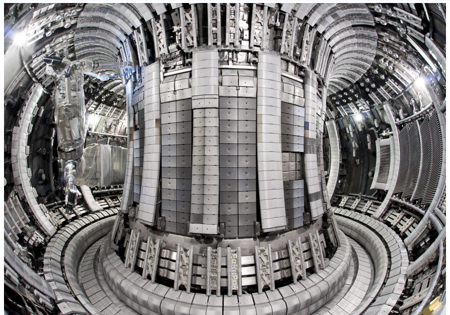
Xavier LITAUDON on behalf of EUROfusion JET contributors

EUROfusion

Overview of JET results in support to ITER

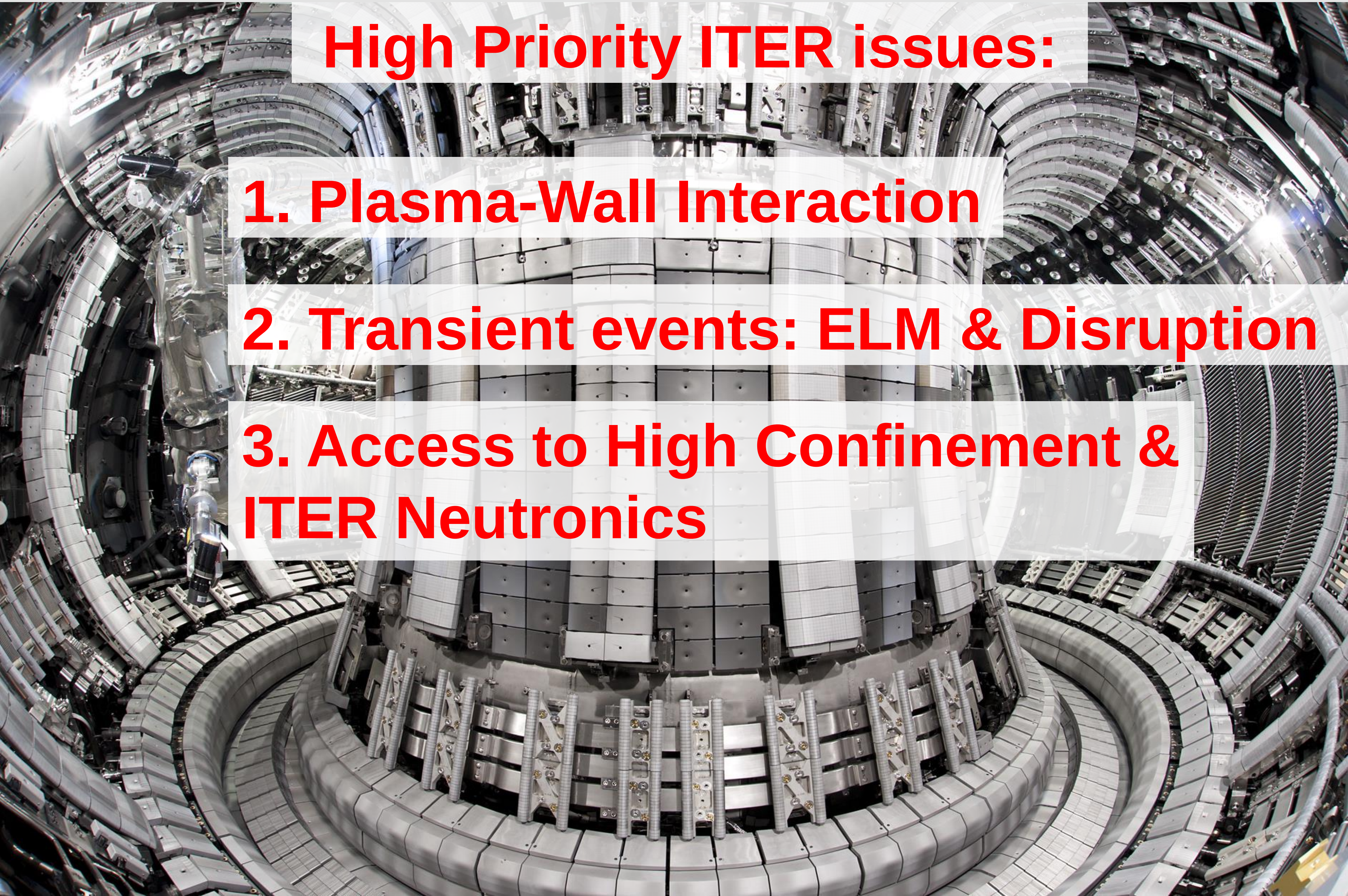
Acknowledgments: The JET Task Force and Project Leaders, the JET secondees, the EUROfusion Programme Management Unit, the JET Exploitation Unit and the JET operator

JET



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 ITER Like Wall Operation: 61h/540GJ



High Priority ITER issues:

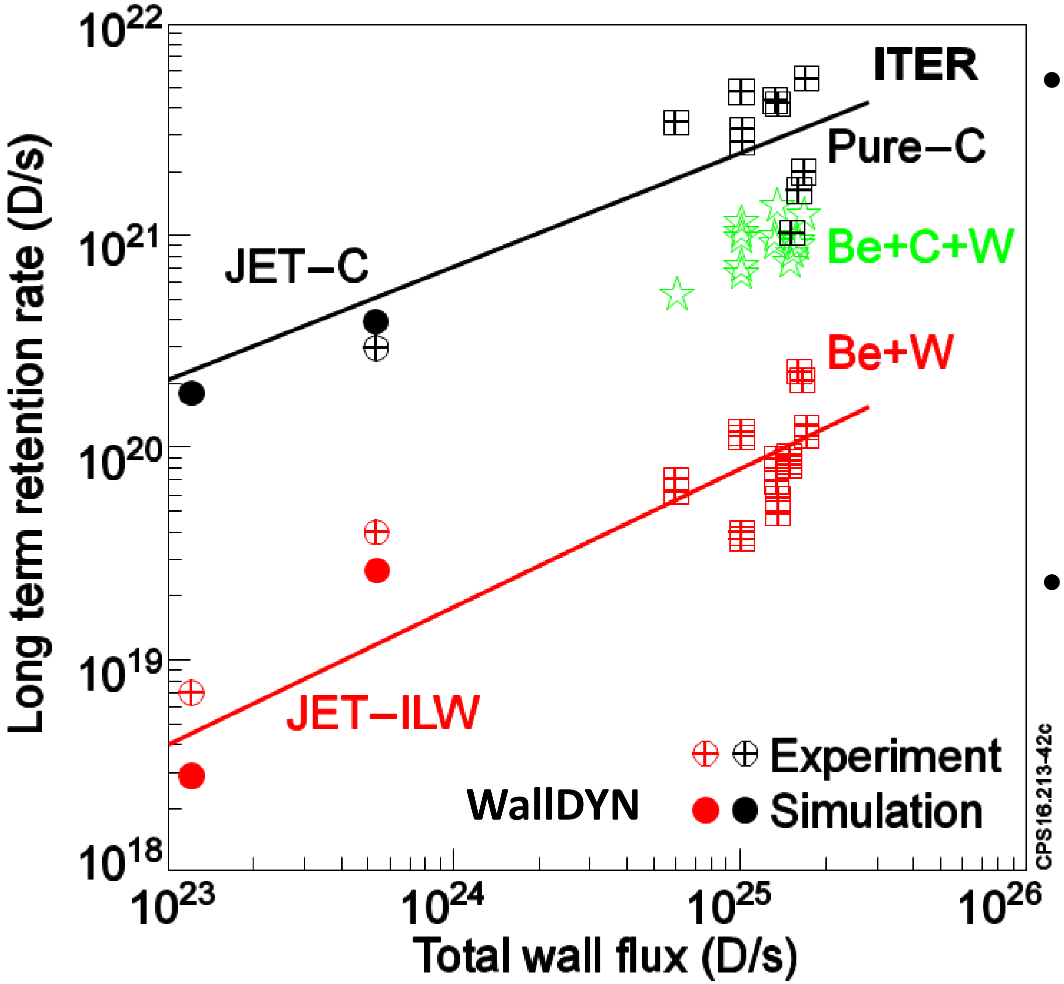
1. Plasma-Wall Interaction

2. Transient events: ELM & Disruption

3. Access to High Confinement & ITER Neutronics

Tritium Retention with ITER materials Be, W

Simulations reproduce retention rate and deposition pattern



[Schmid et al NF 2015]

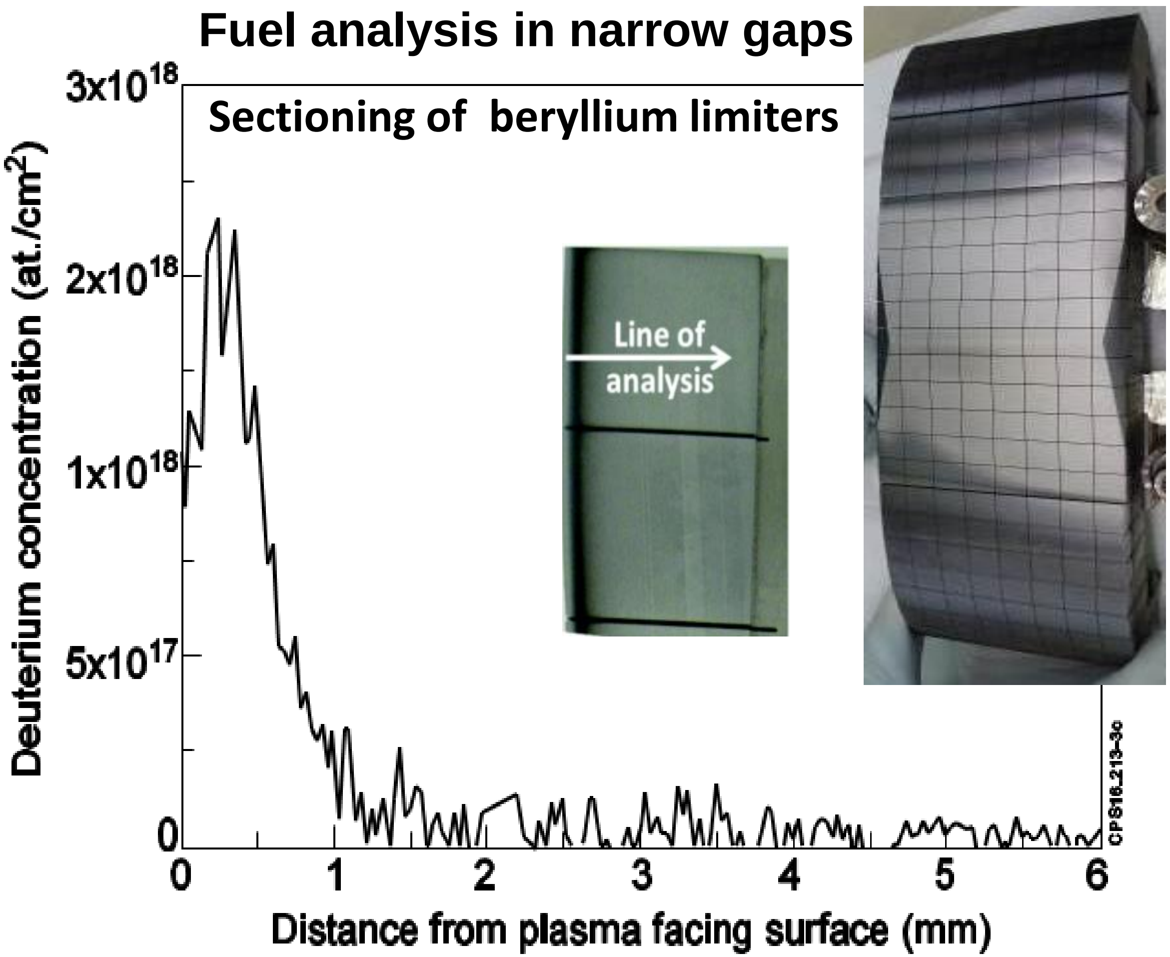
- **~0.3% retention fraction**
  - **reduction by more than one order of magnitude**
  - **gas-balance & post-mortem analyses**
- **Co-deposition in W-Be layers (2/3) dominates over implantation (1/3)**

[Brezinsek et al Nucl Fusion 2013
Widdowson et al FEC 2016 MPT1-3
Rubel et al FEC 2016 EX/P6-1
Brezinsek et al J. of Nuc. Mat. 2015 and SOFT 2016]

JET

Fuel retention in Be castellation gaps

Low contribution (3%) to global fuel inventory



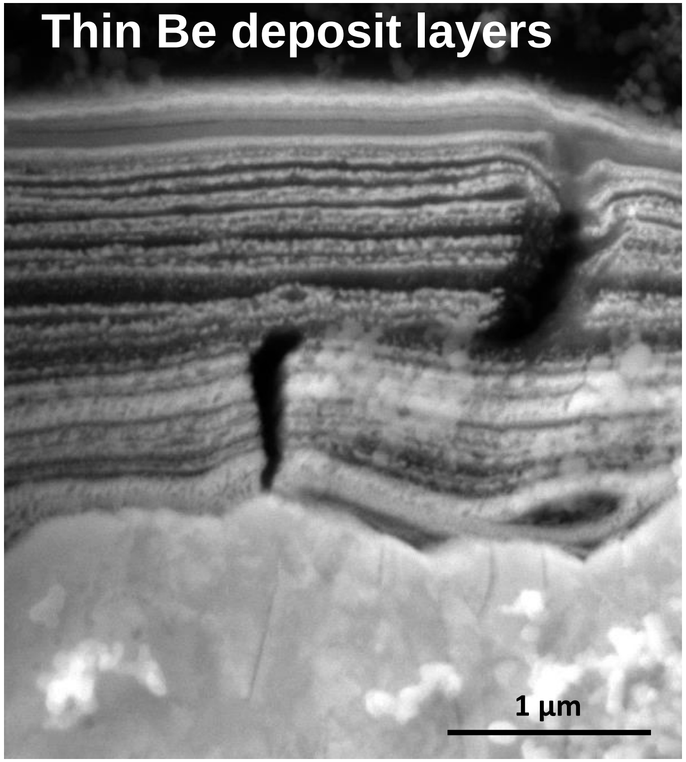
- **JET–ILW:**
  - **170 000 castellations**
  - **L~ 7325 m, S~ 88m^2 !**
- **Fuel retention at the very entrance (<1mm) of grooves**
  - **no transport deeper into gaps**
  - **in agreement with modelling**
- **Narrow gaps (0.4 mm) minimise retention**

[Rubel et al FEC 2016 EX/P6-1]

