EUROfusion

Overview of JET results for optimising ITER operation

J. Mailloux on behalf of JET contributors
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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 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

JET in support of ITER

JET's currently unique set of capabilities:

- Tritium handling
- ITER-like wall (ILW): Be wall and W divertor
- Shattered Pellet Injection (SPI) system
- $R = 3.5\text{m}$, $I_P \leq 4\text{MA}$ & $P_{NBI+ICRH} \leq 40\text{MW} \rightarrow W_P = 12\text{MJ}$
- High D-D & D-T n fluence,

+ Improved set of diagnostics (incl. energetic particles, turbulence, main chamber & divertor impurity spectroscopy, etc)

Focus of plasma programme in 2019-2020:

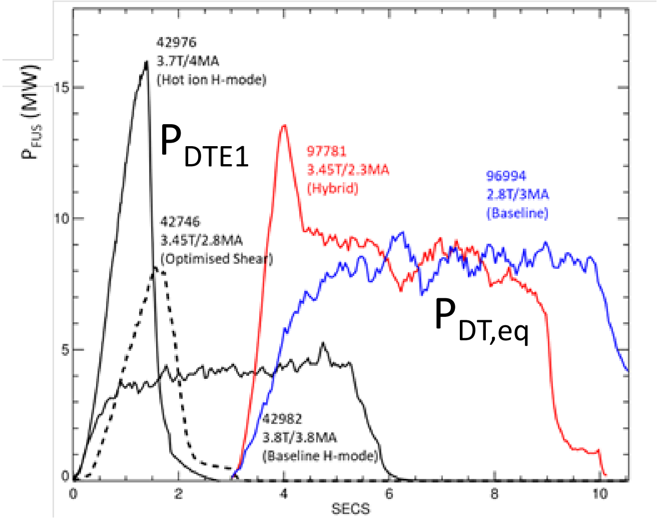
- Preparation for tritium and D-T campaigns
- Disruption and Runaway Electron mitigation with SPI in support of ITER DMS

Outline of selected highlights from 2019-2020

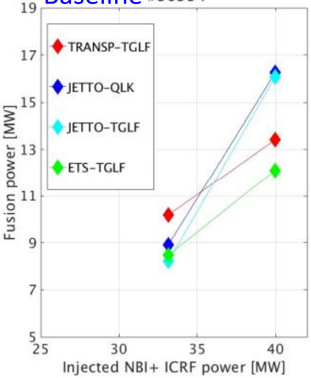
1. Preparation of integrated scenarios for D-T
2. JET SPI results
3. Impact of isotope
4. Long term exposure of Plasma Facing Components in JET-ILW
5. Nuclear technology: exposure to high neutron fluence
6. Summary

+ List of JET contributions at this conference

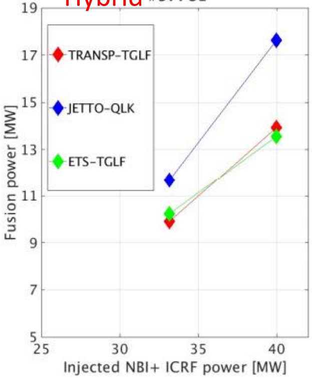
Scenarios for sustained high P_{D-T}



Baseline #96994



Hybrid #97781

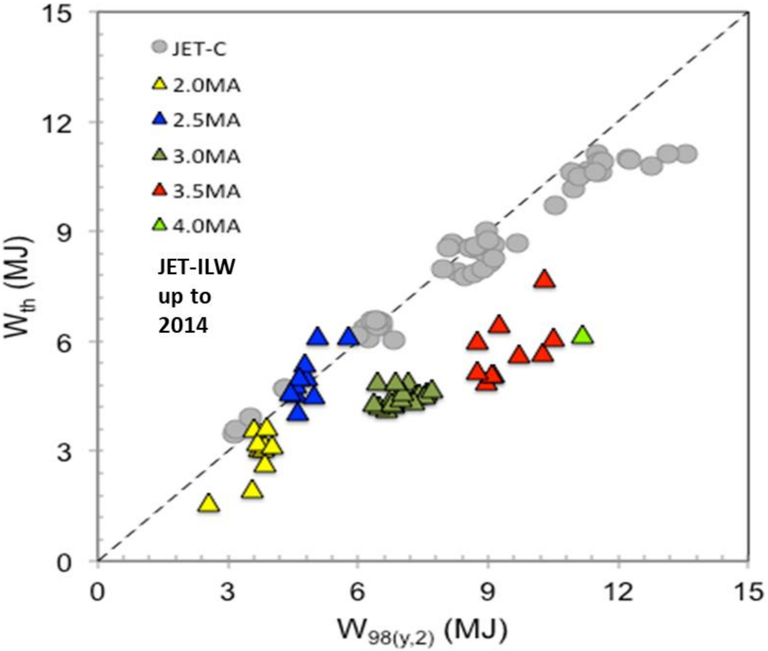


- $P_{DT,eq}$ calculated assuming D thermal profiles but D-T NBI and plasma:
  - Recent plasmas far exceeds sustained fusion power achieved in DTE1
- P_{DT} ~12MW-17MW predicted when including isotope and energetic particle effects

Plasmas ready for DTE2

J. Garcia *et al*, EX/1

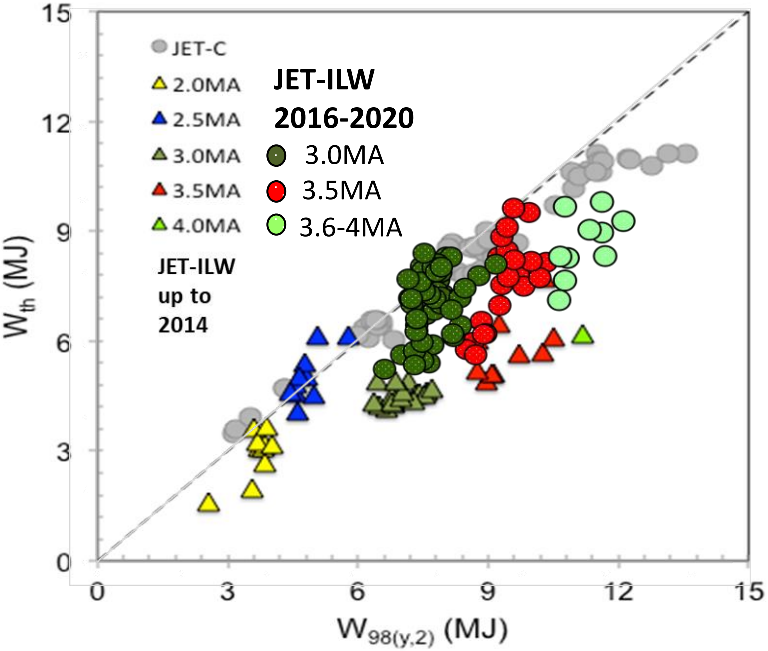
Baseline plasma development to high I_P



I. Nunes, IAEA 2014

- **ILW up to 2014**: lower confinement for I_P>2.5MA than equivalent plasmas in JET with C-wall

