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# Expanding the Operating Space of ICRF on JET with a View to ITER



# The Effect of Field Reversal on the JET MkIIIGB-SRP Divertor

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## **ABSTRACT.**

The paper reports on ITER-relevant ICRF physics investigated on JET in 2003 and early 2004: minority heating of  $^3\text{He}$  and D in H plasmas, minority heating of tritium in D, investigations of finite Larmor radius effects on the RF-induced high-energy tails, and new results on the heating efficiency of ICRF antenna arrays. Studies of the ELMs using fast RF measurements, experimental demonstration of a new ELM-tolerant antenna matching scheme, and technical enhancements planned on the JET ICRF system for 2005, themselves likewise strongly driven by the preparation for ITER, are also summarized.

## **1. INTRODUCTION**

The size and capability of the Joint European Torus (JET) to confine very energetic particles, together with its versatile Ion Cyclotron Resonance Frequency (ICRF) system, provide a unique environment to develop ICRF techniques relevant to the Next Step. During the JET experimental campaigns of 2003 and early 2004, in addition to further development of ICRF as a tool for the experimental programme, several heating and current drive scenarios have been investigated, contributing to the physics understanding and operational expertise required for successful use of ICRF on ITER. The following sections focus on these advances. Three hitherto scarcely documented ‘inverted’ minority heating scenarios, in which the minority ions have a smaller charge to mass ratio than the majority ones, have received special attention: ICRF heating of helium three ( $^3\text{He}$ ) and Deuterium (D) in Hydrogen (H) plasmas, which are the scenarios planned for the start-up phase of ITER (Section 2), and minority heating of Tritium (T), which would be an attractive scenario when ITER starts using T (Section 3). Investigations of finite Larmor radius effects on the RF-induced high-energy tails are summarized in Section 4, and new results on the heating efficiency of ICRF antenna arrays in Section 5. Two sections of a more technical nature follow: studies of the ELMs using fast RF measurements, and experimental demonstration of a new ELM-tolerant antenna matching scheme. Finally, Section 8 presents the technical enhancements planned on the JET ICRF system, themselves likewise strongly driven by the preparation for ITER.

## **2. ICRF HEATING IN HYDROGEN PLASMAS**

In the start-up phase of ITER, activation will at first be minimized by operating in H plasmas. The two reference ICRF scenarios, referred to as ( $^3\text{He}$ )H and (D)H, rely on heating minority  $^3\text{He}$  or D ions at their fundamental cyclotron frequency. In the past very few experiments have been dedicated to these scenarios [1], in which a cut-off of the fast magnetosonic wave occurs on the antenna side of the minority fundamental cyclotron layer. The heating of  $^3\text{He}$  in H has now been explored in a sequence of JET discharges at magnetic fields between 3.3 and 3.6T and a plasma current of 2 MA. The ICRF power was applied at 37 MHz, which positions the cyclotron resonance layer  $\omega=\omega_c^{^3\text{He}}$  centrally. The experiments systematically used ICRF power modulation at a frequency of 20 Hz at the beginning and the end of the power flat-top (see Fig.1), allowing evaluation of the radial profiles of direct wave

absorption by the electrons by means of Fast Fourier Transform (FFT) and Break-In-Slope (BIS) analysis [2, 3] of the electron temperature response. The  $^3\text{He}$  concentration  $[^3\text{He}] = n^3\text{He} / n_e$  was varied from below 1% up to 10%. The expertise developed at JET to estimate and control  $[^3\text{He}]$  in real time [3] was put to full use and levels as low as 1.8% were successfully controlled for the first time. Lower  $[^3\text{He}]$  were obtained by  $^3\text{He}$  gas puffing before the ICRF heating phase.

