First divertor physics studies in Wendelstein 7-X

Thomas Sunn Pedersen[1,2], on behalf of the W7-X team, in particular:

R. König[1], M. Jakubowski[1], Y. Feng[1], A. Ali[1], G. Anda[6], J. Baldzuhn[1], T. Barbui[5], C. Biedermann[1], B. Blackwell[3], H.-S. Bosch[1], S. Bozhenkov[1], R. Brakel[1], S. Brezinsek[4], J. Cai[4], J.W. Coenen[4], J. Cosfeld[4], A. Dinklage[1], T. Dittmar[4], P. Drewelow[1], P. Drews[4], D. Dunai[6], F. Effenberg[5], M. Endler[1], J. Fellinger[1], O. Ford[1], H. Frerichs[5], G. Fuchert[1], J. Geiger[1], Y. Gao[4], A. Goriaev[13,14], M. Henkel[4] , K. Hammond[1], J. Harris[9], D. Hathiramani[1], M. Henkel[4], H. Hölbe[1], Y. Kazakov[13], C. Killer[1], A. Kirschner[4], A. Knieps[4], M. Kobayashi[11]; P. Kornejew[1], M. Krychowiak[1], G. Kocsis[6], S. Lazerzon[7], C. Li[4], Y. Li[4], Y. Liang[4], S. Liu[4], J. Lore[9], S. Masuzaki[11], V. Moncada[15] , O. Neubauer[4], T. T. Ngo[16], H. Niemann[1], J. Oelmann[4], M. Otte[1], V. Perseo[1], F. Pisano[8], A. Puig-Sitjes[1], M. Rack[4], M. Rasinski[4], F. Reimold[1], J. Romazanov[4], L. Rudischhauser[1], J.C. Schmitt[7], G. Schlisio[1], O. Schmitz[5], B. Schweer[4], S. Sereda[4], T. Szepesi[6],Y. Suzuki[11], E. Wang[4], Y. Wei[4], U. Wenzel[1], S. Wiesen[4], V. Winters[5], T. Wauters[13], G. A. Wurden[10], D. Zhang[1], S. Zoletnik[6]

[1]Max-Planck-Institut für Plasmaphysik [2]University of Greifswald, [3]Australian National University, Canberra, Australia [4]Forschungszentrum Jülich[5] University of Wisconsin, Madison, [6]Wigner Institute, [7]Princeton Plasma Physics Laboratory, [8]University of Cagliari, [9]Oak Ridge National Laboratory, [10]Los Alamos National Laboratory,[11]National Institute for Fusion Science , [12]Auburn University [13] Laboratory for Plasma Physics, ERM/KMS Brussels[14] Ghent University
[15]100 Impasse des Houllières, ZA Le Pontet, Meyreuil,France. [16] CEA, IRFM, Saint Paul-lez-Durance, France

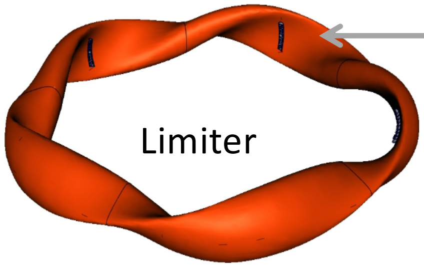
This work was partially funded by the U.S. Department of Energy under grant DE-SC0014210

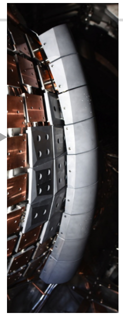
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Overview

- **The path forward for W7-X in terms of upgrades to the PFCs**
- **The W7-X island divertor concept**
- **Heat load patterns during attached operation:**
  - Spatial patterns
  - Scaling of heat fluxes
- **Detachment at lower power, before boronization**
- **Effects of boronization**
- **Detachment at higher power, after boronization**
- **Summary**

