Scientific objectives and preliminary highlights of JET isotopic and DT campaigns

M. Baruzzo on behalf of JET contributors

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.

Outline

- Rationale for JET DT campaign
- DT campaign Objectives
- Technical/Scientific readiness for DT: KPI
- Tritium operation in JET
- Preliminary Scientific Highligths: Plasma scenarios

Outline

- **Rationale for JET DT campaign**
- DT campaign Objectives
- Technical/Scientific readiness for DT: KPI
- Tritium operation in JET
- Preliminary Scientific Highligths: Plasma scenarios

Previous DT campaigns

DT experiments were carried out in:

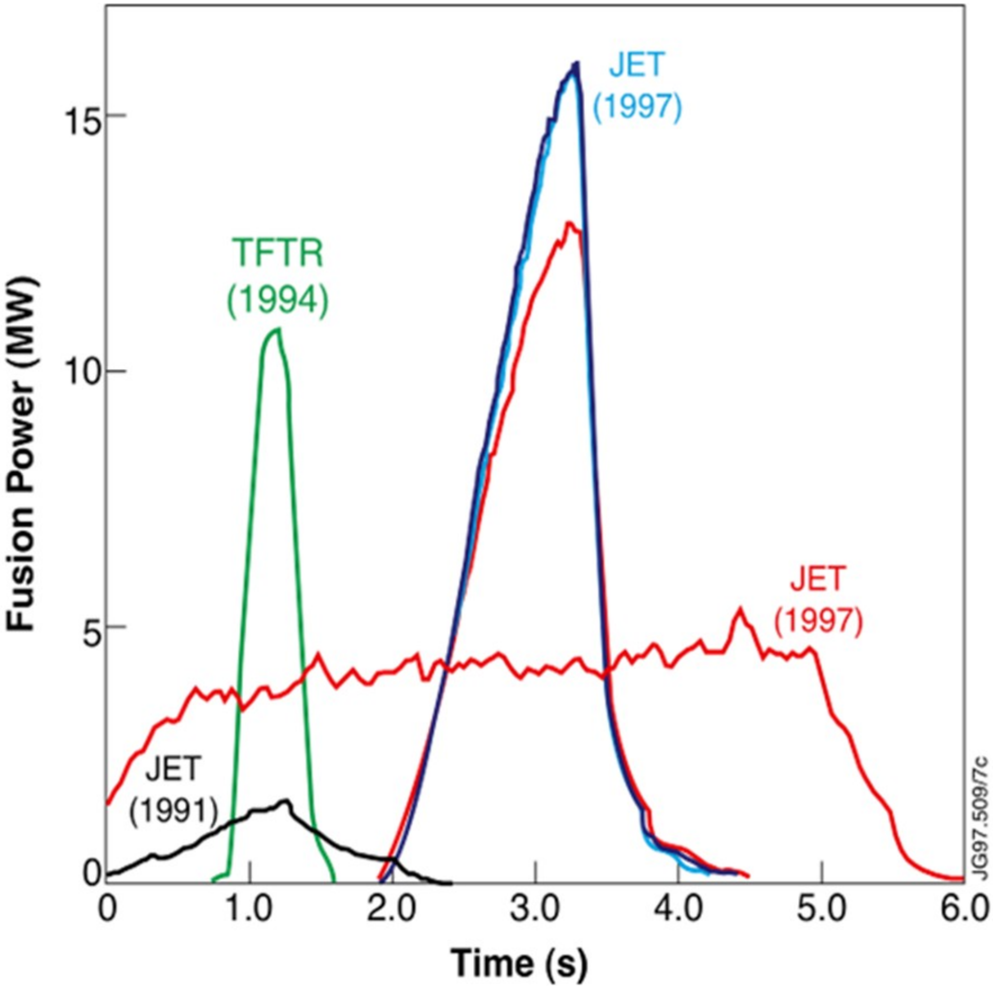
1991 (PTE - JET)

1994-96 (TFTR – Princeton USA)

and 1997 (DTE1 on JET) achieving ~16MW of fusion power transiently and >4MW in steady state (5 s).

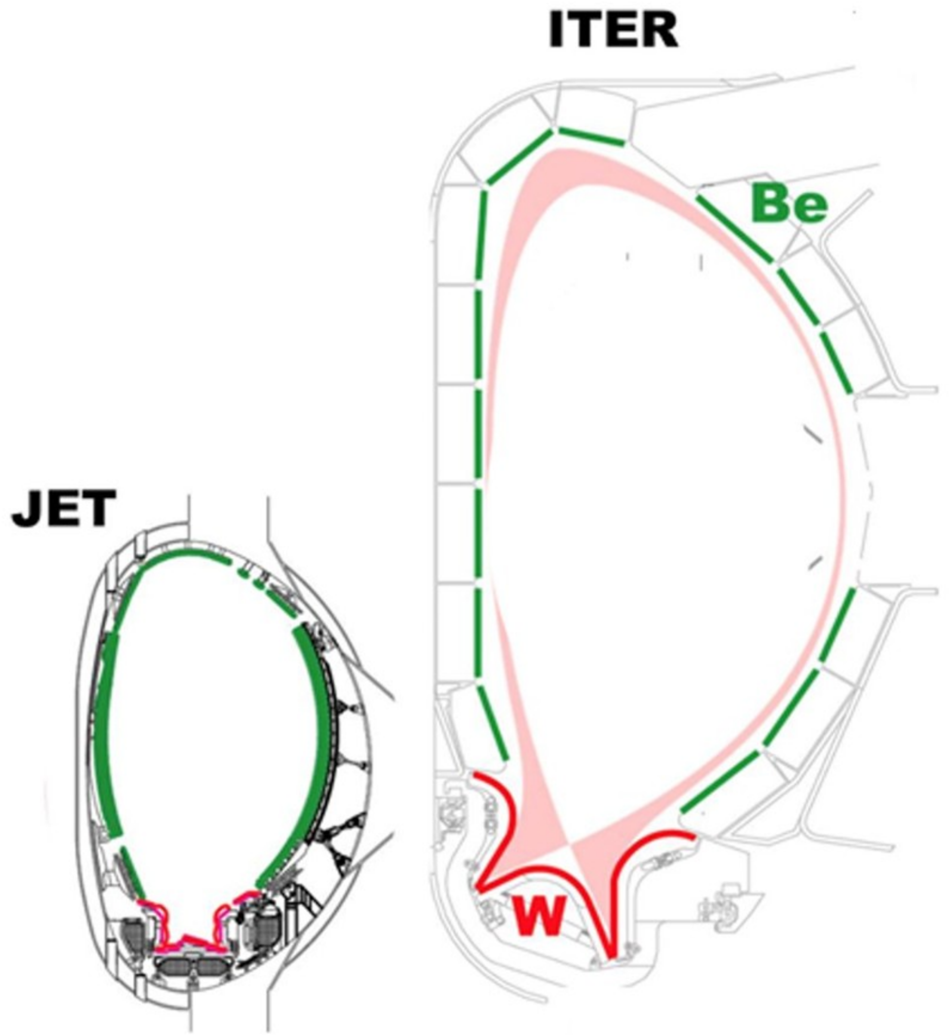
JET DTE1 experiments were carried out with CFC-based plasma facing components.

One of the results was the large retention of tritium in the wall, unacceptable for a reactor.



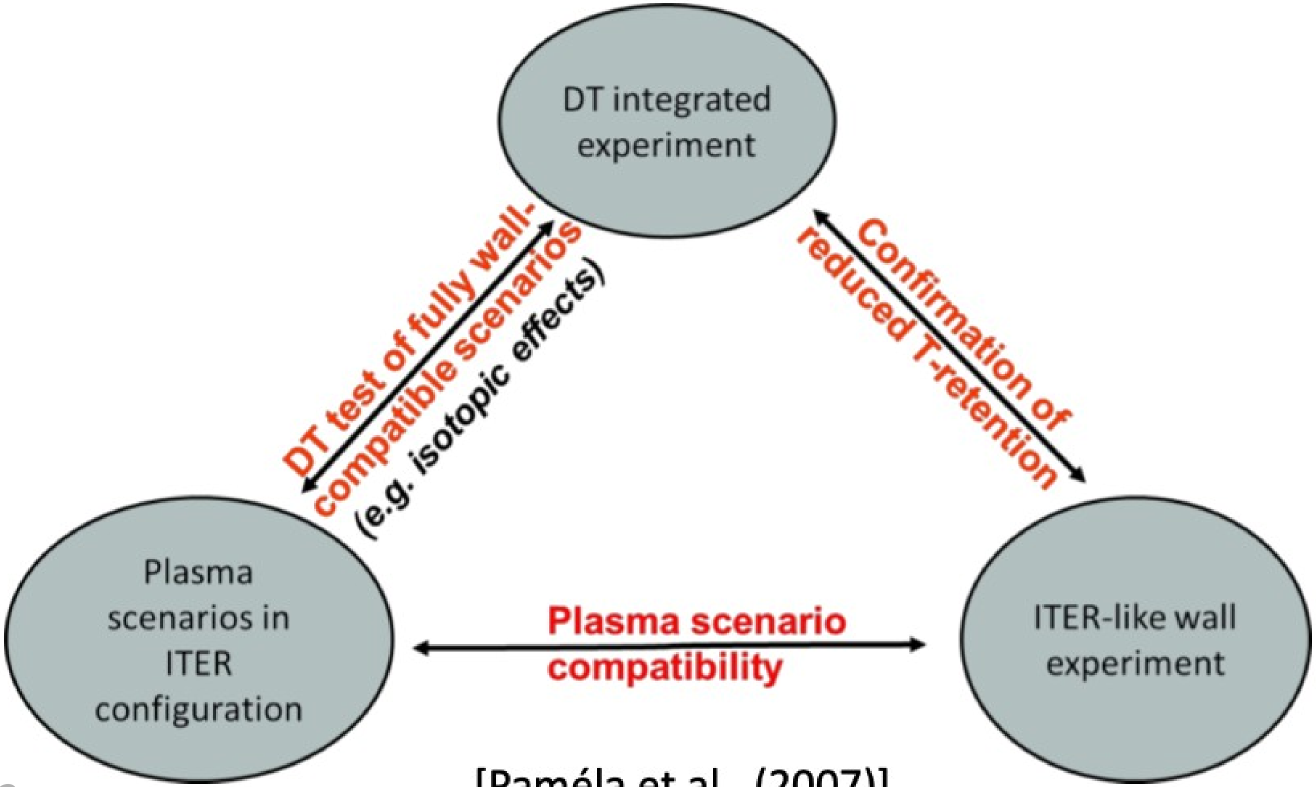
Rationale for JET DT campaign

- Be-W (ITER-like) wall installed in 2009-2011.
- Increased NBI power.
- Improved diagnostics (high-resolution Thomson scattering, neutron spectroscopy, several cameras).
- Focus on stationarity of performance.
- Last opportunity to do DT before ITER in 2034.



