Experimental confirmation of efficient island divertor operation and successful neoclassical transport optimization in Wendelstein 7-X

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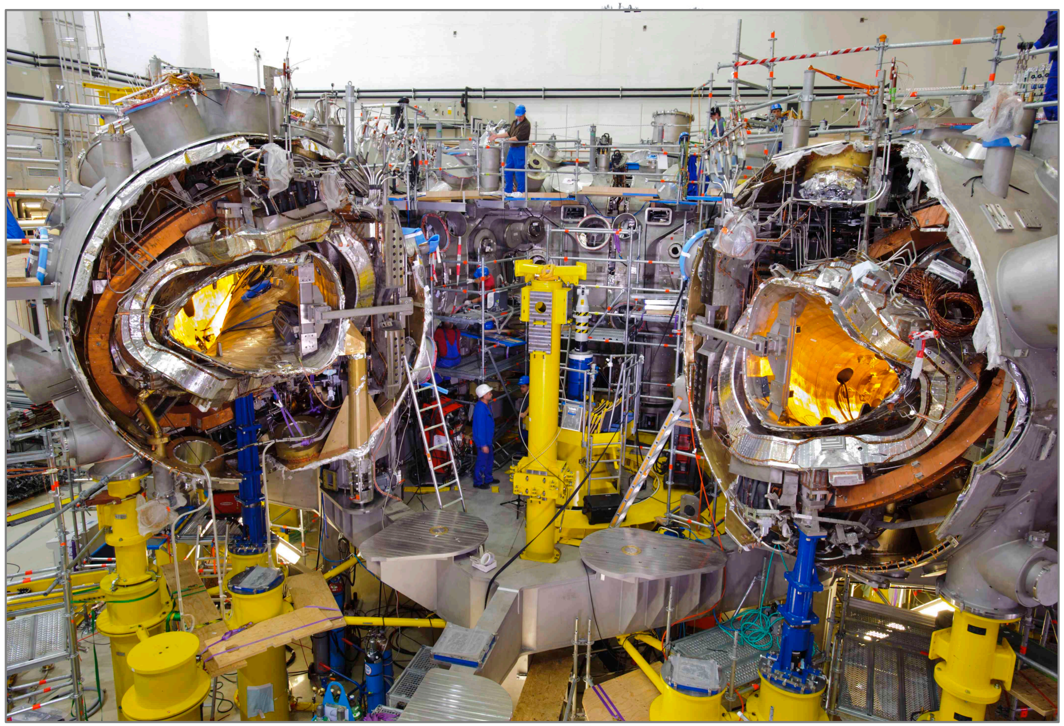
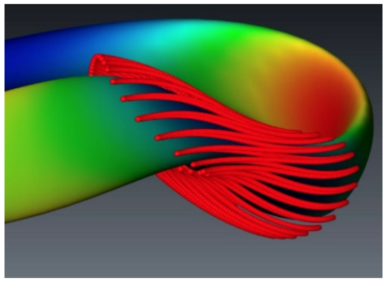
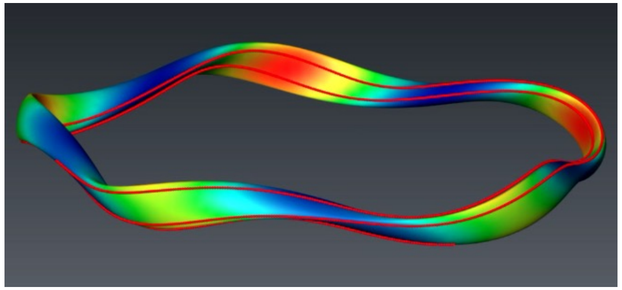
Wendelstein 7-X

Located in Greifswald, Germany.
In preliminary operation three times in the time period 2015-2018
Goal: To experimentally verify the reactor-relevance of optimized stellarators







Major radius: R=5.5 m, minor radius: a=0.5 m

Plasma volume: 30 m^3

Superconducting coils (NbTi), B=2.5 T on axis

Magnetic field topology optimized for

(among other things):

Low neoclassical losses

Stable plasmas up to $\langle\beta\rangle$=5%

A stable and efficient plasma exhaust solution

using the island divertor concept

Quasi-steady-state operation will start in 2022

(Up to 18 GJ eg. 30 minutes at 10 MW ECRH)

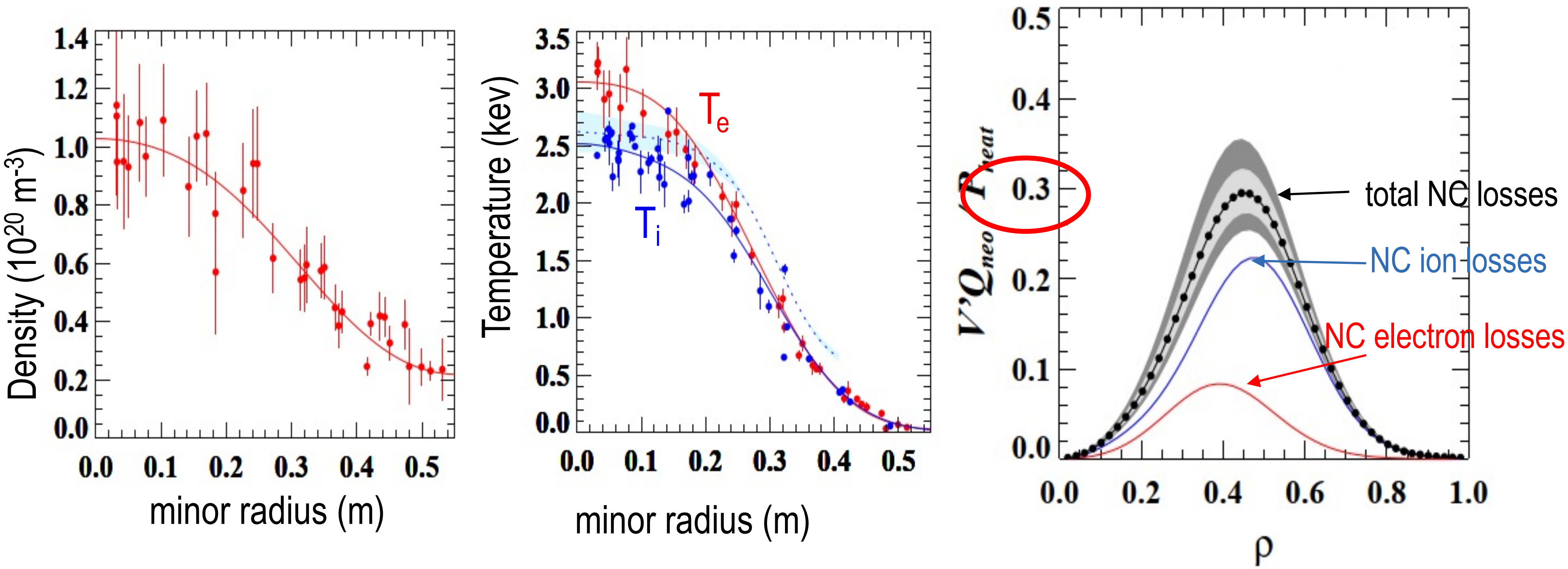
Overview

- Experimental evidence of successful reduction of neoclassical losses
- The role of turbulence and turbulence suppression
- Experimental demonstration of robust, steady-state, complete divertor detachment with efficient particle exhaust
- Outlook: Near-term upgrades and what they might help us achieve

High-performance discharges give proof of NC optimization

Given the measured density and temperature profiles, the neoclassical transport can be calculated with high confidence

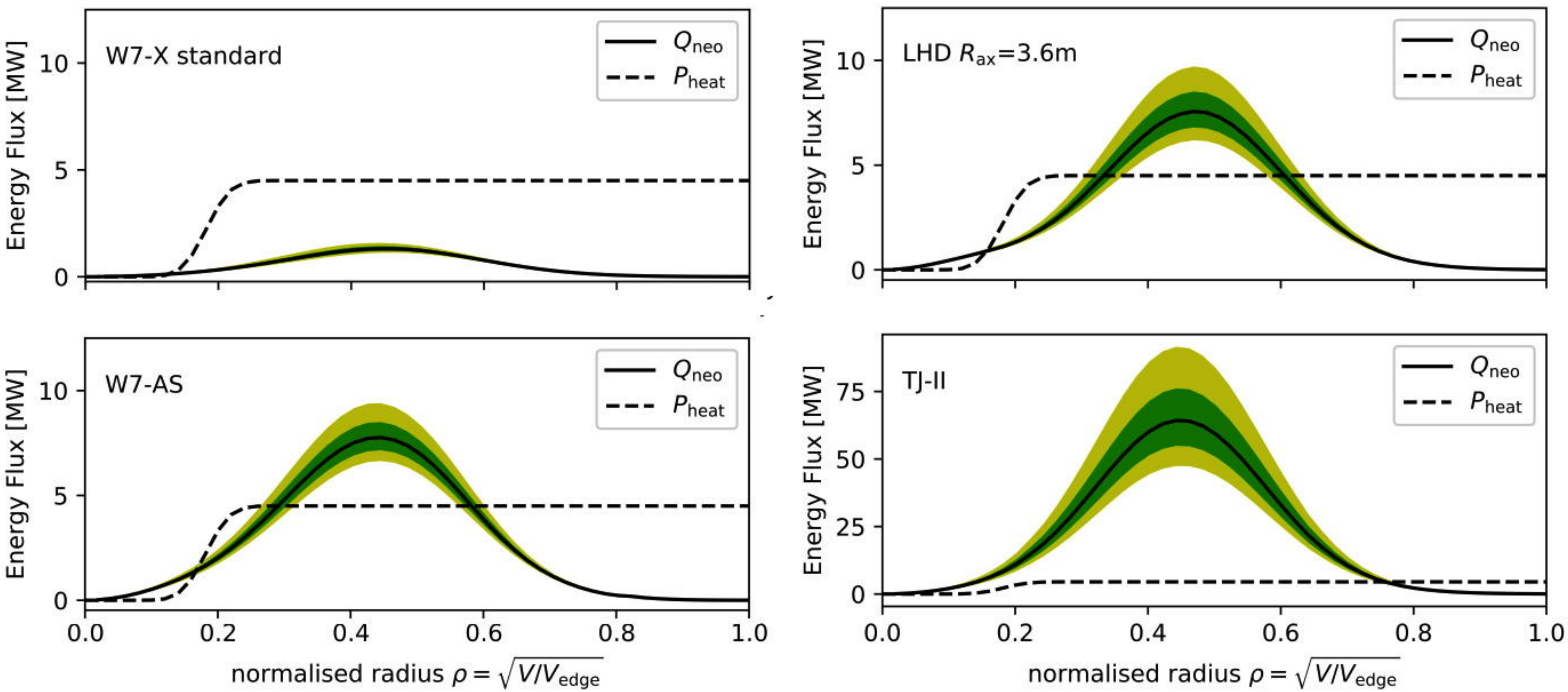
- Shown here: Pellet-fueled discharge with central ECRH heating 4.5 MW and τ_E = 0.23 s
- Most of the transport is due to turbulence (about 70% at mid-radius – even more at other radii).



