

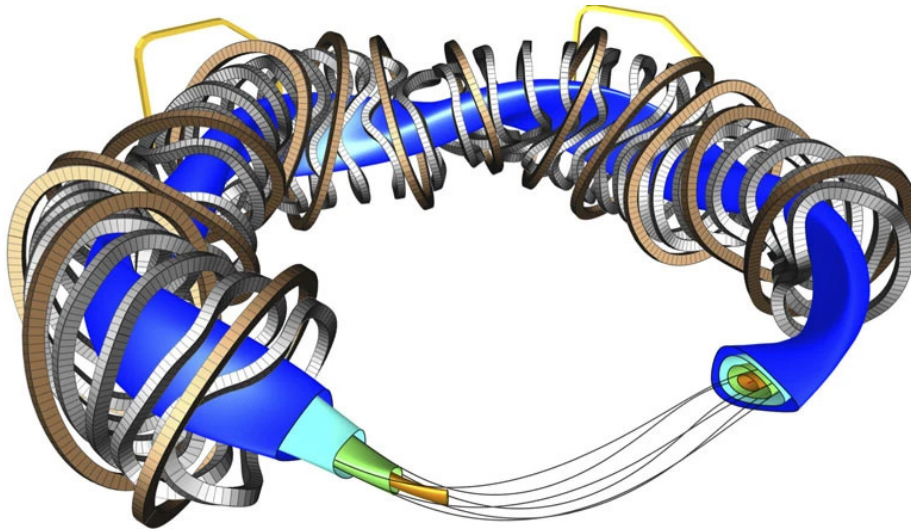


Attaining Tokamak level performance through plasma density profile shaping at Wendelstein 7-X

S. Bannmann, O. Ford, S.A. Bozhenkov, T. Stange, R. Lopez Cansino, A. Langenberg, M.~Wappl, J. Brunner, G. Fuchert, T. Gonda, D. Hartmann, J. Knauer, H.P. Laqua, P. McNeely, N. Pablant, E. Pasch, P. Poloskei, K. Rahbarnia, N. Rust, F. Warmer, R.C. Wolf and the W7X-Team



Optimized Stellarator Wendelstein 7-X



Pedersen

Successfully optimized for **reduced neoclassical transport**



Heat transport now dominated by **turbulence**

Limits core ion
temperature to ~ 1.5 keV
in typical ECRH
discharges

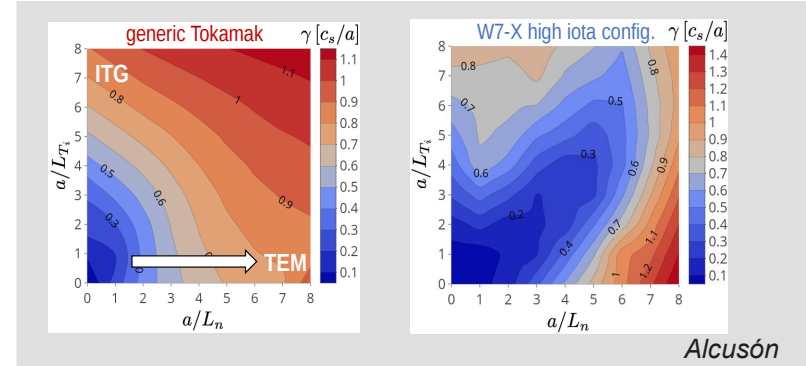
To maximize plasma performance in W7-X need to
reduce turbulent heat transport!

Turbulent heat transport suppression at W7-X

Core density gradients: ITG suppression + TEM stability

Determined by:

- Particle transport regime (diffusion/pinch)
- Core particle source actuators (NBI, pellets)



Reduced turbulent heat transport

Turbulent heat transport suppression at W7-X

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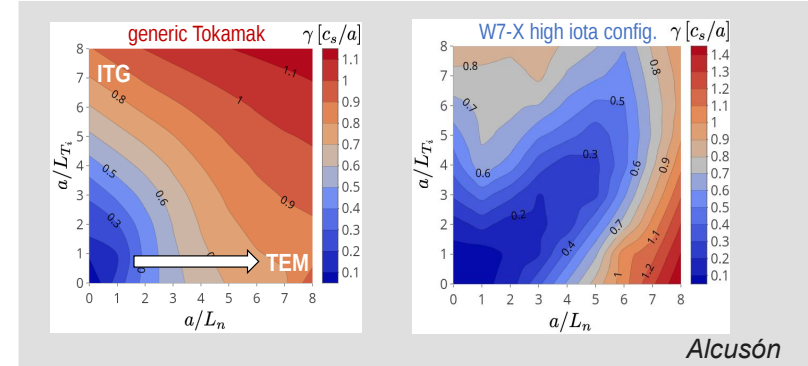
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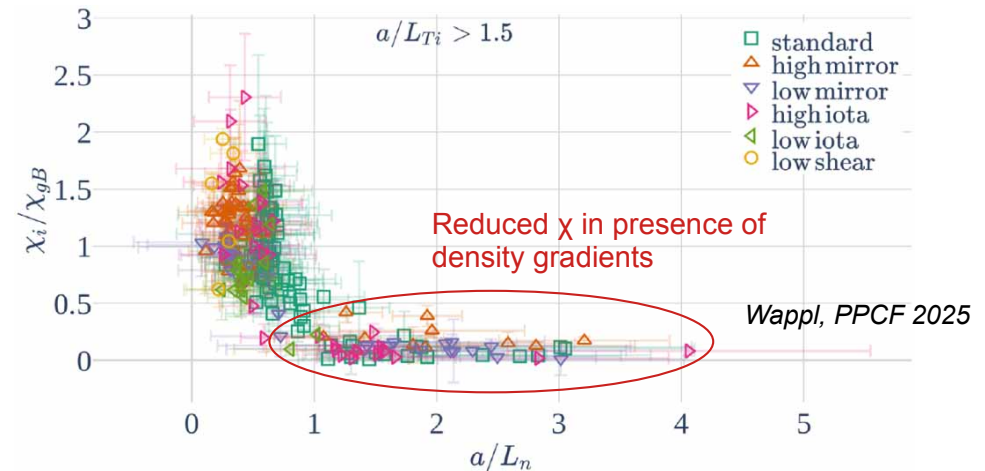


Reduced turbulent heat transport

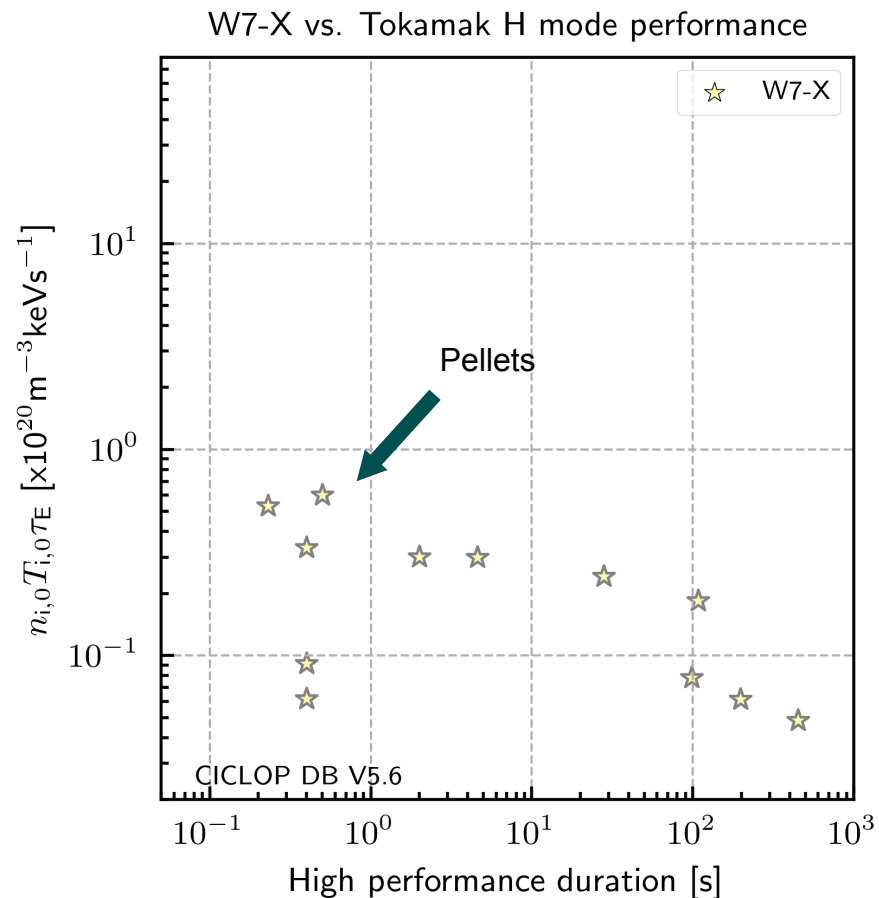
Experimentally seen across magnetic configurations and discharge scenarios



