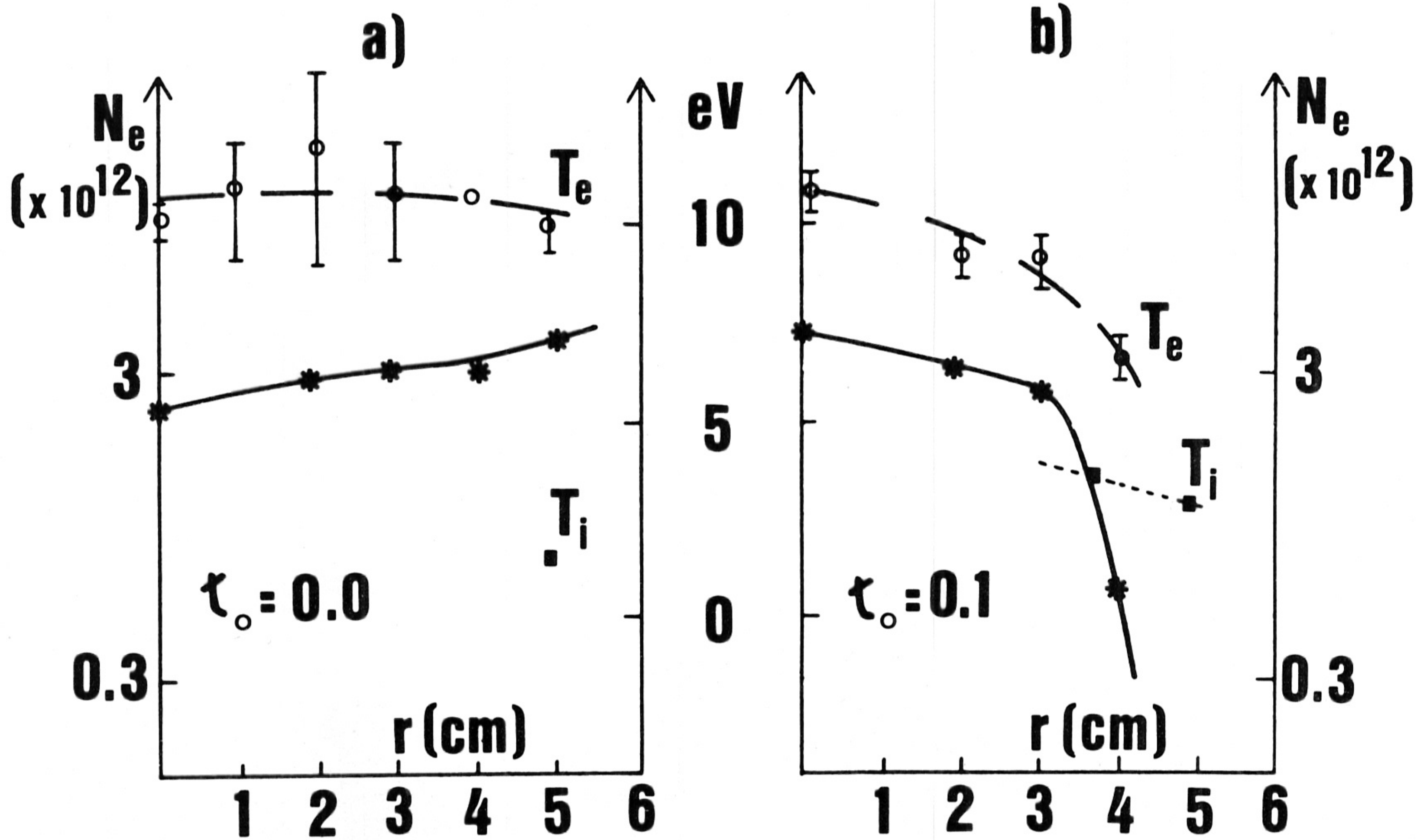


FIG. 2



LISITANO - COIL

