Plasma core transport of D and T and implications for the fuel cycle

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Acknowledgements

F. Casson, C. Challis, D. King, M. Maslov, Z. Stancar and JET Contributors*

Culham Science Centre, UK Atomic Energy Authority, Abingdon, UK.

* See the author list of 'Overview of JET results for optimising ITER operation' by J Mailloux et al 2022 Nucl. Fusion 62 042026

Outline

- Early results from TFTR and JET
- Theoretical analyses
- Mixed plasmas experiments pre JET DTE2
- DTE2 results
- Few words about T cycle
- Conclusions

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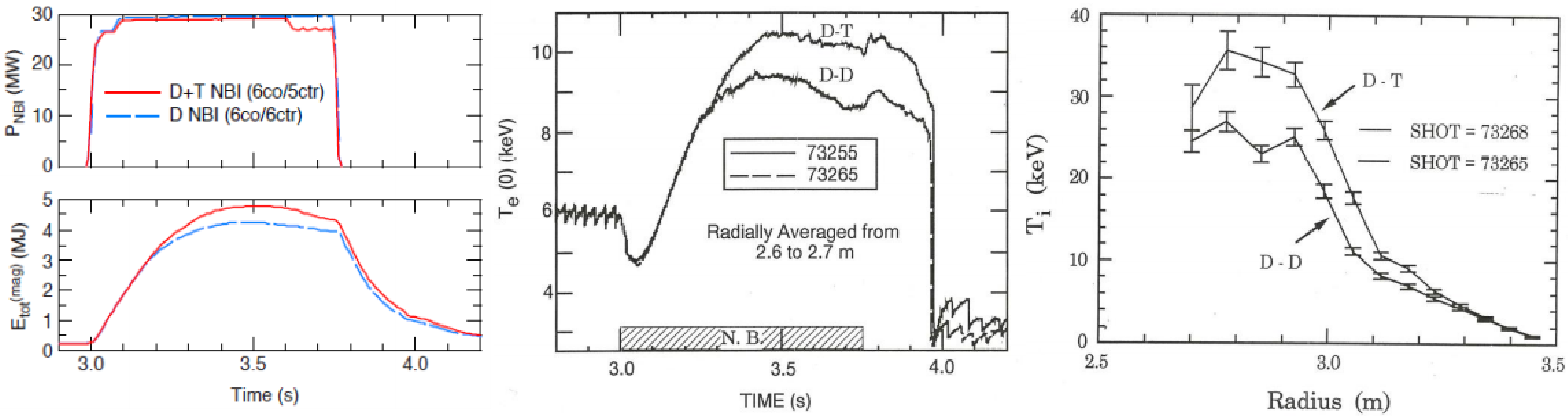
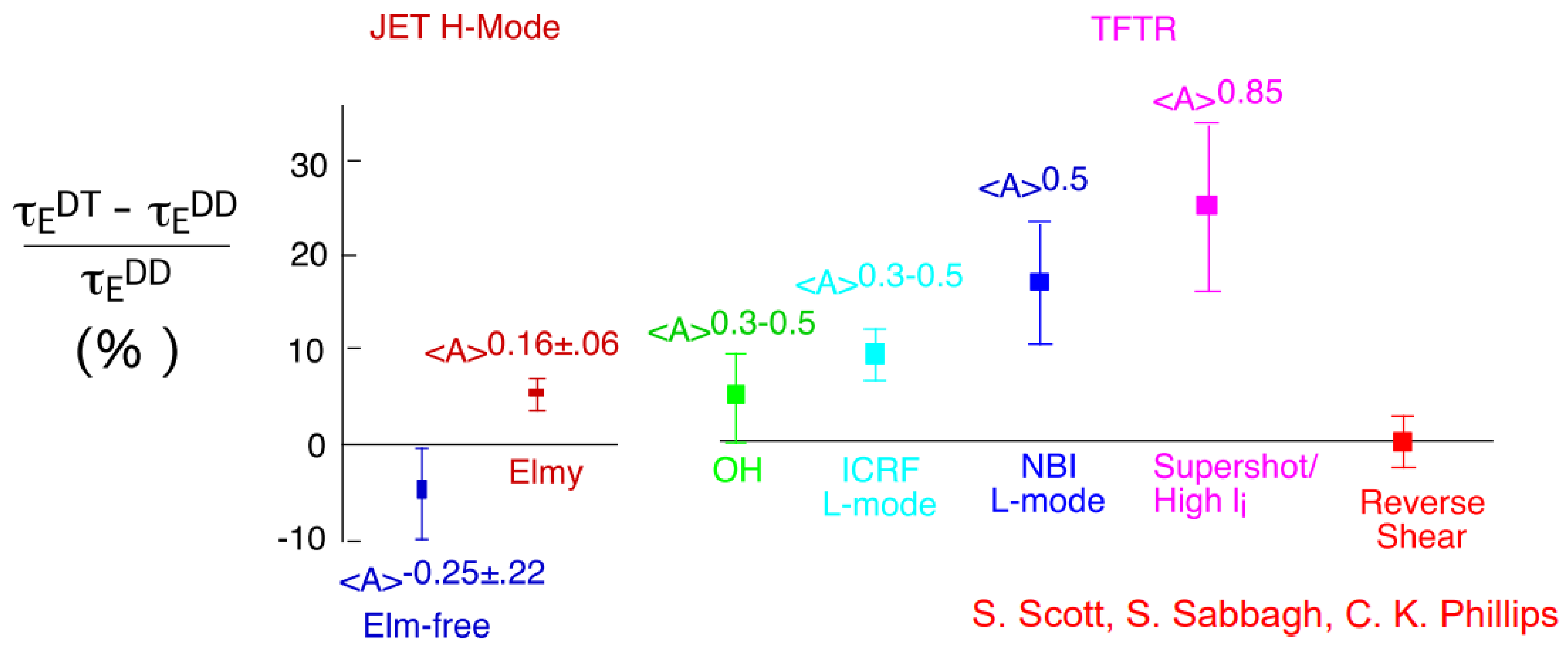
DD vs DT plasmas in TFTR: clear differences



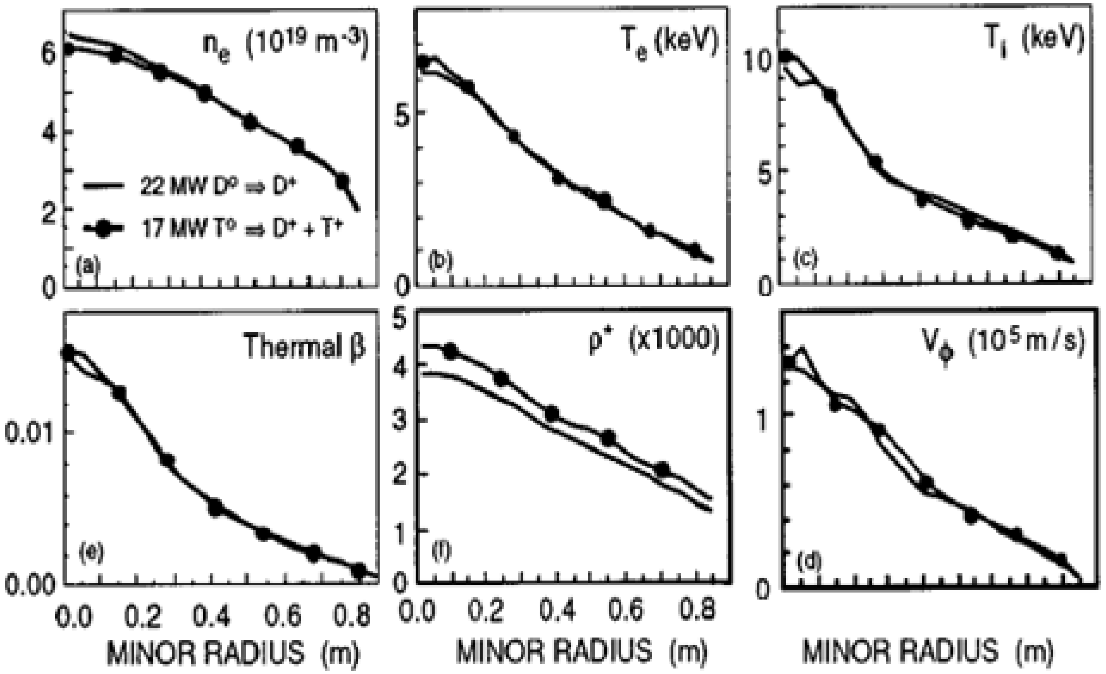
- From the first pulse significant differences between DD and DT plasmas
- Indications of different transport for DD and DT

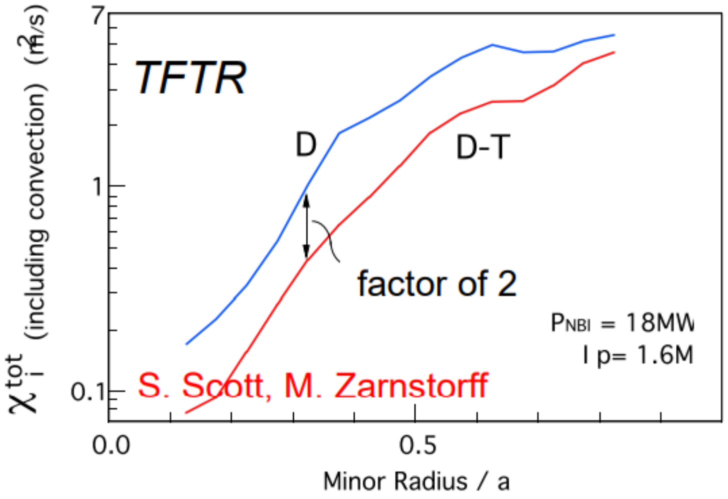
DD vs DT plasmas energy confinement time



- JET vs TFTR confinement time: the complete zoo
- Isotope dependence is plasma configuration dependent
- ITER projection uses:<A>$^{0.2}$

DD vs DT plasmas in TFTR





- Heat transport significantly changes from DD to DT
- Particle transport confinement seems to follow heat transport
- No clear information about D vs T transport
- Theories raised at that time never really validated

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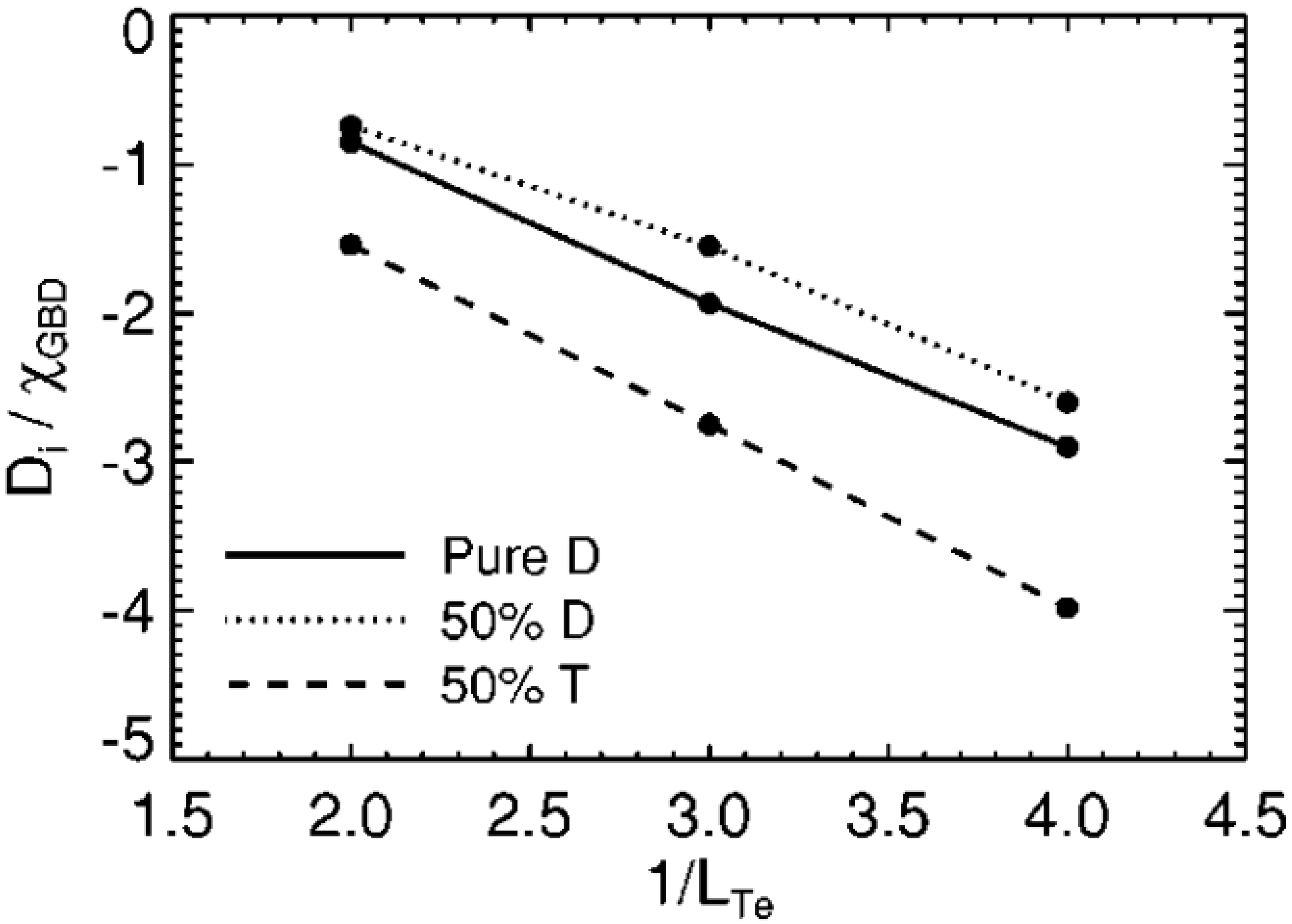
First theoretical studies of D vs T transport