Ion turbulent heat transport coefficient

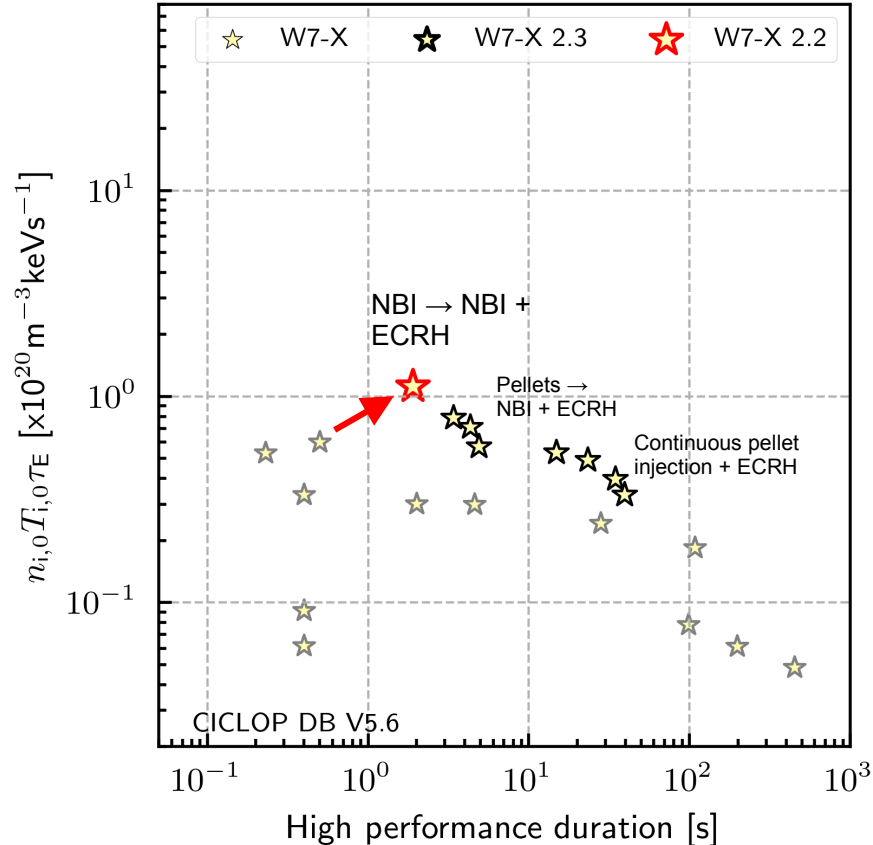


Triple product W7-X



Triple product W7-X

W7-X vs. Tokamak H mode performance

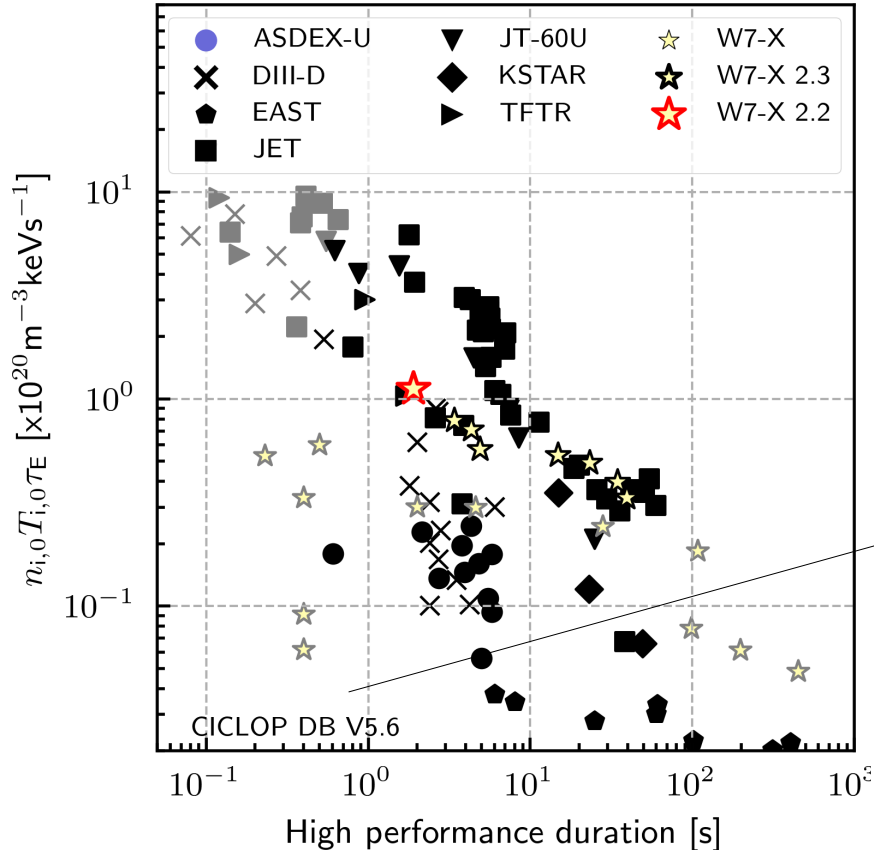


New record triple product achieved at W7-X

$\overline{n_{i,0}T_{i,0}\tau_E}$	$1.10 \pm 0.07 \cdot 10^{20} \text{ m}^{-3} \text{ keVs}$
$n_{i,0}T_{i,0}\tau_E _{\text{max}}$	$1.18 \pm 0.12 \cdot 10^{20} \text{ m}^{-3} \text{ keVs}$

Triple product W7-X

W7-X vs. Tokamak H mode performance



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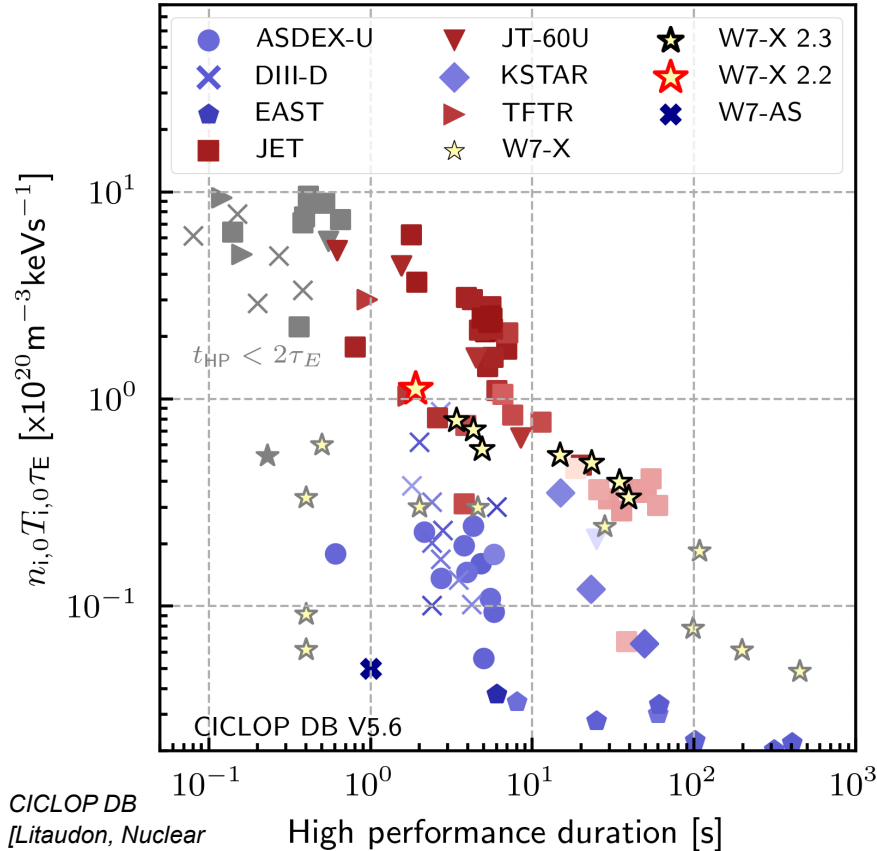
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- Tokamak DB CICLOP [Litaudon, *Nuclear Fusion*, 2023]: range of H-mode operation regimes, e.g. advanced regimes as non-inductive scenarios, negative shear or ITBs