Successive upgrades to plasma-facing components





OP 1.1: 2015 - 2016

Graphite limiter configuration

P < 4.3 MW achieved

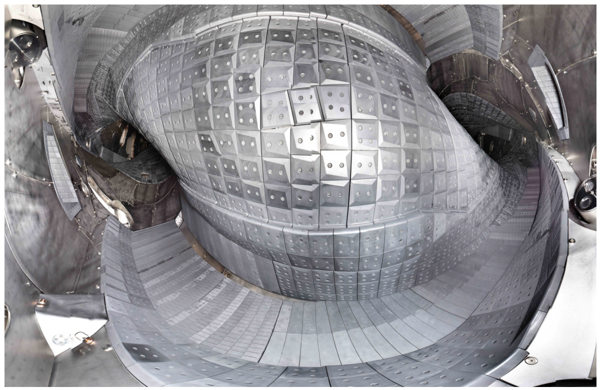
$\int Pdt \leq$ 4 MJ achieved

OP 1.2: 2017 – 2018

Uncooled graphite divertor

P $\leq$ 7 MW achieved

$\int Pdt \leq$ 200 MJ achieved



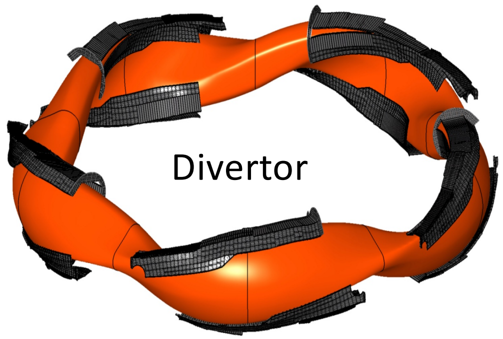
OP 2: 2021 …

Actively cooled CFC divertor

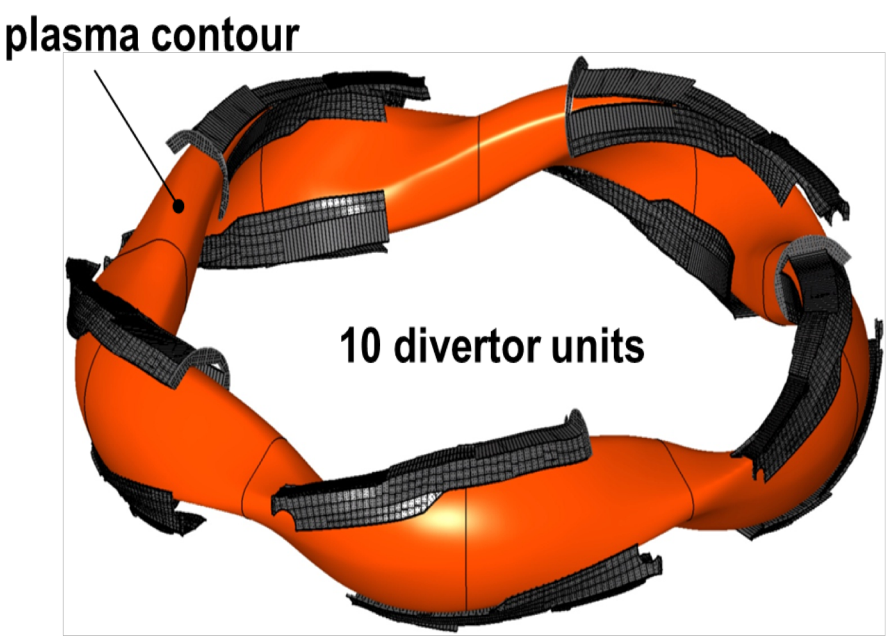
P_{cw} ~ 10 MW (30 mins)

