ANTENNAMARE, A METHOD OF RADIO-FREQUENCY CONDITIONING OF FUSION PLASMA

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(in English)

Abstract

Fusion-relevant conditioning of plasma is to be achieved with high levels of r.f. power launched by means of all-metal, frequency-independent Antennamare structures in the ion cyclotron to lower hybrid frequency range.

1. INTRODUCTION

The availability of low-frequency power and ion absorption makes ion cyclotron frequency heating (ICFH) very attractive for fusion conditioning of plasma in large devices.

As shown in Fig.1, with increasing plasma radius and magnetic field strength, it becomes easier to couple the large levels of ICF power. The diluted density of the heating power should, however, be compensated, as is hoped, by an improved containement time corresponding to an appreciable fraction of the increased volume.

In this regard the Antennamare method of fusion conditioning of plasma should be related to the strategy of large fusion experiments, such as JET. If, in fact, the experimental results on stability and containement of JET plasma do not afford the expected improvement over devices of less volume, one will then have to resort to some other plasma-conditioning scheme yielding larger power densities per unit plasma volume.

As will be seen, the aim of the proposed Antennamare experiment is to tackle the problem of fusion ignition by steady-state operation and coupling of very high levels of r.f. power to the plasma by means of special high power and frequency-independent Antennamare radiators.

In the following, first the Antennamare wave-launching structures are described and then the r.f. plasma conditioning is treated in respect of current drive, plasma-wall separation and heating.

2. ANTENNAMARE

As shown in Fig. 2, the Antennamare structures provide two types of k-spectrum for better matching the requirements of various r.f. heating schemes such as ICF, Alfvén wave and LH.

Both of the Antennamare in Figs. 2 a) and b) consist of long slot transmission lines, the one wound helicoidally in the poloidal direction and the other interdigitally, back and forth, in the toroidal direction. Essentially, the Antennamare are wave-retarding structures having a large wave number k in the toroidal and poloidal directions for the helical and the interdigital types, respectively.

Owing to the high-frequency skin effect, the r.f. field originates from the edges of the slot line from which it radiates towards the plasma; in particular, the r.f. electric field, which is displaced across the slots, determines the polarization of the launched e.m. waves. Such polarization is of a type similar to the $TE_{m,1}$ and $TM_{o,1}$ modes of circular waveguides for the interdigital and the helical Antennamare, respectively.

However, an important property of these divices is that one can obtain such field configurations without meeting the conducting-sheet conditions of cavity resonators, which require large volumes at low frequencies. Moreover, as the Antennamare are made of long transmission lines, they can be excited independently of the frequency in the range from a few tens of Mc/s up to a few Gc/s. This provides great operational flexibility for fusion conditioning of plasmas in vacuum tubes far cut-off for the vacuum wavelengths of the various low-frequency heating schemes such as magnetosonic, Alfvén waves and ICF.

The Antennamare radiators may be shaped in keeping with the form of the discharge tube; in particular, they may be open in the region of stagnation-points of a single-null magnetic divertor. As shown in Fig. 2, the Antennamare are all-metal radiators provided with a metal screen protection for the vacuum-tight feed-through insulator at the coaxial feed point.

The high level of r.f. power for fusion conditioning of plasma is of no concern for the slot radiators, the coaxial coupling of the r.f. power at various feed points of the slot transmission line being exactly the same as that used in recent ICRH megawatt experiments with loop antennae /1/. The great advantage of using slot radiators is the absence of any kind of matching elements and the low voltage at the feed connectors of the matched slot structure.

3. PLASMA CONDITIONING

Antennamare conditioning of fusion plasma is aimed at reaching ignition-relevant temperatures of r.f. heated plasma by trying to improve the equilibrium of the plasma and its separation from the wall by means of r . f . driven currents and strong radial electric fields, also driven by the r.f. near-field surrounding the plasma. This should allow reactor-relevant steady-state operation of the device and substantial reduction of plasma contamination from the walls.