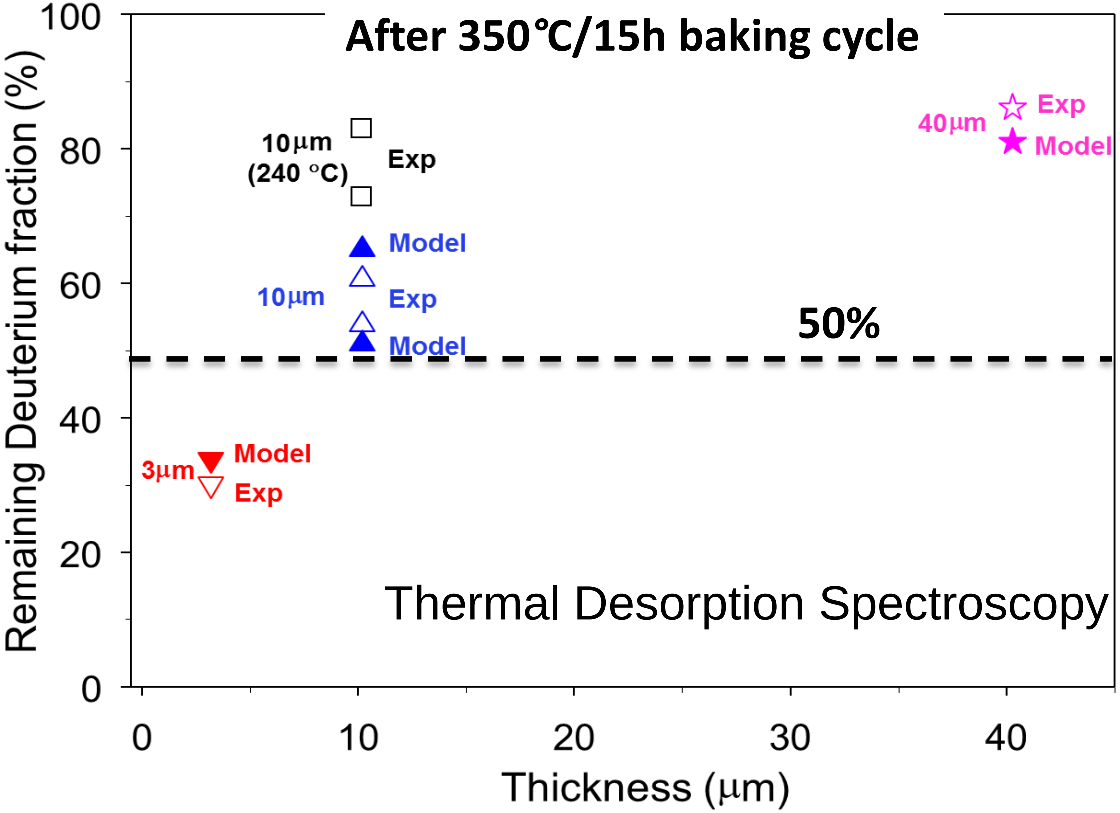
Fuel Removal in Co-Deposited Layers

Low D_2 release from thick Be deposit at ITER baking cycle

- **Experiment in agreement with model** [De Temmerman et al PSI 2016]
- **Role of impurities (C, O_2) in deposits to be investigated**
- **Optimisation Tritium removal strategy for ITER ?**



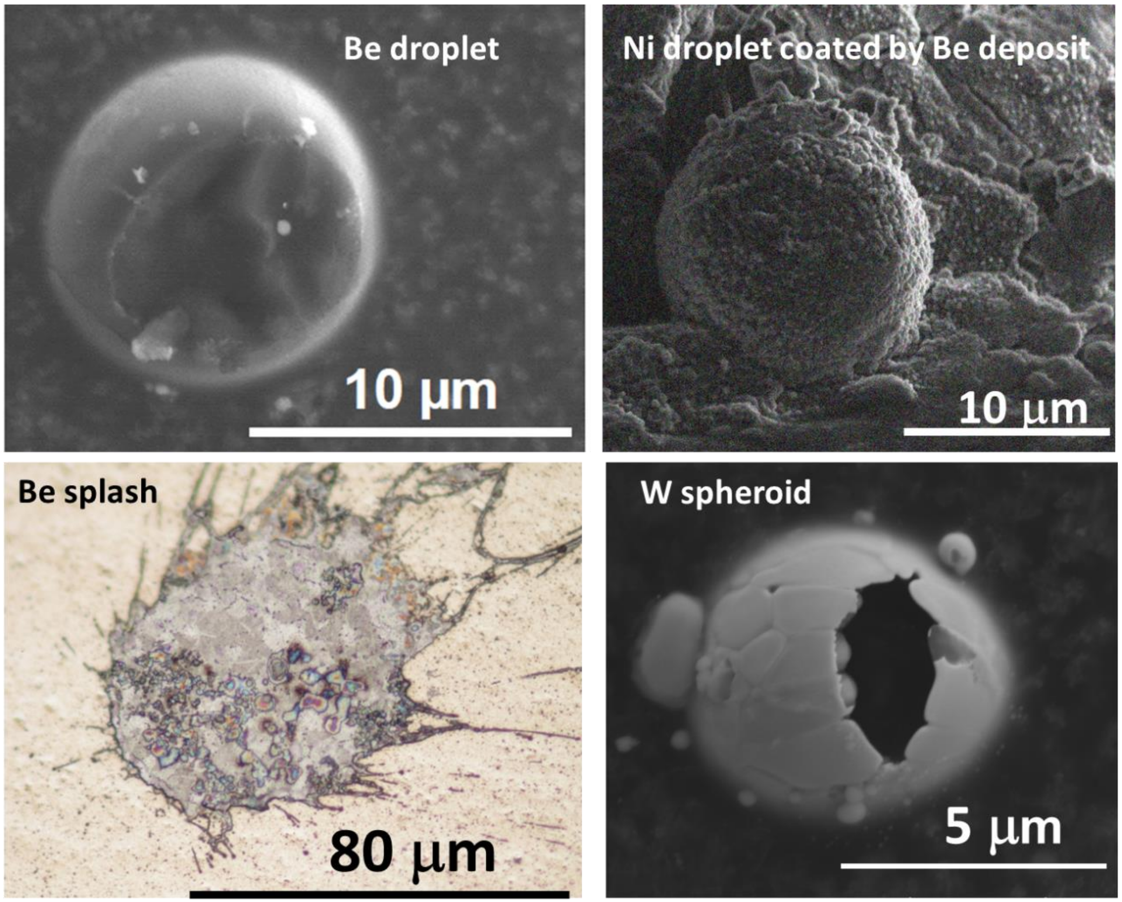
[Widdowson et al FEC 2016 MPT/1-3]
[Tokitani et al SOFT 2016]



[Heinola et al FEC 2016 EXP/P6-2, Likonen PSI 2016]

Comprehensive Dust Particles Survey

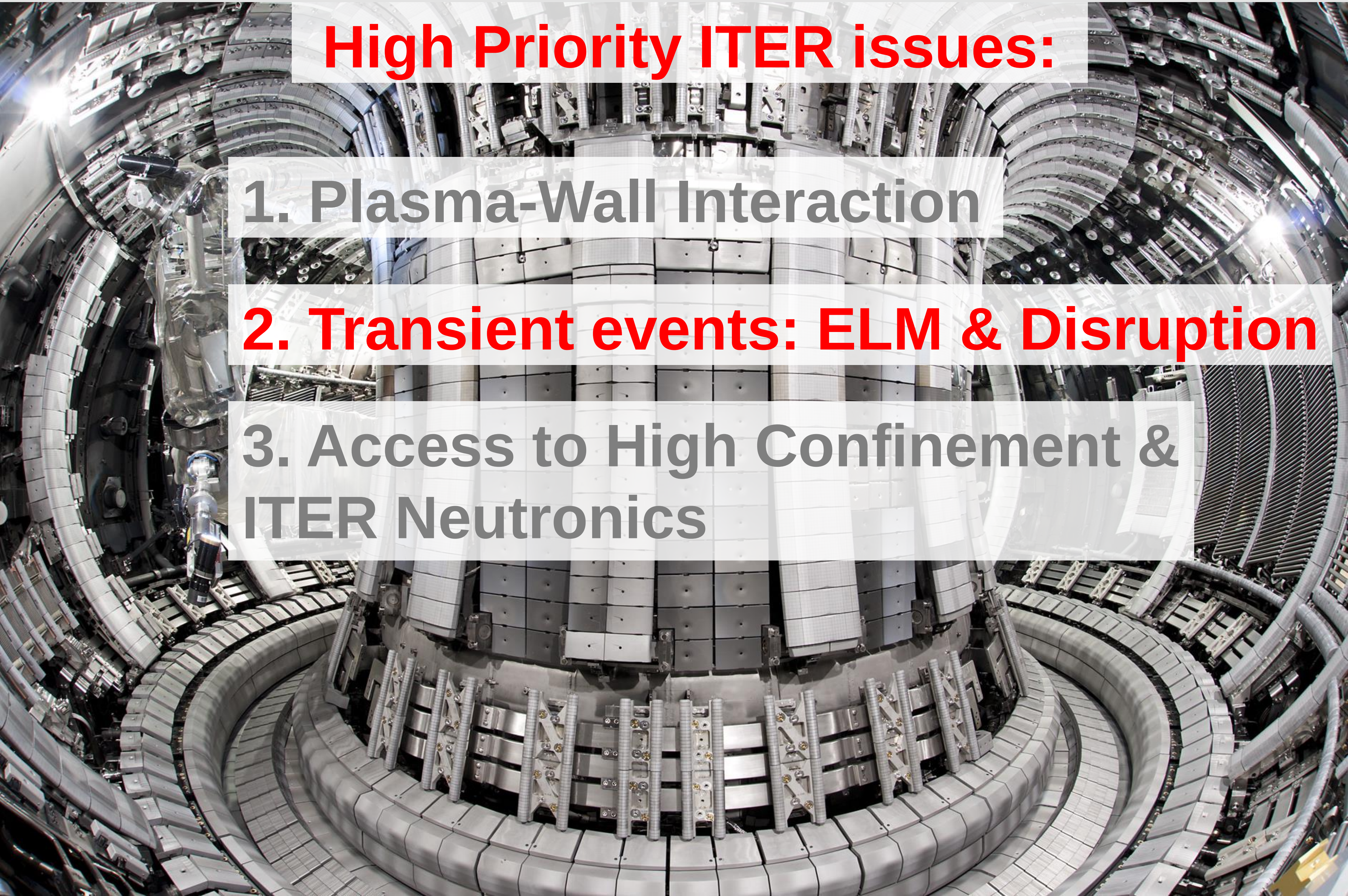
Collected Dust two orders of magnitude less than JET C-Wall



- **1.82g Dust collected:**
  - **vacuum cleaning**
  - **sticky pad**
- **Source**
  - **Predominantly from W-coated tiles**
  - **Be melting from disruptions**
  - **Only 50-70mg from Be co-deposit**
- **Unique data set for ITER safety**

[Fortuna-Zalesna et al FEC 2016 EX/P6-20, Ashikawa et al FEC 2016 EX/P6-10]

JET ITER Like Wall Operation: 61h/540GJ



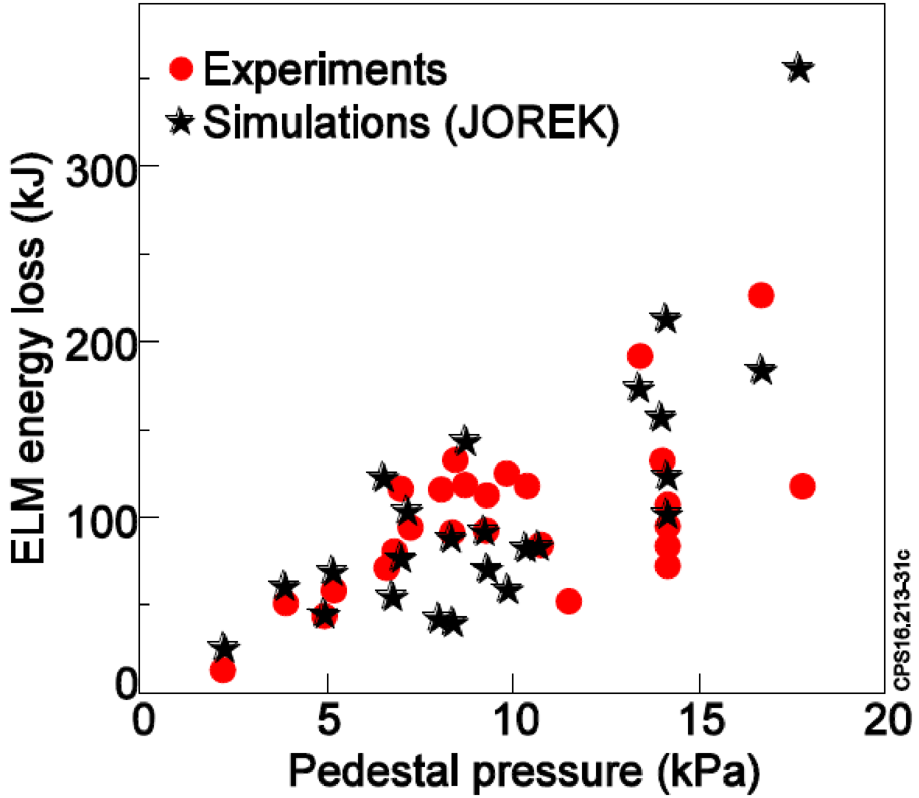
High Priority ITER issues:

1. Plasma-Wall Interaction
2. Transient events: ELM & Disruption
3. Access to High Confinement & ITER Neutronics

ELM First Principle MHD Simulations

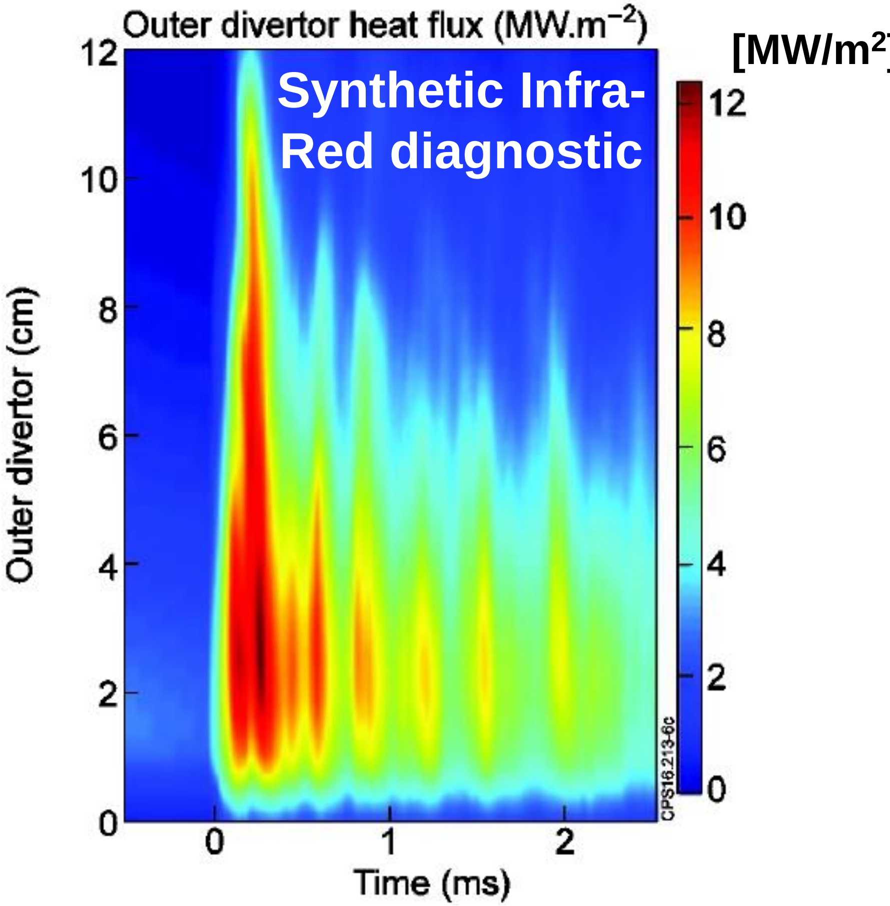
JOREK simulations at low resistivity/viscosity reproduce experimental trends

