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ABSTRACT

Design features of JET A2-antennae including that of remote location of ceramic are outlined. These antennae are being installed in preparation for the new divertor phase of JET that will commence in 1994. The experience of antenna design gained at JET is carried forward to present an outline in blanket/shield design of an antenna for launching fast waves in ITER for heating and current drive. Further, a new wide band antenna the so called "violin antenna" is presented that features high plasma coupling resistance in selected bands in the 20 - 85 MHz frequency range.

1. INTRODUCTION

Ion cyclotron resonance heating antennae that are used to launch fast waves in tokamak plasmas consist of sections of short-circuited strip lines covered by a Faraday screen made of arrays of metal rods. Such antennae have been used for nearly the last two decades with success in plasma heating but the contamination of plasma with additional RF-specific impurity release had been a major concern until 1987. Since then the understanding of the mechanism of impurity release, namely the sputtering caused by the ions accelerated in the field created by rectification in RF sheaths has lead to the following three golden rules to eliminate ICRF specific impurities: (i) use low-Z screen material such as Be (B or C) which has self-sputtering coefficient less than unity, (ii) align the screen rods with the total magnetic field and (iii) use $(0, \pi)$-phasing between the two straps of an antenna. In a less restricted operation of the system, one or more of above rules may be violated, in particular Be-screens allow negligible impurity operation in the current drive phasing for which $\Delta\phi \neq 0$ or π.

A significant contribution has been made by JET in resolving this impurity production problem. The early designs of JET A_{01} and A_{02} antennae (1985 - 86) and the knowledge gained from their operation culminated in the design of A1-antennae having a tilted beryllium screen with two current straps in each antenna so that they can be phased. In conjunction with automated phasing and matching techniques using multiple feedback controls, including that on the antenna-plasma coupling resistance, the ICRH system at JET has become a versatile tool routinely requested by JET operators in a variety of plasma conditions. This has led to new regimes and allowed to maintain high power after transition to advanced confinement regimes. A power of 22 MW for more than 2.5 s to an L-mode plasma and about 3 MW (limited only by in-vessel components) for as long as 1 minute has been coupled to JET plasmas. ICRH produced H-modes, pellet enhanced plasmas (PEP) with H-modes, improved background ion heating in high-minority scenarios, sawteeth control by minority current drive, synergy with the lower hybrid current drive (LHCD) and the high bootstrap current regimes are some of the most notable examples in JET ICRF experiments.

This paper is organised as follows. In Section 2, we present the design features of JET A2-antennae that are being installed for the new divertor phase of JET in 1994. An outline design of fast wave antennae for the next step tokamaks is given in Section 3. In Section 4, we present a new concept of the traditional short-circuited strip line antenna that can operate over a wide frequency band (20 - 85 MHz) which is likely to be required to take full advantage of the fast wave heating and current drive scenarios available for the next step. Discussion and conclusions of this paper are given in Section 5.

2. THE JET A2-ANTENNA

2.1 Background to the A2-Antennae

The so-called A1-antennae have been operating in JET since 1987, originally with water-cooled nickel screens but since 1989 with radiation cooled beryllium screens. These latter screens have demonstrated ICRF operation with negligible impurity production leading to the production of long elm-free H-modes with ICRH alone. A new set of four ICRF antennae structures with four straps each have now been constructed for the pumped divertor phase of JET, in order to maintain good coupling with the much increased distance from the separatrix to the torus wall. These so-called A2-Antennae [1] have several novel features, a number of which are relevant to next step antennae.

2.2 Main Design Features

The A2-antennae have been developed to give good coupling to the new JET divertor plasma for which the separatrix is typically 0.5 m from the low field side vacuum wall. This has enabled the design of a large antenna having a depth to the backwall of typically 0.2 m, which enables efficient coupling with a plasma/screen distance of typically 7 cm. The septa and sidewalls are slotted to a depth of 80 mm in order to minimise the degradation of the spectrum by the image currents, whilst maintaining good isolation between adjacent conductors (measured to be typically 20 dB). A section through this antenna is shown in Fig 1. A typical spectrum of the A2-antenna radiated power in the plasma is shown in Fig 2 for phasing between the straps $\Delta\phi = 0, \pi/2$ and π.

The large projection of the antenna into the torus has the adverse effect that the antenna is very exposed to violent flux changes during disruptions. Design values of 150, 120 and 15 Tesla per second have been used for the vertical, radial, and toroidal fields respectively. At the same time, the maximum load to be supported by the torus was limited to 5 tonnes per antenna side. As a result, the antenna has been fabricated from thin inconel sheet, in the range 0.8 to 3 mm, with a convoluted design which accommodates the consequentially large thermal expansion. Many links to the torus support the antenna against deformation during disruptions. Also, it has been necessary to incorporate resistors in the mounting arms for the screen elements to further reduce disruption forces. These resistors (typically 100 milli-ohm) are formed by nickel plating beryllium oxide substrates. The JET duty cycle 1/60 can be achieved with radiation cooling alone, and no active cooling is provided. These aspects of the design are likely to be peculiar to the particular requirements of the JET pumped divertor. It is to be anticipated that next step devices will have antennae incorporated into, and supported from, the blanket/first wall.

