DT experiments On JET

D Stork
Euratom-UKAEA Fusion Association,
Culham Science Centre,Abingdon, Oxfordshire OX14 3DB, UK

With acknowledgement to many colleagues in the former JET Joint Undertaking and JET EFDA contributors

Outline

- Chronology
- JET's unique DT capability
- The first Deuterium-Tritium Experimental (DTE1) Campaign
- The Trace Tritium Experimental (TTE) Campaign
- Building on DTE1 and TTE for future progress

Chronology

- **Three campaigns with DT operation in JET**
  - **Preliminary Tritium Experiment (PTE) – November 1991**
    - **One day – Two plasma shots(!!).**
    - **Tritium injected by NBI. 10% T concentration plasmas**
    - **> 1.7 MW fusion power for 1 sec.**
  - **Deuterium-Tritium Experimental Campaign 1 (DTE1) – May – November 1997**
    - **~ 500 pulses with DT plasmas**
    - **$10^{-2} < n_T/(n_T+n_D) < 0.95$**
  - **Trace Tritium Experimental Campaign (TTE)**
    - **Tritium introduced into JET on >150 pulses**
    - **$n_T/(n_T+n_D) \approx 3.\ 10^{-2}$**

JET's unique DT capability

- JET has a unique capability to study DT tokamak plasmas and processes coupled with a *Divertor configuration* and an operational *Tritium recycling and purification plant.*
- Several ITER-related DT-specific physics topics can be tackled:
  - 'ELMy H-mode' validation at high density ($n_e \approx n_{Greenwald}$)
    - concept improvement evaluation (impurity seeding, high triangularity, density peaking)
  - 'Advanced Tokamak' regime investigation
    - α-particle confinement with high central q
    - isotope effects (threshold, confinement, core-edge interaction)
  - **core** α-heating physics and MHD characterisation
  - DT compatible RF heating scheme qualification
- 'Live' tritium technology testing
- Validation and demonstration of high gain plasmas ($0.5<Q<1$)

DTE1

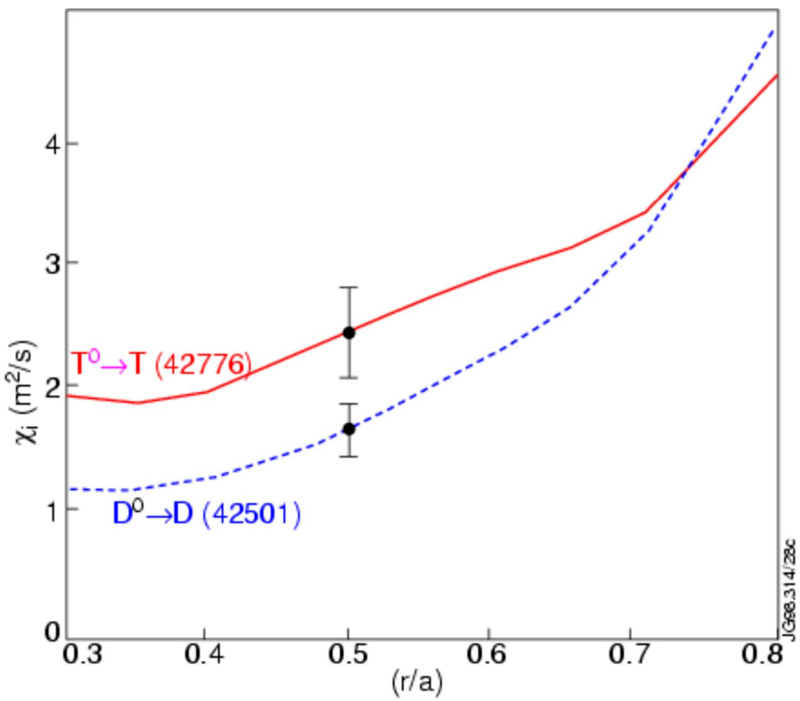
- **Campaign areas**
  - High fusion gain performance (high Q)
    - ELM-free Hot Ion H-mode (transient Q up to ~ 0.9)
    - Advanced scenario ITB plasmas with Optimised Shear
  - ELMy H-mode physics
    - Studies of $\rho*$ scaling
    - Transport studies
    - Isotope effects on confinement and L-H threshold
  - α-heating studies
  - DT-relevant RF heating physics
- Overall phenomenology of tritium retention also emerged from this campaign.

DTE1 results: ELMy H-mode

- Thermal transport in ELMy H-mode DT plasmas similar to DD plasmas (no strong mass dependence $\tau_E \sim A^{0}$);
- Scaling of stored energy is a composite of:
  - stored energy in the edge pedestal showing stronger isotope scaling ($\sim A^{0.5}$) consistent with pressure limit acting over an ion Larmor radius;
  - and 'core' stored energy with a confinement scaling ($\tau_E \sim A^{-0.2}$) – short-wavelength or Gyro-Bohm turbulence.
- H-mode threshold **lower** in DT than in DD ($P_{L\text{-}H} \sim A^{-1}$);
- ELMy H-mode $\rho*$ scaling of DT plasmas shows Gyro-Bohm ($\sim\rho*^{-3}$) behaviour.

DTE1 results: ELMy H-mode

- Analysis shows Ion thermal transport differs in core and edge.
- Pedestal Energy (W_{ped}) at r/a >0.85 shows strong A scaling ($A^{0.5}$) consistent with MHD as the limiting behaviour.
- Underlying core thermal diffusivities are fitted by ~ $A^{0.75}$ –stronger than Gyro-Bohm scaling ($A^{0.5}$)



J G Cordey et al NF**39**(3) (1999)301

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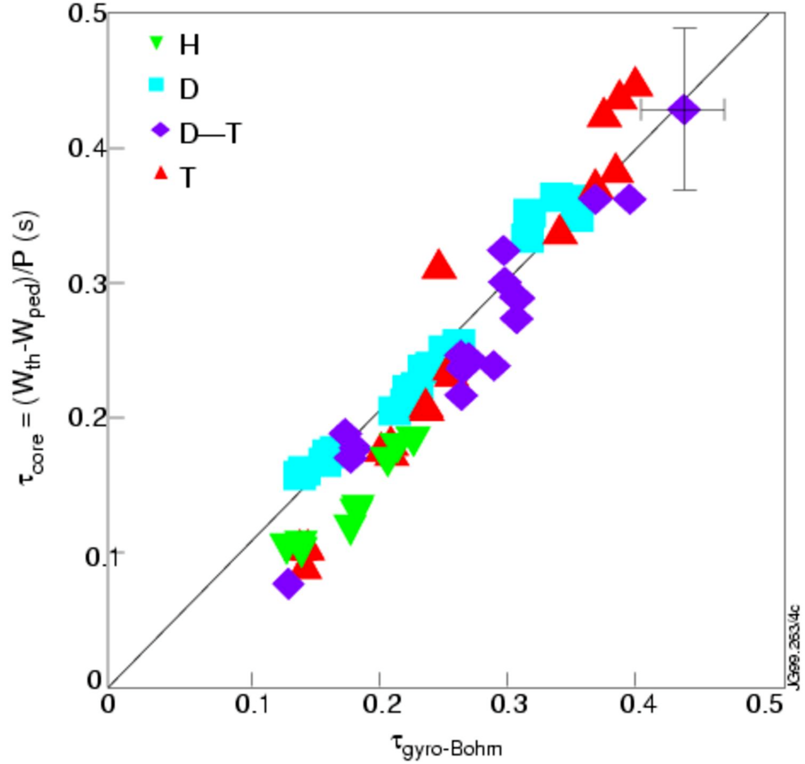
- Underlying core thermal diffusivities are fitted by ~ $A^{0.75}$ –stronger than Gyro-Bohm scaling ($A^{0.5}$)
- If W_{ped} is subtracted from the Total energy – gives the 'Core energy' (W_{core})
- τ_{core} is Gyro-Bohm scaling (best fit is $A^{-0.17\pm0.1}$)

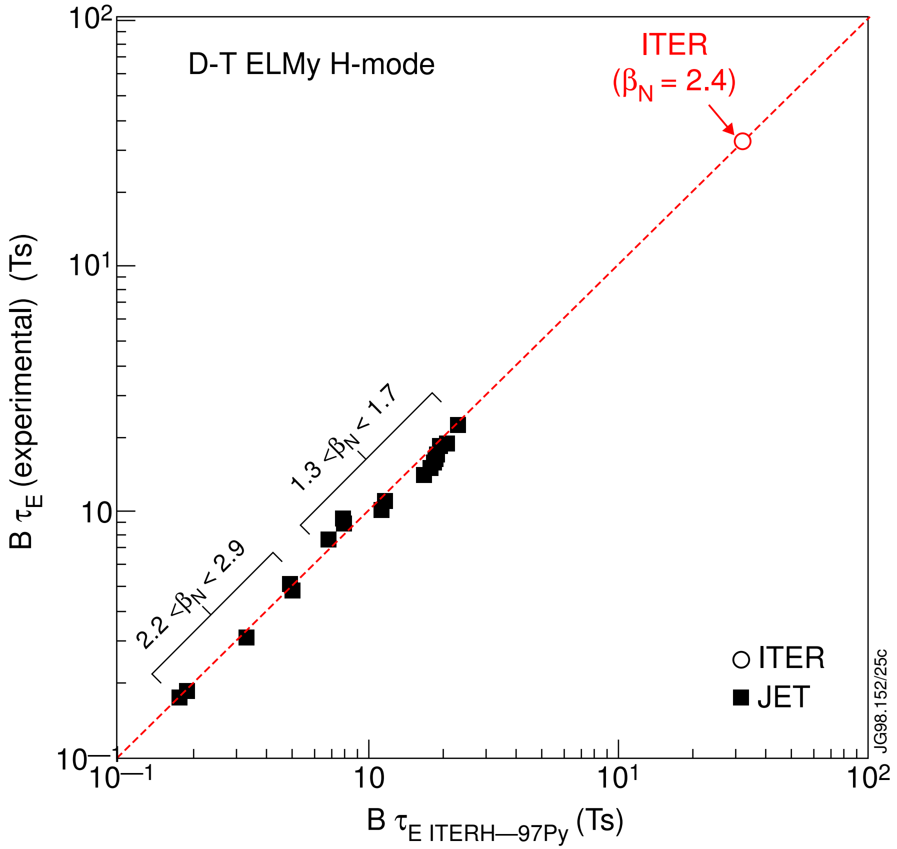


τ_{GB}~ $B^{0.8}a^{3}n^{0.6}P^{-0.6}A^{-0.2}$

J G Cordey et al NF**39**(3) (1999)301

DTE1 results : dimensionless scaling to ITER

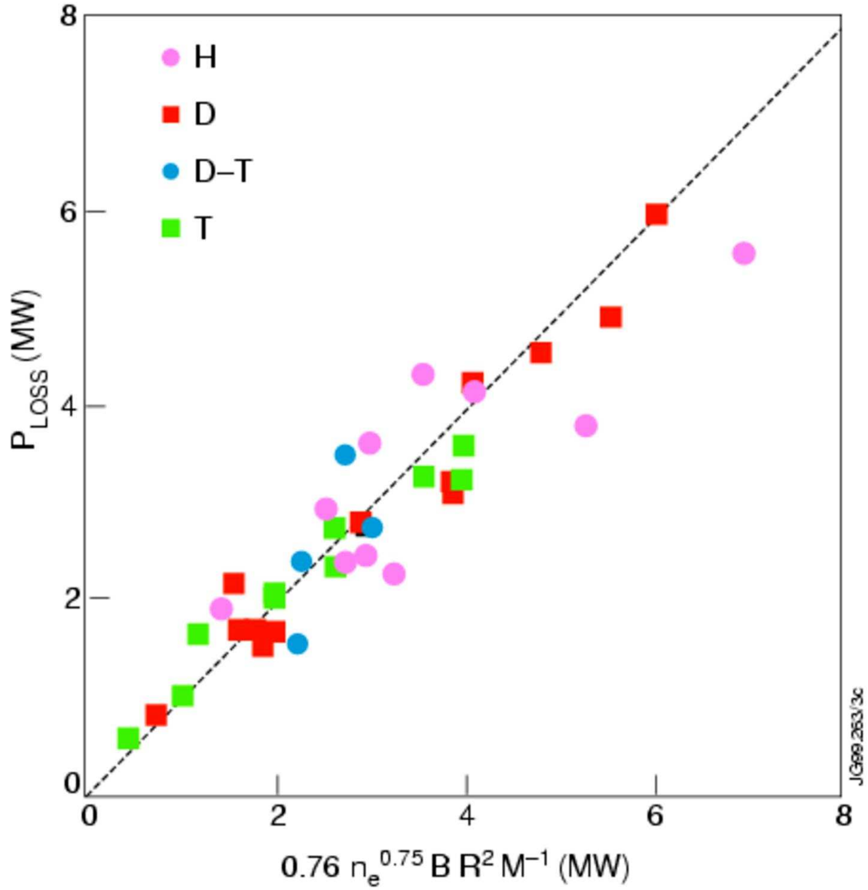
- JET D-T 'wind tunnel' experiments set up ELMy H-modes with the(then) ITER q, β_N and $\nu*$.
- The data set extrapolated to ITER (ITER-EDA shown) using the standard H-mode scaling.
- Global confinement is in the D-T plasmas was close to Gyro-Bohm scaling ($\omega_C\tau_E \sim \rho^{*-3}$)



J Jacquinot et al, Nuc Fus 39(2)(1999), 235

DTE1 results :

L-H transition power is lower in D-T plasmas



DTE1 results: α-heating

- Electron heating by α -particles observed in DT plasmas;
- no TAE or other instabilities seen to be caused by α – particles ($\beta_{\alpha} \sim 10^{-3}$ max).

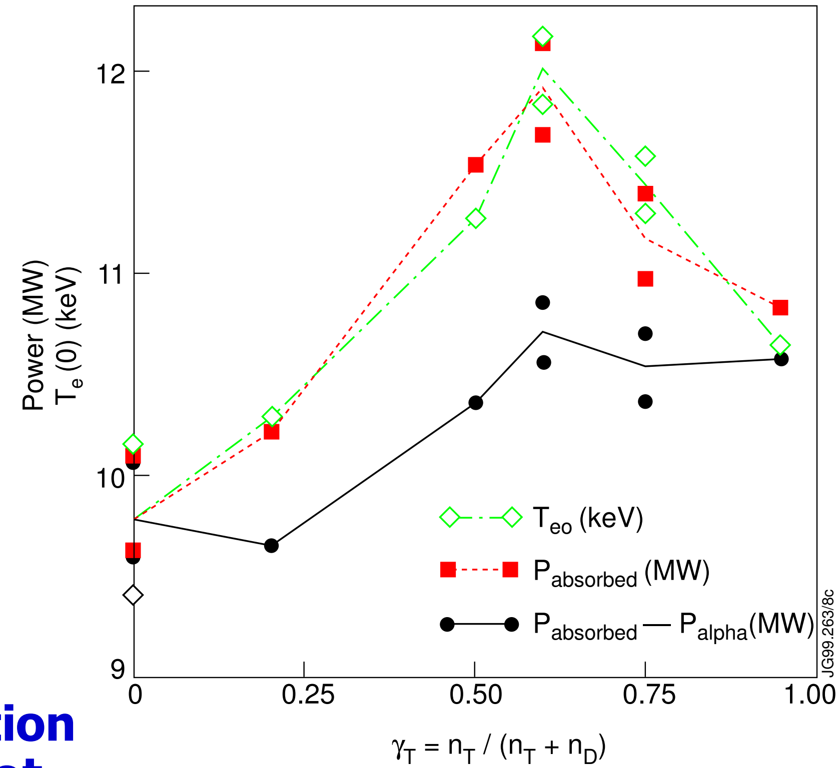
DTE1 results : electron heating by α - particles

- At fixed input power, the ratio of T:D (including the T^0 NBI : D^0 NBI) was varied in otherwise similar ELM-free H-mode plasmas (Q~0.65)

- $R_\alpha \propto n_T n_D$ -- as $\gamma_T = n_T / (n_T + n_D)$ varies, expect to see $P_{\alpha e}$ reach maximum at ~ γ_T ~ 0.5

- These experiments limited to $\langle\beta_\alpha\rangle^{max}$ ~ 4. 10^{-4} –hence well below threshold of expected TAE modes.

