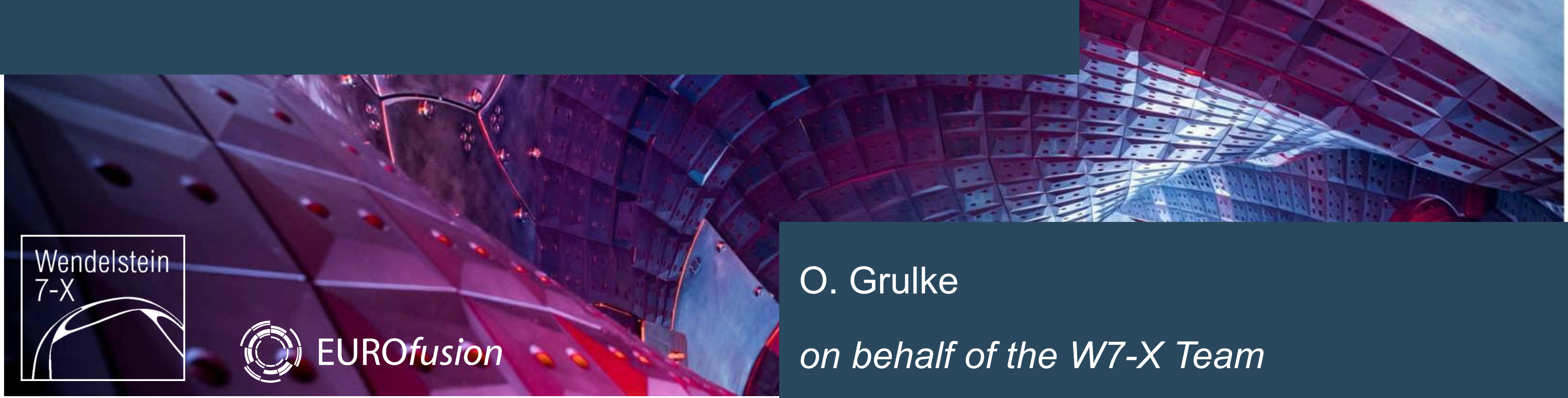
Overview of Wendelstein 7-X High-Performance Operation

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK



O. Grulke

on behalf of the W7-X Team

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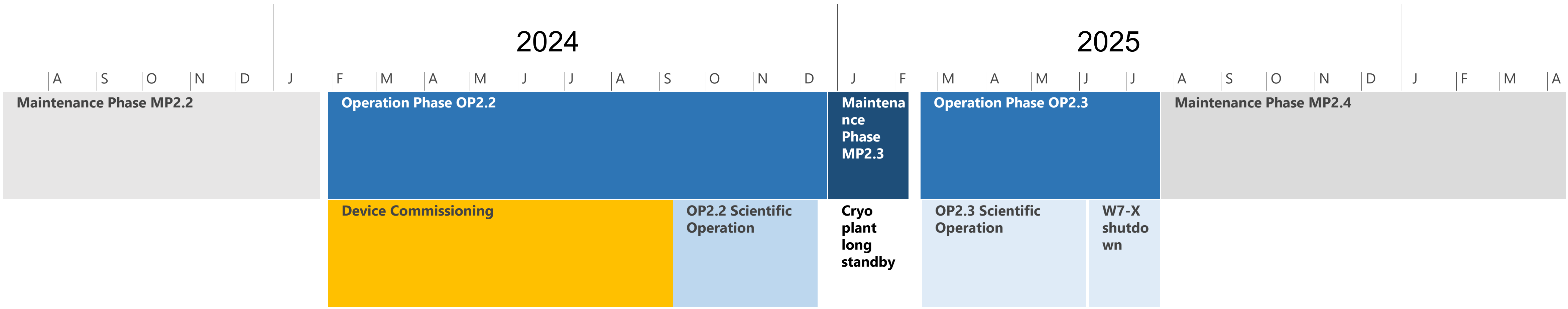
Wendelstein 7-X achieved…

- ✓ Long pulse operation with 1.8GJ energy turnaround
- ✓ A new stellarator record triple product $nT_i\tau_E$
- ✓ Improved confinement exceeding $\tau_{L/R}$
- ✓ W7-X record plasma-β in X3 heating scenario

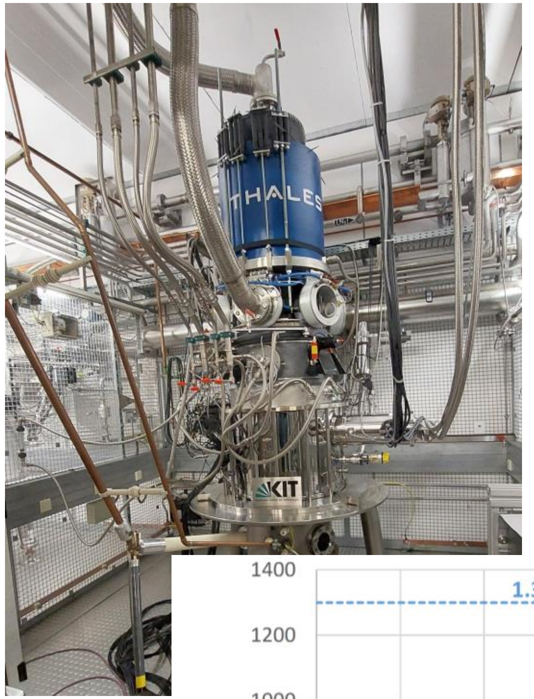
Wendelstein 7-X Operation Overview

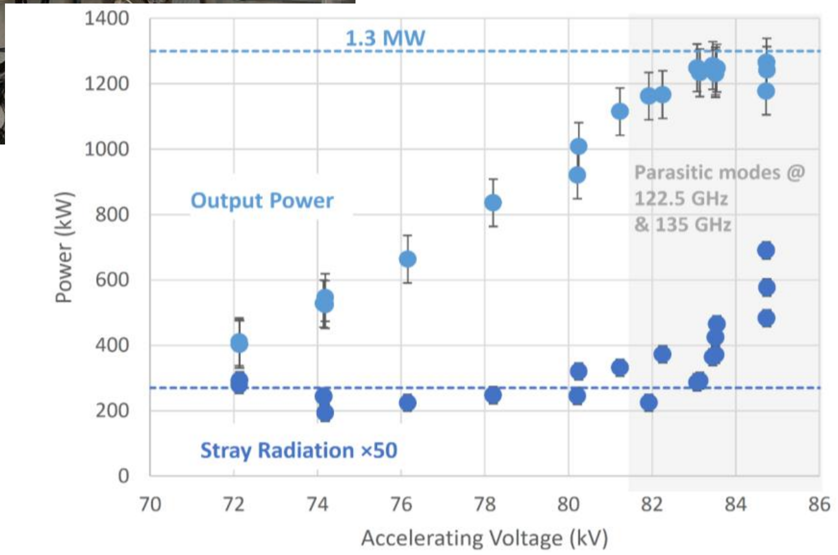


- two full operation campaigns in years 2024/2025
  - ⇨ adjustment of operation schedule to improve efficiency by operating two experimental campaigns with only one commissioning phase
  - ⇨ key operation components (cryo plant, vacuum systems, …) in full operation for more than 1 year
  - ⇨ reliability of device operation better than 1%!
- operation in more than 77 magnetic field configurations, spanning a wide range of edge rotational transform and magnetic mirror ratio

Main new systems and functionalities

- increase of plasma heating power
  - new prototype high-power ECRH gyrotron delivering 1.3MW@140GHz steady-state
  - routinely operated at $P_{ECRH} > 1MW$ during plasma discharges

