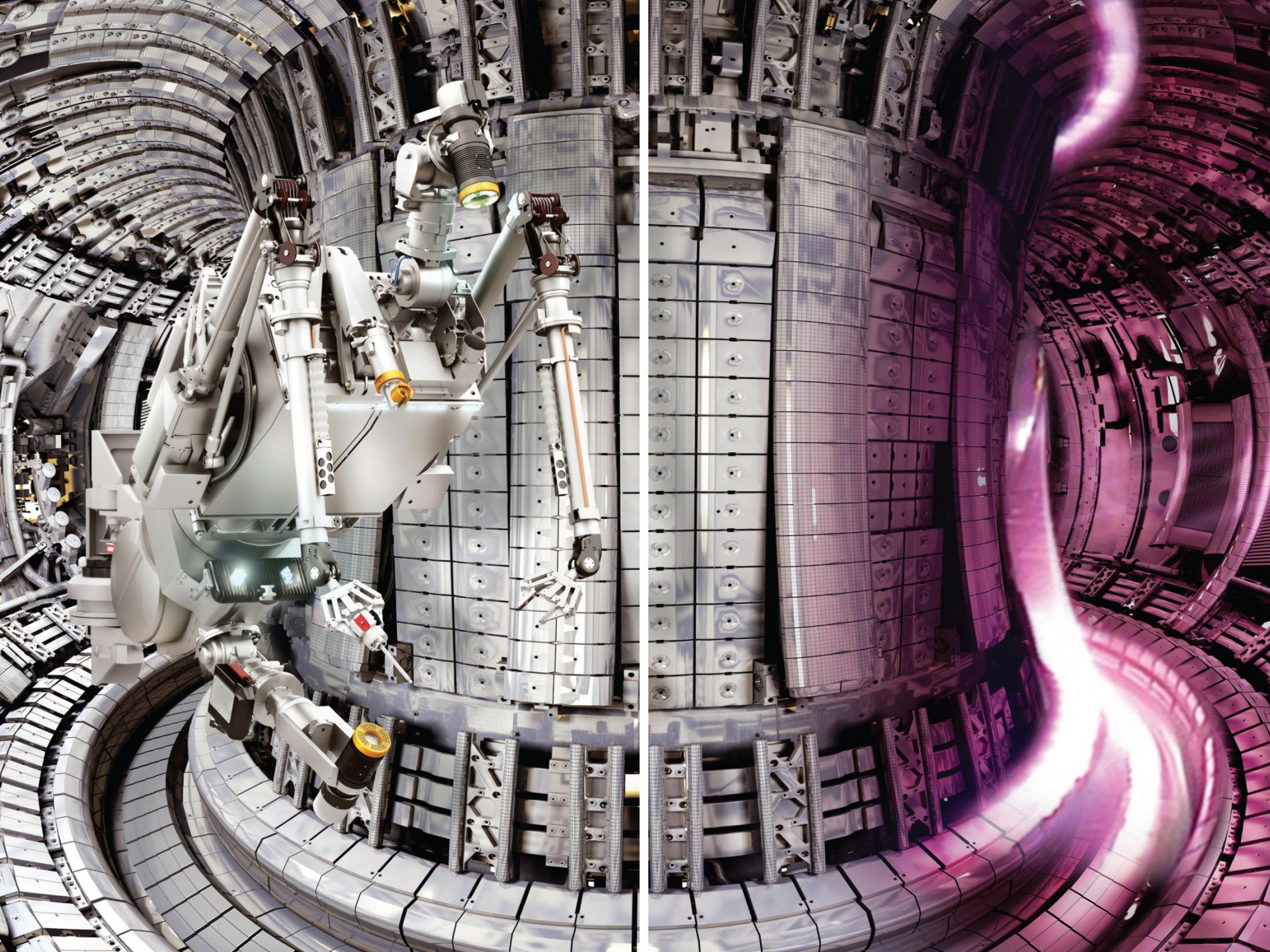
The JET 2018-2019 Program: Isotope effects on transport and confinement in view of D-T

M. Romanelli, JET TFLs and JET contributors

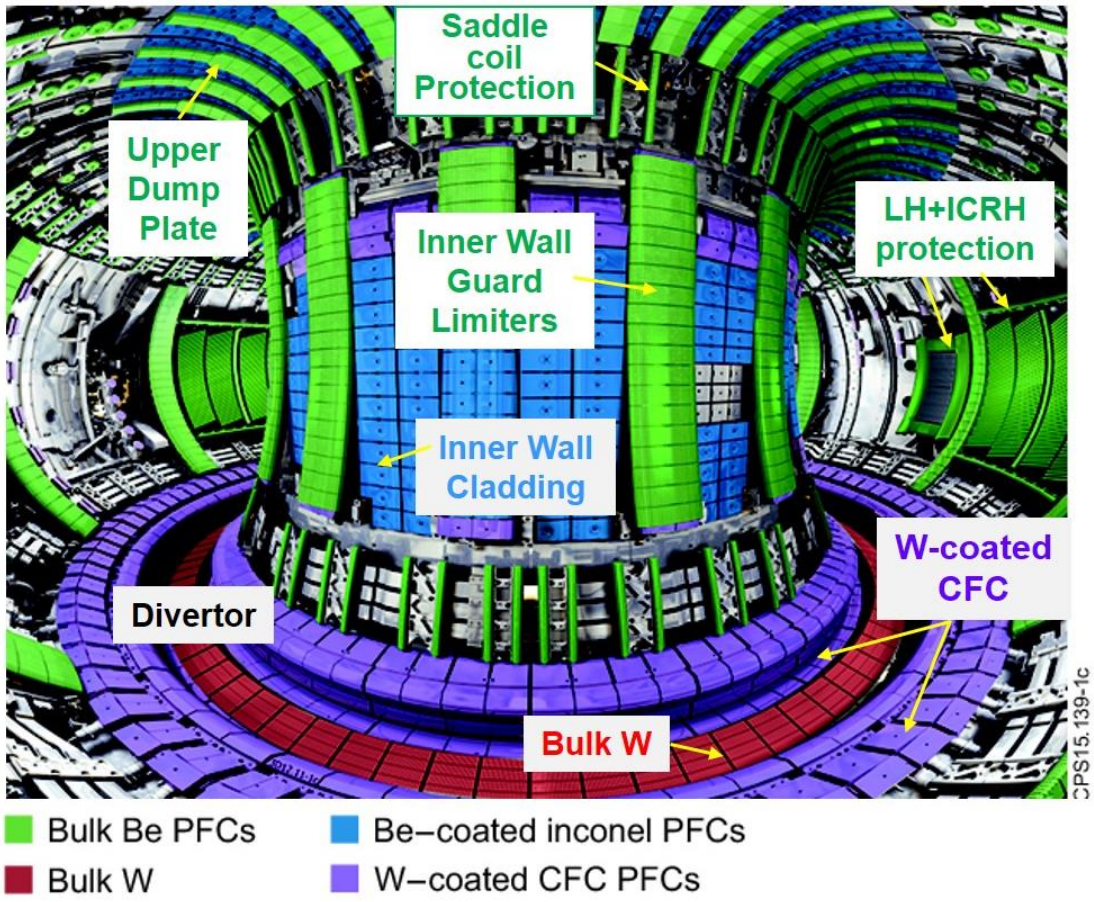
JET, Culham Science Centre, UK

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.



JET can address key physics issues for predicting and designing future tokamaks

- Largest tokamak in use and currently the only one capable of handling tritium
- ITER-like first wall (ILW): W divertor and Be walls
- Recently enhanced heating and diagnostics (including for fast particles)
- Burning plasma physics during D-T campaigns
- Isotope physics with H,D,T and mixtures



JET: **B_T=4T, R=2.96m, a= 0.96m, P_{NBI}=32MW, P_{ICRH}=12MW**

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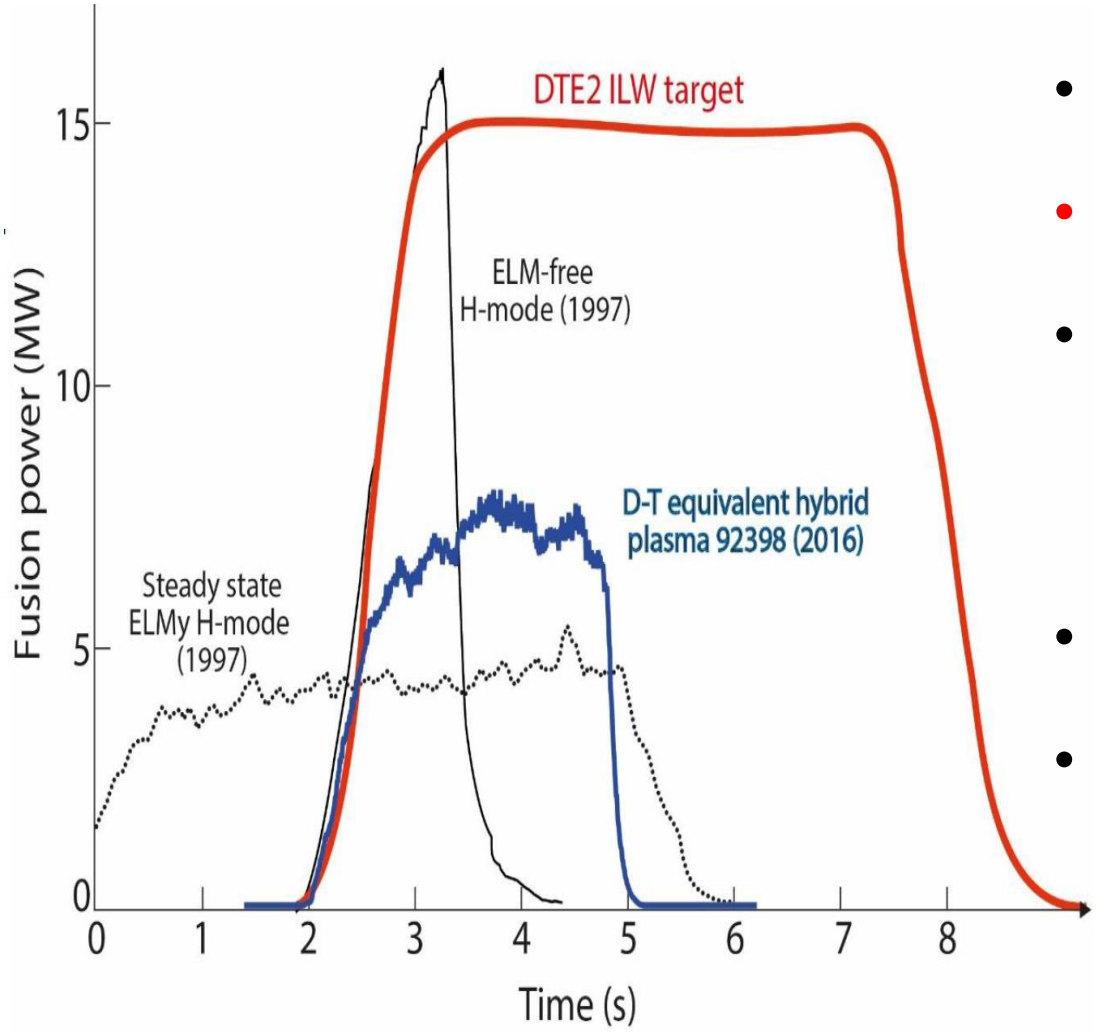
JET = D-T burning plasma + ITER-Like Wall

Challenging target for DTE2: 15MW/5s fusion power



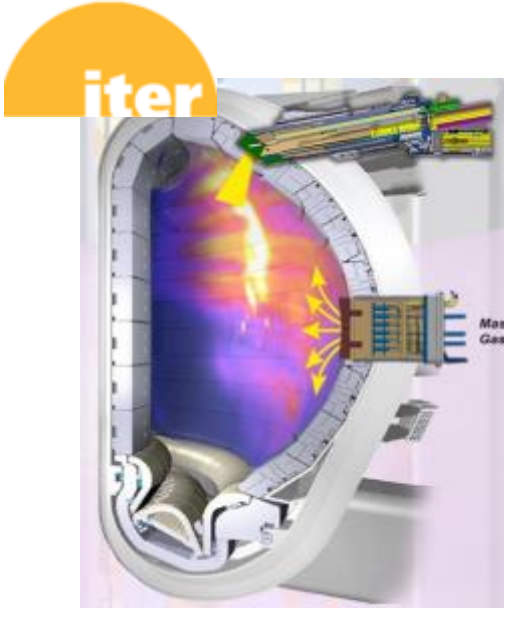
- Plasma Wall Interaction
- ITER integrated scenarios
- **Isotope effects on T&C**
- T-cycle
  - **fuelling, retention, migration, recovery, dust**
- **α–particle physics**
- Fusion technology
  - **calibration, materials under 14MeV neutrons, code validation**

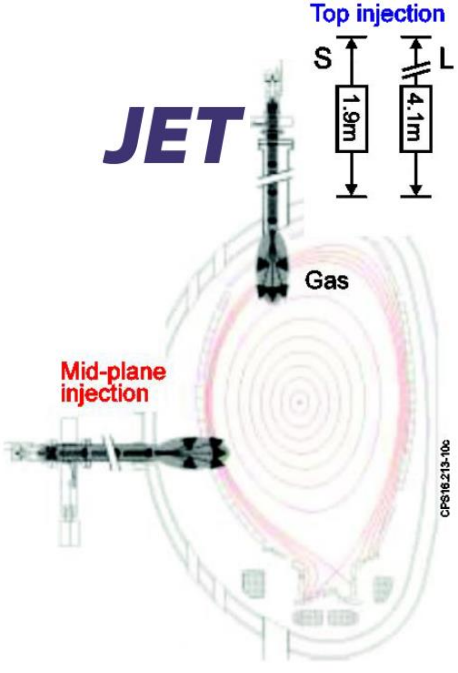
JET [Mantsinen EPS Conf. 2017]

