Long plasma duration operation analyses with an international multi-machines database

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Coordination on International (IEA-IAEA) Challenges on Long duration Operation

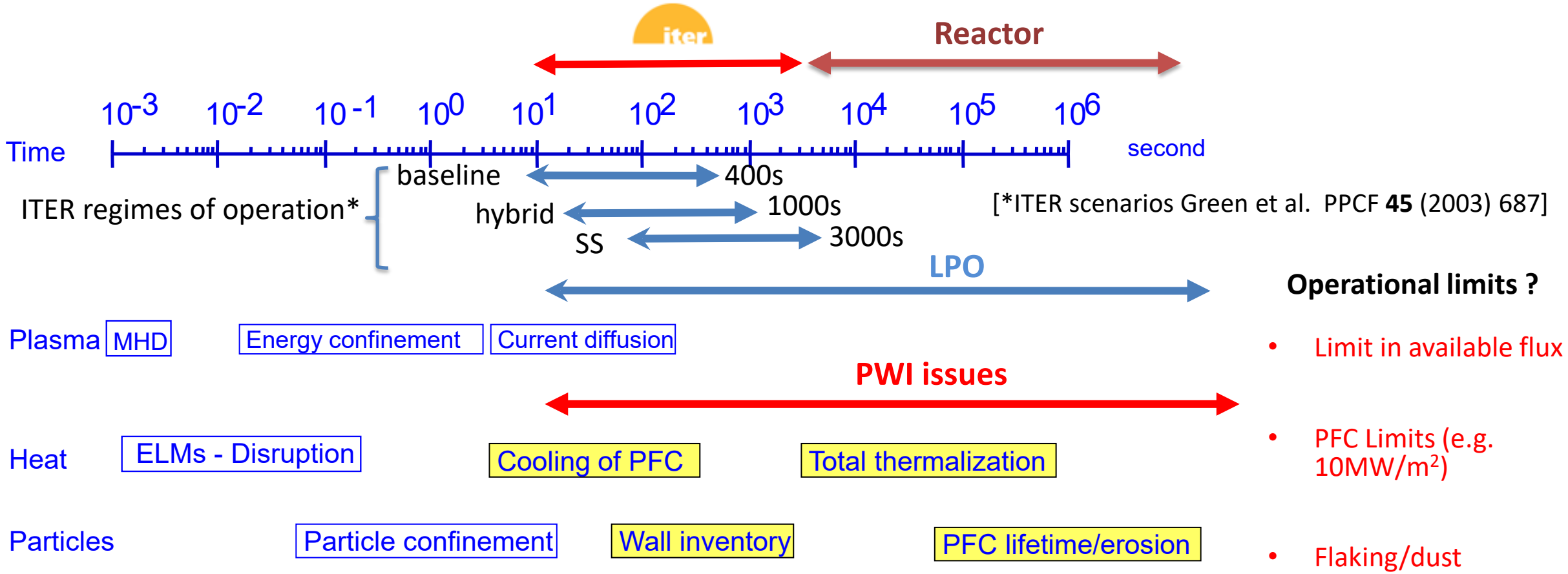
- **Key integration challenge for fusion energy development in magnetic devices: to combine high fusion performance with Long Pulse Operation (LPO)**
- **IEA and IAEA have set-up an international group[1]**
  - to share experience and best practice on **LPO and steady-state**
  - to promote activities, collect and disseminate information on LPO issues
  - to address physics and engineering LPO issues for tokamak and stellarator
- **Terms of reference approved at IEA Fusion Power Co-ordinating Committee on Jan. 2020**
- **Set-up a high level multi-machines database expanding the pioneering work of M. Kikuchi[2]**
- **10 tokamaks: ASDEX Upgrade, DIII-D, EAST, JET, JT60-U, KSTAR, TCV, TFTR, Tore Supra, WEST**
  2 stellarators: LHD and W7-X
  - 109 pulses and around 3200 entries with data obtained up to Dec. 2021
  - Time window averaged quantities

[1https://nucleus.iaea.org/sites/fusionportal/ciclop/SitePages/Home.aspx]

[2*Frontiers in Fusion Research, Springer*]

Long Pulse Operation (LPO) ?

- **LPO is adressing control of stable plasma for duration well above the plasma confinement time and approaching plasma wall integration time scales**
  - ITER 400s H-mode regime belongs to the LPO category



[Joffrin, IAEA Technical meeting on steady state Operation, Japan 2015]