FIG. 3



$B_O = 7$ kG ; $p_{H2} = 7 \cdot 10^{-5}$; $t = 3.0$ ms

FIG. 4

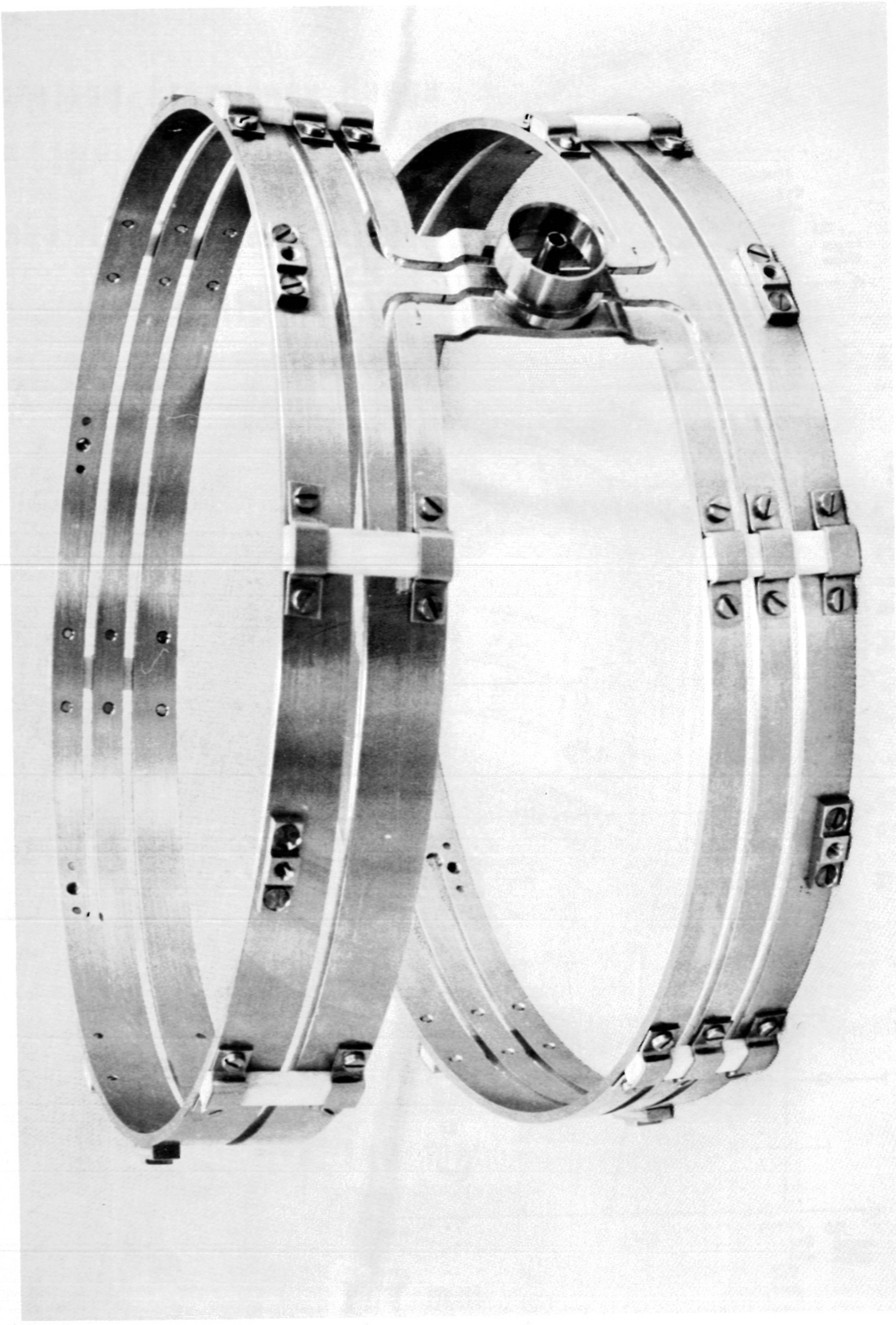