Disruption Mitigation Studies for ITER

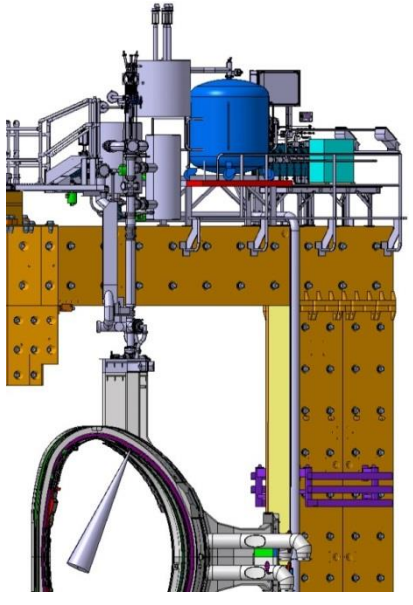
Disruptions is a Challenge for ITER

- Operate ITER Disruption Mitigation Systems as on ITER
- Test ITER disruption avoidance, predictors and control
- Disruption avoidance by controlling MHD modes
- Disruption mitigation scheme with ITER-like system





Installation of SPI on JET (under international collaboration)



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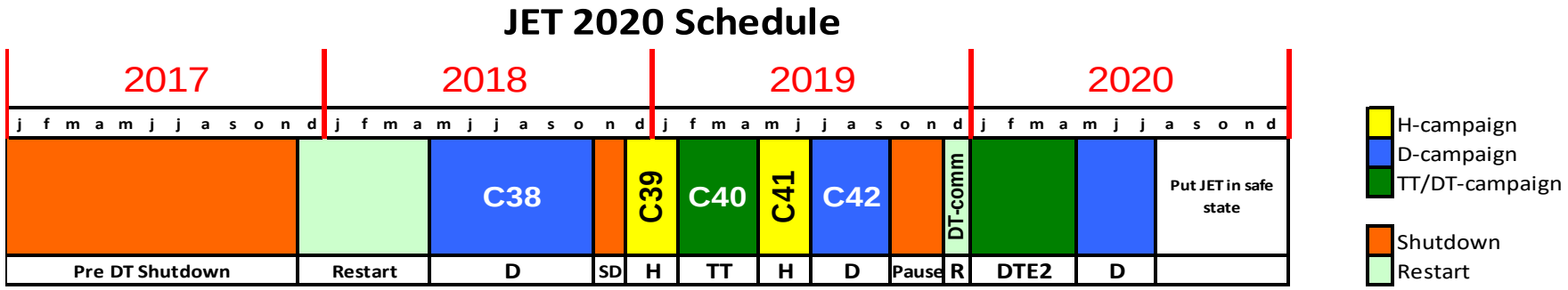
Priorities for JET programme 2018-2020

- Objective 1: Prepare scenarios for sustained fusion performance and α-particle physics
- Objective 2: Determine the isotopes dependence of H-mode physics, SOL conditions and fuel retention
- Objective 3: Quantify the efficacy of SPI versus MGI on runaway and disruption energy dissipation and extrapolate to ITER

Other physics issues essential for the exploitation of the JET T & DT campaigns and for extrapolation to ITER



https://users.euro-fusion.org/tfwiki/index.php/Main_Page

Isotope effects on Transport and Confinement

Results from last campaigns

- **L-H transition**
- **Particle transport in core and SOL**
- **Heat and momentum transport in core and SOL**
- **Global confinement**

2018-2019 JET campaigns

- **New experiments and tasks addressing isotope effects on transport and confinement**
- **Conclusion**

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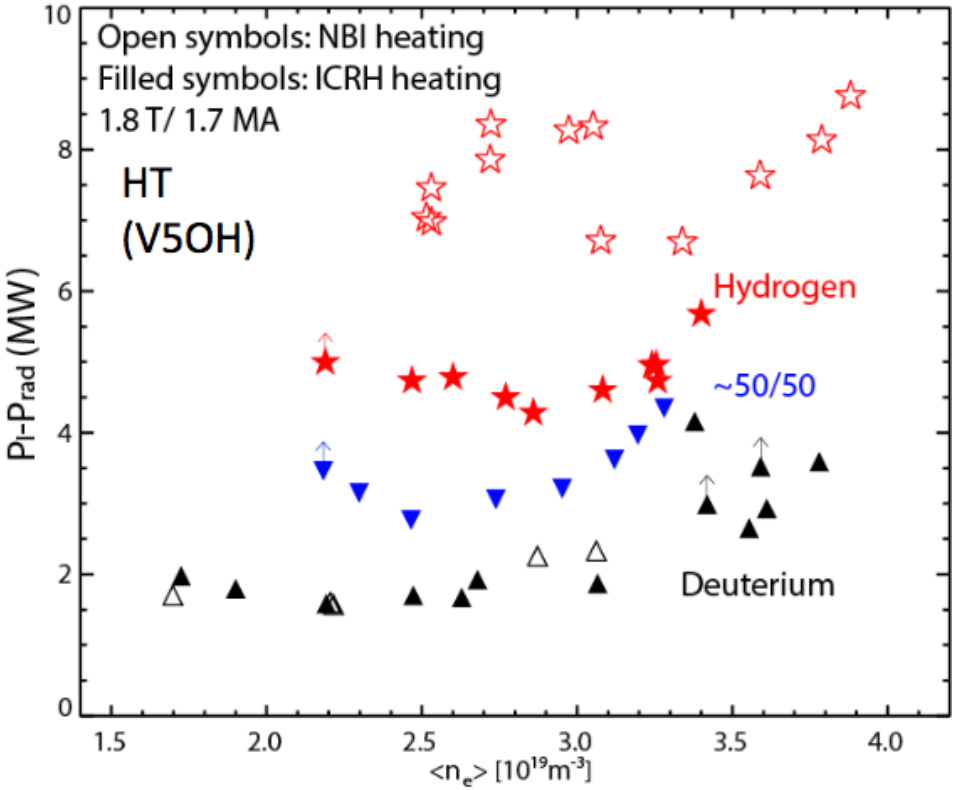
L-H threshold studies with isotopes

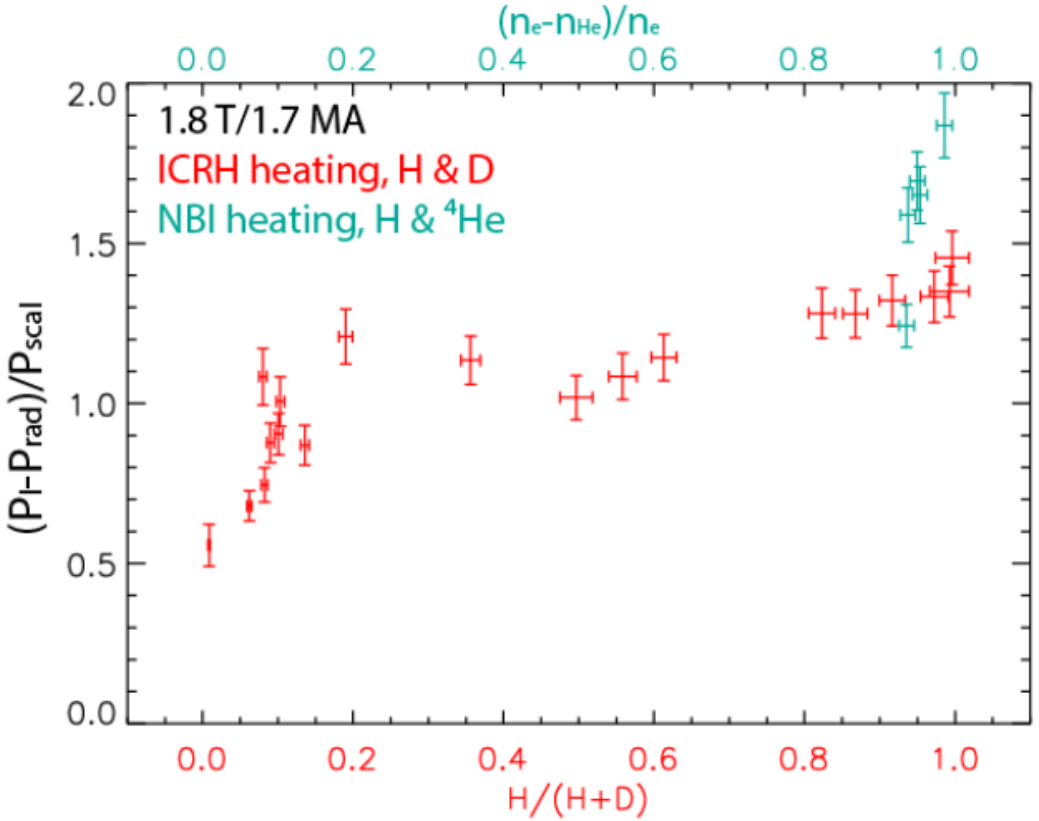
- For ICRH heated plasmas, threshold in H about twice D, generally consistent with most past results
- Similar to Gohil NF 2010, threshold much higher in hydrogen with more input torque
- Isotope dependence stronger in low density branch than high density branch



J. Hillesheim

L-H threshold studies with isotopes

- Largest variations observed at high and low H/(H+D)
- Little variation in range $0.2 < \frac{H}{(H+D)} < 0.8$
- Experiments at end of campaign with H-^{4}He mixtures show drop of power threshold with helium seeding in hydrogen plasmas
  - Effect could be used during non-active phase of ITER operation



$$P_{scal} = 0.0488 < n_e >^{0.717} B_T^{0.803} S^{0.941}$$

…. Plasma composition matters … what is the impact of e.g. seeded impurities on L-H threshold?

J. Hillesheim

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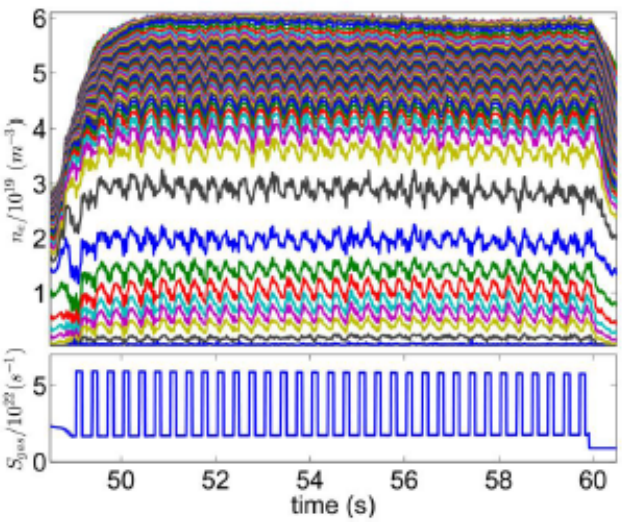
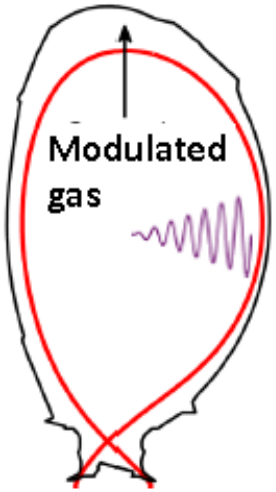
Dependence of fuelling on isotopes

NEW: systematic study of fuel transport mechanisms at SOL/edge boundary

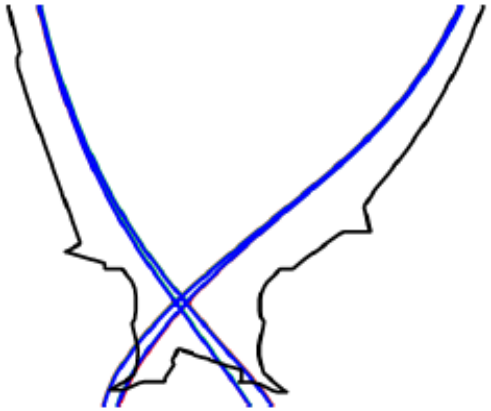




- 3 Hz gas modulation from top of the machine
- Study the inward propagation of the electron density wave

Different GIMS lead to different edge modulation response

- For these experiments a high frequency strike point sweeping was commissioned and used for the first time **P. Lomas**
- Wiggle the legs while keeping the main plasma intact
- Use constant gas fuelling, modulate recycling



New: Strike point sweeping works only in tile 5 configuration

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Dependence of fuelling on isotopes

- In Hydrogen the limited NB power prevented reaching dimensionless comparison shots against Deuterium plasmas
  - Diagnostics requirement (Bt > 1.9T) lead to too high LH threshold
- Corner configuration was used as the main scenario since it allowed easy ne control and dimensionless scans BUT has the drawback on suboptimal SOL diagnostics and L/H transitions when sweeping
  - Limited amount of data in tile-5

- Modelling is starting to bear fruit and add to our understanding of the important phenomena
  - EDGE2D/EIRENE direct fueling is in anti-phase with gas injection suggesting transport to be the main player in plasma fueling

