High Fusion Performance ICRF-Heated Plasmas in JET

G A Cottrell, B Balet, L G Eriksson, C Gormezano, J Jacquinot.

JET Joint Undertaking, Abingdon, Oxon, OX14 3EA.

HIGH FUSION PERFORMANCE ICRF-HEATED PLASMAS IN JET

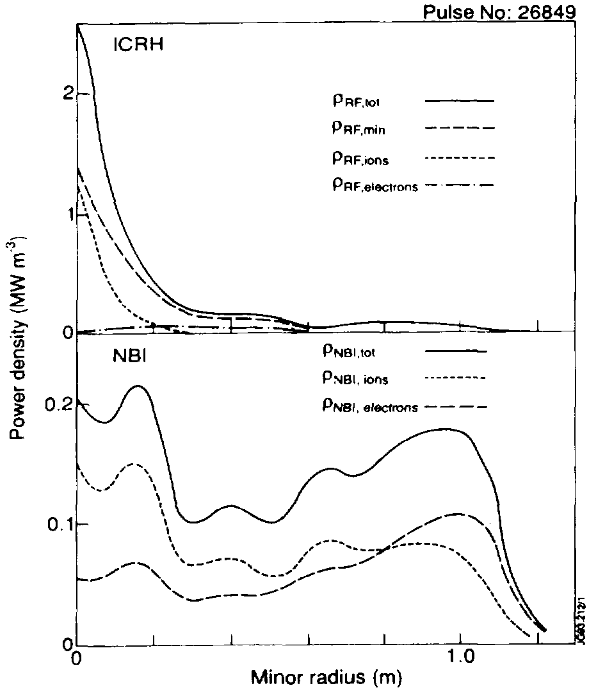
G.A.Cottrell, B.Balet, L.-G. Eriksson, C.Gormezano and J.Jacquinot
JET Joint Undertaking, Abingdon, Oxfordshire, OX14 3EA, United Kingdom

Introduction. The aim of this paper is to predict the fusion power P_{fus} of ICRF-heated DT plasmas on JET. A long-pulse high fusion energy scenario would use a high density, strongly radiating divertor plasma. A possible high Q tritium experiment (where $Q \equiv P_{fus}/P_{add}$, and P_{add} is the additional heating power) would be a hot-ion H-mode, similar to the preliminary tritium experiment (PTE) /1/, but with a 50:50 DT mixture. The predictions are based on simulated JET deuterium discharges which can be extrapolated to DT mixtures. It is also possible to assess conceptual reactor scenarios on the route to ignition, such as the use of enhanced reactivity from ICRF heating of minority deuterons in tritium - the (D)T scheme - or the pellet enhanced performance (PEP) mode /2/. The TRANSP simulation and transport code /3/ is used to solve the time-dependant equilibrium and magnetic field diffusion equations, infer directly the local transport coefficients, determine the origin of the measured neutron fluxes and predict equivalent DT performance. The total ICRF power deposition profile ($\rho_{RF,tot}$) is obtained with a reduced order full-wave model - SPRUCE /4/ - which computes the RF power densities damped on minority ions ($\rho_{RF,min}$), second harmonic damping on the ions ($\rho_{RF,ions}$), direct damping on the electrons ($\rho_{RF,electrons}$) and mode conversion. The energetic minority ion tail and its collisional heating rates with the electrons and ions are described using a bounce-averaged Fokker-Planck model - FPPRF /5/. When a significant deuterium tail is produced by second harmonic acceleration, its non-thermal reactivity can be estimated independently using the self-consistent PION code /6/. The diagnostic data is checked, initially, using TRANSP to simulate the measured diamagnetic stored energy, total neutron flux, and surface voltage. The equivalent DT fusion performance is then assessed by replacing D with a given DT mixture.

High Density ICRH and NBI Discharges. A high density 2.8 MA X-point discharge is JET pulse No. 26849 (Table I) with NBI and (H)D ICRF heating. This discharge has low values of effective plasma charge $Z_{eff} \sim 1.4$ and stable conditions (for several seconds) up to the end of the heating pulse.