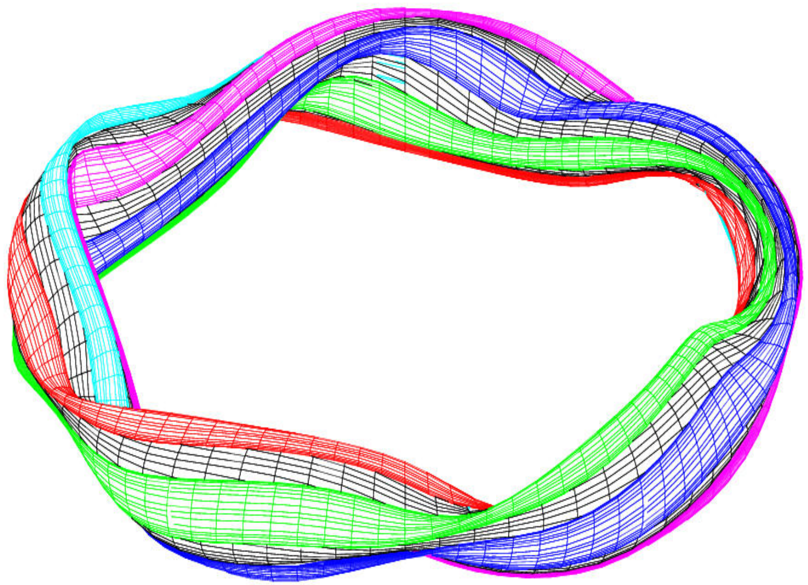
Divertor $\Gamma \leq$ 10 MW/m²

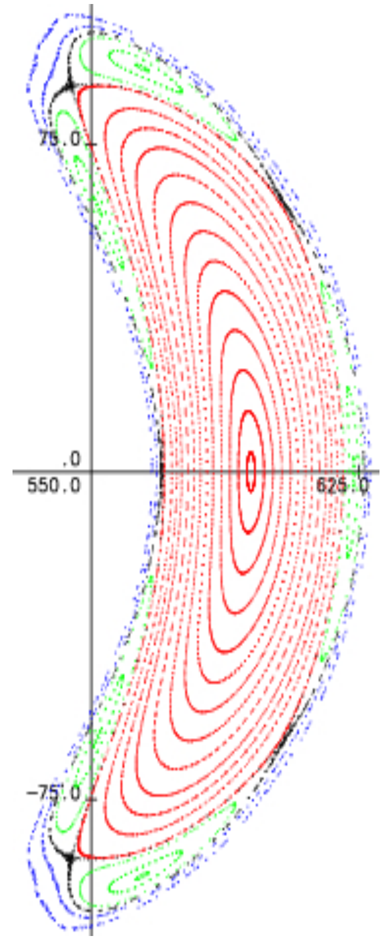
$\int$ P dt $\leq$ 18000 MJ



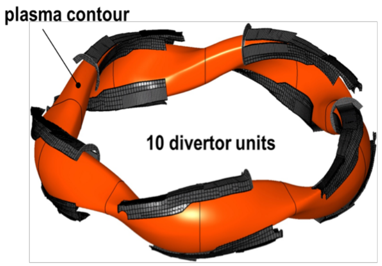
Introducing the W7-X island divertor

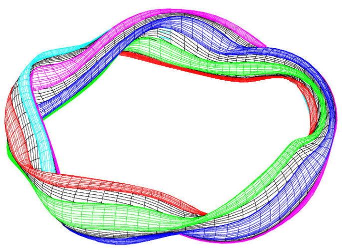


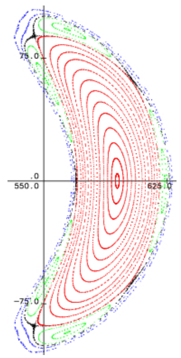


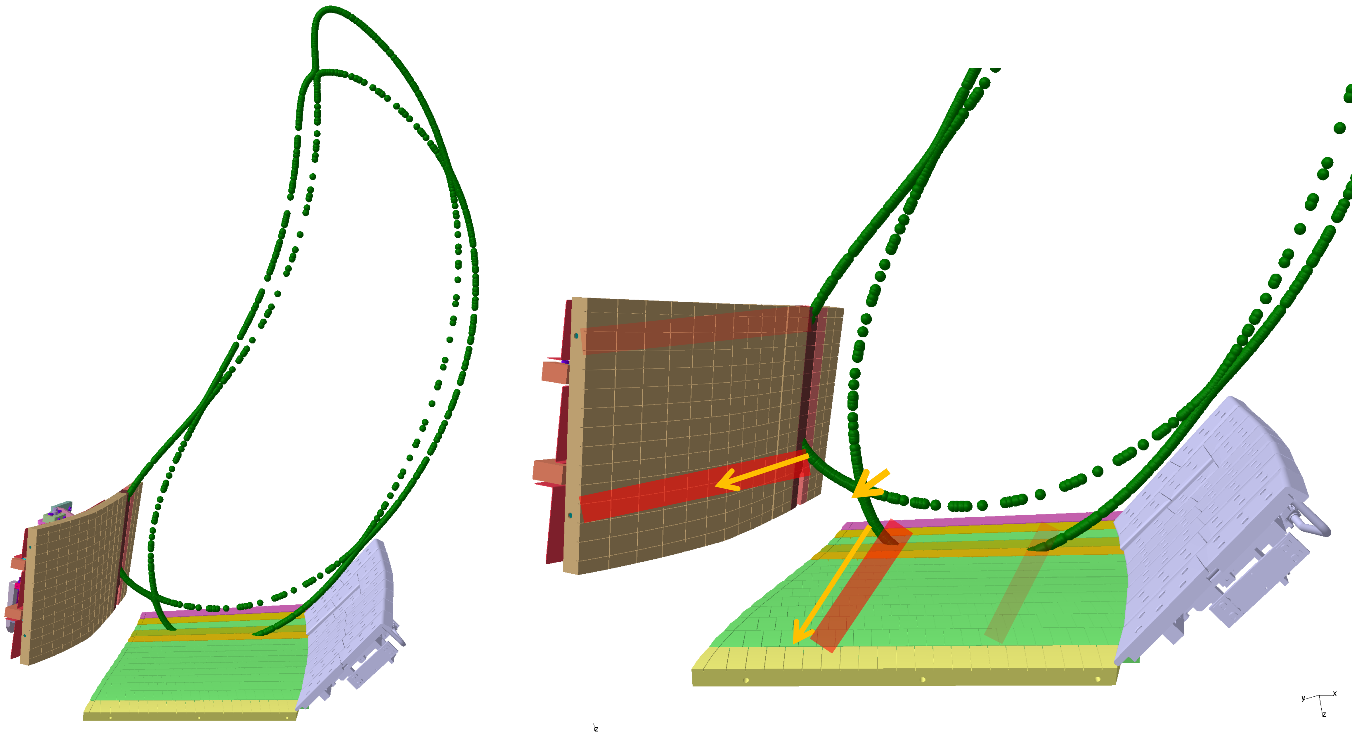


Introducing the W7-X island divertor

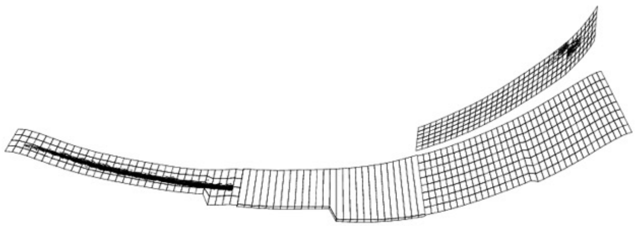




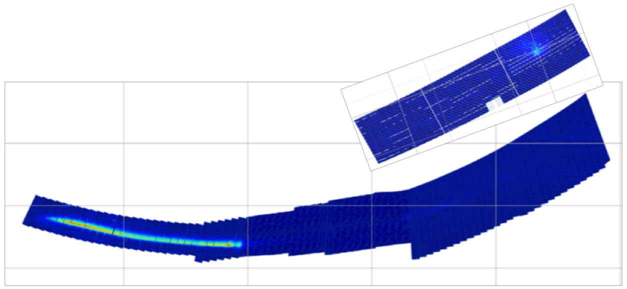


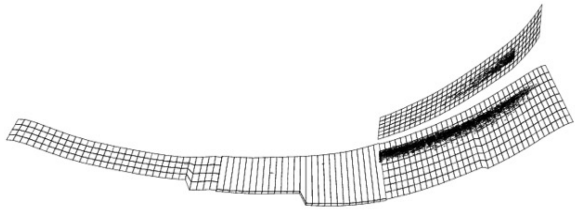


Divertor heat load patterns for attached plasmas

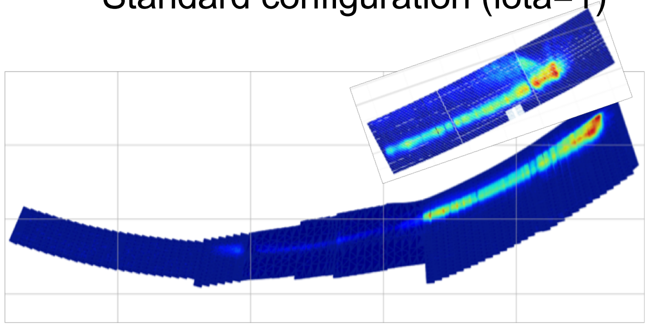


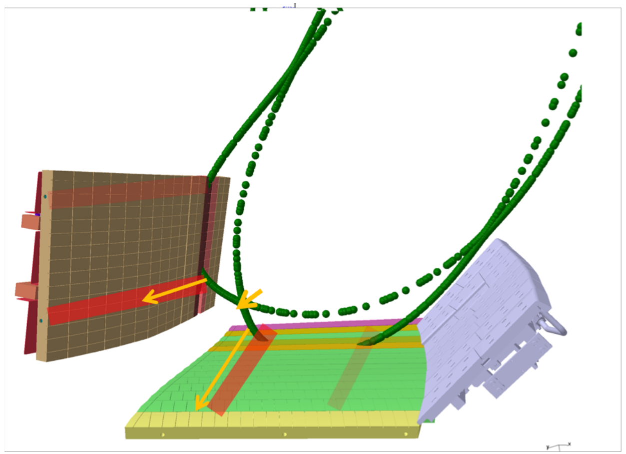
High-iota configuration (iota=5/4)





Standard configuration (iota=1)