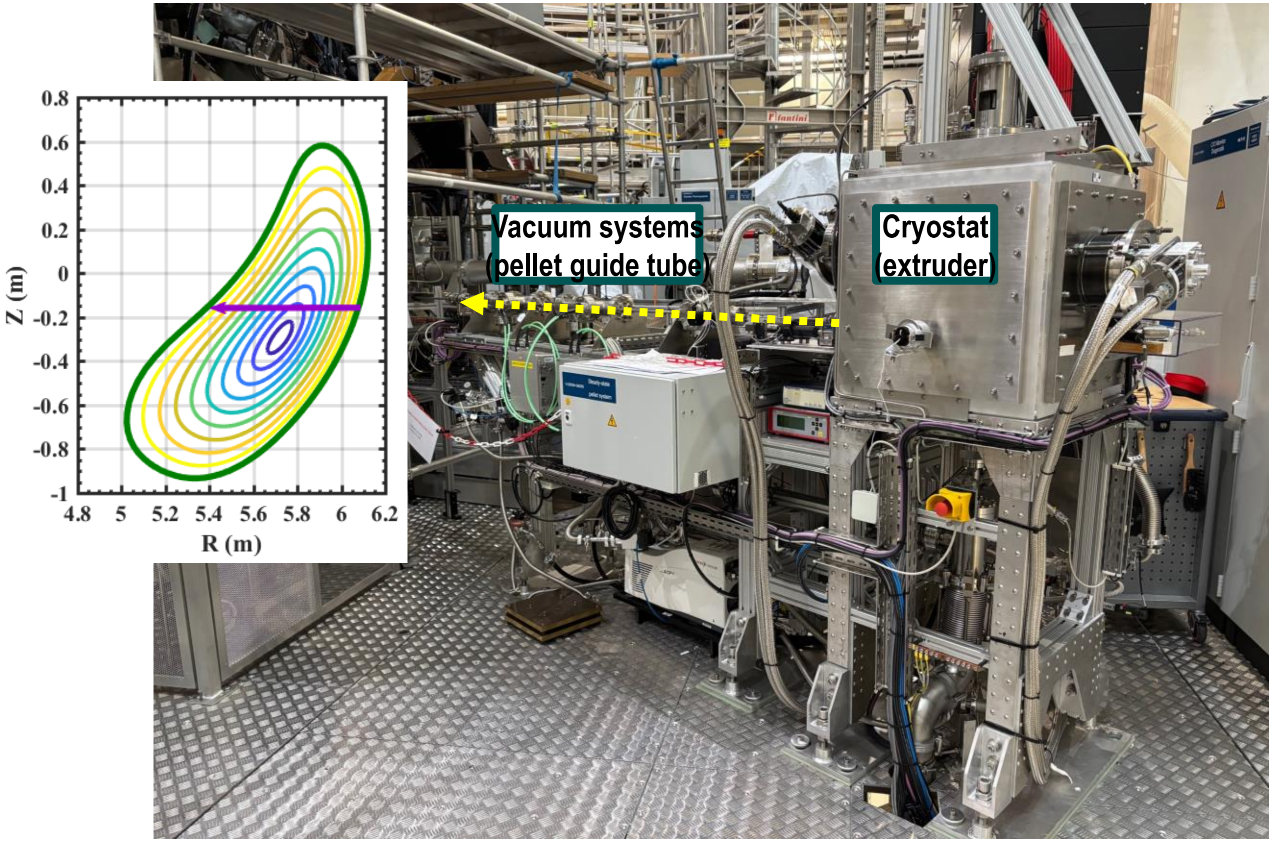




S. Ponomarenko et al., IEEE Electr. Device L. ***45*** *(2024)*

Main new systems and functionalities

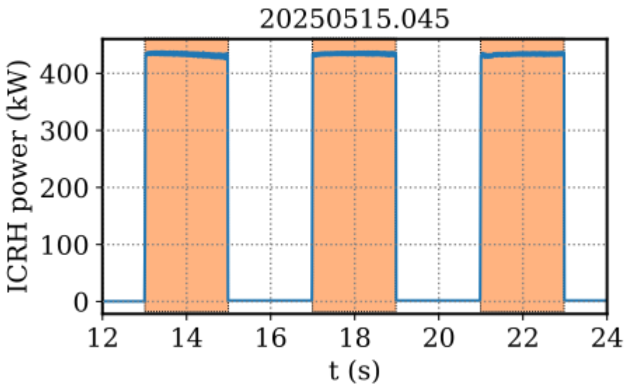
- increase of plasma heating power
- operation of new steady-state pellet injector
  - ➢ injection trajectory near plasma center
  - ➢ adjustable pellet size (2-3mm)
  - ➢ repetition frequency up to 10Hz
  - ➢ pellet speed 250-1000 m/s
  - ➢ up to 30min injection duration

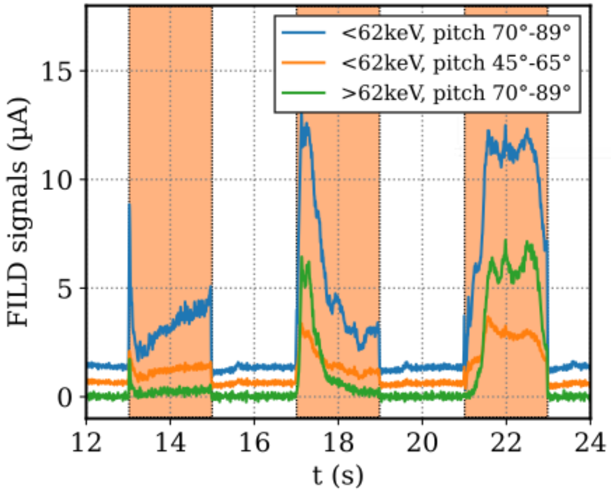


S.J. Meitner et al. IEEE T. Plasma. Sci. ***48*** *(2020)*

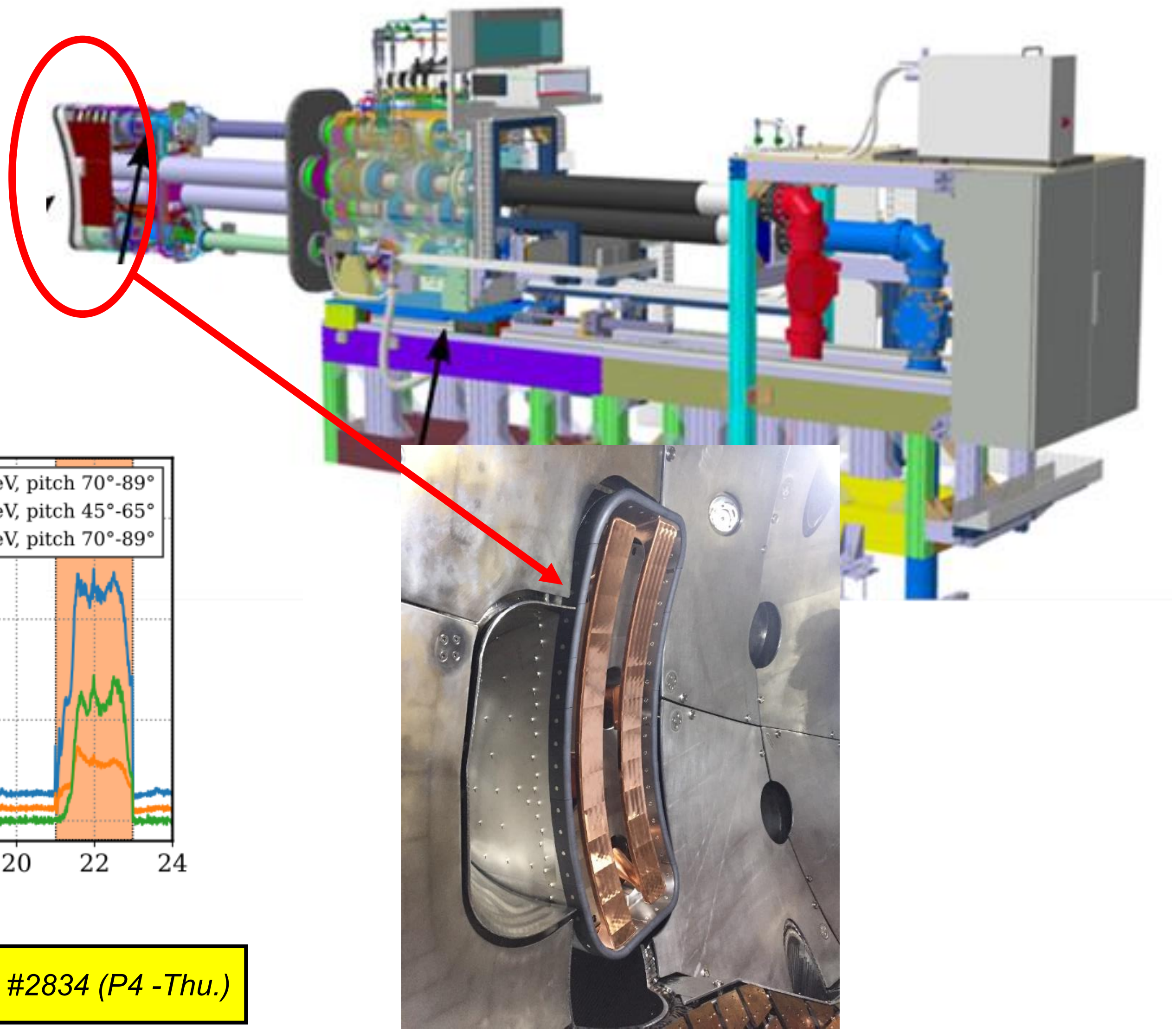
Main new systems and functionalities

- increase of plasma heating power
- operation of new steady-state pellet injector
- reliable operation of new ICRF system
  - radial antenna (double strap) position system
  - frequency range 25-38MHz@P_{rf}≤1.5MW
  - first results from minority heating ^{4}He-(^{3}He)-H