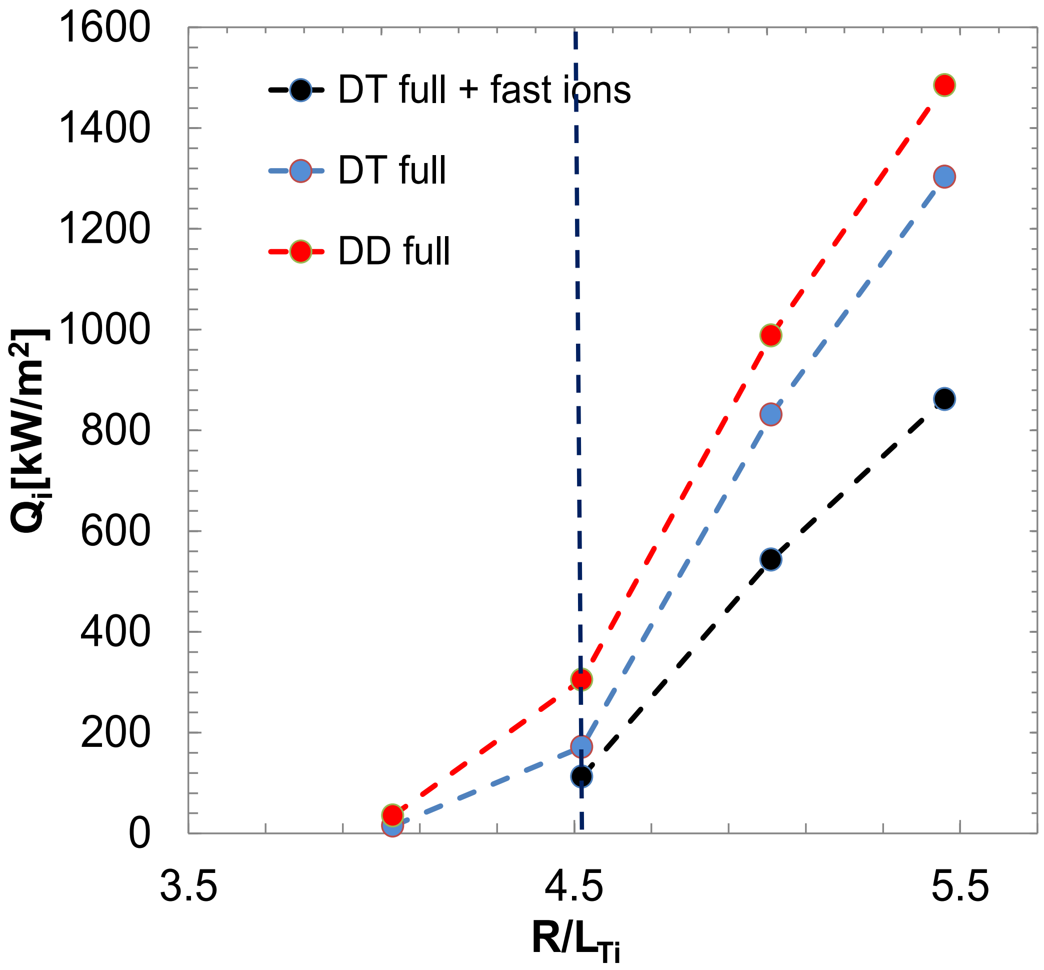


[Estrada-Mila POP 2005]

- Gyrokinetic simulations: asymmetry between D and T particle transport
- Higher inward pinch for T
- Important assumptions
  - 50%D-50%T
  - $1/L_{Te,i}(D)=1/L_{Te,i}(T)$
  - $1/L_{ne,i}(D)=1/L_{ne,i}(T)$

Isotope effects in DT ITER plasmas: heat flux reduction

GK Non-linear results of ITER hybrid scenario with GENE at $\rho = 0.33$



[J. Garcia et al. NF17]

[J. Garcia et al. POP18]

- Including finite beta and ExB effects (full simulation)
  - Ion heat flux reduction of 42% from DD to DT
  - 3 times reduction of heat flux from DD to full DT+ fast ions

Important assumptions

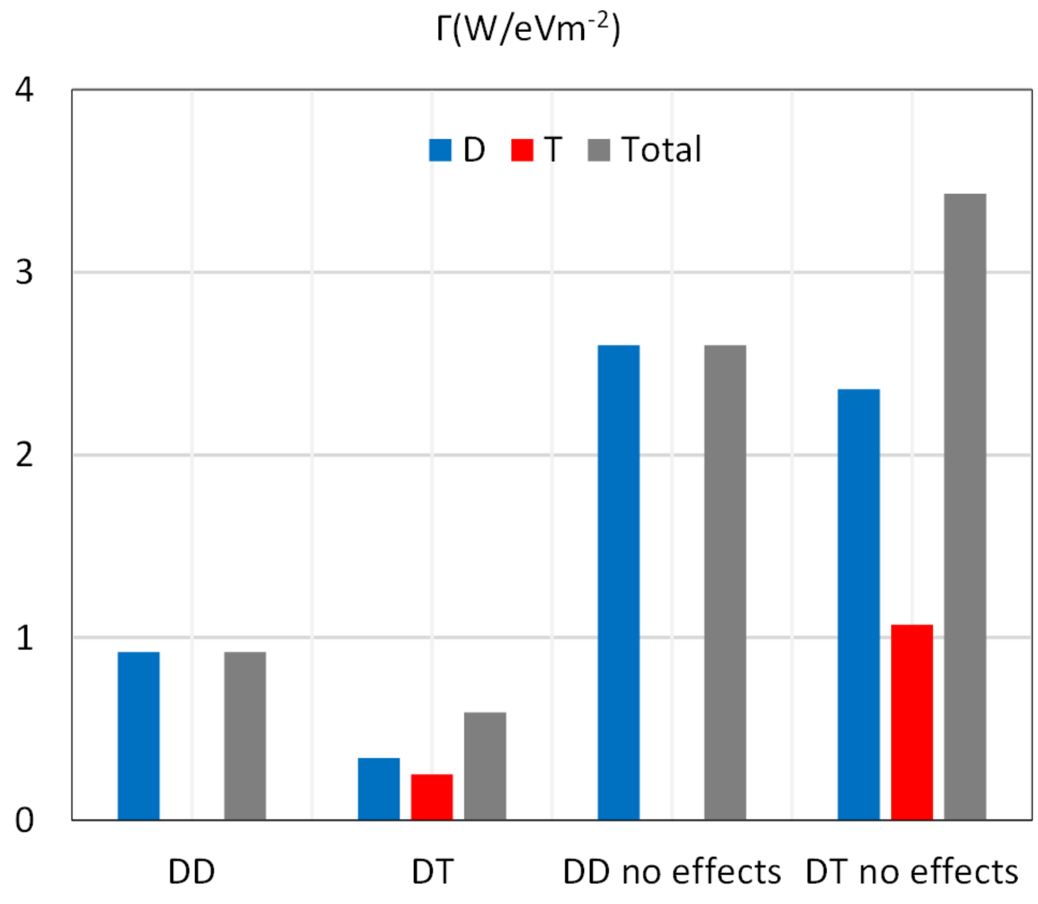
50%D-50%T

$1/L_{Te,i}(D)=1/L_{Te,i}(T)$

$1/L_{ne,i}(D)=1/L_{ne,i}(T)$

Isotope effects in DT ITER plasmas: D vs T transport

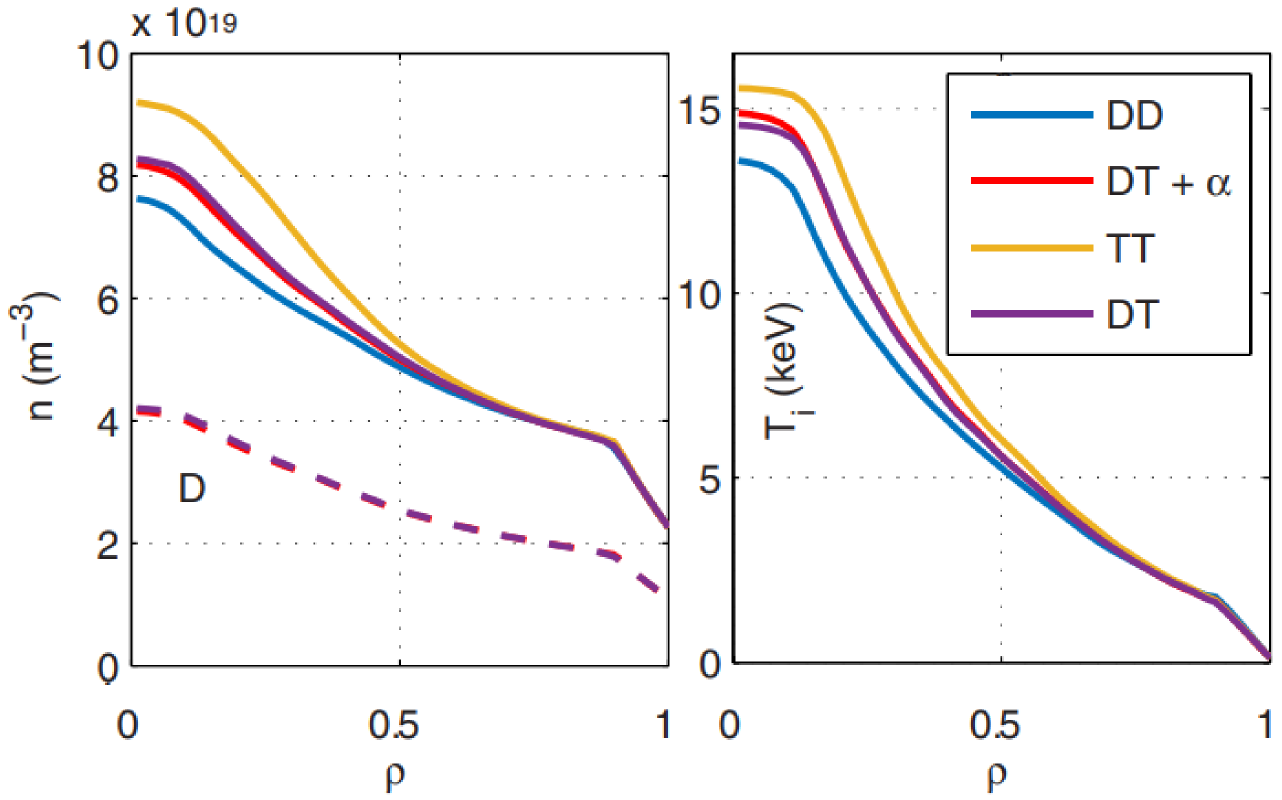
GK Non-linear results of ITER hybrid scenario with GENE at $\rho = 0.33$



[J. Garcia et al. POP 18]
[J. Garcia et al. PPCF 22]

- Total ion particle transport reduction from DD to DT
- Same trend as for heat transport
- D vs T particle transport more complex:
    - Asymmetry between D vs T particle transport
    - Lower T than D particle flux

Preparation for JET-DT: modeling activities



[F. Casson et al. NF 20]

- Core particle transport studied for JET-DT preparation
- JET-DT extrapolation from DD: JINTRAC and qualikiz transport model
- Improved heat and particle confinement with increasing mass
- Assuming 50/50% D/T source → nearly identical D and T densities in DT

