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INVESTIGATING LONG-DURATION PLASMA OPERATION WITH THE INTERNATIONAL MULTI-MACHINE DATABASE

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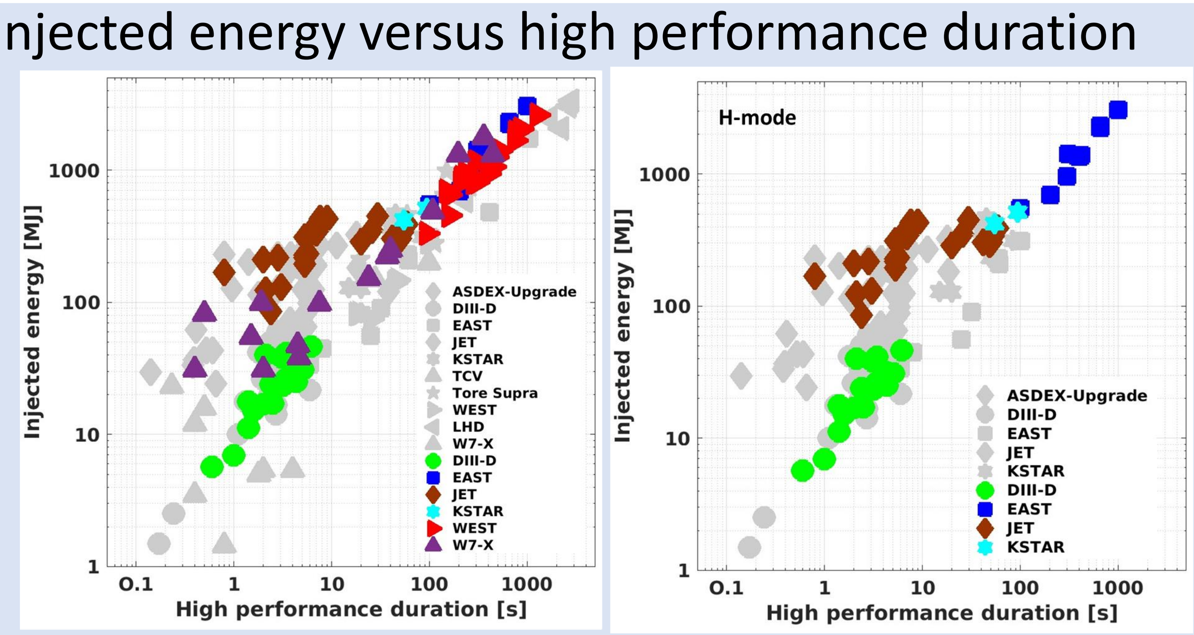
BACKGROUND

- Since the 2023 FEC, significant progress achieved in tokamaks and stellarators, with recent advancements in duration and performance
- Data gathered by the IEA-IAEA **CICLOP** group: **C**oordination on **I**nternational **C**hallenges on **L**ong duration **OP**eration
- The published database*, data up to Jan. 2022, has been updated for the 2025 FEC to incorporate the 2023-2025 experiments (up to May 2025) including recent records performance with new entries provided by DIII-D, EAST, JET, KSTAR, WEST, and W7-X [*Litaudon X. et al 2024 Nucl. Fusion 64 015001]
- Additional variables:
  - stored energy, H-factors, radiated power, T_{eo} & N_{eo}, pedestal densities and temperatures for electron and ion
  - information on operational limits: machine/engineering or physics
  - Updated database now comprises a total of 238 pulses (vs 109) with a up to 54 entries per pulse (vs. 29)