Rationale for JET DT campaign

- **Full exploitation of the ITER-like Wall [2006]**
- **Scientific case review [*EFDA STAC 2011]***
- **Operational and technology case [*EFDA STAC 2013*]**



[Paméla et al., (2007)]

Outline

- Rationale for JET DT campaign
- **DT campaign Objectives**
- Technical/Scientific readiness for DT: KPI
- Tritium operation in JET
- Preliminary Scientific Highligths: Plasma scenarios

DT campaign Objectives

- Demonstrate fusion power up to 15 MW, sustained for 5 s
- Demonstrate integrated radiative scenarios in plasma conditions relevant to ITER
- Demonstrate clear alpha particle effects
- Clarify isotope effects on energy and particle transport and explore consequences of mixed species plasma
- Address key plasma-wall interaction issues
- Demonstrate RF schemes relevant to ITER D-T operation

- All aspects of DTE2 are interconnected and the high performance scenarios integrate the information and the results provided by different research areas.

Outline

- Rationale for JET DT campaign
- DT campaign Objectives
- **Technical/Scientific readiness for DT: KPI**
- Tritium operation in JET
- Preliminary Scientific Highligths: Plasma scenarios

Technical/Scientific readiness for DT: KPI

- **Ad Hoc Group (R. J. Hawryluk–chair) to assess the level of technical and scientific readiness [STAC , GA 2015]**
- **Set-up Key Performance Indicators to track progress [2015]**
  - inform the discussion in the General Assembly as to whether or not to proceed to DT operation in JET, but that achieving all of these KPIs in full will not be considered a priori as essential
- **STAC AHG (R. Wolf-chair) to assess KPI progress, focusing on the capability to produce significant scientific output [2019]**
- **AHG review on the progress regarding the achievement of the KPIs [Jan. & May 2020]**

Technical/Scientific readiness for DT: KPI

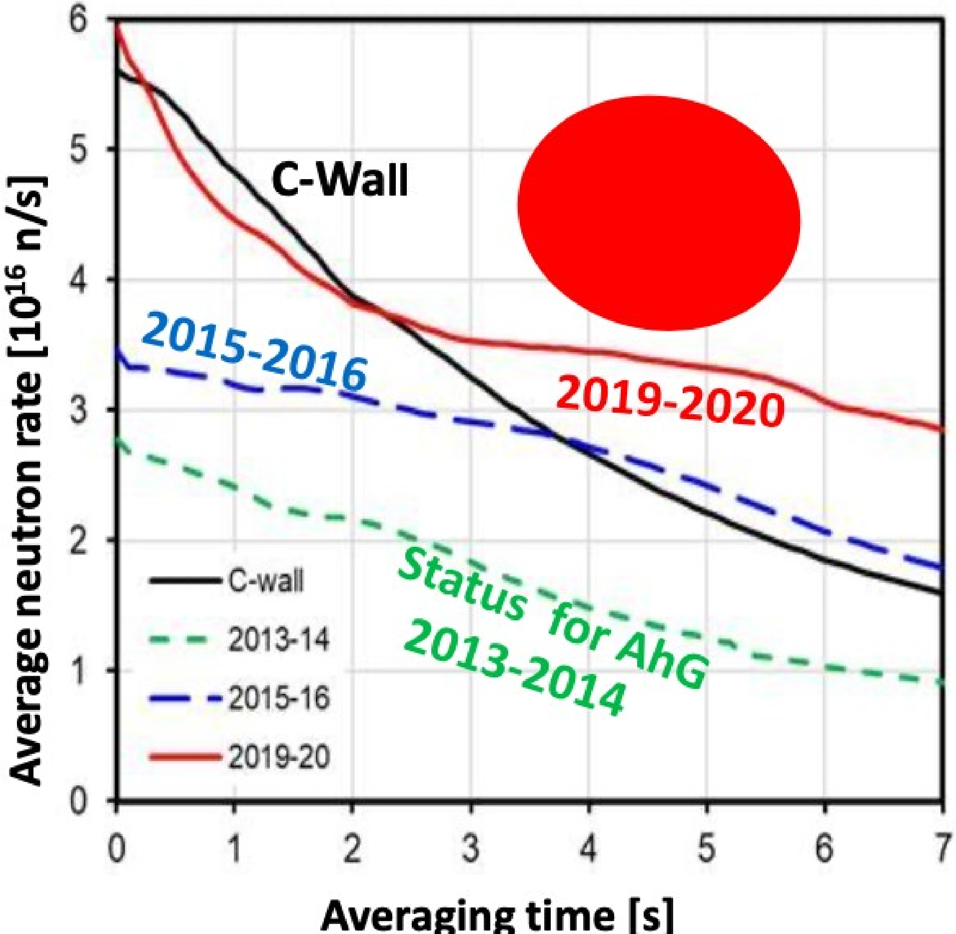
Category	KPI title and status
Fusion performance	Beam power
	ICRH power
	Neutron rate
D-T-prediction	Equivalent DT fusion yield
Alpha physics	Alpha particle effects
Isotope physics	H campaign
	D to match H
Reference pulses	For use in tritium
Diagnostics	Ti for high performance
	Ti for tritium reference pulses
	TAE damping in X-pt plasma
	Toroidal mode number
	14 MeV neutron calibration
	DT-compatible cameras
DTE2 technical preparations	DT rehearsal
	DT safety case adopted
	Tritium gas fuelling
	DT first wall protection
	Tritium deliverables

Assesment of DT readiness in July 2020

Achieve a stationary fusion plasma with ITER-Like-wall with W ~ 50-75MJ, P ~ 10-15MW for 5s fusion fusion

Technical/Scientific readiness for DT: 2020

Stationary fusion performance (5s) above C- Wall record



[C. Challis et al. 2020]

- Significant progress with reliable & steady high NBI power
- Peak (50ms) neutron rate significantly higher than in 2016, slightly above C-wall reference !

X Litaudon JET DT Task force meeting| 10th Sept 2020

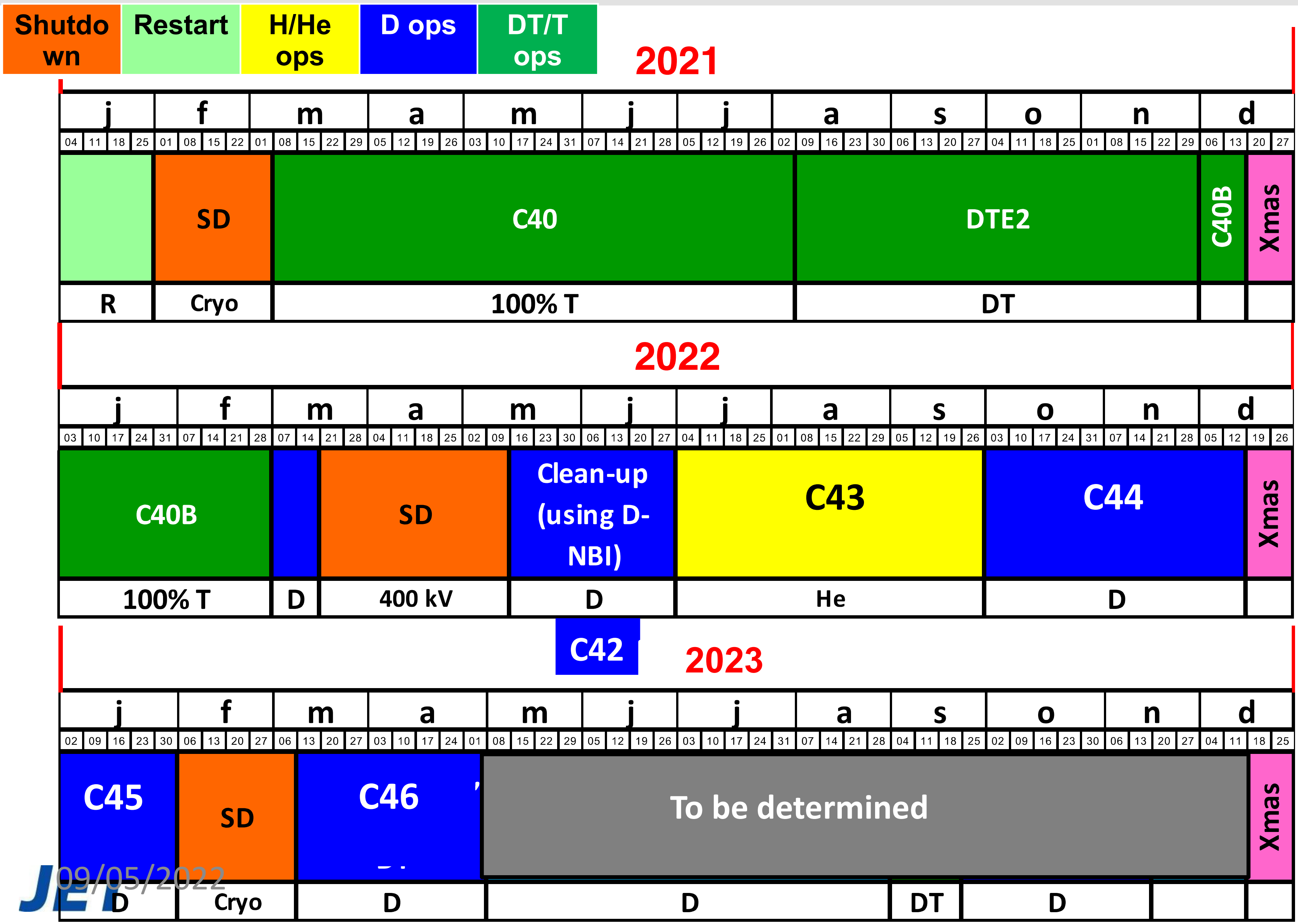
Technical/Scientific readiness for DT: KPI

