Overview of Transport, Fast Particle and heating and current-drive Physics using Tritium in JET plasmas

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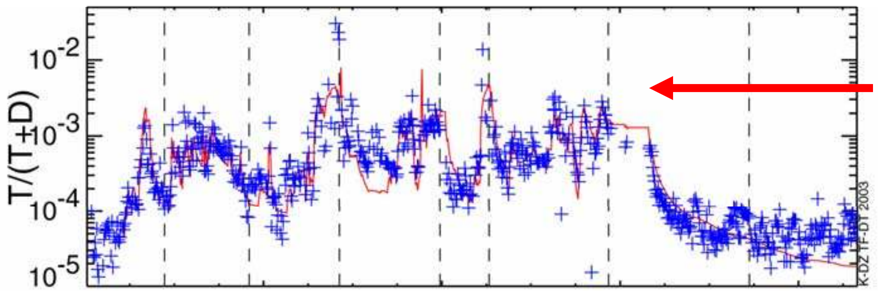
The JET “Trace Tritium” campaign

- The JET Trace Tritium Experiment (**TTE**) took place in September-October 2003.
- 20 dedicated experiments in 6 weeks
- Tritium present in plasmas in ‘trace’ quantities **$n_T/(n_T+n_D) \leq 3\%$.**
- Tritium introduced by short T_2 gas puffs (≤**6 mg**), or T^0 beam injection (~ **100-300 ms** ‘ blips’)



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

Physics with Trace Tritium

- Thermal particle transport
  - Diffusion (D_T) and convection (v_T) scaling and systematics including $\rho*,\nu*,\beta$ scaling studies **(McDonald—EX/6-6) ;**
  - Fuelling;
  - Effects of MHD phenomena on particle transport.
- Fast particle physics
  - Beam ion transport in Current Hole plasmas;
  - Fusion product confinement/transport **(Yavorskij –TH/P4-49)**
- Neutron diagnostic development **(Murari-- OV/P4-9)**
- RF heating physics **(Lamalle-- P5-165)**

All TTE experiments were non-perturbative (D_T and v_T measured in plasmas where all relevant global and local background parameters were in steady-state).

Thermal Tritium Transport

- ***D_T* and *v_T* can be measured separately.**
  (unlike pure steady-state deuterium plasmas where only *D_D/v_D* is evaluated

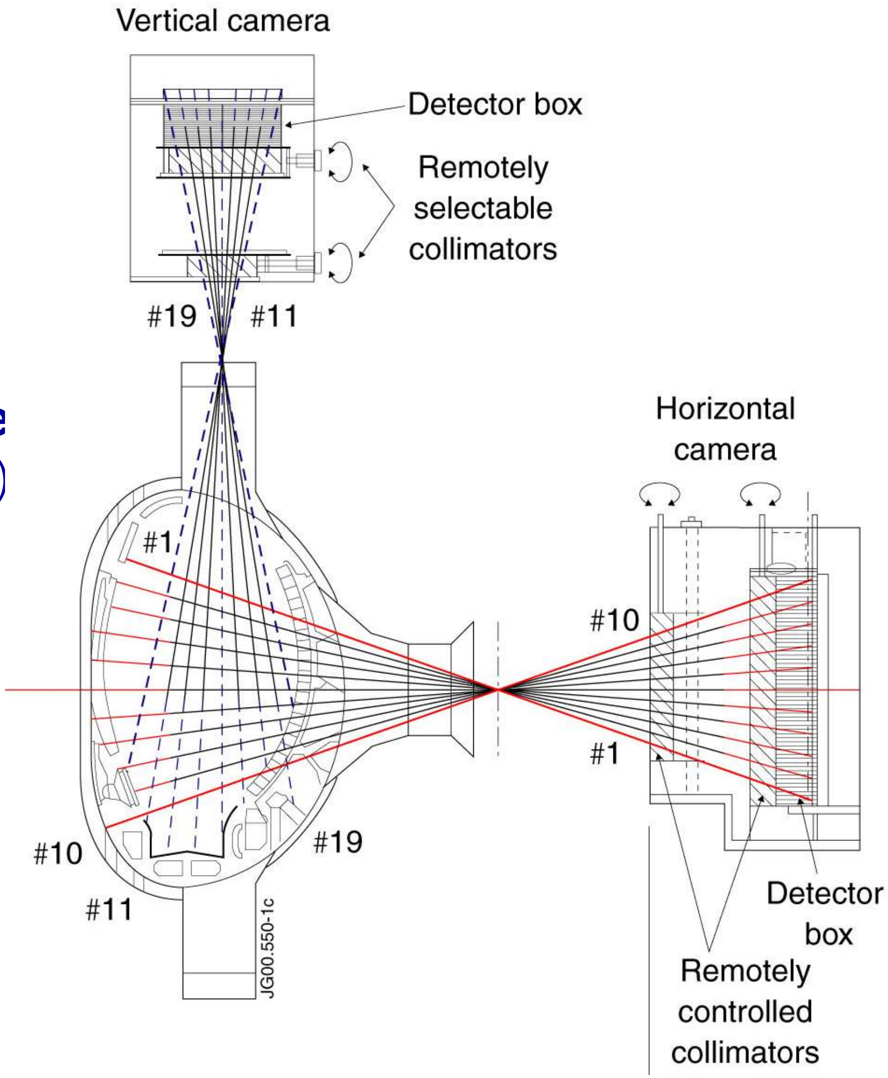
$$\frac{\partial n}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}\left(r\Gamma\right) + \sigma(t)$$

