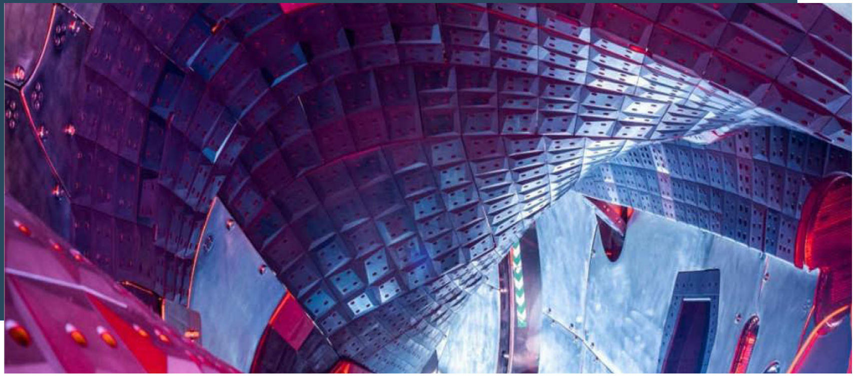
MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

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



EUROfusion

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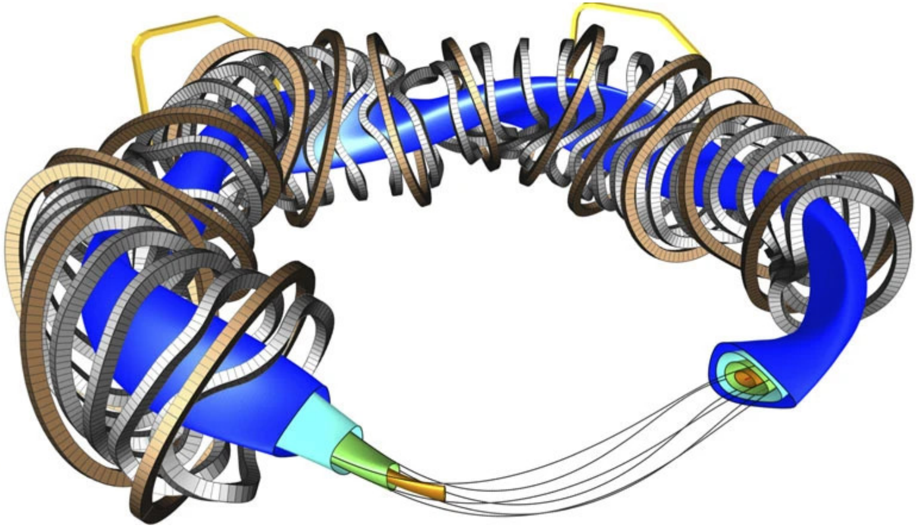
Optimized Stellarator Wendelstein 7-X



TS Pedersen et al.

Successfully optimized for **reduced neoclassical transport**

Heat transport now dominated by **turbulence**

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

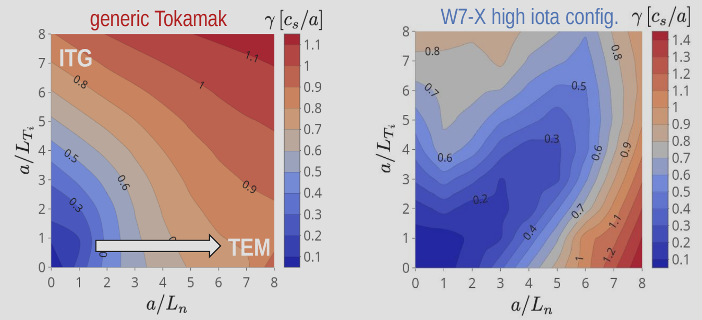
To maximize plasma performance in W7-X need to reduce turbulent heat transport!

Turbulent heat transport suppression at W7-X

Core density gradients: ITG suppression + TEM stabilty

Determined by:

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



JA Alcusón et al., PPCF 2020

Reduced turbulent heat transport

Turbulent heat transport suppression at W7-X

Core density gradients: ITG suppression + TEM stabilty

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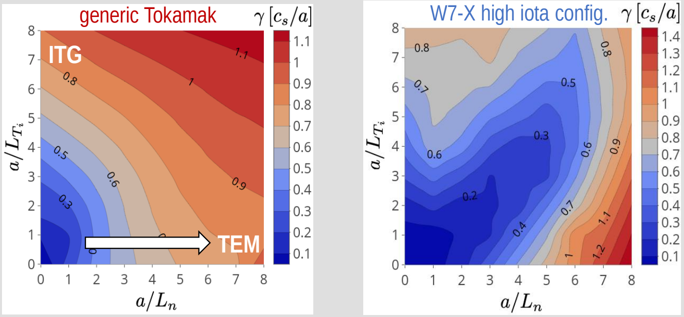
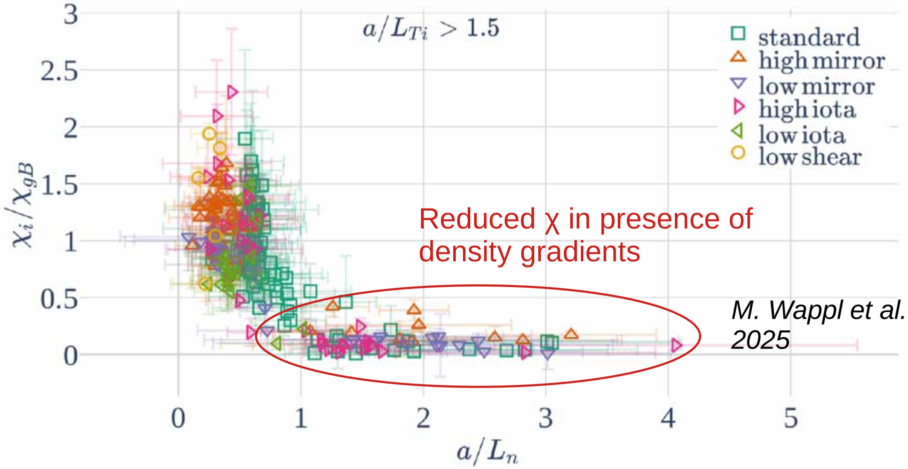
Reduced turbulent heat transport

