



Preparation and Execution of final Deuterium Tritium Campaigns at JET

(Baseline Scenario)

Scientific Coordinators

D.Frigione, L. Garzotti, *F.Rimini*, D.Van Eester, V.K. Zotta

JET



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Contributors



L. Garzotti¹, D. Frigione², P. Lomas¹, F. Rimini¹, D. Van Eester³, S. Aleiferis¹, E. Alessi⁴, F. Auriemma⁵, R B Morales¹, I. S. Carvalho⁶, P. Carvalho¹, A. Chomiczewska⁷, E. De La Luna⁸, D. R. Ferreira⁶, A. Field¹, M. Fontana¹, L. Frassinetti⁹, S. Gabriellini¹⁰, E. Giovannozzi¹¹, C. Giroud¹, W. Gromelski⁷, I. Ivanova-Stanik⁷, V. Kiptily¹, K. Kirov¹, M. Lennholm¹, C. Lowry¹, C. F. Maggi¹, J. Mailloux¹, S. Menmuir¹, S. Nowak⁴, V. Parail¹, A. Pau¹², C. Perez von Thun⁷, L. Piron¹³, G. Pucella¹¹, C. Reux¹⁴, E. Solano⁸, O. Sauter¹², C. Sozzi⁴, Ž. Štancar¹, C. Stuart¹, H. Sun¹, G. Telesca⁷, D. Tskakaja¹⁵, M. Valovič¹, N. Wendler⁷, V. K. Zotta¹⁰ and JET Contributors

Note: V.K. Zotta led the coordination team during the final part of the Baseline experiment and is presently in charge of coordinating the analysis and interpretation of the data taken during its run.

Plan of the Talk

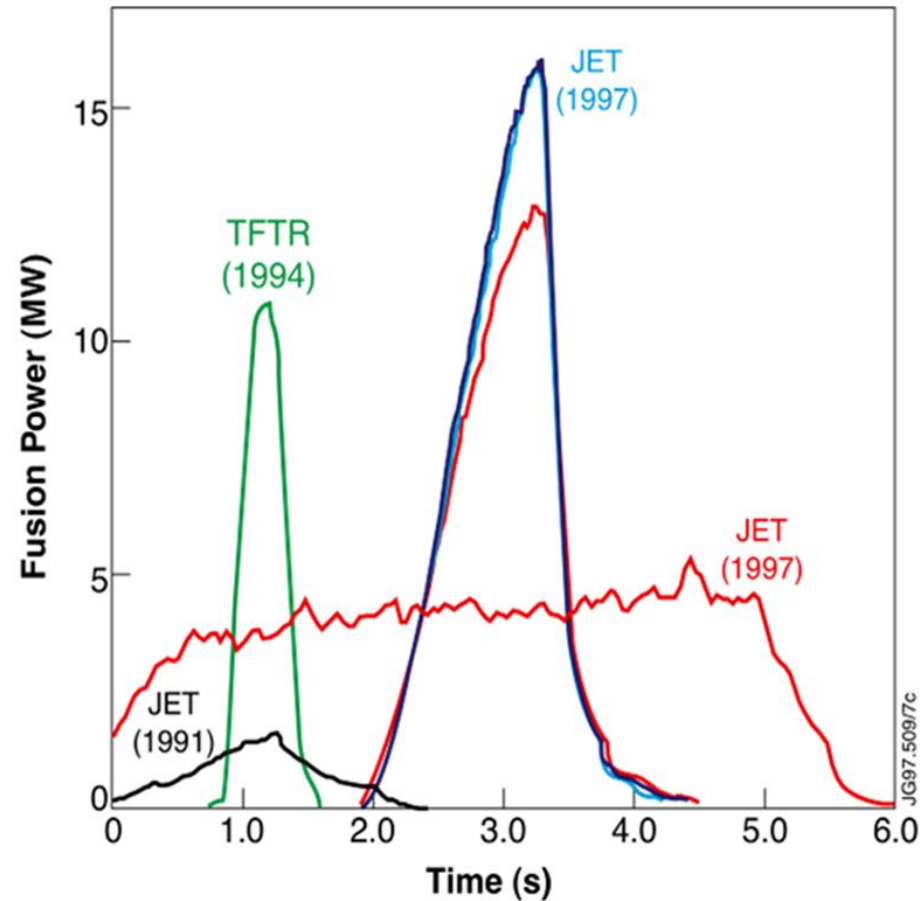


- Introduction
- **New tools and new objectives** of DT experiments
- **Baseline results with former Carbon wall**
- Preparation and execution of **Baseline experiments in DTE2**
- **Extention with a new campaign (DTE3)** devoted to completion and stability.
- Conclusion

DTE1 Campaign with Carbon Wall



- **DTE1** experiments were carried out in **1997** after a Trace Tritium experiment in 1991
- Achievements: **~16MW of transient P_{FUS} and ~4MW quasi-steady for around 5 sec.**
- **A large tritium retention was observed** in the C-wall , well beyond acceptable projected limits to ITER.
- A **project to install a Be-W wall in JET was started to minimize this effect (ILW)**



