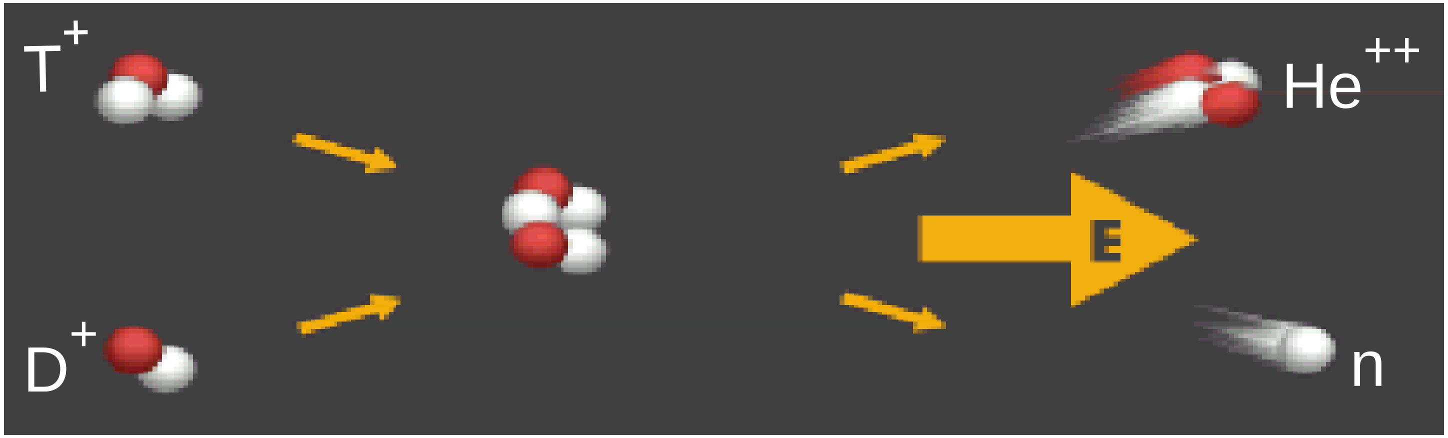


Basic Research of Tritium Confinement

D J Campbell

ITER Organization, Cadarache

Acknowledgements:
Many colleagues in the JET and TFTR teams

Summary of Presentation

- **The aim and planning of DT experiments in present tokamaks**

- **Major results of DT experiments in JET and TFTR:**
  - Plasma energy confinement
  - Particle transport studies
  - MHD stability
  - α-particle behaviour
  - Fusion power production

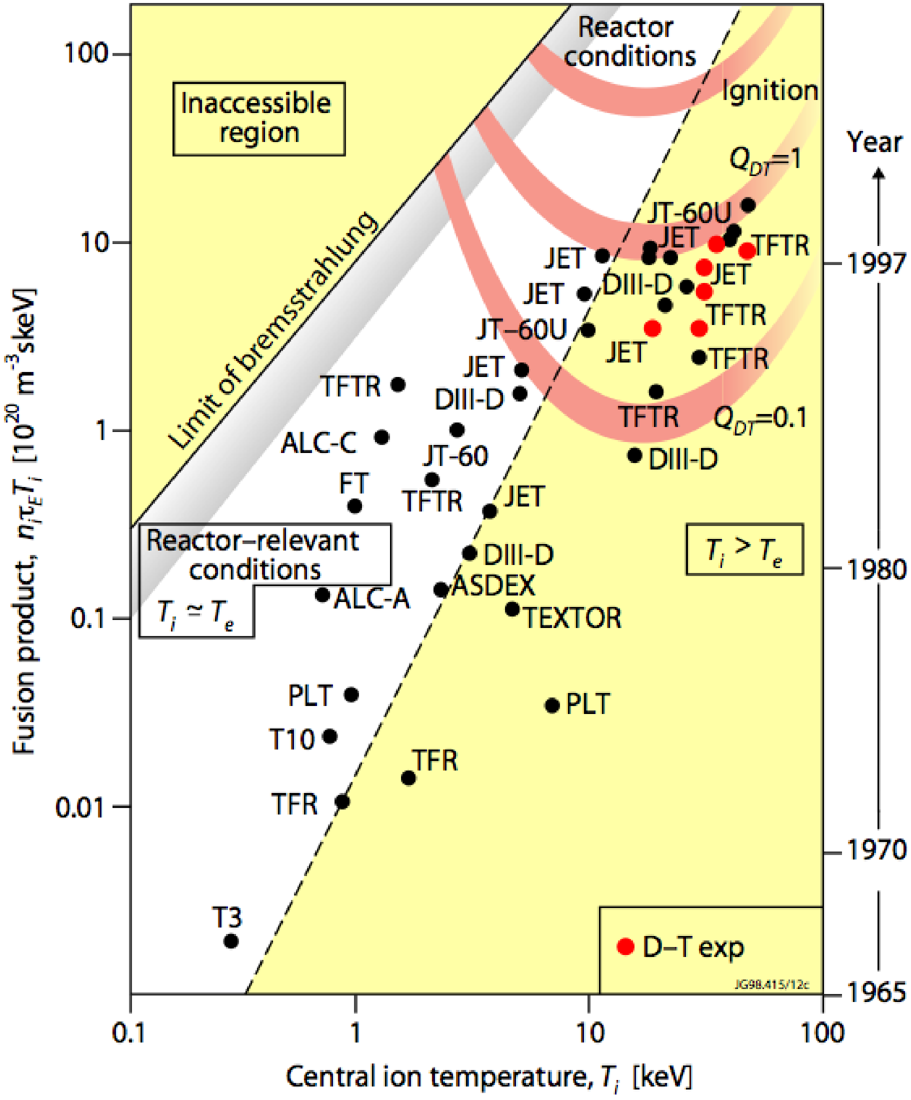
- **Conclusions**

Aim of DT Experiments

- **Over the last 4 decades, fusion research has made significant progress towards the goal of energy production:**

$$Q = \frac{\text{Fusion Power}}{\text{Input Power}} \sim n_i T_i \tau_E$$

- **DT experiments allow:**
  - direct test of predictions of fusion performance
  - analysis of behaviour of tritium in the tokamak environment
  - studies of plasma behaviour with DT mixtures
  - investigation of α-particle behaviour and impact on plasmas



Planning DT Experiments

Progress from DD to DT experiments is a major (and exciting!) step for the magnetic fusion programme

- **DT fuel brings a new approach to the organization of the tokamak experimental programme:**
    - Tritium is itself radioactive
    - Limited amounts of tritium are stored on-site to limit licensing requirements
    - Amount of tritium trapped inside vacuum vessel must be limited
    - DT fusion reactivity factor of >100 greater than DD reactivity
    - 14 MeV neutrons vs 2.4 MeV neutrons ⇒ additional activation products

⇒ experimental programme must be planned with great care to minimize use of tritium and activation of the device structure

⇒ rehearsal of plasma scenarios in deuterium and careful development to optimize use of tritium

Planning DT Experiments

Sequence of DT Programmes

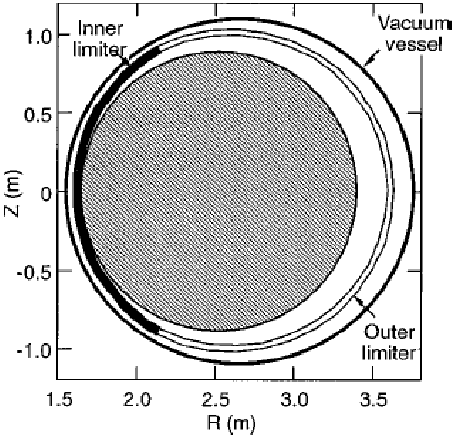
- **A series of DT experiments has been carried out within the tokamak programme:**
    - 1991: JET Preliminary Tritium Experiment (PTE) - $n_T/(n_D+n_T) < 11\%$
    - 1994-1997: TFTR DT experiments - $n_T/(n_D+n_T) < 90\%$
    - 1997: JET Deuterium-Tritium Experiment (DTE) - $n_T/(n_D+n_T) < 90\%$
    - 2003: JET Trace Tritium Experiment (TTE) - $n_T/(n_D+n_T) < 3\%$

⇒ **provided gradually increasing experience of handling tritium in quantities relevant to tokamak experimental requirements**

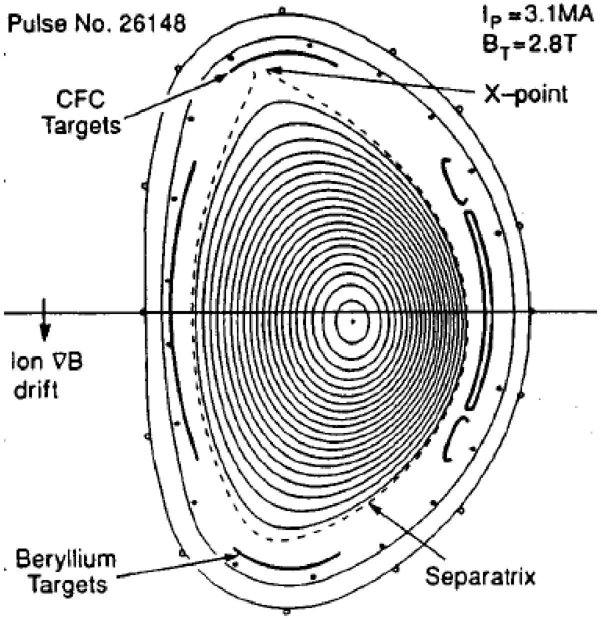
⇒ **allowed wide range of physics studies to be developed in DT plasmas in a range of plasma regimes**

⇒ **produced maximum fusion power of 16MW**

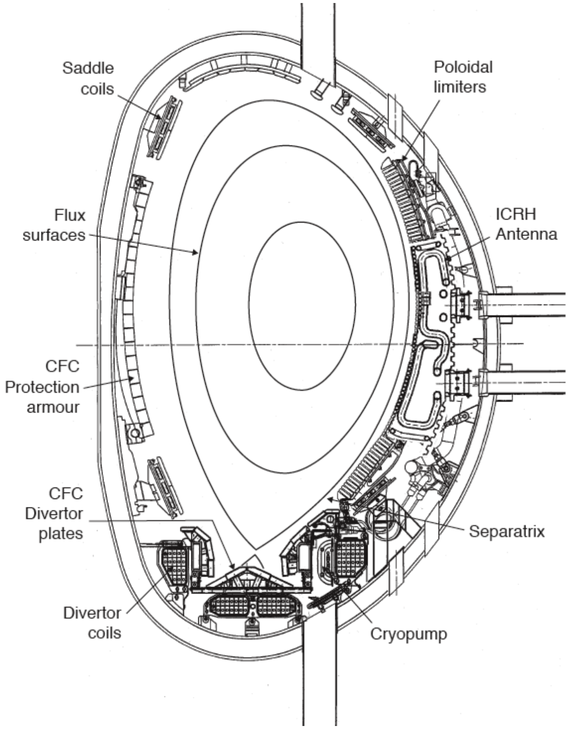
Planning DT Experiments
Experimental Configurations



