Radio Frequency
Heating of
Toroidal Plasmas

COAXIAL ANTENNA FOR LOWER HYBRID HEATING

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-- Abstract --

A coaxial antenna for the heating of toroidal plasmas has been conceived and constructed. Being wholly metallic (stainless steel), the several coaxial ceramic passages assuring the transit of the H.F. energy into vacuum being situated far from the plasma, the use of such antennas can be envisaged in next generation machines where the environment is particularily severe. The coaxial design (having a lower internal impedance than a wave guide) reduces the electric fields present in the antenna-plasma interface, assuring, at the same time, a spatial uniformity of the fields making possible a substantial reduction in the transmitted power density. The main technological advantages (with respect to a wave guide grill structure) are: (a) simplification of the construction especially in multi-channel systems (b) quasi-elimination of the problems associated with the ceramic windows transmitting the H.F. energy (c) absence of a low frequency cut-off making possible to place launching structures in vertical chimneys where space is limited (d) an eventual reduction of certain phenomena inherent to this type of heating such as particle acceleration, space charge separation, pondemotive forces etc.

Experimentally, when an attempt is made to heat a toroidal plasma by an injection of high frequency energy around and above the lower hybrid frequency, the expected rise in the plasma temperature is always much lower than that which could be hoped for, given the amount of power sent into the vacuum chamber. The power is either reflected by some phenomenon occurring in the launching structure or dissipated elsewhere than inside the plasma. Furthermore, disagreeable secondary effects appear such as production of high energy particles, rise in the amount of impurities, and often the plasma column stability itself is affected. A reduction of the high frequency fields appearing at the mouth of the launching structure could limit the noxious secondary effects existing in that region.

The operating principle of the proposed coaxial antenna (in figure 1 can be seen a two channel model) is the following: a long thin curved blade, the excitation electrode, is fed by several cylindrical coaxial lines in parallel (same phase applied to all lines). The structure formed by the several cylindrical feed lines is prolongated up to the plasma surface by the equipotential blade, which constitutes in itself a rectangular coaxial structure. It can be arranged that the characteristic impedance of the coaxial feed lines divided by the number of lines be made equal to the characteristic impedance of the equipotential blade structure. In this manner no change of impedance is encountered inside the vacuum chamber

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which limits the amplitude of possible standing waves. The sudden change in geometry, in coming from the coaxial lines onto the blade, in spite of the identity of the characteristic impedances, can cause some undesirable reflection but this effect can be limited by proper design.

Since it is desired to assure the equipotentiality of the blade at the launching frequency, the distance along the blade, between two adjacent feed lines should not be greater than about a quarter of a wave length. At all frequencies below this value the distance between adjacent coaxial feed lines is less than a quarter of a wave length and the equipotentiality of the blade is assured down to zero frequency. The absence of a low frequency cut-off in the TEM fondamental coaxial mode makes possible the utilisation of such antennas in Tokamak vertical access ports where space is limited, where a wave guide structure could not function.

The radial width of the blade (in the direction normal to the plasma surface) should also be limited to a relatively small part of a wave length to avoid parasitical modes in the structure, but this limitation is not imperative.

The two channel model shown is all metal up to the three coaxial ceramic passages which transit the H.F. power into the toroidal vacuum chamber. The absence of insulating materials inside the vacuum chamber close to the plasma offers the possibility of employing this type of antenna (or a multi-channel version) in a reactor environment. The use of small ceramic coaxial feed throughs simplify the problems encountered with ceramic windows in a multi-channel wave guide grill launching structure.

Furthermore, considering the vacuum conditions prevailing in the region between the toroidal plasma and the wall of the vacuum chamber, experimentally a H.F. electric field of the order of 10 KV peak per cm. can be sustained at a pressure of 10^{-3} mm. of Hg. in hydrogen, provided the distance between conductors does not exceed a centimeter (Paschen's law). At a pressure of 10^{-4} mm. of Hg. in hydrogen, the electric field tolerated, at such a distance between conductors, is an order of magnitude higher. The condition for breakdown is to assure that the triple product - potential x pressure x distance - not exceed a certain value.

In figure 2 is shown a two channel wave guide grill (with 0°-180° phasing) and the equivalent two channel coaxial antenna configuration. The expressions giving the amplitudes of the fields at the mouths of the structures for the TE_{10} wave guide mode and the fondamental TEM coaxial mode are shown, considering a progressive wave penetration into the plasma without reflection. The expressions for the fields in the coaxial mode do not apply to the end regions where the fields become curvilinear. As it will be shown further on, these curvilinear end fields can be suppressed.