JET DTE2 campaign



Goals

- The **Main goal** was to achieve **fusion power up to 10 MW, sustained for 5 s with the new metal wall.**
- Demonstrate **reduced Tritium Retention**

New Tools

- **Increased NBI heating** power: from 24 MW to 34 MW.
- **Better diagnostics:** e. g. High Resolution Thomson Scattering (HRTS), Time Of Flight neutron spectroscopy (TOF).
- Improved **Real Time Control** capabilities. (RTC)

Main Scenarios



- **Baseline: peaked, relaxed low q-profile, high current, low β_N (below 2.0)**
 - Good confinement relying on high plasma current ($I_p \geq 3.0$ MA).
 - No q-profile shaping techniques required
- **Hybrid: controlled flat high q-profile, high β_N (larger than 2)**
 - Good confinement relying on high β_N ($I_p \leq 2.5$ MA).
 - q-profile shaping techniques required (timing of heating during, RF current drive etc.)
- **Tritium Rich: Hybrid-like with Optimized fuel mix.**
 - Based on hybrid scenario with T-rich plasma composition
 - T rich puffing background plus D neutral beams to **maximise beam-target fusion power.**
- The **scenarios actually studied in DT were prepared in advance in D and T** to be projected to DT and compared with the experimental results.



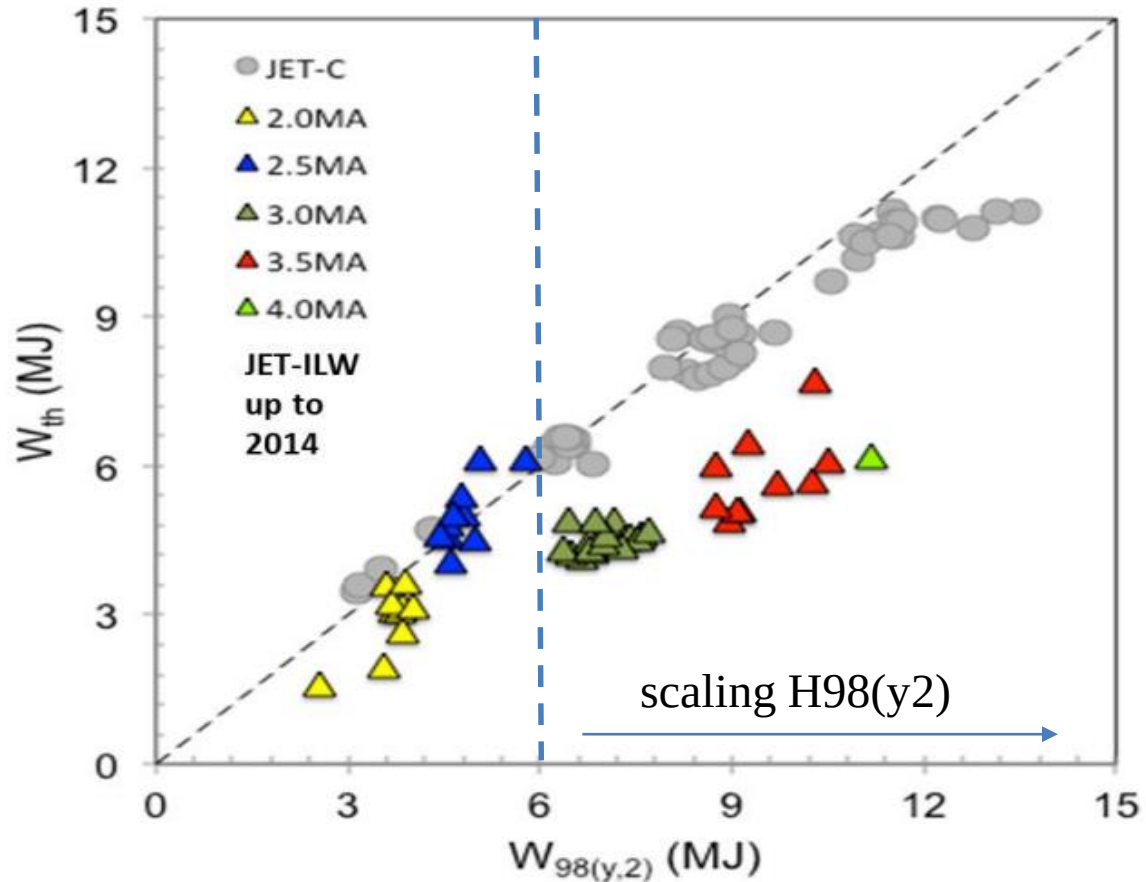
Here we shall concentrate on the

Baseline experiments

Initial observations in D with ILW



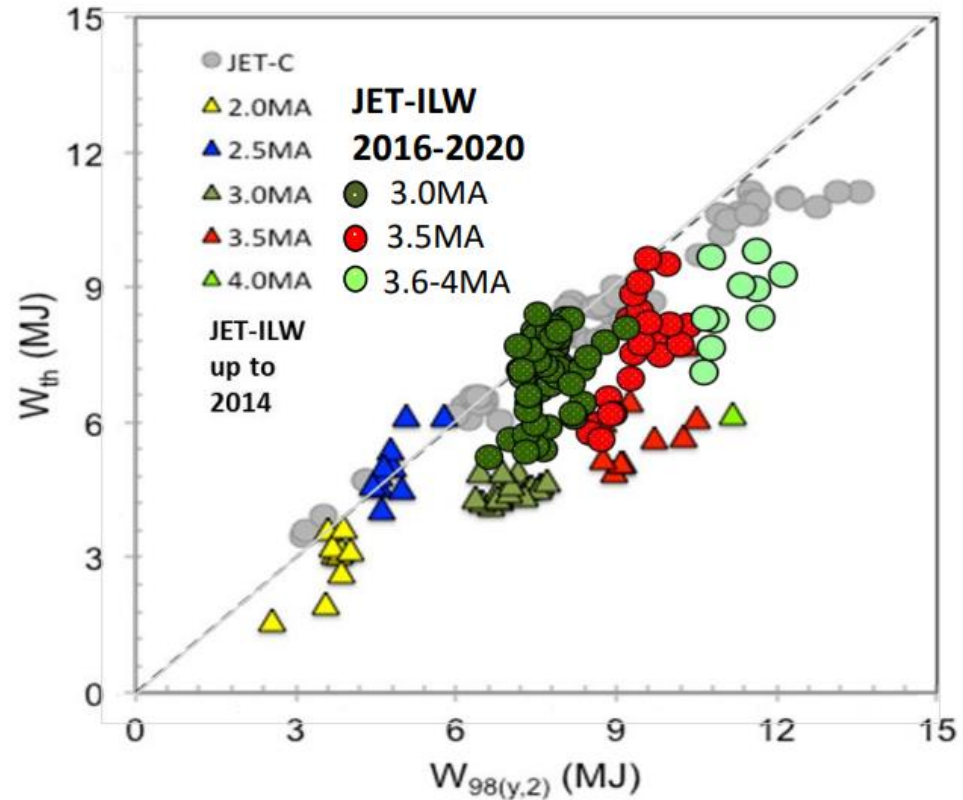
- Confinement with ILW was, at **low-medium plasma energy content ($I_p \leq 2,5$ MA)**, in line with C-Wall and H98(y,2) scaling. (Yellow and Green)
- Yet, **pulses at higher current, initially showed lower confinement** than their C-Wall counterpart.
- Such behaviour was attributed to an impact of the **isotope mass on particle transport** producing different density and imputiy behaviour



Performance recovered in D



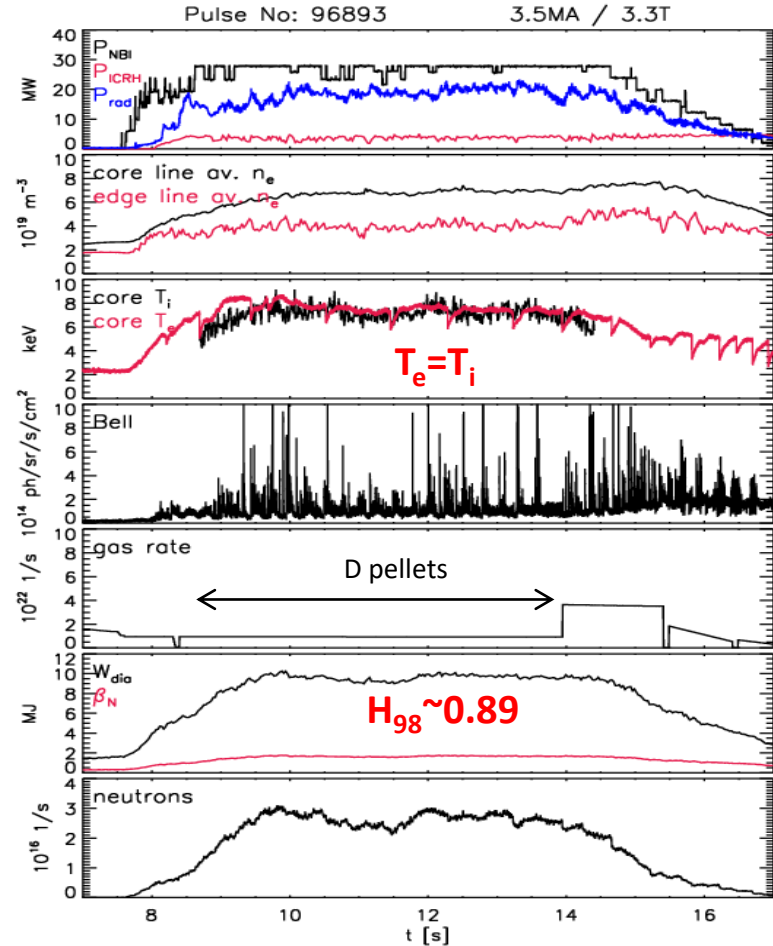
- **Confinement improved, at higher current (up to 3.6 MA)** thanks to
 - **Use of Pellets** for ELM triggering to flush out impurities
 - **Low gas dosing**, for improved pedestal and core confinement.
- **Some scoping pulses were executed at 4 MA.** At this current, more caution was needed **to avoid or mitigate very harmful disruptions.**



