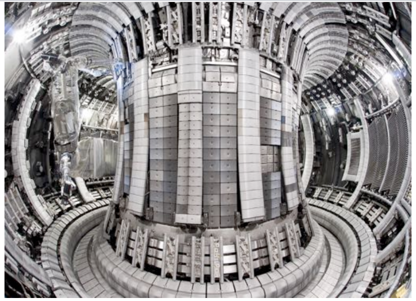
# Overview of the JET preparation for Deuterium-Tritium Operation with the ITER Like-Wall

E. Joffrin, on behalf of EUROfusion JET contributors

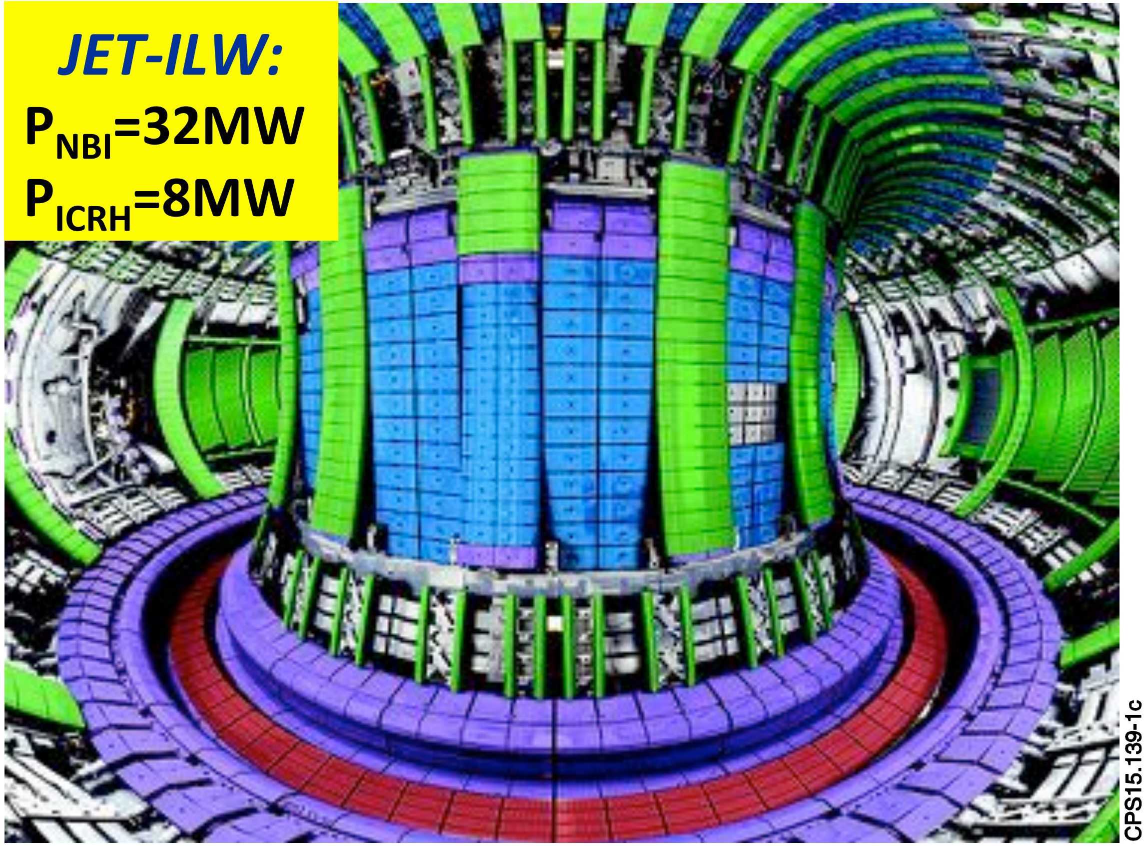
**Acknowledgments**: to the JET Task Force and Project Leaders, JET secondees, EUROfusion Programme Management Unit, JET Exploitation Unit and JET operator



This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

# JET is designed for fusion power studies in support of ITER

**1975 JET design proposal:** ***"…describes a large Tokamak experiment, which aims to study plasma behaviour in conditions and dimensions approaching those required in a fusion reactor".***



***JET-ILW:***

**$P_{NBI}$=32MW**

**$P_{ICRH}$=8MW**

CPS15.139-1c

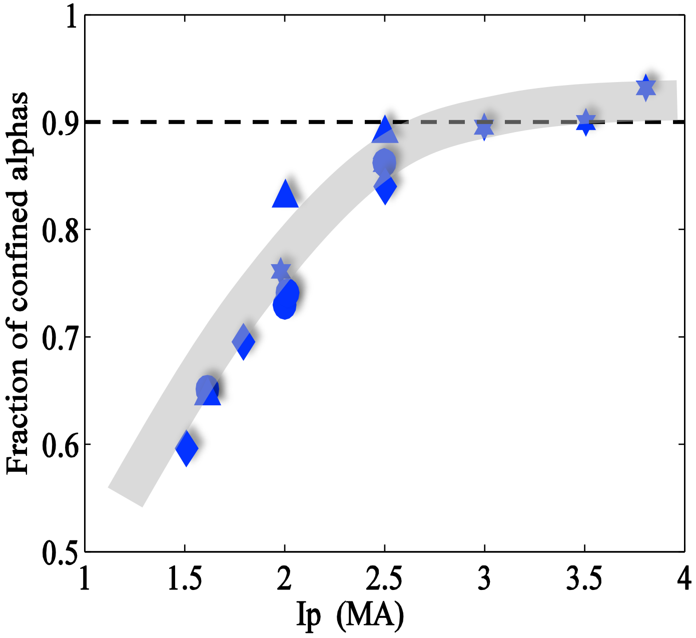
🟩 Bulk Be PFCs

🟦 Be−coated inconel PFCs

🟥 Bulk W

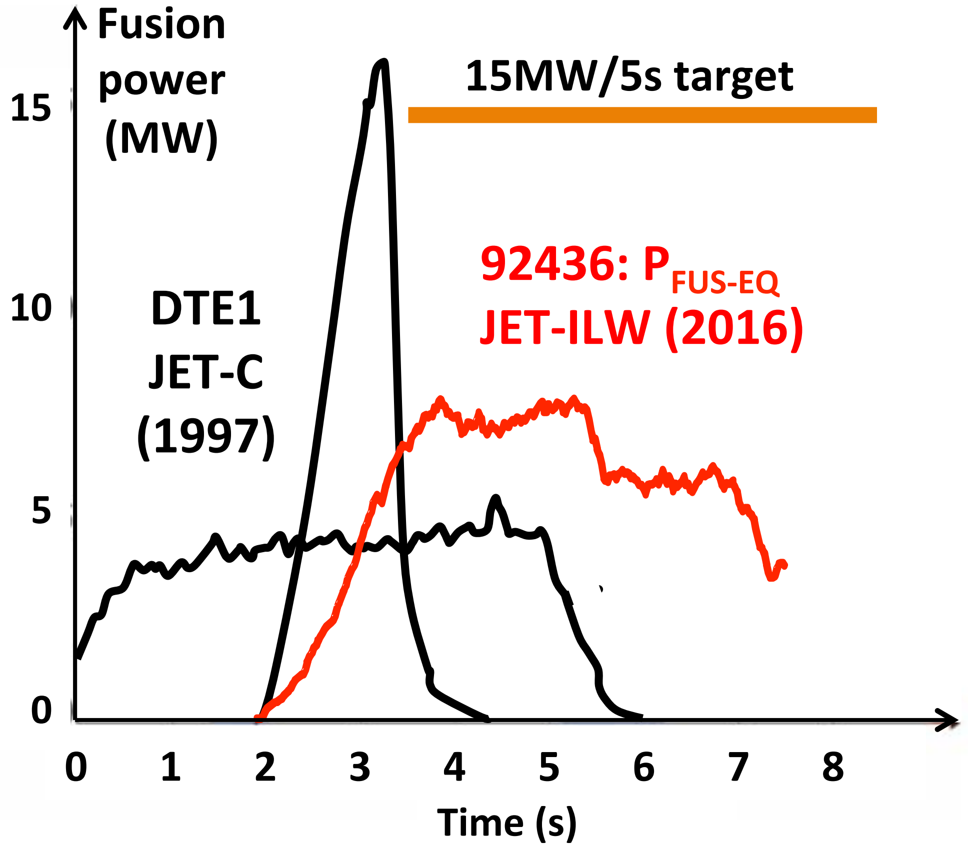
🟪 W−coated CFC PFCs

**JET is capable of confining 90% of alpha particle for Ip above 2.5MA**



# Objectives and outline

**EUROfusion research roadmap: Secure the success of future ITER operation via specific preparation and experiments, including D-T operation of JET.**



**Develop D-T scenario and fusion power prediction**

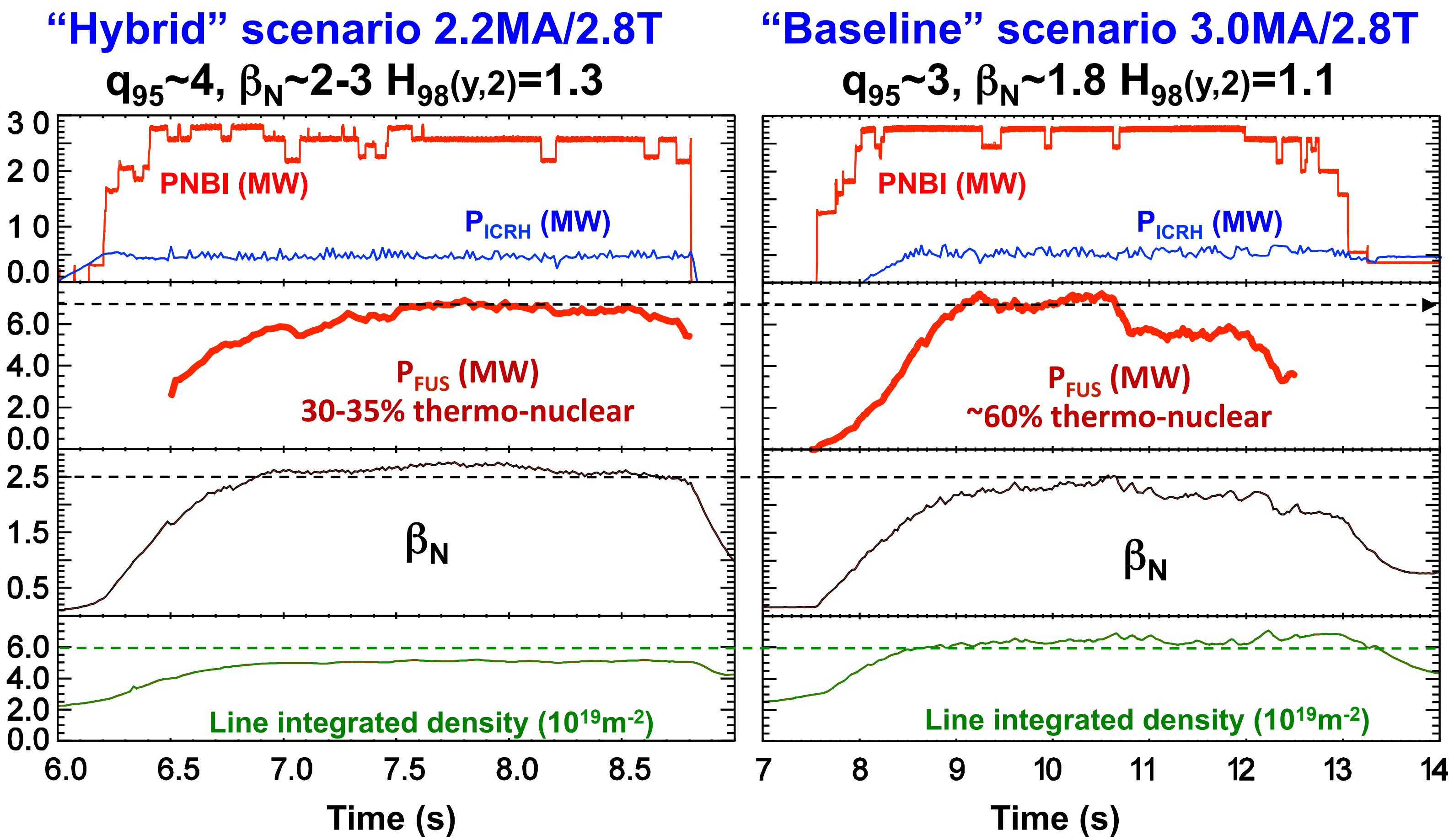
**Understand isotope physics**

**Prepare the operation in D-T**

*DTE1 in 1997-98: M. Keilhacker Nuc Fus 39 (1999) 209 & J. Jacquinot Nuc Fus 39 (1999) 235*