- Note that the ELM-free phase duration ~ 1-2 $\tau_{s\alpha}$ thus the experiment does not test steady state

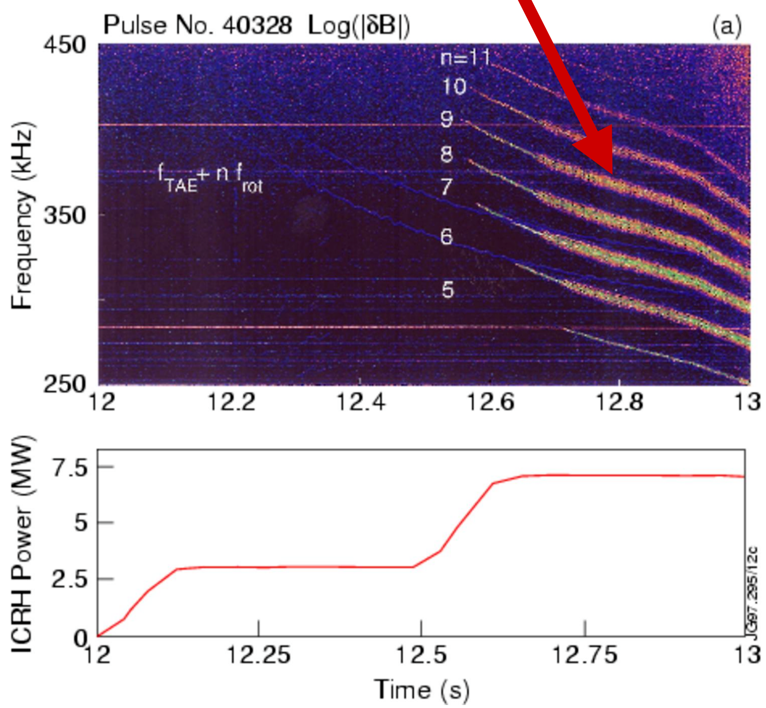


P R Thomas et al, PRL 25(1998),5548

DTE1 results :
α - particle instabilities absent

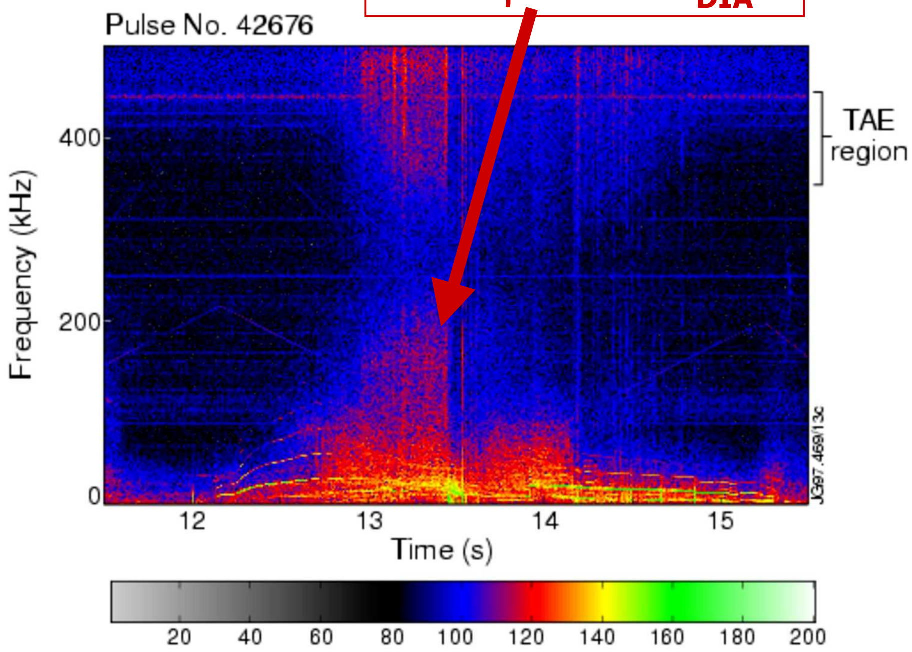
- **Clear TAE activity seen in RF heated ($2\omega_{CT}$) DT discharges**

TAE activity from >1 MeV tritons



- **But no TAE activity seen in High performance Hot-Ion DT H-modes**

Peak β from W_{DIA}



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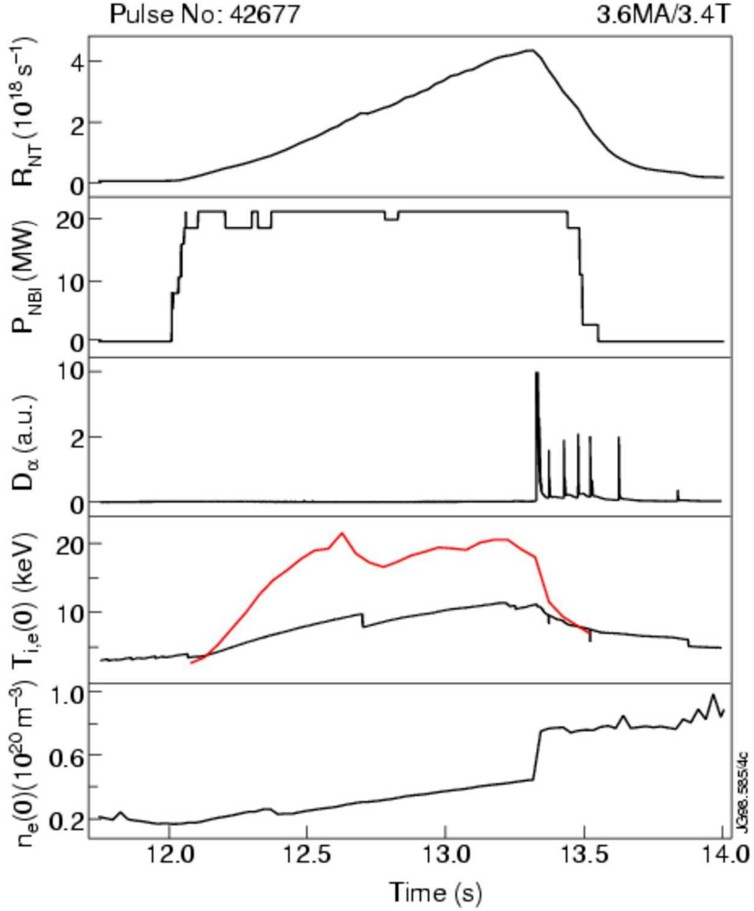


- **ELM-free H-mode DT discharges in DTE1 reached $<\beta_\alpha>$~ 8.10^{-4} – 10^{-3} (~ half foreseen ITER-EDA value), with $\beta_\alpha(0)$ ~ 6.10^{-3}.**

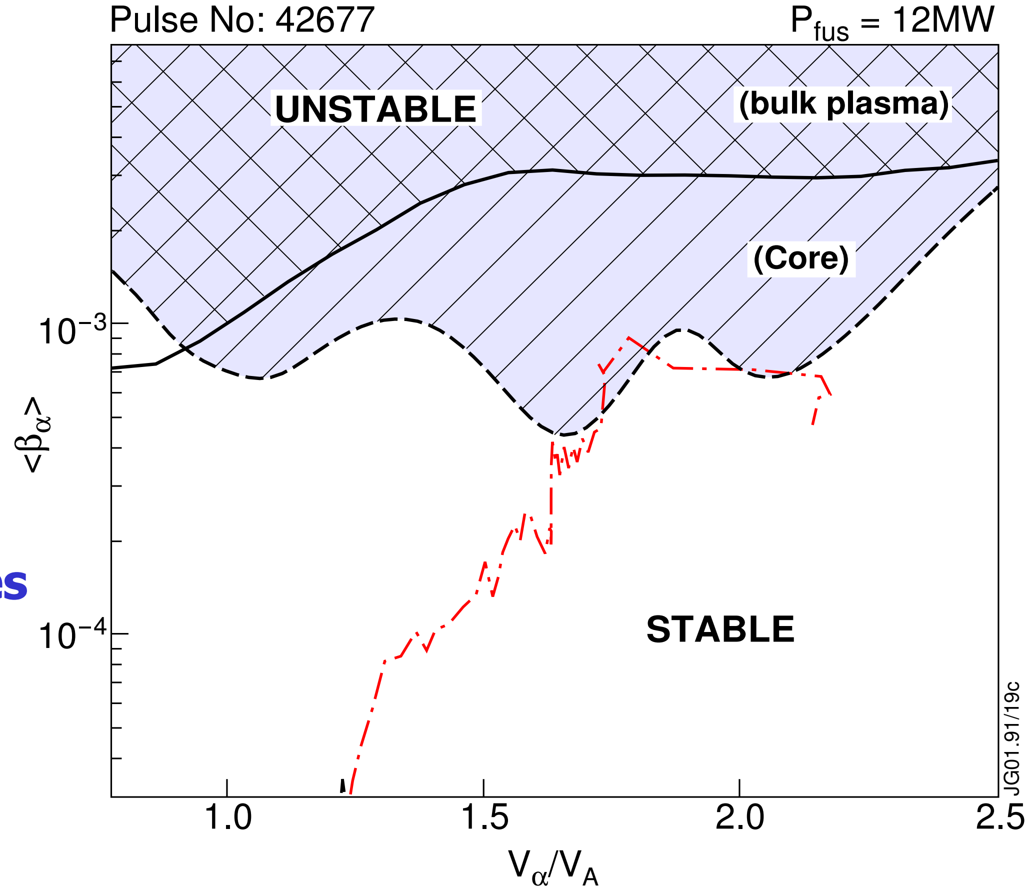
S Sharapov et al Nucl Fus **39**(3) (1999) 373

Q (=P_{fus}/P_{in})~0.65; P_α~2.4 MW

DTE1 results :
α - particle instabilities absent

- **ELM-free H-mode DT discharges in DTE1 reached $<\beta_\alpha>$~ $8.10^{-4} - 10^{-3}$ (~ half foreseen ITER-EDA value), with $\beta_\alpha(0)$ ~ 6.10^{-3}.**

- **These discharges were close to the lower stable boundaries for core TAE modes – no instabilities seen.**

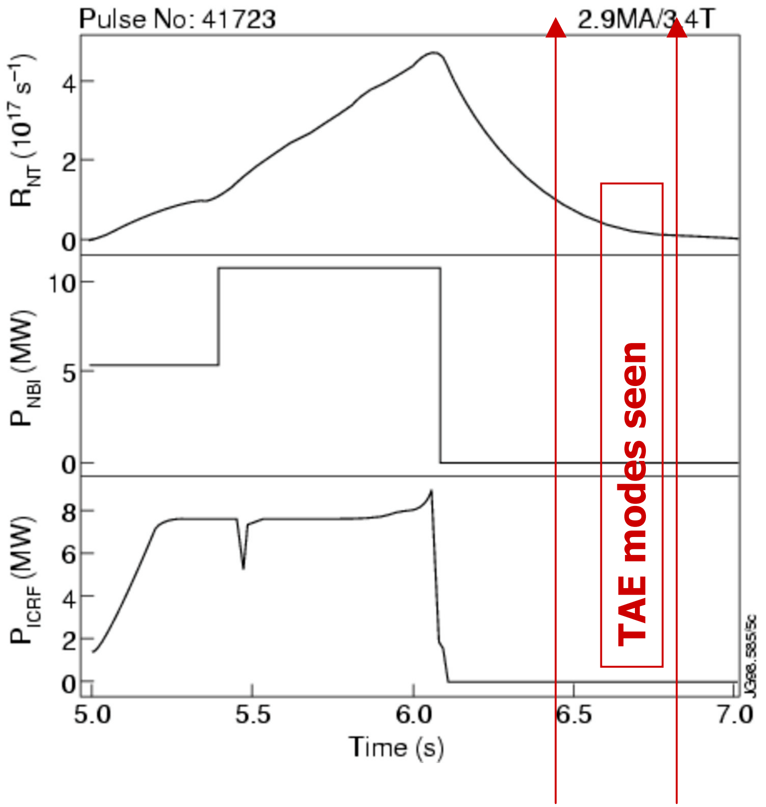


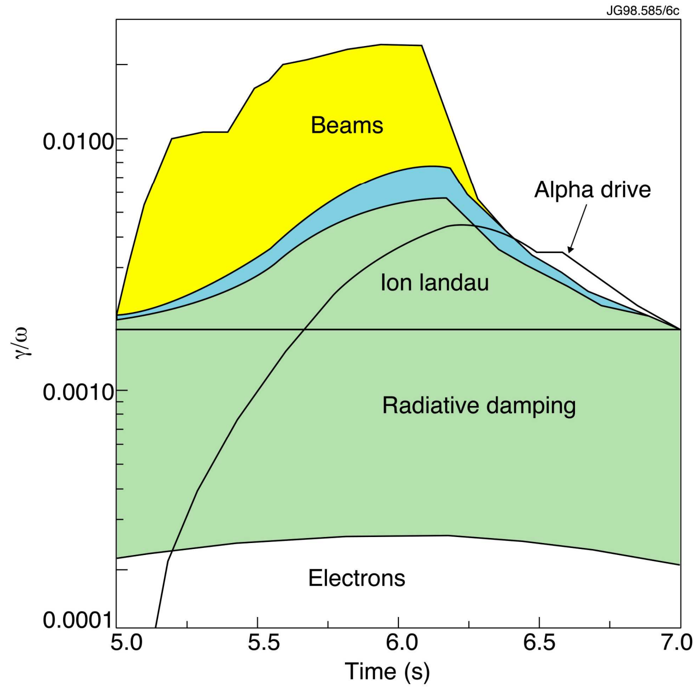
S Sharapov et al Nucl Fus **39**(3) (1999) 373

Q (=P_{fus}/P_{in})~0.65; P_α~2.4 MW

DTE1 Results:
Dependence of TAE excitation thresholds

- **After the high β phase in DT ITB plasma. TAE modes were seen from ~6.5s**
- **AE fusion alphas drive terms overcome damping in afterglow after NBI switch-off**





Sharapov, Borba, Fasoli et al NF39 (1999) 373

DTE1 results : RF heating

- 3 schemes tested:
  - (D)T with low concentration D (<20 %);
  - (^{3}He)DT proposed ITER scheme (at the time);
  - ($2\omega_{CT}$)DT another possible ITER scheme
- Results for all schemes show good agreement with prediction from the PION code.
- ^{3}He minority scheme showed much higher efficiency than ($2\omega_{CT}$).
  Poor efficiency of the second harmonic scheme partly due to very large orbits from highly accelerated tritons – losses from plasma as orbits intersect the walls.

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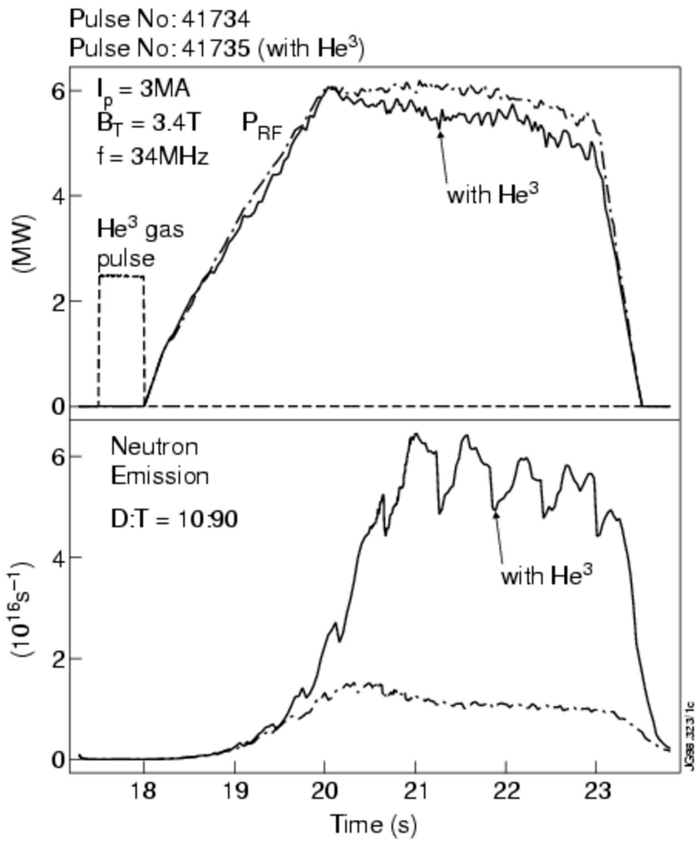
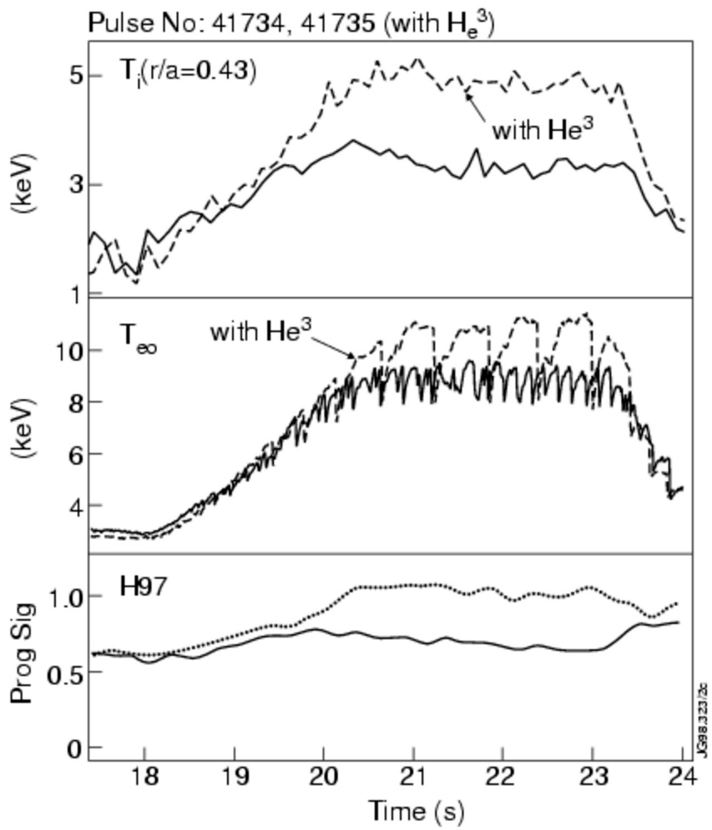
DTE1 results : RF heating

- Adding ^{3}He minority increases RF heating fusion yield
- This is due to improved Ion heating efficiency





