The U.S. Collaboration on the Wendelstein 7-X Stellarator

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presented to
Fusion Energy Sciences Advisory Committee
Bethesda, MD
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Outline

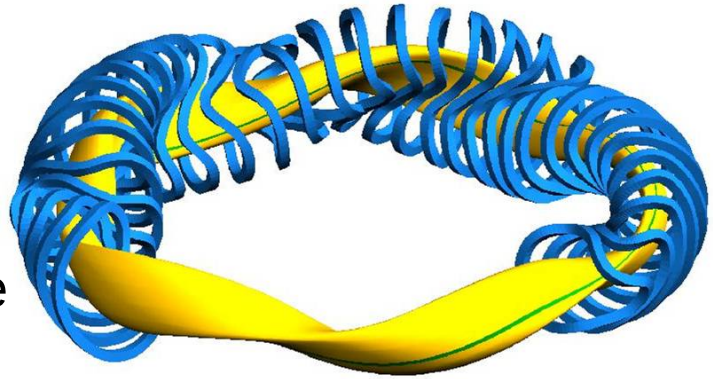
- What is W7-X?
- U.S. Research Agenda
- Program opportunities and needs going forward

What is Wendelstein (W7-X)?

- A new 3D toroidal magnetic confinement experiment (a “stellarator”)
- Large-scale test of an innovative computer-optimized machine design.
  - R_{maj} = 5.5 m, ⟨a⟩ = 0.5 m, B_0 = 3 T, $P_{heat} \leq$ 20 MW
- Capability for long-pulse (≤ 30 min.) plasma operation.

New physics

- Can it sustain a stable, high performance plasma for long times as predicted?
- Can plasma boundary conditions be made compatible with both high plasma performance and long wall material lifetimes?



A key element of EU’s roadmap to fusion electricity:

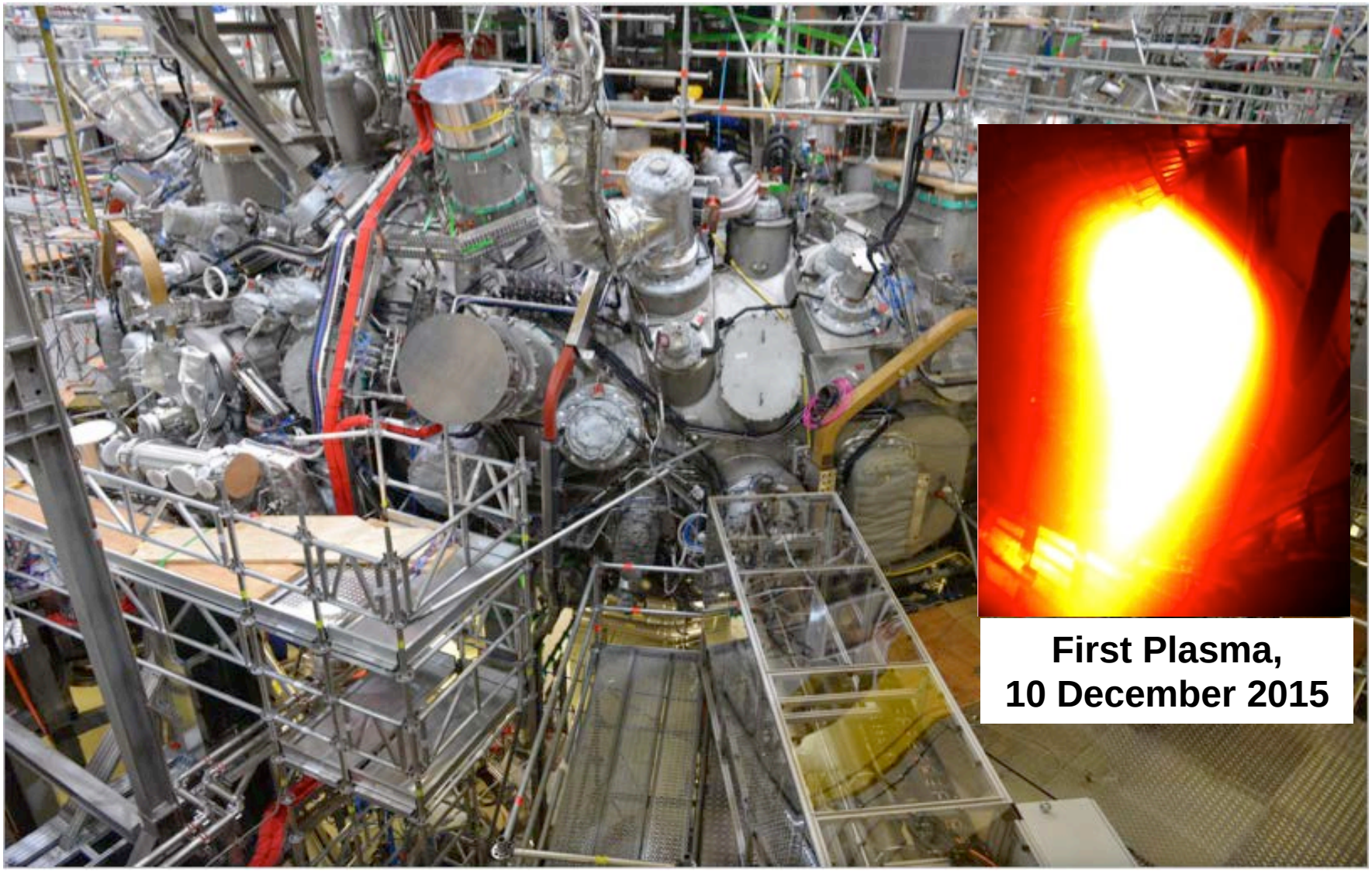
- Mission 8: “scientific exploitation of the W7-X experiment in validating the energy and particle confinement of optimised stellarators and qualifying the island divertor.”

