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Stability and confinement optimisation in the range q_0=1-3 at JET

C D Challis[1], B Alper[1], M Baruzzo[2], J Bucalossi[3], P Buratti[4], R Buttery[1], M Brix[1], G Calabro[4], R Cesario[4], F Crisanti[4], J Ferron[5], O Ford[1], C Giroud[1], M Gryaznevich[1], T C Hender[1], J Hobirk[6], D Howell[1], F Imbeaux[3], I Jenkins[1], E Joffrin[3], H Leggate[1], T Luce[5], D McDonald[1], M Murakami[7], V Pericoli-Ridolfini[4], M Tsalas[8], P de Vries[1]
and JET EFDA contributors*

JET-EFDA, Culham Science Centre, Abingdon, OX14 3DB, UK

[1]*Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK*

[2]*Consorzio RFX, Associazione EURATOM-ENEA sulla Fusione, 35137 Padova, Italy*

[3]*Association Euration-CEA, DSM/DRFC, Cadarache F-13108, France*

[4]*Euratom-ENEA Association, C.R. Frascati, CP65, 00044 Frascati, Italy*

[5]*General Atomics, PO Box 85608, San Diego, Ca 92186-5608, USA*

[6]*Max-Planck-Institut für Plasmaphysik, Euratom Association, 85748 Garching, Germany*

[7]*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6169, USA*

[8]*Association EURATOM-Hellas, NCSR "Demokritos", Agia Paraskevi Attica, Greece*

Introduction

Steady-state operation of ITER at Q≈5 is envisaged with a plasma current of ≈9MA, a large fraction of which must be provided by the bootstrap mechanism. In these conditions q_{95} will be ≈5 and the minimum value of q (q_{min}) is expected to be >1. Experiments have been performed on JET to vary the q-profile shape in this domain to investigate the effect on stability and confinement. The large ratio of resistive time (τ_R) to energy confinement time (τ_E) on JET (τ_R≈4-8s and τ_R/τ_E≈20-50 in these experiments at 1.1-1.6MA/1.6-2.3T) has allowed the study of a wide range of q-profile shapes without the need for fully non-inductive current drive. In these experiments two favourable domains have been identified: one with q_{min} in the range 1.0-1.5; and the other at q_{min}≳2.

Experiments with q_{min}≈1.0-1.5

In this domain good stability was obtained with β_N≈4 for many τ_E, as shown in Fig 1. Neutral beam heating was applied roughly at the time q_0 reached 1 due to current penetration during the initial phase of the pulse. The main obstacle to the prolongation of the high β_N phase was the onset of m=2, n=1 MHD instabilities, the time of which is indicated in Fig 1. It is not thought that the resistive wall mode limit has been reached in these experiments and the

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2/1 mode quickly develop a tearing character [1]. During the main heating phase β was raised slowly under feedback control using the neutral beam injection, as seen in Fig 1. With this optimisation the 2/1 mode tended to appear on a timsescale long compared with τ_E, but short compared with τ_R. In plasmas of the type shown in Fig 1 the current density profile broadened during the heating phase, gradually shrinking the radius of the q=2 surface until the 2/1 mode became unstable. In this case the radial location, local magnetic shear and pressure gradient at the q=2 surface were being simultaneously modified, all of which may affect the stability of the observed mode.

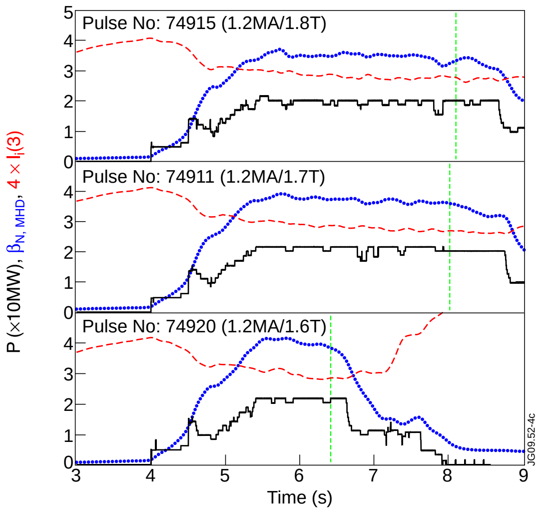

Fig 1. β_N, power and $4l_i$ for pulses with $q_{min}\approx1.0$-1.5. Vertical broken lines indicate onset of 2/1