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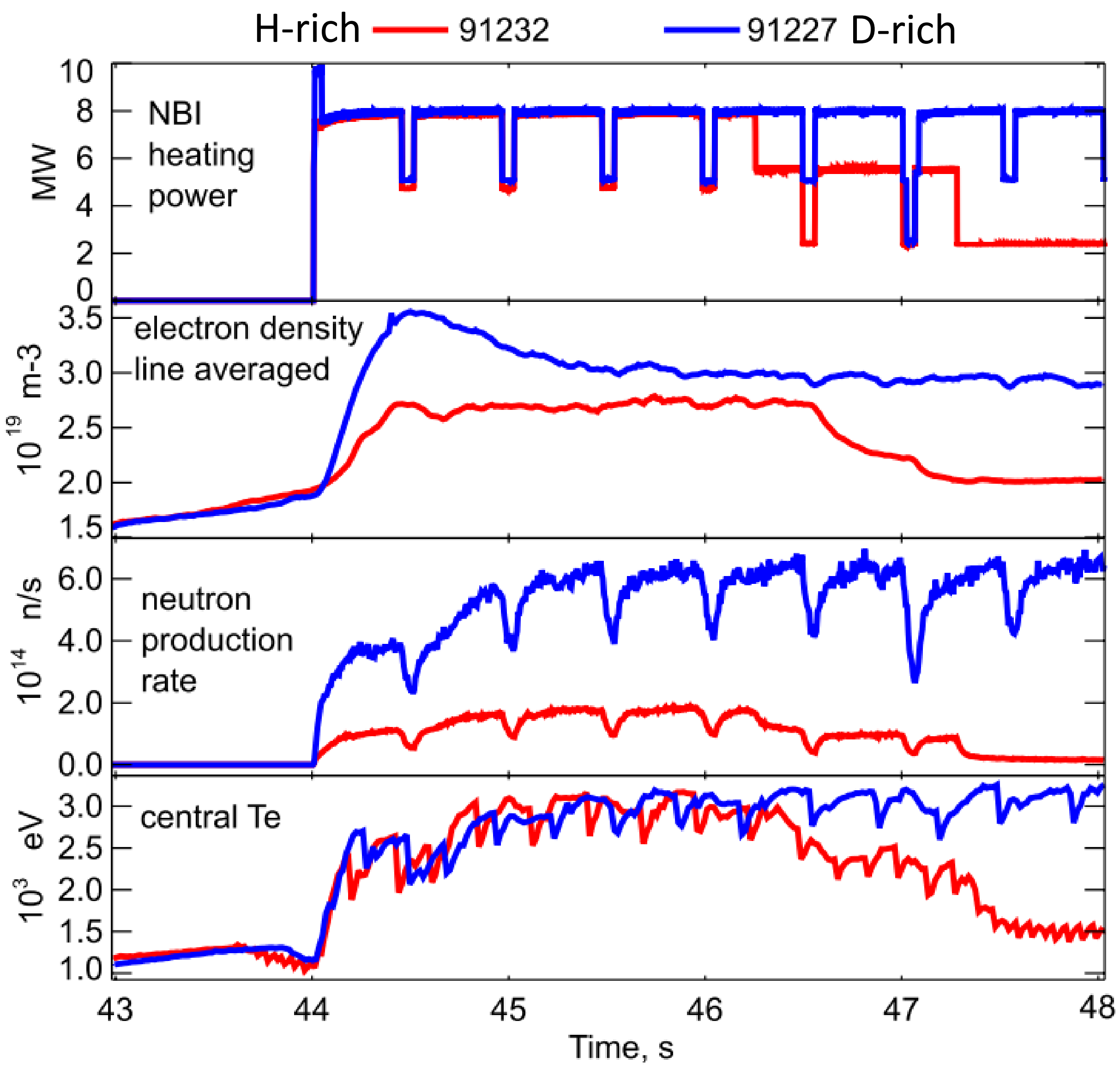
Preparation for JET-DT: experiment activities



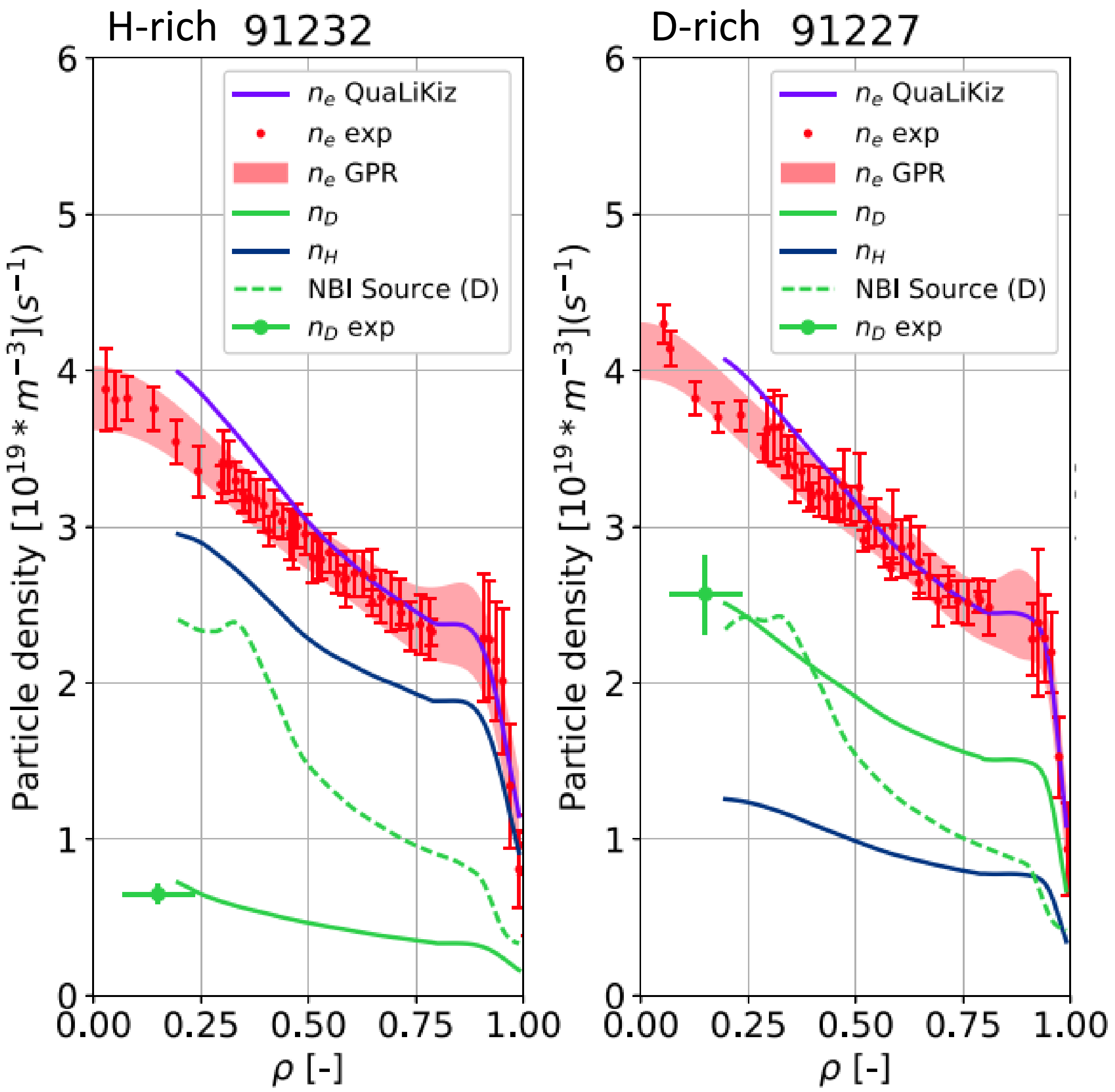
[M. Maslov et al. NF 18]

Table 1. Measured and calculated edge and core D/H isotope concentrations.

Pulse number	91232	91227
$n_D/(n_D + n_H)$ edge—measured	0.14	0.67
$n_H/(n_D + n_H)$ edge—measured	0.86	0.33
$n_D/(n_D + n_H)$ core—derived	0.157	0.676
$n_H/(n_D + n_H)$ core—derived	0.843	0.324

- D beams injected into H-rich or D-rich plasma
- Measured edge H/D concentration similar to derived core concentration
- Insensitivity to core particle source

Fast ions mixing concept in multi ions plasmas



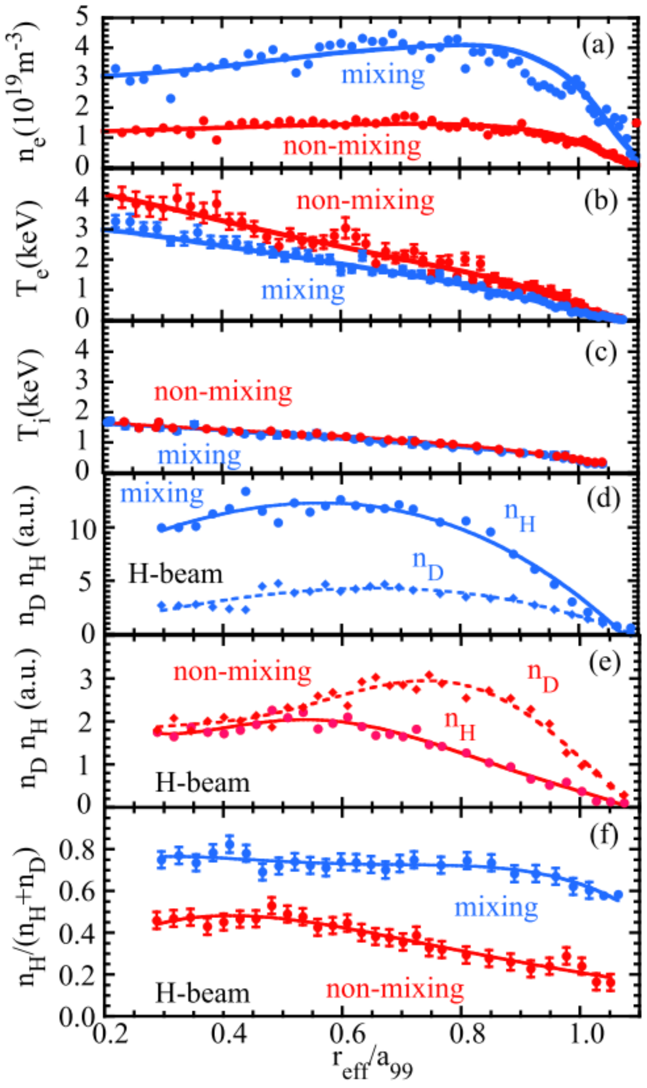
[M. Marin et al. NF 21]

- Theoretically analysed in the Quasi-linear GK approximation

[C. Bourdelle et al. NF 18]

- Ion densities determined by transport in ITG regime
- Fast ion mixing→ core ion density insensitive to core particle sources
- Shown in multi-ion integrated modelling simulations with QuaLiKiz

Mixing and non-mixing states in LHD



[Ida PRL 2019; Ida NF 2021]

- Plasma behavior observed in LHD characterized as either
  - Mixing, where isotope ratio is flat and insensitive to particle sources
  - Non-mixing, where isotope ratio in non-uniform

Table 2. Linear gyrokinetic simulation results for the plasma with isotope non-mixing and mixing state

	Non-mixing state	Mixing state
Edge $r_{\mathrm{eff}}/a_{99} = 0.9$	TEM destabilized	TEM stabilized
Core $r_{\mathrm{eff}}/a_{99} = 0.5$	ITG destabilized	ITG destabilized