U.S. Interests in Wendelstein 7-X

- Opportunity to deepen understanding of 3D plasma physics using the world's most advanced stellarator.
- Opportunity to advance long-pulse PMI science in a toroidal confinement system.
- Opportunity to advance an ITER-relevant model for research collaboration on a multi-national, Europe-sited facility.

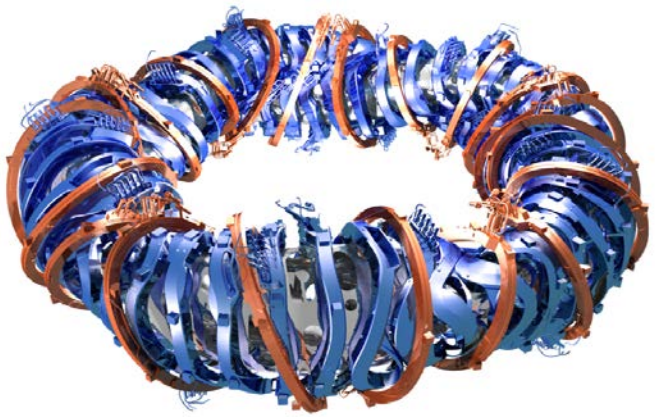
Advances FES goals under Long Pulse Burning Plasma Science.

The W7-X Machine is built …and operating!



First Plasma,
10 December 2015

Vacuum Flux Surface Measurements Confirm the Accuracy of the 3D Superconducting Magnet System



- 50 non-planar coils
- 20 planar coils
- 7 independent circuits.

Tested to 2.5 T.

- Intrinsic island chain geometry (size, phase, helicity) matches predictions.
- No significant error field detected.

The U.S. Research Agenda for W7-X

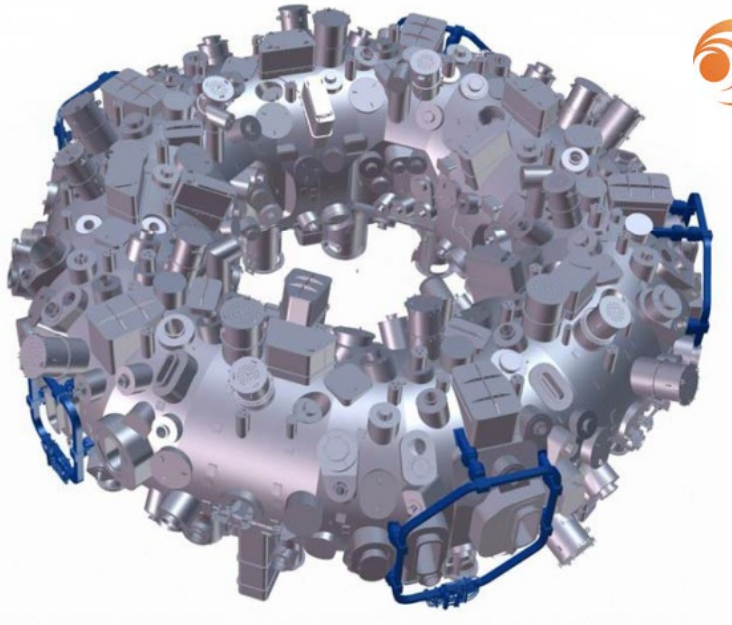
Theme: Control of high-performance steady-state 3D plasmas.

- How well can we diagnose and control the 3D equilibrium from start-up thru high-β steady-state?
- Can we control the divertor well enough to:
  - keep the heat exhaust flowing uniformly to high heat-flux surfaces while protecting sensitive components?
  - control impurities and maintain plasma purity?
- What governs transport?
- Can we control the density profile for optimum performance?