The screen elements themselves are solid beryllium rods 24 mm in diameter, tilted to be parallel to the magnetic field to avoid the formation of RF sheaths and reducing the impurity production. The antennae are protected to the sides by poloidal limiters with graphite or beryllium tiles projecting 17 mm in front of the screen, and to the top and bottom by dedicated carbon fibre tiles projecting 3 mm in front of the screens.

As originally conceived, the current straps were supported from the housing by ceramic tubes. Following extensive high power RF testing, and subsequent mechanical tests, the antennae are being installed in JET without these supports. This gives an assembly which closely simulates a potential

ITER design (see Fig 3) of current strap and vacuum transmission line, where ceramics are precluded by the high neutron flux.

The antennae are mounted in pairs in each quadrant of the torus. The design is such that the four conductors are nearly equispaced in the slim plasma configuration. In the first instance, the antennae will be installed to match the fat plasma, and in this case the spacing between the central two straps is some 50 mm larger. Combined with the slotted sidewalls, this array of straps gives these antennae a good potential fast wave current drive capability [2].

The residual coupling between current straps in such an array complicates the matching of the antennae and reduces the maximum coupled power when operating at other than 0 or 180 degree phase shift between straps. A so-called conjugate matching network is being installed at JET to compensate for this coupling. This may also be an essential aspect of next step designs.

2.3 Current Status of the A2-Antennae

The A2-antennae are presently being prepared for installation in the torus (see Fig 4), which should be complete before the end of 1993. The prototype antenna has been extensively tested [3] in the JET RF test bed up to full voltage (42 kV peak) and duty cycle (60 :1). In addition, critical components such as the resistors and vacuum transmission lines have been individually RF tested. Operation of these antennae should start early in 1994.

3. ANTENNAE FOR NEXT STEP TOKAMAKS

3.1 General Requirements

The design of ICRF antennae for next step tokamaks will have important additional requirements when compared to present generation systems. In particular, the intense neutron flux both restricts the materials which can be used in the antenna and vacuum transmission lines, and imposes critical requirements on the reliability and low maintenance of the system. The antennae must achieve the same low levels of maintenance as required of the blanket. Experience with present systems shows that this can only be achieved by simplification of the designs, in particular in the vacuum transmission lines. Incorporation of the antenna into the blanket, with no independent remote maintenance requirement, with mechanical support/magnetic shielding from the blanket structure and with near line-of-sight access for the transmission lines offers the best potential for achieving this critical requirement.

The antennae are likely to be located near the mid plane for efficient fast wave current drive and must therefore be protected from the local intense alpha particle flux. In addition, there may be substantial erosion of the plasma facing surface due to the intense heat flux during a disruption although experience at JET indicates a net deposition of material on the outer wall. Such erosion would necessitate a remote refurbishing capability. Power dissipation in the antenna becomes dominated by the neutron flux, and efficient active cooling is essential.

The reliability required of the antenna also demands a fail-safe arc detection system. Melting of stainless steel at an arc may result from a few hundreds of joules energy deposition in a system delivering four megawatts to the plasma. This will require further development of back-up protection systems, possibly optically based.

3.2 Outline Designs Based on JET Experience

A conceptual antenna for a next step tokamak based on JET experience has been produced for NET [4]. The basic structure is a helical pipe forming the screen and cooling the housing, in conjunction with a large section current strap of sufficient stiffness to not require insulating supports inside the vacuum window.

An extension of this design has been proposed also for ITER [5] as illustrated in Fig 5. This uses the same basic helical coil structure, but has been increased substantially in length. This enables the use of a so-called 'violin' current strap (see below), with the feeder line connection close to one end. Such a design fits into the proposed blanket with direct line of sight access for the transmission line and no ceramics inside the vacuum vessel. The conductor size is sufficient to water cool the six megawatt dissipation in the lower blanket and may be used for this purpose, with the return via the adjacent antenna.

This antenna design is in a number of respects simulated by the JET A2-antenna. Also shown in Fig 3 is a representation of the A2-antenna with the current straps straightened, drawn to the same scale.

The power dissipations in this antenna have been estimated as in Table 1. The power is dominated by the neutron dissipation, which requires a low residence time of the cooling water in the high flux region. A number of parallel screen cooling loops are therefore required. Stainless steel is anticipated for the current strap and housing, with no surface coating. The increased RF losses are modest (~ 2% of generator power) and do not justify the technical risk of surface coatings.