- Consistent with JET results for ITG plasmas

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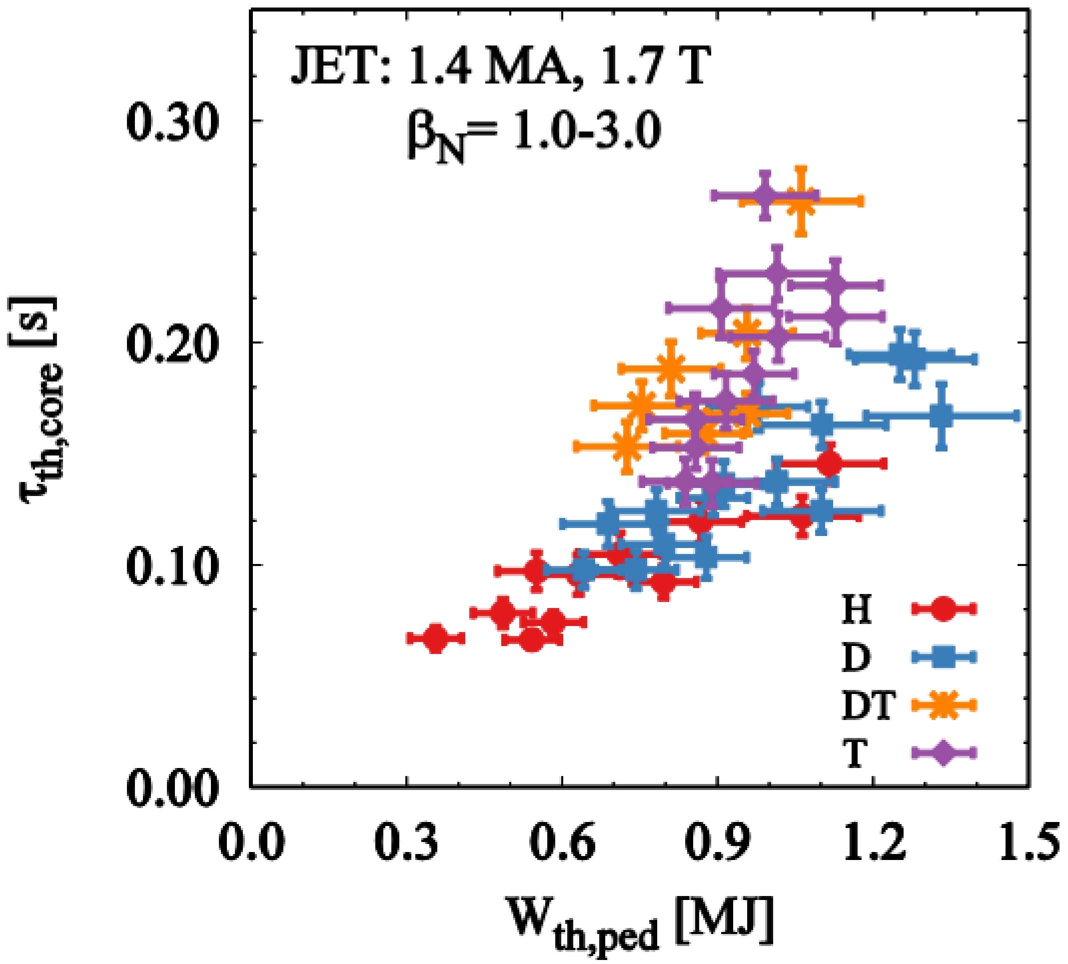
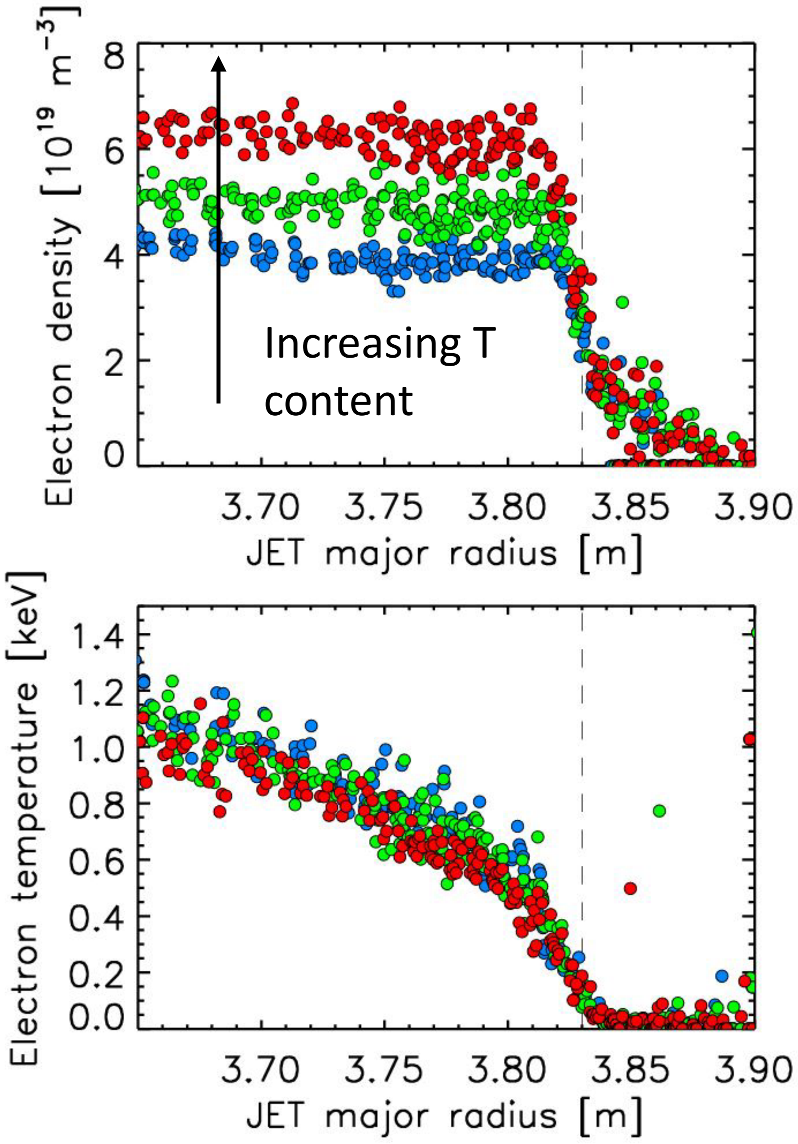
Core energy confinement



[P. Schneider AAPPS conference 2021]

- T and DT plasmas show higher core energy confinement than D and H
- Notably at high input power
- In agreement with previous theoretical studies
- Heat transport reduced in D→T with:
  - Rotation [Garcia NF17]
  - Beta [Casson NF20]
  - Collisonality [Mariani NF21]

Variation of H-mode pedestal structure with D-T fuel mix



- Increased pedestal density from H to D

[CF Maggi et al., PPCF 2018]
[L Horvath et al., NF 2021]
[P Schneider et al., NF 2022]

- Changes on transport characteristics

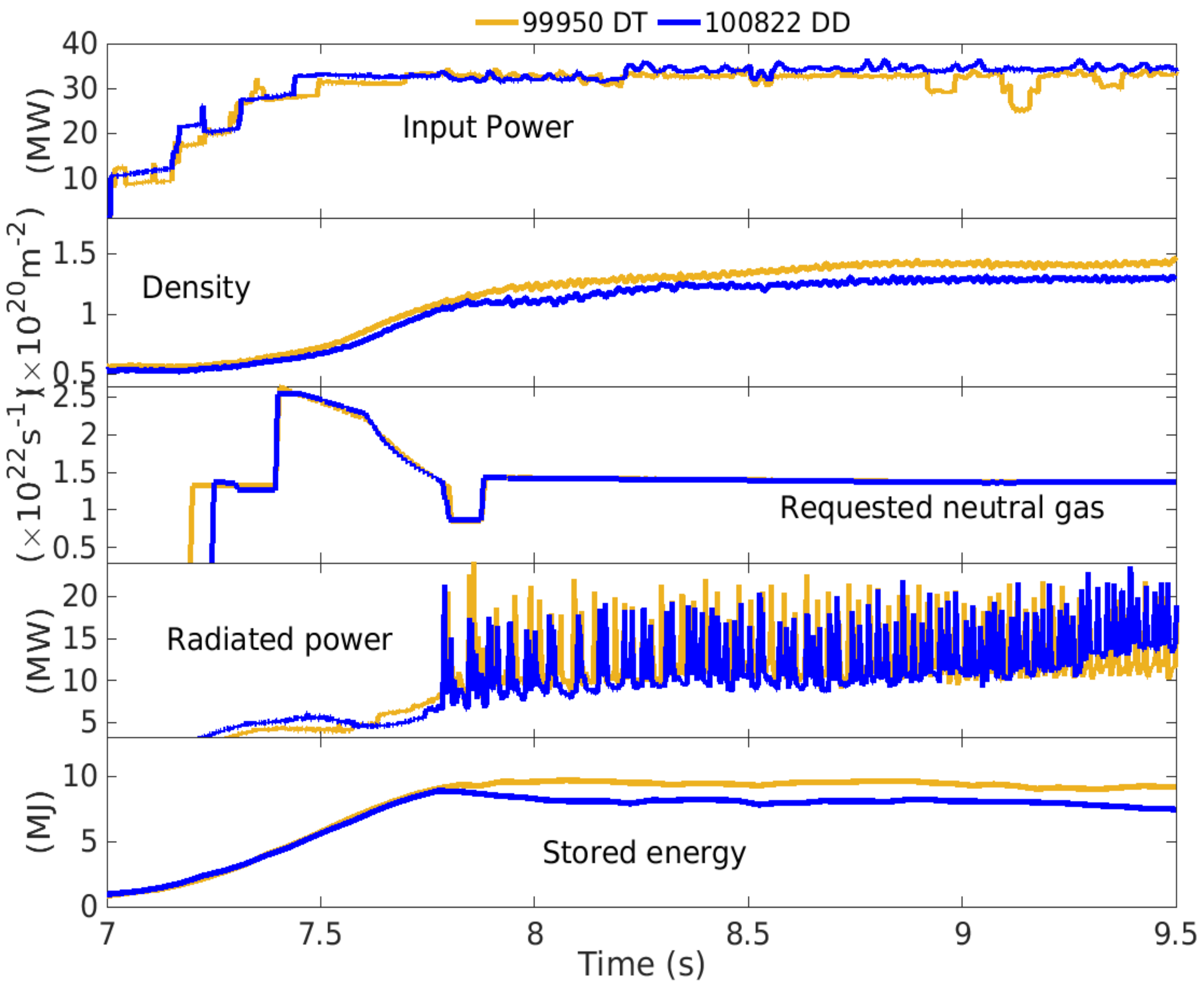
[Horvath NF21]

- Pedestal density also increases in D→T
- Crucial data for improving ITER predictions

Controlled D-T fuel mix scan at constant β_N
(obtained with feedback control on injected power)

[L Frassinetti et al.]

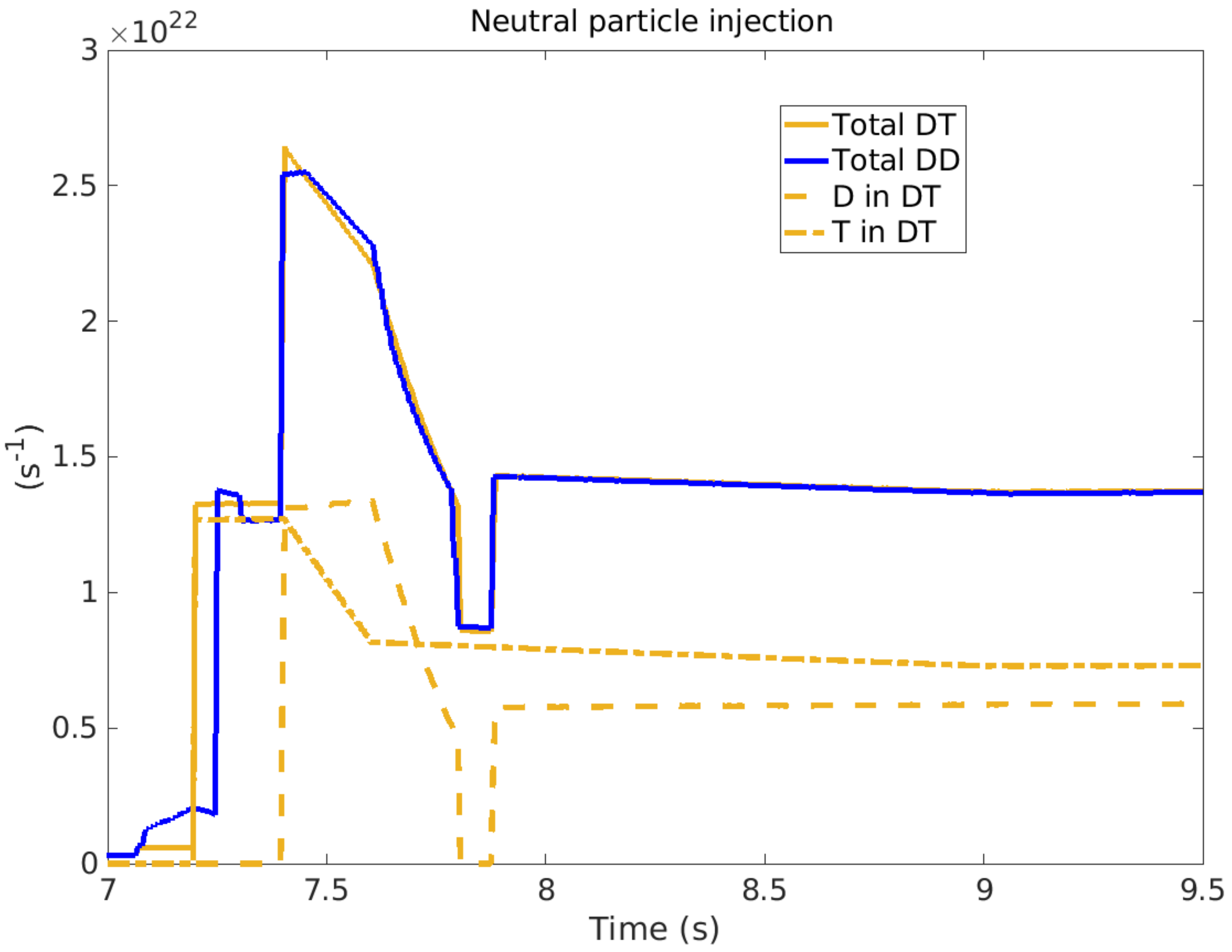
Hybrid scenario at high beta: DD vs DT



[A. Kappatou APS-DPP conference 2022]