Operational limits for the high fusion performance and long pulse duration

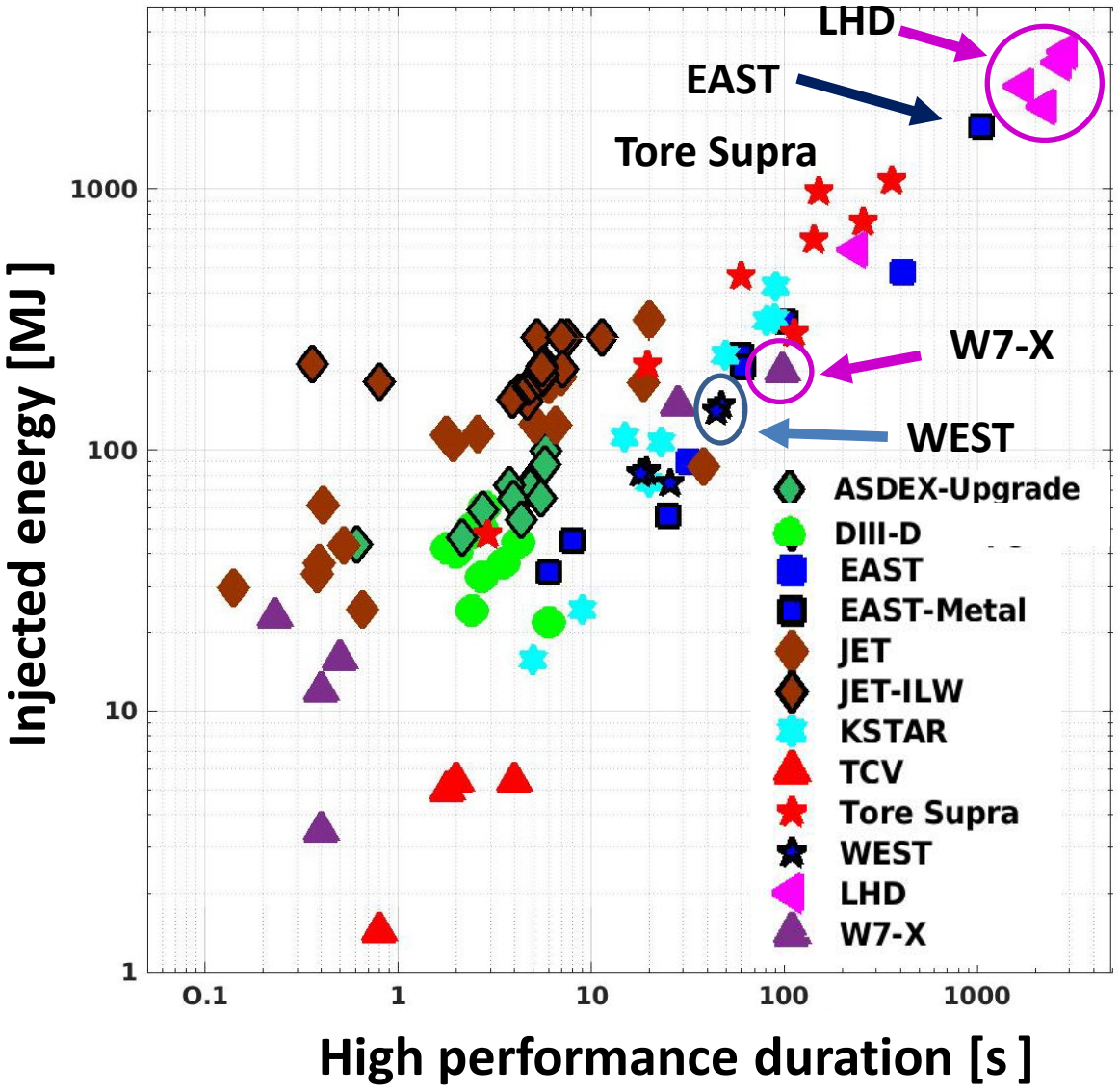
Machine / Wall limits

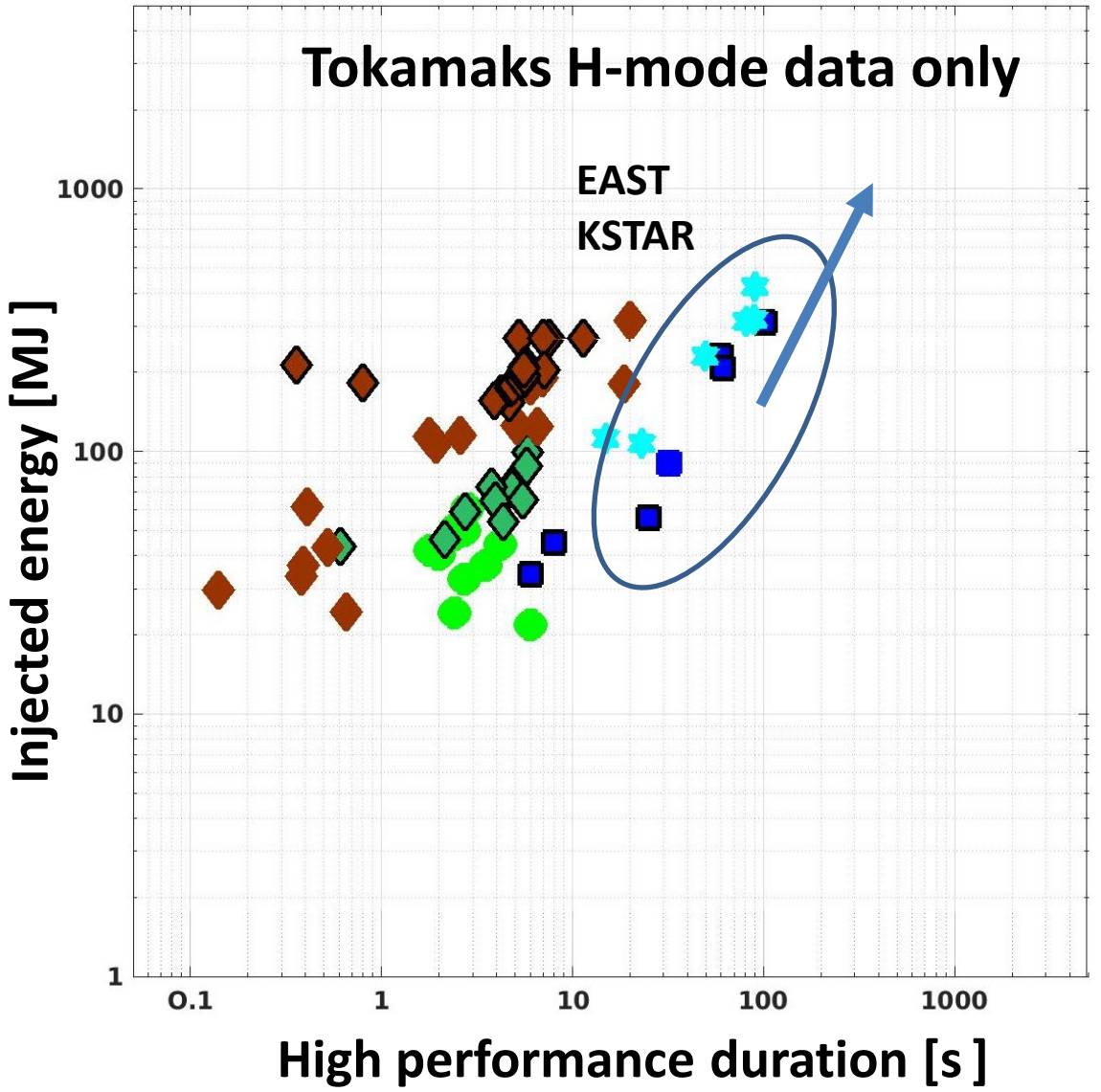
- **Limit in available flux**
- **Limit in energy (I^2t limit) or forces for the coils**
- **Limit in injected power and/or Energy**
  - Max Energy limit that can be exhausted by the cooling system is reached
  - Max. power reached
  - Max duration of injected power reached
- **Limit in power/energy/ temperature for PFC**
  - Limit on wall or divertor temperature is reached
  - Limit on heating systems
- **Limit in wall/divertor erosion**
  - Flakes or dusts production (that can detached and lead to disruptions)
  - Erosion and migration
- **Limits in measurements in control system**
  - Current plasma measurement drift
  - Neutron limits, Gas limits

Plasma physics limits

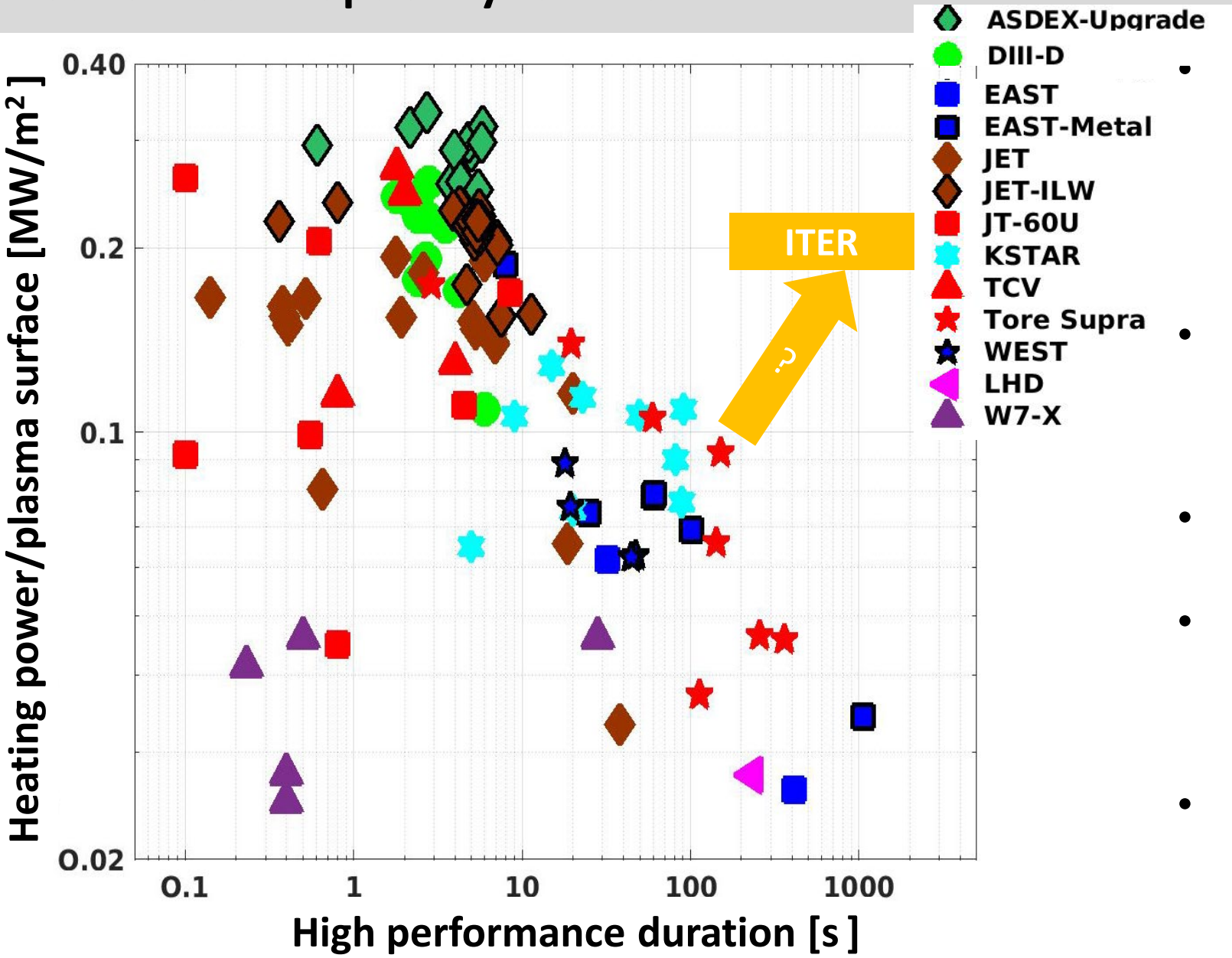
- **Limit in MHD stability (current and pressure)**
  - Pressure/Beta limits
  - Current instabilities
  - Disruption force
- **Limit in core/pedestal confinement**
  - Core instabilities
  - Limits in pedestal pressure
- **Limit in plasma radiations**
  - Core impurity accumulations (e.g. W in the core)
  - UFO resulting from erosion leading to radiative collapses
- **Limit in density**
  - Uncontrolled density evolution (wall recycling evolution)
  - Stability limit approaching density limits

LPO in L & H modes: injected energy vs high performance duration





Heat exhaust capability for LPO ?