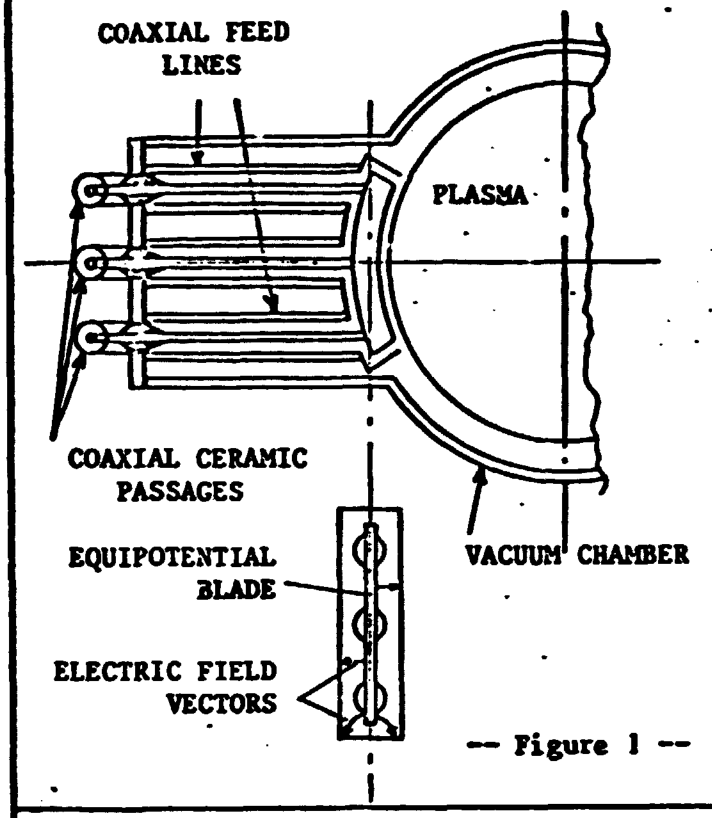
In the wave guide version the electric field has a sinusoidal spatial variation across the guide, becoming a maximum at the center. The large toroidal plasma, which passes vertically in front of the launching structures in the figure, never sees an electric field at the extremities of the guides.On the other hand, the electric field in the coaxial blade structure is a constant nearly over the entire length of the blade. The power density is uniform. When side "a" is very large the maximum power density in the guide is twice that of the coaxial structure. As "a" approches the lower cut-off frequency ($a = \lambda/2$),the ratio of power density, guide with respect to the coaxial structure, tends towards infinity. In most pratical cases, the reduction in the power density is of the order of 3 in favor of the coaxial structure.

The E/H ratio, constant spatially in the coaxial version, varies continuously in the wave guide structure. The instantaneous spatial impedance of the guides, as seen by the plasma, is never the same.

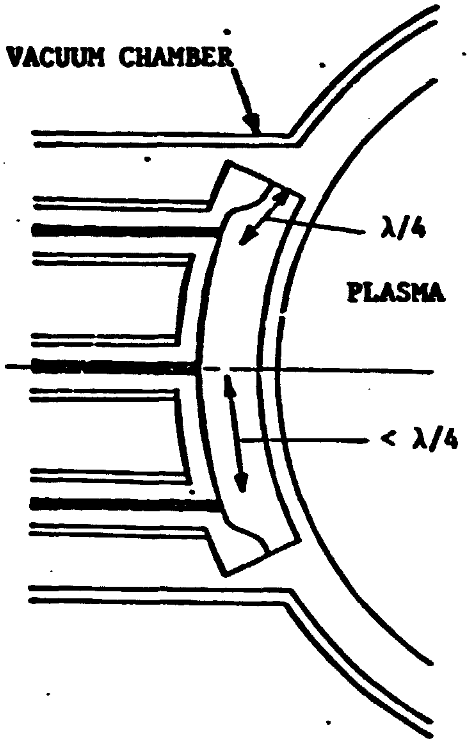
In figure 3 is shown a 3 coaxial line feed-in structure (which in this view is not limited to two channels) modified to suppress the curvilinear fields at the ends of the equipotential blade. A prolongation of the equipotential blade up to the metal housing, provided the distance between the axis of the end coaxial feed line and the housing be close to a quarter of a wave length, accomplishes this. The structure can now only function over a band of frequencies, the center of which is defined by length of the finger ($\ell = \lambda/4$). The narrower is the finger radially, the larger is the pass band. Experimentally the curvilinear fields disappear in this region and the electric field between the blade and the housing drops gradually to zero in the last one eigth of a wave length distance from the housing.