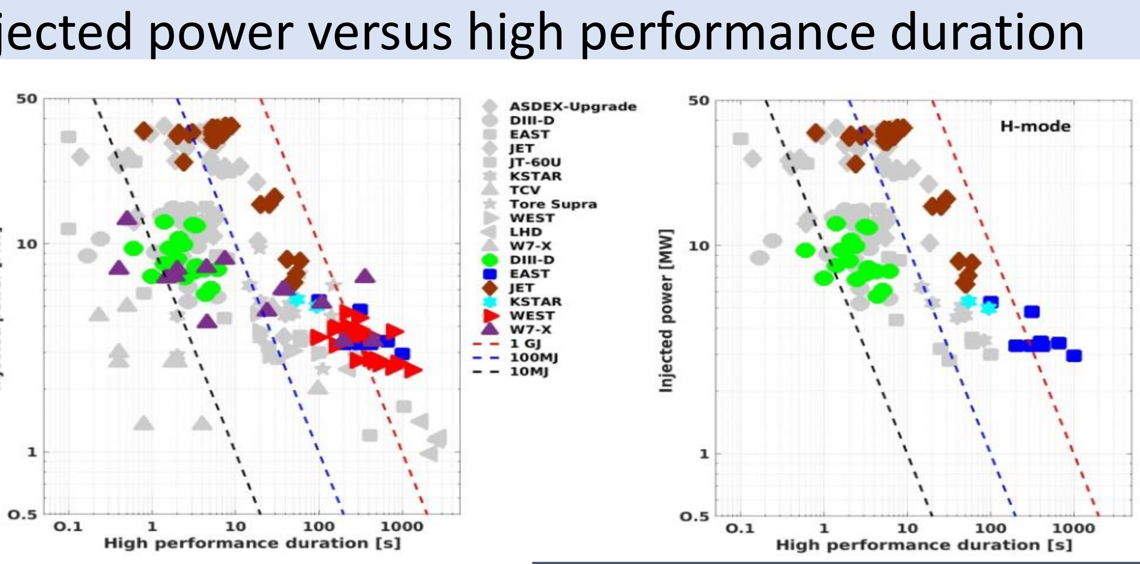
RECENT EXPANSION OF THE OPERATIONAL DOMAIN FOR LONG PULSE OPERATION (LPO)

- EAST (2025) achieved repeatable LPO with an H mode edge (up 1066 s) in fully non-inductive conditions utilizing a water-cooled tungsten lower divertor [Gong X. et al. this conference] [Huang J. et al. Second IAEA Technical Meeting on Long-Pulse Operation of Fusion Devices, 14-18 Oct. 2024, https://conferences.iaea.org/event/381/]
- WEST (2025) demonstrated LPO (up to 1337 s) with a full ITER-grade tungsten divertor, reaching up to 2.6 GJ of injected energy in fully non-inductive conditions [Bucalossi J. et al. 2025 this conference] [Dumont R. et al. this conference]
- KSTAR (2024) achieved a 102 s high-performance LPO using its newly installed W-shaped tungsten divertor [Kim H.-S et al 2025 this conference]
- W7-X (2025) [Grulke O. et al 2025 this conference]
  - achieved 480 s of operation with 1.3 GJ and up to 1.8 GJ for 360 s, using its actively water-cooled C-divertor
  - sustained high-performance discharges with a record $nT\tau_E$ = 0.077 atm·s for up to 24 s and 0.06 atm s up to 40s, enabled by quasi-steady-state fueling from its new CW pellet injector
- JET (2023) [Lerche E. et al. 2025 Plasma Phys. Control. Fusion 67 095022] [King D B et al 2025 Plasma Phys. Control. Fusion 67 085011]
  - set its own record for injected energy in ELMy H-mode (up to 450MJ, up to 60s) with the inertially cooled tungsten divertor
  - maintained balanced core ion and electron temperatures with an H-mode for up 60s achieving $nT\tau_E$ = 0.055–0.06 atm·s

Injected energy versus high performance duration



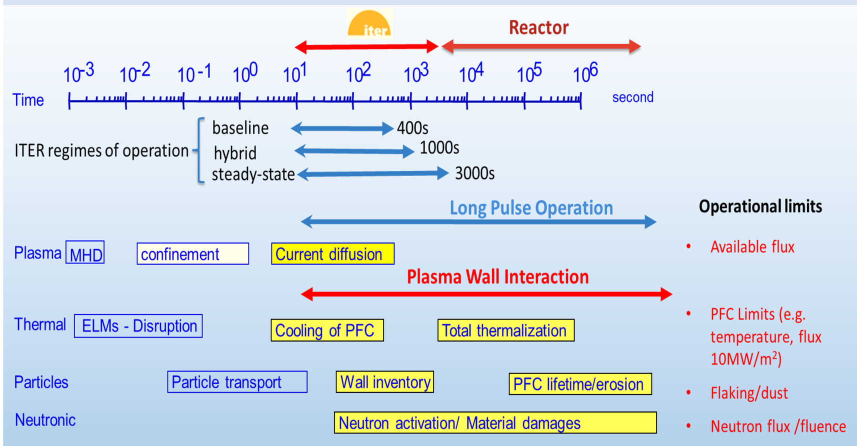
Injected power versus high performance duration