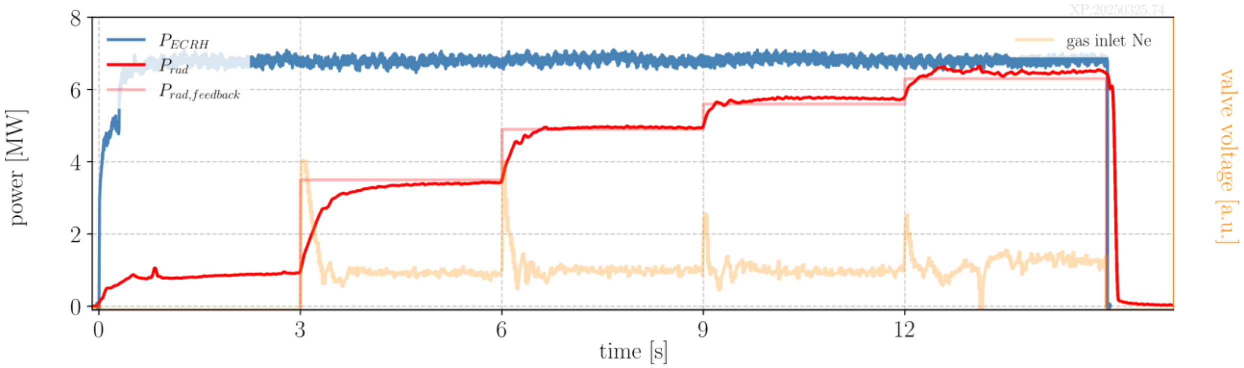


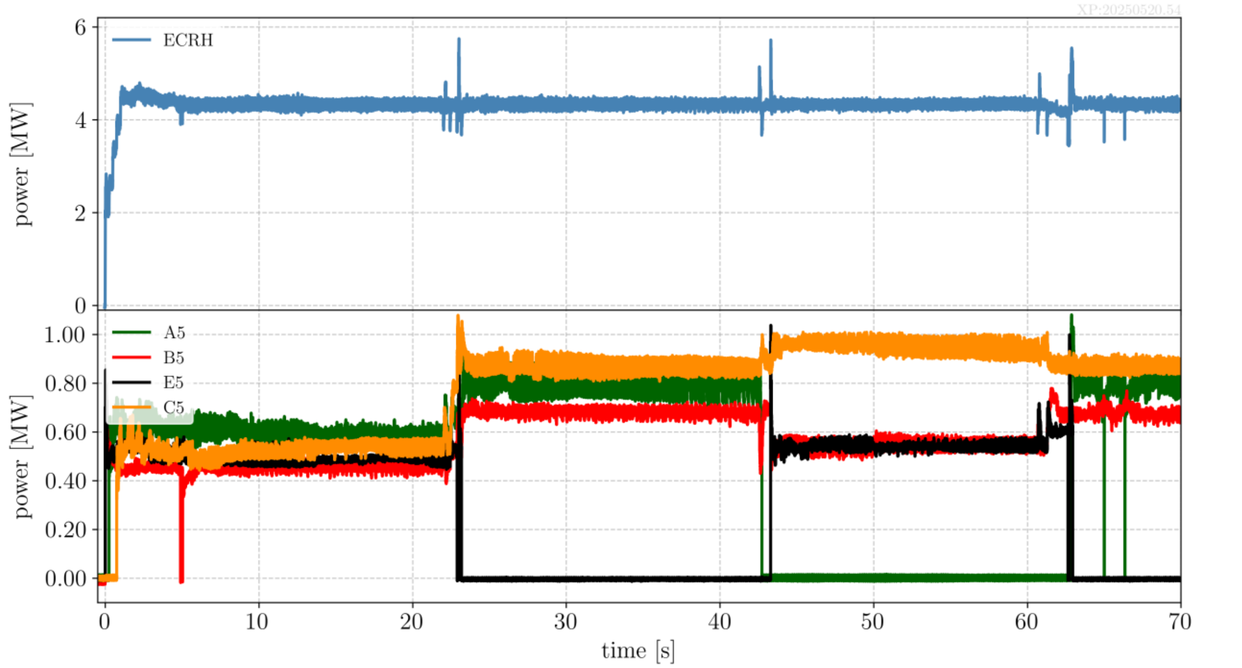
J. Ongena, #2834 (P4 -Thu.)



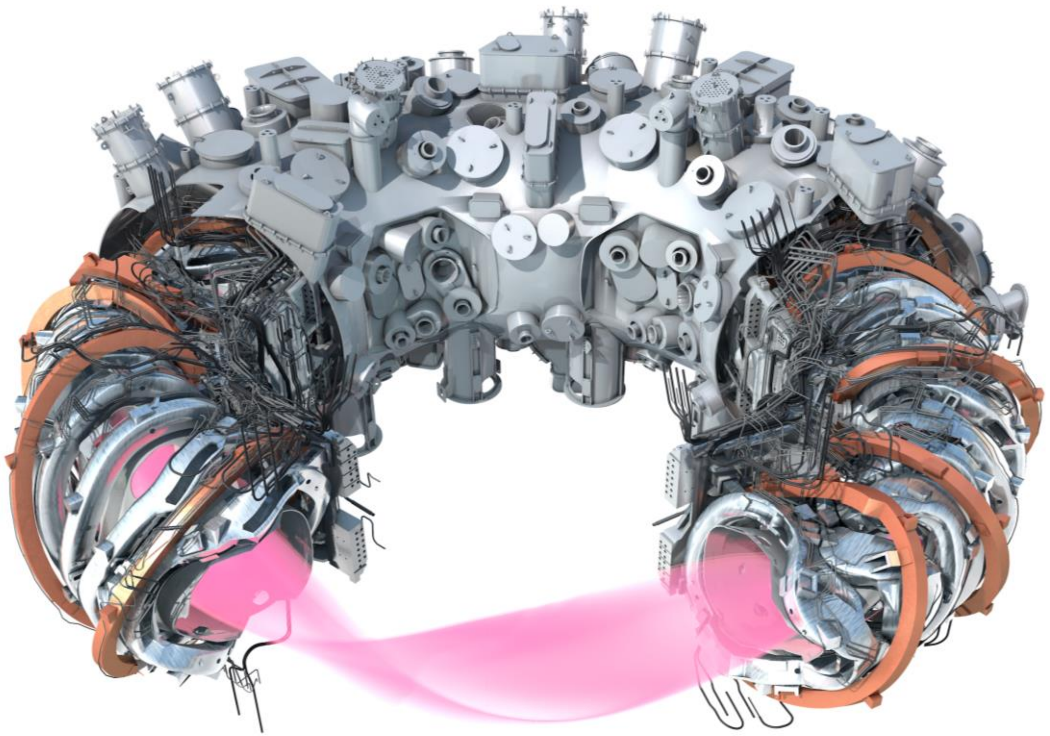
Main new systems and functionalities

- increase of plasma heating power
- operation of new steady-state pellet injector
- reliable operation of new ICRF system
- new plasma feedback control systems
  - plasma radiation control by feedback impurity seeding
  - ECRH power stabilization for long-pulse operation and possibility to re-start gyrotrons





Wendelstein 7-X – operation parameters



- near future enhancements
  - increase of plasma heating power by further upgrades of the ECRH and NBI systems
  - Deuterium operation in preparation

quantity	unit	value
magnetic induction	T	1.8, 2.5
rotational transform	2π	5/6 … 5/4
ECRH power	MW	8.5 (>10)
NBI power	MW	7 (>10)
neutral gas		H_2, He (D_2)
PFCs		C + Fe + W
plasma volume	m^3	30
divertor heat flux	MW/m^2	10
heating energy	GJ	2 (18)

Content

1. Long-pulse operation

- discharge scenario and achievement

2. Operation with improved confinement

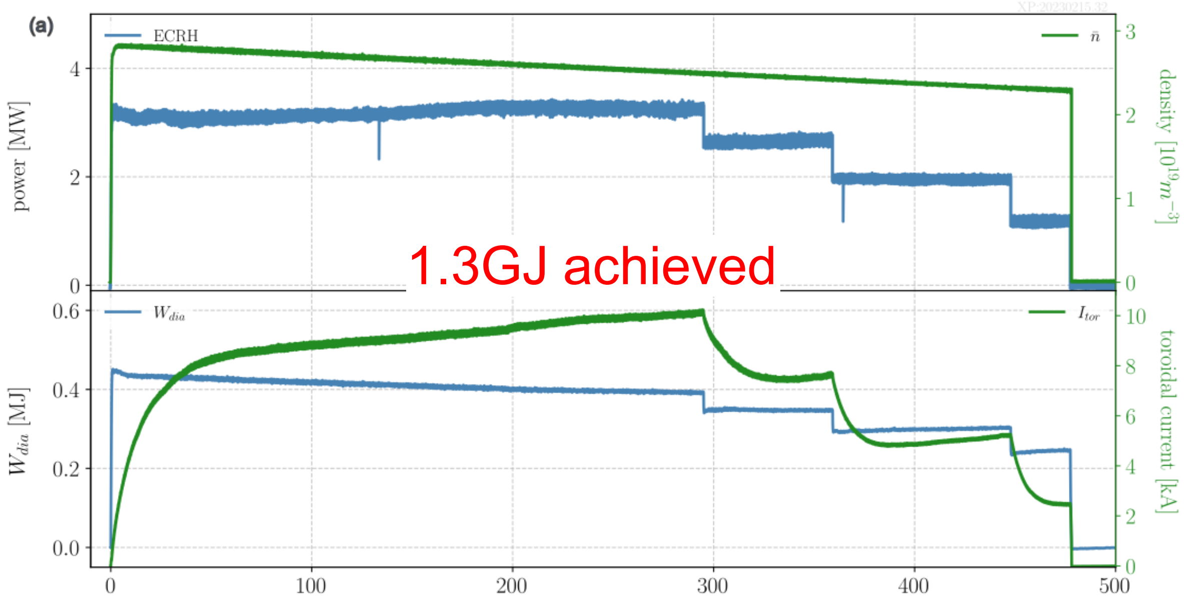
- discharge scenarios
- characteristics of improved confinement

3. Operation at high plasma-β

- development of a new operation regime
- discharge characteristics and achievements