Analysis ongoing: the dependence of fuelling on isotopes is still not characterised. New experiment planned for 2018 (M18-24) uses experience developed to provide the necessary information

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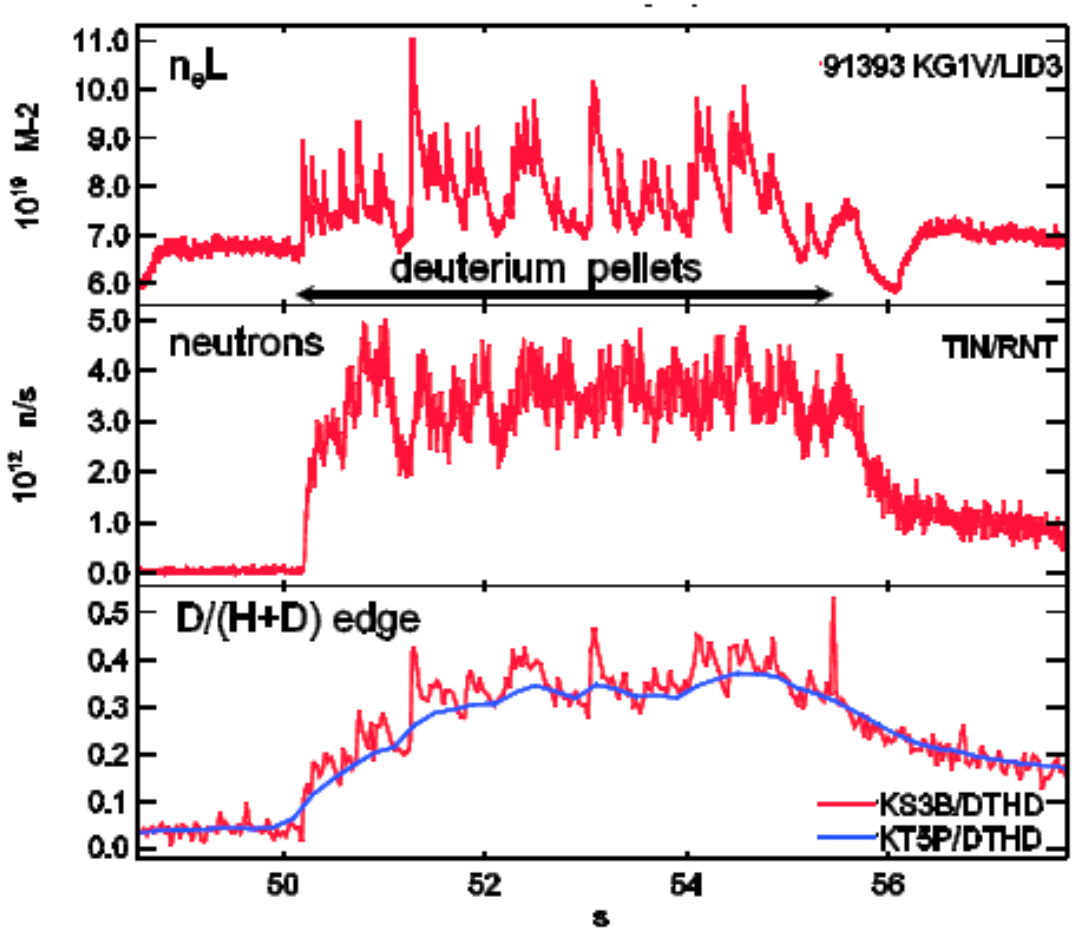
Dependence of fuelling on isotopes - pellets



M. Valovic

- Clean hydrogen plasma before pellets (no neutrons)
- At the edge $n_D/(n_D+n_H) \sim 0.35$

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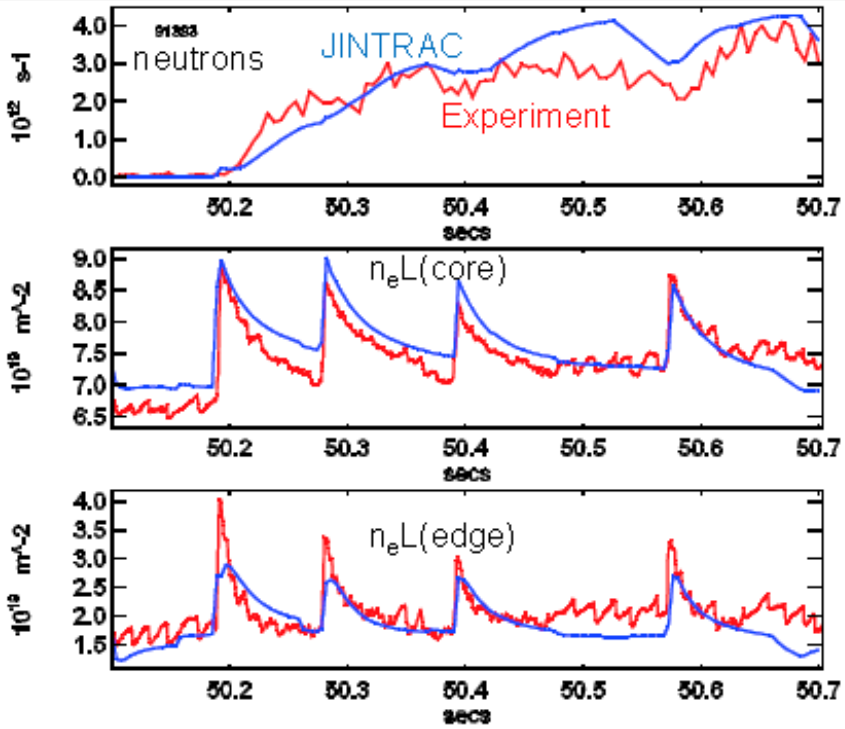
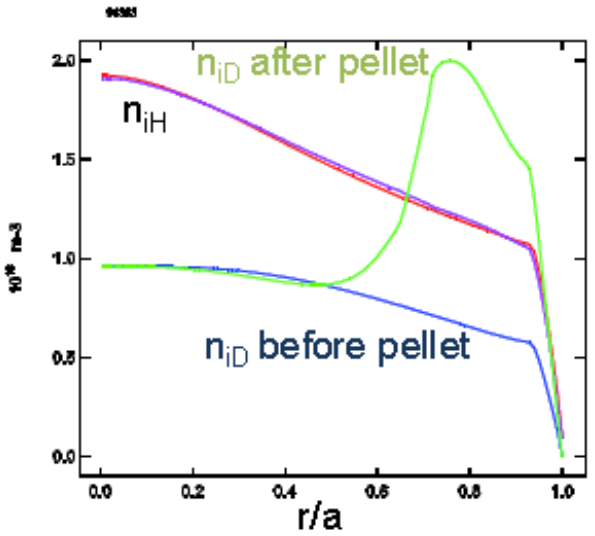
Dependence of fuelling on isotopes - pellets





- n_e and neutrons matched with:
  - $D_{iD} = D_{iH} = 1.5\langle\chi_{BgB,e,i}\rangle$, $v/D = -0.4\ r/a^2$, $\alpha_{crit} = 1$, $\Phi_H \sim 3\times10^{21}$ el/s,
  - Extra post-pellet convective loss τ=50ms, r/a>0.75, v_0=7m/s
- Code predicts:
  - On axis $n_D/(n_D+n_H) \sim 0.33$, close to spectroscopy value
  - new situation with opposite density gradients for D and H after pellet
  - at r/a=0.5 $D_{iD} \sim 0.22\ \chi_{i,eff} \sim 0.37\ \chi_{e,eff}$

Y. Baranov

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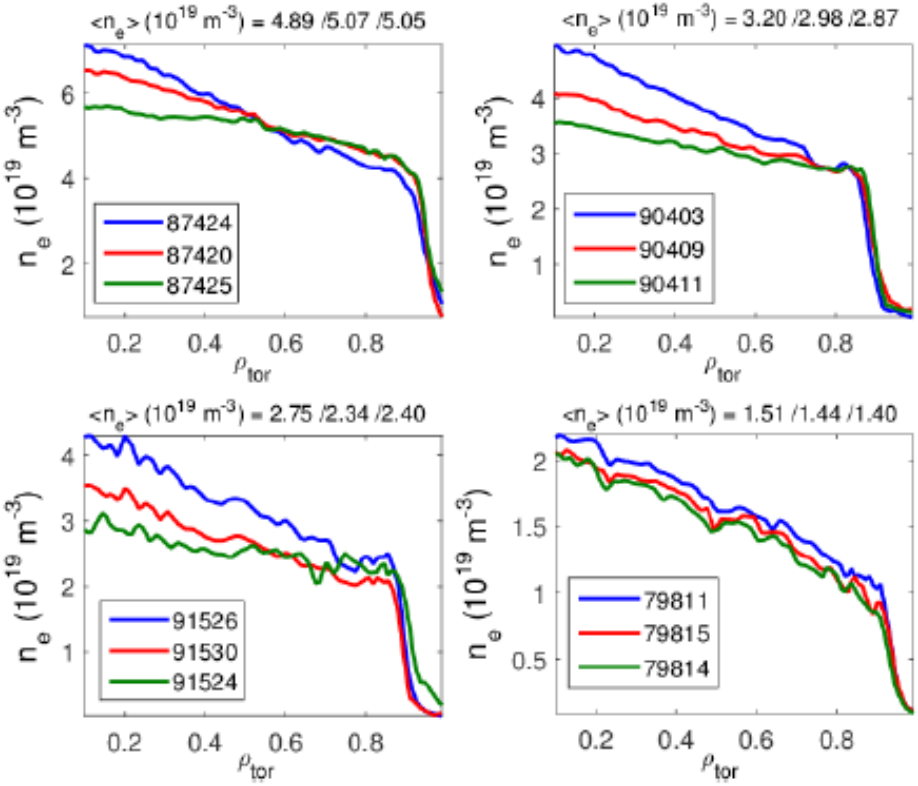
Density peaking at different collisionalities

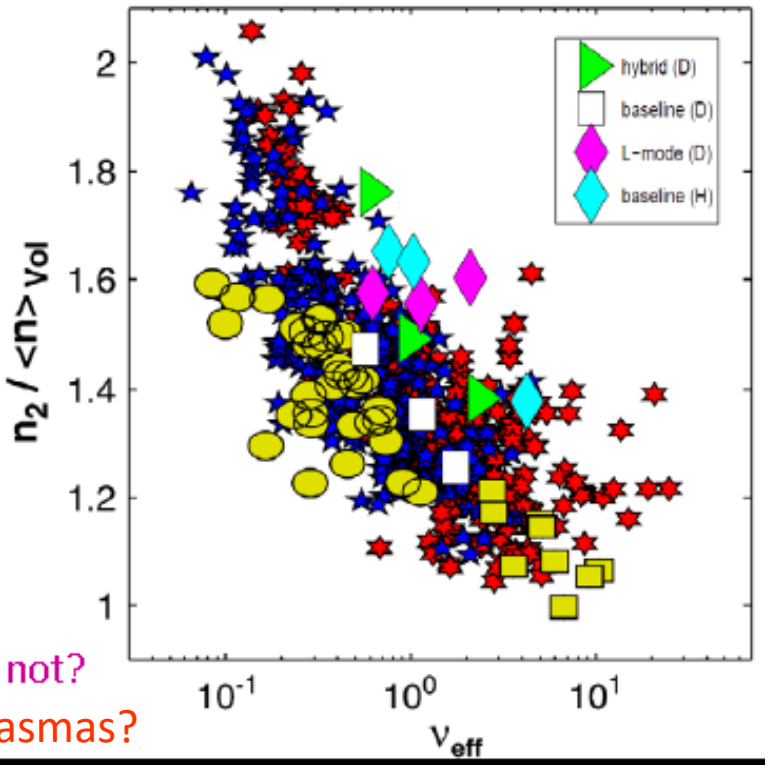
ELMy H-mode,
M13-24

Hybrid-like plasma
B15-02

T. Tala



(high υ*)
(middle υ*)
(low υ*)



ELMy H-mode in Hydrogen
H16-10

L-mode plasma

Density peaking Tritium plasma, similar or not?
2018 proposal ..and in mixed isotope plasmas?