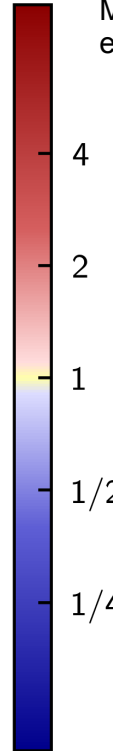


Triple product W7-X

W7-X vs. Tokamak H mode performance



More stored magnetic energy than W7-X



Less stored magnetic energy than W7-X

$$E_B = VB_0^2/2\mu_0$$

New record triple product achieved at W7-X

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W7-X achieved competitive triple product given its stored magnetic energy



Gyro-Bohm scaling of high confinement discharges

Gyro-Bohm scaling

$$\omega\tau_{E,gb} \propto (\rho^*)^{-3}$$

Definition from kinetic profiles and heating power

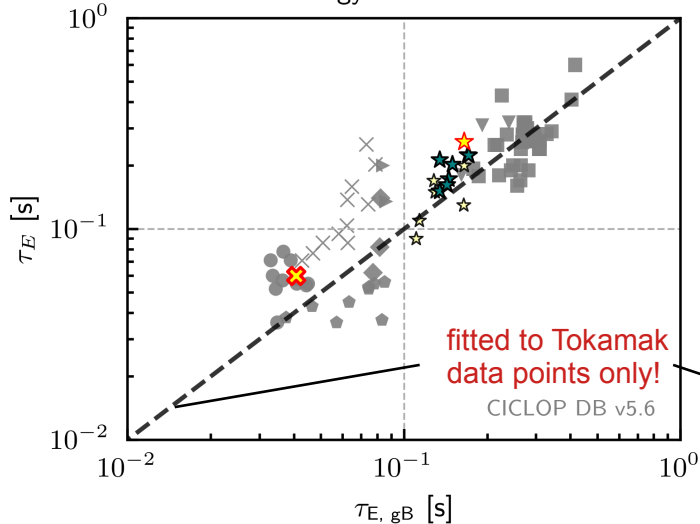
$$\tau_E = \frac{W}{P_H} = \frac{3nkT}{P_H}$$

Achieved energy confinement time and ion temperature in line with Tokamak gyro-Bohm H mode scaling

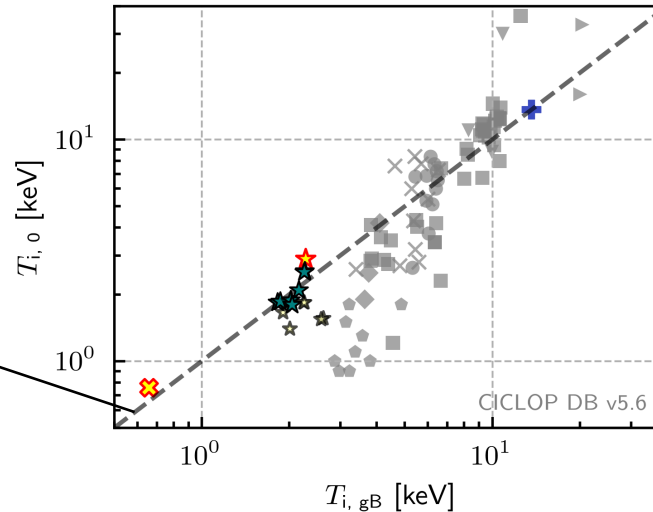
$$\tau_{E,gB} = c_2 a^3 \epsilon^{0.6} m^{-0.2} \left(\frac{P_H}{n} \right)^{-0.6} B^{0.8}$$

$$T_{gB} = c_1 \epsilon^{-0.4} m^{-0.2} \left(\frac{P_H}{n} \right)^{0.4} B^{0.8}$$

Energy confinement



Ion Temperature



- ★ W7X OP2.2
- ✚ HELIAS
- ✚ W7-AS
- ★ W7-X OP2.3
- ASDEX-U
- ✕ DIII-D
- EAST
- JET
- ▼ JT-60U
- ◆ KSTAR
- ▲ TFTR
- ★ W7-X



Gyro-Bohm scaling of high confinement discharges

Gyro-Bohm scaling

Definition from kinetic profiles and heating power

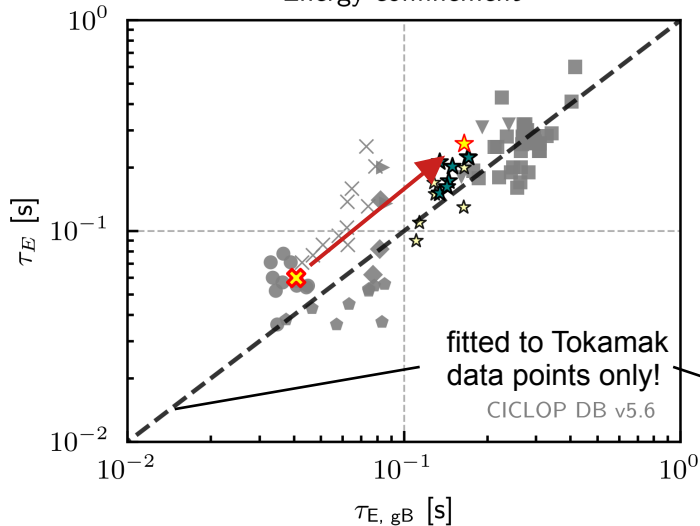
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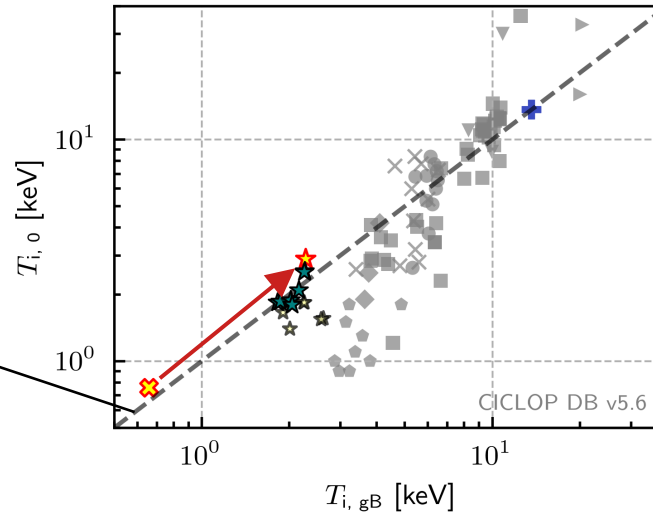
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Energy confinement