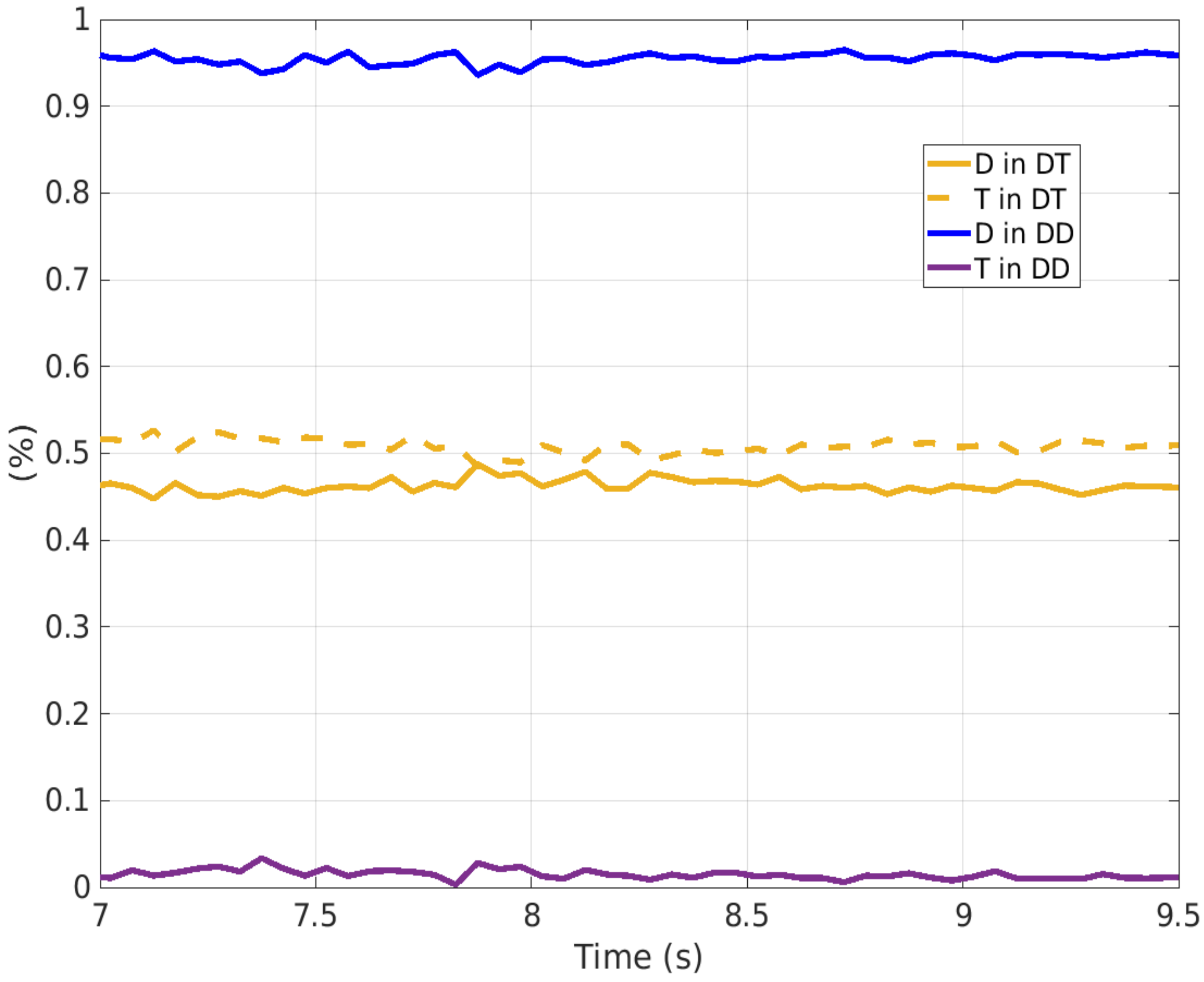
- Hybrid scenario (high beta) in DT (~50%/50%) and DD
- Same input power (alpha power compensated by NBI power)
- Same requested neutral gas injection
- 50/50% D-T beams
- Higher density and stored energy in DT
- Better confinement in DT

T and D gas injection in hybrid



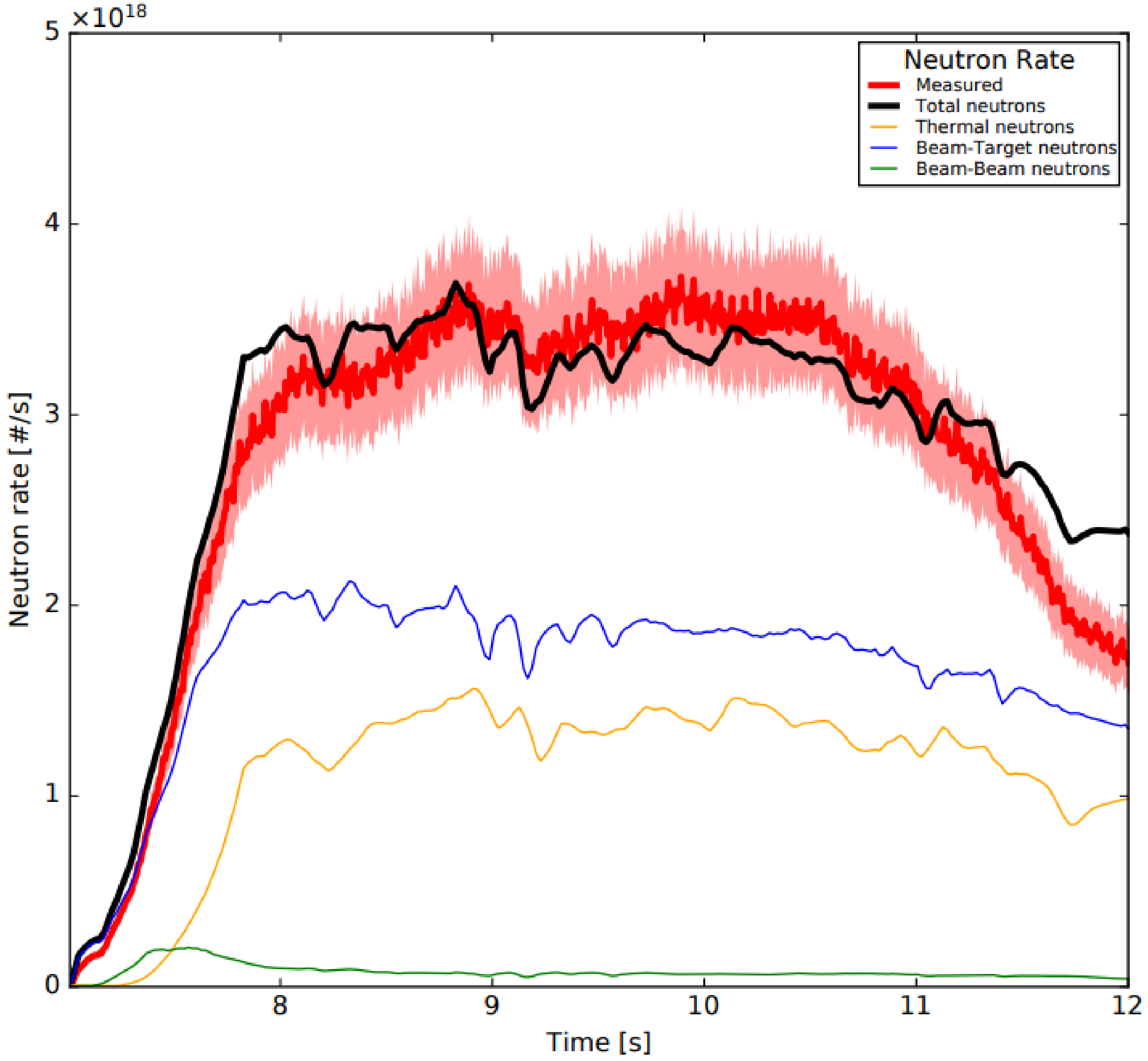
- Equivalent neutral gas injection rate requested in DD and DT
- Similar T and D gases injected

Measured D/T fraction at the plasma edge



- Equivalent neutral gas injection rate requested in DD and DT
- Similar T and D gases injected
- D/T fraction measured at the divertor: ~50/50%
- For the DD case ~95% of D

Neutron rate reproduced witn TRANSP and edge measurements

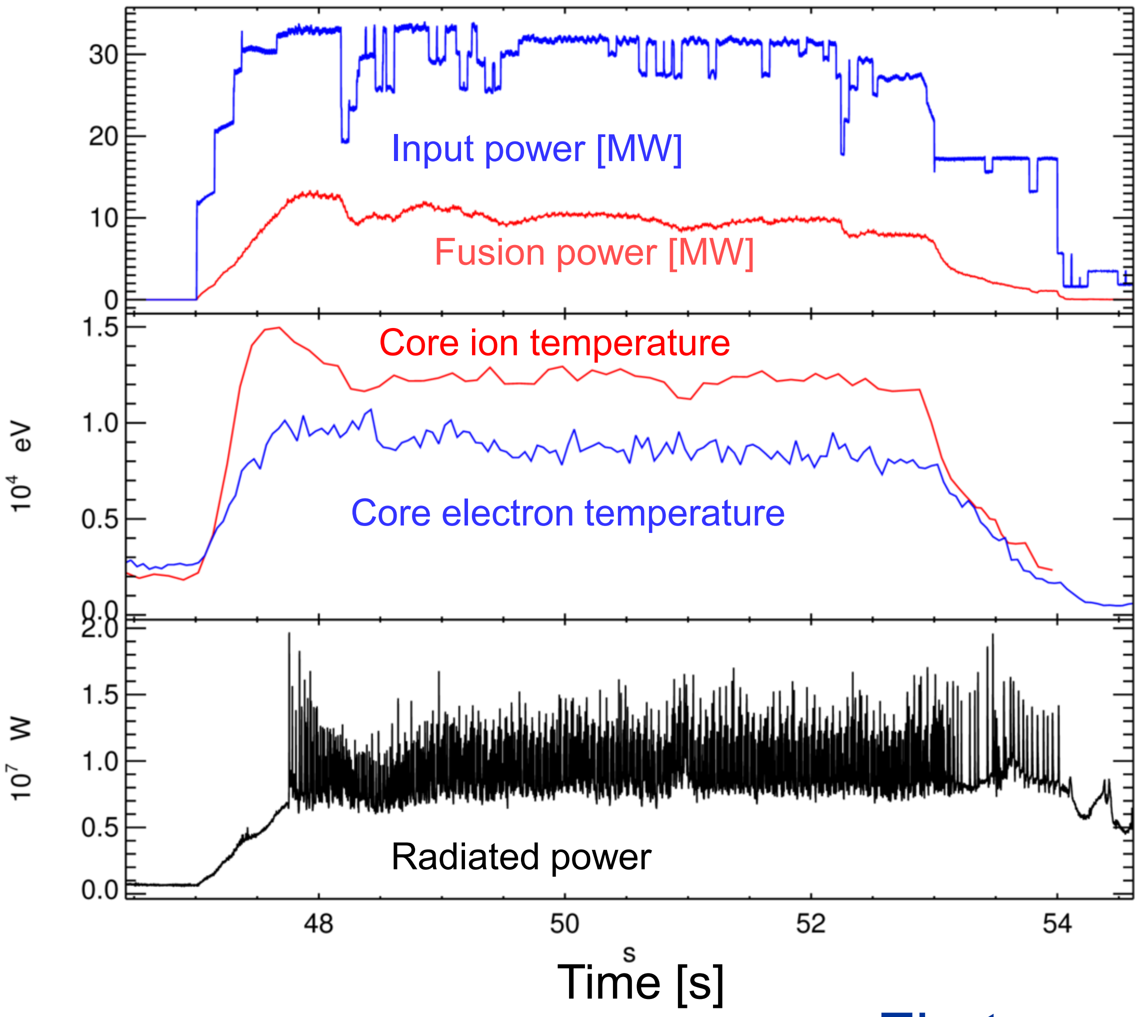


[Z. Stancar APS-DPP conference 2022]