ELM energy losses



[S. Pamela et al FEC 2016 TH/8-2,
Futatani et al FEC 2016 TH/P1-25]

Divertor heat flux pattern ELM crash

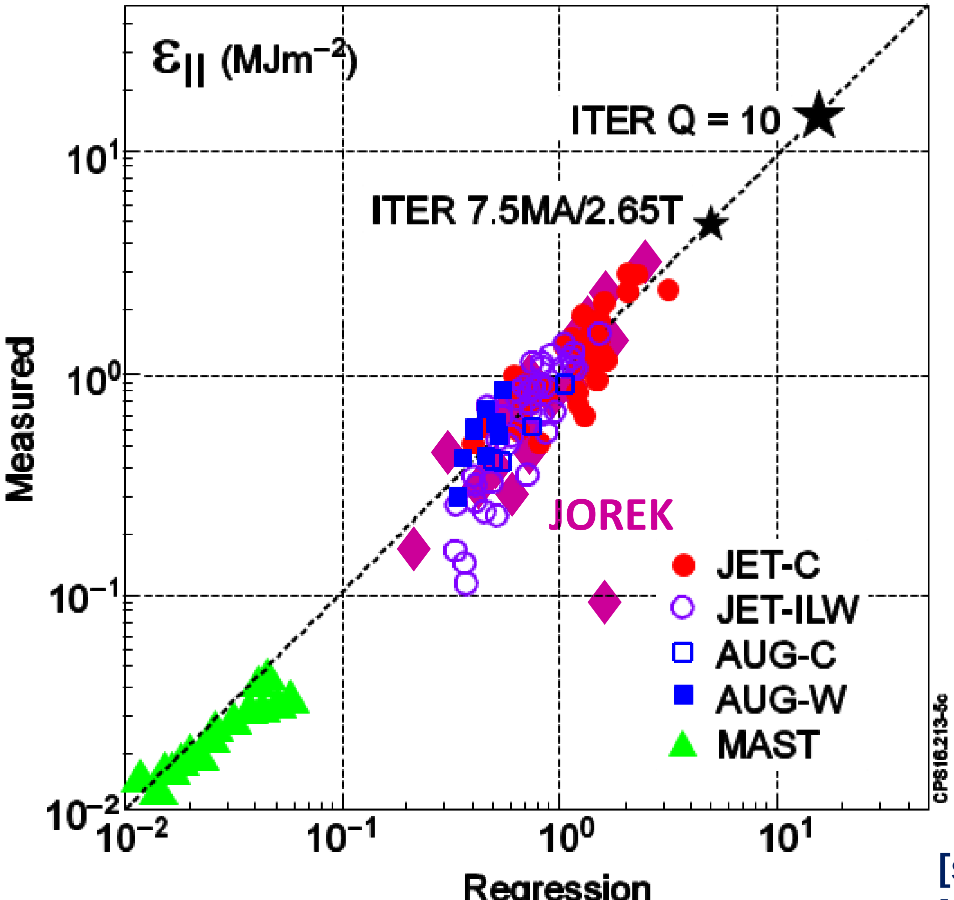


ELM Divertor Heat Load Scaling to ITER

Multi-machines scaling type-I ELM energy flux // B

$$\varepsilon_{II,scal}\left[\frac{MJ}{m^2}\right] \propto R_{geo}^{1.01\pm0.40} \times n_{e,ped}^{0.75\pm0.15} \times T_{e,ped}^{0.98\pm0.1} \times \left(\frac{E_{ELM}}{W_{plasma}}\right)^{0.52\pm0.16}$$

[Eich et al PSI 2016]



- Proportional to machine size and pedestal pressure
  - Trade-off performance vs material limits ?

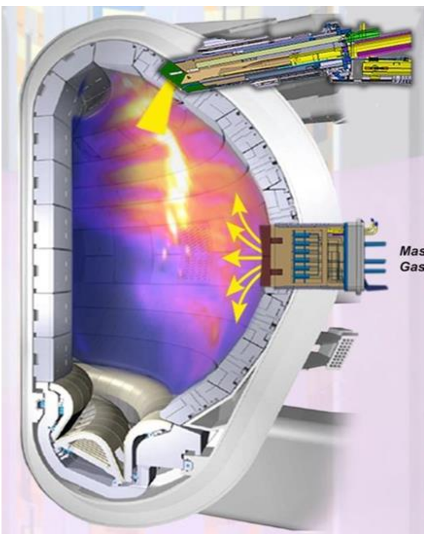
    [Sieglin et al FEC 2016 EX/7-3Ra]
- Scaling and ITER extrapolation agree with JOREK MHD simulation

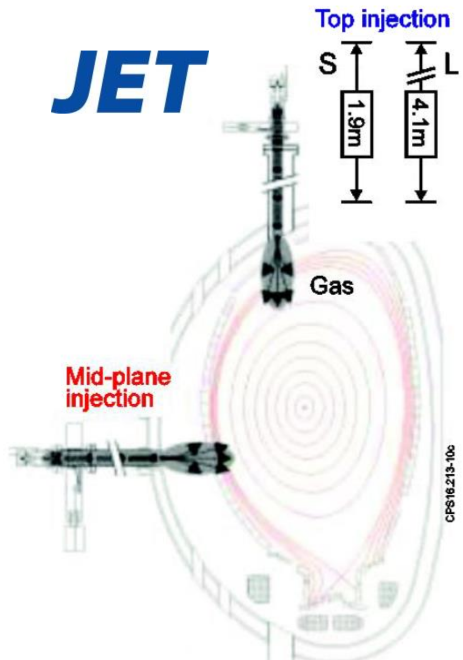
  [S. Pamela et al FEC 2016 TH/8-2]

[see also EU Medium Size Tokamaks Overview by Meyer et al OV/P-12]

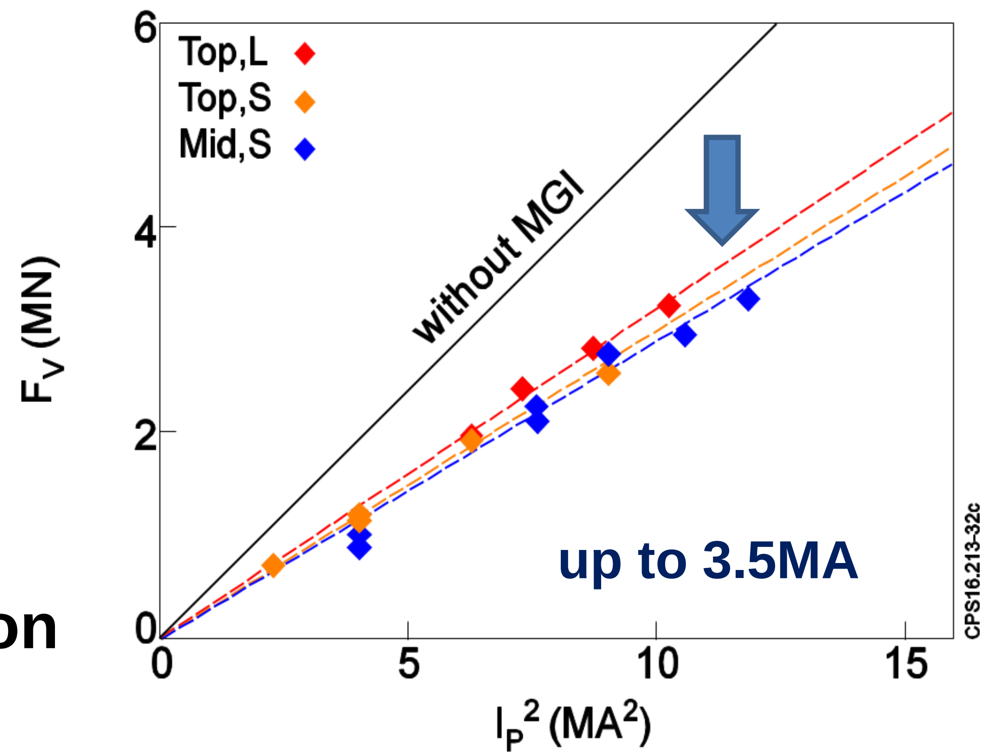
Disruption Mitigation Studies for ITER

JET Disruption Mitigation System with three Massive Gas Injectors to mimic ITER set-up





Vessel force mitigation



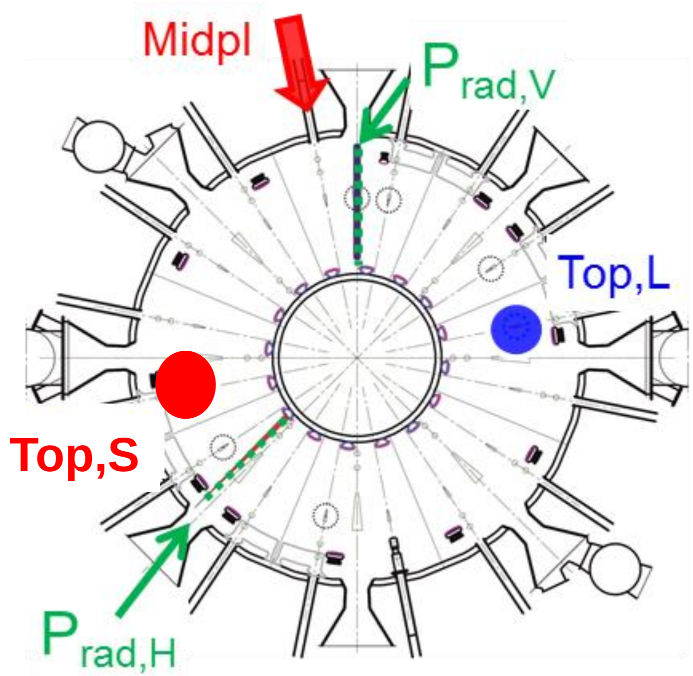
- **Constant 40% force reduction**
- **No influence of Injection Location**

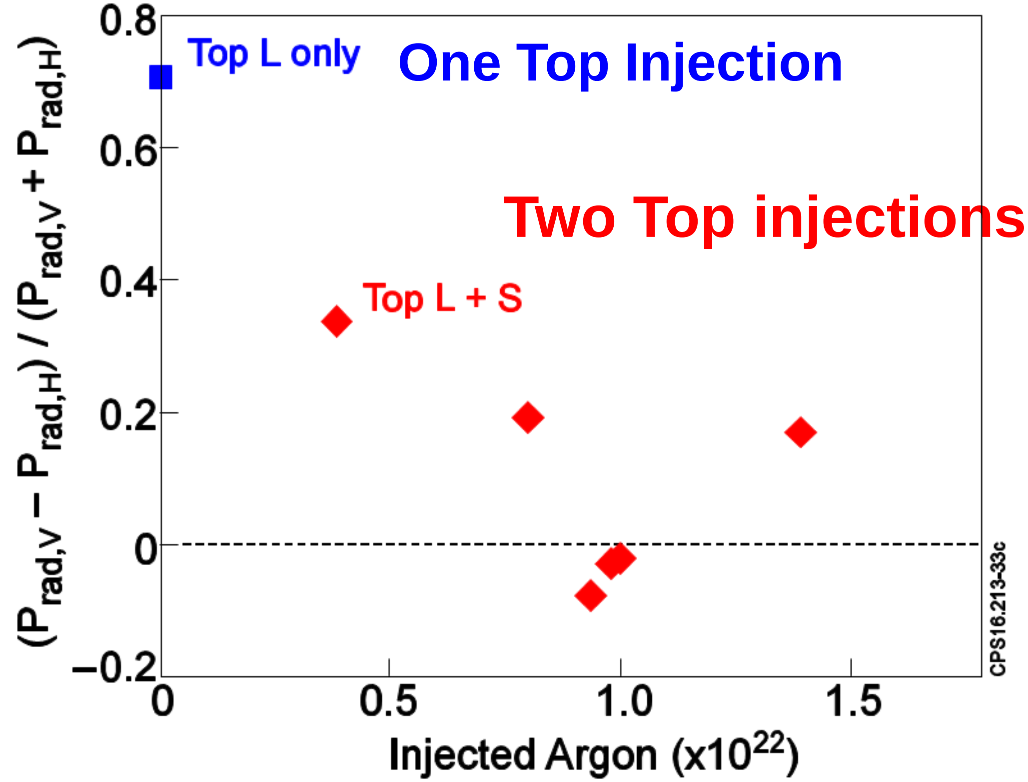
[Jachmich et al EPS & PSI 2016]

[Lehnen et al Nucl Fus 2015 , Joffrin et al FEC 2016 EX/9-1]

Radiation Asymmetry Mitigation

- **ITER: reduction localised radiation on first wall where 80% of energy lost in thermal quench?**
- **JET: reduction radiation asymmetry with two top injectors support the current ITER choice**



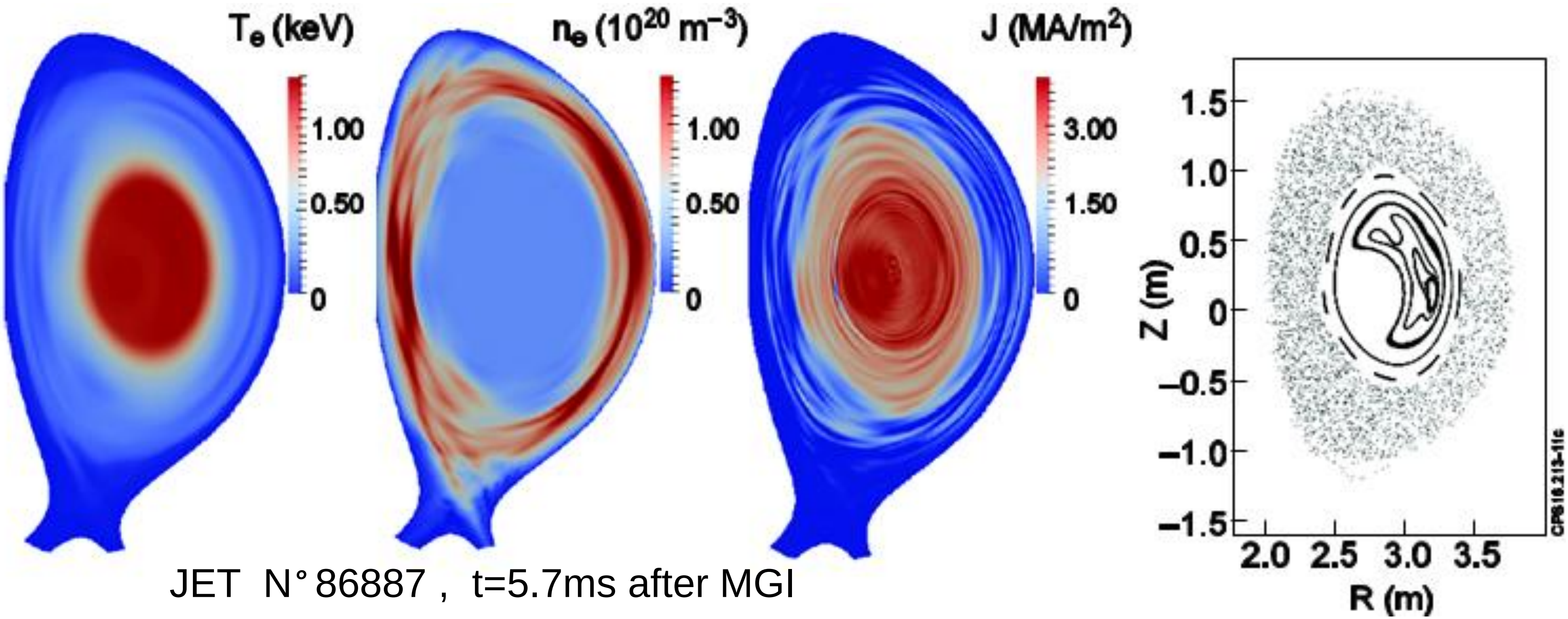


[Lehnen et al Nucl. Fus. 2015, Joffrin et al FEC 2016 EX/9-1]