TFTR 1994-1997



JET 1991



JET 1997, 2003

- **TFTR and JET use different magnetic configurations:**
  - TFTR DT experiments in limiter plasmas: L-mode, “supershot”, ITB scenarios
  - JET DT experiments in diverted plasmas: L-mode, H-mode, ITB scenarios

Planning DT Experiments

Fuelling DT Plasmas

- **Optimization of the fusion power in a DT plasma raises the requirement to be able to control the ratio D:T (ideally 50:50) - implies a need for:**
    - measuring the “fuel ratio”
    - providing controlled amounts of deuterium and tritium

- **Generally the plasmas which will be discussed here were fuelled by a mixture of**
    - gas fuelling
    - neutral beam injection
    - recycling from plasma facing surfaces

- **Control of the fuel content of the plasma facing surfaces was therefore an important aspect of the DT experiments carried out in JET and TFTR**

Experimental Results in DT Plasmas:

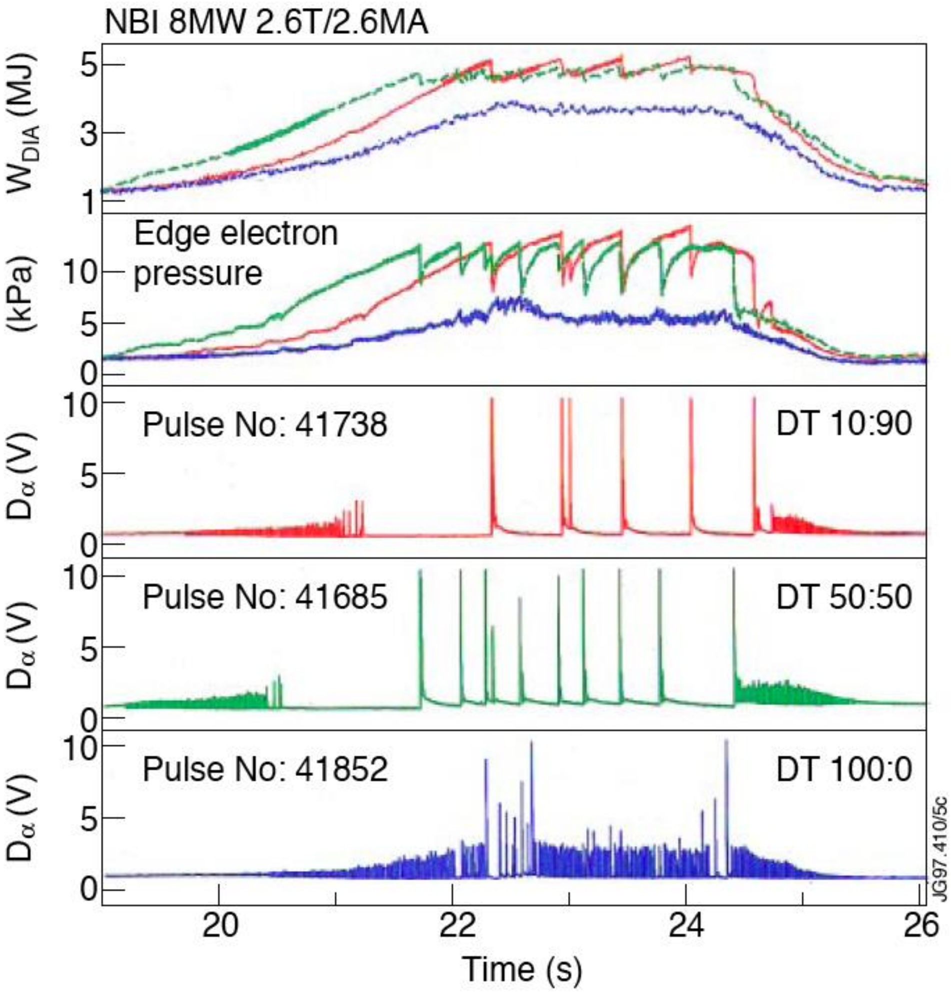
Plasma Energy Confinement

Plasma Energy Confinement

Tritium in Plasmas

- **Presence of tritium in plasmas has an effect on plasma behaviour which is independent of the production of fusion power**

⇒ Isotope effect



JET H-modes

Plasma Energy Confinement

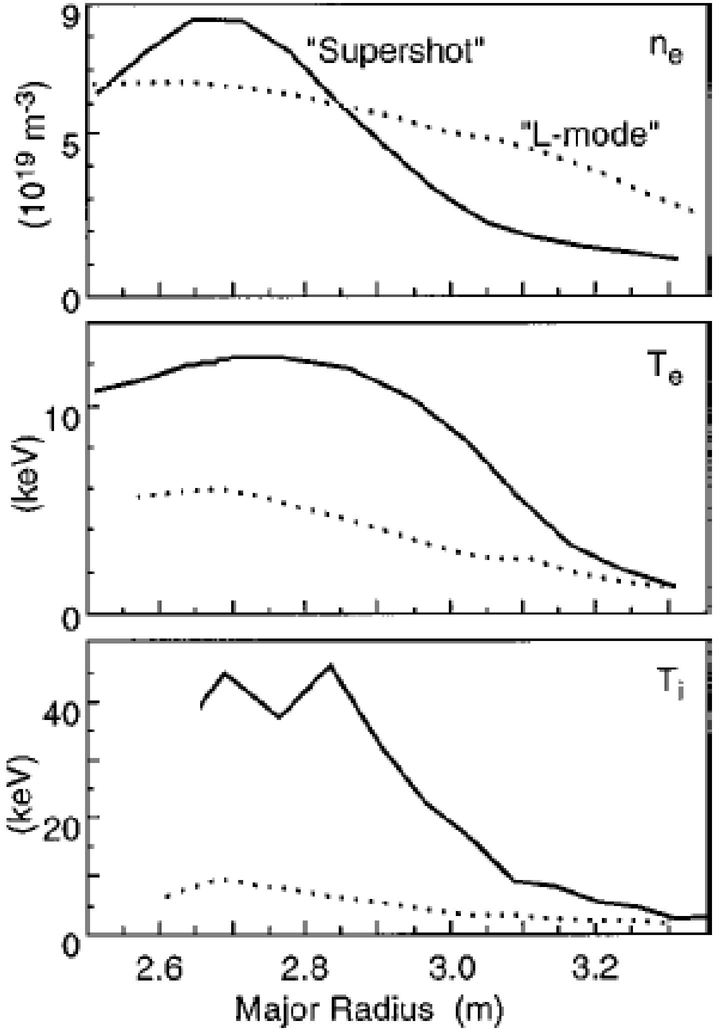
1. TFTR "Supershots"

- **"Supershots" are limiter plasmas in TFTR with well conditioned walls and high power neutral beam injection:**
  - large reduction of central transport with peaked density and temperature profiles
  - associated with rotational shear suppression of turbulence in plasma core
- **DT experiments showed:**

$$\tau_E^{\mathrm{thermal}} \propto \langle A \rangle^{0.89}$$

$$\chi_i^{\mathrm{tot}} \propto \langle A \rangle^{-2.6}$$

  - ie a strong dependence on the isotope mass, A



J D Strachan et al, Phys Rev Lett **58** 1004 (1987)

Plasma Energy Confinement

2. JET L-modes

- **JET L-mode experiments :**

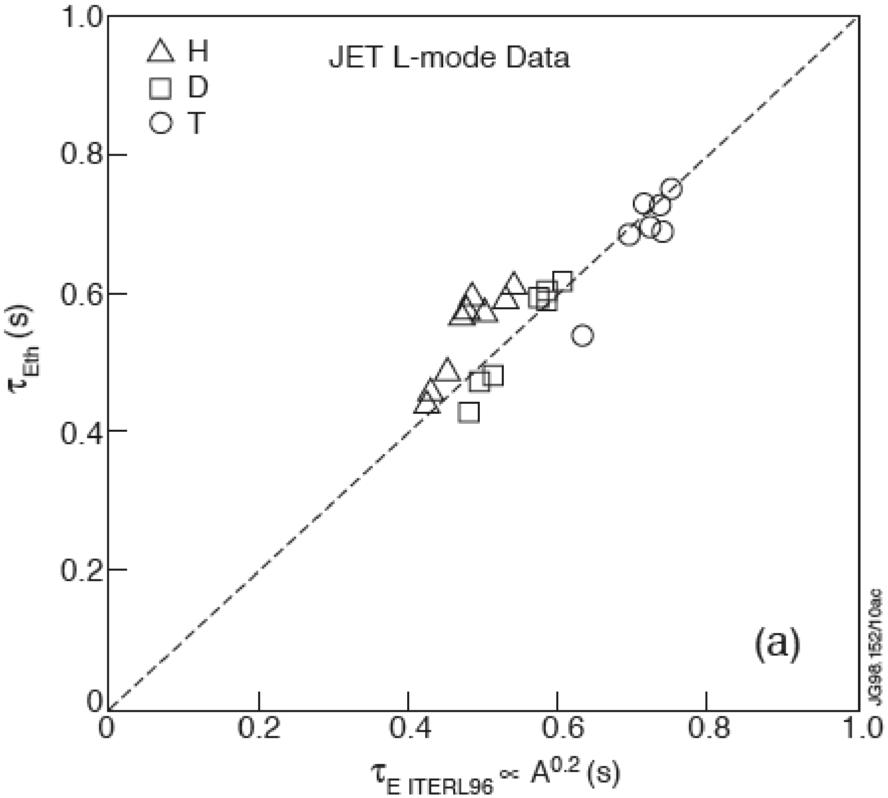
$$\tau_E^L \propto \langle A \rangle^{0.0} - \langle A \rangle^{0.2}$$

  - comparable to L-mode global confinement scaling

- **For comparison, TFTR L-mode plasmas yielded:**

$$\tau_E^L \propto \langle A \rangle^{0.3} - \langle A \rangle^{0.5}$$

  - A possible explanation lies in low input power of JET pulses - possible source of the discrepancy as plasmas are "quasi-ohmic".