Content

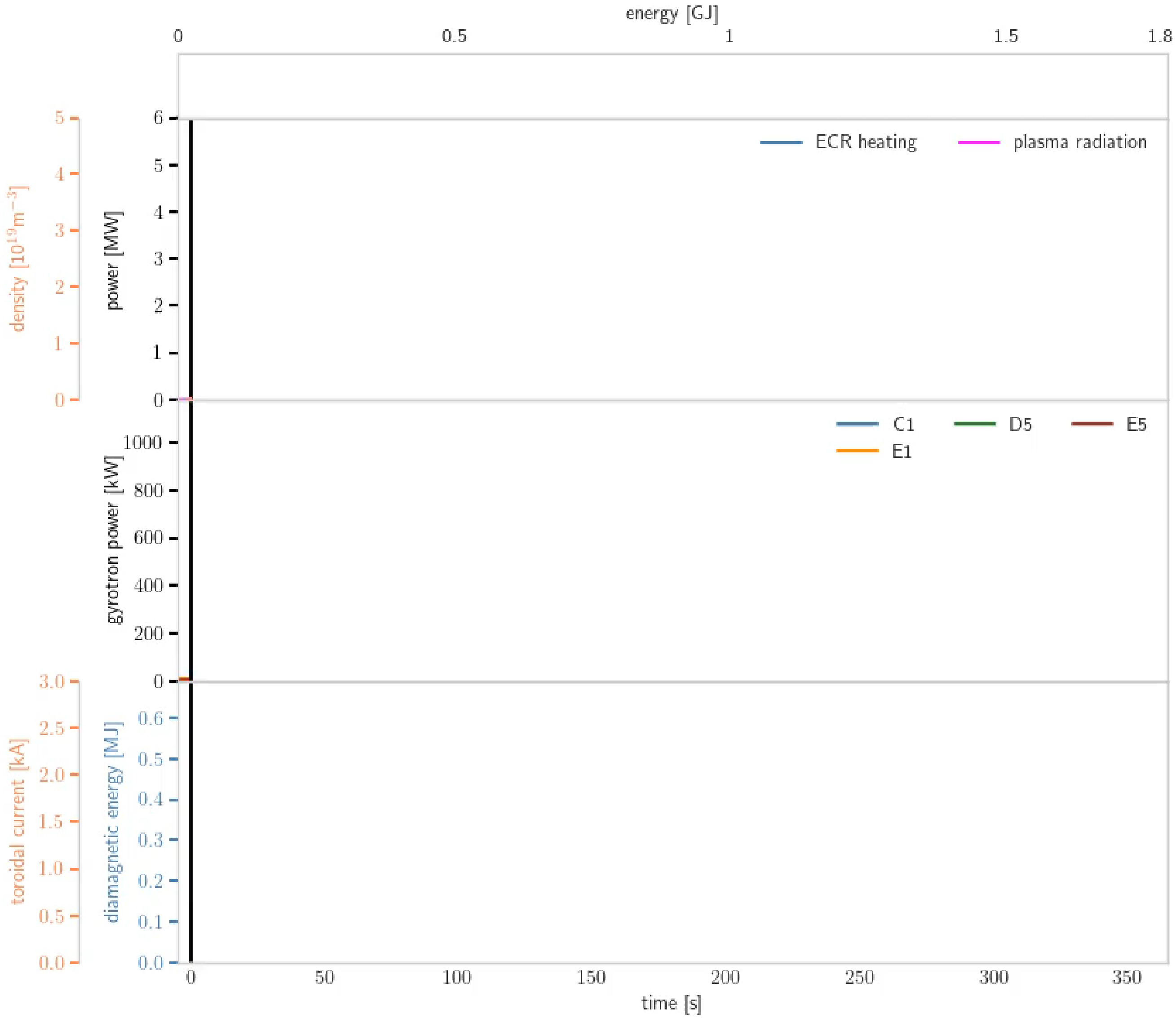
Long-pulse operation: previous results



O. Grulke et al. Nucl. Fusion **64** (2024).

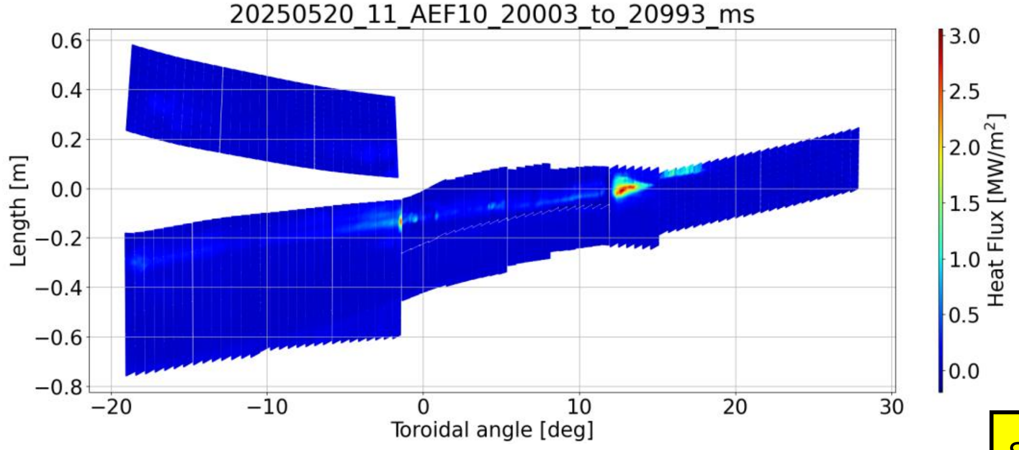
- scenario issues:
  - ➢ plasma heating power not constant due to failures of individual gyrotrons
  - ➢ heating power limited due to divertor hot spots/leading edges
  - ➢ bootstrap current approaches W7-X safety limit
    - ⇨ operation with X2 ECRH (good single-pass absorption) and detached divertor via radiation feedback control
    - ⇨ feedback stabilization of ECRH to keep heating power constant
    - ⇨ counter ECCD to control amplitude of total toroidal current (bootstrap + ECCD)

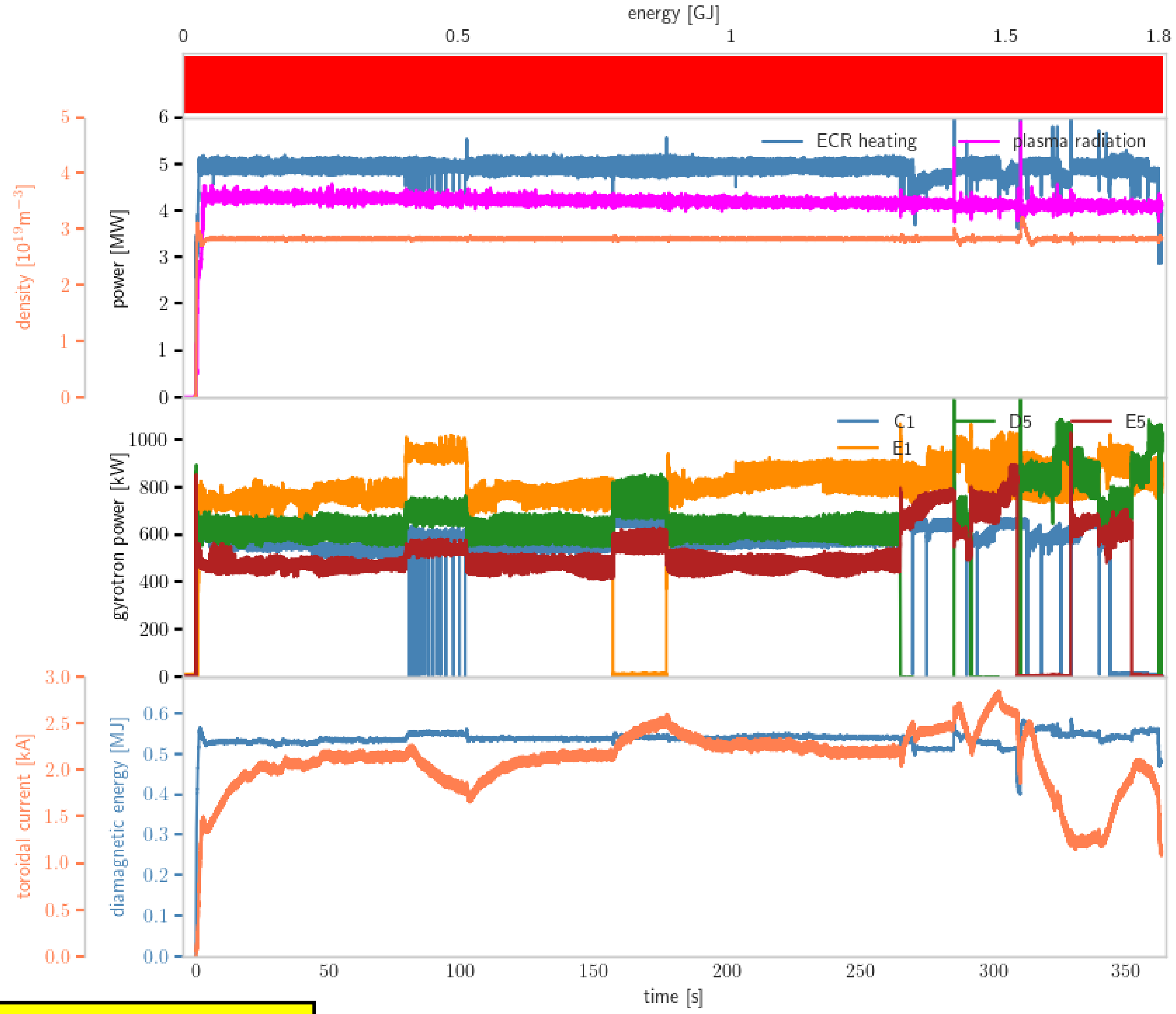
Long-pulse operation



Long-pulse operation

- heating energy of 1.8GJ achieved
  ➪ heat control issues within ECRH beamline
- ECRH power stabilization regulated heating power to constant level
- toroidal current remains small $I_{tor} \leq 3kA$
- detachment via radiation feedback keeps divertor heat loads small and well below specification