Table I. Plasma Parameters of Selected High Performance Discharges

Pulse No.	P_{NBI} (MW)	P_{ICRF} (MW)	n_{e0} (10^{19} m^{-3})	T_{e0} (keV)	T_{i0} (keV)	R_{NT}(10^{16} s^{-1})
26849	12	10	7.5	≈ 6	≈ 6.5	0.8
26038	15	0	3.5	9.6	24	3.0
26043	15	2	3.2	11.4	26	3.9



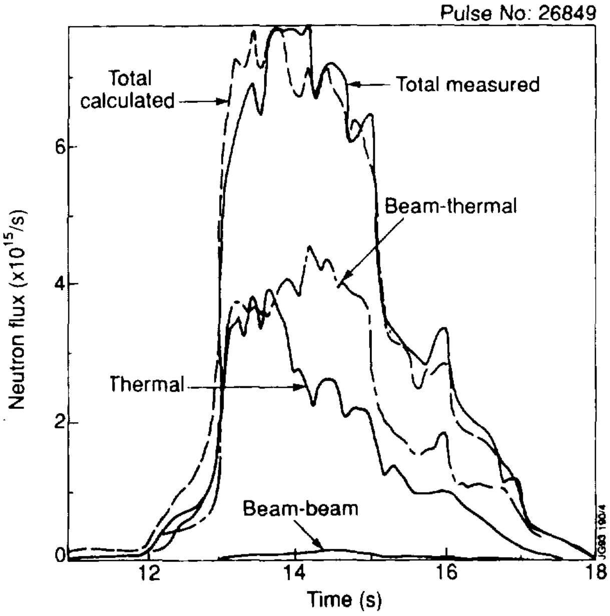


Fig. 1: Upper: ICRH and lower: NBI power deposition profiles calculated by TRANSP.

Fig. 2: Comparison of the measured and computed neutron flux (TRANSP).

The energy confinement time in pulse No. 26849 is a factor ~ 1.4 times the L-mode Goldston scaling /7/ value. The RF power density profile is peaked (Fig.1) with a full-width at half-maximum of ~ 0.2 m. At this density, however, few of the injected 80 keV neutral beam ions are able to penetrate to the core and the corresponding NBI deposition profile is broad. The collisional NBI power densities are shown in Fig. 1. TRANSP simulation shows that the dominant contributions to the neutron flux R_{NT} (Fig. 2) are from thermal and beam-thermal fusion reactions. The high neutron flux phase of this discharge terminates when the ICRH and NBI power waveforms are ramped down, in a descending staircase pattern, from time 15 sec onwards. The fraction of the additional power radiated is ~ 75%, with ~ 13% lost as charge-exchange neutrals and ~ 10% conducted to the X-point target tiles.

RF Performance in Hot Ion H-mode Discharges. During preparations for the JET PTE /1/, some ICRF power was coupled to several hot-ion H-mode discharges in the (H)D scheme. TRANSP modelling of pulse No. 26043 (Table I) - a 3.1 MA double-null X-point discharge - simulates well the neutron emission (Fig.3). This discharge is compared with reference pulse No. 26038 with no ICRH added. The added RF power increases the central electron temperature T_{e0} by 1.8 keV and there is a corresponding 30% increase in R_{NT}.

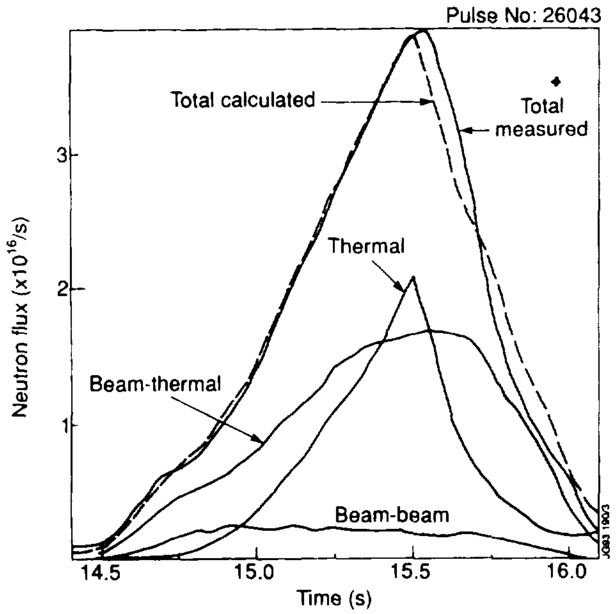


Fig. 3: Comparison of measured and (TRANSP) computed neutron fluxes.

TRANSP results indicate that the increase in the beam slowing-down time should cause R_{NT} to increase by only ~ 5%. A TRANSP run with T_{e0} increased by 20% and the ion thermal diffusivity χ_i kept constant, causes the central ion temperature T_{i0} to increase from 24 keV to 26 keV and the neutron flux by 13%. The observed increase in R_{NT} can therefore partly be explained by the increase in T_e which reduces the power drain from the ions by equipartition and raises the critical energy of the beam ions allowing more ion heating by the neutral beams. The high performance phase of pulse No. 26043 terminates in less than one second at an X-event (at ~ 15.5 sec); the termination is associated with impurity influx. The Z_{eff} value is ~ 1.8 up to 15.5 sec, thereafter it rises rapidly to values > 4. The radiated power fraction is ~ 10% prior to the collapse.