[Jachmich et al EPS & PSI 2016]

First Principle Disruption Simulations

Thermal Quench Simulated with 3-D Non-Linear MHD JOREK code



JET N° 86887 , t=5.7ms after MGI

Growth of magnetic island chains → Stochastic layer → Fast loss of thermal energy

[Nardon et al EPS/PPCF 2016, Nardon et al Nucl. Fus. 2016, Fil et al PoP 2015]

JET ITER Like Wall Operation: 61h/540GJ

High Priority ITER issues:

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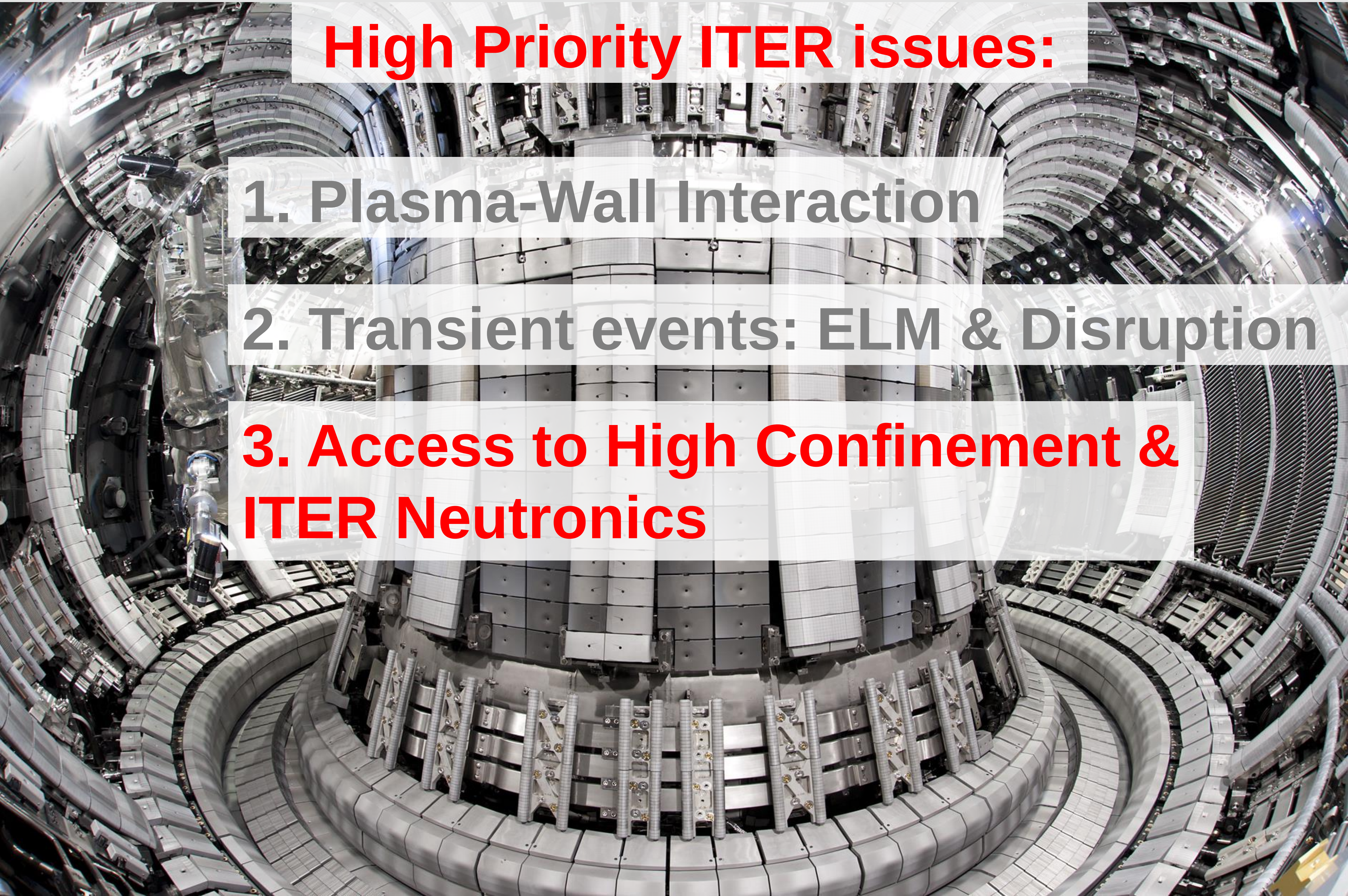
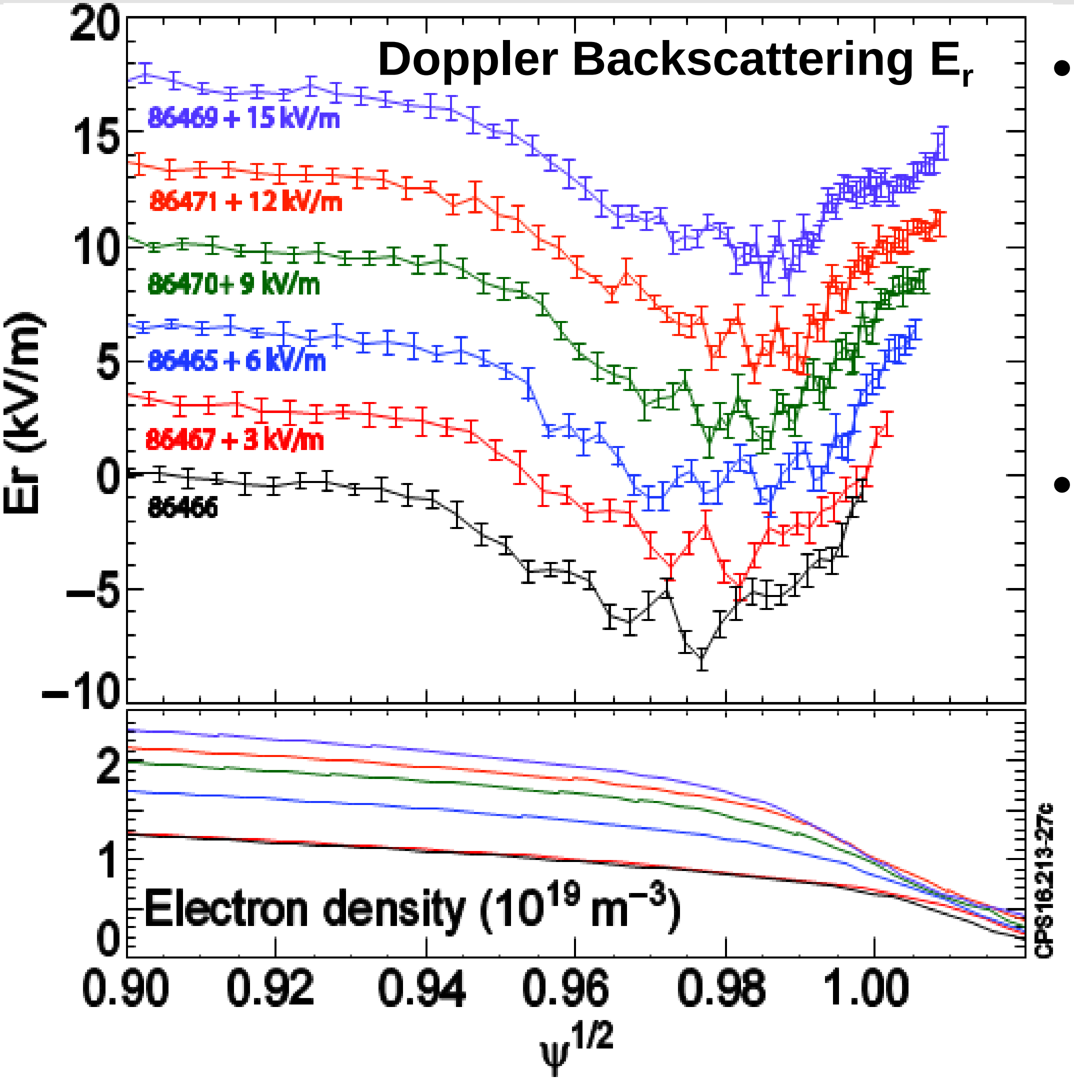


H-mode Access with ITER Wall Materials



[Hillesheim et al PRL 2016
Hillesheim et al FEC 2016 EX/5-2]

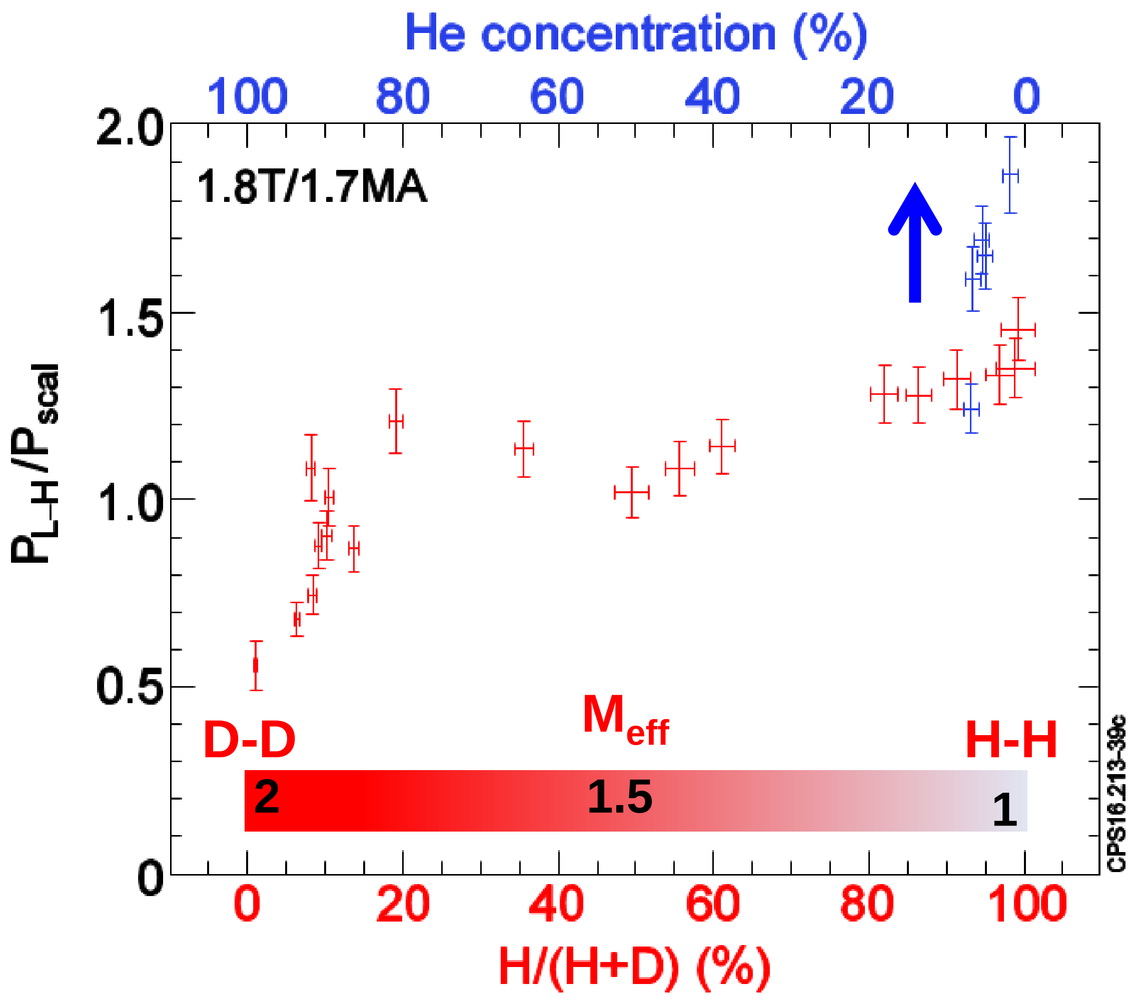
- **Stationary Zonal Flows measured during edge barrier formation**
  - **Radial scale wave numbers $k_r\rho_i \approx 0.4$–0.8**
- **Importance of divertor configuration**
  - **SOL $E_r \times B$ in 2D fluid/neutral EDGE2D-EIRENE simulations**
  - **Role of SOL physics for L-H transition**

[Chankin et al PSI 2016,
Delabie et al APS 2015]

JET

ITER Non-Active Operation: H-mode Access

Non-linear mass dependence on L-H power threshold



- **Fine mass scan 2→1 via H/(H+D) control**
- **Trace He quantity in H-plasma:**
  - **Significant P_{L-H} reduction**
- **Impact on ITER non-active phase to be investigated**
  - **helium campaign ?**

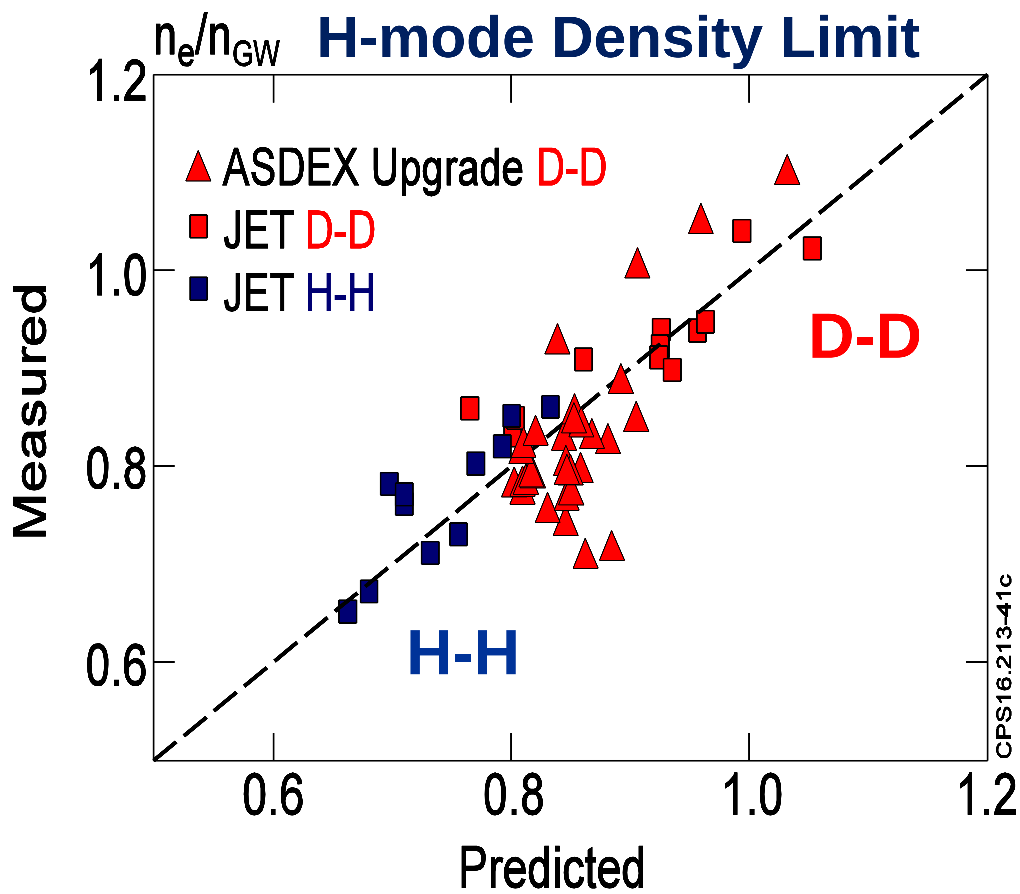
[Nunes et al FEC 2016 Post Deadline Proposal Hillesheim et al FEC 2016 EX/5-2]