S. Marsen, #2805 (P3 – Thu.)

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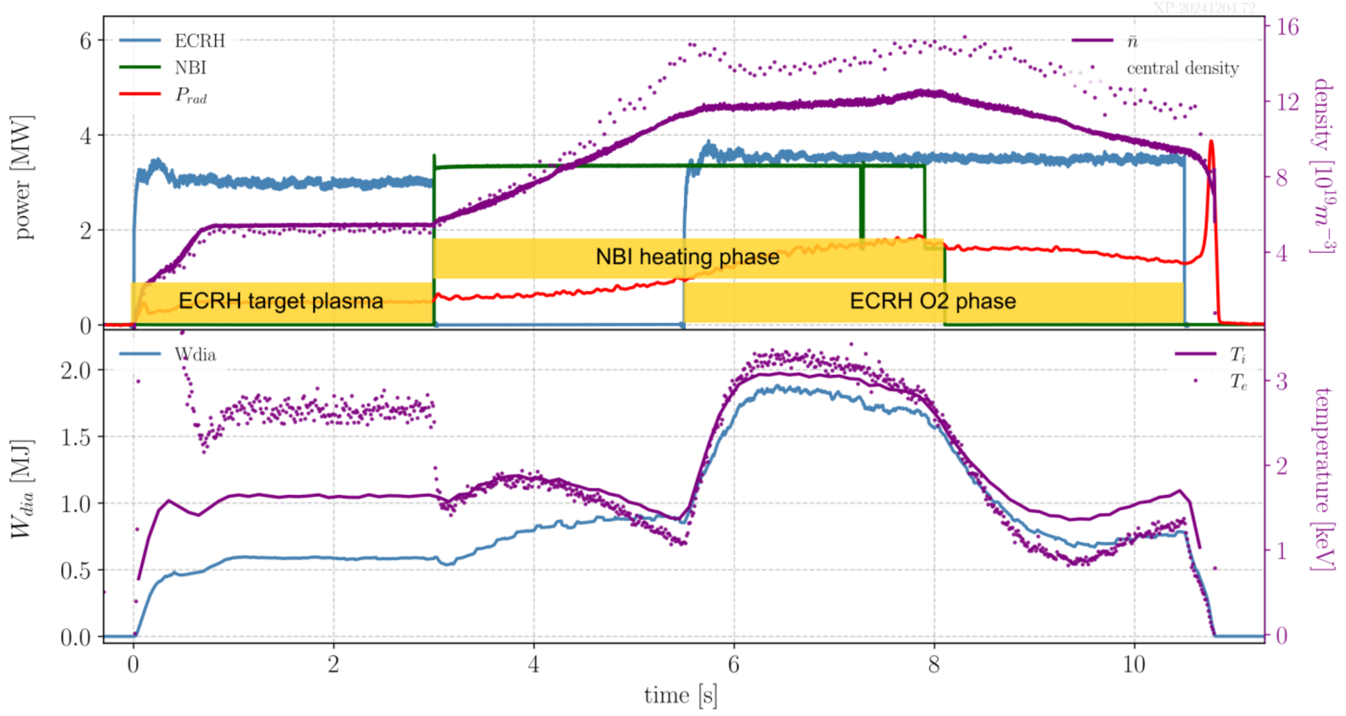
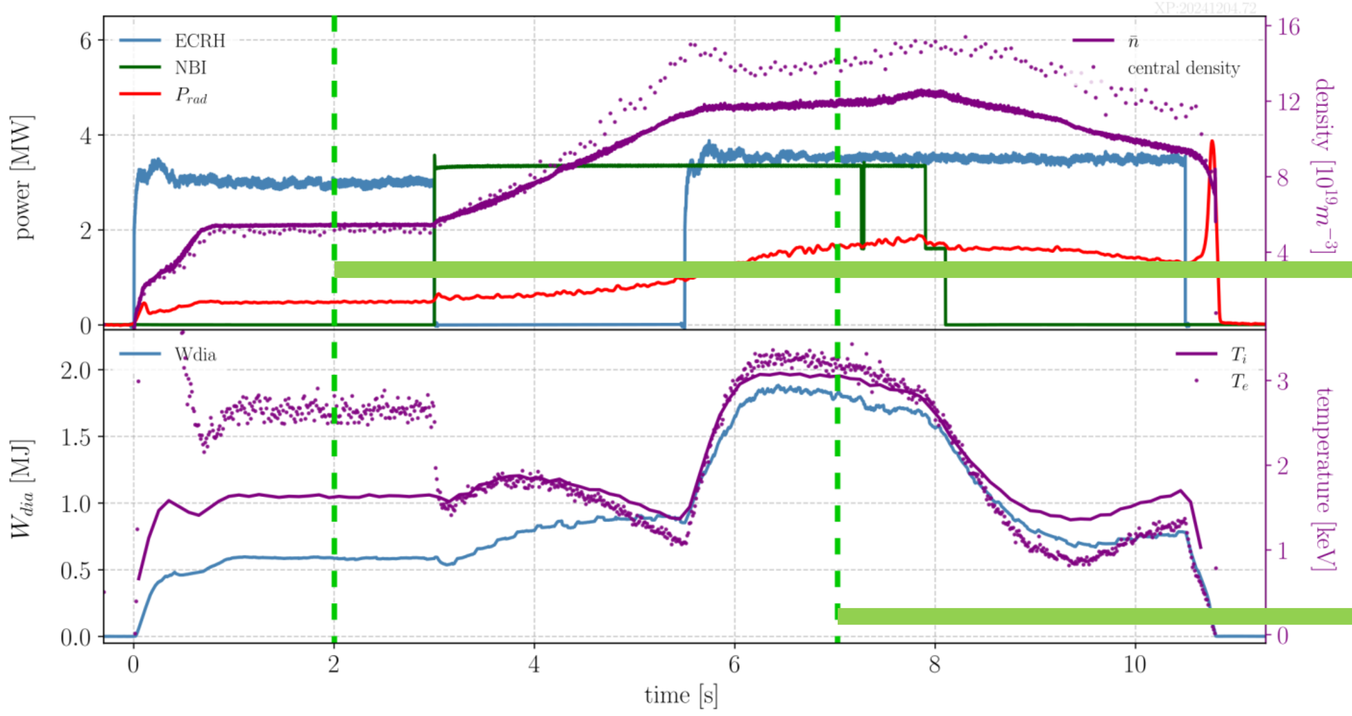
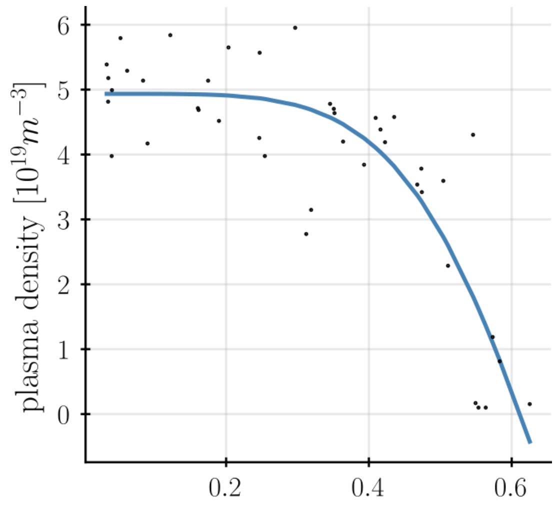
Improved confinement I: Combined NBI and ECRH

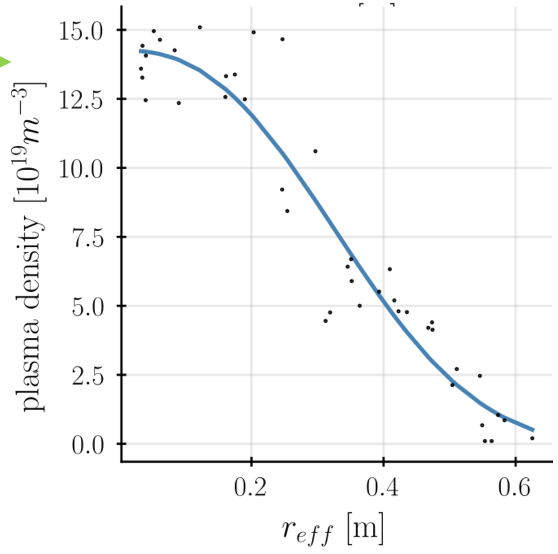


- combined NBI and ECRH discharge
  - pure NBI heating phase, re-introduction of ECRH in O2 polarization
  - steep rise of stored energy to $W_{dia} = 1.8MJ$, equilibrated temperatures to $T_e = T_i = 2.8\ keV$ for a period of $\approx 2s$

Improved confinement I: Combined NBI and ECRH







- combined NBI and ECRH discharge
  - pure NBI heating phase, re-introduction of ECRH in O2 polarization
  - steep rise of stored energy to $W_{dia} = 1.8MJ$, increased equilibrated temperatures to $T_e = T_i = 2.8\ keV$ for a period of $\approx 2s$
  - improved confinement at times with central plasma density peaking due to a combination of core (NBI) fueling and reduction of particle transport