J G Cordey et al, Nucl Fusion **39** 301 (1999)

Plasma Energy Confinement

3. JET H-modes

- **Simple analysis of JET ELMy H-mode experiments suggested:**

$$\tau_E^H \propto \langle A \rangle^{0.16}$$

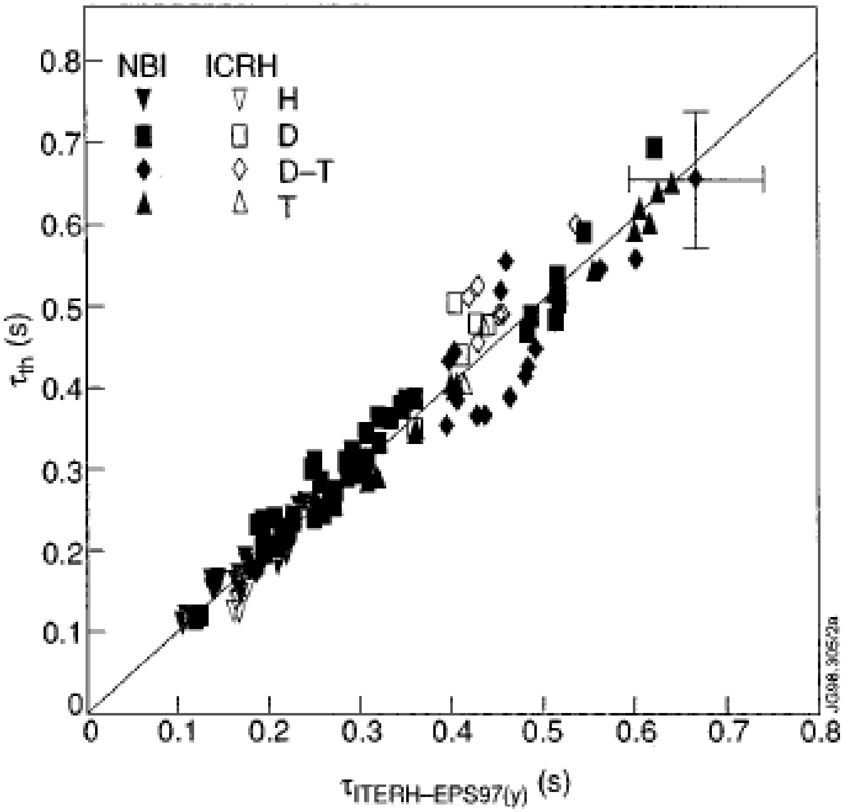
- **However, better matching of power and density data yielded:**

$$\tau_E^H \propto \langle A \rangle^{0.03}$$

- **Finally, when core and pedestal energy contributions separated:**

$$W_{core}^H \propto \langle A \rangle^{-0.17}$$

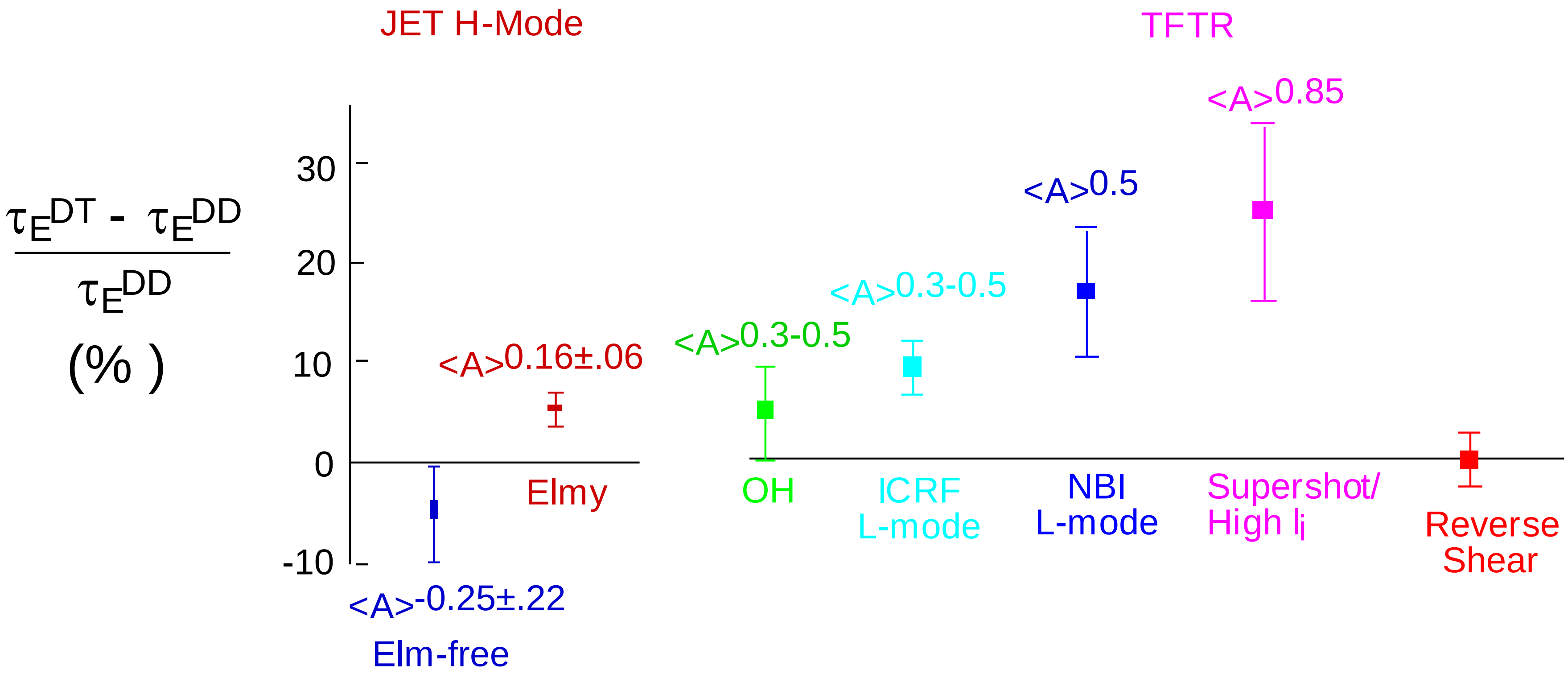
  - this is close to $A^{-0.2}$ scaling expected from gyro-Bohm transport model



J G Cordey et al, Nucl Fusion **39** 301 (1999)

Plasma Energy Confinement

Overview



- **Overall, the isotope dependence of confinement has been found to vary widely, depending on plasma operating regime:**
  - indicates different processes influencing confinement and their varying importance in different plasma regimes

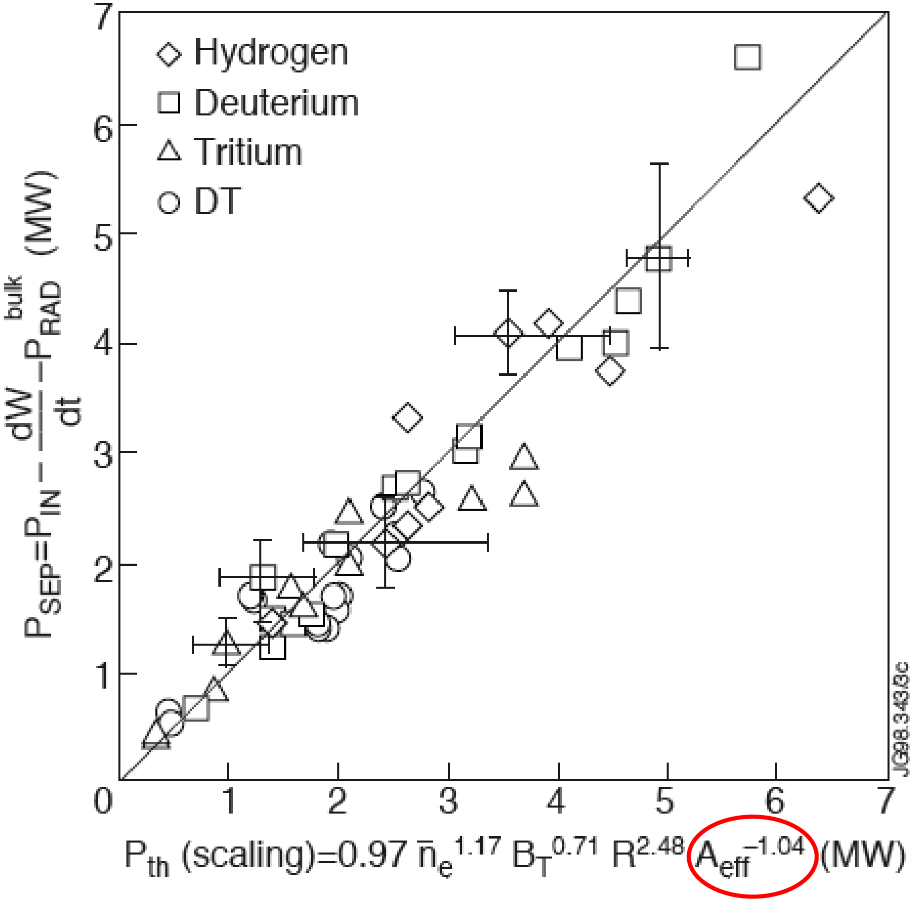
Plasma Energy Confinement

H-mode Power Threshold

- **JET analysis of the power required to access the H-mode confirmed that:**

$$P_{th} \propto \langle A \rangle^{-1}$$

- **This result is important for ITER in that it indicates that access to the H-mode will be easiest in DT operation**



E Righi et al, Nucl Fusion **39** 309 (1999)