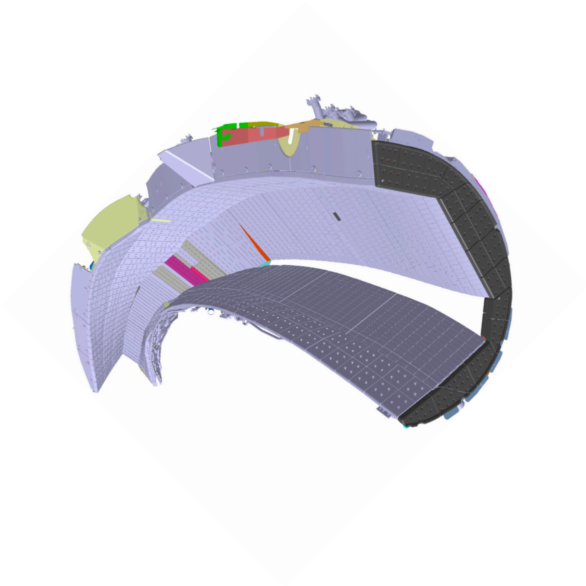


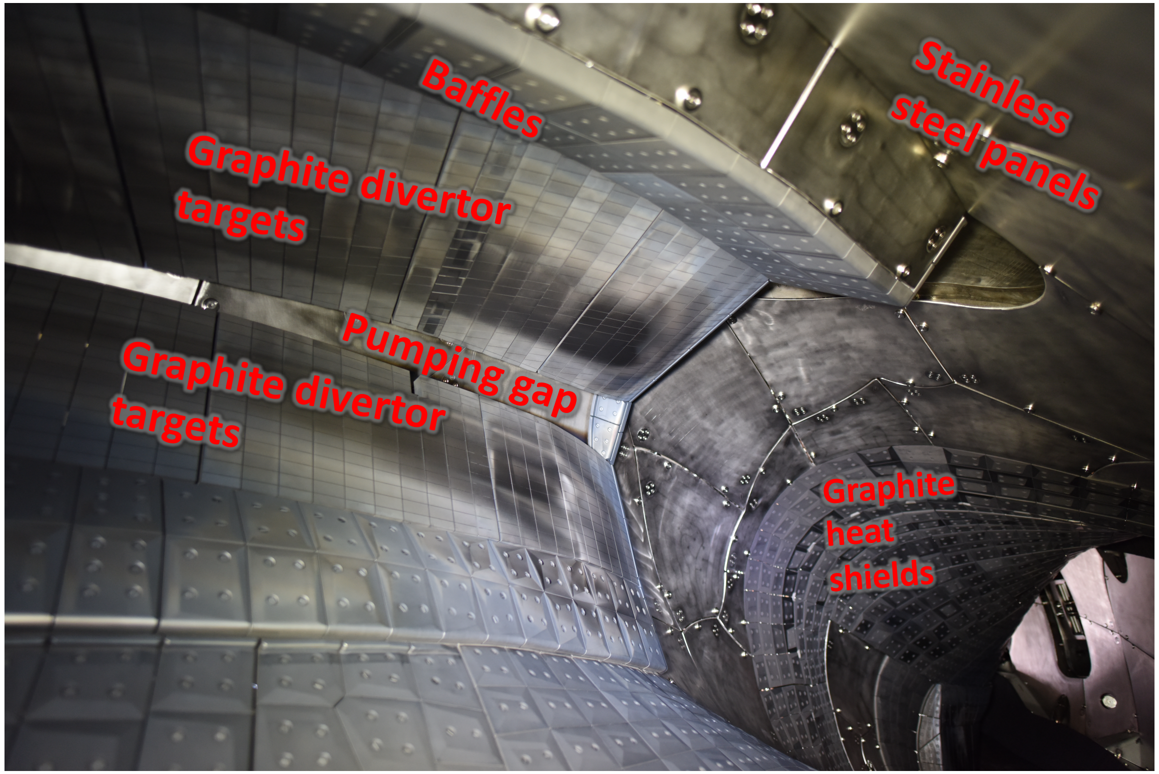


Heat load patterns generally as expected,
See also M Jakubowski et al., this conference

For strike line motion and general issues with those: see J. D. Lore et al., this conference

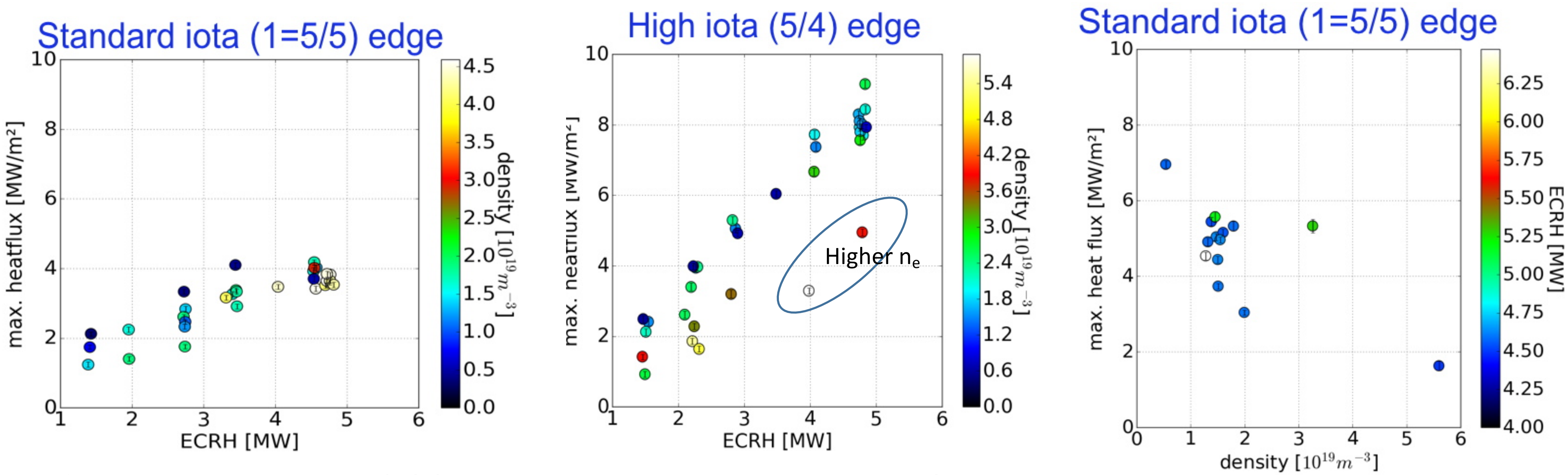
A look onto a divertor unit halfway through OP1.2





- View into torus after OP1.2a: Visible signs of plasma-divertor contact
- The OP1.2 test divertors are uncooled, robust against overload ⇒ Ideal testbed for later operation with the water-cooled divertor which has a 10 MW/m^2 heat flux design specification