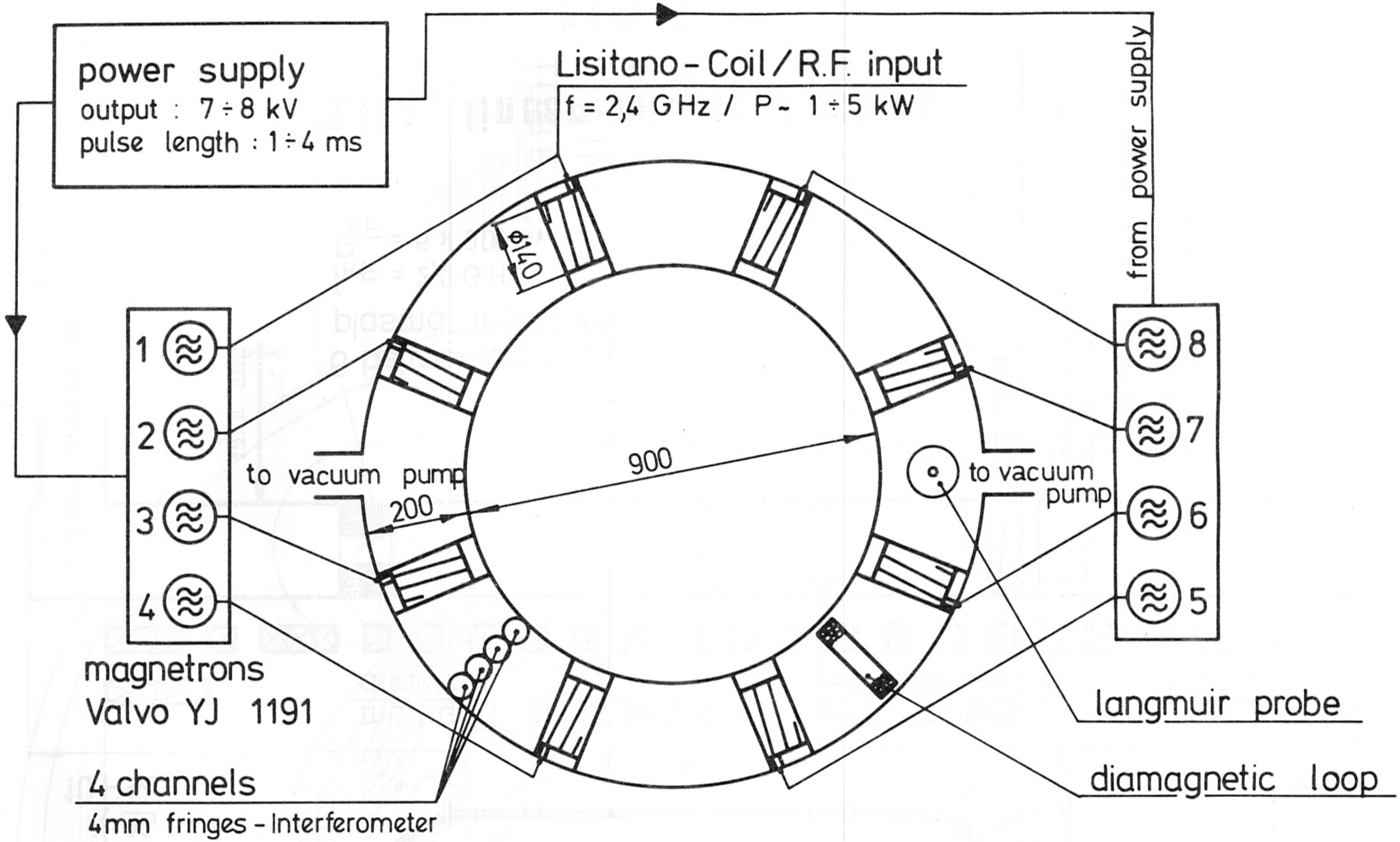
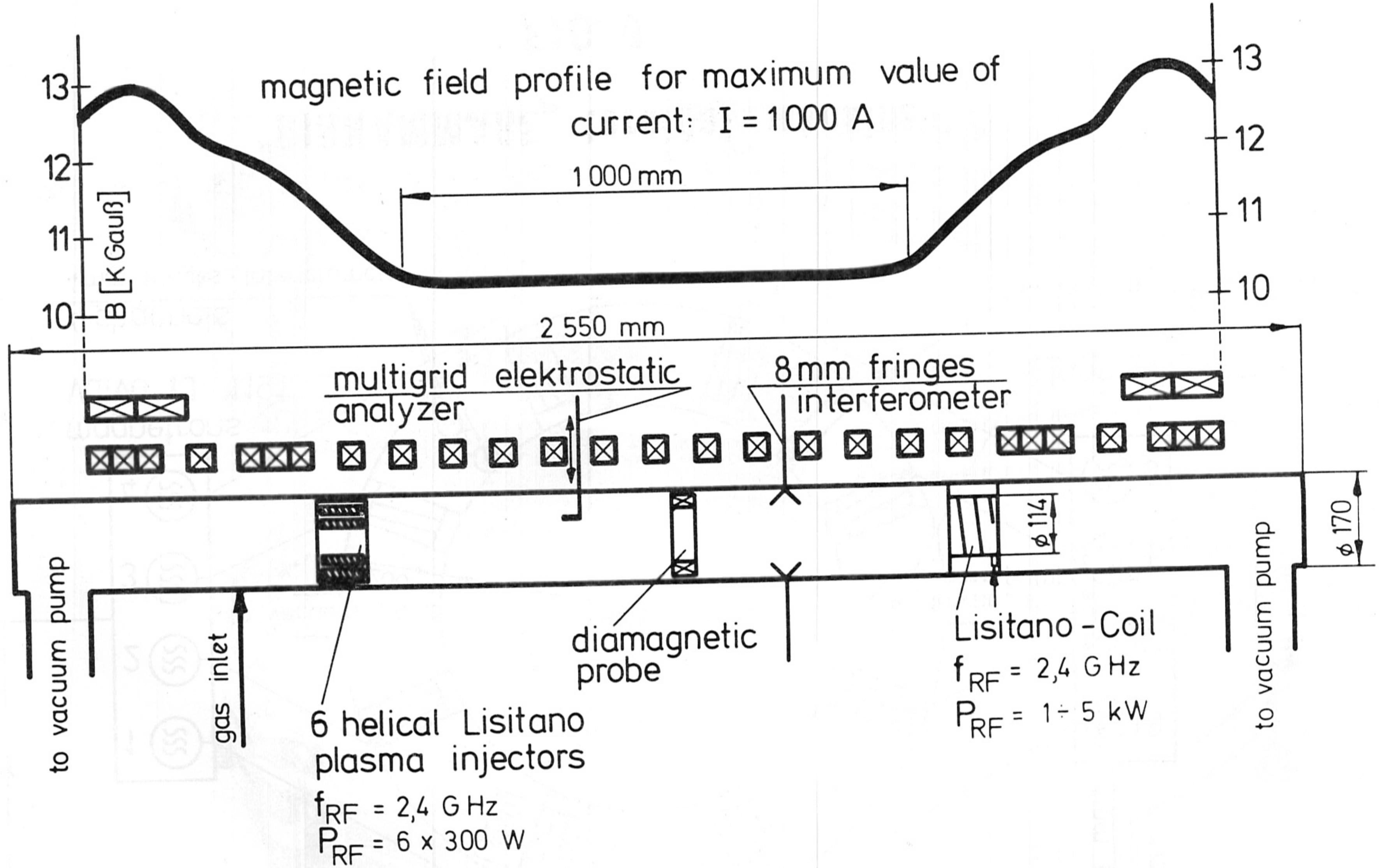