3.1. Current drive

To the author's knowledge the first documented radio-frequency current drive experiment in a toroidal discharge was performed by means of all-metal wave-retarding slot structures, from which the Antennamare radiators proposed in this paper are derived /2/. Despite the fact that, at that time, the r.f. current drive was not optimized, an r.f. driven current of 1 A for 2 W of applied r.f. power was measured. The figure of merit $\Delta I\, n\, R/P_{rf} = 0.2$ (kA 10^{15} cm^{-2} kW^{-1}) of this experiment compares well with those reported from recent experiments on LH current drive /3/.

The intriguing property of that first current-drive experiment was that the current was not driven by any of the schemes now proposed. The frequency of the applied r.f. power of 2.4 Gc/s was far from the electron or ion cyclotron values and even from lower hybrid or plasma frequency current-drive schemes. The mechanism of that current drive may be understood with the help of Fig. 3. Three slotted coils were mounted in the WIIb stellarator with k-vectors in opposite directions in order not to produce appreciable current drive with a $i_o = 0.1$ (the iota produced by the current in the helical windings alone). Although no OH field was applied, a current drive in one or the other direction was obtained by applying an increasing vertical B_z field in the one or in the other direction, as shown in Fig. 3b). In this way the suprathermal electrons moving in one direction were preferentially lost, whereas the confinement of those moving in the other direction was improved.

The current drive mechanism in this first experiment is exactly the same as that recently proposed /4/ where an ion cyclotron wave near the minority ion cyclotron frequency is to be launched unidirectionally in the toroidal direction of a tokamak.

With the proposed Antennamare structures a current drive at the ion cyclotron frequency could be preferentially obtained by exciting helical antennae with their k-vector oriented in the toroidal direction, whereas the interdigital ones, with their k-vector oriented in the poloidal direction, should be preferentially used for magnetoelectric divertor effects and heating, as will be shown.

3.2. Magnetoelectric divertor

The near-field of e.m. wave radiators always produce electrostatic fields caused by preferential losses of one particle species of the plasma. If the electrostatic E field generated is random, or uncontrollably distributed, ExB drift forces may enhance the plasma losses, which in turn the confining properties of the magnetostatic field impair.

With the Antennamare r.f. radiators, the radial, homogeneous electrostatic field produced by interaction of the r.f. near-field with the plasma edges may be utilized to solve the problem of separation of the plasma edges from the container walls, in a very simple way. In fact, the strength of the electrostatic field depends on that of the r.f. near-field at the plasma edges, where an ExB drift flow of plasma in the poloidal direction is generated.

The minute inhomogeneity of the poloidal plasma flow closest to the walls causes enhanced plasma losses in a plasma-free gap of about 2 cm between the inner wall of the Antennamare and the plasma edges. In the plasma-free gap the losses of single particles are also enhanced by finite Larmor radius effects the closer they approach the r.f. near-field at the edges of the slotted transmission line.

Regarding impurities, it should be noted that the same r.f. driven divertor effect mechanism will deflect the impurities to the walls, where they are neutralized as soon as they are produced. As seen in Fig. 2, most of the neutralizer plate surface is located behind the slot line radiators, where it may be gettered or pumped out. When, however, a material limiter is replaced by the magnetoelectric ExB divertor effect, contamination of the plasma will be substantially reduced.

The magnetoelectric separation of the plasma from the inner walls of slotted-line radiators has invariably been observed over a decade of experimentation with these devices /5,6/. In an experimental study of ExB drift forces, these have even been utilized to excite KARMAN' trail of plasma vortices which better isolated the dense central plasma from the ExB excited vortex flow surrounding it /7,8/. These experiments revealed the possibility of generating a strong plasma potential well which was clearly dependent on the strength of the r.f. near-field /7/.

For the proposed magnetoelectric non-material limiter the interdigital Antennamare radiators are most convenient for exciting the ExB divertor effect since the r.f. electric field is displaced transversally to both the slots and the confining magnetostatic field/9,10/.

During the conditioning phase of fusion plasma by means of Antennamare structures, it will be necessary to time and dose the r.f. power level for both current drive and plasma separation from the walls. Only after reaching optimum conditioning of these two parameters may one go through the third phase of r.f. heating of plasma.

3.3. Heating

As demonstrated by experiments /1,3,11,12/, the most delicate element of ion cyclotron and lower hybrid heating is certainly the wave-launching antenna, which has to meet the complicated wave-coupling requirements for the k-spectrum of the plasma waves.