EUROfusion MST1 task Force: H. Meyer, OV2-1

# Stationary Scenarios for the DT phase achieved ~7-8MW of equivalent $P_{FUS}$



“Hybrid” scenario 2.2MA/2.8T

$q_{95}$~4, $\beta_N$~2-3 $H_{98}(y,2)$=1.3

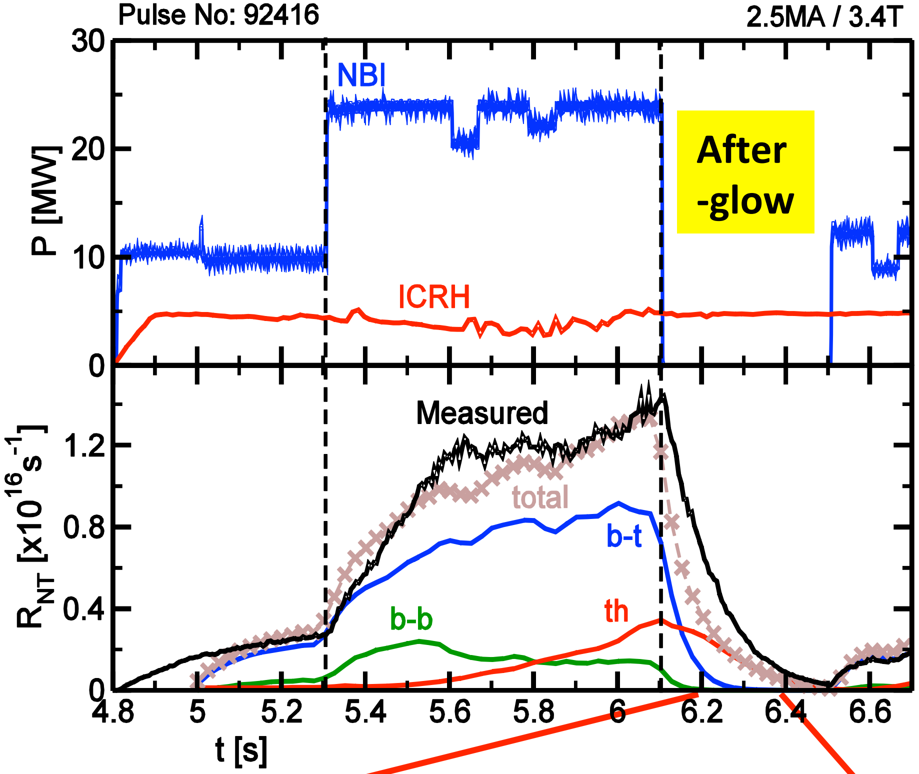
“Baseline” scenario 3.0MA/2.8T

$q_{95}$~3, $\beta_N$~1.8 $H_{98}(y,2)$=1.1

**Fusion equivalent power for a 50/50 D/T mix:**
**7-8MW of fusion power for both scenarios**

*L. Garzotti, EX/3-6*
*E. De la Luna, EX/2-1*

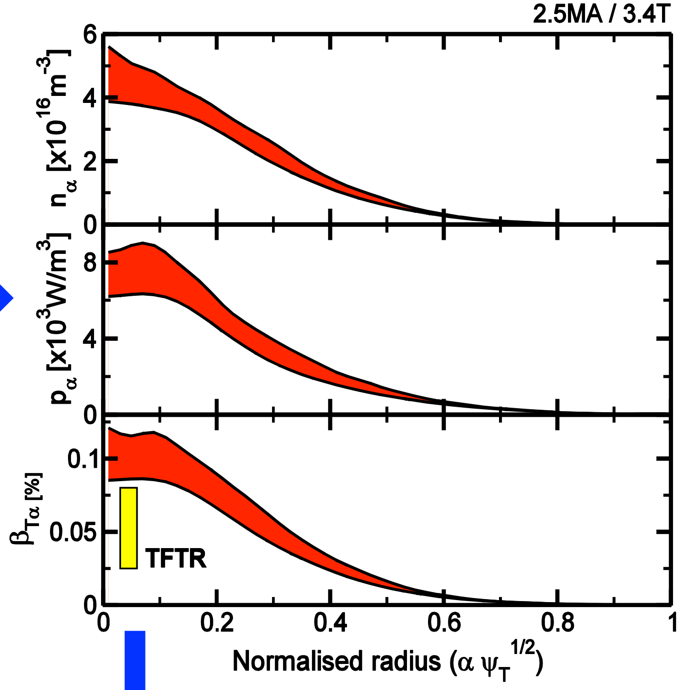
# "After-glow" ITB scenario shows promising route for alpha-driven mode studies