- **On 26th June 2020, the AHG (R. Wolf –Chair) updated the progress made towards achieving the JET Key Performance Indicators:**
  - "once the technical preparations of the Active Gas Handling System and the Exhaust Detritiation System are completed, the AHG does not see fundamental issues for proceeding towards the JET tritium and the D-T-campaigns"
- **General Assembly (July 2020) approved unanimously the JET readiness for proceeding towards the JET tritium and the D-T-campaigns following the recommendations contained in the AHG report** ("EUROFUSION GA (20) 30 - 4.2b - JET KPI assessment - update - v3")

Outline

- Rationale for JET DT campaign
- DT campaign Objectives
- Technical/Scientific readiness for DT: KPI
- **Tritium operation in JET**
- Preliminary Scientific Highligths: Plasma scenarios

JET DT campaign schedule



Operational budgets

- Operational Pattern: In order to keep up with tritium reprocessing and accounting, DTE2 will be on a five-week cycle with three weeks of operation following by one week of tritium reprocessing and one week of tritium accounting. There will be four days of operation in the first week and then three operational days in the second and third weeks. Operation during Campaign C42 will revert to five double-shift days per week.

- Neutron budget: The 14 MeV neutron budget for DTE2 (C41) is 1.3×10^{21}. A 14 MeV neutron budget of 5×10^{19} is reserved for Campaign C42.

- Tritium budget: The DT safety case limits the amount of releasable tritium inside the vacuum vessel stored on the cryopanels to 11 g (44 bar-l). It is planned to carry out daily (overnight) regeneration of all cryopanels. This requires approximately 8 hours and so tritium usage in any one day is limited to 44 bar-l.

- Hydrogen isotope budget: During DTE2, the maximum amount of hydrogen (i.e. including all three isotopes) that can be supplied to the torus and the NIB operating in tritium is 450 bar-l per operational week. Deuterium supplied to the second NIB is not counted against this limit as it is processed in AGHS via a separate process.

Campaign management

- DTE2, together with T campaign, is the culmination of years of scientific, engineering and regulatory preparation at JET
  → unique opportunity
  → we need to create the best scientific output, with strong impact on international fusion research

- Campaign will have pulsed-based approach (not sessions), as in T campaigns C39T and C40

- No plasma development time in D-T (as in T)

- Planning and control of T-gas (44 bar L daily) and 14 MeV neutron budget (1.5 x 10^{21} n for DTE2 campaign)

  → Reference discharges, T-consumption, n-budget required in the experimental proposals !

Outline

- Rationale for JET DT campaign
- DT campaign Objectives
- Technical/Scientific readiness for DT: KPI
- Tritium operation in JET
- **Preliminary Scientific Highligths: Plasma scenarios**

Scenarios for high performance

- **High current scenario.**
  - Good confinement relying on high plasma current (I_p>3.5 MA).
  - Referred to as ‘baseline scenario’.

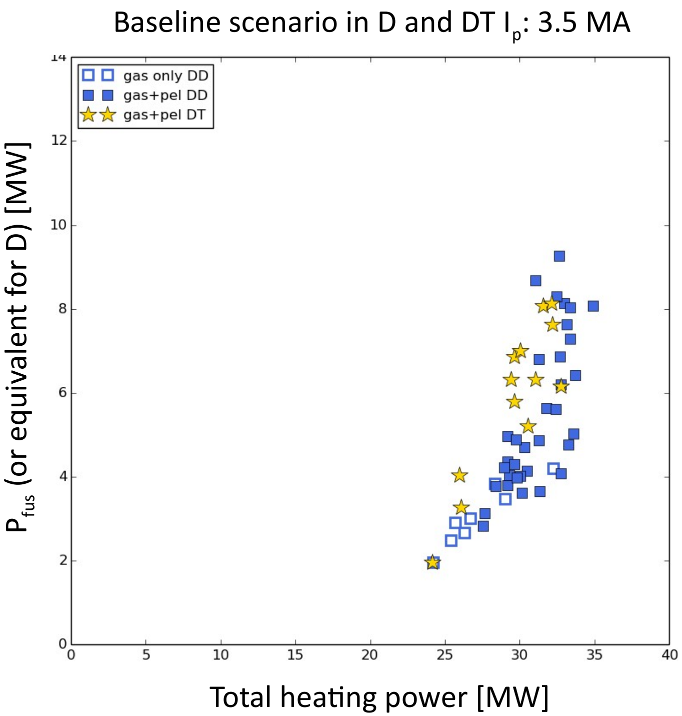
- **High β scenario.**
  - Good confinement predicated on high β_p at lower plasma current (I_p<2.5 MA).
  - Referred as ‘hybrid scenario’.

- **Optimized fuel mix scenario.**
  - Based on hybrid scenario.
  - T rich and D beam to maximise beam target fusion power.
  - Optimised for JET.

- Reference scenarios prepared in D and T.

Conditions for success

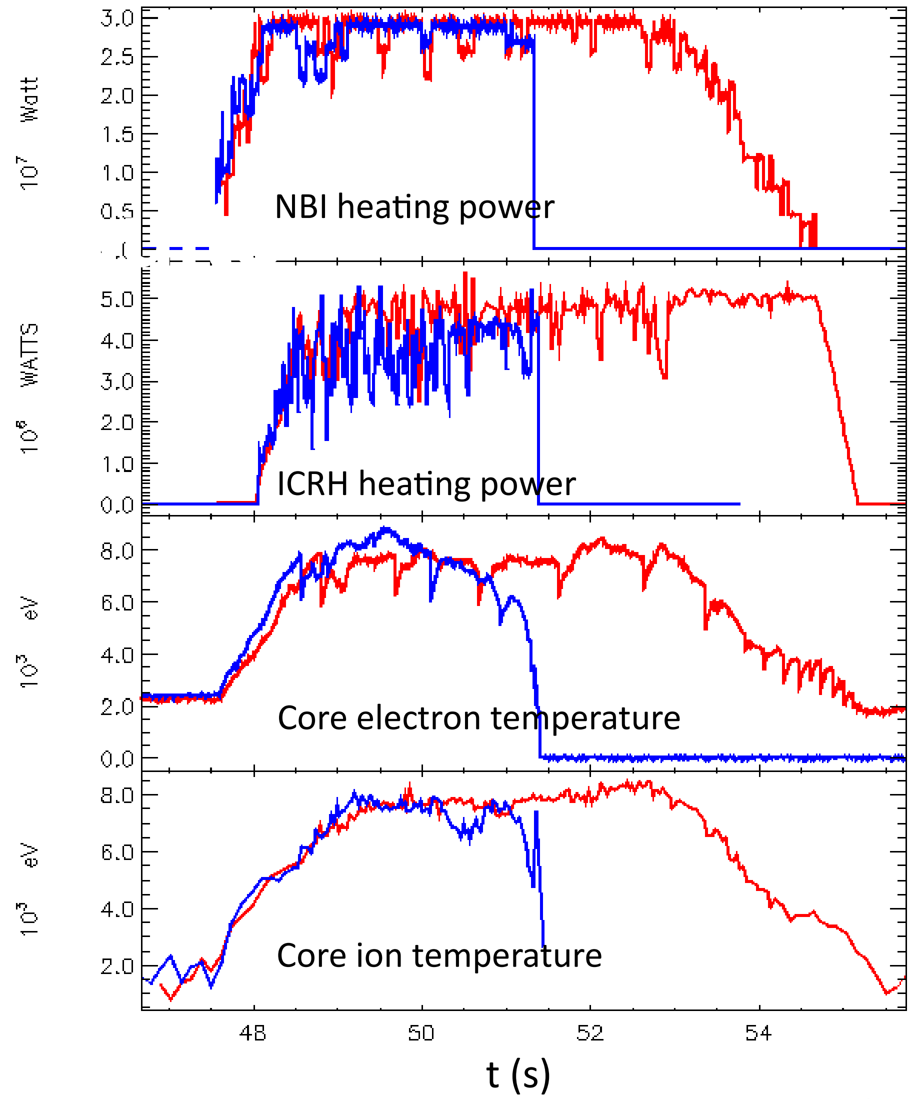
- All scenarios operate in **high confinement mode (H-mode)** exhibiting more or less regular edge localized modes (ELMs) expelling particle and heat from the plasma in bursts.
- All scenarios rely on high **auxiliary heating power**.
- All scenarios **affected by heavy impurity accumulation** (mainly W).
- Scenario optimization is a **delicate balance between operating in condition of optimized confinement, high input power and good impurity flushing/screening** (provided by ELMs and neoclassical transport).
- Important physics implication on the plasma behaviour in each scenario.



Baseline scenario results

- Peak fusion power ~8.3 MW.
- 50-50 thermal/beam-target.
- Additional heating power: ~29 MW NBI, ~4 MW ICRH.
- T_i~T_e (7 keV)
- In D-T limited by impurity accumulation in a region of the plasma situated on the low field side.