Ion Temperature



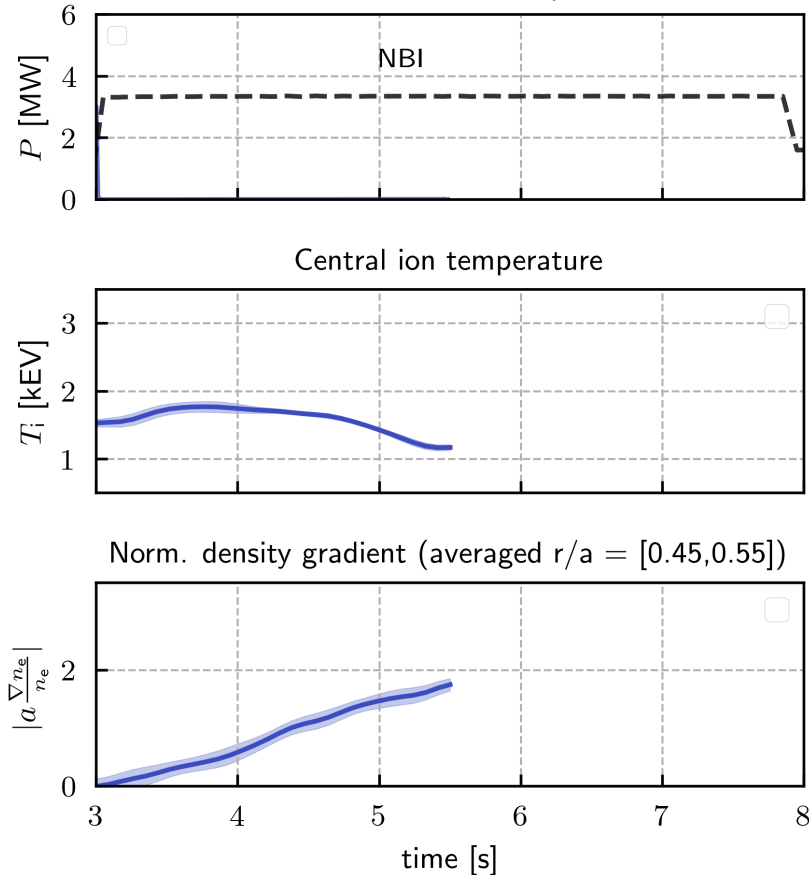
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Achieved energy confinement time and ion temperature in line with Tokamak gyro-Bohm H mode scaling

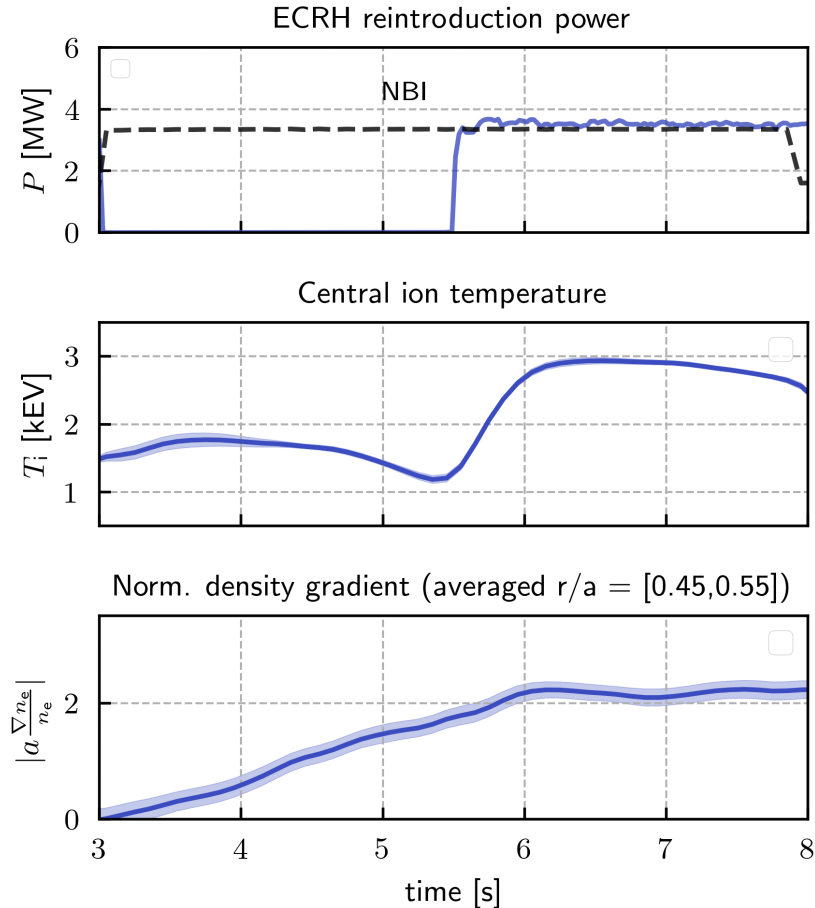
W7-AS to W7-X (similar plasma regime): Follows the Tokamak fitted gyro-Bohm scaling

Accessing and stabilizing high performance plasmas

- I. Pure NBI heating:
 - a) core density gradient develops
 - b) low ion temperature due to low power

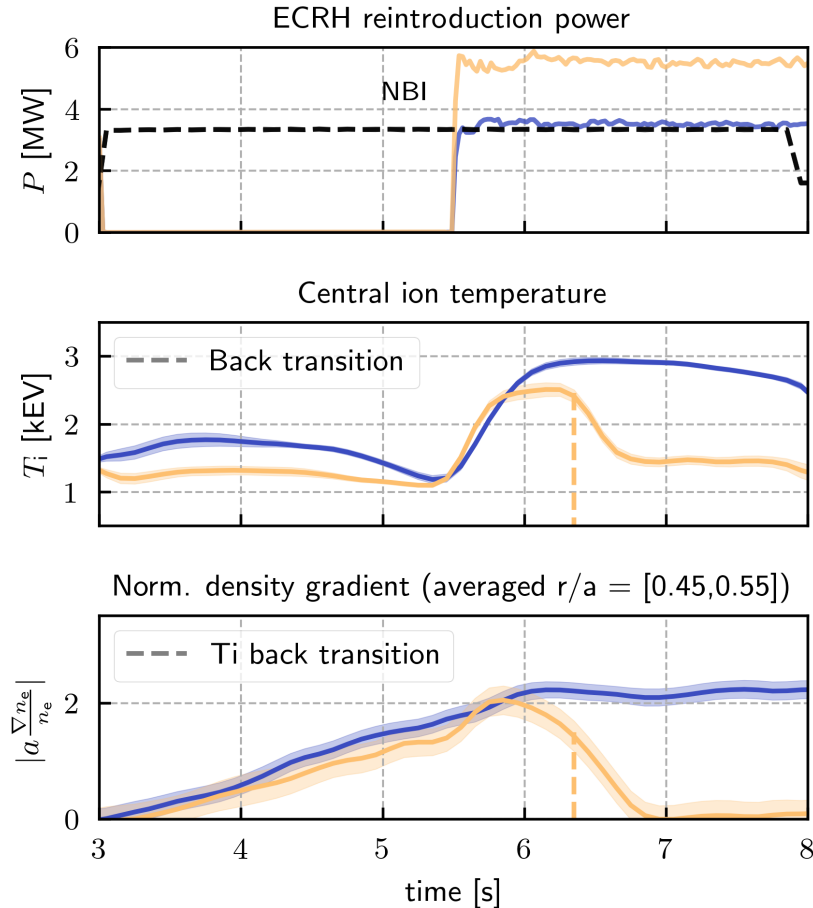


Accessing and stabilizing high performance plasmas



- I. Pure NBI heating:
 - a) core density gradient develops
 - b) low ion temperature due to low power
- II. Add ECRH:
 - a) Core ion temperature increases
 - b) Core density pump-out: stabilizes gradient

Accessing and stabilizing high performance plasmas



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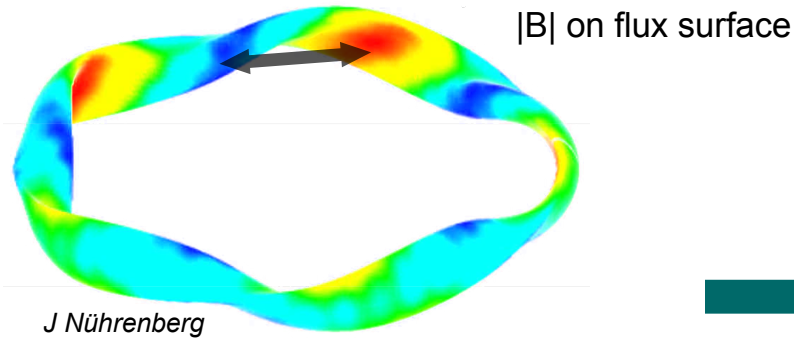
Adding too much ECRH: Core density gradient reduction until back transition to higher heat transport regime



Need to find balance ECRH power!

