EUROfusion

Overview of JET T and D-T experiments

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JET

MAX-PLANCK-INSTITUT
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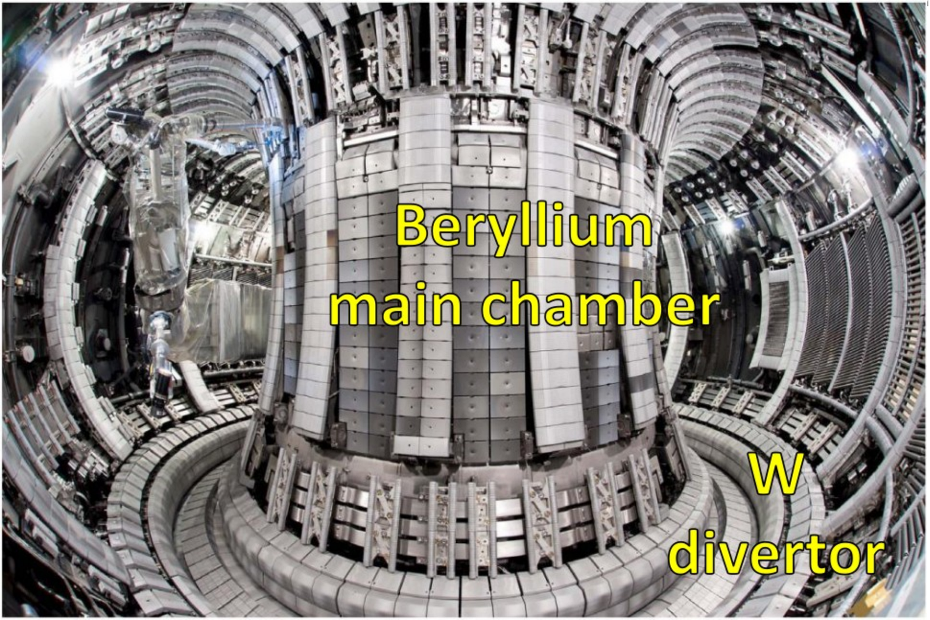
Outline

- Introduction
- L-H transition in different isotopes
- Isotope impact on pedestal
- Hybrid scenario development in D
  - Edge ion temperature gradient screening of impurities
- Transition to Tritium
- Reaching high fusion performance in 50:50 D-T mix.
- Tritium rich plasmas
- Alpha particle physics
- Summary and conclusion



More information in:

Nucl. Fusion special issue
on JET D-T plasmas
to be published before the
IAEA FEC conference 2023

Motivation for isotope experiments

The size of a reactor depends critically on the energy confinement time:

$$\tau_{E\,\mathrm{IPB98}} = 0.056\; I_p^{0.93} B^{0.15} P_{heat}^{-0.69} n^{0.41} \boxed{M^{0.19}} R^{1.39} a^{0.58} k^{0.78}$$

The envisaged heating power depends critically on the L-H power threshold:

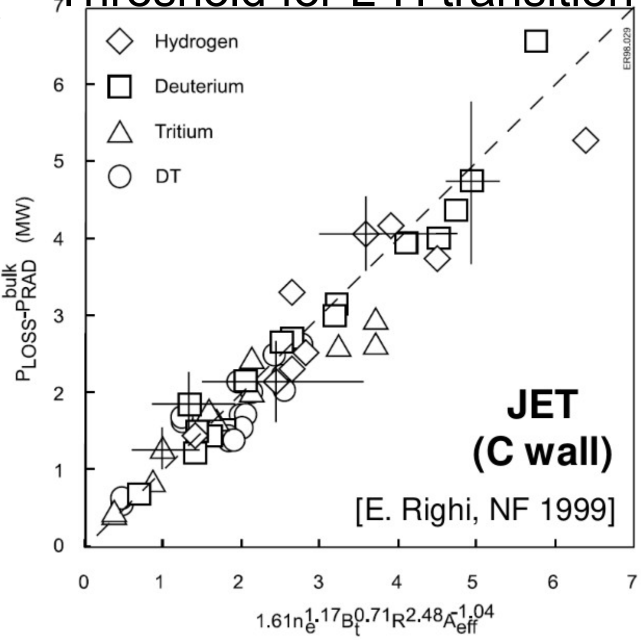
ITPA scaling: $P_{\mathrm{scal}} = 0.049 \bar{n}_{\mathrm{e}}^{\;0.72} B_{\mathrm{T}}^{\;0.80} S^{0.94}$

[Y. Martin, JoP:CS 2008]

But also: $P_{LH} \sim 1/A_{eff}$

JET is the only machine to use T!

Threshold for L-H transition

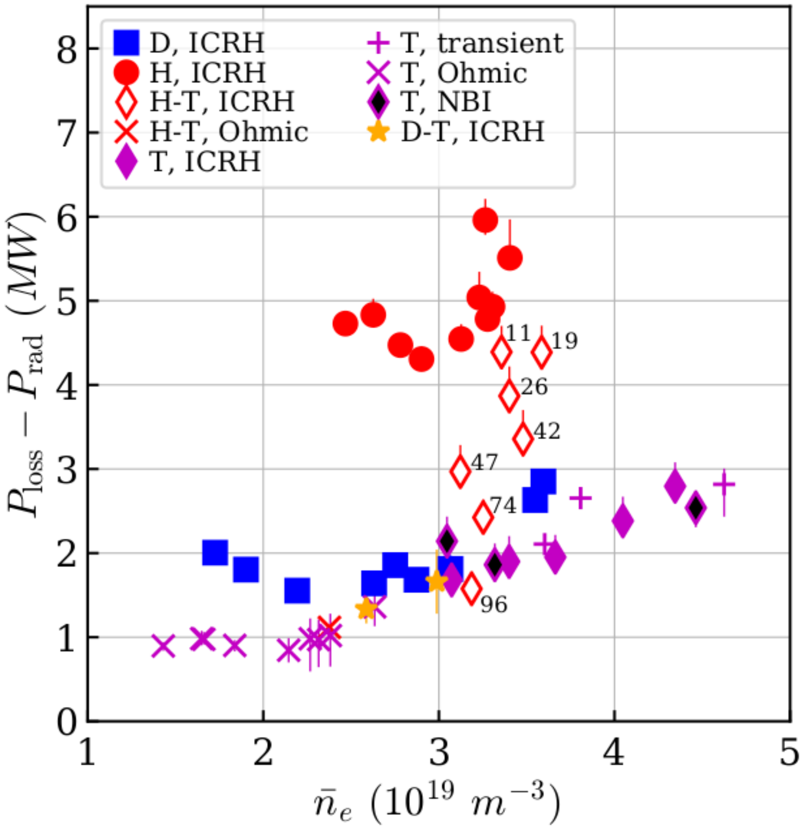


[E. Righi, NF 1999]

First L-H transition studies in T and D-T with metallic wall

First L-H transition studies in T and D-T plasmas with metallic wall:

- B_t = 1.8 T, I_p = 1.7 MA, horizontal target
- $P_{loss} = P_{Ohm} + P_{aux} - dW/dt$
- Non-monotonic dependence of P_{LH} on plasma density (minimum experimentally shown to depend on A_{eff})



*G. Birkenmeier et al., Nucl. Fusion **62** (2022) 086005*
*G. Birkenmeier et al., PPCF **65** (2023) 054001*
E. Solano et al., accepted in Nucl. Fusion special issue

→ Talk by U. Plank later today

The goals of the JET DTE2 campaign

1. Demonstrate high P_{fus}>10MW sustained for 5s
2. Demonstrate integrated radiative scenarios in plasma conditions relevant to ITER → Not discussed here, good results + DTE3
3. Demonstrate clear α-particle effects
4. Clarify isotope effects on energy and particle transport and explore consequences of mixed species plasmas
5. Address key plasma-wall interaction issues
6. Demonstrate RF schemes relevant to ITER D-T operation

Deuterium → **Tritium** → **Deuterium-Tritium**

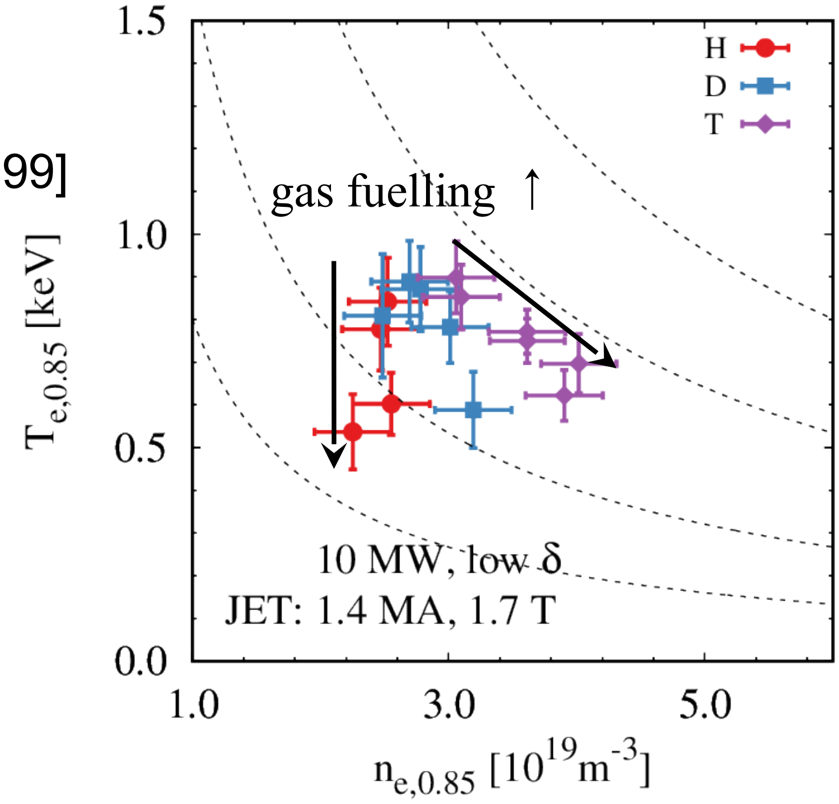
- Useful input to ITER on:
  - *Rapid scenario adaptation when changing isotopes*