Experimentally seen across magnetic configurations and discharge scenarios



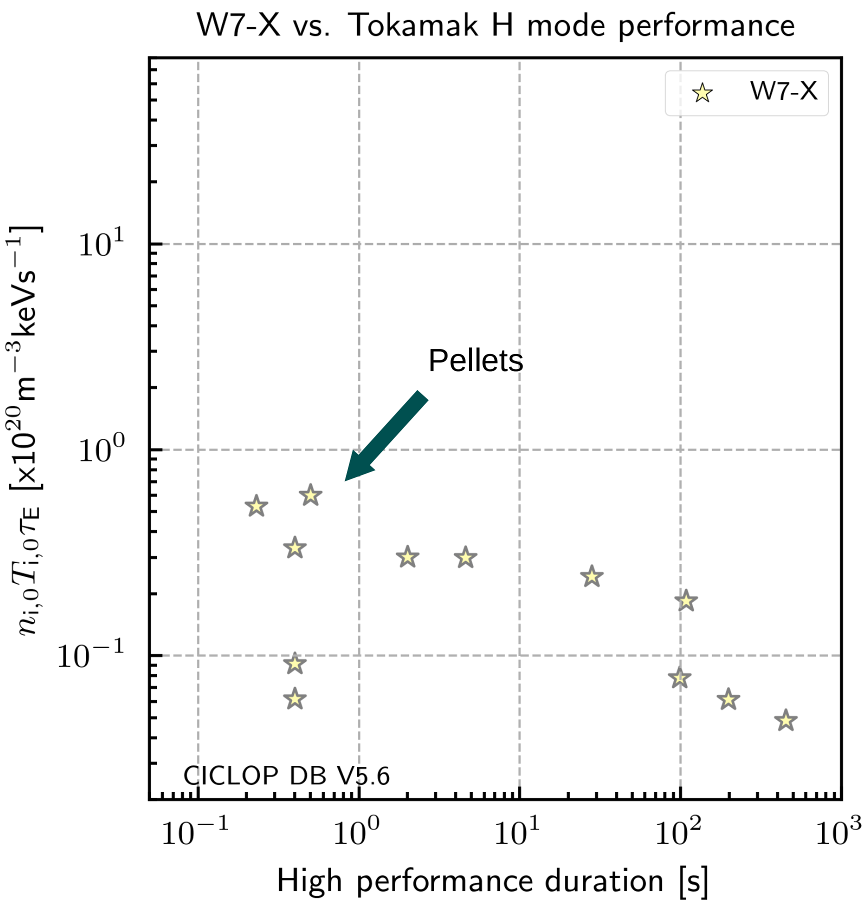
JA Alcusón et al., PPCF 2020

Ion turbulent heat transport coefficient



M. Wappl et al., PPCF 2025

Triple product W7-X



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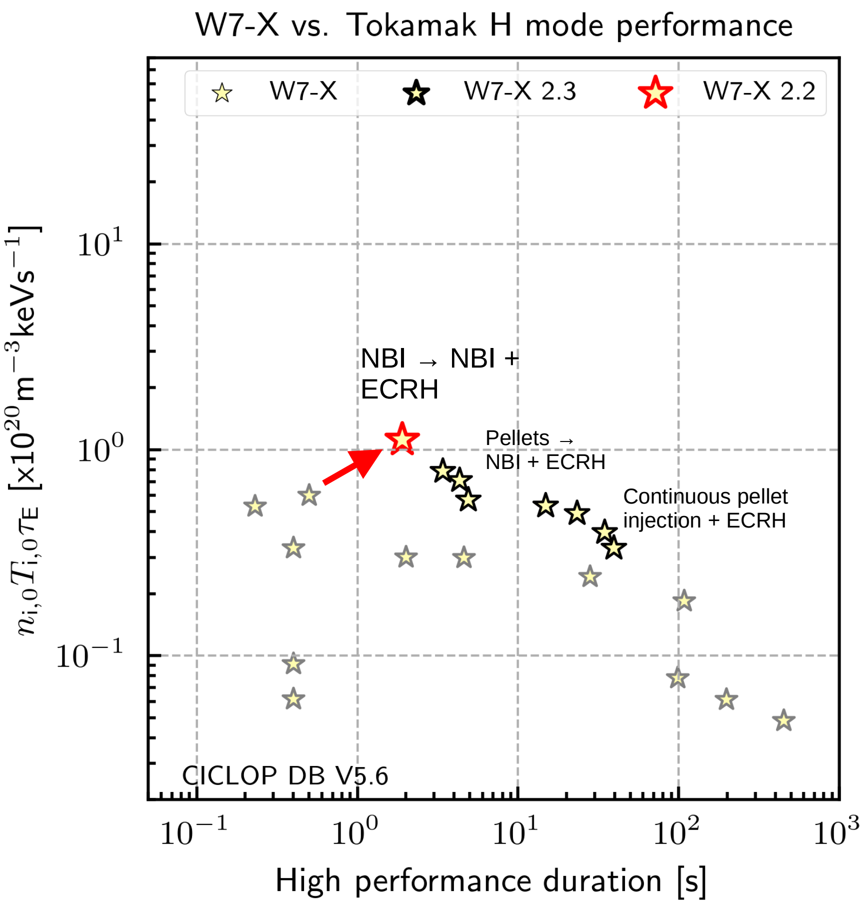

New record triple product achieved at W7-X

$\overline{n_{i,0}T_{i,0}\tau_E}$	1.10	± 0.07	$10^{20}\mathrm{m}^{-3}\mathrm{keVs}$
$n_{i,0}T_{i,0}\tau_E\|^{max}$	1.18	± 0.12	$10^{20}\mathrm{m}^{-3}\mathrm{keVs}$

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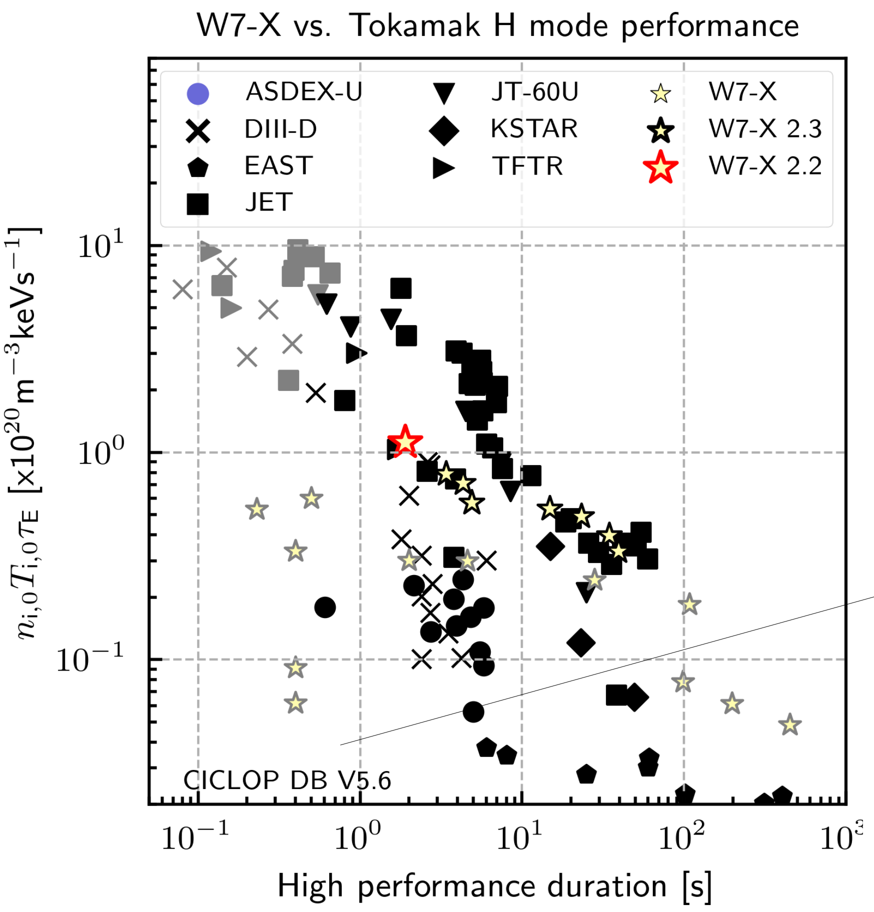

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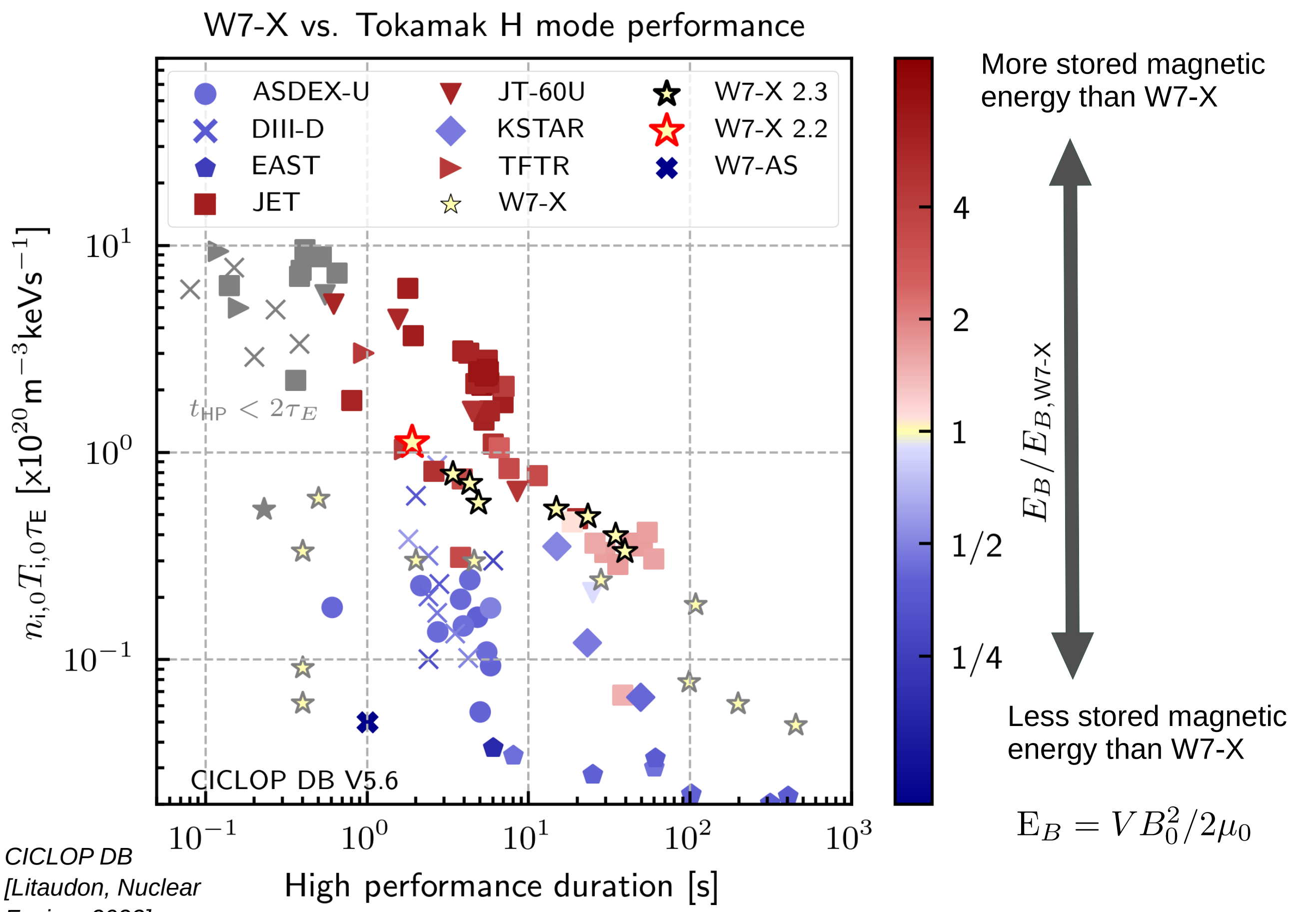
Tokamak DB CICLOP [X. *Litaudon, Nuclear Fusion, 2023]*: range of H-mode operation regimes, e.g. advanced regimes as non-inductive scenarios, negative shear or ITBs