DFH Start et al, NF39(1999),321

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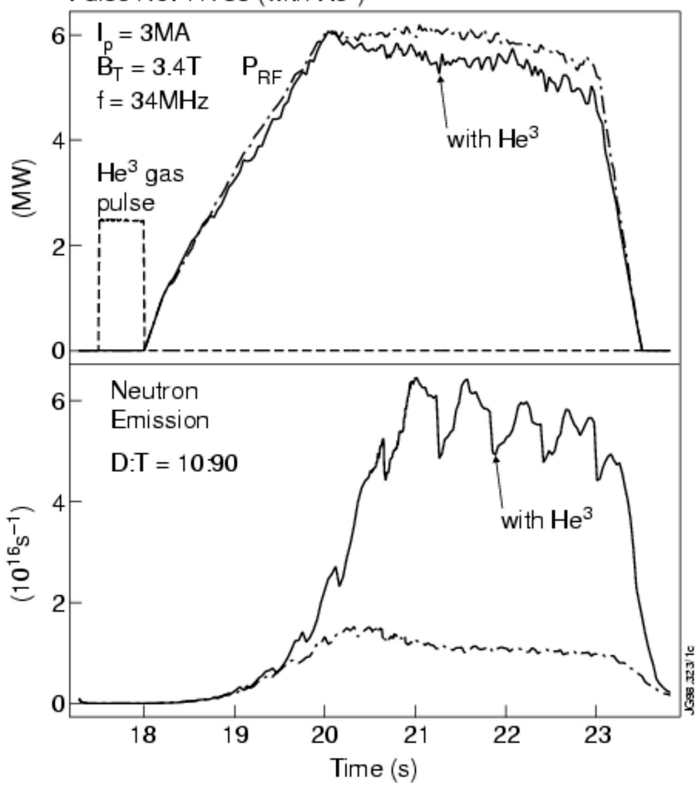
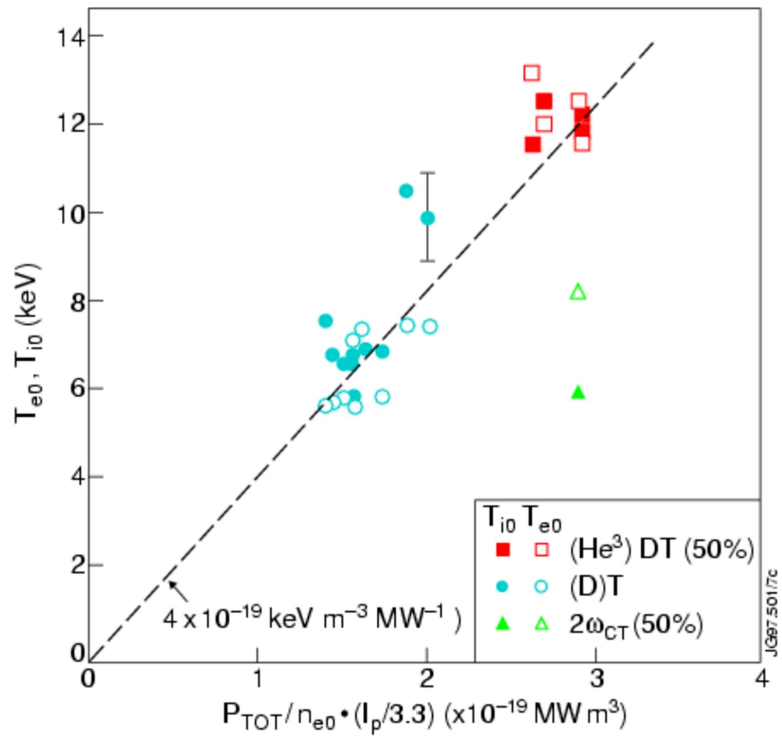
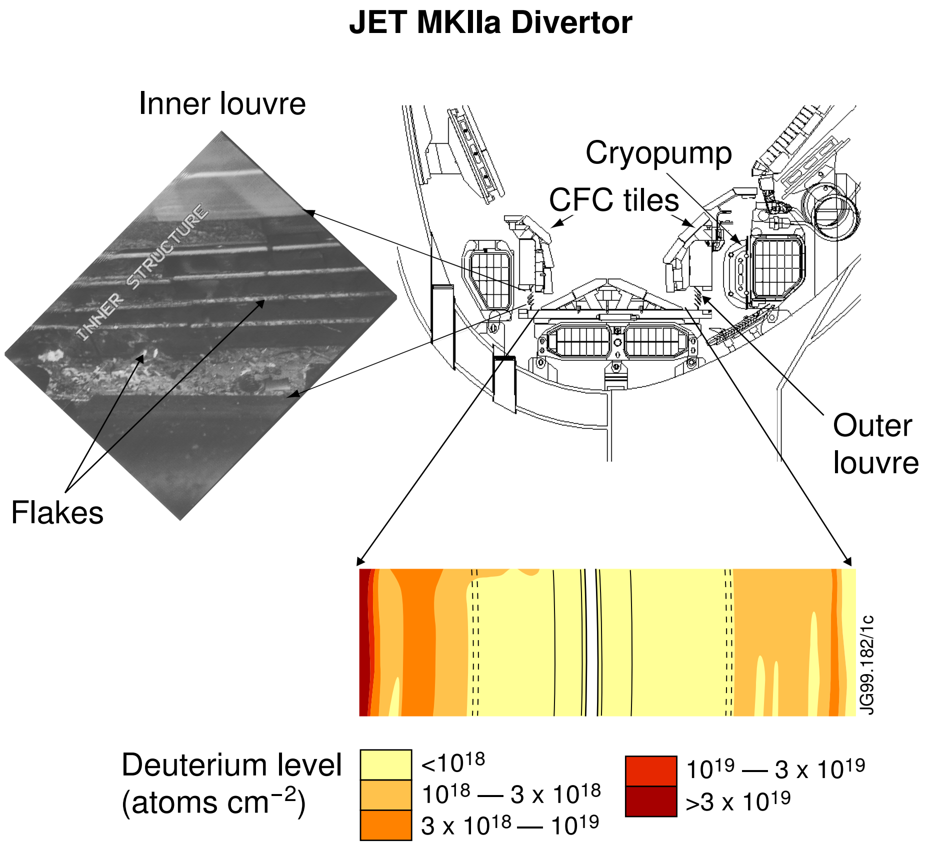


DFH Start et al, NF39(1999),321

- This is due to improved Ion heating efficiency
- Efficiency of ^{3}He minority is > efficiency for $2\omega_{CT}$ due to the latter's orbit losses



DTE1 results : Tritium retention in Torus

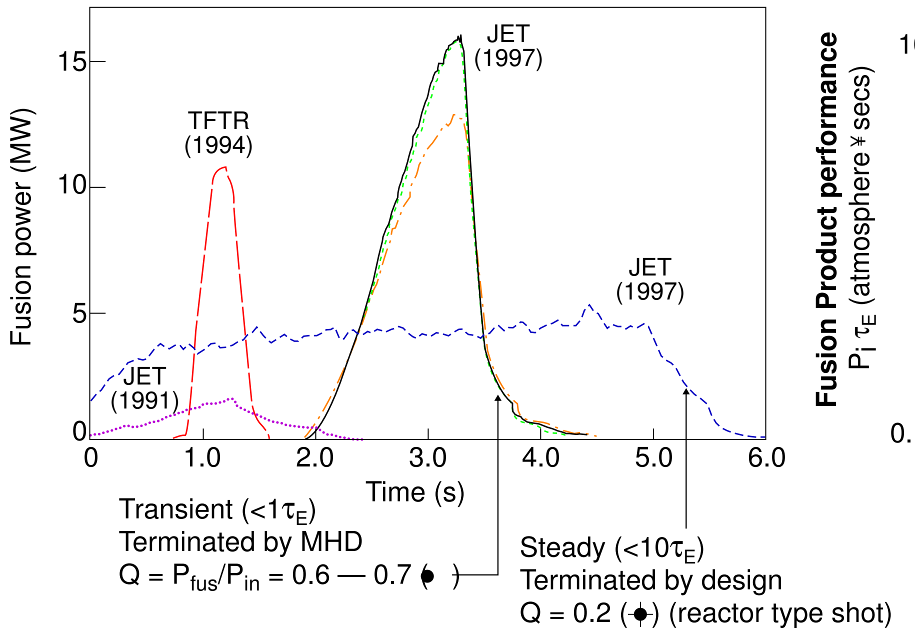


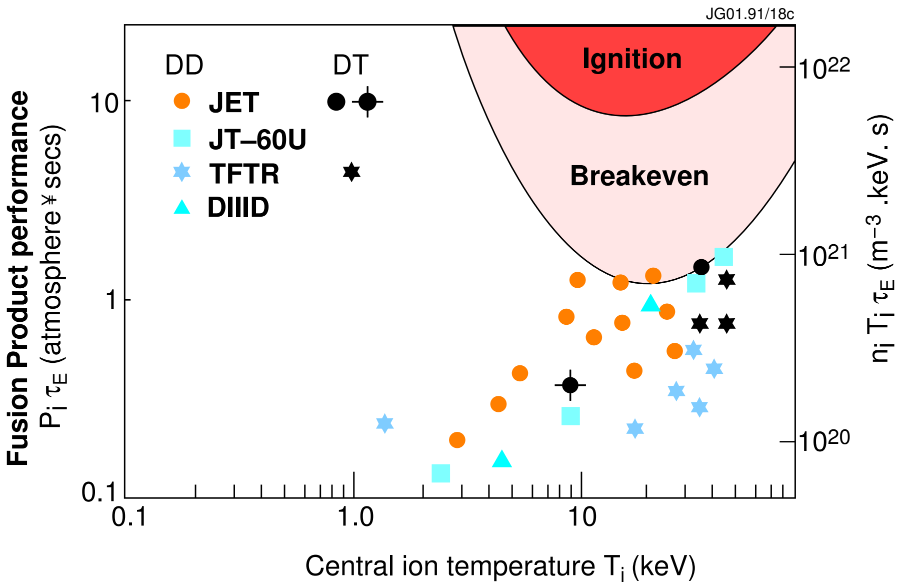
P L Andrew, J P Coad at al., J Nucl Mater 1999

- 6 g out of 35 g tritium retained ***Most retained in carbon flakes at inner Divertor louvres***
- Strong SOL flow drives impurities to inner target
- Inner divertor plate is colder, thus deposition dominates
- Flakes may result from C_2H_x release from hydrogen-rich amorphous films
- Serious consequences for ITER/reactor if not solved - rules out CFC for reactors?

DTE1 results :

transient and 'steady-state' fusion power



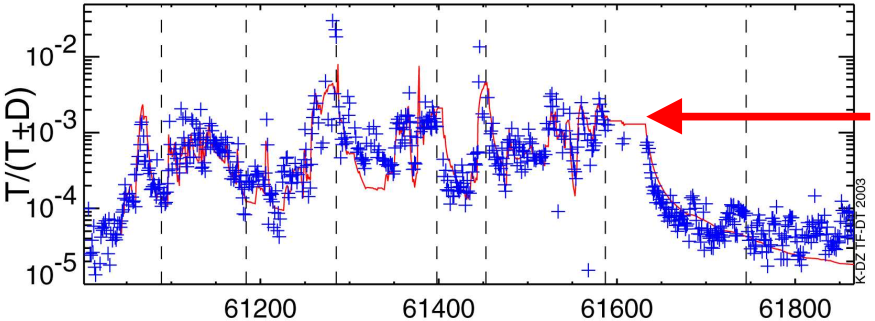


JET: M Keilhacker et al, Nucl Fus 39(2)(1999), 209
J Jacquinot et al, Nucl Fus 39(2)(1999), 235
TFTR: K McGuire et al, Fusion Energy 1996 (Vol 1), 19
(IAEA-CN-64/01-2)

•Back

The JET "Trace Tritium" campaign

- The Trace Tritium Experiment (**TTE**) took place in September-October 2003.
  - Plasmas used Tritium in 'trace' quantities $\mathbf{n_T/(n_T+n_D) \leq 3\%}$ introduced by:
    short T_2 gas puffs (≤ **6 mg**);
    or T^0 beam injection (**~ 100-300 ms** ' blips')
  - At these levels, the plasma 14 MeV and 2.5 MeV neutron yields are ~ equal - gives maximum statistical precision from JET's neutron detectors.



Data derived from S/S 2.5:14 MeV neutrons

During TTE the **wall tritium fraction** kept at <0.5% by frequent pure **DD cleanup pulses**.

Ensured minimisation of background effects - enabled accurate quantification of tritium source

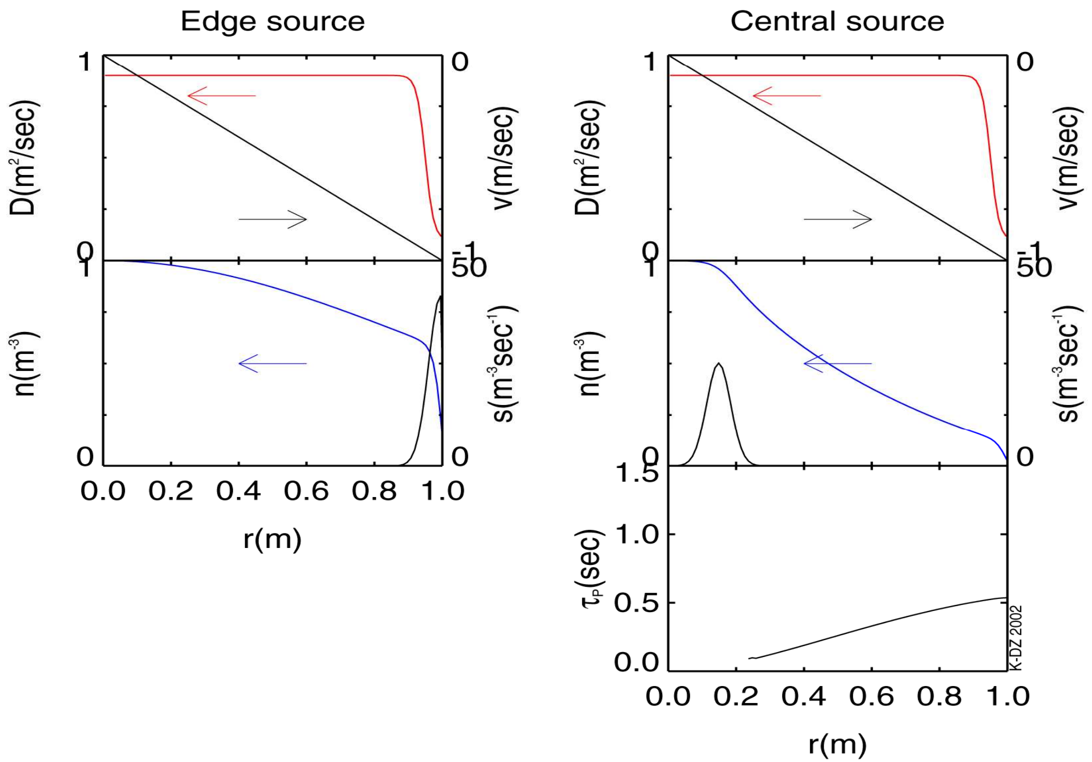
Use of tritium in Particle transport studies:

the ambiguity problem in steady-state

- What are the scalings of Fuel Ion transport in steady state?
- In principle solve the particle transport equations by fitting density profile and using sources.

$$\frac{\partial n}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(r\Gamma) + \sigma(t)$$

$$\Gamma = -D\frac{\partial n}{\partial r} + vn$$



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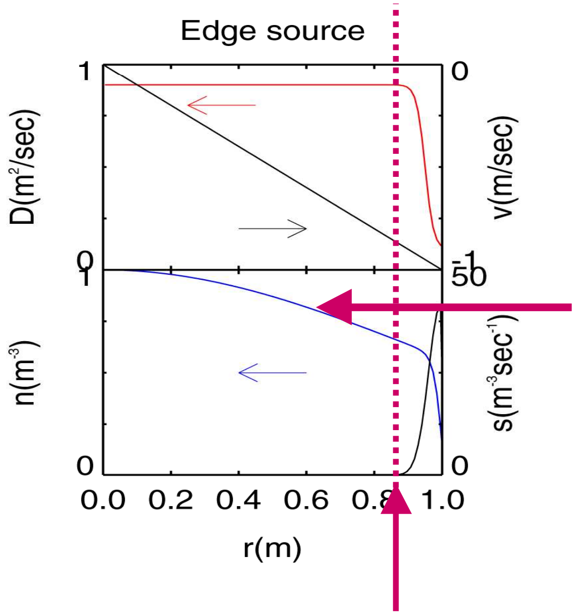

In eg.source-free case we can in principle integrate within r_{source}

$$n(r) = n(r_S)\exp\left(-\int_r^{r_S}\frac{v(r)}{D(r)}dr\right)$$

$$n(r_S) = \frac{\Gamma_0\lambda}{D(r_S < r < a)}$$

- Same solution obtained for $2\times\Gamma_0$, $2\times D$ and $2\times v$ etc.
- Transient experiments needed to resolve *D* and *v* separately

Use of tritium in Particle transport studies

- **All TTE experiments essentially non-perturbative in nature.**
- **Tritium introduction into plasmas where all relevant background parameters (T_e , n_e etc) remained in steady-state.**
- **D_T and v_T can be measured separately.** (unlike pure steady-state deuterium plasmas where only D_D/v_D is evaluated

$$\frac{\partial n}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(r\Gamma) + \sigma(t)$$