96482 D, 99948 DT 3.5 MA / 3.35 T

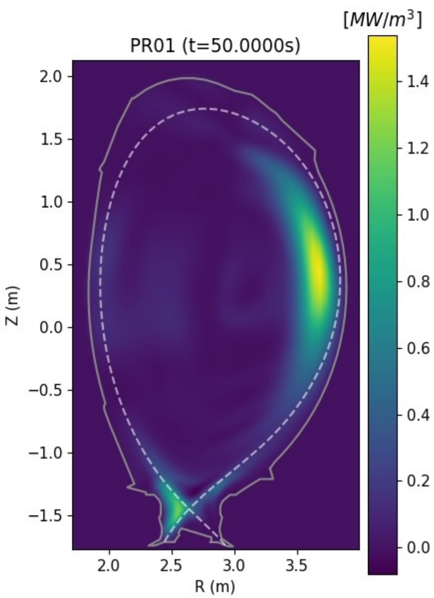


Luca Garzotti | IoP 48th Annual Plasma Physics Conference | 11th – 14th April 2022 | Liverpool, UK

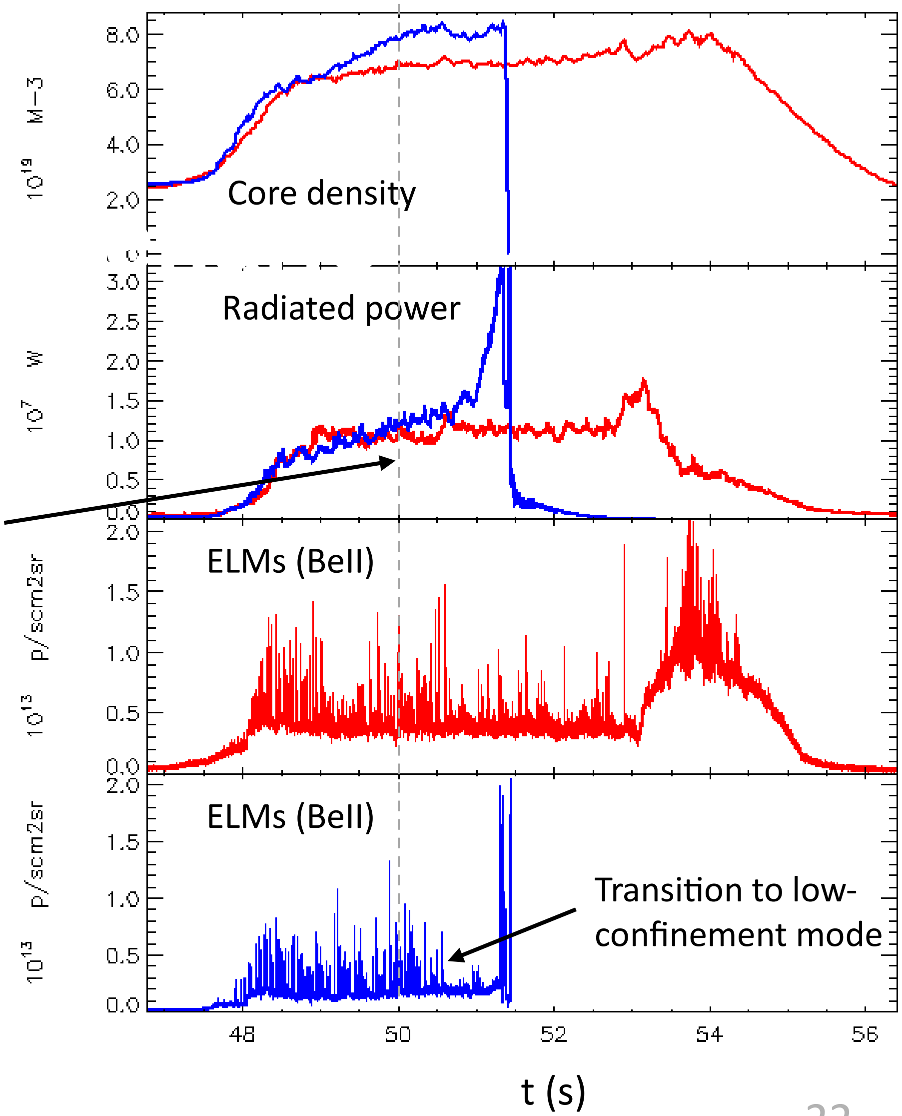
Physics of baseline scenario

- High current implies high density.
- Density constantly increasing in T (better controlled in D).
- Margin above H-mode power threshold reduced.
- ELM impurity flushing becomes less effective.
- Impurities concentration and radiation increase leading to disruption.

Luca Garzotti | IoP 48th Annual Plasma Physics Conference | 11th – 14th April 2022 | Liverpool, UK

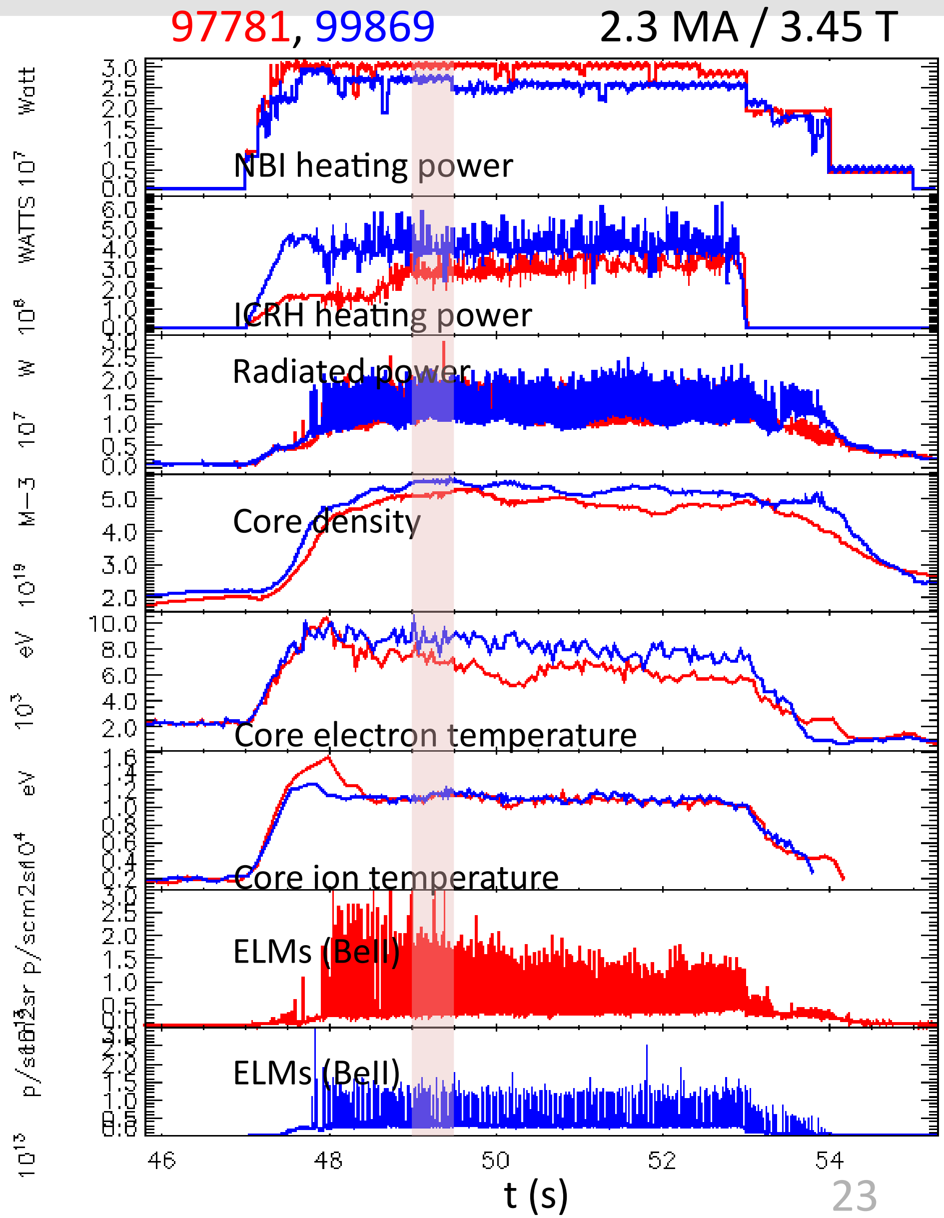


96482 D, 99948 DT 3.5 MA / 3.35 T



Hybrid scenario

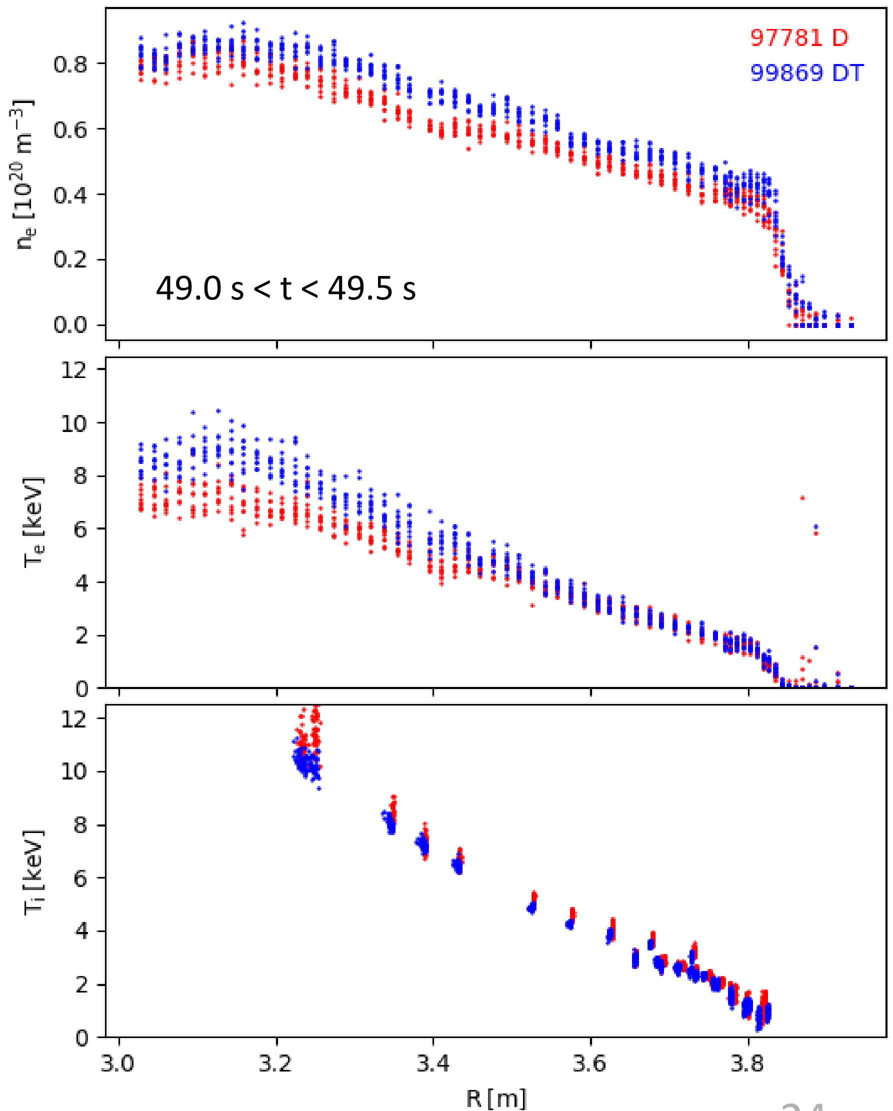
- Performed for first time in DT.
- 42 MJ fusion energy produced.
- 40-60 thermal/beam-target.
- High confinement predicated on high β_p (lower plasma current).
- Low current implies low density.
- More comfortable power margin above H-mode power threshold.
- Regular type-I ELMs.