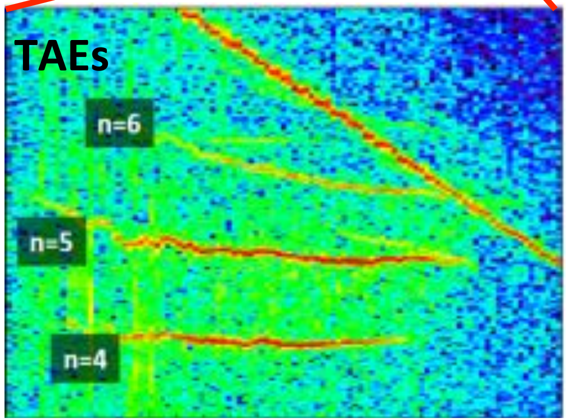


**50/50 D-T**

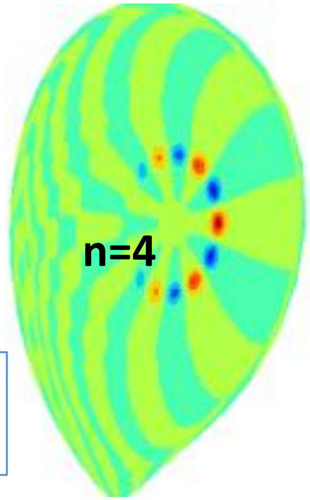
**Prediction**

**(TRANSP)**



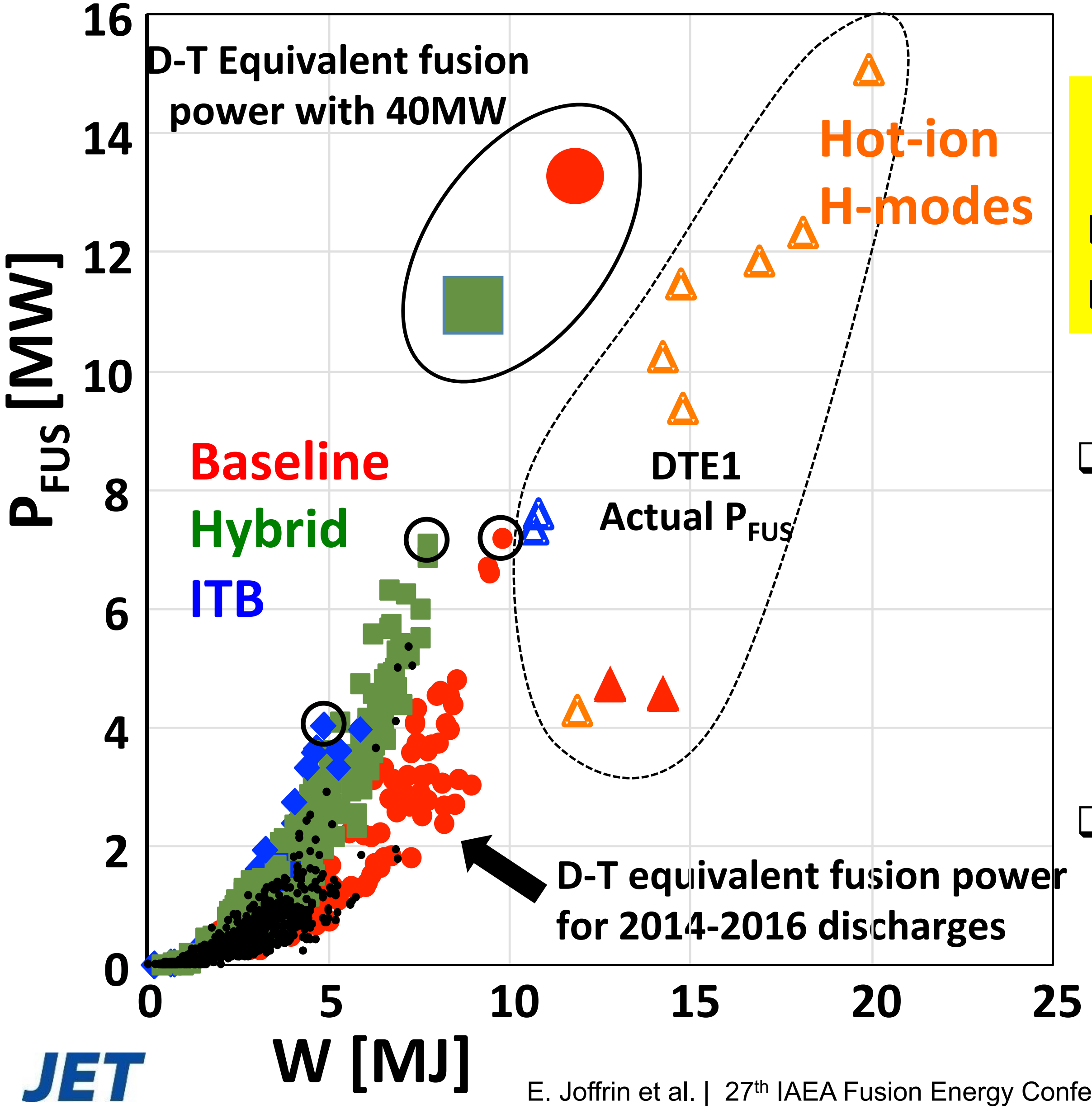


**Stability calculation (MISHKA)**



*R. Dumont, Nuc. Fus. 2018*
*S. Sharapov, EX/P1-28*

# Prospects for 10 to 15MW of fusion power in stationary scenarios in JET-ILW



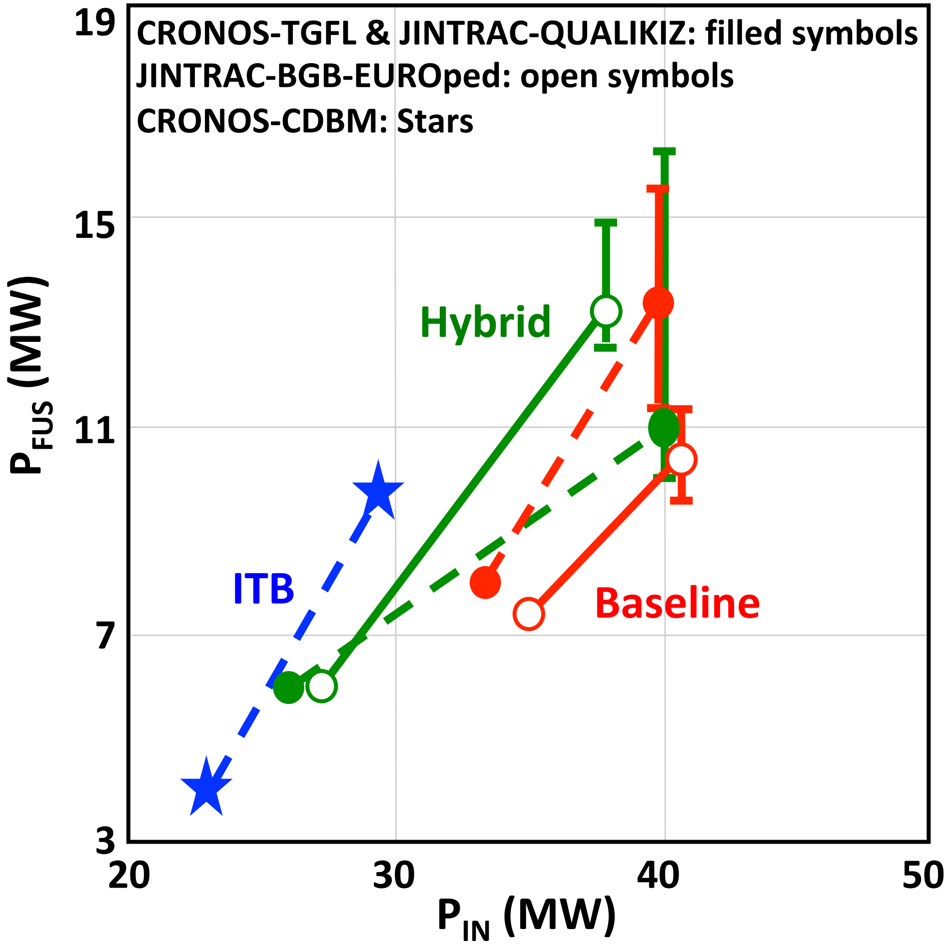
**D-T equivalent fusion power**

**50/50 D/T mix for identical plasma parameters**

- ☐ No credit for isotope effects
- ☐ No credit for α-power

- ☐ Equivalent fusion power reaching similar level than in the 1998 D-T campaign (DTE1) with two stationary scenarios: baseline and hybrid.
- ☐ Transient ITB scenario for α-particle driven mode studies

# 10-16MW of fusion power also predicted in D-T by first principle based modelling



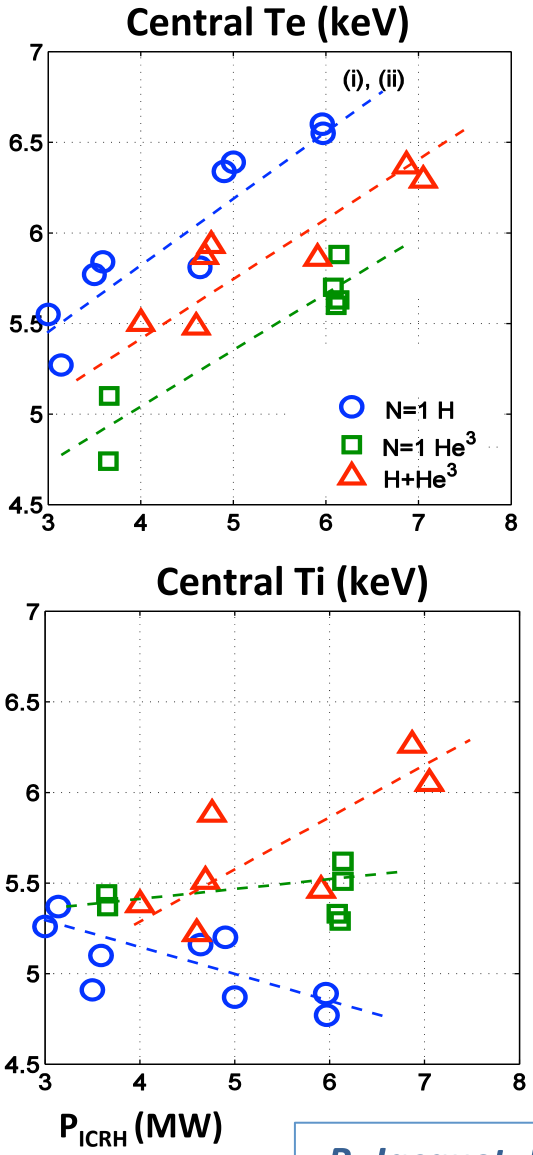
*J. Garcia, TH/3-1*
*F. Casson, TH/3-2*
*S. Saarelma, PPCF 2017*

**Taking into account additional effect:**

- ☐ **Isotope effect from ExB shear stabilisation or energy exchange.**
- ☐ **Alpha power contribution**
- ☐ **Auto-consistent modelling with core (BGB)-pedestal (EUROped) with no isotope effects.**

**Uncertainty in $P_{FUS}$ accounts for different plasma current and bootstrap models**

# ICRH power can efficiently control W accumulation in D-T scenario



## ICRH schemes developed for D-T

- ☐ n=1 H minority
  ➔ electron heating

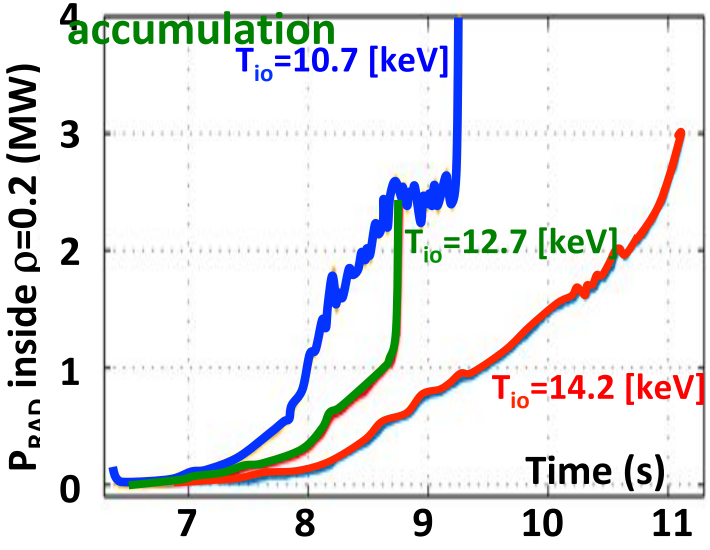
**Demonstrated experimentally**

*E. Lerche, Nucl. Fus. 2016*
*M. Goniche, PPCF 2017*

- ☐ n=1 He3 minority
  ➔ ion heating

- ☐ Combination of both

**Ion heating predicted to provide resilience to high-Z accumulation**



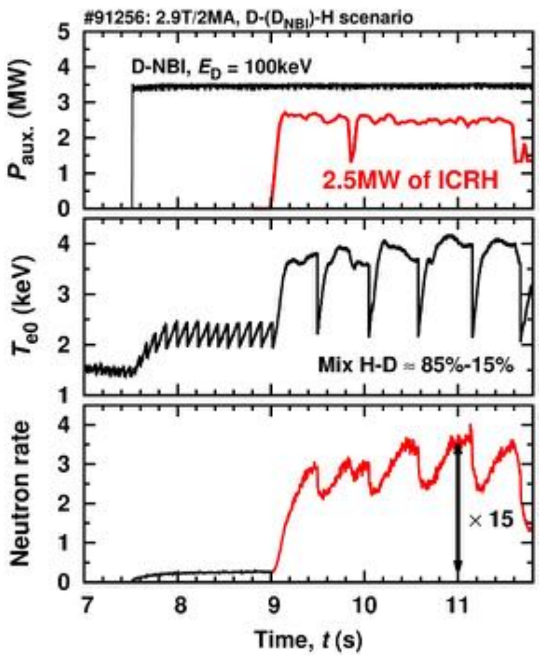
**First principle prediction of D-T scenario with 40MW & Ti>Te**

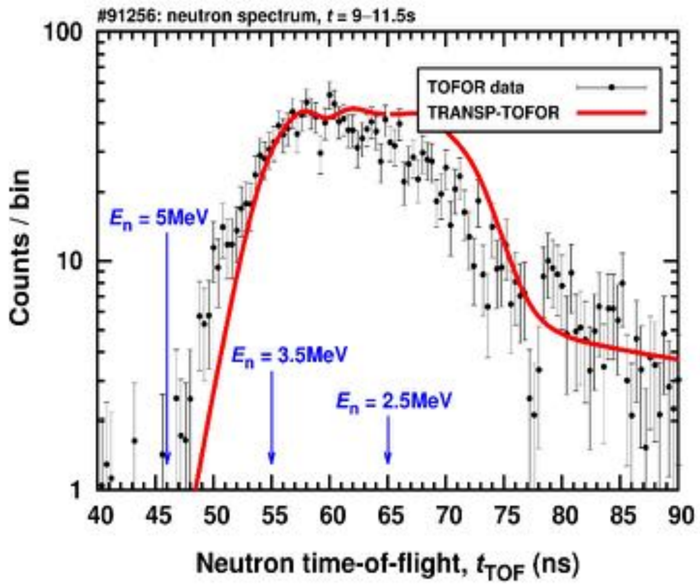
*F. Casson, TH/3-2*

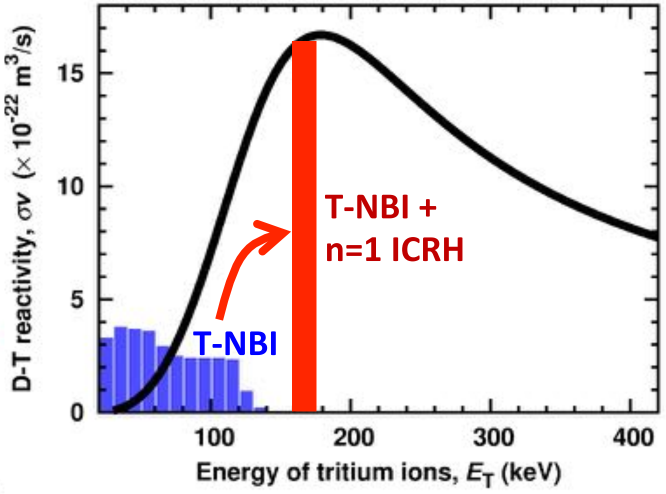
*P. Jacquet, Nucl. Fus. 2016*
*D. van Eester, IAEA 2016*