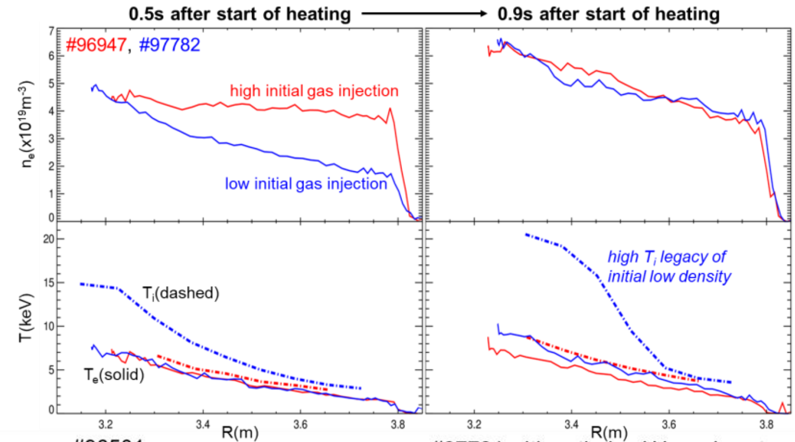
Baseline plasma development to high I_P

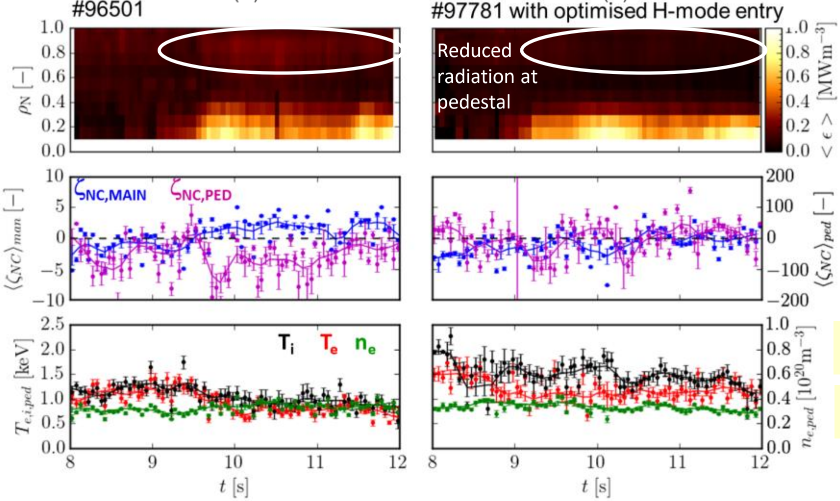


- **ILW up to 2014**: lower confinement for I_P>2.5MA than equivalent plasmas in JET with C-wall
- **ILW 2016**: Confinement recovered at 3MA, thanks to:
  - Pellets for ELM pacing for impurity flushing
  - Low gas dosing, for improved pedestal and core confinement
- **ILW 2019-2020**: successful recipe extended to 3.5MA, with clear progress at 3.6-4MA

High performance at high I_P compatible with ILW

Hybrid H-mode entry key to sustained performance





- Hybrid entry to H-mode optimised with low initial gas for access to:
  - low initial edge n_e
  - high edge and core T_i
  - low plasma radiation
  - high thermal and total fusion power

  Leads to steady high performance and impurity control

- **For the first time, evidence of W screening at pedestal as predicted for ITER[1]**

A. Field *et al*, in preparation

J. Garcia *et al*, EX/1

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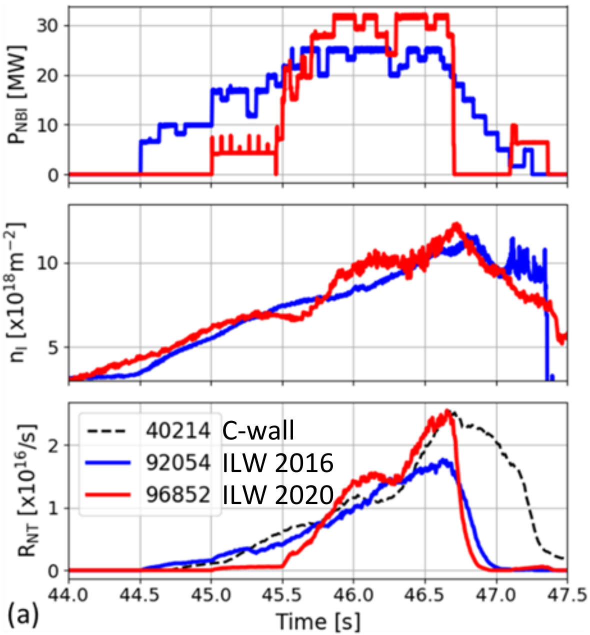
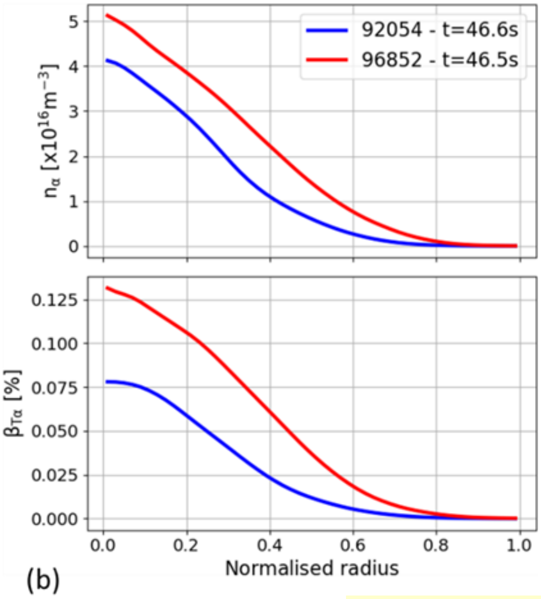
[1] R. Dux *et al.*. Nucl. Materials and Energy 12 (2017)

High q_{min} scenario for α-driven TAE in DT

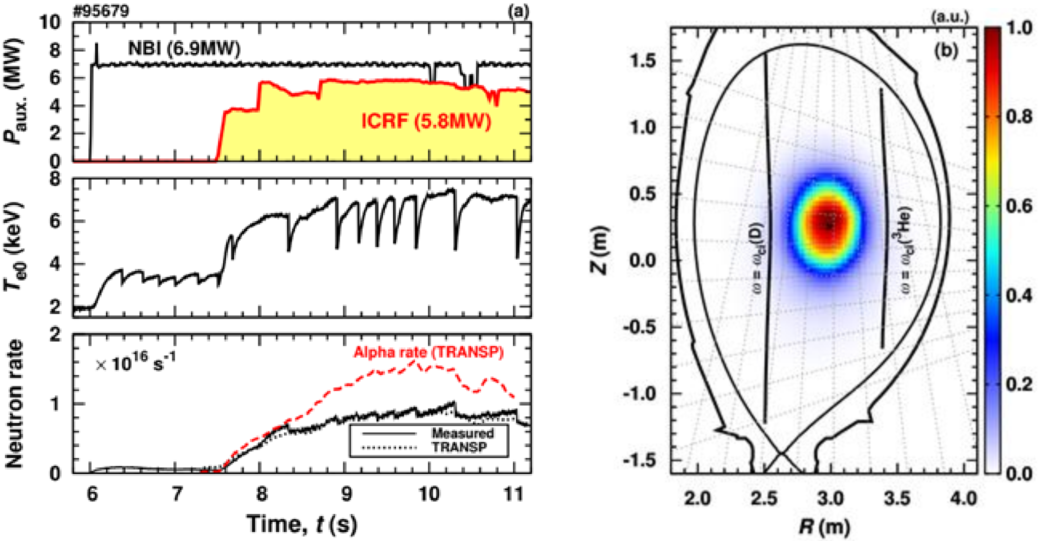




R. Dumont *et al*, EX/8

- Highest neutron rate in NBI-only plasma, based on ITB at q=2
- Afterglow phase triggered in real-time at neutron rollover
- High α pressure predicted → **will test α-driven TAE predictions in DTE2**