The appearance of neoclassical tearing modes (NTMs) with higher toroidal mode numbers can also degrade the plasma confinement and the avoidance of these has allowed improved confinement with respect to the IPB98(y,2) scaling to be achieved. The method used, analogous to the technique for avoiding the 2/1 mode, was to increase the radius of low order rational q-surfaces with q>1 where deleterious instabilities can be encountered. To avoid large q=1 sawteeth q_0 was simultaneously kept as high as possible, leading to an optimum q-profile with $q_{min}\approx1$ and a wide region of very low magnetic shear in the plasma core. This class of q-profile has been exploited on many tokamaks in what is commonly called the hybrid regime.

The location of NTMs is an important factor in the resulting impact on confinement. This is illustrated in Fig 2 where confinement relative to the IPB98(y,2) scaling is plotted against the radius of the n=2 mode for plasmas in the range q_{95}=4-5. The mode location was determined from fast electron cyclotron emission measurements as described in [2]. Despite the fact that none of these plasmas had a clear internal transport barrier (ITB), $H_{IPB98(y,2)}>1$ could be obtained with $q_{min}\approx1$ where NTMs associated with low order rational q-surfaces were either absent of restricted to the plasma

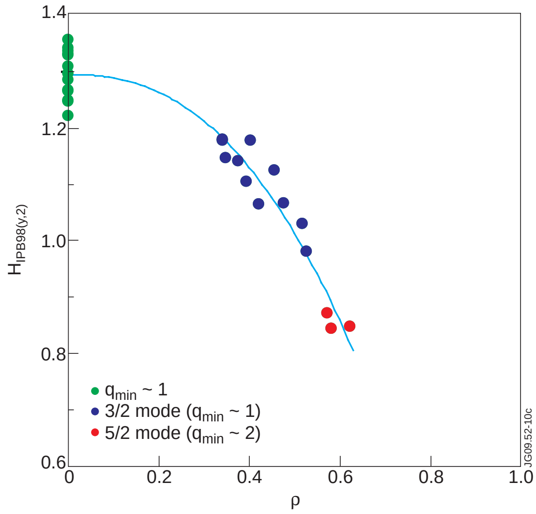

Fig 2. Confinement H-factor versus radius of n=2 NTM. Pulses without a clear n=2 mode are plotted at ρ=0. The line is a fit to the data.

core. Avoidance of low n NTMs was achieved using a plasma current overshoot just before the main heating was applied to generate the wide region of low magnetic shear close to q=1. This technique was developed for the hybrid regime on JET [3] and has led to good confinement ($H_{IPB98(y,2)}$≈1.3-1.4) and good stability (β_N≈2.8) for of order a resistive time. During these pulses the radius of the q=1.5 surface tended to decrease until a 3/2 NTM was triggered and the confinement was degraded.

Experiments with q_{min}~2.0

Previous JET experiments at q_{min}>1.5 suggested that, for plasmas without an internal transport barrier (ITB), both stability and confinement were degraded compared with low q_{min} plasmas such that $H_{IPB98(y,2)}$ was ≤1 and β_N was typically ≤2.5 [4]. Recent experiments at q_{min}=1.5-2.0 have confirmed the difficulty to avoid performance degrading 2/1 MHD, unlike DIII-D where high performance plasma can be obtained in this domain [5]. However, at JET a second favourable domain was found at q_{min}≳2 where β_N≈3 has been achieved for many τ_E [6]. The duration of the high performance phase was typically limited due to the slow q-profile evolution into the q_{min}<2 domain, in accordance with modelling that suggests the gradual increase in magnetic shear at the q=2 surface eventually leads to instability [7].