Confinement → The pedestal pressure is mass dependent

- Changing the plasma fuel has an impact on the plasma pedestal
- Mass dependence found in the pedestal
  - Same as in DTE1 [e.g. Saibene et al, NF 1999]

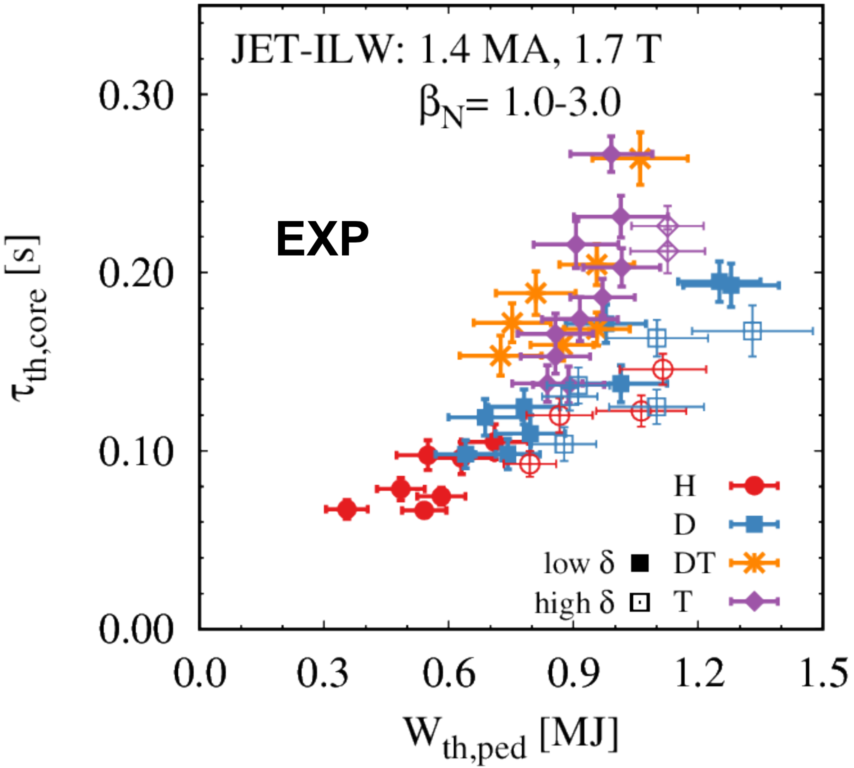
- But in DTE2 it was also identified that this mass dependence changes with gas fueling
  - low Γ: $n_e \propto M^{0.13}$
  - high Γ: $n_e \propto M^{0.39}$
  - T plasmas do not degrade with gas fuelling

- **The edge mass dependence is not scalable**



H & D: P.A. Schneider et al 2022 Nucl. Fusion 62 026014
T & DT: P.A. Schneider et al, accepted in Nucl. Fusion, SI

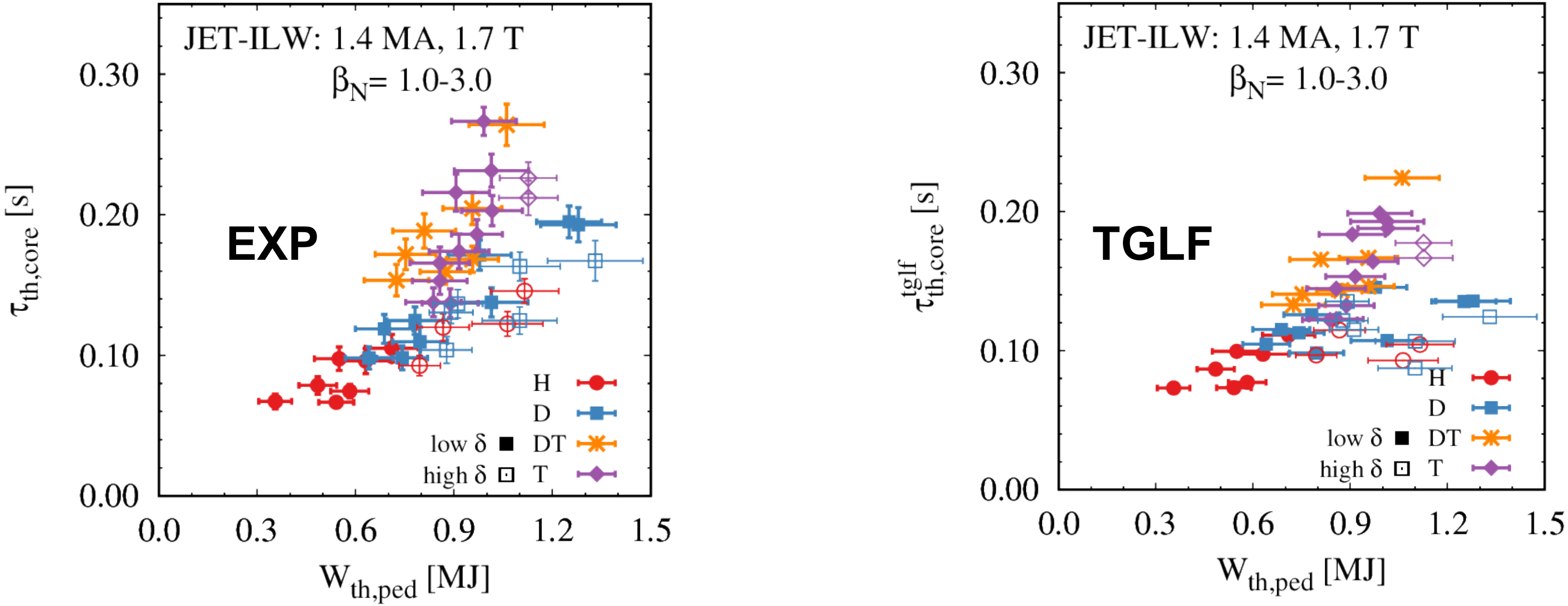
Pedestal isotope dependence propagates to the core



- Matched pedestal is important to distinguish between the impact of isotope mass and pedestal energy on the core transport
  - Ordering by isotope mass originates from the pedestal
- No systematic difference between H and D for matched pedestal energy
- Taking different radiation into account separates H, D from T, D-T
- Better core confinement at constant $W_{th,ped}$ for plasmas with T and D-T

H & D: P.A. Schneider et al 2022 Nucl. Fusion 62 026014
T & DT: P.A. Schneider et al, accepted in Nucl. Fusion, SI

Main trends reproduced with TGLF prediction



- Main trends in core transport reproduced with TGLF prediction
  - No “special” isotope physics included in the code
  - Deviations between TGLF and experiment larger at high β_N or low gB heat fluxes
- No indications for isotope dependence

H & D: P.A. Schneider et al 2022 Nucl. Fusion 62 026014
T & DT: P.A. Schneider et al, accepted in Nucl. Fusion, SI

Scenario choice for high fusion power

Baseline

- High I_p,q_{95}=3
  ITER Q=10
- I_p=3-4MA
- Pellets for
  ELM triggering

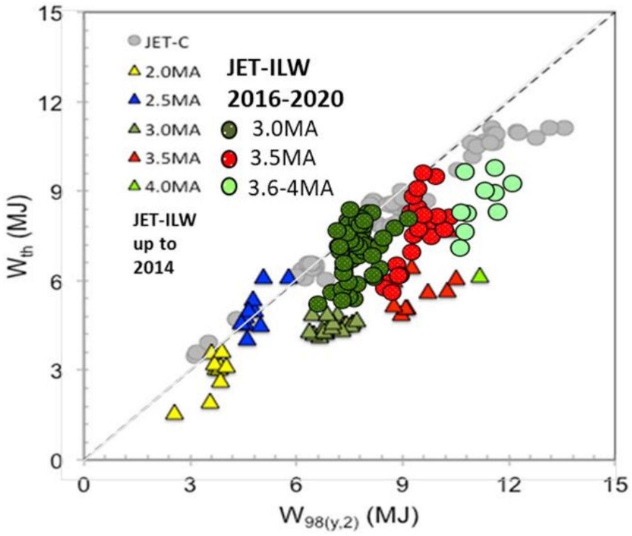
Tried in T and D-T
but mainly because
of technical difficulties
not full performance/
duration

L. Garzotti, Nucl. Fusion, SI

Seeded scenario

- Heat exhaust !
- Not discussed here

C. Giroud, Nucl. Fusion, SI



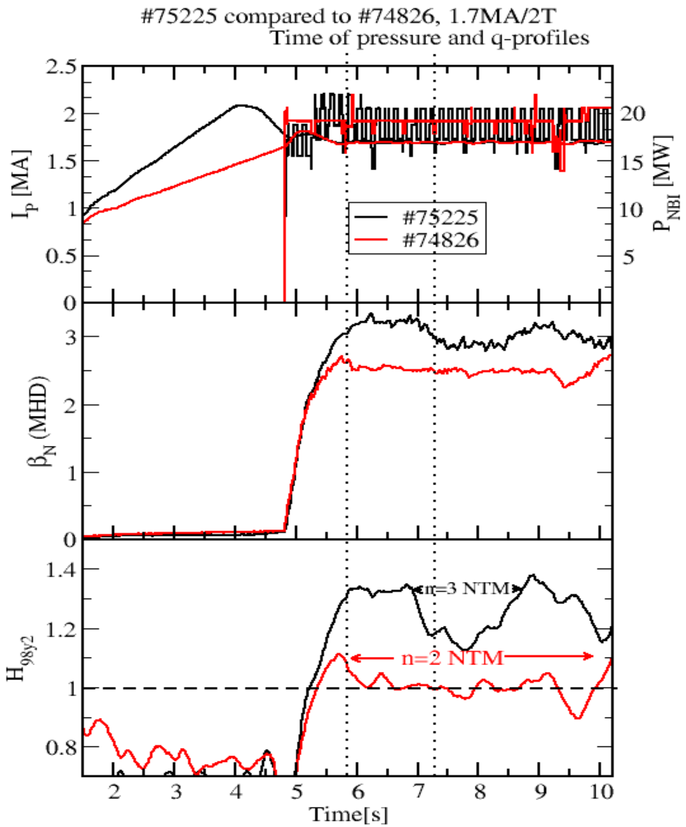
I Nunes, IAEA 2014
J Mailloux, IAEA 2021