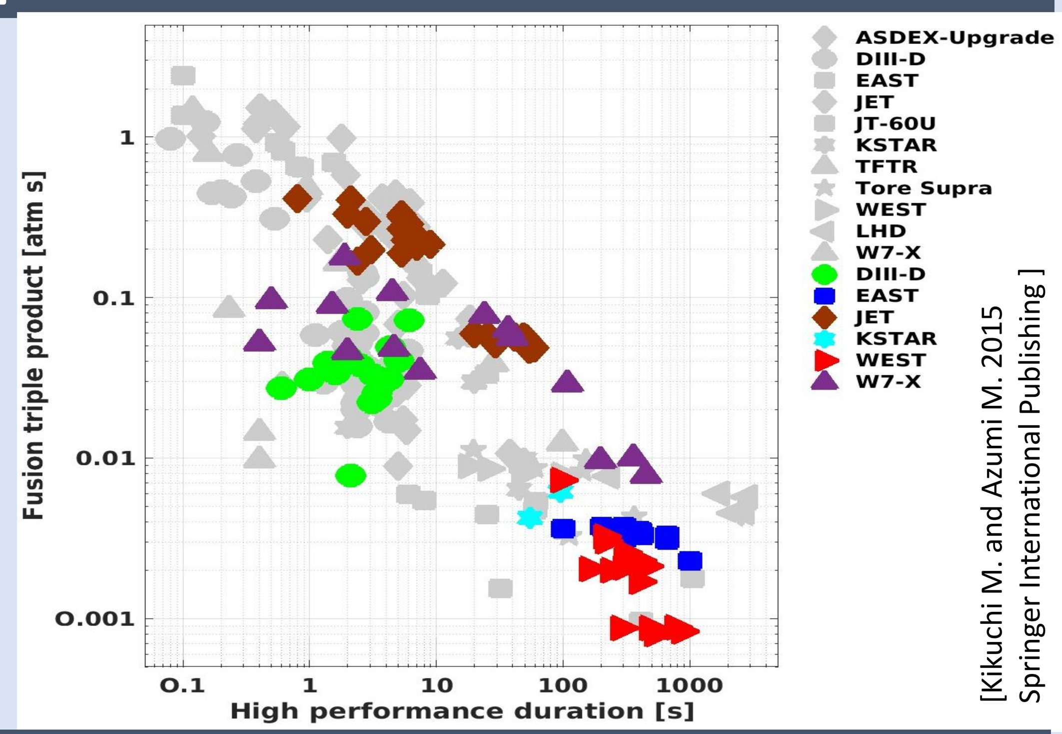


experiments performed before the 2023 IAEA FEC have symbols in grey

Fusion triple product [atm s] versus duration