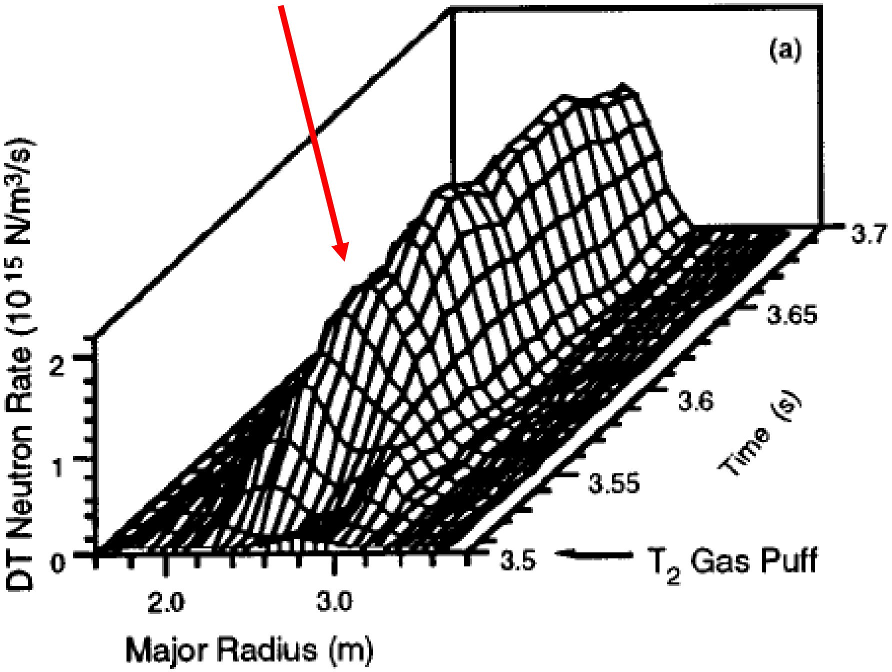
Experimental Results in DT Plasmas:

Particle Transport Studies

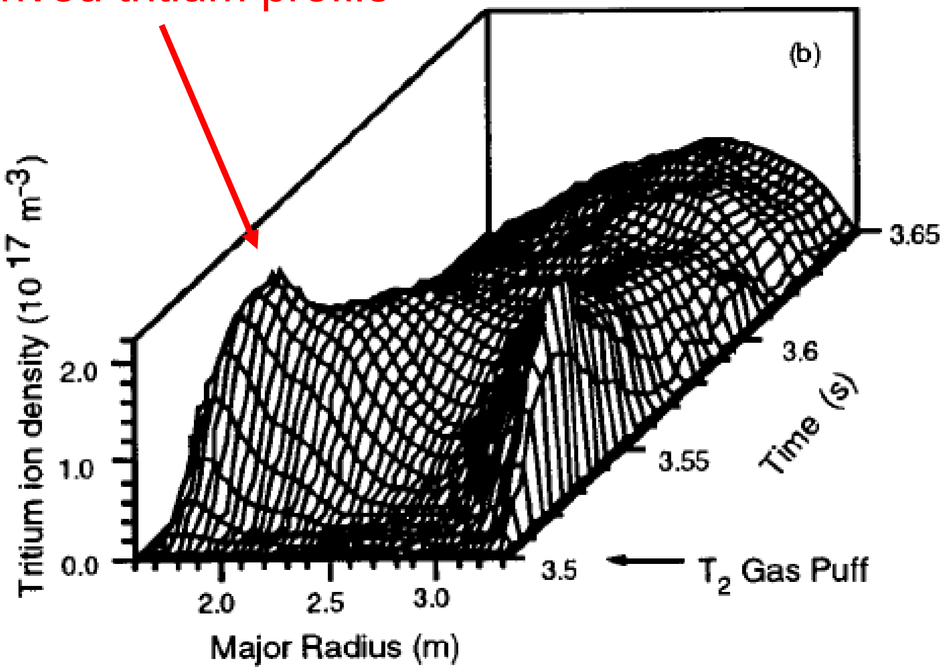
Particle Transport Studies

Principle

14MeV neutron signal



Derived tritium profile

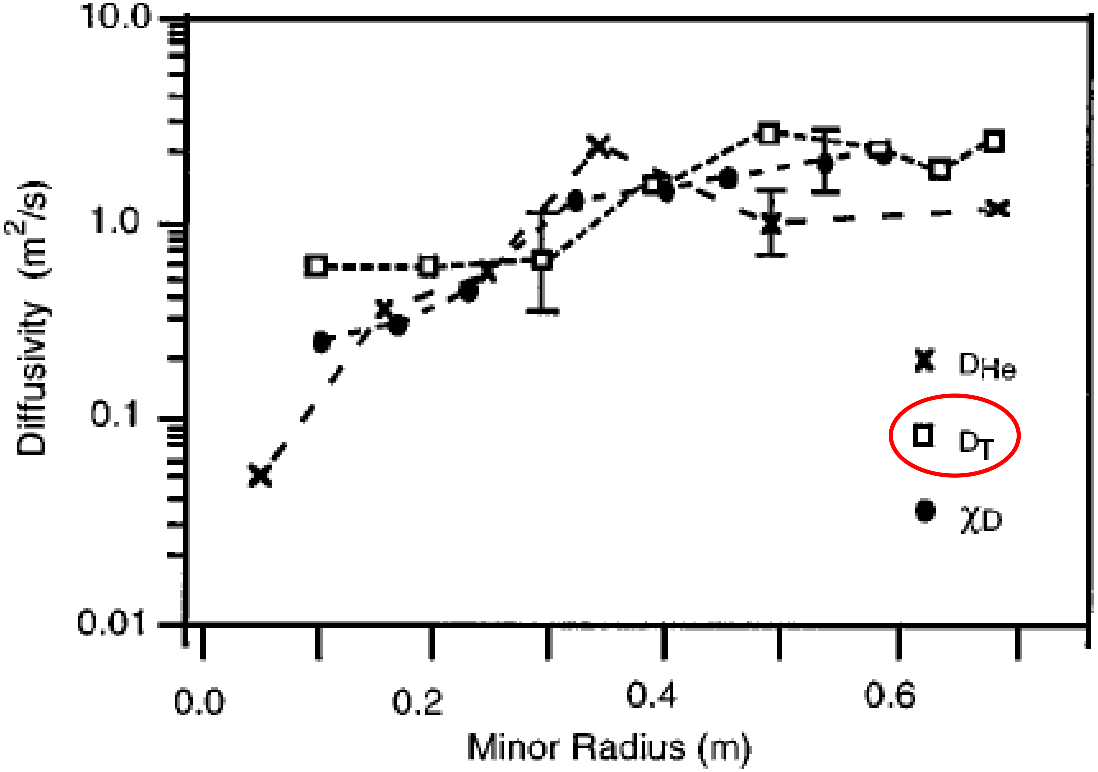


P C Efthimion et al, Phys Rev Lett **75** 85 (1995)

- **Puffing a small amount of tritium into the edge of a deuterium plasma allows hydrogenic particle transport to be investigated:**
  - The 14MeV neutron signal provides a distinct marker for the location of the tritium as it diffuses into the plasma

Particle Transport Studies

1. TFTR “Supershots”



P C Efthimion et al, Phys Rev Lett **75** 85 (1995)

- **In “supershot” plasmas, the tritium particle diffusivity was very similar to the electron and helium particle diffusivity:**

Particle Transport Studies

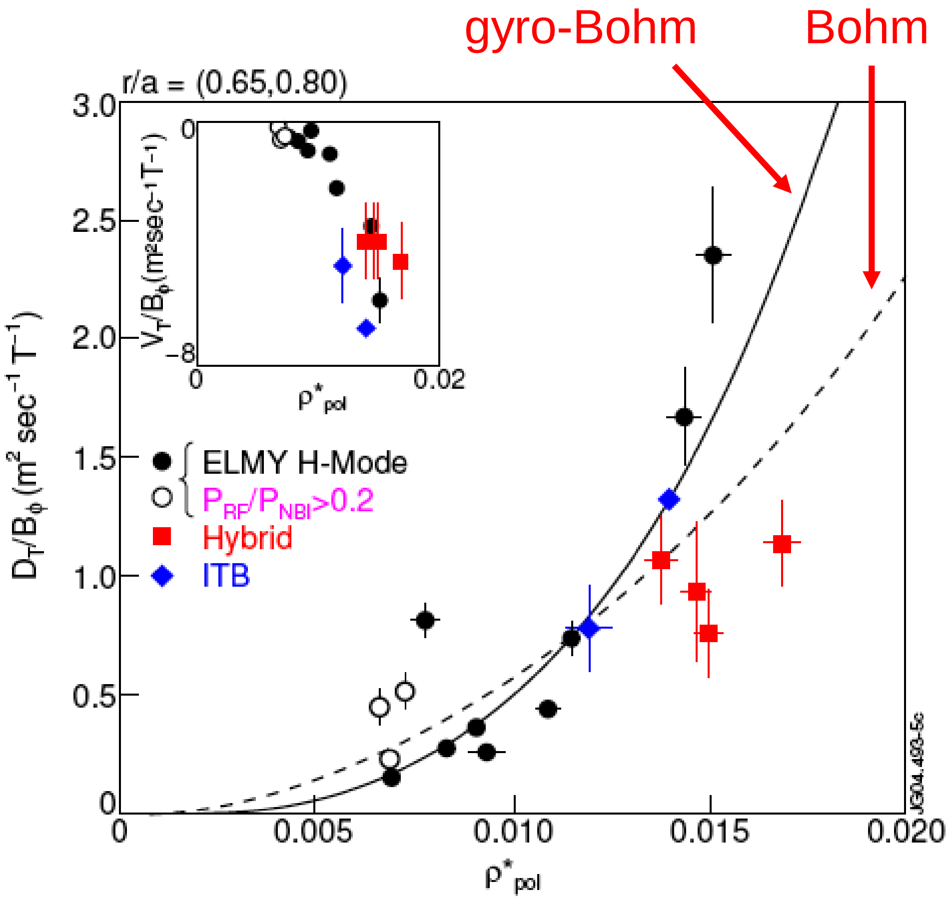
2. JET non-dimensional scans

- **Studies of tritium particle diffusivity in "non-dimensional" studies showed that in ELMy H-modes:**
  - particle diffusivity in the radial region 0.65 < r/a < 0.8 was well correlated with gyro-Bohm scaling:

$$\frac{D_T}{B_\phi} \propto \rho_{pol}^{*\,3}$$

  - rather than Bohm scaling:

$$\frac{D_T}{B_\phi} \propto \rho_{pol}^{*\,2}$$



D Stork et al, IAEA-20, Vilamoura (2004)

Experimental Results in DT Plasmas:

MHD Stability

Alfvén Eigenmodes

- **In a tokamak plasma, the Alfvén wave continuum splits into a series of bands, with the gaps associated with various features of the equilibrium:**
  - a series of discrete frequency Alfvén eigenmodes can exist in these gaps**:**

toroidicity-induced (TAE)	gap created by toroidicity
ellipticity-induced (EAE)	gap created by elongation
triangularity-induced (NAE)	gap created by additional non-circular effects
beta-induced (BAE)	gap created by field compressibility
kinetic toroidal (KTAE)	gap created by non-ideal effects such as finite Larmor radius

… and others!