Physics of hybrid scenario

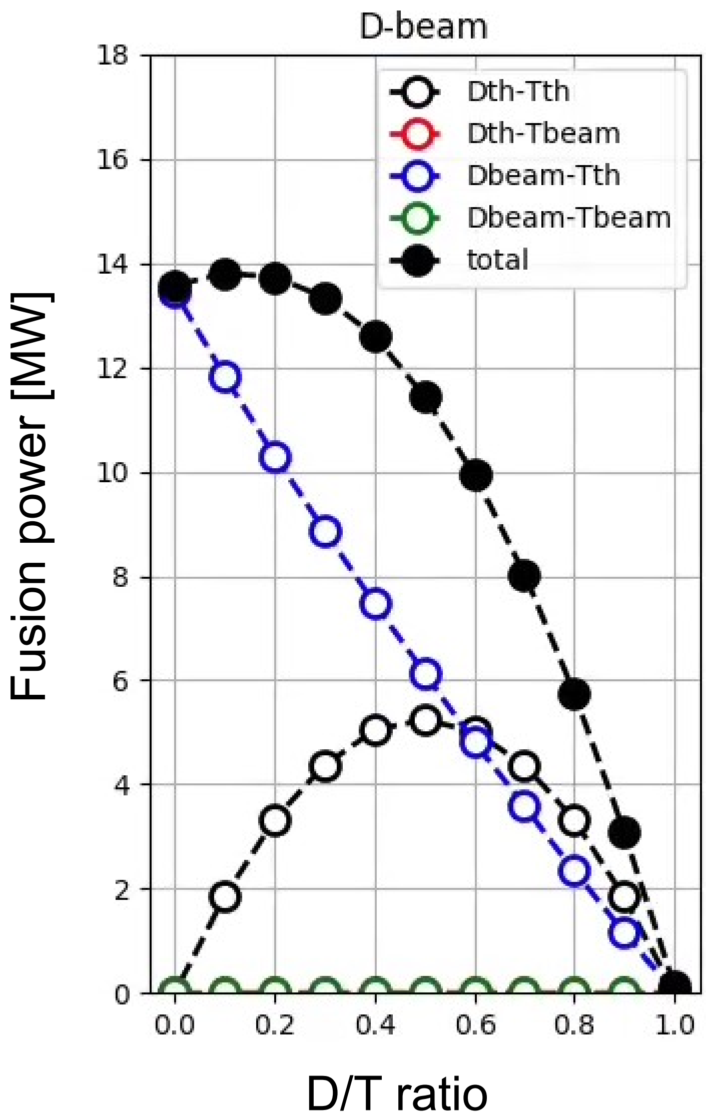
- Dominant screening of impurity in the pedestal as opposed to flushing with ELMs (as in baseline).
- Develop access to H-mode to set up pedestal impurity screening.
- Temperature gradient favourable.
- Density gradient detrimental.
- Regular ELMs maintain pedestal condition: high temperature, low density In D and DT.
- $T_i > T_e$

2.3 MA / 3.4 T



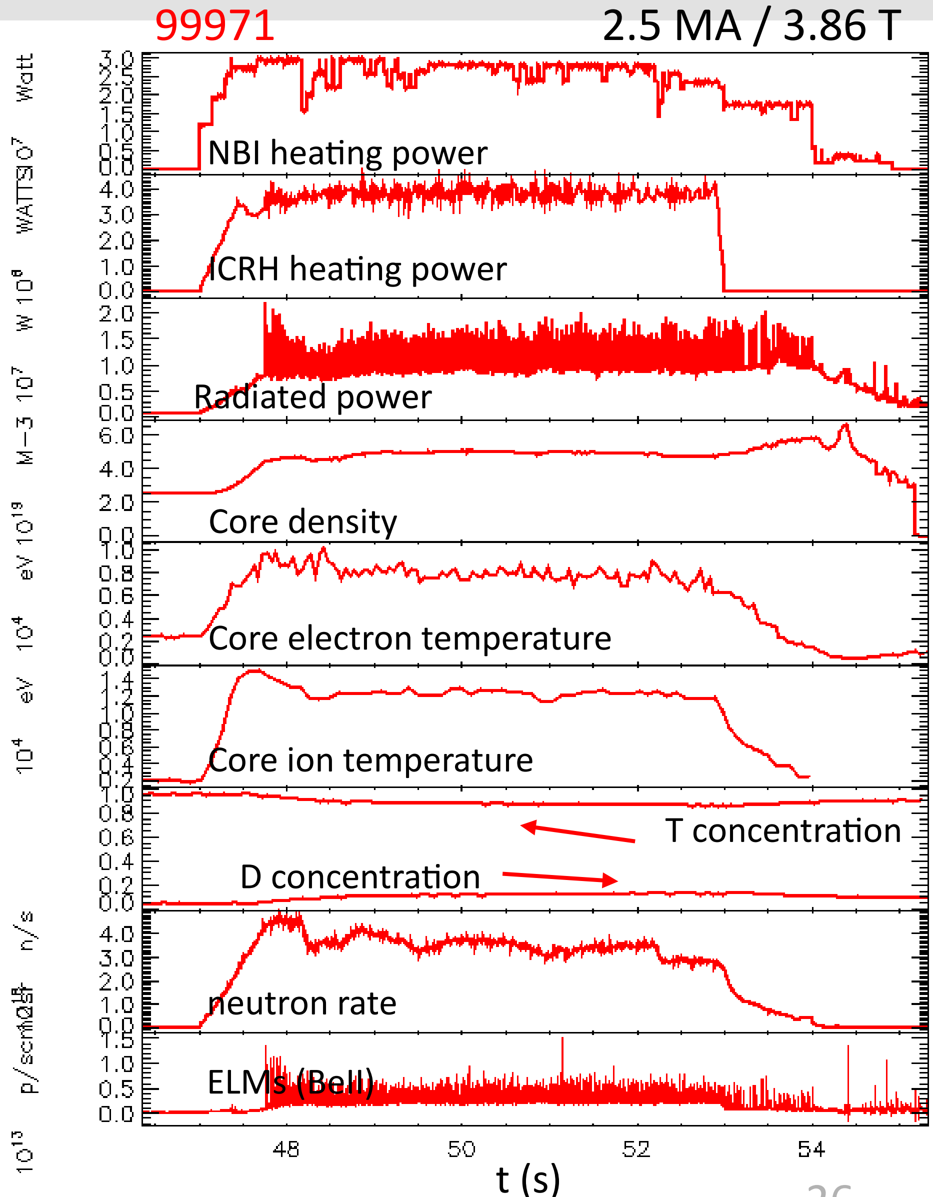
Principle of optimised fuel mix scenario

- Maximize non-thermal contribution to fusion power.
- T plasma heated with D neutral beams. D/T ratio determined by beam fuelling.
- Maintaining a T rich plasma for a sufficient time can be challenging.



Optimised fuel mix results

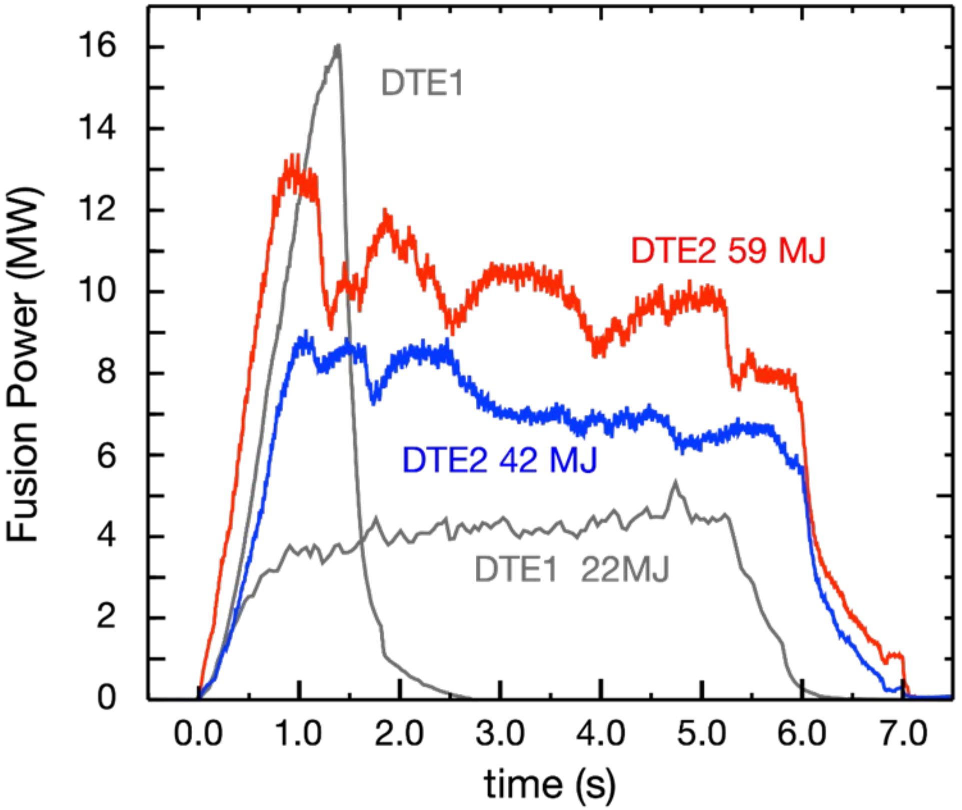
- Hybrid scenario better suited to this kind of optimization (low density, central NBI deposition).
- D-minority ICRH heating scheme – requires high TF,
- Steady high performance T rich plasma achieved.
- 59 MJ fusion energy produced.
- 25/75 thermal/beam target from modelling neutron spectra.
- Neutron rate follows closely NBI waveform.