The minority heating regime was observed at low concentrations (up to ~2%). Presence of a fast  $^3\text{He}$  ion population was detected by (i) its contribution to the neutron rate through the nuclear reaction  $^9\text{Be}(^3\text{He},n)^{11}\text{C}$ ; (ii) gamma-ray spectrometry [4] based upon nuclear reactions between energetic  $^3\text{He}$ ,  $^9\text{Be}$  and  $^{12}\text{C}$  impurities, and (iii) low- and high-energy Neutral Particle Analysis (NPA) [5]. Figure 1 shows three discharges with  $[^3\text{He}] < 1\%$  and 5MW of ICRF in different A2 antenna phasings [6]: dipole ( $0\pi/0\pi$ ) launches waves with a symmetric toroidal spectrum;  $+90^\circ$  and  $-90^\circ$  progressive phasings launch dominantly co- and counter-current waves, respectively. A maximum electron temperature of 6.2 keV was reached with  $+90^\circ$ . Higher neutron rate, fast  $^3\text{He}$  energy content, NPA flux and  $\gamma$ -ray emissivity are obtained with  $+90^\circ$  than with matching discharges in the other phasings. Such behaviour can be explained in terms of an inward fast ion orbit pinch produced by the  $+90^\circ$  wave spectrum [7, 8], for which multiple evidence has previously been accumulated in phased ICRF experiments on JET.

As  $(^3\text{He})$  was increased above 2%, a sudden transition was reproducibly observed to the Mode Conversion (MC) regime, in which the ICRF fast wave couples to a short wavelength mode, leading to efficient direct electron heating. The first indication of a change in the heating regime was the disappearance of the fast  $^3\text{He}$  population. The related changes in  $\gamma$ -ray emission, for which the threshold  $^3\text{He}$  energy is 0.9MeV, are shown on Fig.2 for three discharges differing only by their  $(^3\text{He})$ . In Pulse No: 63319 with  $(^3\text{He}) < 1.8\%$  a high signal was collected throughout. In Pulse No: 63320, as  $(^3\text{He})$  increased above 2% at around 6.3s, the  $\gamma$ -ray signal began to decrease to finally disappear. In Pulse No: 63324, almost no signal was collected. Moreover, as  $(^3\text{He})$  increased, the temperature response to the ICRF power modulation gradually changed, indicating a change in power deposition. In the MH regime, electron heating takes place indirectly by collisions with fast ions and the period of the ICRF power modulation (0.05s) associated with an estimated fast  $^3\text{He}$  slowing- down time of about 0.2s prevented observation of a clearcut  $T_e$  response. In contrast, electron heating in the mode conversion regime takes place directly by wave Landau damping and a prompt  $T_e$  response was observed. The transition to the MC regime was also confirmed by the FFT and BIS analyses which showed the appearance of a narrow electron power deposition profile at the estimated location of the ion-ion hybrid layer. Figure 3 presents an overview of two discharges in the MC regime ( $(^3\text{He}) \sim 3.5\%$ ) with dipole and  $+90^\circ$  phasing. In order to maximize the central  $T_e$ , the toroidal field was lowered to 3.3T, positioning the ion-ion hybrid layer at around 2.9m. A maximum temperature of 8keV was obtained with dipole phasing. A comparative code analysis of the two discharges is under way to confirm the difference in dominant  $k_{\parallel}$  as the origin of the higher temperature obtained in dipole.

In strong contrast with  $^3\text{He}$ , the use of D minority heating in hydrogen plasmas was not successful. This is attributed to the  $\text{C}^{6+}$  impurity (and contributions from any other impurity with  $Z/A=1/2$ ), which has the same cyclotron layer as D, thus influencing wave propagation like a much higher equivalent D concentration. Presence of carbon at levels of 1 to 2% directly leads into the mode conversion regime or even expels the mode conversion layer from the plasma. This effect virtually rules out the (D)H scenario, leaving ( $^3\text{He}$ )H as the only viable scenario for the non-active phase of ITER.

### 3. MINORITY HEATING OF TRITIUM

Plasmas with low tritium concentration will occur when ITER starts using T. ICRF minority heating of T at its fundamental cyclotron frequency ( $\omega = \omega_{cT}$ ) is a physically attractive though technically challenging heating scenario. Although currently outside the ITER RF system frequency range, it would be quite relevant during its operation at low to moderate T concentrations. It was first very briefly investigated during the JET DTE1 experimental campaign of 1997 [9, 10] with  $\sim 5\%$  T and on TFTR [9] with up to 20% T. On JET it requires the highest equilibrium magnetic fields ( $B_0 = 3.9$  to 4T) and the lowest available generator frequency ( $\sim 23\text{MHz}$ ), at which only modest levels of ICRF power  $\sim 1.5\text{MW}$  are available.