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

- **Accurate timing/ time profile of source**
  (T$_2$ gas ~ 10ms; thermalised NBI similar)
- **Evolution of tritium profiles derived from 14 MeV Neutron profiles**

JET neutron profile monitor

- absolutely calibrated for 2.5 & 14 MeV neutrons.
- 19 channels at r/a< 0.85
- 10 ms time resolution



Particle transport in many regimes

- Internal Transport Barrier (ITB) plasmas
- Hybrid scenarios (q_0~ 1, +ve shear,no sawteeth)
  - effect of plasma current and triangularity
- ELMy H-modes
  - scans of dimensionless parameters $\rho*,\nu*,\beta$;
  - variation of density;
  - effect of sawteeth;
  - [effect of heating profile(RF); impurity seeding].
- MHD effects --Neoclassical Tearing Modes (NTMs)
- Fuelling

In practically all regimes, particle transport found to be very much higher than neo-classical:

(except ITB region and high n_e near Greenwald density)

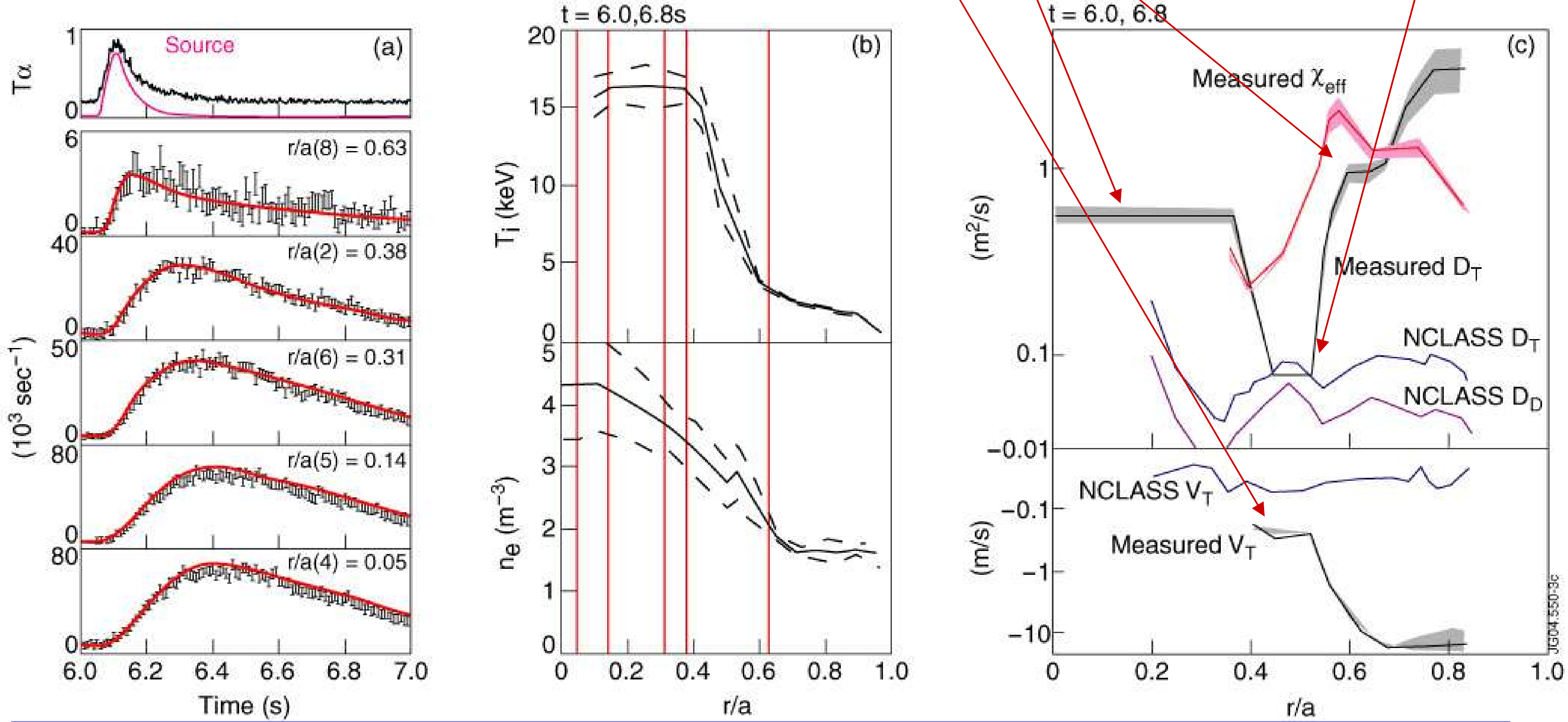
ITB particle transport

Pulse 61352
I_P= 2.5 MA;
B_T= 3.2 T

Reduction of D_T to neoclassical in the barrier region

Otherwise diffusion>>neoclassical