Luca Garzotti | IoP 48th Annual Plasma Physics Conference | 11th – 14th April 2022 | Liverpool, UK

Fusion power

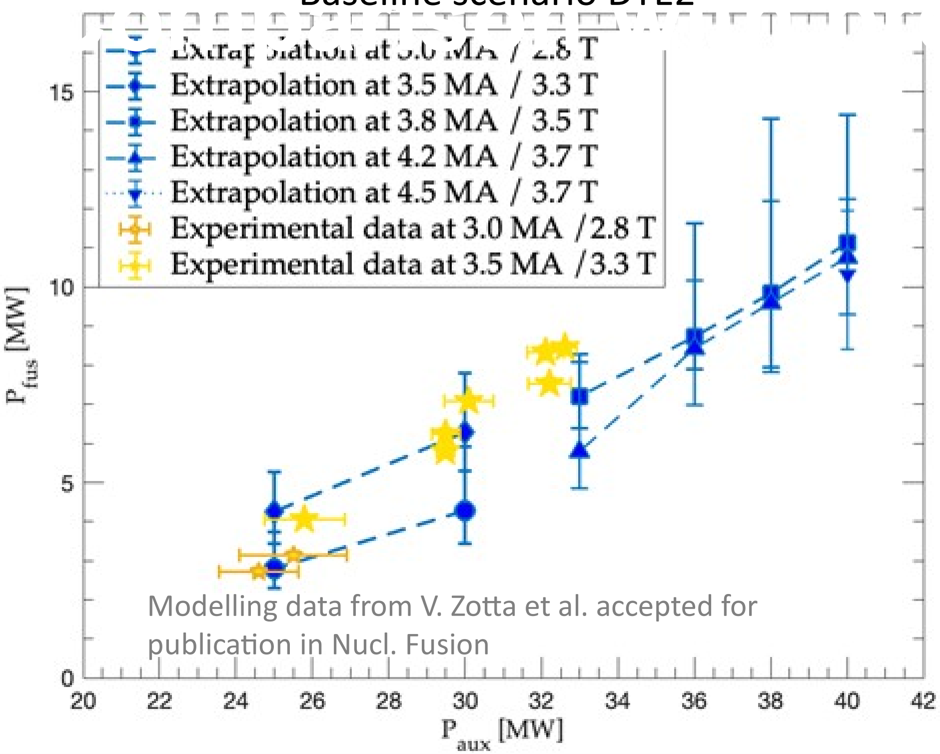
- Fusion performance in DTE2 with ITER-like wall beyond that of DTE1 with C wall.
- High performance sustained for 5s.



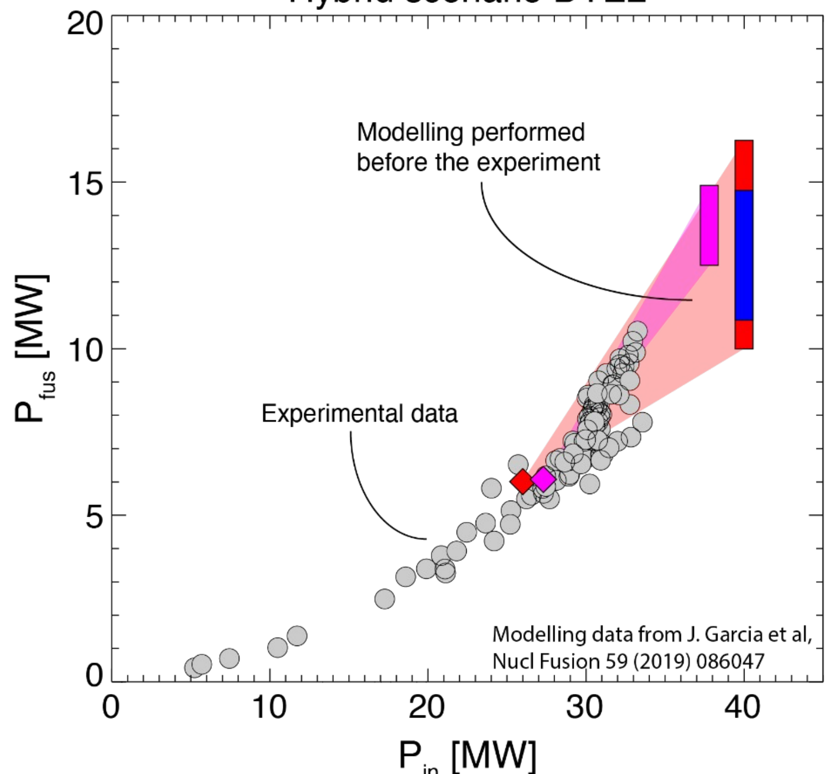
Comparison with predictions

The results compare well with predictions made using state-of-the-art transport models up to the maximum heating power achieved (NBI+ICRH ~34 MW).
Gives us confidence in our capability to predict the plasma behaviour in ITER.

Baseline scenario DTE2



Hybrid scenario DTE2



Open questions (for plasma scenarios)

- Several aspects of the physics underpinning the behaviour of the different scenarios are understood.
- There are open questions for more detailed physics studies:
  - Dynamics of the main gas density in D, T and DT and implications for stationarity.
  - Impurity build-up and avoidance strategies.
  - ELM dynamics (in particular of irregular ELMs typical of high current scenario).
  - Effect of MHD (including fast particle induced MHD) on fusion performance.
- More pulses in D to come later in 2022 to finalize the scenario studies.

Conclusions

- A successful DT campaign was conducted at JET in 2021 thanks to the joint effort of a wide team of European scientists.
- Three scenarios were developed for high performance.
- Hybrid and optimised fuel mix gave record performance sustained for 5 s
- Baseline gave performance in line with predictions but could not be sustained for 5 s.
- Several ITER-relevant physics aspects of the scenario development were highlighted during the DT campaign and the preparation of the reference shots in D.
- Rich database of plasmas has been collected awaiting in depth analysis, which has just started and will last for several months.

ENEA participation (science)

- ENEA has participated intensively in the success achieved in the DT campaign, several scientific studies were carried out:

Run-away suppression with the SPI (P. Buratti)
MHD studies in the hybrid scenario on JET (P. Buratti, E. Giovannozzi, G. Pucella)
MHD studies in the baseline scenario on JET (E. Giovannozzi, G. Pucella)
Control of electron temperature profile by using ICRH and RT data coming from Electro Cyclotron Emission (M. Cappelli, M. Zerbini)
Fully predictive simulations for moderate beta baseline scenario on JET (V. K. Zotta, R. Gatto, C. Mazzotta, G. Pucella, in collaboration with Uni Tor Vergata)
Effects of Ne seeding on performance of JET baseline scenario (S. Gabriellini, V. K. Zotta, R. Gatto, E. Giovannozzi, G. Pucella, in collaboration with Uni Tor Vergata)
Integrated Tokamak Scenario simulations using RAPTOR code (C. Piron)
JET neutron camera monitoring/exploitation s (D. Marocco)
JET Compact Neutron Spectrometers monitoring/exploitation (F. Belli)
JET ICRH studies (C. Castaldo)
JET Scrape Off Layer Modelling using SOLEDGE2D (N. Carlevaro)
Runaway Electron beam control in JET (G. Artaserse)
Investigation of differences in Electron Temperatures measurements by ECE and Thomson scatterin in high performance DT plasmas (F. Orsitto, L. Senni)
Analysis of isotopic effects on JET polarimetry measurements (F. Orsitto, L. Senni)
Support to JET operational tools and shifts (M. Baruzzo, P. Buratti, M. Zerbini, G.Artaserse, G. Pucella)

ENEA participation (operation)

- In total 20 Session Leader shifts were cover, with extensive preparation work of discharge programming as Reference Session Leader for several C40 and C41 experiments: M18-03, M18-18, M21-09, M21-11, M21-16, M21-21. 11 Diagnostic coordinator shifts were covered, and 32 MHD expert shifts, contributing significantly in the achievement of record Nuclear Fusion energy produced in DT pulses.

  In 2021 several operational shifts were covered as RDE (Rostered Diagnostic Expert) for magnetic diagnostics during Tritium-ops experimental sessions, to monitor scientific relevant data acquisition systems KC1E, KC1H, KC1M for experimental purposes

ENEA involvement in DT analysis

My view on where ENEA could be effective in producing new and interesting results from existing DT data (DT analysis and modelling 2022), but beware the EUROfusion funds are limited!

- **Demonstrate fusion power up to 15 MW, sustained for 5 s**
  - **Integrated Scenario modelling**
  - **MHD stability of DT Scenarios**
- **Demonstrate integrated radiative scenarios in plasma conditions relevant to ITER (would be a bonus for DTT, to be carried out in future JET Ecp)**
- **Demonstrate clear alpha particle effects**
  - **Characterization of fusion products**
  - **Alpha particle effects analysis and modelling**
- Clarify isotope effects on energy and particle transport and explore consequences of mixed species plasma
- Address key plasma-wall interaction issues
- **Demonstrate RF schemes relevant to ITER D-T operation**
  - Validation of ITER-like heating schemes
  - Study of RF-induced impurity source

Backup slides

Peak fusion power ~8.3 MW.

50-50 thermal/beam-target.