Good progress with 3-ions scheme



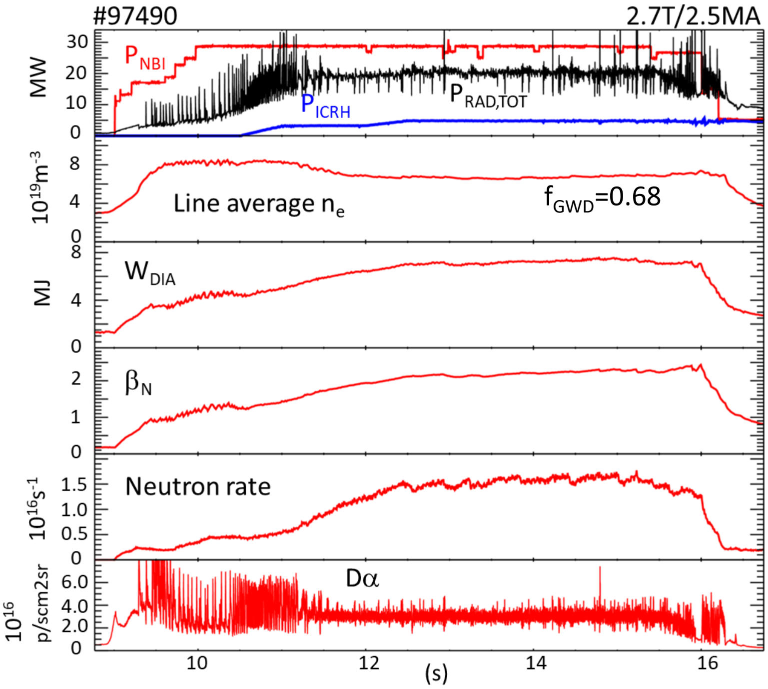
D-^{3}He fusion-born α (tomographic reconstruction of γ emission with new detectors)

- D-(D$_{NBI}$)-^{3}He scheme used to generate α & demonstrate new diagnostic capabilities
- MeV ions = strong e-heating → transport relevant to ITER with α heating
- Also demonstrated ^{4}He-(^{3}He)-H heating of plasmas in H + ^{4}He

→3-ion scheme versatile tool for physics studies

Y. Kazakov *et al*, P/4-1231
M. Nocente *et al.*, P/3-1106

Seeded scenario with high core performance



δ_{UP}=0.4, strike-point on vertical divertor tiles

C. Giroud *et al.*, P/3-977

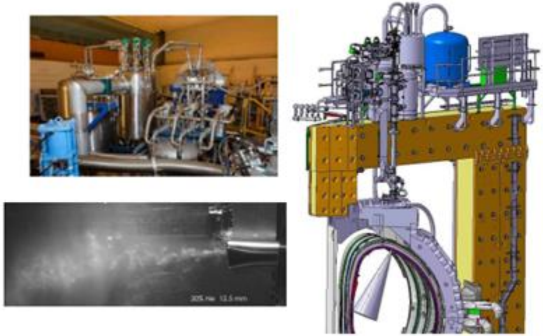
- For the first time, plasma with Neon seeding shows high core performance (P_{TOT} = 33MW, $H_{98(y,2)}$~0.9 & f_{RAD}=0.72) with small ELMs and partially detached divertor
- Compared to N_2, Ne leads to:
  - higher $T_{i,PED}$ & lower $n_{e,PED}$
  - higher P_{FUS} at same W_P
- SOLPS-ITER divertor target profile and radiation distributions show fair agreement with experiments

E. Kaveeva *et al.*, PSI 2020
V. Rozhansky *et al.*, TH/3

→ Suggests Neon suitable as seed gas for ITER

2- Experiments exploiting JET SPI

JET Shattered Pellet Injection system



L. Baylor *et al.,* NF 2019 & TECH/1-7

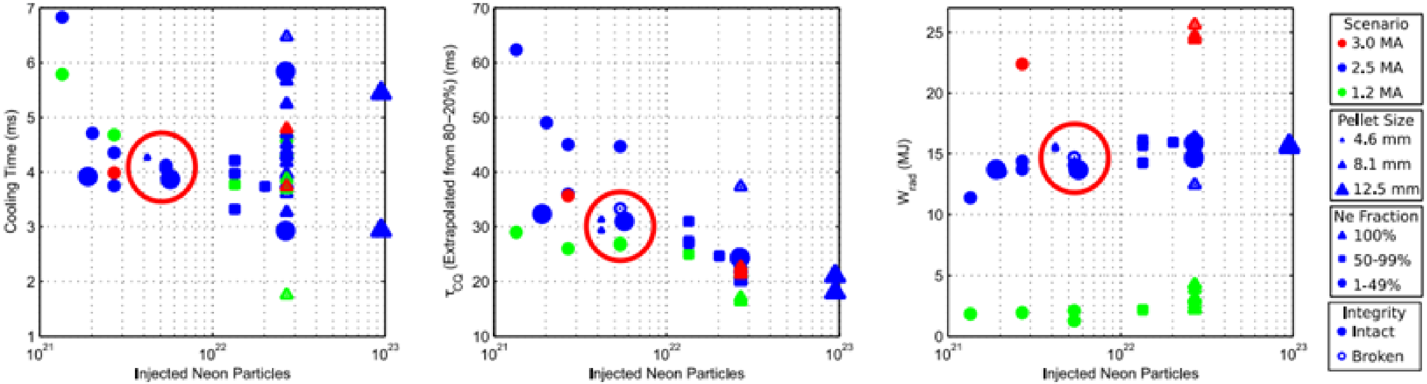
Collaboration ITER organization, US DOE, EUROfusion and JET Operator

Main characteristics:

- Three-barrel injector
- Vertical SPI mounting tube with shatter plume aimed toward the plasma to intercept RE
- Ne, D, Ar and mixed pellets
- Variable Pellet velocity, hence shards size and speed

Wide ranging set of experiments performed in 2019-2020 with good SPI reliability though with some pellets breakage

SPI successfully reduces disruption thermal load

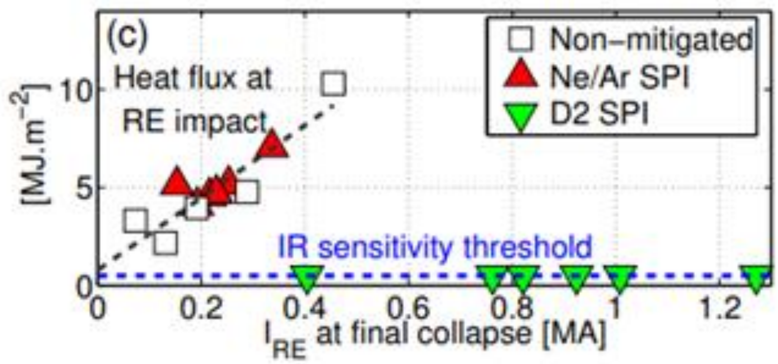


Red circles: fixed neon content in three pellet sizes

- Disruption current quench time controlled by varying neon content in SPI pellets, covering range required by ITER
- Pellet integrity and size has only a minor impact on the current quench
- duration
- Experiments extended to 3MA / 7 MJ H-mode plasmas → unique dataset for ITER in terms of magnetic and thermal energy