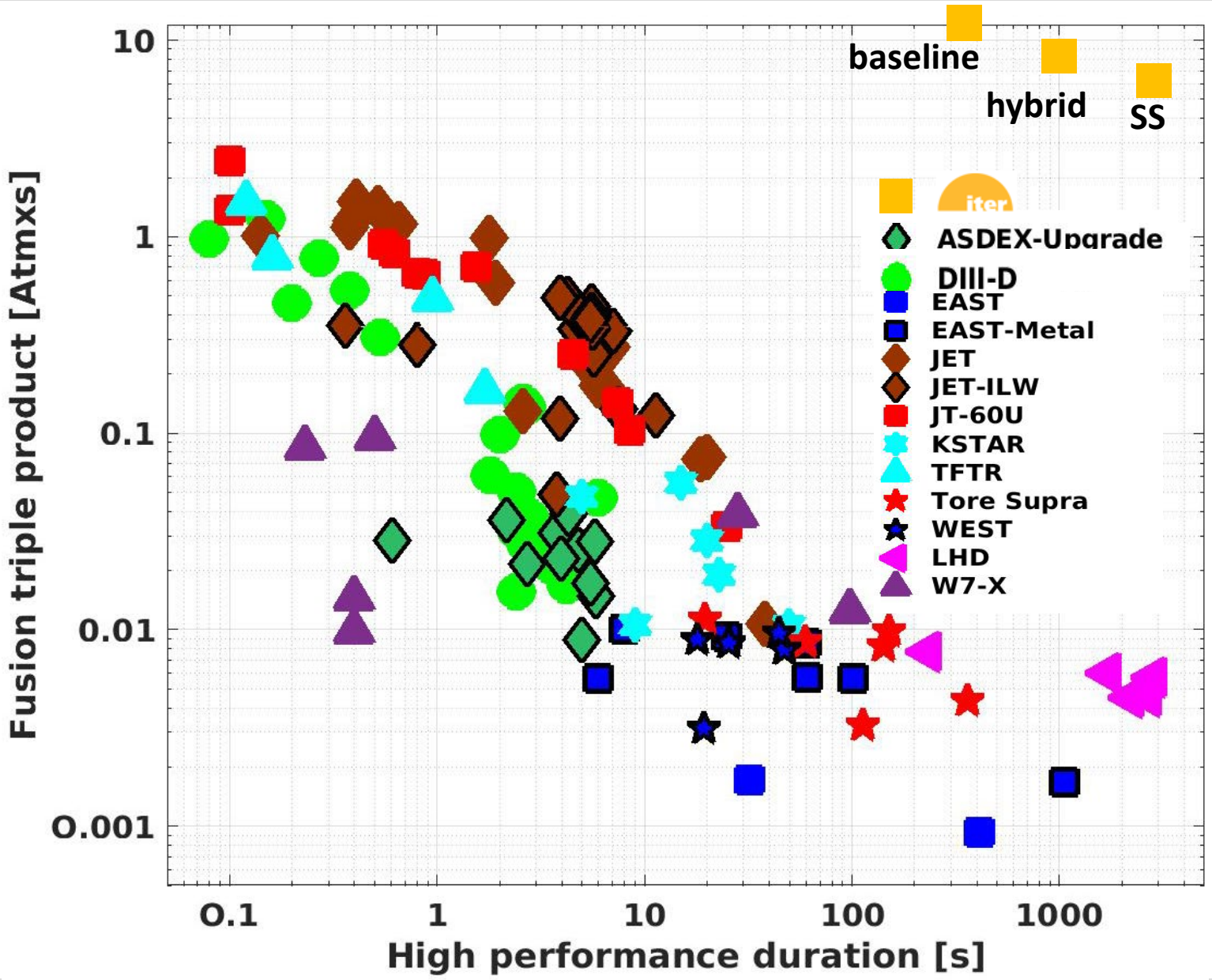


- **Plasma heating power normalised to the plasma surface as a proxy for heat exhaust capability**
- **Highest values on ASDEX-Upgrade**
  - P/S ~ 0.3MW/m^2 up to machine limits
- **LPO >10s with P/S <0.1MW/m^2**
- **ITER target**
  - $(P_{inj}+P_{\alpha})/S$ ~0.2MW/m^2 for 400s to 3000s
- **WEST with ITER Plasma Facing Units will develop 1000s LPO approaching ITER target**

Present limits and status of Long Pulses Operation

- **LPO > 100s achieved at reduced power below ~5MW and P/S below 0.1MW/m^2**
- **Injected Energy record on LHD with 3.3GJ**
  - Limit: C flakes and radiative collapses with C walls
- **EAST reached 1.7GJ/1056s (Dec. 2021) with metalic walls**
  - Limit: hot-spots in the RF/LHCD systems. Ongoing optimisation
- **W7-X reached up to 100s with 2MW/ECRH**
  - Limit: no active cooled divertor
  - Actived cooled divertor installed in 2021 and operation starts in 2022
- **WEST reached 49s/3MW**
  - Limit: absence of active cooling of the lower divertor configuration
  - Fully actively cooled divertor with ITER Plasma Facing Unit installed in 2021 and operation starts in 2022
- **EAST and KSTAR sustained H-mode operation**
  - Limits:
    - available transformer flux when not fully inductive
    - ELMs and slow evolution of edge conditions could lead to degradation
    - coupled power

Core ion pressure [Atm] x confinement time [s] vs high performance duration



- **Reduction of fusion performance by 2 orders of magnitude when increasing duration from ~1s to 100s**
- **Significant progress with metallic wall operation in support to ITER & DEMO**
  - ASDEX-Upgrade, EAST, JET, WEST
  - JET with sustained DT fusion power ~10MW/5s - 59MJ