- Equivalent neutral gas injection rate requested in DD and DT
- Similar T and D gases injected
- D/T Ratio measured at the divertor: ~50/50%
- For the DD case ~95% of D
- Neutron rate calculated with TRANSP
- Agreement with measurement assuming D/T ratio in the core as in the edge

H-mode scenario with optimized non-thermal fusion power

15%D - 85%T plasma with D-NBI (2.5MA/3.86T)

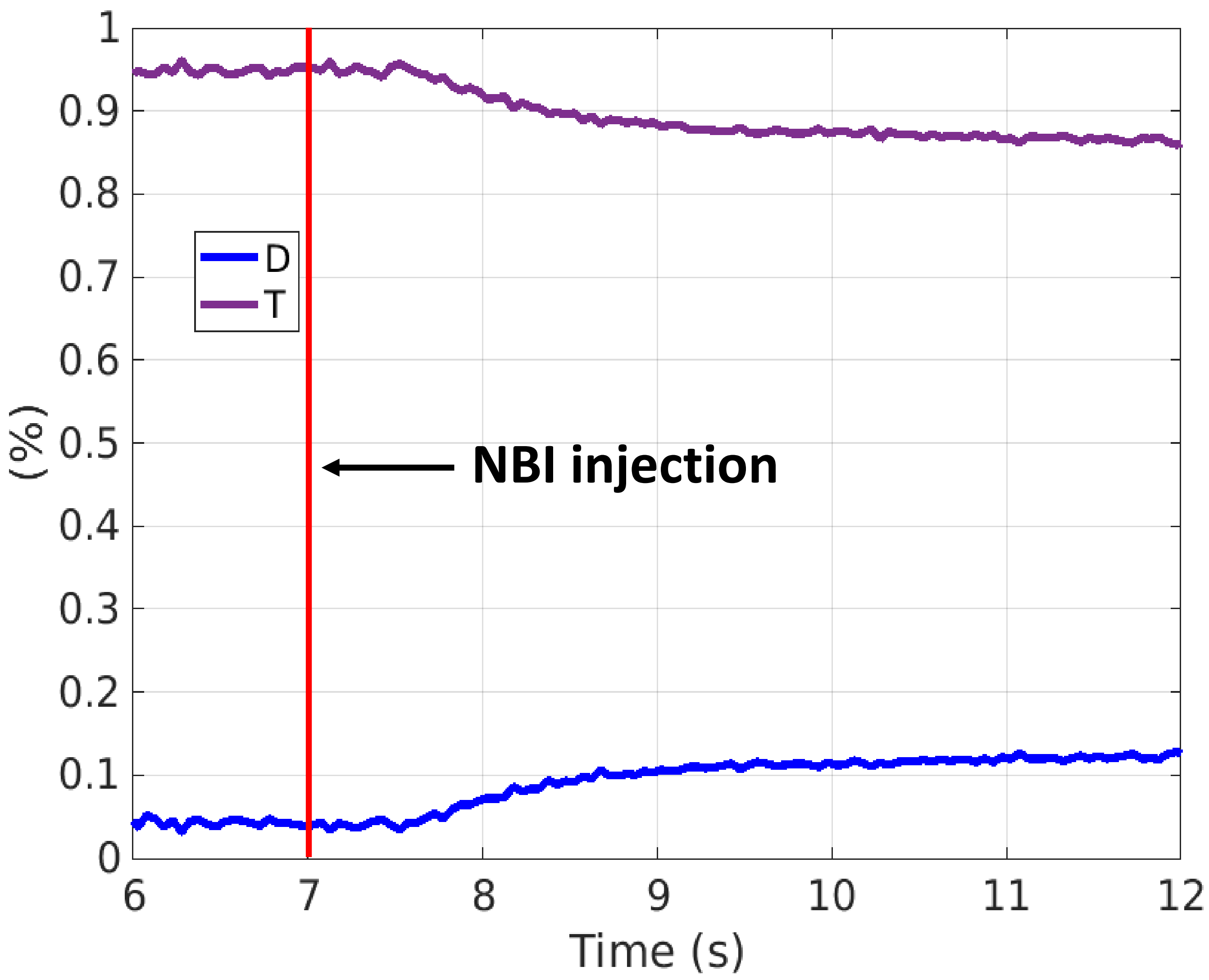


- Plasma composition: 15%D - 85%T
- Max pure Deuterium NBI heating (30 MW)
- Record steady fusion energy: E_{fus}= 59MJ
- Non-thermal fusion production dominant

[M. Maslov]

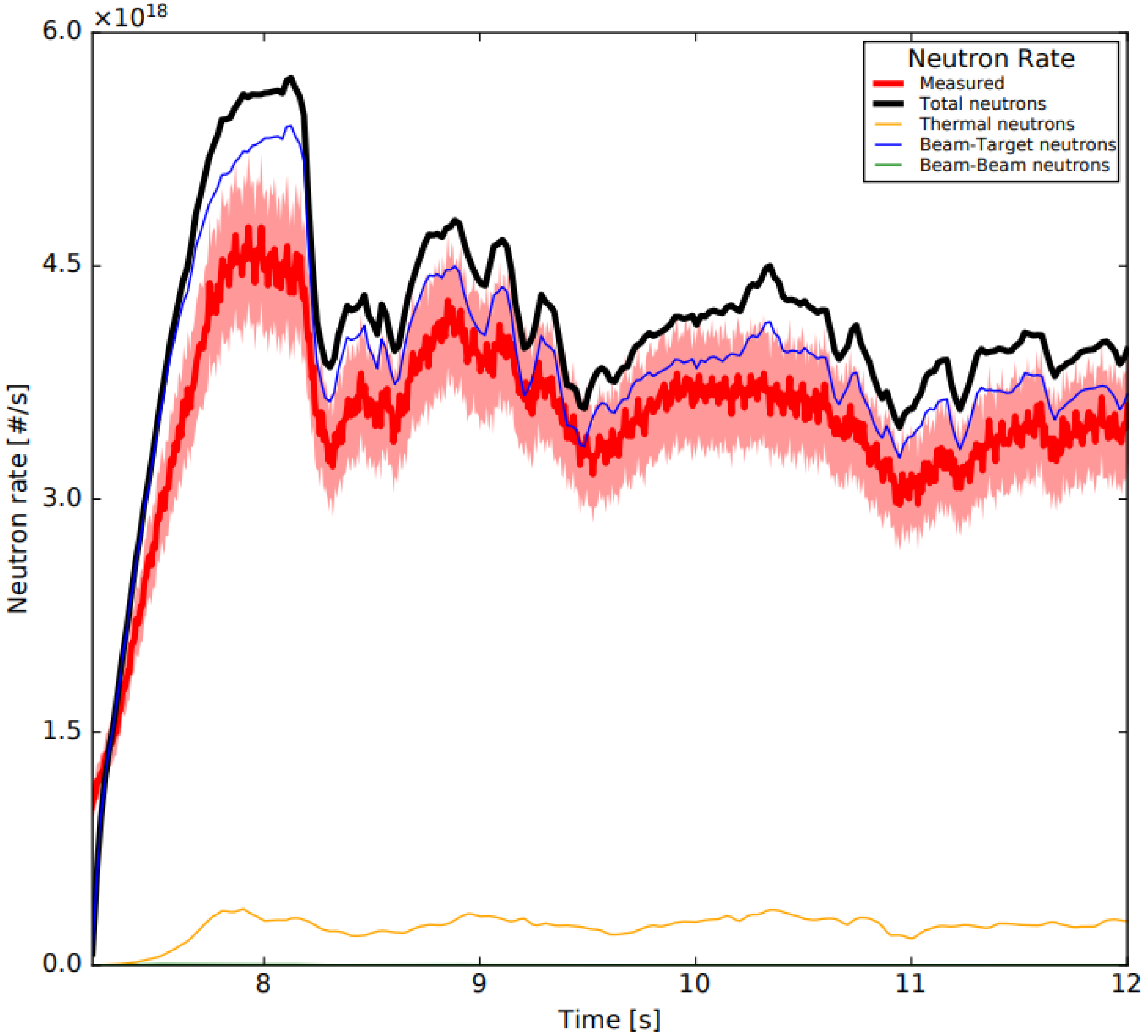
First ever tested on JET or anywhere else

Measured D/T ratio at the plasma edge: NBI source influence



- Measured D/T ratio at the plasma edge→ ~85%T
- Clear influence of the D beam injection

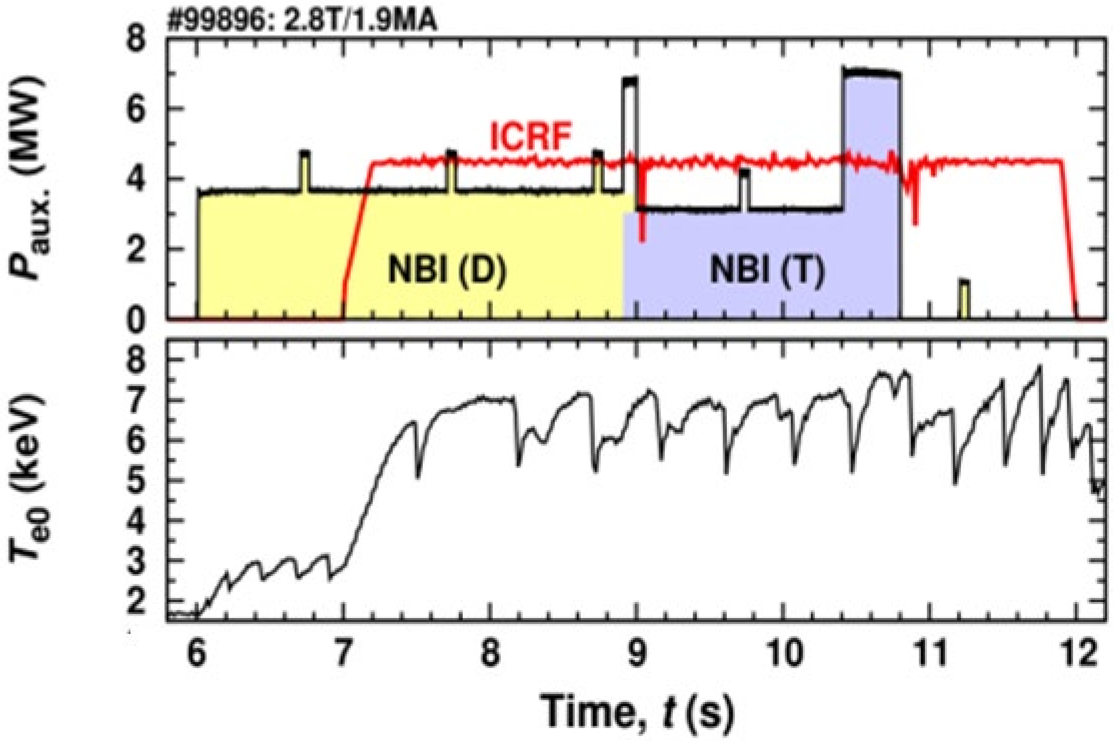
Neutron rate reproduced with TRANSP and edge measurements



[Z. Stancar APS-DPP conference 2022]

- Measured D/T ratio at the plasma edge→ ~85%T
- Clear influence of the D beam injection
- Neutron rate well reproduced by TRANSP assuming core and edge same D/T ratio
- Neutron rate dominated by beam-target fusion reactions