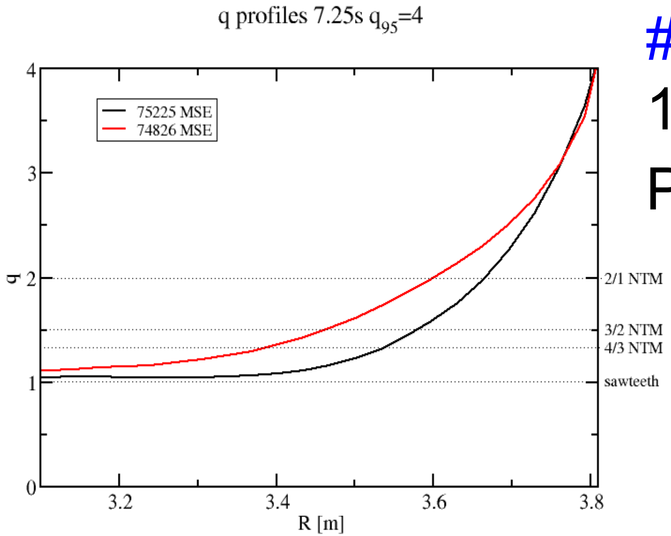
Hybrid

- Moderate I_p,q_{95}=4-5
  ITER alternative
- H_{98y2}>1
- q-profile modified
- I_p=2-2.5MA

Less technical constraints
more successful →
Main scenario presented!

Current over-shoot on JET-C provides good performance





#75225 (D) JET-C
1.7MA, 2T, q_{95}~3.7,
P_{in}~20MW

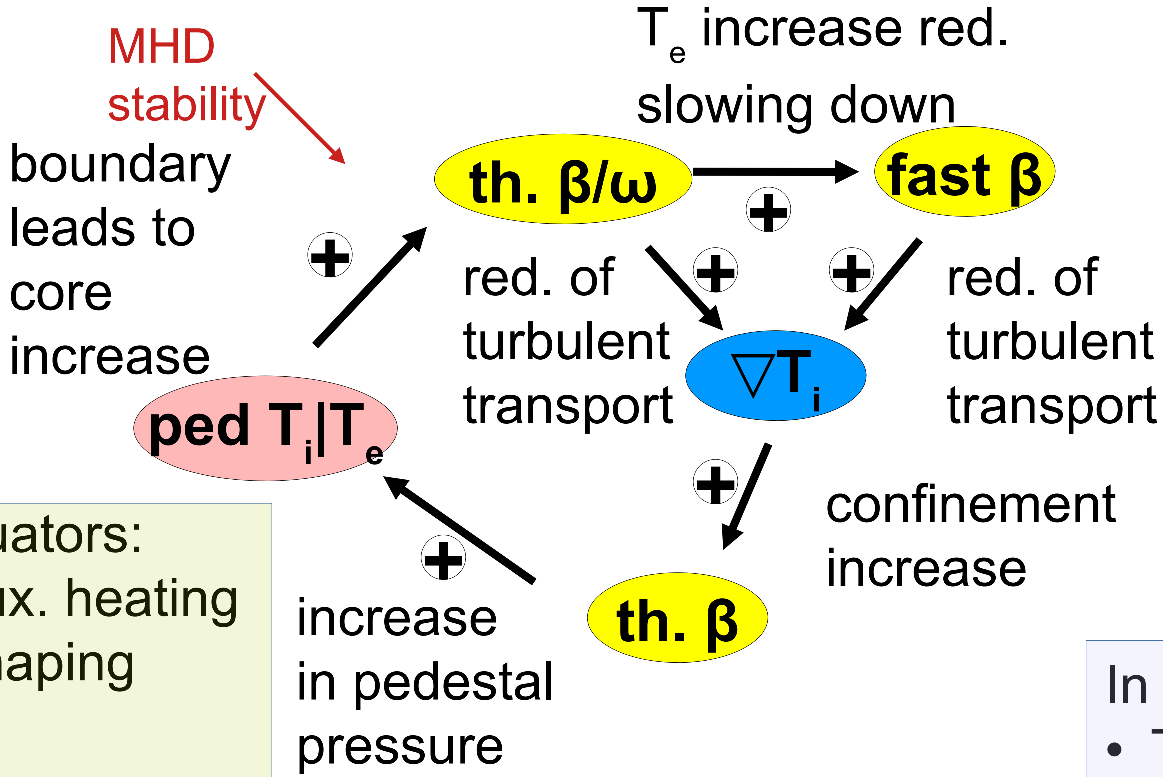
Confinement clearly improved - non stiff T_i

- Except q-profile and confinement the pulses are similar
- Different MHD stability

J. Hobirk *et al*, 2012, PPCF **54**, 095001

Confinement improvement → non-linear loop

J. Garcia *et al*, 2015, NF **55**, 053007
J. Citrin et al., 2013, PRL **111** 155001
J. Citrin et al., 2015, PPCF **57**, 014032
A. Di Siena et al., 2018, NF **58**, 054002



MHD stability

boundary leads to core increase

ped T_i|T_e

th. β/ω

T_e increase red. slowing down

fast β

red. of turbulent transport

∇T_i

red. of turbulent transport

confinement increase

th. β

increase in pedestal pressure

→ **Talk by A. Di Siena later**

← low shear can help

Actuators:
- aux. heating
- shaping
- I_p

S. Saarelma *et al*, 2018, PPCF **60**, 014042

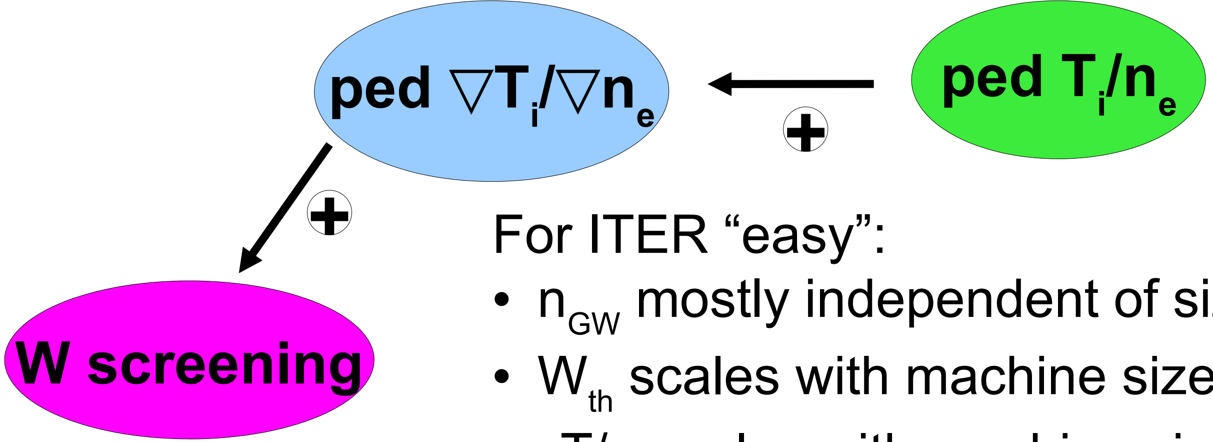
In addition:
- T_i/T_e ratio increases (NBI)
- current diffusion slows

Impurity control → non-linear loop

$$R\langle \Gamma_z^{\mathrm{neo}}\cdot\nabla r\rangle \propto n_i T_i \nu_{ii} Z \left[\boxed{P_A}\left(\overset{\text{Pinch}}{\boxed{-\frac{R}{L_{n_i}}}} + \overset{\text{Screening}}{\boxed{\frac{1}{2}\frac{R}{L_{T_i}}}} + \overset{\text{Diffusion}}{\boxed{\frac{1}{Z}\frac{R}{L_{n_z}}}}\right) - 0.33\boxed{P_B} f_c \boxed{\frac{R}{L_{T_i}}}\right]$$

radial transport

Poloidal asymmetry factors



For ITER "easy":

- n_{GW} mostly independent of size
- W_{th} scales with machine size

→ T/n scales with machine size

*R. Dux et al., 2017, NMaE, **12**,28-35*

Can the regime be reached in JET?