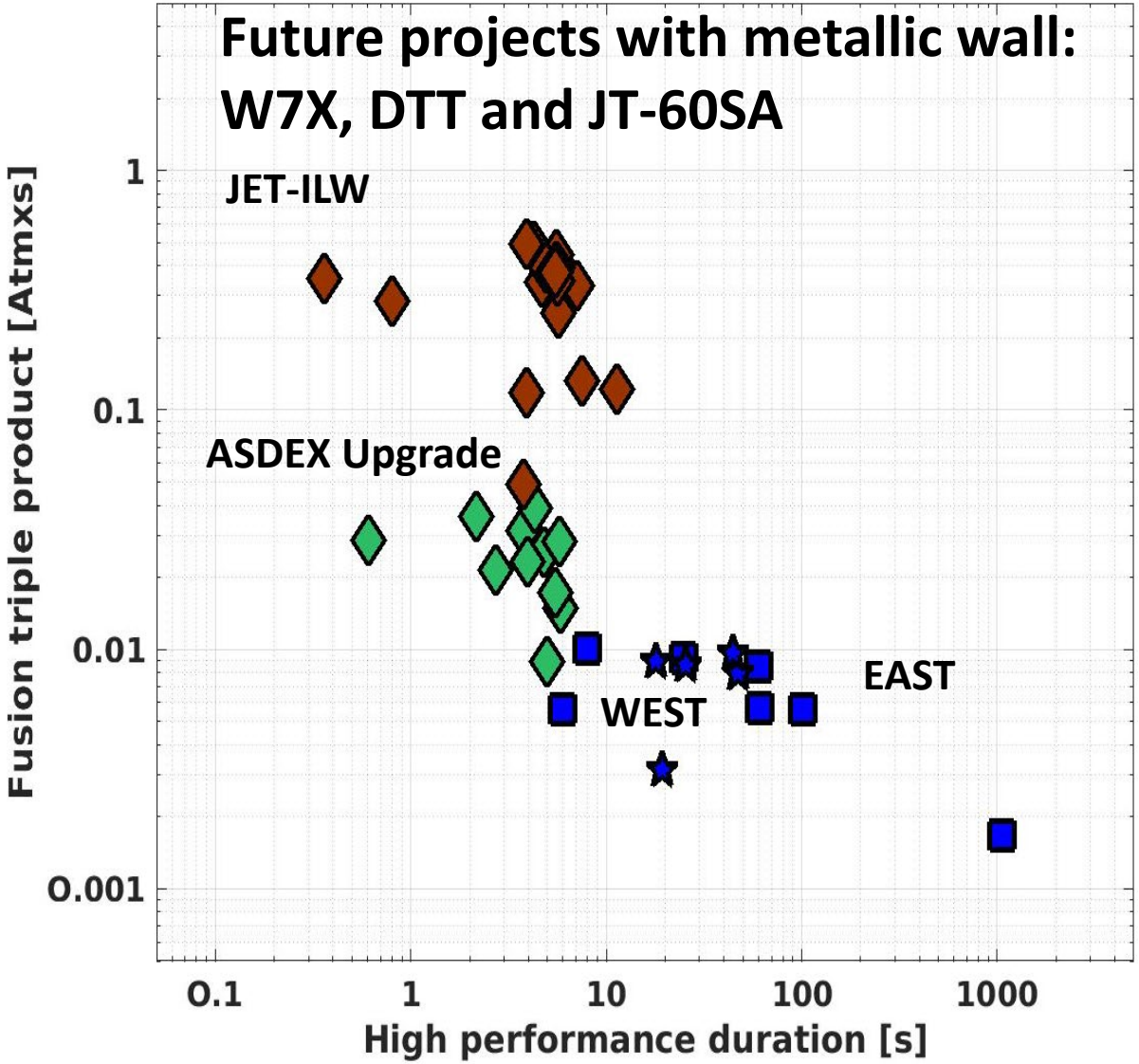
  [Tonné, Villari, Milnes SOFT 2022]

  [Mailloux, Giroud EPS 2022]

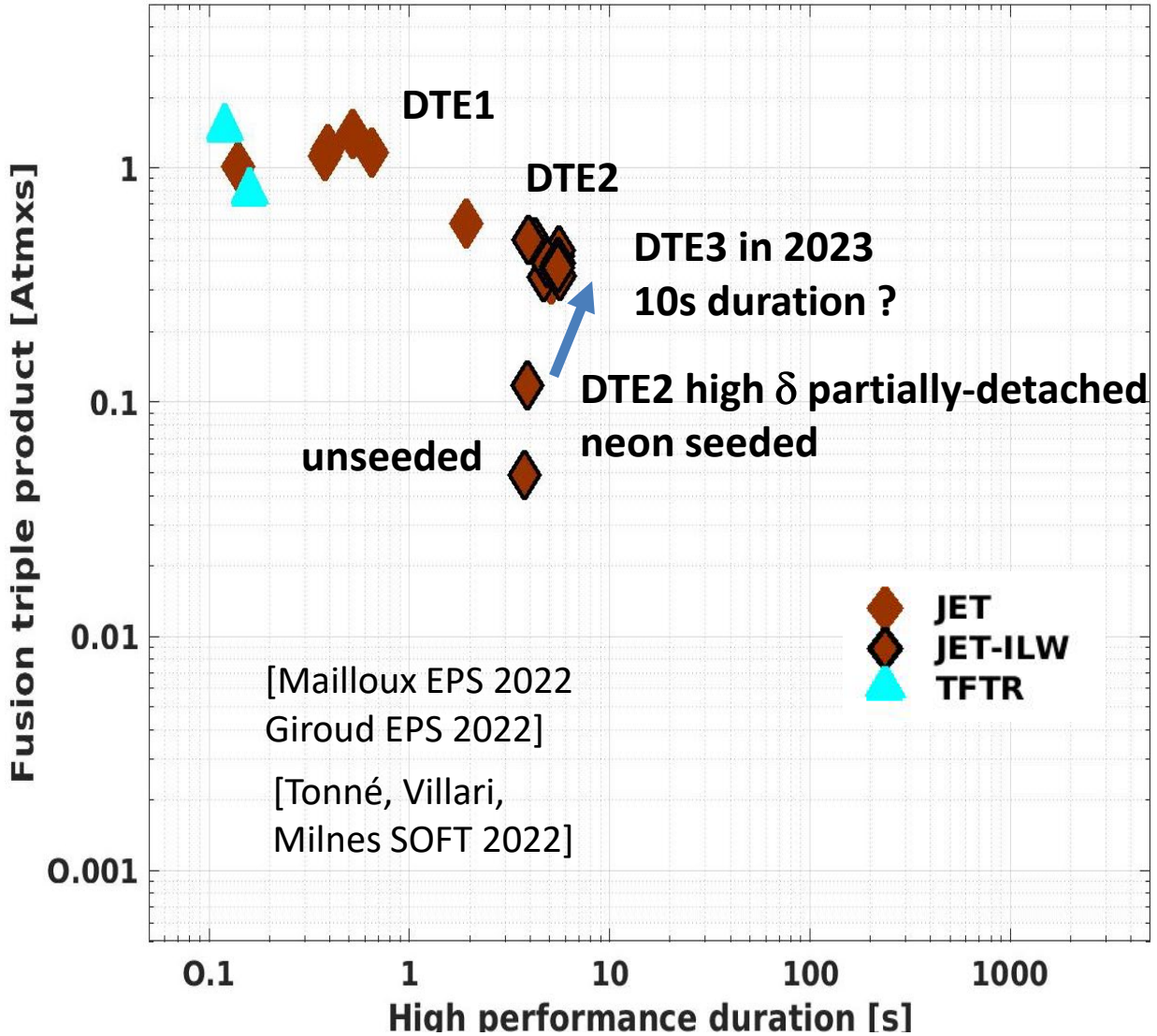
[ITER scenarios Green et al. PPCF **45** (2003) 687]