It has now been intensively studied at low concentrations in D plasmas during the Trace Tritium Experimental (TTE) campaign [11, 12, 13], in which T was introduced in the discharge by gas puffs resulting in concentrations up to  $\sim 3\%$  (in a few discharges neutral beam T injection was used instead). Energetic T tails of 80 to 120keV were observed, close to the maximum of the D-T reaction rate, boosting the D-T neutron yield by direct T acceleration, and simultaneously providing good bulk electron heating. The moderate triton tail energies also provide good ion heating (off-axis in the JET configuration). This confirms the scenario as an attractive heating scheme at low concentration. Its possible incorporation in the ITER ICRF design should be revisited after further experiments at intermediate T concentrations, e.g. during a full D-T campaign on JET. Detailed interpretation and modelling of the TTE ICRF experiments benefit from the neutron and gamma ray emissivity data, which allow interesting code benchmarks and enhancements. Fig. 5 shows the good agreement found between the High-Field-Side (HFS) peaking of the 2D neutron emissivity profile and the corresponding fast triton midplane density simulated with the SELFO code [14], which also correctly estimates the experimental neutron yield and T tail temperature.

### 4. FINITE LARMOR RADIUS (FLR) EFFECTS ON THE ICRH MINORITY ION TAILS

Wave absorption at the second ion cyclotron harmonic ( $\omega = 2\omega_c$ ) depends on the ratio of the particle Larmor radius to the wavelength. Theory predicts a maximum absorption when this ratio increases to  $\sim 0.5$ , followed by a decrease to much smaller levels at higher ratios. This behaviour defines a characteristic particle energy  $E^*$  at which the RF quasilinear diffusion coefficient has a first minimum. This absorption-free region acts as a barrier preventing particles from reaching higher energies.

Minority hydrogen ions were heated at their second cyclotron harmonic with 3 to 5MW of ICRF (51MHz, dipole phasing) in 1.65T, 1.65MA JET deuterium discharges with central electron densities between  $3$  and  $4 \times 10^{19} \text{ m}^{-3}$  (i.e. different wavelengths). Fast hydrogen energy distributions were measured with a high-energy Neutral Particle Analyzer (NPA) [15]. Figure 6 shows that, at similar heating powers per particle and Stix effective H tail temperatures  $T_{\text{eff}}$ , a higher plasma density yields a less energetic H tail with a lower local temperature. This provides clear evidence that FLR effects play an important role in determining the shape of the high energy part of the distribution. FIDO [16] code simulations are in good agreement with these measurements [17]. Note that this type of experiment requires confining protons in the MeV range and can thus only be performed on JET.

## 5. NEW INVESTIGATIONS OF THE ICRF HEATING EFFICIENCY

Several L-mode discharges at  $B_T = 2.7\text{T}$ ,  $I_p = 2$  and  $2.8\text{MA}$  were compared to further investigate the behaviour of the core plasma heating efficiency  $\eta$  of the A2 ICRF antennas [18]. As well known, this quantity is maximum in toroidal dipole phasing of the straps ( $0\pi 0\pi$ ), but about half as much in monopole (0000) despite the much higher antenna loading [19]. ICRF power ramps up to 8MW in monopole and dipole, using minority heating of hydrogen at 42MHz, confirmed the earlier observations. Moreover, analysis of the plasma energy content and of the minority fast ion tails measured by the NPA showed that the poor core heating was not due to an increase of transport. The measured thermal and non-thermal contributions to the plasma diamagnetic energy were compared with code simulations. Agreement was found between the time evolutions after assuming a 50% reduction of the coupled monopole power in the simulations. Other experiments were carried out in which only part of each A2 array was fed. Interestingly, antennas with only one or two active in-phase straps heated the plasma with an efficiency 1.5 times higher than the standard monopole antenna with four active straps. In all cases the coupling resistance remained 1.5-2 times higher in monopole than in dipole throughout the discharges.

These results, as well as independent evidence derived from fast wave heating and current drive experiments in internal transport barrier plasmas, confirm the strong dependence of  $\eta$  on the radiated parallel wavenumber spectrum of the antenna and are consistent with parasitic ICRF absorption by RF sheath voltage rectification [20]. This is further supported by the fact that the fraction of the ICRF coupled power not accounted for in the core is neither detected in the measured radiation nor in the divertor heat loss channels. Finally, the RF power absorbed in the plasma core is comparable with the estimated wave single pass absorption, both in monopole and dipole. This gives hope that monopole heating might prove a viable option on ITER, where the single pass absorption for this phasing is large. Validation of this conjecture would make operation at the associated higher antenna loading very attractive.