# 3 ion schemes H-($D_{NBI}$)-D: a new development in support of D-T

**Efficient acceleration of NBI ions to higher energies with $n$ = 1 ICRH in mixed plasmas**







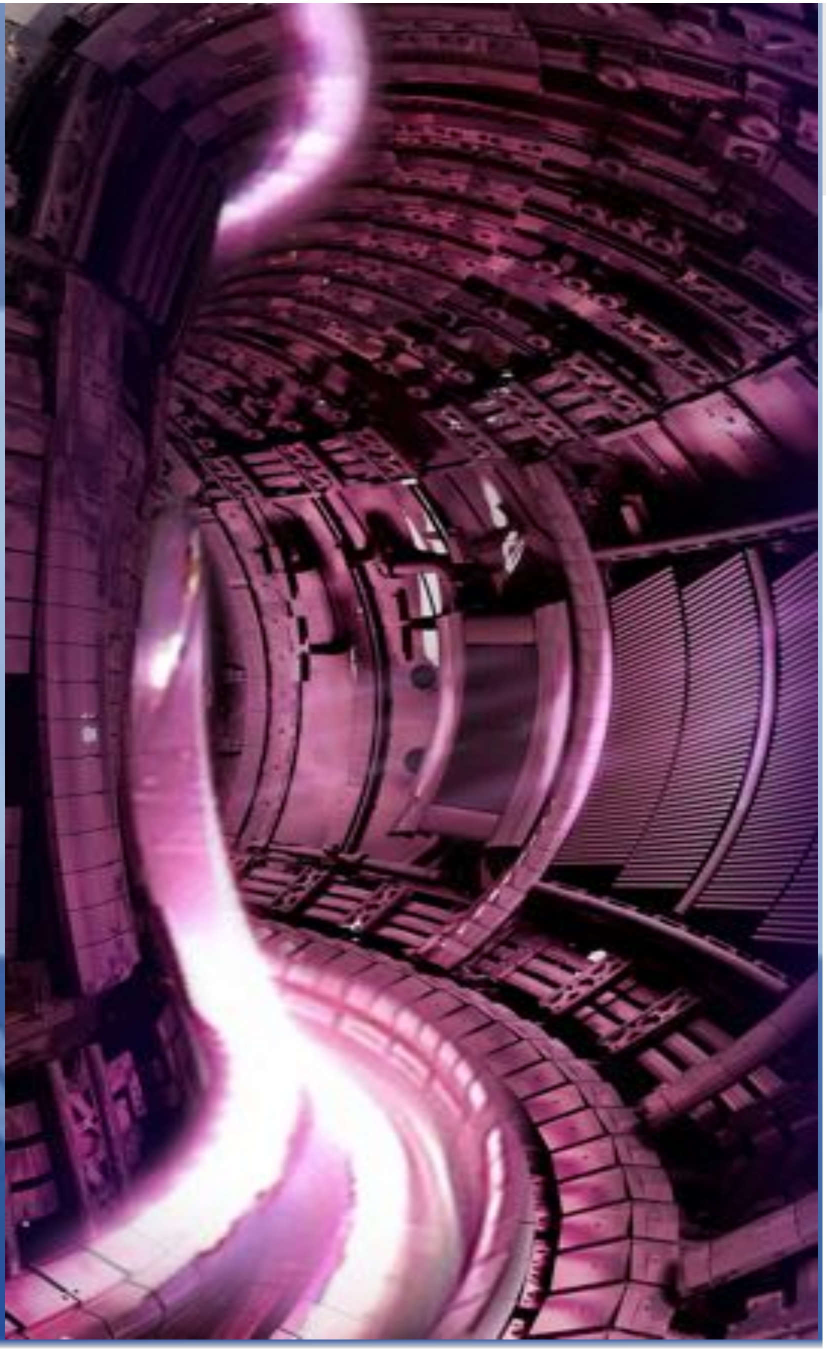
- ☐ **H-D plasmas**: increase in neutron rate due to accelerating D-NBI ions to $E_D \approx$ 1-2MeV,
- ☐ Confirmed with TOFOR, $\gamma$-ray measurements and ICRH modeling

**D-T plasmas:** optimize $Q$ and fusion power using NBI+ICRH synergies:

$E_{T\text{-}NBI}$ = 118keV, → $\langle E_T \rangle \approx$ 200keV (off-axis $n$ = 1 ICRH)

*Y. Kazakov, EX/8-1 & Nat. Phys. 2017*
*J. Ongena, RF Conf. 2017*

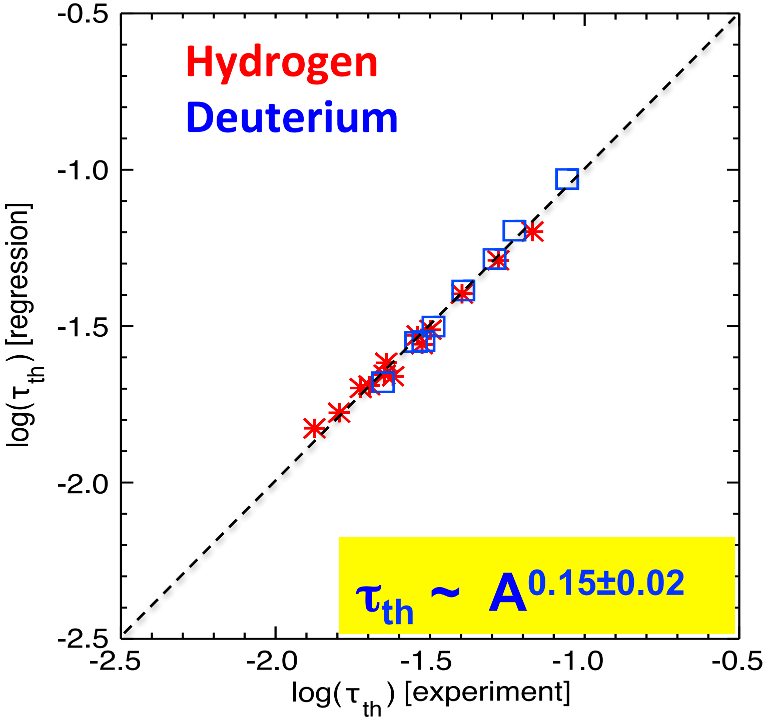
# Understand isotope physics



# L-mode: weak positive isotope dependence on confinement & transport

**L-mode confinement scaling with mass**

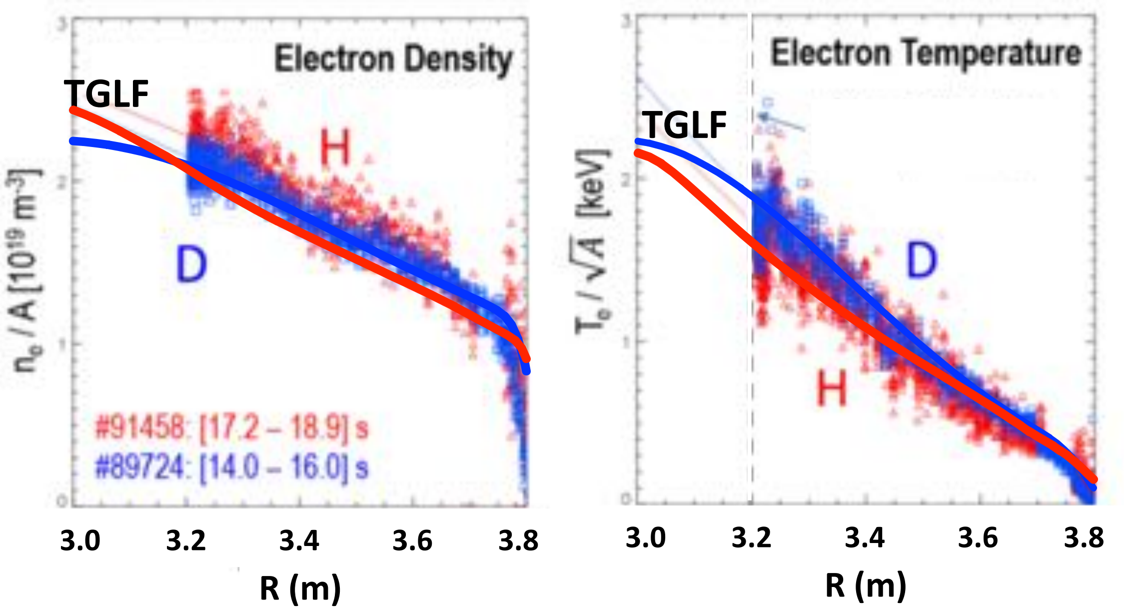
**($P_{IN}$ scan at $n_e$=cst, Ti~Te; BT=2.9 T, Ip=2.5 MA)**



- ☐ **Small positive isotope dependence of $\tau_{th}$**
- ☐ **Consistent with the H97L scaling $\tau \sim A^{0.2}$**

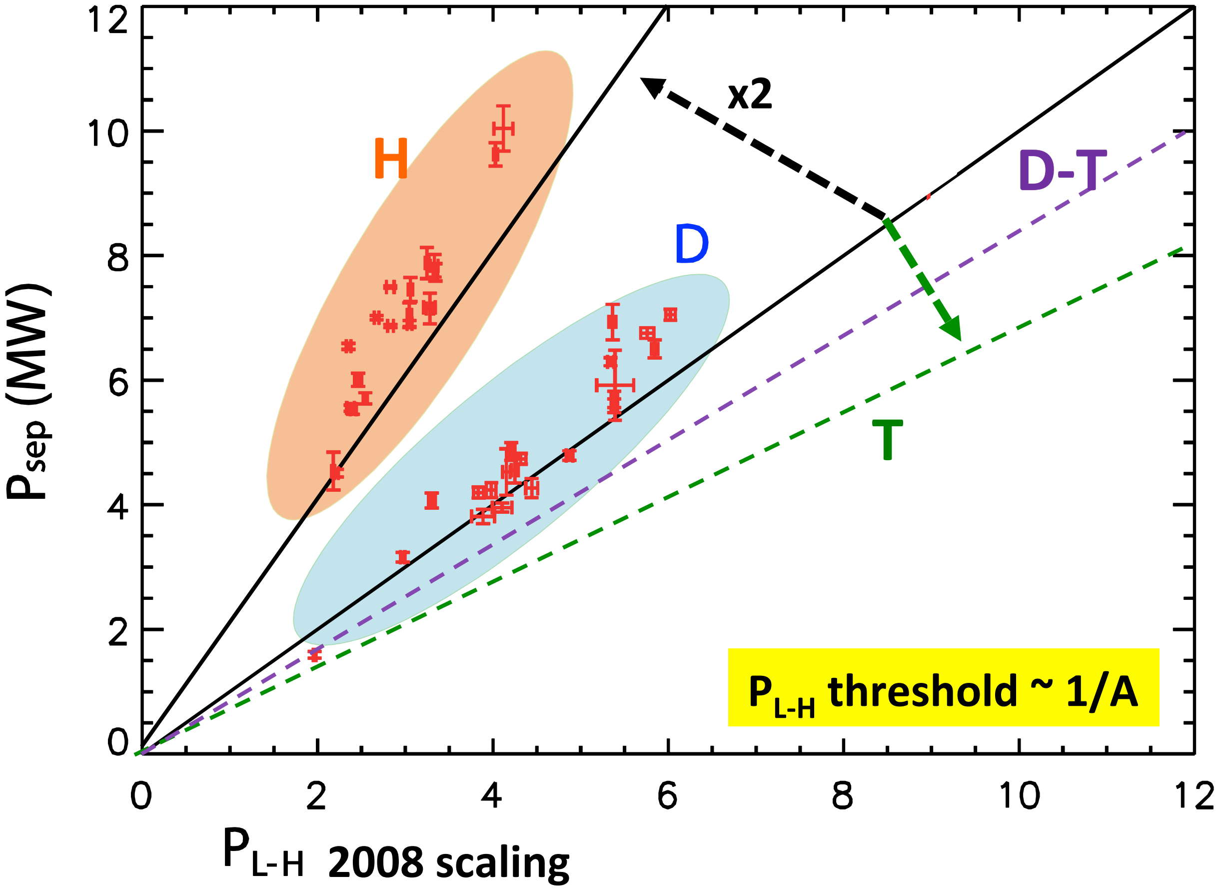
***H. Weisen, EX/P1-4***
***P. Strand, TH/P6-14***
***C. Maggi, PPCF 2018***

**Match of $\rho^*$, $\beta$, $\nu^*$ H/D pair satisfies scale invariance (same $\omega_{ci}\tau_{Eth}$ )**



- ☐ **No additional isotope dependence needed**
- ☐ **Agreement achieved with modelling for the identity pair**
- ☐ **Difference with 0D scaling being examined**

# L-H power threshold likely to be lower in Tritium for D-T scenario



$P_{L\text{-}H}$ threshold ~ 1/A

Prediction with non-linear fluid turbulence code (HESEL) reproduces strong dependence: ~ $1/A^{1.4}$