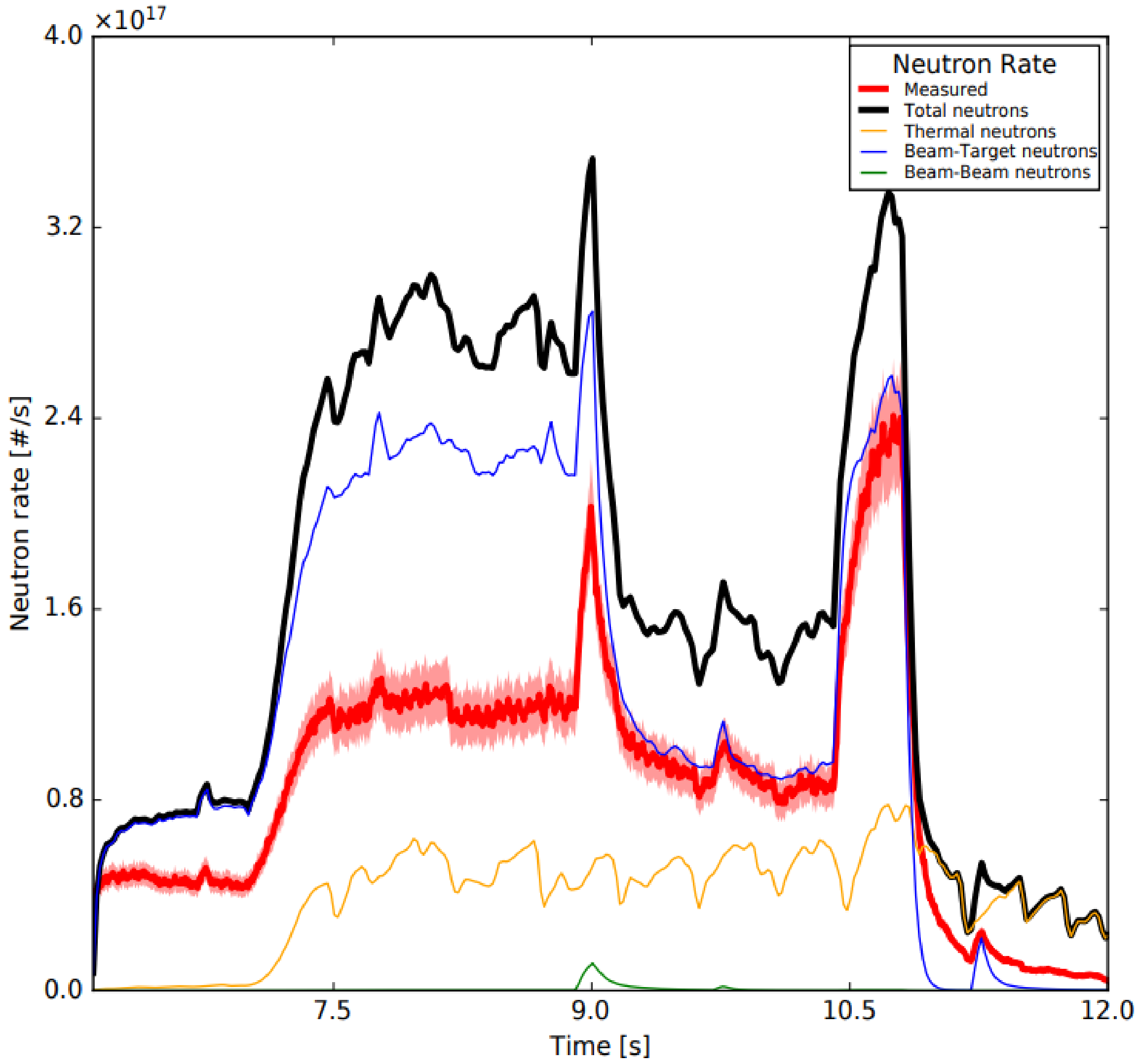
Neutron rate prediction at low input power



[Y. Kazakov]

- ~50%/50% DT plasma with T or D beams
- High ICRF power injected

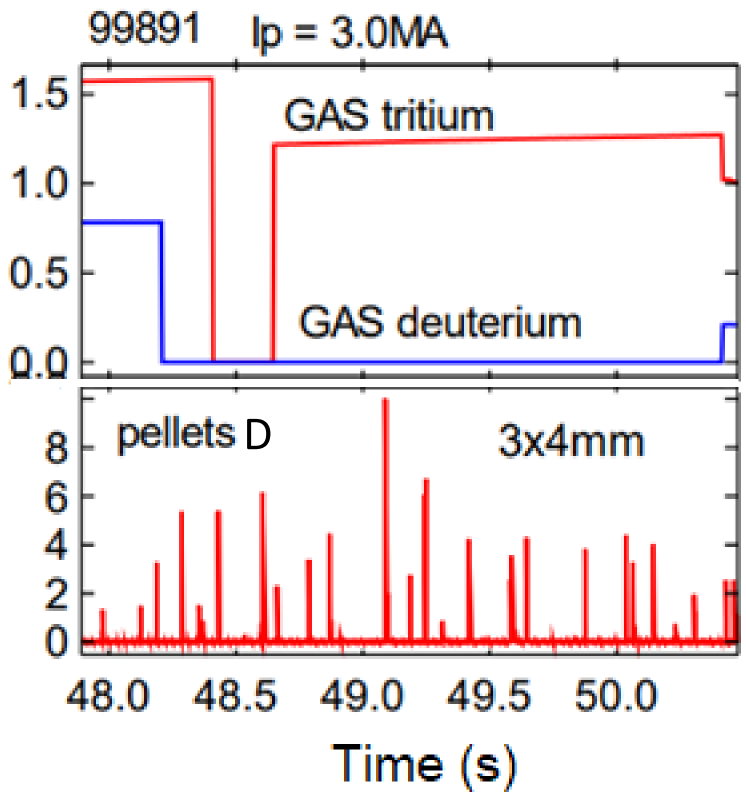
Neutron rate prediction at low input power



[Z. Stancar APS-DPP conference 2022]

- ~50%/50% DT plasma with T or D beams
- High ICRF power injected
- Experimental neutron rate overestimated by TRANSP in both D and T beams phases
- In general, overestimation of neutron rate at low input power
- Regardless ICRF vs NBI power
- Reasons under investigation

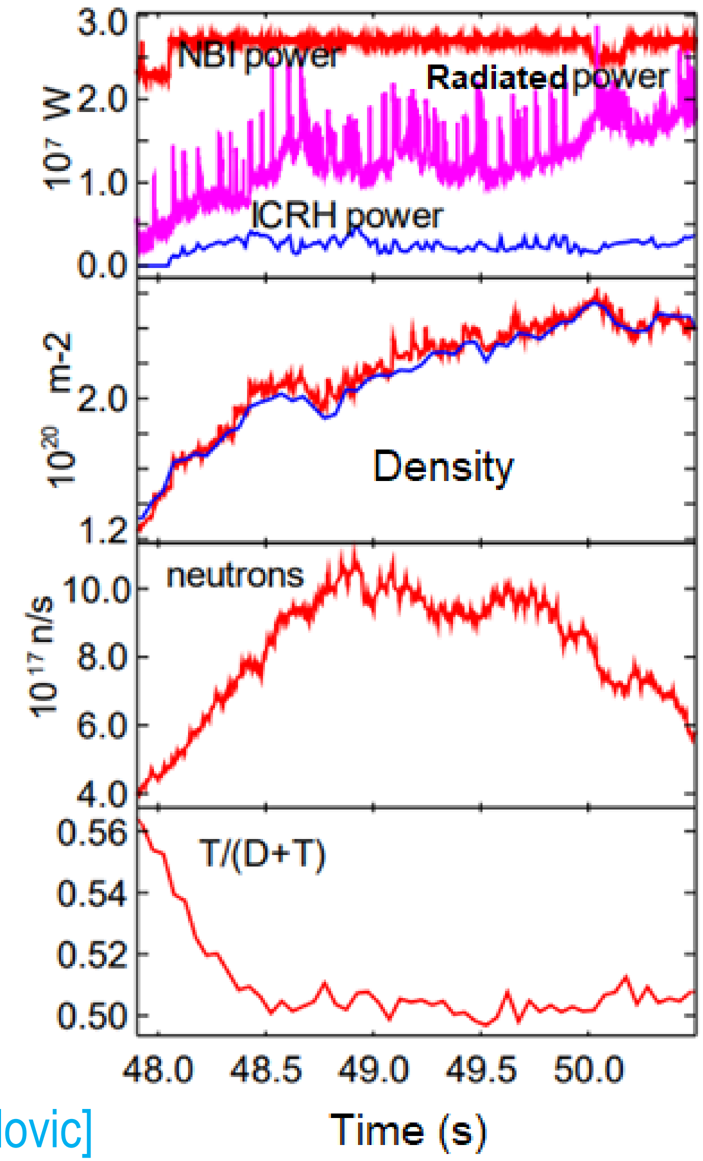
D-T mixture control: pellets vs neutral gas



[M. Valovic]

- Different D-T plasma fueling tested
  - Neutral Gas Injection
  - Pellets
- Can the 50-50% DT mixture be controlled?

D-T mixture control: pellets vs neutral gas



[M. Valovic]

- Different D-T plasma fueling tested
  - Neutral Gas Injection
  - Pellets
- Can the 50-50% DT mixture be controlled?
- 50-50% mix achieved and controlled by adjusting pellet frequency
- High neutron level show potential 50-50% mixture in the core→ being analyzed
- Essential information for ITER

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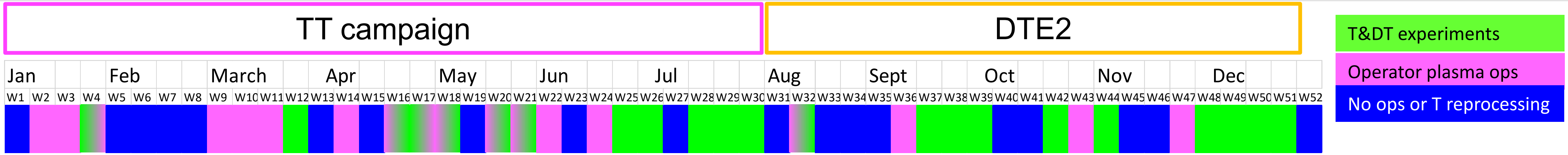
Tritium budget & reprocessing



The Active Gas Handling System (AGHS) was extensively refurbished for DTE2 to provide:

- Daily gas feed to torus & NBI
- Daily gas exhaust recovery and overnight storage
- Weekly reprocessing and accountancy every 3 weeks
- (but note schedule changes for technical machine issues)

In addition to the total available gas, we had a *daily* limit of 11g on the inventory allowed on the torus & NBI cryopanels (Safety Case) ➔ see later for budget management

Tritium *used*:

T + D-T (until Dec 2021) : ~ 170g (TIMs) and ~ 680g (T-NBI)

DTE1 : ~ 35g (shorter campaign + one NBI box + single TIM)

Tritium on site for DTE2 was ~68g (21g in DTE1)

T and DTE2 : experiments & budgets management

T and D-T experiments managed very differently from usual JET ops in D:

- each experiment split into Scientific goals, each with its own allocation of pulses (good/max) / tritium & neutrons
- experiments were given a number of pulses in a day, rather than entire sessions
- strict daily control of tritium and neutron budget (on the basis of improved offline & online pre-pulse validation tools)
- preparation and validation of pulses much earlier than usual (months instead of days), with extensive documentation for each pulse & clear processes for updates
- both high priority and back-up / top-up pulses fully prepared