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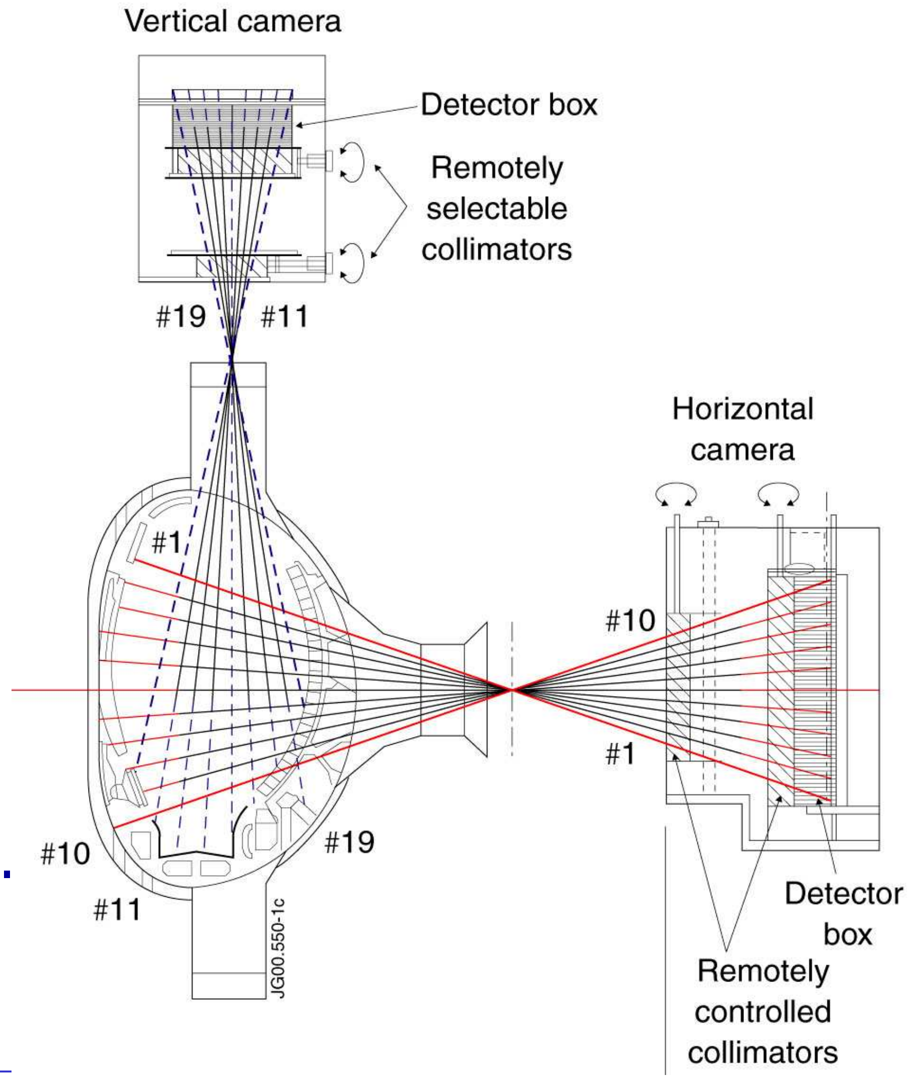
JET neutron profile monitor

- absolute 2.5 & 14 MeV neutron calibration.
- 19 channels at r/a<0.85
- 10 ms time resolution



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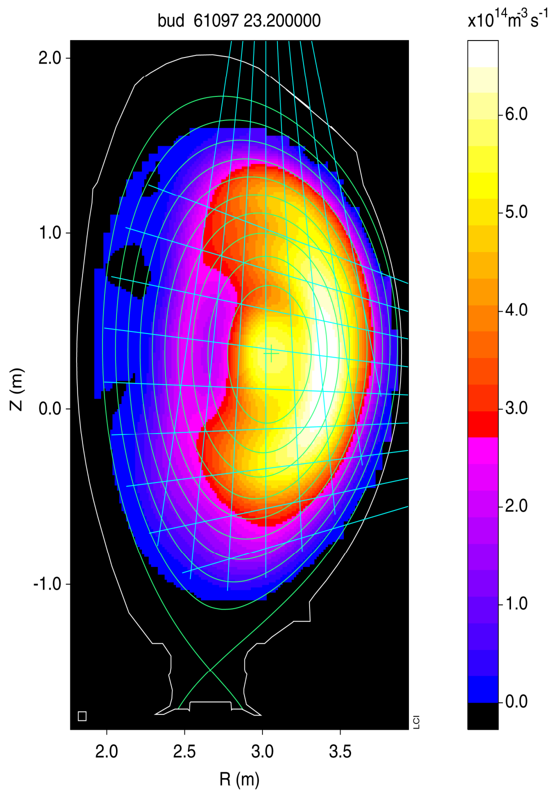
14 MeV emissivity contours: example immediately after T_2 gas puff



T_2 density is hollow: Fast D^+ from NBI are mainly outboard (trapped <u>and</u> passing)

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JET neutron profile monitor

- absolute 2.5 & 14 MeV neutron calibration
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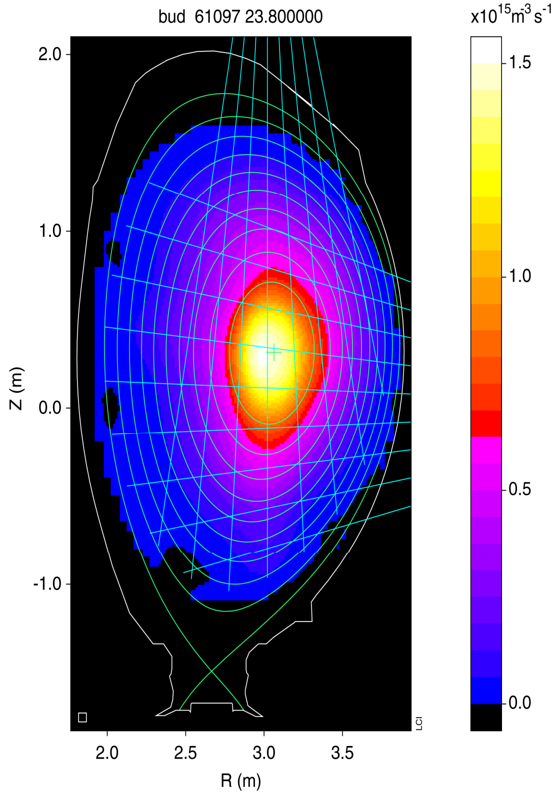
- 10 ms time resolution

14 MeV emissivity contours: 800 ms after T_2 puff



Profile peaks like 2.5 MeV emissivity once T^+ density has fully relaxed

TTE Campaign Issues

- Thermal particle transport
  - comparison of regimes with neoclassical and other models;
  - MHD effects
- Fast Particle transport
  - specific effects of Current Holes
  - NBI deposition profile effects
  - Fusion products confinement
- Diagnostic developments

TTE Campaign Issues

- Thermal particle transport
  - comparison of regimes with neoclassical and other models;
  - MHD effects

↓

Plasma regimes studied are those of relevance to ITER:
--> Internal Transport Barrier scenarios
(reversed shear and high central q)
--> 'Hybrid scenarios' (q_0 ~ 1, sawtooth-free)
--> ELMy H-modes (mainly type I ELMs)

D_T denotes diffusion of thermal Tritium
v_T denotes advection of thermal Tritium

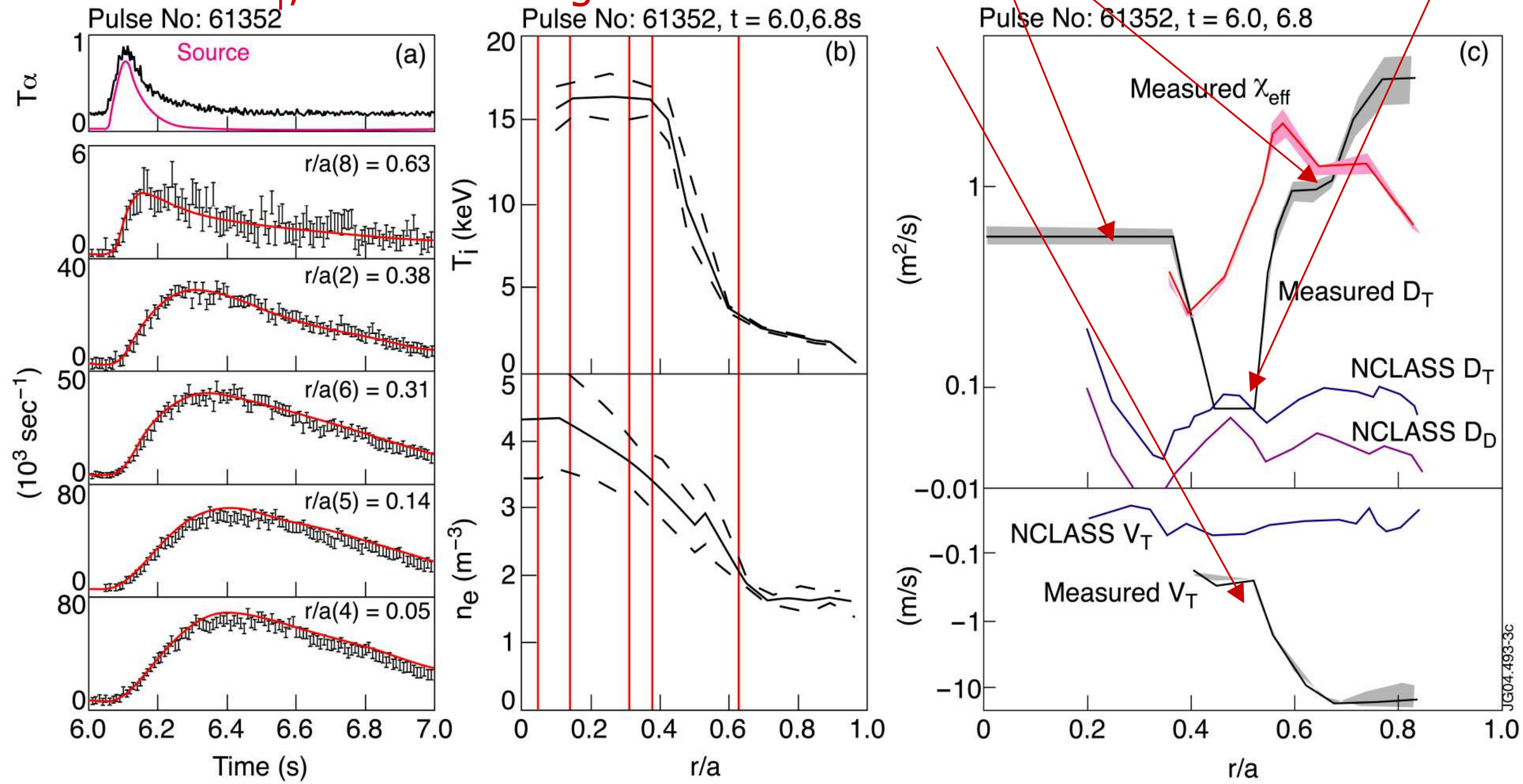
TTE: ITB particle transport

I_P=2.5 MA;
B_T=3.2 T

Reduction of D_T to neoclassical in the barrier region

Otherwise diffusion>>neoclassical

ITB reduces v_T, but still stronger than neoclassical



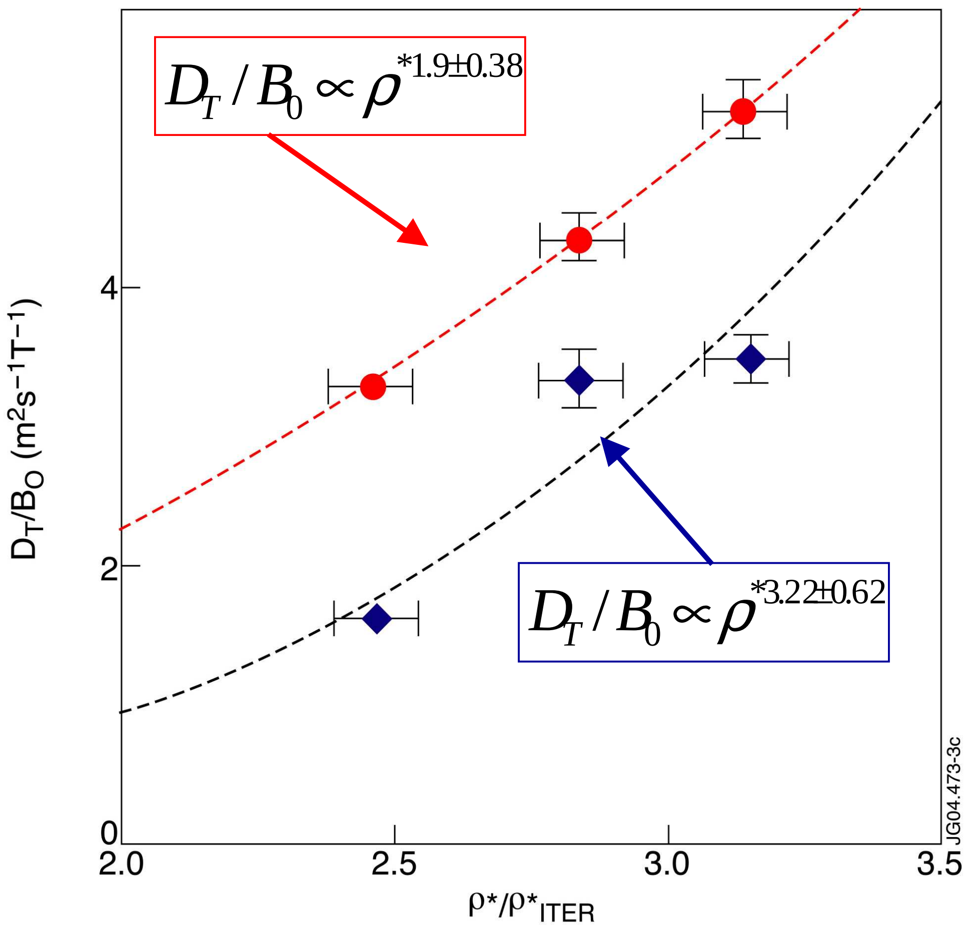
TTE: ELMy H-mode particle transport

- **Parametric dependence of Fuel-ion particle transport by:**
  - **Examining dependence on dimensionless plasma parameters used in transport studies:**
    ρ* - Ion Larmor radius normalised to plasma radius;
    ν* - Normalised collisionality $(\sim naq/T_e^2)$;
    β - Normalised pressure.
  - **Variation of transport vs density.**
  - **Variation of transport with additional heating mix (RF+NBI vs NBI only)**
  - **Effect on transport of Impurity seeding with Argon (high P_{RAD} fraction ELMy H-modes).**
- **In addition, specific MHD effects were charted:**
  - **sawteeth;**
  - **and Neo-classical Tearing Modes (NTMs)**
    NTMs generally absent from dataset, D_π, v_T are averaged over ELMs and sawteeth.

ELMy H-mode particle transport:

Dimensionless parameter scans

- Specific data set consists of NBI-heated ELMy H-modes with constant q_{95} (~2.8) and δ (~0.2):
  - T_2 gas puffs injected into steady-state phases.
  - 3-point ρ∗ scan with ,ν∗ and β held ~ constant;
  - 2-point ν∗ scan with ρ∗, β held ~ constant;
  - 2-point β scan with ρ∗, ν∗ held ~ constant.



- Inner plasma shows Gyro-Bohm particle transport
- Outer plasma shows Bohm particle transport

D McDonald et al -- IAEA FEC 2004 -- sub to PPCF

ELMy H-mode particle transport:

Dimensionless parameter scans (II)

- Particle transport β and ν* scans show inverse behaviour of D_T:

  for r/a<0.6

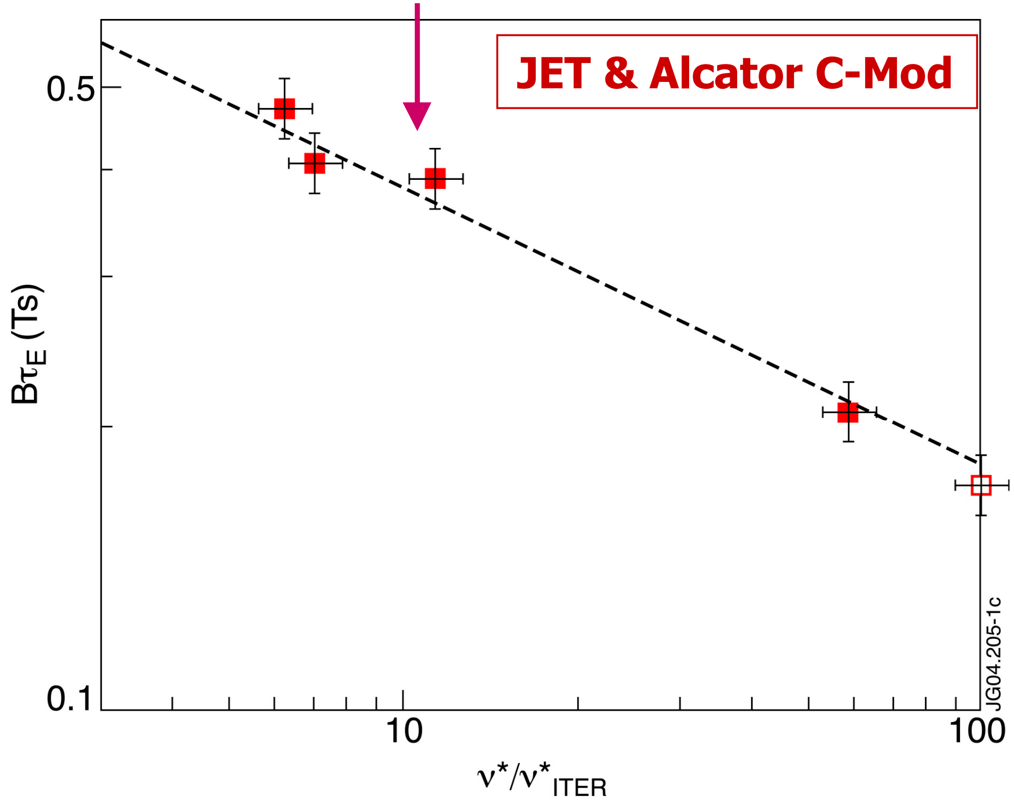
  $$D_{T,inner}/B_0 \propto \beta^{-0.34\pm0.08} \quad \& \quad \propto \nu^{*-0.51\pm0.17}$$

  and r/a>0.6

  $$D_{T,outer}/B_0 \propto \beta^{-0.55\pm0.09} \quad \& \quad \propto \nu^{*-0.4\pm0.15}$$

