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Deuterium-tritium experiments in JET with the ITER-like wall

J. Garcia

on behalf of the JET Contributors

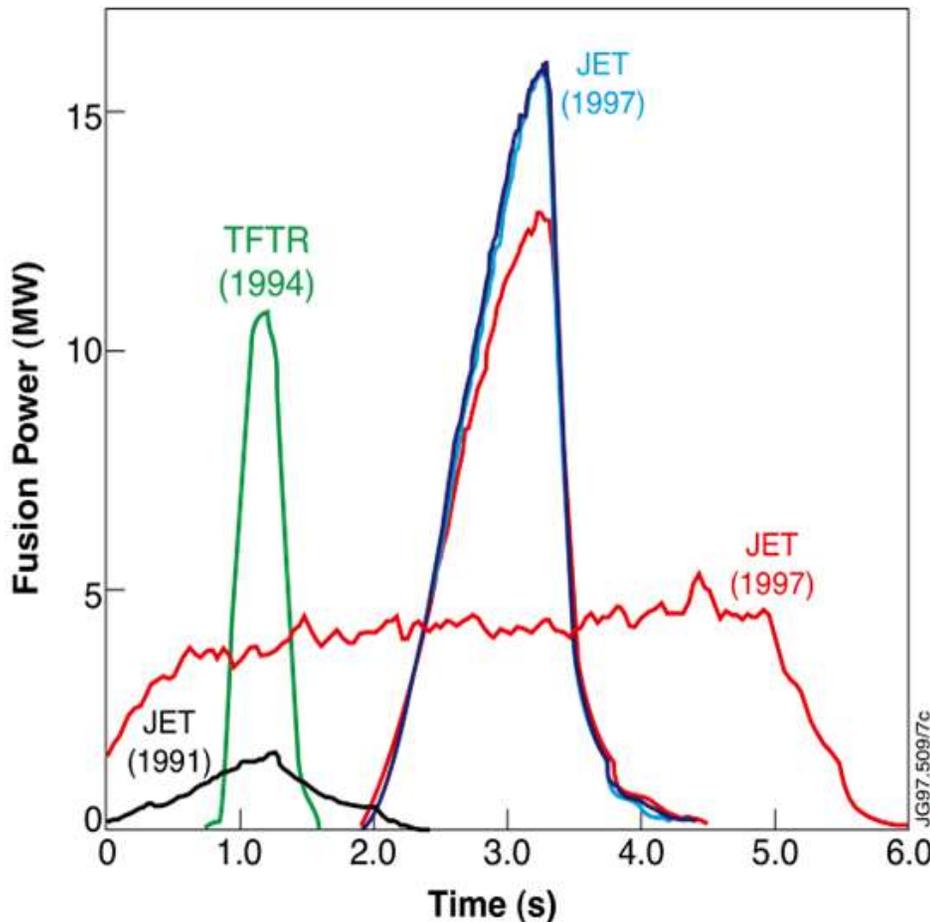
EUROfusion Consortium and CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France.

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.

D-T in Magnetic Confinement Fusion before 2021



DT experiments were carried out in
1991 (PTE - JET)
1994-96 (TFTR – Princeton USA)
and 1997 (DTE1 on JET)

Clearly demonstrating:

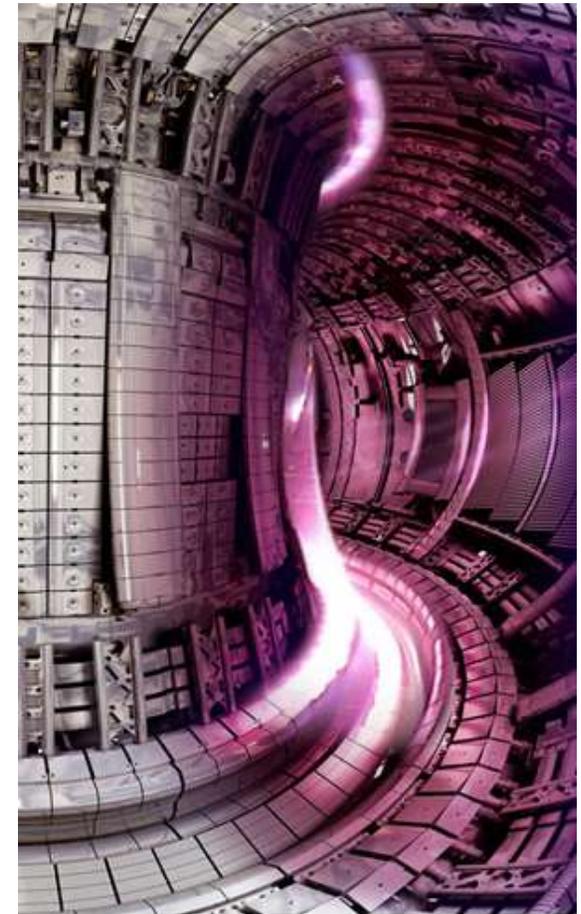
- D-T Fusion production (14MeV neutrons)
- plasma physics effects linked to use of D-T mixture (*isotope effects*)

Note : although some α -particles effects were observed on TFTR (MHD) , JET results were more ambiguous



DTE1: first DT operation at JET, *unsolved issues*

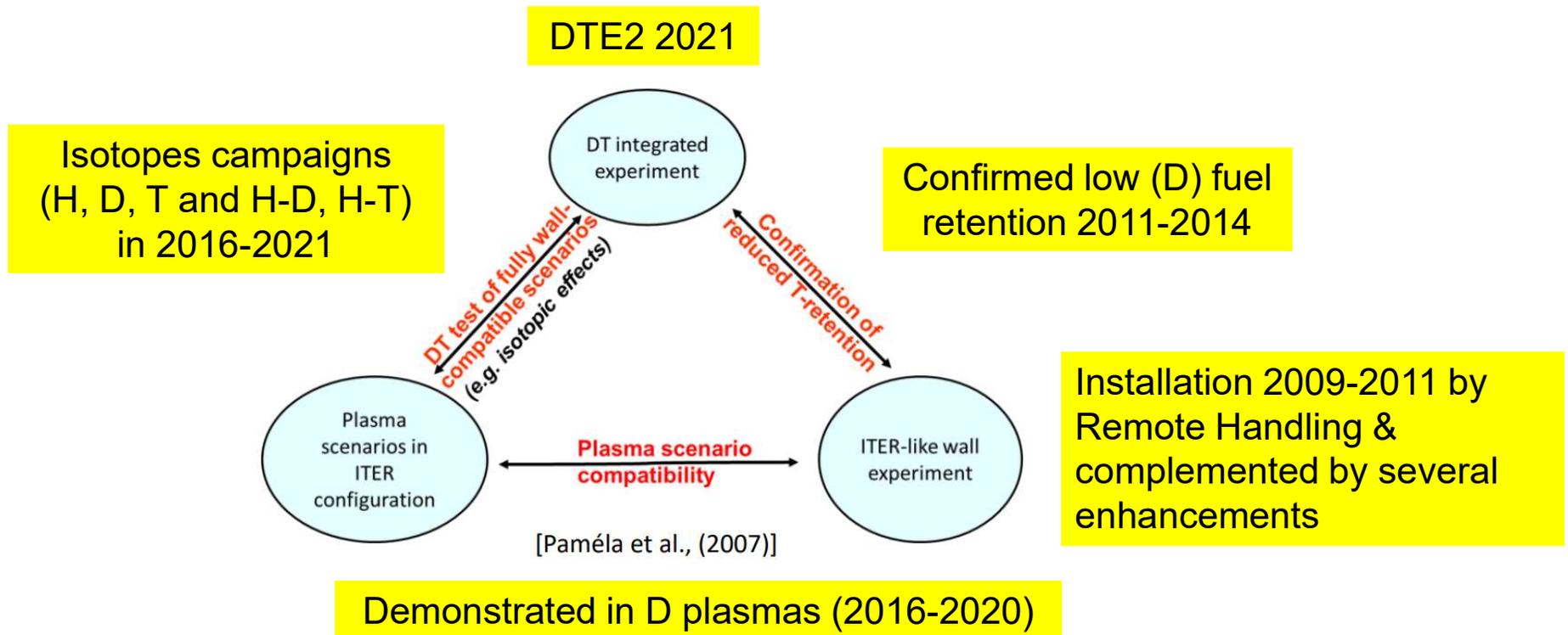
- Hot-ion DTE1 plasmas were obtained in plasma conditions less relevant to ITER:
 - ELM free
 - very low density
 - $T_i \gg T_e$
 - transient regime
- H-mode type I ELM plasmas obtained at low power (no high beta plasmas)
- Plasmas obtained in C-wall (high T retention)
- Alpha particle effects weak and difficult to understand
- Isotope effects in contradiction to TFTR