Fusion performance vs duration: metallic wall and Deuterium-Tritium plasmas

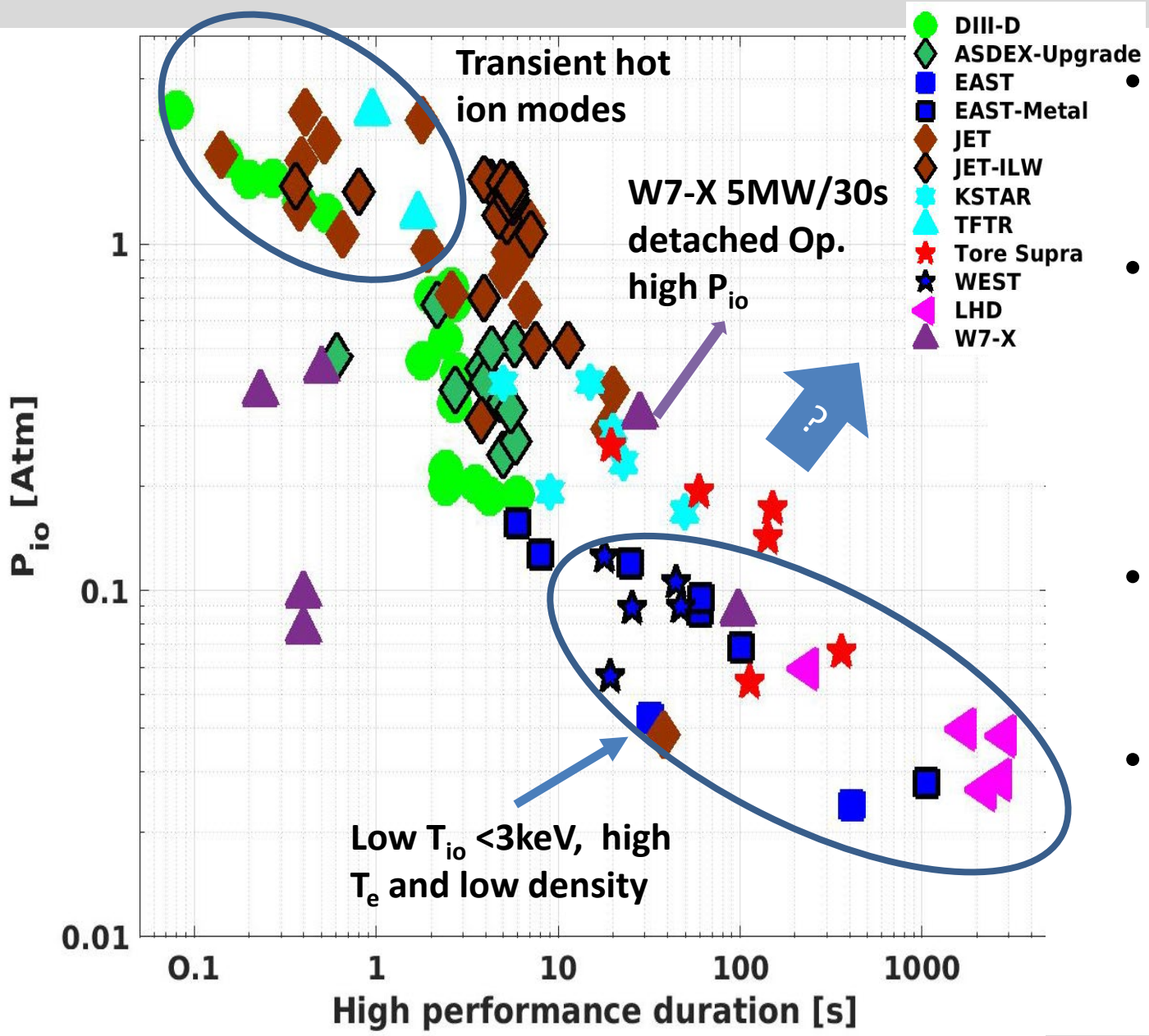
metallic wall devices



Deuterium-Tritium



Optimise core ion pressure in LPO ?



- **Pressure ↑ in tokamaks & stellerators?**
  - ion heating ↑ + density profile optimization ?

  [Beurskens NF **61** (2021) 116072 & NF 2022]
- **LPO in tokamaks achieved in a domain of dominant electron-heating at reduced density for Current Drive (CD) but low T_{io} (<3keV)** [Song 2022, Bucalossi 2022]
- **KSTAR optimisation of T_{io} ~10keV/20-30s at low loop voltage but reduced density**

  [Han Nature 2022, Wang SOFT 2022]
- **LPO in stellarators achievable at higher density since magnetic configurations intrinsically stable without non-inductive CD** [Jakubowski NF **61** (2021) 106003]

Conclusion: significant worldwide effort to prepare ITER LPO operation

- **Significant progress and upgrades for extending the duration and performance, e.g.**
  - EAST world record in pulse duration for tokamaks following upgrades
  - EAST and KSTAR long pulses H mode regime
  - JET has sustained D-D and D-T operation for 5s with ITER like wall [Donné SOFT 2022, Milnes SOFT 2022, Mailloux EPS 2022]
  - WEST installed actively cooled divertor (2021) with ITER Plasma Facing Units, operation in 2022 [Bucalossi Nuc. Fusion 2022]
  - LHD D-D operation and advanced control algorithms to avoid radiative collapses
  - W7X installed actively cooled divertor (2021), operation in 2022 [Bosch SOFT 2022]
- **LPO**
  - Tokamaks: dominant electron heating at reduced density, low P_i. Need to increase density, maximize P_i and address non-inductive current challenge at higher densities
  - Stellarators: higher density & P_i since external non-inductive CD not required
  - For all: increase power& energy but evolving wall interaction could lead to discharges crossing unstable domain
- **Higher performance/duration expected with actively cooled metallic wall in near future**
- **Full W Divertor Test Tokamak project has been initiated in EU**

ON BEHALF OF THE CICLOP TEAM and JET contributors (for the JET DT data)

