U.S. Research on International Stellarators

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Presented to:
NAS Committee for a Strategic Plan for U.S. Burning Plasma Research

Overview

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1. The motivation and options for international stellarator research

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3. How to enhance international stellarator research within the United States

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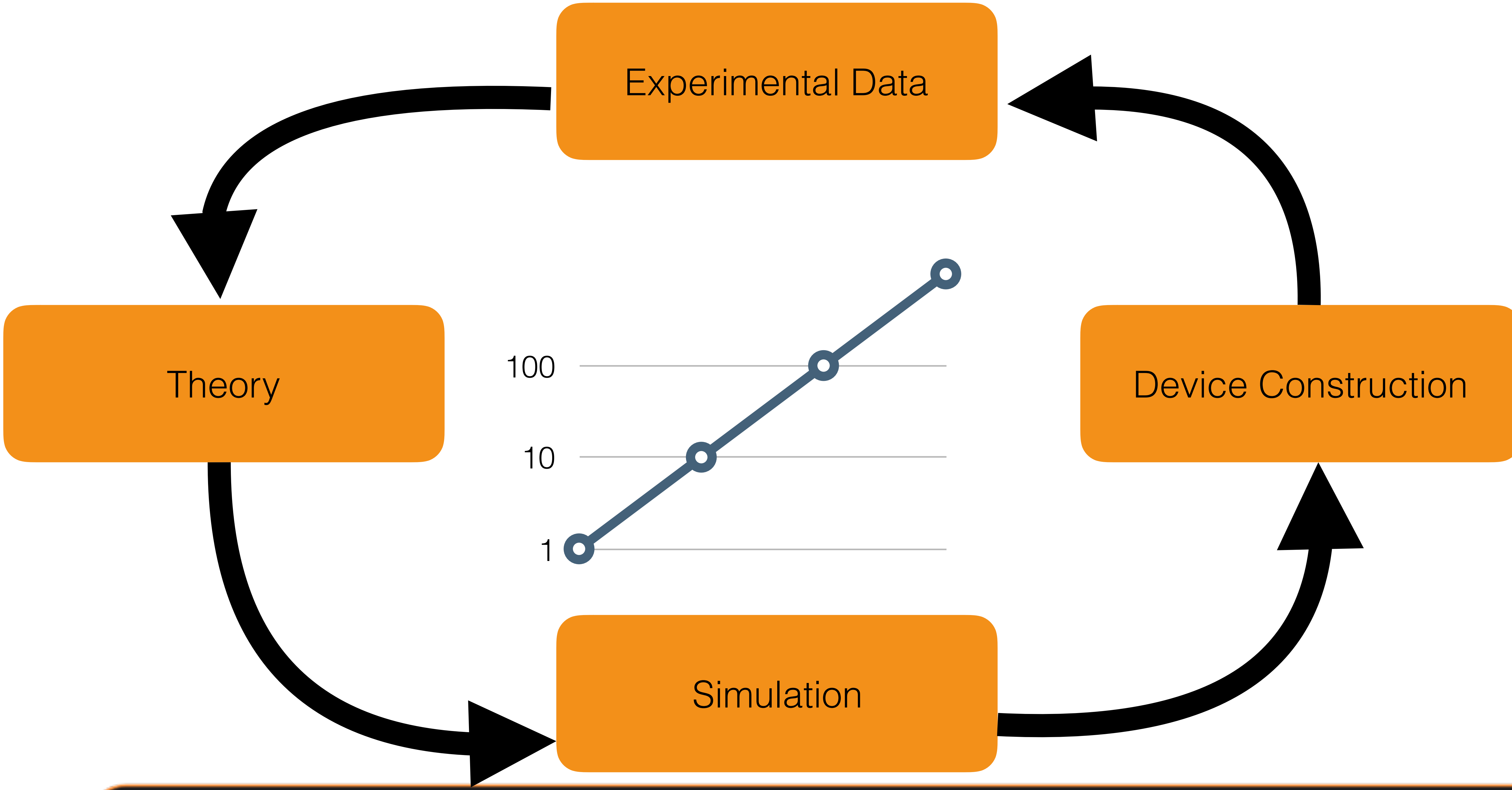
2. My experience as a collaborator on the Wendelstein 7-X stellarator
3. How to enhance international stellarator research within the United States
4. Strategic elements that might broadly advance fusion research in the U.S. and promote leadership in the field.

Stellarators provide a clear path toward fusion energy

The stellarator concept poses the challenge of achieving a burning plasma state, as a purely design problem.

- Steady-state is intrinsic
- Fully non-inductive operation
- Stability limits are soft
- Transients are non-disruptive
- The challenge is to build in the confinement

Stellarator performance hinges on new devices with increased capability



Stellarators allow us to address the needs of burning plasmas now

Problems they solve

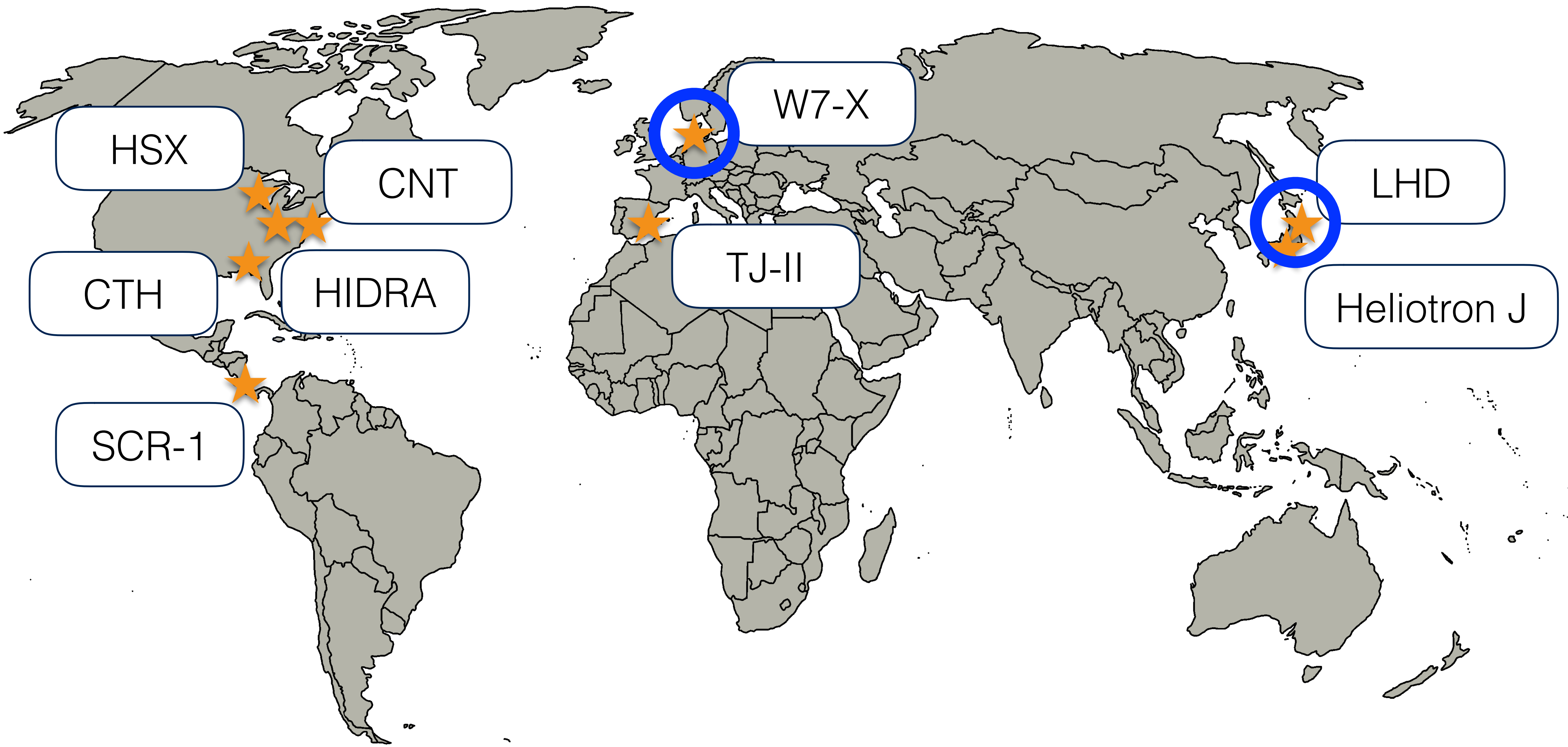
- Steady-state
- Transient-free
- Non-inductive