Characteristic timescales and associated operational limits

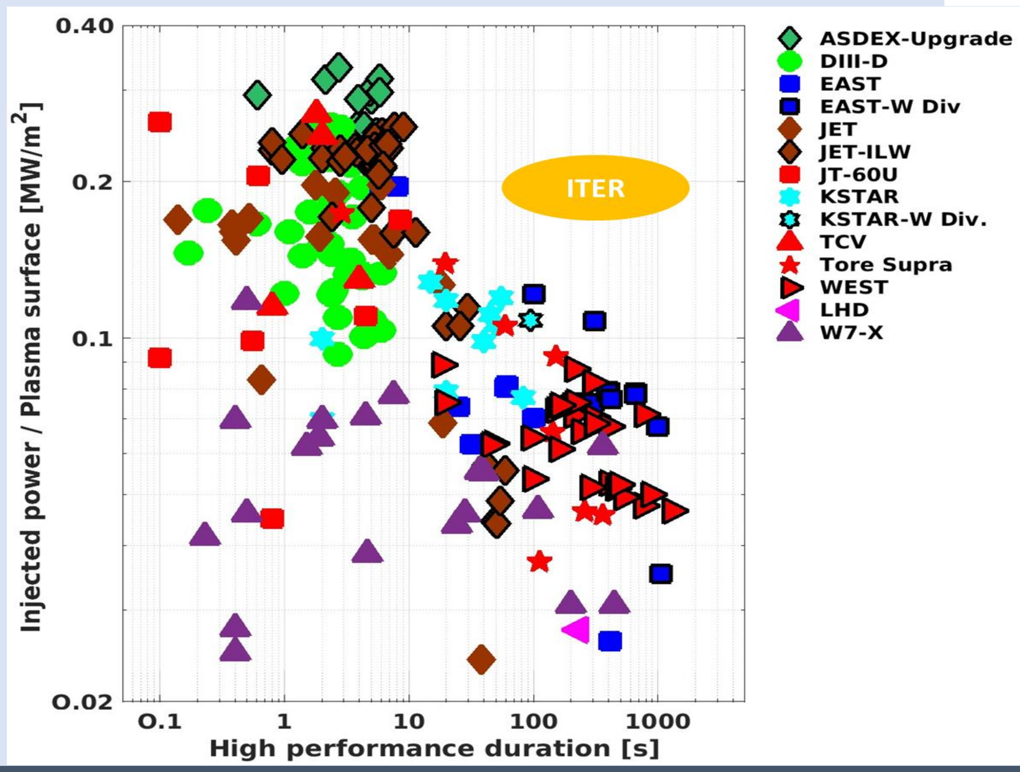


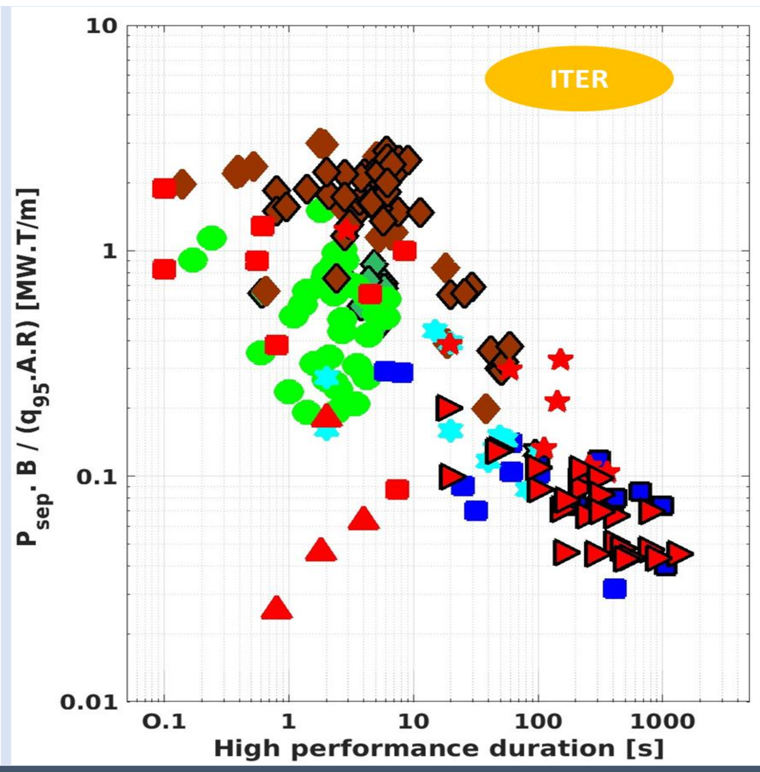


[Kikuchi M. and Azumi M. 2015 Springer International Publishing]