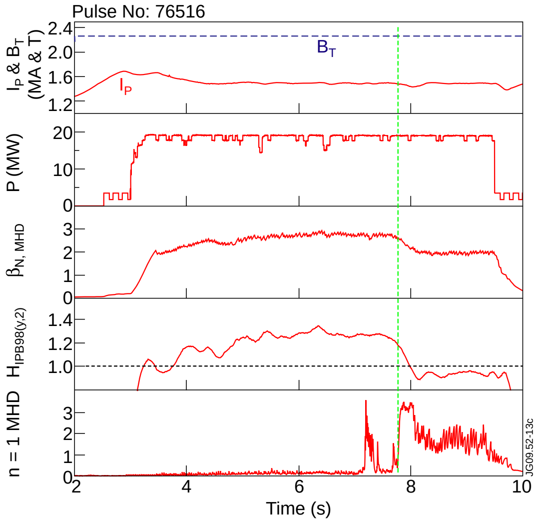

Fig 3. Time evolution of plasma with q_{min}~2 following a current overshoot. Broken vertical line indicates onset of 2/1 mode.

Extending the use of the current overshoot technique to plasmas with q_{min}~2 has resulted in the achievement of good confinement ($H_{IPB98(y,2)}$≈1.25) without the steep internal pressure gradients associated with ITBs. The time evolution of a typical case is shown in Fig 3 where β_N≈2.75 was obtained, giving an estimated bootstrap fraction of 40%. As with the q_{min}~1 domain it was possible to avoid n=1 or n=2 NTMs for many τ_E by generating a wide region of low magnetic shear in the plasma core, this time close to q=2.

The q-profiles of typical cases from the q_{min}~1 and q_{min}~2 domains are illustrated in Fig 4. Also shown is the q-profile after 3 resistive times for a plasma in the domain q_{min}~1. The measured q-profile evolution follows closely the expected path modelled using necoclassical resistivity and non-inductive drive due to beams and the bootstrap effect. The non-inductive component is typically 40-60% in these experiments and the application of

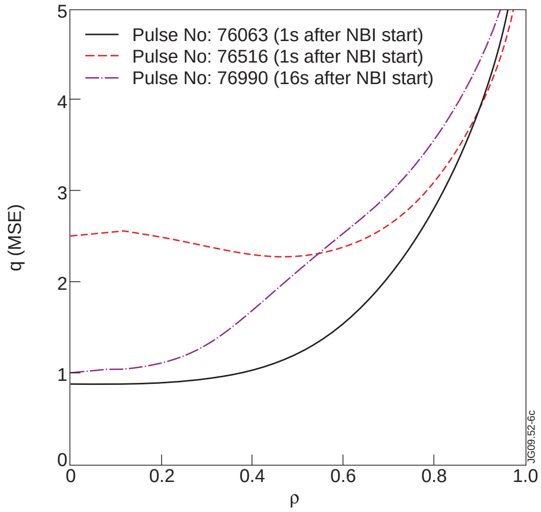

Fig 4. q-profiles after 1 second of main heating following a current overshoot and at 16 seconds to illustrate fully diffused profile.

further non-inductive drive is required in the region ρ=0.4-0.6 to prevent the relaxation of the low magnetic shear region in the core.

Conclusions

Two favourable q-profile domains have been identified of relevance to steady-state tokamak operation. With q_{min}~1 good stability and confinement were achieved. But peripheral bootstrap current at high β_P tends to reduce the size of the low magnetic shear region close to q=1, limiting the attractiveness of this regime for steady-state operation. In plasmas with q_{min}~2, but without a clear ITB, confinement and stability have been improved compared with previous JET experiments, although the performance is inferior to that of the q_{min}~1 domain. However, the plasmas obtained are more compatible with bootstrap current drive, both in term of efficiency (due to the weaker core poloidal field) and alignment, and sustainment of this class of q-profile may be feasible using off-axis non-inductive current drive at ρ=0.4-0.6. This q-profile domain has been used for steady-state scenario development at higher current and field at JET [8].

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