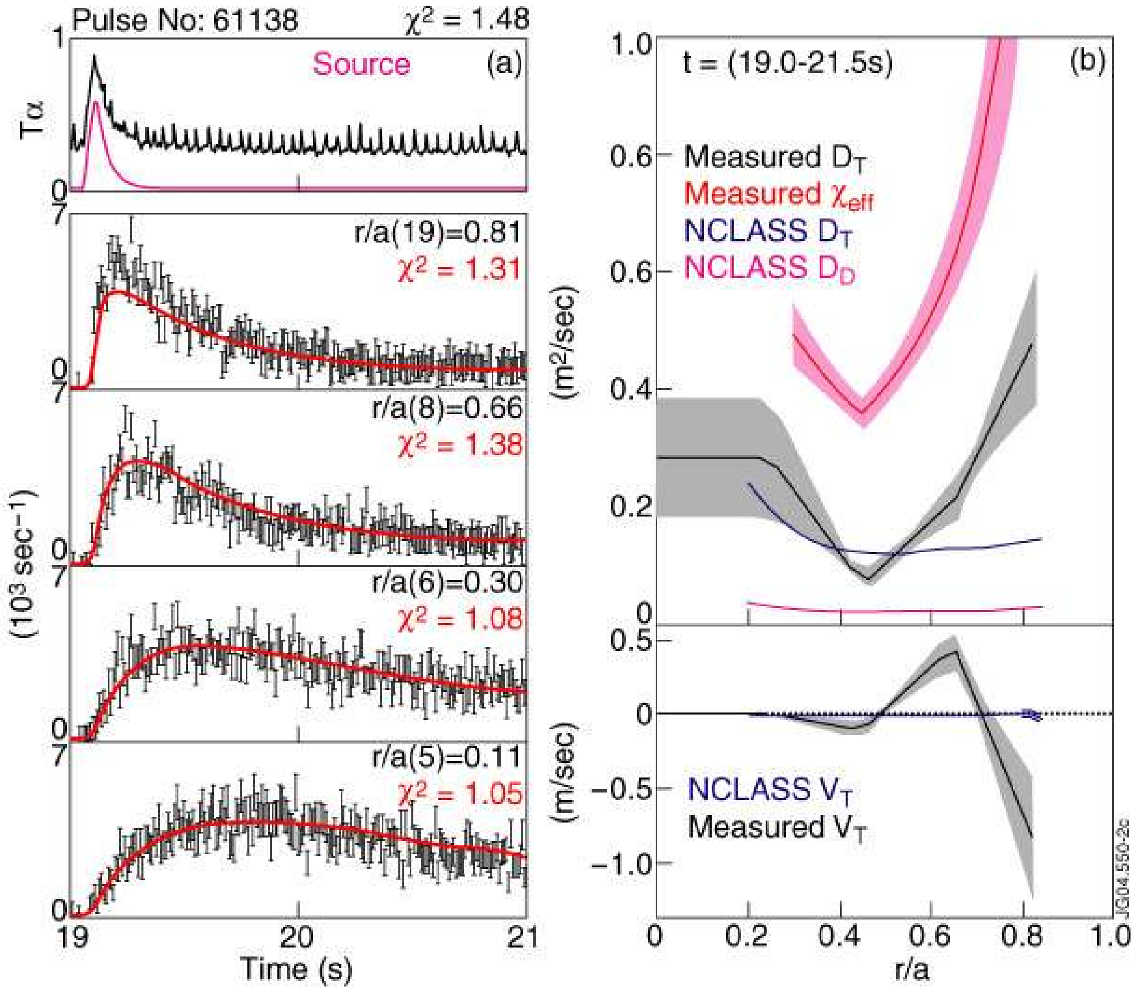
ITB reduces v_T, but still stronger than neoclassical



ELMy H-mode particle transport

Greenwald density shot at $I_P = 2.5$ MA

- ELMy H-mode results are averaged over ELMs and sawteeth.
- Diffusion is found to be strongly anomalous at low density:
  as $n_e \sim n_{GREENWALD}$ then D_T approaches $D_{NEO,T}$ for $r/a < 0.6$
- Thermal diffusion varies less strongly with density than particle diffusion: thus χ_{eff}/D_T is density dependent.



ELMy H-mode particle transport:

Dimensionless parameter scans

- Each of $\rho*, \nu*$ (~ naq/T_e^2) and β were scanned in discharge pairs with T_2 gas puffs:
  - remaining two parameters held constant over the scan;
  - particle transport and energy transport results compared

McDonald :EX/6-6

- Inner (r/a< 0.6) plasma shows Gyro-Bohm particle transport $D_T / B_0 \propto \rho^{*3.2}$
- Outer (r/a> 0.6) plasma shows Bohm particle transport $D_T / B_0 \propto \rho^{*1.9}$
- β and $\nu*$ tritium transport fits contrast with Energy confinement

  for plasma r/a< 0.6 particles: $D_{T,inner}/B_0 \propto \beta^{-0.34}$ and $\propto \nu^{*-0.51}$