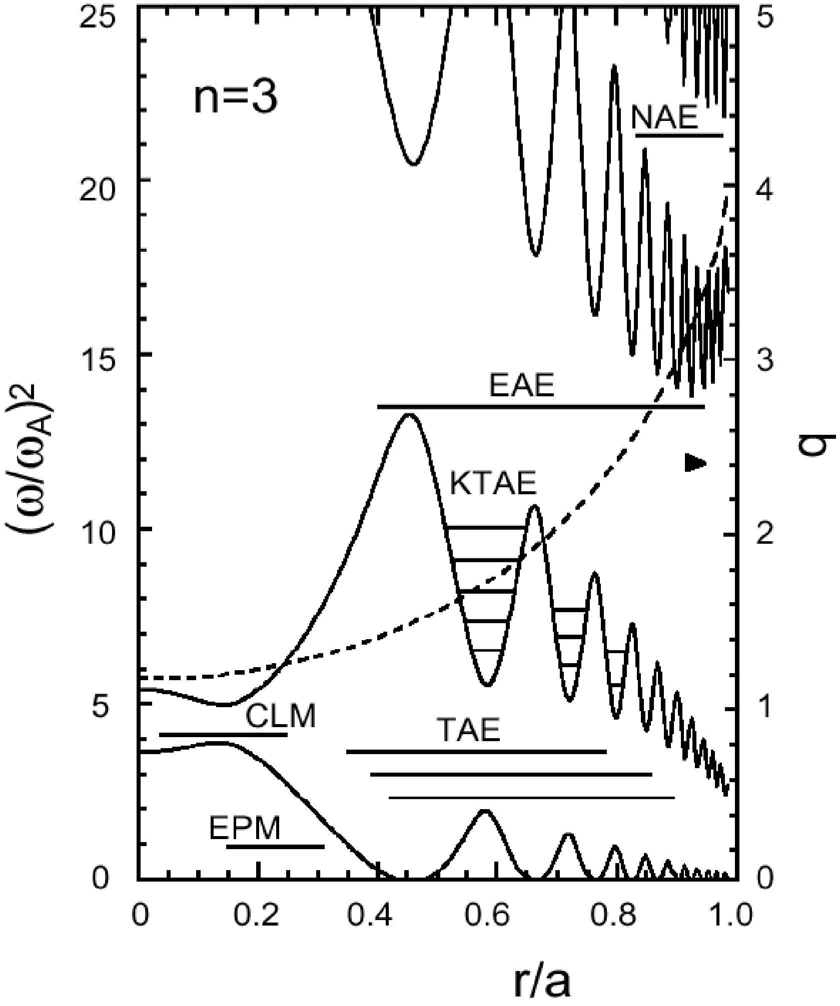
- **These modes can be driven unstable by the free energy arising from energetic particle populations with velocities above the Alfvén velocity, eg α-particles**

Alfvén Eigenmode Spectra

- **Characteristic Alfvén frequency defined:**

$$\omega_A = \frac{v_A}{qR}$$

  - TAE centred near $\omega_A/2$
  - EAE centred near ω_A
  - NAE centred near $3\omega_A/2$
  - BAE centred near $\omega_{TAE}/2$
- **Each AE is specified by a specific toroidal mode number, n:**
  - for each n, mode structure consists of a superposition of poloidal harmonics, with the m-harmonic peaking near q=m/n



G J Kramer et al, Phys Rev Lett **80** 2594 (1998)

Key Energetic Ion Parameters

The influence of energetic ion populations on plasma stability can be expressed through a small number of parameters

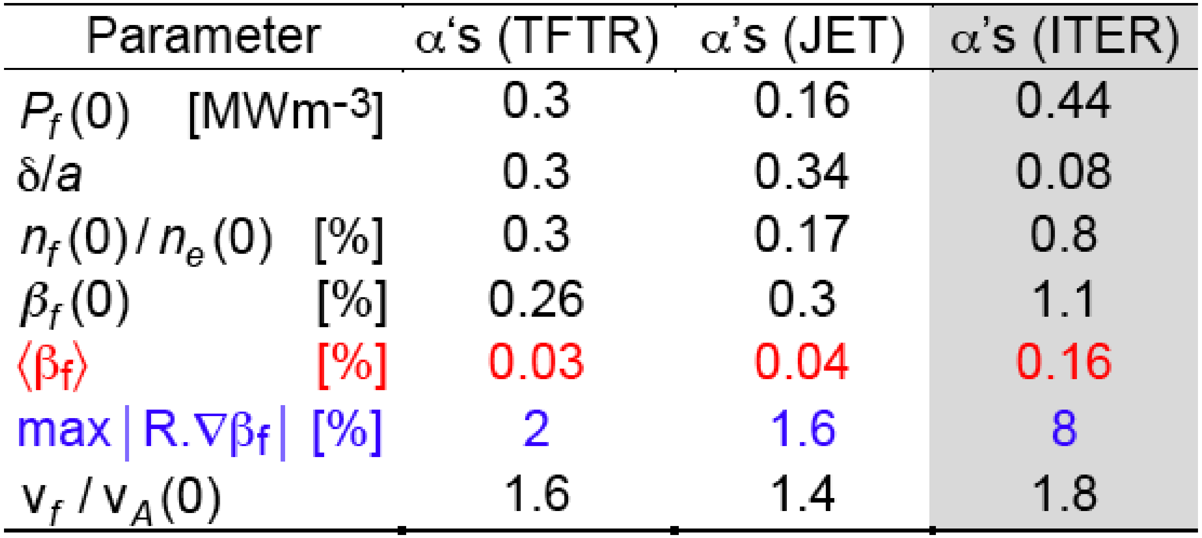
- $\frac{\delta_f}{a} = \frac{q}{\varepsilon^{0.5}} \frac{r_f}{a}$ **- normalized half-width of fast ion banana orbit**
- n_f / n_e **- fractional density of fast ions**
- $\beta_f(0)$ **- normalized axial fast ion pressure**
- $\max\left|R.\nabla\beta_f\right|$ **- dimensionless fast ion pressure gradient**
- $v_f / v_A(0)$ **- ratio of fast ion velocity to central Alfvén velocity**

$$v_A = \frac{B}{\sqrt{\mu_o \rho_{mass}}}$$

α-Particle Physics in Advanced Scenarios

- **Excitation of AEs and their influence on α-particle confinement is a central question for viability of advanced scenarios**

- **α-particle parameters in TFTR and JET might allow access to relevant range where α-driven instabilities and their influence on α-particle transport could be studied:**



Parameter	α's (TFTR)	α's (JET)	α's (ITER)
$P_f(0)$ [$\mathrm{MWm^{-3}}$]	0.3	0.16	0.44
δ/a	0.3	0.34	0.08
$n_f(0)/n_e(0)$ [%]	0.3	0.17	0.8
$\beta_f(0)$ [%]	0.26	0.3	1.1
$\langle\beta_f\rangle$ [%]	0.03	0.04	0.16
$\max\lvert R.\nabla\beta_f\rvert$ [%]	2	1.6	8
$v_f/v_A(0)$	1.6	1.4	1.8

- **Higher power density in reactor could be even more challenging $\Rightarrow$ ITER programme aims to move in this direction**

Alfvén Eigenmode Stability

Linear stability:

- **Pressure gradient of resonant particles with v ~ v_A provides source of free energy which excites the mode:**
  - both passing and trapped particles can resonate with the AE
  - a resonant sideband also exists at $v_A/3$ for TAEs
  - several damping mechanisms exist which complicate estimation of instability thresholds
  - experiments in “advanced scenarios” with non-monotonic q-profiles show a rich population of AEs can be excited

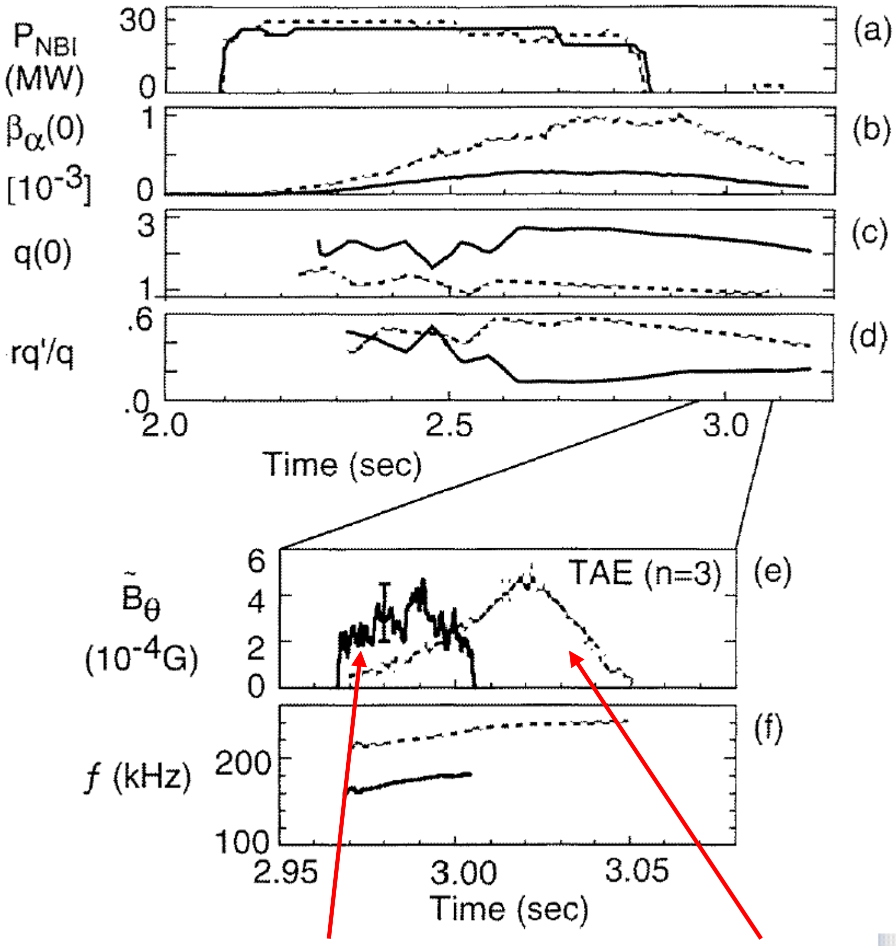
Non-linear behaviour:

- **Redistribution of resonant particles can occur by finite amplitude waves**
- **Overlap of multiple modes can lead to enhancement of energetic ion transport**