Discharge 20180918.045 at t = 3.35 s. From C. Beidler et al., submitted to Nature

Comparison to other magnetic configurations

- We can calculate the equivalent neoclassical losses in less optimized configurations
  - Assume same density and temperature profiles and, for other devices, similar V_p and B-field
  - Result: much higher neoclassical losses, often larger than applied heating power

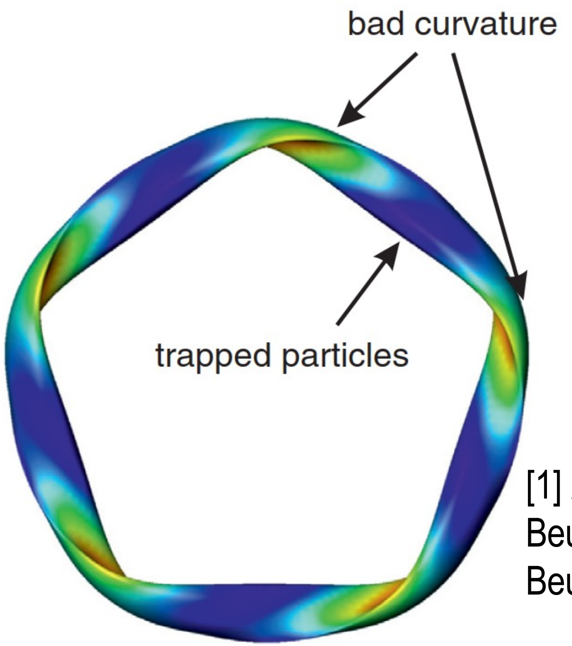


Proves efficacy of neoclassical optimization of W7-X.

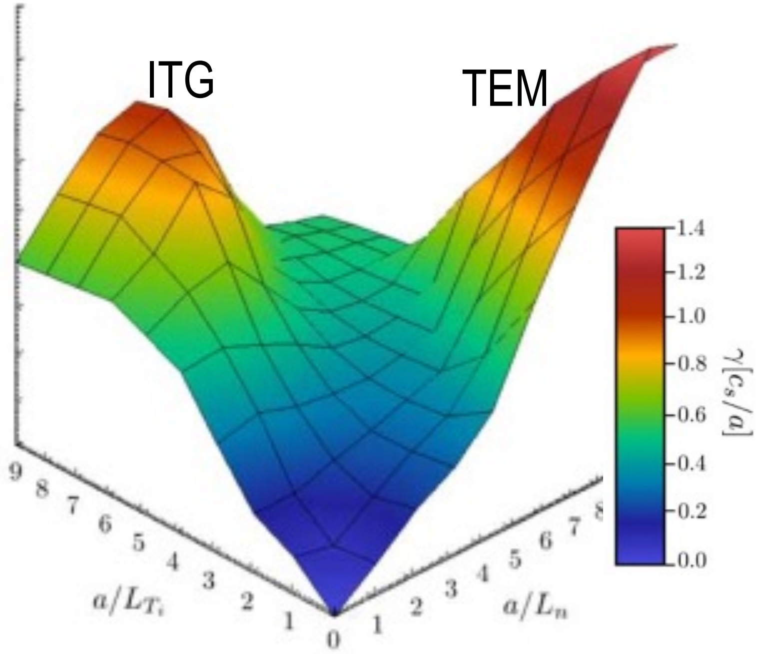
Beidler et al, submitted to Nature (2020)

What about the turbulence then?

- One important feature of the W7-X optimization: TEM's rather benign
  - Trapped particles reside in regions of relatively <u>good</u> curvature.
  - The addition of a density gradient can be <u>stabilizing</u>
  - Results hold also for nonlinear simulations [1]



[1] Xanthopoulos, Bozhenkov, Beurskens et al, PRL 2020, and Beurskens, this conference

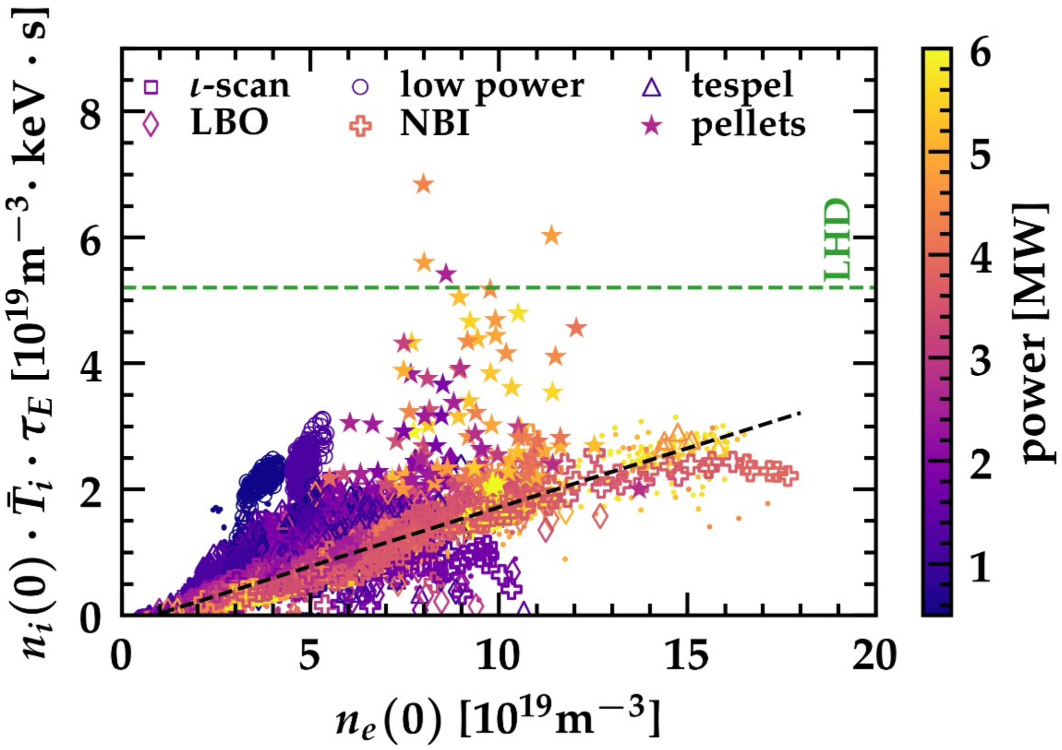


Growth rate vs density and temperature gradients

Proll, Helander, Connor and Plunk, PRL 2012
Helander et al, NF 2015
Alcuson, Xanthopoulos et al, PPCF 2020

Most plasmas are strongly dominated by turbulent losses

- Most discharges have strong (ITG) turbulence and low ion temperatures; confinement times similar to tokamak L-mode
  - See also M. Beurskens et al, this conference
- Pellet fueling appears to be key to higher performance (lower turbulent transport); confinement times similar to tokamak H-mode



Why do most discharges end up with lower performance?

- Vicious cycle starts with source terms, is perpetuated by subtleties of ITG stability

Edge particle source (gas puffing)

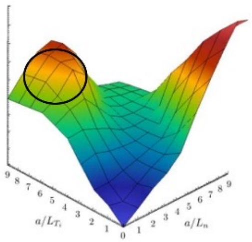
Electrons heated by ECRH in core

Ions heated by collisions with electrons $\sim n(T_e - T_i)/T_e^{1.5}$

n_e profile flat

T_e profile peaked

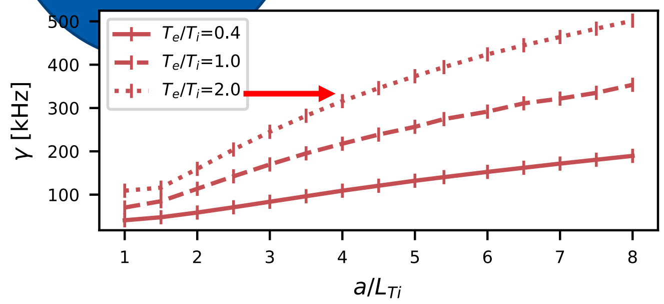
$T_e/T_i = 1+x$



$a/L_n \ll a/L_T$: profiles outside "stability valley" Stronger ITG drive

If T_e/T_i increases ITG increases

ITG leads to: Increased particle diffusion increased ion thermal losses



Starting a virtuous cycle with a central particle source

- Central particle source can allow the plasma to hang on to a virtuous cycle

Central particle source (eg. pellet fueling)