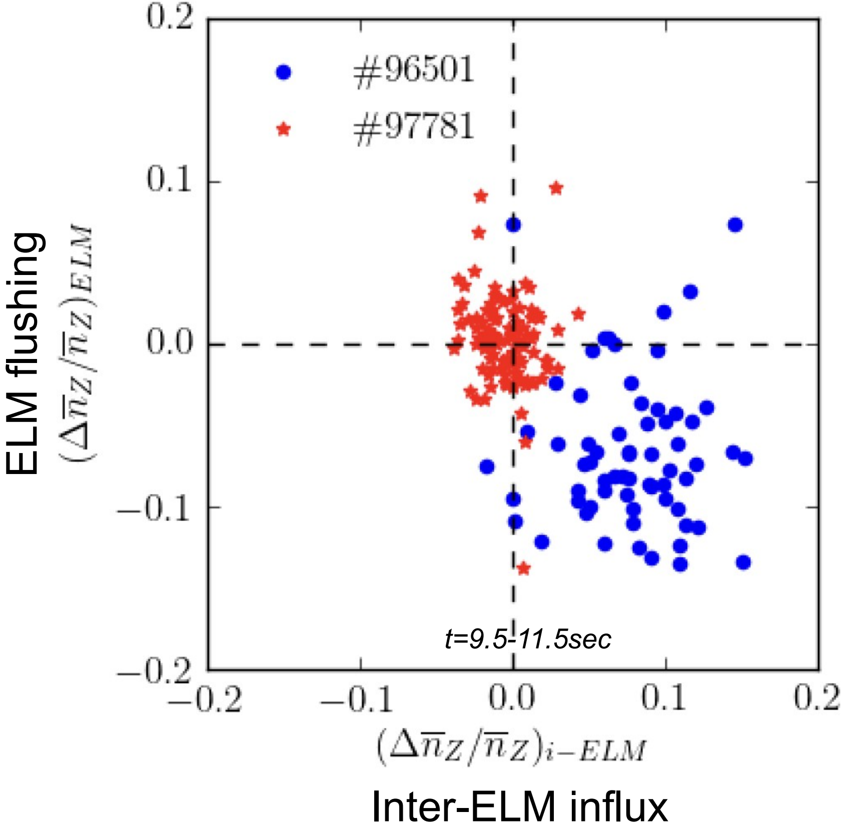
Peripheral impurity screening in optimised pulse

Detailed analysis of fast bolometry signals allows the differentiation of two different regimes:
ELM flushing vs
peripheral screening behavior

A. Field et al, 2023, Nucl. Fusion ***63****, 016028*

- **Enhanced by the stronger rotation in #97781**, in low collisionality conditions
- Not only in the beginning but persisting also later in the pulse, despite same fuelling

Change in W content due to:



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D.Fajardo et al, 2023, PPCF ***65,*** *035021*

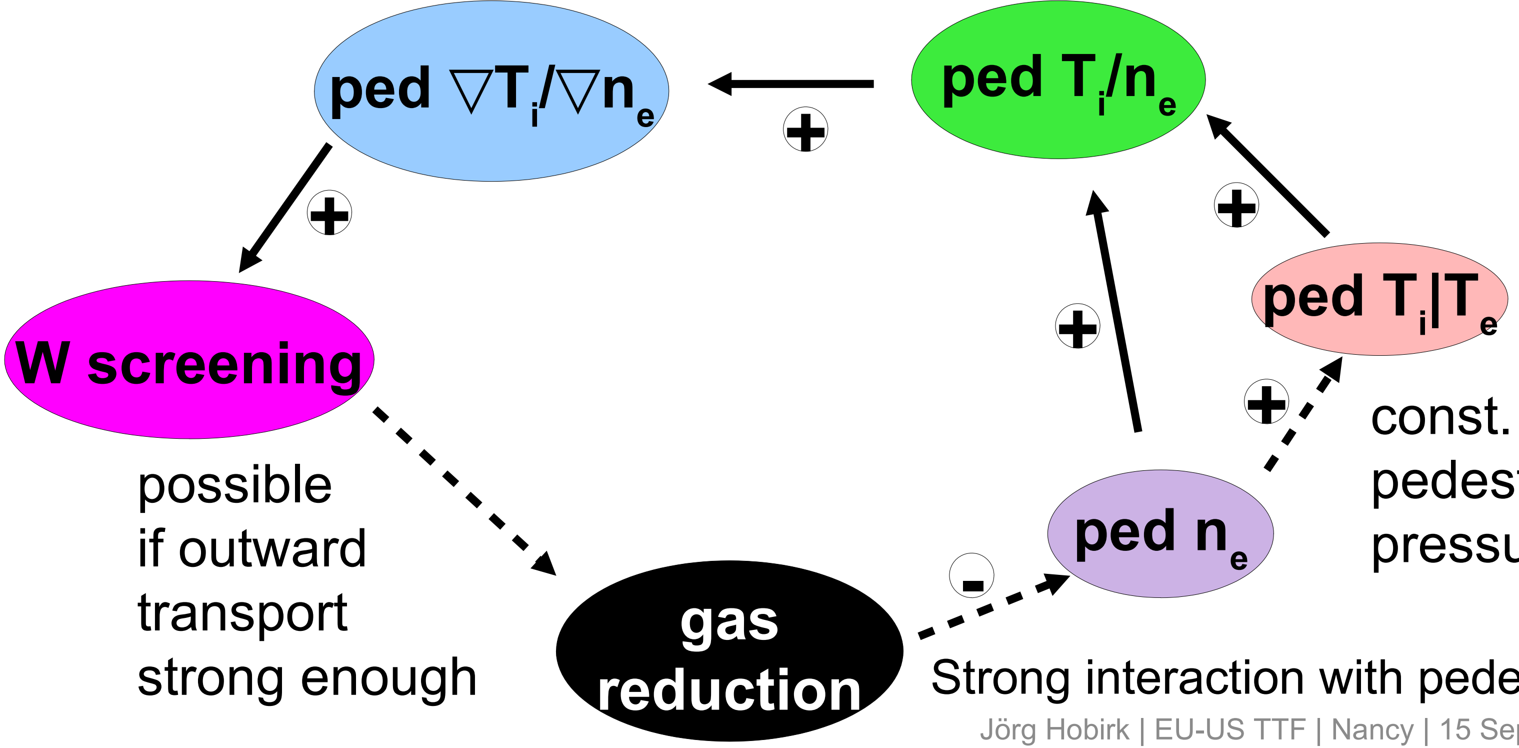
Impurity control → non-linear loop

Pinch Screening Diffusion

$$R\langle \Gamma_z^{\mathrm{neo}}\cdot\nabla r\rangle \propto n_i T_i \nu_{ii} Z \left[\boxed{P_A}\left(\boxed{-\frac{R}{L_{n_i}}}+\boxed{\frac{1}{2}\frac{R}{L_{T_i}}}+\boxed{\frac{1}{Z}\frac{R}{L_{n_z}}}\right)-0.33\boxed{P_B}f_c\boxed{\frac{R}{L_{T_i}}}\right]$$

radial transport

Poloidal asymmetry factors

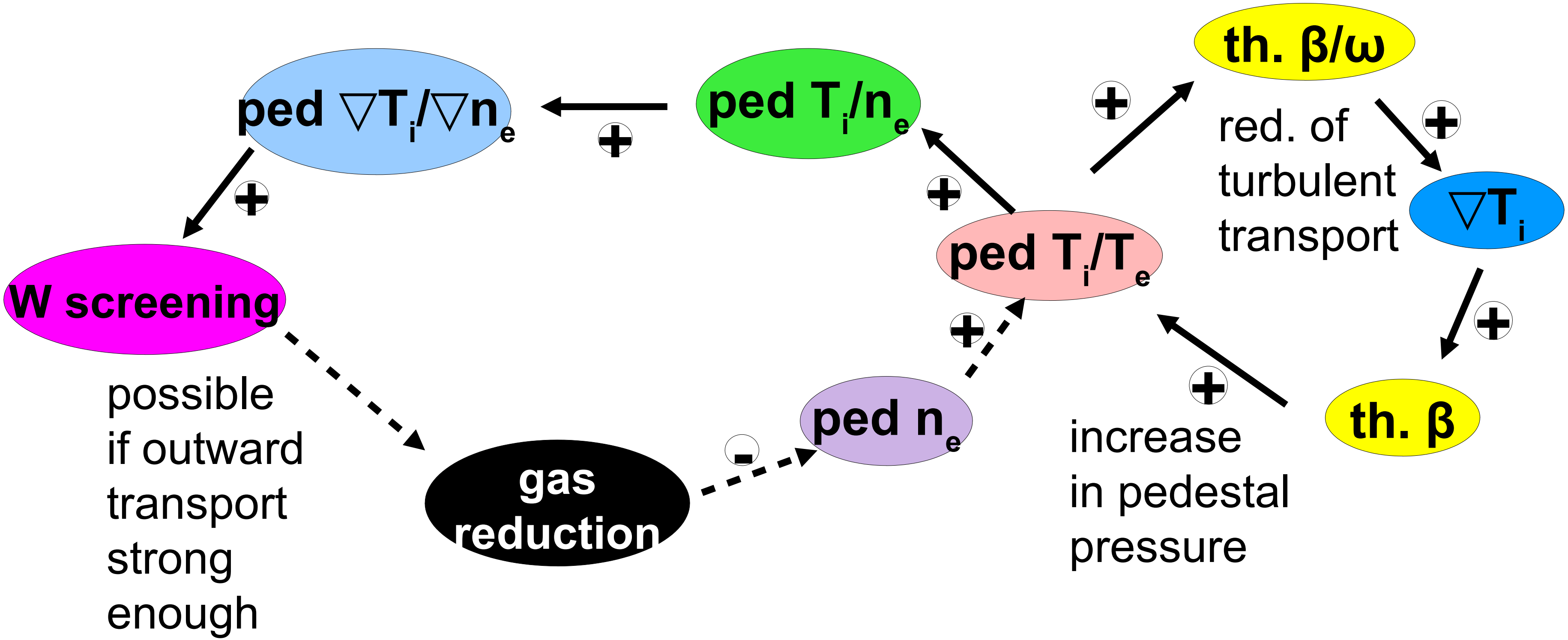


possible if outward transport strong enough

const. pedestal pressure

Strong interaction with pedestal stab.