S. Jachmich *et al.*, EX/5-TH/6
U. Sheikh *et al.*, P/3-921

RE suppression demonstrated with D_2 SPI



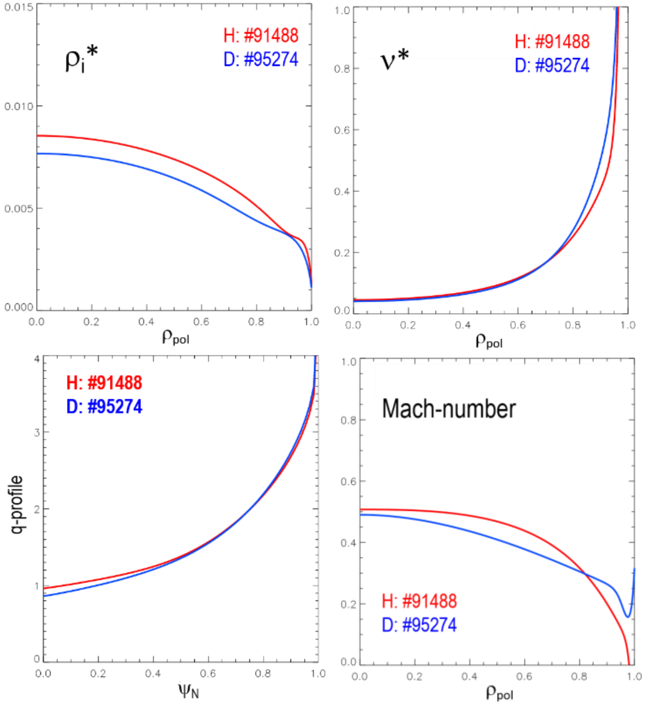
C. Reux *et al* accepted for publication in PRL
S. Jachmich *et al.*, EX/5-TH/6

- RE suppression with SPI demonstrated
- D_2 SPI applied to high current RE beam leads to benign impacts on the first wall
  - RE beams of up to 1.5MA safely terminated by sustaining RE beam for more than 2.6s, with controlled I_P ramp-down, with D_2 SPI
  - Also shown in ITER relevant scenario of a vertically moving beam

→ D_2 SPI potential new solution for RE control in ITER

3 – Selected highlights from impact of isotope and plasma species

Isotope identity achieved in D and H L-mode and H-mode



Exploiting the change in isotope mass A = mi/mp, L-mode and type I ELMy H-mode pairs obtained in **H and D with similar dimensionless profiles**

Predictive flux driven simulations of core transport in good agreement with experiment: stiff core heat transport overcomes local gyro-Bohm scaling of TGLF, explaining

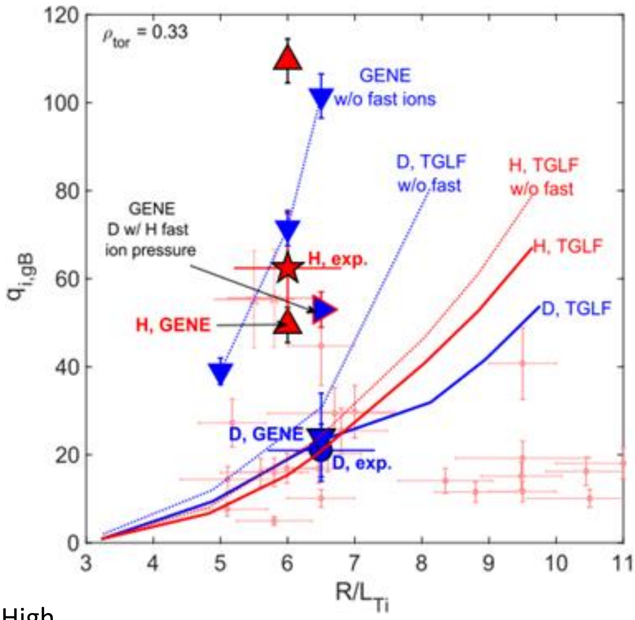
- **Lack of isotope mass dependence of core confinement in L-mode**
- **Increase of confinement with A in H-mode, originating in pedestal region**

CF Maggi *et al.*, Nucl Fusion 2019

CF Maggi *et al.*, talk EX/6

Impact of EP on core transport differs in D & H plasmas

D_2 H_2



High heating case

N. Bonanomi *et al*, NF 2019

- Isotope effects in plasma core can be large in regimes with high Fast Ion (FI) content, beta and rotation [J. Garcia, NF 2018].

  Impact of FI studied in D and H L-mode plasmas by varying IC ^{3}He resonance

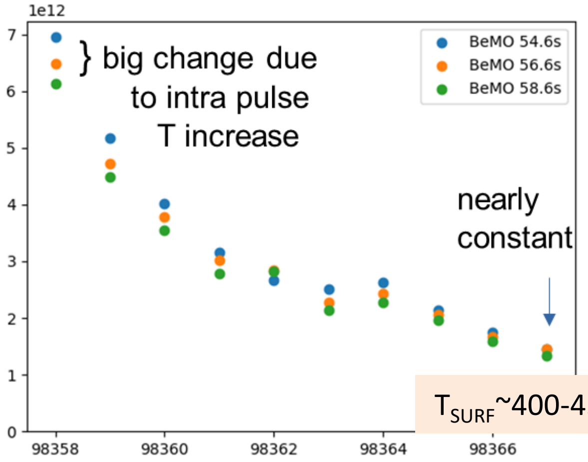
  Isotope mass affects FI pressure gradient via:
  - Heating deposition
  - FI slowing down time

  Core GK modelling (GENE) show that **differences in FI in H vs D lead to strong deviations from GB scaling of core transport**
  - Discrepancy of TGLF-SAT results in H motivated TGLF model revision

CAPS suppression at Be limiters demonstrated in H

CAPS molecules (BeH) radiation,
via A-X 498 nm band intensity

T_{SURF}~180-250^{0}C



T_{SURF}~400-450^{0}C

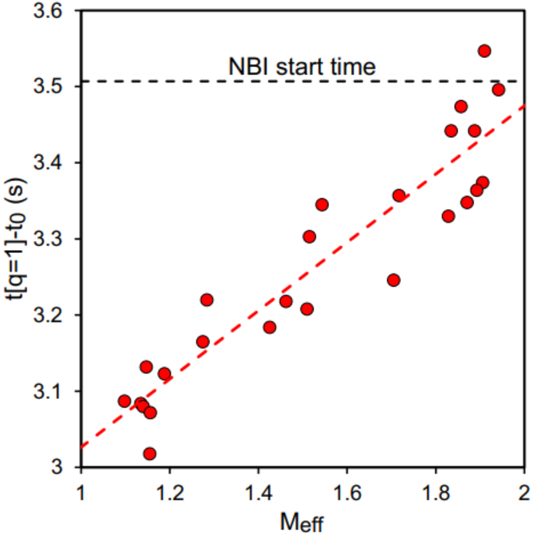
- Full suppression of chemically assisted physical sputtering at Be limiter in H plasmas occurs at T_{SURF}~400-450^{o}C, similar to D, and consistent with predictions [E. Safi *et al.* J. Phys. D: Appl. Phys. 50 (2017)] : **no isotope impact on temperature for CAPS suppression**
- Data used to validate plasma backgrounds in plasma-wall interaction codes such as ERO2.0, now including diagnostics lines of sight & surface roughness