Magnetic field configuration space Wendelstein 7-X

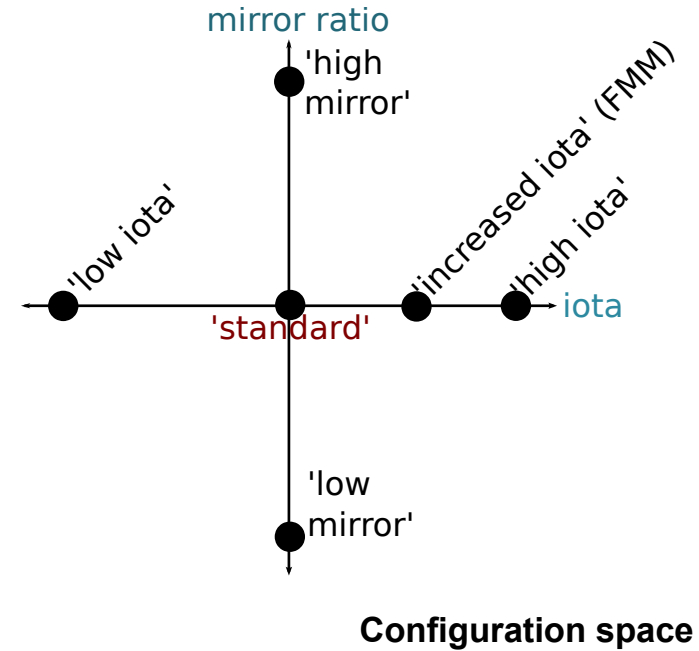
Mirror ratio



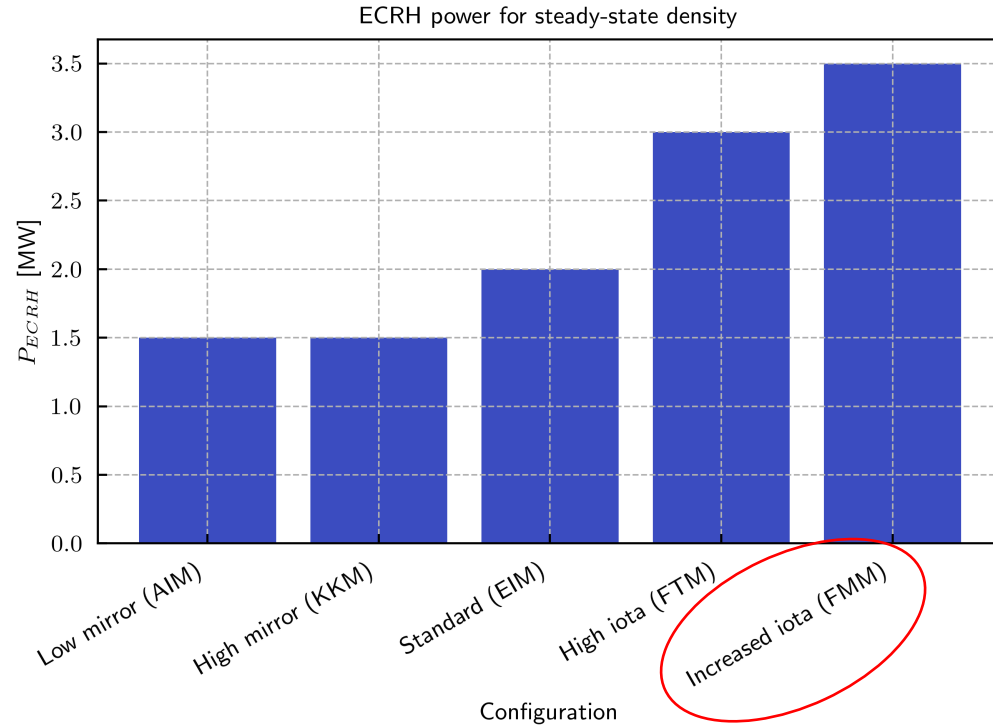
iota

$$\iota = 1/q$$

Adjustable via coil currents and additional control coils



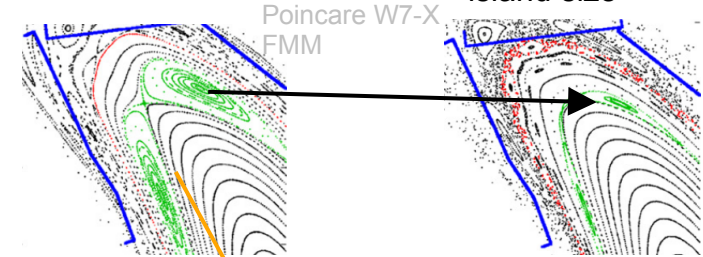
Accessing and stabilizing high performance plasmas – different magnetic configurations



Best performance achieved in *iota scan* configuration

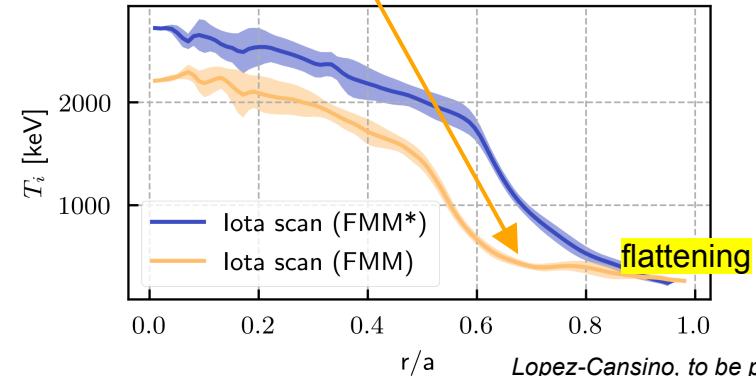
FMM: limiter type configuration with internal islands

FMM* has reduced internal island size



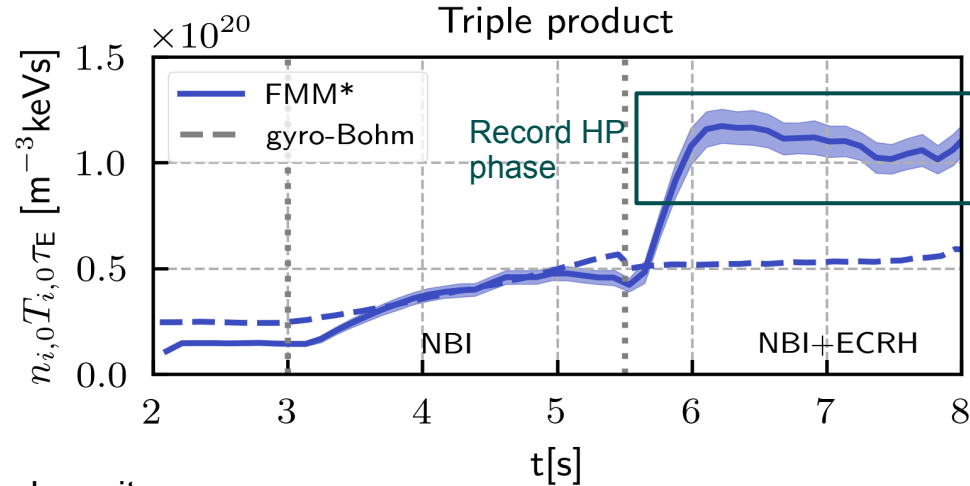
Andreeva, NF, 2022

CICERS T_i profiles in HP phase



Lopez-Cansino, to be published

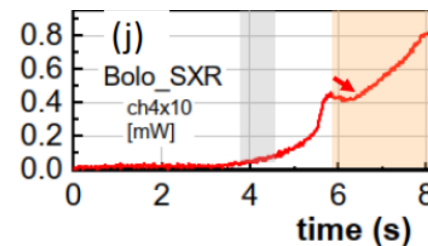
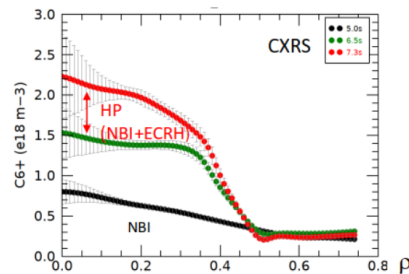
Time evolution of plasma performance in FMM*



Extension?
W7-X: solvable technical limitations +
divertor heat load

Reactor?