Baseline scenario in D



- The figure beside shows one of the best pulses run during the preparation phase:
#96893: 3.5 MA, 3.3 T, q_{95} 3.0, pacing Pellets
- Optimal fuelling: lowest gas rate** compatible with Type1 ELM regime (good confinement).
- Small pacing D pellets at 45 Hz** at H-mode entry then reduced to **35 Hz**.
- Obtained a **neutron yield of $\sim 2.6 \cdot 10^{16}$ neutrons/s averaged over 5 s.** with the potential to deliver an **average 7.7 MW of fusion power for 5 s when extrapolated to D-T**



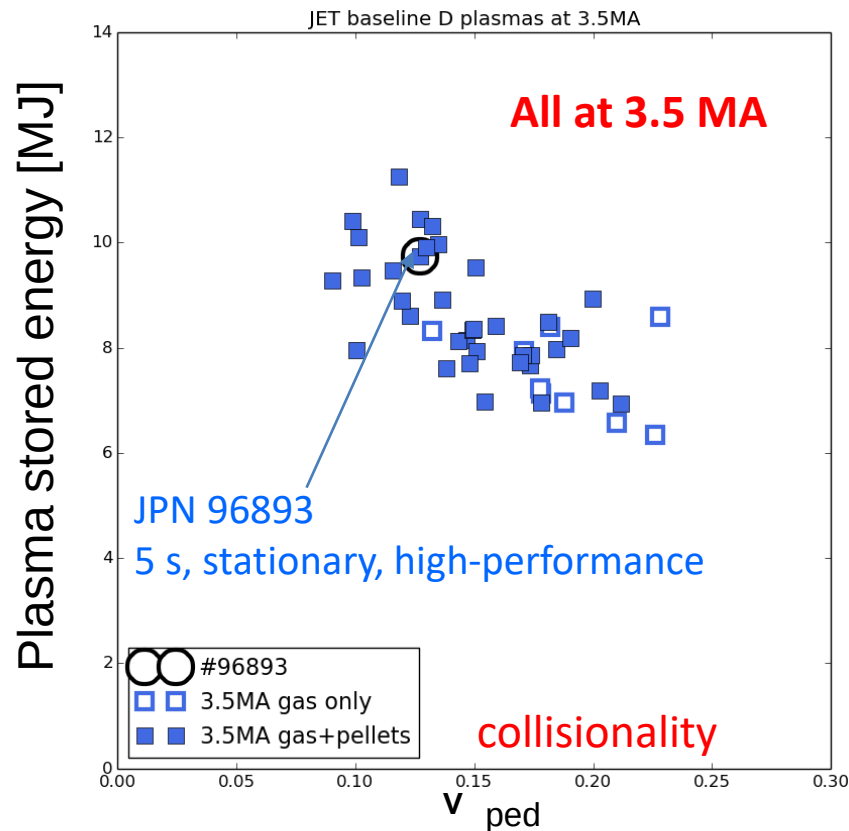
Path to high current, high performance Baseline



- **Keep pedestal collisionality low** by optimizing pellets and gas-puffing.
- **Use pellets, triggering ELMs, allows to flush out impurities** and reduce gas puff which is beneficial for confinement.
- **High heating power** (≥ 34 MW tot.) to sustain plasma in H-mode well above the LH threshold. The latter increases with magnetic field and density.

$$P_{\text{LH}} \propto n^{0.7} B^{0.8}$$

JET baseline database at 3.5 MA



Disruptions



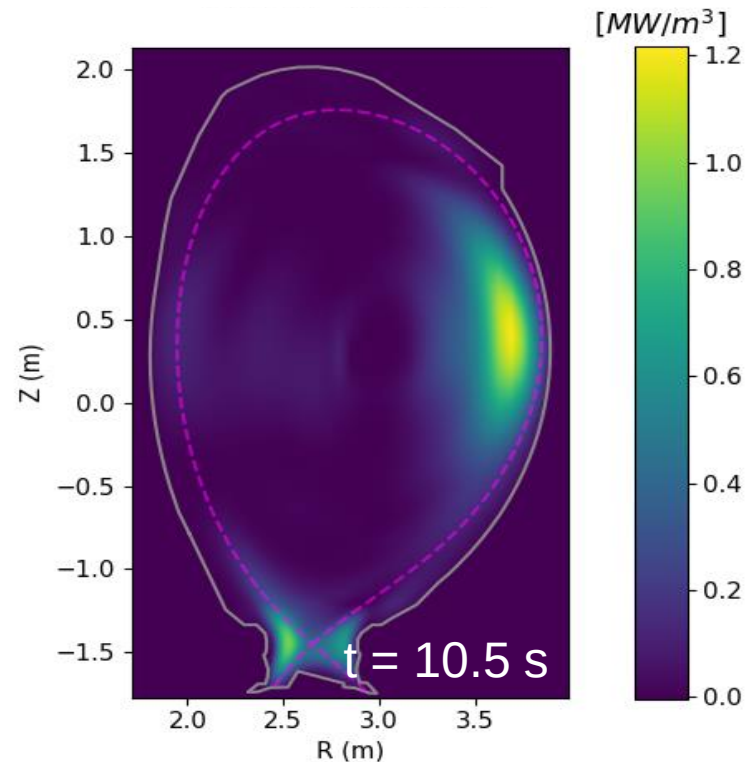
- **Disruptions are unwanted, sudden fast termination of the discharge..** Such events can be **minimized with a proper pulse design or mitigated in real time during the pulse** when programmed alarms are issued to the RTC system.
- **High performance Baseline operated close to JET operational limits** in terms of plasma current, toroidal field and shape. This implies is a domain where the risk of **disruptions is higher and their impact is stronger.**
- The occurrence of disruptions when approaching the operational limits is difficult to predict and/or avoid. **The disruptively at 3.5 MA floats around 60%.**
- **ENEA Frascati has substantially contributed** to the understanding of plasma termination issues proposing also remedial actions. (Pucella, Giovannozzi)