Combined loops show strong synergy



ped $\nabla T_i/\nabla n_e$

ped T_i/n_e

th. β/ω

red. of
turbulent
transport

∇T_i

W screening

ped T_i/T_e

possible
if outward
transport
strong
enough

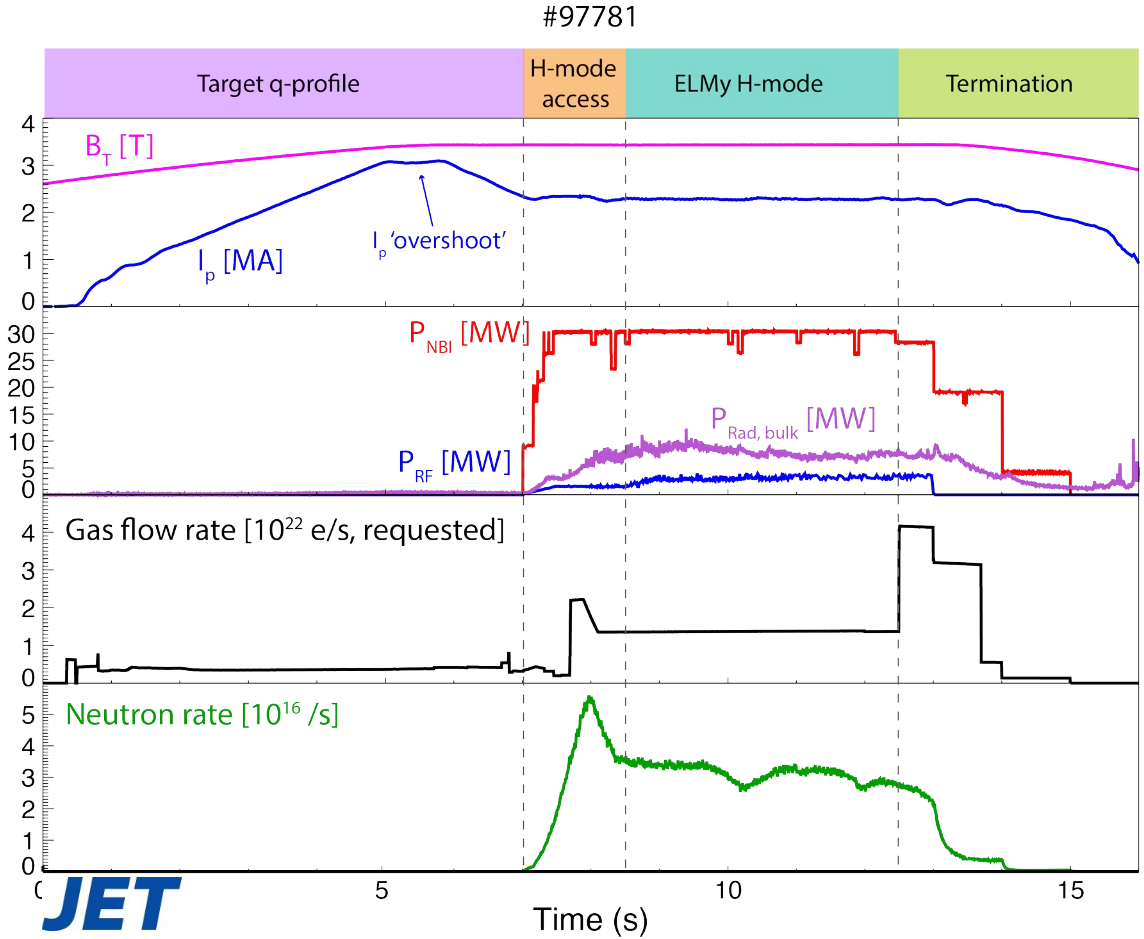
**gas
reduction**

ped n_e

increase
in pedestal
pressure

th. β

Building a successful hybrid scenario pulse in the ILW



#97781 (D)

2.3MA, 3.4T, q_{95}~4.8,P_{in}~33MW

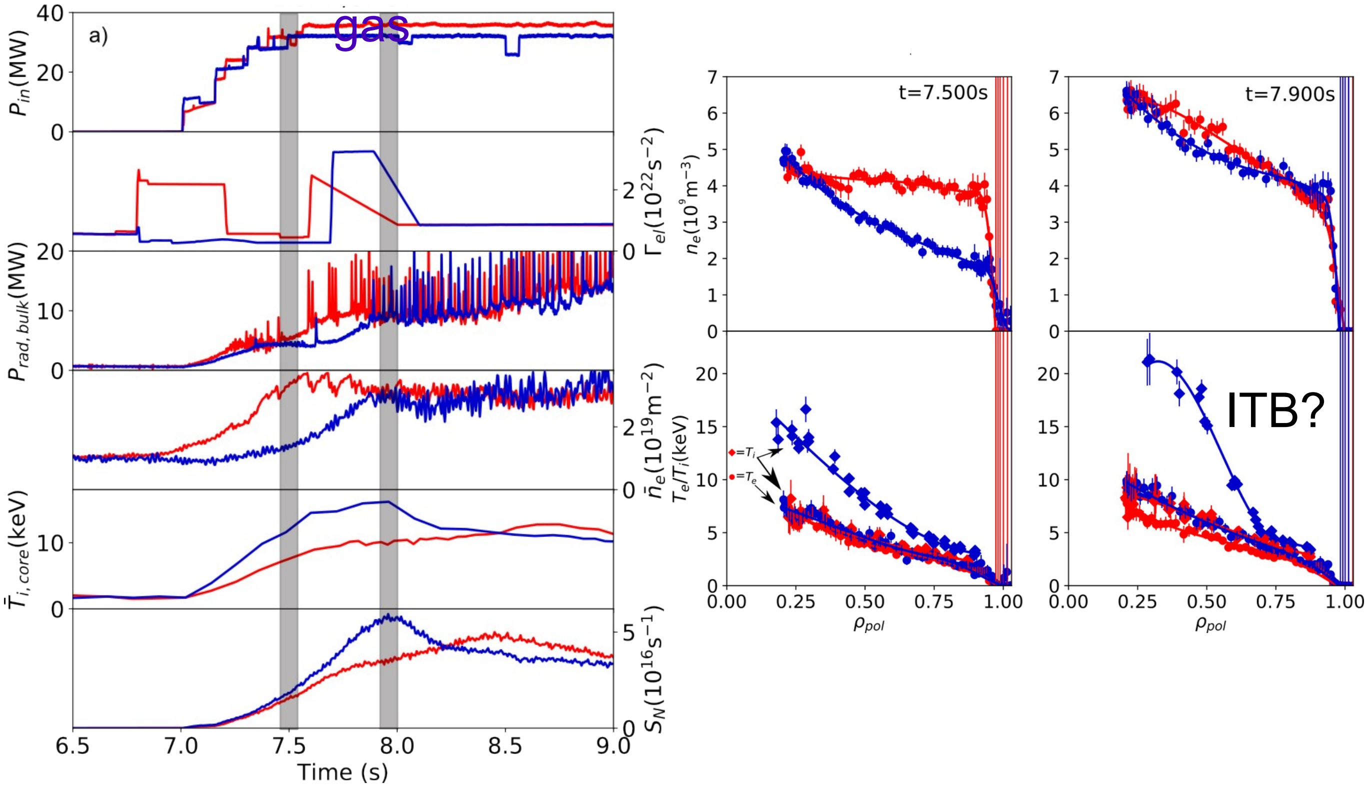
- **I_p** constrained by need for good confinement without excessive density
- **B_T** constrained by need for on-axis ICRF
- SP sweeping for heat loads

J. Hobirk *et al*, accepted in Nucl. Fusion, SI
C.D. Challis, EPS 2022, oral
A. Kappatou, APS 2022, invited
E. Lerche, APCPP 2022, invited

H-mode entry, late gas important!

- Late gas leads to high transient performance
- Density and temperature profiles are shaped by the gas and heating trajectory
- Edge T_i screening of impurities can be achieved