Electrons heated by ECRH in core

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n_e profile peaked

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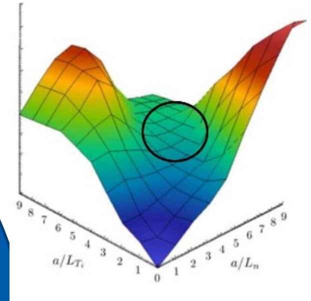
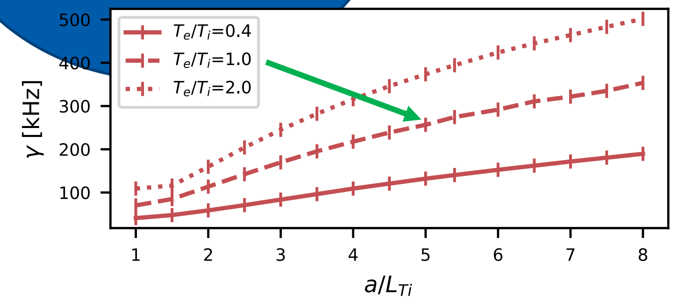


$a/L_n \sim a/L_T$: inside "stability valley" Weaker ITG drive

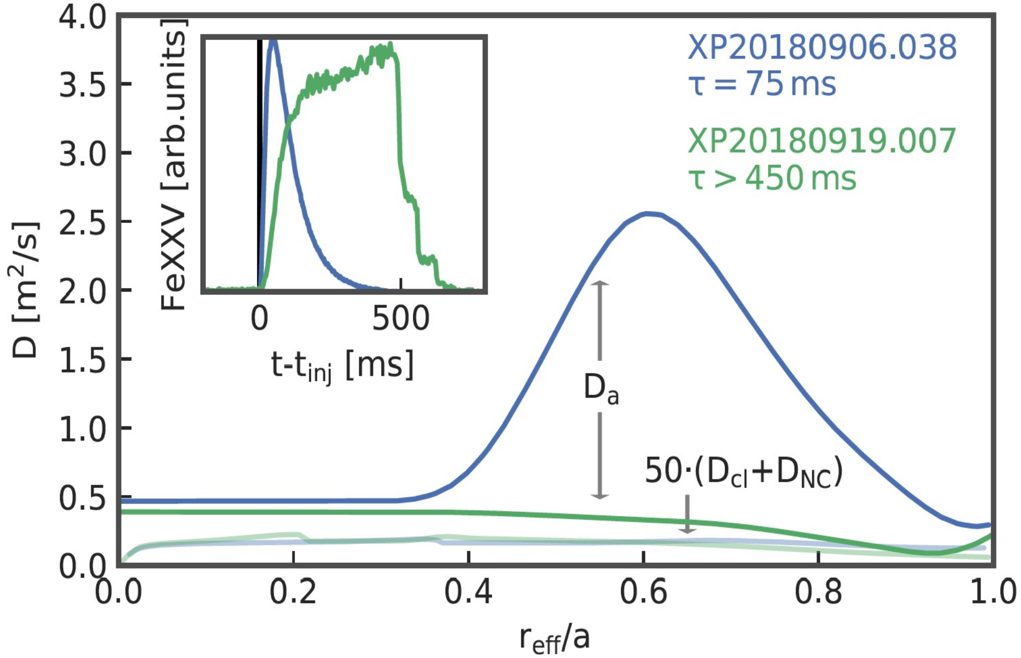
ITG weak: Low particle diffusion Low ion thermal losses

$T_e/T_i \sim 1$ ITG turbulence not further destabilized



But the virtuous cycle has a dark side, and the vicious cycle has a bright side

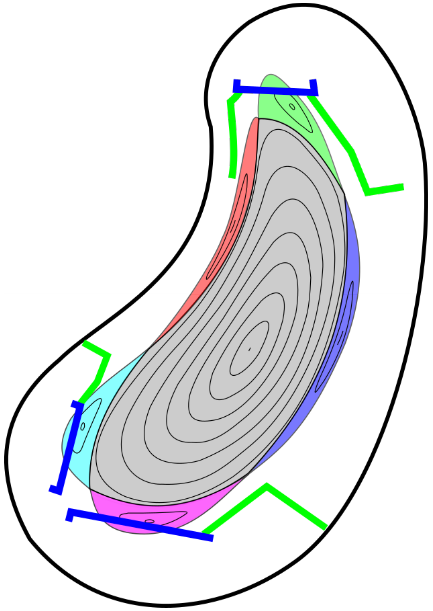
- During turbulent phases, the impurity confinement is very low, of order 100 ms
- During turbulence-suppressed phases, impurity particle confinement is dramatically increased
- Impurity accumulation is clearly seen [1]
- New frontier in stellarator optimization: Optimization of turbulent transport But not necessarily to zero!
- The enhanced particle transport in ITG turbulence may also be advantageous for isotope mixing in a D-T reactor [2]

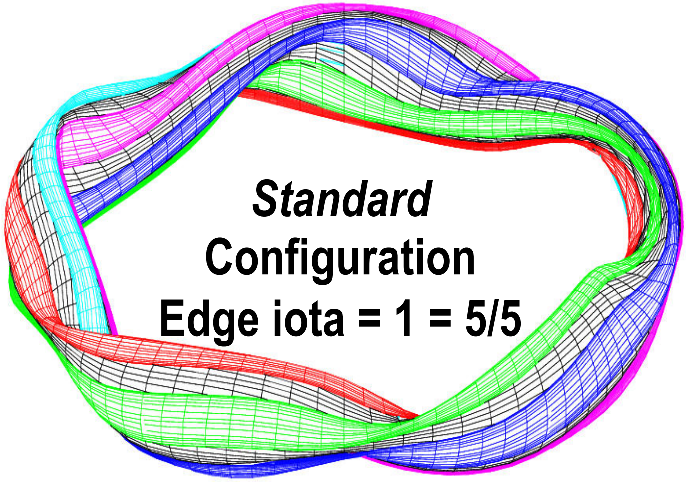


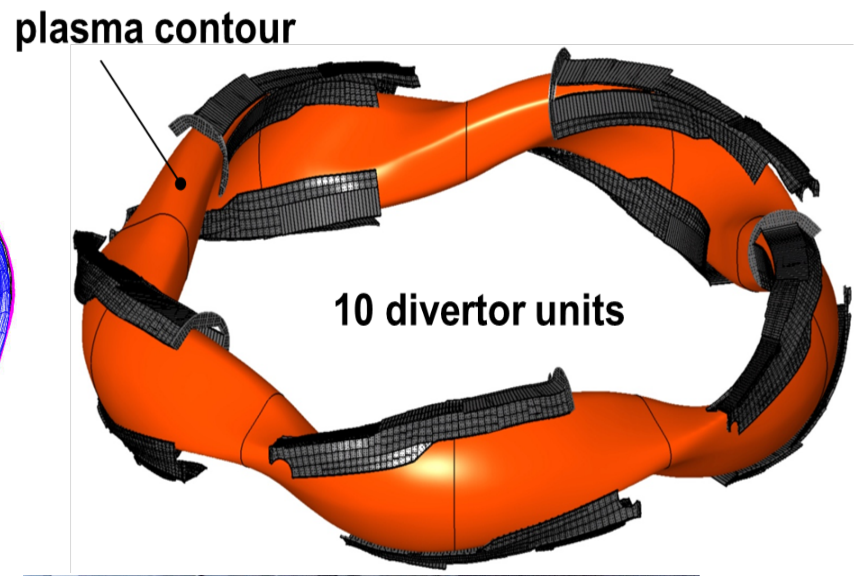
[1] A Stechow et al, "Suppression of core turbulence by profile shaping in Wendelstein 7-X", submitted (2021)

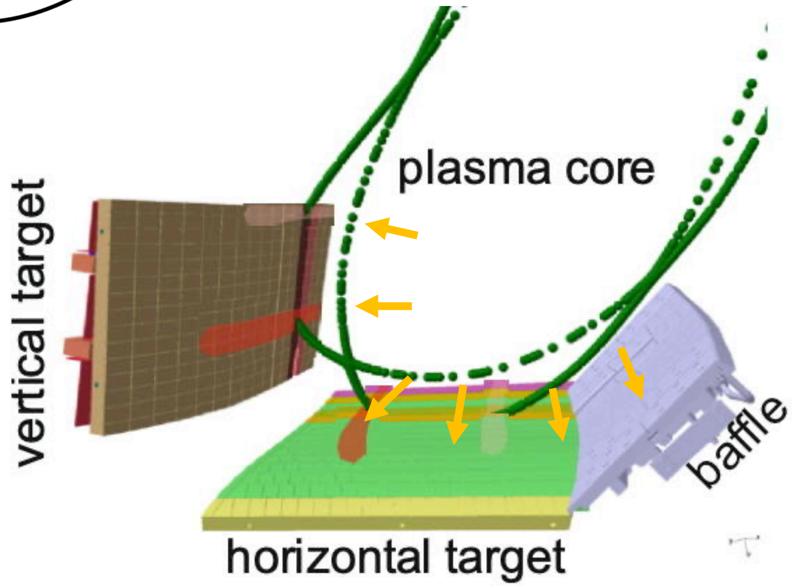
[2] K. Ida et al, Phys. Rev. Lett. 124, 025002 (2020), K. Ida et al. this conference