→ Poster P4 X. Litaudon

Triple product 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

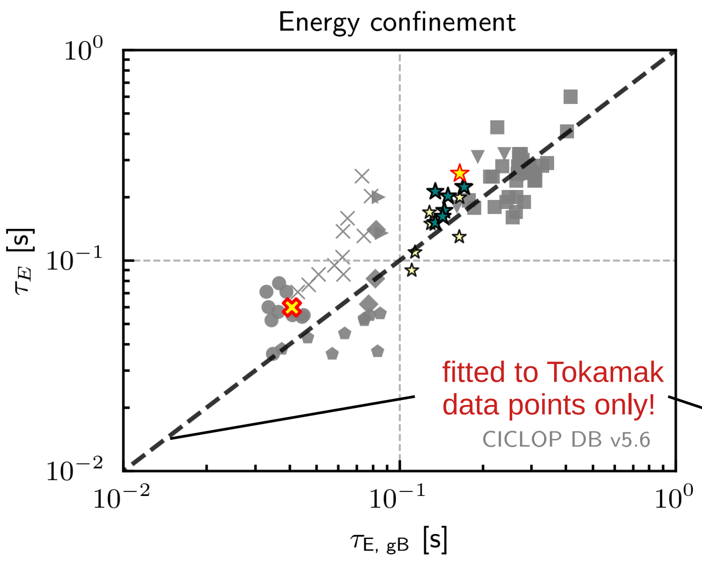
$$\omega \tau_{E,gb} \propto (\rho^*)^{-3}$$

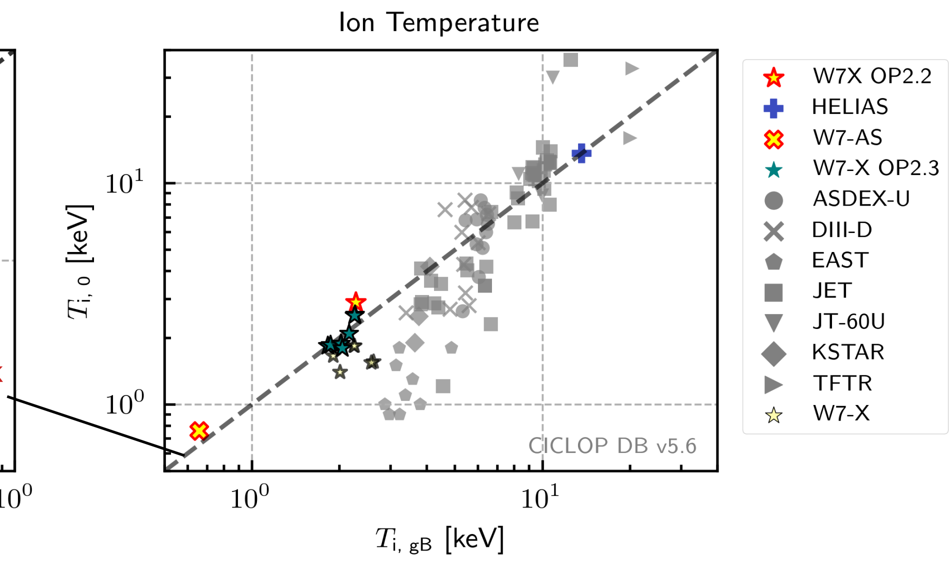
Definition from kinetic profiles and heating power

$$\tau_\mathrm{E} = \frac{W}{P_\mathrm{H}} = \frac{3nkT}{P_\mathrm{H}}$$

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

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





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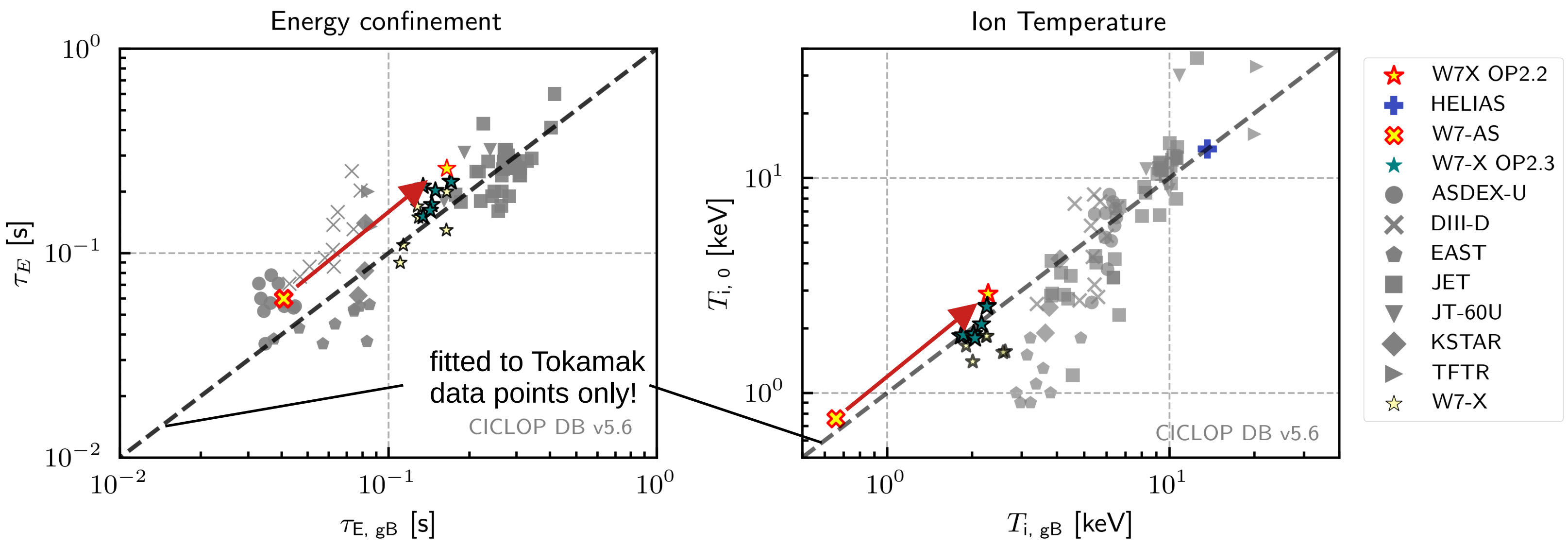
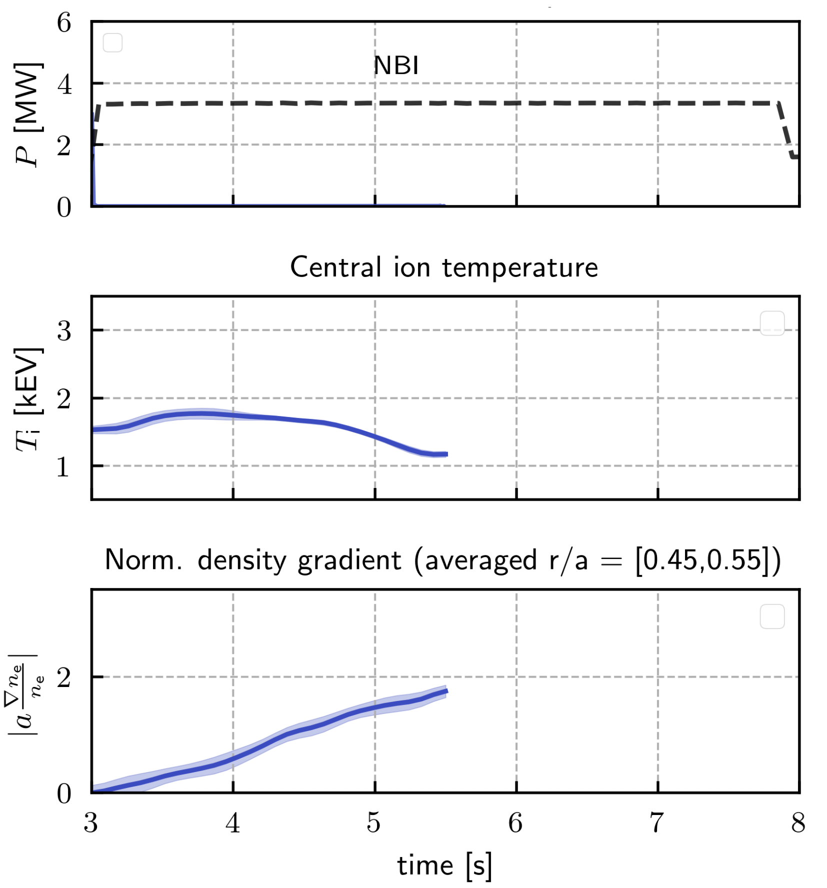