#96947 early gas, #97882 late gas



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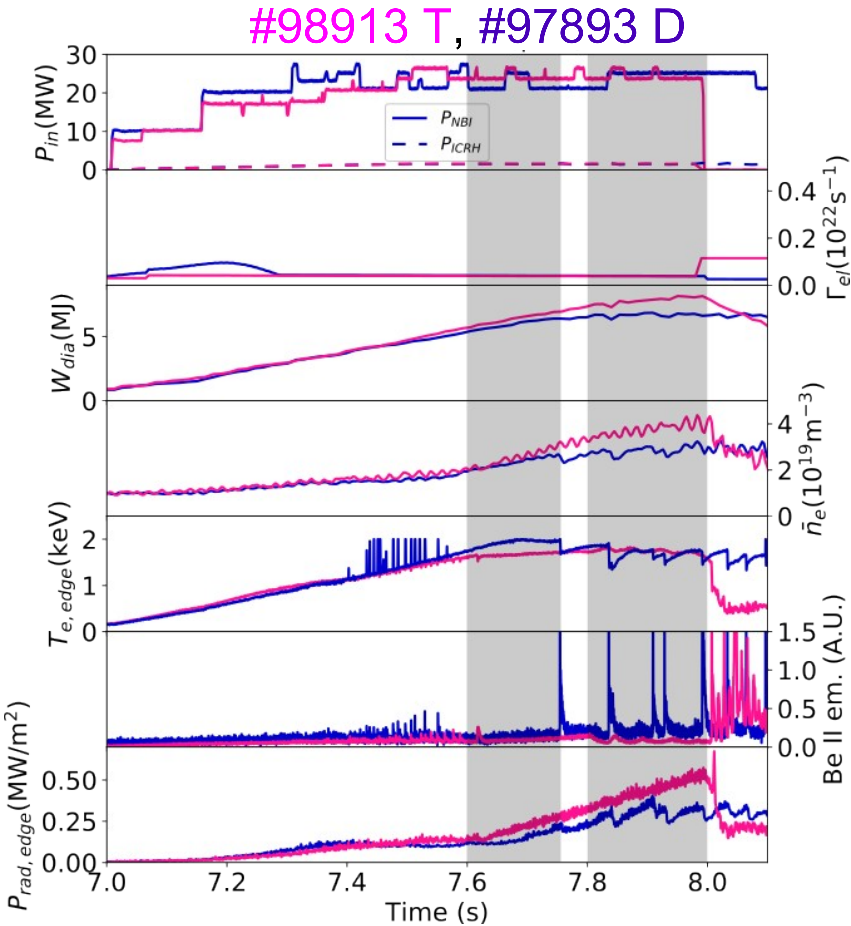
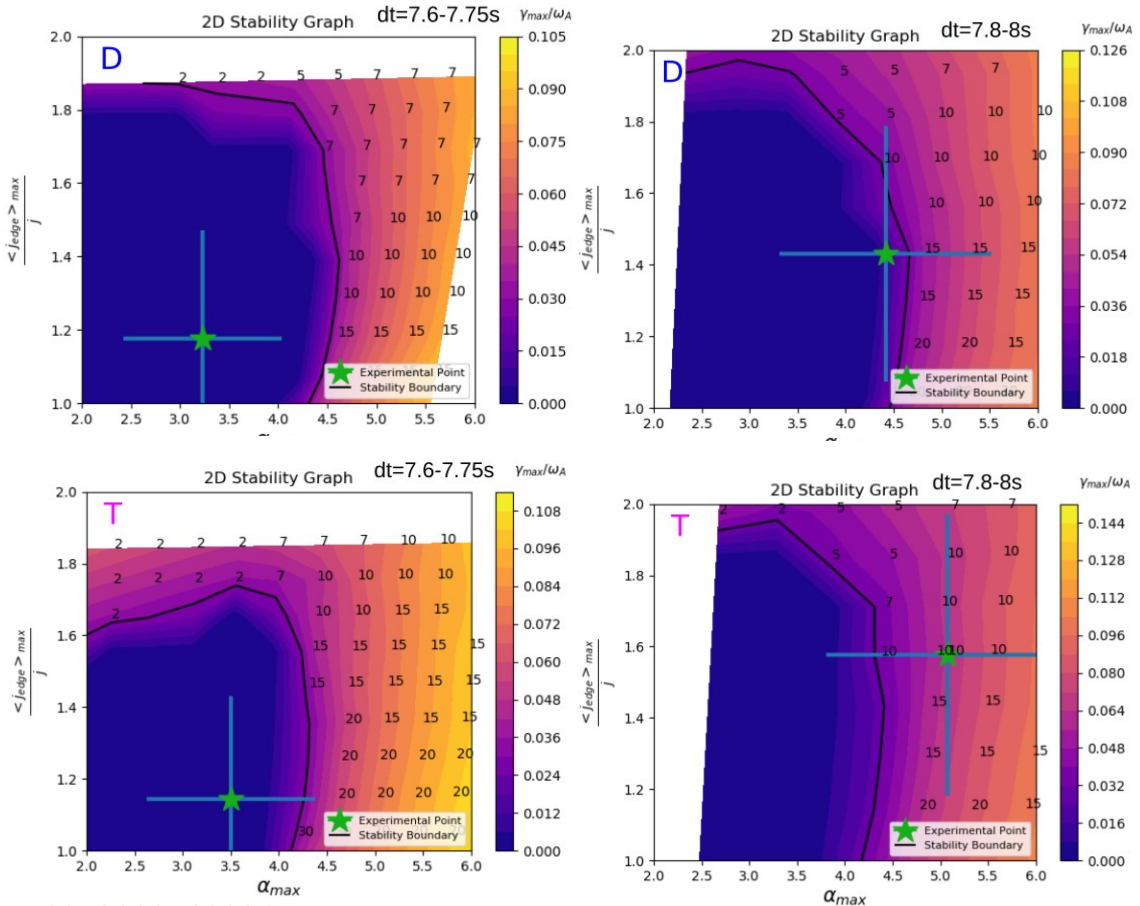
In T, H-mode entry more difficult, 1st ELM late

- Pedestal formation after H-mode entry different in T
- 1st ELM delayed significantly
- Higher density but also higher stored energy
- Other pulses radiation unstable
- In D-T the same effect occurs



Pedestal stability for 1st ELM in T improved

- Stability point for 1st D ELM very similar in D compared to T
- For 1st T ELM the D stability is close to the limit (reg ELMs)
- For 1st T ELM the T stability is improved higher p_{ped} translates to higher α_{max}

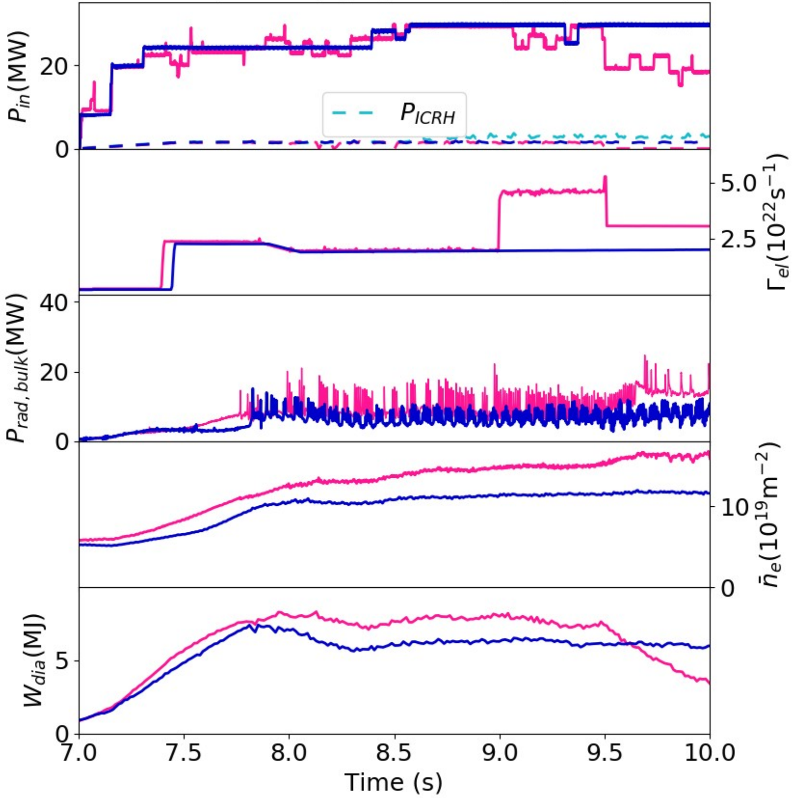


Physics in: Nyström *et al.*, Nucl. Fusion **62**, 2022, 126045

Higher initial + flattop gas makes stable pulses

- Higher pre-H-mode gas solves H-mode entry but performance lost
- Higher flattop gas solves impurity problems by much higher ELM frequency
- Improved stored energy by ~20% compared to engineering reference! (expected 8% from IBP98y2)
- Strategy in D-T different

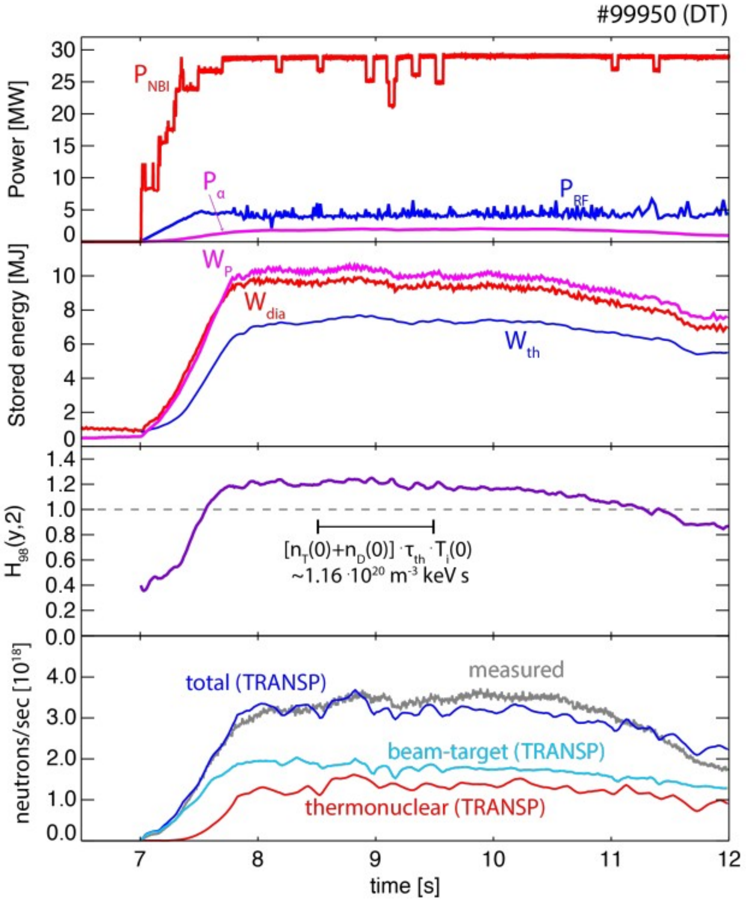
#99163 T, #100854 D



JET

In D-T high fusion power reached

- H-mode entry caused similar problems as in T
- Amount of gas similar but timing earlier
- High performance in hybrid domain reached
- E_{fus}=45.8MJ
- β_N=2.5,β_{pol}=1.4,H_{98y2}~1.2
- 40% thermal,
- 60% beam-target neutrons
- nτT~1.16x10^{20} m^{-3} keV s
- Q_{fus}=0.32