Carrying out the U.S. Agenda…

Diagnosis and control of 3D equilibrium

U.S. supplied the W7-X trim coil system *and* led experiments showing that they affect the magnetic configuration as expected



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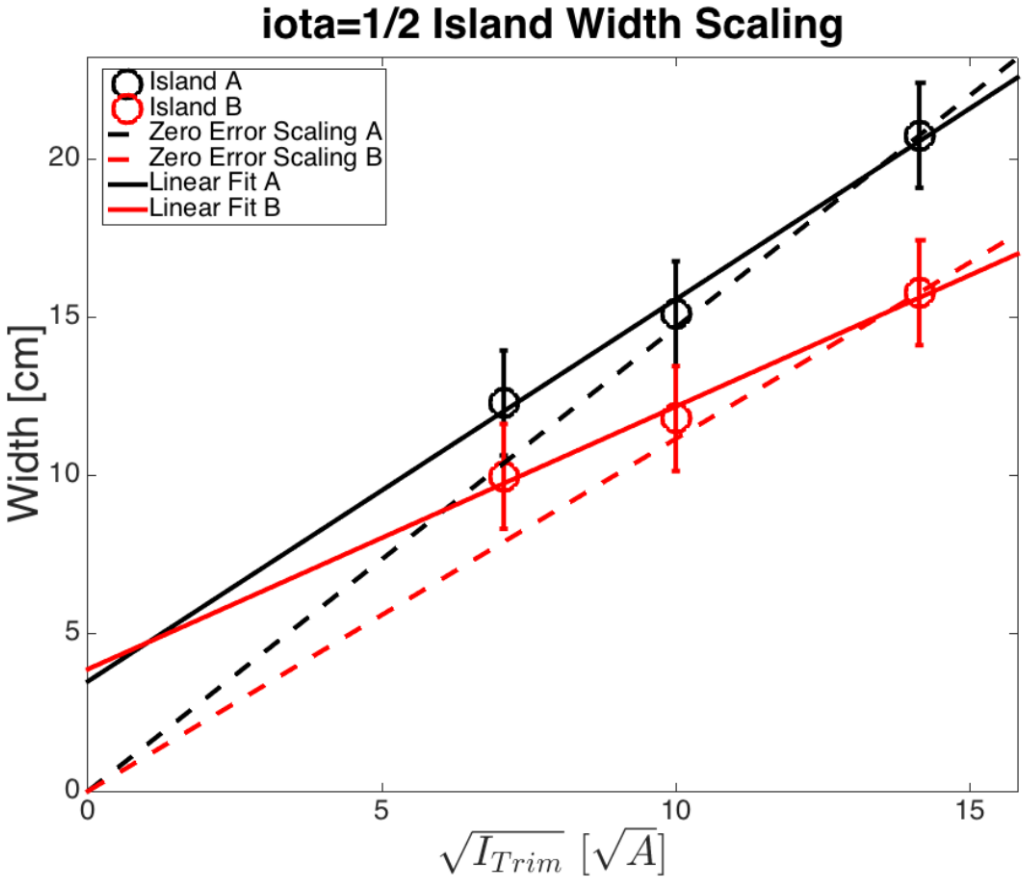
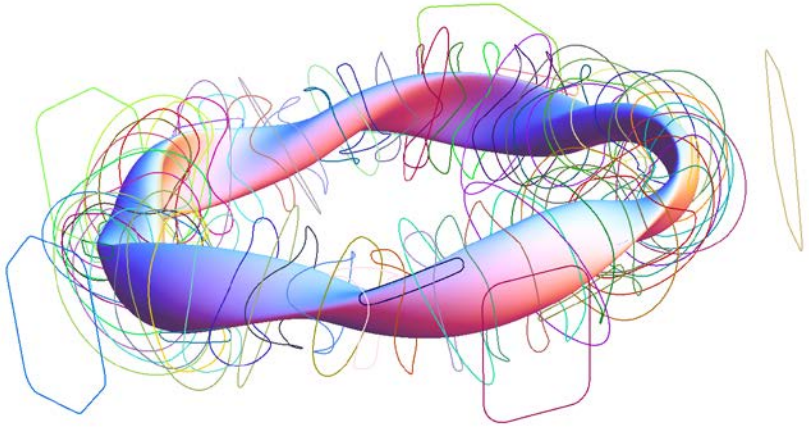


- Island width should be $\propto I_{trim}^{1/2}$
- Data: small residual island may exist, consistent with estimated construction errors.