JET DTE2: culmination of plan started in 2006



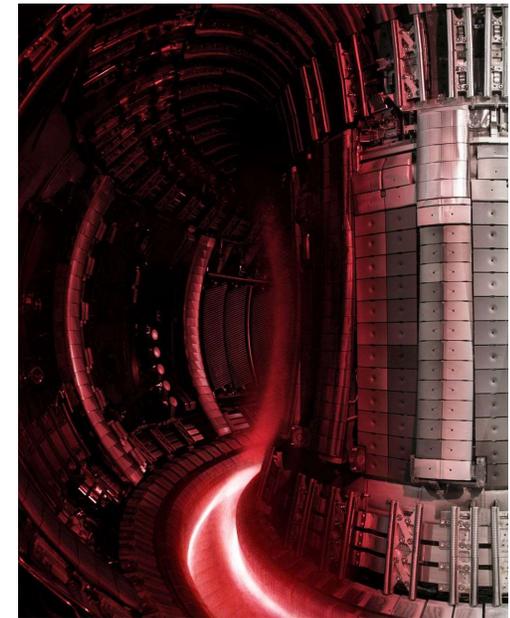
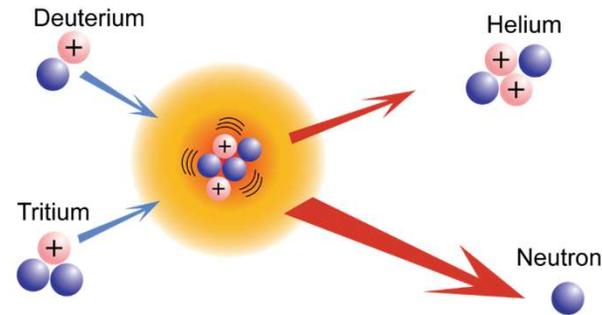
- Be / W ITER-like wall motivated by DTE1 results of too high tritium retention by the C-wall
- Needed demonstration of compatibility with high fusion power operation



JET DTE2 goals



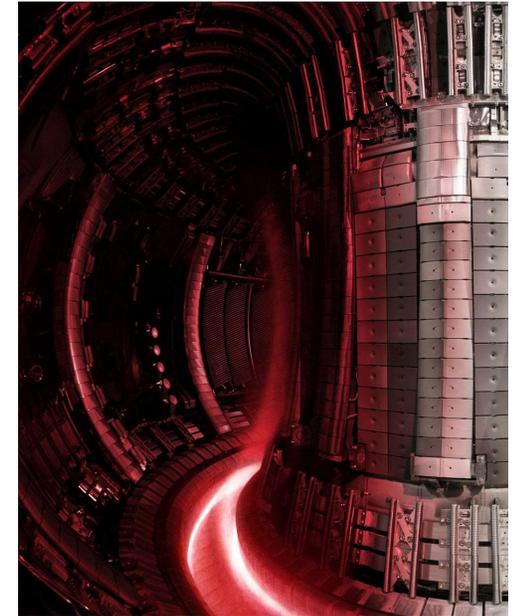
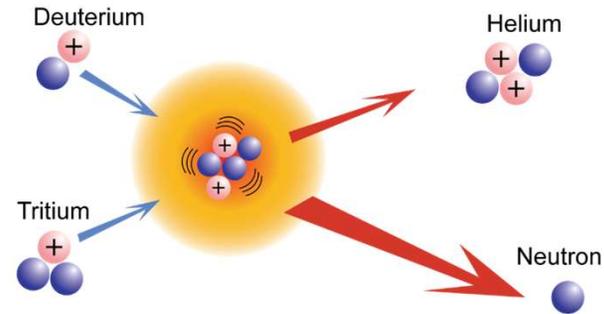
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6. Demonstrate RF schemes relevant to ITER D-T operation



JET DTE2 goals



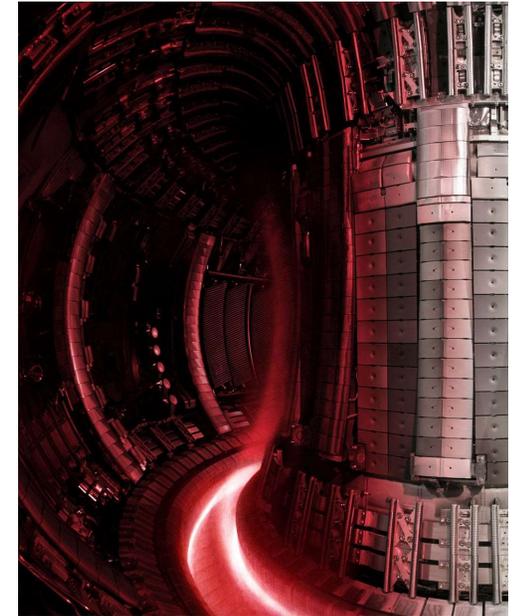
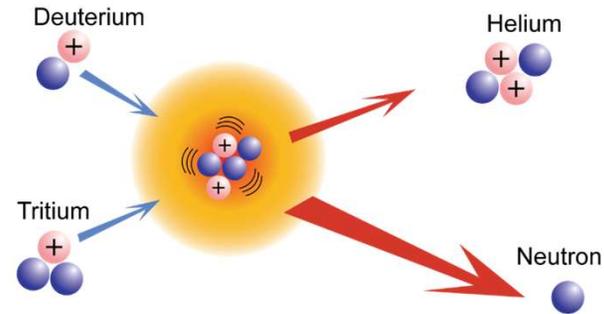
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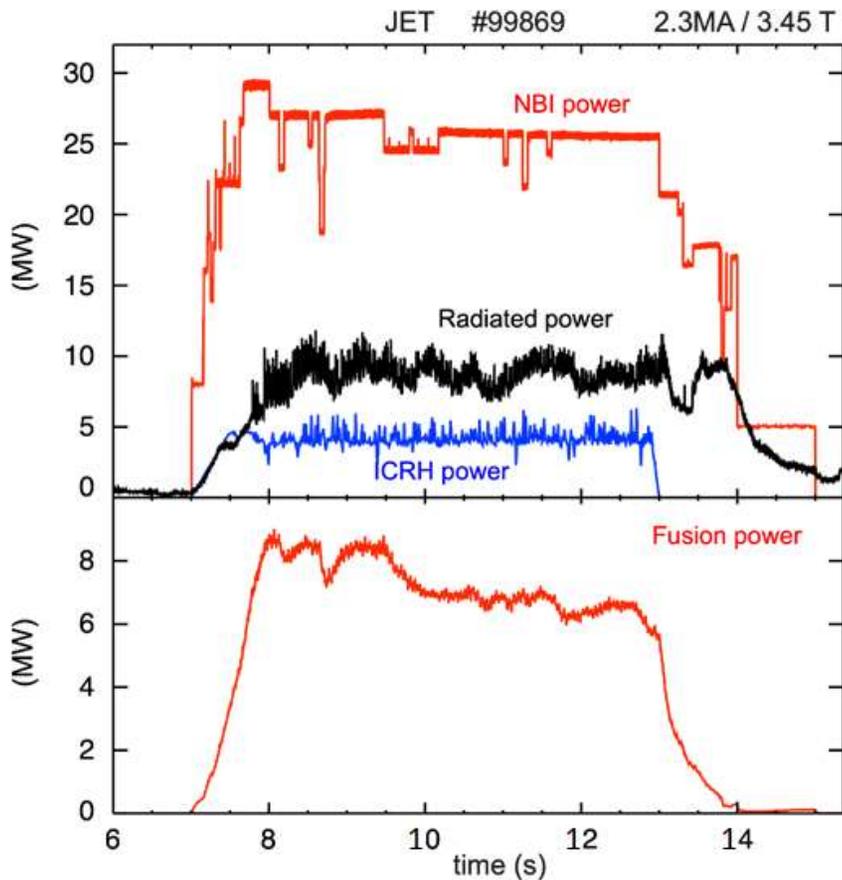
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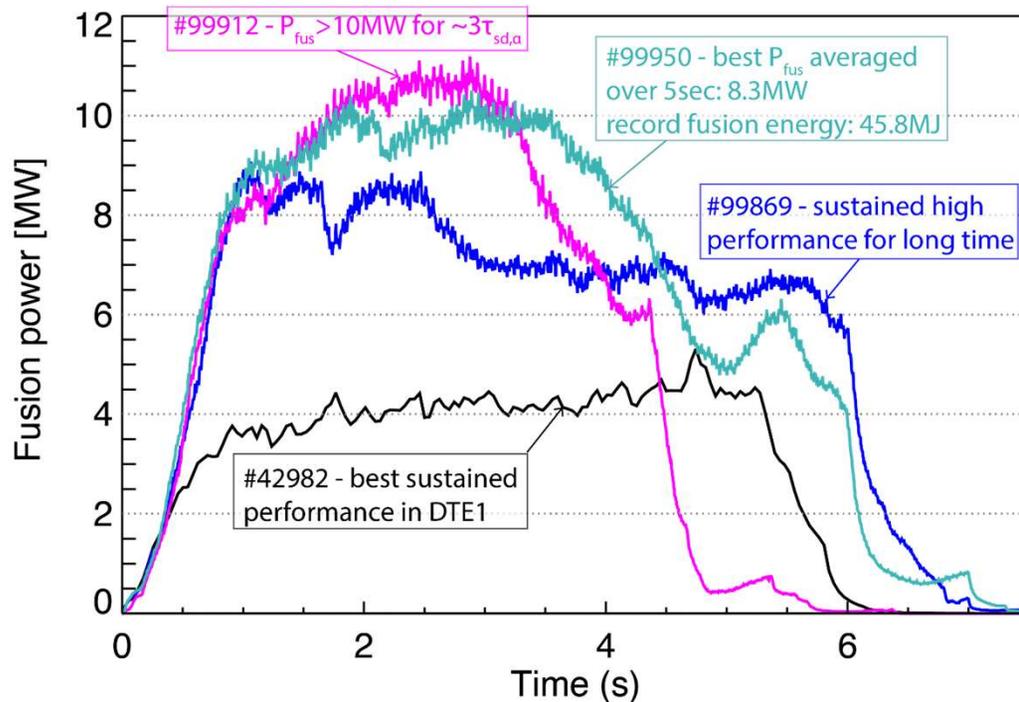