The ICF loop antenna used to date can, however, only provide excitation of simple propagation modes in empty cavity resonators or waveguides. Being reactive λ/4 transmission line elements, the loop antennae concentrate the high E-field voltages at the antenna imput. This may be the cause of the observed production of metallic impurities during the r.f. pulse, which limit the pumped ICRH power up to about 2 MW /11/.

The frequency dependence of the reactive loop antennae, since it involves high-power impedance matching elements, also limits their operational flexibility. On the other hand, lower hybrid waveguide "grill" launchers are also affected by serious problems of ceramic vacuum window, arcing and plasma load impedance matching.

From the experimental data obtained up to date it seems clear that ICF-loop and LH-grill antennae are far from being capable of pumping r.f. power in the range of tens of megawatts, as is required for ignition.

As has been mentioned, the Antennamare radiating structures should avoid these problems. For vacuum wavelengths larger than the antenna diameter, the Antennamare may be regarded as an open-ended cavity outside which the propagation of r.f. waves is allowed in the plasma only /13/. This avoids the coaxial mode coupling of ICF waves launched with loop antennae between the plasma column and the walls of the discharge chamber.

Another important property of the Antennamare structures is that they allow reflection-free coupling of ion cyclotron and lower hybrid waves from the high-field side of the toroidal magnetic field, as the wave travel along the slot transmission line, from the outer wall to the inside wall of the torus. This property is also important for single-null magnetic divertors where the ExB drift forces may be used to sustain actively the magnetic divertor effect.

For such devices as JET which are not provided with magnetic divertor, however, the advantage of plasma conditioning with ExB divertor effect will be dramatically indicated simply by monitoring the neutral-gas pressure in the discharge chamber. As has been routinely observed in using slot structures /6,7,8,13/, the neutral pressure gauge will monitor a decrease of more than one order of magnitude as soon as the plasma detaches itself from the structure and is confined by the strong near-field surrounding it.

The plasma is now ready to be loaded with high levels of r.f. heating power, which has to be carefully regulated in order to maintain the plasma equilibrium, given by the steady-state current drive, and the magnetoelectric confining effect. Helical antennae may then be used to excite Alfvén waves and slow ion cyclotron waves, whereas lower hybrid waves and fast ion cyclotron waves should be launched with interdigital antennae.

However, as the coupled r.f. power per unit plasma volume increases over a certain level, what has been routinely observed in slotted-coil r.f. discharges of small volume may happen, viz. the heating resonance becomes very broad, probably owing to stochastic heating or some other cause /14,15/.

4. CONCLUSION

The simple mechanical structure, moderate size and cost of the proposed Antennamare conditioning method provides flexible experimental facilities for steady-state operation of r.f. driven current, magnetoelectric divertor and fusion-relevant heating of plasma in existing large fusion devices.
In particular:

1) Large fusion devices which are not provided with magnetic divertor may substantially reduce the contamination of plasma by means of the r.f. driven divertor effect of the Antennamare structure which replaces the material limiter.
2) Single-null-operated magnetic divertors of large fusion devices may be improved in combination with the "active" r.f. driven divertor effect of Antennamare.

3) Steady-state current driven by the e.m. wave spectrum launched by Antennamare, should be efficent in the high-density range of fusion-relevant plasma parameters.
4) The high-power generators at the ion cyclotron and lower hybrid frequencies provided for large fusion experiments may be used to excite the same Antennamare structure. As compared with the ICF-loop and LH-grill structures, this provides a better distributed wave vector spectrum and accessibility from the high-field side of the confining magnetostatic field.
5) Antennamare r.f. radiators may easily be shaped and assembled to surround poloidally the plasma of existing large fusion devices. Contrary to ICF-loop radiators, which distribute the ICF power coaxially all around the device, the Antennamare behavies like a cavity. This provides ignition-relevant concentration of r.f. power density per unit plasma volume, which is otherwise impossible to achieve with the ICF power provided for these large fusion devices.