## 6. COUPLING STUDIES DURING ELMS

ELM-resolved RF measurements on the ICRH antennas provide invaluable data to estimate the

performance of future launchers [21]. Systematic observations of the perturbations of RF signals associated with the rise of type I ELMs have shown that these perturbations propagate in the counter-current direction (the same direction as the electron diamagnetic drift), in agreement with the fast magnetic measurements. Typical toroidal velocities  $\sim 200\text{km/s}$  (generally between 50 and 1200km/s) are observed, corresponding to a toroidal period  $\sim 120\mu\text{s}$ . The highest measured velocities were observed with low density discharges.

Therefore for most of the observed ELMs, the delays between the antenna straps situated in the same toroidal octant should have marginal or negligible effect on the operation of the compensation networks of the ELM-resilient ICRF systems described in the next Sections.

## **7. ELM TOLERANT MATCHING PROOF OF PRINCIPLE**

A prototype ELM-tolerant ICRF antenna matching system has been successfully tested at JET [22]. The technique is based on the same principle as proposed for ITER [23], but uses a matching circuit tuned to a low reference impedance by coaxial line stretchers outside the tokamak vacuum vessel, like the alternative ITER ICRF design option proposed in [24]. Further impedance transformation to the main power transmission line is achieved by a conventional variable stub and trombone tuner. The experimental setup involved one pair of adjacent straps of the A2 antenna array powered by a single RF amplifier. The tests fully confirm the feasibility of the matching scheme. Clear evidence of high load tolerance was observed during plasma sawtooth activity and ELMs, see Fig.7. Reliable trip-free performance was demonstrated from 32 to 51MHz at 1MW power levels. This approach appears a viable alternative to in-vessel matching schemes and offers additional advantages such as exclusive reliance on well-established coaxial line technology, manageable tuning accuracy requirements, separation of launching and matching sub-systems, and capability to conjugate remote antenna straps.

## **8. THE ITER-LIKE ANTENNA FOR JET**

A major JET enhancement is under way with the scheduled installation of an additional ITER-like ICRF antenna in 2005 [25], which will be a key test of the ITER concept. It aims at validating novel antenna design principles in conditions as relevant as possible to ITER by coupling  $\sim 7.2\text{MW}$  to ELMy H-mode plasmas in a frequency range from 30 to 55MHz. The high power density (about  $8\text{MW/m}^2$ ) is maximized for a given maximum voltage in the circuit by using poloidally short straps, and the resilience to fast varying RF loads by matching pairs of straps in so-called conjugate-T circuits. This is accompanied by the addition of 3dB hybrid couplers in the transmission systems of two of the four existing antennas. Both measures will also provide additional power for a wide range of JET plasma conditions, in particular at low frequency (minority heating of  $^3\text{He}$ , second harmonic heating of T, relevant to a future D-T campaign), and in presence of ELMs, further expanding the relevance of the JET ICRF system for ITER.

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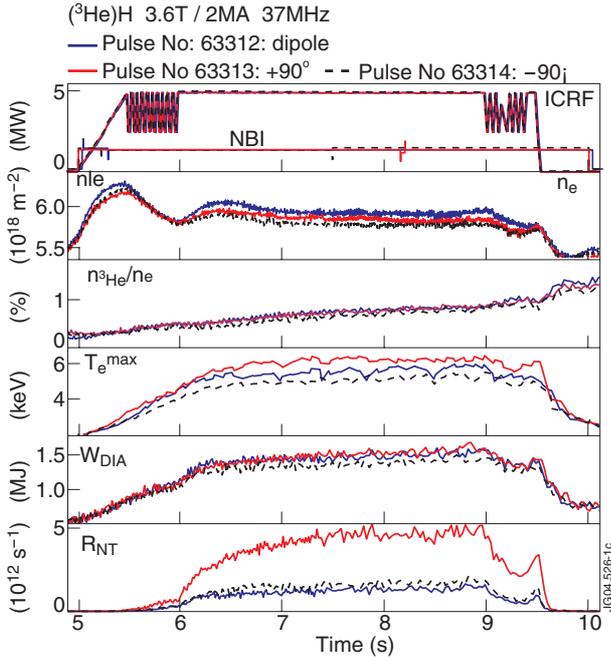


Figure 1:  $(^3\text{He})\text{H}$  minority heating at  $(^3\text{He}) < 1\%$  with dipole,  $+90^\circ$  and  $-90^\circ$  antenna phasings (resp. red, blue, green). Note the much higher neutron yield RNT achieved with  $+90^\circ$ .