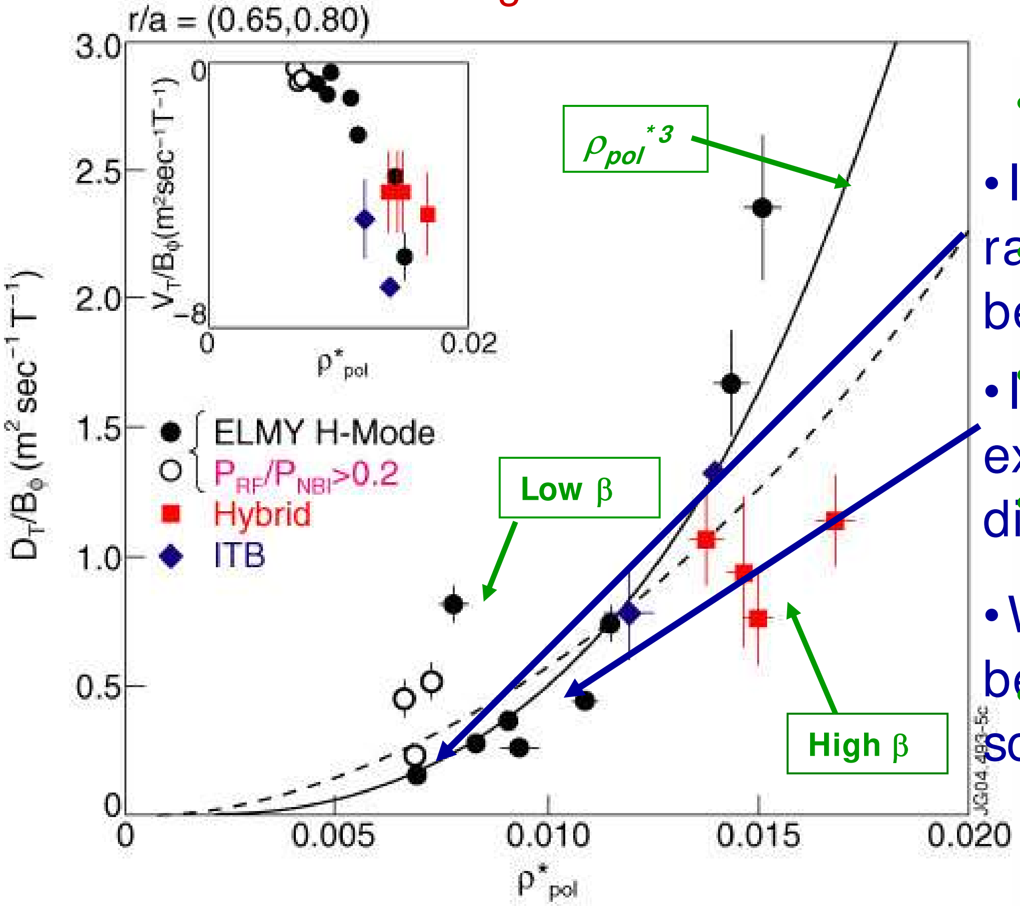
  for plasma r/a> 0.6 particles: $D_{T,outer}/B_0 \propto \beta^{-0.55}$ and $\propto \nu^{*-0.4}$

- whereas energy confinement is largely independent of β and decreases weakly with $\nu*$

Thermal particle transport:

Systematics and ITER operational scenario comparison

Systematics between ITER scenarios are best compared outside the central region --no sawteeth or reversed shear etc.



- Strong correlation in all scenarios for D_T vs q_{95}
- Try $\rho_{pol}^* = q \times \rho^*$ as ordering parameter.
- ELMy H-modes show ~ Gyro-Bohm scaling in ρ_{pol}^*.
- Also see 1/β dependence when Hybrid scenarios are included
- Note also stronger convective v_T in ITBs.

- Inside the sawtooth inversion radius, we expect differences between all three scenarios
- Inside the ITB footpoint we expect differences in ITB discharges
- We should see consistent behaviour for all three scenarios at r/a> 0.6

Multiparameter fit (NBI ELMy H-modes only)