The coaxial structure described can only have a 0 to 180° phase shift in the fields developped on each side of the blade. The imposed phase shift, between successive electric fields, in a N channel structure is equal to $\pm$ 360°/N. In this way a three blade coaxial antenna (4 channel structure) will impose a $\pm$ 90° phase shift between adjacent fields. However, in order for the fields to have the same amplitude, if the potential of blade 1 is $\sin \omega t$, the potentials that must be assigned to blade 2 and 3 are, respectively, $\sin \omega t + \cos \omega t$ and $\cos \omega t$.

-- TWO CHANNEL COAXIAL ANTENNA --

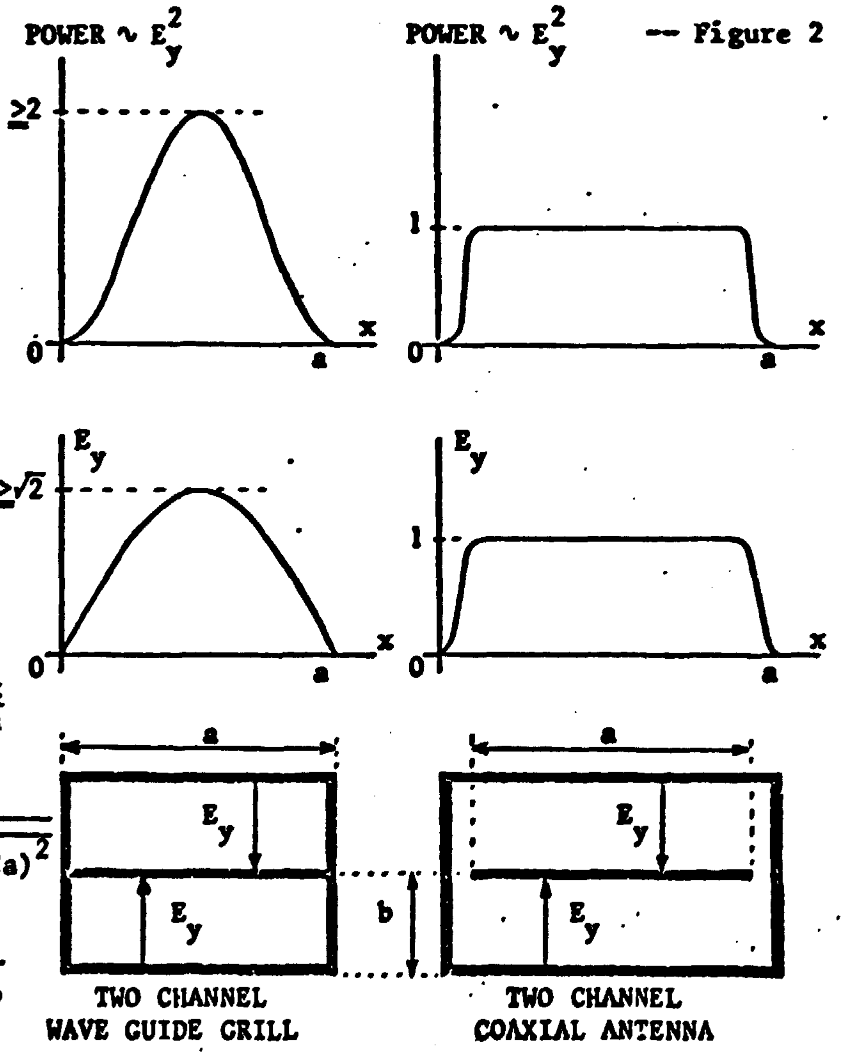


-- Figure 1 --



-- Figure 3 --

-- Figure 2 --



$$E_y = E_o \sin\frac{\pi x}{a}$$

$$H_x = \frac{-E_o}{Z_{TE}} \sin\frac{\pi x}{a}$$

$$H_z = j\frac{E_o}{\eta}\left(\frac{\lambda}{2a}\right)\cos\frac{\pi x}{a}$$

$$Z_{TE} = \frac{\eta}{\sqrt{1-(\lambda/2a)^2}}$$

$$\eta = \sqrt{\mu_o/\varepsilon_o}$$

$$E_y = E_o$$

$$H_x = j\frac{E_o}{\eta}$$

$$Z_c = \frac{b\eta}{2a}$$