Hybrid scenario plasma in 50-50 D-T



- ‘Hybrid’ scenario plasmas operate at **lower current** and **higher $\beta_p \geq 1$** than baseline plasmas [Garcia PRL10]:
 - $2.2\text{MA} \leq I_p \leq 2.5\text{MA}$, $B_t = 3.45\text{T}$
 - $4.5 \leq q_{95} \leq 5.0$
 - $\beta_p \geq 1$ and $\beta_N \sim 2$
 - Type-I ELMs
- One of the candidate scenarios for ITER
- Had never been tested with T or D-T fuel before
- Highly sensitive to input power

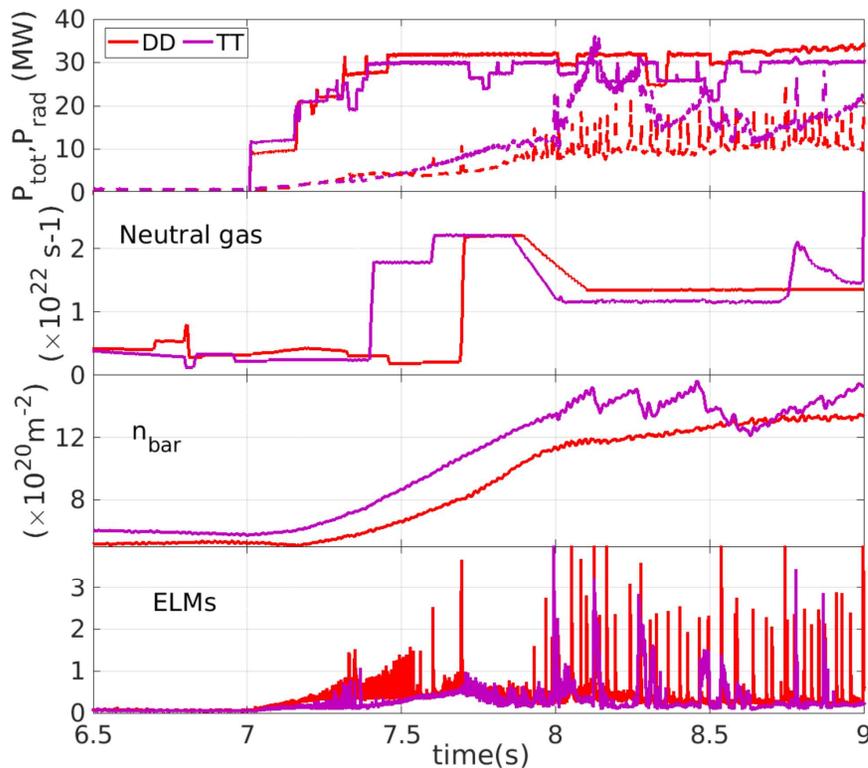
Significant progress since DTE1 using 'hybrid' plasmas



Hybrid scenario plasmas have succeeded in delivering:

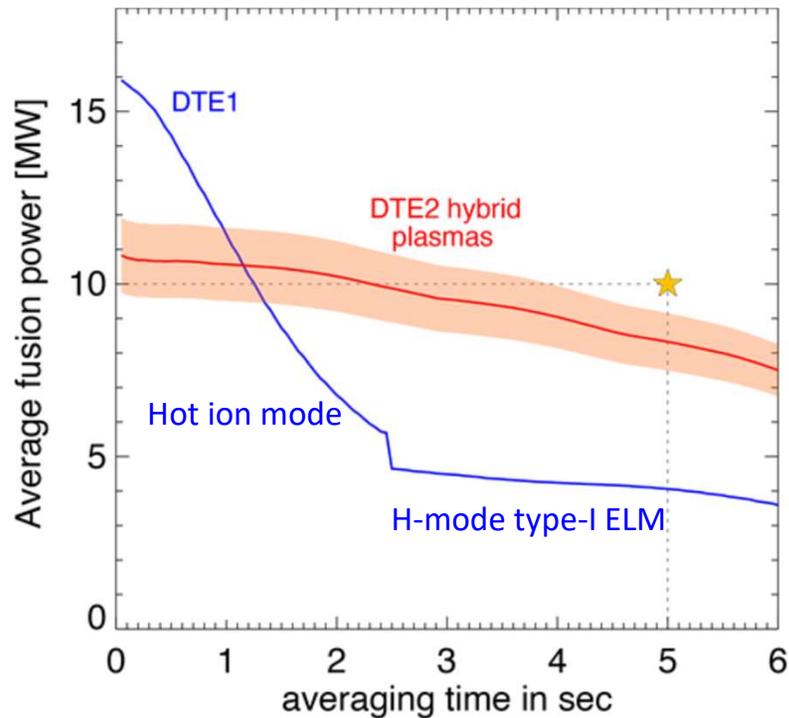
- sustained high fusion power for long time
- record $\sim 50/50$ D-T fusion power averaged over 5sec ~ 8.3 MW and record D-T fusion energy ~ 45.8 MJ
- very high D-T fusion power > 10 MW for more than 3 α -particle slowing down times

Impurity behaviour in DD vs TT



- DD scenarios highly resilient to high Z core impurity accumulation [Mailloux NF22]
- Pedestal or core neoclassical transport screening at high Ti and rotation and low ν [Garcia POP22][Field in preparation]
- Closest repeat of DD recipes in TT became challenging
- Change in profile gradients in T being investigated
- Transferability of DD recipes to TT and DT might not be straightforward

Sustained high fusion power achieved with the 'hybrid' scenario in D-T plasmas

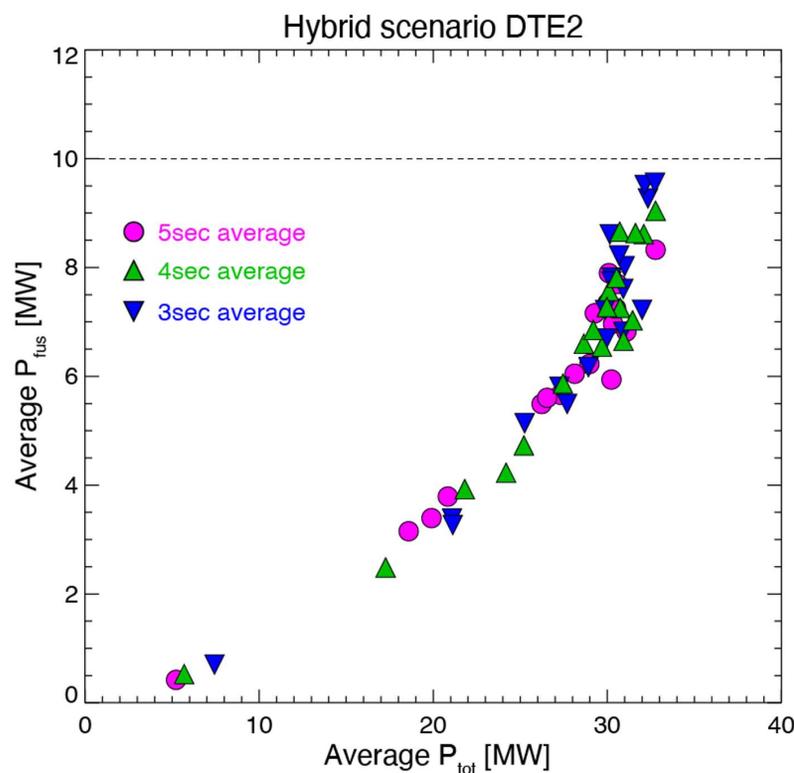


'Hybrid' scenario plasmas achieved **sustained high D-T fusion power**

- Higher levels of fusion power and fusion gain averaged over 5sec with respect to the previous JET D-T campaign (DTE1)
- At confinement at or above the scaling used for ITER

Record fusion energy produced in a ~50/50 D-T plasma: 45.8 MJ

'hybrid' scenario performance strongly depending on available heating power

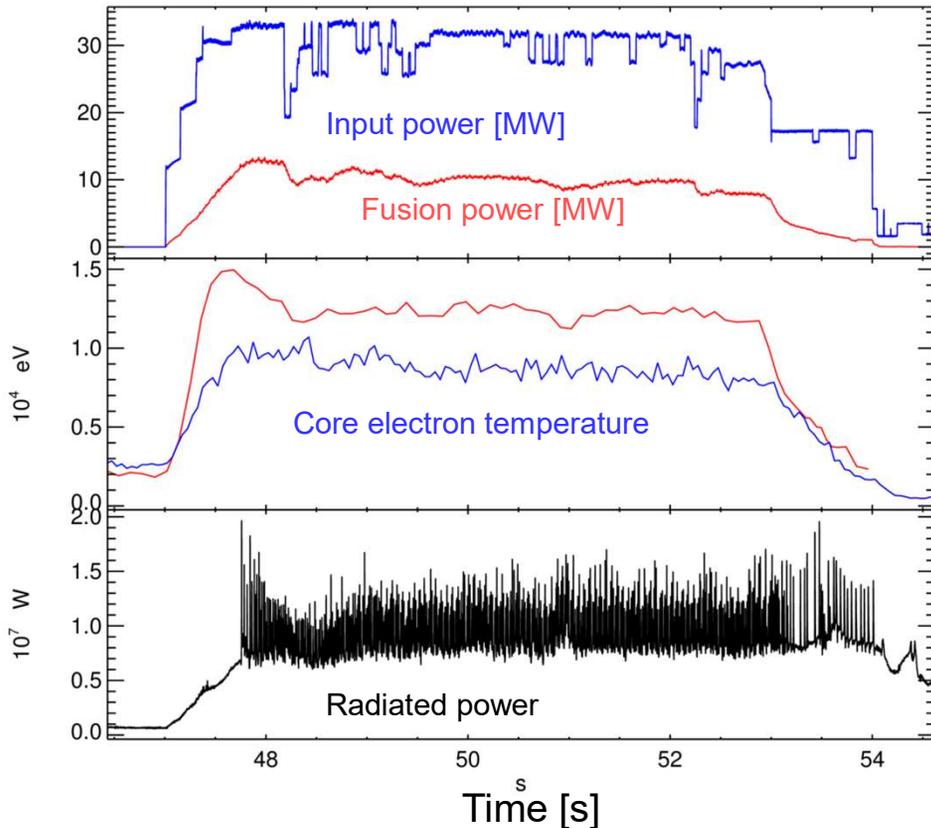


- High input power is important for the generation of high fusion power
 - Fusion power increased faster than linearly with additional heating power
 - Q increases with heating power
 - ~40/60% thermal/beam-target 14MeV neutrons
- Transport/Turbulence expected to decrease with increasing power as in DD:
 - Rotation, beta, isotope effects, fast ions
[Challis NF15] [Garcia NF15]