$$D_T/B_0 = c.\rho*^{2.4}.q^{1.8}.\beta^{-1.08}.\nu*^{-0.13}$$

UKAEA Fusion Working in Europe

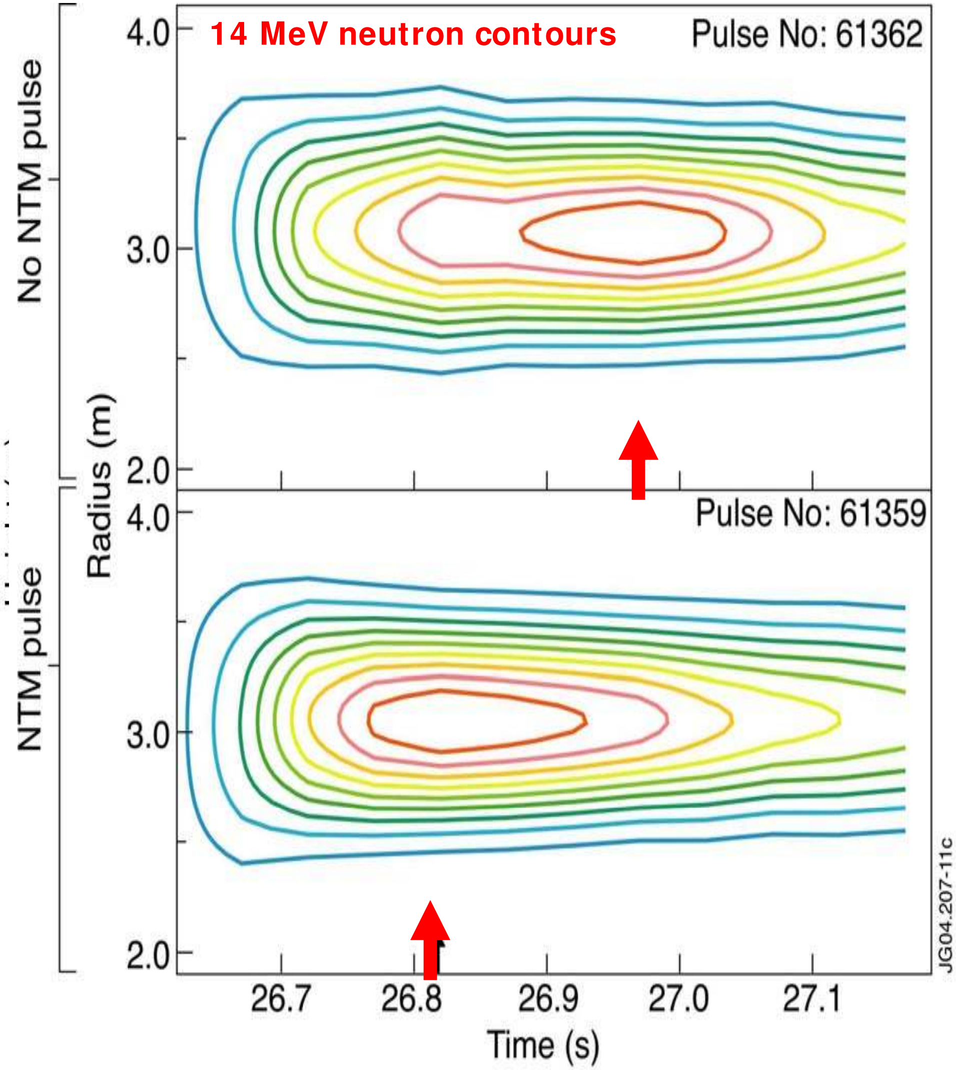
Particle transport with NTMs

Otherwise identical discharges set up with and without Neoclassical Tearing Modes.
Tritium gas puffs injected during the NTM period and evolution of the 14 MeV neutron profiles observed.

NTM transport effects are confined to within the q=3/2 surface.

Shots with NTM show more rapid transit of Tritium to the plasma centre, and a quicker decay of tritium profile.

Effects can be explained by:
higher D_T within q=3/2; or
larger inward v_T at q=3/2 surface.



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

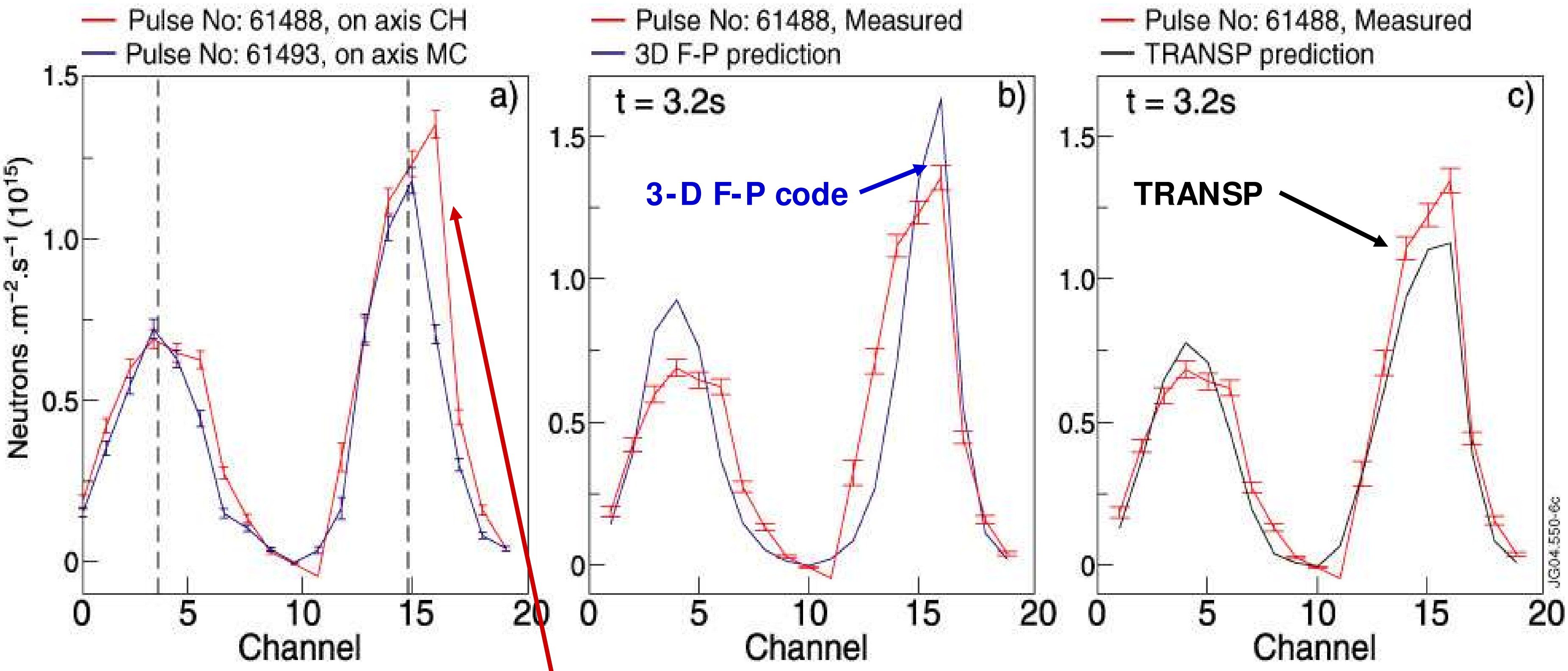
  Fusion product confinement/ transport ←