The critical area of this outline design is the stress in the screen tubes during a disruption. This determines the depth of slotting of the sidewalls and probably requires the use of high strength alloys such as Inconel 718. A low Z material coating (preferably Beryllium) of the plasma facing surface is required and must be repairable in-situ.

4. VIOLIN ANTENNA CONCEPT

A new concept of the traditional short-circuited strip-line antenna [5], the so-called "violin antenna", see Fig 6, is used in which a long strap is connected in parallel with a very short section. The latter acts as a matching element located within the antenna and improves the power coupling capability especially at low frequencies where the plasma coupling is generally poor. The short section also supports the feed-line central conductor. This design is based on a long length (2.6 m) of the shielded strip line antenna (which is possible to accommodate in the next step devices) such that its electric length is quarter-wave long at a low frequency (~ 10 MHz) and becomes multiples of $\lambda/4$ in the frequency range of interest (20 - 85 MHz). The effect of the plasma on the strip line is included by a radiation resistance R_r (Ω/m) which increases with frequency for the fast wave. Plasma effects reduce the inductance of the antenna but this reduction is practically independent of frequency. For ITER-EDA parameters, R_r can be expressed as $R_r(\Omega/m) = R_{ro}(\Omega/m) \cdot \exp(\alpha_f \cdot f(\mathrm{MHz}))$ where $R_{ro} = 2.5\ \Omega/m$ and $\alpha_f = 0.02$.

The antenna coupling resistance R_c is defined as Z_o where Z_o is the characteristic impedance of the feeding line and s is the voltage standing wave ratio in the line. For a long stripline, R_c exhibits multiple resonances when the real part of the antenna input admittance is close to the characteristic admittance of the line ($Y_o = 1/Z_o$). The magnitude of R_c at these peaks increases with frequency since R_r increases with frequency. R_c is smaller at lower frequencies.

The addition of a short (0.4 m) strip line section in parallel with the long one (2.6 m) has the effect of cancelling the reactive part of the input admittance of the long section. This reduces the value of s in the line and increases R_c particularly at certain lower frequencies which can be chosen by selecting the relative lengths of the two sections. The cancellation of the reactive part at higher frequencies becomes weaker and the improvement in R_c is small. This is acceptable as R_c at higher frequency is already significantly high. For an input power of 2 MW, the maximum voltages on the feeder and the antenna straps are shown in Fig 7 in which parameter 'a', the distance of the last closed flux surface of the ITER plasma, is about 0.2 m from the central conductor front surface. It is noted that at the desired frequencies for heating and current drive of ITER: 22 MHz (e-TTMP current drive), 43 MHz (heating at $f = f_{CD}$), 60 MHz (heating and $f = 2\ f_{CT}$) and 75 MHz (minority ion current drive), the maximum voltage in the feeder line $|V_{L\ max}| \leq 20$ kV and that in the antenna $|V_{A\ max}| \leq 35$ kV. The latter would reduce if the plasma is brought closer to the antenna.

At higher frequencies, when the antenna becomes longer than $\lambda/4$, the current flowing on the antenna reverses its sign depending on the number of times the current node appears on the antenna. A study of the radiated power as a functional of the poloidal mode number ($n_y = k_y\ r_A$ where r_A is the minor radius of the antenna location) shows that the radiated power decreases by a factor of about 0.85 in a case when electric length becomes > $\lambda/4$ (22 MHz) as compared to that when the length is < $\lambda/4$ (10 MHz).

5. DISCUSSION AND CONCLUSIONS

As mentioned in the last section, the poloidal length of the violin antenna for ITER is about 3 m. We have neglected the effect of finite length of the antenna which can also affect the reactive part of the antenna impedance. This must also be taken into account in the final design. Modules of 6-strap (see Fig 8) at six locations around the torus that do not block any main horizontal access ports can be used. However, the directivity of such an array for TTMP current drive at 22 MHz suffers, particularly at the low toroidal mode numbers (70 % at $n_\phi = 10$) which are required for efficient current drive. Alternatively, 36 antenna straps can be placed in a row covering a quadrant of the torus. In such a case, the directivity is improved to 90 % at $n_\phi = 10$ and it is 98 % at $n_\phi = 20$. The power per strap can be used in the range of 2.5 - 4 MW for maximum voltages in the line of 30 kV. It is preferable to locate the antennae centred on the mid plane as otherwise the current drive efficiency decreases due to $k_{||}$-upshift due to poloidal field effects. When the toroidal field and the plasma currents are co-directional, the antenna located about 1.8 m below the mid plane suffers a degradation in current drive efficiency by a factor of 0.65 as compared to that at the mid plane.