Alfvén Eigenmode Observation

- **In both TFTR and JET DT experiments, excitation of AEs by α-particles proved elusive. TFTR succeeded by:**
  - raising central q, to increase instability drive
  - observing in post-NBI phase, where (beam) ion Landau damping is reduced, but α-drive remains
  - TAE may have been generated through excitation of so-called “Cascade” mode
- **JET reported observations of ICRH-driven TAEs for which α-particles contributed to instability drive**

R Nazikian et al, Phys Rev Lett **78** 2976 (1997)



q(0) ≈ 1.1

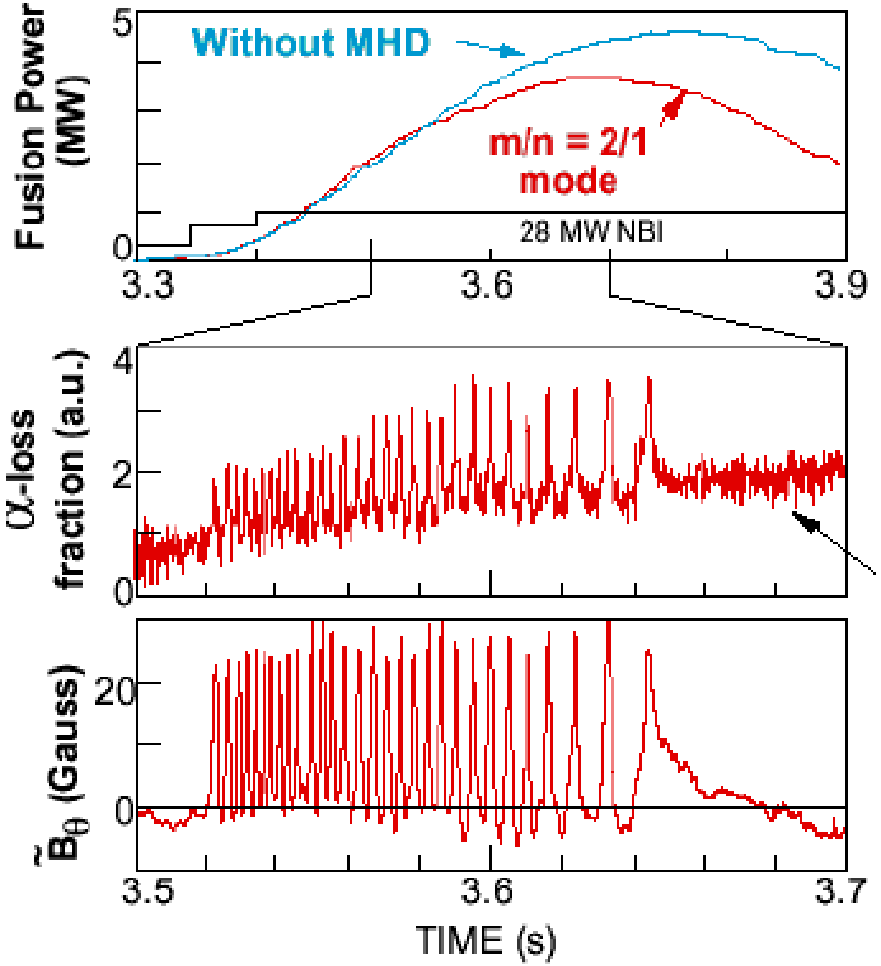
q(0) ≈ 2.1

Alpha Particles and MHD

Enhanced losses through instabilities

- **In TFTR, strong anisotropic loss was observed as the NTM mode was rotating:**
  - Disruptions, kinetic ballooning modes and sawteeth were also observed to generate α-particle losses

- **Typically, sawteeth produced a large radial redistribution of α-particles**



K M McGuire et al, IAEA-16, Montreal (1996)

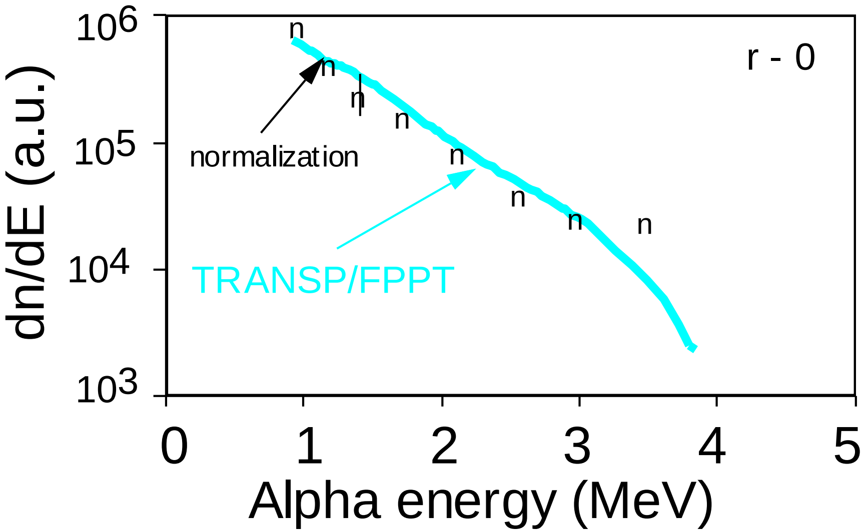
Experimental Results in DT Plasmas:

α-Particle Behaviour

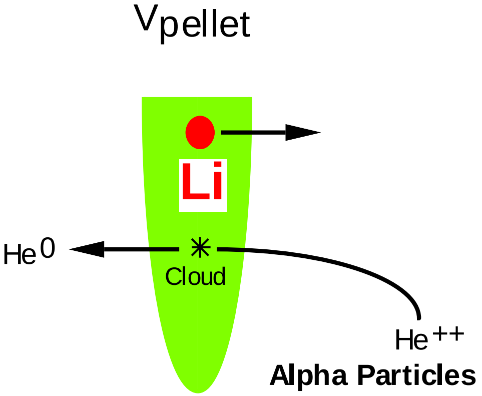
α-Particle Behaviour

Classical slowing down

- **In TFTR, measurements were made of the slowing down spectrum of α-particles:**
  - Both charge exchange spectroscopy on lithium pellets and charge exchange spectroscopy on neutral beams confirmed classically calculated slowing down spectrum



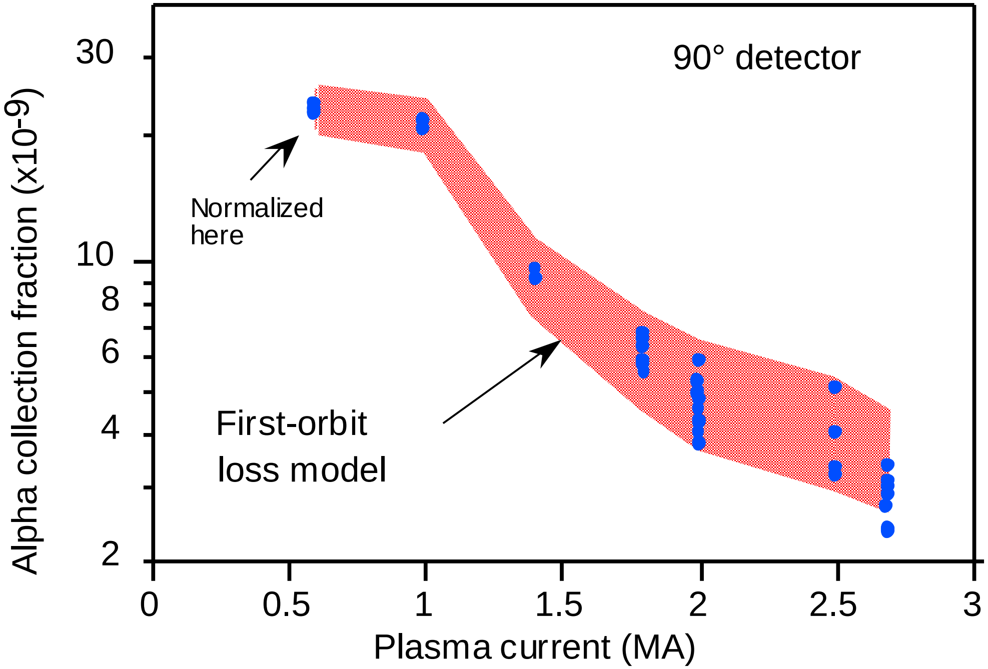
- **Confirms interaction between 3.5MeV α-particles and thermal plasma is as expected theoretically**

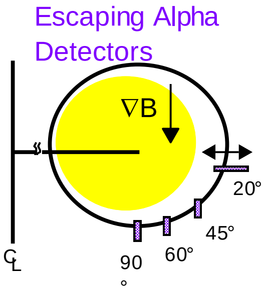


R K Fischer et al, Phys Rev Lett **78** 846 (1995)