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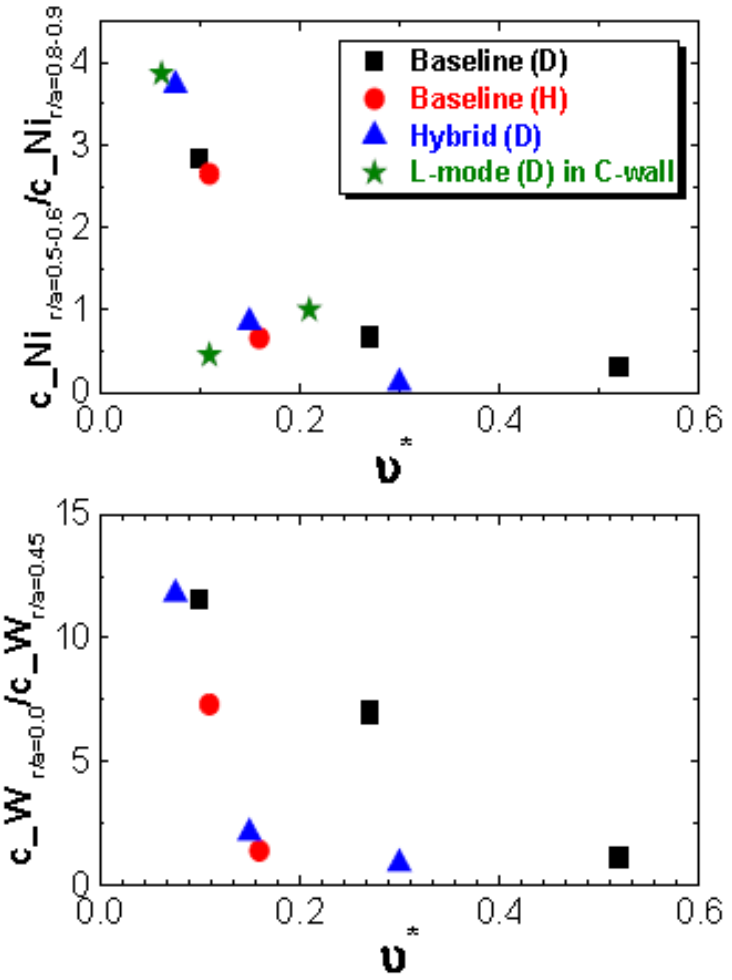
Density peaking at different collisionalities

- W and Ni impurities are less peaked at higher υ^* in H-mode
- However, this is maybe (even probably) not due to variations in υ^*, but due to increased main ion density peaking dependence on υ^*
- Neo-classical transport probably dominates here (transport modelling on-going).

A. Czarnecka



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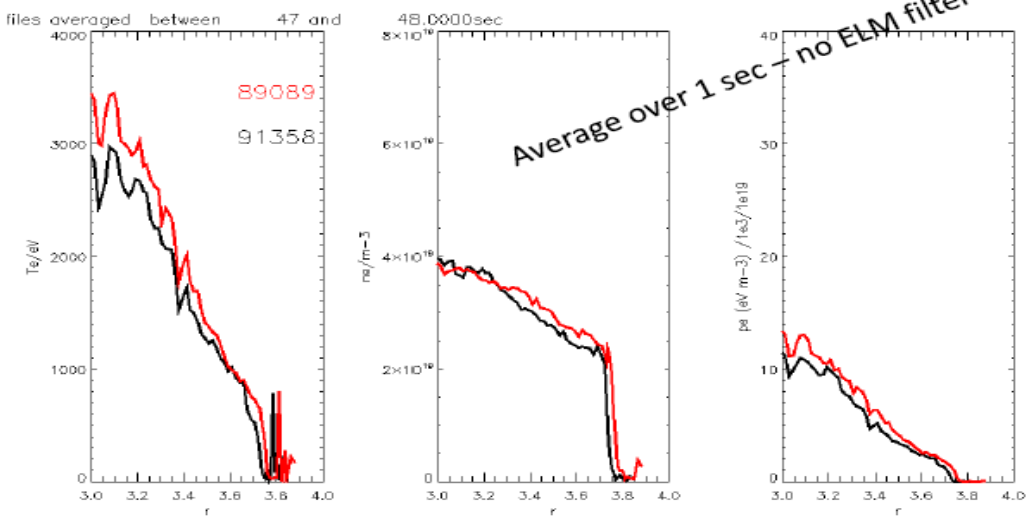
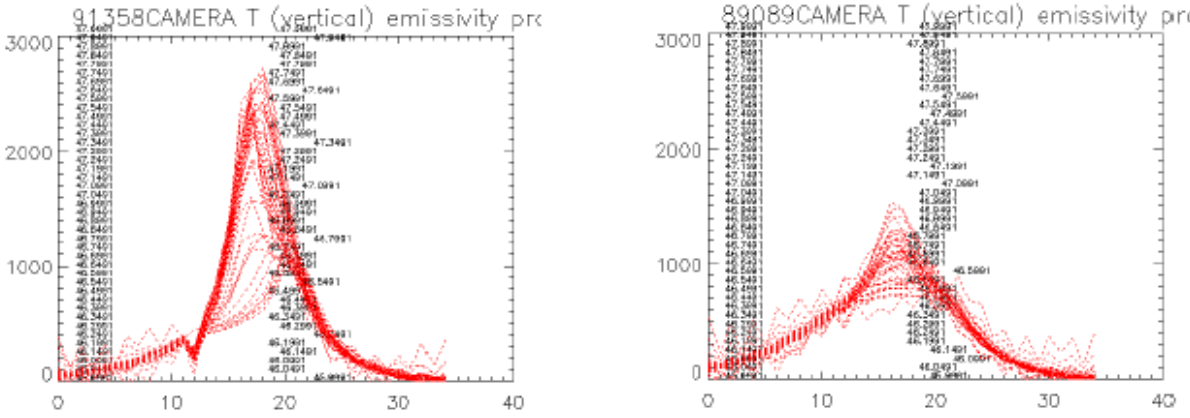
Density peaking at different collisionalities

- Pair of discharges with same Ip/Bt /NBI and similar e-flow. ELMfreq: 64, 40





M. Valisa

Confirms previously shown indication of W to peak more in H than in D

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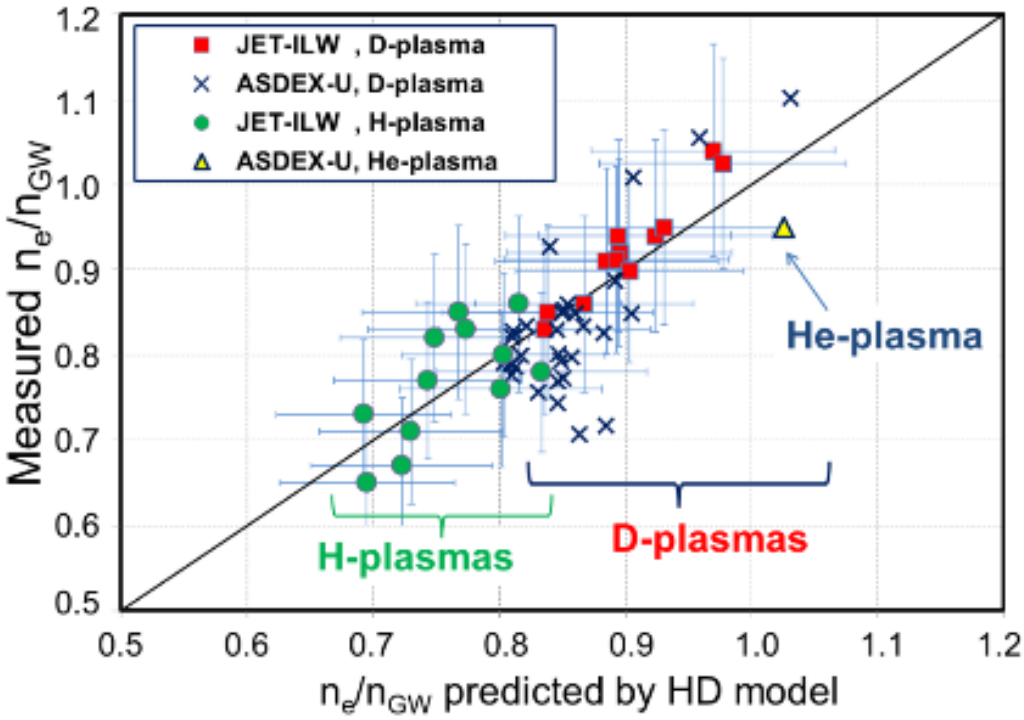
H-mode density limit

- The density limit is not related to an inward collapse of the hot discharge core induced by overcooling of the plasma periphery by radiation.
- It was observed in D- and H-plasmas that neither detachment, nor the X-point MARFE itself, do trigger the H-L transition and that they thus do not present a limit on the plasma density.
- The DL shows a strong dependence on the isotopic mass effect, the DL is up to 35% lower in the H-plasma than in the deuterium plasma.
- The density limit in H mode on JET-ILW is nearly independent of the power



The measured Greenwald fractions are found to be consistent with the predictions from a theoretical model based on MHD instability theory in the near-SOL.

A. Huber et al., Nucl. Fusion **57** (2017)

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2018-2019 JET campaigns

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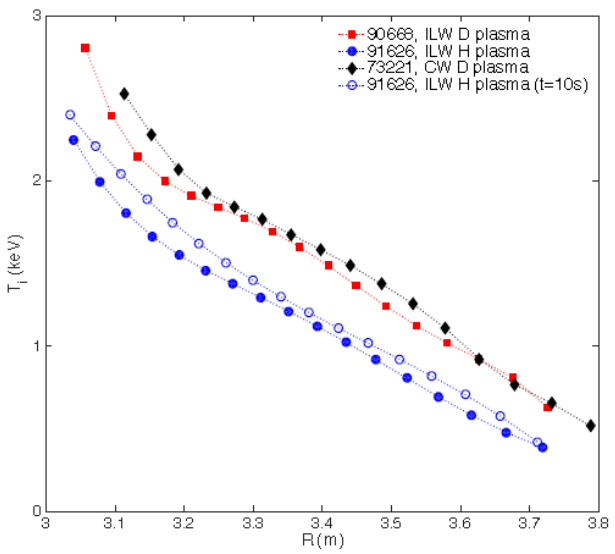
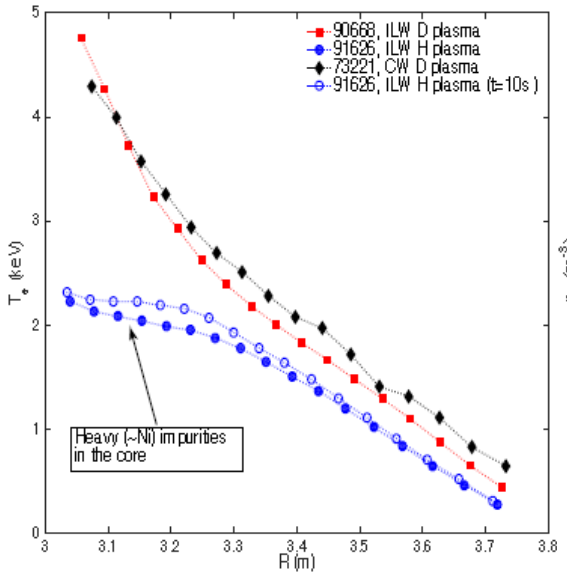
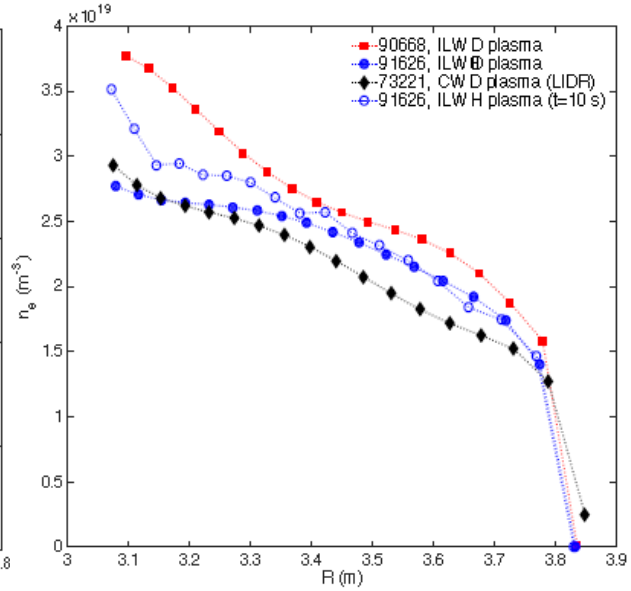
Heat transport in D and H

Dedicated core transport studies are performed in L-mode (avoid ELM/pedestal complexity) – 3 identical L-mode plasmas have been obtained/ analysed







Ion heat flux calculated by PION . All points are consistent with gB scaling. Similar threshold values and high stiffness at 0.33 in both D and H.
However, due to high stiffness, it is impossible to discriminate the mass dependence. Still, this means that R/LTi is similar betwen H and D in the core, and the difference we see in the absolute value of Ti must come from edge