Topics to be addressed

- High-performance
- Impurity confinement
- Plasma-wall interactions
- Tritium Breeding
- Magnet Design

Why international stellarator research?

Of the operating stellarators in the world only two are capable of long pulse, high beta operation.



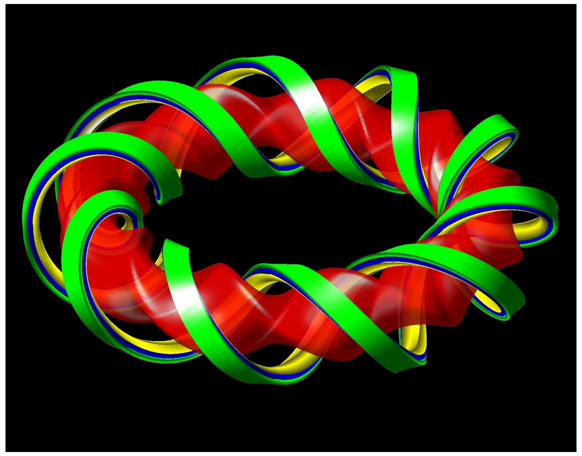
The U.S. has a growing international collaborative effort

In the past decade the U.S. has had active (funded) collaborations on both the LHD and W7-X devices.

LHD

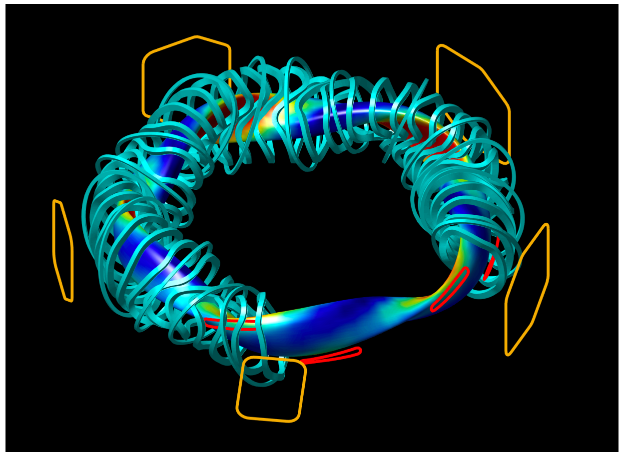
-Xray Imaging Crystal Spectrometer

-Equilibrium Reconstruction



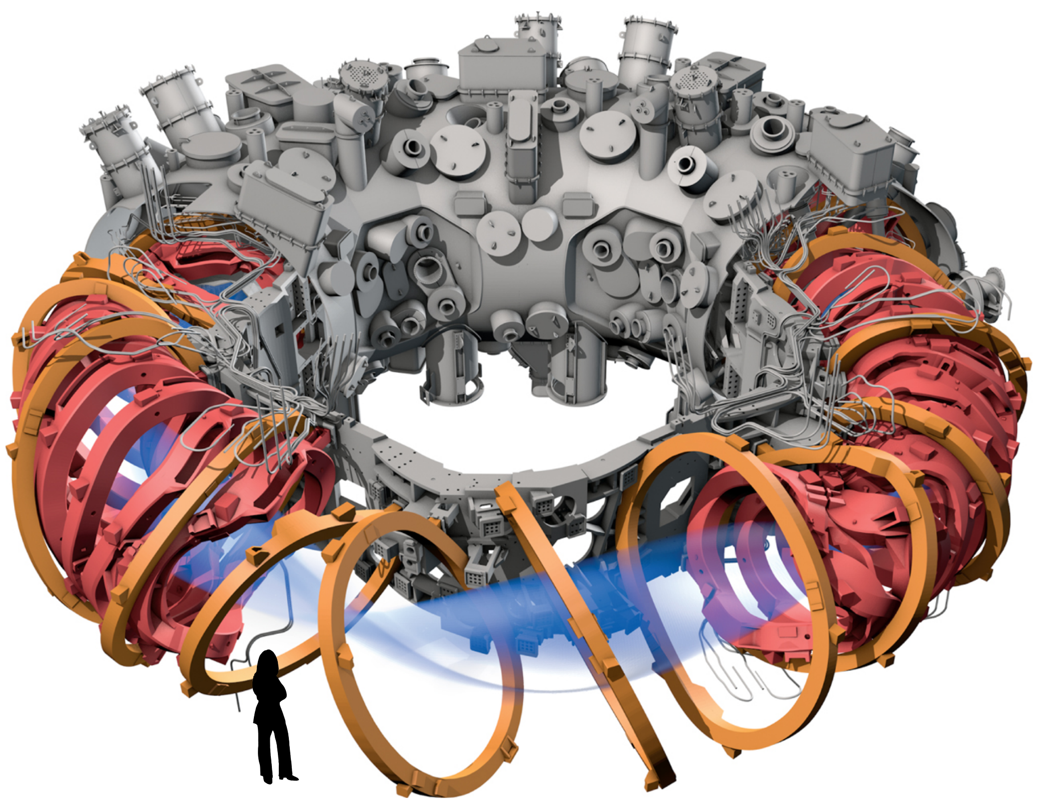
W7-X

- Xray Imaging Crystal Spectrometer
- U.S. Built Trim Coil System
- Equilibrium reconstruction
- Divertor Scraper Element Program
- Phase Contrast Imaging System
- Island divertor physics program