FIG. 5



"DINNAMMARE„ toroidal machine

FIG. 6



"LISA" linear mirror machine

FIG. 7

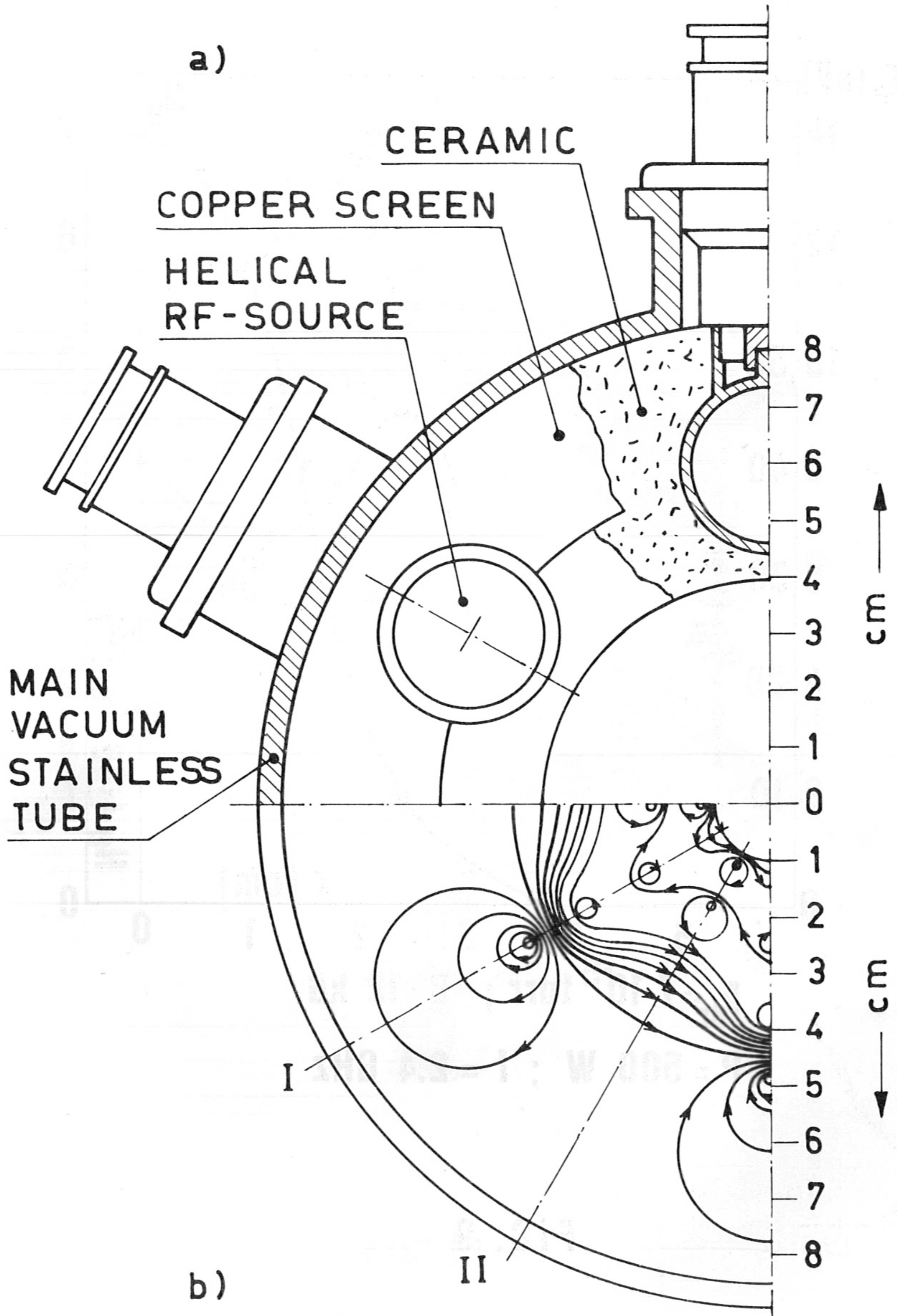
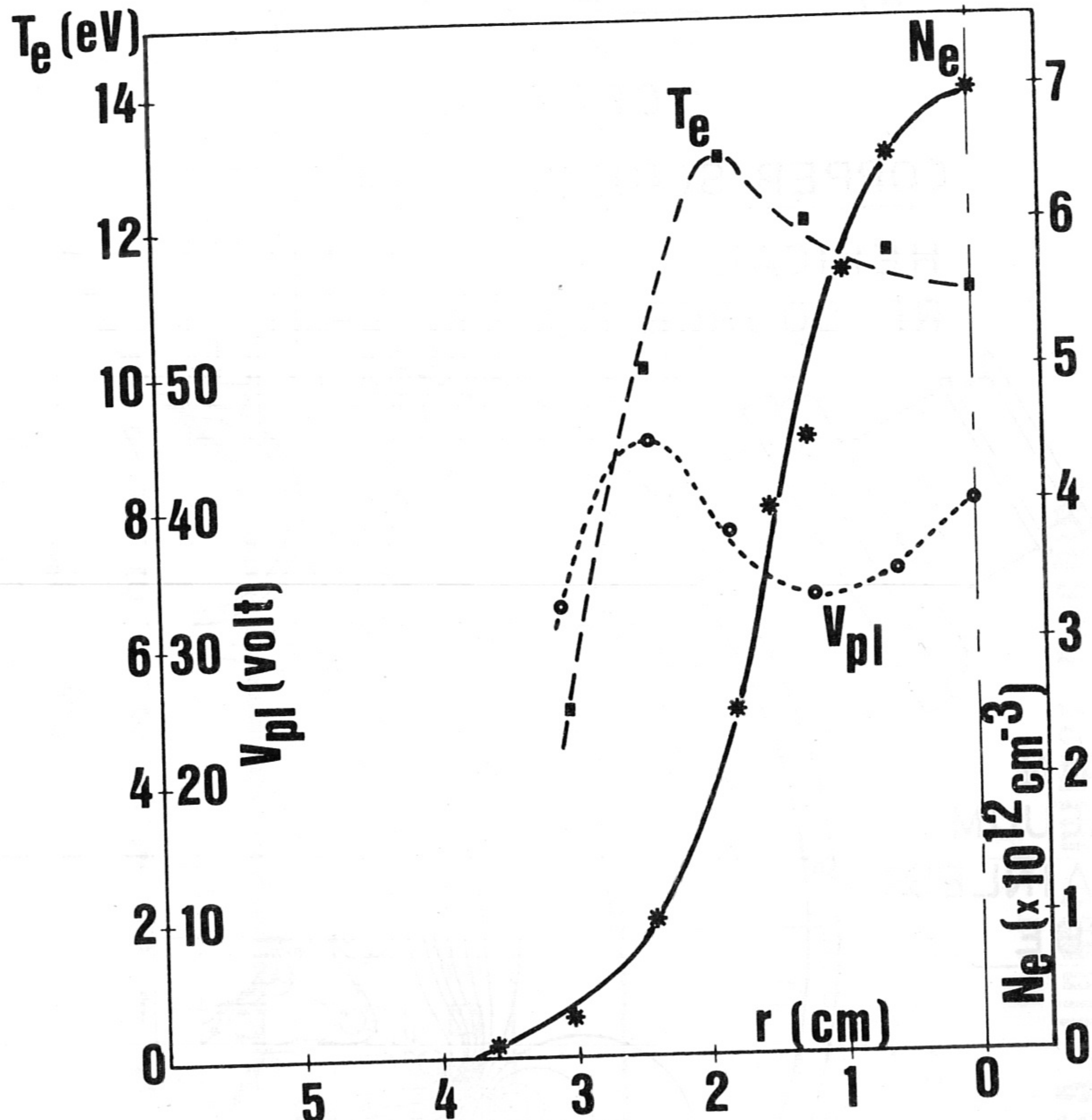