P. Mantica

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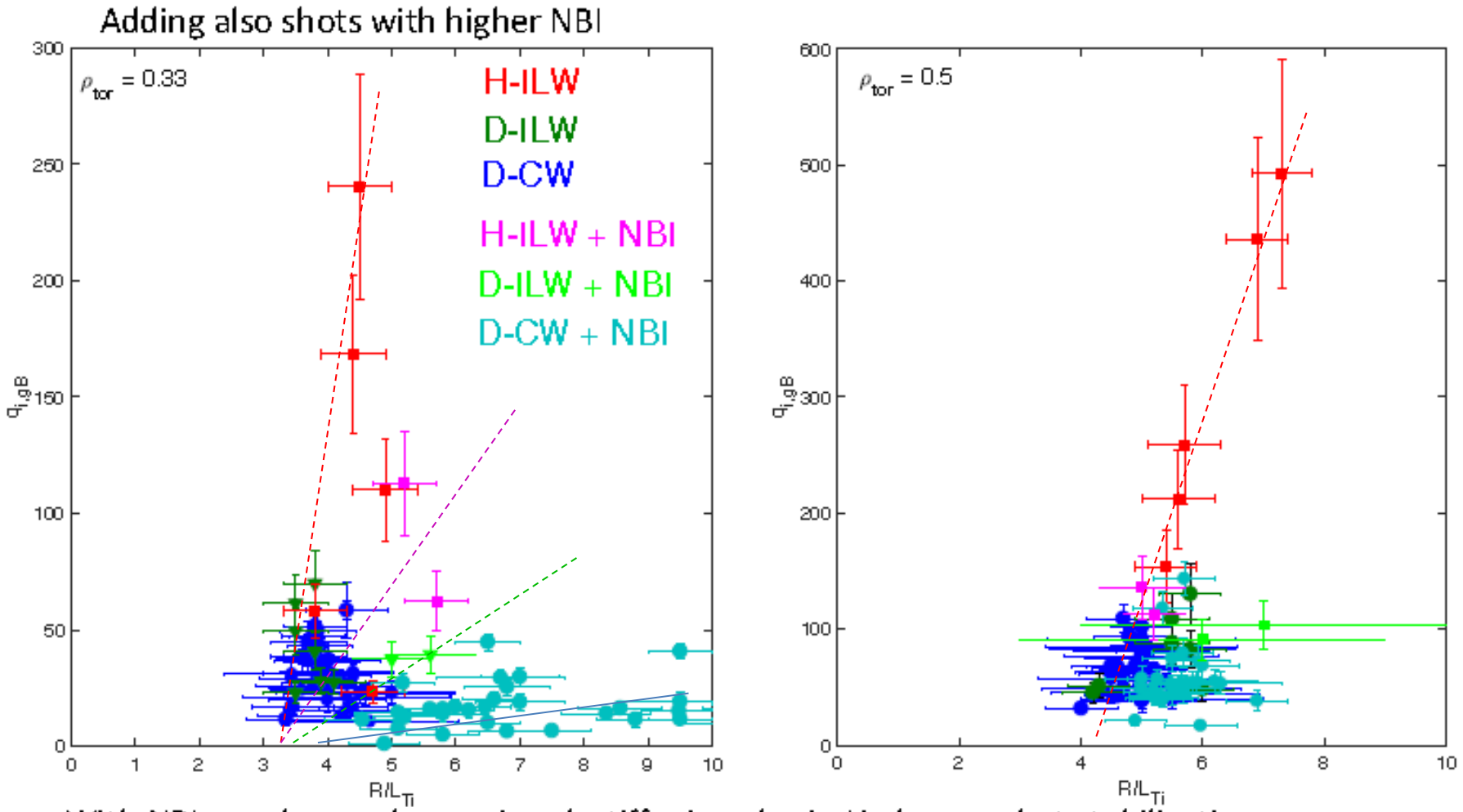
Heat transport in D and H



With NBI we observed some ion destiffening also in H plasmas, but stabilization seems quantitatively smaller. To be investigated.

P. Mantica

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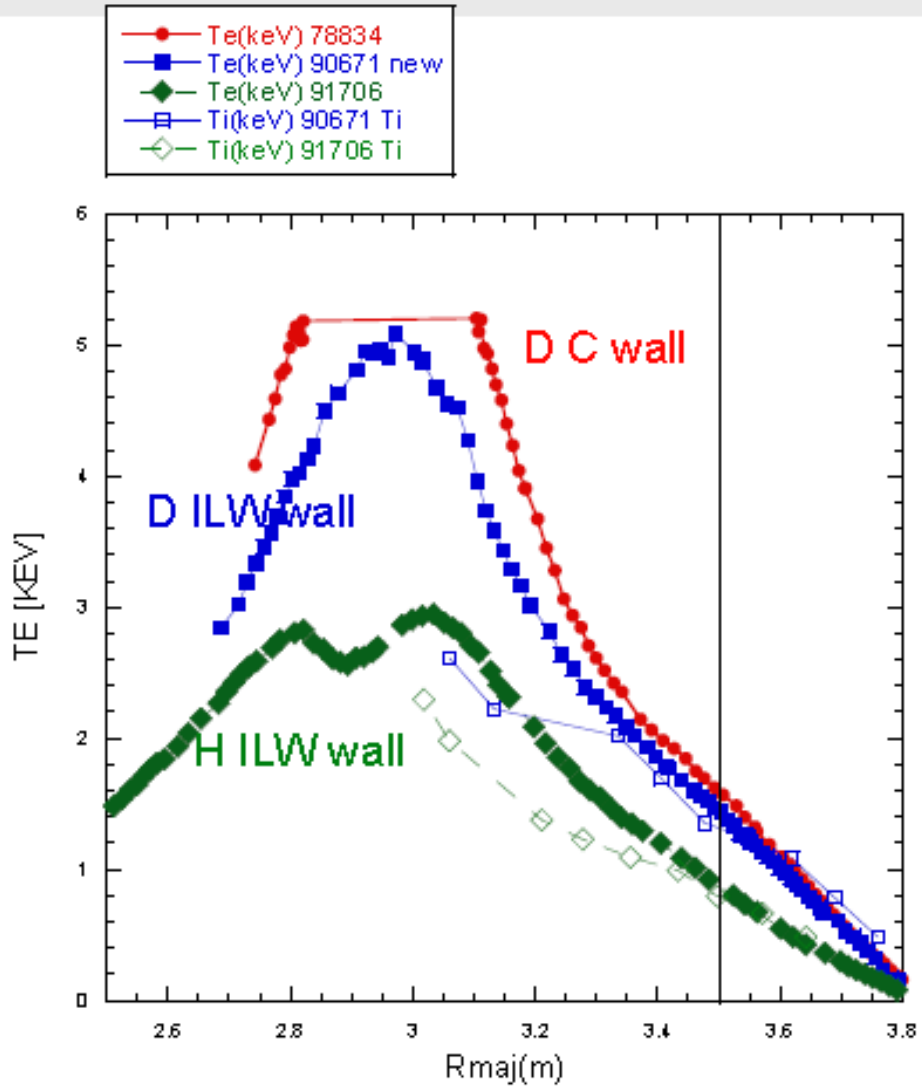
Heat transport in D and H



Te is lower already in the edge region, leading to higher R/LTe

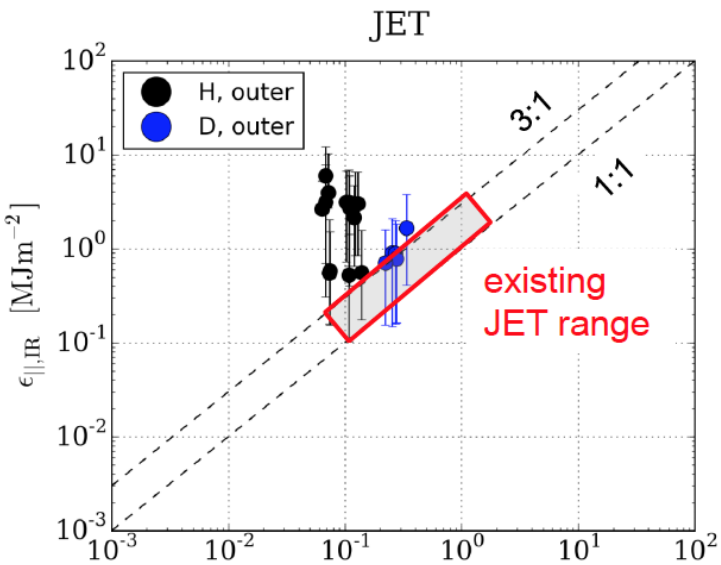
Possibly due to higher Pei in H (twice than in D for same parameters), which drags the electron heating to ions, with stronger ITGs which stabilize the ETGs. To be verified by GK simulations.

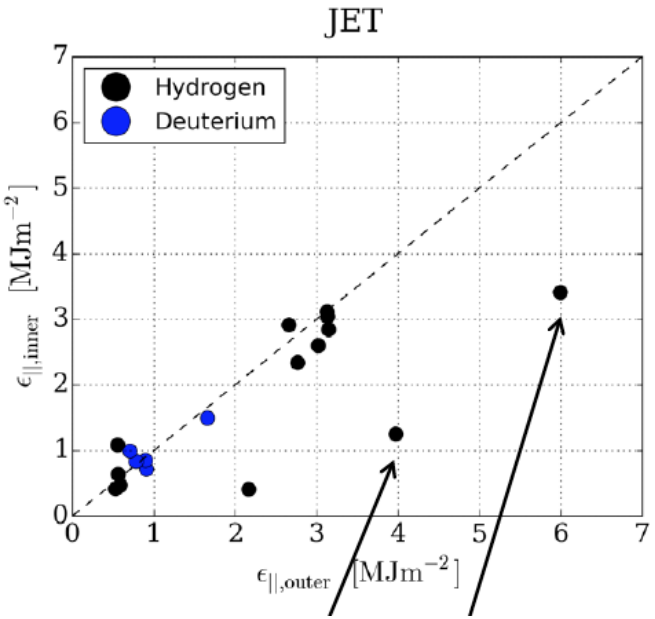
Different turbulence regime in Identity H and D plasmas

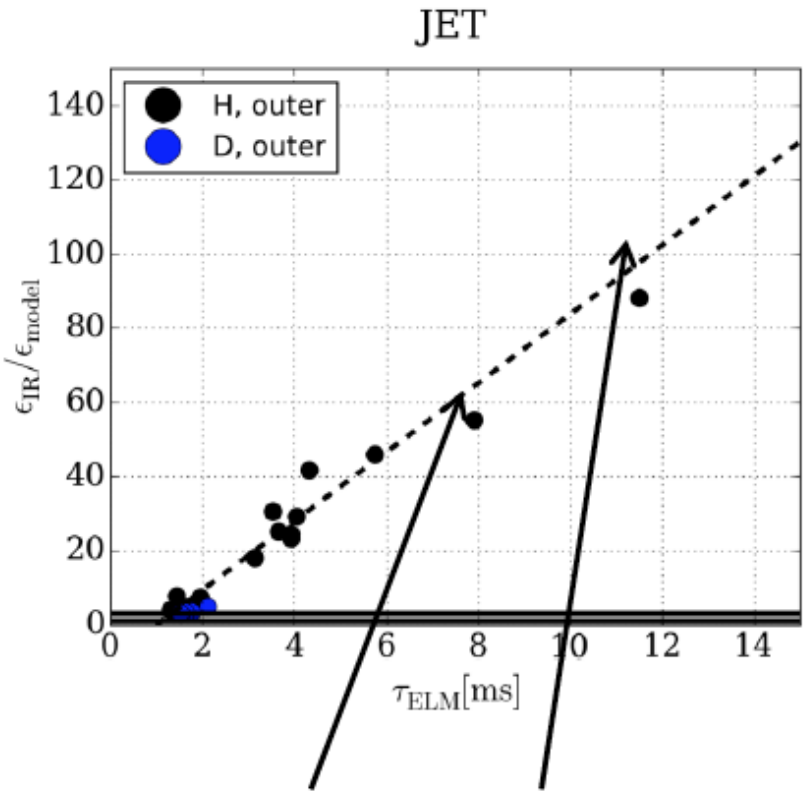
More experiments proposed in 2018 - 2019

P. Mantica

Energy fluence to divertor







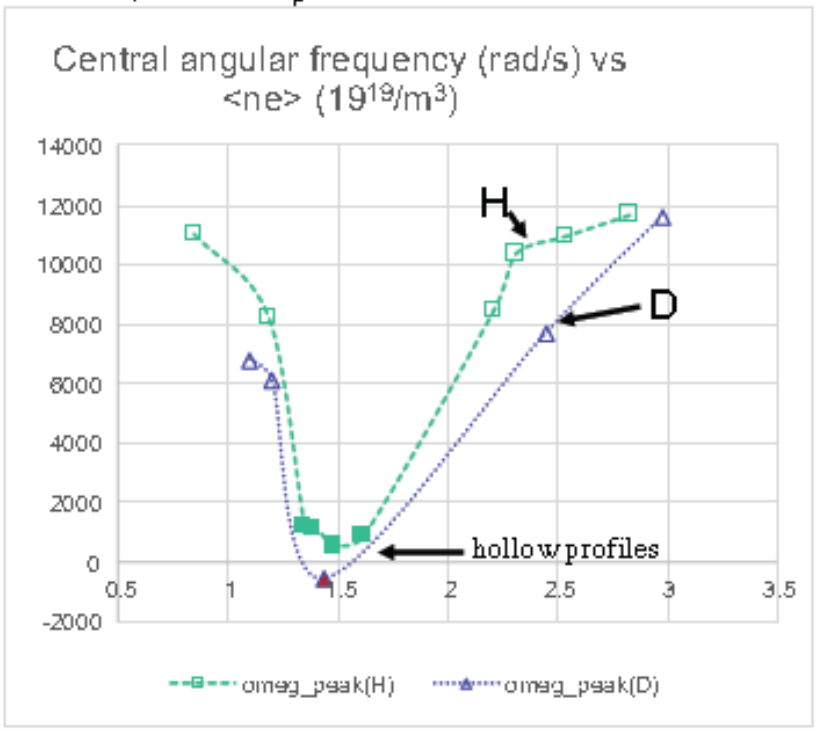
ELM duration most likely overestimated

Energy fluence: differences between H and D

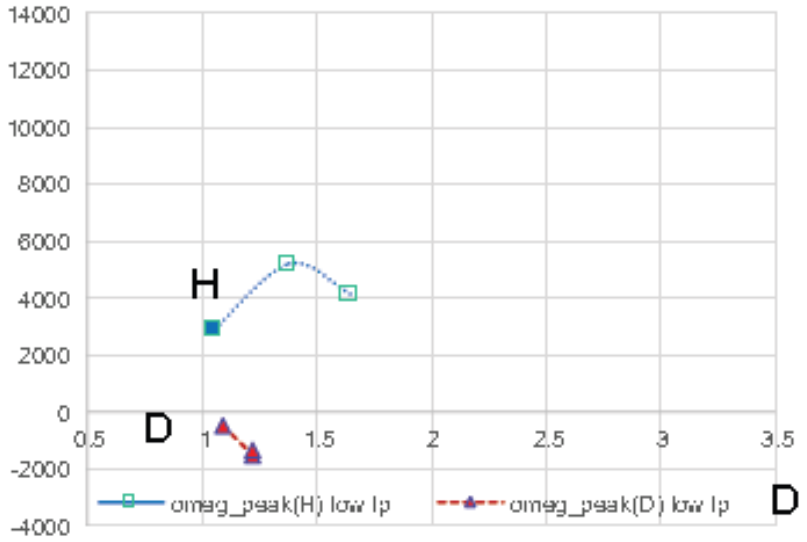
M. Faitsch

Momentum transport – Intrinsic rotation

B_T=2.6 T, I_p=2.3 MA



B_T=2.6 T, I_p=1.6 MA



F. Nave

NB. Rotation reversals observed for I_p=2.3 MA. Not enough data points for conclusions at the lower I_p.