Long-Pulse Operation: heat exhaust capability

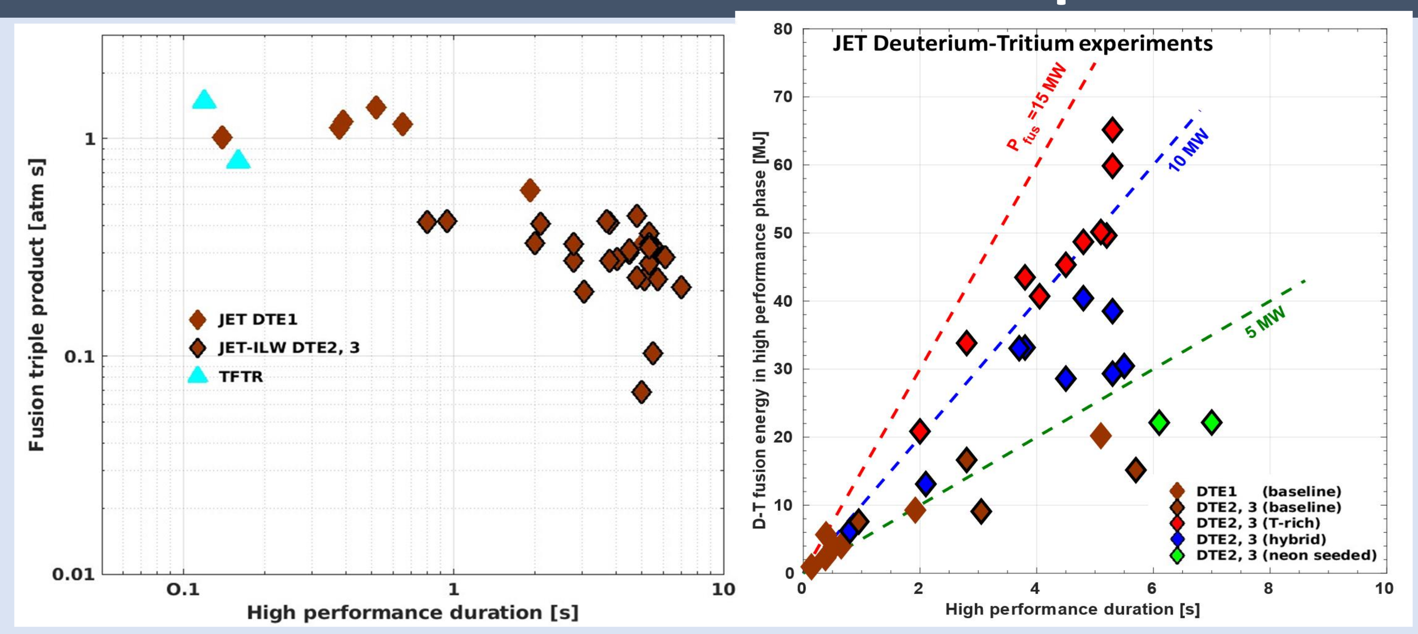
- P/S : heating power, P, normalized to the plasma surface, S
- $P_{sep}B_{tor}/(q_{95}AR)$ figure of merit of divertor heat exhaust based on scaling of the power decay length with the poloidal gyroradius





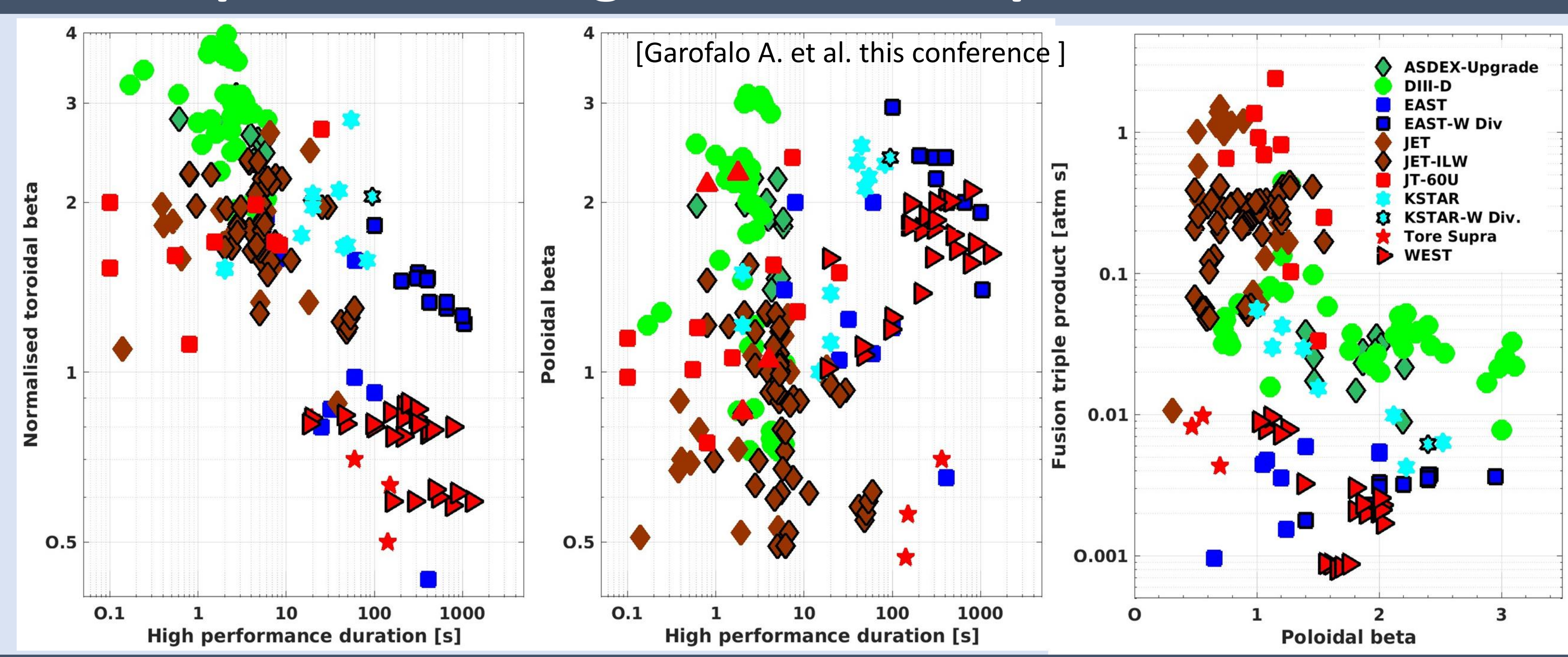
[Zohm H. et al. 2017 Nucl. Fusion 57 086002]