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FIGURE CAPTIONS

Fig. 1 Overview of the total r.f. power levels, P_{RF}, as a function of the plasma radius, a, for various r.f. power densities per unit volume; an aspect ratio R/a = 3 has been assumed for the toroidal plasma. For a fundamental mode of propagation, $a_{m,n}$, the refractive index

$$n = \frac{k c}{\omega} = \frac{a_{m,n}}{\pi} \frac{\lambda o}{2 a}$$

is given as a function of plasma radius and ion cyclotron frequency f_{ci}.

Fig. 2 Antennamare radiators: a) helical and b) interdigital. 1) central conductor; 2) lateral conductor; 3) slot; 4) vacuum-tight feed-through insulator located in the coaxial transmission line; 5) Screen protection for the vacuum-tight insulator; 6) gas feed hollow rod, insulated.

Fig.3 a) Current-drive experiment with helical slotted coils in WIIb stellarator. Applied r.f. power P_{RF} 800 W, 2.4 Gc/s.
b) Current drive as a function of the vertical magnetic field B_z. (Curtesy of Ref. 2)

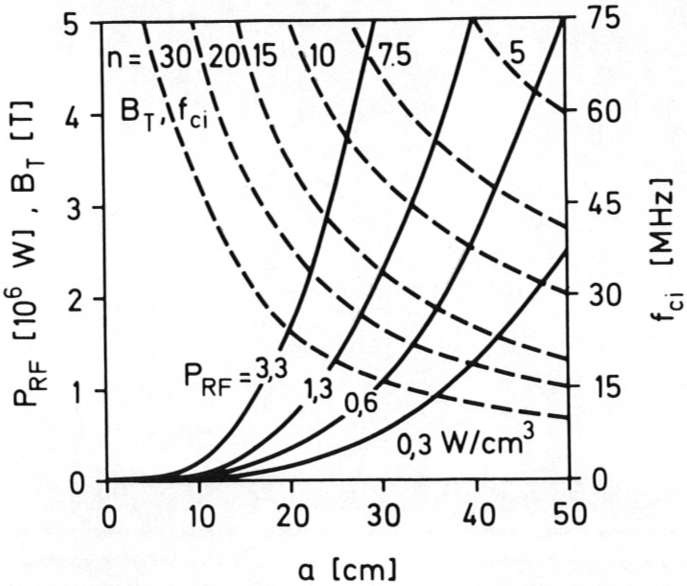

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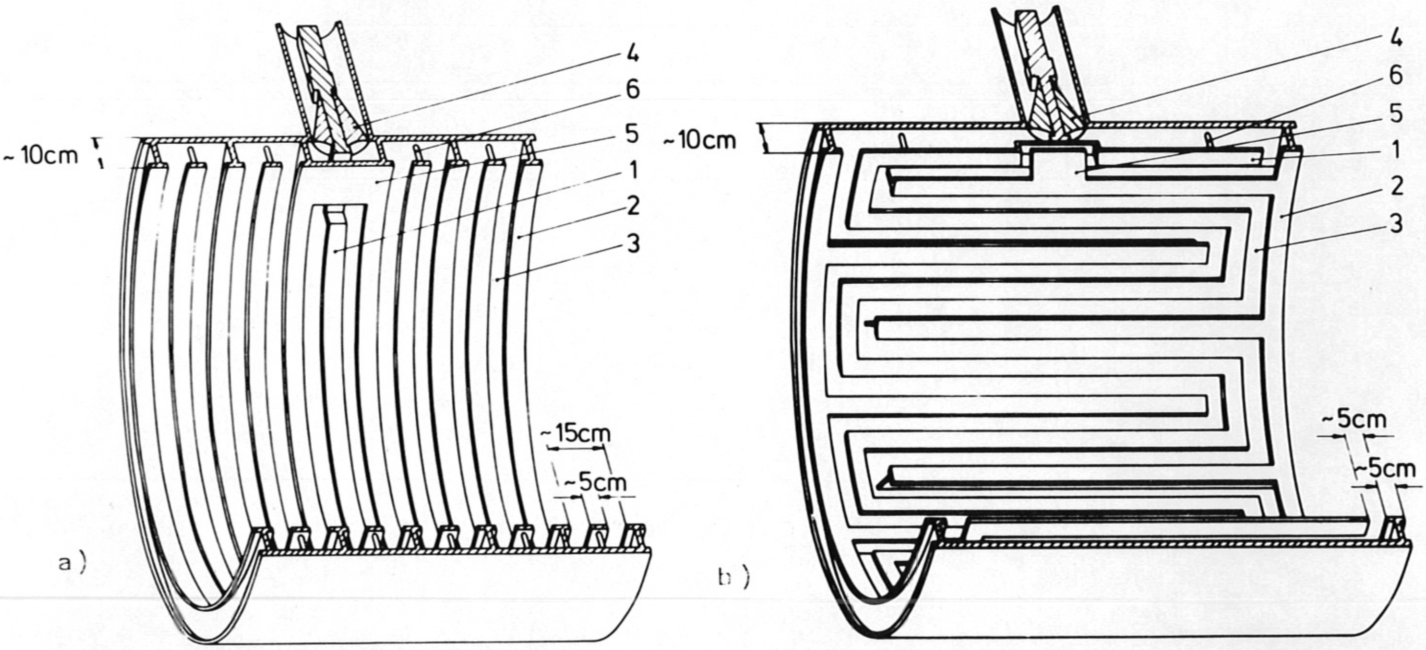
Fig. 1