Impurity
accumulation



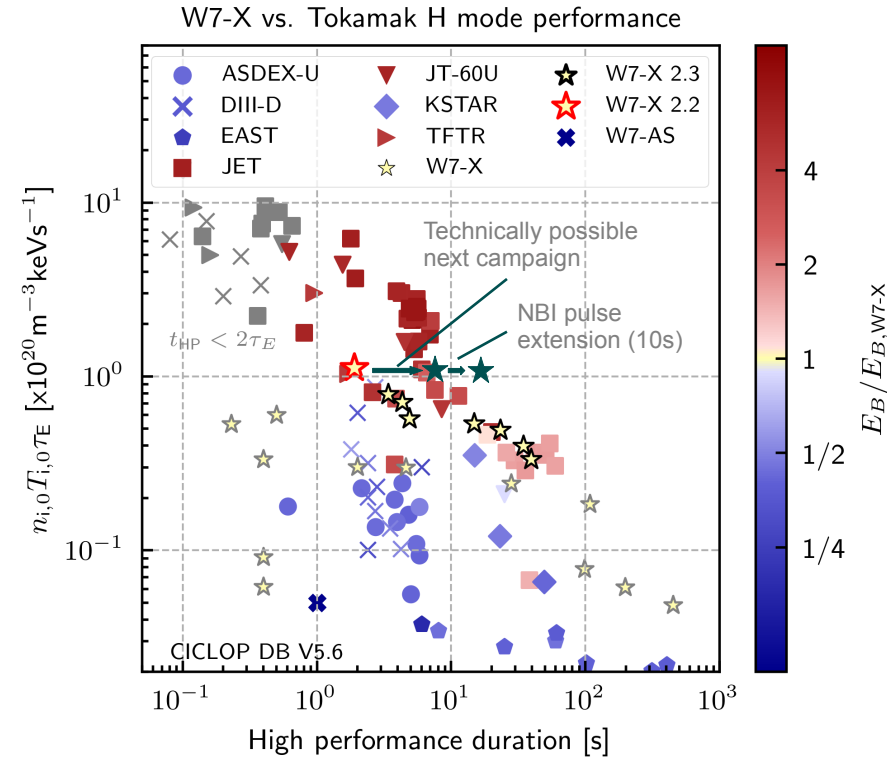
D. Zhang → Poster P1-2634

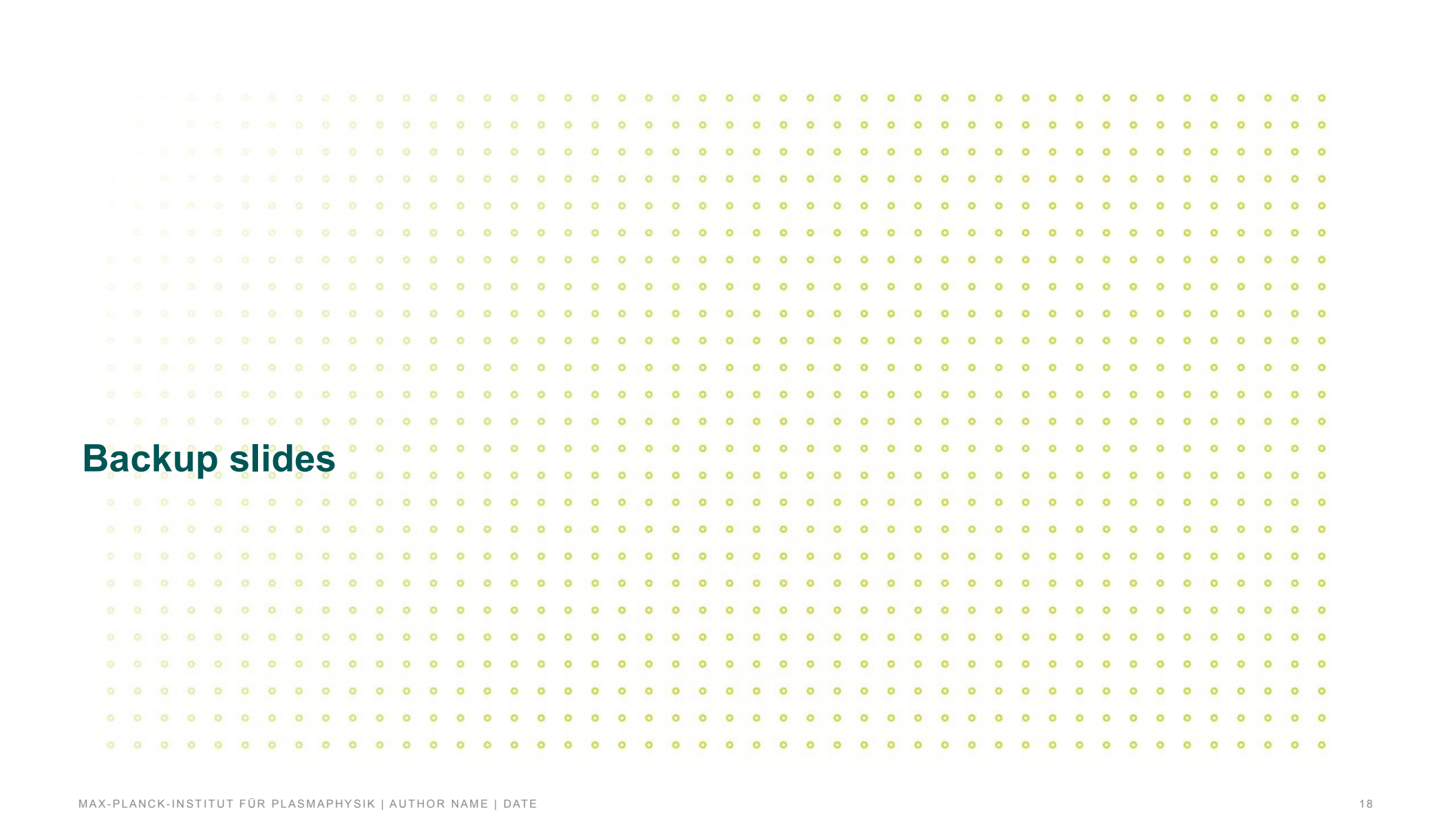
Need to control impurity
transport (e.g. core electron
root regime)

Particle pinch for core
gradient creation

Conclusion

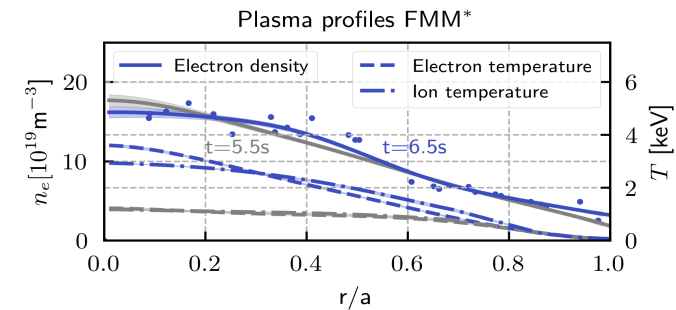
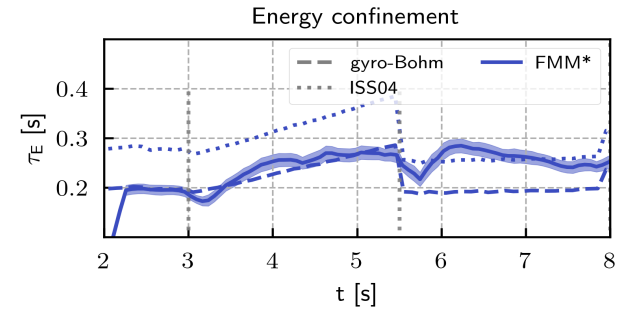
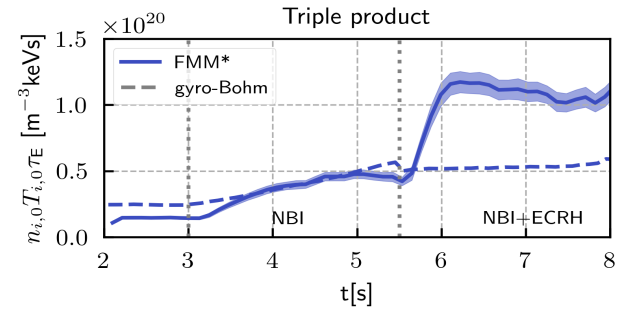
- In W7-X unprecedented Stellarator performance in terms of the triple product and was achieved
- Performance on par with Tokamak H-mode regimes given the stored magnetic energy of W7-X
- Comparing to a similar high confinement discharge scenario from W7-AS **good agreement with reactor favorable gyro-Bohm scaling was found**
- **Stability of the core gradient** achieved with combined NBI+ECR heating
- ECRH power for steady-state peaked density profiles found to be magnetic configuration dependent
- Extension of HP phase in W7-X or scaling to reactor: **Critical Impurity accumulation in HP phase**