Achieved energy confinement time and ion temperature in line with Tokamak gyro-Bohm H mode scaling

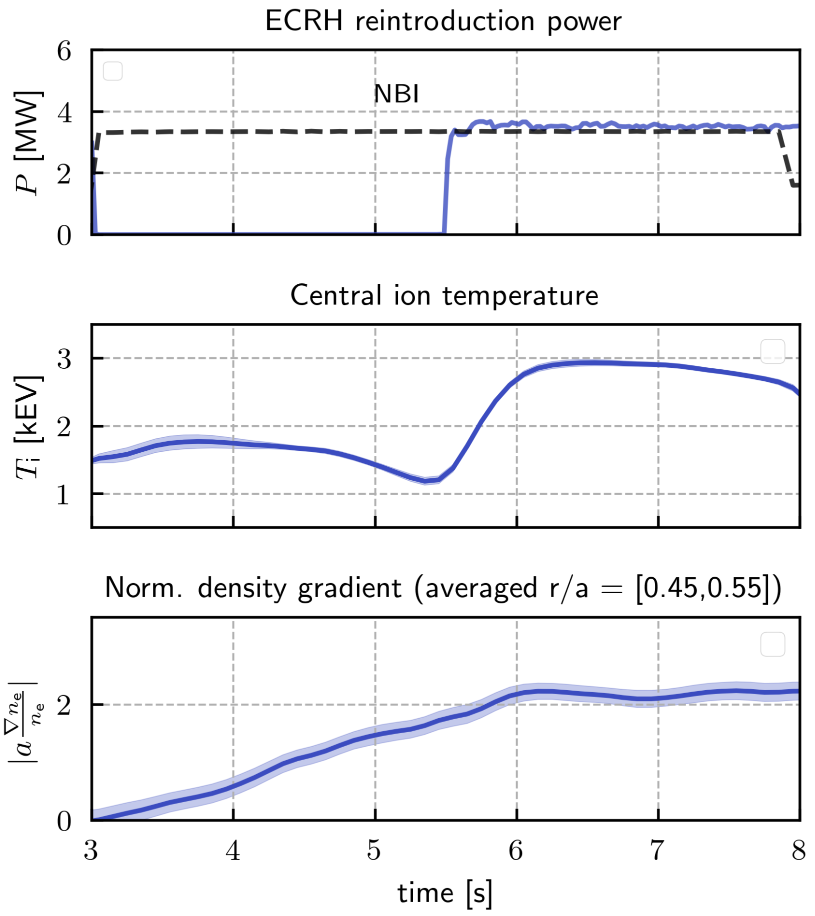
W7-AS to W7-X (similar plasma regime): Follows the Tokamak fitted gyro-Bohm scaling

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



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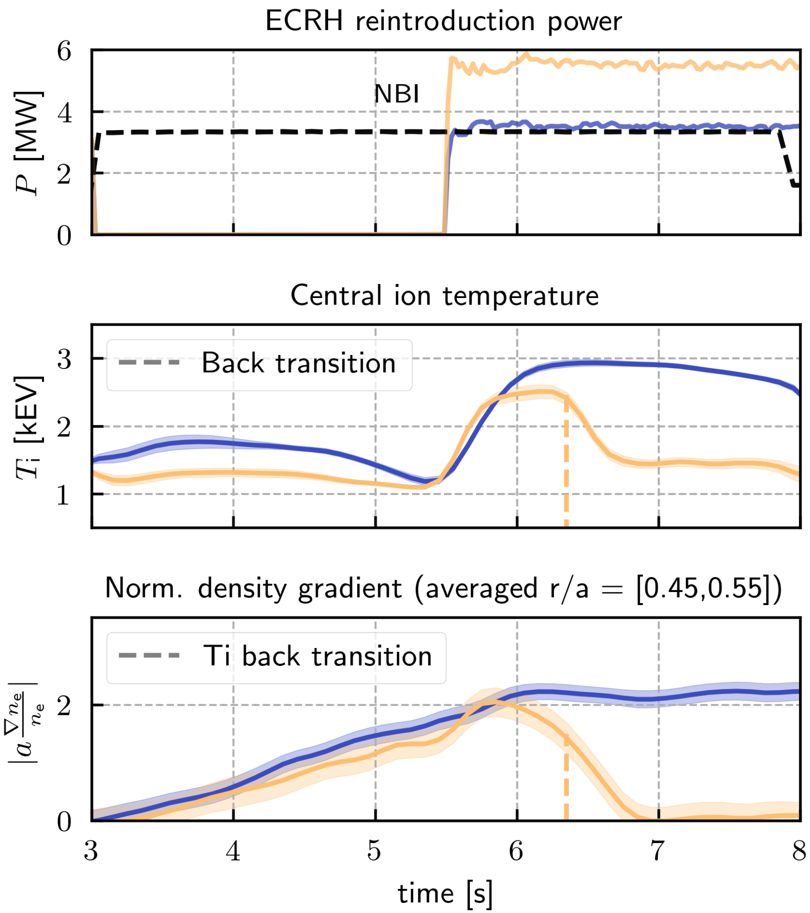
II. Add ECRH:
   a) Core ion temperature increases
   b) Core density pump-out: stabilizes gradient

Accessing and stabilizing high performance plasmas



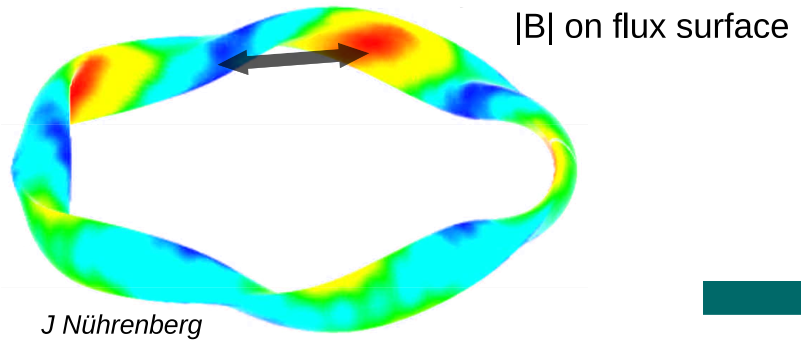
I. Pure NBI heating:
   a) core density gradient develops
   b) low ion temperature due to low power
II. Add ECRH:
   a) Core ion temperature increases
   b) Core density pump-out: stabilizes gradient

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

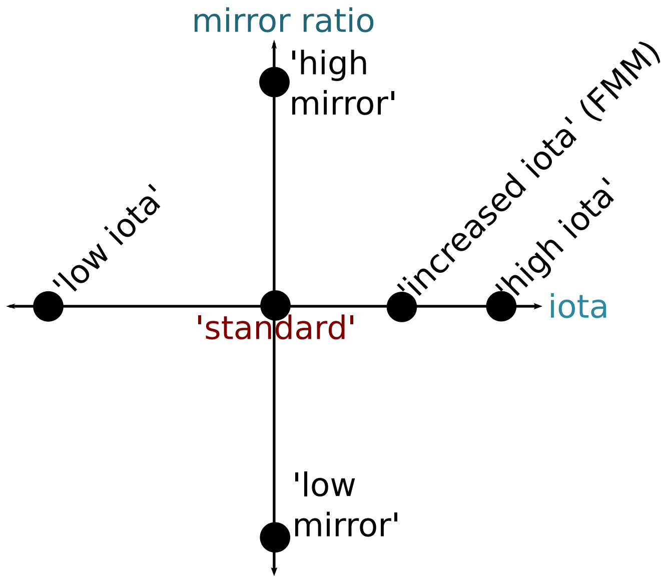
Need to find balance ECRH power!