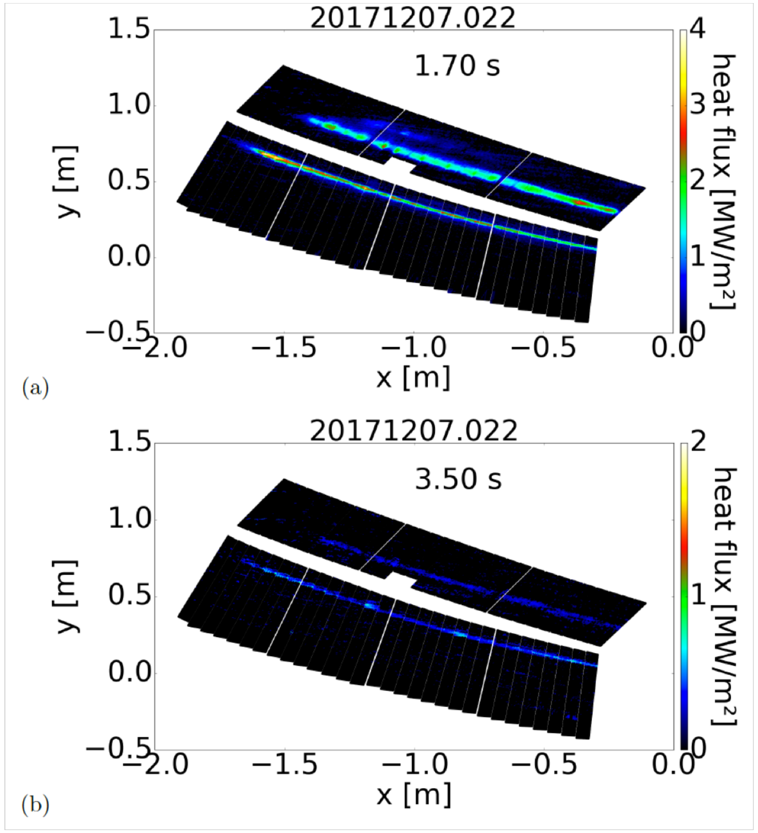
Attached divertor operation: heat loads are a function of density



- Standard island chain (5/5): scaling to P=10 MW looks good (L_c~240 m)[1]
- High iota island chain (5/4): Scaling presents a challenge at low density (L_c~130 m)[1]
- Higher density features more desirable scaling
- Primarily due to increased radiation but also indicative of large wetted area (up to 1.5 m^2)

[1] P. Sinha et al., Nucl. Fusion 58, 016027 (2017)

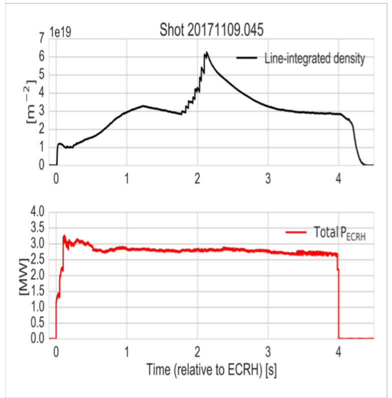
Full heat-flux detachment at high n_e, low P~3 MW

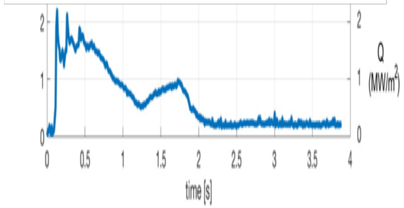


Complete detachment for t> 2 s on all 10 divertors (one shown)

Heat flux essentially disappears from target for t>2 s, persisting until end of plasma heating at t=4 s