Wendelstein 7-X

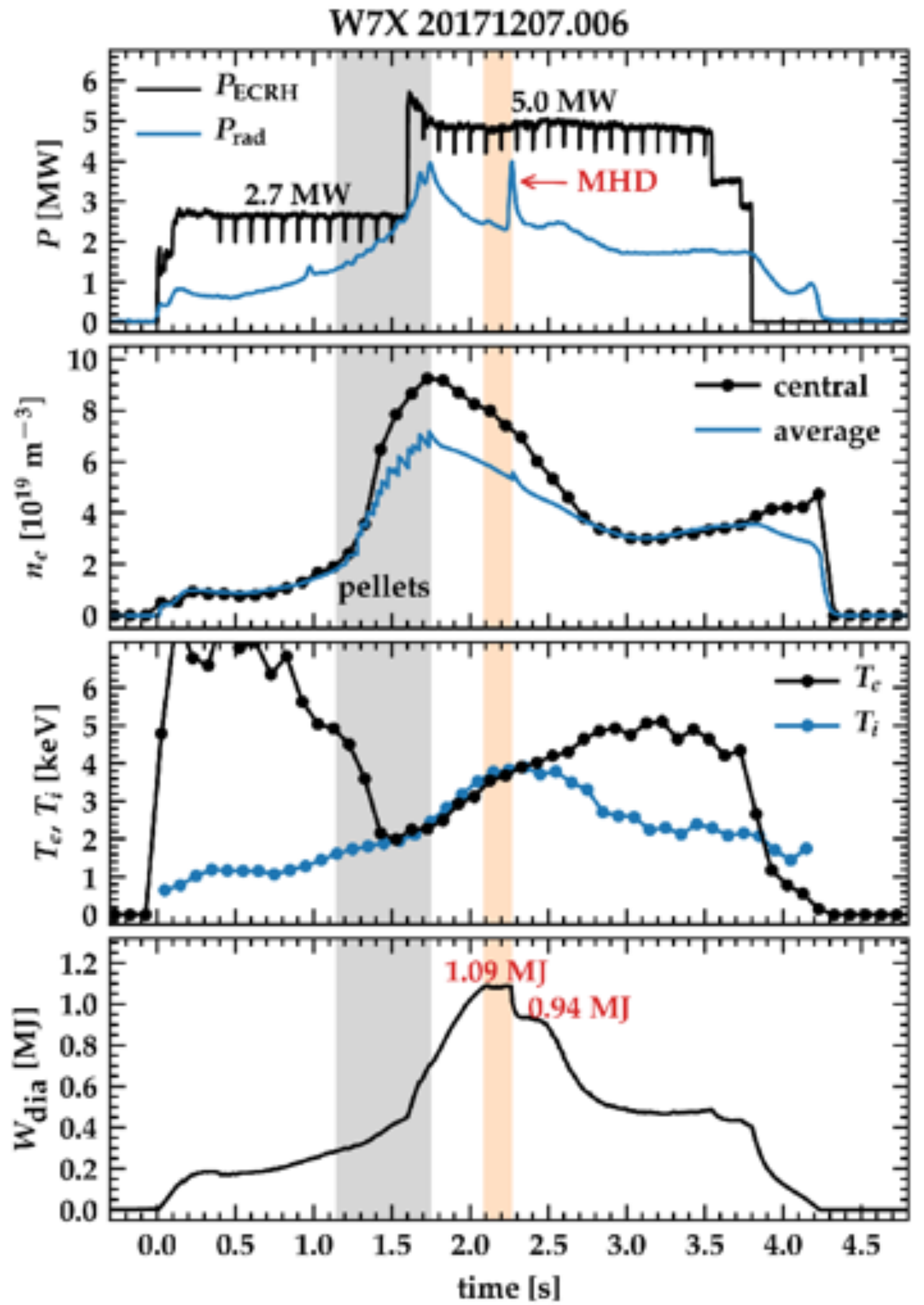
Wendelstein 7-X is the worlds first high-performance optimized stellarator



Operation started in 2015

- Quasi-isodynamic optimization
- 1800 second plasmas planned
- 10 MW steady-state heating
- 3D divertor geometry
- Stored energies in excess of 1 MJ
- 27 m^3 plasma volume

W7-X has already achieved 1% beta



- 5 MW X-mode discharge
- Low density heating mode
- Electron gradients steep core-edge
- Possible MHD limit observed

Slide courtesy Sergey Bozhenkov (IPP-HGW)