Impurity Radiation Losses



- With the new ILW, radiation was **dominated by the W generated in the Divertor** via sputtering.
- **Radiation was mainly confined at the low field side. W did not accumulate in the centre.** When this happens the temperature profile becomes hollow, the performance deteriorates leading eventually to a disruption,
- W accumulation is prevented by the **screening provided by the ICRH central heating.**
- **The flushing due to ELMs contributes to reduce W entrance** in the core region.

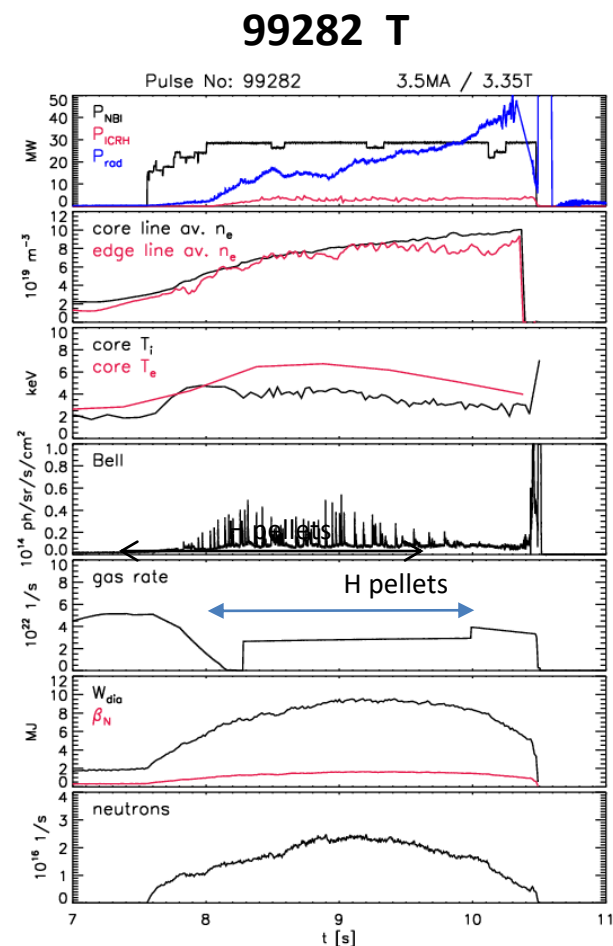
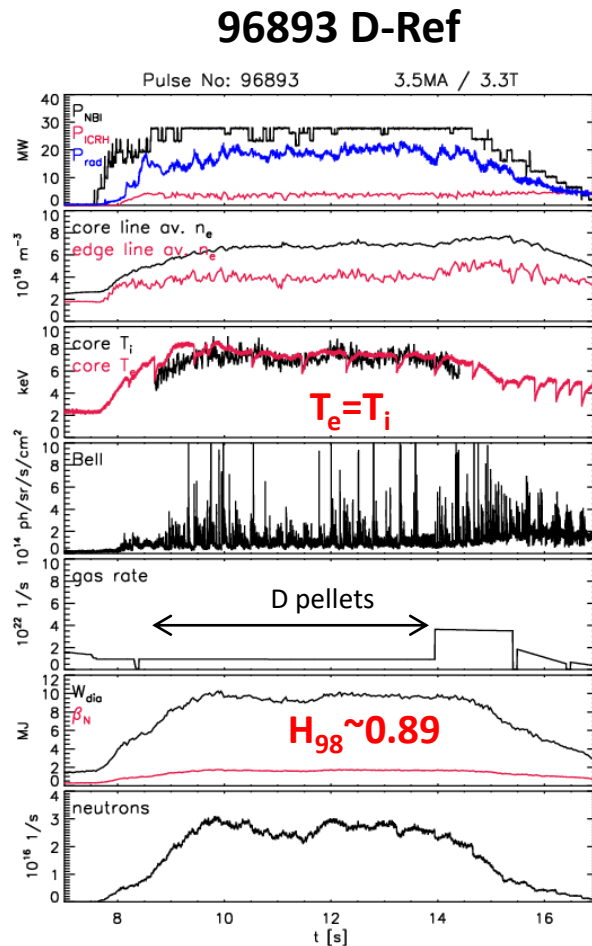
JPN 96893 - 3.5 MA / 3.35 T