[P_{scal} from ITPA scaling J. Phys. (2008)]

ITER Operation: H-Mode Density Limit

H-mode Density limit consistent with Goldston's prediction

[Goldston J of Nuc Materials 2015]



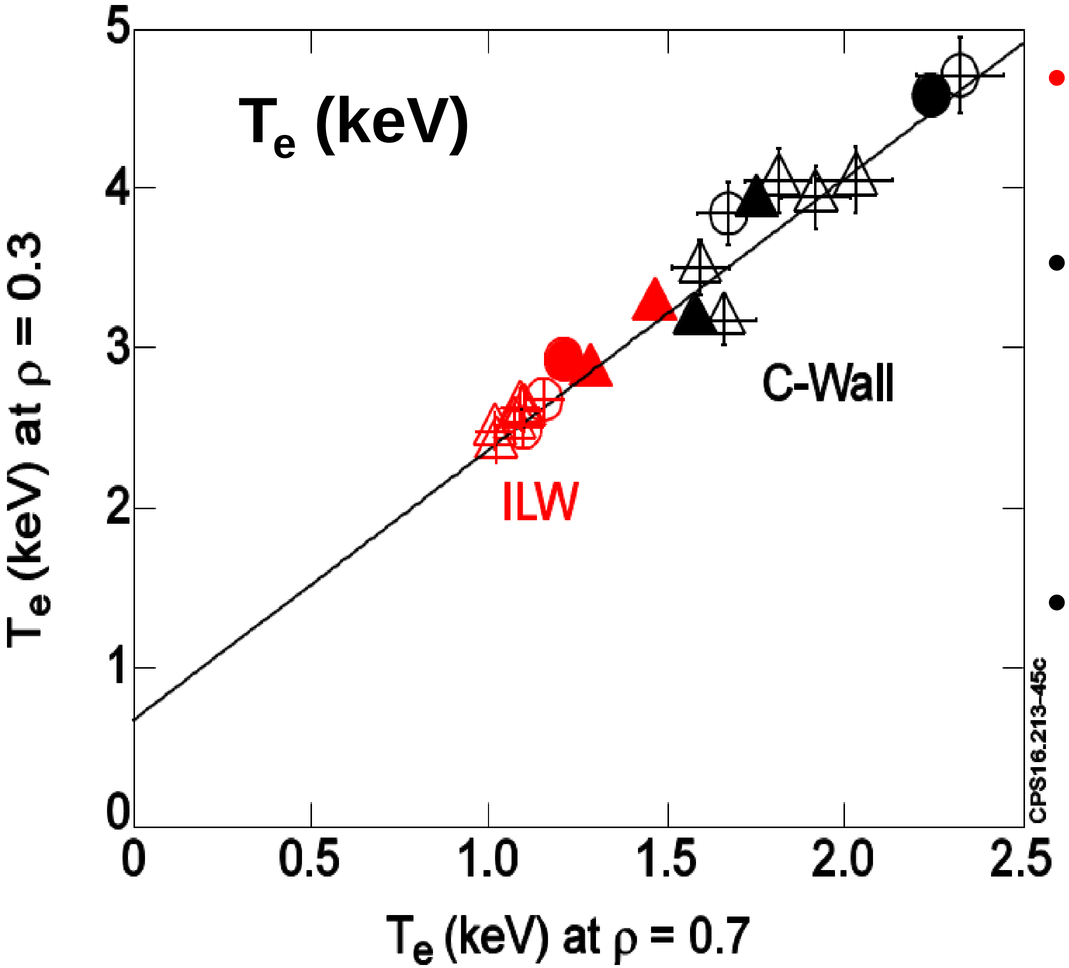
- Mass dependence $\propto M^{9/16}$
- Weak power dependence
- H-mode Density limit
  - SOL MHD instability
- Wider ITER operational boundaries in T-T and D-T
  - When $M_{eff}\uparrow$: $P_{L\text{-}H}\downarrow$ & $n_{DL}/n_{GW}\uparrow$

[Huber et al FEC 2016 Post Deadline Proposal]

[Goldston Nuc. Fus 2012,
Eich et al PRL 2011 & Nuc Fus 2013]

Thermal Confinement with ITER-Like Wall

Impact on ITER Q=10 performance



- **Be/W Wall similar core confinement as C-Wall**
- **Change of global confinement:**
  - **reduction of electron temperature pedestal**
- **Electron transport:**
  - **importance of small radial scale ETG instabilities**

[Bonanomi/Mantica et al FEC 2016 EX/P6-14]

[Hyun-Tae Kim et al, PPCF 57 (2015) 065002]

Dimensionless Scans in Low Triangularity ITER Baseline Plasmas

ρ* scaling

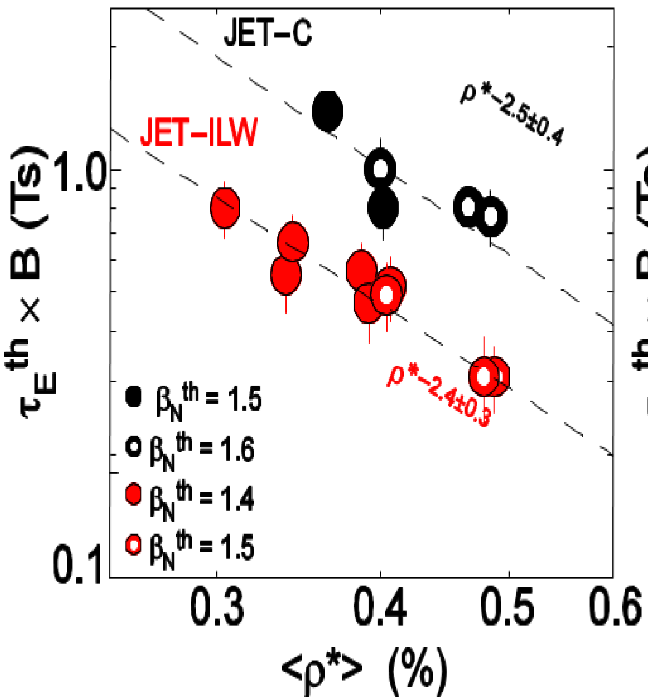
- gyro-Bohm
- no change pedestal limit

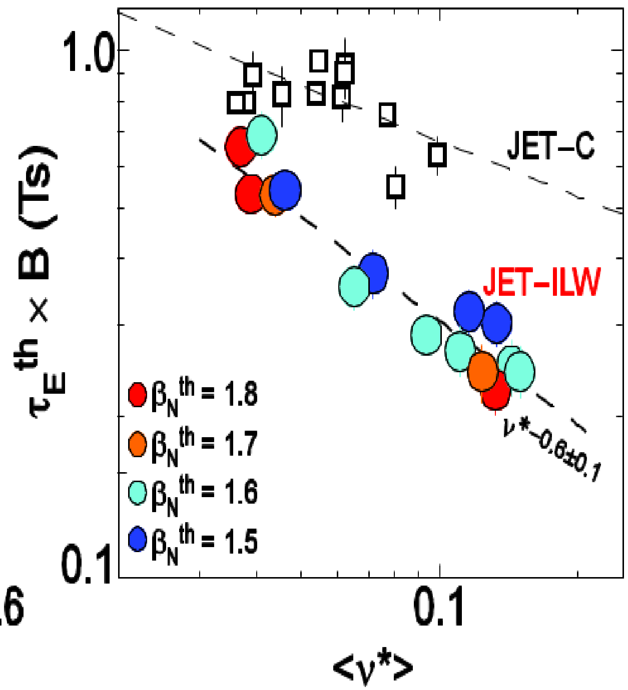
ν* scaling

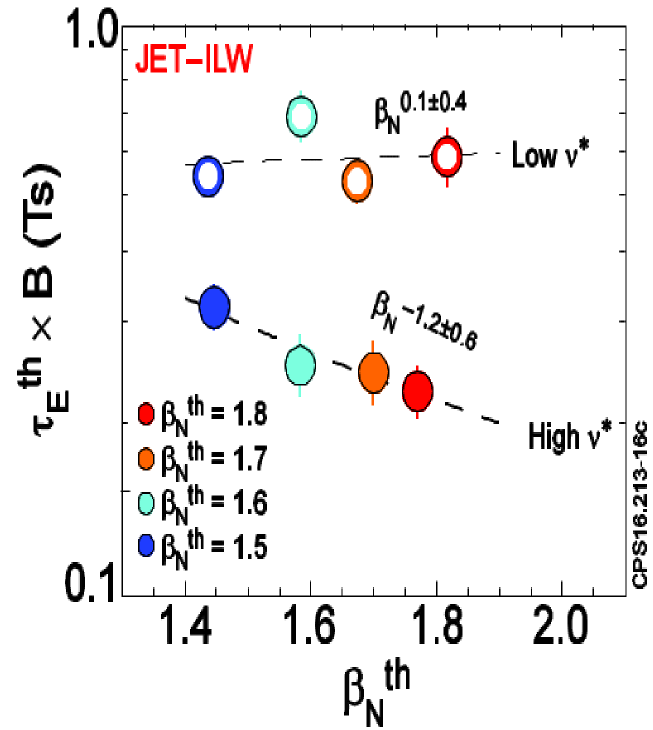
- stronger dependence as ITPA scaling
- pedestal stability improves at low ν*

β scaling $\beta_N \leq 1.8$

- low ν* : no dependence of transport
- high ν* → degradation due to pedestal





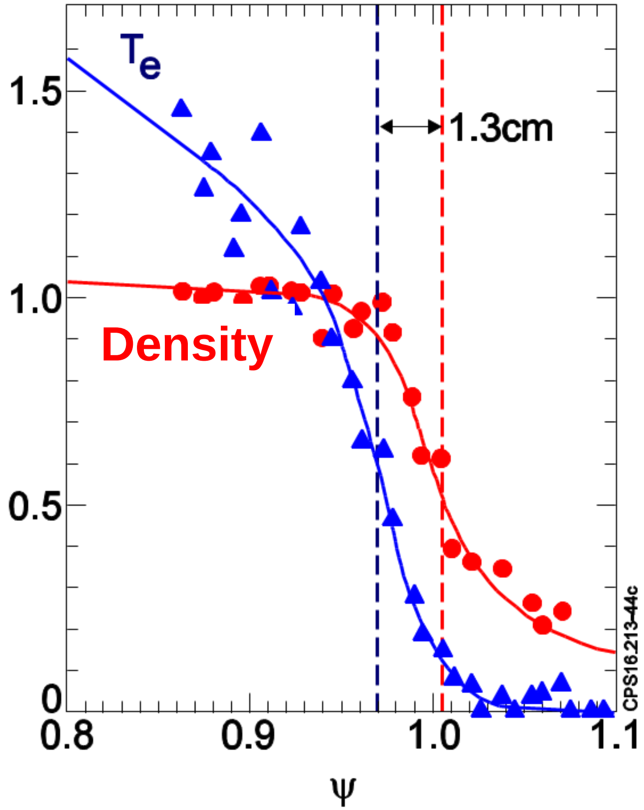


[Frassinetti et al EPS/PPCF 2016, Nucl. Fusion 2016, Tala et al FEC 2016 EX/P6-12]

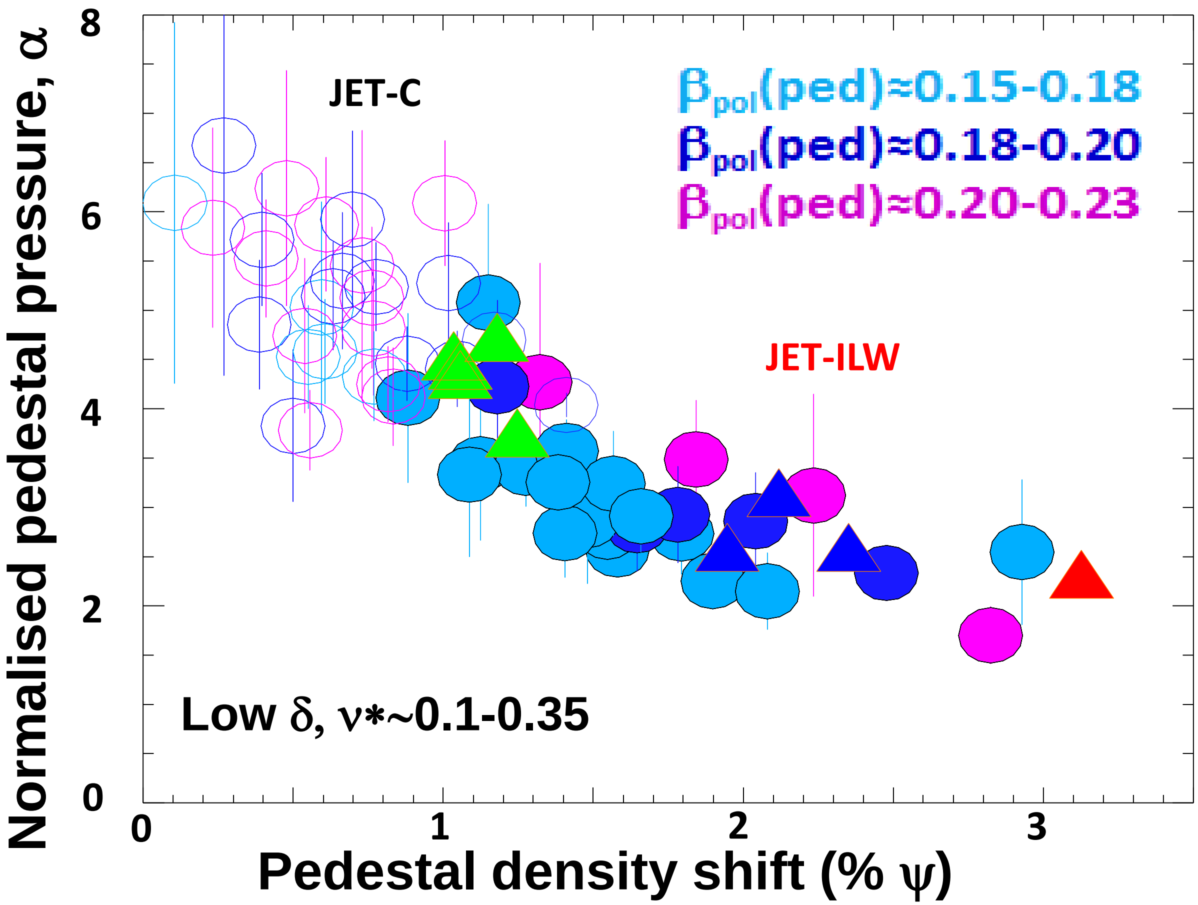
Radial shift between N_e and T_e pedestal

Pedestal stability improves with reduced radial shift

JET-ILW tends to have larger relative shift than JET-C



Also in ASDEX Upgrade [Dunne et al EPS 2016] **and DIII-D**



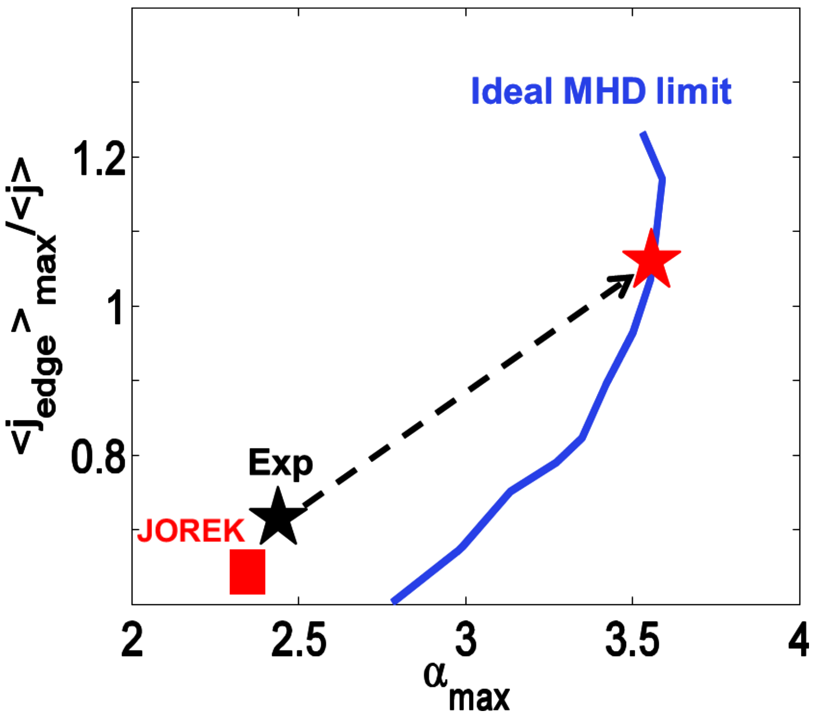
[Stefanikova et al EPS 2016, Frassinetti et al EPS/PPCF 2016, Giroud et al FEC 2016 EX/P6-13]

JET

Pedestal Pressure Limit: Transport vs MHD?