Hybrid scenario with optimized non-thermal fusion power



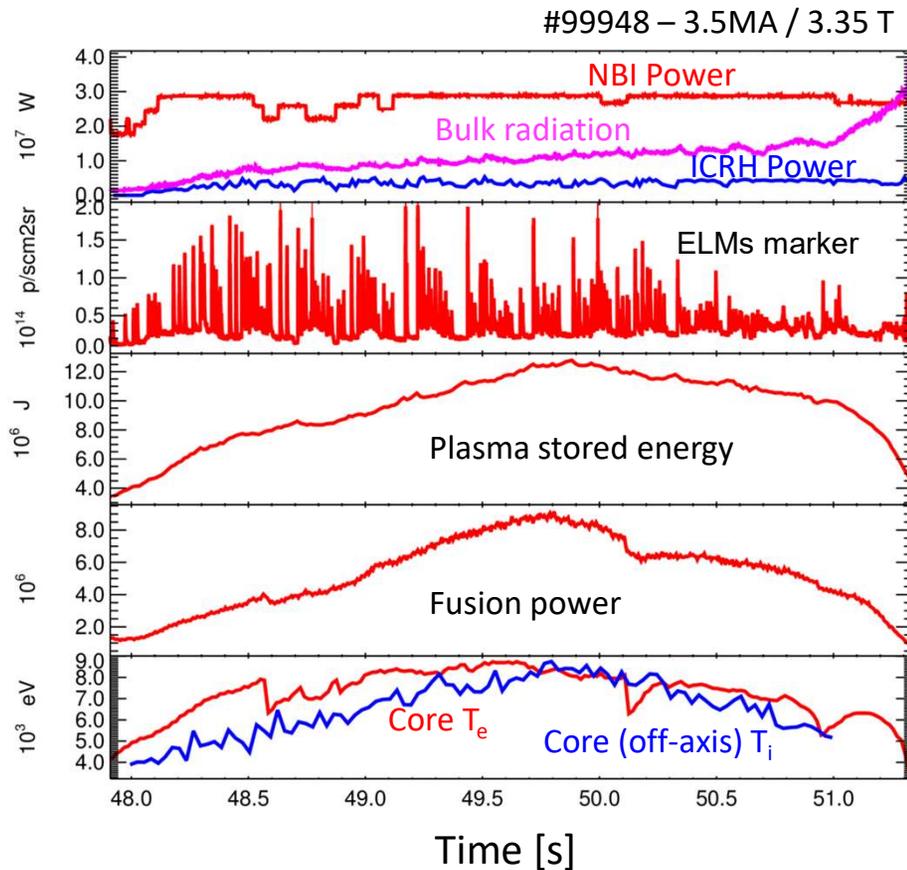
15%D - 85%T plasma with D-NBI (2.5MA/3.86T)



- Plasma composition: 15%D - 85%T
- Max Deuterium NBI heating
- Ion-Cyclotron heating resonant with Deuterium & D-NBI fuel ions in plasma core
- **Record steady fusion energy: $E_{\text{fus}} = 59\text{MJ}$**
- Non-thermal fusion production dominant
- **Spontaneous high frequency small ELM regime as obtained in DD** [Garcia POP 22][de la Luna IAEA21]

First ever tested on JET or anywhere else

Baseline scenario plasma ($q_{95} = 3$) in 50-50 D-T



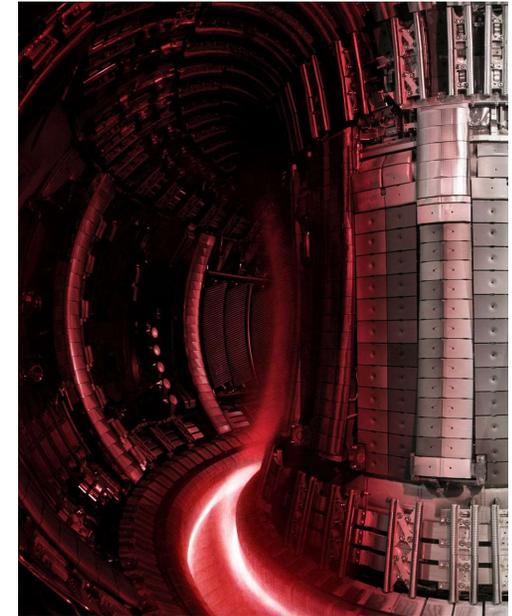
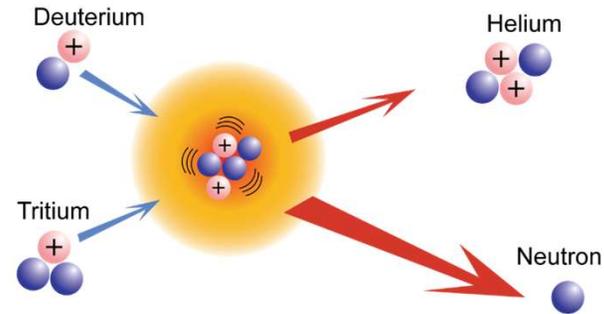
• Baseline scenario at JET is characterized:

- high toroidal current $I_p \geq 3.0$ MA
- $q_{95} \sim 3$
- $\beta_p < 1$ and $\beta_N \sim 2$
- D-pellets used to control ELMs
- High confinement stationary plasmas obtained in DD [Mailloux NF 22] [Garcia POP 22]
- **In DT, stopped by too high radiation**
- Cause of pulse degradation under investigation → important to understand this for ITER