D. Borodin *et al*., 47th EPS 2021

J. Romazanov *et al*., P/4-1029

Isotope mass impacts Hybrid q-profile evolution

H+D plasmas

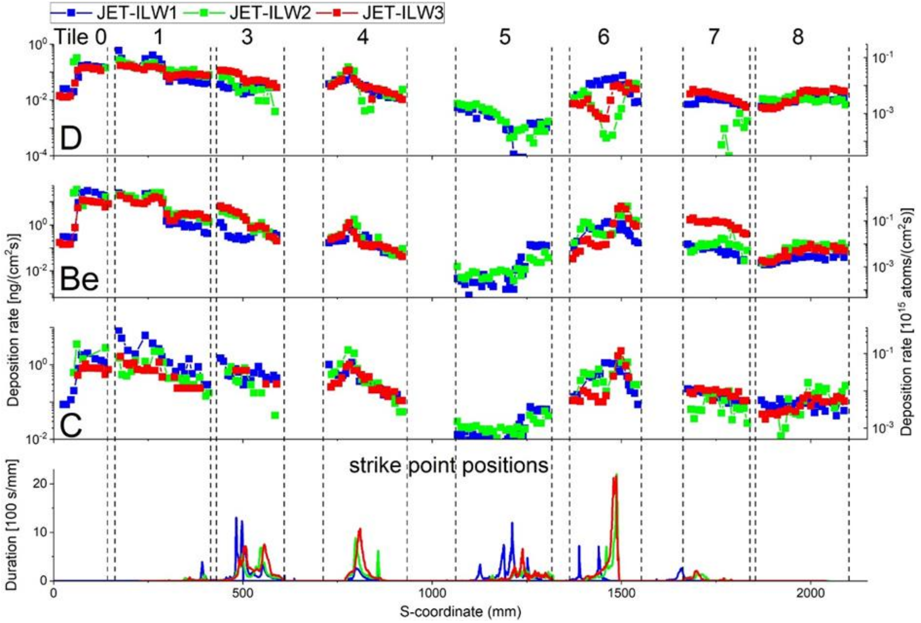


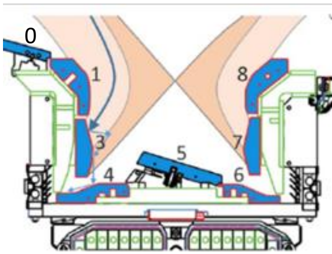
C. D. Challis *et al* NF 60 (2020) 086008

- q_0 at start of current flat-top increases with main ion isotope mass
  - Caused by increased central impurity radiation due to changes in sputtering and transport → reduced $T_{e0}/\langle T_e \rangle$
  - Excessive central cooling can lead to shear reversal ➔ 2,1 double tearing modes ➔ locked mode & disruption
- Recent tritium experiments confirm empirical extrapolation and modelling predictions:
  - **Increasing isotope mass slows q-profile evolution**
  - Desired q-profile recovered by increasing n_e & thus $T_{e0}/\langle T_e \rangle$

4 – Long term exposure of Plasma Facing Components in ILW environment

Material migration & fuel retention in W & W-coated divertor tiles

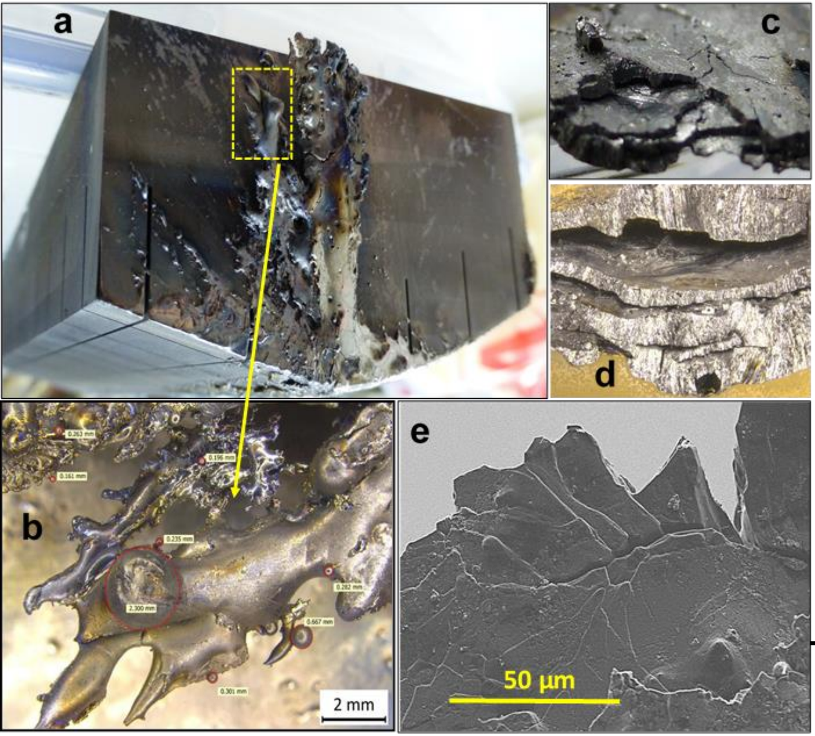




S. Krat *et al.,* Phys. Scr. T171 (2020)

- D content consistent with strike-point location, likely due to higher peak surface T and low compared to JET-C → **confirms lower fuel retention of JET-ILW**
- Significant reduction of C deposition campaign-to-campaign (absolute amount and accumulation rates) → **no damage to W coated tiles**

Analysis of Upper Dump Plates (UDP) Be melting and splashing



(a) Melt damage across poloidal direction on UDP-8; (b) close-up on waterfall-like Be flake with (c) cracked and (d) stratified structures; (e) electron micrograph revealing detailed features.

- Fast transient damage to Be UDP due to rare unmitigated disruptions (VDEs)

I. Jepu *et al.*, NF 59 (2019)

- Very small Be dust amount in ILW - consistent with strong adherence of splashed Be droplets to surfaces and no impact to loose dust formation.

M. Rubel et al., Phys. Scr. T171 (2020)

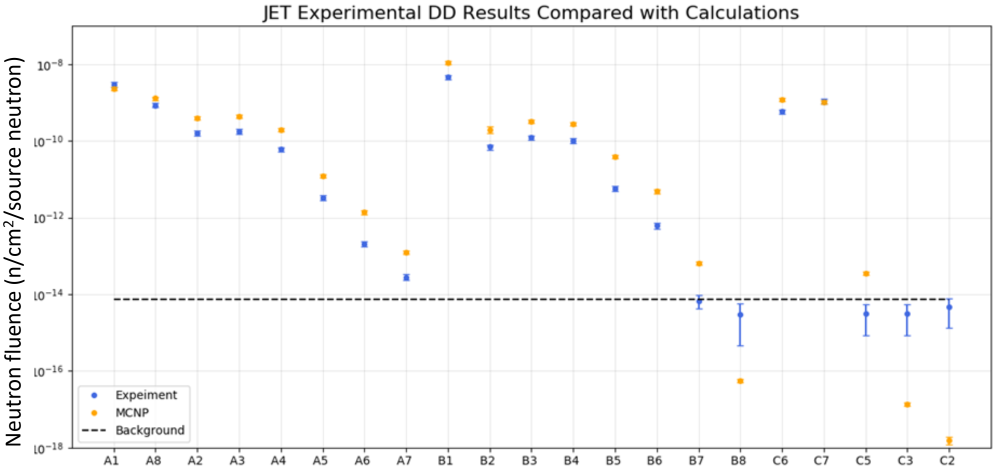
- Code MEMOS-U reproduces the key processes involved in melt motion