S. Lazerson *et al.*, APS-DPP Meeting, Nov. 2015

3D Equilibrium Analysis Will Enable Diagnosis, Understanding, and Control



3D equilibrium model of the W7-X plasma obtained with **V3FIT.**

Measurement data: magnetics, profiles, coil currents

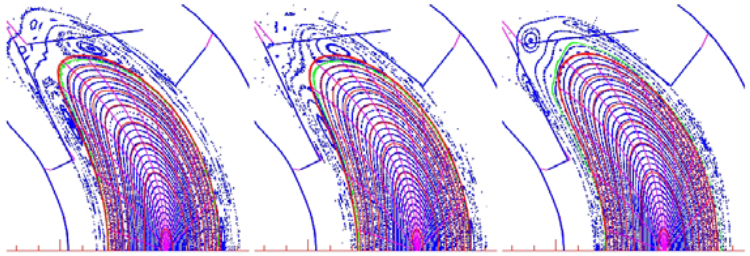
↓

Reconstructed 3D equilibrium

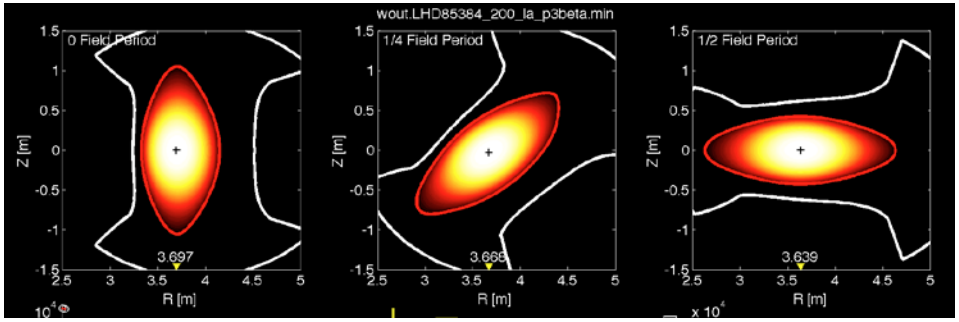
↓

Chordal data inversion, e.g. XICS

Physics analysis, e.g. EMC3-EIRENE



VMEC and w7-extender surfaces with varying bootstrap current



LHD equilibrium reconstruction using **STELLOPT** and **DIAGNO**

AUBURN UNIVERSITY

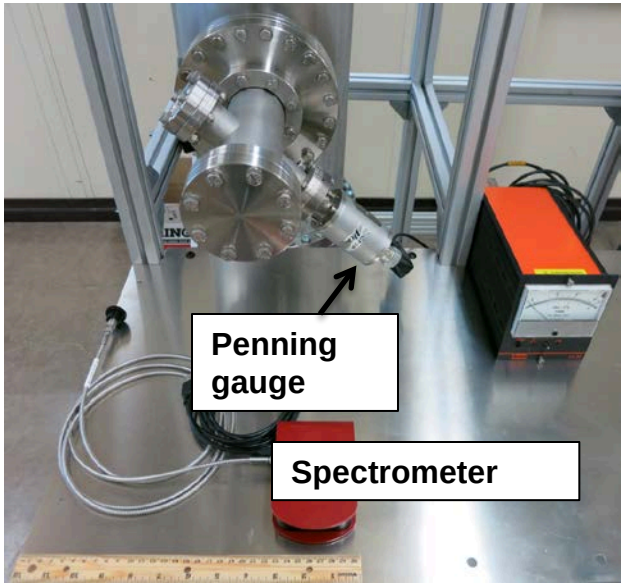
OAK RIDGE National Laboratory

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Carrying out the U.S. Agenda…