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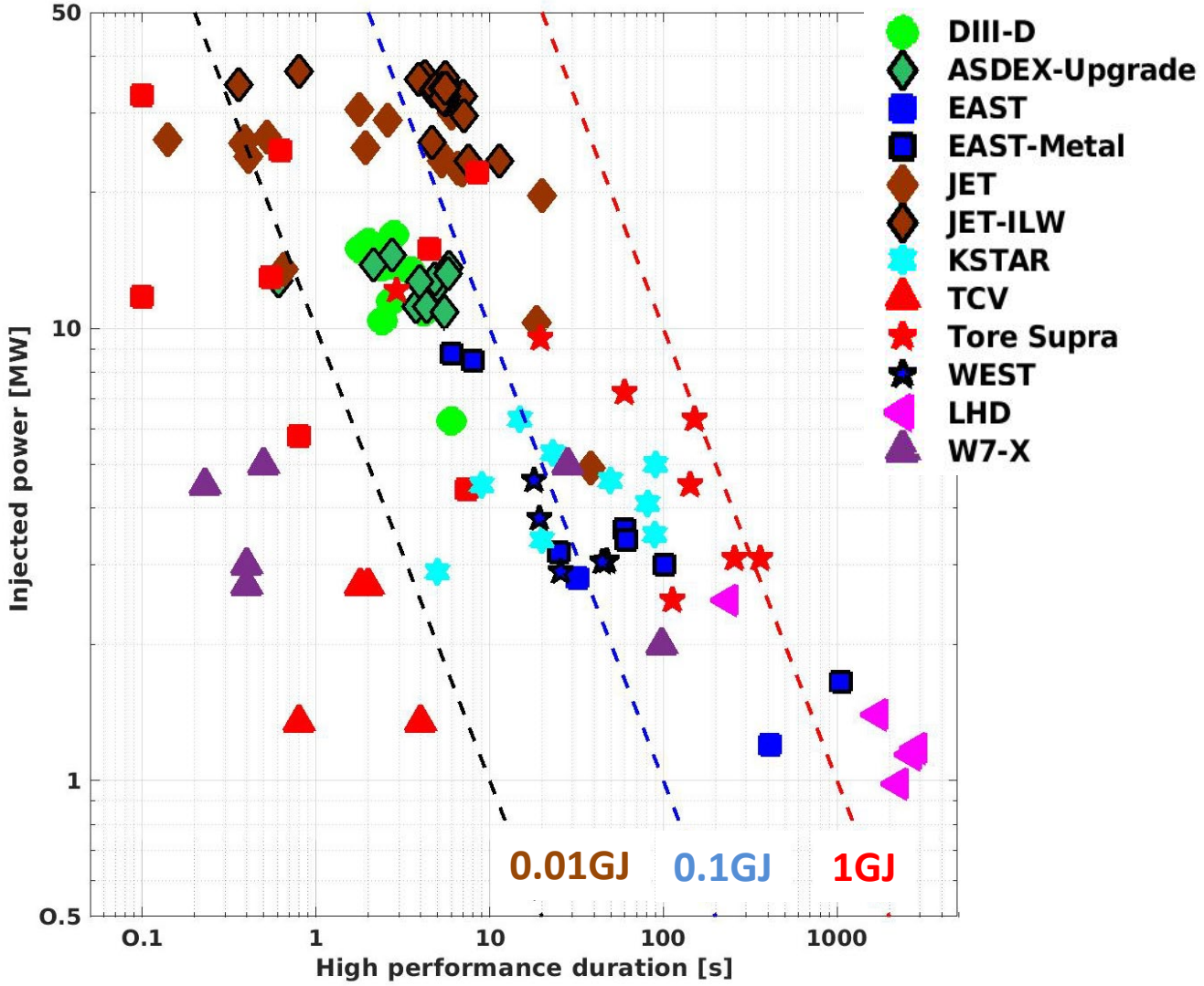
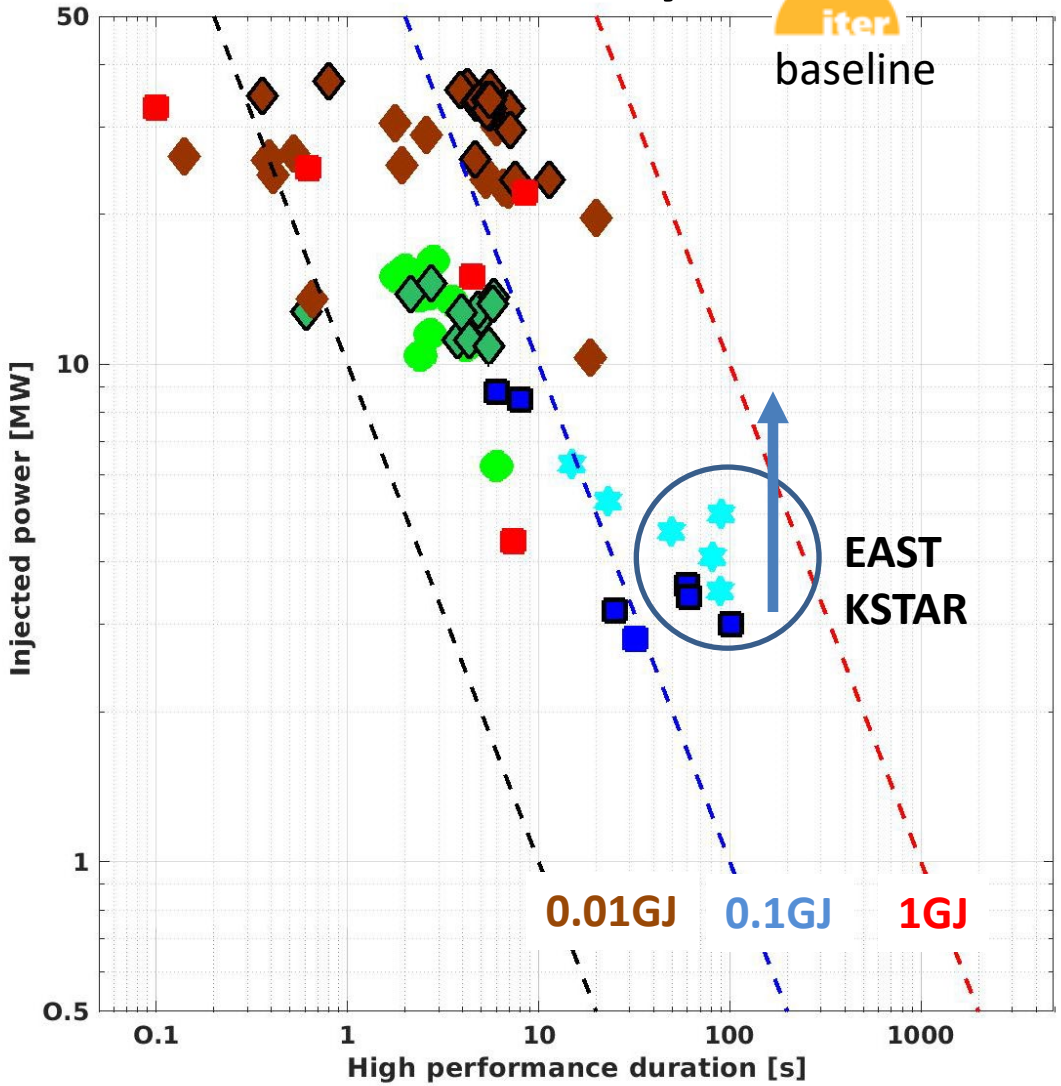
Back-up

Long Pulses Operation in L & H modes: Injected power vs high performance duration

hybrid SS



H-mode data only



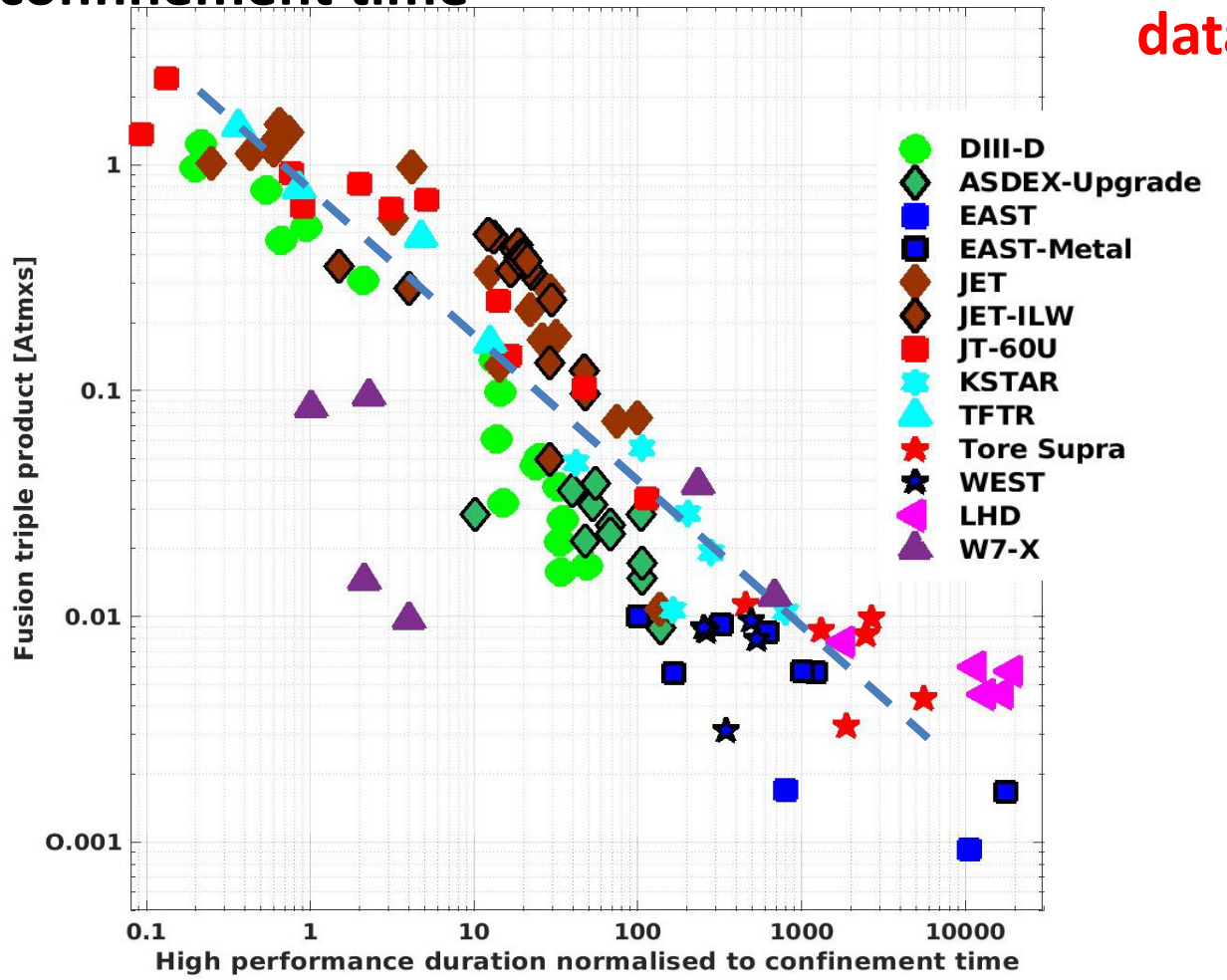
Fusion performance vs duration normalised to confinement or current diffusion time