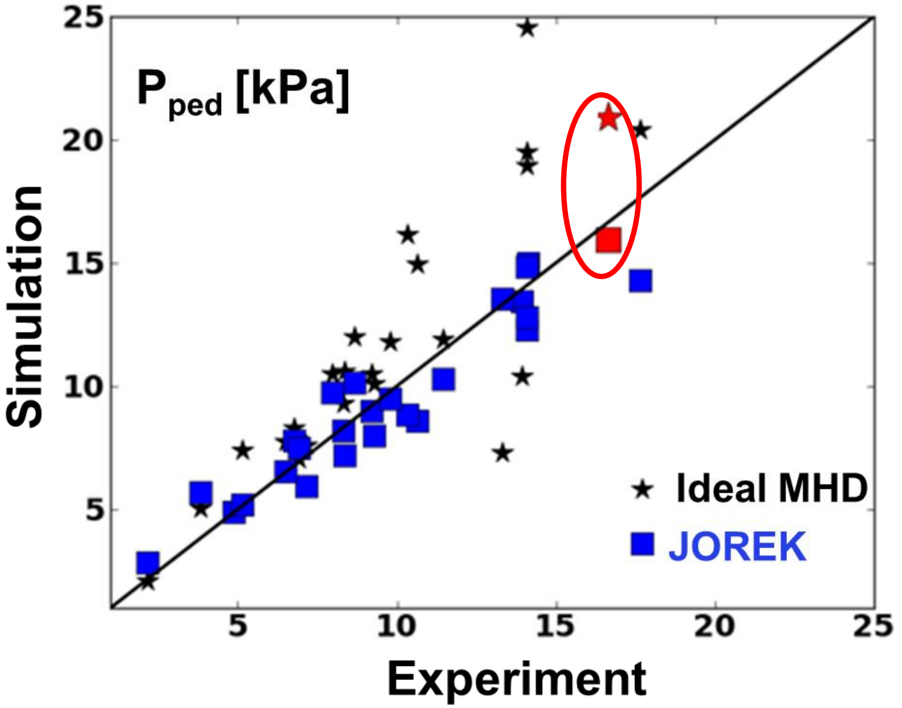
- **Pedestal pressure in the ideal stable domain despite ELMs ?**

[Maggi et al Nucl. Fusion 2015]



- **Non-ideal MHD JOREK predict instabilities closer to exp.**
  - **resistivity, viscosity, diamagnetic effects, physics process to be isolated ?**

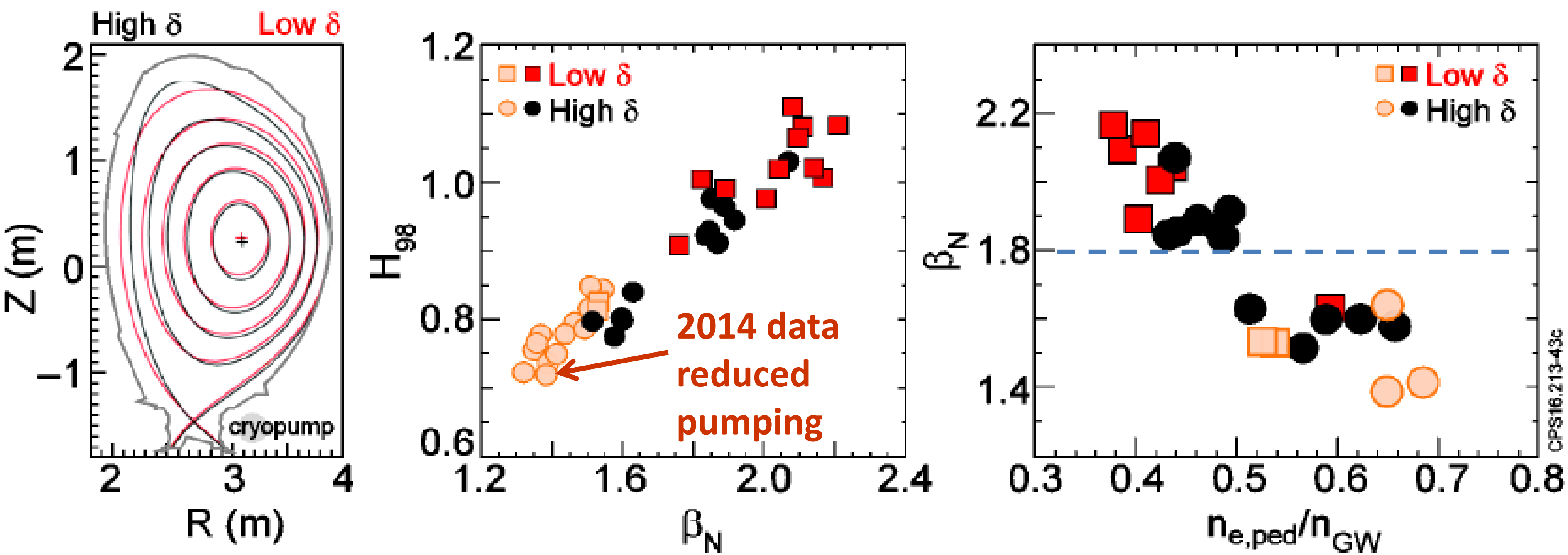
[S. Pamela et al TH 8-2]



[S. Pamela et al TH 8-2, Aiba et al TH/8-1, Maggi et al EX/3-3, Chapman et al EX3-6, Urano et al EX/3-4]

High-Triangularity ITER H-mode Operation

- **First time, with the ILW, stationary (5s) ITER Baseline Operation at high-δ (δ_{av}~0.4) achieved at 2MA/2.2T**
  - **New high-δ configuration optimized for pumping**
  - **H=1-1.1, q_{95}=3.2, β_N=1.8-2.1, P/P_{L-H}~2 but n/n_{GW}~ 0.5**

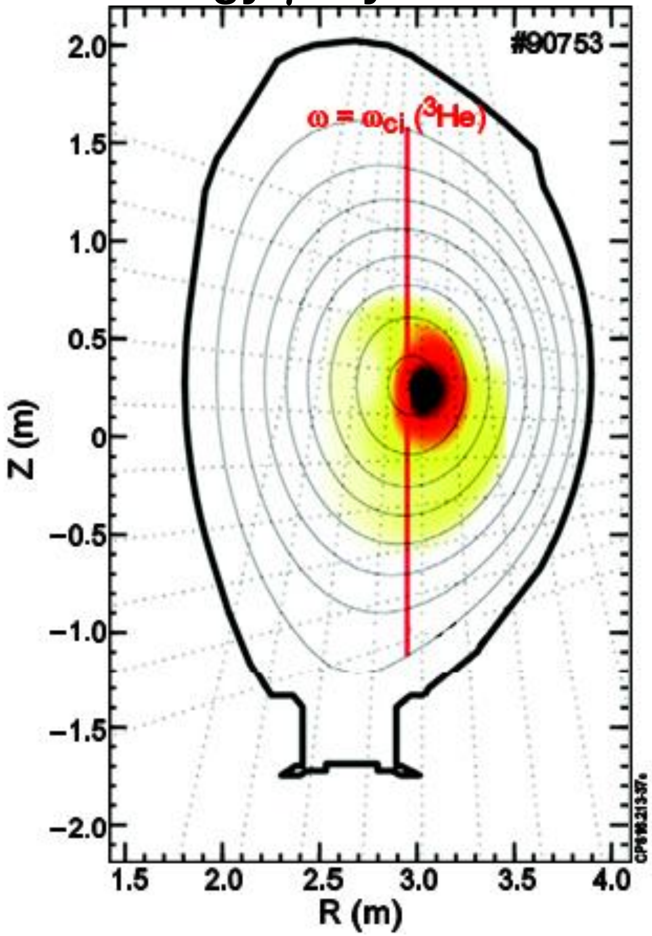


[De La Luna et al FEC 2016 EX/P6-11]

[Sips et al FEC 2016 EX/P6-42]

Novel Three-Ions ICRF Heating Scheme

fast ^{3}He ions from high-energy γ-ray emission



4.2 MW ICRH/33.0 MHz/3.2T

^{3}He @ 0.2%, H/(H+D)~0.75 -0.90

[Kazakov et al Nucl. Fus 2015]

- **D-(^{3}He)-H RF scheme**
  - **^{3}He resonance at the ion-ion (D-H) hybrid layer**
  - **Enhanced left-hand RF field**
  - **Efficient absorption with ^{3}He ~0.1%–1%**
  - **JET and Alcator C-Mod**

[Wright et al FEC 2016 EX/P3-5]

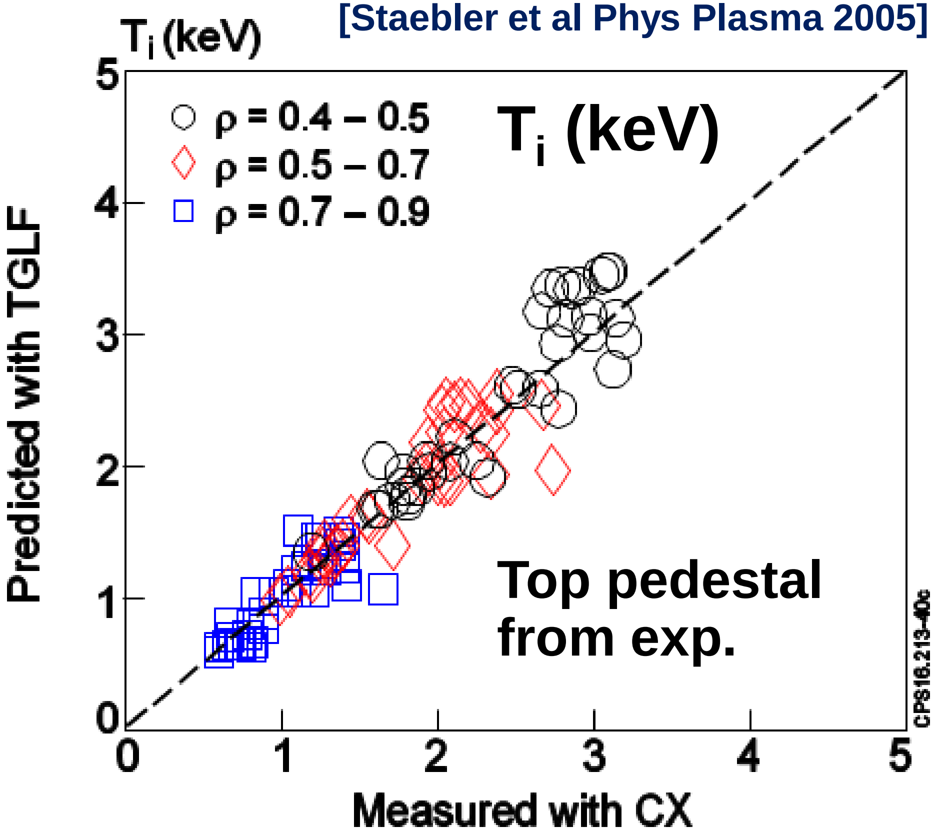
- **Potential ITER applications**
  - **non-active phase ^{9}Be-(^{4}He)-H to mimic fusion-born alpha**
  - **D-T operation T-(^{9}Be)-D**

[Kazakov et al Phys. Plasmas 2015]

[Van Eester et al EX/P6-10, Goniche et al EX/P6-16, Krasilnikov Post Deadline Proposal]

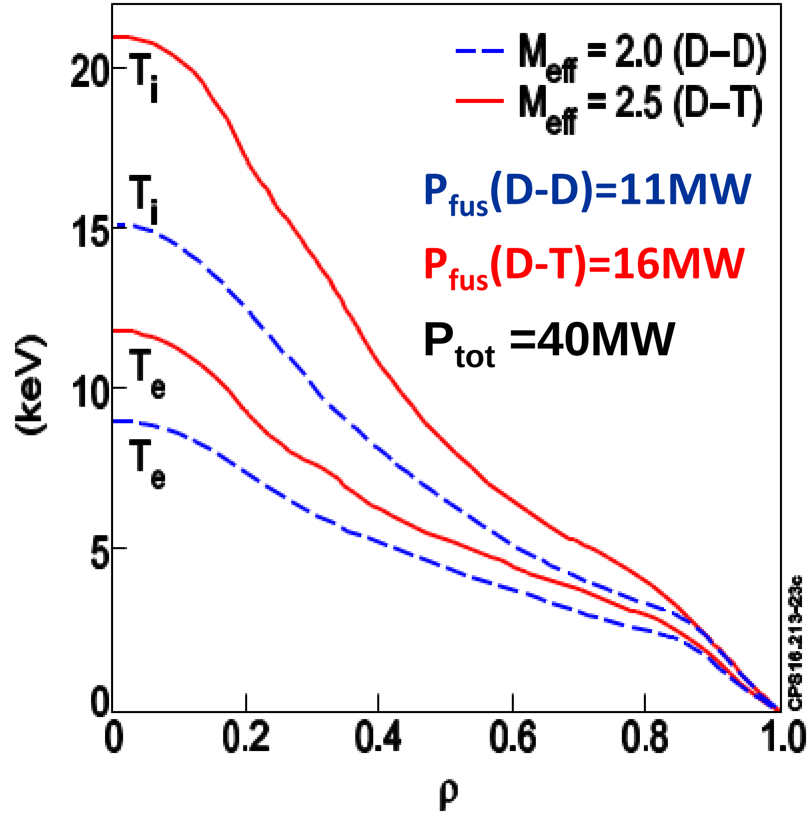
Core transport modelling with TGLF: strong isotope effect on performance to be validated in T-T and D-T experiments