- Thus τ_P increases with β and $\nu*$

- whereas energy confinement is largely independent of β and decreases weakly with ν*



D McDonald et al -- IAEA FEC 2004 -- sub to PPCF

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ELMy H-mode particle transport:

Parameter fits

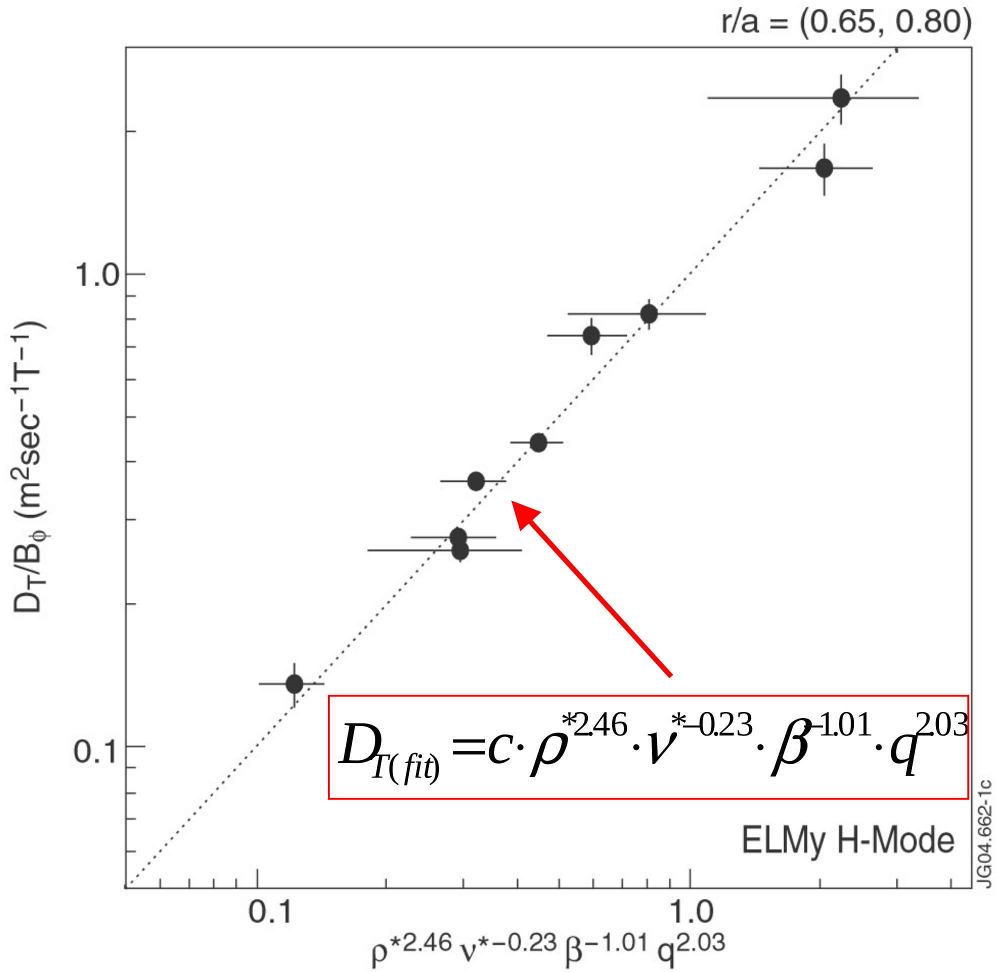
Multi-parameter fit to D_T for all ELMy H-mode dataset, shows:

-$\rho*$ behaviour between Bohm and Gyro-Bohm;

- strong inverse dependence on β;

- weak inverse dependence on $\nu*$;

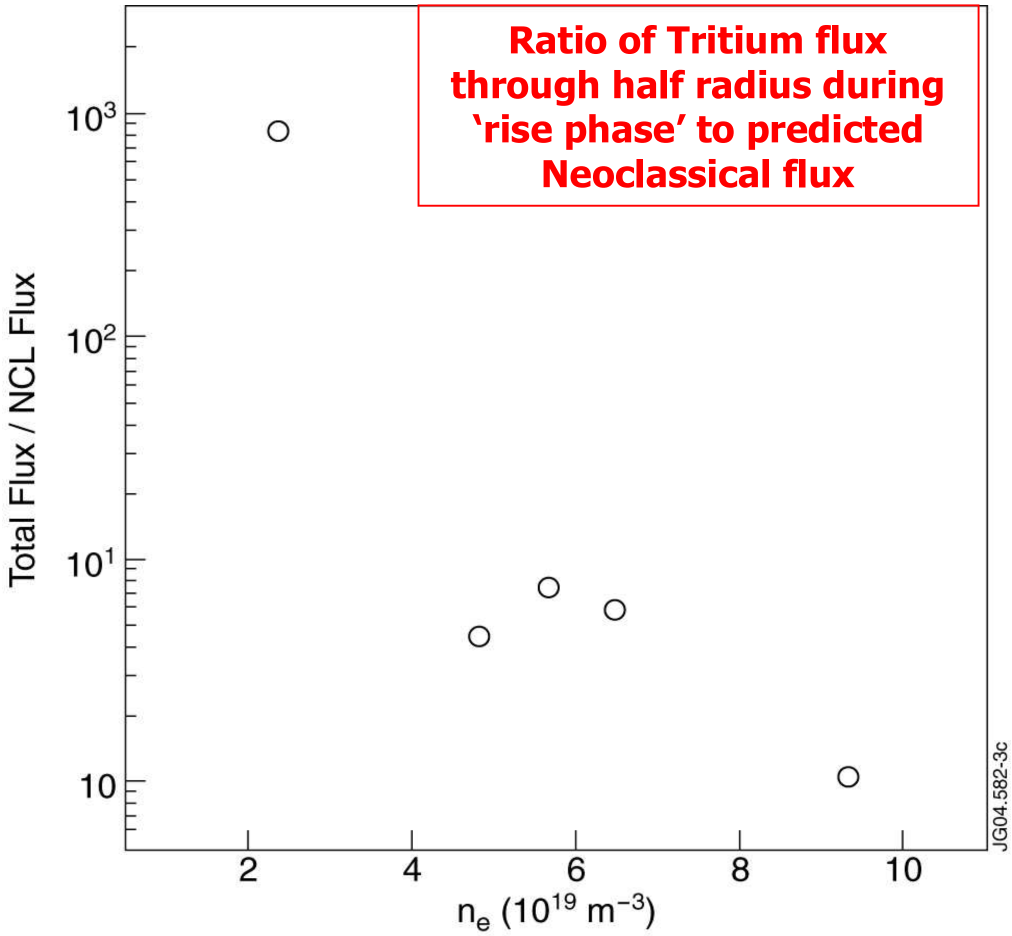
-strong dependence on local value of *q*.



TTE: ELMy H-mode particle transport:

Density variation

- Diffusion found to be strongly anomalous at low density.
- Tritium flux through r/a=0.5 greatly exceeds Neoclassical value at low n_e
- D_T dependence on n_e is consistent with picture for $\nu*$



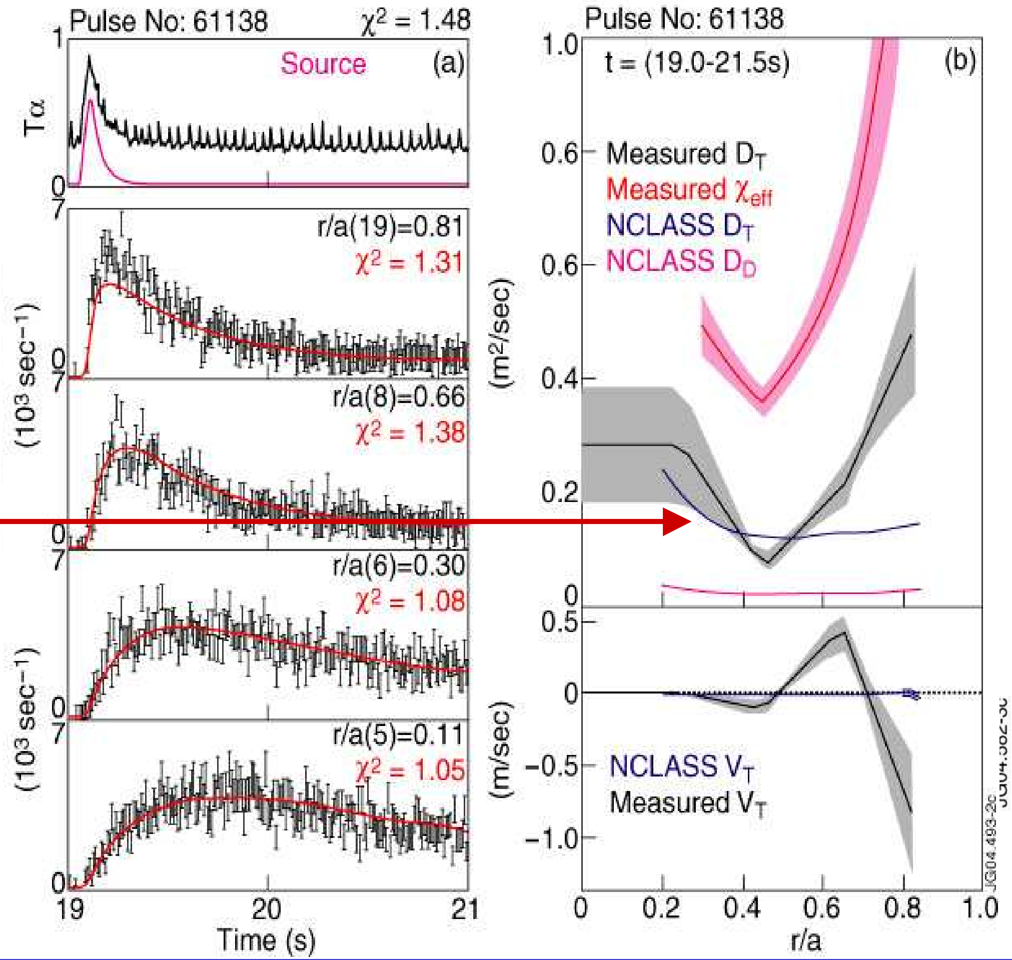
I Voitsekhovitch et al PoP (sub)

TTE: ELMy H-mode particle transport:

Density variation

Greenwald density shot at I_P=2.5 MA

- Diffusion found to be strongly anomalous at low density.
- Tritium flux through r/a=0.5 greatly exceeds Neoclassical value at low n_e
- D_T dependence on n_e is consistent with picture for $\nu*$
- Only as $n_e \sim n_{GREENWALD}$ then D_T approaches $D_{NEO,T}$ for r/a<0.6

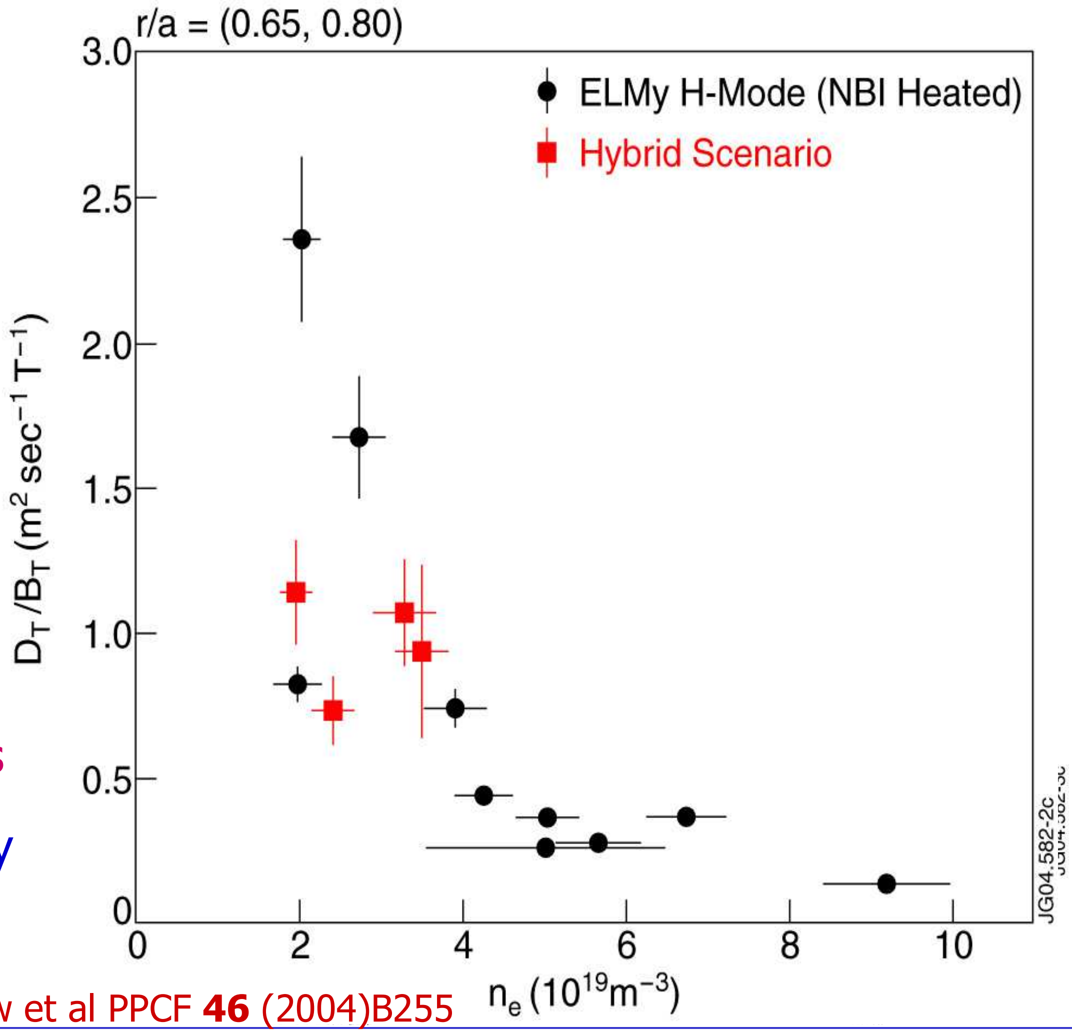


I Voitsekhovitch et al PoP (sub)

TTE: ELMy H-mode particle transport:

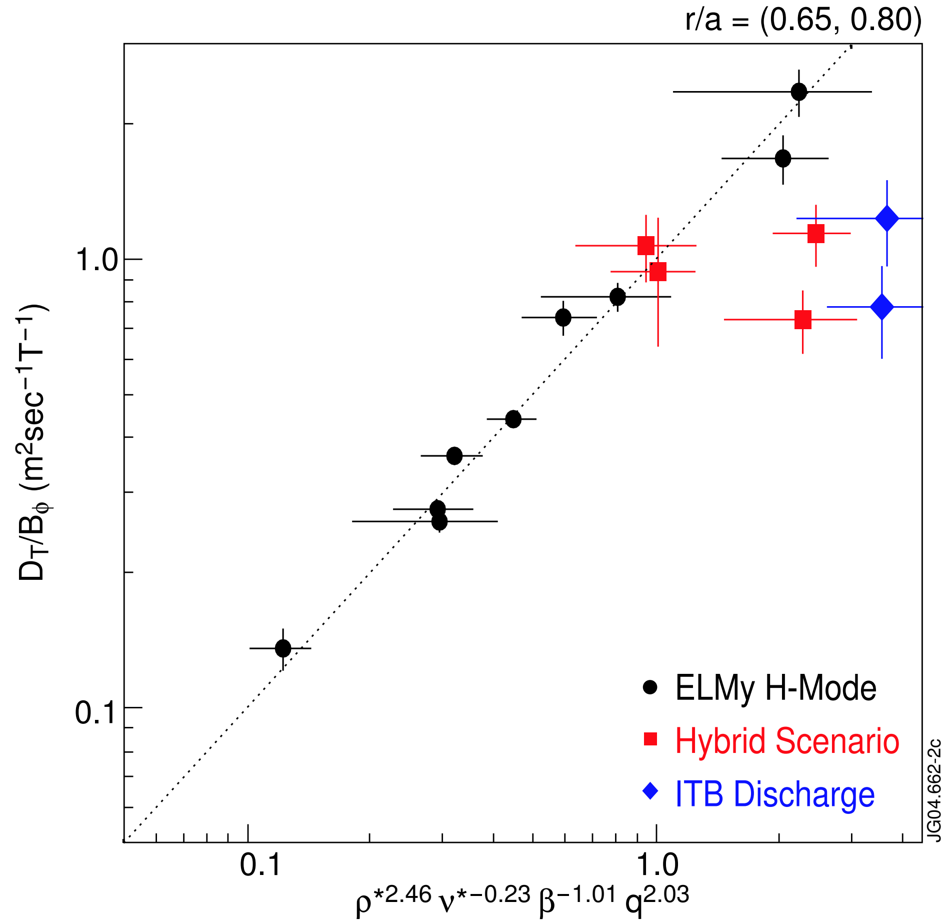
Density variation

- Diffusion found to be strongly anomalous at low density.
- Tritium flux through r/a=0.5 greatly exceeds Neoclassical value at low n_e
- D_T dependence on n_e is consistent with picture for $\nu*$
- Only as $n_e \sim n_{GREENWALD}$ then D_T approaches $D_{NEO,T}$ for r/a<0.6
- D_T shows inverse density behaviour for all plasma regions
- Thermal diffusion is less density dependent:-> $\chi_{eff}/D_T \propto n_e$