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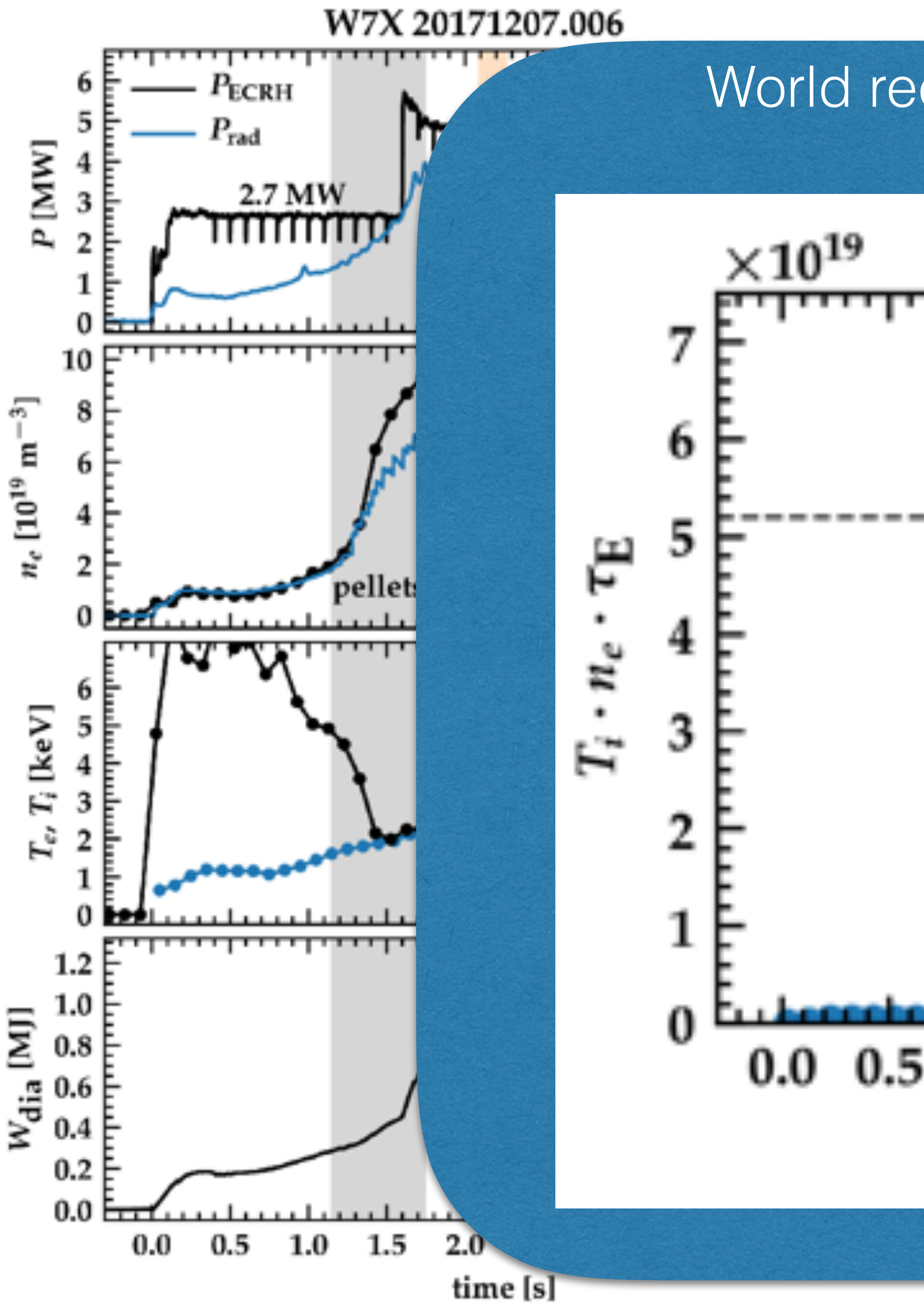
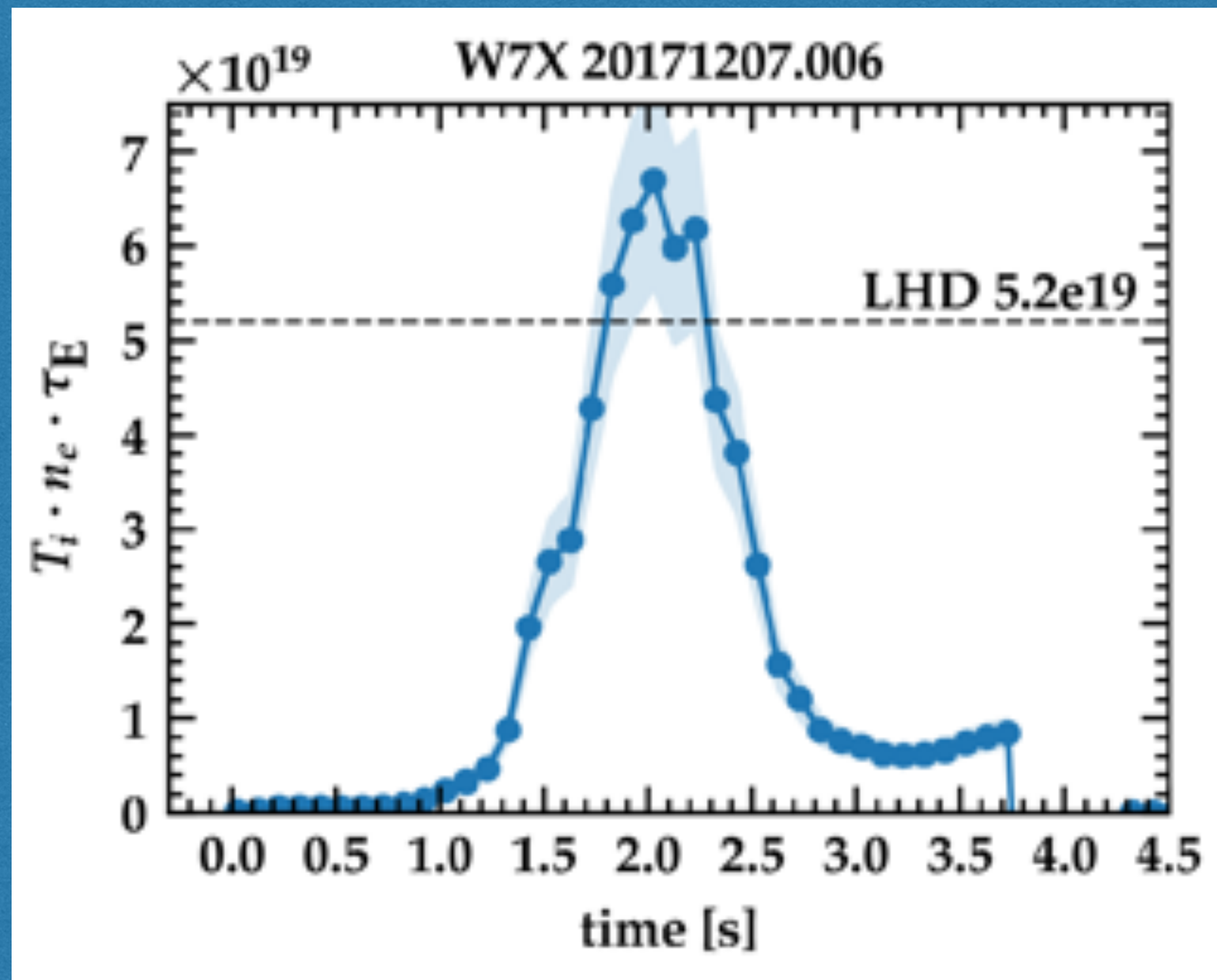