S. Ratynskaia *et al.*, NF 60 (2020)

5 – Material exposure to high neutron fluence

Neutron Streaming Experiment validates neutron calculations

- Neutron detectors at 22 locations in torus hall exposed to neutron yields of $3.68\text{x}10^{19}$ to $5.18\text{x}10^{19}$ n during D campaigns



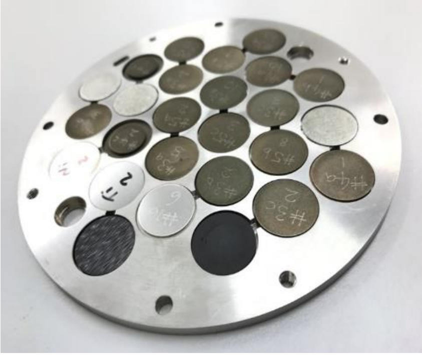
3 sets of detectors, each shown in increasing distance from torus

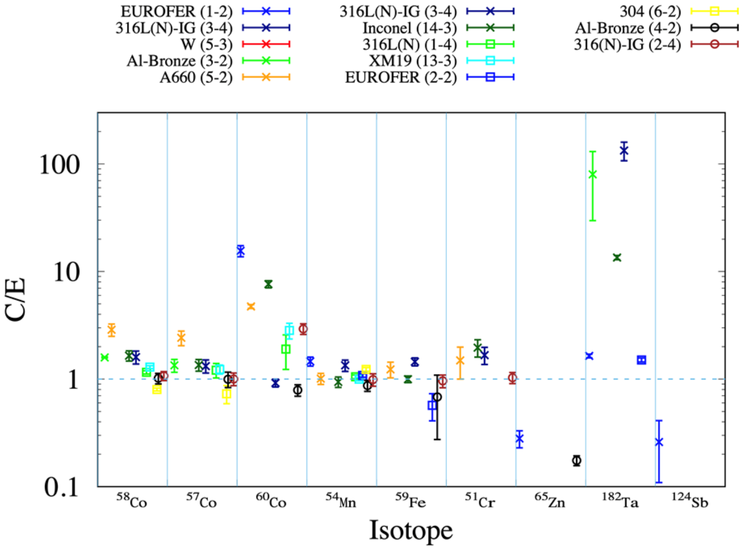
J. D. Naish *et al.*, submitted to Fusion Eng. Design

- Neutron fluence calculated with MCNP coupled with ADVANTG:
  - Good agreement over large range of n fluence
  - Overestimated fluence for largest distances due to lack of detailed Torus Hall equipment description
- More accurate measurements expected for highly shielded locations from higher neutron yield and energy during DTE2

Neutron induced activation and damage in ITER materials

Samples in long term irradiation station holder





- 27 samples of real ITER materials provided by F4E exposed to ~2×10^{14} n/cm^2, e.g.:
    - EUROFER 97-3 steel (coil casings, etc)
    - Inconel 718, CuCrZr and 316L SS for blanket modules
    - NbSn toroidal field coil strands
- Neutron induced activity measurements allow to identify samples' composition, with evidence of impurity found, e.g ^{182}Ta → Ta impurity present in Inconel analysed
- Samples will be exposed to 14MeV neutrons in DTE2

L. W. Packer, P/7-1297

Summary & outlook

- The preparation for T and DT operations is complete:
  - Technical & procedural preparation for safe operation with tritium
  - Plasmas to be run in T and DT
- The scenario development expanded ILW parameter space, leading to new physics, e.g. W screening in hot pedestal, small ELMs scenarios, Ne comparing favourably to N_2 as seed gas
- A wide range of experiments on isotope impact confirmed or challenged assumptions and models used for predicting ITER
- JET SPI experiments provided ITER with important information for preparing its DMS
- JET unique environment provided key results for PFC and nuclear technology, in support of validating assumptions and codes for the design & operation of ITER and DEMO.

The tritium campaign with T-NBI is underway, with D-T campaign from July 2021

Talks including JET material at IAEA-FEC

11th May

- J. Garcia *et al*., Integrated scenario development at JET for DT operation and ITER risk mitigation
- L.R. Baylor *et al*., Design and Performance of Shattered Pellet Injection Systems for JET and KSTAR Disruption Mitigation Research in Support of ITER

12th May

- V. Rozhansky *et al*., Multi-machine SOLPS-ITER comparison of impurity seeded H-mode radiative divertor regimes with metal walls
- L. Frassinetti *et al*., Role of the separatrix density in the pedestal performance in JET-ILW and JET-C
- E.R. Solano *et al.,* L-H transition studies at JET: H, D, 4He and T

13th May

- E. de la Luna *et al*., Exploring the physics of a high-performance H-mode with small ELMs and zero gas puffing in JET-ILW

14th May

- S. Jachmich *et al*., Shattered Pellet Injection experiments at JET in support of the ITER Disruption Mitigation System design
- E. Nardon *et al*., Theory and Modelling activities for the ITER Disruption Mitigation System
- C. F. Maggi *et al*., Isotope identity experiments in JET with ITER-like wall
- S. Henderson et al., Experimental impurity concentrations required to reach detachment in AUG and JET

15th May

- R. Dumont *et al*., Scenario preparation for the observation of alpha-driven instabilities and transport of alpha particles in JET DT plasmas

Posters with JET material at IAEA-FEC

Experiments and modelling with SPI

- U. Sheikh et al., Disruption Thermal Load Mitigation with JET SPI
- C. Paz-Soldan et al., A Novel Path to Runaway Electron Mitigation via Deuterium Injection and Current-Driven Kink Instability
- M. Hoppe et al., Polarized synchrotron radiation as a tool for studying runaway electrons
- M. T. Beidler et al., Spatially Dependent Simulations and Model Validation of Runaway Electron Dissipation Via Impurity Injection in DIII-D and JET Using KORC
- D. Shirake et al., DIII-D and International Research Towards Extrapolating Shattered Pellet Injection Performance to ITER

Disruption avoidance

- C. Sozzi et al., Termination of discharges in high performance scenarios in JET
- W. Tang et al., Implementation of AI/deep learning disruption predictor into a plasma control system

Disruption and runaway electron modelling

- S. C. Jardin et al., Vessel Forces from a Vertical Displacement Event in ITER
- T. Fullop et al., Towards self-consistent modelling of runaway dynamics in tokamak disruptions

Turbulent transport

- N. Kumar et al., Investigation of Turbulent Transport in the Inner core of JET H-mode Plasmas and Applications to ITER
- A. Mariani et al., Experimental Investigation and Gyro-kinetic Simulations of multi-scale electron heat transport in JET, AUG and TCVN.
- Kumar et al., Investigation of Turbulent Transport in the Inner core of JET H-mode Plasmas and Applications to ITER
- L. van de Plassche et al., Fast modelling of turbulent transport in fusion plasmas using neural networks
- J. Citrin et al., Predict First: flux-driven multi-channel integrated modelling over multiple confinement times with the gyrokinetic turbulent transport model QuaLiKiz