I Voitsekhovitch et al PoP (sub) K-D Zastrow et al PPCF **46** (2004)B255

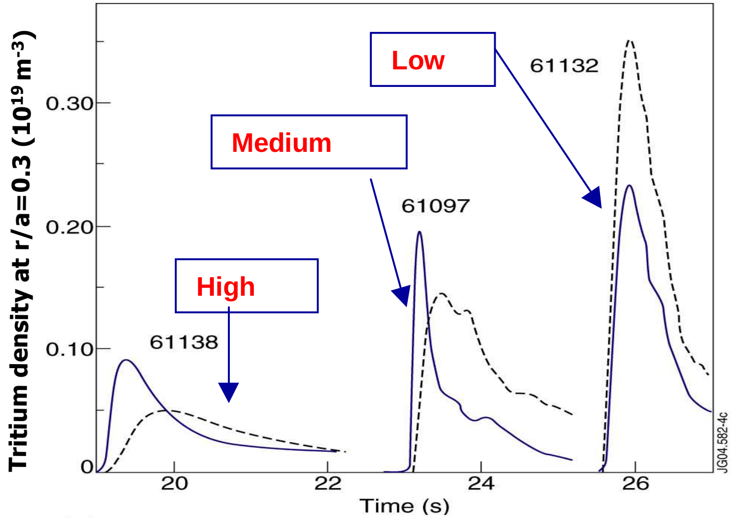
TTE: Comparison of different regimes



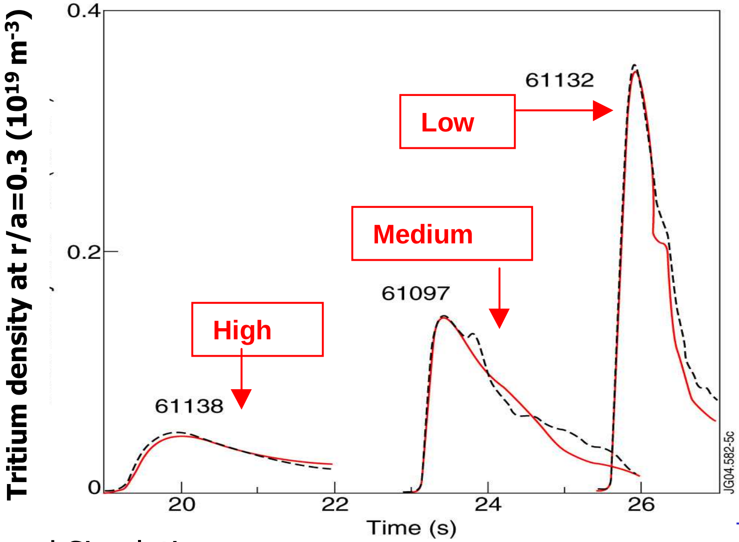
ELMy H-mode particle transport:

Electromagnetic model explains density dependence

- Tritium profile evolution was simulated with the Multi-mode model (MMM)
  - electrostatic turbulence.



- Tritium behaviour is not well-described, (though MMM gives reasonable fits for thermal profiles). ⇒ ES turbulence not stabilised with density.
- Diffusion dependent on density *(and hence collisionality)* could result from Electromagnetic turbulence (Island size ~ skin depth~ $1/n_e^{0.5}$)
- Semi-empirical model with modified neoclassical diffusion in stochastic magnetic field may explain transition to anomalous transport with density

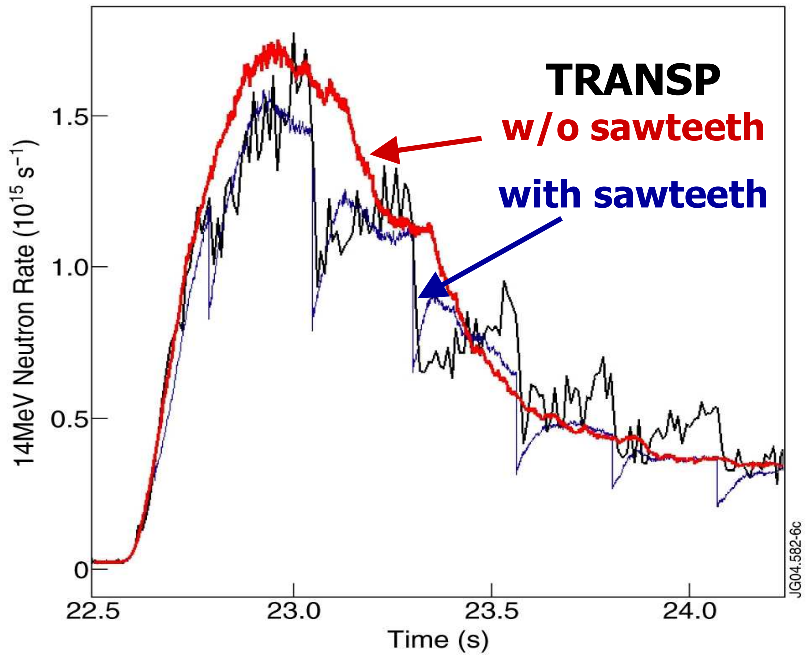


TTE Campaign

- Thermal particle transport
  - comparison of regimes with neoclassical and other models;
  - MHD effects -- sawteeth
    -- Neo-classical Tearing Modes
- Fast Particle transport
  - specific effects of Current Holes
  - NBI deposition profiles
  - Fusion products confinement
- Diagnostic developments

TTE: MHD Effects - Sawteeth

- Effects of sawteeth were seen in most ELMy H-mode plasmas
  - D_T and v_T were nevertheless averaged over the sawteeth.
- **Sawtooth mixing of both Fast NBI D^+ and thermal Tritium is necessary to explain the 14 MeV neutron time history;**
  - sawtooth effects most prominent at low density (peaked D beam deposition);
  - Fast D beam has peaked profile ⇒ beam particles removed from core during the sawtooth crash;



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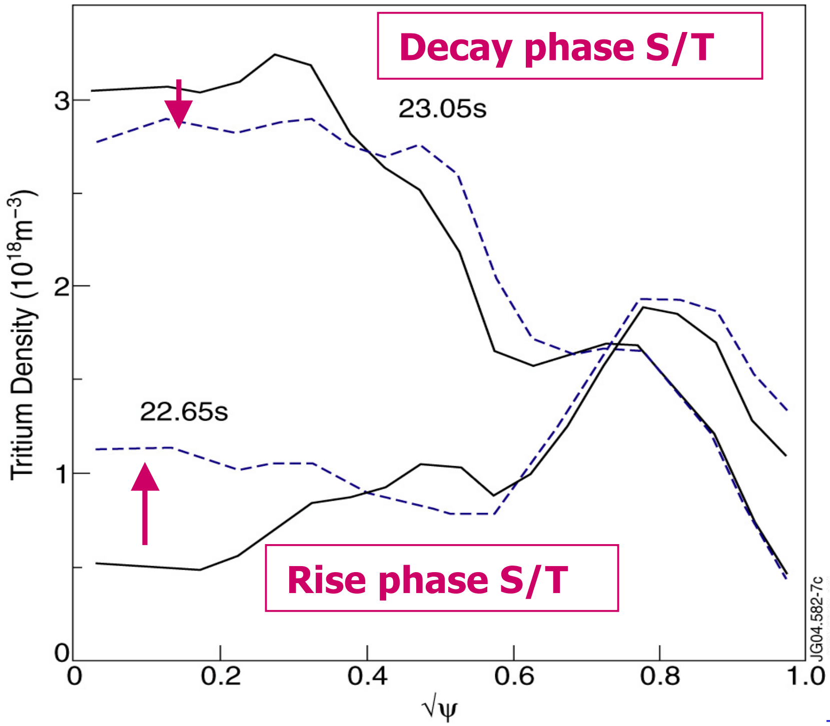
but
  - sawteeth accelerate T penetration during the rise phase;
  - and its removal during the decay phase;



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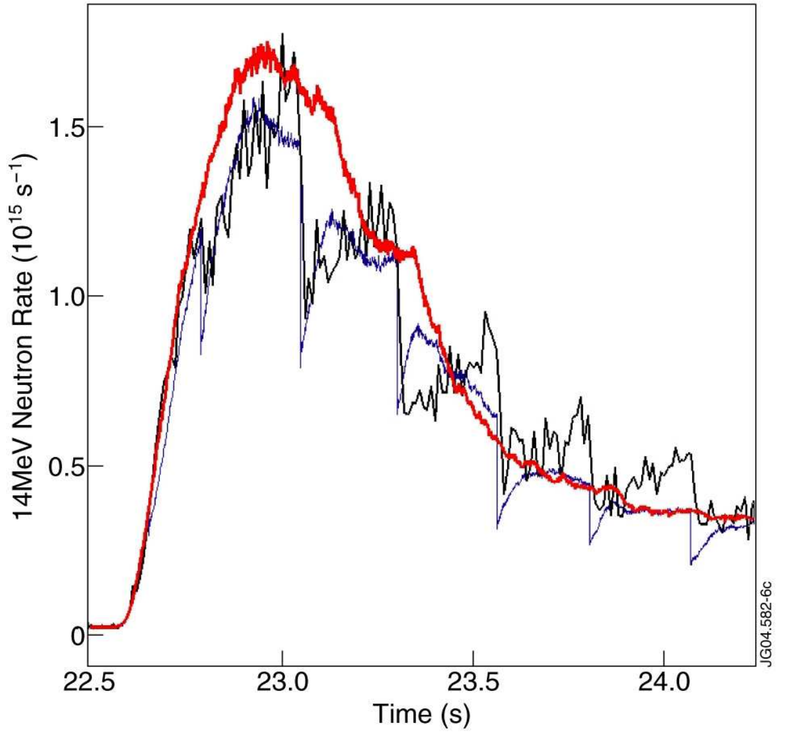
but • sawteeth accelerate T penetration during the rise phase;

• and its removal during the decay phase;

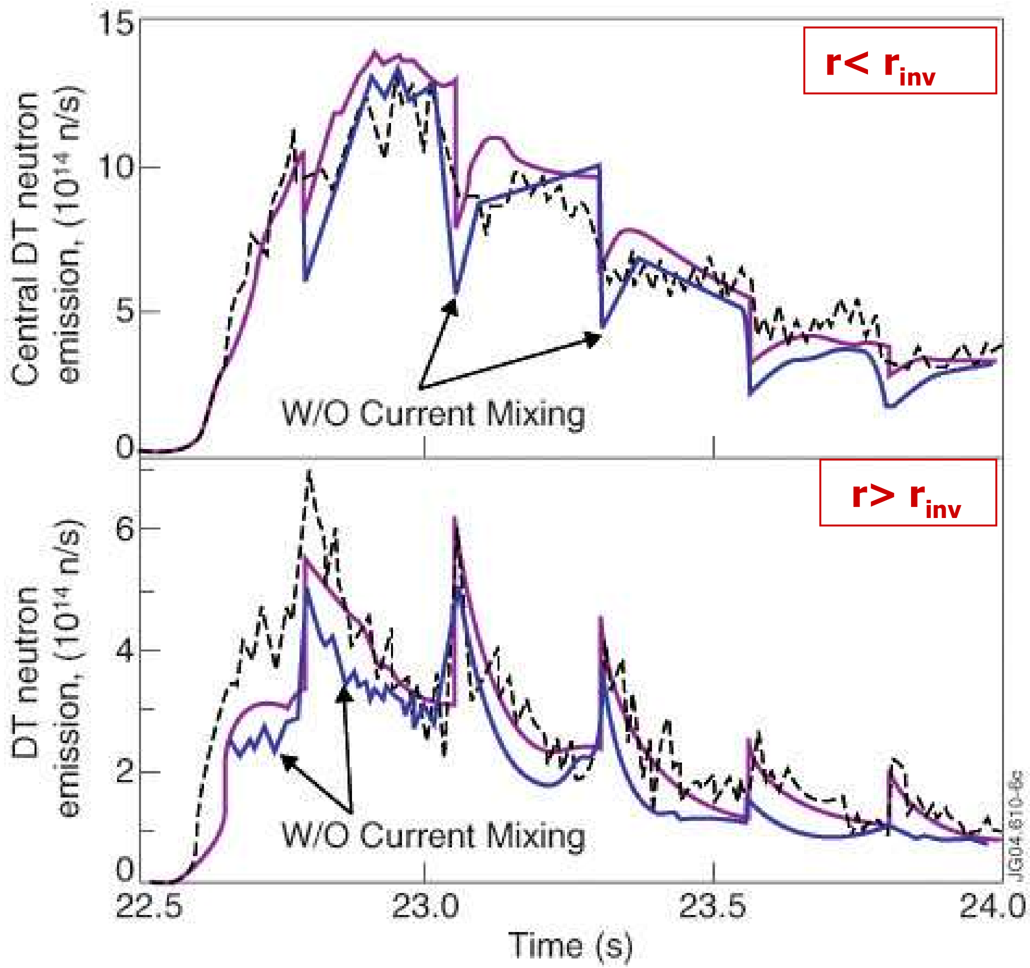
thus • oscillations of neutron emission weak or absent during the rise phase, but are enhanced during decay phase.



TTE: MHD Effects

Neutron sawteeth simulations

- TRANSP simulations of 14 MeV neutron time-histories have used:
    - full current reconnection (Kadomtsev) model (q_0 remains ~ 1);
    - partial reconnection (no current mixing) model (q_0 down to ~ 0.5 -- larger inversion radius)
- Full reconnection models the 'neutron sawteeth' more accurately.



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TTE: Fast Particle physics

In the TTE Campaign, Fast particle physics results were obtained either :

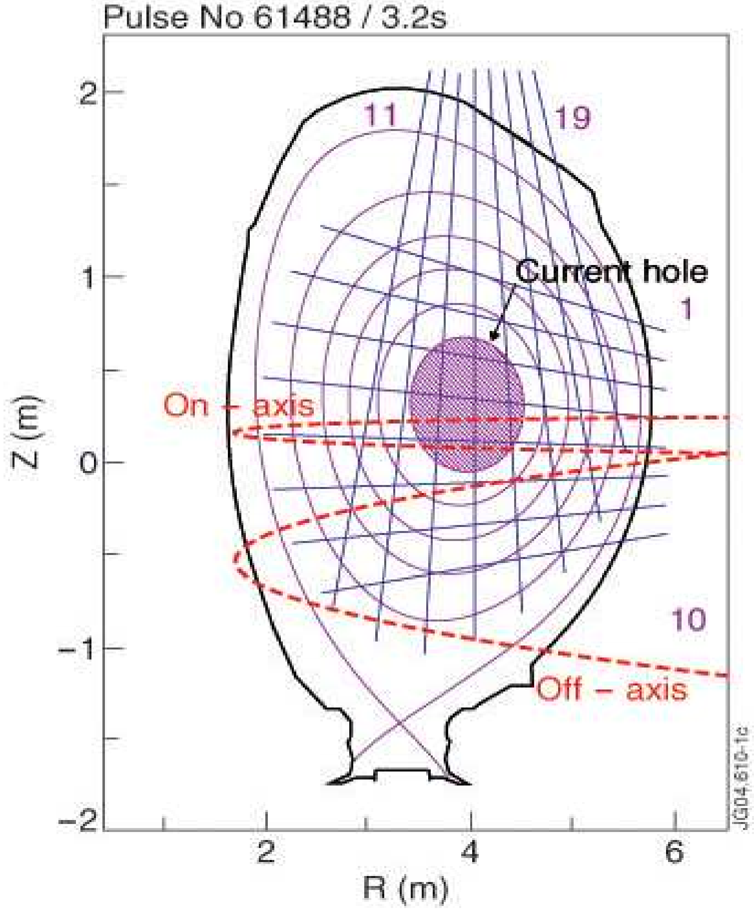
- using NBI Tritons directly
  - Beam ion transport in Current Holes; ←
  - Transport of beam ions at low-q; ←
- using T^0 NBI-derived Fusion products
  - Fusion product confinement/ transport
- detecting effects of RF-accelerated protons pT fusion

TTE: Fast Particle physics:

NBI transport in Current Holes

- Current Hole (CH) plasmas have near-zero Toroidal current density in plasma centre r/a < 0.3 - 0.5
- typically an ITB at the CH edge.
- Good thermal energy confinement inside the ITB, but CH expected to confine Fast Ions poorly due to low-central B_θ.
- 105 keV Tritons injected into Monotonic Current profiles (MC) and CH plasmas, CH effects demonstrated by 14 MeV neutron profiles from T_{fast}->D reactions.