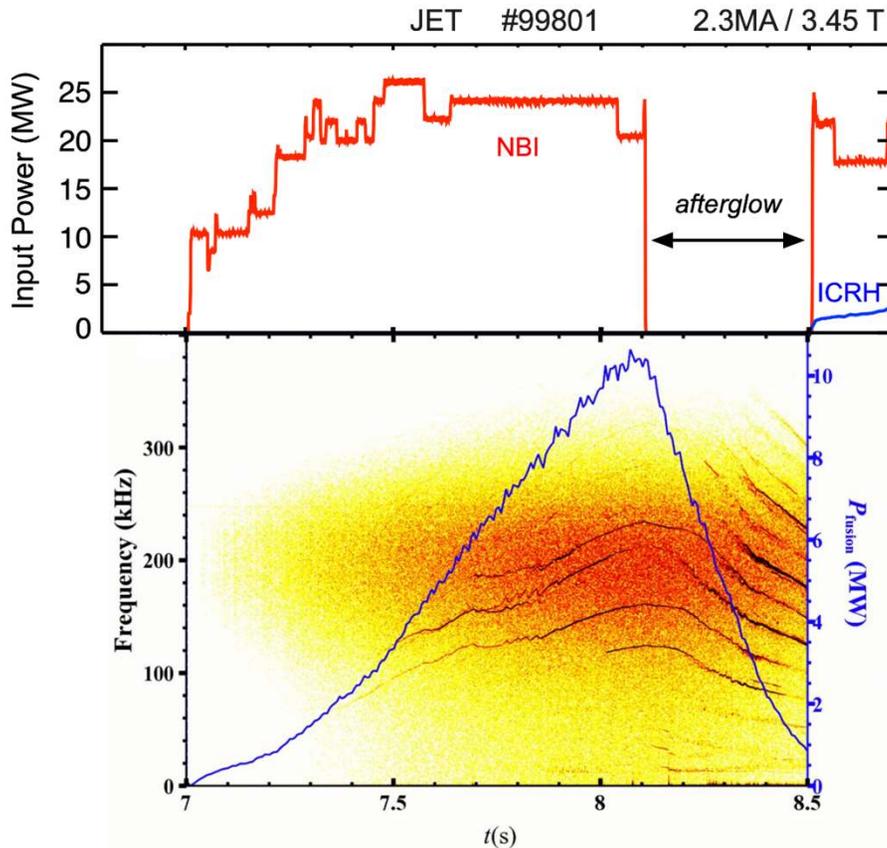
JET DTE2 goals



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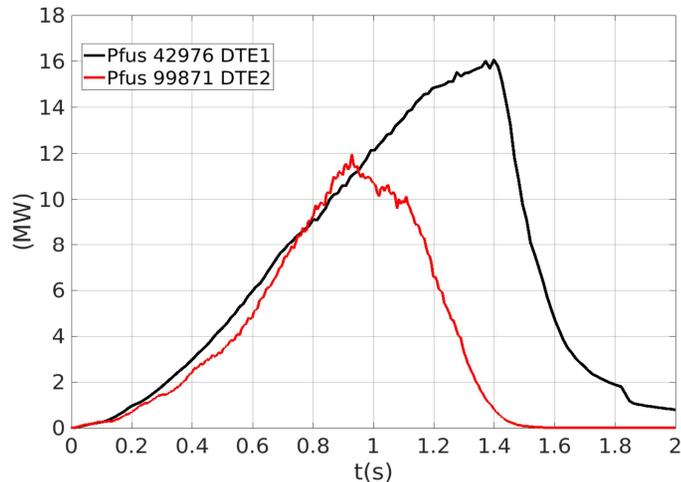
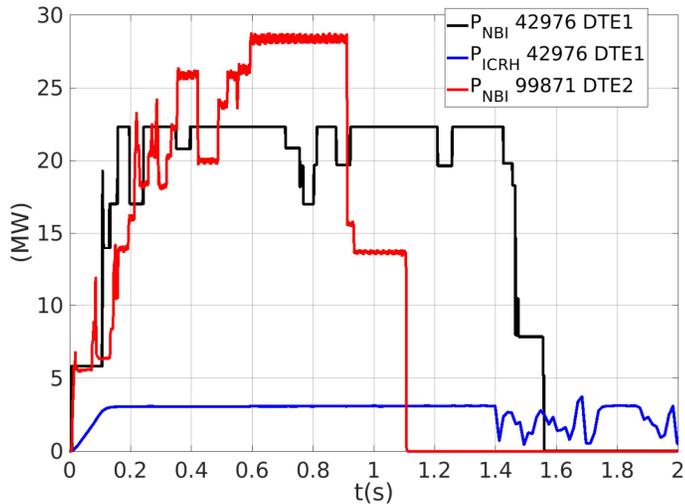


Clear observation of instabilities triggered by α -particles



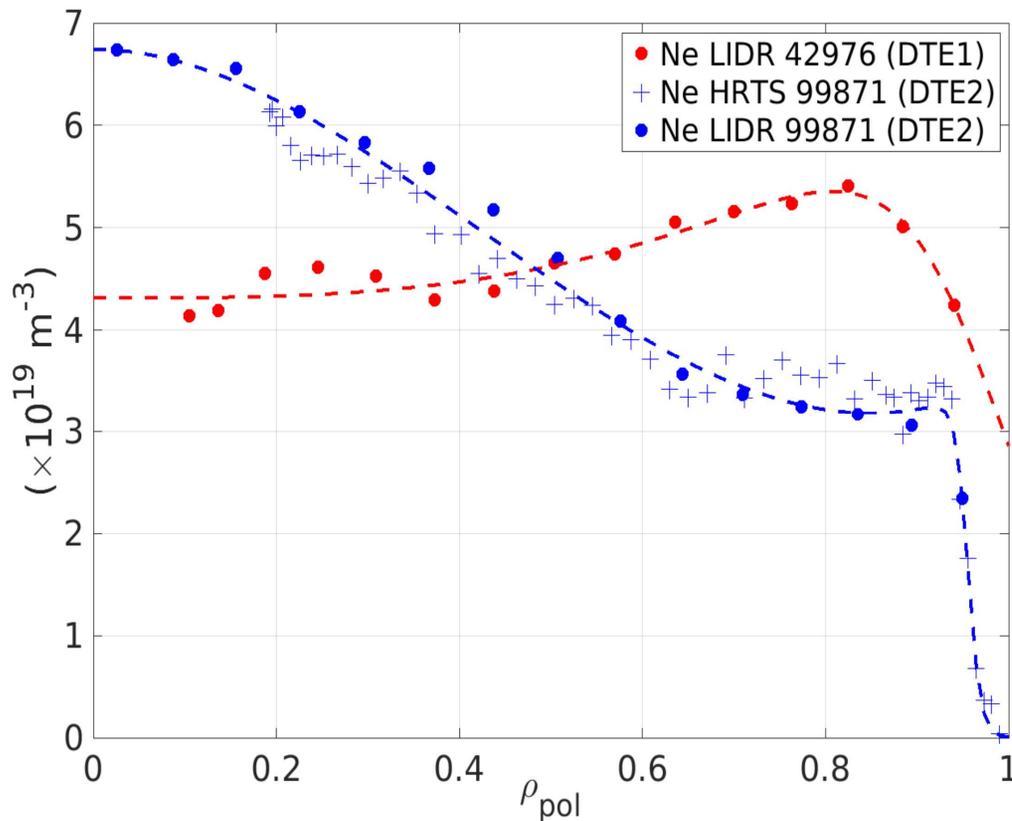
- AE modes observed in TFTR DT plasmas with afterglow technique [Budny NF92, Spong NF95, Nazikian PRL97]
- NBI heating afterglow scenario developed in JET-DT based on hybrid scenario
- High frequency instabilities observed during the afterglow...
- ...but also long before!
- Instabilities being analysed

Similarities with DTE1...



- Afterglow plasmas in DTE2 share characteristics with DTE1 fusion Hot-ion mode record:
 - ELM free
 - Hot Ion mode ($T_i \gg T_e$)
 - High rotation
 - High NBI power injected
 - Fusion power evolution

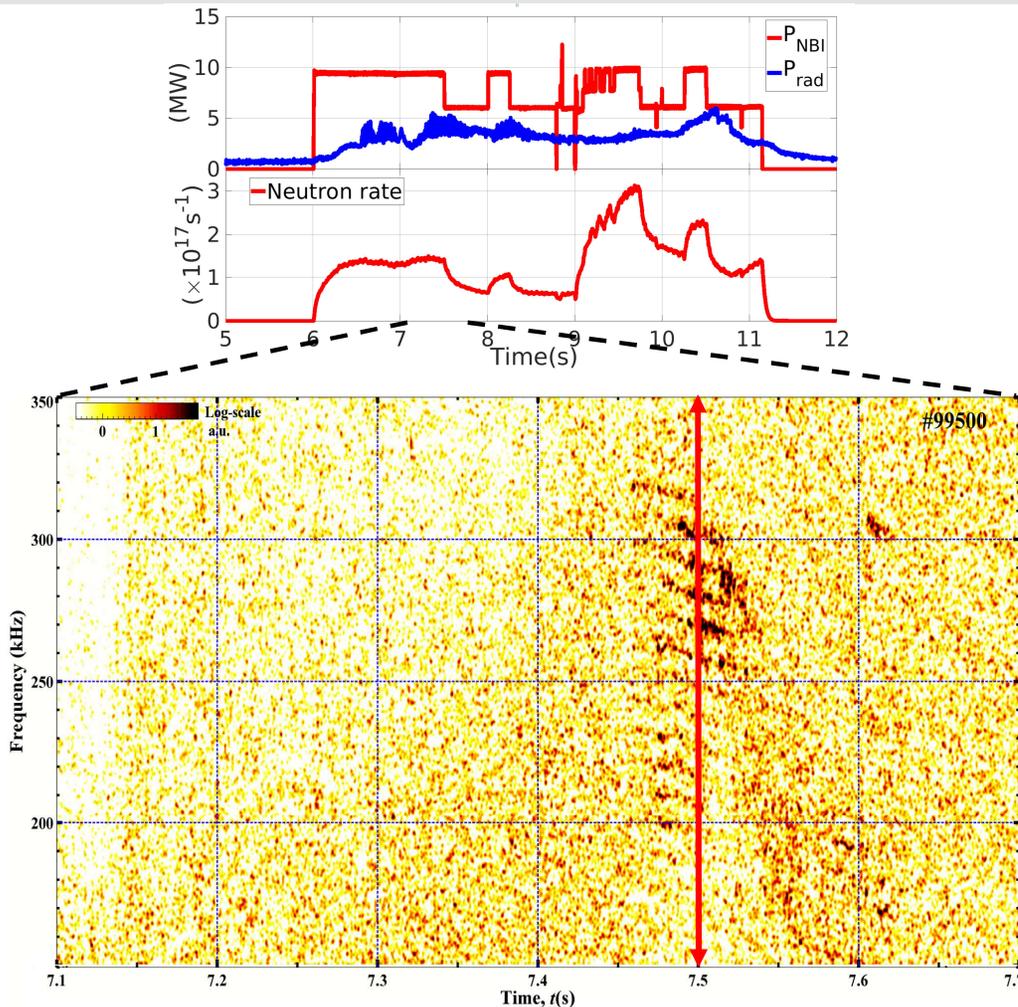
...and strong differences



- Density behaviour quite different in DTE1 (C-wall) and DTE2 (ILW)
- Strong differences in the central density and density peaking
- Expected **high impact on the α -particles slowing down time**



α -particles modes in fast transient events



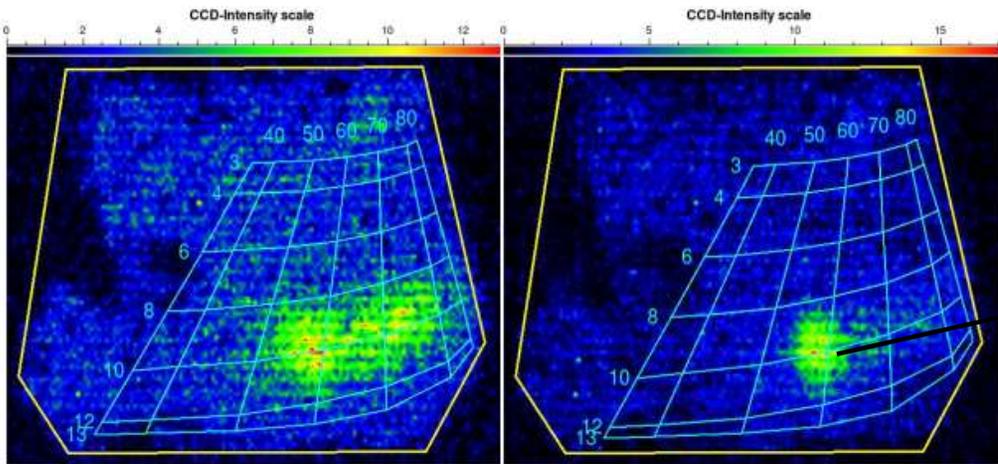
- In JET D-³He, sawteeth may have generated a bump-on tail distribution [Kiptily NF21]
- In DT plasmas, NBI modulation used to generate fast fusion power variations
- High frequency modes obtained
- Results are essential to understand α heating during fast events in ITER