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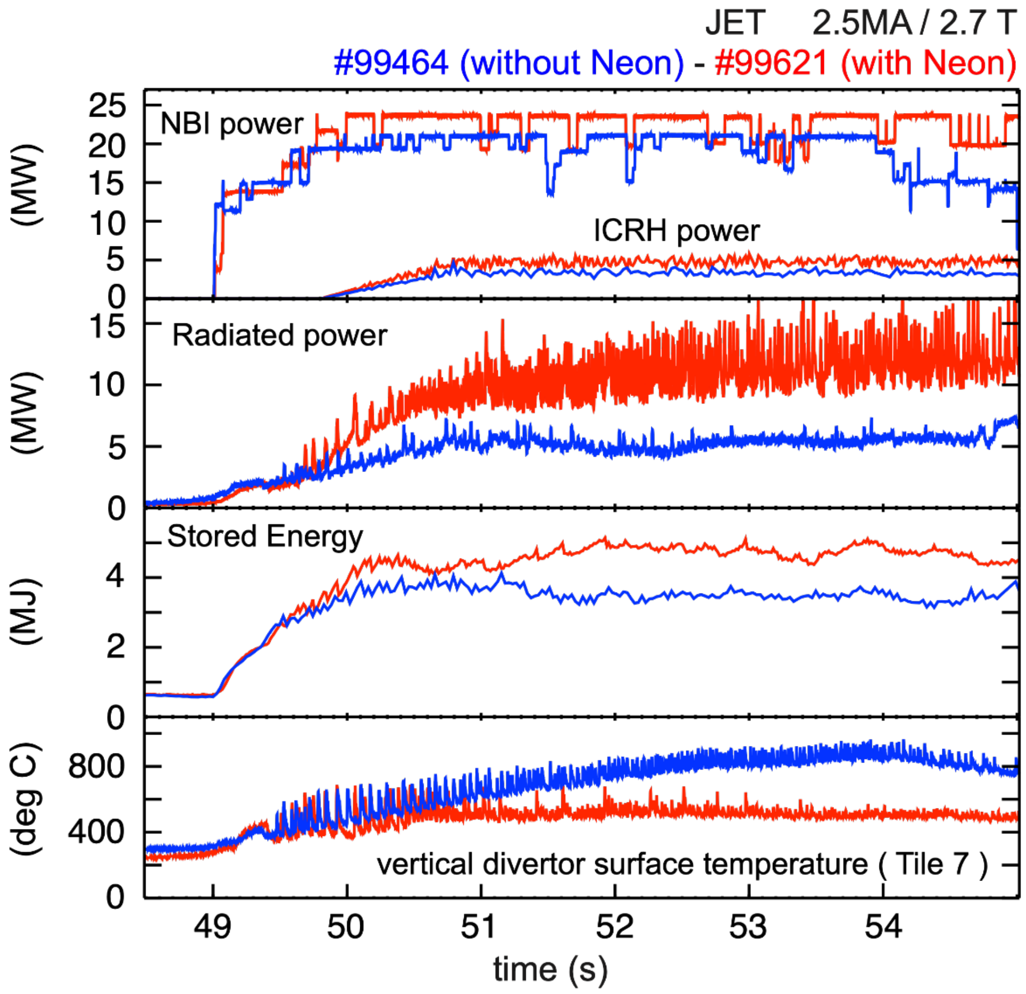
Conclusions

- D and T transport is not symmetrical → isotope effects in heat and particle transport
- In ITG regime multi ions plasmas, core ion densities largely insensitive to core fuelling
- In high power JET DT plasmas, core D/T ratio largely in agreement with edge ratio
- Insensitive to particular details of NBI fuelling
- Neutron rate well predicted by TRANSP
- Core D/T ratio relatively easy to control with neutral gas injection, including very high density plasmas
- Low power JET DT plasmas might show deviations from this picture→ being analysed

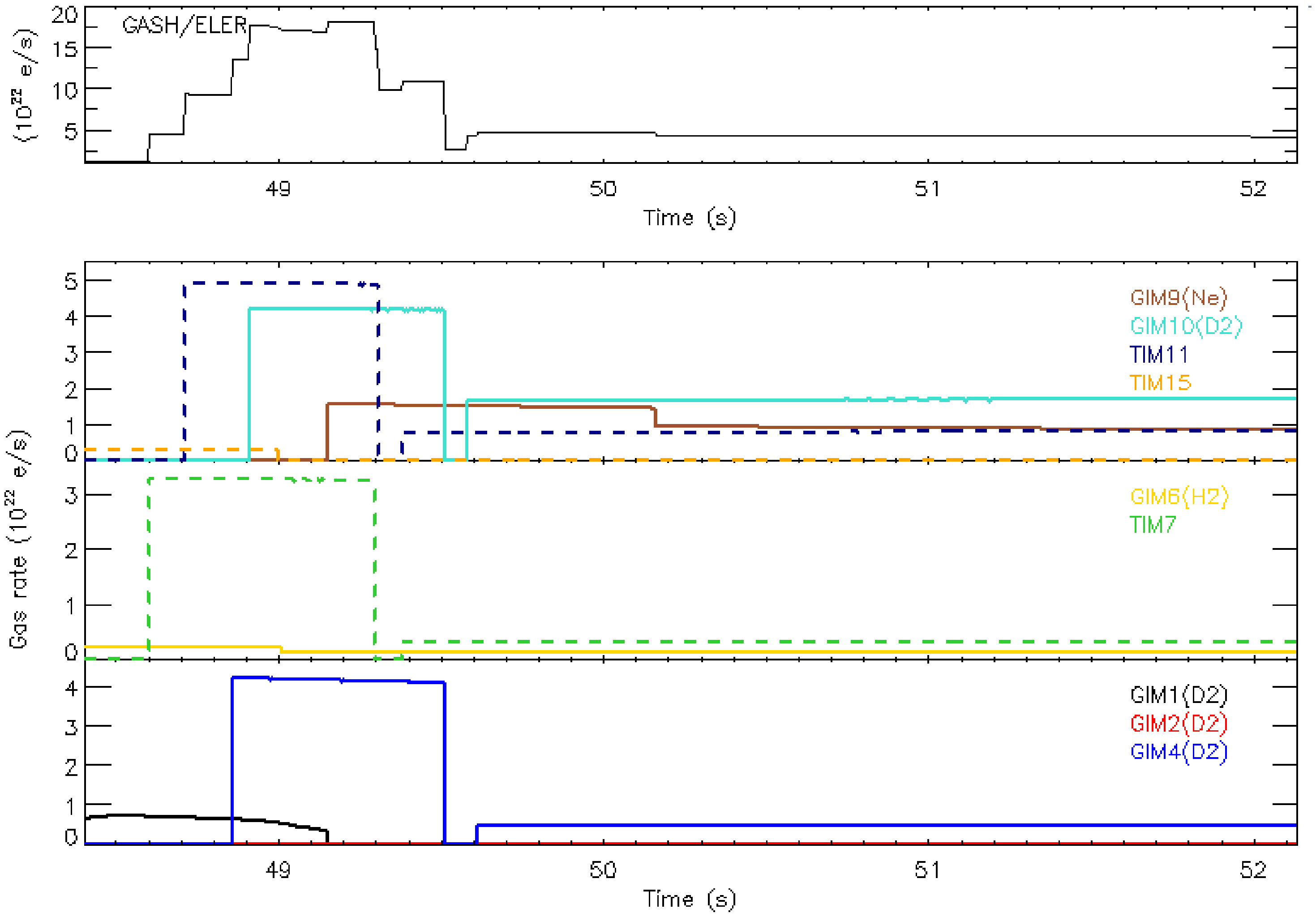
backup

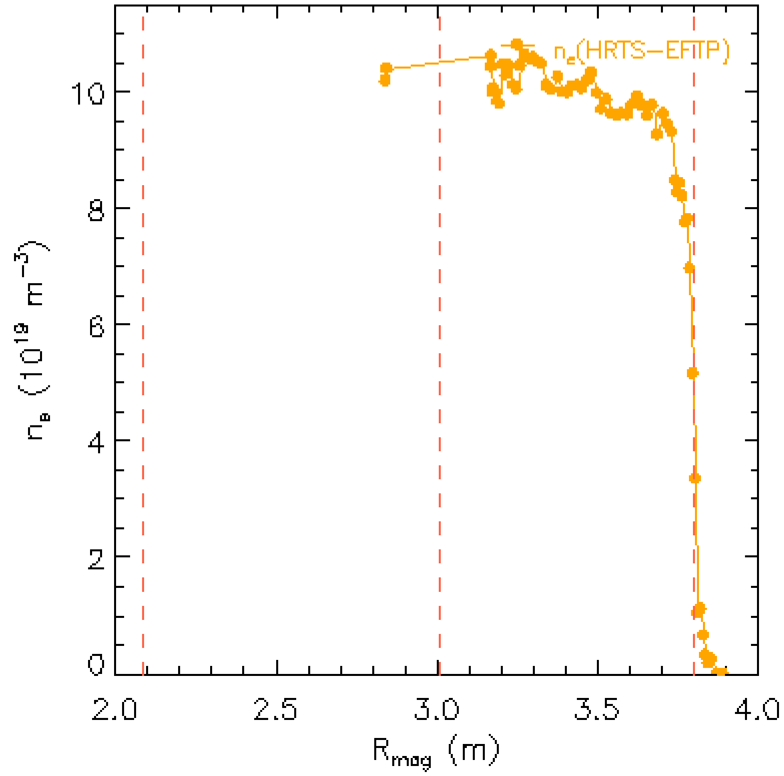
Integrated Ne seeded radiative H-mode achieved in D-T

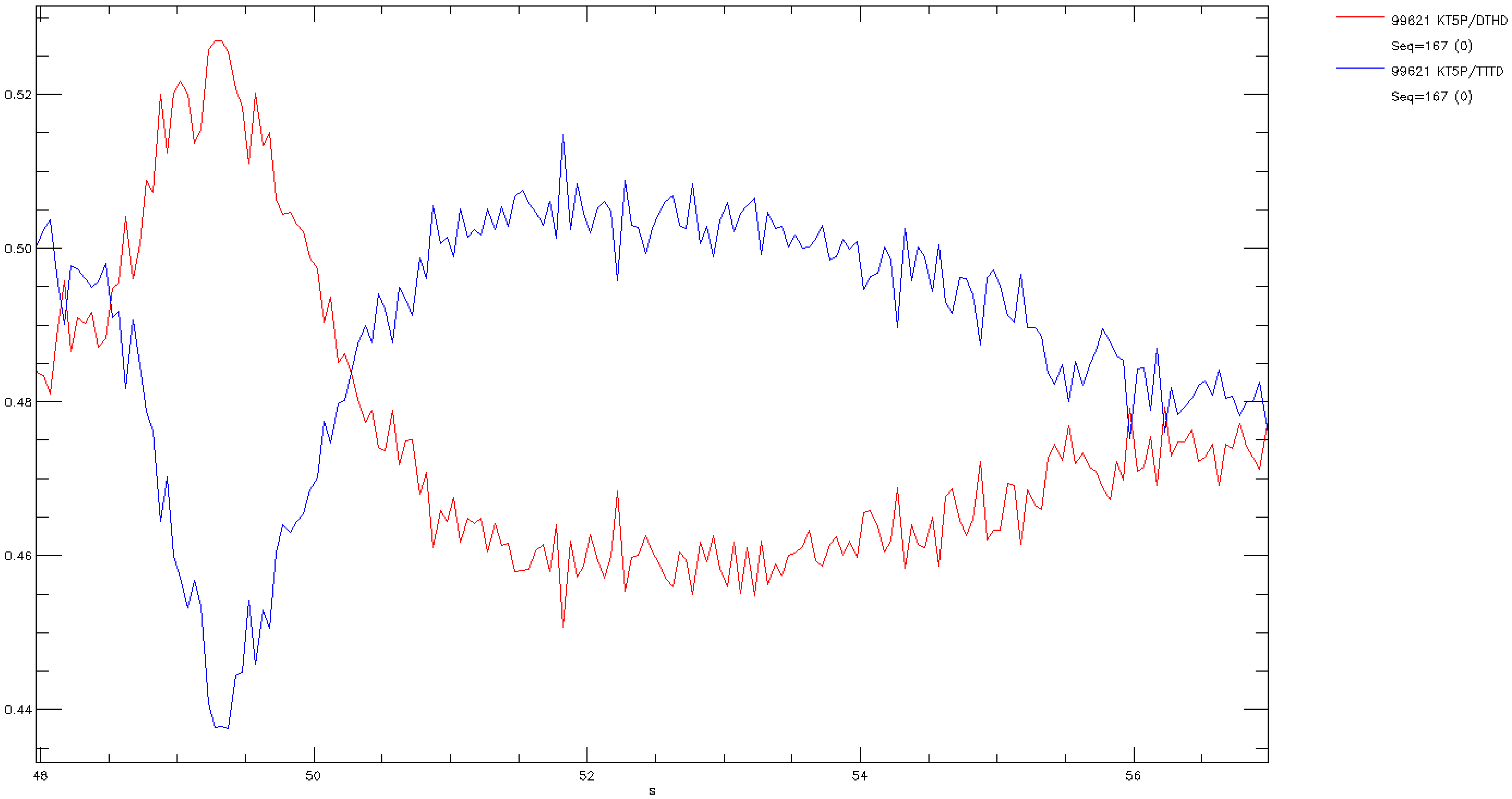
- **Integrated scenario with Ne seeding demonstrated for the first time in D-T with ITER-relevant Be/W wall**
- Well-controlled long pulse
- With detached divertor plasma (f_{RAD} ~ 0.6)
- With good plasma energy confinement
- Confirms Ne as promising extrinsic radiator for ITER



Strongly reduced divertor temperature with Ne seeding


GASH/ELER
(10²² e/s)
Time (s)
Gas rate (10²² e/s)
GIM9(Ne)
GIM10(D2)
TIM11
TIM15
GIM6(H2)
TIM7
GIM1(D2)
GIM2(D2)
GIM4(D2)
Time (s)


n_e(HRTS−EFITP)
n_e (10^19 m^-3)
R_mag (m)



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0.50
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99621 KT5P/DTHD
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99621 KT5P/TTTD
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