N C Hawkes et al, PPCF Dec 2004



TTE: Fast Particle physics:

NBI transport in Current Holes

On-axis -->Outward profile shift seen in CH plasmas compared to MC plasmas

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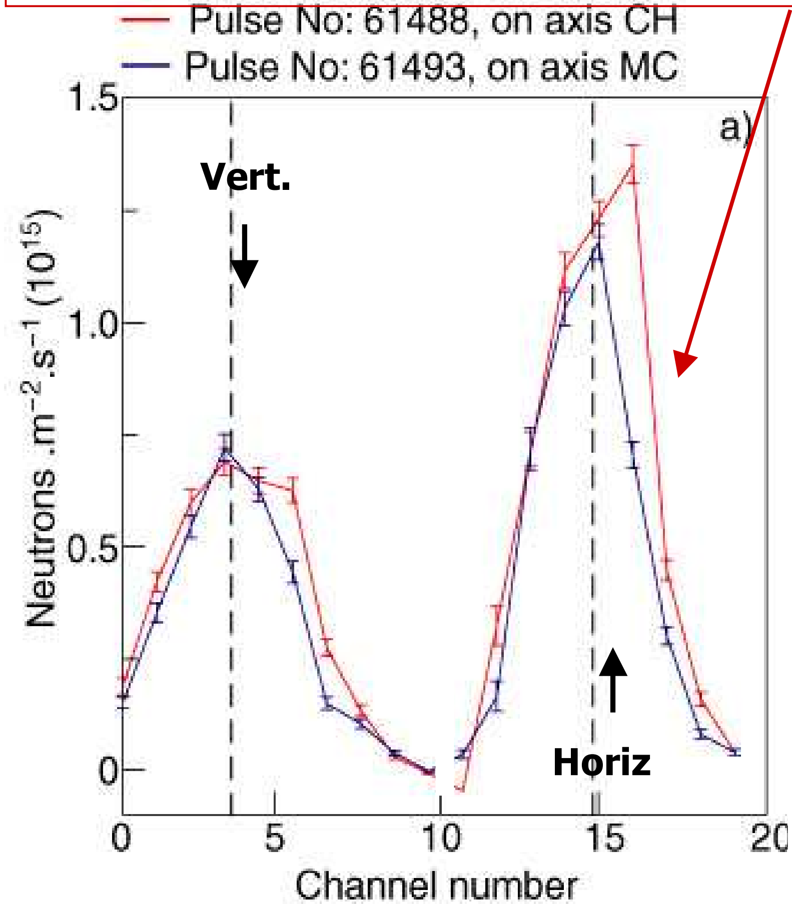
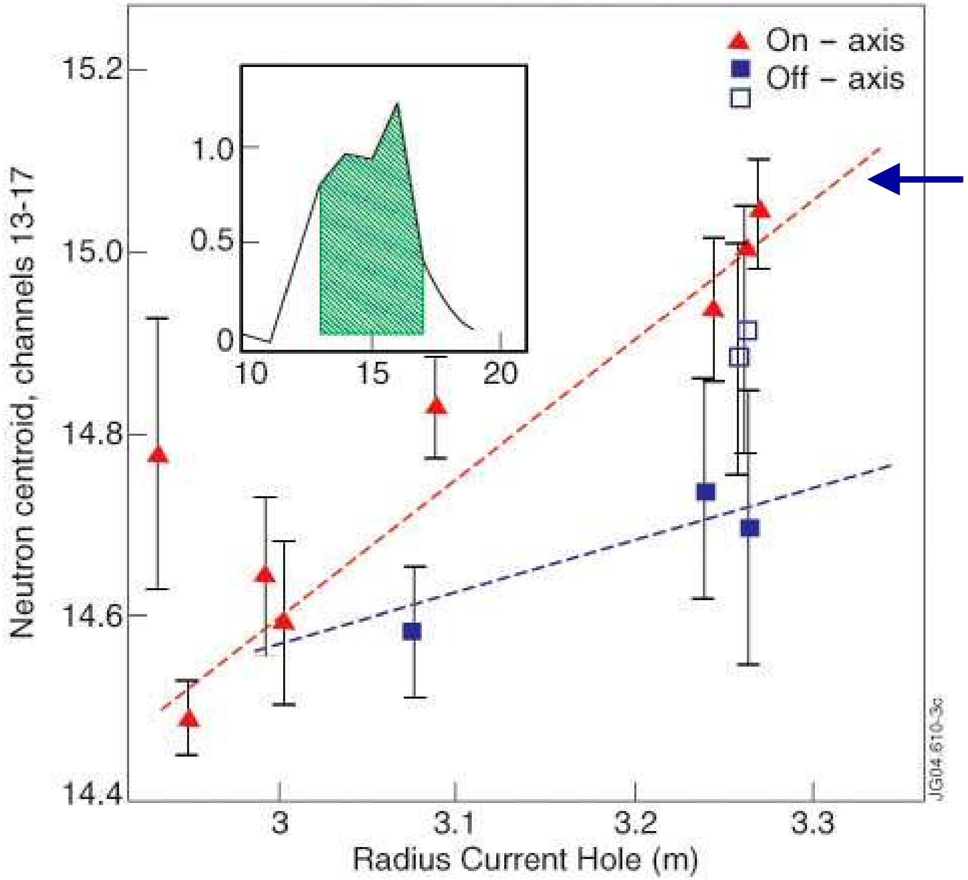


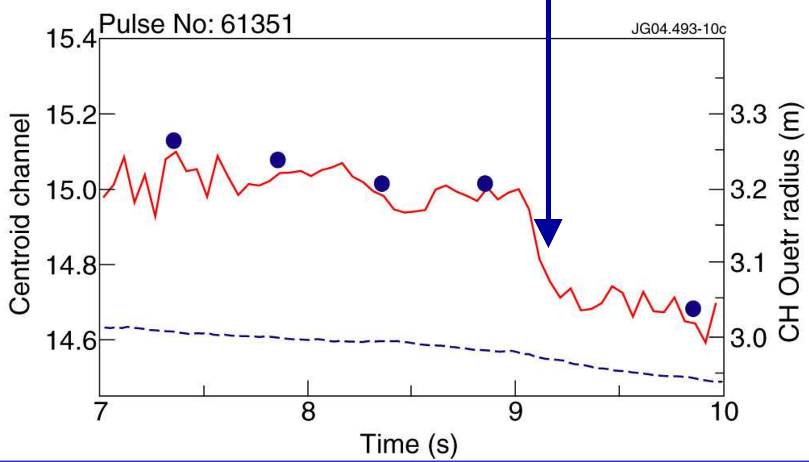
TTE: Fast Particle physics:

NBI transport in Current Holes

- Fitting Neutron camera channel signals gives centroid of NBI triton peaks.



- For series of CH discharges, NBI triton centroids correlate with edges of CH measured by fit to MSE B_Z profile.
- Sudden erosion of CH, eg. By MHD activity, is seen as NBI triton centroid makes sudden jump.



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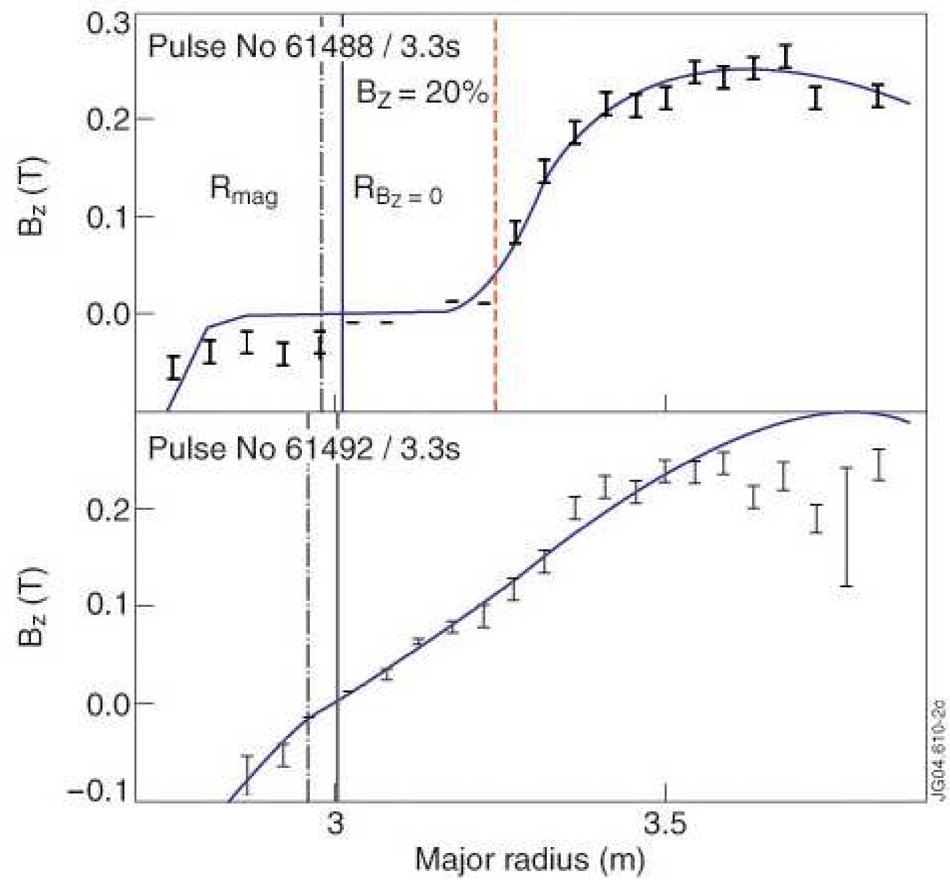
NBI transport in Current Holes

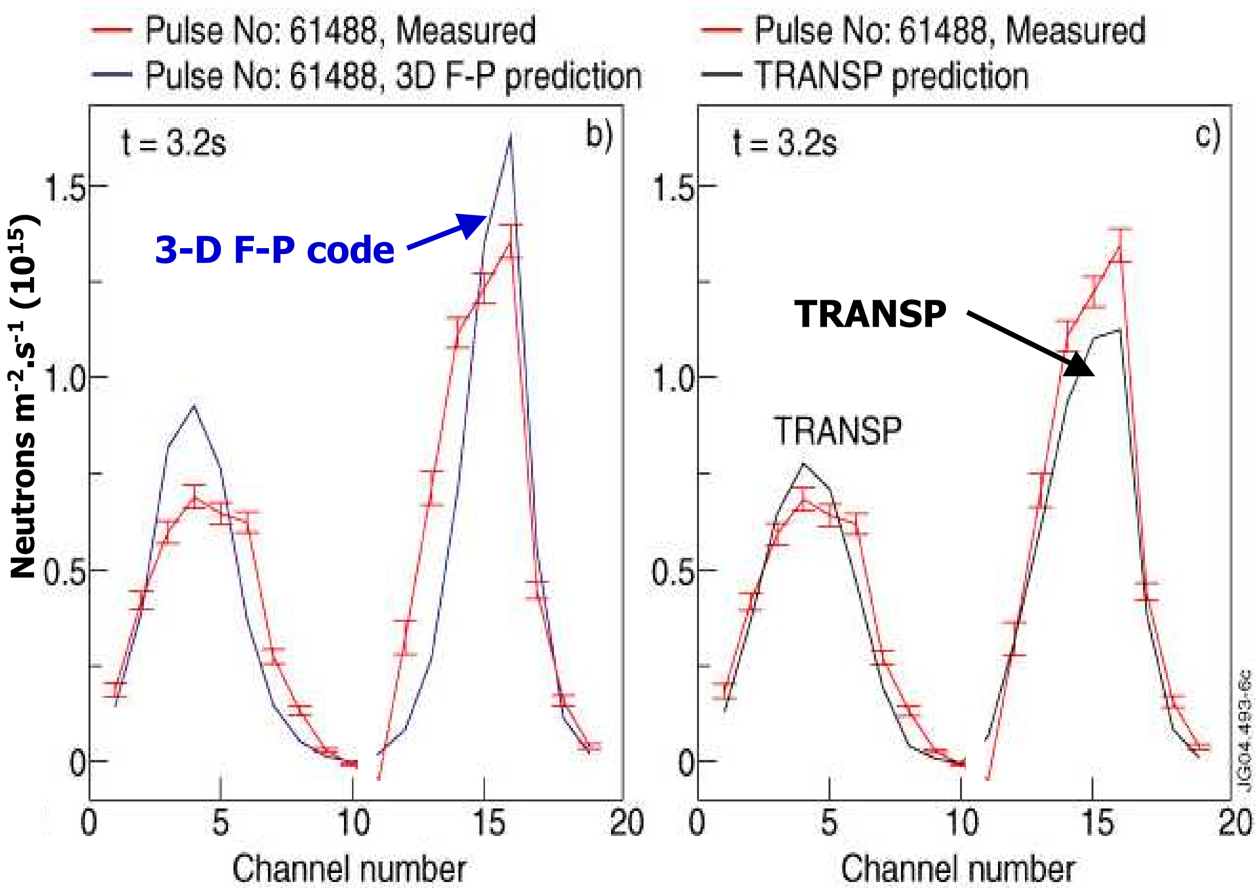


Outward shift of NBI triton peak is due to shift of 'stagnation orbits' of the tritons in the very low central B_Z field.

N C Hawkes et al, PPCF 2004

TTE: Fast Particle physics:

NBI transport in Current Holes



Outward shift of NBI triton peak is due to shift of 'stagnation orbits' of the tritons in the very low central B_Z field.

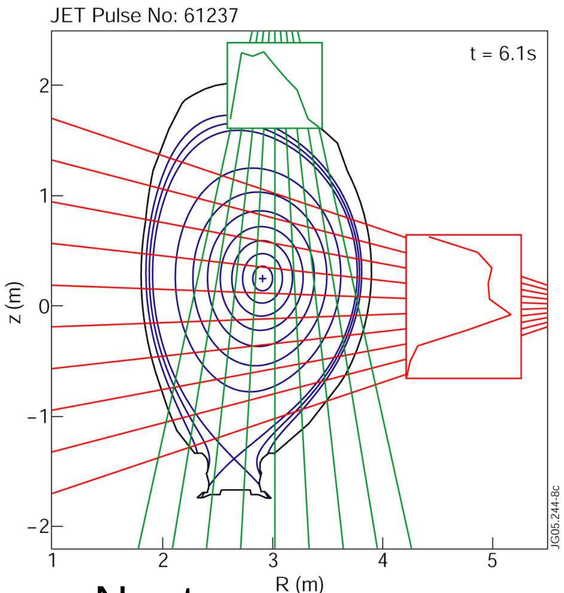
This can be qualitatively modelled by either 3-D Fokker Planck code or by TRANSP Monte Carlo

14 MeV neutron profiles Data/simulations -- on-axis NBI tritons

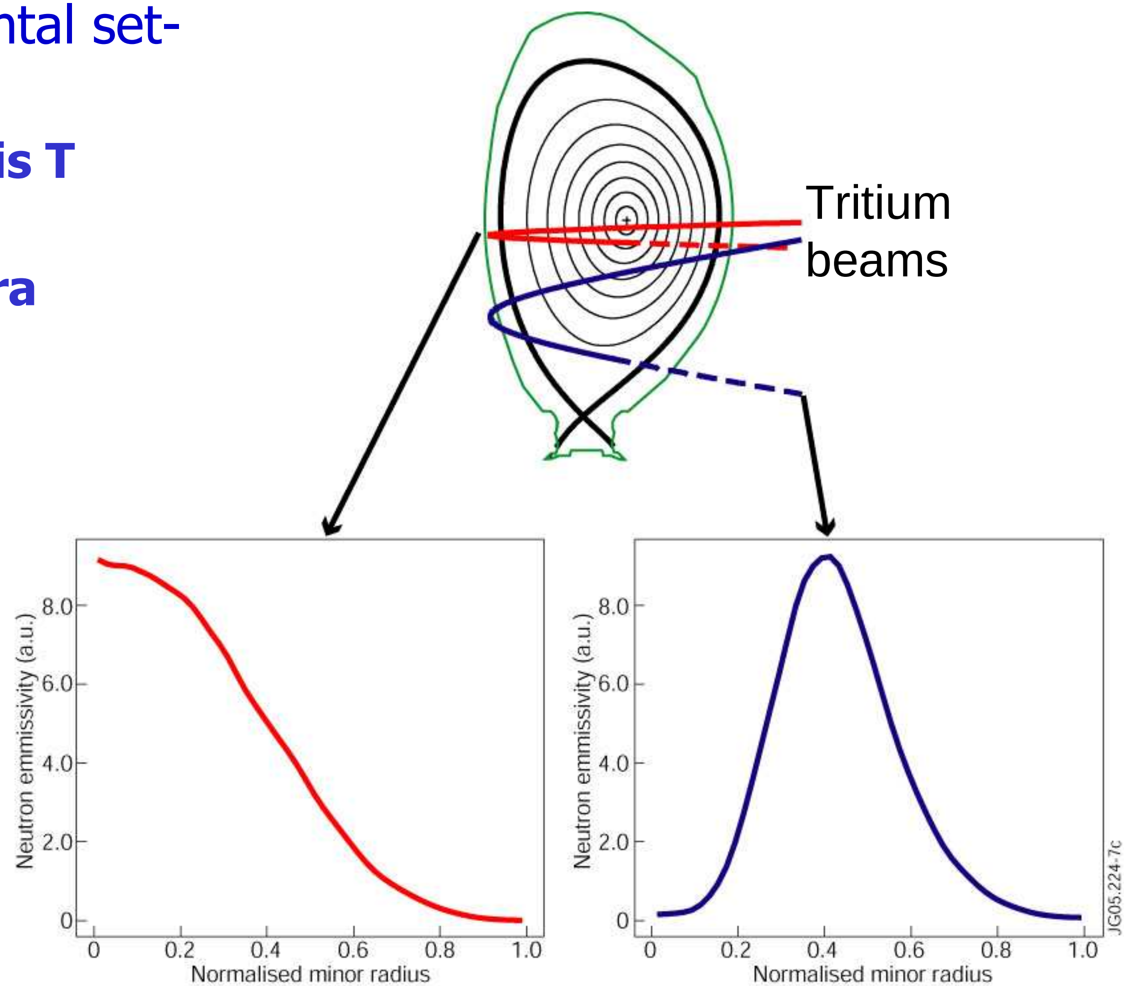
N C Hawkes et al, PPCF 2004

TTE : NBI fast ion studies

- Reminder of experimental set-up:
  - **on-axis and off-axis T beams were used**
  - **2-D neutron camera**