Posters with JET material at IAEA-FEC

Integrated scenario development for DT & analysis

- C. Giroud *et al*., High performance ITER-Baseline Discharges in Deuterium with nitrogen and neon seeding in JET-ILW.
- S. Nowak *et al*., Predictive dynamics of tearing modes for plasma stability in DT and TT scenarios considering JET Baseline and Hybrid discharges with mixture of isotopes
- I. Ivanova-Stanik *et al*., Influence of the impurities in the hybrid discharges with high power in JET ILW
- G. Telesca *et al*., Impurity behavior in JET-ILW plasmas fuelled with gas and/or with pellets: a comparative study with the transport code COREDIV
- H.-T. Kim et al., Verification and validation of plasma burn-through simulations in preparation for ITER first plasma

RF schemes for DT and ITER

- M. J. Mantsinen *et al*., Recent key contributions of ICRF heating in support of plasma scenario development and fast ion studies on JET and ASDEX Upgrade
- Y. Kazakov *et al.,* Recent applications of 3-ion ICRF schemes on ASDEX Upgrade and JET in support of ITER
- L. Colas *et al*., The geometry of ICRF induced wave-SOL interaction: a multi-machine experimental review in view of ITER operation

Preparation of diagnostics and analysis tools for DT

- J. Figueiredo et al., Overview of JET Diagnostic Enhancements Experimental Results in Preparation for Scientific Exploitation During DT Operations
- P. Siren et al., JETPEAK-ASCOT: Database-coupled user interface and intershot capability for fast particle analysis and DT extrapolation
- Z. Stancar et al., Experimental validation of an integrated modelling approach to neutron emission studies at JET

JET D-T expertise

- A. Murari et al., Preparation for the Systematic use of D-T in the Next Generation of Tomakaks on JET

Posters with JET material at IAEA-FEC

Impact of isotope and plasma species

- P. A. Schneider et al., The dependence of confinement on the isotope mass in the core and the edge of AUG and JET H-mode plasmas
- H. Weisen et al., Analysis of the inter-species power balance in JET plasmas
- T. J. J. Tala et al., Comparison of Particle Transport and Confinement Properties between the ICRH and NBI heated Dimensionless Identity Plasmas on JET
- M. Valovic et al., Control of H/D isotope mix by pellets in H-mode plasma in JET
- M. Marin et al., First-Principle-Based integrated modelling of multiple isotope pellet cycles at JET

Pedestal and divertor physics

- D. Hatch et al., Understanding pedestal transport through gyrokinetic and edge modelling
- C. Ham et al., Understanding reactor relevant tokamak pedestals
- N. Vianello et al., SOL profile and fluctuations in different divertor recycling conditions in H-Mode plasmas
- J. Dominski et al., Influence of tungsten on pedestal physics in JET-ILW simulations using XGC
- C. S. Chang et al., New predictive scaling formula for ITER’s divertor heat-load width informed by gyrokinetic simulation, physics discovery, and machine learning
- M. Kotschenreuther et al., Regimes of weak ITG/TEM for transport barriers without velocity shear
- H. Sun et al., The role of edge plasma parameters in H-mode density limit on the JET-ILW
- L. Aho-Mantila et al., Role of drifts, impurities and neutrals for credible predictions of radiation and power flux asymmetries in the DEMO scrape-off layer

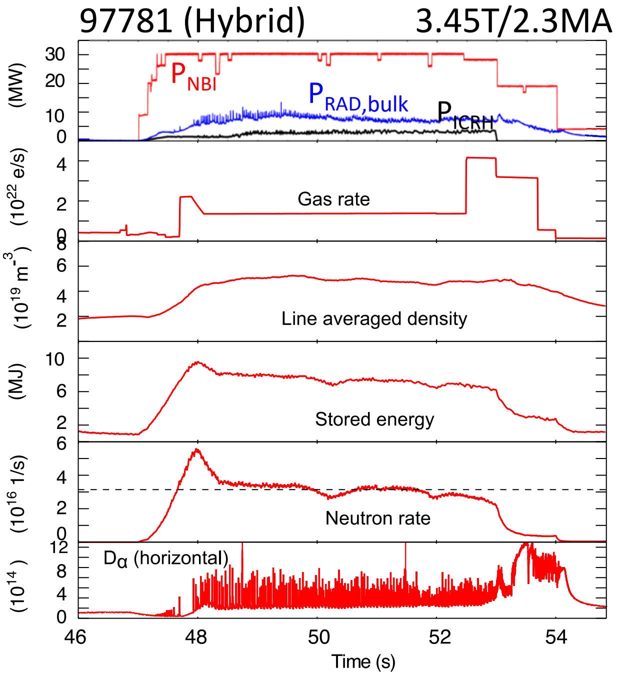
Posters with JET material at IAEA-FEC

Energetic particles and EP driven instabilities

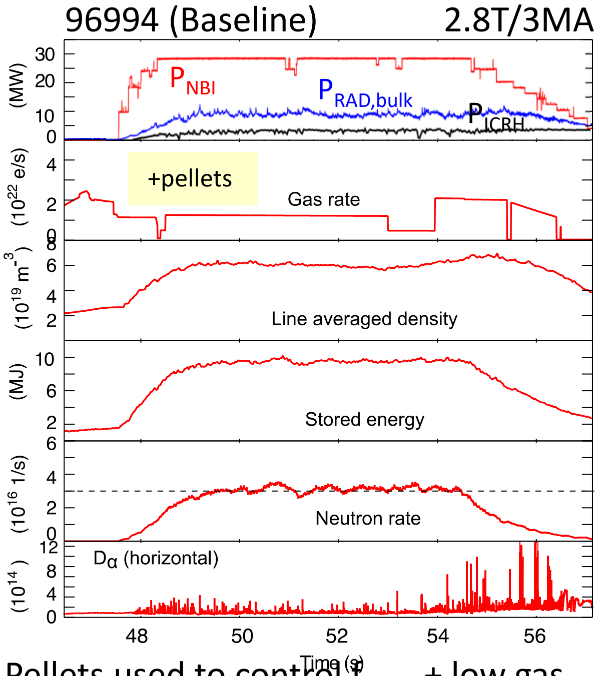
- M. Nocente et al., Facets of alpha particle physics anticipated in D-3He plasmas in preparation for deuterium-tritium at the Joint European Torus
- M. Iliasova et al., Gamma-ray spectrometry for confined fast ion studies in D3He plasma experiments on JET
- R. A. Tinguely et al., Experimental and computational investigations of Alfven Eigenmode stability in JET plasmas through active antenna excitation
- M. Porkolab et al., Experimental and computational investigations of Alfven Eigenmode stability in JET plasmas through active antenna excitation
- A. A. Teplukhina et al., Investigation of fast ion transport induced by ICRF heating and MHD instabilities in JET plasma discharges
- P. Rodrigues et al., High-order coupling of shear and sonic continua in JET plasmas