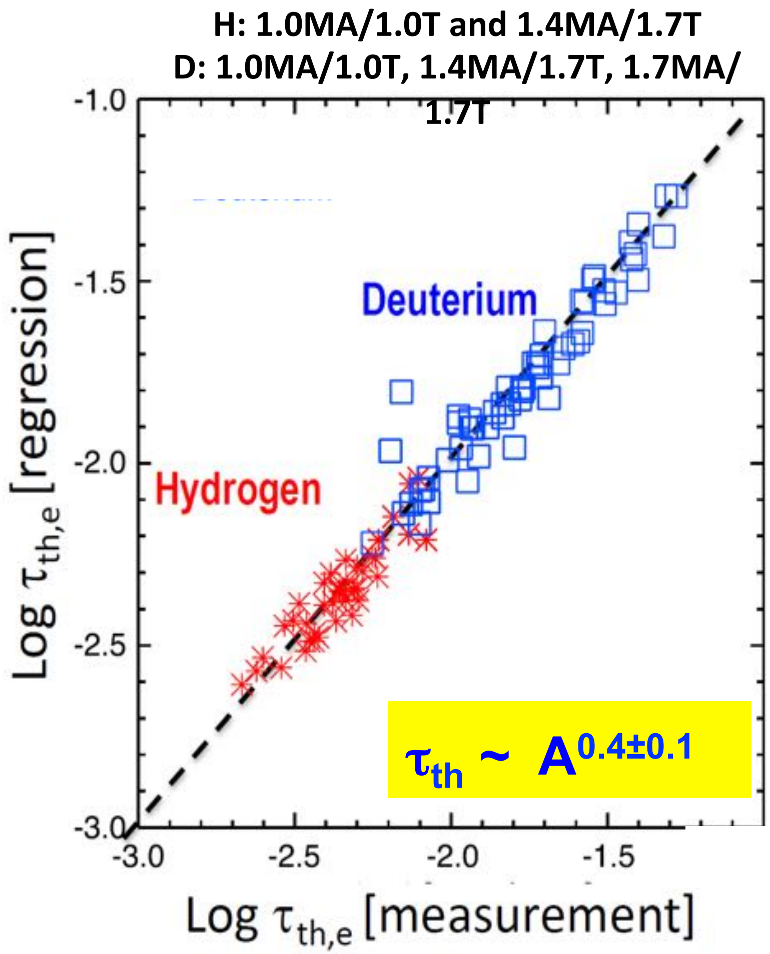
*J. Hillesheim, EX/4-1*

- ☐ $P_{L\text{-}H}$ threshold likely to be reduced by 2/3 in tritium and 1/3 in D-T.
- ☐ Consistent with past DTE1 results (Righi et al. 1999).

*C. Maggi, PPCF 2017*

# Type I ELMy H-mode: strong positive isotope dependence on thermal confinement

**H-mode confinement scaling with mass**



$\tau_{th} \sim A^{0.4\pm0.1}$

- ❑ Stronger isotope dependence than in JET-C and IPB98(y,2) (~$A^{0.2}$)
- ❑ Global momentum ~ $A^{0.5\pm0.15}$
- ❑ Global particle ~ $A^{0.5\pm0.06}$

All scalings robust against the set of variables chosen for the regression.

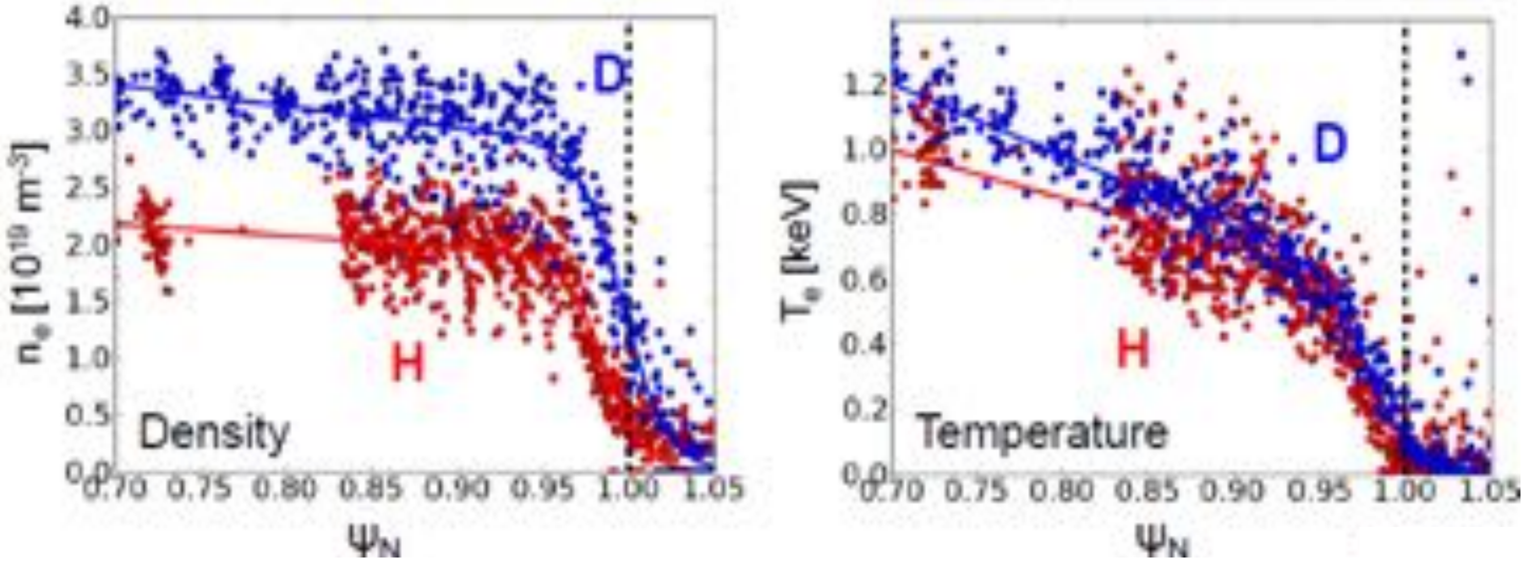
Note: Density systematically lower in H at same external fuelling

*H. Weisen, EX/P1-4*
*C. Maggi, PPCF 2018*

**The pedestal is an important player in the observed isotope dependence**

# Larger pedestal pressure in D than H at same power and gas fuelling rate

**$I_P$=1.4MA; $B_T$=1.7T; $P_{IN}$=10MW ELMs; same fuelling rate: 19Hz in D and 31Hz in H**

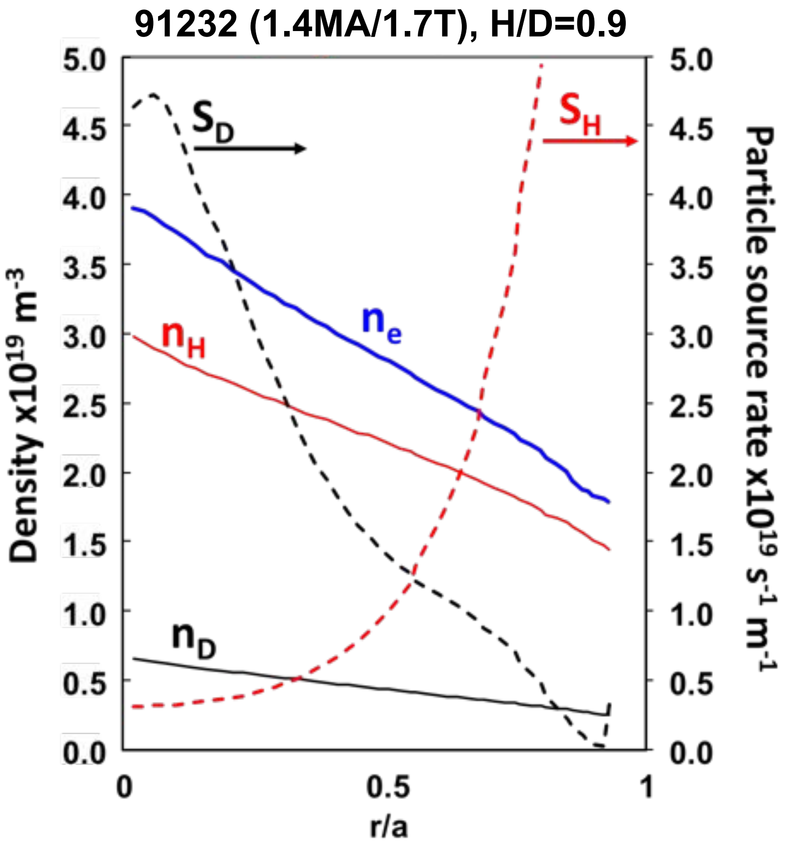


**Lower density observed in H for equivalent external gas injection rate**

- ❑ **Isotope effect peeling-ballooning is weak for same separatrix Te.**
- ❑ **Different separatrix temperature in H and D could change pedestal stability.**
- ❑ **Inter-ELM particle loss different in H and D.**

*L. Horwarth, Nuc. Fusion in preparation*

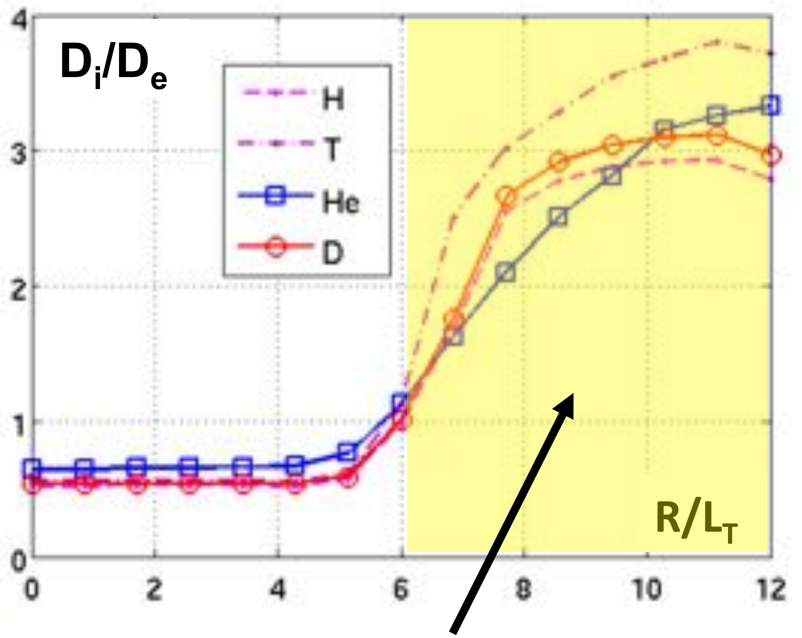
# Isotope mixing: key particle transport effect for D-T scenario



$n_D$ and $n_H$ $R/L_n$ similar and independent of the source.