Neutron camera

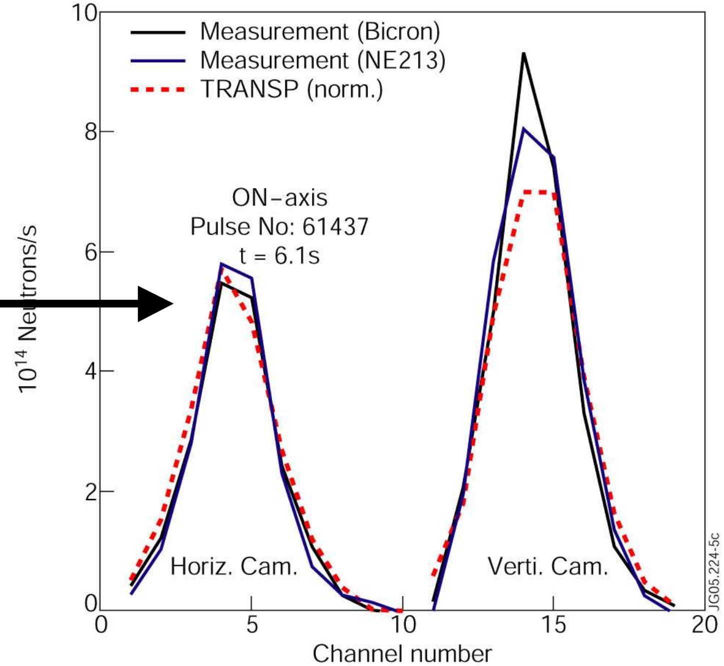


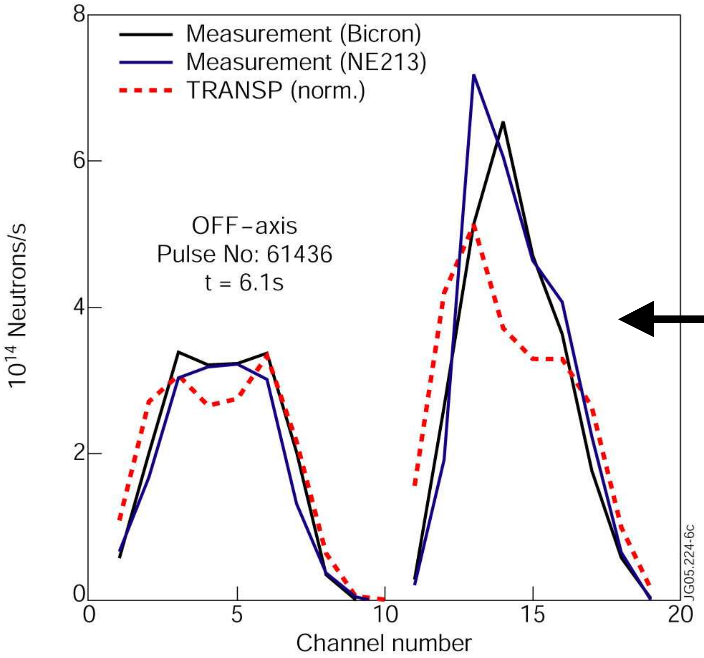
EUROPEAN FUSION DEVELOPMENT AGREEMENT

TTE: NBI fast ion studies

I Jenkins et al, 32nd EPS Tarragona

- **Results for monotonic q-profile:**
  - Neutron profiles agree with calculation at high q_{95} (~8.5)
  - Modelling reproduces on-axis beam case at low q_{95} (~3.3)





... but not off-axis beam case

- **Conclusions:**
  - Suggests fast ion redistribution
  - No clear MHD cause
  - Further work needed to clarify cause and implications

TTE Campaign

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EUROPEAN FUSION DEVELOPMENT AGREEMENT

Diagnostic developments in TTE

- TTE Campaign saw significant Diagnostic activity with relevance to diagnosis of Burning Plasma Experiments.
- Already covered:
  - **14 MeV neutron camera** -- much useful asymmetric profile data -- ***shows that ITER will need radial and vertical cameras;***
- In addition:
  - **Gamma-ray diagnosis of alphas** -- profiles also obtained with the camera detecting gammas from RF accelerated ^{4}He alpha simulation -- need to install ^{6}LiH collimators on the JET Neutron camera to shield out the 14 MeV background for Fusion Product profile work
  - first calibration/use of Carbon Vapour Deposit (CVD) diamond detector with Tokamak plasmas;
  - Magnetic Proton Recoil (MPR) spectrometer gave 14 MeV neutron spectrum from RF heated tritium minority (ω_{cT} and $2\omega_{cT}$) -->triton 'tail temperature';
  - Compact organic NE213 and Stilbene ($C_{14}H_{12}$) detectors tested.

TTE: Diagnostics:

γ–ray detection of Fusion products transport/confinement

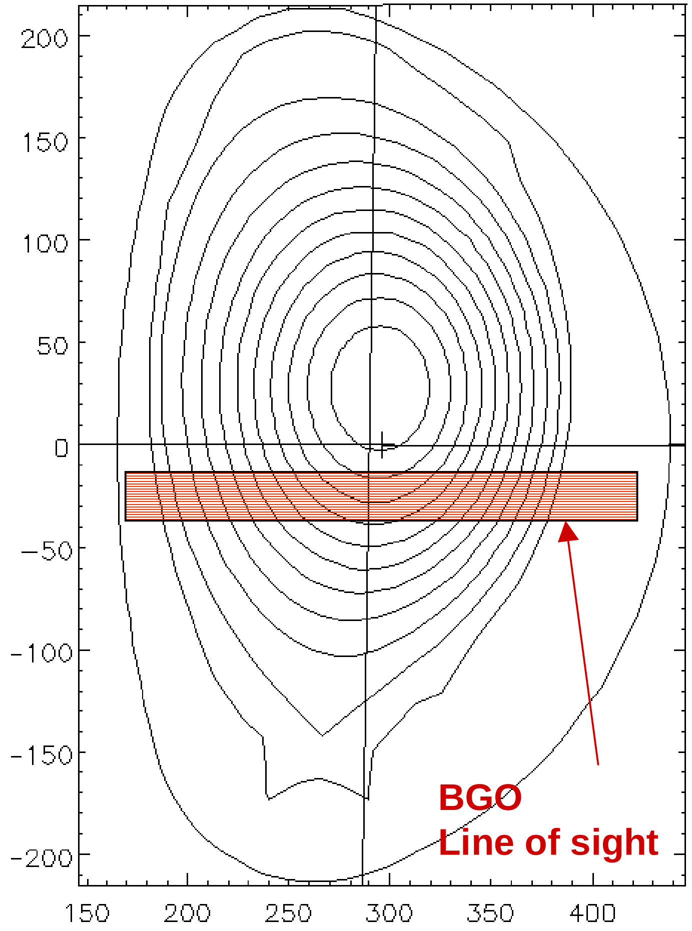
γ-ray spectrometry has provided information on the behaviour of fusion α- particles in TTE

α-particle diagnosis was based on nuclear reaction $^{9}Be(\alpha,n\gamma)^{12}C$

following α-production in

$T_{(F)} + D > n + \alpha$

4.44-MeV γ-ray emission measures changes in the LOS density of the fast α-particles with E_α > 1.7 MeV post-NBI.



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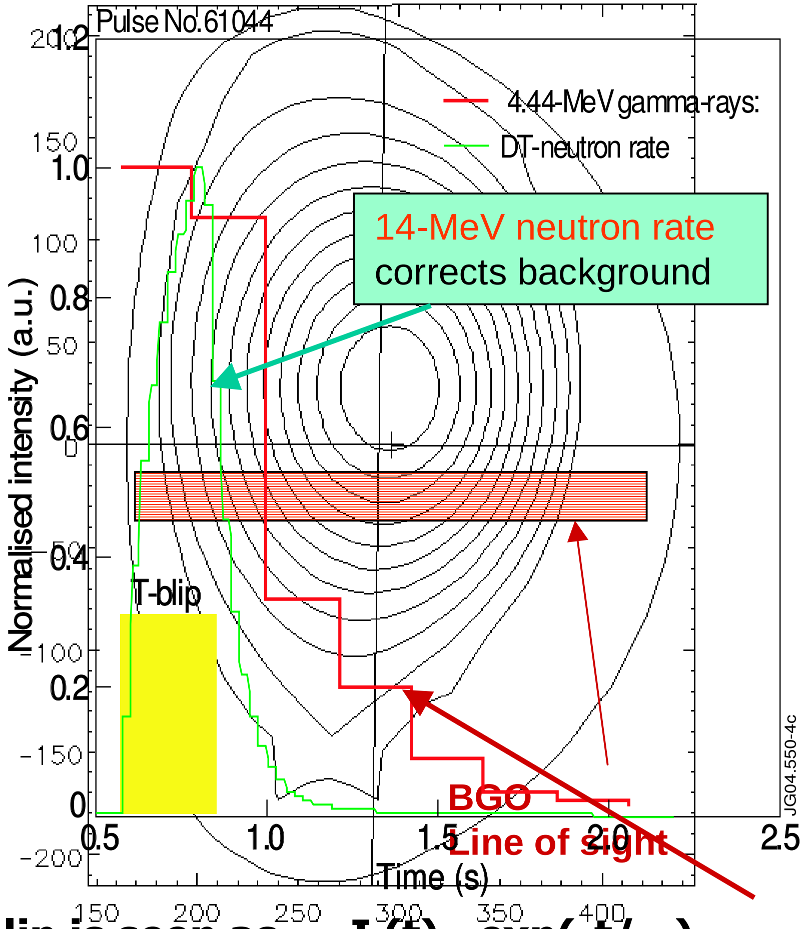


γ-ray intensity after the T-blip is seen as ~ $I_\gamma(t) \propto \exp(-t/\tau_\gamma)$

EUROPEAN FUSION DEVELOPMENT AGREEMENT

TTE: Diagnostics:

γ–ray detection of Fusion products transport/confinement (II)

For a wide range of discharges compare two quantities

- τ_γ - measured 4.44-MeV γ-ray decay rate
- $\tau_T + \tau_\alpha$ - calculated classical combined slowing down parameter

tritons from 105 keV to 40 keV

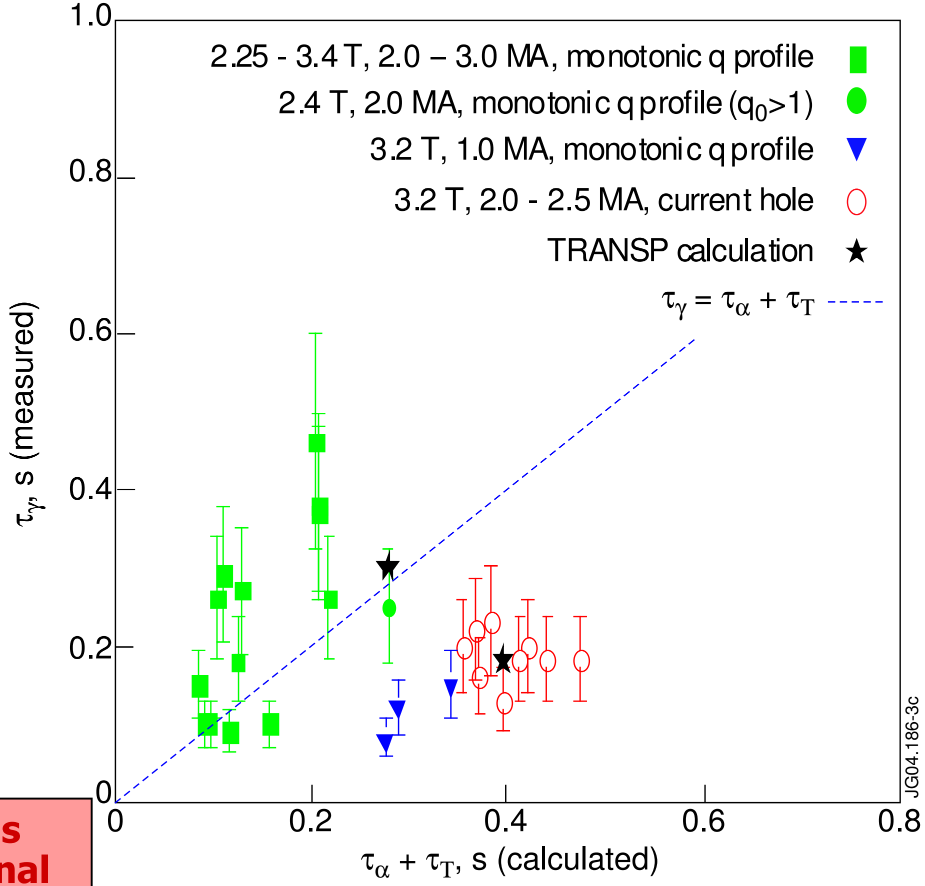
plus

α's from 3.5+ MeV to 1.7 MeV

$\tau_\gamma^{exp} \geq \tau_\alpha + \tau_T$

$\tau_\gamma^{exp} < \tau_\alpha + \tau_T$

This group also has reduced initial signal (First orbit losses)



V G Kiptily et al., PRL 93 (2004) 115001

TTE: Diagnostics:

γ–ray detection of Fusion products transport/confinement (III)

$\tau_\gamma^{exp} \geq \tau_\alpha + \tau_T$ → Good α-confinement: Critical plasma current I_{CR} > 1.5-2MA to avoid significant orbit losses/drift → Discharges with monotonic *q*-profiles: B_T = 2.2-3.2T, I_p = 2.0-3.0MA

$\tau_\gamma^{exp} < \tau_\alpha + \tau_T$ → Poor α-confinement: **drift &** orbit loss
- → Low plasma current : 1MA
- → 'Current Hole' Discharges

Current hole effect equates to an increase of the critical plasma current: $I_{CR} \propto 1/(1-x_H^{1/2})$, $x_H = r_H / a$:
for α's when $x_H = 0.35$ $I_{CR} \approx 3.7$ MA

Technique still in infancy, but shows promise – see Yavorskij et al 32nd EPS Tarragona

Building on DTE1 and subsequent progress

a new agenda for '50:50' DT plasmas

- DTE1 was a great success, but several issues addressable in a 'sub-burning plasma' were not satisfactorily resolved and since then new advances have opened up, or may open up, new experimental opportunities.
  - ELMy H-mode -- JET now works routinely near $n_e \sim n_{GW}$ -- $T_e \sim T_i$ regimes -- scaling to ITER?
  - Optimised/ Reversed shear/ Advanced Tokamak -- never satisfactorily demonstrated in DT (scenario problems, fuel control) -- develop to steady state -- **higher P_{add} available**; ←
  - α - particle physics -- higher P_α would be available in SS OS/AT plasma; ←
  - RF DT scenarios , systematic work with polychrome heating to overcome high tail temperatures in $2\omega_{CT}$-- more exploration of (^3He)DT -- mixture control and 'ash' build-up?.

α–pressure levels in various JET discharges

- **Alpha levels in past JET discharges at high performance are similar to 'ITER/reactor' levels.**
- **Much lower threshold seen for ICRF-driven AEs in RS and OS discharges cf. ELMy H-modes (result of higher central q – energetic ion coupling to AE increases in efficiency as $\gamma/\omega \sim q^2$).**

Parameter	Alphas (JET Hot Ion mode #42976)	Alphas (JET OS mode #42746)	Alphas (ITER-EDA ELMy-H)	Fast ^{3}He Ions (JET ICRH 15MW ^{3}He)
β_f (0) [%]	0.7	0.44	0.7	1-3
$\langle\beta_f\rangle$ [%]	0.12	0.07	0.2	0.5
Max $\lvert R\nabla\beta_f \rvert$	0.035	0.033	0.06	~0.1

relatively high $R\nabla\beta_f$ in OS/RS plasmas --good candidates for fusion-driven AEs

- **Simple scaling of JET Performance when higher power available (2009) shows (**Pamela, Stork et al., NF42(8) (2002) 1014**):**
  - **- for 38 MW I/p (27 NBI/11 RF) at 3.5MA/3.4T and if β_N=3 accessible**
  - **- 17.5 MW fusion power and $<\beta_\alpha> \sim 0.1\%$ – should test stability limits**

Building on TTE and subsequent progress

a new agenda for trace - T plasmas

- The efficacy of controlled Trace-tritium studies for thermal and fast particle transport is demonstrated.
- ELMy H-mode studies reveal interesting dependences different from energy confinement, but:
  - in neo-classical terms, some of the discharges (low I_p) are in the plateau-regime -- do these scalings hold when dataset dominated by banana-regime? (include 4 MA plasmas)
- ITB plasmas studies show neo-classical behaviour of the barrier and potential fuelling efficiency problems inside barrier, but:
  - particle transport scaling in ITB plasmas remains to be identified (scaling studies needed and direct comparison with He ash transport required).
- Hybrid scenario-- only a few basic results -- must build on these.
- Fast particle studies
  - γ -ray detector shows great promise - now need to convert the multiple channels of the KN3 camera -- ^{6}LiH collimators needed.
  - NBI current drive profiles - more investigation of systematics at low-q

Finally….

- **We still know very little about Tritium Retention in Tokamak surfaces … even Carbon!**
  - **Some evidence from TTE that plasma clean-up methods had improved since DTE1 - no time to pursue this.**
- **It is absolutely essential that JET returns to Tritium operation before the wall material is changed and that particular attention is paid to retention within the divertor surfaces.**
  Comparison can then be with the Beryllium/Tungsten wall mix installed when the new JET wall goes in.