WIIb WENDELSTEIN STELLARATOR

l=2 m=5

Fig. 2

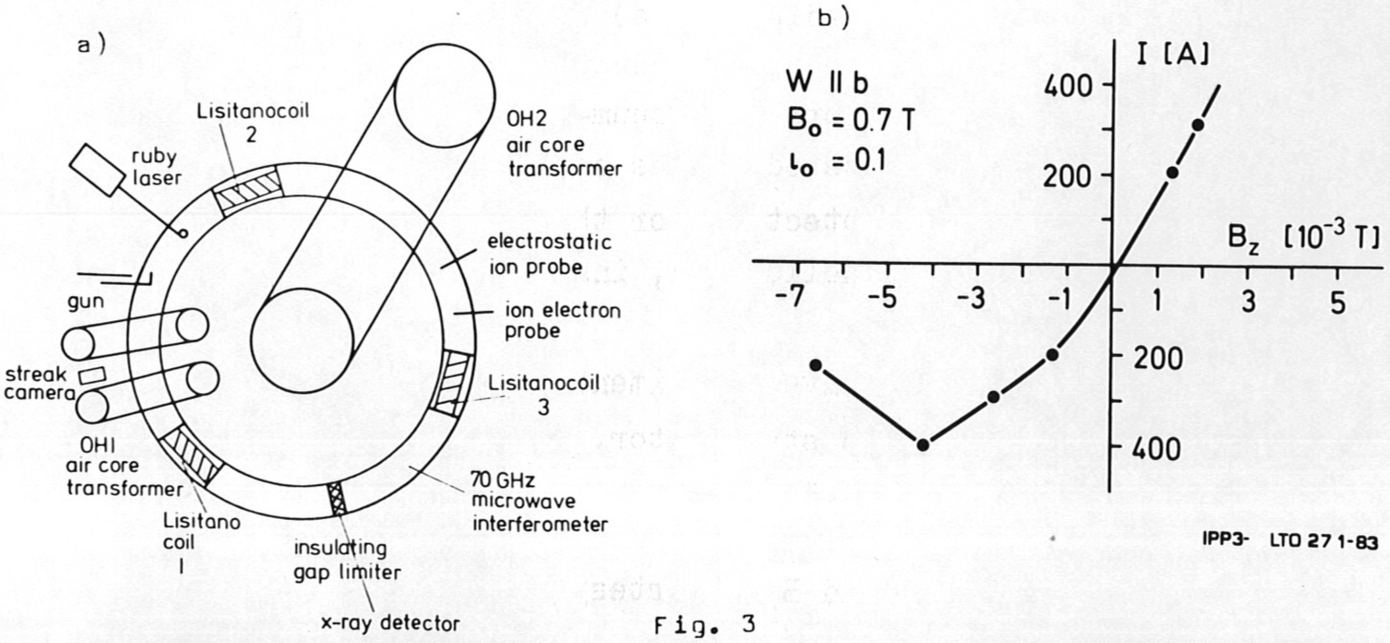


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Fig. 3