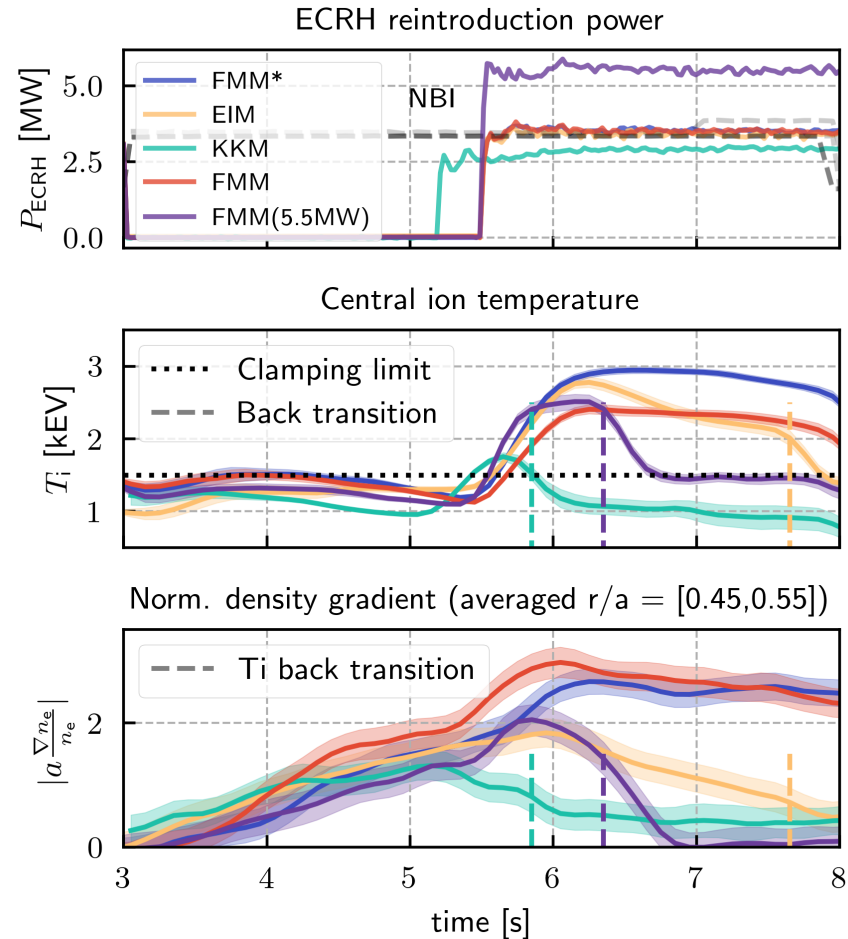


Backup slides

Time evolution of plasma performance in FMM



Time evolution of plasma profiles in different magnetic configurations





Gyro-Bohm scaling

Gyro-Bohm scaling

Assuming dominant heat transport gyro-Bohm scaling in ρ^* (ITG) and weak dependence on β and ν^* as in Tokamak H mode [37]:

$$\omega\tau_{E,gb} \propto (\rho^*)^{-3} \quad (3)$$

$$\omega = \frac{qB}{2\pi m} \quad (4)$$

$$\rho^* = \frac{\rho_L}{a} = \frac{mv_\perp}{a \cdot qB} = \frac{(2kTm)^{\frac{1}{2}}}{a \cdot qB} \quad (5)$$

$$v_\perp = \frac{2}{3}v_{th} \quad (6)$$

$$\tau_{E,gb} \propto \frac{1}{\omega} \left(\frac{(2kTm)^{\frac{1}{2}}}{a \cdot qB} \right)^{-3} \propto m^{-\frac{1}{2}} T^{-\frac{3}{2}} a^3 q^2 B^2 \quad (7)$$

Combining with the definition of τ_E via the kinetic profiles and heating power

$$\tau_E = \frac{W}{P_H} = \frac{3nkT}{P_H} \quad (8)$$

gyro-Bohm scalings for T and τ_E can be written in terms of geometric quantities, density n and heating power P_H :

$$T_{gB} = c_1 \epsilon^{-0.4} m^{-0.2} \left(\frac{P_H}{n} \right)^{0.4} B^{0.8} \quad (9)$$

$$\tau_{E,gB} = c_2 a^3 \epsilon^{0.6} m^{-0.2} \left(\frac{P_H}{n} \right)^{-0.6} B^{0.8} \quad (10)$$

Consequently, if gyro-Bohm scaling holds the triple product F scales as:

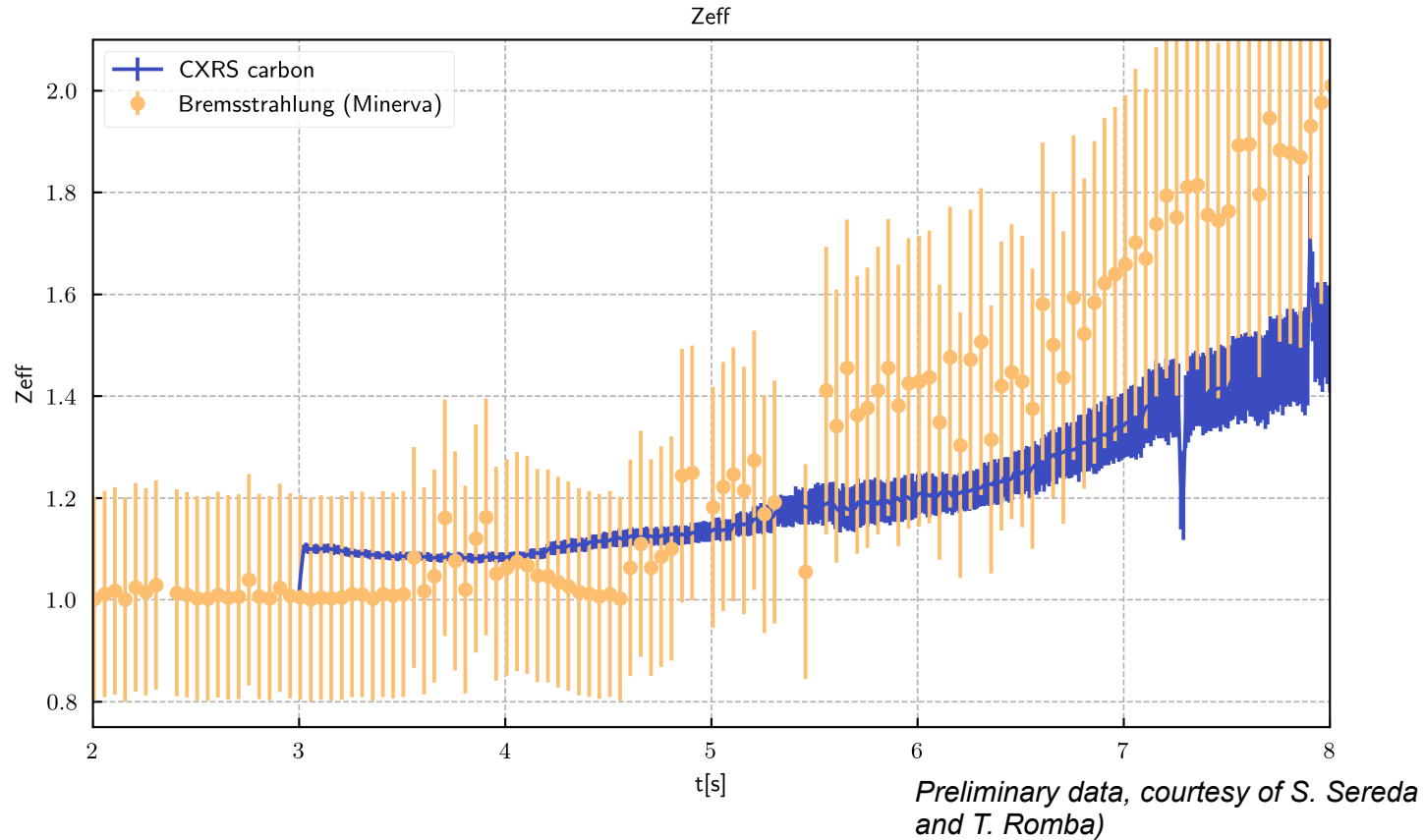
$$F \propto a^3 \epsilon^{0.2} m^{-0.4} n^{1.2} P_H^{-0.2} B^{1.6} \quad (11)$$