Exhaust concept in W7-X: Island Divertor

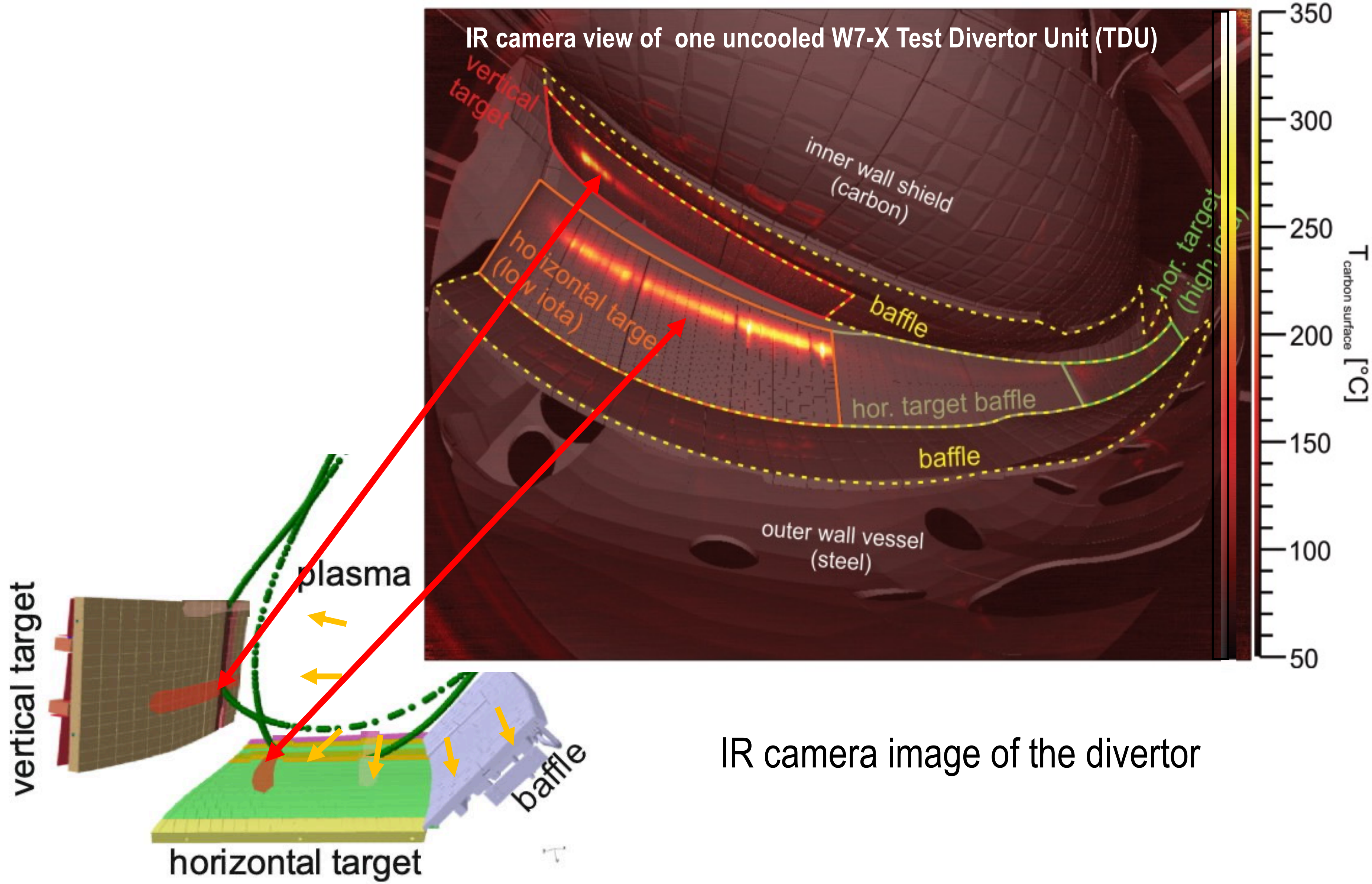






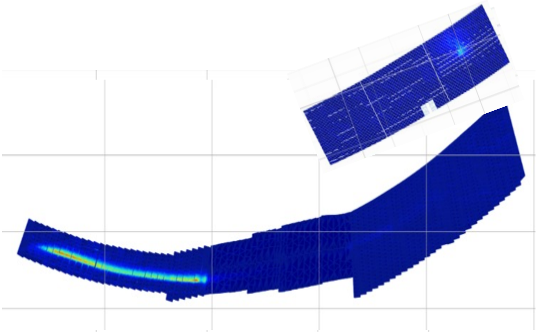


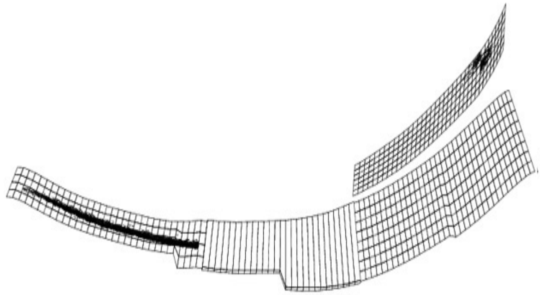
Island divertor in operation

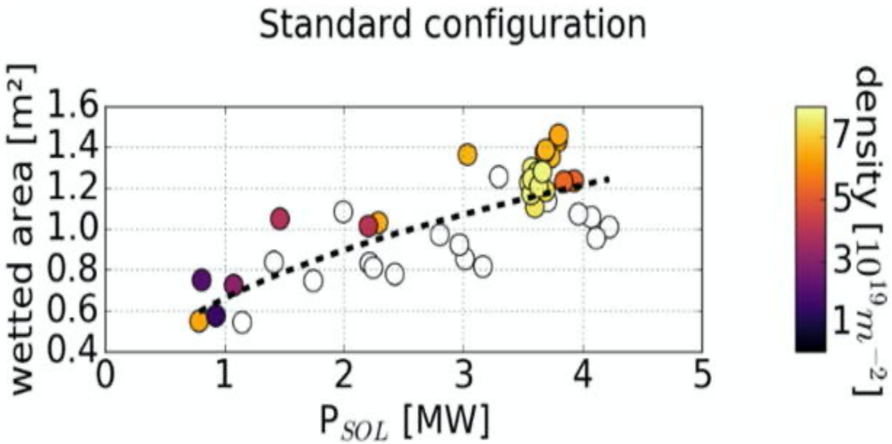


IR camera image of the divertor

Power exhaust (during attached operation)







Heat flux patterns well understood

There are some interesting subtleties and details [1-3]

Since the divertor is rated at 10 MW/m^2 a wetted areas above 1 m^2 will allow steady state operation @ 10 MW

We observe large wetted areas (up to 1.5 m^2), even increasing at higher heating power [4]

However, overload of the PFCs could still occur due to a combination of:

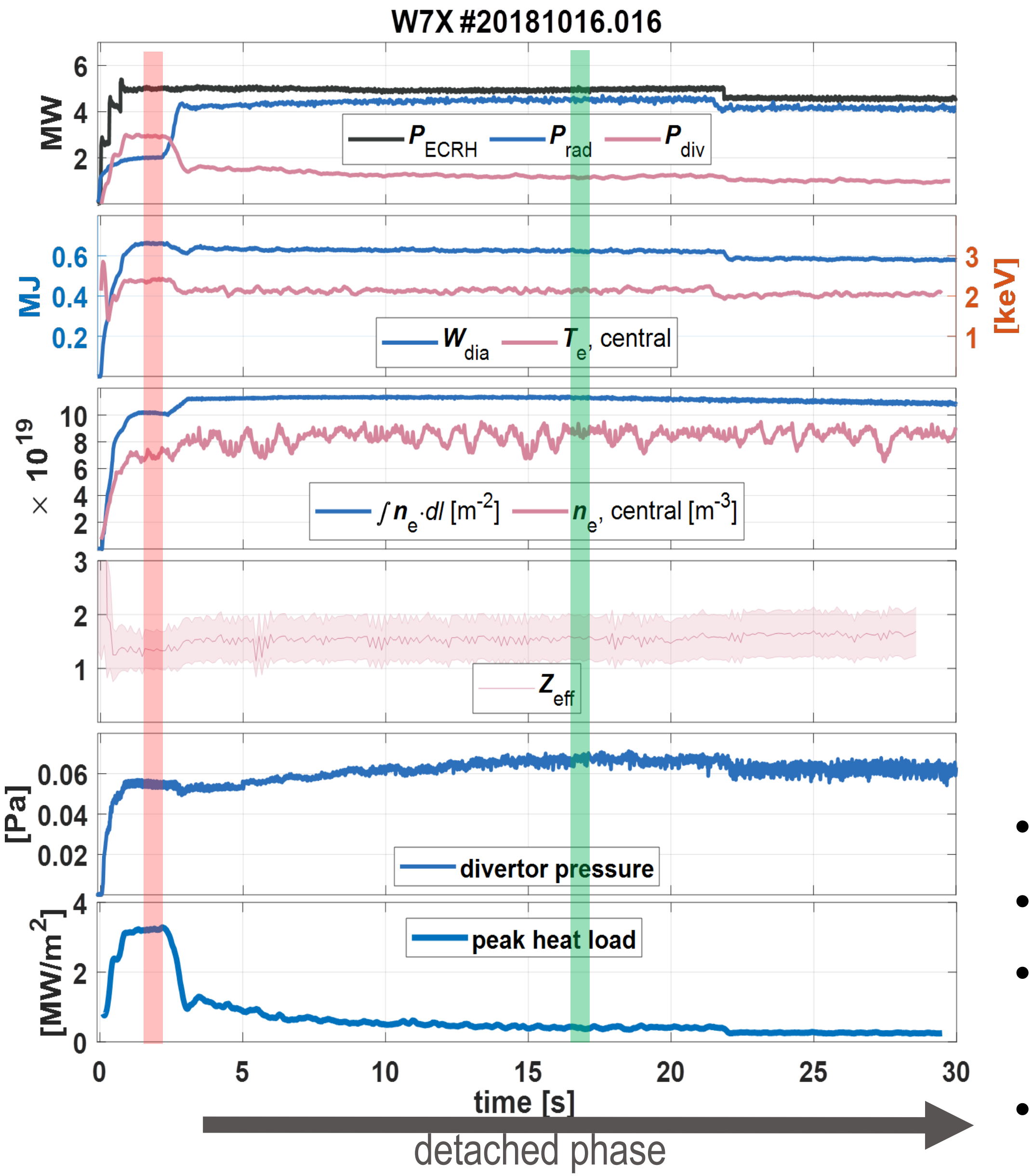
Low plasma density, heating power well above 10 MW,