Baseline scenario in T



- **Motivation: to explore isotope effect** for a better grounding of projections to D-T.
- **99282**: similar operational parameters as D reference (99693). 3.5 MA 3.35 T
- Outcome: **scenario sustained for no longer than 2 s in H-mode**. Slow core density increase

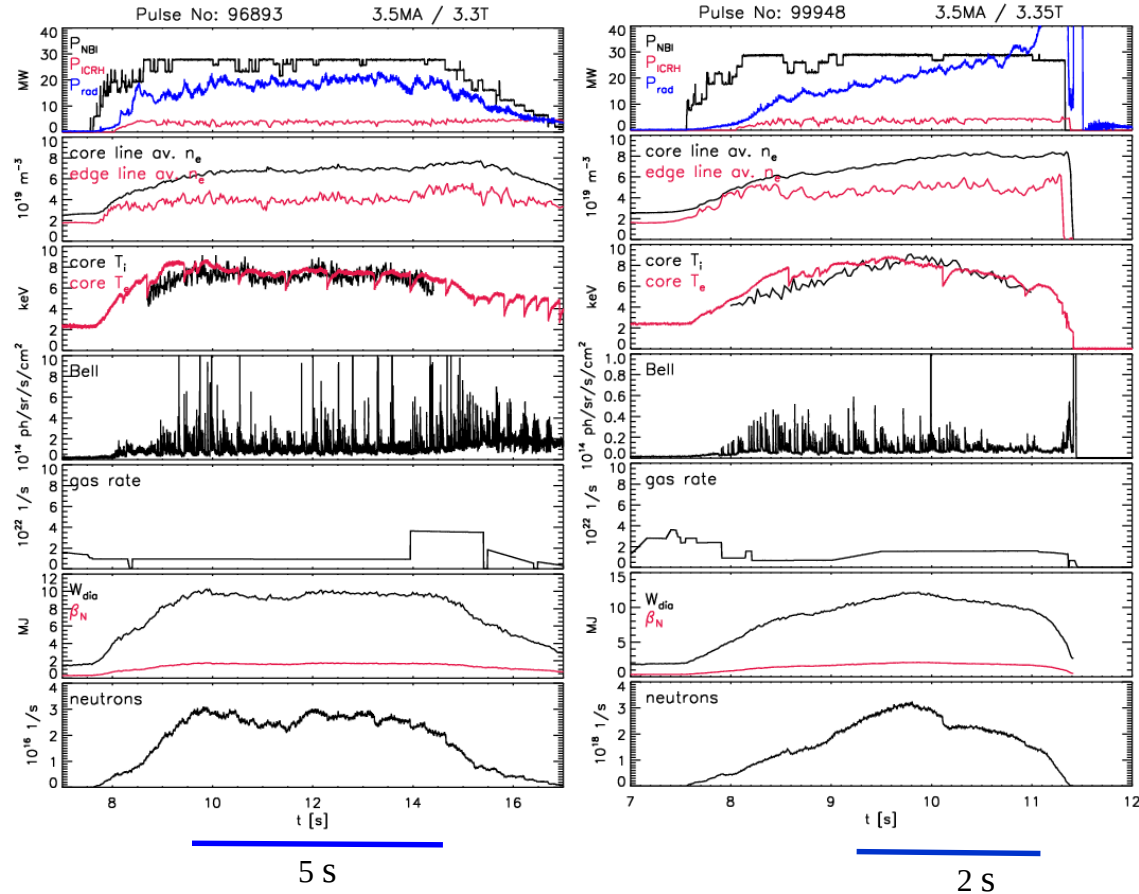


Baseline in DT



D 96893 ← ILW → DT 99948

- Slightly larger P_{NBI} same P_{ICRH} in DT .
Larger and increasing P_{RAD} .
- **Larger increasing core density in DT.**
Similar core electron and ion temperatures
- **Smaller and decreasing ELM size in DT (weaker impurity flushing).**
Slightly larger gas rate during H-mode in DT to try and sustain ELMs.
- Decreasing internal energy starting from 10 s. Similar ramp up.



NOTE: DIFFERENT TIME SCALES



- The passage from D to T and DT produced the following main effects.
 1. **ELMs** became less frequent and of smaller amplitude.
 2. **Density and radiation** were increasing during H-mode.
 1. **The H-mode was sustained** for only 2 sec instead of 5.

Comparison DTE2 vs DTE1 in numbers



	99948 best D-T pulse 2021	42982 best D-T pulse 1997
I_p [MA]	3.5	3.8
B_T [T]	3.35	3.8
NBI [MW]	29	22
ICRH [MW]	3.7 (H-minority)	2 (^3He minority)
P_{rad} [MW]	10-15 (increasing to 30)	5.6 (inter-ELM)
P_{fus} [MW]	8.3 (peak)	>4 (steady)
H_{98}	0.91	0.89
ELMs	Compound	Type-I

- Type 1 ELMs in DTE1, made the control of density and radiation easier..
- PFUS in DTE1 (red) stayed for 5 s above 4 MW. In DTE2 P_{fus} was unstable with a peak of 8.3 MW, after staying around 2 s, in H-mode it disrupted.