Discharge IDs – magnetic configurations

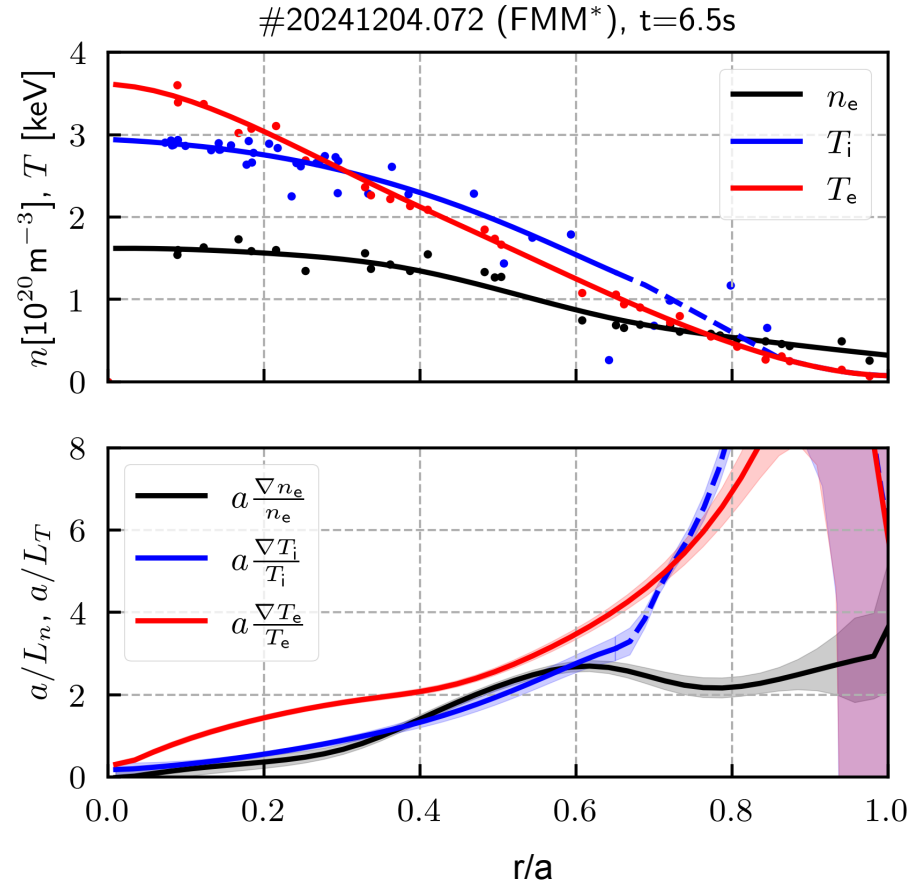
TABLE II. Experimentally determined ECRH pump-out balance for two NBI sources (3.5MW) in several magnetic configurations and the best achieved core plasma parameters. Note that a final optimisation of T_i , W_{dia} and τ_E was completed only for Standard (EIM) and iota scan (FMM) configurations.

Configuration	$\iota_{2/3}$	$\epsilon_{\text{eff},1/2}$	a [m]	P_{ECRH} steady [MW]	T_i [keV]	W_{dia} [MJ]	τ_E [ms]	Program ID
Low mirror (AIM)	0.97	0.018	0.53	1.5	1.6	0.8	180	20230316.069
High mirror (KKM)	0.97	0.022	0.51	1.5	1.6	0.8	180	20250227.082
Standard (EIM)	0.97	0.0065	0.52	2.0	2.6	1.2	180	20241205.066
High iota (FTM)	1.20	0.013	0.48	3.0	2.1	1.2	150	20241022.039
Iota scan, limiter with internal islands (FMM)	1.08	0.008	0.55	3.5	2.3	1.2	170	20241204.063
Iota scan, limiter with suppressed islands (FMM*)	1.08	0.008	0.55	3.5	2.9	1.8	260	20241204.072

Zeff record iota scan shot (#20241204.072)



Plasma profiles in HP phase



Plasma profiles in different magnetic configurations

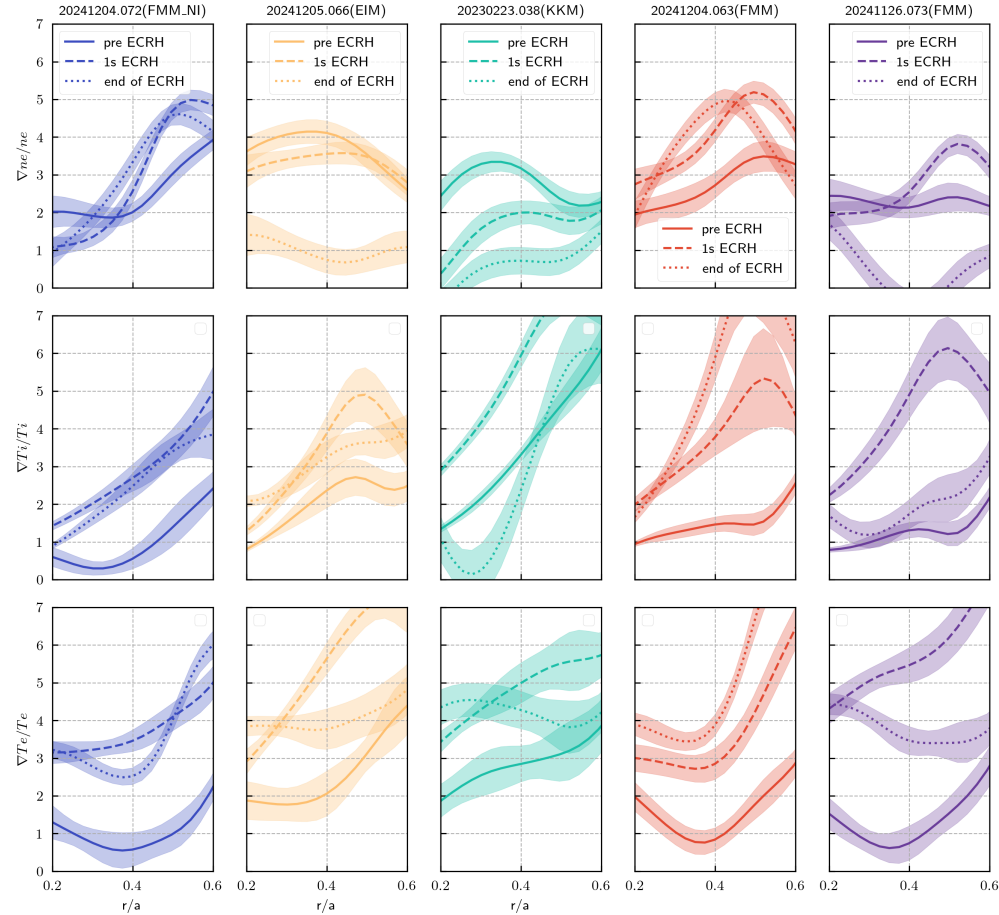




TABLE I. Energy confinement time and triple product in high performance phase of discharge #20241204.072.

Parameter	Value	Error	Unit	f_{ren}
$\overline{\tau_E}$	260	± 15	ms	1.14
τ_E^{max}	286	± 19	ms	1.25
τ_E , ISS04	227	± 12	ms	1.0
$\overline{n_{i,0} T_{i,0} \tau_E}$	1.10	± 0.07	$10^{20} \text{m}^{-3} \text{keVs}$	
$n_{i,0} T_{i,0} \tau_E ^{\text{max}}$	1.18	± 0.12	$10^{20} \text{m}^{-3} \text{keVs}$	

r/a

Neoclassical limit W7-X