**Multiple ion plasma: more freedom on ambipolarity constraint.**

➔ ion flux not tied to electron flux



**In typical JET scenario:**

➔ $D_i/D_e>1$ and $V_i/V_e>1$

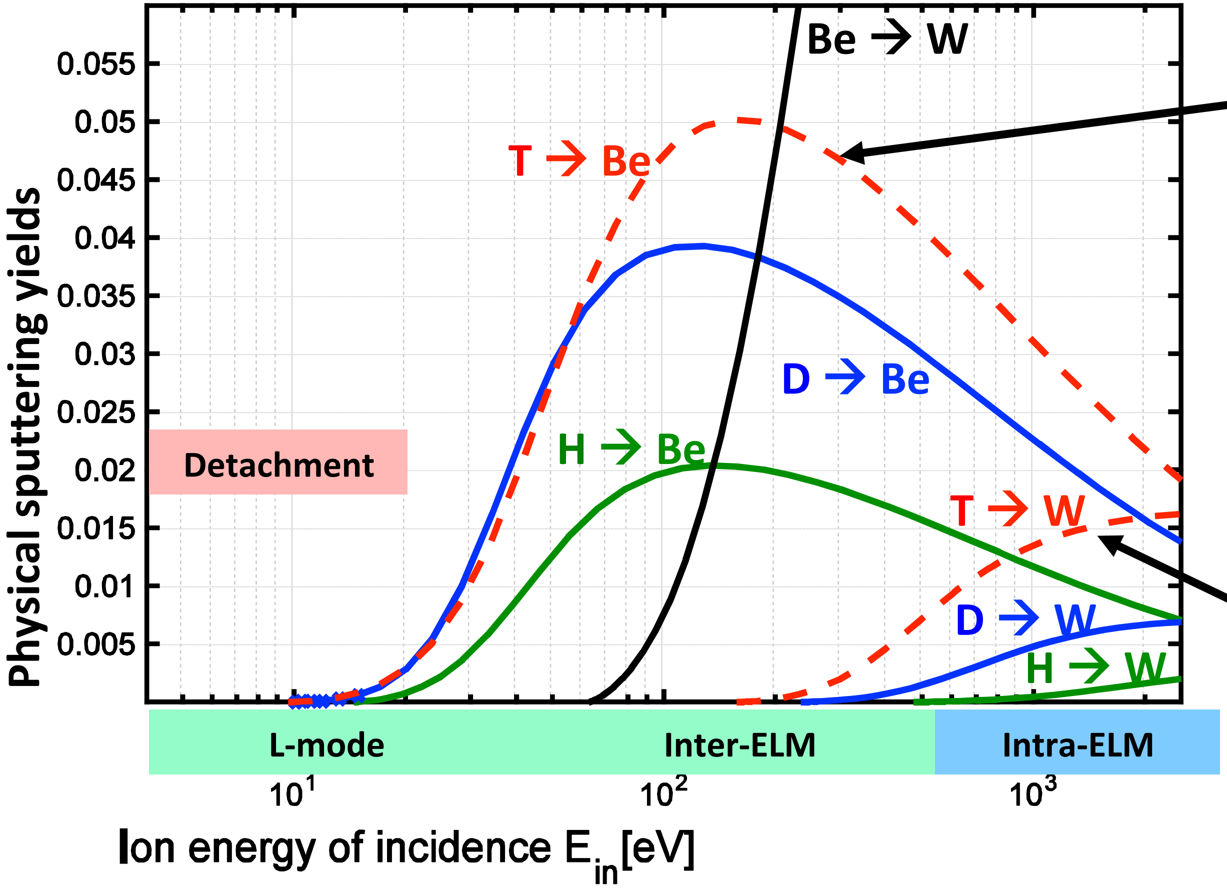
**Important for isotope fuelling & control in JET and ITER.**

*C. Bourdelle Nuc Fus 2018*
*M. Maslov Nuc Fusion 2018*
*C. Angioni, Phys. Plasmas 2018*

JET

# Be and W physical sputtering will increase with Tritium

From binary collision approximation (SDTtrimSP code)



**Increase of Be sputtering by tritium in inter-ELM phase**

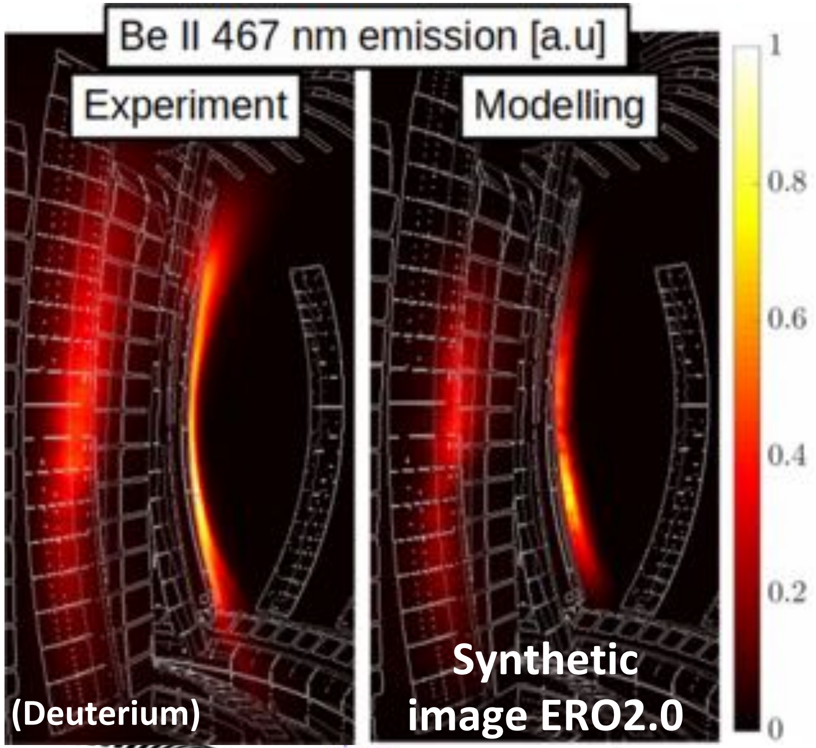
**Increase of W sputtering yields and threshold energy by tritium in intra-ELM phase.**

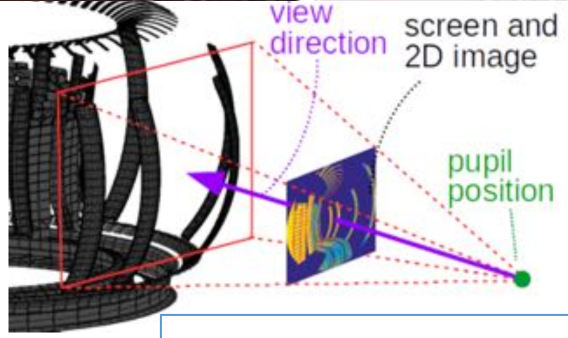
*D. Borodin, EX/P1-14*
*S. Brezinsek, EX/9-4*

**The increase of Be physical sputtering by tritium can lead to an increase of W sputtering by Be**

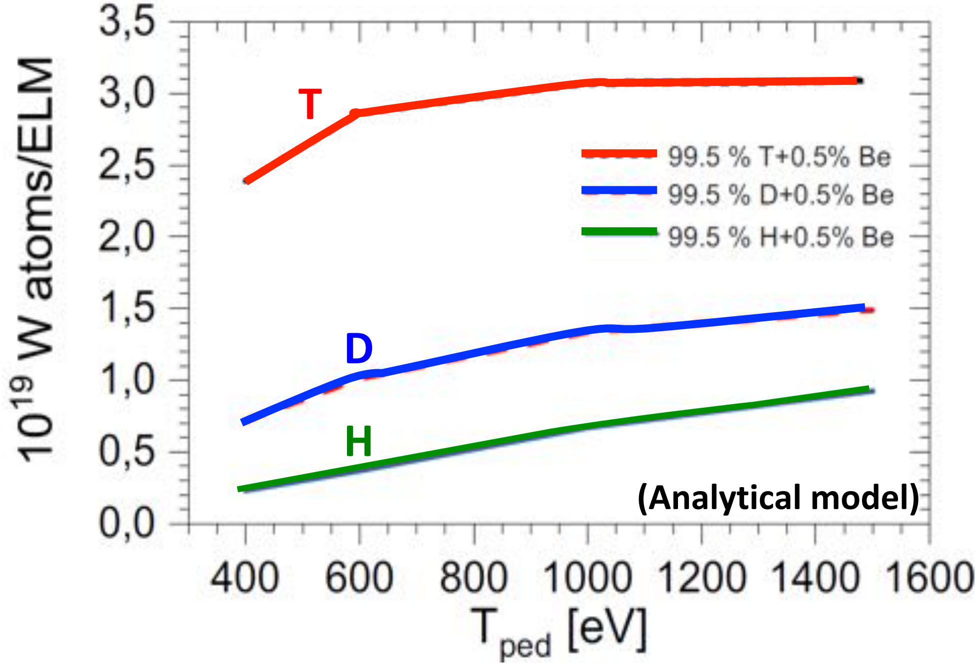
# Intra-ELM sputtering will dominate W sputtering in tritium

**Be erosion** → **Tungsten erosion with isotope**





*J. Romazanov, PSI 2018*



**Intra-ELM: ~70% of the gross-erosion**

*Borodkina, Nuc. Mater. Energy 2017*

**From post-mortem analysis in D:**

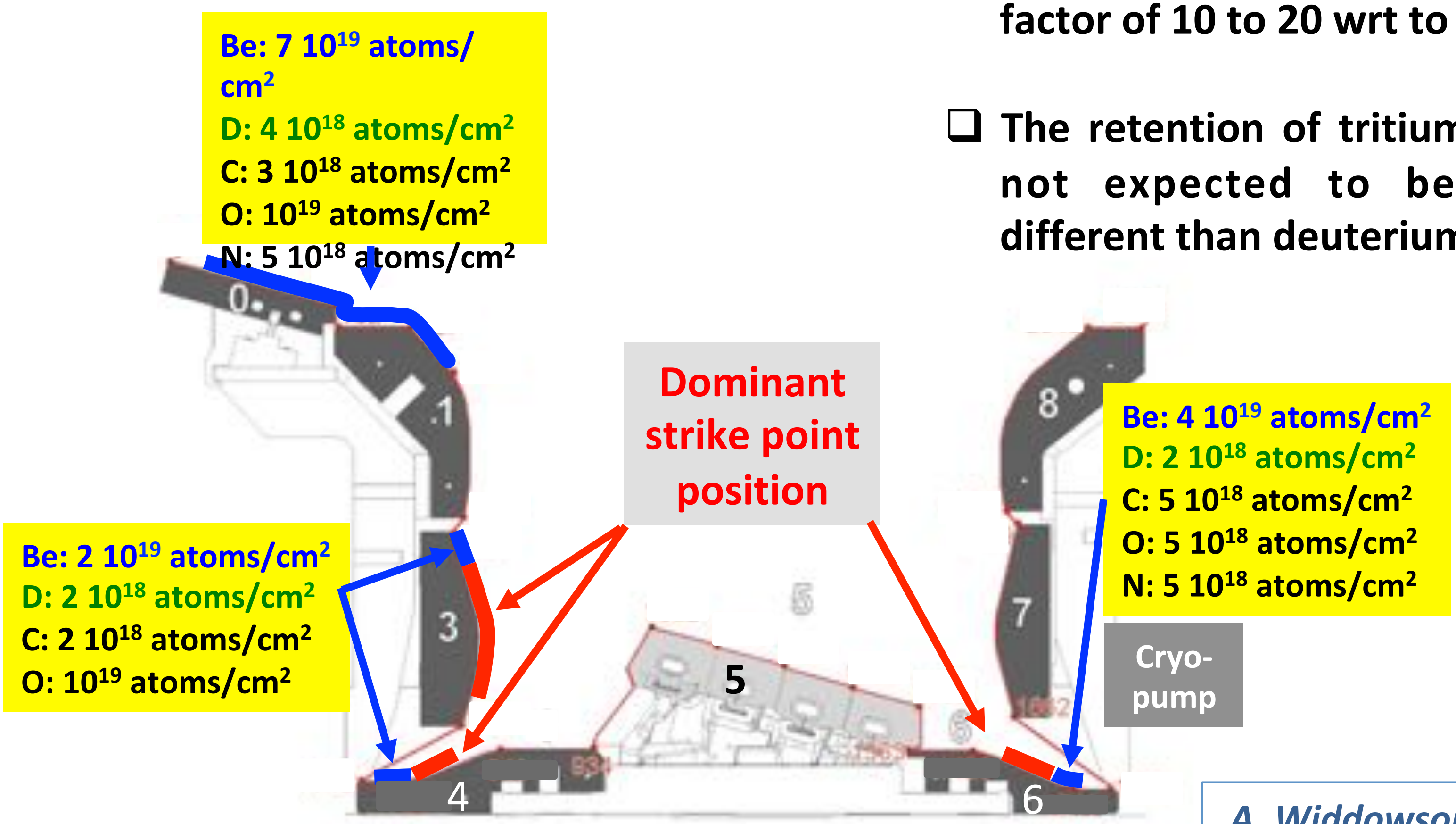
- **W gross erosion: 40-60 g**
- **W net erosion: 2.4-4.8 g**
- **90% of prompt redeposition**