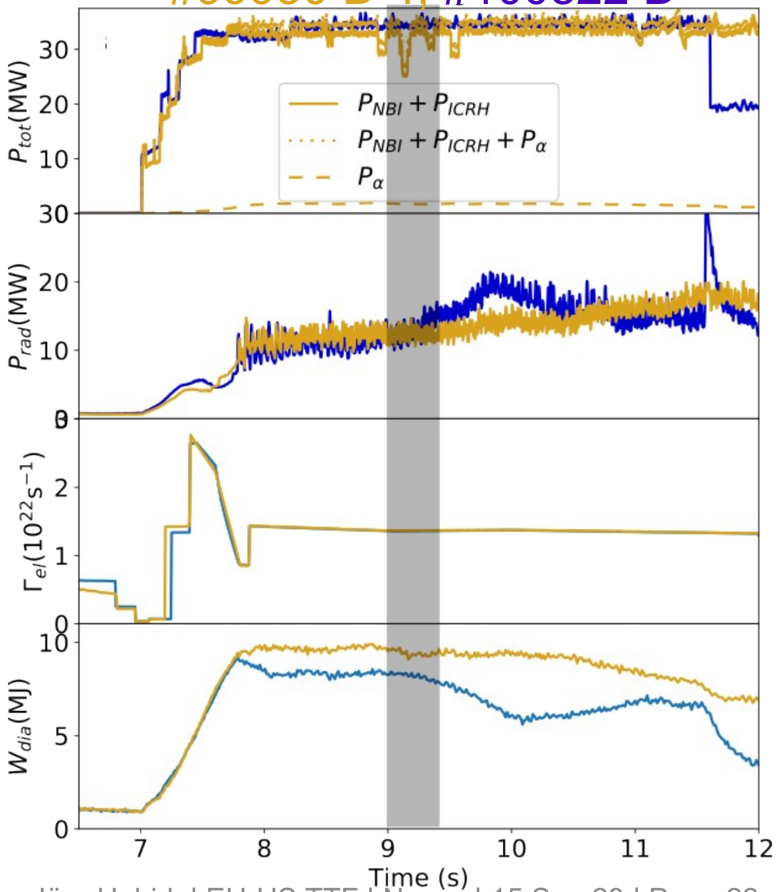
JET

Engineering reference shows D-T improved confinement

D
DT

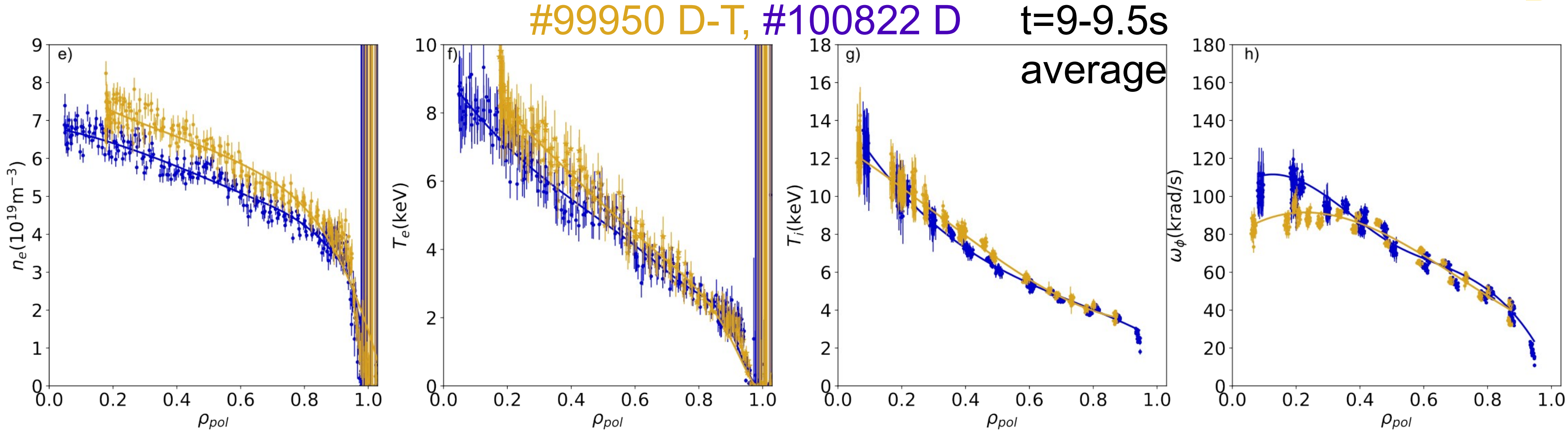
- Stored energy by 18% higher in D-T (from scaling expected ~ 5%)
- Input power + α-power matched
- Same gas injection
- Deuterium pulse less radiation stable

#99950 D-T, #100822 D



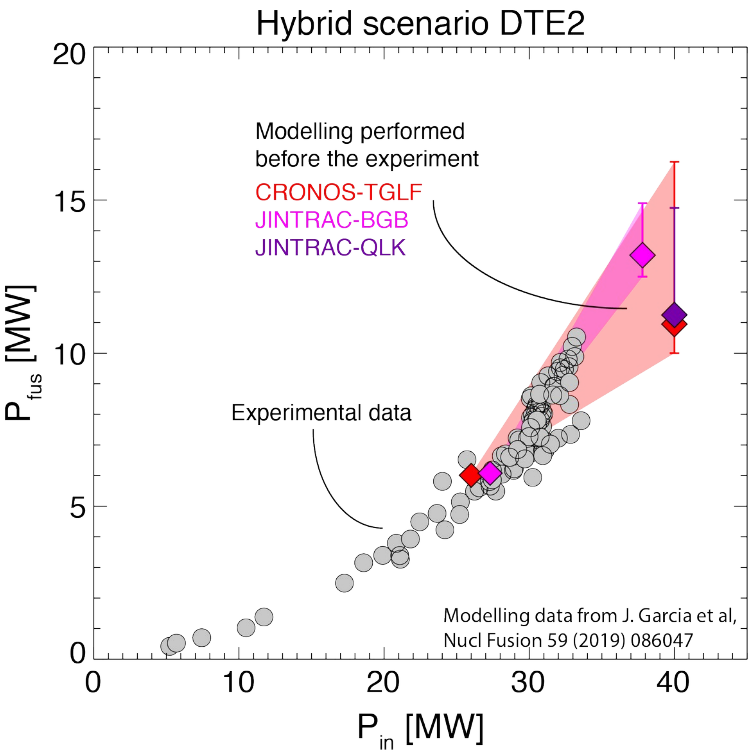
JET

Profile comparison shows higher n_e and T_e



- Ion temperature and rotation between D and D-T very similar
  - Also heating profile very similar, different NBI sources in D compensate
    to a great extend for T NBI penetration and α-particle heating
- Electron density higher but also electron temperature higher

Predictions of fusion power largely consistent with obtained experimental data



Modelling performed **before** DTE2:

CRONOS-TGLF, JINTRAC-BGB, JINTRAC-QLK

- Various assumptions on transport model, pedestal
- Error bars correspond to different bootstrap current models, isotope effects and total current

Exp. data averaged over various time intervals

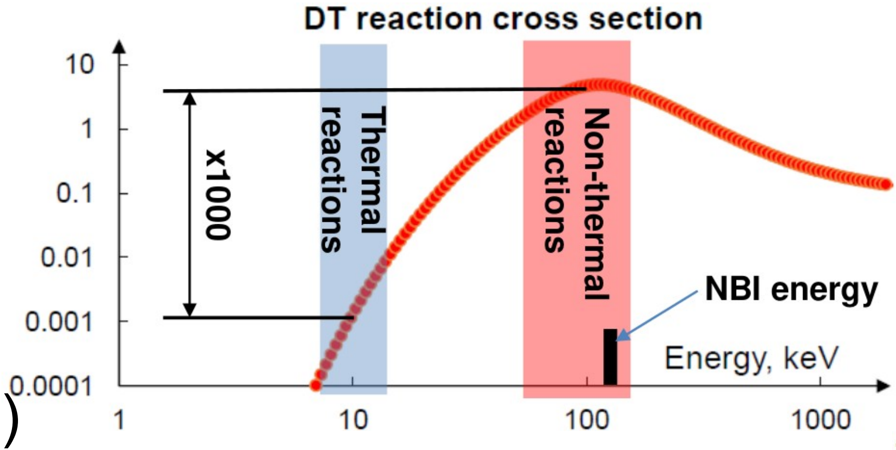
✓ **Fusion power achieved in DTE2 largely consistent with the predictions**

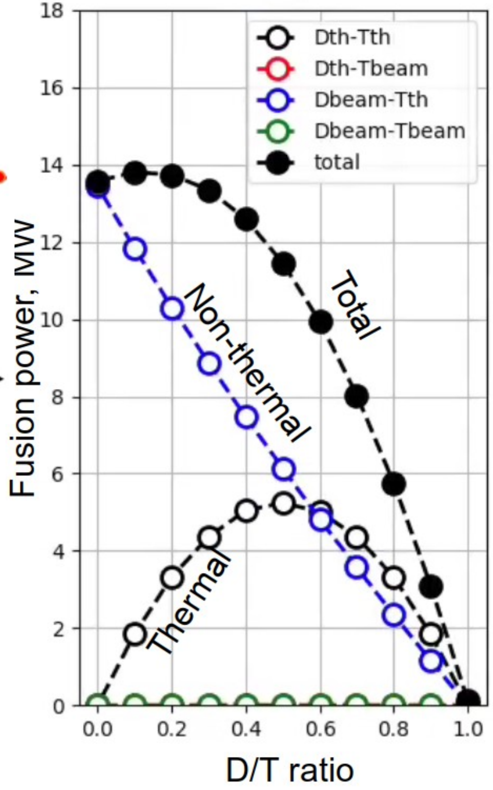
✓ Stringent test of the predictive capabilities of the modelling suites now that experimental data in D-T are available → extrapolations to ITER operation

✓ The work to disentangle the various effects governing DT plasmas continues

T-rich plasmas to improve fusion power

- DT fusion cross section maximised for D-NBI energies or ICRH accel. particles (fund. D)
- Fusion power can be maximised by high T concentrations
- → **T-rich plasmas with pure D NBI and fundamental D resonance ICRH heating will maximise fusion power output**