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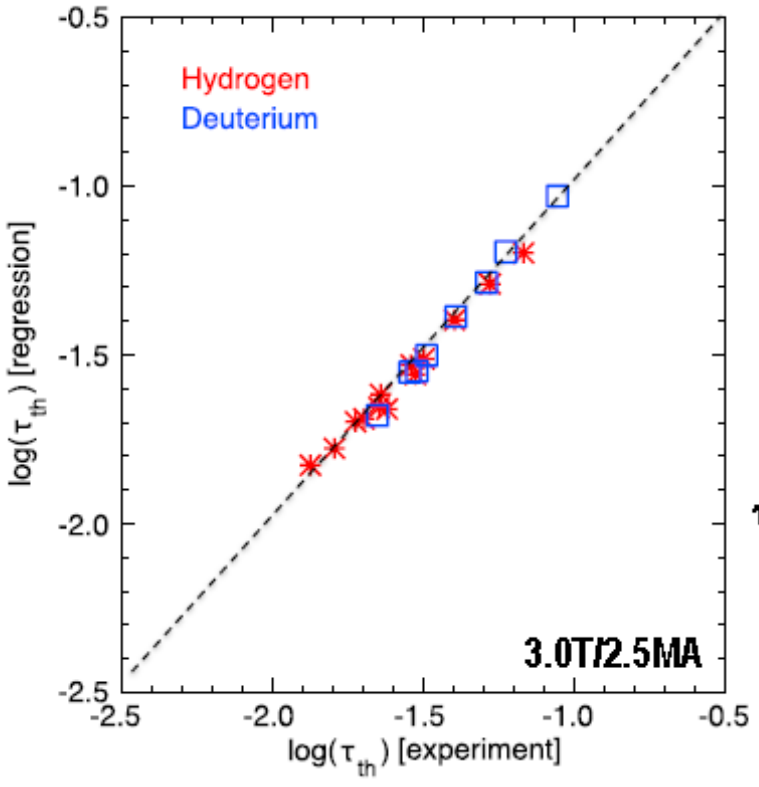
Isotope dependence of global confinement



- Controlled NBI power scan in H and D
- at **constant plasma density**
- Isotope purity ≥ 99%
- $T_i \sim T_e$

$$\tau_{th} \sim A^{0.15\pm0.02} P_{abs}^{-0.63\pm0.02}$$

$$\tau_{th}\ (\text{ITER97-L}) = 0.023\ I_p^{0.96}\ B_T^{0.03}\ P_{abs}^{-0.73}\ n_e^{0.40}\ A^{0.2}$$

- Isotope dependence broadly consistent with ITER97-L scaling (slightly weaker P degradation)

Positive isotope dependence of τ_{th}, in contradiction of gyro-Bohm scaling

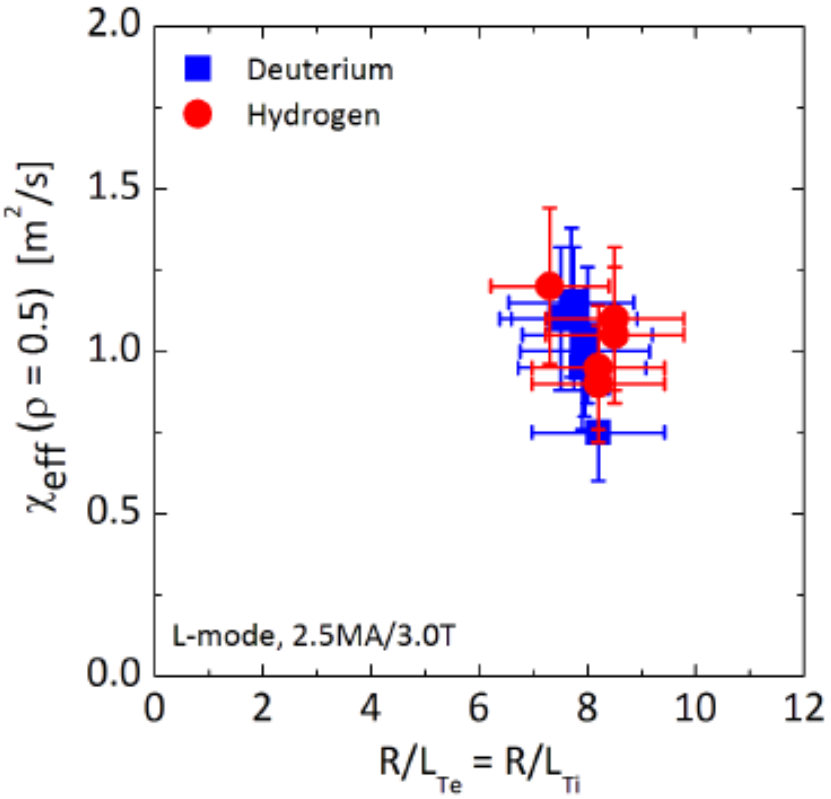
L-mode

C. Maggi

JET

Isotope dependence of global confinement

TRANSP power balance, with $T_i = T_e$ → $P_{e-i} \sim n^2 (T_e - T_i) / (A T_e^{3/2}) = 0$



- Same NB ion & e- heating in H and D
- Both in H and in D:
  - **$T_i \sim T_e$ across entire dataset**
  - **Same R/L_{Te} ($\cong R/L_{Ti}$)**
- Electrons and ions are coupled, electrons and/or ions are stiff

C. Maggi

Same core χ_{eff} for H and D → ≠ from gyro-Bohm dependence: $\chi \sim A^{1/2}$

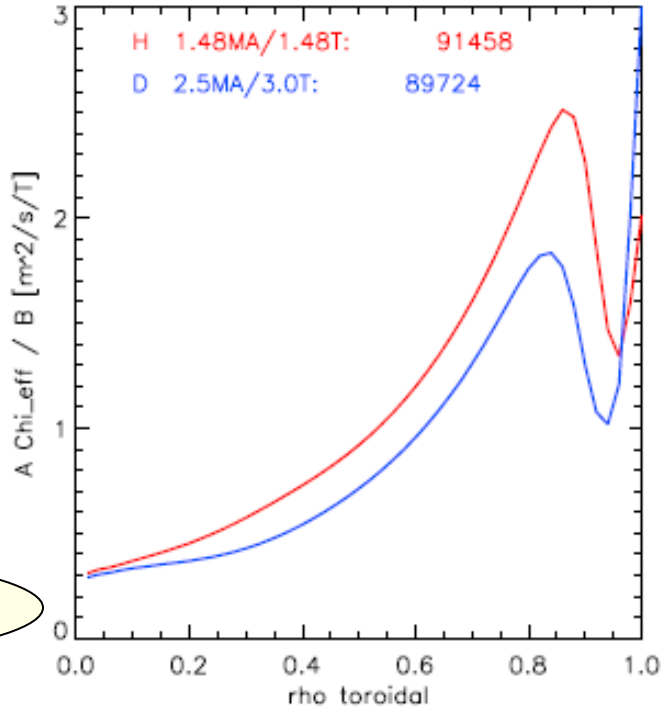
L-mode

JET

Isotope dependence of global confinement

- H and D pairs with **matching** profiles of dimensionless parameters: q, ρ^*, ν^*, β
- B_T , $I_P \sim A^{3/4}$; then n_e and T_e should scale as : $n_e \sim A$; $T_e \sim A^{1/2}$

Pulse #	91458	89724
Isotope	H	D
Time interval [s]	17.1 – 18.9	14.0 – 16.0
B [T]	1.74	2.95
I_P [MA]	1.44	2.46
P_{loss} [MW]	2.65	6.4
$P/B^{5/3}$ [MW/$T^{5/3}$]	1.05	1.05
τ_{th} [s]	0.155	0.19
$B\,\tau_{th}/A$ [Ts]	0.27	0.28



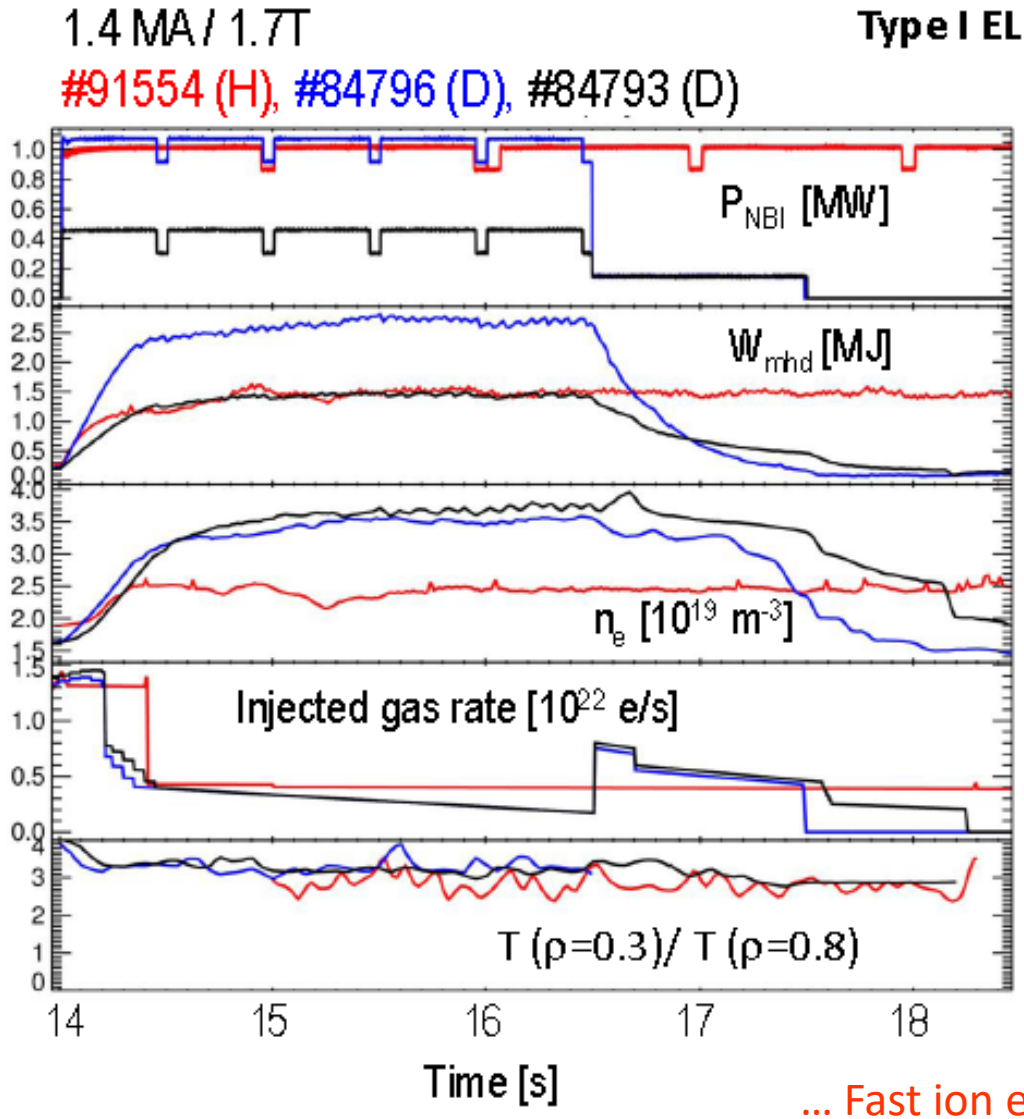
- $T_i = T_e$ in TRANSP runs (T_i and T_e very close to each other experimentally) → χ_{eff}
- Neutron yield and stored energies accurately reproduced by TRANSP
- Dimensionless thermal diffusivities $A\,\chi_{eff} / B$ matched within error bars in plasma core → confinement scale invariance principle satisfied