Divertor-related understanding and control

U.S. Edge / PMI Research Tools Are Installed and Getting Data

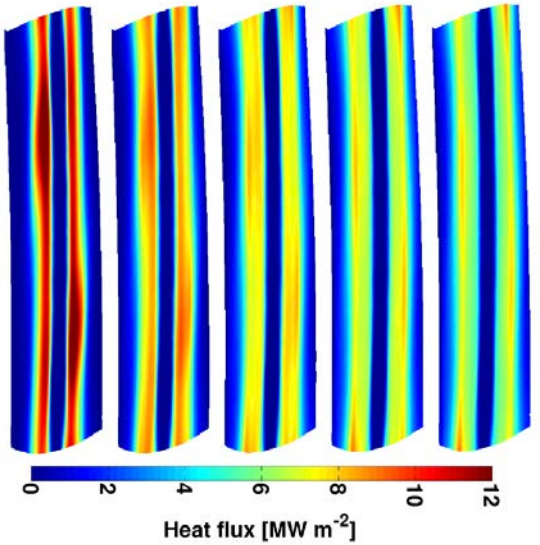


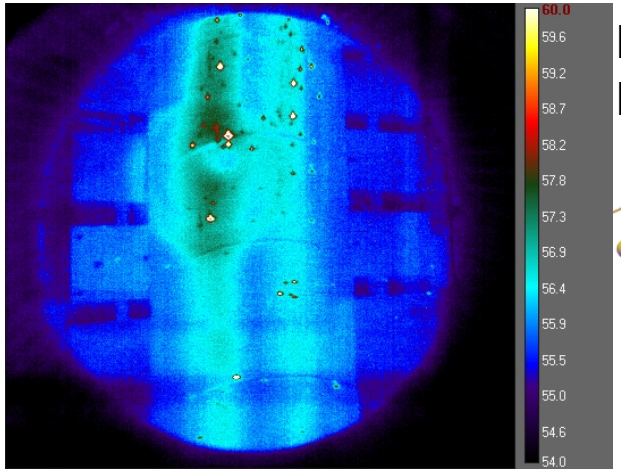
High resolution neutral gas analyzer

THE UNIVERSITY of WISCONSIN MADISON

Scaling of limiter heat fluxes

1.0 x 10^{19} m^{-3} → Density scan → 8.0 x 10^{19} m^{-3}





High resolution Infrared camera

Los Alamos NATIONAL LABORATORY

Edge transport and PMI modeling predictions with EMC3-EIRENE

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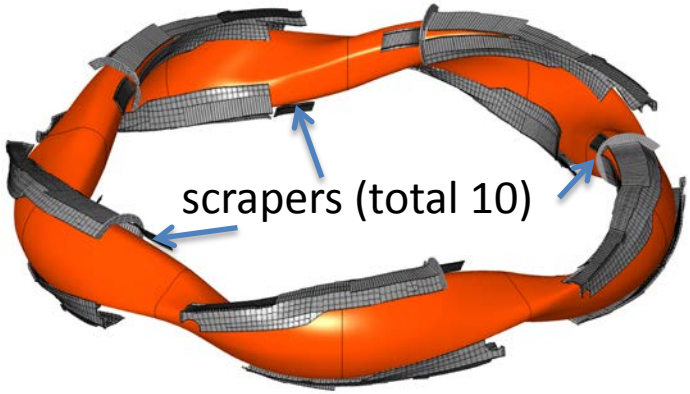
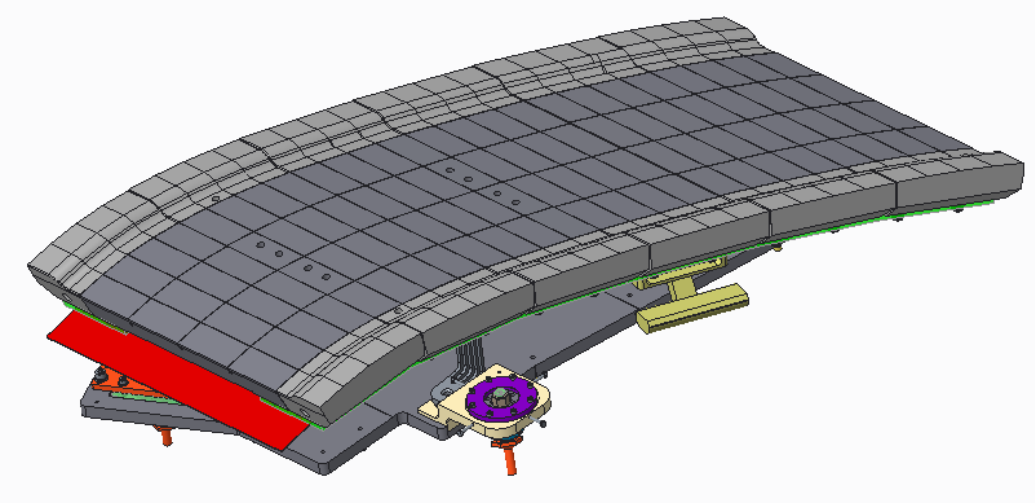
and… Edge plasma spectroscopy filterscopes

OAK RIDGE National Laboratory

Instrumented Divertor “Scraper” will enable edge plasma and PMI control studies

n=5/m=5 island divertor





	U.S.	IPP
Thermocouples		✓
Langmuir Probe	✓	✓
Plenum pressure		✓
Visible cameras		✓
Infrared cameras	✓	✓
Magnetics modeling	✓	✓
Plasma modeling	✓	✓

Design / fab. by ORNL / PPPL / IPP team. Delivery in Sept. 2016

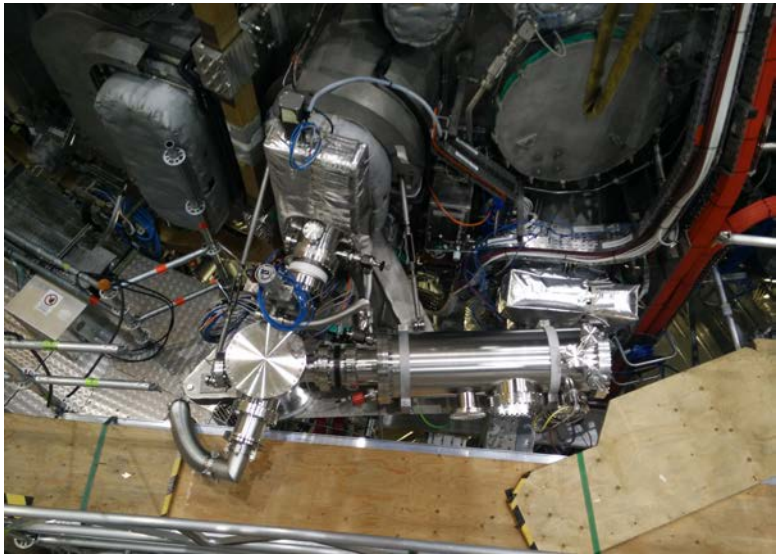
- **Will the scraper protect the divertor target edges as predicted?**
- **How will divertor pumping be affected?**