*A. Kirschner PPCF 2018*

# Decrease of material deposition rate by x4-9 compared to JET-C

## Since 2011, operation with JET-ILW: 60h of plasma and 600MJ of input energy

- ☐ **Deuterium retention decreased by a factor of 10 to 20 wrt to JET-C.**
- ☐ **The retention of tritium in deposits is not expected to be significantly different than deuterium.**



**Be: 7 $10^{19}$ atoms/cm$^2$**
**D: 4 $10^{18}$ atoms/cm$^2$**
**C: 3 $10^{18}$ atoms/cm$^2$**
**O: $10^{19}$ atoms/cm$^2$**
**N: 5 $10^{18}$ atoms/cm$^2$**

**Be: 2 $10^{19}$ atoms/cm$^2$**
**D: 2 $10^{18}$ atoms/cm$^2$**
**C: 2 $10^{18}$ atoms/cm$^2$**
**O: $10^{19}$ atoms/cm$^2$**

**Dominant strike point position**

**Be: 4 $10^{19}$ atoms/cm$^2$**
**D: 2 $10^{18}$ atoms/cm$^2$**
**C: 5 $10^{18}$ atoms/cm$^2$**
**O: 5 $10^{18}$ atoms/cm$^2$**
**N: 5 $10^{18}$ atoms/cm$^2$**

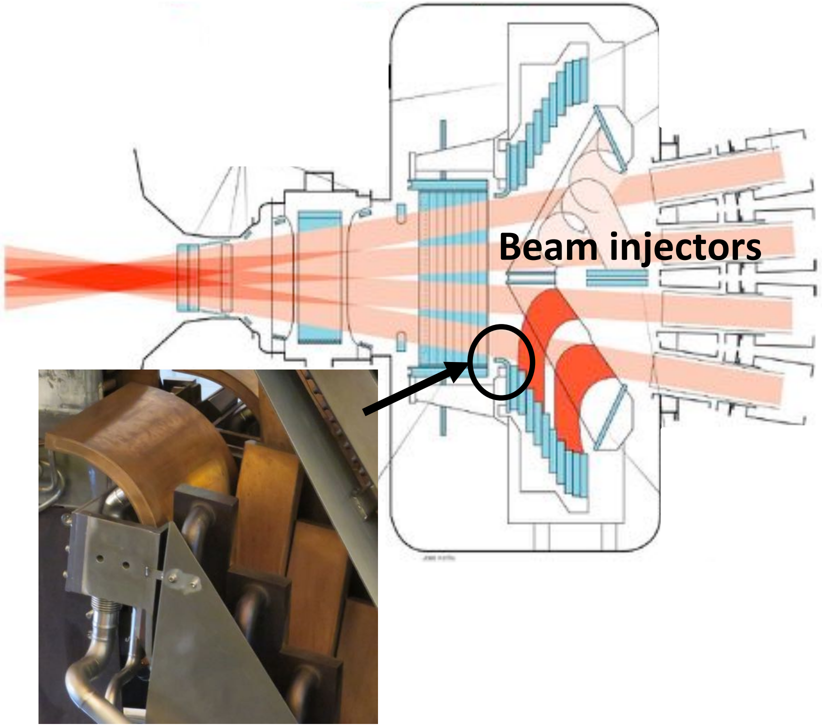
*A. Widdowson, Phys. Script. 2018*
*M. Mayer, EX/P1/15*

EUROfusion

# Prepare the operation in D-T

# Upgrades for D-T: NBI and T injection

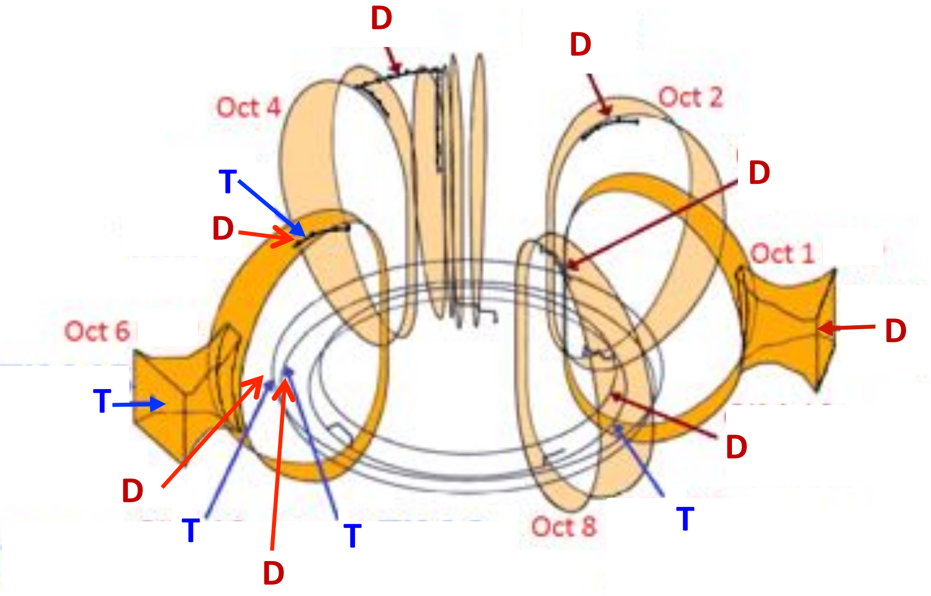
**Maximum NBI power so far limited by one of ion dumps component cooling capabilities.**



**New plates with optimised cooling removing the limits to beam voltage and pulse length**
**➔ 34MW in D-T (21MW in DTE1)**

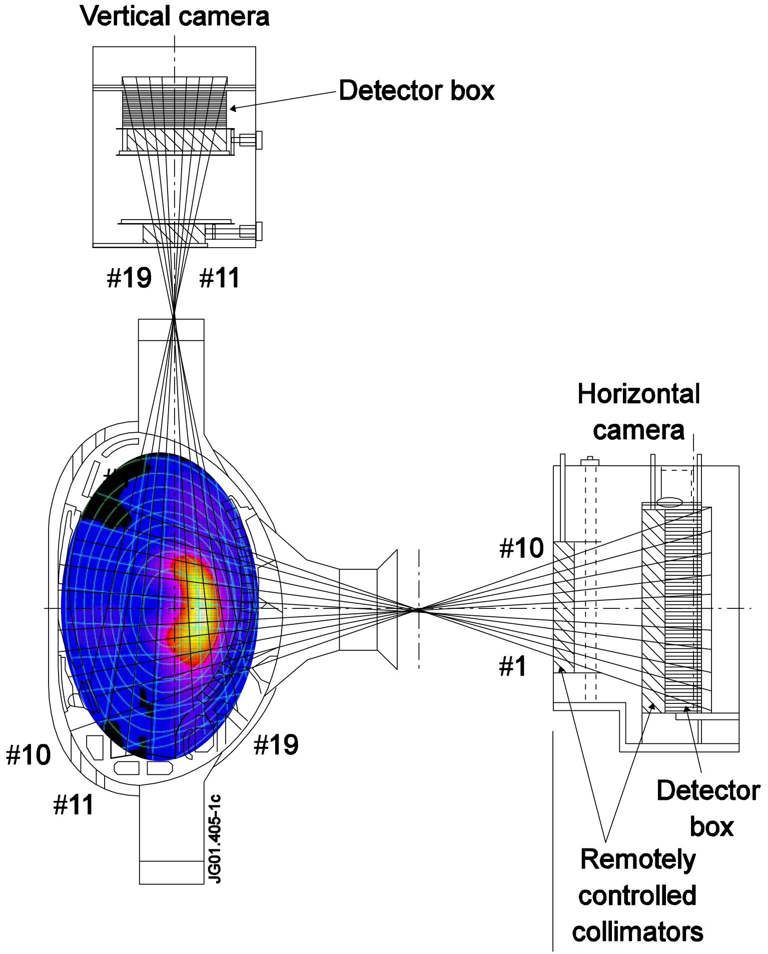
*A. Shepherd, 29th SOFT 2016*

**5 new tritium gas injection modules,**
**(Only one existing in DTE1)**



*I. Carvalho, 29th SOFT 2016*

# Unique set of new diagnostics in place for alpha physics and burning plasma studies in DTE2



**Visualization of fast particle orbits with γ-ray tomography**

*J. Figueiredo, EX/P7-42*
*S. Sharapov, EX/P1-28*

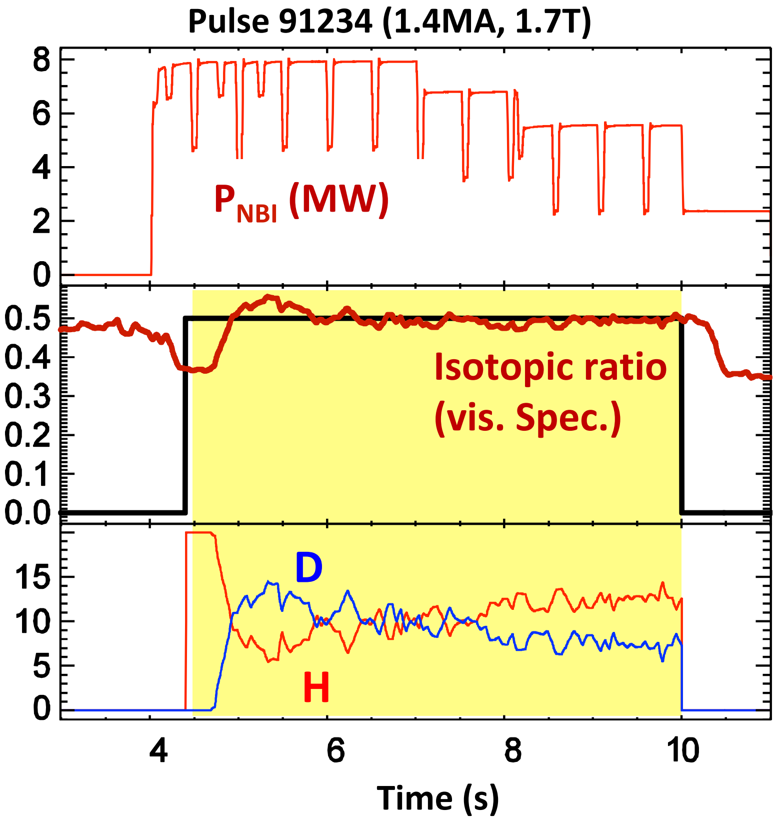
**Several burning plasma diagnostics ready for the D-T phase.**

| |
|---|
| Charge Exchange ($T_i$) |
| TAE antenna |
| Neutron Camera |
| Vertical Neutron Spectrometer |
| γ-Ray Camera |
| Horizontal γ-Ray Spectrometer for alpha-Particle Diagnostic |
| Upgrade of the scintillator based Fast-Ion Loss Detector (FILD) |

