OPTIMIZATION OF THE DISCHARGE CHAMBER LENGTH OF THE RF-ION SOURCE RIG 10

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ABSTRACT

For additional heating of a fusion plasma by neutral injection a very uniform beam-profile, i.e. an analogous radial ion density-profile is necessary. The influence of the chamber length on this profile has been investigated experimentally and theoretically. A first tendency is described.

1. INTRODUCTION

Additional fusion-plasma heating by injection of high energetic hydrogen (deuterium) atom beams demands a very homogeneous beam profile, i.e. the variation of the current density must not exceed 5% across the usable source radius.

For the gas-discharge this means an analogous radial homogeneity of the ion saturation current density at the extraction area.

Assuming ionizing electron-neutral collisions as the only carrier production process in the discharge and wall recombination as the only loss mechanism (which is allowed in the pressure range of about 10 µbar), the discharge behaviour is dominantly influenced by the relation of plasma volume to vessel surface.

Searching an optimal radial carrier-distribution this means an optimization of the chamber length at a given vessel diameter (here: 10 cm; RIG 10: Radio-frequency Injection Generator).

2. EXPERIMENTAL

2.1 Description of the measuring conditions

We used a hydrogen rf-ion source (10 cm in diameter, 9 cm maximum height) made of quartz. The discharge vessel is surrounded by the induction coil (2 turns/cm) of an rf-transmitter with an rf-power of 500 W (5 MHz) (Fig. 1).

The plasma diagnostic was executed by a cylindrical double probe (length: 3 mm, diameter: 1 mm, mutual distance of probes: 3 mm) radial movable along the vessel bottom. The bottom itself could be moved axially to reach different chamber-lenghts.

With regard to later applications, the discharge pressure was accommodated to the different vessel-lengths by maximizing the saturation current density on the vessel axis at constant rf-power. This results in optimal discharge pressures from 10 to 17 μbar, corresponding to vessel-lengths from 90 to 40 mm.

3. ION CURRENT DENSITY PROFILES (Experimental Results)

3.1 Density-Profiles at Various Chamber-Lengths

The plot of the saturation current density versus the chamber radius shows a decrease of current density with increasing vessel-length. Starting at the vessel axis, the current density shows no continuous diminution in radial direction, but has a pronounced maximum at a radius of about 2 to 3 cm, depending on different chamber lengths (Fig. 2). (The percentage values give the profile raise relative to the axis.) The increasing of the optimal gas-pressure for decreasing vessel lengths can't be the purpose for these variations in profile.

On the contrary, an increasing gas-pressure at constant discharge volume would cause an intensified radial decrease in ion density, starting from the vessel axis (1).

The extremely decreasing current density on the vessel axis for short tubes (40 ÷ 60 mm) causes an early reaching of the tolerable 5%-limit in variation at a radius of about 1 cm. ($R_{5\%}$: radius, at which the variation exceeds 5%.) Only chamber lengths from 70 to 90 mm are usable for ion extraction, because the profile-raise at 2 cm radius does not transgress the 5%-limit (Fig. 2).

3.2 Superposition of a Weak Magnetic Field

The use of shorter vessel-lengths (due to their higher current-densities) becomes possible by superposing a weak magnetic field, causing an increase of carrier concentration at the vessel axis, i.e. a correction of the radial current density distribution (Fig. 3). (At 1 ampere coil current the magnetic field strength amounts $1 \cdot 10^{-4}$ Tesla on the vessel axis 3 cm from the top.) A favourable magnetic field configuration for this purpose shows the graph in Fig. 3.

This field has a predominant axial component on the vessel axis and a main radial field-component on the wall surface. As S. Reineck (2) shows in detail, the superposition of magnetic fields leads to a changed movement of electrons (gyration and drift) causing a predominant energy flux to the vessel center, i.e. to increasing generation rates. Simultaneously, this leads to a intensified density drop near the chamber wall. Thus the usable area for extraction is reduced (Fig. 3).

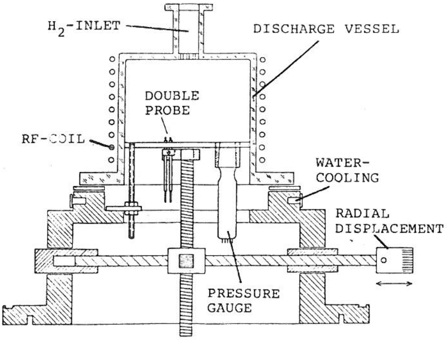

Fig. 1: Discharge chamber with measuring device

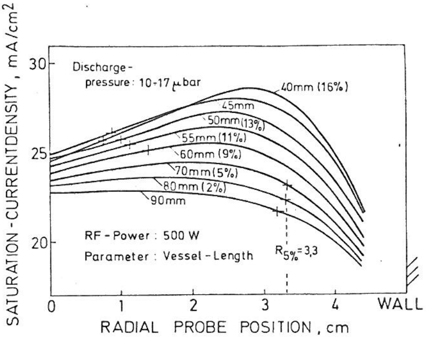

Fig. 2: Radial ion current profile at various chamber lengths

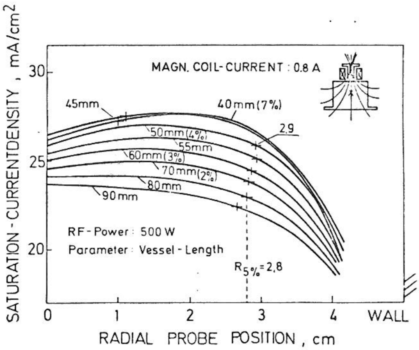

Fig. 3: Radial ion current density profile with superposition of an auxiliary magnetic field