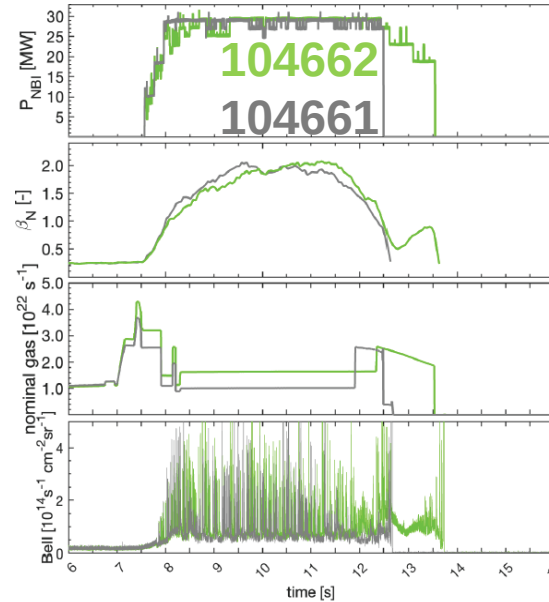
Recovery Campaign (DTE3)



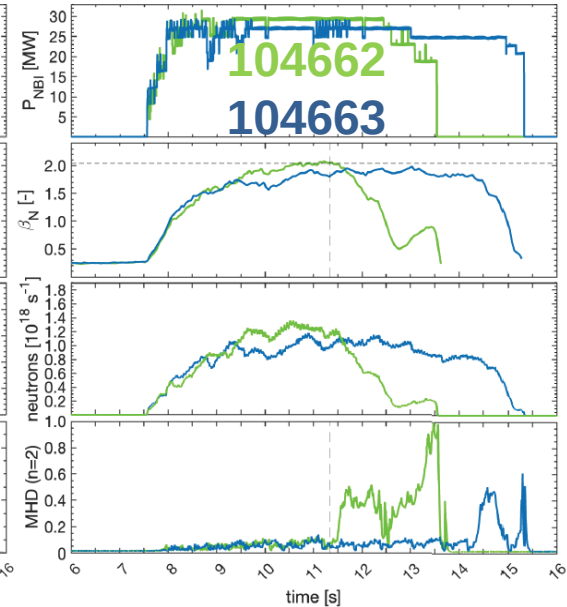
- **An extra experimental Campaign, DTE3**, was run before the final JET shut-down.
- A few shots were dedicated to Baseline run **at 3.0 MA / 2.9 T**.
- **Obtaining a long lived discharge** was the main objective of DTE3
- Such objective was actually achieved thanks to **fuelling and power optimization (#104663)**

- 104663 3.0 MA, 2.9 T, 27 MW NBI, 3 MW ICRH, β_N 1.9, Fuel $1.8 \cdot 10^{22}$ el/s
- 104662 -----, 30 MW NBI,, β_N 2.0,

Increasing gas rate



Increasing gas rate



- Priority given to stability and duration.
- Fuelling raised up to $1.8 \cdot 10^{22}$ el/s.
- Achieved 5 sec. But at reduced P_{FUS} (2.3 MW)

Conclusions



- Even if the initial goals were not fully achieved, **the possibility of operating at good performance in DT with a metal wall (ILW) was demonstrated at JET**. The results will be a good start point for future experiments including ITER
- In particular, a high-current baseline scenario for high fusion performance was successfully developed in JT-ILW in D at 3.5 MA / 3.3 T with the potential to deliver an **average 7.7 MW of fusion power for 5 s when extrapolated to D-T** with additional total heating power of around 34 MW (NBI plus ICRH).
- In the actual experiment, the scenario with 50-50 % D-T fuel mix, could only be sustained at good performance ($P_{\text{FUS}} \geq 7 \text{ MW}$) for 2 seconds only
- In an additional campaign (DTE3) all effort was concentrated on stability and duration. **At 3.0 MA a duration of 5 sec was achieved at the cost of a reduced P_{FUS} (2.3 MW)**. This was achieved by increasing the gas fuelling to favour ELM impurity flushing, and slightly reducing the heating power.