- [detecting effects of RF-accelerated protons pT fusion]

Fast Particle physics:

NBI transport in Current Holes

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



Behaviour (due to outward movement of ‘stagnation orbits’ of the tritons) successfully modelled by 3-D Fokker Planck code and by TRANSP Monte Carlo

Outward profile shift seen in CH plasmas compared to MC plasmas

Fast Particle physics:

Fusion product transport/ confinement (Yavorskij –TH/P4-49)

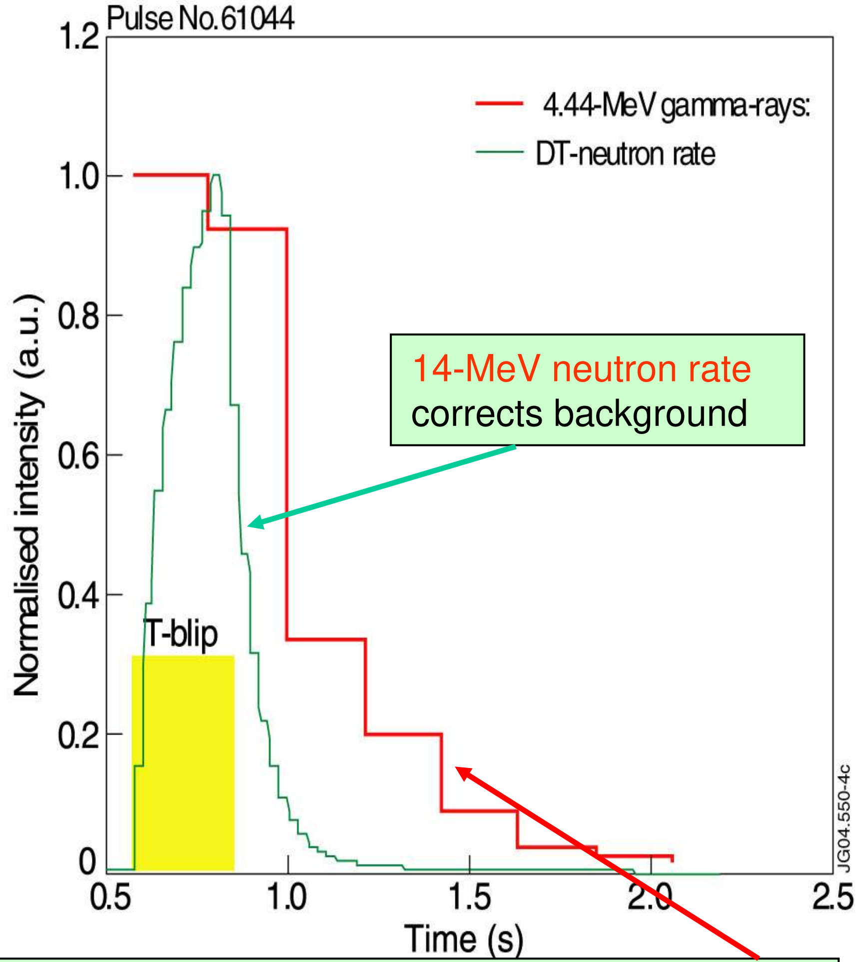
γ -ray spectrometry has provided information on distribution function of fusion α- particles in TTE

α-particle diagnosis was based on nuclear reaction ^{9}Be(α,nγ)^{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.