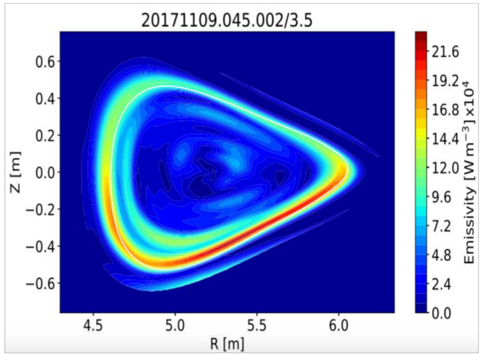
t_E~100 ms rather constant for over 1 s



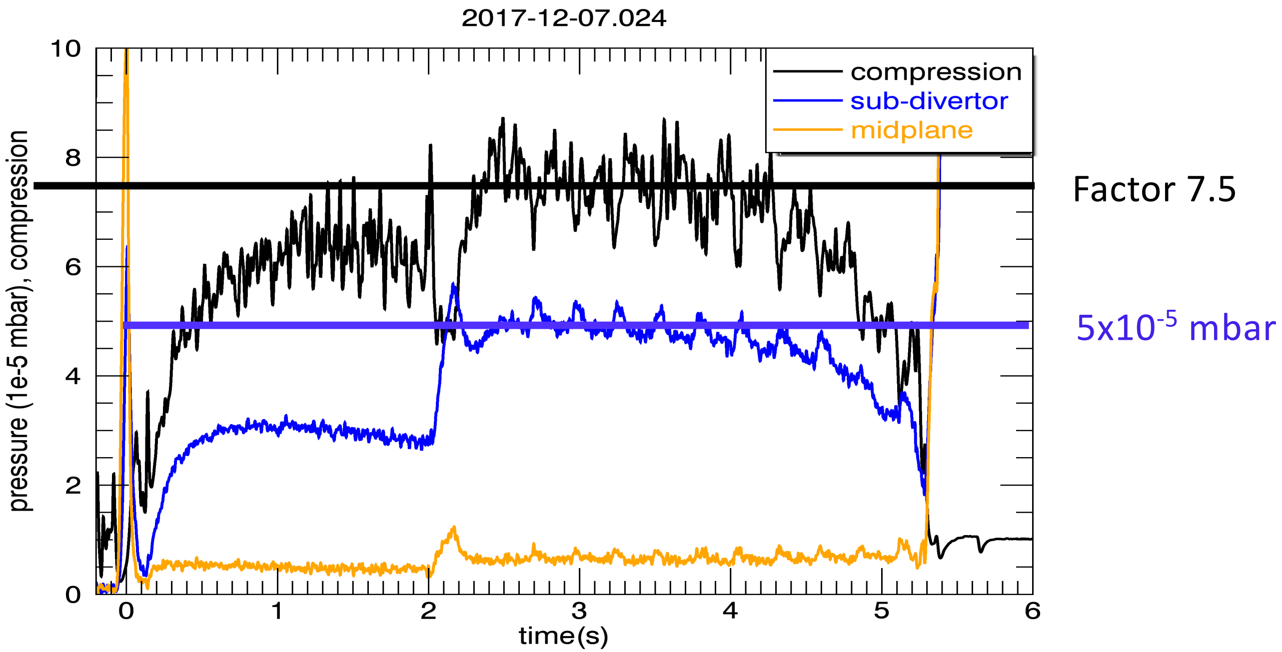


Heat flux derived from IR camera data

Increased radiation near the LCFS

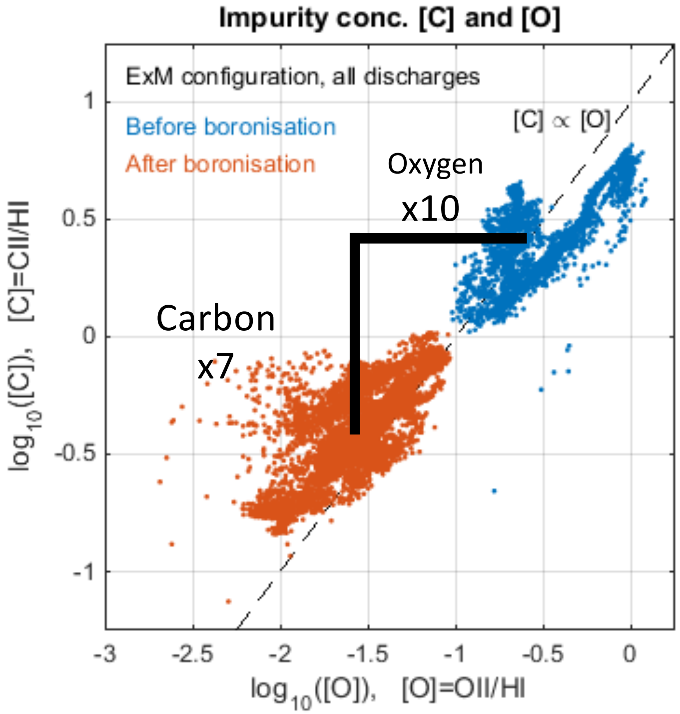


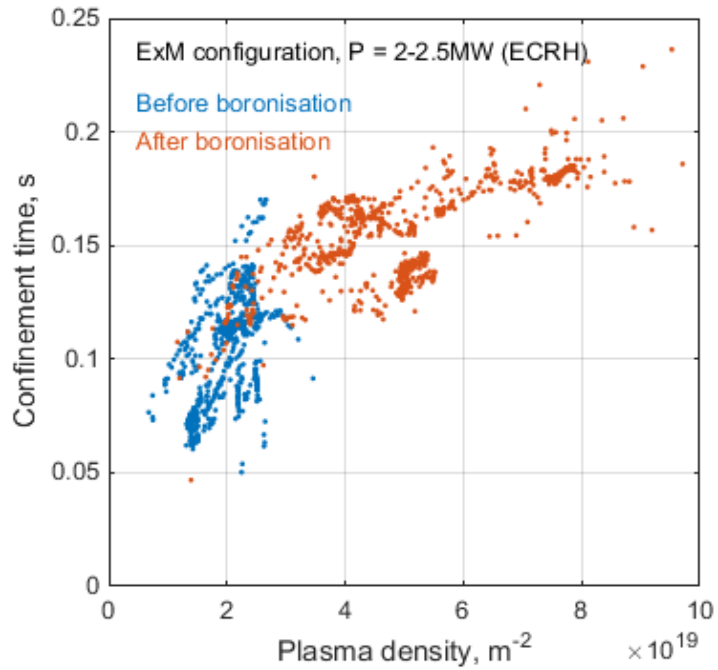
But what about the particle exhaust (P~3 MW)?



- For low-power detachment, the subdivertor neutral pressure reaches about 5×10^{-5} mbar
  - In OP1.2: 2×10^{4} l/s pumping rate (divertor turbopumps)
- The exhaust rate is therefore about 1 mbar-liter/s~2×10^{19} particles/s
- Compression ratio: About 7.5
- Expected/hoped: compression ratios of more than 30, subdivertor pressure 5-10×10^{-4} mbar

After boronization: Reduced edge radiation, higher density

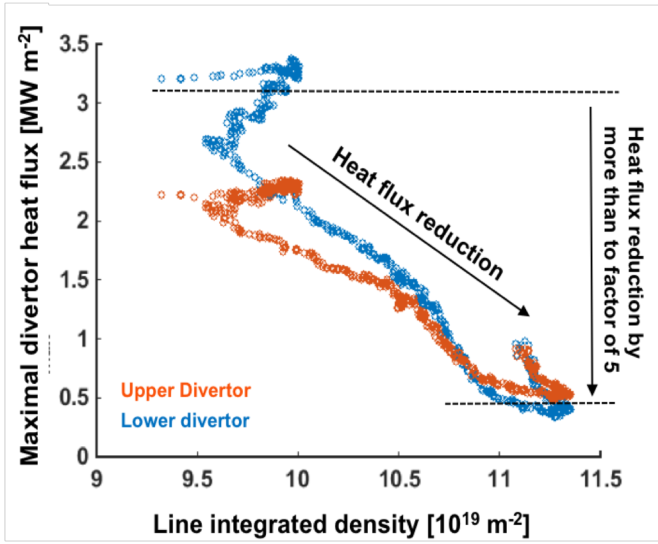


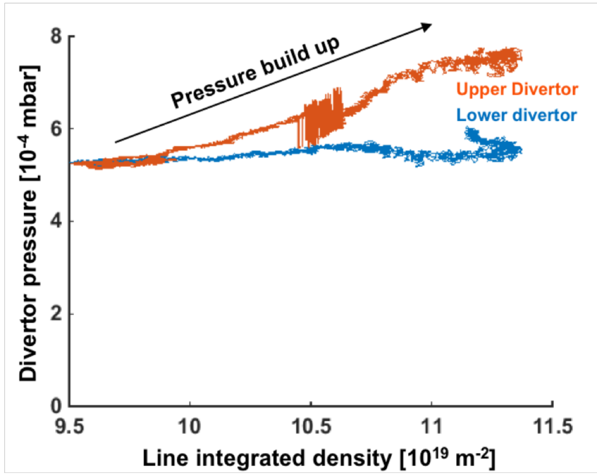


- Edge impurity concentrations (relative to hydrogen density):
  - Oxygen reduced by a factor of 10 (or a lot more, in some cases)
  - Carbon reduced by about a factor of 7