triple product vs duration normalised to confinement time

baseline

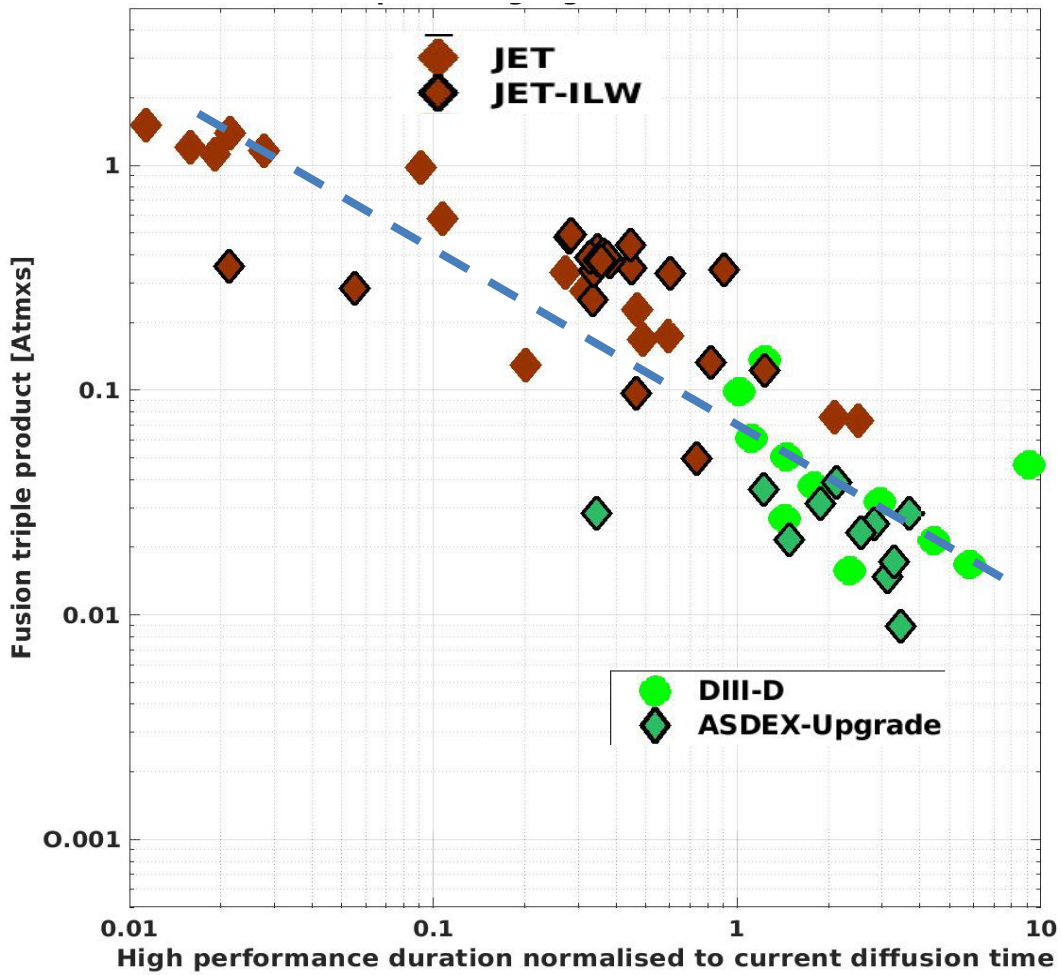
hybrid

SS



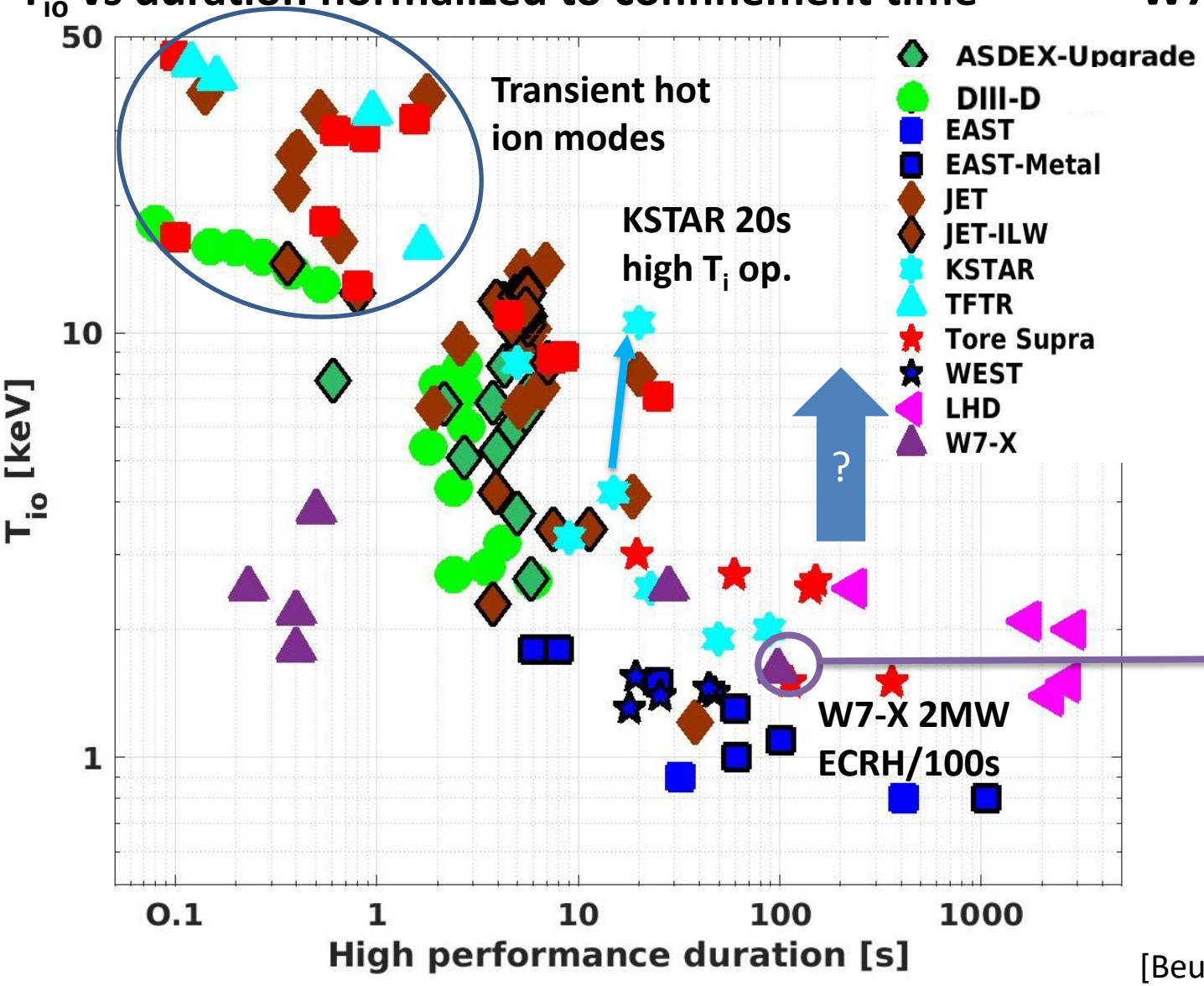
More aligned data ?