T_i~T_e

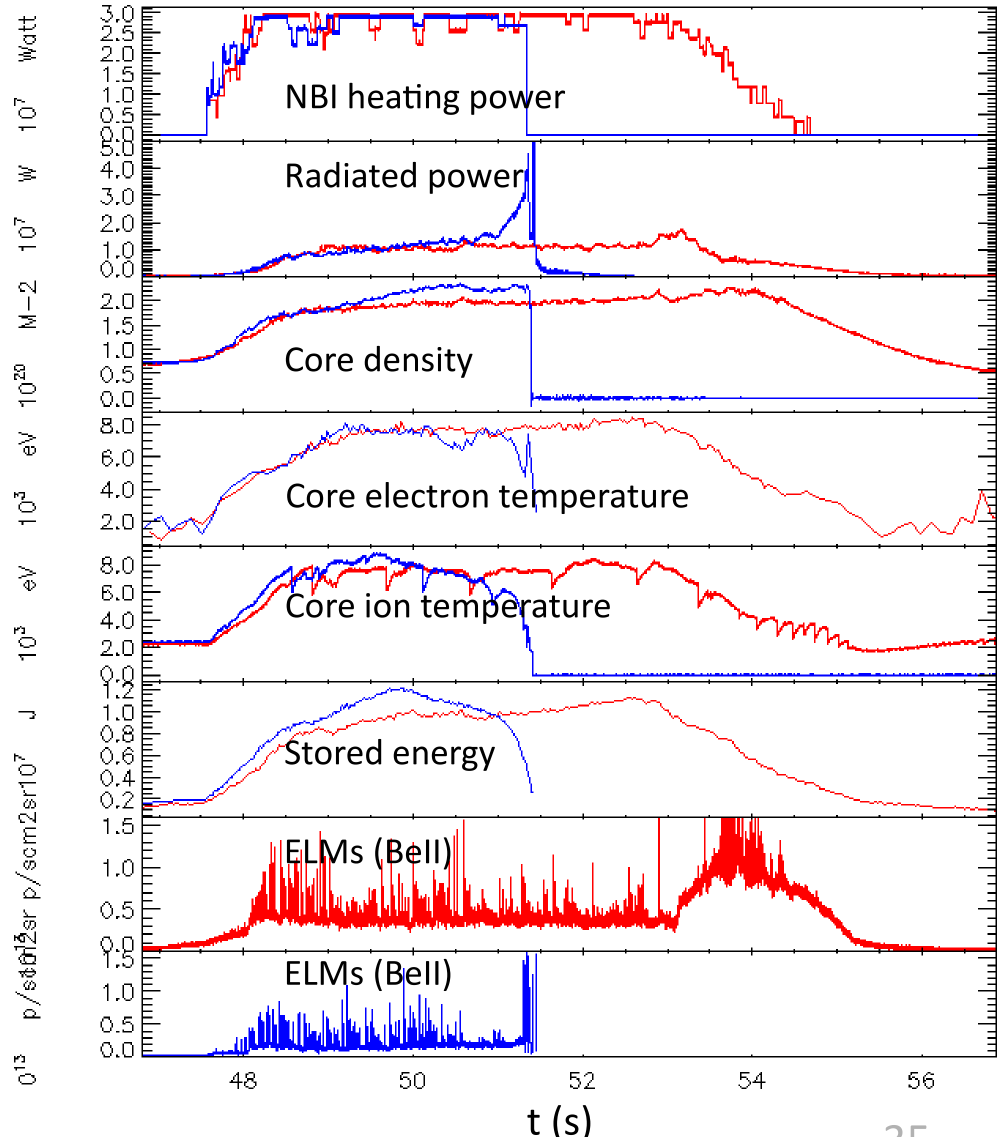
ELM pacing D pellets inducing compound ELMs.

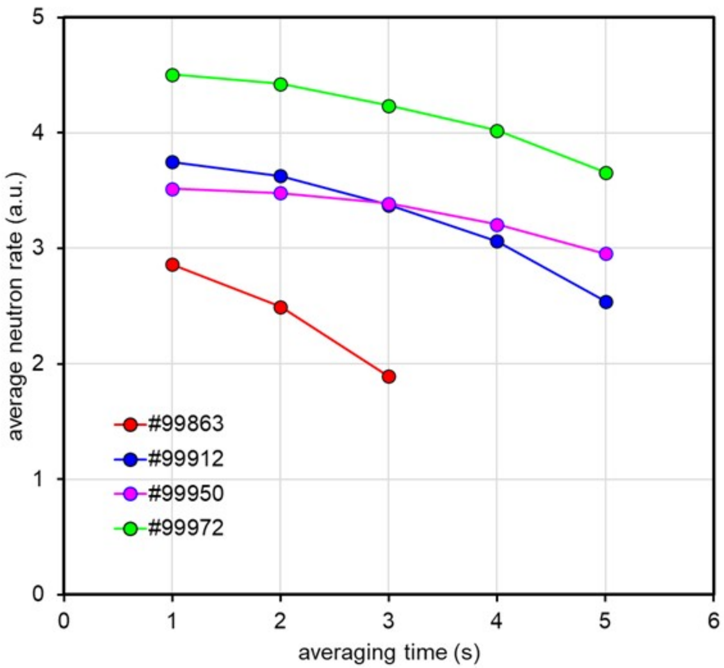
Marginally above L-H power threshold.

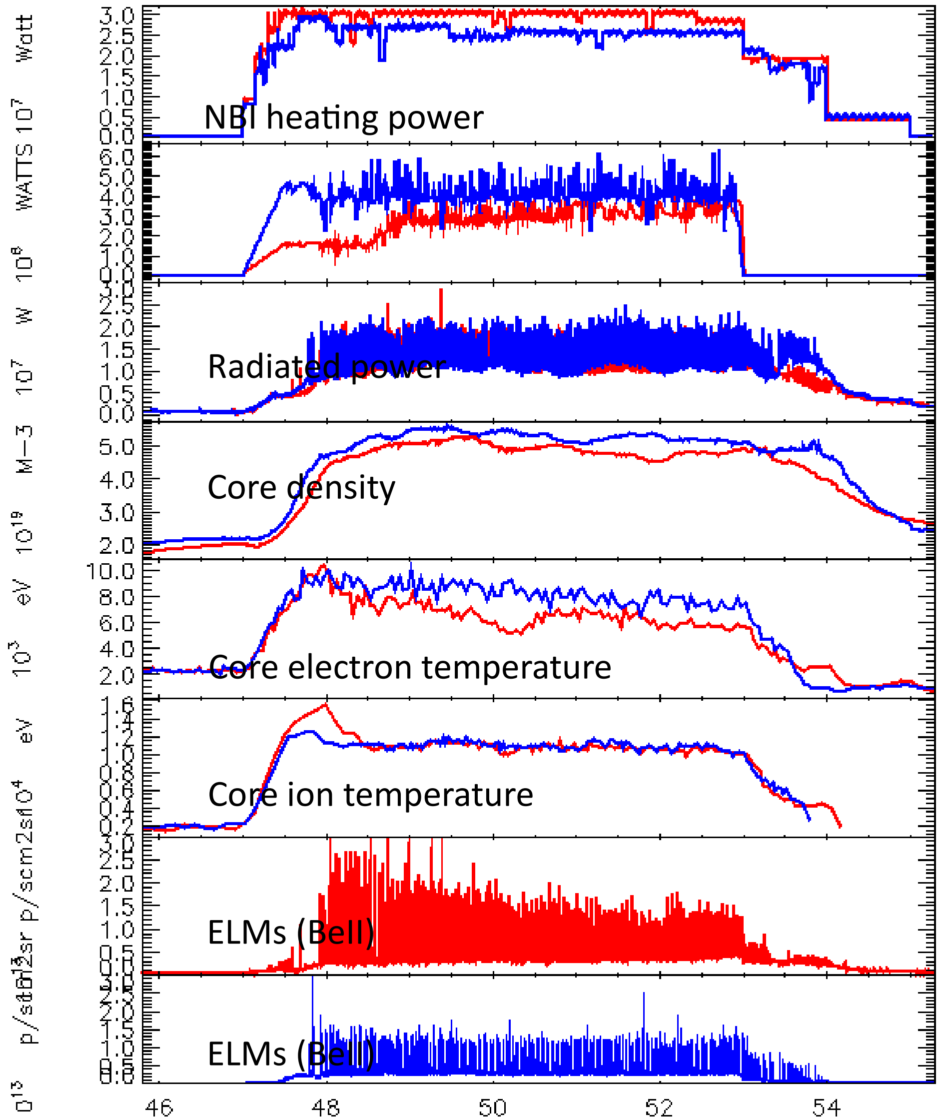
In D-T limited by impurity accumulation.