The implementation of ICRF antenna on next step tokamaks is well based on present technology. Nonetheless, technical developments are required in a number of areas, most notably beryllium coating technology, arc protection, and alpha particle limiters. If materials other than water cooled nickel alloys are imposed to minimise active waste, much further understanding of alternative materials is required, but this would parallel similar first wall and blanket studies. Much detailed design needs to be undertaken on the basis of existing technology with regard to stresses in the screen structure, cooling, selection of materials, optimisation of the spectrum and location in the torus, and realisation of 4 MW windows. The technology of ICRF antennae is nonetheless in good state to enable the implementation of such equipment in next step devices.

In conclusion, a viable outline proposal of fast wave antenna for ITER has been discussed. The violin antenna concept allows operation at a number of frequencies in a wide band (20 - 85 MHz) and dispenses with the need of a ceramic in the immediate vicinity of the antenna that will be subjected to a harsh neutron environment in a reactor. The use of continuous tubular helices that surround the central conductor forming the water cooled screen (without any welding joints facing the plasma) and the cooled housing represents a feasible technical design of the antenna. The water cooling channels through the central conductor itself reduce the number of pipes near the antenna. The neutron shielding properties of water in the cooling system of the antenna screen and that of the central conductor can be optimised and used to advantage for recovering some of the loss of shielding due to the antenna placement.

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Table 1

	MW
RF Losses	0.09
Plasma Radiation	0.42
Neutron Dissipation	0.60
Total Power Losses	1.1

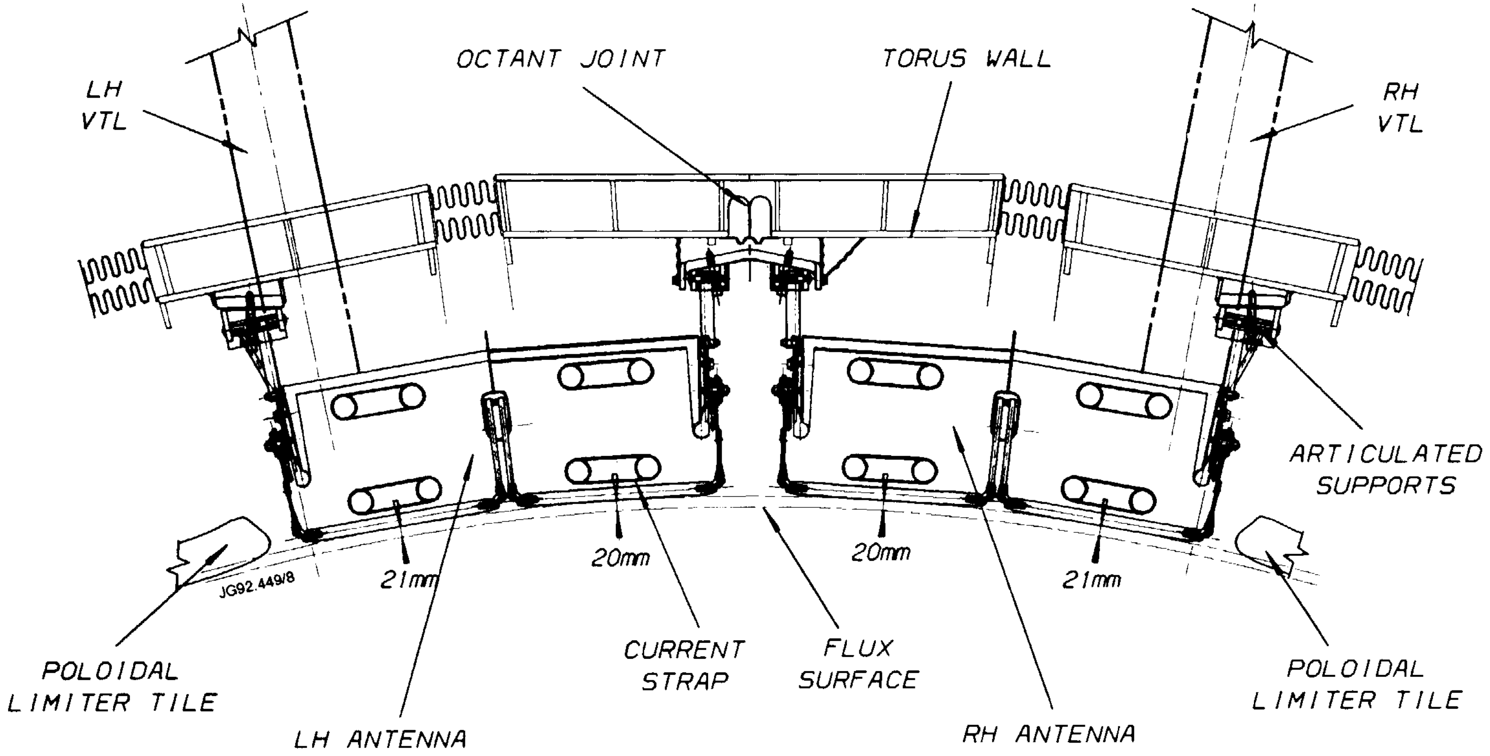

Fig 1. A horizontal section through a pair of the JET A2-antenna as installed in the torus.