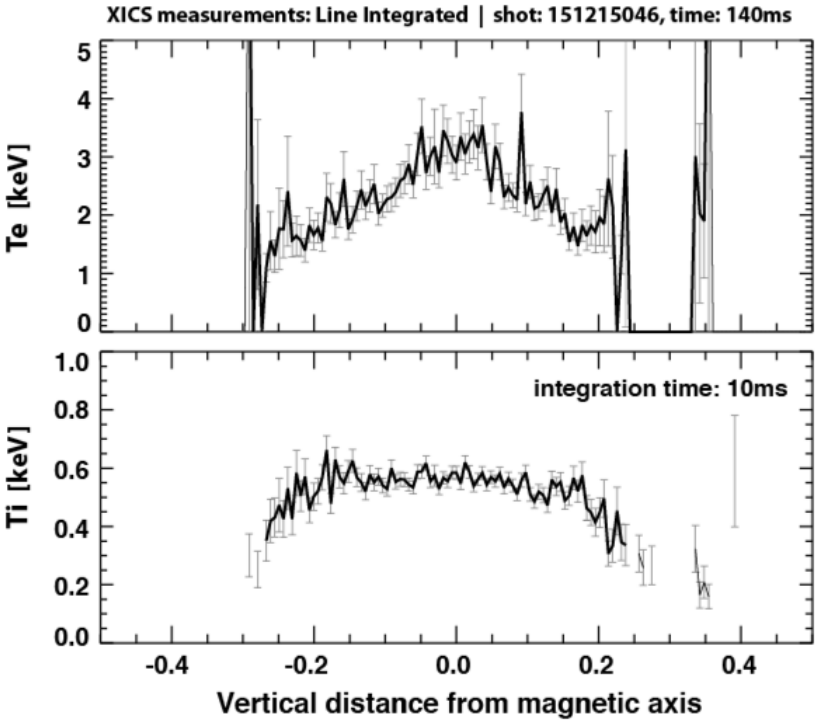
Carrying out the U.S. Agenda…

What governs transport?

First Temperature Profile Measurements!
(Preliminary)

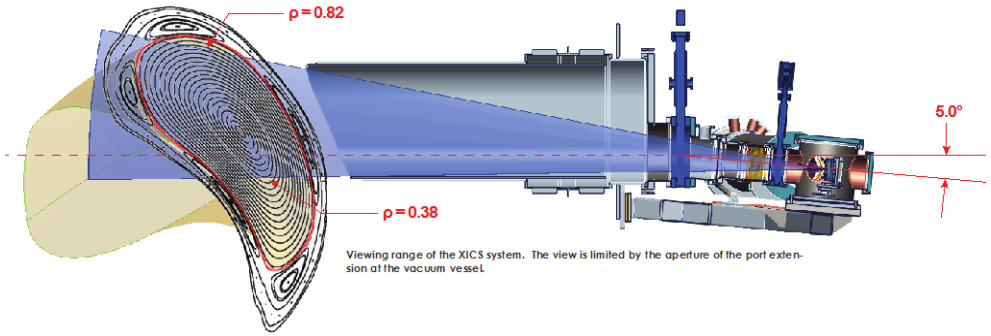
X-ray Imaging Crystal Spectrometer





PPPL PRINCETON PLASMA PHYSICS LABORATORY

IPP Max-Planck-Institut für Plasmaphysik



Viewing range of the XICS system. The view is limited by the aperture of the port extension at the vacuum vessel

Will measure profiles of:

- Ion temperature
- Electron temperature
- Plasma flow
- Impurity density

Fluctuation Diagnostics in Preparation

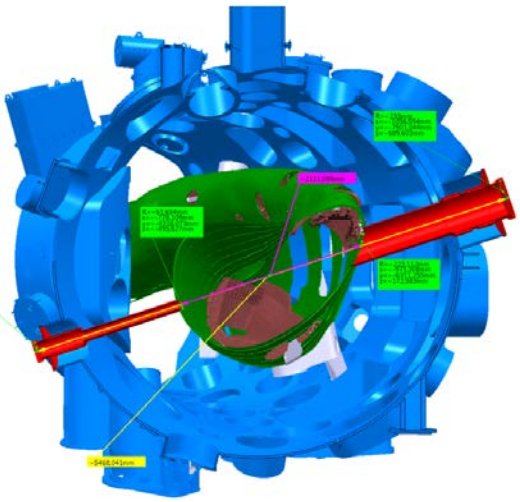
Phase Contrast Imaging

- Measure turbulent fluctuations, e.g., ITG, TEM and ETG with frequencies ≤ 1 MHz and $k \leq 30$ cm^{-1}.
- Currently used on Alcator C-Mod, DIII-D, LHD, TCV for edge and core fluctuations.

Gas Puff Imaging

- Measure plasma edge turbulence using fast (~1 ms) 2D imaging of emission from an edge-localized gas puff.
- Also possible to study island divertor dynamics

PCI beam geometry In W7-X



Heavy Ion Beam Probe

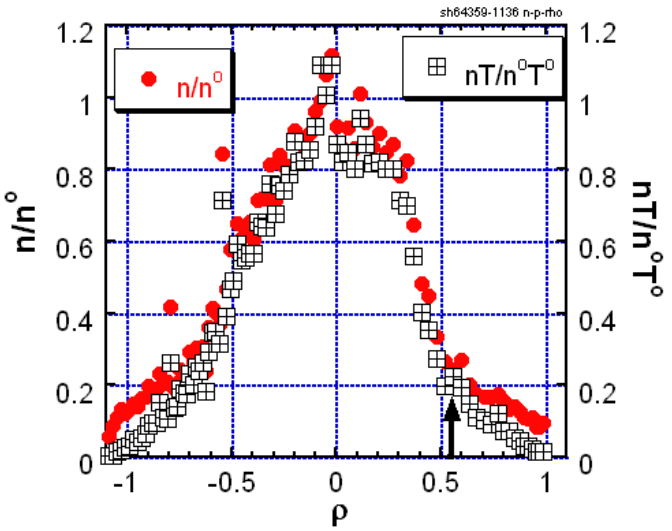
- Simultaneously measure density and potential fluctuations, $E_r(r)$
- Use equipment developed and operated on TEXT-U.
- Feasibility study in progress.