L-mode

C. Maggi

JET

Isotope dependence of global confinement



C. Maggi

H and D at same Power
H and D at same W

Lower W_{mhd} and W_{th} (TRANSP) in H at same P_{NBI}

← **Lower n_e in Hydrogen**

At same injected gas rate

← **For stiff T profiles, suggests isotope effect originating from pedestal**

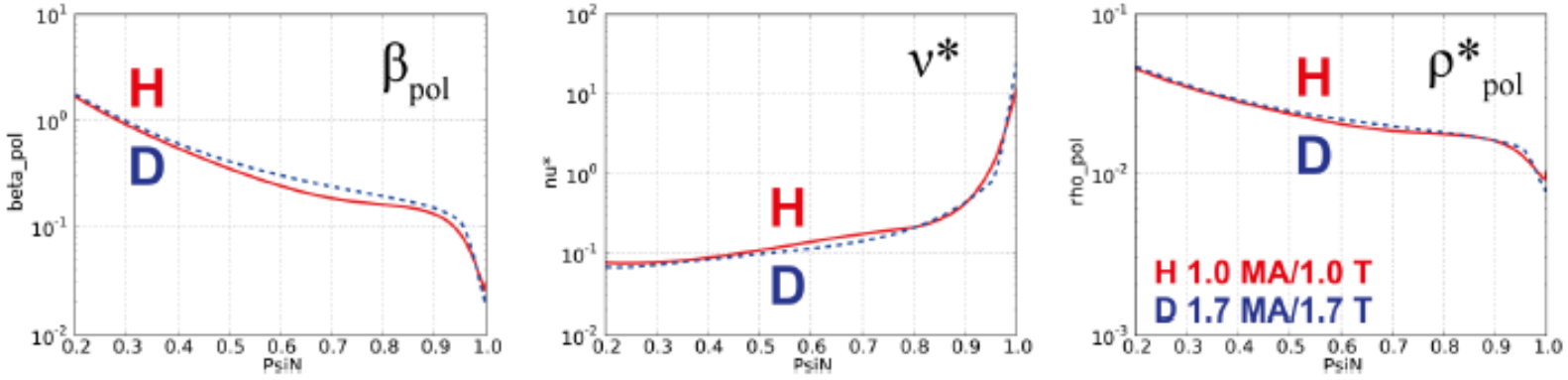
… Fast ion energy different in H and D

JET

Isotope dependence of global confinement

- H and D pairs with **matching pre-ELM** profiles of dimensionless parameters

C. Maggi

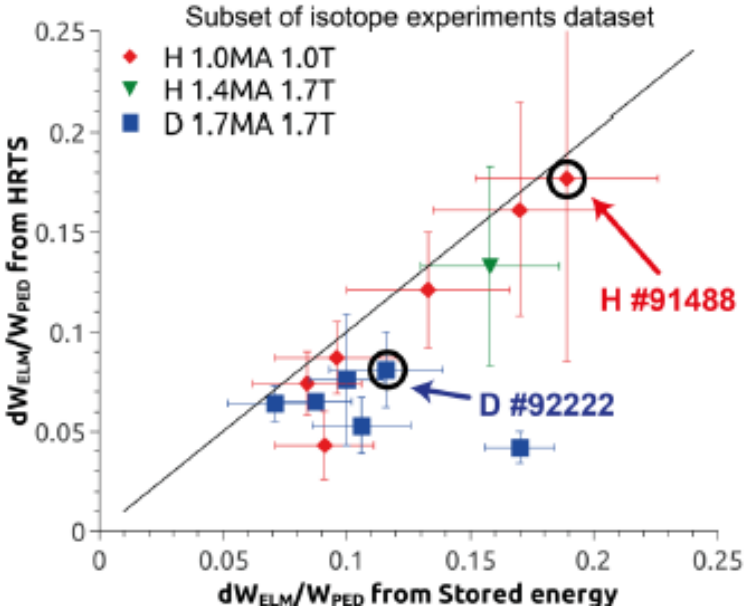


- B_T , $I_P \sim A^{3/4}$; $n_e \sim A$; $T_e \sim A^{1/2}$
- Larger ELM losses in H than in D
- ELM-averaged profiles not matched:

  $A\, f_{ELM} / B$ not matched 40/58 [Hz/T]

  $B\, \tau_{E,th} / A$ not matched 0.102/0.148 [T s]

→ **Suggests that pedestal cannot be described by canonical plasma physics parameters only ...**

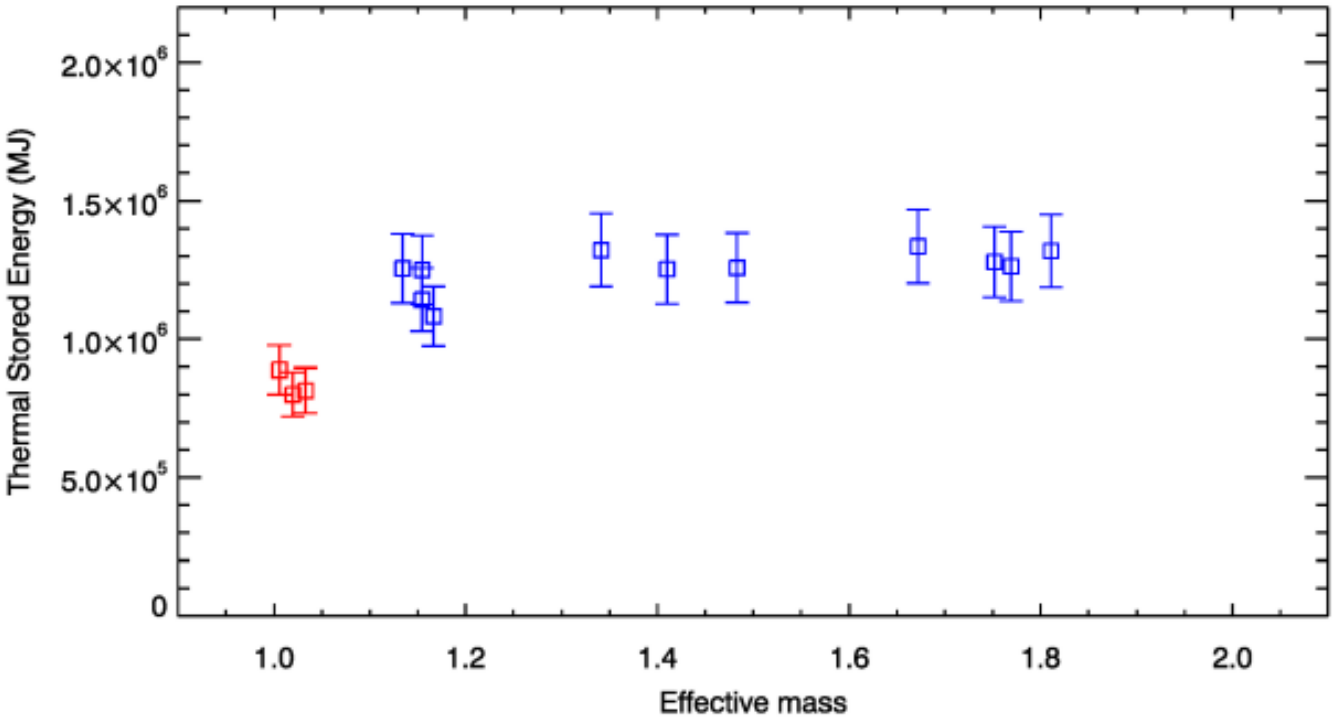


... Heat and particle sources are different in H and D -> exp proposals

JET

Global confinement in mixed isotopes plasmas

- Isotope ratio was scanned from $1.2<M_{eff}<1.8$ with similar input power (8-10MW) and gas fuelling (~1e22el/s).
- Thermal stored energy by integrating kinetic profiles.
- Including pulses with $1.1<M_{eff}<1.2$ shows a more significant change.
- L-H threshold expected to be 8-9MW at full hydrogen



D. King

Isotope effects on Transport and Confinement

Results from last campaigns

- **L-H transition**
- **Particle transport in core and SOL**
- **Heat and momentum transport in core and SOL**
- **Global confinement**

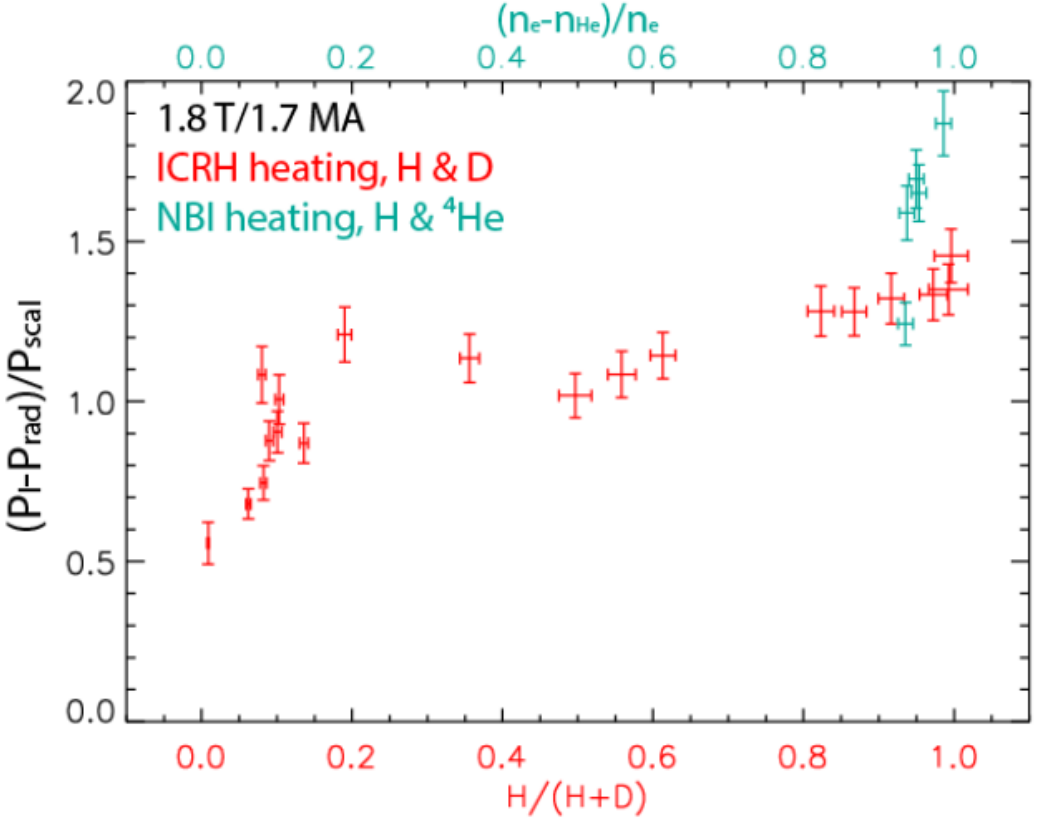
2018-2019 JET campaigns

- **New experiments and tasks addressing isotope effects on transport and confinement**
- **Conclusion**

2018-2019 JET experiments and tasks

- M18-13 - H/He mixtures for non-active phase of ITER operation
- M18-14 - Isotope effects on L-H transition power threshold
- M18-15 - Access to type-I ELMs with reduced torque

- Largest variations observed at high and low H/(H+D)
- Little variation in range $0.2 < \frac{H}{(H+D)} < 0.8$
- Experiments at end of campaign with H-^{4}He mixtures show drop of power threshold with helium seeding in hydrogen plasmas
  - Effect could be used during non-active phase of ITER operation



$$P_{scal} = 0.0488 < n_e >^{0.717} B_T^{0.803} S^{0.941}$$

J. Hillesheim

L-H transition modelling XGC

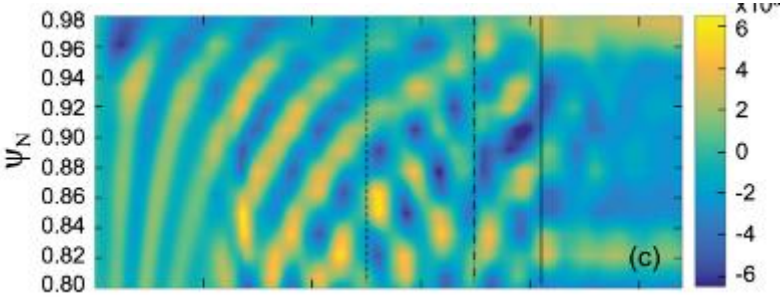
XGC results show that turbulent Reynolds-stress act in concert with neoclassical orbit loss to quench turbulent transport and form a transport barrier just inside the last closed magnetic flux surface.
Differences with isotopes and mixed species?

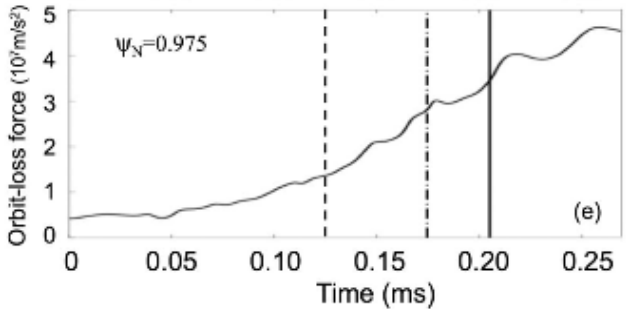
C. S. Chang et al, PRL 118, 175001 (2017)

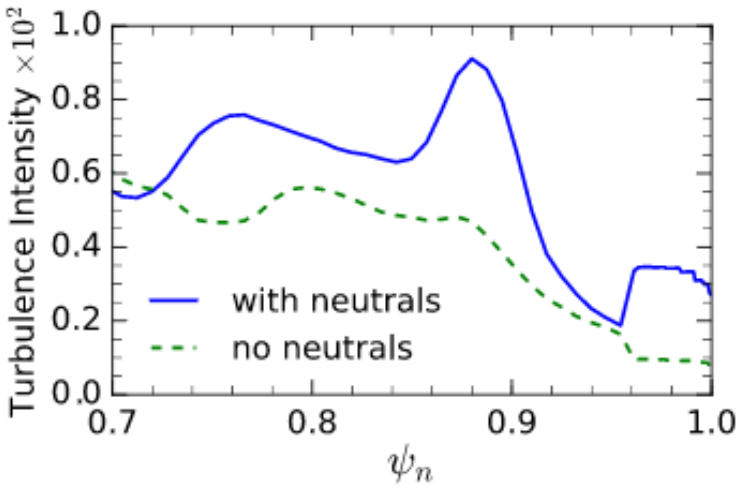
Impact of neutrals on turbulence has been documented in a recent paper by Stotler

D.P. Stotler et al 2017 Nucl. Fusion 57 086028

Different isotopes have different neutral distribution due to differences in the ionization cross section. Simulations of ETB / SOL turbulence with different isotopes is crucial to understand JET results.