Validation of TGLF in D-D



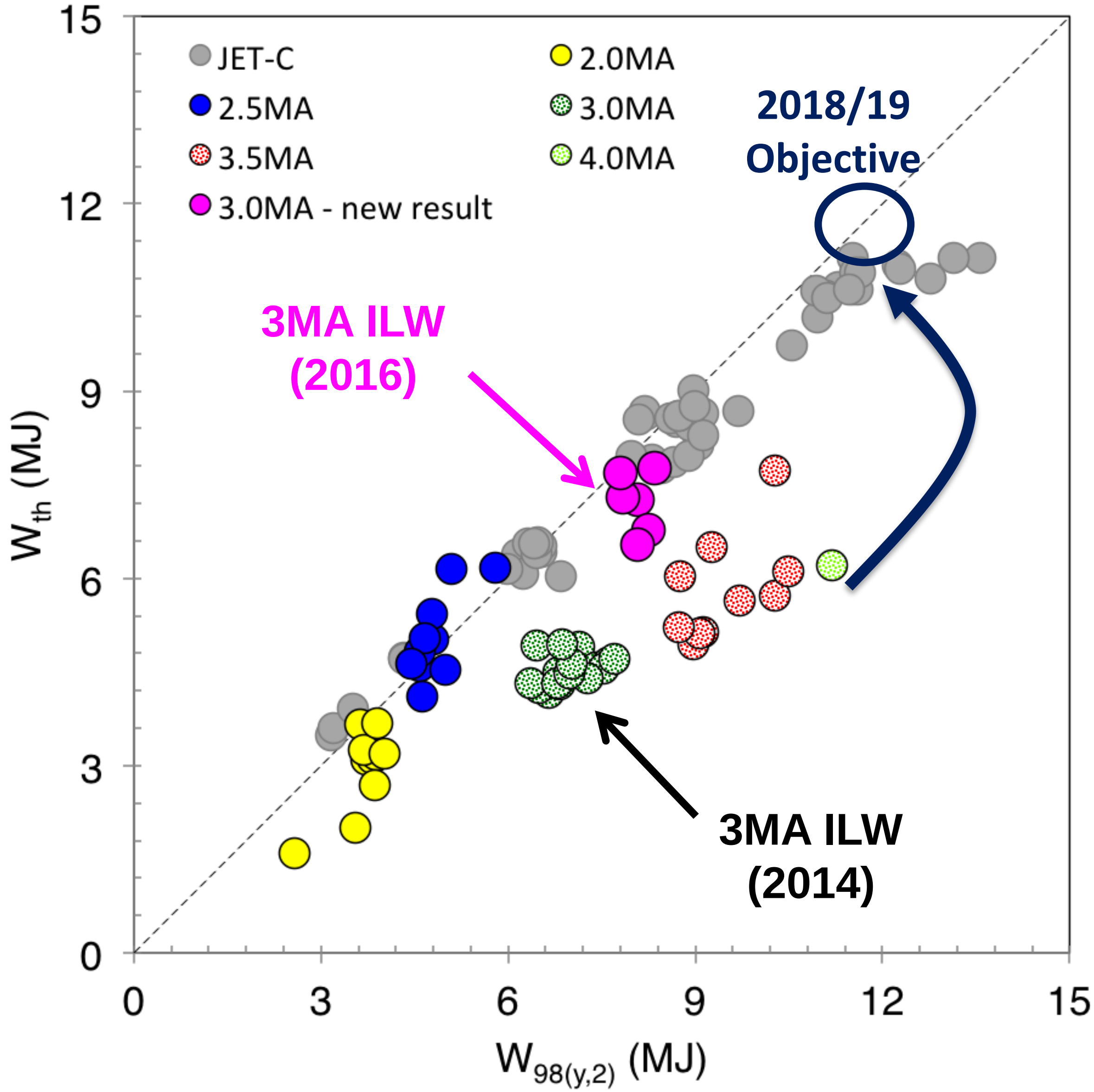
[Hyun-Tae Kim et al FEC 2016 TH/P2-17]

Integrated core/pedestal simulations



[Garcia et al EPS /PPCF 2016 , Budny et al FEC 2016 TH/P2-16, Weisen et al EX/P6-18]

Latest progress ITER Baseline Operation at ~30MW 3MA/2.7T



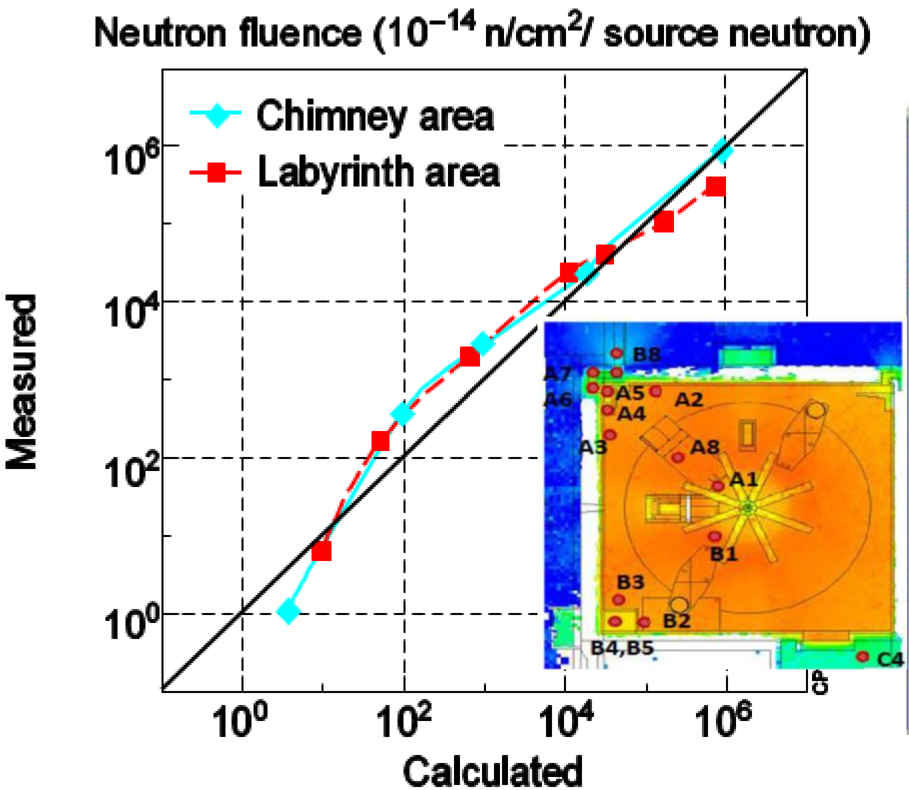
[Nunes PPCF 2016]

[October 2016 Exp.]

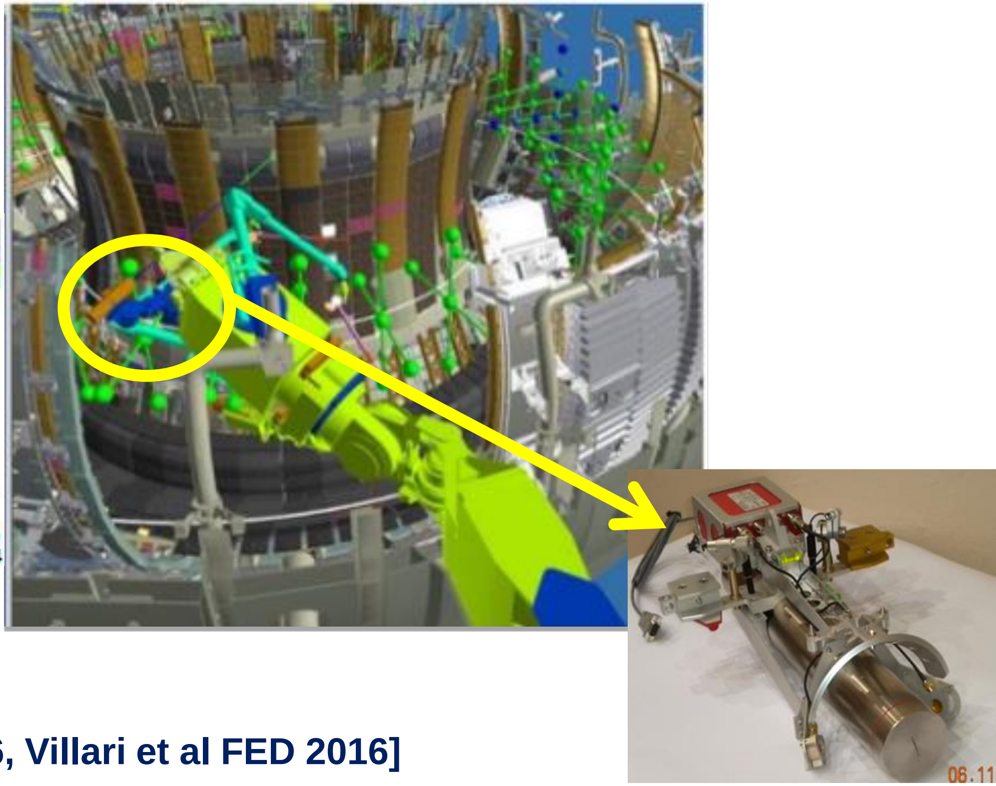
JET

Neutronics for ITER

- **Validation of ITER codes**
  - **Shutdown dose rate and neutron streaming codes**



- **Fusion power measurement procedure for ITER**
  - **Diagnostic calibration with 14MeV neutron source to be deployed by remote handling**



[Batistoni et al Nucl. Fusion 2015 and SOFT 2016, Villari et al FED 2016]

[Horton et al Fusion Eng and Des. 2016]

CONCLUSION

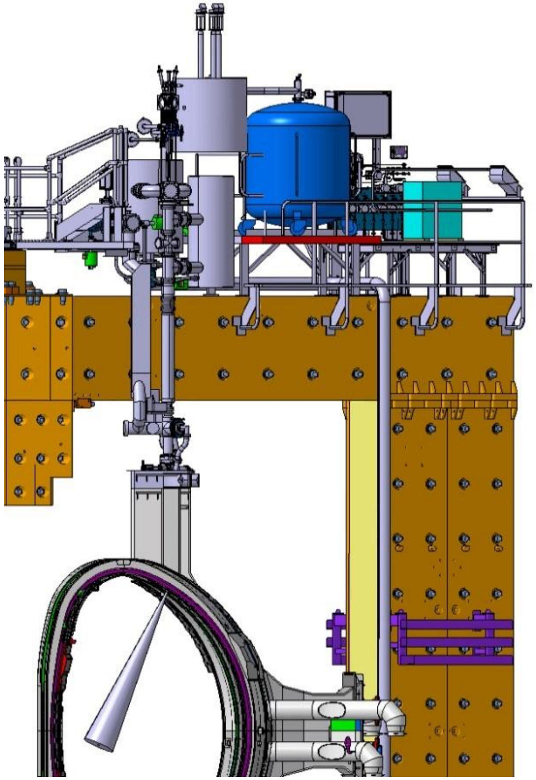
- **JET results impact the preparation of ITER active and non-active integrated operation**
  - **Optimise the path towards ITER Q=10 operation**
  - **Provide a comprehensive "fusion nuclear technology case" with the surrounding tritium, beryllium and remote handling facilities**

- **JET ITER Like Wall operation and its physics understanding require developing an integrated vision**
  - **Wall materials + Plasma Surface Interaction + SOL + Pedestal + Core physics are strongly coupled**
  - **New paradigm to be developed beyond simple scaling**

PROSPECTS

- **Up to 2020, focus remains the completion of T-T (2018) and D-T (2019-20) operation in support of ITER**

- **Mid-Nov. 2016-2017 shutdown**
  - **Upgrade Neutral Beam heating components to improve reliability above 30 MW**
  - **Shattered Pellet Injector for ITER disruption mitigation system (under international collaboration framework)**



- **In parallel, a proposal is being elaborated to extend JET as ITER test-bed facility until the start of ITER operation**

Thank you for your attention on behalf of the EUROfusion contributors

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THE NETHERLANDS

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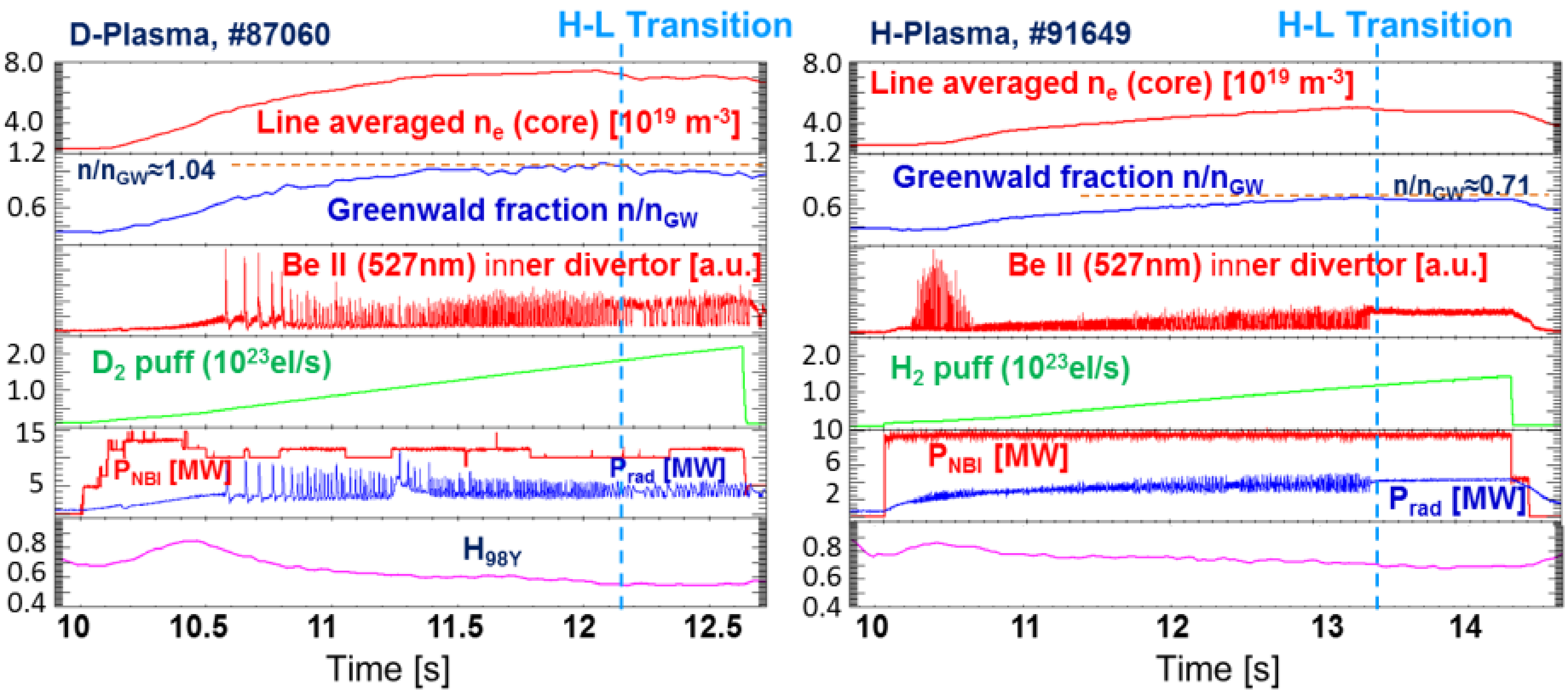
UNITED KINGDOM