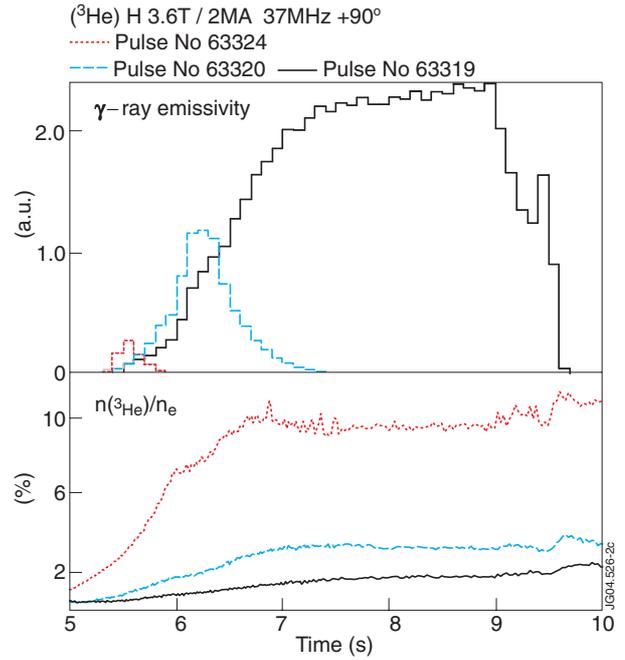


Figure 2: Time evolution of the  $\gamma$ -ray emissivity and  $^3\text{He}$  concentration for three discharge, demonstrating disappearance of the fast  $^3\text{He}$  population as  $(^3\text{He})$  was increased above 2%

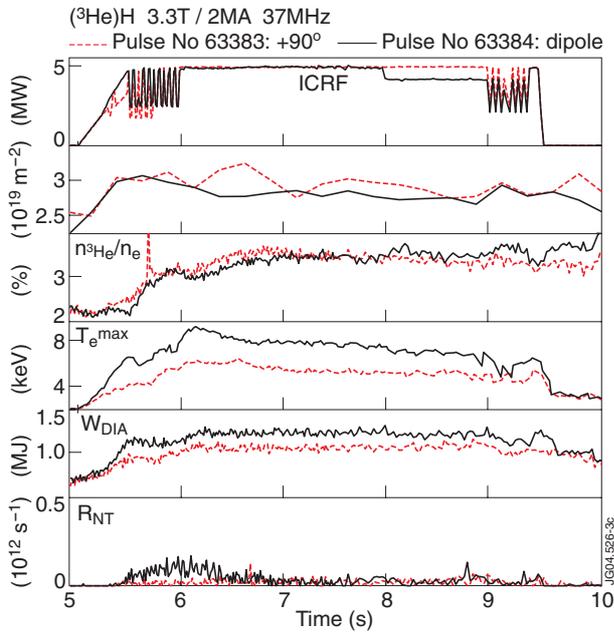


Figure 3: Mode conversion heating regime with  $2 < (^3\text{He}) < 4\%$ , dipole (blue) and  $+90^\circ$  (red) phasings. The ion-ion hybrid layer is located at  $R \approx 2.9\text{m}$ .