96482, 99948

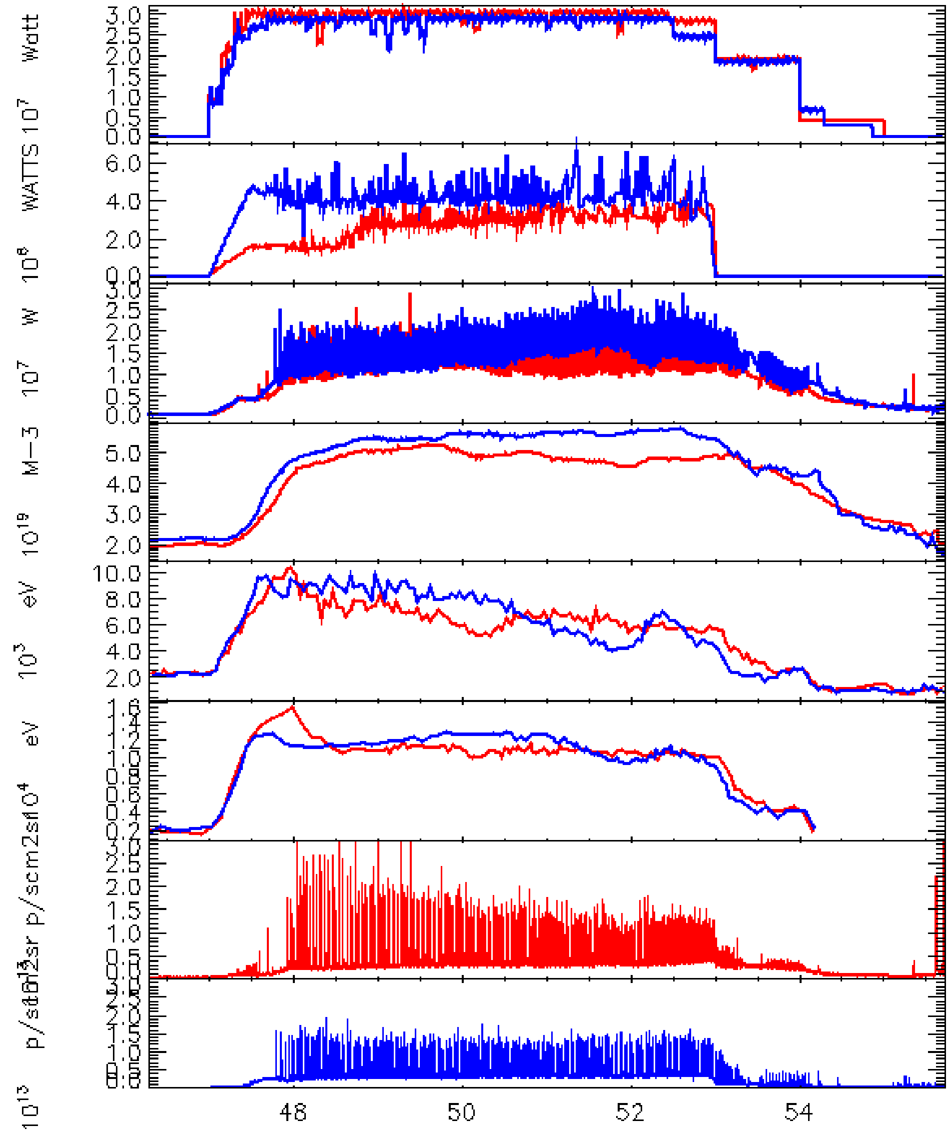
3.5 MA / 3.35 T





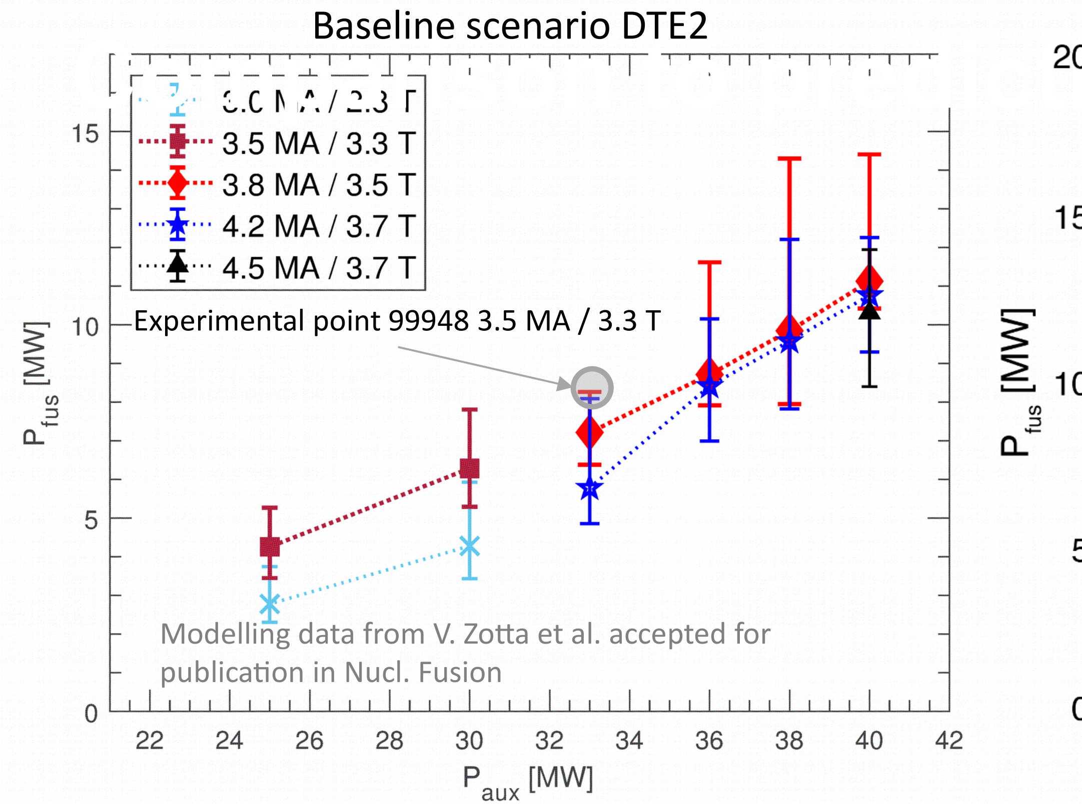


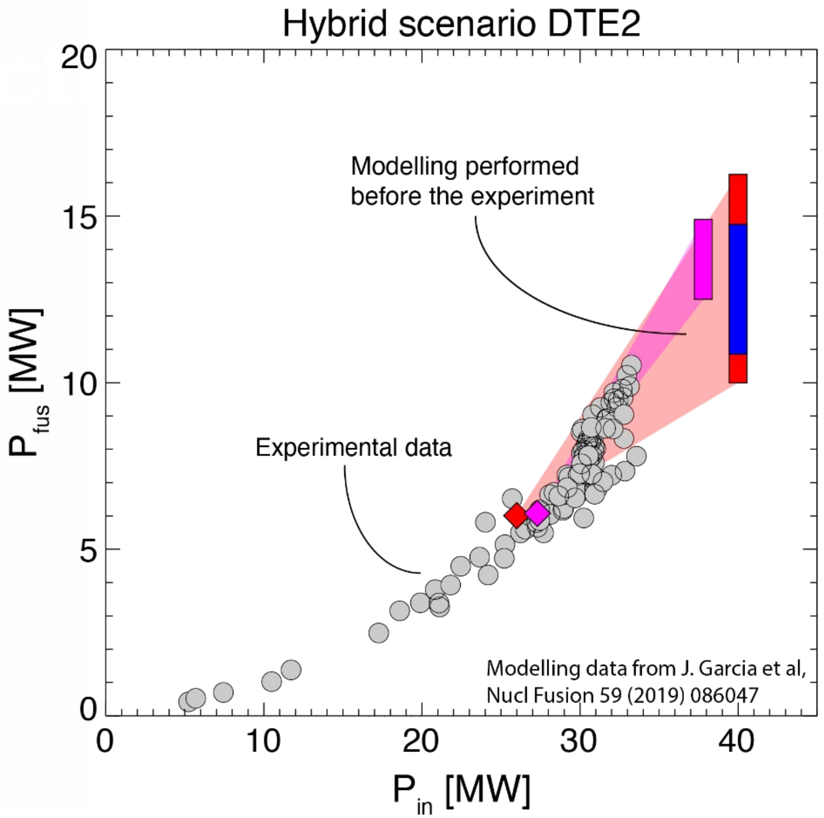
Stored energy



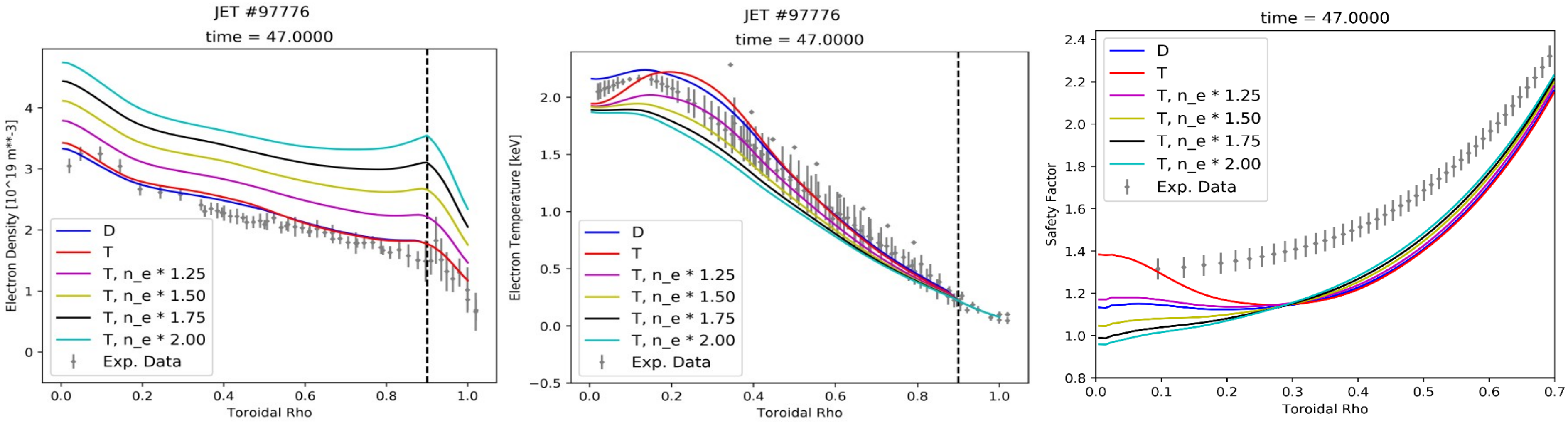
Watt
WATTS 10⁷
10⁶
W
10⁷
M−3
10¹⁹
eV
10³
eV
p/scm2sr
10¹³
48
50
52
54

The results compare well with predictions made using state-of-the-art transport models.
Maximum heating power achieved (NBI+ICRH) ~34 MW.





Potential MHD at high beta requires careful tailoring of the current profile.
Transport simulations predicted and experimental evidence confirmed an increased hollowness of the temperature profile with isotope mass affecting the evolution of the q profile.
Density increase of 20-30% necessary when going from D to T in order to get the same q profile at the end of the current ramp.
Fine tuning of fuelling different in D, T and DT.



A. Ho, APS Plasma Physics division 2021