Change of mode characteristics appear after a drop of T-beam power

α -particles losses

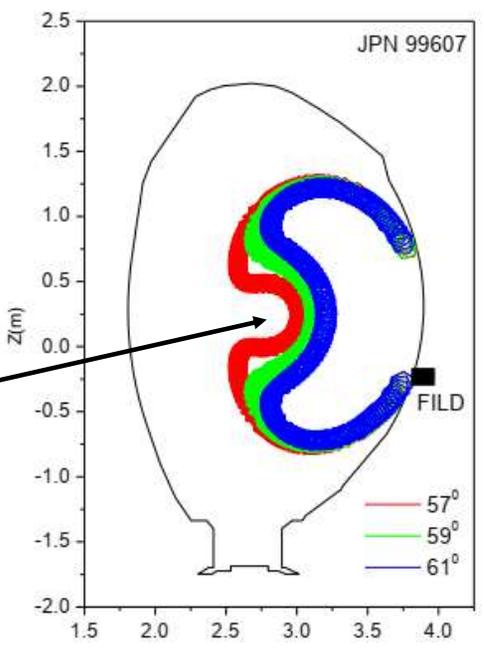


Striking difference in the structure of α -particle losses: core localized at $I_p = 2.0\text{MA}$, with double-hump pattern at $I_p = 2.5\text{MA}$



Reconstructed orbits of α -particles:
Core generation of α -particles

Orbits of lost α 's

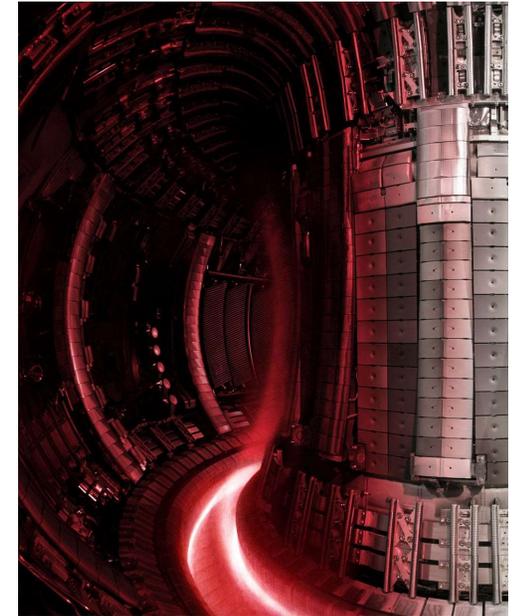
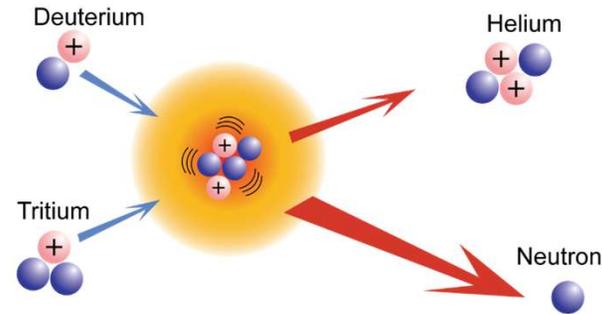


- Impact of fast ion transport or MHD being analysed
- Alpha loss diagnostic provides key observations for comparison to predictions

JET DTE2 goals



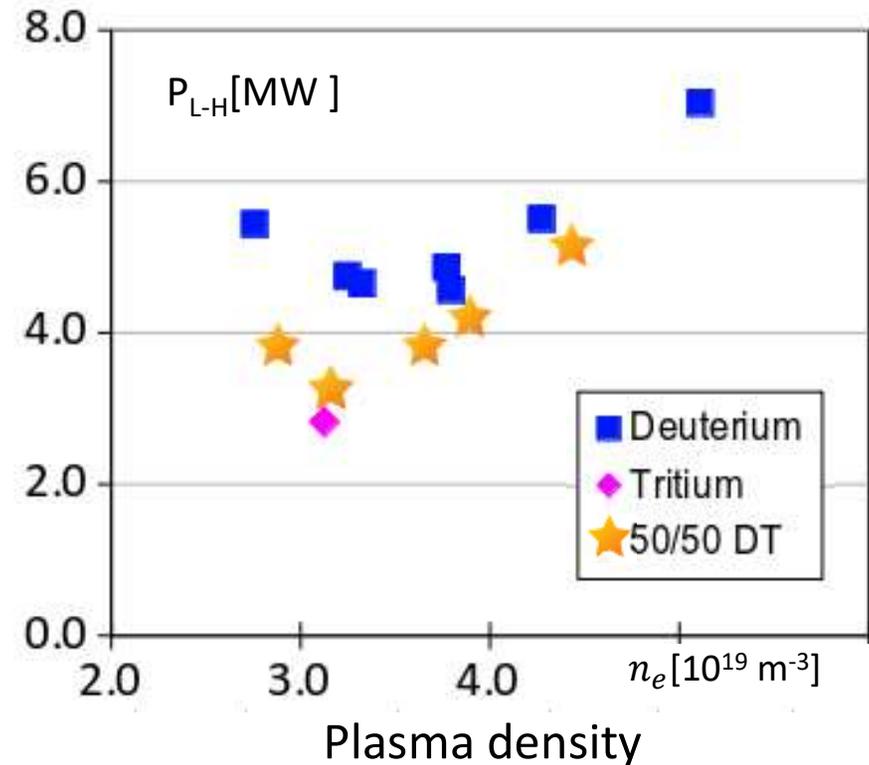
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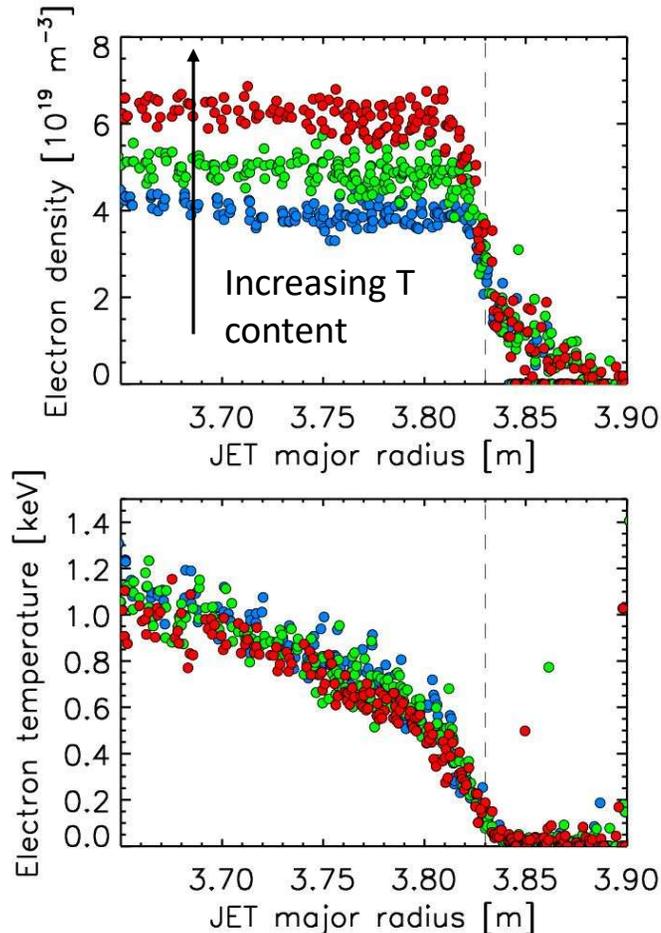
Impact of fuel mass on L-H transition



- L-H transition studies are essential to ITER
- $n_{e,min}$ and P_{L-H} are different in H, D and H+D mixtures at JET [Maggi PPCF18]
- Similar trend found in D vs T plasmas → **Lower P_{L-H} for T** [Solano NF22]
- DT plasmas are found between D and T