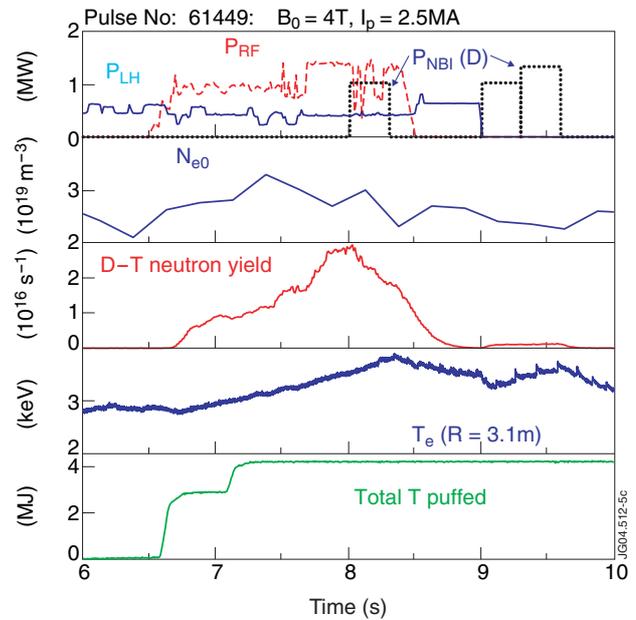


Figure 4: Fundamental ICRF heating of minority  $T$  introduced by gas puff (23MHz, 4T). Maximum neutron yield  $2.9 \cdot 10^{16}/\text{s}$ , maximum coupled RF power 1.4MW.

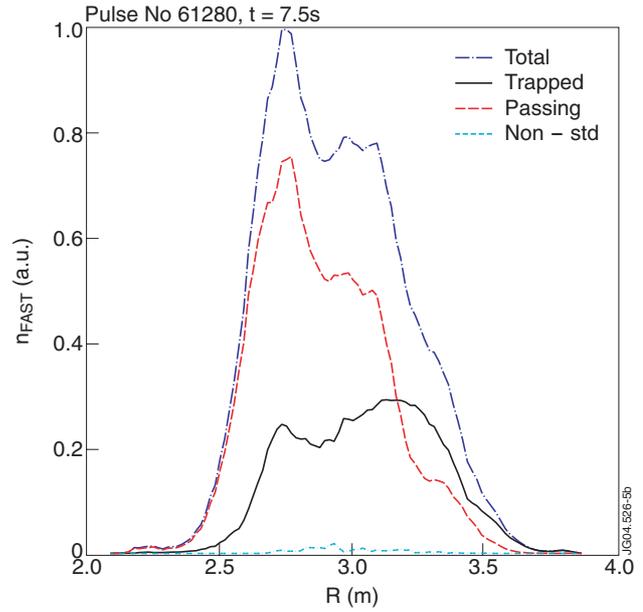
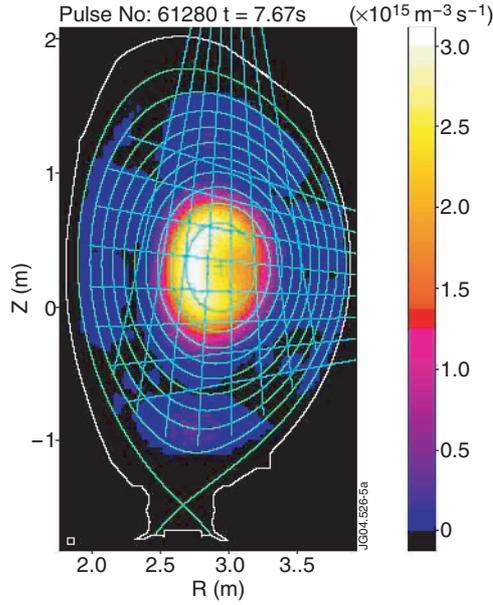


Figure 5: Left:  $D-T$  neutron emissivity profile at  $t=7.7s$  for  $(T)D$  ICRF heating (dipole phasing,  $23MHz$ ). Right: fast ( $E>50keV$ ) triton midplane density simulated with the SELFO code for the same discharge (Pulse No: 61280), showing contributions from passing, trapped and non-standard orbits. The majority of  $D-T$  neutrons originate from passing tritons. Their higher density on the HFS of the magnetic axis is due to the longer time spent there, and is in good agreement with the observed neutron profile.