JET

2018-2019 JET experiments and tasks

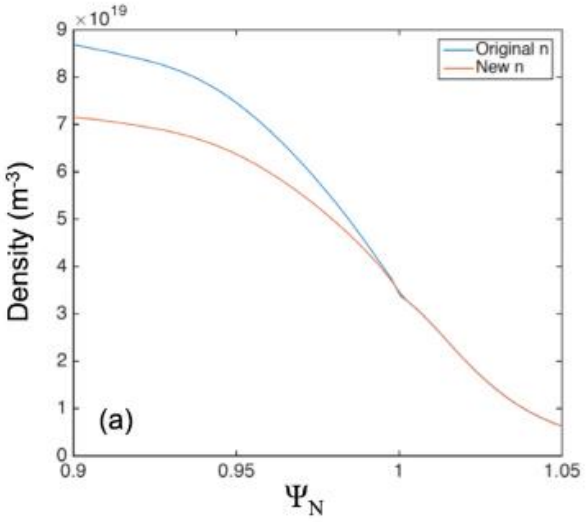
Neutrals & pedestal

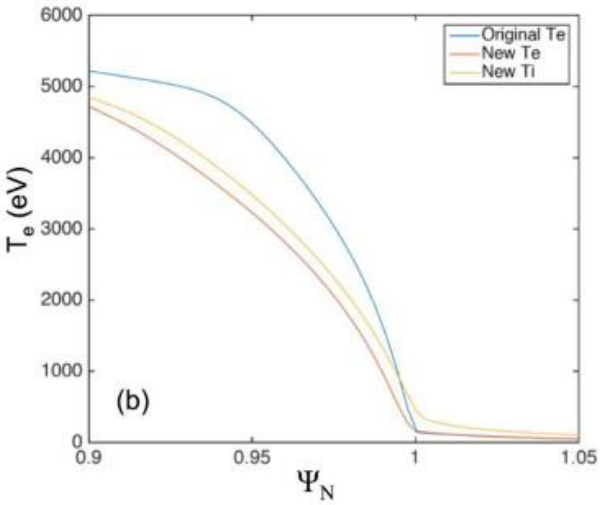
- M18-16 - Impact of neutrals and impurities on SOL and pedestal
- M18-17 - **Power width scaling and ELM losses at high current**
- M18-18 - Determine W source including ELM, RF and isotope effects
- M18-20 - Dependence of pedestal structure on fuelling at constant beta
- T17-05 - Pedestal analysis and isotope effect
- T18-02 - **Scrape-off layer and SOL-pedestal interaction**

Modelling of SOL width with XGC

JET plasma profiles from JINTRAC

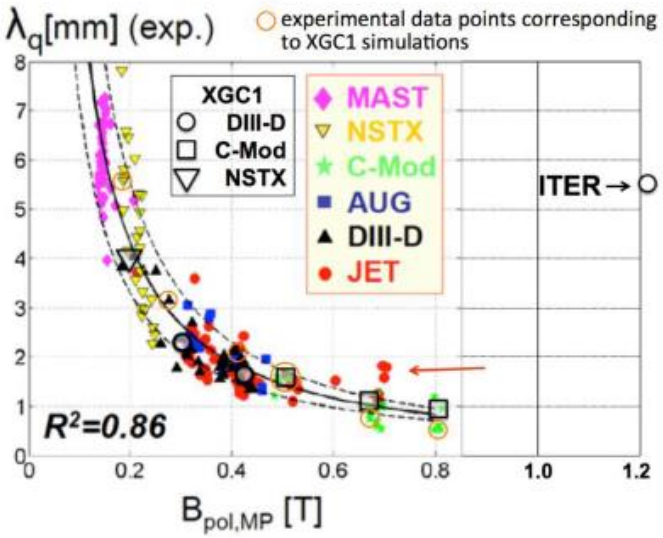
Work ongoing

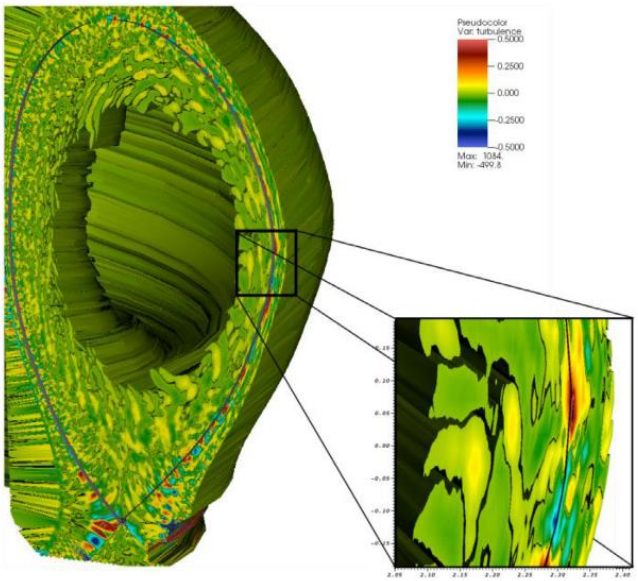




Collaboration JET/PPPL

C.S. Chang *et al*, **Gyrokinetic projection of the divertor heat-flux width from present tokamaks to ITER**, 2017 Nucl. Fusion 57 116023

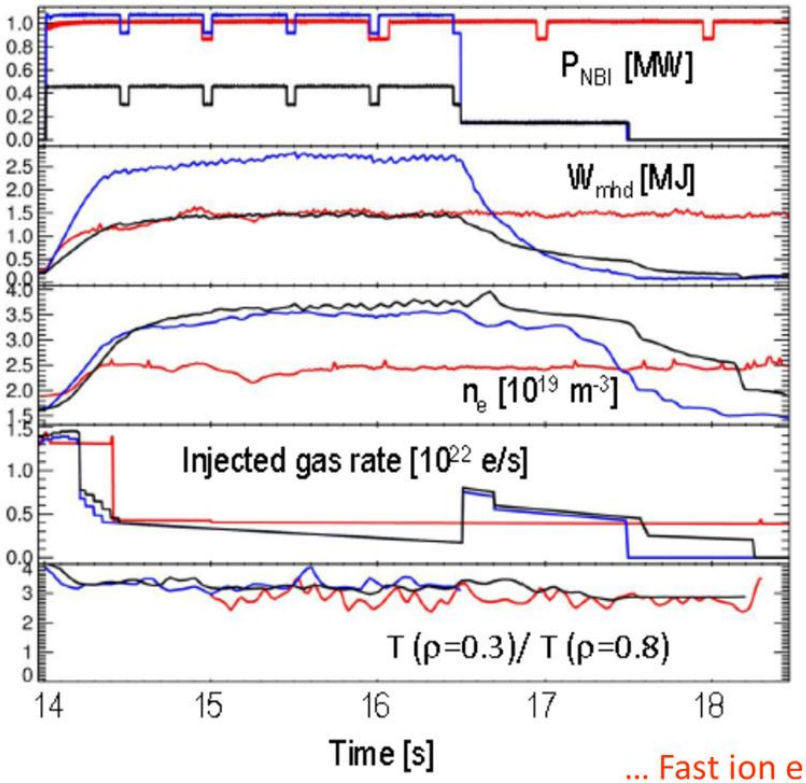




JET

2018-2019 JET experiments and tasks

- M18-19 - Isotope effects on confinement and transport
- M18-21 - Confinement and transport in mixed isotope plasmas
- M18-22 - Electron and ion threshold and stiffness in pure and mixed isotopes
- M18-23 - Rotation shear effect on ion transport with different isotopes
- M18-24 - Particle transport in pure and mixed isotopes
- M18-25 - Pellet injection for ELM pacing and isotope ratio control
- T18-03 - Transport modelling with isotopes (T17-04 & T17-10)

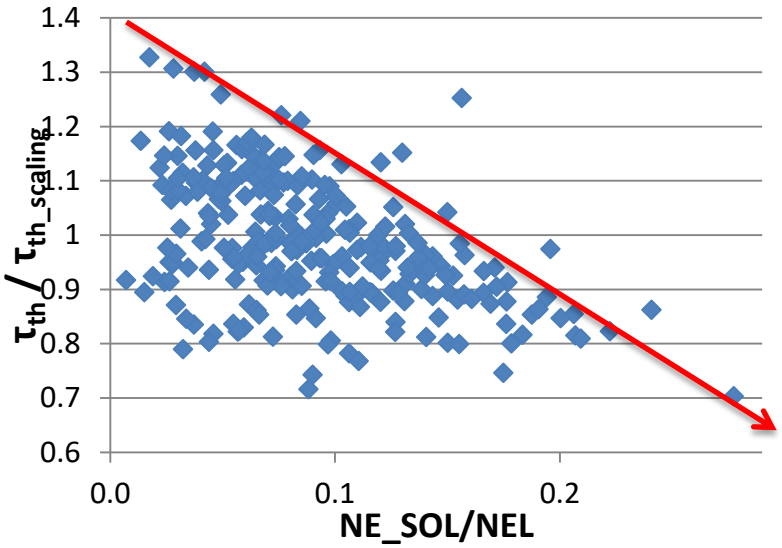


Not yet investigated: plasmas with Ti/Te ≠ 1, plasmas with high content of fast particles

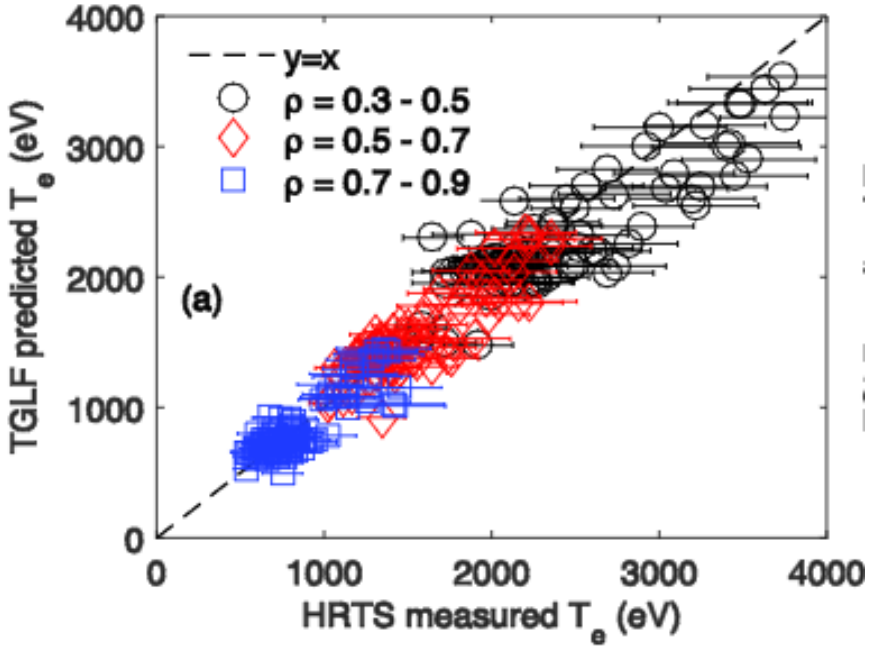
JET

TRANSP and databases

- Interpretative and predictive transport modelling using TRANSP: DT predictions (D. King et al), model validation (Hyun Tae Kim et al), impact of NTM (F. Poli et al), alpha heating (R. Budny *et al*)
- Use of BEAST in the JET control room in 2018
- Review of ITER scaling law (S. Kaye)



M. Maslov



Hyun-Tae Kim et al 2017 Nucl. Fusion 57 066032

JET

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- **Conclusion**

Conclusion

- The JET 2020 program* will address key physics issues of operating with different and mixed hydrogen isotopes
- The joint US/EU exploitation of the SPI on JET will provide crucial answers to ITER for disruption control (formal agreement between EU/ITER/DOE)
- The 2019 T campaign* will provide essential information for the predictions to D-T performance and for ITER

- D-T operation in 2020* will allow to demonstrate steady fusion power in the ILW environment
- Demonstration of W control and prevention of accumulation along with fuel mix control
- Alpha physics will be uniquely addressed and we will have the chance to demonstrate alpha heating before ITER operation

- PPPL collaborators are welcome to participate in existing official collaborations (upon submission of a workplan). Any new topics of collaborations need approval from EUROfusion** (contact the JET TFLs at JET1-TFL@euro-fusion.org).

*Pending agreement on resources beyond 2018. **No JET internationalization

JET