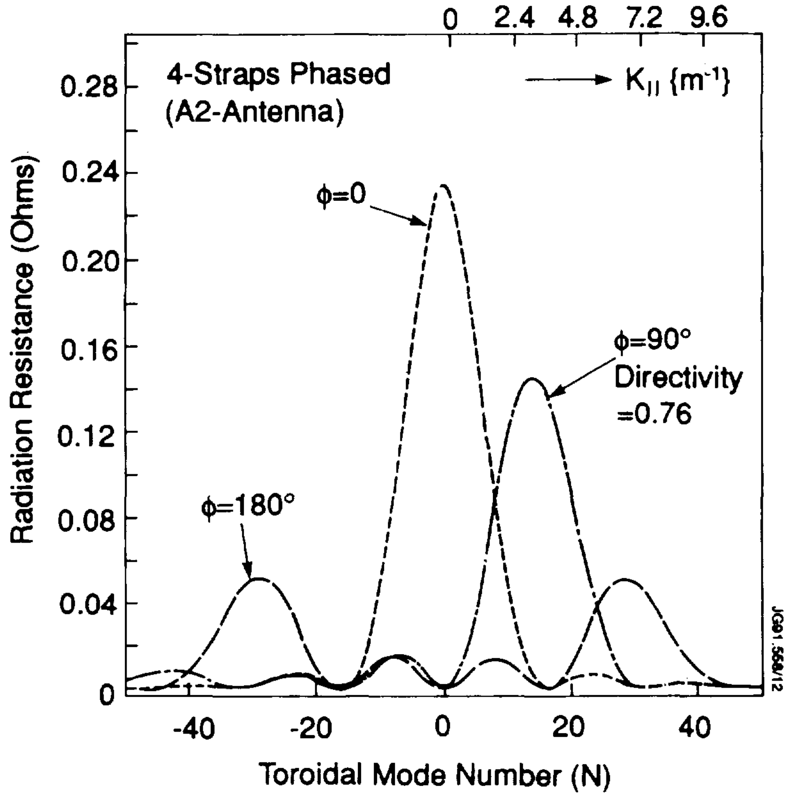

Fig 2. Typical computed radiated power spectrum in the plasma for 4-strap A2-antenna with a phase shift $\Delta\phi$ = 0,90° and 180°.

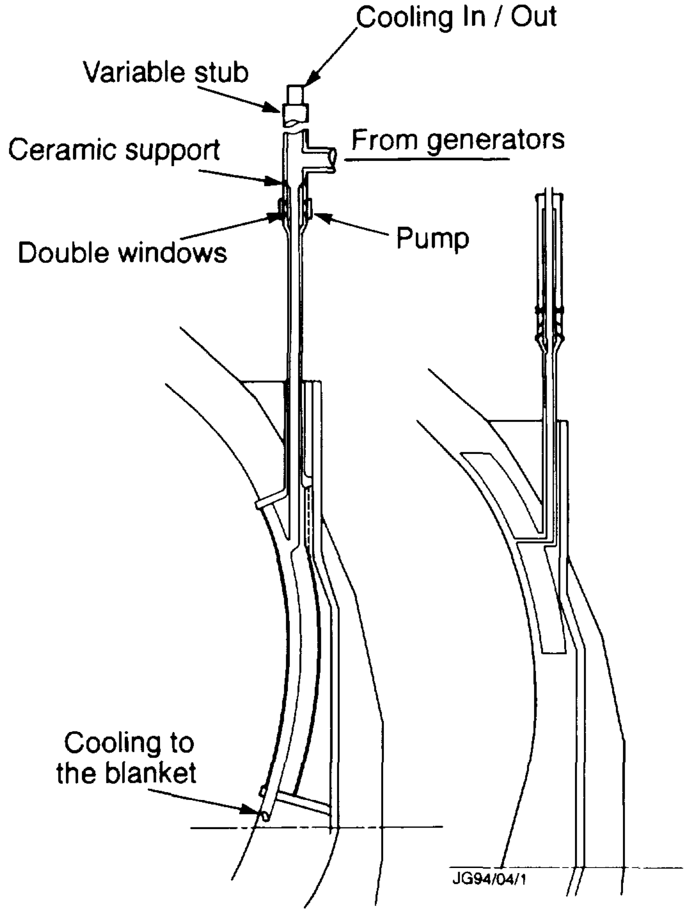

Fig 3. A poloidal view of a proposed "violin antenna" for ITER, together with a stylised view (distorted to allow a dimensional comparison) of the JET A2-antenna to the same scale.