α-Particle Behaviour

Classical confinement



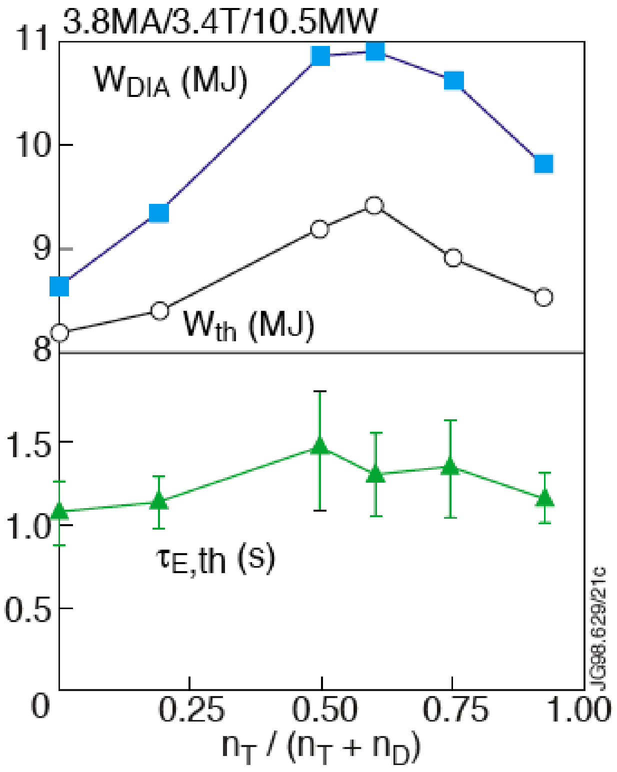


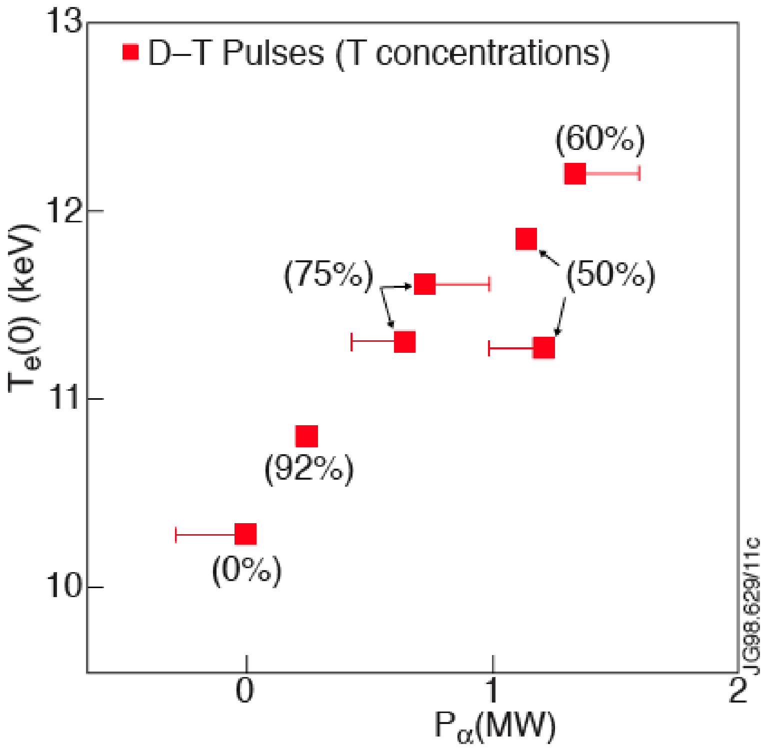
- **Measurements made of escaping α-particles at 90º to midplane as a function of plasma current:**
  - escaping α-particle flux was observed to be consistent with classical first orbit losses

R J Hawryluk et al, IAEA-15, Seville (1994)

α-Particle Behaviour

Electron heating





P R Thomas et al, Phys Rev Lett **80** 5548 (1998)

- **In JET, a controlled scan of tritium concentration demonstrated that maximum stored energy and electron temperature correlated with maximum fusion power and optimum DT mix:**
  - confirms that α-particles heat the electrons efficiently as expected

Experimental Results in DT Plasmas:

Fusion Power Production

Fusion Power Production

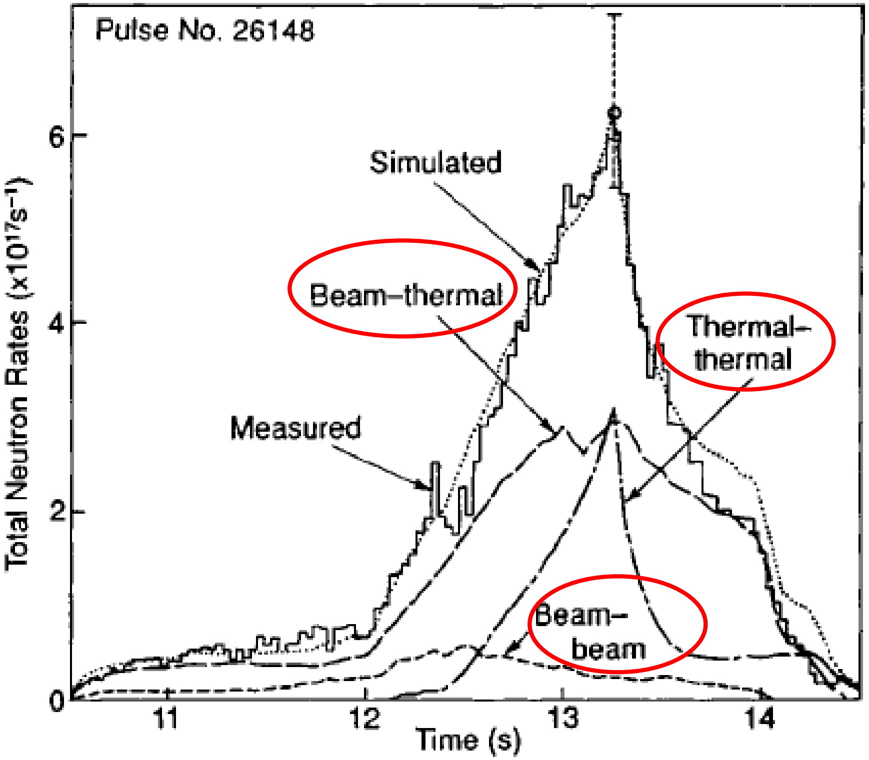
- **During the 1990s a series of experiments were designed to optimize DT fusion power production from tokamak plasmas:**
  - To achieve highest possible fusion power and highest Q values
  - To investigate highest powers which could be achieved in stationary operation
  - To allow α-particle heating of plasmas to be detected
- **Plasmas were optimized to achieve the maximum total power achievable:**
  - typically this involved developing low density target plasmas into which high power neutral beams were injected:
    - JET: hot-ion H-mode
    - TFTR: supershot

Fusion Power Production

Contributions to Fusion Reactivity

- **In present devices, the fusion power production is made up of several components:**
  - reactions between thermal plasma particles (thermal- thermal)
  - reactions between injected beam ions and thermal particles (beam-thermal)
  - reactions between injected beam ions themselves (beam-beam)
- **Figure shows a comparison between measured total neutron yield and calculated components of neutron production in JET PTE (11% tritium)**

JET Team, Nucl Fusion **32** 187 (1992)

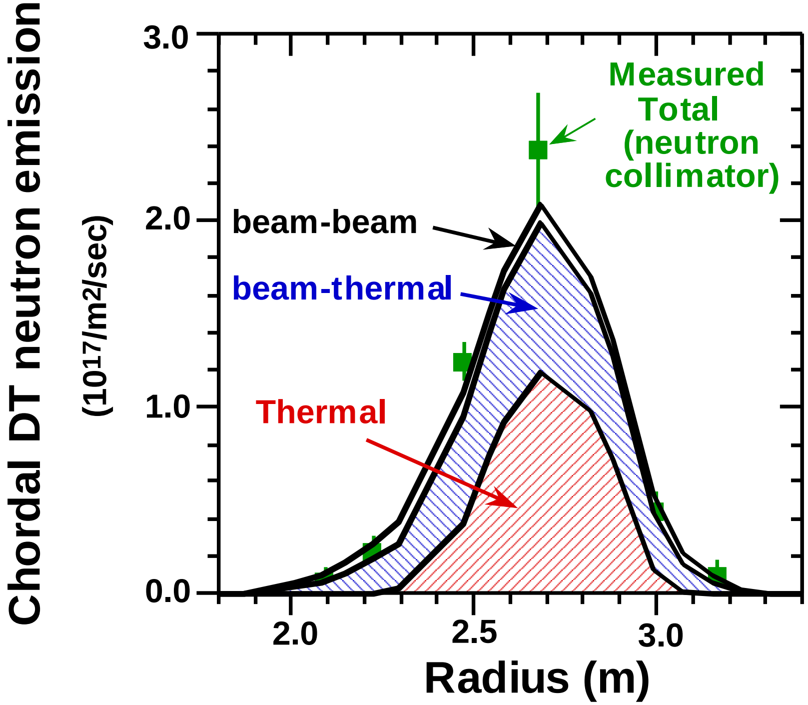


JET PTE (1991)
1.7MW fusion power

Fusion Power Production

Contributions to Fusion Reactivity

- **Analysis of TFTR supershots shows a similar behaviour:**
  - for a measurement chord through the plasma core, thermal and beam-thermal reactions contribute ~50% of total
  - towards plasma edge, lower plasma temperatures imply that beam-thermal contribution gradually dominates - but at significantly lower reaction rate



TFTR DT (1994-1997)

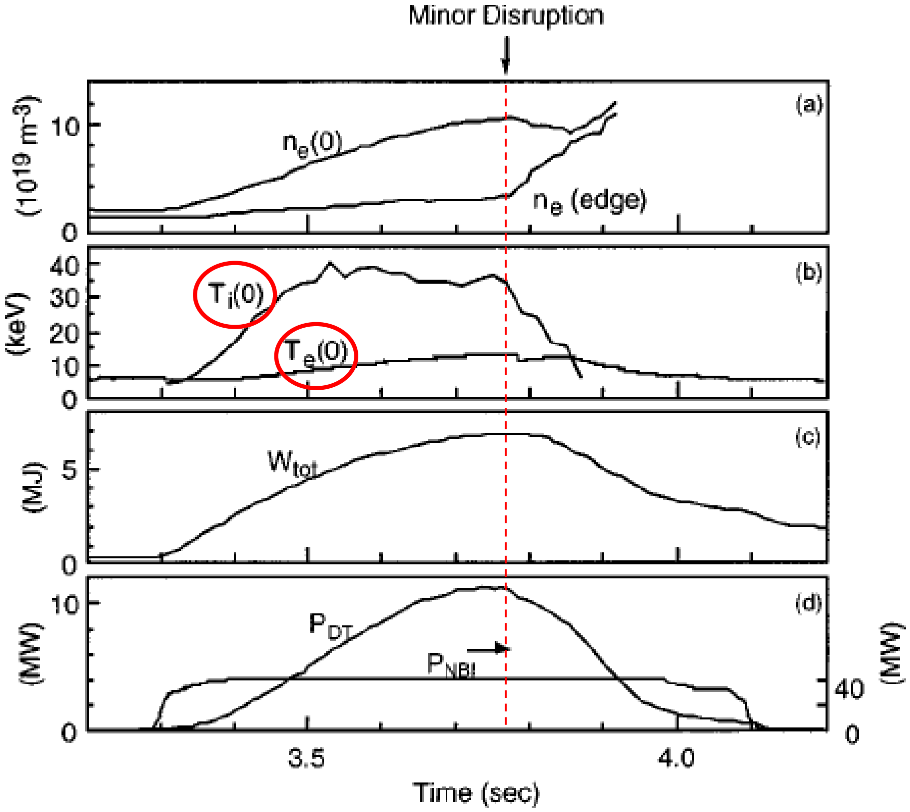
R V Budny et al, Nucl Fusion **35** 1497 (1995)

Fusion Power Production

TFTR Supershot

- **The best TFTR supershot produced 11MW of DT fusion power with ~40MW of NB input power:**
  - Q = 0.27

- **The high fusion power pulse lasts less than 1s due to a combination of MHD instability and a subsequent influx of impurities ("carbon bloom')**