World record stellarator triple product



rge

node

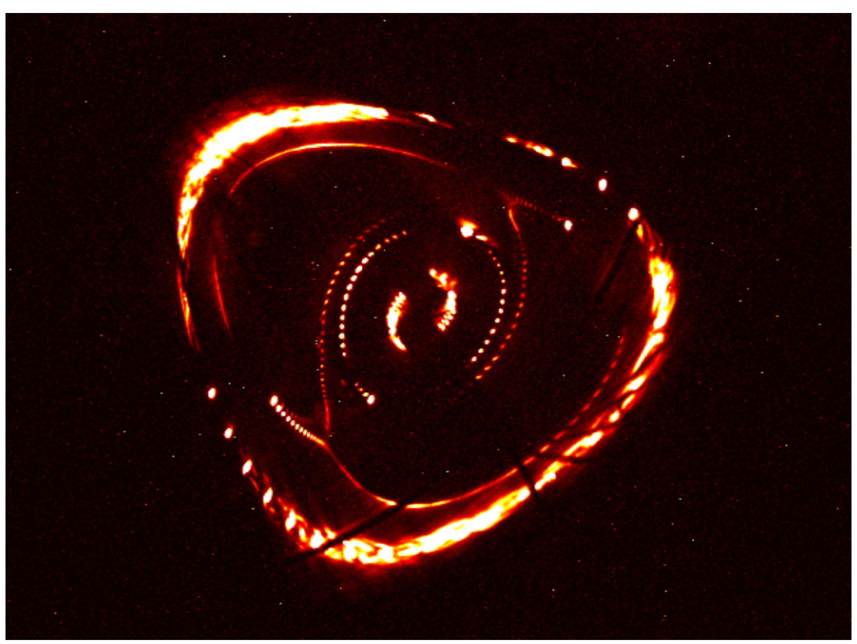
ep

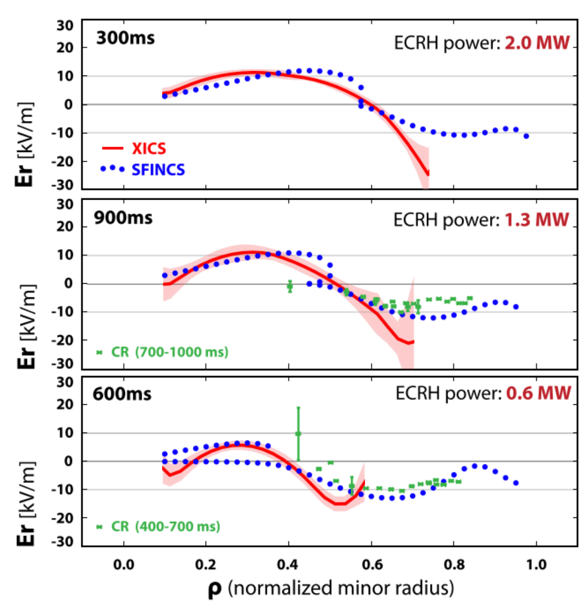
served

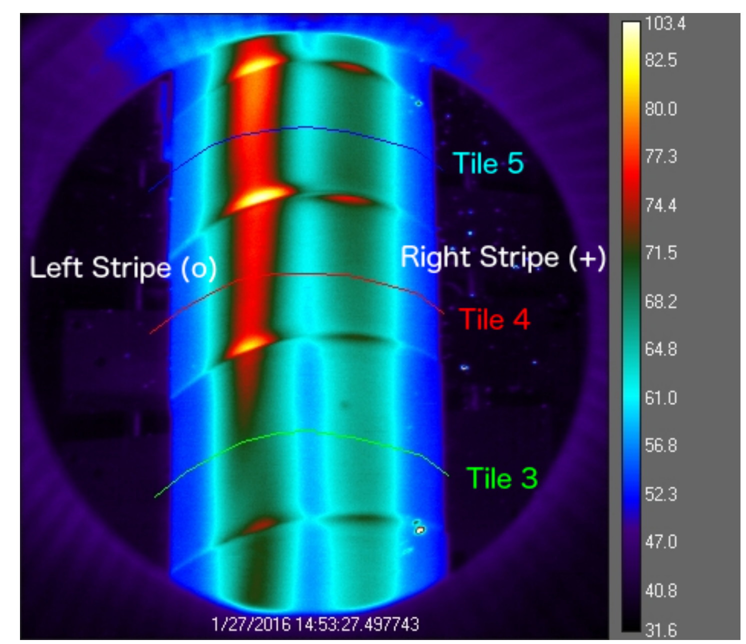
Slide courtesy Sergey Bozhenkov (IPP-HGW)

The U.S. fills key roles in the W7-X experimental program

- Assessment of error fields in stellarators
- Role of 3D fields in power exhaust
- Confirmation of optimization and confinement
- Development of divertor concepts for steady-state power exhaust
- Direct input to the planning of the experimental campaign



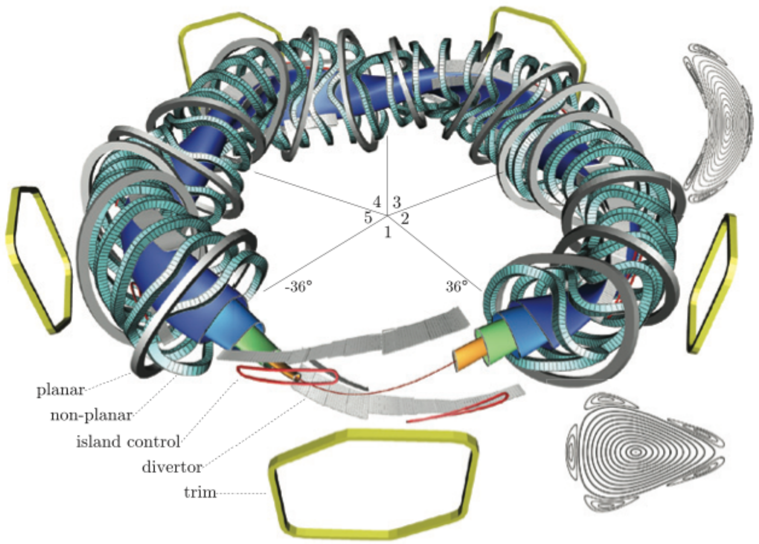




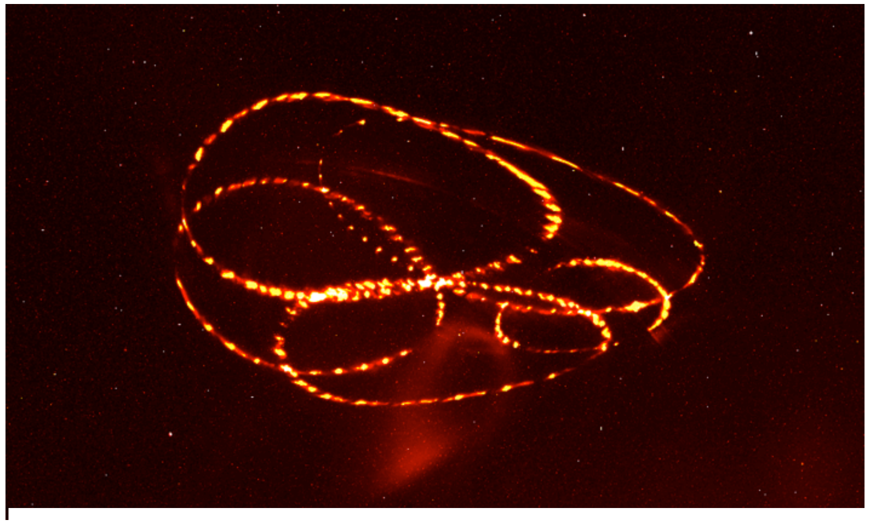
U.S. Trim Coils play major role in W7-X scientific exploitation

- First confirmation of coil assembly accuracy
- First actuation of limiter heat loads
- First assessment of coil deformation due to EM loads
- Essential to long-pulse operation through divertor load symmetrization

IPP engineers and scientists standing inside a trim coil after delivery.



The trim coils are 5 water cooled copper steady-state coils on W7-X.

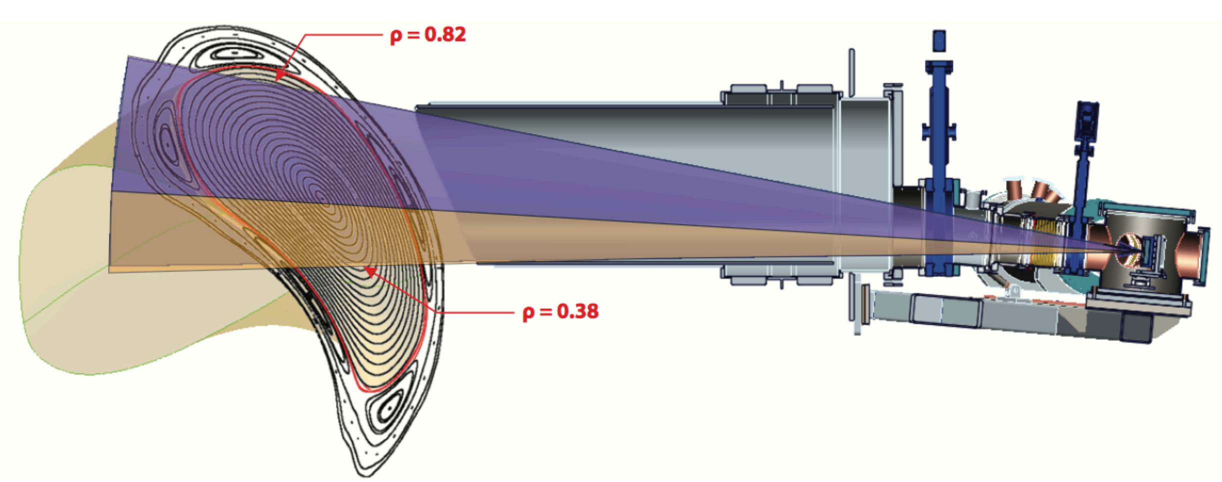


Superposition of 5 flux surface images, showing actuation of configuration by the trim coils