a)
CERAMIC
COPPER SCREEN
HELICAL
RF-SOURCE
MAIN
VACUUM
STAINLESS
TUBE
8
7
6
5
4
3
2
1
0
1
2
3
4
5
6
7
8
cm
cm
I
II
b)

FIG. 8



$p_{Ar} = 7 \cdot 10^{-5}$ torr ; B = 12 kG

P = 500 W ; f = 2.4 GHz

FIG. 9

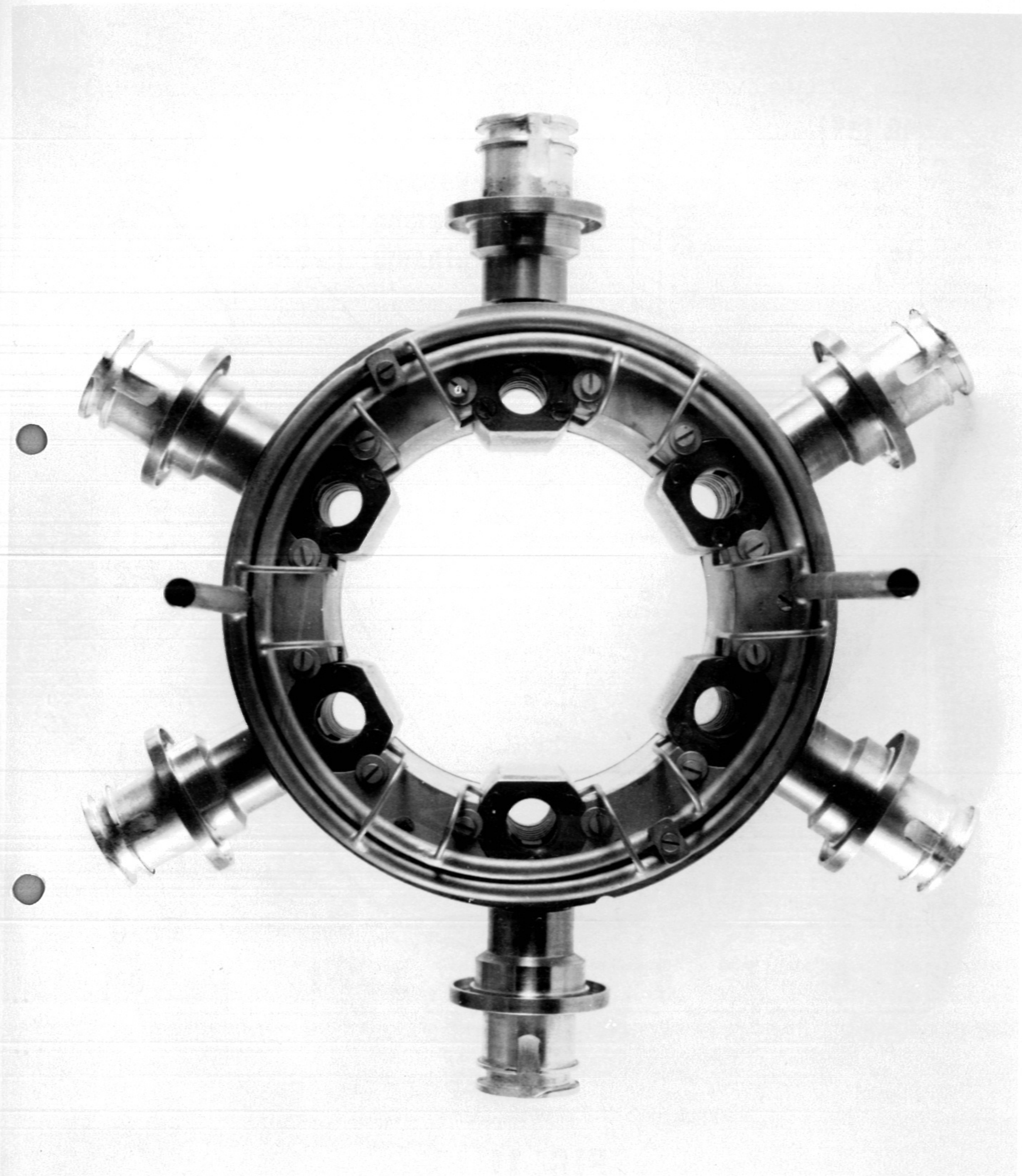


FIG. 10