XANTHO *Xantho Technologies, LLC*

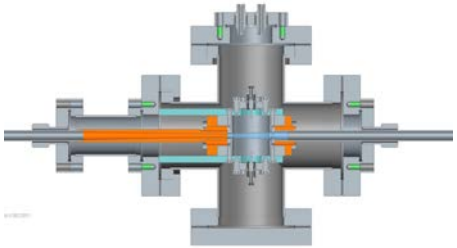
Carrying out the U.S. Agenda…

Density profile control

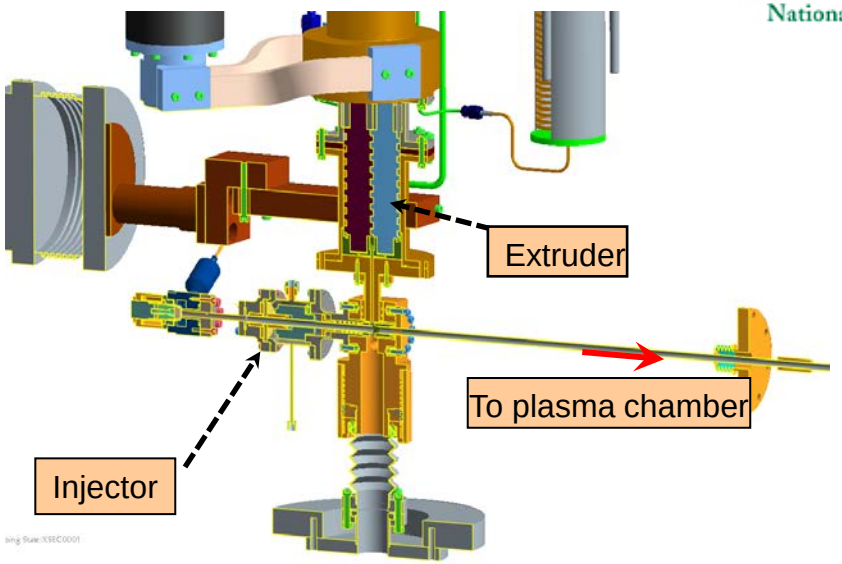
U.S.-IPP Collaboration in Pellet Injection for W7-X



LHD achieves peaked density profiles, best performance with pellets.



Phase 1: U.S. will supply pellet mass detectors for existing short-pulse injector.



Phase 2: Steady-state system combining U.S.-supplied frozen hydrogen extruder with IPP injector.

- Will provide steady-state core fueling and a field test of U.S.-developed ITER extruder technology.

MDSplus Data Acquisition & Management at W7-X

- W7X is now using MDSplus to support a subset (currently 7) of their diagnostics.
  - Diagnostics from outside collaborators (MIT, PPPL, CIEMAT) are being delivered on-site with MDSplus
  - All data stored by the native CODAC system is also available through MDSplus.
- Several more diagnostics (10-20) will be added to MDSplus for the next campaign.
  - This is a temporary solution while W7-X CODAC development is continuing.
- W7-X has adopted MDSplus for remote data access. As at JET and AUG, this is advantageous for remote collaborators.
- US DOE supports this effort under general MDSplus funding at MIT.

W7-X Offers Unique Opportunities to Advance FES Research Priorities

Example: Plasma-Material Interactions (ref., PMI Workshop PRDs)

- Mid-term: Exploit U.S. investments in the divertor scraper, trim coils, and PMI-related diagnostics.
  - Tests the innovative island divertor concept (PRD 1)
  - Compatibility with an optimized core (PRD 5)
  - Test trim coils as an actuator for controlling loading uniformity among the 10 divertors (PRD 1)
- Long-term: Extend in-situ PMI material capabilities developed on U.S. machines to long-pulse. (PRD 1, 3)
  - Flexible sample exposure techniques, e.g., DIMES.
  - In-vacuo post-exposure surface analysis, e.g. MAPP probe.
  - Large wall area material evolution, e.g. accelerator based in-situ material surveillance (AIMS)

W7-X doors are wide open to U.S. scientists.
Opportunities are only limited by our ability to participate.