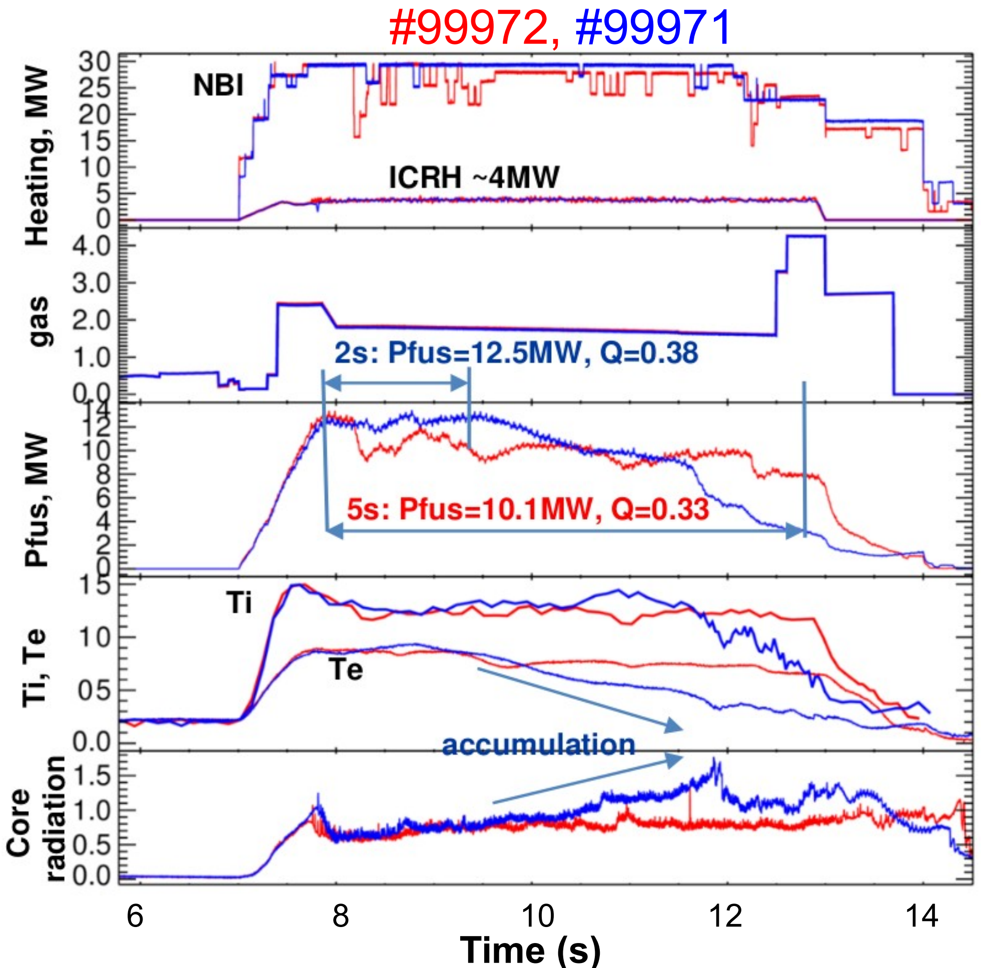


M. Maslov, E. Lerche, APS 2022
M. Maslov *et al.*, Nucl. Fusion special issue

Record fusion power/energy reached in T-rich

DT

- Scenario developed together with hybrid, most aspects the same but:
  - 2.5MA/3.86T
  - Stronger ramp in B_T during current ramp
- Averaged P_{fus}>10MW for t>5s
- E_{fus}~59MJ



M. Maslov, E. Lerche, APS 2022
M. Maslov *et al.*, Nucl. Fusion special issue

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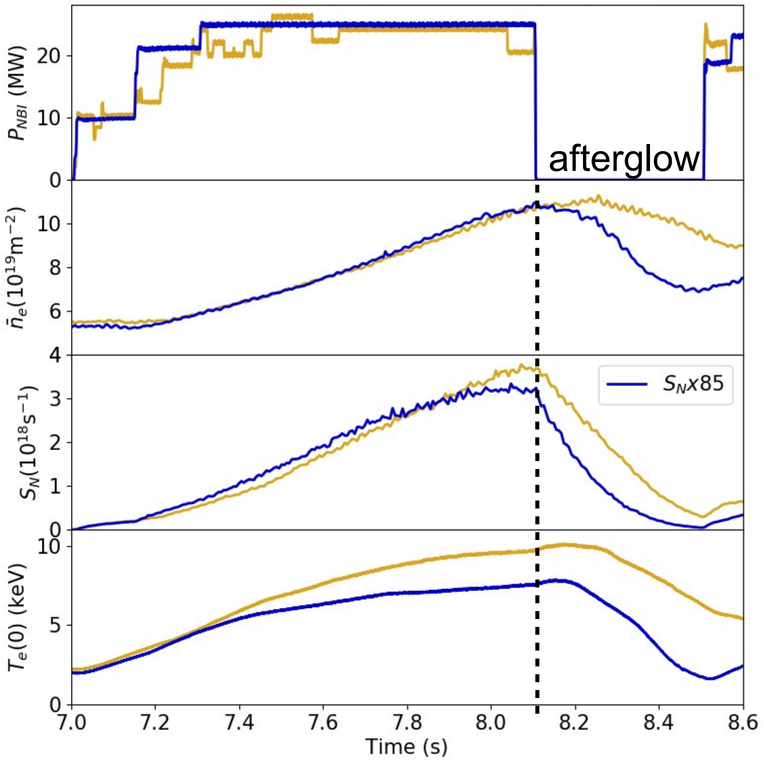
α-particle heating observed!

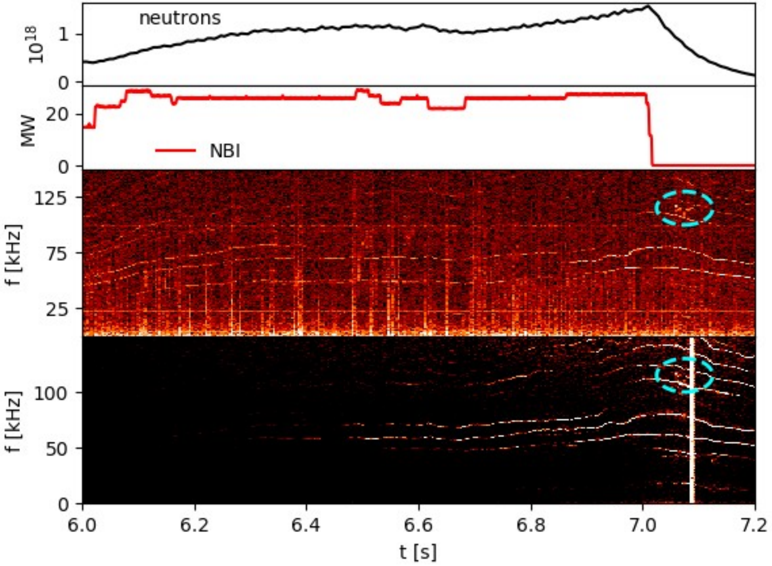
- $\tau_{SL,\alpha} > \tau_{SL,NBI}$ → plasmas with NBI switch off and without ICRH → α-particle dominated FP distr.
- Important because NBI FP damping of α-particle induced TAEs predicted
- High P_{fus} plasmas
  with low q_0 (hybrid)
  and ITB plasmas (higher q_0)
- H-mode maintained much longer
- Still electron heating after initial NBI slowing down

#99801 D-T, #100793 D

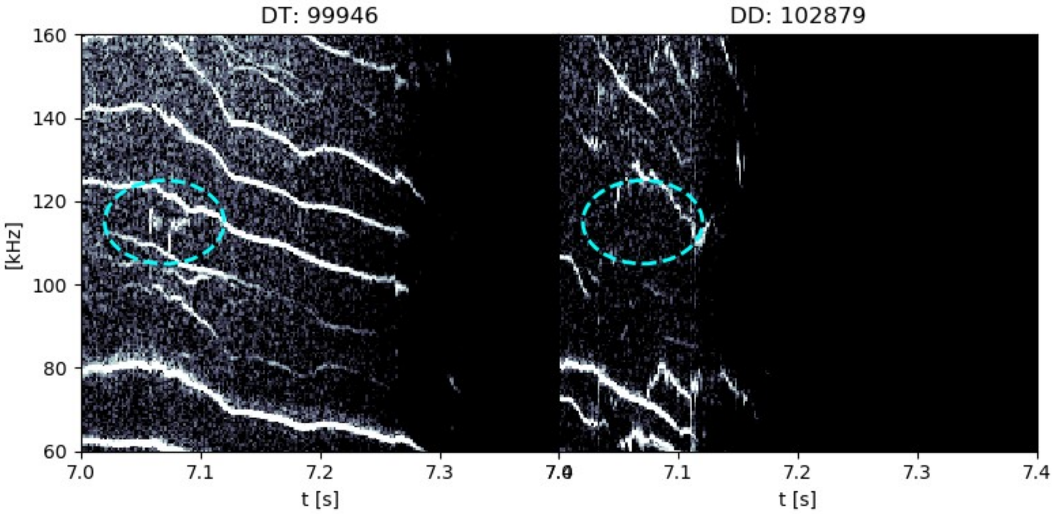


JET VG Kiptily, R Dumont, M Fitzgerald, D Keeling *et al.*, 2023, PRL **131**, 075101

Alpha driven TAE



SXR



Internal Transport Barrier scenario – high q_0

P_{fus}=4.4MW

M. Fitzgerald, R Dumont, D Keeling, EPS 2022
M. Fitzgerald *et al.*, Nucl. Fusion special issue

Conclusion

- DTE2 campaign has exploited JET unique capabilities: T handling, ITER-like metal wall, size (closest to ITER), heating and diagnostic enhancements

- JET DTE2 has demonstrated the highest ever fusion energy sustained (5s) using a metallic wall environment including W

- JET DTE2 has demonstrated α-paticle heating

- JET T and DT experiments have yielded a wealth of exceptional data in a broad range of physics areas for improving predictions for ITER

- Experiments at JET with its ITER-like wall and using a D-T plasma mixture have shown the challenge to transfer operation from D to T & D-T, providing useful information that will help to mitigate risks in the ITER research plan
- Detailed analysis of the data is ongoing. A new campaign DTE3 is ongoing, concentrating on completion of data and radiative scenarios.