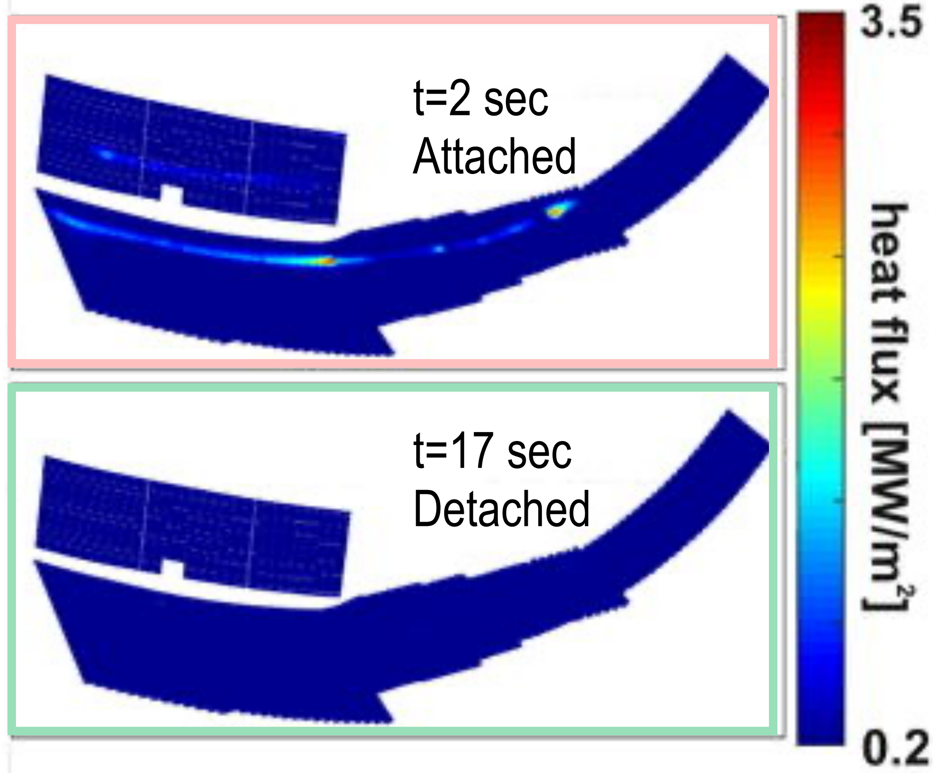
Attached operation in high-iota configuration (factor of ~2 lower wetted area)

Can we achieve detachment?

[1] Y. Gao et al., Nuclear Fusion 60 096012 (2020), [2] K. Hammond et al., PPCF 61 125001 (2019)
[3] V. Perseo et al, Nuclear Fusion (Letter), 59 124003 2019
[4] H. Niemann, P. Drewelow, M. W. Jakubowski, et al: Nuclear Fusion (Letter), 2020

Long, Complete Stable Detachment (>26 s) at W7-X

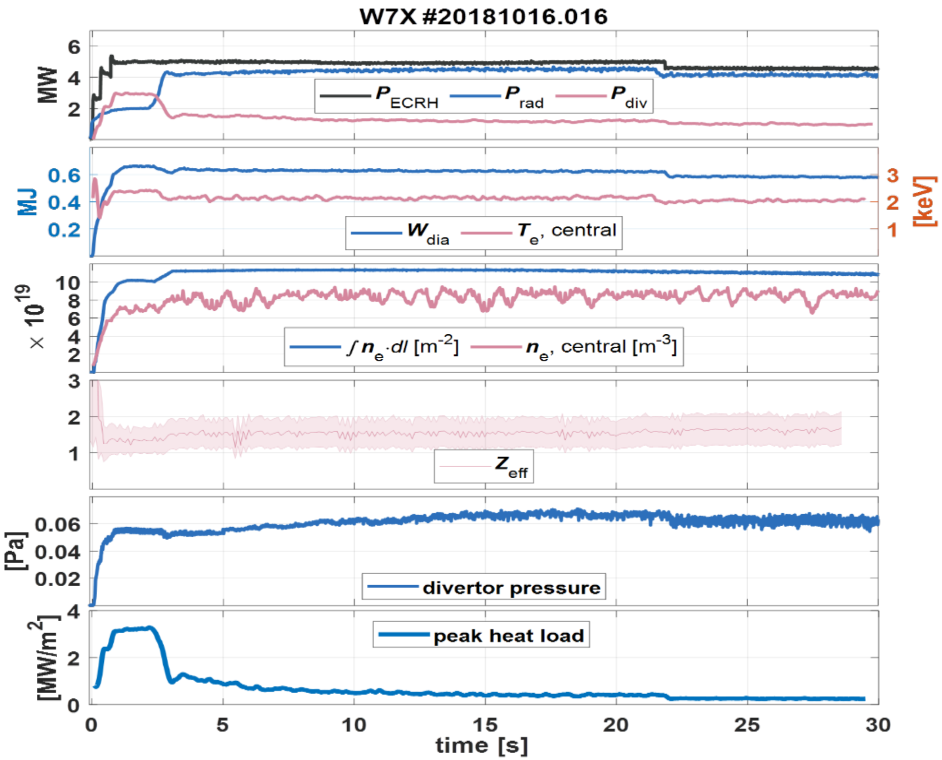


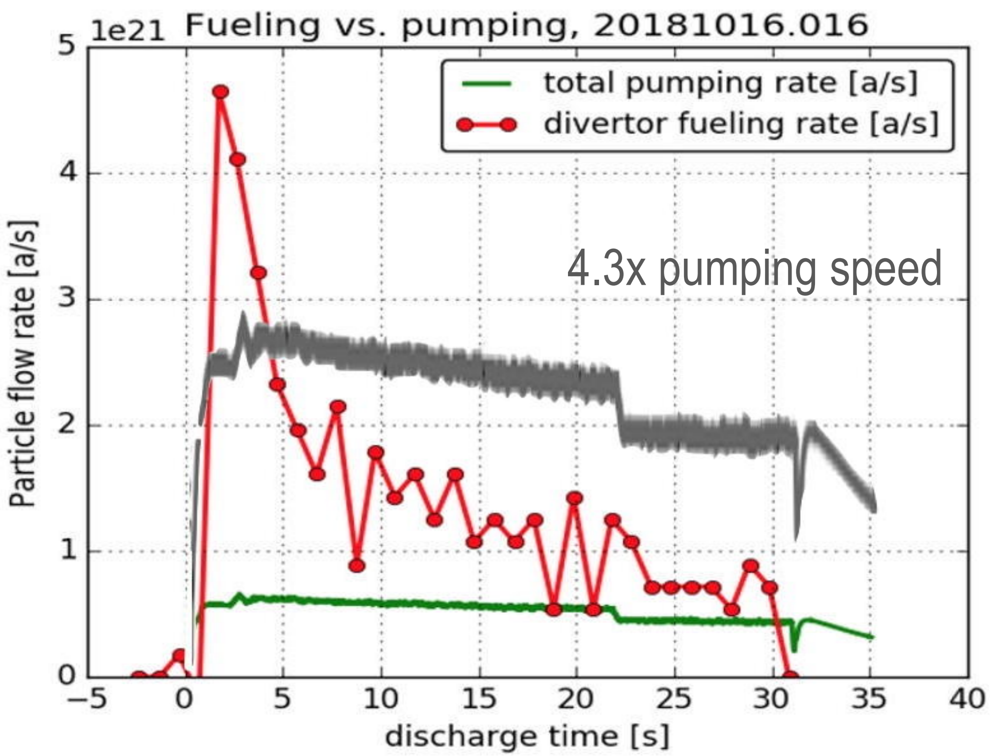


- Convective heat loads effectively disappear.
- Low and stable impurity content (Z_{eff}<2)
- Drop in stored energy ≲ 10% during detachment
- Efficient exhaust: neutral pressure compression factor p_{div}/p_{main}~20-30

(Schmitz et al NF 2021)

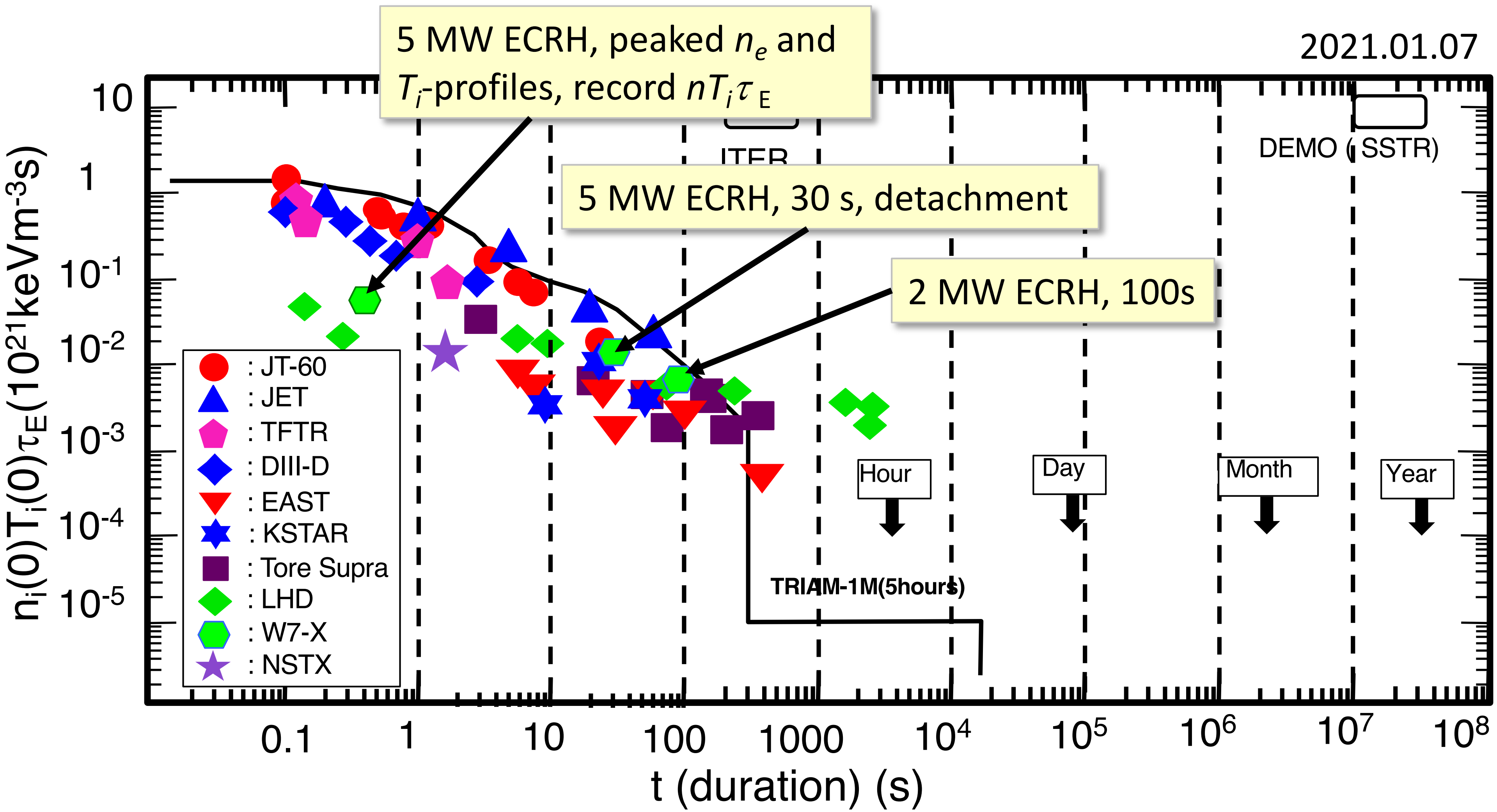
Divertor particle exhaust approaching steady-state