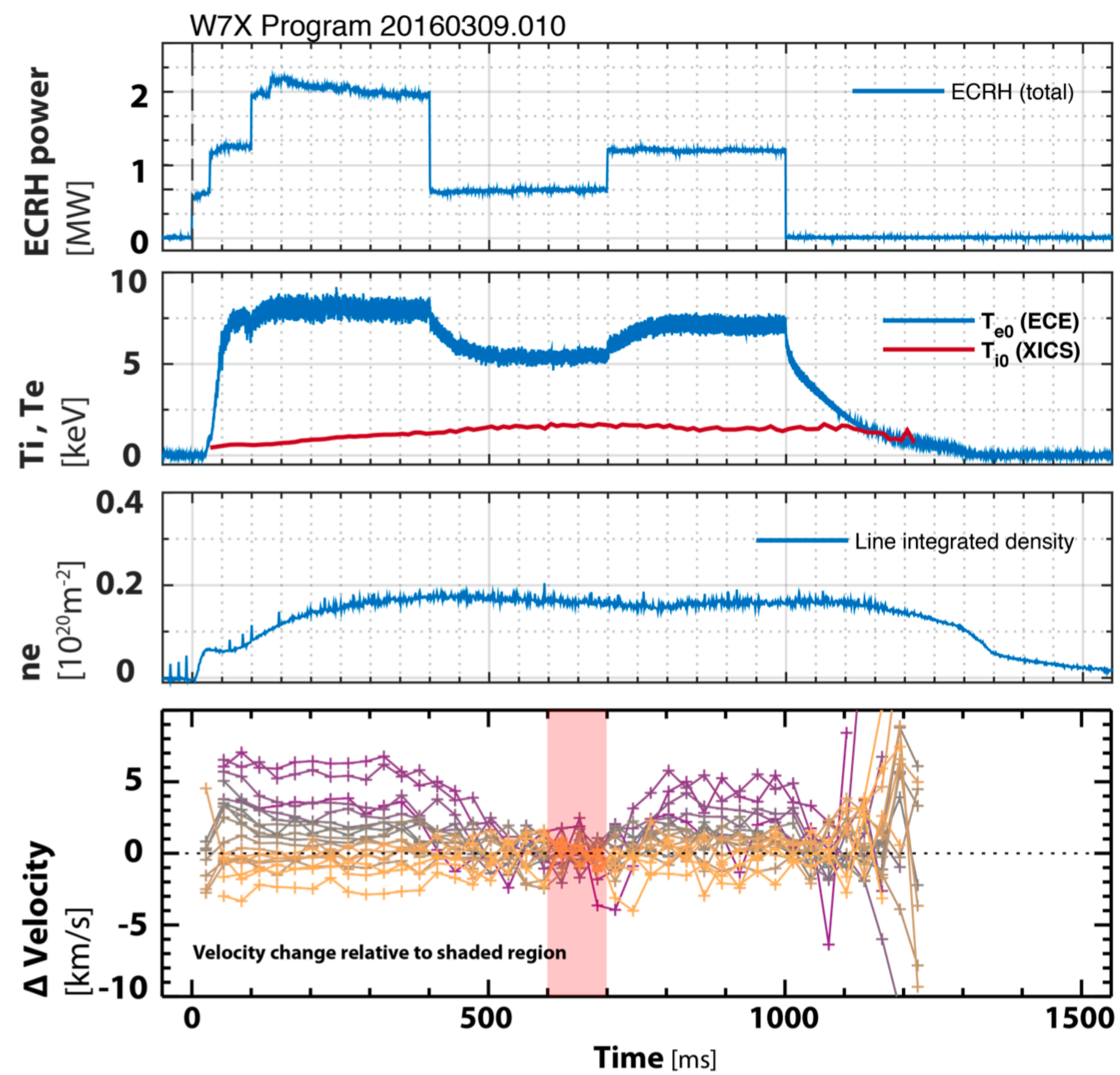
Lazerson *et al.* 2016 *Nucl. Fusion* **56** 106005

X-Ray Imaging Crystal Spectrometer (XICS) is confirming optimization of W7-X

- First measurement of ion temperature in W7-X
- First measurements of poloidal flows on W7-X
- Actively being used to assess impurity transport
- Provides data essential to confirming optimization



Geometry of the XICS viewing chords in W7-X.

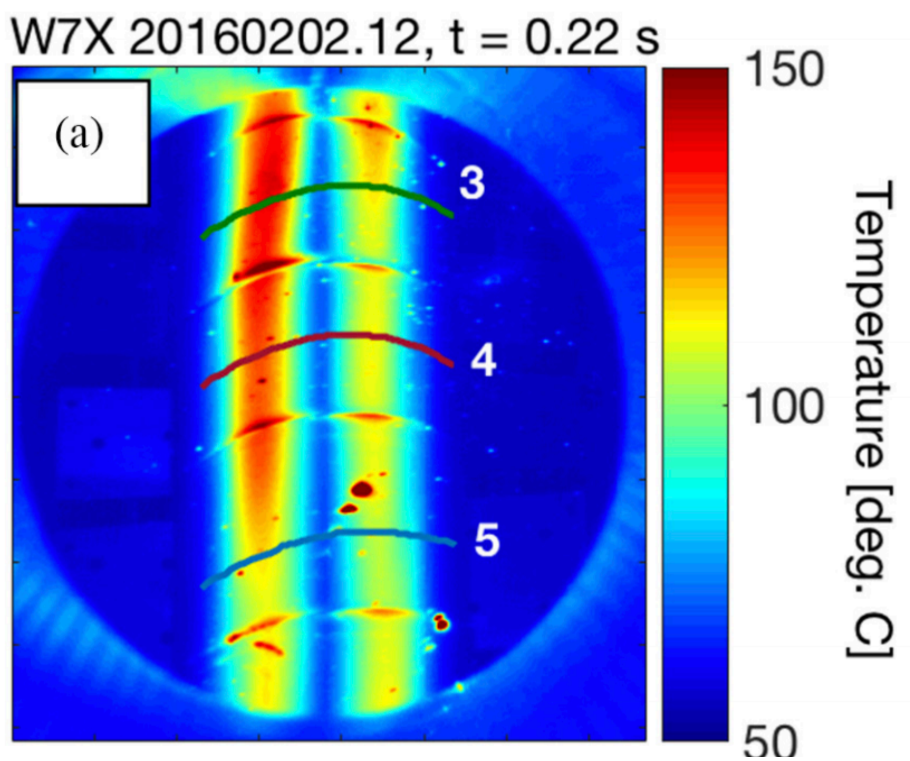


Ion temperatures routinely measured in W7-X by XICS.