Magnetic field configuration space Wendelstein 7-X

Mirror ratio



Adjustable via coil currents and additional control coils

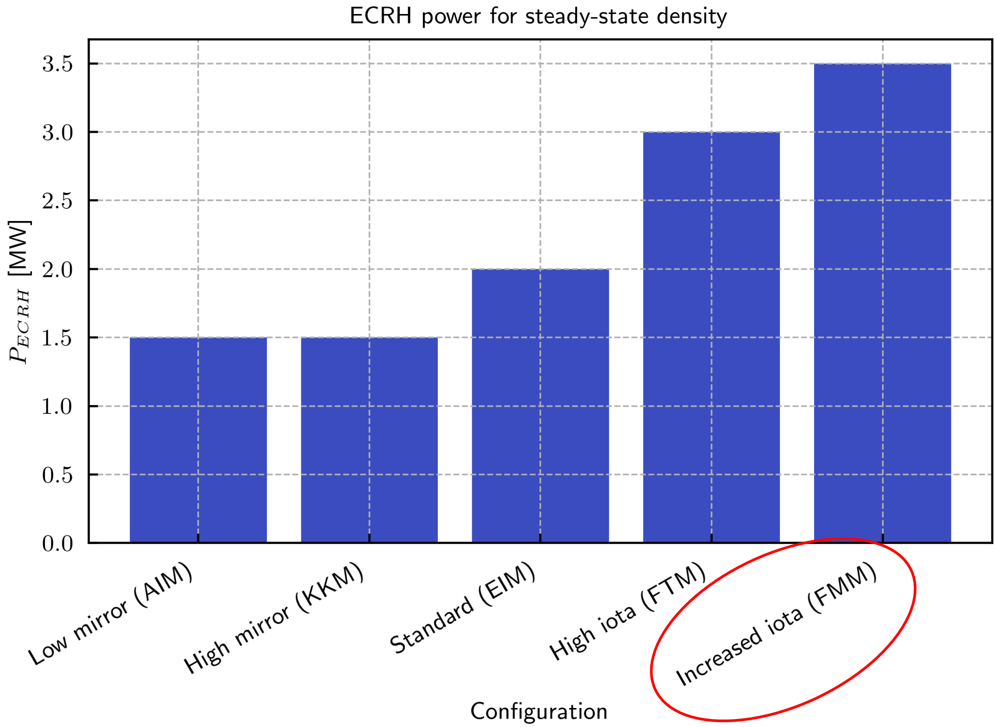


Iota

$$\iota = 1/q$$

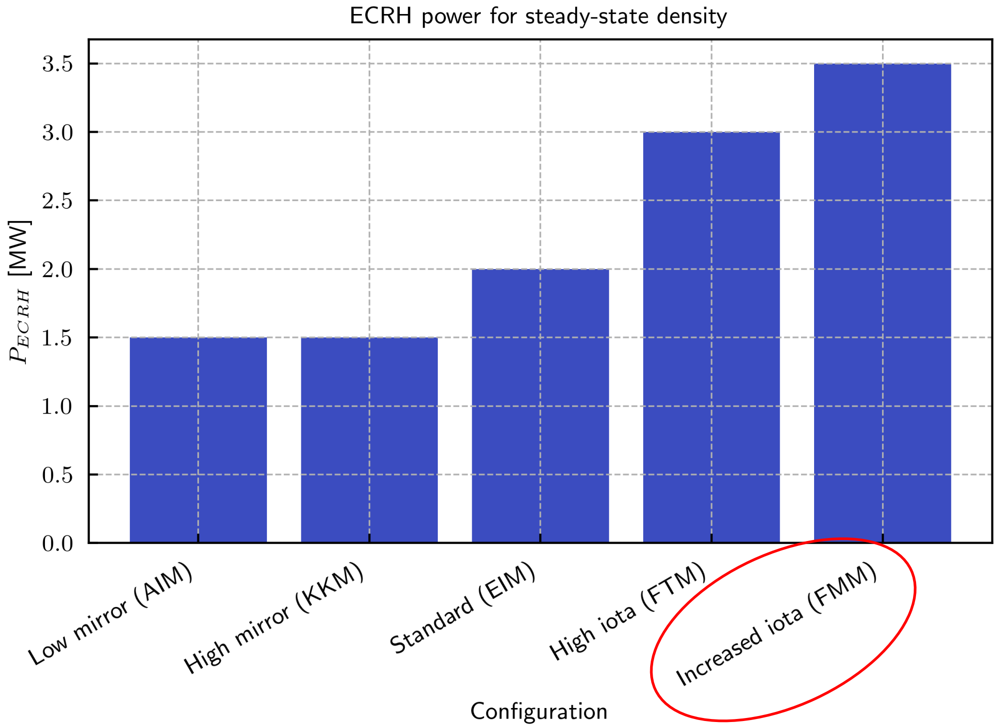
Configuration space

Accessing and stabilizing high performance plasmas – different magnetic configurations



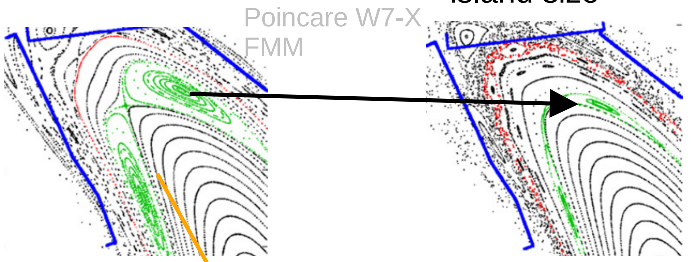
Best performance achieved in *iota scan* configuration

Accessing and stabilizing high performance plasmas – different magnetic configurations

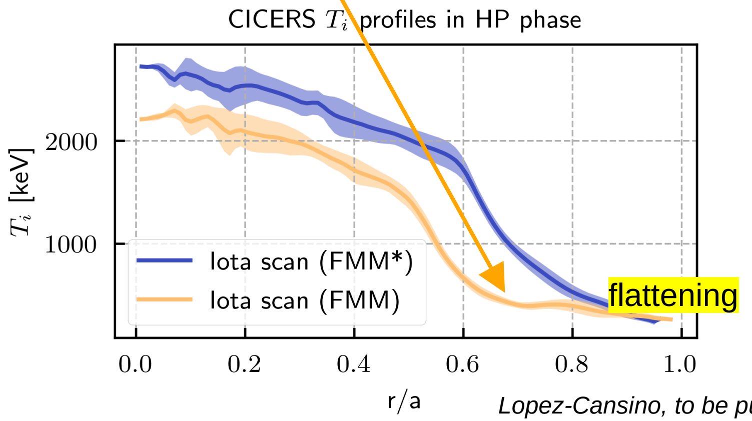


FMM: limiter type configuration with internal islands

FMM* has reduced internal island size



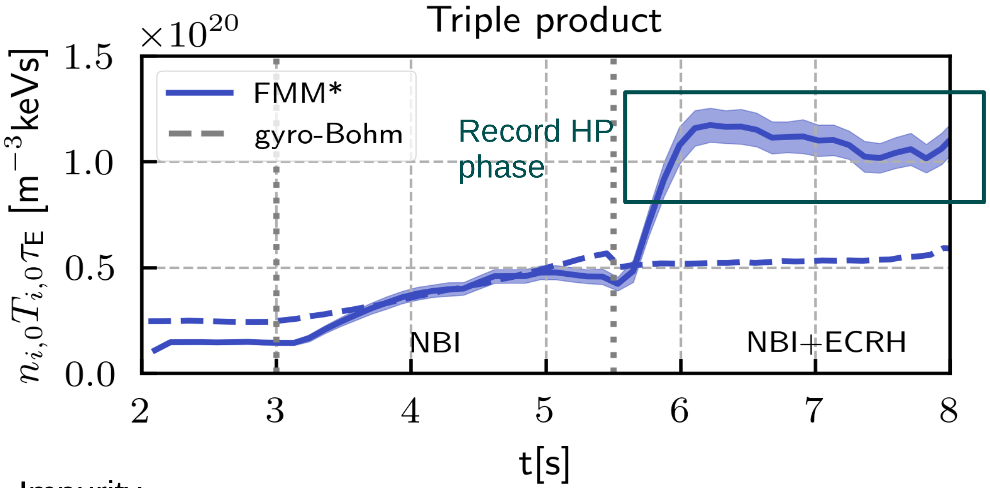
Andreeva, NF, 2022



Lopez-Cansino, to be published

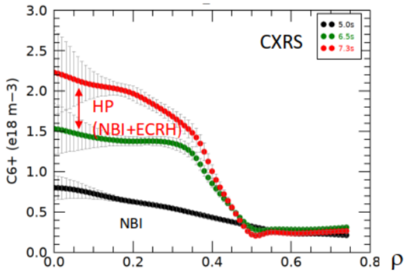
Best performance achieved in *iota scan* configuration