- Achieved hydrogen densities increased by factor >3:
  - avoidance of MARFE-like phenomena
- Achieved confinement times increased by ~60%
  - consistent with the increased density ($\tau_{E,ISS04} \propto n^{0.54}$), so:
- Boronization was not the direct cause of increased confinement
  - Plasma core generally clean before and after boronization

Post-boronization detachment: Efficient exhaust

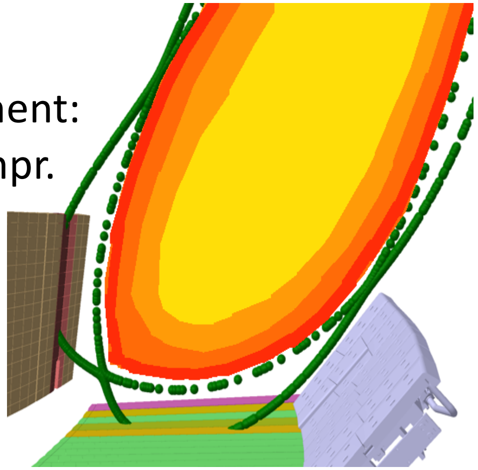




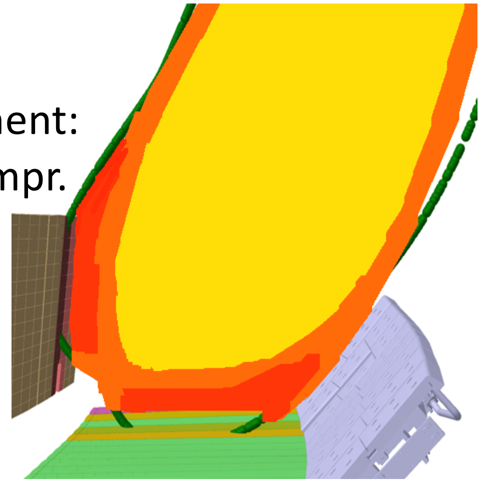
- High-density, higher-power (5-6 MW) detachment achieved after boronization
- Strong heat flux reduction
- Triggered in narrow density range in both upper and lower divertors
- Strong neutral compression now (x30):
  - p_n =5 to 8x10^{-4} mbar now (p_n =0.5x10^{-4} mbar for low-power detachment)
- All divertors detach but a somewhat stronger neutral compression (30%) is seen in the upper divertors.
- The particle removal rate is ~13 mbar-liter/s~2.6x10^{20} particles/s – projects well to OP2 with divertor cryo-pumps and a 4x higher pumping rate:
  - Should result in 10^{21} particles/s removed – about the amount expected to be needed

Why the difference in neutral compression?

Low-power detachment:
Factor 7 neutral compr.



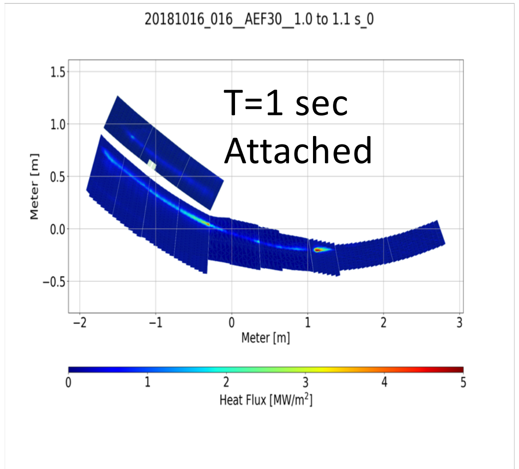
High-power detachment:
Factor 30 neutral compr.

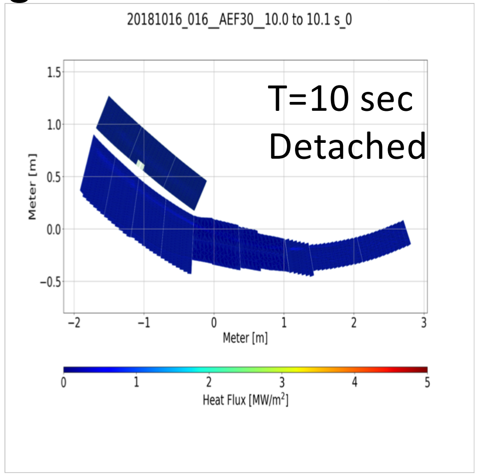


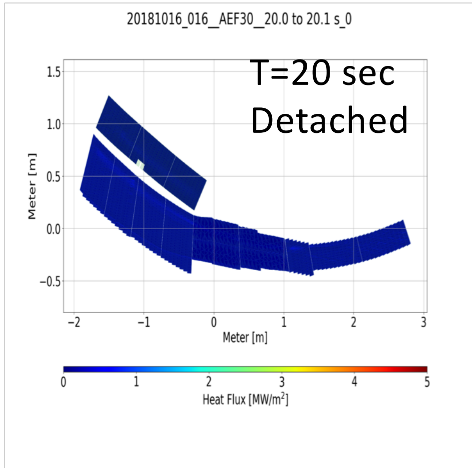
- **Hypothesis (illustrated with cartoons):**
  - **At low power**, the plasma "runs out of energy" near the edge and radiates its energy away before it arrives at the island and the divertor
  - Oxygen and carbon act as "radiating mantle"
  - Therefore, the plasma does not "plug" the hole – neutrals can escape divertor region
  - See also Florian Effenberg's talk directly following this one – using neon to trigger the same physics
  - **At high power**, after boronization, the plasma radiation cooling and condensation occurs further out, in the divertor
  - Therefore the plasma effectively "plugs the hole" – neutrals cannot escape divertor region (as designed…!)
- **The surprising thing is that also the low-power detachment can be stable without feedback stabilization.**

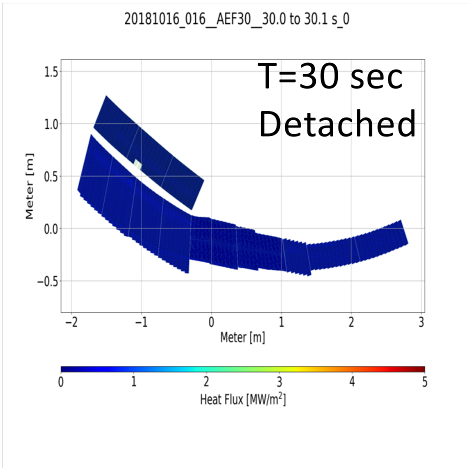
W7-X divertor works: Efficient particle exhaust, stable detachment