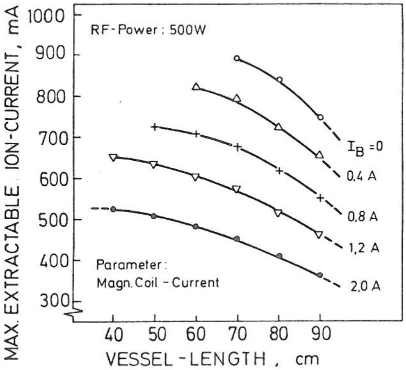

Fig. 4: Theoretical maximal extractable ion current at different vessel length. Parameter: Current of the auxiliary static magnetic field

4. OPTIMAL CHAMBER-LENGTH

Comparing the theoretical extractable ion currents by integration of the current densities across the usable extraction area, leads to the advantageous vessel lengths (Fig. 4).

Depending on the magnetic field strength there exist various optimal chamber lengths. At these lengths, the radial profile-raise reaches the 5%-variation limit.

Shorter chamber-lengths cannot be utilized for extraction without enhancing the magnetic field strength. The 70 mm-vessel turns out to be optimal at an rf-power of 500 W.

5. CALCULATION OF THE RADIAL ION DENSITY PROFILE

Assuming ionizing electron-neutral collisions as the only particle production process in the plasma and wall recombination as the only loss mechanism (which is allowed in the pressure range considered) the radial component $j_r(r,z)$ and the longitudinal component $j_z(r,z)$ of the ion diffusion current density $j = (j_r, 0, j_z)$ must satisfy the continuity equation

$$\frac{1}{r}\frac{\partial}{\partial r}(r j_r) + \frac{j_z}{\partial z} = |e| \nu_i \, n$$

r = radial
z = longitudinal coordinate
e = elementary charge
$_i$ = ionization collision frequency
n = plasma density

expressing conservation of mass or charge.
In the limiting cases of very long and very short discharge

vessels, respectively, the continuity equation could easily be solved. In the general case of a discharge vessel with finite length we obtain

$$j_r(r,z) = k_1 \frac{n_\infty(z)}{n(0,0)} |e| \frac{1}{r} \int_0^r \nu_i n_\infty(r')r'dr'$$

and

$$j_z(r,z) = k_2 \frac{n_\infty(r)}{n(0,0)} e \int_0^z \nu_i n_\infty(z')dz'$$

with constants k_1 and k_2 as well as $k_1 + k_2 = 1$.
The plasma density distribution $n(r,z)$ has been written as the product of a radial function n (r) and a longitudinal function n (z) in the following way:

$$n(r,z) = n(0,0)n_\infty(r)n_\infty(z)$$

where the subscript " ∞ " characterizes the both limiting cases mentioned above.
With respect to the experimental results we are interested in the current density distribution at the extraction area:

$$j_z(r,\tfrac{\ell}{2}) = k_2 \frac{n_\infty(r)}{n(0,0)} e \int_0^{\ell/2} \nu_i n_\infty(z')dz'$$

ℓ = discharge vessel length

Representing the plasma density distribution $n(r,z)$ as a power series

$$n(r,z) = n(0,0) \sum_{k,m=0}^{\infty} a_k b_m (\frac{r}{r_0})^{2k} (\frac{2z}{\ell})^{2m}$$

with coefficients a_k and b_m
and the ionization collision frequency ν_i as

$$\nu_i(r) = \nu_i(0,0) \sum_{j=0}^{\infty} t_j (\frac{r}{r_0})^{2j}$$

with coefficients t_j.

Assuming only a radial dependancy with respect to the radial behaviour of the electron temperature, we finally get

$$j_z(r,\tfrac{\ell}{2}) = |e| \nu_i(0,0)n(0,0)\frac{\ell}{2} k_2 \sum_{w,j,k=0}^{\infty} \frac{b_m t_j a_k}{2m+1} (\frac{r}{r_0})^{2(k+j)}$$

where the radial dependency of j_z is given by

$$R(r) = \sum_{w,j,k=0}^{\infty} \frac{b_m t_j a_k}{2m+1} (\frac{r}{r_0})^{2(k+j)}$$

In practical cases only a few coefficients are essentially different from zero. For example we get a rather good approximation of experimental results by the following set of coefficients:

$a_0 = b_0 = t_0 = 1, \; a_2 = b_2 = -0.7, \; t_1 = 0.3, \; t_2 = 0.7$

In this case the function R(r) would be a polynomial of the order of eight. The shift of the characteristic maximum in the current density distribution could be represented by variation of the coefficients t_1, which is equivalent to a longitudinal dependency of the electron temperature profile.

Presently we are working at the completion of our theory.

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