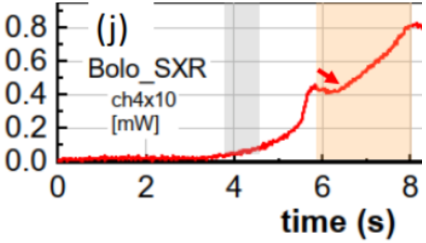
Time evolution of plasma performance in FMM*



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

Impurity accumulation





D. Zhang → Poster P1-2634

Reactor?

Talk on Saturday F. Warmer

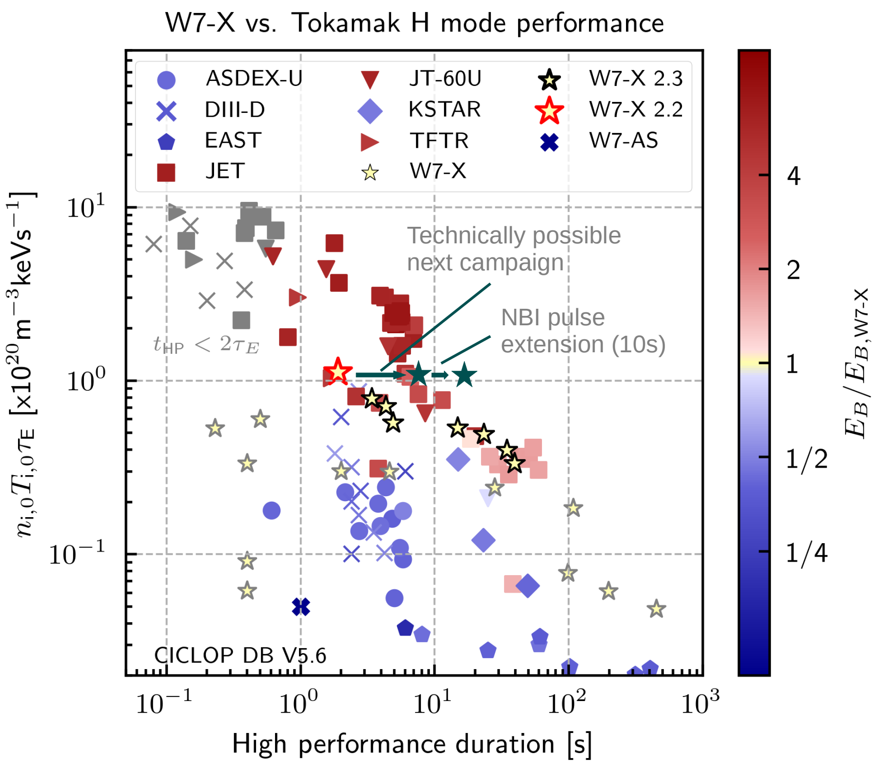
Need to control impurity transport (e.g. core electron root regime)

Particle pinch for core gradient creation

Conclusion

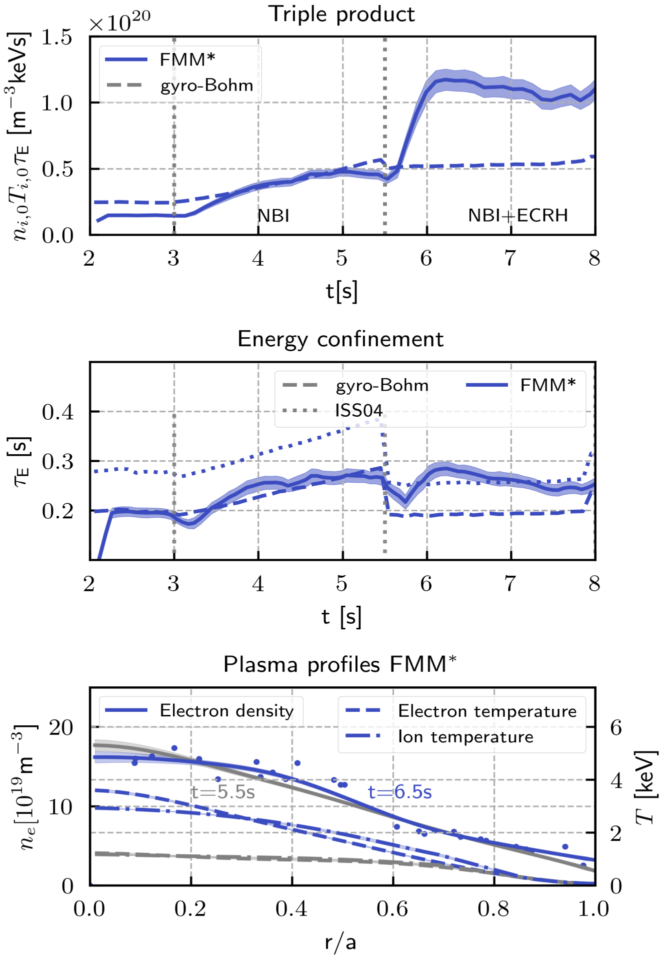
- **In W7-X unprecedented Stellarator performance in terms of the triple product was achieved**
- Performance on par with Tokamak H-mode regimes given the stored magnetic energy of W7-X
- Comparing to a similar high confinement discharge scenario from W7-AS **good agreement with reactor favorable gyro-Bohm 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**