Toward a Scientifically Productive Collaboration on an Overseas Facility

Lessons learned from what has worked and what hasn't…

Some requirements:

1. U.S. contributions to essential capabilities, and involvement from Day 1. ✓
2. Research staffing sufficient to extract the science from our hardware contributions.
   - Dedicated core team to ensure key U.S. leadership roles, first-author science publications, visible representation at conferences.
3. A strong, permanent on-site team for effective integration with the host team, other partners, and program planning.
   - Currently an open need.
4. An effective remote collaboration model, designed to optimize U.S. scientific productivity.
   - BPO model for ITER* has excellent ideas adaptable for W7-X.
   - Survey of W7-X collaborators (and many others) is in progress, soliciting input needed to set requirements.

* M. Greenwald, *et al.,* "Recommendations for ITER Experimental Operation, U.S. Team Formation and Participation," U.S. BPO Report, April 2015.

Summary

- A scientifically promising U.S. collaboration with W7-X is off to an excellent start.
- The program is rich in opportunities to advance U.S. science interests. The doors are wide open to us.
- Transition from equipment preparation to scientific exploitation is challenging, but successful precedents exist.

W7-X web site: http://www.ipp.mpg.de/16900/w7x

U.S. W7-X information: http://advprojects.pppl.gov/home/w7-x

Backup

Summary of Current U.S. Team Participation in W7-X

Massachusetts Institute of Technology

- Phase contrast imaging, gas puff imaging, MDS-plus

University of Wisconsin

- Penning gauge neutral gas analyzer, edge transport / PMI simulation

Auburn University

- Equilibrium analysis, x-ray imaging crystal spectrometer (w/PPPL).

Xantho Technologies

- Heavy ion beam probe feasibility study.

Oak Ridge National Laboratory

- Divertor scraper design, edge filterscopes.

Los Alamos National Laboratory

- Infrared imaging

Princeton Plasma Physics Laboratory

- Field mapping experiments, magnetic configuration control (trim coils), high-resolution temperature/velocity profiles (x-ray imaging crystal spectrometer), divertor scraper design (w/ORNL) and fabrication, national coordination

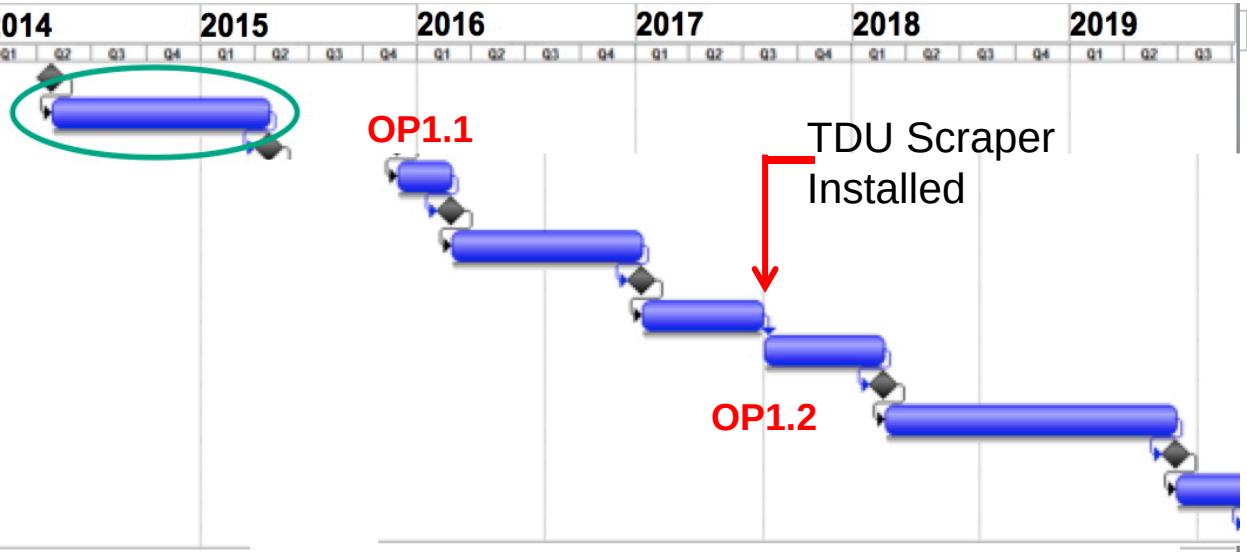
Near-term planning „updated“

device commissioning

test divertor assembly

HHF divertor assembly

Nr.	task	weeks
1	Milestone Closure of Cryostat	0 W
2	Device Commissioning	52 W
3	Milestone 1st Plasma	0 W
4	OP1.1 (<1s 2MW)	13 W
5	Milestone OP1.1 Completed	0 W
6	KiP2 Assembly	46 W
7	Milestone KiP2 Complete	0 W
8	OP1.2 (5-10s 8 MW)	29 W
9	OP1.2 (5-10s 8 MW)	29 W
10	Milestone OP1.2 Completed	0 W
11	KiP3 Assembly	70 W
12	Milestone KiP3 Complete	0 W
13	Device Commissioning	20 W
14	Milestone Start OP2	0 W



plasma commissioning diagnostics/control first investigations

1st plasma w/o divertor

1st divertor plasmas

science

steady-state plasmas 2020