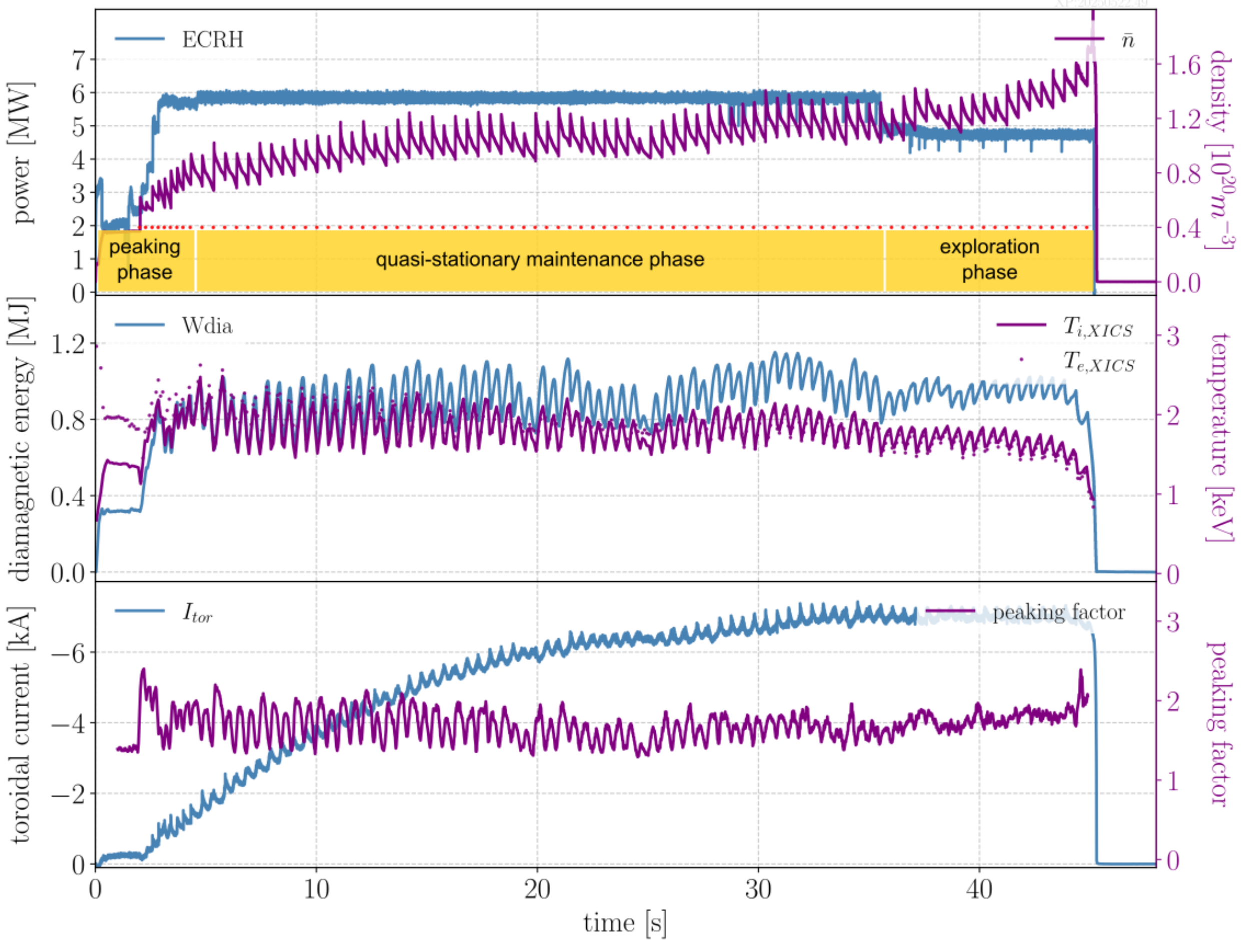
S. Bannmann et al. Nucl Fusion ***64*** *(2024).*

S. Bannmann, #3085 (O -Thu.)

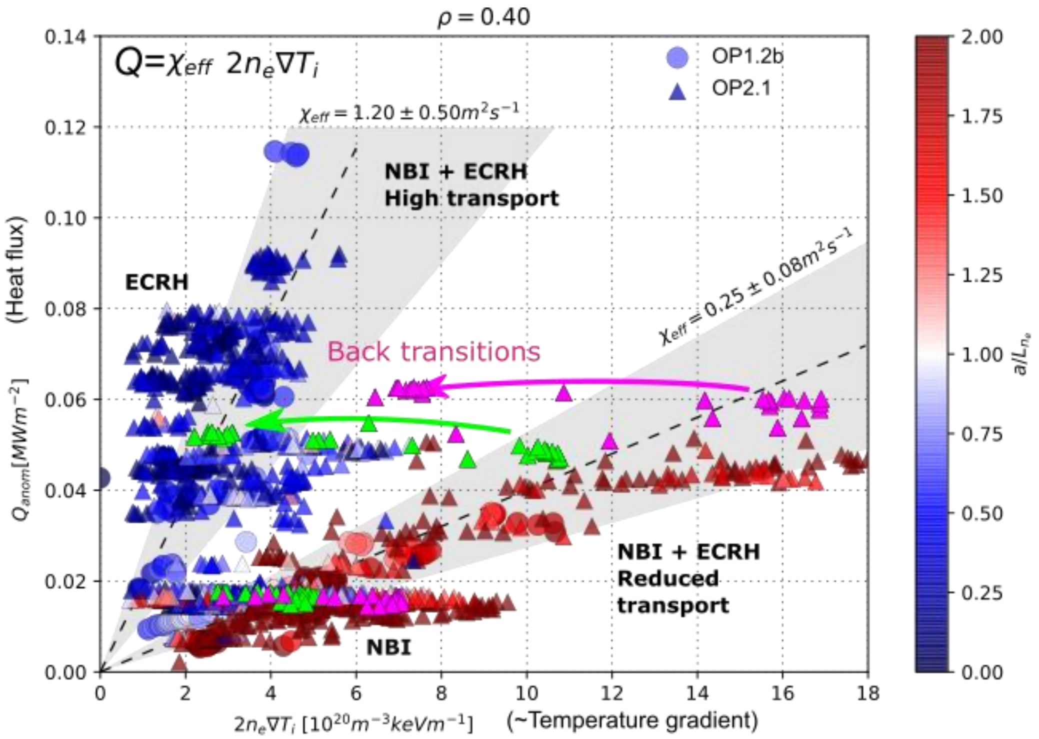
Improved confinement II: Long-pulse pellet fueling

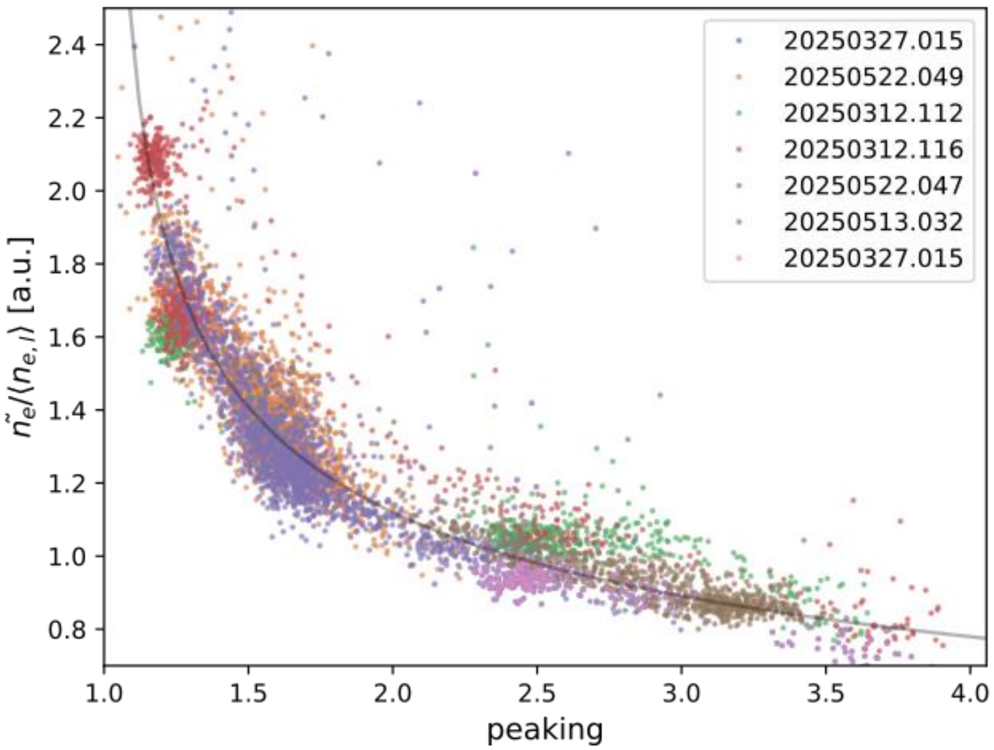
- combined ECRH and pellet fueling
  - initial rapid pellet injection and heating power step-up to achieve central density peaking
  - feed-forward prolongation of peaking with reduced pellet injection frequency to $t > {}^{L}/_{R}$
  - increased equilibrated temperatures $T_e = T_i = 2\ keV$
  - divertor heat flux control via feedback radiation control
  - loss of quasi-stationarity when ECRH power is reduced, highlighting the crucial interplay between plasma heating and pellet fueling