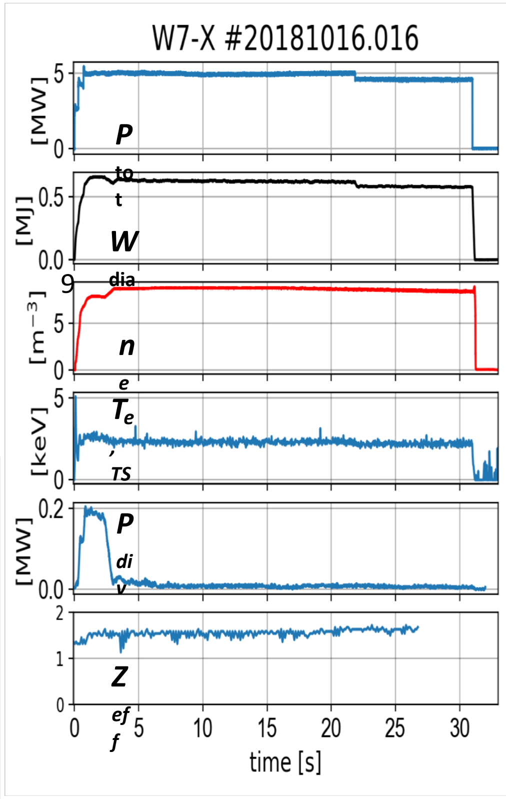
32 second discharge from last week, detached for the last 28 seconds





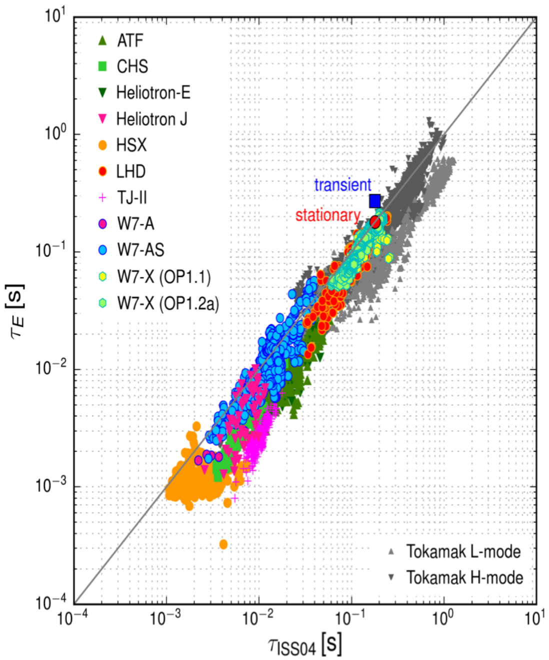


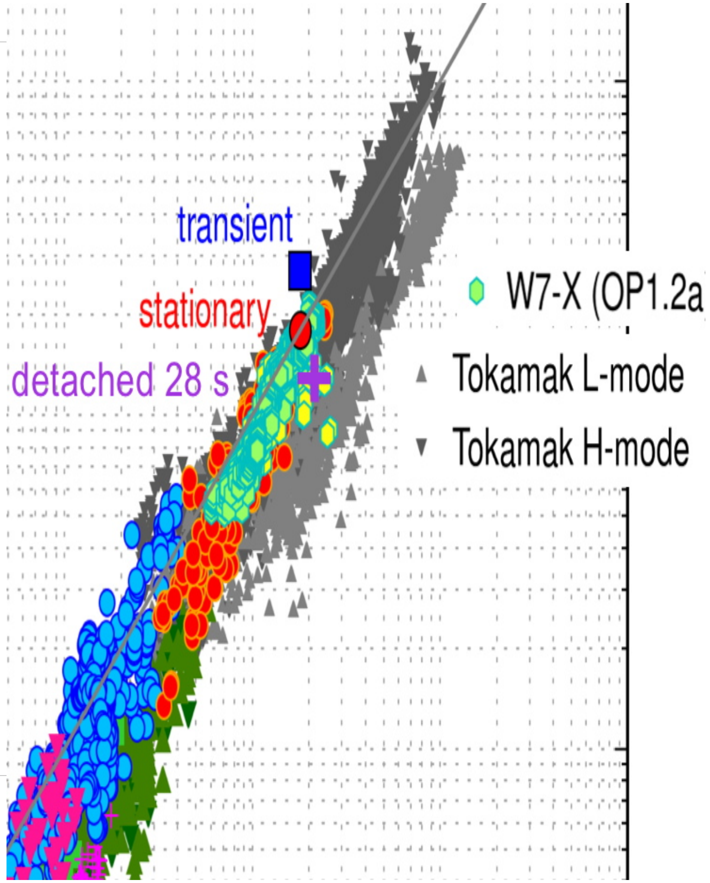




- Pulse terminates as preprogrammed – could have been extended
- Energy confinement time ~120 ms constant
- Efficient exhaust
  - Divertor neutral pressure ~ 6-7x10^{-4} mbar
- Low impurity content

W7-X in general has very good confinement: 28-second detached discharge had H-L mode confinement





- W7-X discharges lie with the same range that regular tokamak H-mode discharges do.
- The 28 sec detached discharge has confinement between H- and L-mode
- The triple product record shot (labeled "transient" here) lies above the H-mode scaling, and had reduced turbulent fluctuations (re. Th. Klinger overview talk)

Summary

- **First results with the W7-X island divertor were very successful**
  - The divertor heat load patterns were generally as expected
  - In attached operation, we observe large wetted areas and acceptable heat fluxes:
    - Projects well to future operation with water-cooled divertor
    - An indication of the benefits of long connection lengths
  - Stable detachment was achieved (two varieties)
    - Low-power, volumetric, limited particle exhaust
    - High-power, with high neutral compression, efficient particle exhaust
      - All divertors detached stably for 28 seconds @ 5MW – could have lasted much longer
- **Boronization was key; it enabled:**
  - Strong reduction of oxygen and carbon in SOL
  - Stable high hydrogen density operation
  - Access to detachment with efficient exhaust