triple product vs duration normalised to current diffusion time



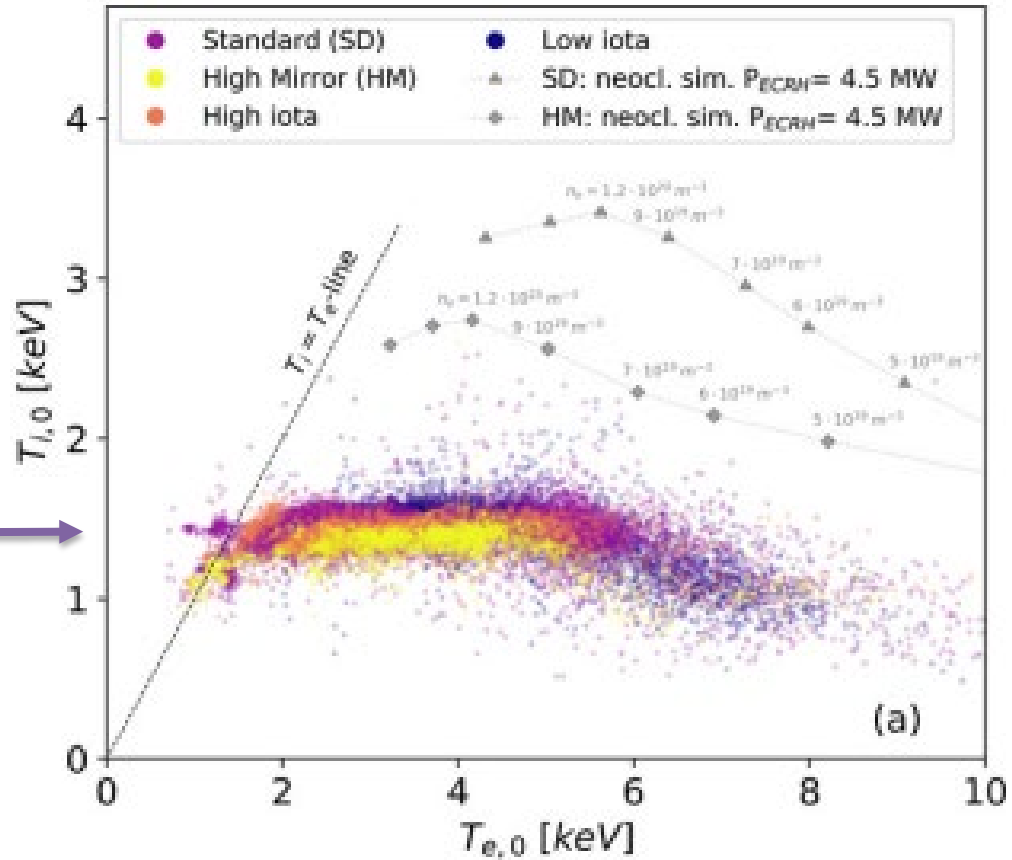
How to increase ion temperature in LPO ?

T_{io} vs duration normalized to confinement time



W7-X electron cyclotron heated plasmas

- ion-turbulent-heat transport leads to T_i clamping
- Similar mechanism observed in tokamak (AUG)
- $T_i \uparrow$: ion heating ↑ + density profile optimization ?



[Beurskens et al. NF **61** (2021) 116072 & NF 2022 for AUG L-mode]

Logos

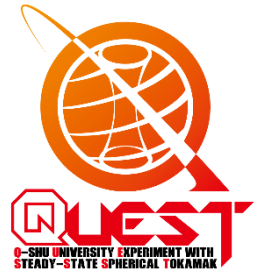

cea


IAEA
International Atomic Energy Agency
Atoms for Peace and Development


MAX PLANCK INSTITUTE
FOR PLASMA PHYSICS


JÜLICH
Forschungszentrum


EPFL


QUEST
Q-SHU UNIVERSITY EXPERIMENT WITH
STEADY-STATE SPHERICAL TOKAMAK

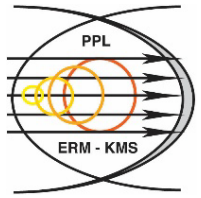

Lawrence Livermore
National Laboratory
SCIENCE & TECHNOLOGY ON A MISSION


GENERAL ATOMICS


QST


RRC "Kurchatov
Institute"


CCFE
CULHAM CENTRE FOR
FUSION ENERGY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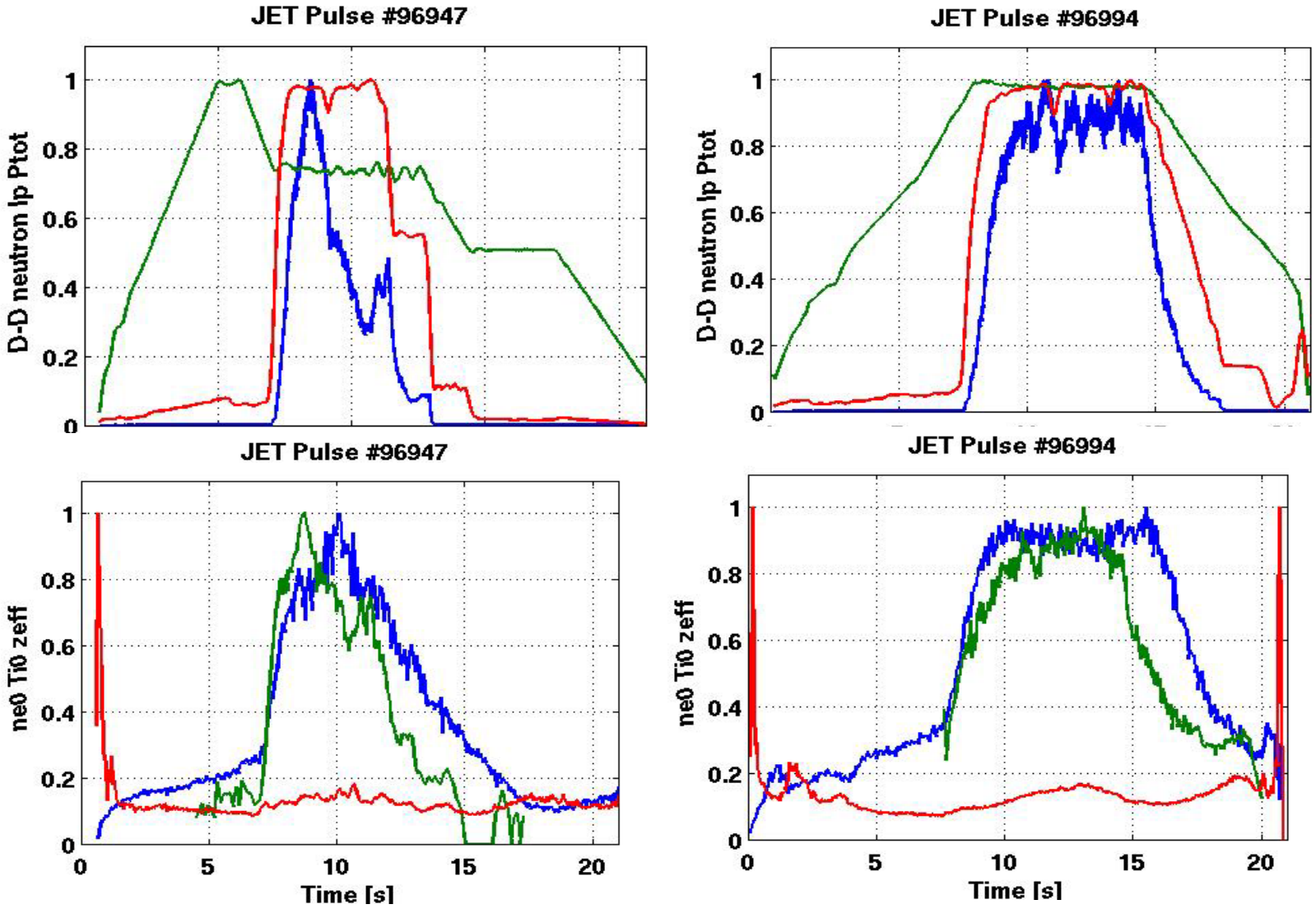
KFE
한국핵융합에너지연구원
KOREA INSTITUTE OF FUSION ENERGY

Window averaged quantities and Definition of stationarity level

- **The fusion performance is stationary when the averaged $\langle Y \rangle_{\tau}$ does not vary with respect to time , i.e. any value of τ**
  - First moment remain constant independently of the time window , τ (this is the definition of the weak-sense stationarity)
- **One can quantify a level of stationarity, S_{τ} , for a given time constant by the ratio of the averaged performance $\langle Y \rangle_{\tau}$ to $\langle Y \rangle_{\tau_1}$ where τ_1 is lower than τ**
  - $S_{\tau} = \langle Y \rangle_{\tau} / \langle Y \rangle_{\tau 1}$ for any $\tau_1 < \tau$
  - A stationary pulse should have S_{τ} close to one

Illustration/application with two JET discharges



Stationarity level