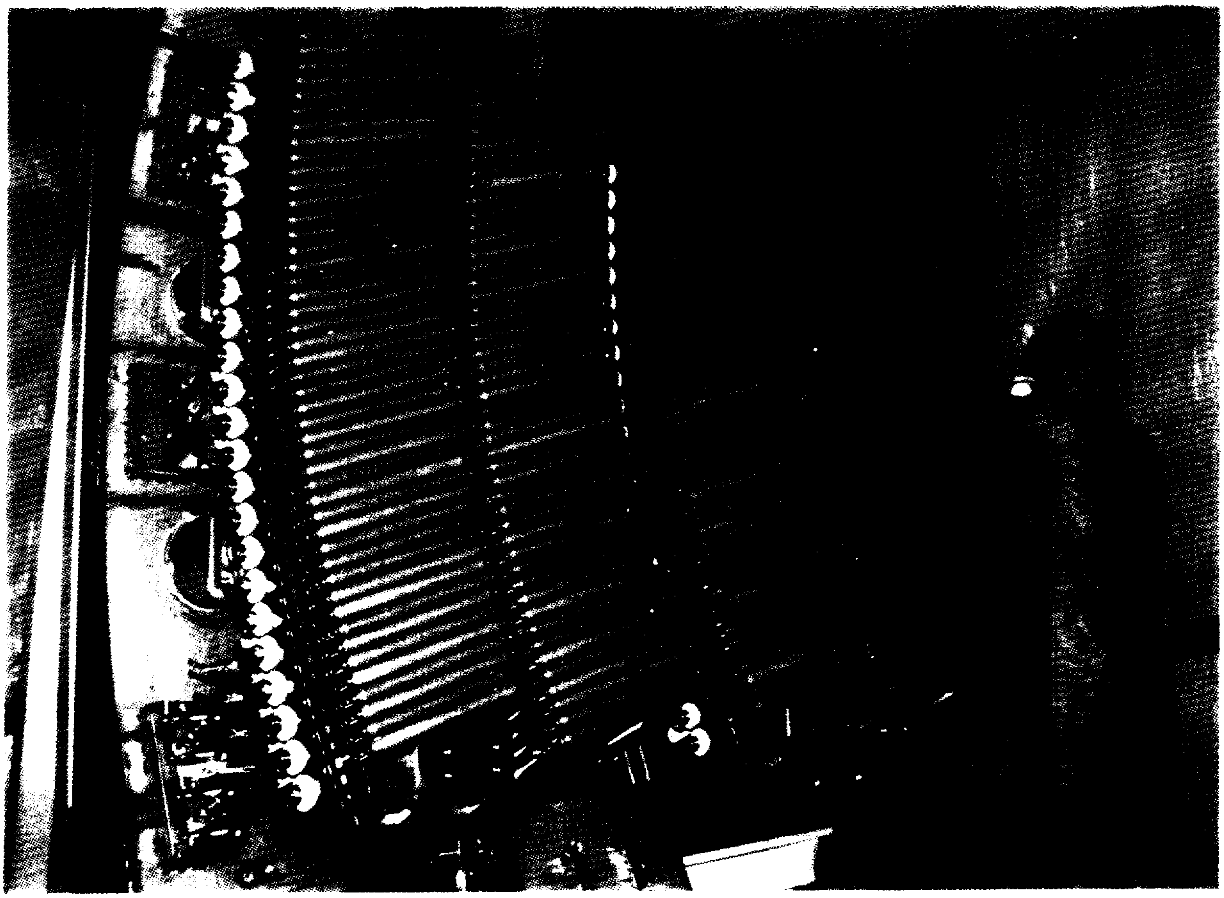

Fig 4. A photograph of a JET 4-strap A2-antenna with Be screen prepared for installation in the torus.