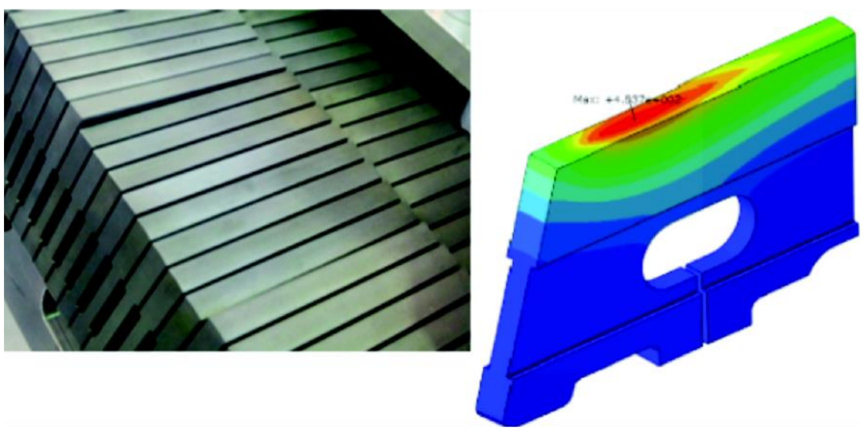
Isotope effect on H-Mode Density Limit

- **Strong dependence on the isotopic mass effect**
  - 35% lower in the H-H vs D-D
  - Similar vertical target magnetic field configuration with I_p/B_T=1.9MA/1.8T and q_{95}=2.8



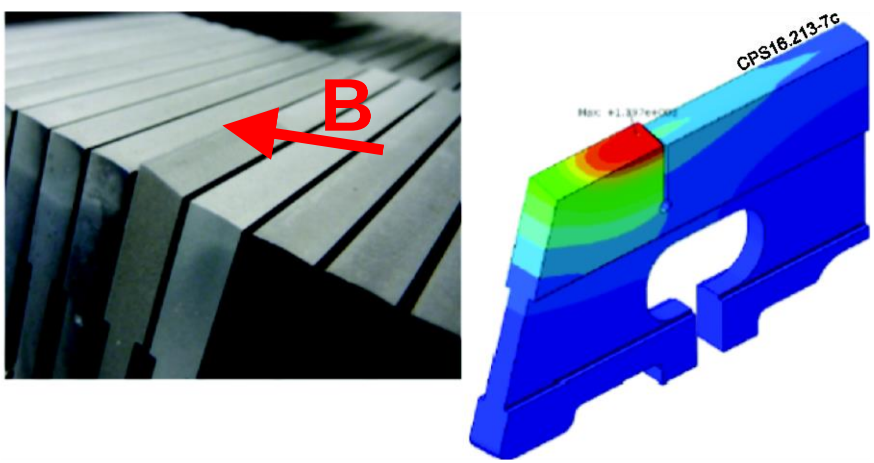
Divertor Heat Load Studies for ITER [1/2]

- **Multiple ELM-induced melting (2013)**
  - **W module with "protruding" lamella (2013)**
  - **2-D thermal analysis could not reproduce IR measurement**



[Coenen et al Nuc Fus 2015, Matthews et al Phys. Scr. T167 2016]

- **New lamella installed (2014-2015 shutdown)**
  - **Improved IR measurement resolution**

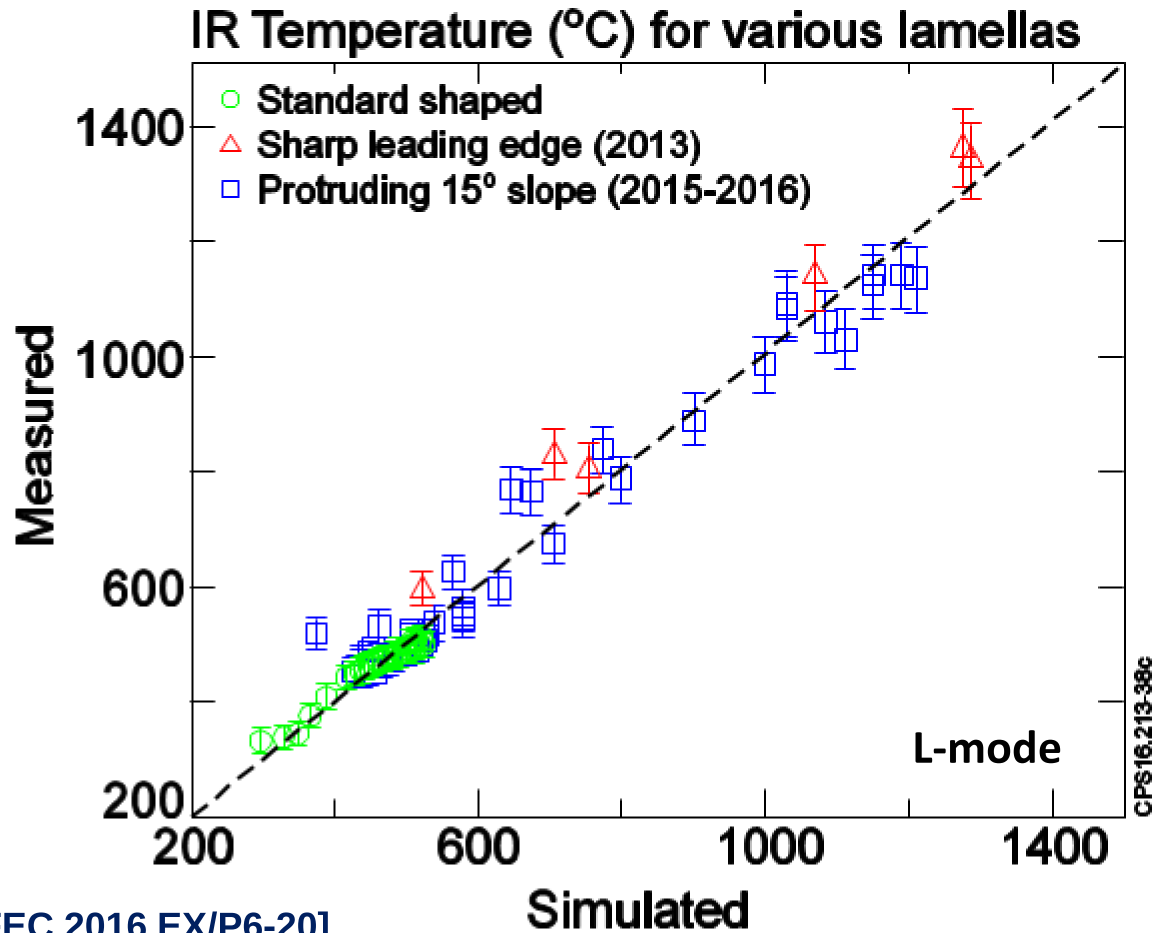


[Corre et al FEC 2016 EX/P6-20]

JET

Divertor Heat Load Studies for ITER [2/2]

Thermal Analysis revisited:
Good agreement with improved 3-D model of the plasma heat load and heat diffusion



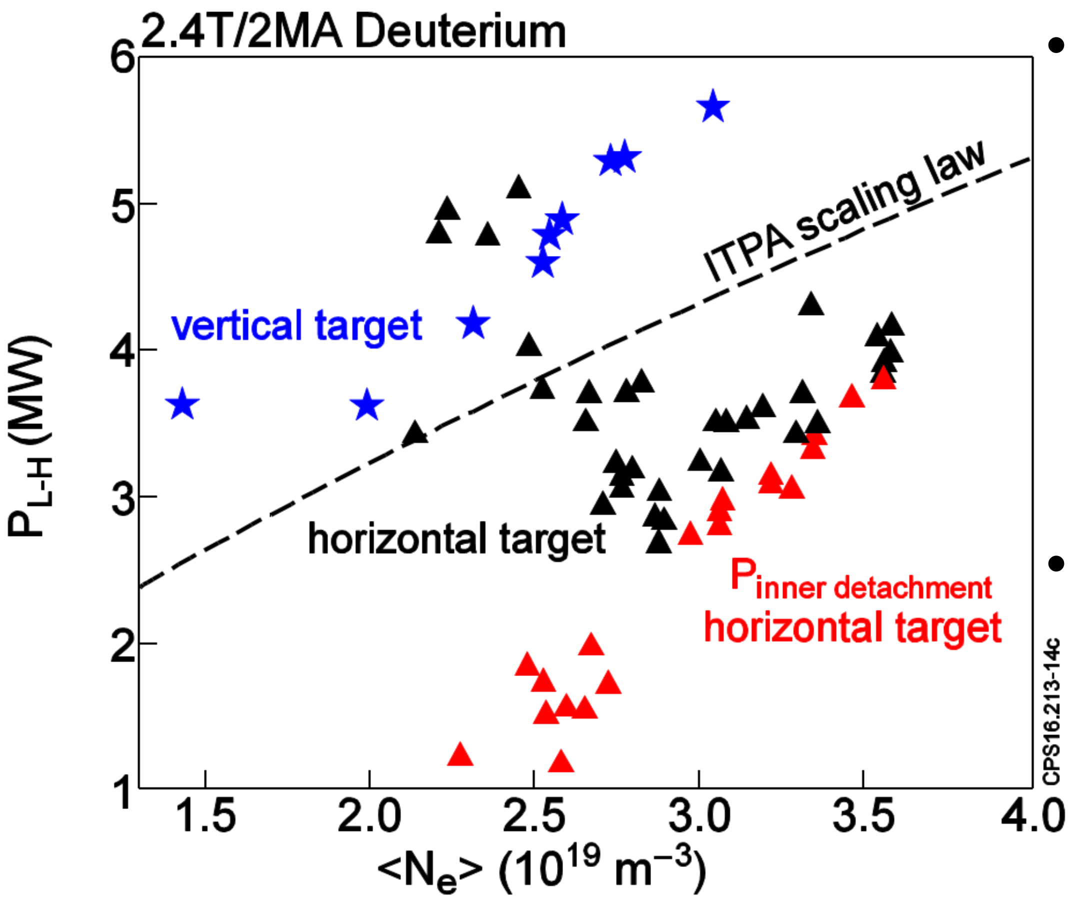
Also on ASDEX Upgrade and COMPASS

[Krieger et al PSI 2016 Dejarnac et al PSI 2016]

[Corre et al FEC 2016 EX/P6-20]

H-mode Access with ITER Wall Materials

Crucial Importance of the SOL physics for L-H transition



[Delabie et al APS 2015]

- **Importance of divertor configuration**
  - **Simulated via changes in SOL $E_r \times B$ in EDGE2D-EIRENE**

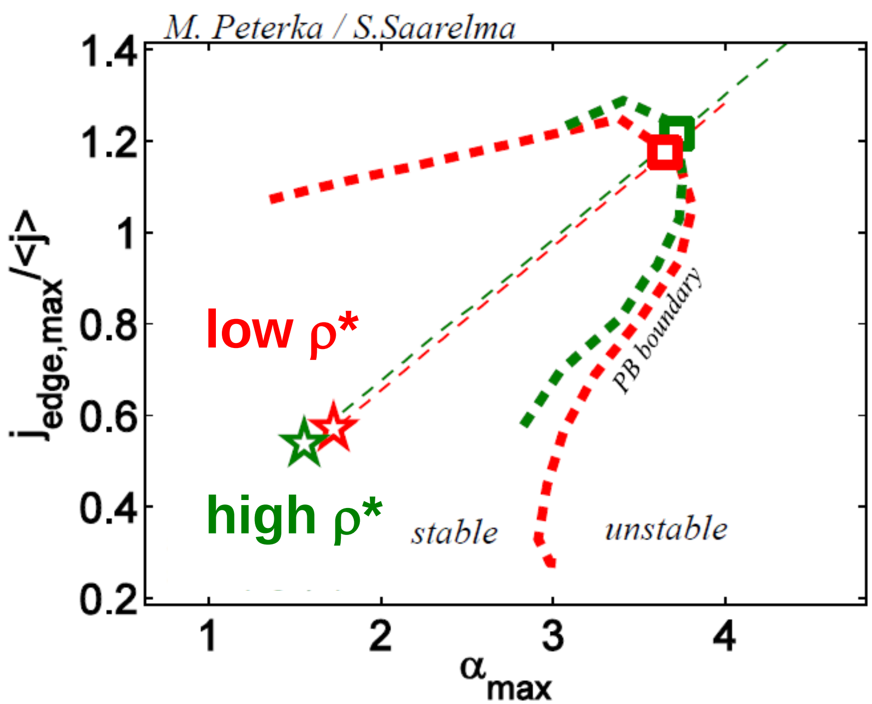
  [Chankin et al PSI 2016]

- **Stationary Zonal Flows measured during edge barrier formation**

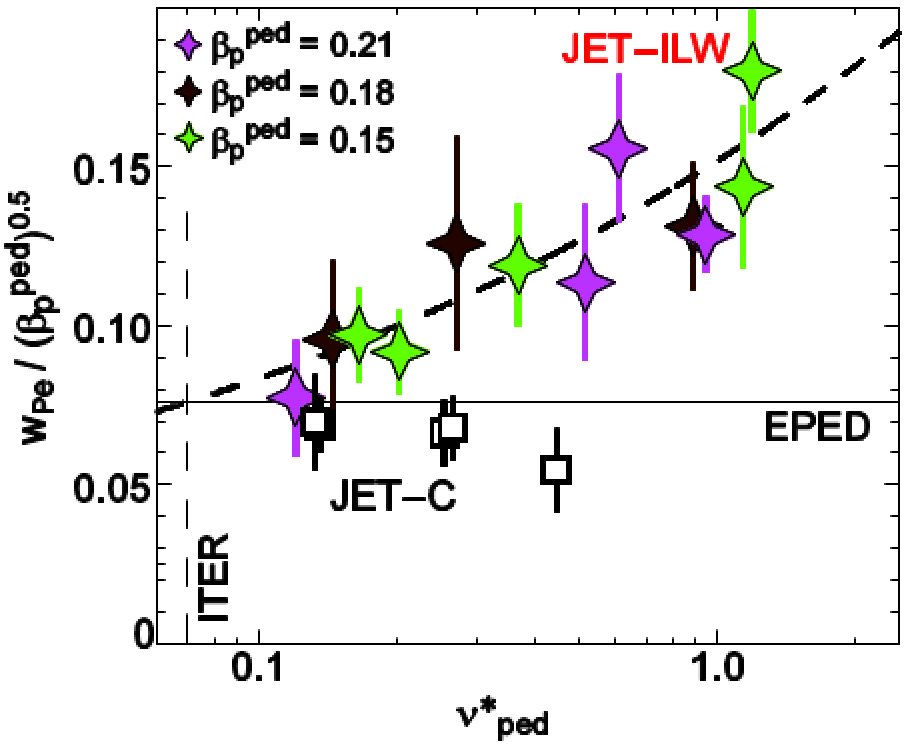
  [Hillesheim et al PRL 2016
  Hillesheim et al FEC 2016 EX/5-2]

Pedestal confinement

- ρ^* scaling:
  - no degradation at low ρ^*
  - good for ITER extrapolations



- ν^* scaling:
  - stability increase at low ν^*
  - role of atomic physics ?



[Frassinetti et al EPS/PPCF 2016] [FEC 2016 : Maggi et al EX/3-3, Chapman et al EX3-6, Urano et al EX/3-4, Aiba et al TH/8-1, Pamela et al TH 8-2]