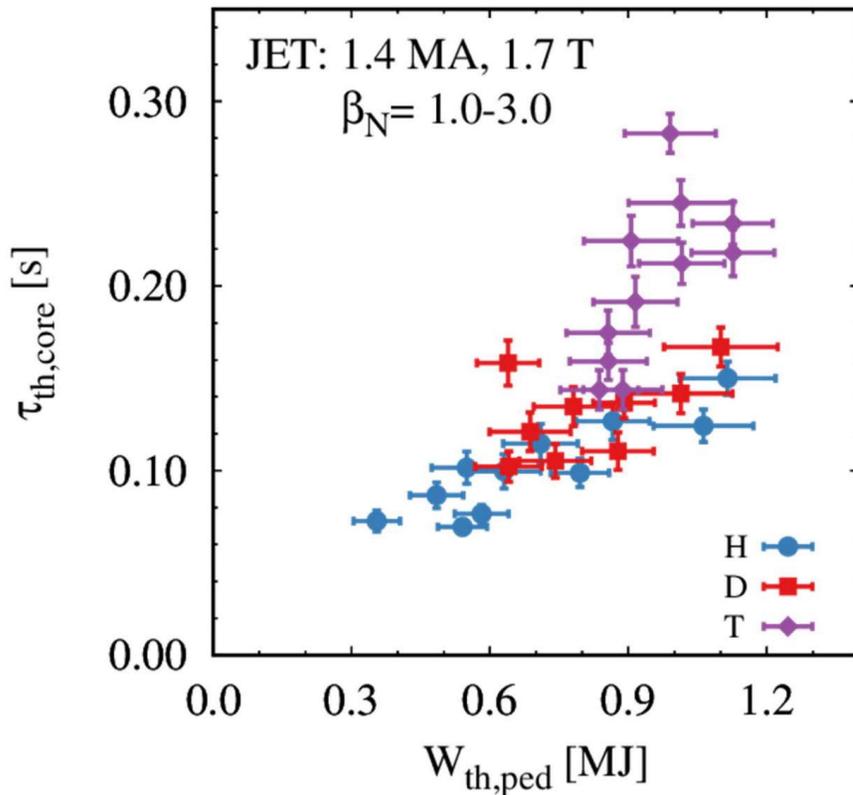
Variation of H-mode pedestal structure with D-T fuel mix



- In DTE1, effect of fuel mass on flow of heat and particles clearly shown
- Increased pedestal density and reduced ELM frequency from H to D [Maggi PPCF18]
- Inter/intra ELMs changes on transport characteristics [Horvath NF21]
- Pedestal density also increases in D \rightarrow T
- Crucial data for improving ITER predictions

Controlled D-T fuel mix scan at constant β_N
(obtained with feedback control on injected power)

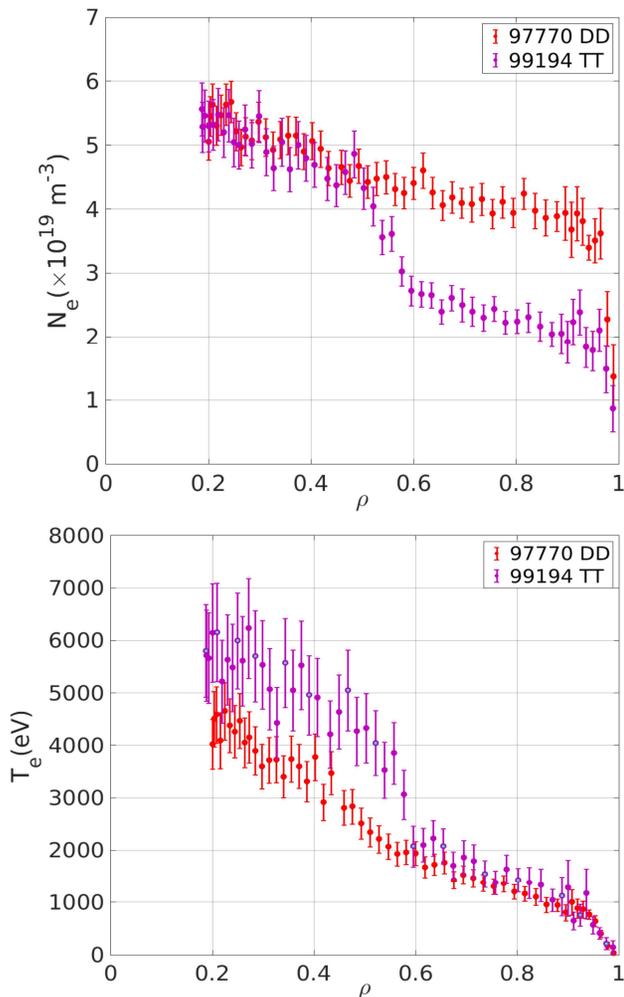
Core isotope effects in pure T plasmas



P. Schneider AAPPs conference 2021

- Pure T plasmas show a strong core isotope effect
- Notably at high input power
- In agreement with previous GK theoretical studies
- Strong isotope effect from D \rightarrow T:
 - Rotation, beta, collisionality, fast ion content
[Garcia NF16] [Garcia POP18][Garcia NF19][Casson NF20][Mariani NF21][Garcia PPCF22]
- Isotope effects in DT being analysed

Isotope effects in ITB plasmas

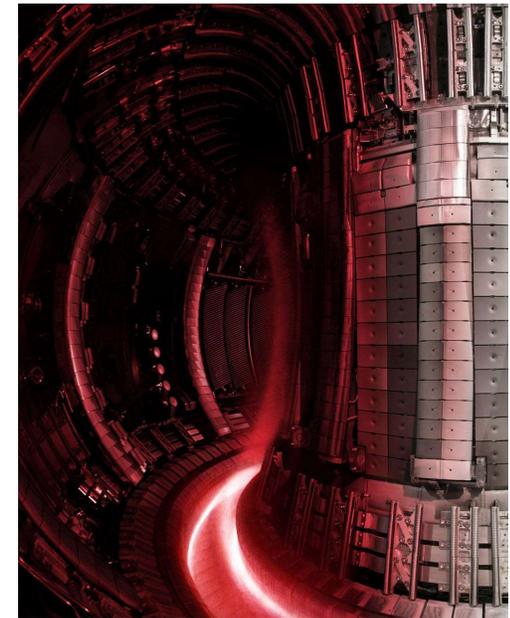
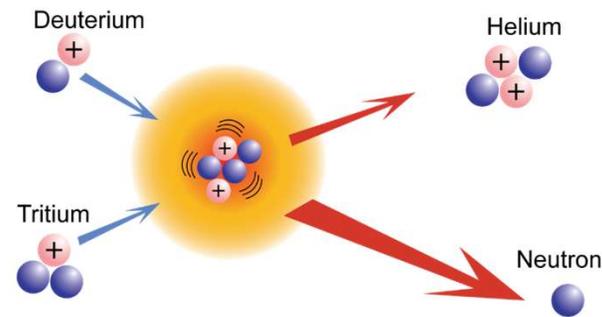


- ITB type-III ELMs plasmas also used for afterglow experiments [Dumont NF18] [Dumont IAEA21]
- ITB formation compared in D (with D pellets) vs T (H-pellets)
- At **same NBI input power and neutral gas injection**:
 - Pedestal density lower in T
 - Clear ITB formation in T, not in D
- **Significant Core transport changes in D vs T**
- Whether pure isotope effects or plasma conditions changes under analysis



JET DTE2 goals

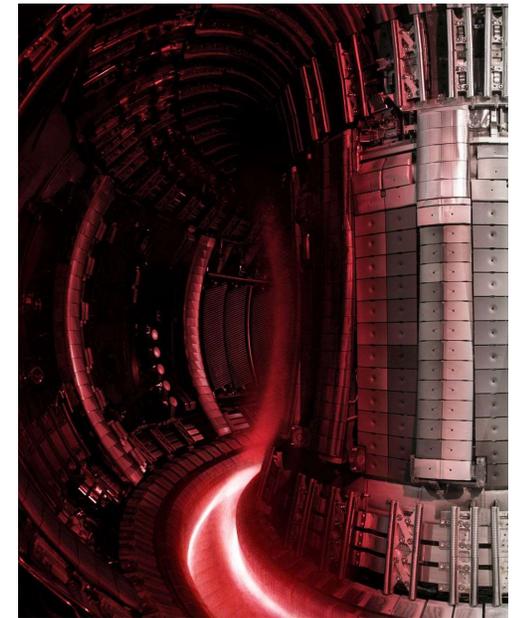
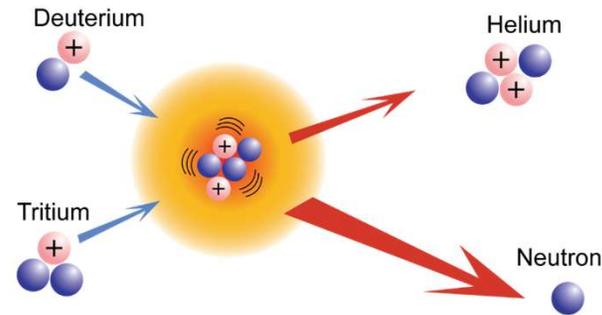
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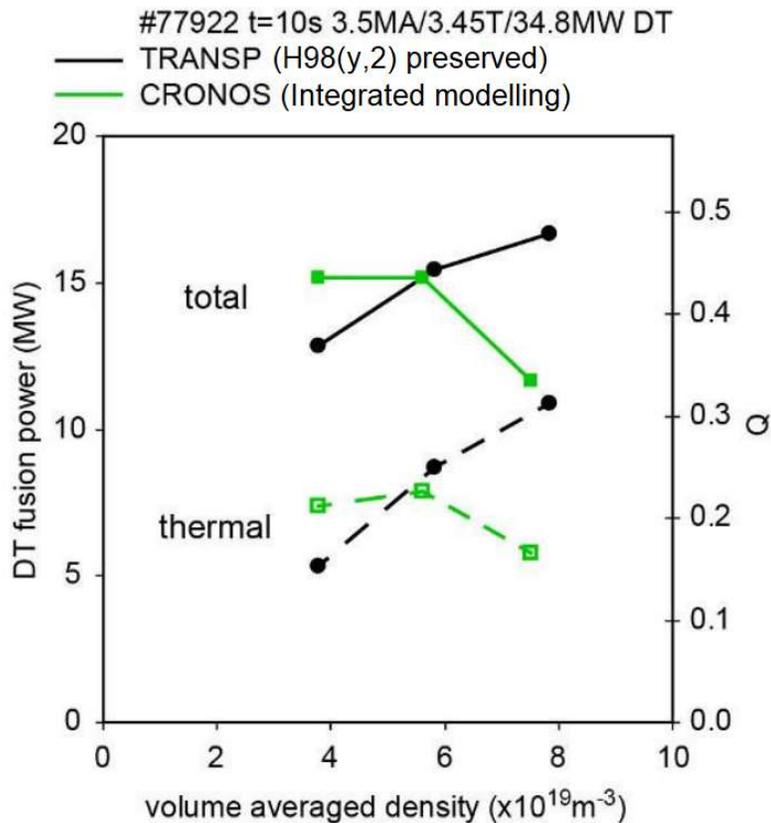
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7. **Predict First**