Additional slides

high power scenario development overcame ILW challenges



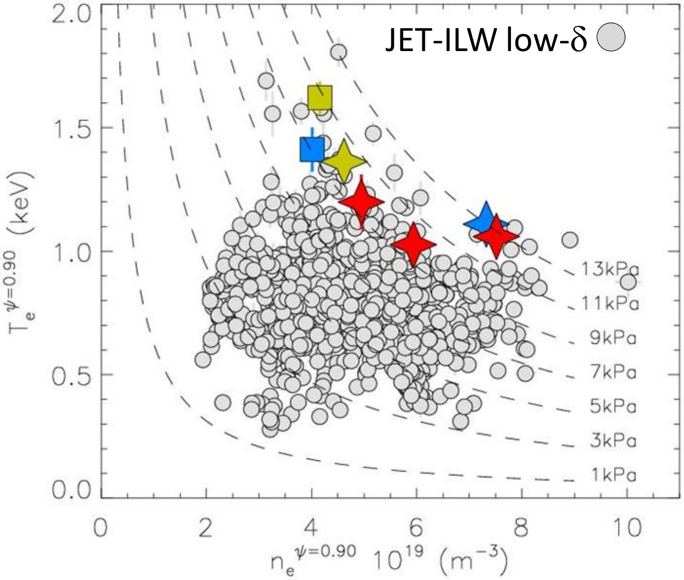
Improved H-mode entry with low initial gas flow → access to high edge & core Ti, low plasma radiation and high fusion power

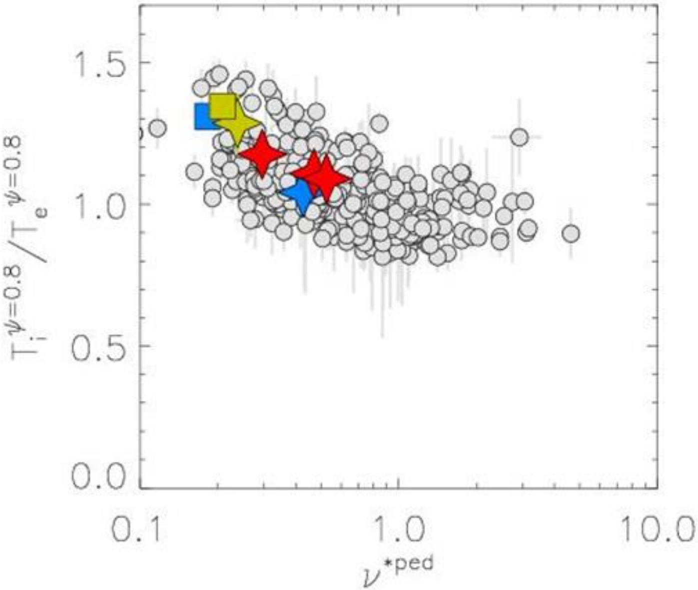


Pellets used to control f_{ELMs} + low gas dosing → Good pedestal and core confinement

Small amount of neon helps steadiness

Pedestal improvement key to performance



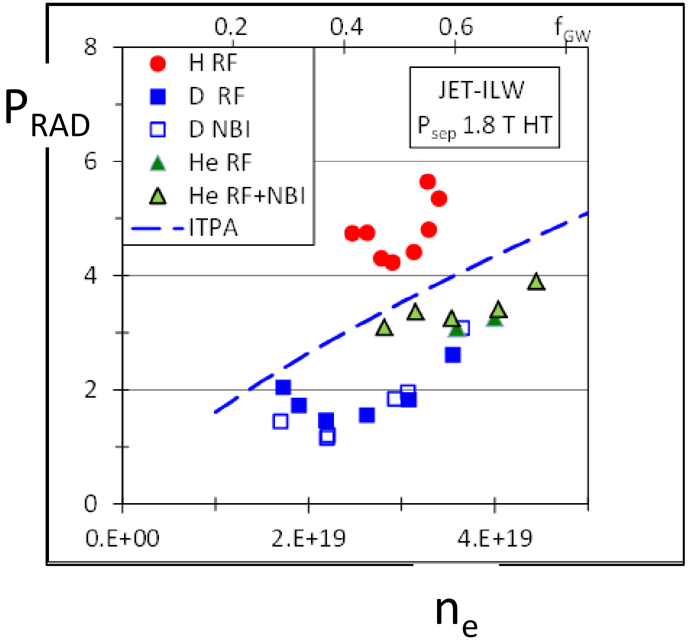


	2014	2020		
Hybrid	🟦	🟨		
Baseline	✦	✦	✦	**@ 3.5MA, 3.8MA, 4MA**

$T_{i,PED}/T_{e,PED}>1$ at lowest v*

L-H in ^{4}He compared to H & D

$$P_{SEP} = P_{AUX} + P_{Ohm} - dW/dt - P_{RAD}$$



- $n_{e,min}$ shifted to higher values in ^{4}He relative to D and H
  ⇨ would raise P_{aux} for ITER access to H-mode in Helium (because P_{sep}~n_e)
- In high n_e branch, P_{sep}(He) ~ P_{sep}(D), lower than earlier result P_{sep}(He) ~ 1.4xP_{sep}(D)
  ⇨ lowers P_{aux} for ITER access to H-mode in Helium

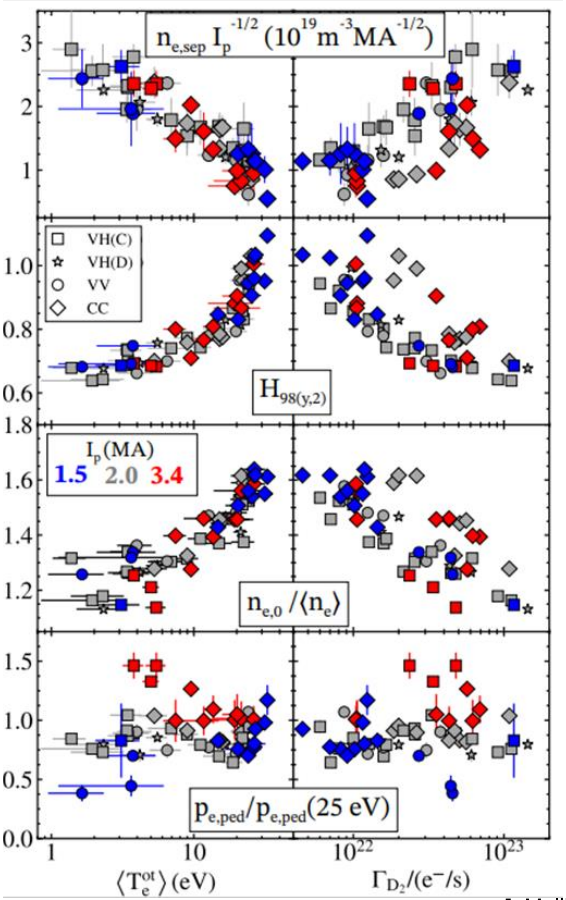
⇨ both effects compensate each other, same overall predicted P_{sep} for ITER.

- But P_{rad}(He)~2 MW above P_{rad}(H)

⇨ near $n_{e,min}$ of each species the same P_{aux} allows access to H-mode in Helium and Hydrogen

E. Solano *et al*, EX/2

Target T_e key parameter for divertor physics



- $T_{e,ot}$ from Balmer photo-recombination continuum spectroscopy [B. Lomanowski *et al.*,PPCF 2020]
- Key parameter linking recycling particle source and detachment to plasma performance in D plasmas
- Changes in $H_{98(y,2)}$, ν^*, n_e peaking, $n_{e,sep}$ with D_2 fuelling rate and divertor configuration condense into single trend if mapped to $T_{e,ot}$

→ Helps clarify impact of divertor configuration when applying JET results to ITER

B. Lomanowski *et al*, invited talk at 62nd APS-DPP