⇨ longest improved confinement scenario achieved in W7-X so far



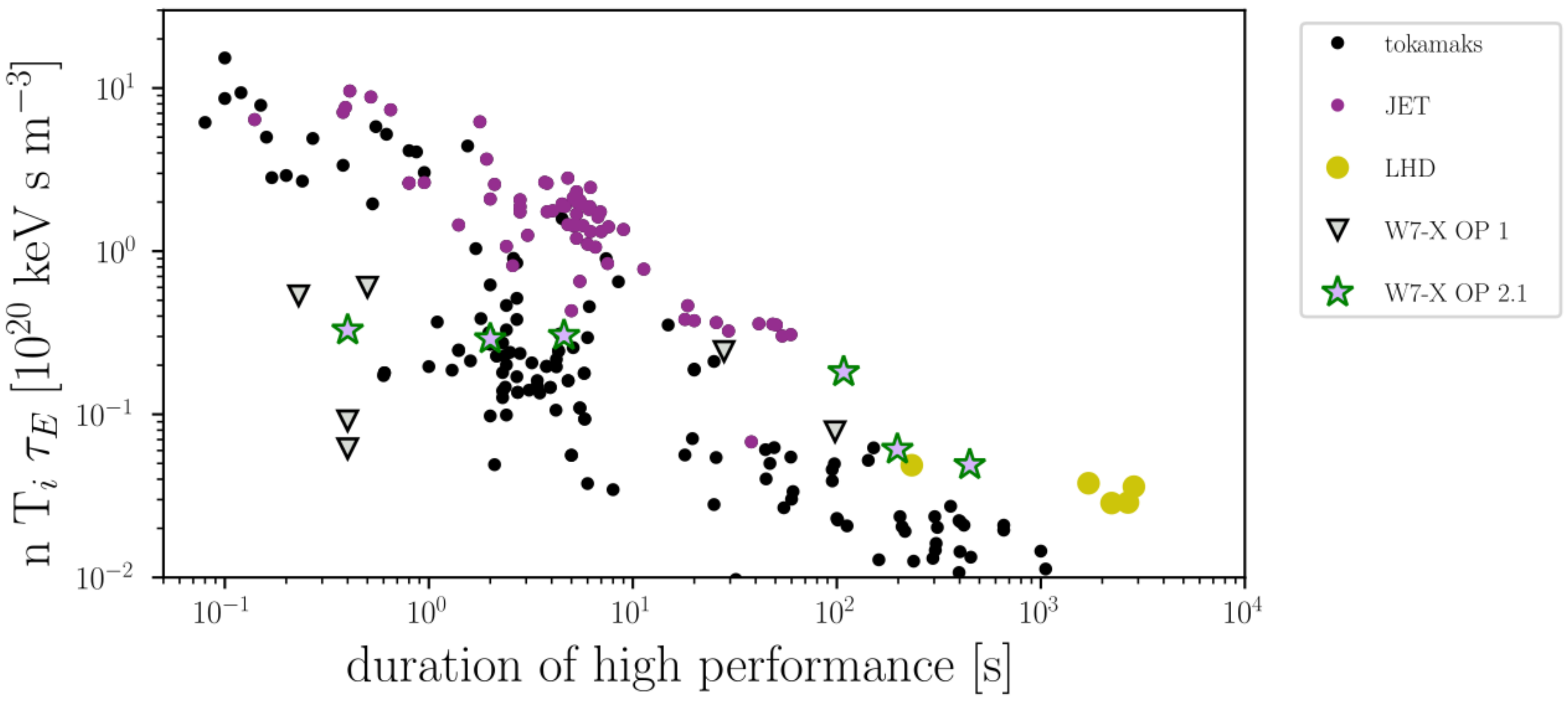
Physics mechanisms



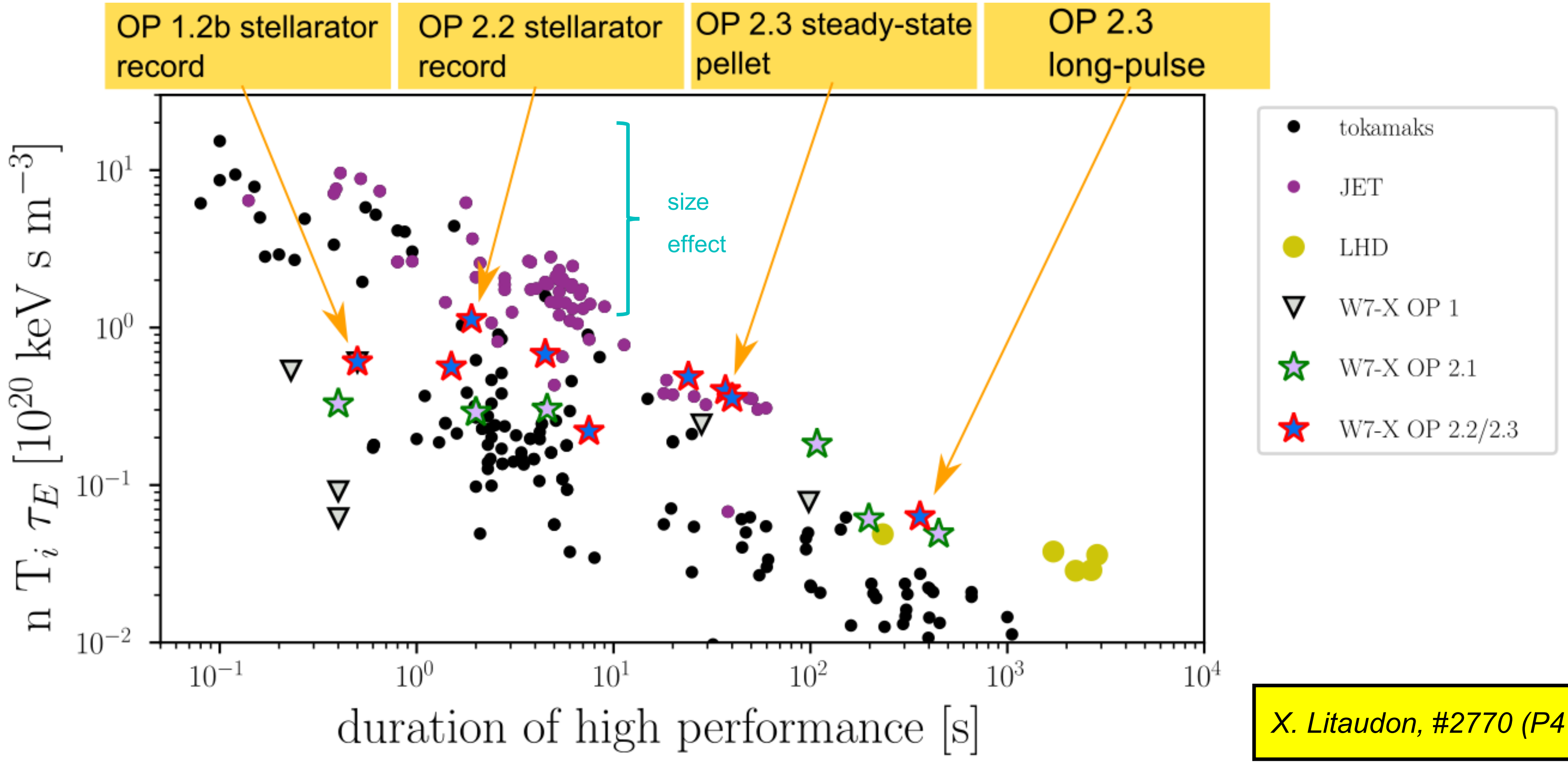


- turbulent heat transport forms into two distinct regimes
  - ➢ considerable difference in heat diffusivity by a factor of 4-5
  - ➢ “critical” normalized density gradient ${}^{a}/_{L_n} \approx 1$
- direct observation of relative turbulent fluctuation amplitude reduction with increase of core density gradient due to a reduction of ITG transport

Fusion triple product



Fusion triple product



X. Litaudon, #2770 (P4 -Thu.)

- stellarator record triple product increased in value <u>and</u> duration ($1.12 \cdot 10^{20}\, {}^{keV\,s}/_{m^3}$ for $2s$)
- W7-X displays comparatively little decrease of performance for long-pulse operation

⇨ demonstrates the advantage of the optimized stellarator concept for long-pulse high performance operation