Predict first: successful modeling/analyses/extrapolation strategy

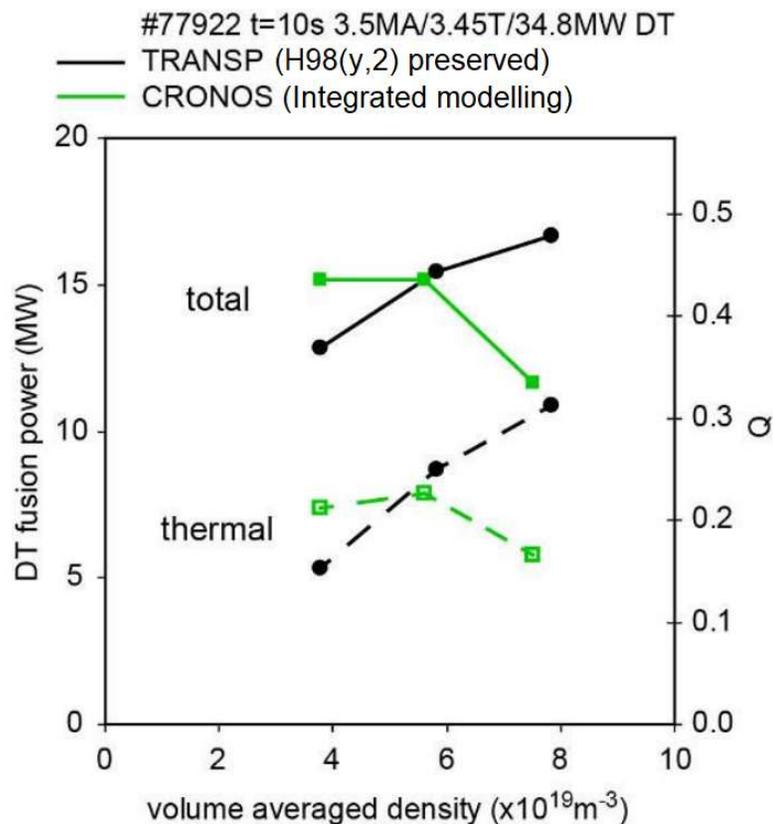


- Since 2008, “Predict first” activity has been helpful to:
 - Identify physics that boost alpha power generation
 - Identify differences between DD and DT plasmas
 - Guide DD experiments and assess DT fusion power

[Sips Internal report 11] [Weisen POP 14]



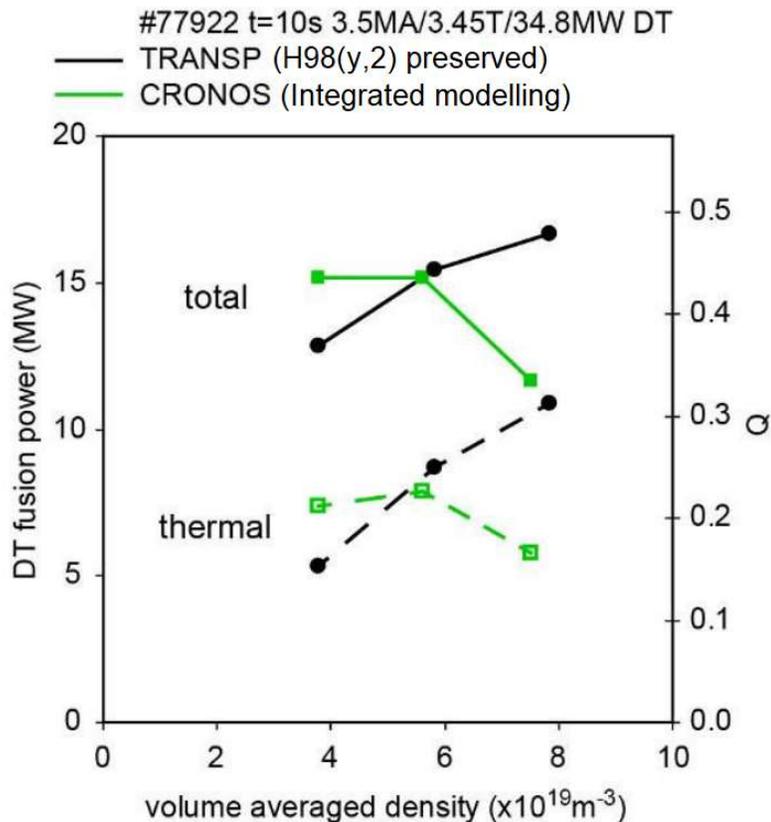
Predict first: successful modeling/analyses/extrapolation strategy



- Since 2008, “Predict first” activity has been helpful to:
 - Identify physics that boost alpha power generation
 - Identify differences between DD and DT plasmas
 - Guide DD experiments and assess DT fusion power
- Initially, extrapolations based on scaling laws
- Some results were in strong contradiction to other approaches
- Change of strategy towards more reliable predictions.

[Sips Internal report 11] [Weisen POP 14]

Predict first: successful modelling/analyses/extrapolation strategy



[Sips Internal report 11] [Weisen POP 14]

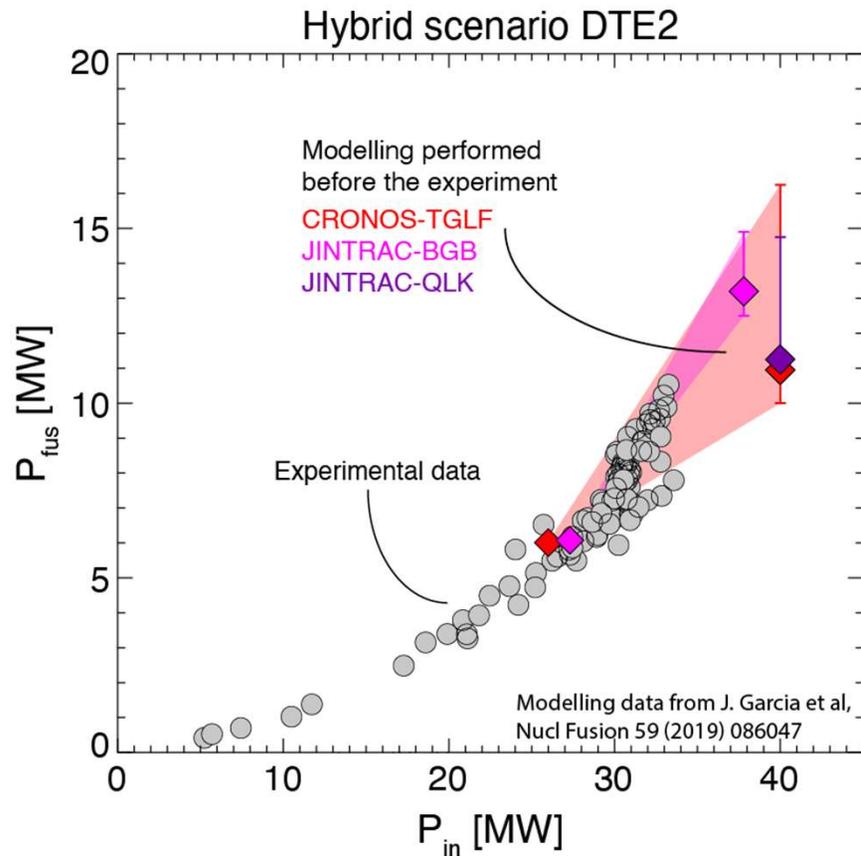
- Validation of transport and pedestal models on plasmas in D and H
- Validation of a **extrapolation capability with existing D plasmas** when changing power, I_p and B_t .
- Validation of the **extrapolation strategy with future D plasmas**
- Close the 'gap' with respect to DT physics: **Validation of models with first JET DT campaign**
- First-principle modelling supporting the extrapolation strategy

[Garcia PPCF16]



JET-DT predictions

D-T fusion power confirms modelling predictions



- Several simplified models for core transport and pedestal characteristics used
- Several integrated modelling codes used
- **D-T fusion power achieved is in broader agreement with predictions**
- Does not mean models are fully correct!
- Weaknesses of simplified models are known but can be treated with new DT data.
- **Essential for ITER and future reactors predictions.**

JET DTE2 experiments bring fusion energy closer



- Exploiting JET's unique set of capabilities: T handling, ITER-like wall, size, heating & diagnostics enhancements:
 - JET D-T experiments have demonstrated highest ever fusion energy production
 - In conditions closest to ITER as we can with any fusion facility in the world
 - Providing a new set of physics results in DT
 - Confirming modelling predictions for the fusion power, giving confidence for predictions of ITER and future reactors
 - Will help accelerate ITER research plan (risk mitigator for ITER)
- While doing so, we have also trained a new generation of scientists, engineers and technicians, transferring unique knowledge and skills to ITER



Back-up slides