Projection of ICRF Heated Discharges to a DT Mixture. In the (D)T heating scheme, the optimum Q occurs when the average energy of the D tail is ~ 100 keV, close to the maximum in the DT cross-section. Criteria for optimising the D concentration have been discussed /8/. PION is used to project the high density pulse No. 26849 with 20 MW of ICRH power coupled to the plasma with dipole antenna phasing. We take fixed plasma parameters and make no allowance for any effect of the increased effective ion mass on confinement. With a mixture of 20 % D in T, it is found that ~ 70 % of the ICRH power is damped on the D. The total DT fusion power is ~ 5.4 MW, giving a Q of ~ 0.27. This figure breaks down into a non-thermal Q of ~ 0.17 and a thermal Q of ~ 0.1. Assuming the same plasma parameters but with $Z_{eff} = 1$, we predict Q ~ 0.4. If we further assume that the ion and electron temperatures are increased such that the global confinement time is equal to twice the Goldston value - typical of the H-mode quality which might be achieved with the new JET divertor configuration - then the total Q increases to ~ 0.45, equivalent to ~ 9 MW of fusion power. The role of combined ICRH and NBI is investigated in projecting a hot-ion H-mode (pulse No. 26043) to DT. We have assumed one of the NBI boxes changed to mixed 80 keV and 140 keV tritium beams and the other kept with 140 keV D beams. TRANSP predicts a fusion power of 9 MW and a Q of ~ 0.5. Beam-thermal and thermal contributions are comparable. Assuming T_{e0} to increase by 20%, by adding a further 2 MW of ICRH power, TRANSP predicts a T_i increase of ~ 12%, a thermal DT reactivity increase of ~ 19% and a total reactivity increase of ~ 10% corresponding to a fusion power of ~ 10 MW. The total Q decreases by ~ 2 %. Thermal and non-thermal contributions are approximately equal. If the discharge is assumed not to terminate by an X-event, then a quasi steady-state of Q ~ 1 is reached after a few seconds. Optimisation of ICRH in a second tritium experiment, assumed to be free of X-events, is currently under investigation.

Summary. In hot-ion H-mode discharges, TRANSP shows that centrally deposited ICRH can play a significant role in increasing T_{e0}, (thus reducing the ion energy drain and increasing T_{i0}) as well as the fast ion slowing-down time and the fusion reactivity. In typical low density DT plasmas, a fusion power of ~ 9 MW and a Q ~ 0.5 is predicted. Adding 2 MW of ICRH power increases the fusion power to ~ 10 MW and decreases Q marginally. However, low density plasmas are prone to terminate, after ~ 1 sec, as a result of the large power fluxes conducted to the dump plates, releasing impurities and diluting the fuel. In the presence of an X-event, the total DT fusion energy release in low density conditions is ~ 10 MJ. In high density plasmas, ICRH power is deposited efficiently in the centre when the plasma attenuation to injected beams of 80 keV - 140 keV deuterons is large. In discharges with 20 MW of pure ICRH in the (D)T scheme, ~ 5.4 MW of fusion power (Q ~ 0.27) is predicted, rising to ~ 8 MW (Q ~ 0.4) when Z_{eff} = 1 is assumed, and to ~ 9 MW (Q ~ 0.45) for typical H-mode confinement. The high reactivity phase ceases when the additional power is removed, and is not caused by impurity influx. If impurity generation can be limited for 20 seconds, ICRH alone could produce a total fusion energy release > 100 MJ. To utilise the JET pumped divertor at large power (> 20 MW) and for long pulses, it will be necessary to radiate > 70 % of the discharge power thereby minimising the concentrated power loading on plasma-facing surfaces - a condition already achieved in high density discharges where the low temperature divertor exhaust strongly reduces the impurity sputtering rate. In conclusion, future experiments in JET will be well-suited to test the (D)T ICRF fusion scenario jointly with high-density divertor operation and will thus be doubly relevant to the ITER device.

References

/1/ The JET TEAM, *Nuclear Fusion* **32** (2) (1992) 187.
/2/ M.Bures, B.Balet, G.A.Cottrell, et al., this conference.
/3/ R.J.Goldston, D.C.McCune, H.H. Towner et al., *J.Comput. Phys.* **43** (1981) 61.
/4/ D.N.Smithe et al. *Nuclear Fusion* **27** (1987) 1319.
/5/ G.W.Hammett, Ph.D Thesis (Princeton Plasma Physics Laboratory, USA, 1986).
/6/ L.-G. Eriksson, T. Hellsten and U.Willen. Sub. *Nuclear Fusion* (1993). And JET-P(93)01.
/7/ R.J.Goldston, *Plasma Physics and Controlled Fusion* **26** (1A) (1984) 87.
/8/ G.A.Cottrell, et al., *Plasma Physics and Controlled Fusion* **31** (11) (1989) 1727.