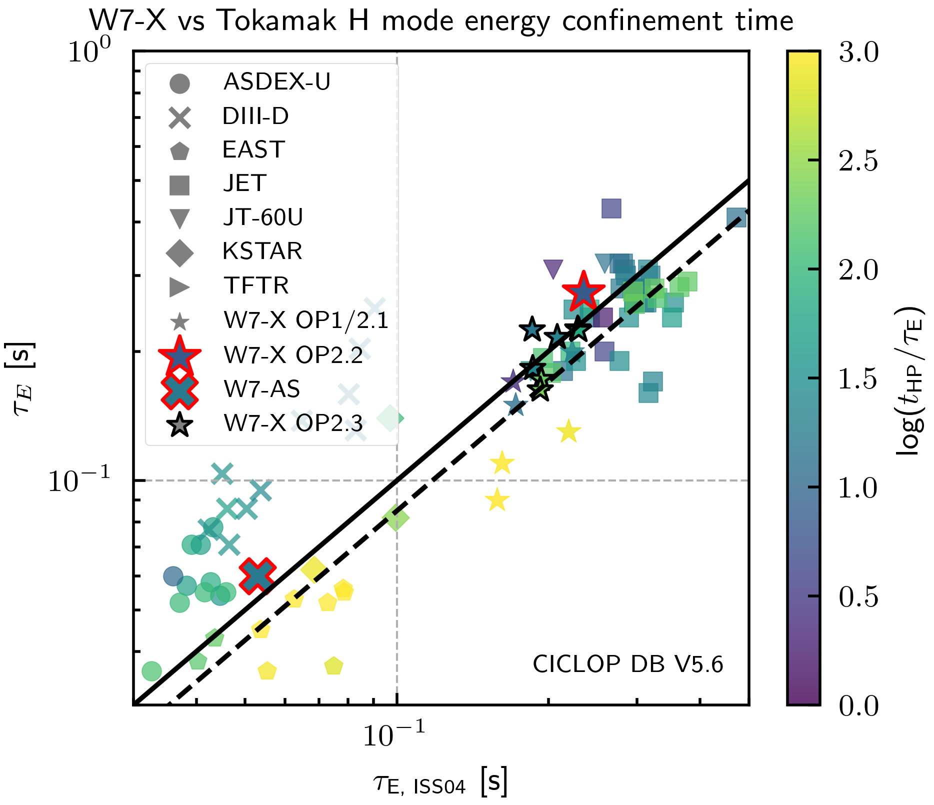


Backup slides

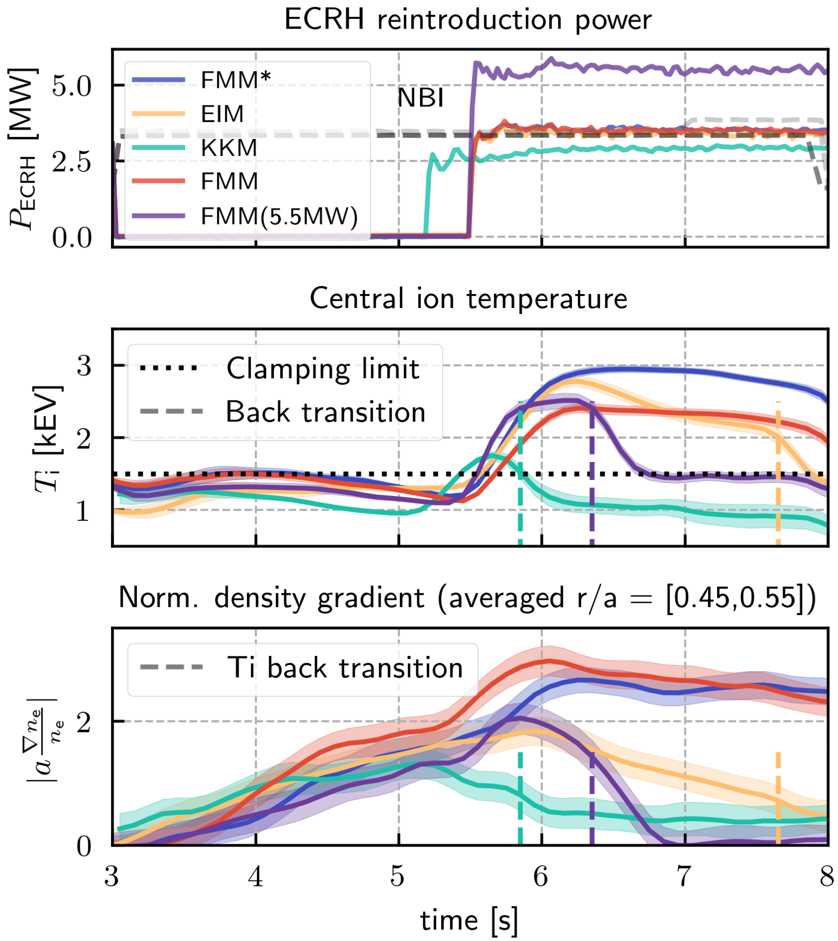
Time evolution of plasma performance in FMM



Energy confinement time scaling: ISS04



Time evolution of plasma profiles in different magnetic configurations



Gyro-Bohm scaling

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

$$\omega = \frac{qB}{2\pi m}$$

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

$$v_\perp = \frac{2}{3}v_{\mathrm{th}}$$

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

Combining with the definition of τ_{E} via the kinetic profiles and heating power

$$\tau_{\mathrm{E}} = \frac{W}{P_{\mathrm{H}}} = \frac{3nkT}{P_{\mathrm{H}}} \tag{8}$$

gyro-Bohm scalings for T and τ_{E} can be written in terms of geometric quantities, density n and heating power P_{H}:

$$T_{\mathrm{gB}} = c_1\kappa^{-0.4}m^{-0.2}\left(\frac{P_{\mathrm{H}}}{n}\right)^{0.4}B^{0.8} \tag{9}$$

$$\tau_{E,gB} = c_2a^3\kappa^{0.6}m^{-0.2}\left(\frac{P_{\mathrm{H}}}{n}\right)^{-0.6}B^{0.8} \tag{10}$$

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

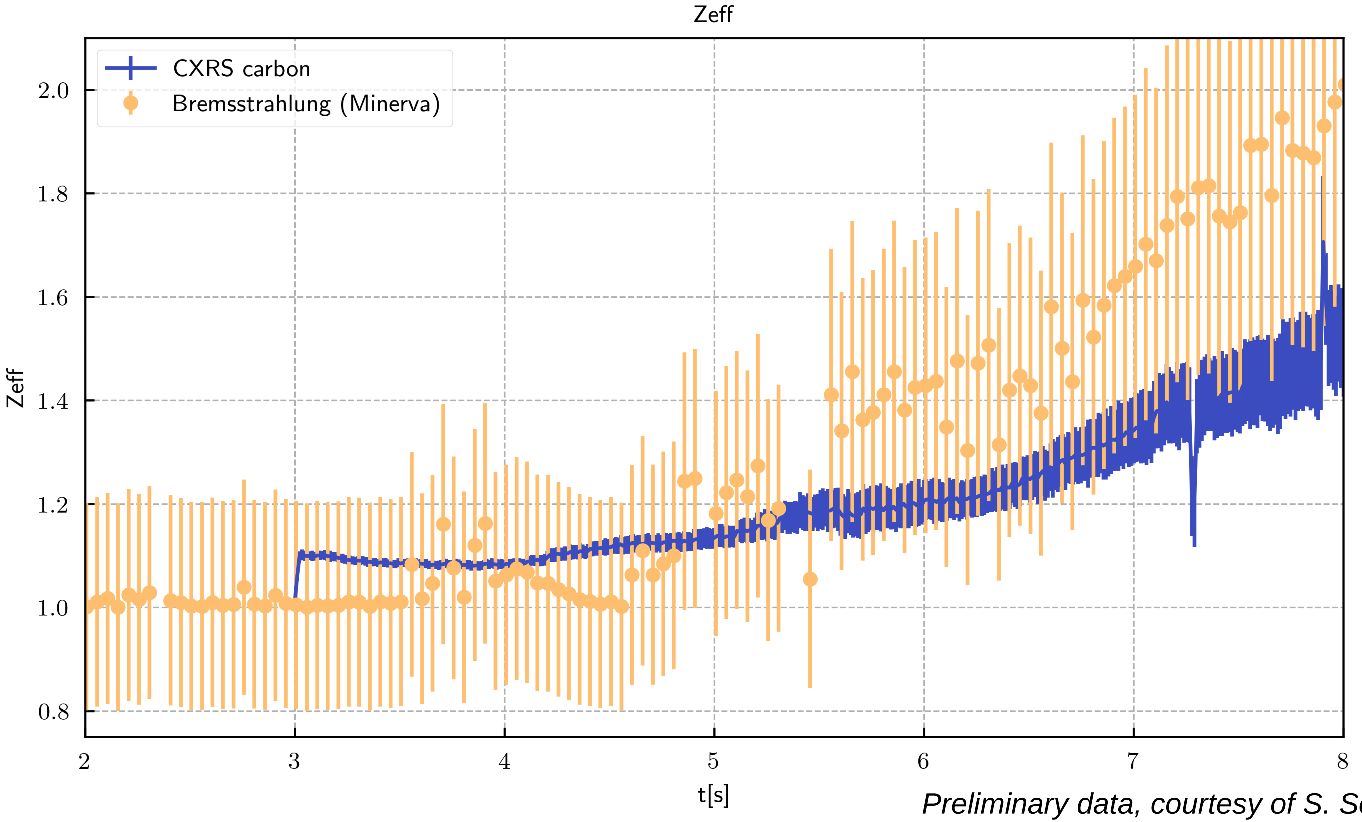
$$F \propto a^3\kappa^{0.2}m^{-0.4}n^{1.2}P_{\mathrm{H}}^{-0.2}B^{1.6} \tag{11}$$

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.