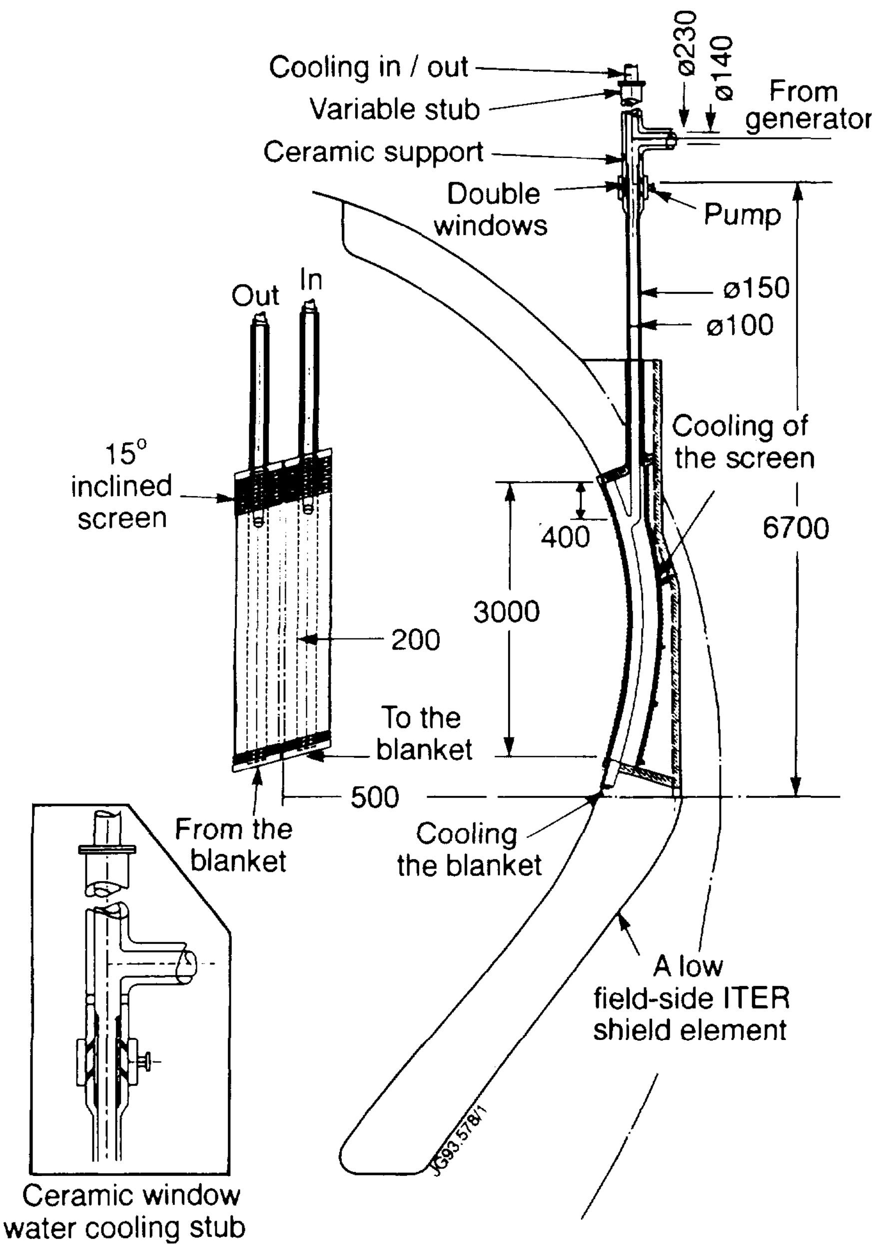

Fig 5: A poloidal section of the "violin antenna" integrated into the low field side ITER first wall/shield blanket. Inset shows a stub through which water cooling is introduced via the central conductor.

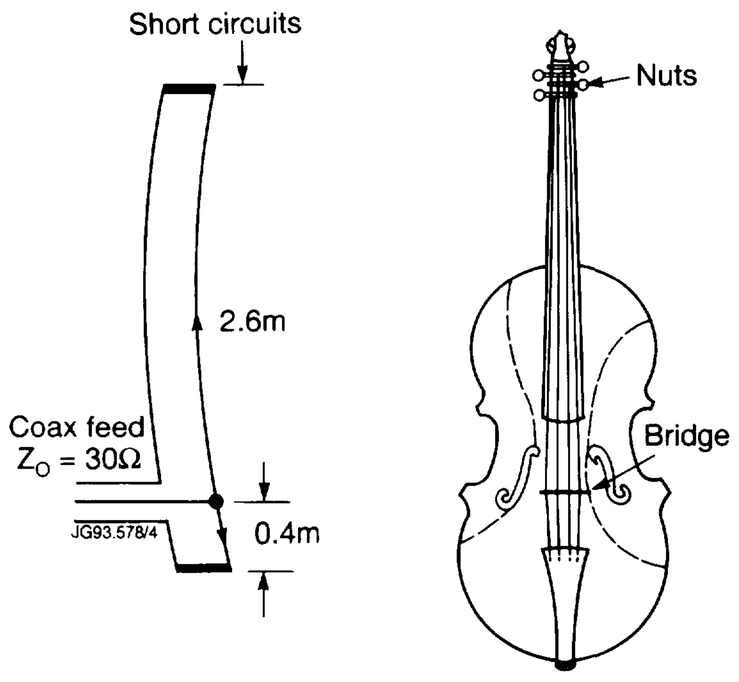

Fig 6: A schematic of the asymmetrically excited multiple resonance wide band antenna, the so-called "violin antenna".