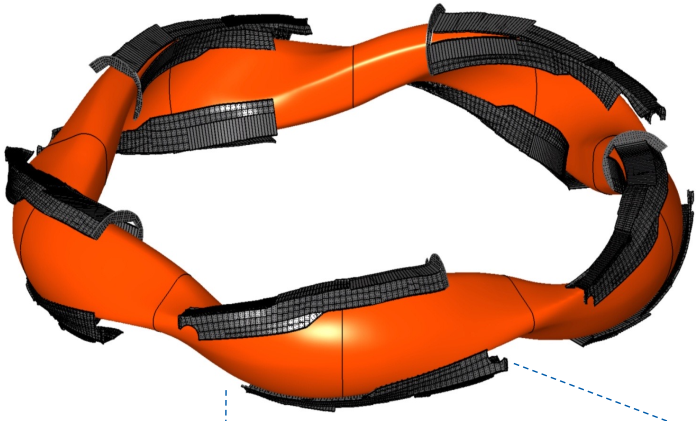
- Density control was demonstrated in long discharges with minor wall-pumping
- For the next phase, cryopumps will increase pumping speed by factor 4.3
- For more on divertor and SOL results, see
    - M. Jakubowski et al, F. Reimold et al, V. Perseo et al., C.Killer et al., this conference

Overall performance achieved so far (with uncooled divertor)



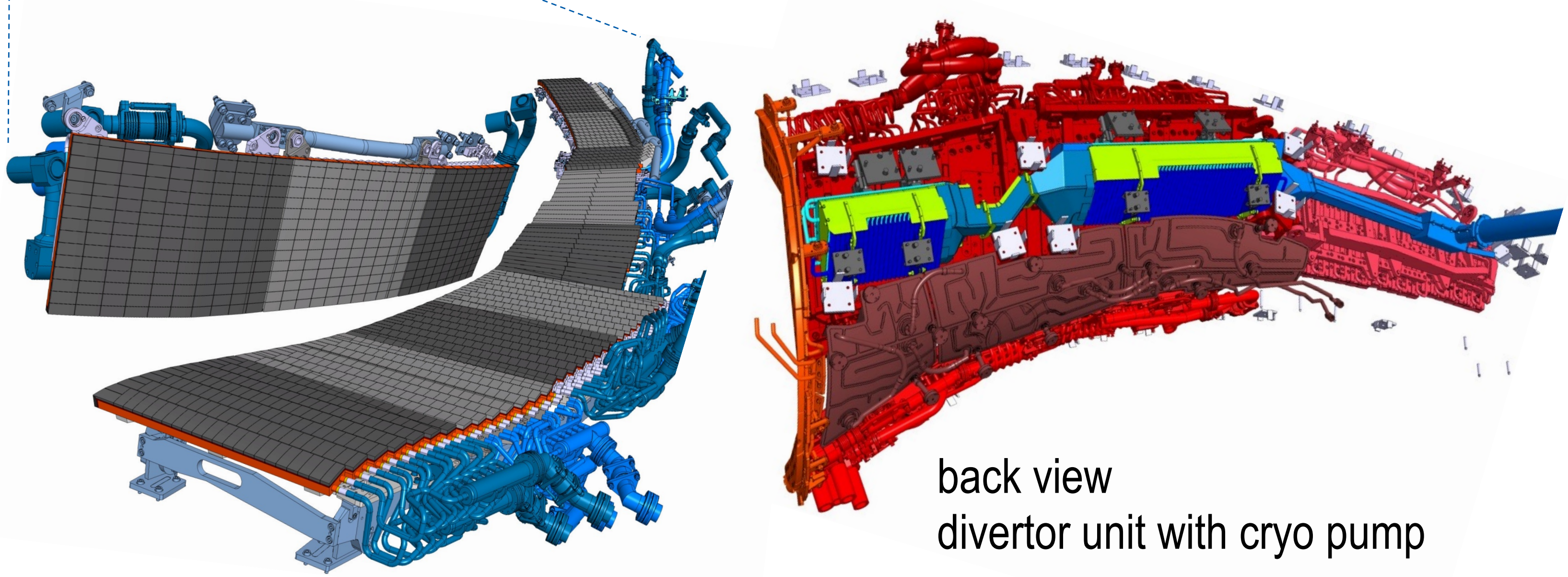
Courtesy of M. Kikuchi

Integration of the actively cooled divertor



High-heat-flux divertor on Wendelstein 7-X

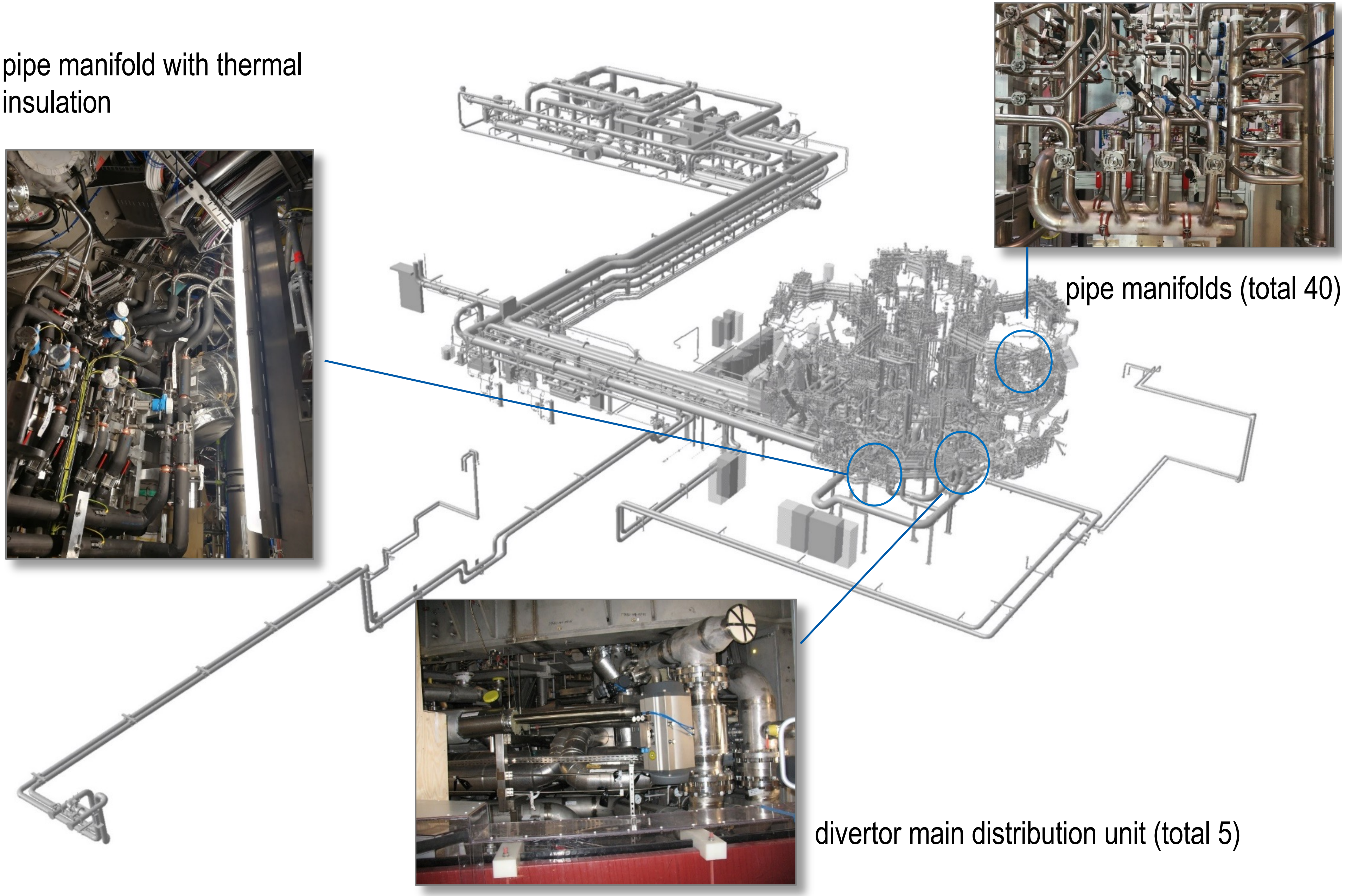
- Steady-state heat flux removal up to 10 MW/m^2
- Cryopumps are also being installed – giving >4x higher pumping speed