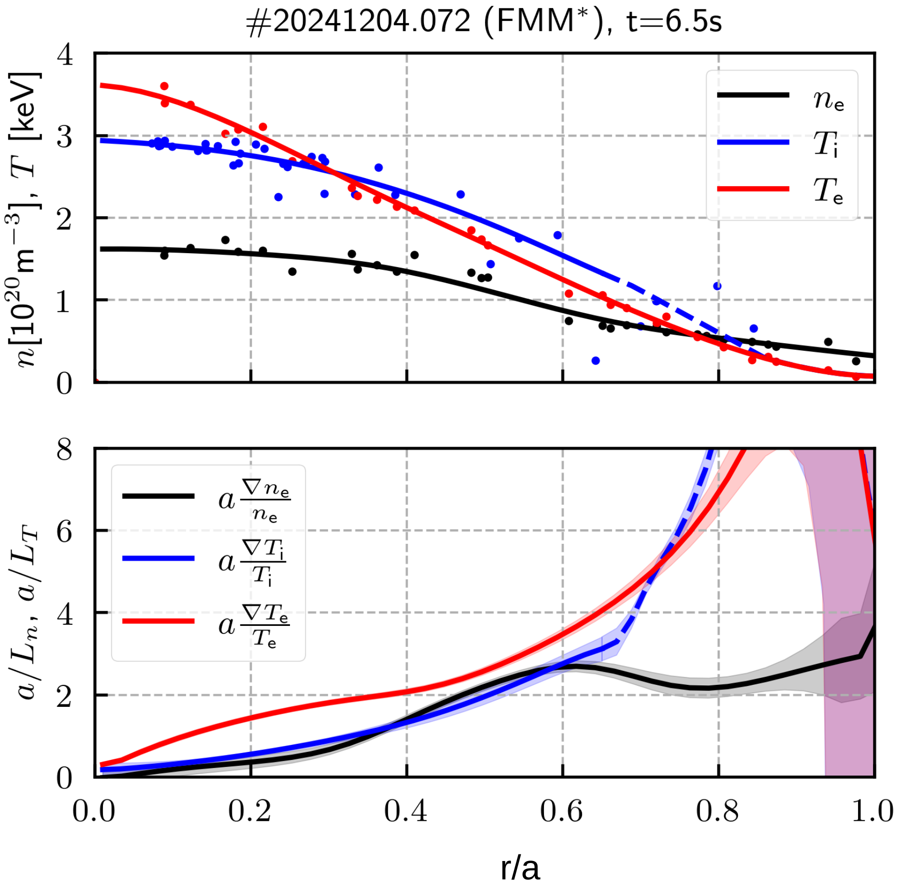
Configuration	$\iota_{2/3}$	$\epsilon_{\text{eff},1/2}$	a [m]	P_{ECRH} steady [MW]	T_i [keV]	W_{dia} [MJ]	τ_E [ms]	Program ID
Low mirror (AIM)	0.97	0.018	0.53	1.5	1.6	0.8	180	20230316.069
High mirror (KKM)	0.97	0.022	0.51	1.5	1.6	0.8	180	20250227.082
Standard (EIM)	0.97	0.0065	0.52	2.0	2.6	1.2	180	20241205.066
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)

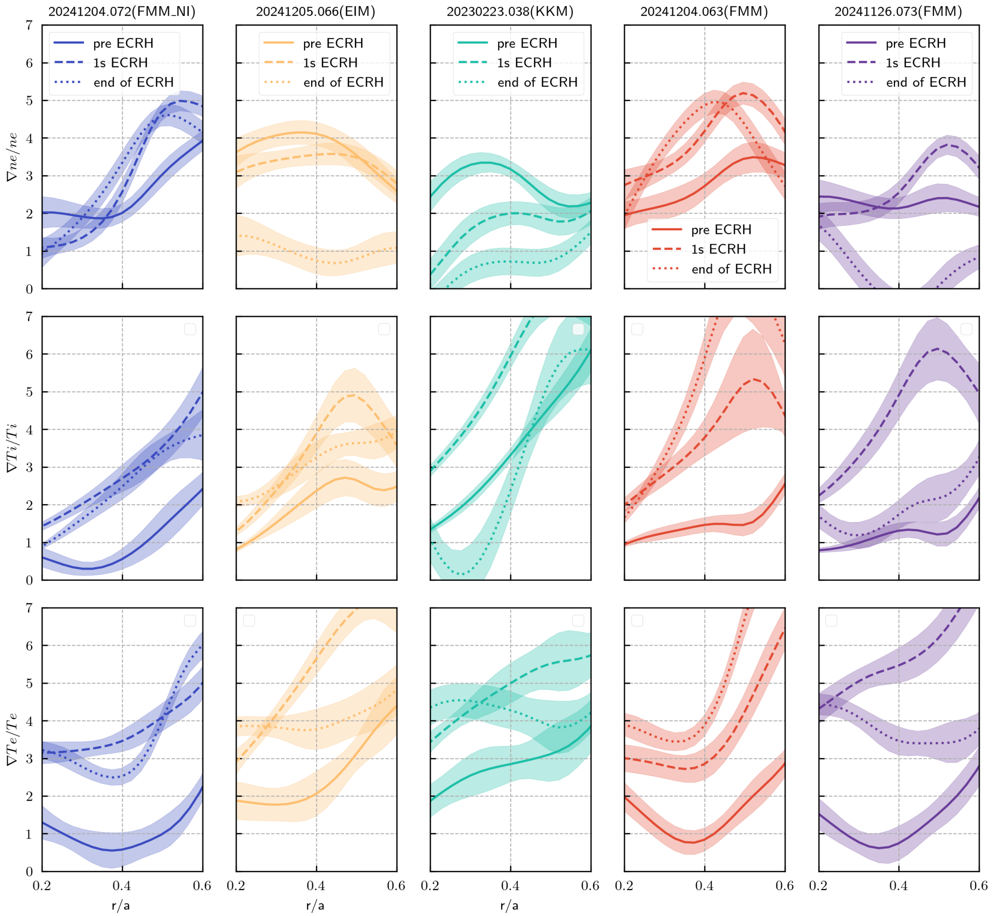


Preliminary data, courtesy of S. Sereda and T. Romba)

Plasma profiles in HP phase



Plasma profiles in different magnetic configurations



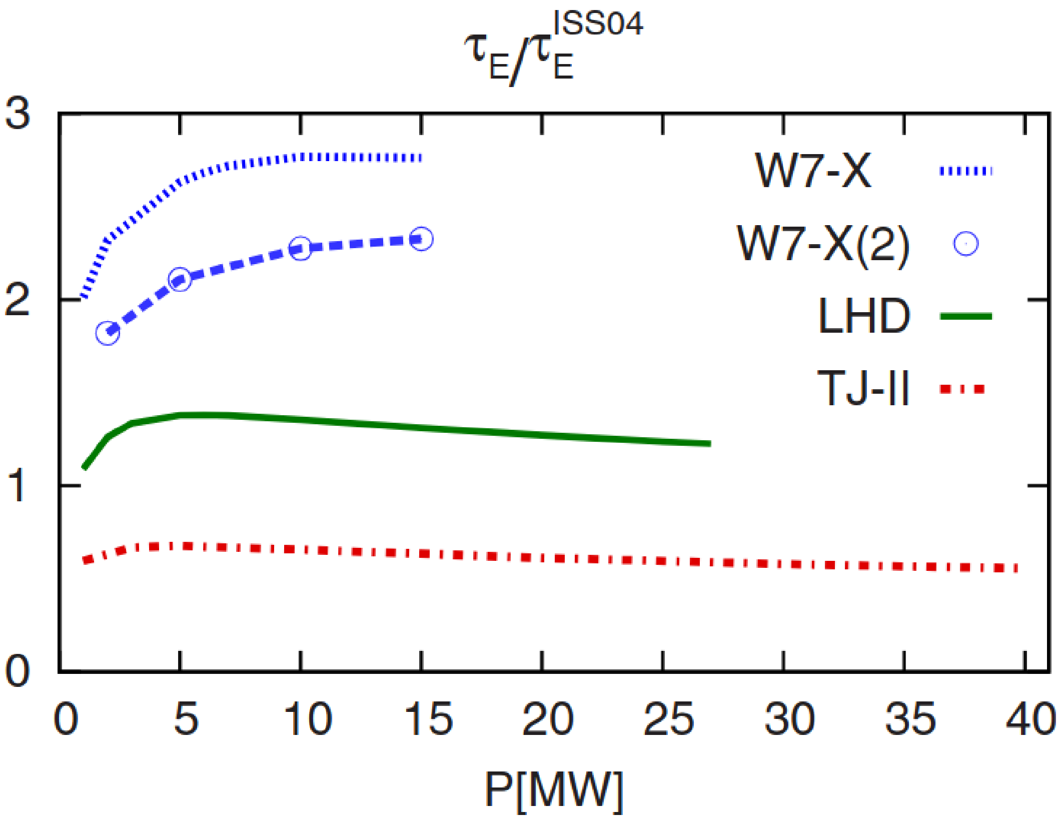
fren record shot

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

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

r/a

Neoclassical limit W7-X



r/a