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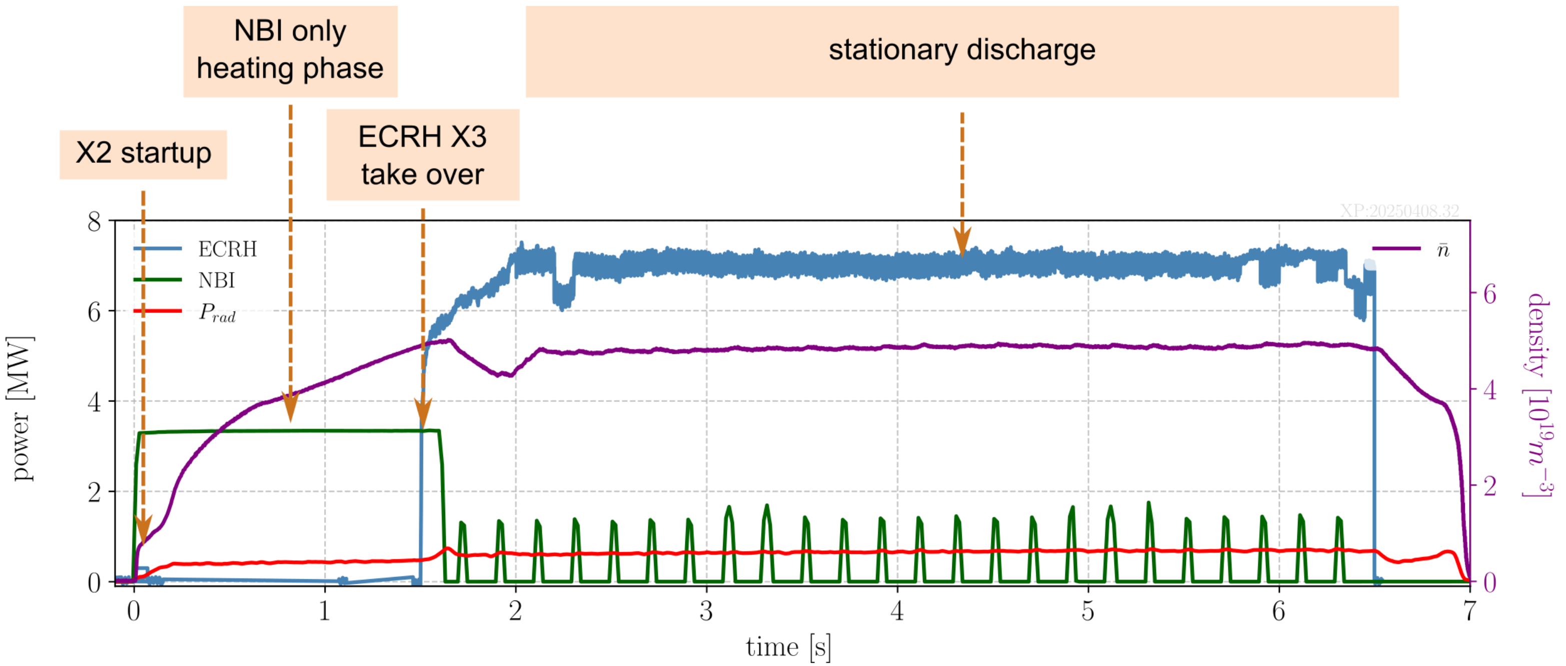
Scenario development for operation at high plasma-β



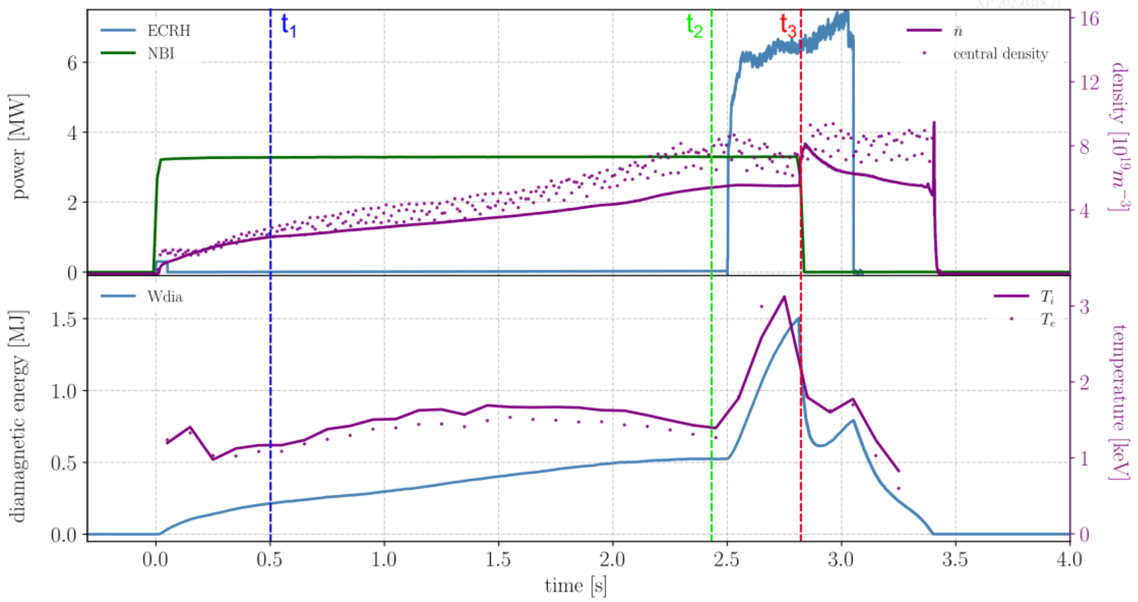
- assuming $\tau_E^{ISS04} \sim n_e^{-0.54} P^{-0.61} B^{0.84}$, reduced magnetic field leads to enhanced plasma-$\beta \sim {}^{1}/_{B^2}$
- $B = 1.8T$ allows for X2 ECRH startup via de-tuned gyrotron (frequency of 101GHz)
- X3 ECR heating (140GHz) on-axis at increased plasma-β
  - ⇨ absorption strongly temperature dependent: $P_{abs} \sim n_e T_e^2$
  - ⇨ pure NBI heating phase to increase n, T_e

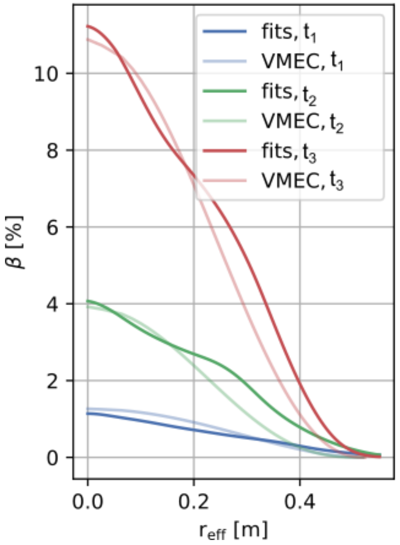
Plasma-β achievement

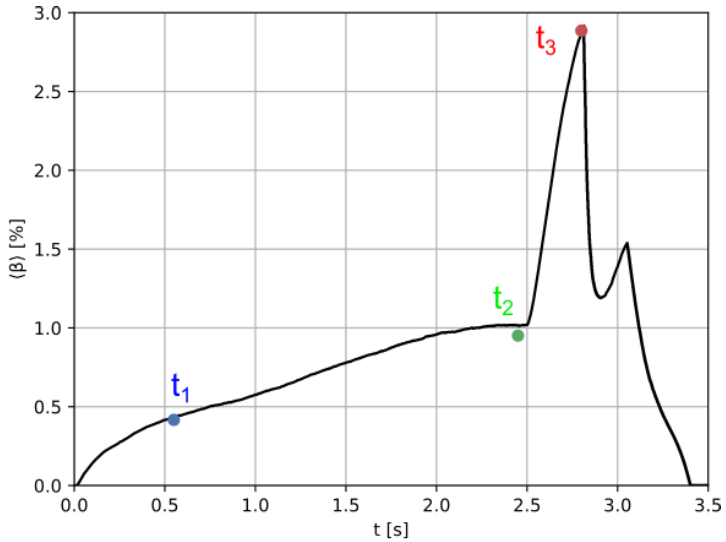
- operation at B=1.8T with increased overlap of NBI phase and ECRH
- moderate peak plasma-β<2% in intial discharge phase incrased to 4% during pure NBI heating
- strong increase of plasma-β in combined heating phase

  - ➢ increase of peak plasma-β>10%
  - ➢ volume-averaged <β>=2.8% transiently achieved

⇨ highest achieved plasma-β in W7-X so far







Summary

- W7-X successfully finished long phase of plasma operation with very solid device, heating, and diagnostics operation, considerably broadening the oepration map in magnetic field and plasma parameter space.
- A reliable scenario for long-pulse operation was developed and an energy turnaround of 1.8GJ was demonstrated.
- A new record triple product (combined NBI and ECRH) was achieved and long-pulse operation (pellet fueling) exhibited improved confinement and a core-edge compatible scenario.
- A new regime of ECR X3 heating at reduced magnetic field was successfully developed and already W7-X record values in plasma-β were achieved.

Wendelstein 7-X related contribution to IAEA FEC 2025

D. Moseev et al.	*First fast ion measurements by the collective Thomson scattering and ion cyclotron emission diagnostics at Wendelstein 7-X.*	*#3050 (P3 – Thu.)*
D. Zhang et al.	*Impurity Accumulation and Radiation Dynamics in advanced Scenarios in W7-X*	*#2634 (P1 – Wed.)*
S. Bannmann et al.	*Attaining Tokamak level performance through plasma density profile shaping at Wendelstein 7-X*	*#3085 (O – Thu.)*
C. Killer et al.	*Drift flows impact island divertor operation in Wendelstein 7-X*	*#3182 (O – Thu.)*
Y. Gao et al.	*Observation and control of 3D heat flux on the plasma facing component in Wendelstein 7-X*	*#2668 (P6 – Fri.)*
S. Marsen et al.	*The Wendelstein 7-X ECRH plant – Experience with reliable long pulse operation of a multi MW gyrotron installation*	*#2805 (P3 – Thu.)*
J. Ongena et al.	*Progress with commissioning the icrh system for the large optimized stellarator Wendelstein 7-X*	*#2834 (P4 – Thu.)*
Y. Feng et al.	*First quantification of volume recombination in W7-X with EMC3-EIRENE*	*#3024 (P5 – Fri.)*