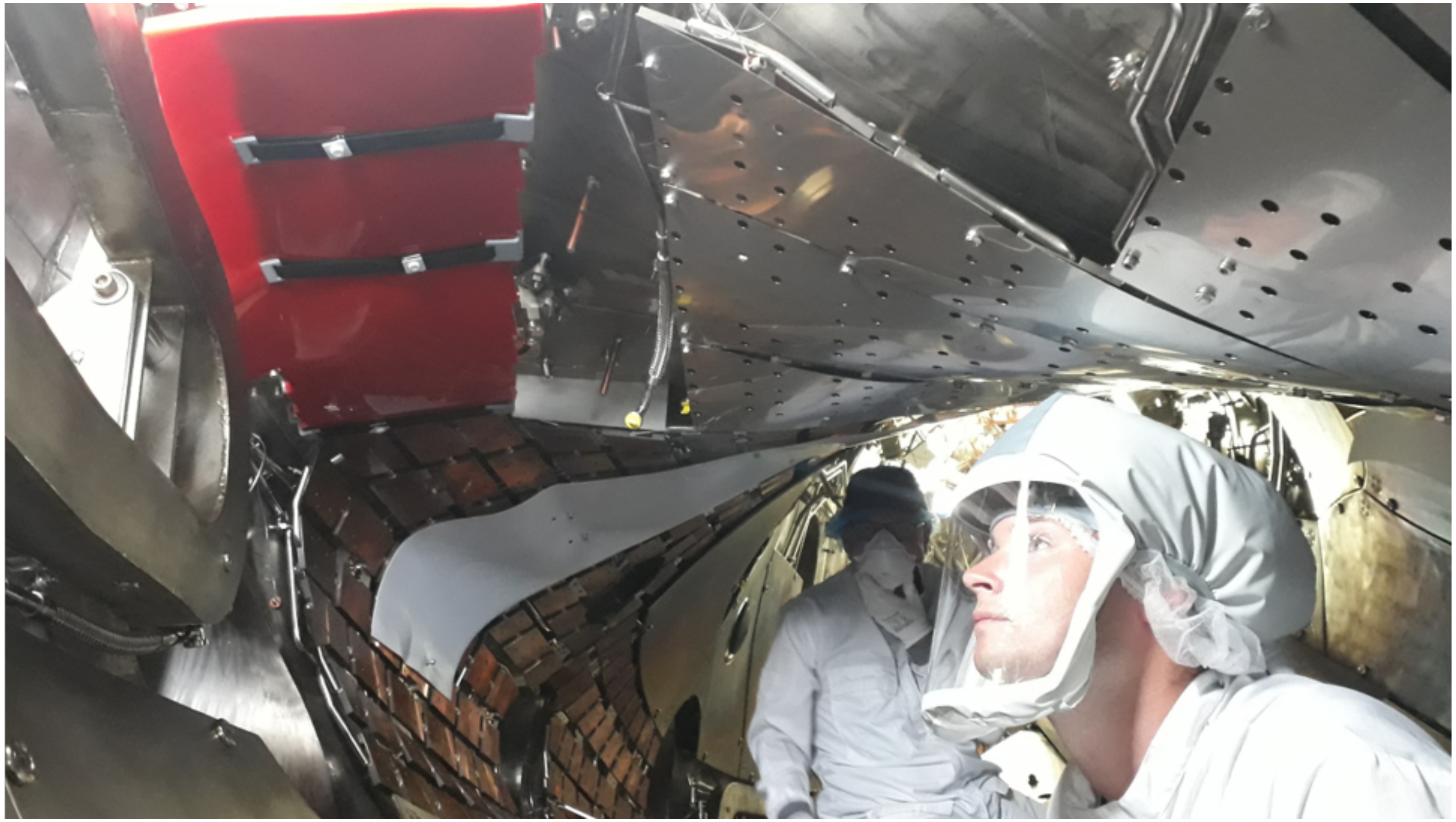
front view
divertor unit

back view
divertor unit with cryo pump

Infrastructure: Cryo-supply lines, water piping, etc

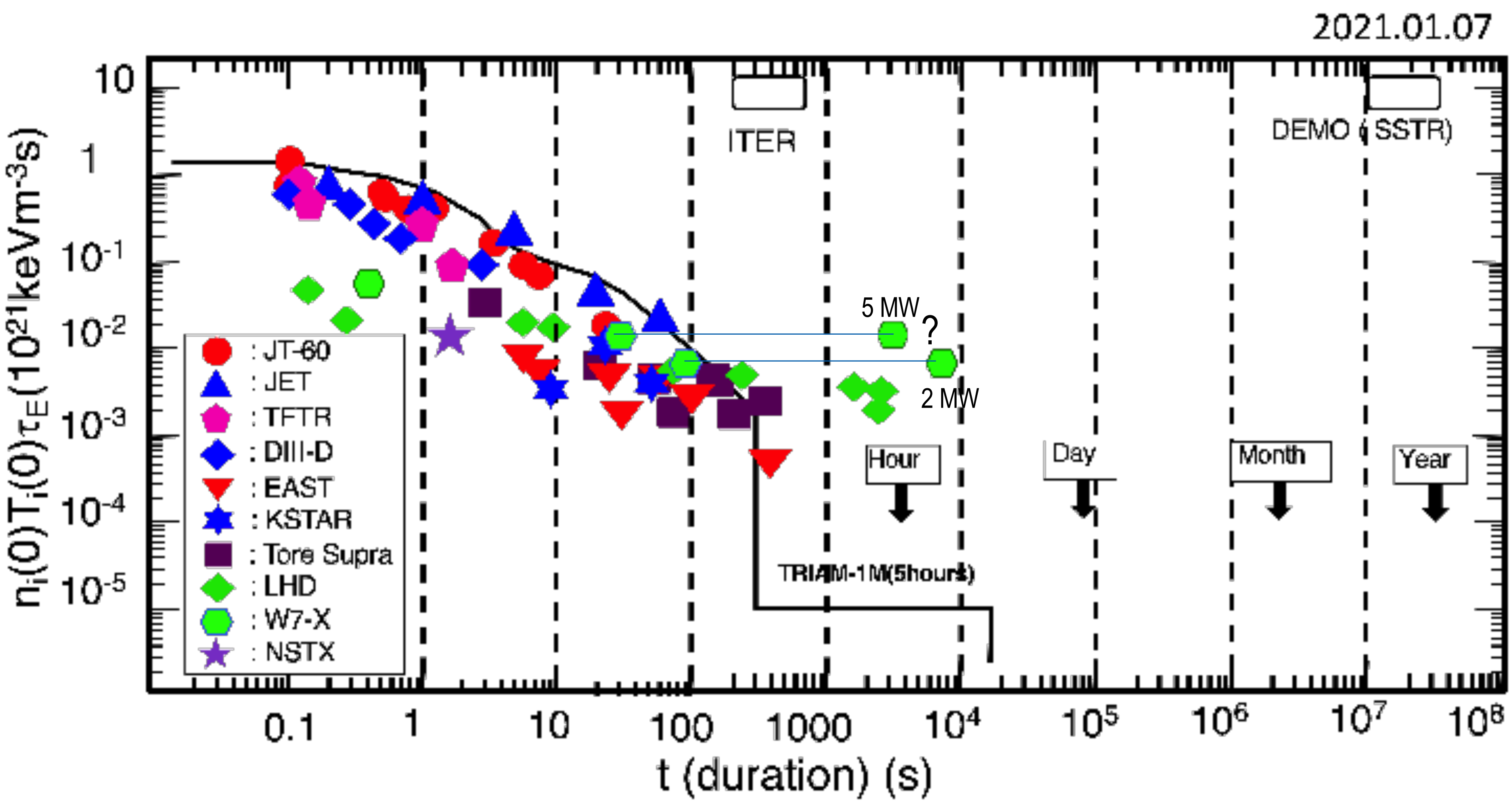


In-vessel assembly continues despite COVID-19



Effective countermeasures allowed restart of in-vessel work in July 2020,
on track to be completed Dec 2021

Conservatively extrapolated performance



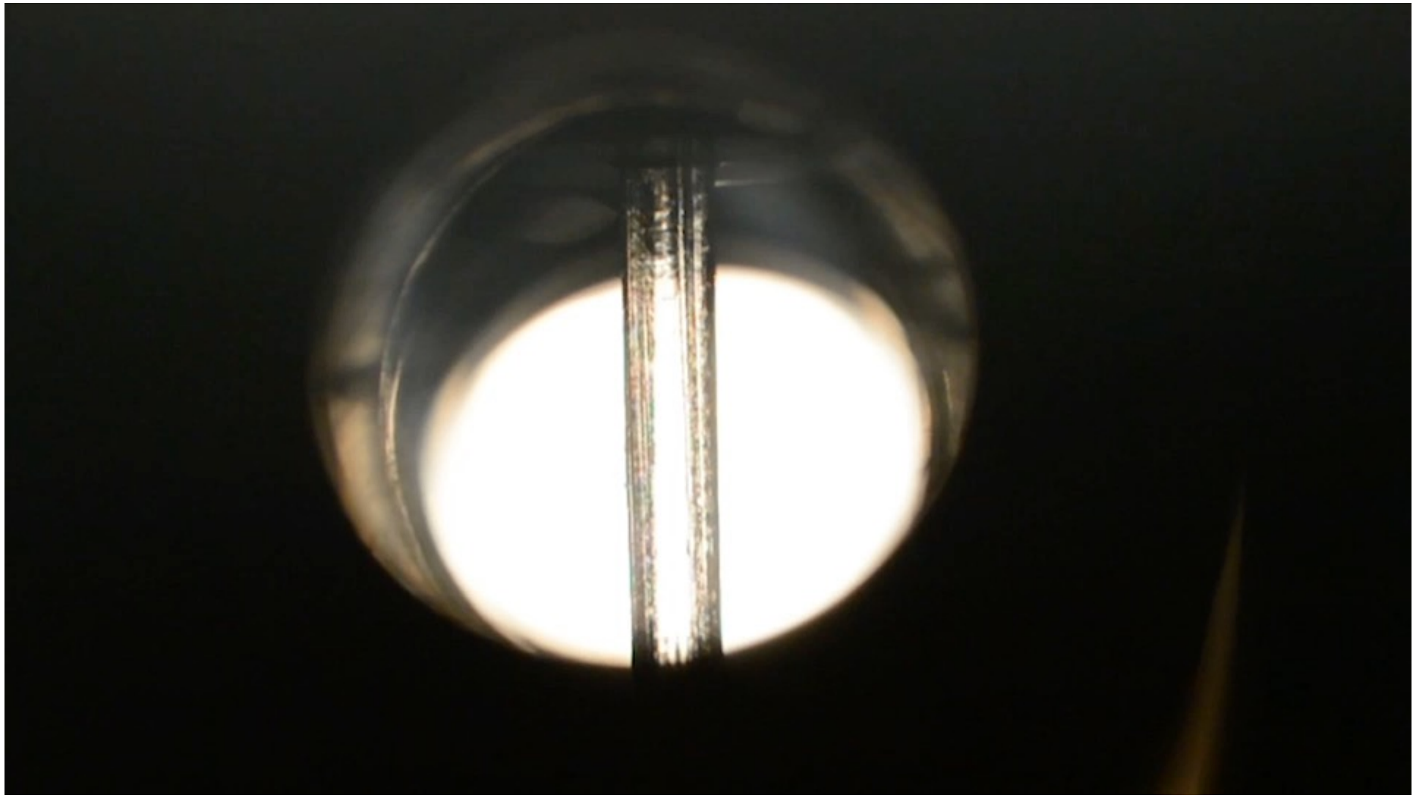
18 GJ per plasma pulse corresponds to 2 MW for 9000 sec, 5 MW for 1 hour, 10 MW for 30 minutes, etc.