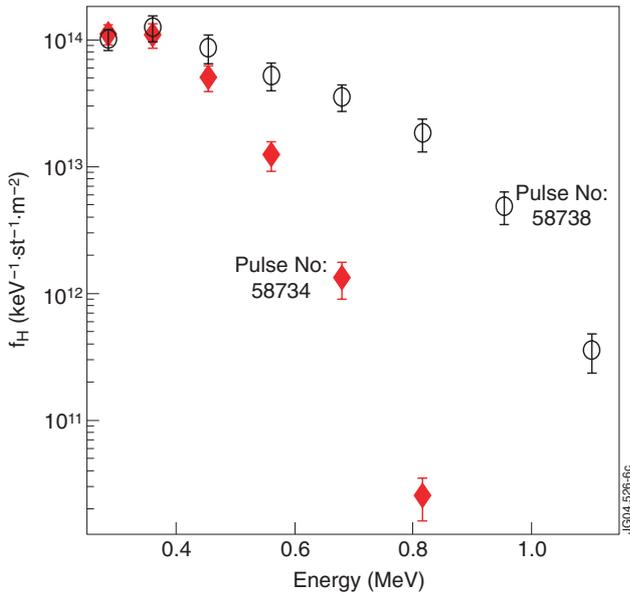


Figure 6: Perpendicular proton energy distributions measured with the NPA. Pulse No's: 8734 and 58738 respectively have  $P_{RF} = 5$  and  $3MW$ ,  $N_{e0} = 4$  and  $3 \times 10^{19} m^{-3}$ , similar absorbed powers per particle and effective Stix tail temperatures.

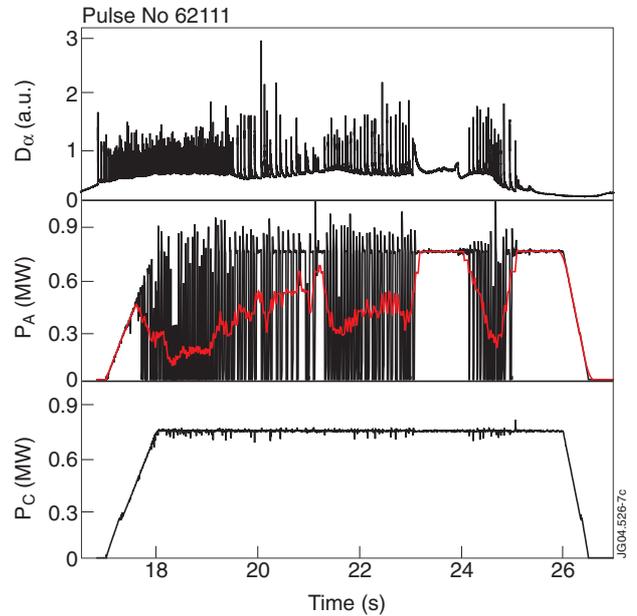


Figure 7: ICRF coupling to an ELMy plasma, showing powers  $P_A$  from standard A2 antenna and  $P_C$  from half antenna equipped with prototype load resilient external conjugate T system.

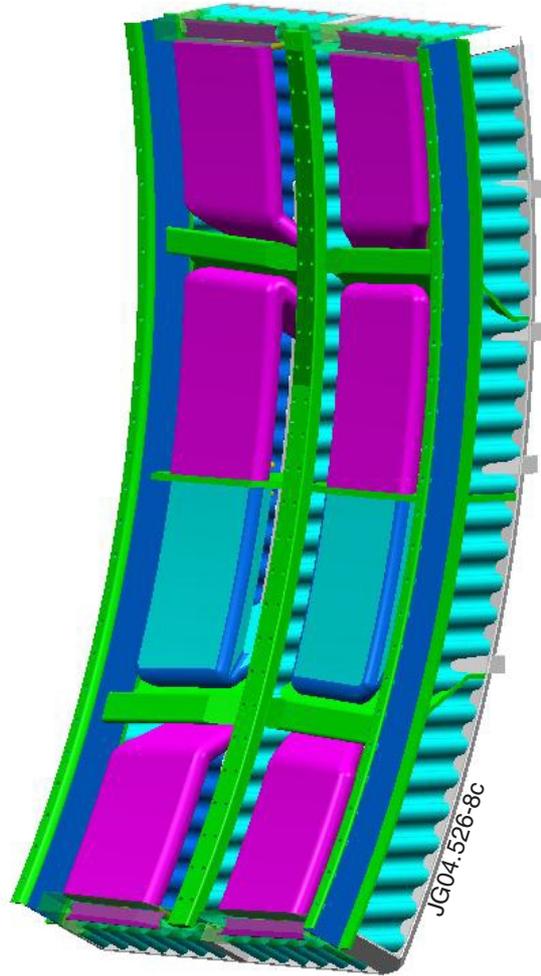


Figure 8: The JET ITER-like ICRF antenna.