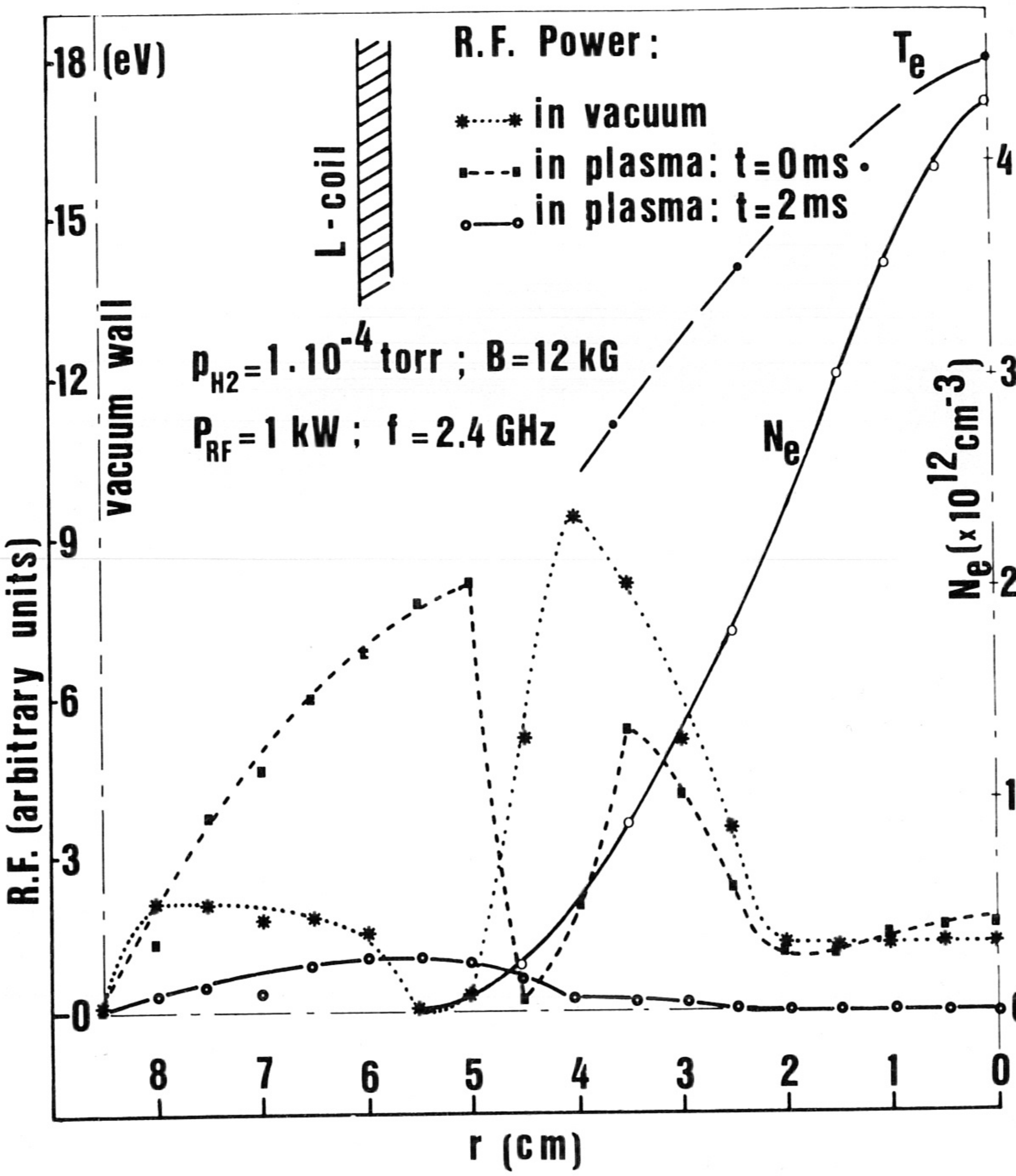

R.F. Power :
in vacuum
in plasma: t=0ms
in plasma: t=2ms
L-coil
vacuum wall
p_{H2}=1.10^{-4} torr ; B=12 kG
P_{RF}=1 kW ; f =2.4 GHz
18 (eV)
15
12
9
6
3
0
T_e
N_e
4
3
2
1
0
N_e (x10^{12}cm^{-3})
R.F. (arbitrary units)
8
7
6
5
4
3
2
1
0
r (cm)

FIG. 11