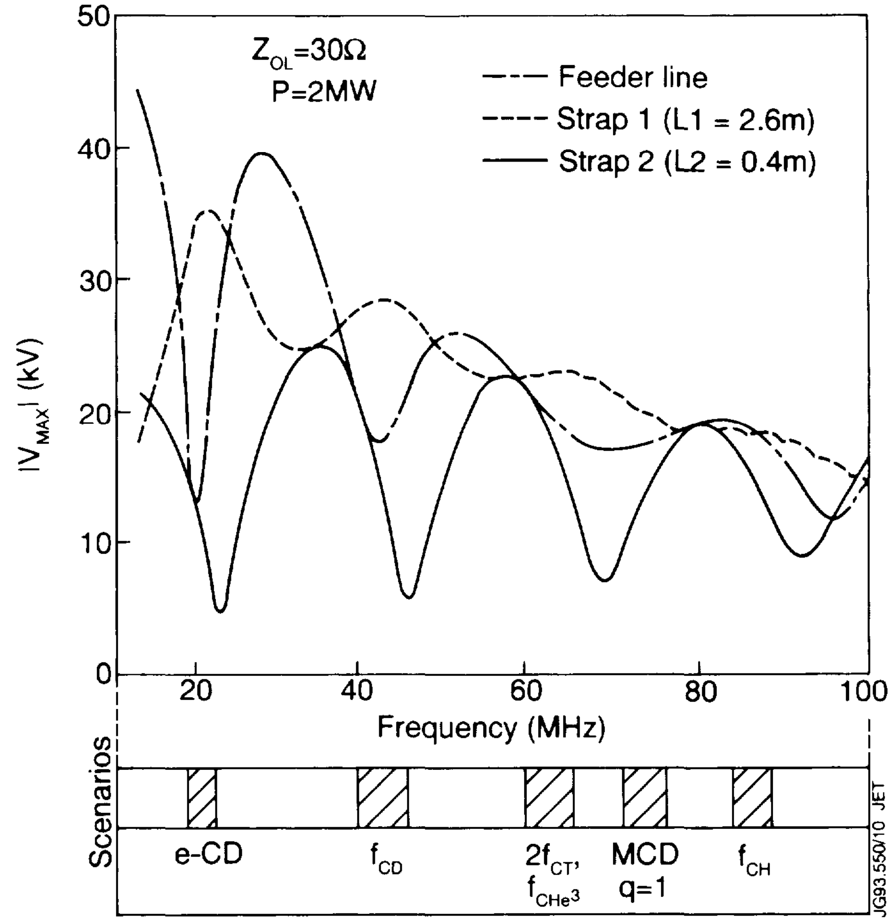

Fig 7: Magnitude of the maximum voltage in the feeder line and the two sections of the strip line "violin antenna" is plotted as a function of frequency. The shaded areas show the frequency bands of the fast wave scenarios of ITER-EDA.

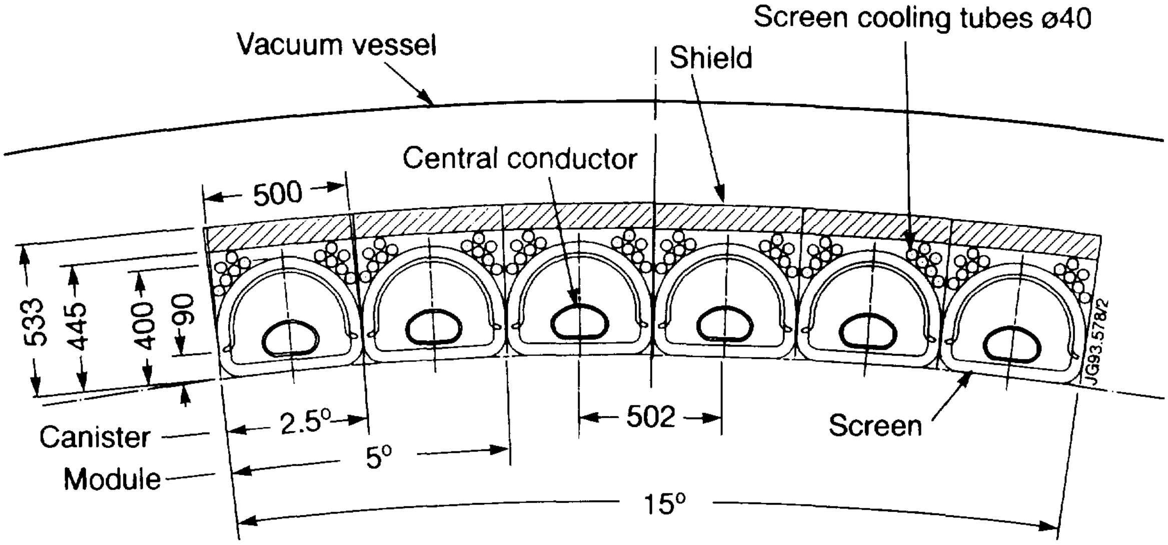

Fig 8: A plan view of a 6-strap version of the fast wave antenna for ITER-EDA.