Major upgrade: Continuous pellet-fueling system

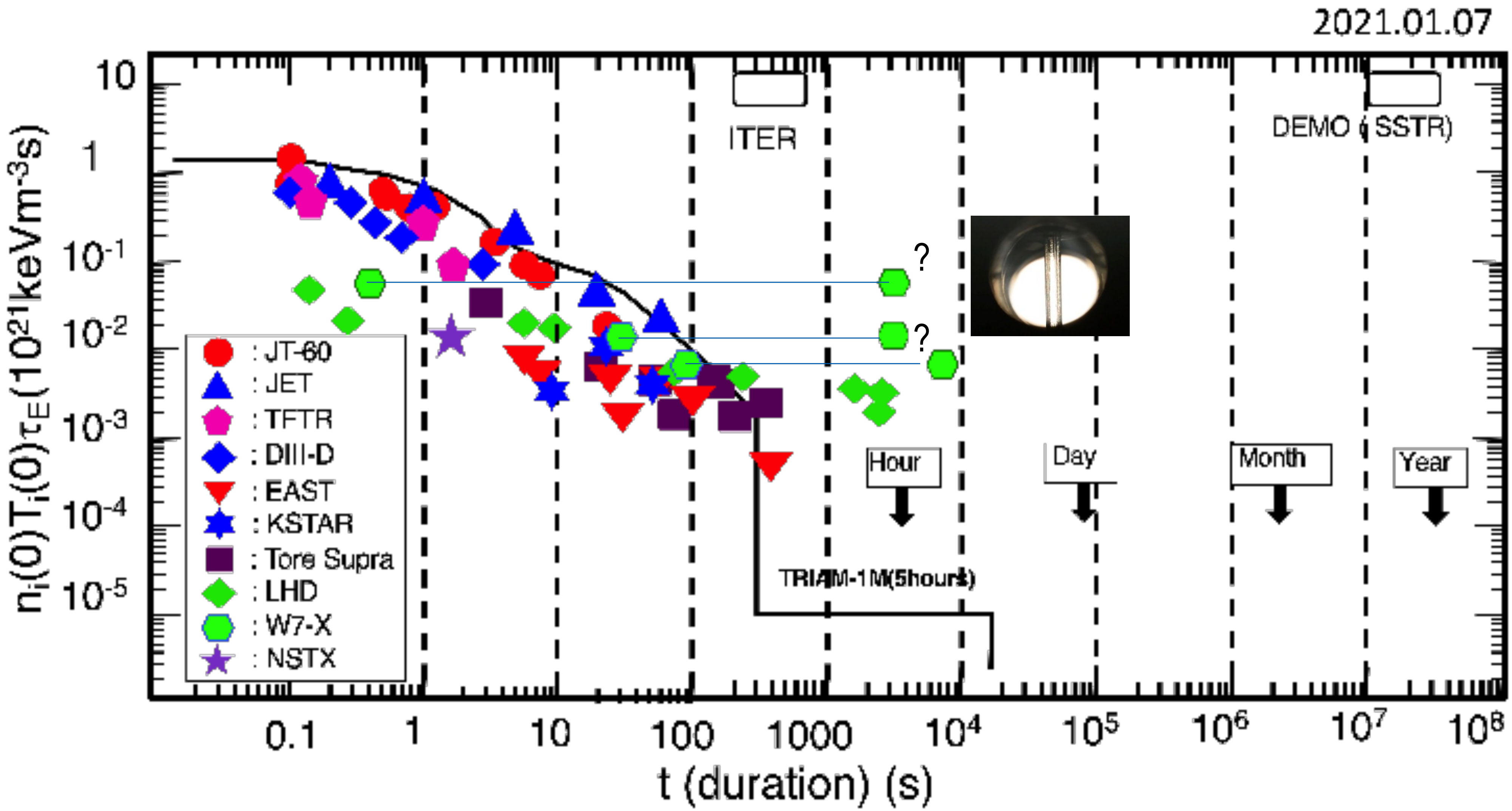
- The pellet system in the previous phase was only capable of short bursts of pellets, and could only sustain density peaking and high performance for brief periods
- The continuous pellet fueling system should be ready early in next operation phase
  Major collaboration led by US partners (ORNL and PPPL), also including NIFS in Japan.

Continuous extrusion of H ice has been achieved at a rate of 1.2×10^{22} atoms/sec (should be adequate)

Much higher pellet speeds expected (x3), adjustable pellet size



If high-performance can then be sustained…



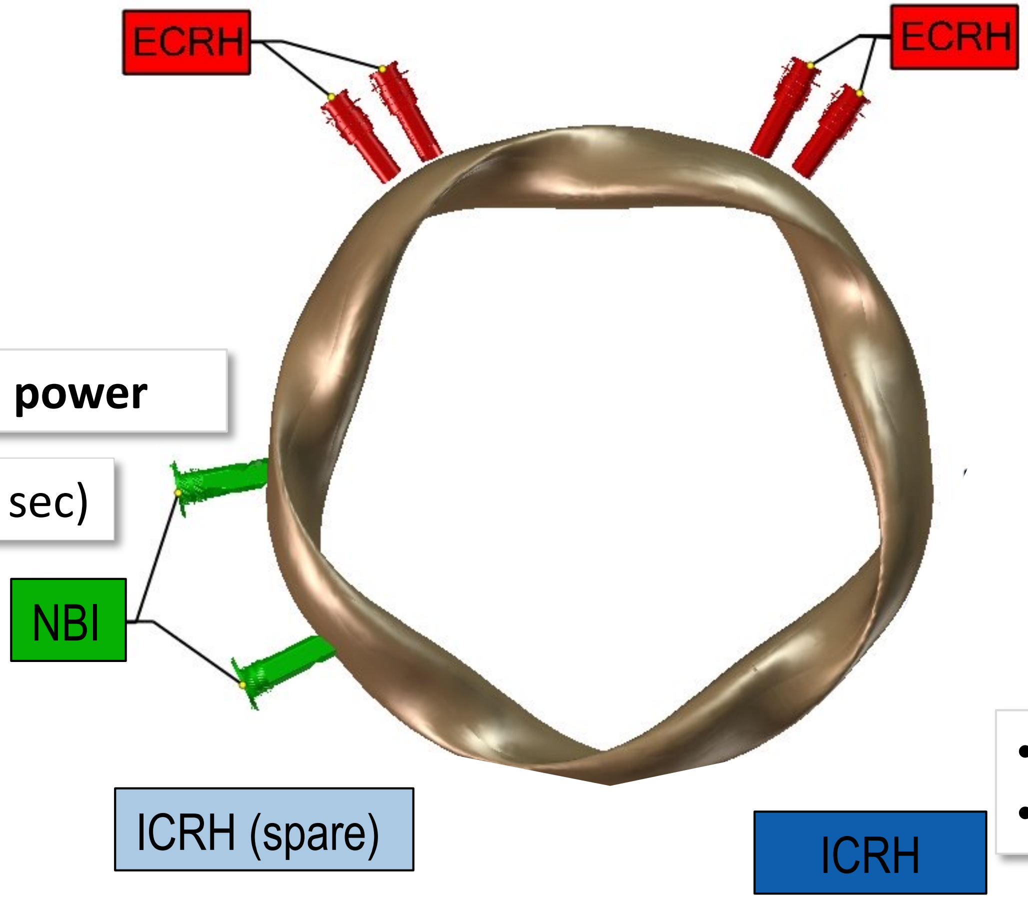
Near-term extensions of heating systems

- **Extension of ECRH facility from 10 to 12 gyrotrons**
- **Program to upgrade from 1 MW to 1.5 MW per gyrotron**

2nd harmonic @ 140 GHz
Steady-state (30 minutes)

- **Doubling NBI power**

Pulsed (~ 10 sec)



- **Adding ICRH**
- ≤ 1.5 MW (25-38 MHz)

Pulsed (~ 10 sec)

Summary

- A number of milestones and results have been achieved already in early operation of W7-X:
  - Proof that the optimization to reduce neoclassical transport is successful
  - First examples of turbulence-suppressed plasmas – qualitative understood
  - Stable, complete divertor detachment, with good exhaust efficiency
  - Good divertor impurity screening and retention
  - Core impurity accumulation seen only in turbulence-suppressed discharges
- Preparations are well underway for steady-state operation with significantly enhanced fueling, pumping, and heating capabilities
  - End of in-vessel installation projected for December 2021
  - First plasma operation with a water-cooled divertor expected for September 2022