14-MeV neutron rate corrects background

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

UKAEA Fusion Working in Europe

Fast Particle physics:

Fusion product 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

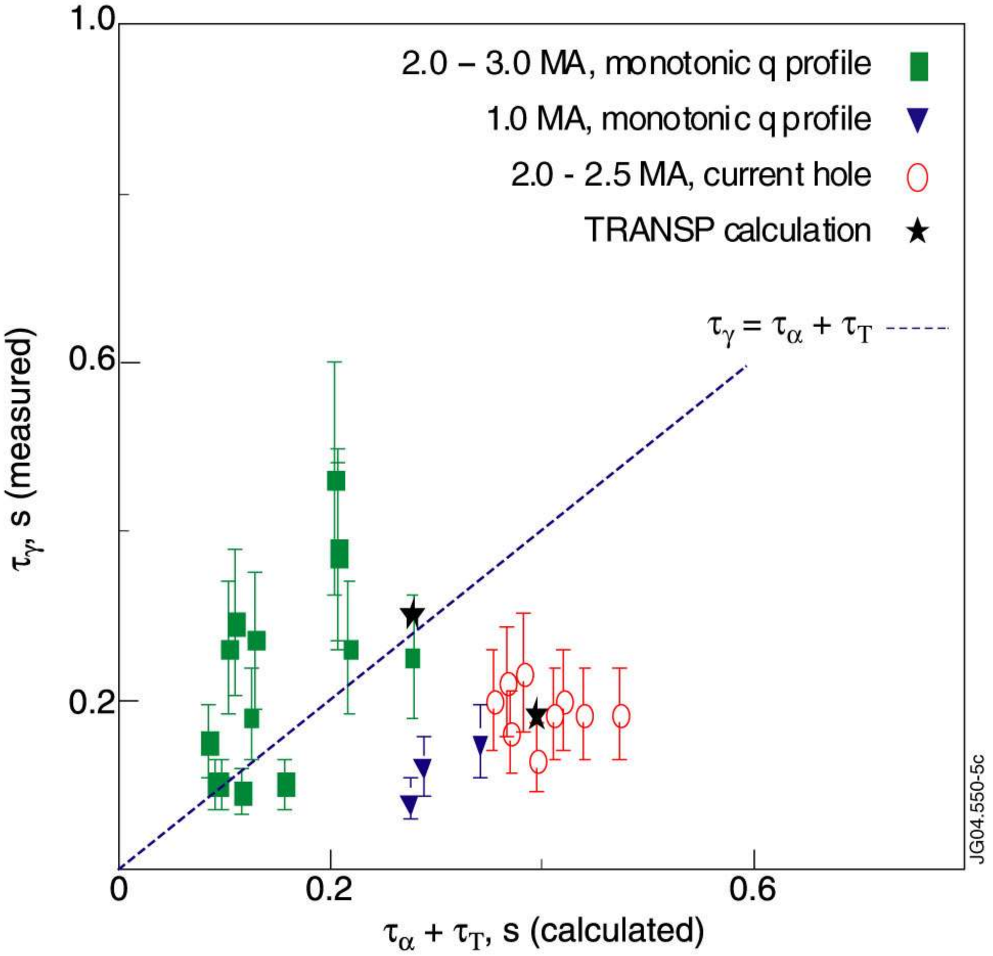
tritons from 105 keV to 40 keV

plus

α's from 3.5+ MeV to 1.7 MeV

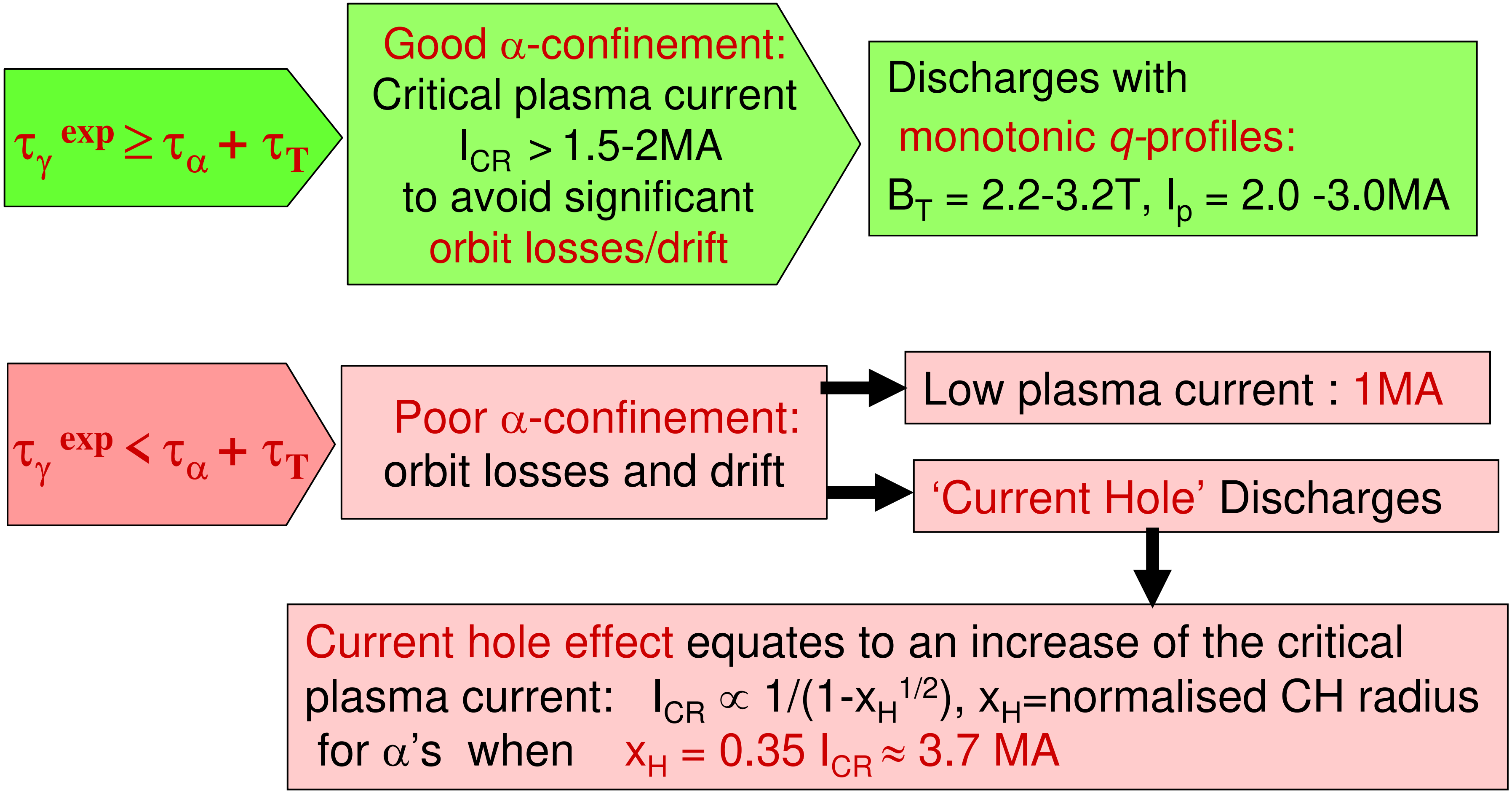
$\tau_\gamma^{\,exp} \geq \tau_\alpha + \tau_T$