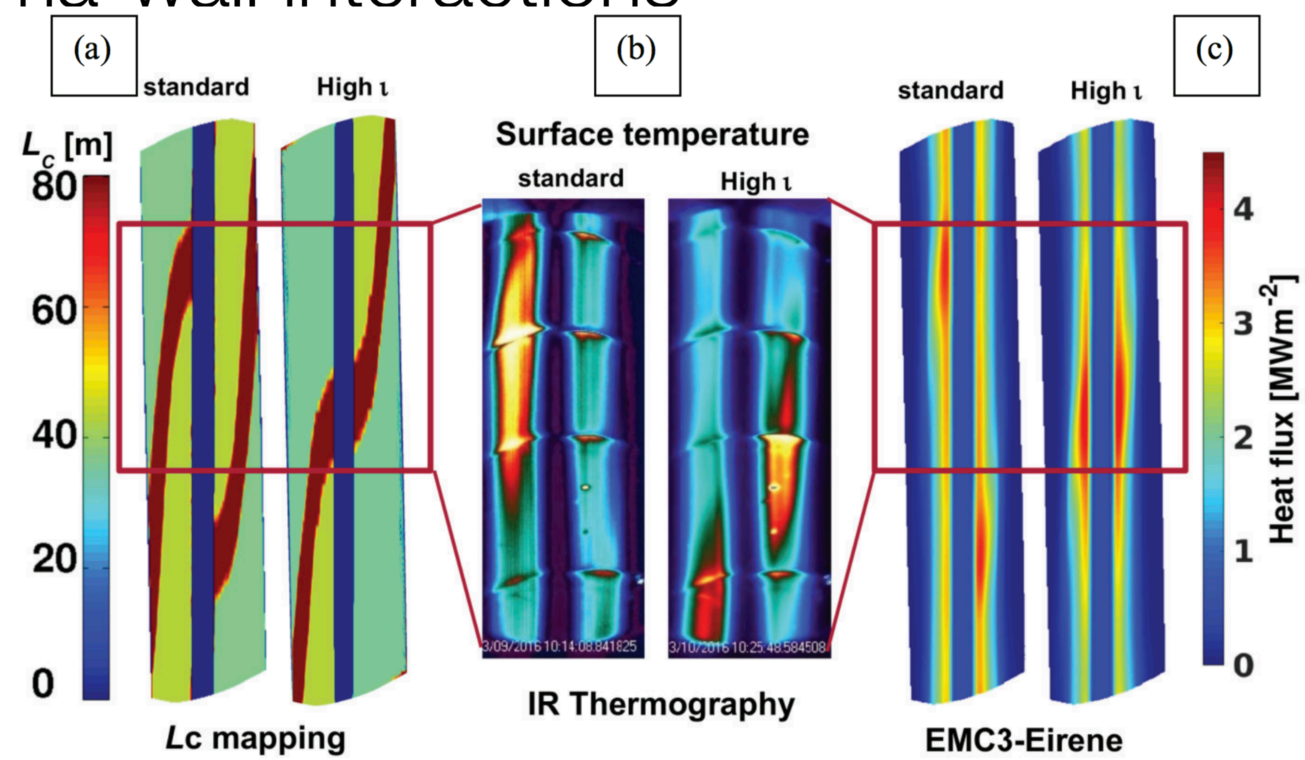
Pablant *et al.* 2018 *Phys. Of Plas.* **25** 022508

High resolution infrared camera program played key role in the limiter campaign

- Provided first measurement of heat flux to limiters in first operational campaign
- Provided data key to scrap-off-layer modeling
- Provided first confirmation of plasma-wall interactions



Typical image from LANL FLIR camera of limiter during first experimental campaign.

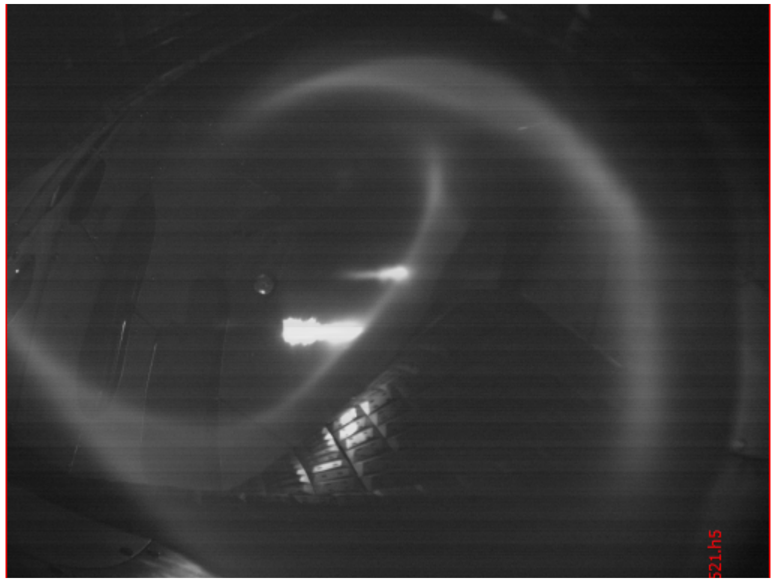


FLIR images (b) confirmed ability to use both field line connection length (a) and EMC3_EIRENE simulation (c) for predictive estimates of heat loads

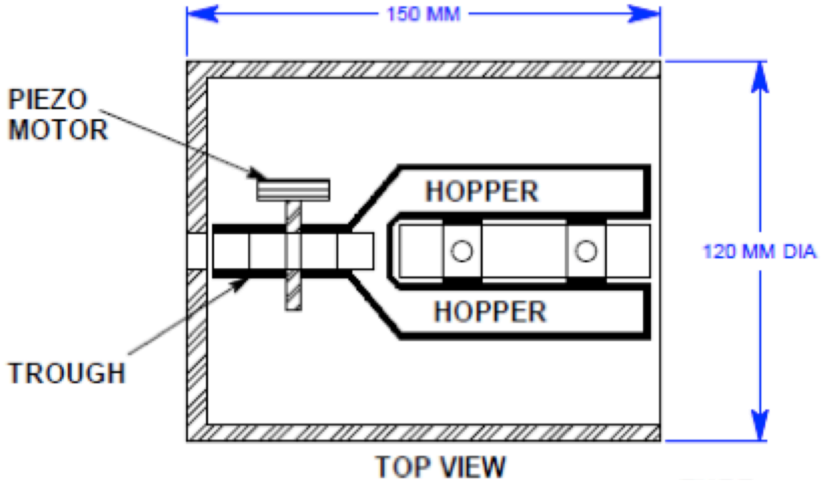
Wurden *et al.* 2017 *Nucl. Fusion* **57** 056036

The U.S. is poised to tackle serious reactor-relevant issues using W7-X in the next 5 years

- Steady-state fueling (Pellet Injector Program)
- Steady-state wall conditioning (Boron Powder System)
- Transport control (XICS Program, Heavy Ion Beam Program)
- Steady-state heat exhaust (Divertor Program)