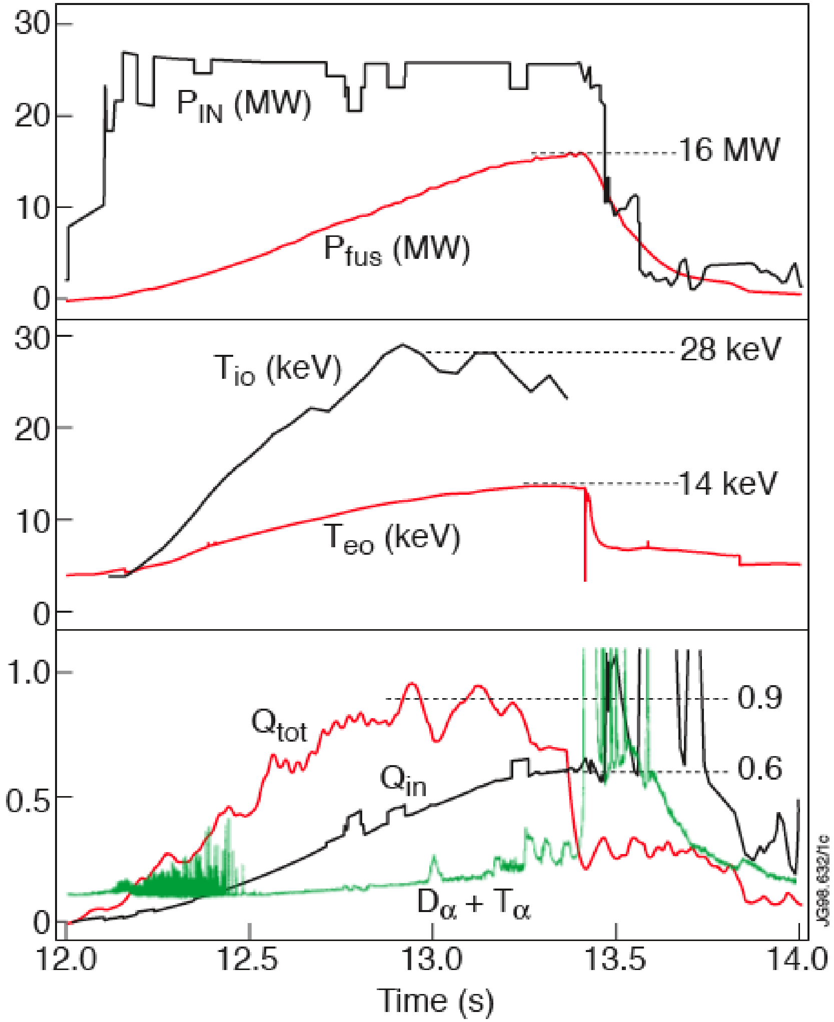


R J Hawryluk et al, Phys Plasmas **5** 1577 (1998)

Fusion Power Production

JET Hot-Ion H-mode

- **JET hot-ion H-modes follow a similar time behaviour to TFTR supershots:**
  - P_{fus} = 16MW
  - Q = 0.6
- **The high fusion power pulse again lasts about 1s due to a combination of MHD instability and a subsequent influx of impurities ("carbon bloom')**



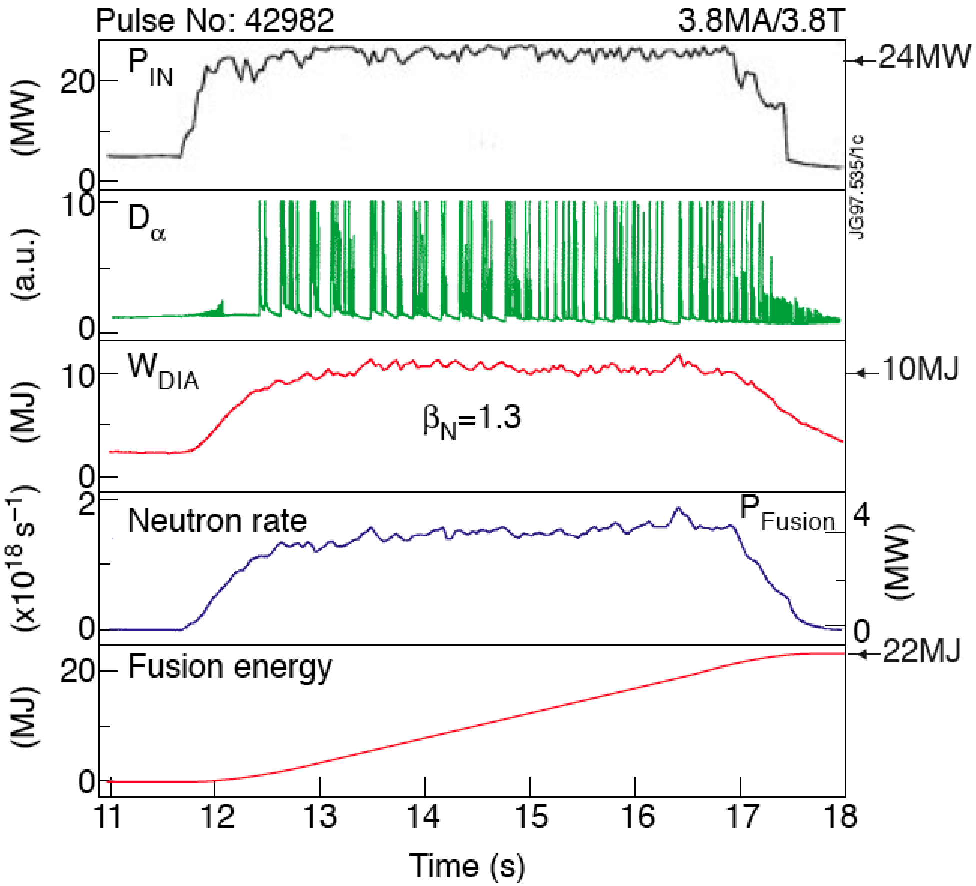
M Keilhacker et al, Nucl Fusion **39** 209 (1999)

Fusion Power Production

JET ELMy H-mode

- **Stationary fusion power production can be established in an ELMy H-mode - here 5s:**
  - P_{fus} = 4MW
  - Q = 0.16
  - E_{fus} = 22MJ
- **The duration of fusion power production in this type of plasma is limited to 5s by choice of the experimentalists:**
  - duration of 5s allows stationary conditions to be demonstrated

⇒ ITER reference plasma

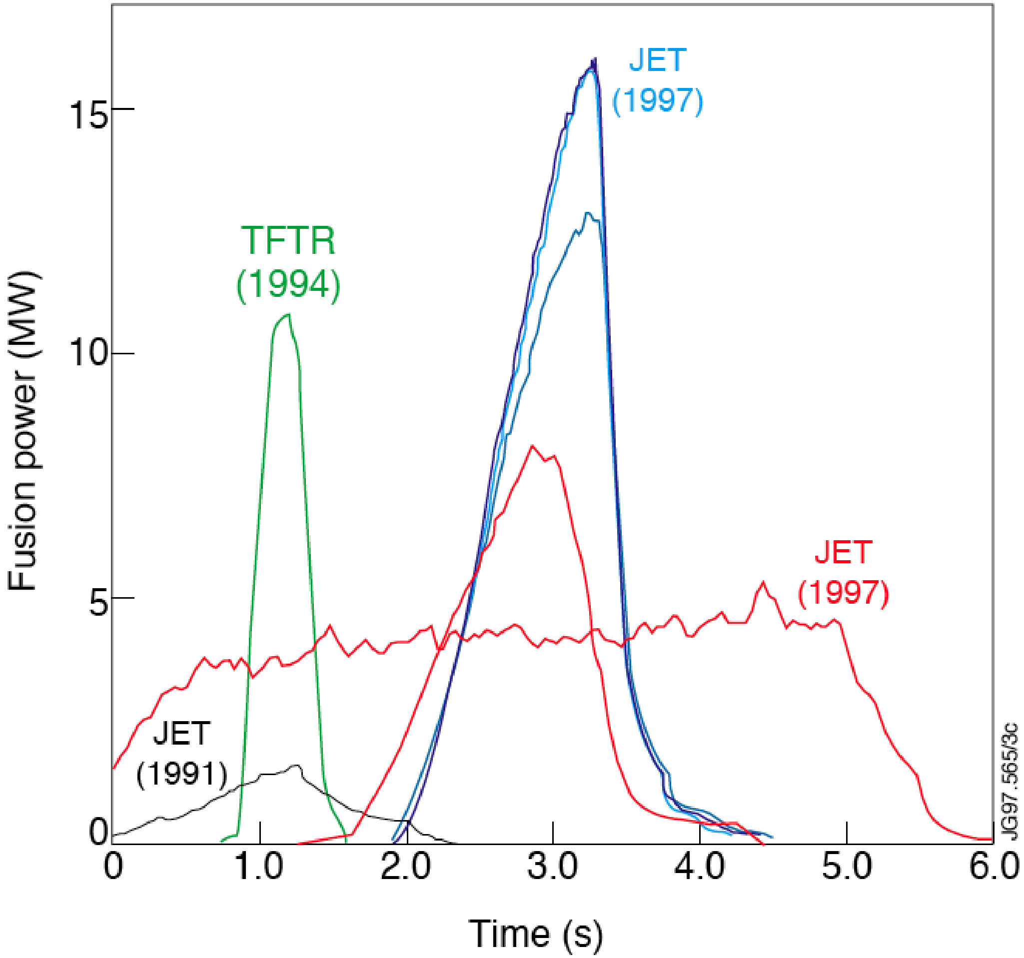


J Jacquinot et al, Nucl Fusion **39** 235 (1999)

Fusion Power Production

Overview

- **Summary of best fusion power performance achieved in DT experiments in JET and TFTR**



Conclusions

- **The magnetic fusion programme made the significant transition to operation with DT fuel mixtures during the 1990s**

- **Experiments in JET and TFTR made significant contributions to the progress of fusion energy research:**
  - demonstrated of safe handling of tritium
  - developed understanding of influence of tritium on plasma performance
  - Characterized behaviour of plasmas with significant α-particle content
  - confirmed expected behaviour of α-particles $\Rightarrow$ demonstrated α-particle heating of plasmas
  - demonstrated fusion power production and verified code predictions of plasma fusion performance
  - addressed tritium retention and studied means for removal of tritium from vacuum vessel
  - subsequently, safe remote maintenance of tokamak

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