SPARE SLIDES

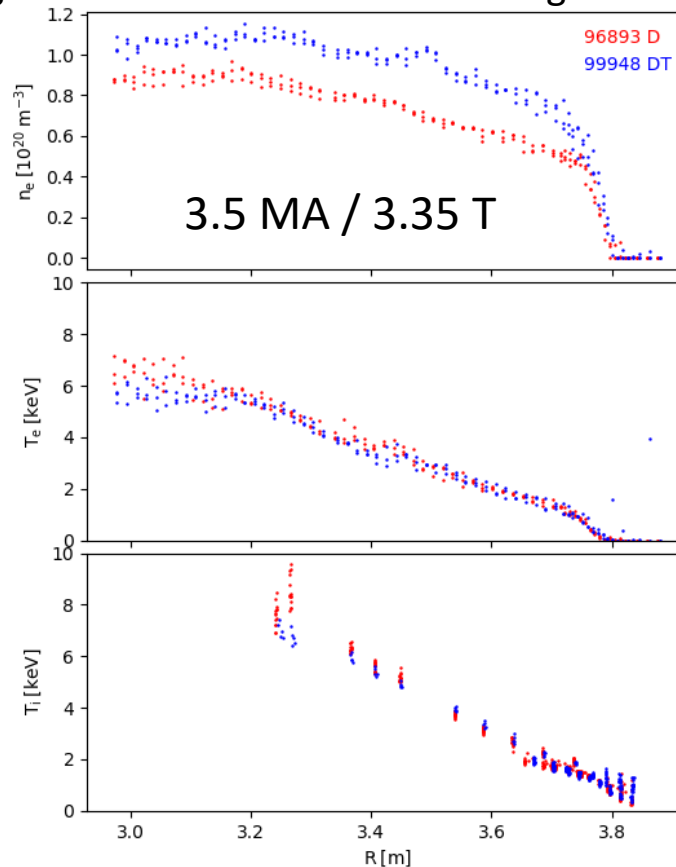
Comparison between D and D-T



Comparison D vs DT

- Same profiles at H-mode entrance ($t = 9.0\text{s}$)
- After 3 s into the H-mode, the density was increasingly higher in D-T than in D.
- Temperature profiles very similar.

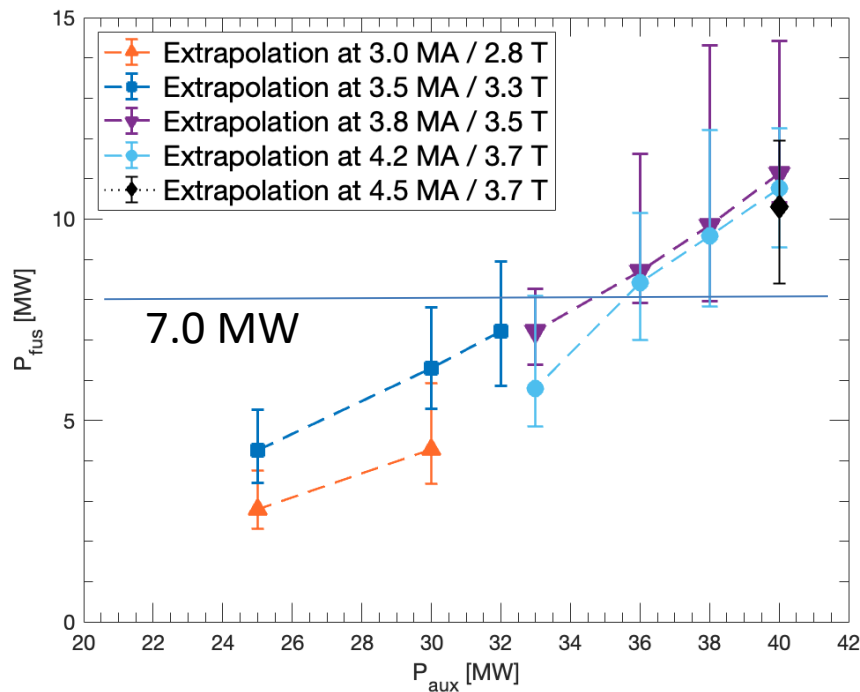
High-resolution Thomson scattering at $t = 10.57\text{ s}$



Extrapolation from D to D-T



- **Simple extrapolation to a 50-50 D-T plasma** gives:
 - $P_{\text{FUS}} \sim 8.8$ MW transient
 - $P_{\text{FUS}} \sim 7.0$ MW over 5 s.
- **More sophisticated first approach using JINTRAC** integrated suite of codes with **QuaLiKiZ** transport model gives similar performance.



Lessons learnt



- **The transfer of experience gained in D to go to T or DT operation is not straightforward.** Relevant operational issues arise in the control of density, ELMs and, consequently, of radiation when changing the isotope mass.
- **The fuelling needed to find the optimal compromise between fusion power and duration is not easily predictable.** More experimental time should have been needed to find an empirical optimal point.
- On JET, with a Be wall and W divertor, given the available power, a baseline scenario sustained for 5 s was obtained at a plasma current of 3.0 MA but at the cost of a reduced performance. More time would have been needed to optimise the ELM and Radiation control and to explore higher current domain.
- In addition, **a metal wall needs more caution in terms of plasma-wall interaction** to prevent damages and dangerous disruptions when operating at high current and field as requested in Baseline. Heating power marginality adds up to all this.
- JET experimental results are certainly relevant for ITER and inform ITER operation especially when approaching the burning phase.

Baseline scenario in D-T (DTE2)



LEFT: #99948

96893 D-Ref

99948 DT

- #99948: similar heating power as in D and T.
- 50-50 % D-T mixture.
- Average Fusion Power of 7.9 MW obtained for 2 s.
- Of which, 60% was thermal and 40% beam-target.
- Early termination was due to radiative collapse

RIGHT : D vs DT PROFILES @ 11 sec.

- Same profiles at H-mode entrance ($t = 9.0$ s)
- After 3 s into the H-mode, the density was increasingly higher in D-T than in D.
- Temperature profiles very similar.