Extension of duration in deuterium-tritium operation



[Kappatou A. et al 2025 Plasma Phys. Control. Fusion 67 045039] [Giroud et al 2025 this conference]

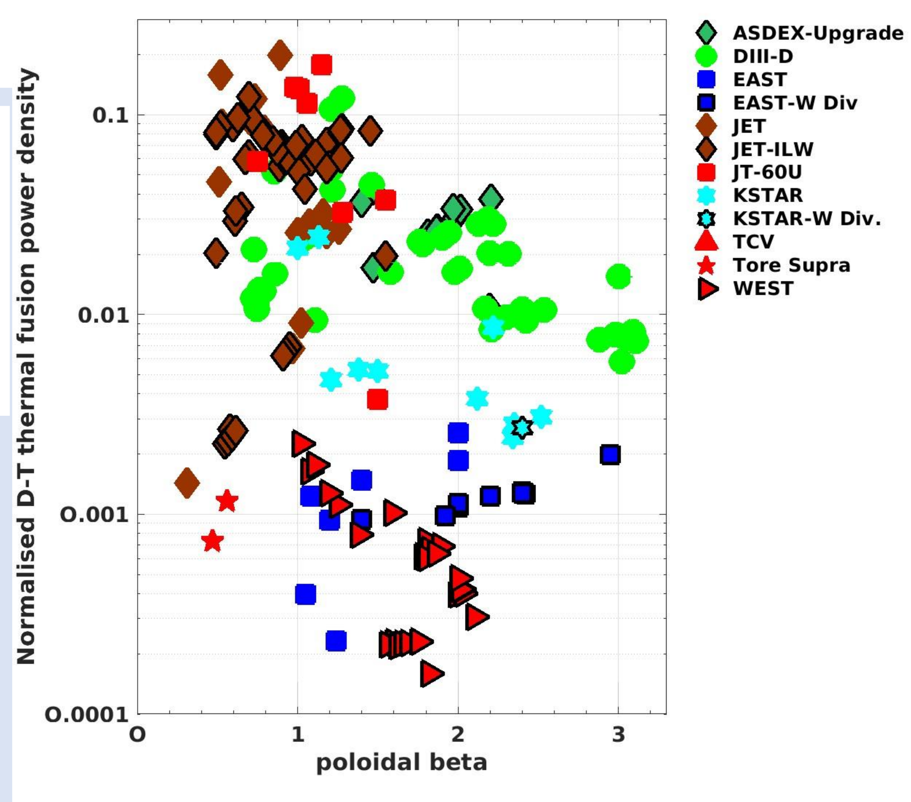
Long-Pulse Operation at high-normalized pressure



Multi-Machine Database projection

- Thermal fusion power density (normalized to ITER values) calculated following the method described in [Sarazin Y. et al 2020 Nucl. Fusion 60 016010]

$$\widehat{P}_{\text{fus}} = \frac{C_{\text{fus}} C_I^2}{C_\beta^2} \frac{\kappa \varepsilon^4}{q^2} \beta_N^2 R^3 B^4.$$



Prospects:

[Turco F. et al 2023 Nucl. Fusion 63 036020]

- Long-pulse performance projections for ITER will be estimated using a dimensionless analysis based on ρ* scaling of the CICLOP database

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