**Most diagnostics included synthetically in modelling suites for code validation**

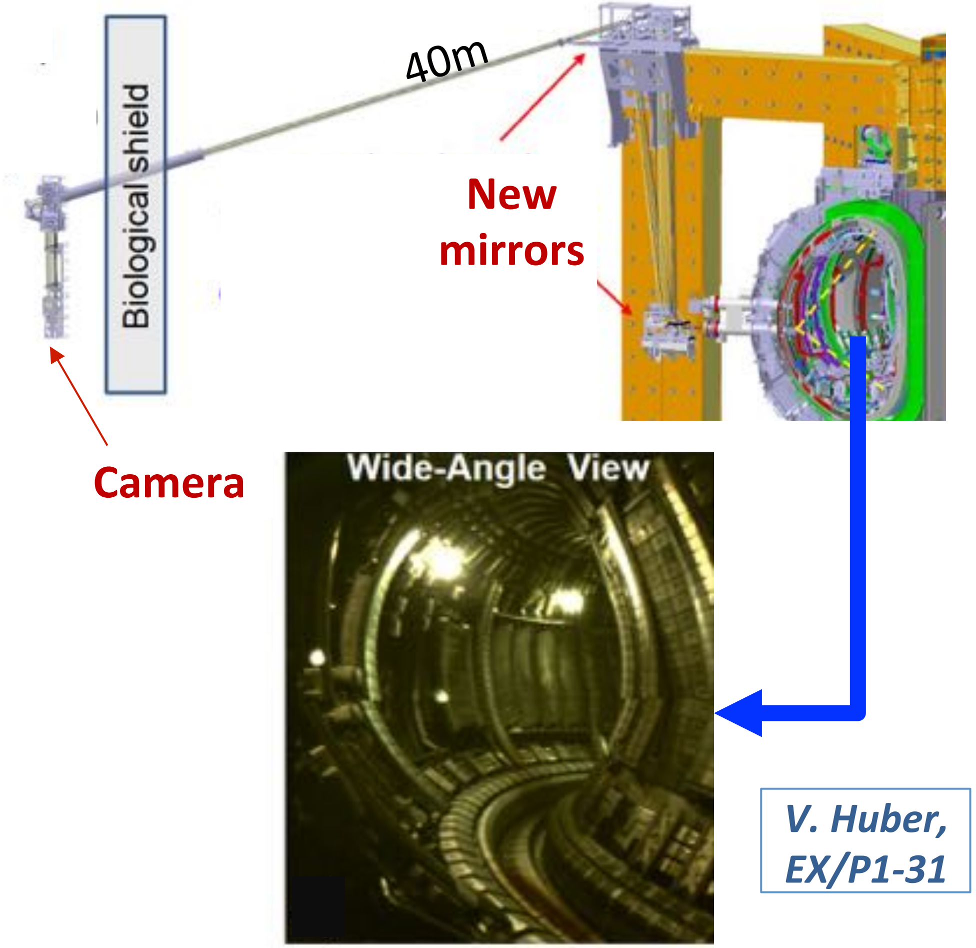
# New tools developed for burning plasma

## Isotope ratio controlled at 50% in H-mode



*M. Lennholm & D. Valcarcel, FED 2017*

## Infra-red protection camera moved outside the biological shield

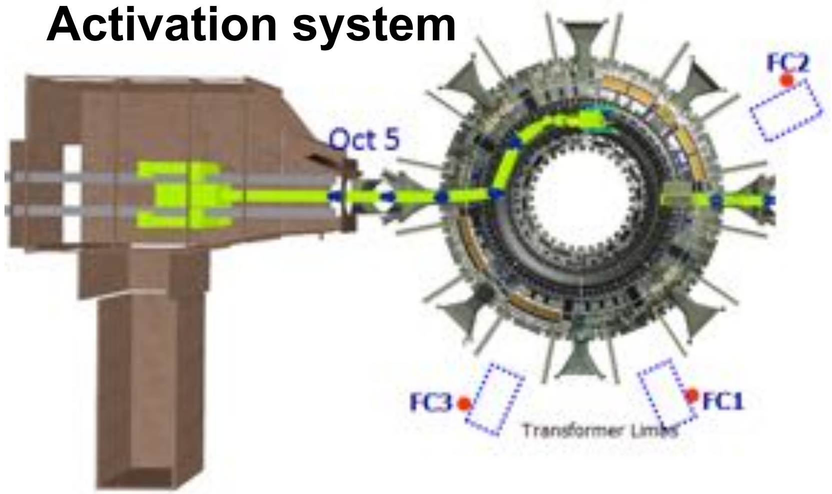


*V. Huber, EX/P1-31*

**Both techniques will be essential for ITER D-T operations**

# 14MeV neutron detector for the D-T phase calibrated with an accuracy of ±6%.

**3 Fission ($^{235}$U) chambers and 1 Activation system**



- ☐ **14MeV neutron generator deployed inside JET vessel by remote handling**
  - ▪ **76h of irradiation in 73 different poloidal and toroidal positions**
  - ▪ **Calibration within ±6%**
- ☐ **Neutronic modelling carried out and codes validated for ITER.**

**➔ Procedure transferable to ITER.**

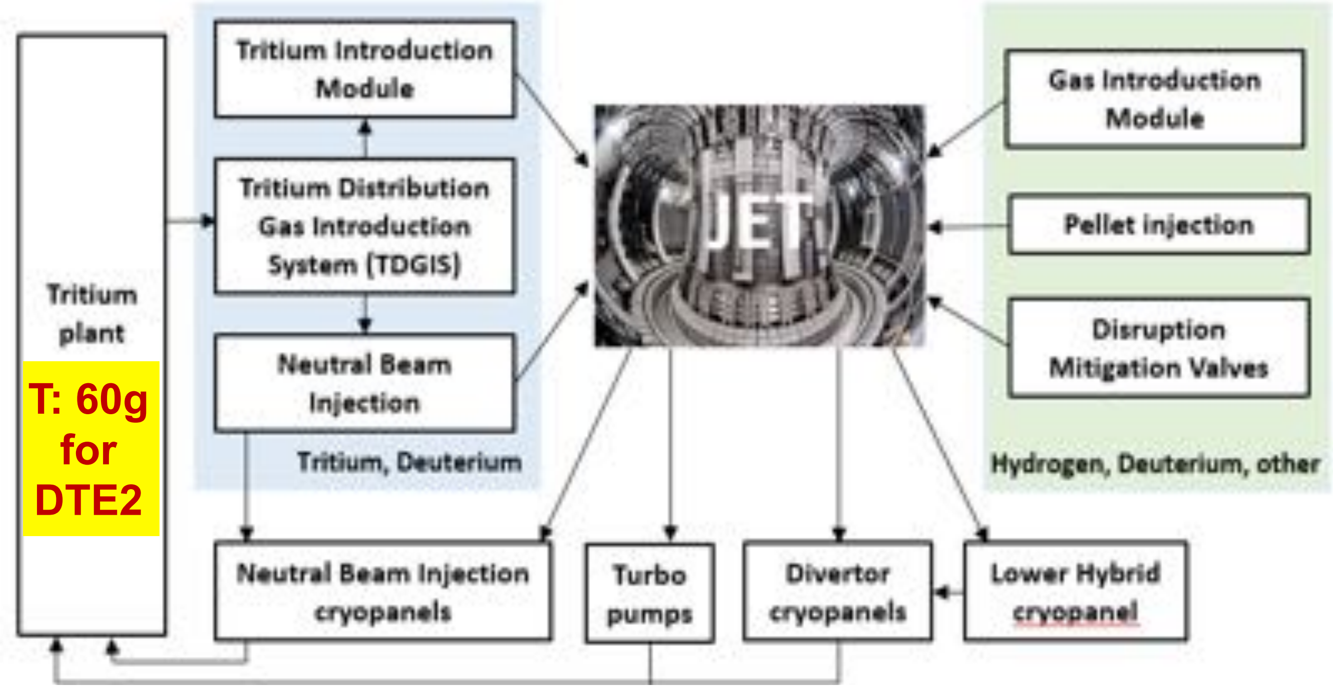
*P. Batistoni, Nuc Fus 2018,*
*E. Laszynska, SOFT 2018 ,*
*T. Vasilopoulou, SOFT 2018,*
*S. R. Villari, SOFT 2018*

# Tritium operation with JET-ILW: x5 more neutron budget than in DTE1

| | DTE1 | TT | DTE2 |
|---|---|---|---|
| **Neutron** | $3.\ 10^{20}$ | $0.1\ 10^{21}$ | $1.55\ 10^{21}$ |
| **Tritium injected** | 35g | ~300g | ~150g |

→

**Strict accounting of tritium used <11g in cryo panels regenerated every day**



**T: 60g for DTE2**

**Restricted access to area where neutron activation and γ radiation can be high.**

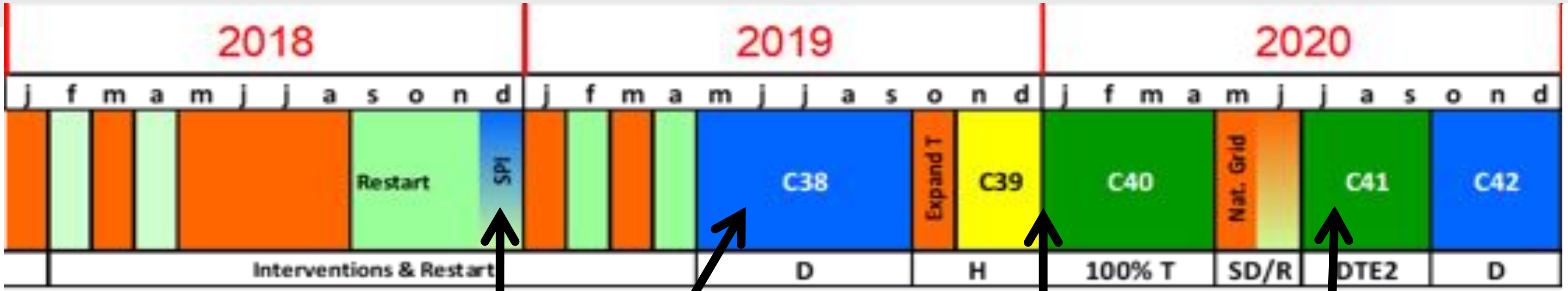
*E. Belonohy, SOFT 2016*

**Plasma operation rehearsal planned during the D campaign**

# Highlights of the preparation for D-T

- ☐ Existing D-T scenarios have reached 7-8MW/2.5s equivalent fusion power and can attain 10 to 16MW of fusion power with 40MW of input power in the JET ITER-like wall
- ☐ After-glow ITB scenario is a credible route for alpha particle driven instabilities study and code validation for ITER
- ☐ Confinement and particle transport show strong positive isotope dependences and is also investigated for ITER conditions
- ☐ Tritium will modify the SOL conditions and plasma surface interactions significantly but retention is expected to stay low
- ☐ JET has developed a comprehensive set of diagnostics, tools and procedures in support of ITER burning plasma operation

# Next JET timeline and Prospects



## D campaign

- ➢ D-T scenario preparation
- ➢ Disruption/RE studies

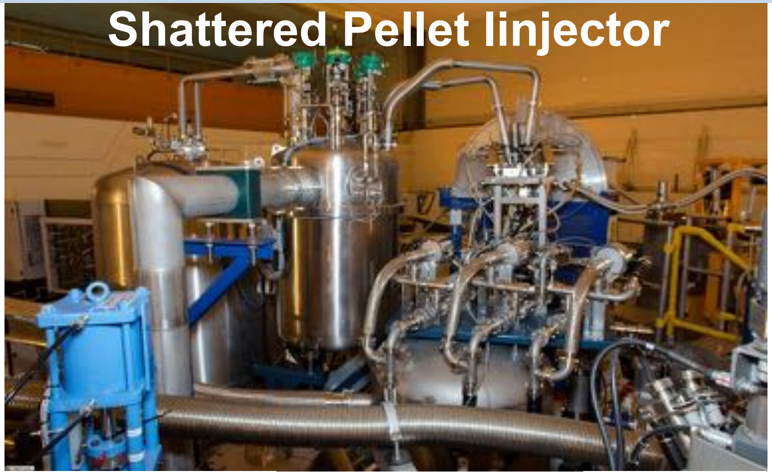
## H & T

- ➢ Isotope campaigns

## D-T campaign

- ➢ 15 MW of fusion power for 5s in stationary conditions
- ➢ Study of alpha physics

**Shattered Pellet Iinjector**



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