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



Fast Particle physics:

Fusion product transport/ confinement (III)



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

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

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

Poor α-confinement:
orbit losses and drift

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=normalised CH radius for α's when $x_H = 0.35$ $I_{CR} \approx 3.7$ MA

Conclusions

- **Turbulence dominates thermal particle transport for most regimes**
  - Large inward v_T correlates with high D_T
  - Neo-classical only for : high n_e ELMy H & in ITBs.
- **Dimensionless parameters scans show:**
  - Gyro-Bohm particle transport ($D_T \sim \rho^{*3}$) for Inner plasma;
  - Bohm particle transport ($D_T \sim \rho^{*2}$) for Outer plasma;
  - but when q scans are included behaviour is more like Gyro-Bohm in outer plasma ($D_T \sim \rho_{POL}^{*3}$, where $\rho_{POL}^{*} = q\ x\ \rho^{*}$);
  - particle transport has an inverse β and $\nu *$ dependence.
- **Redistribution of fast deuterium and thermal tritium by sawteeth and NTMs is observed**
- **Current Hole plasmas show effects on Fast Ion transport and confinement, which can be modelled qualitatively by 3-D Fokker Planck code or TRANSP.**

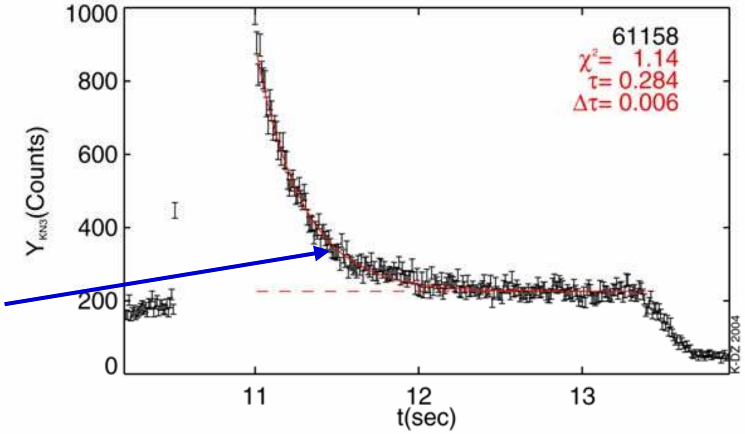
Reserve slides

Hybrid scenarios

Hybrid scenario results

- T_2 gas puff and T^0 NBI were injected into ‘Hybrid scenario’ plasmas [Joffrin -EX/4-2]
  - triangularity scan (δ= 0.2 -0.46) at fixed confinement ($H\beta_N/q_{95}^2$ ~ 0.32, $H\beta_N$~ 5-5.5);
  - I_P (1.4 MA -> 2.0 MA) scan at constant q, and low δ

- A global particle confinement time (τ_P) can be established approximately from the decay of the 14 MeV neutrons after thermalisation of fast NBI-ions



- The effect of wall recycling on this value of τ_P is negligible
- Global τ_P increases by ~ 50% over the δ scan and scales ~ with I_P

Hybrid scenario results (II)

- Global τ_P increases by ~50% over the δ scan and scales ~ with I_P.
- The fits to the 14 MeV profiles maintain this result quantitatively.
  - For triangularity scan, difference appears as reduction of D_T across the whole plasma, as $\delta \uparrow$.
  - For current (not shown) there is a less significant reduction in D_T for r/a>0.5 as I_P increases