Fast camera image of high field side pellet injection

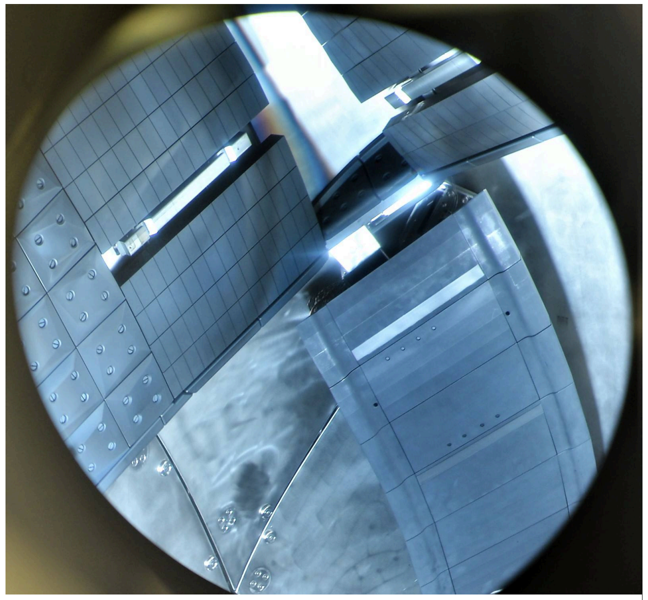

IR camera view of scraper element installed in W7-X



Depiction of boron powder head for manipulator

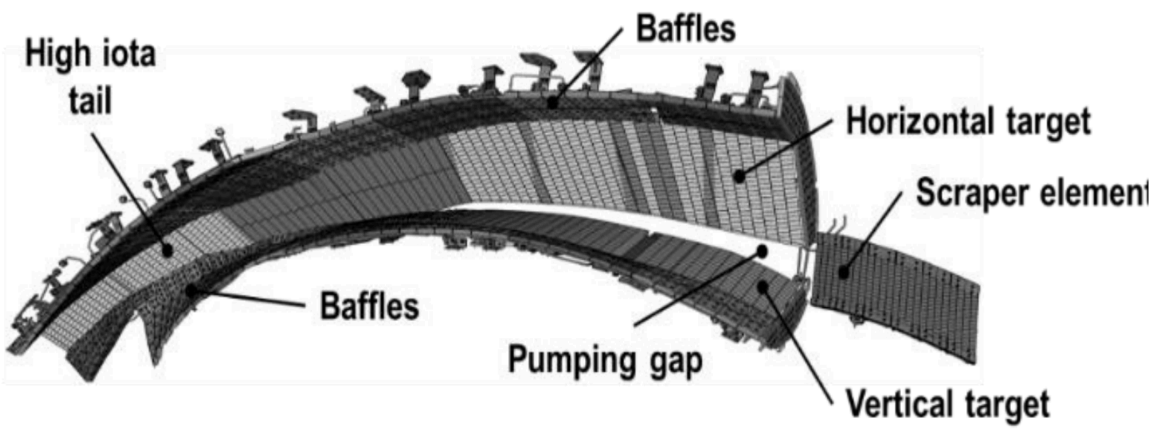
U.S. divertor program poised to make a large impact in the upcoming campaign (OP1.2b 2018)

- First test of divertor protection element (scraper)
- IR cameras to assess heat loads
- Langmuir probe array to assess plasma edge
- Filter-scope system to assess impurities

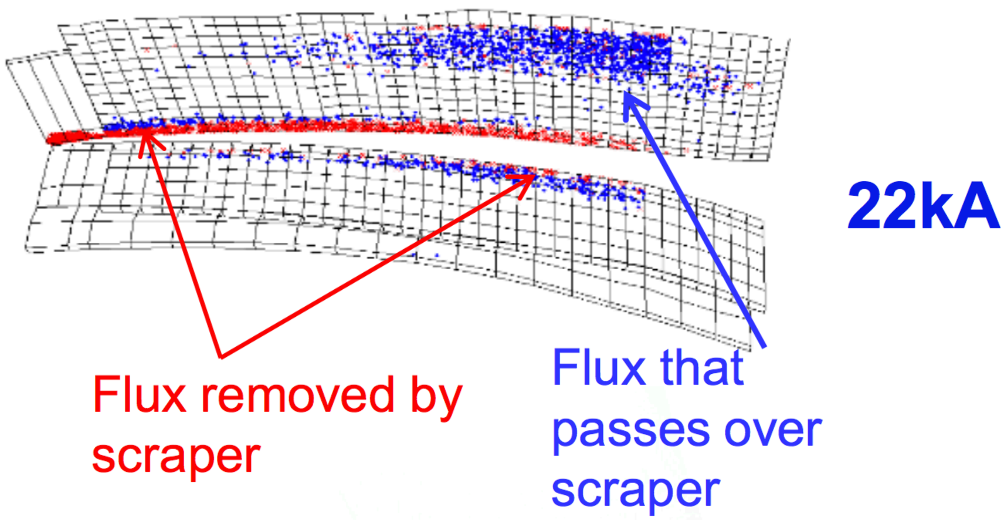


Current status: Ready!

Los Alamos National Laboratory EST. 1943
Wisconsin University of Wisconsin–Madison
Oak Ridge National Laboratory
Auburn University



One of the 10 W7-X divertor modules showing the scraper element installed.



Simulations showing protection of divertor edges by scraper element.

Lore *et al.* 2014 *IEEE Trans. On Plas. Sci.* **42** 3, p.539

The U.S. program on W7-X is a partnership

- The ‘one-team’ approach
- On-site, on-time, <u>on-needs</u>
  - Error field correction = Trim Coils
  - Ion Temperature = XICS
  - Divertor protection = Scraper Element
  - Wall conditioning = Boron Powder Dropper
  - Fueling = Steady-State Pellet Injector
- Bilateral success metrics
- Committed team of scientists and engineers

We are not alone!

Stellarator research greatly benefits from collaboration on international devices in the near future

W7-X and LHD provide capabilities to address critical issues in burning plasma science before ITER operation begins

- Steady-state operations
- A facility to assess plasma-wall interactions
- Assess the role of 3D fields on confinement
- Operations in a regulated, reactor-like, environment

Future U.S. collaboration opportunities exist at W7-X

- Steady-state pellet injector
- Heavy-ion beam probe program
- Energetic Particle Physics
  - 8 MW of NBI coming online in 2018
  - 1-2 MW of ICRH in 2020
- Divertor Physics
  - 10 MW/m^2 for 30 minutes 2020
- Steady-state wall conditioning

An international view on a 20 year strategy

Goal: U.S. delivery of a world-class burning plasma science facility by 2040.

1. Aggressively pursue collaboration on the international superconducting devices
   - W7-X: Long pulse, high ß, island divertor, fueling, and PMI
   - LHD: Deuterium campaign, high ß, helical divertor
2. Initiate national design and optimization activity for an improved quasi-symmetric stellarator
3. Develop a conceptual design for a next-step mid-sized US facility to extend quasi-symmetry into the hot ion regime
   - Focus on benefits of flow and symmetries which cannot be investigated on the large international facilities
   - Define the minimum scope, needs and capabilities of such a system