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

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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.
  – \( R_{maj} = 5.5 \text{ m}, \langle a \rangle = 0.5 \text{ m}, B_0 = 3 \text{ T}, P_{\text{heat}} \leq 20 \text{ MW} \)
• 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 multinational, 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

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

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

Tested to 2.5 T.
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.

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

S. Lazerson et al., APS-DPP Meeting, Nov. 2015
3D equilibrium model of the W7-X plasma obtained with **V3FIT**.

**VMEC** and w7-extender surfaces with varying bootstrap current

Measurement data: magnetics, profiles, coil currents

Reconstructed 3D equilibrium

Chordal data inversion, e.g. XICS

Physics analysis, e.g. EMC3-EIRENE

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

Scaling of limiter heat fluxes

1.0 x 10^{19} m^{-3} \rightarrow \text{Density scan} \rightarrow 8.0 x 10^{19} m^{-3}

High resolution Infrared camera

Edge transport and PMI modeling predictions with EMC3-EIRENE

and... Edge plasma spectroscopy filterscopes
Instrumented Divertor “Scraper” will enable edge plasma and PMI control studies

n=5/m=5 island divertor

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

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What governs transport?
First Temperature Profile Measurements!  
(Preliminary)

X-ray Imaging Crystal Spectrometer

Will measure profiles of:
- Ion temperature
- Electron temperature
- Plasma flow
- Impurity density
**Phase Contrast Imaging**

- Measure turbulent fluctuations, e.g., ITG, TEM and ETG with frequencies $\leq 1$ 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

**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.
Density profile control
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.
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.

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“

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- **1st plasma w/o divertor**
- **1st divertor plasmas**
- **steady-state plasmas 2020**
- **plasma commissioning**
- **diagnostics/control**
- **first investigations**

**TDU Scraper**

- **Installed**

**OP1.1**

**OP1.2**