US Collaboration on the W7-X Stellarator

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Abstract

The new American-German collaboration on the W7-X stellarator in Greifswald, Germany, is in its first year as an ICC project. Los Alamos, Princeton, and Oak Ridge have organized an effort centered on applications of 3D magnetic fields to improve the performance and design of toroidal confinement devices. In particular, presently we have three focus areas: providing copper trim coils to be mounted externally on the W7-X cryostat, developing a scraper element for the divertor, and working control issues under the theme of 3D Diverted Plasmas. The trim coils must be designed and built on a fast schedule, to meet assembly timelines. ORNL has recently contributed to the design of the support fixtures for the room temperature to cyrogenic coil connections. The LANL effort involves theoretical modeling of whether the stellarator bootstrap current depends on the radial electric field, and an experimental investigation (IR imaging) of the heat loading and wall interactions in the W7-X 3-dimensional divertor. W7-X is a modular niobium-titanium superconducting stellarator of the helias type, with 5-fold symmetry, and the outer vessel is 16 meters in diameter, not including port extensions. It is presently 4/5 assembled, with the last module being moved into place this year. There are more than 250 ports (being insulated and welded into place now), although only ~150 are available for diagnostics...i.e., 30 per sector. First plasma is scheduled for August 2014. Other opportunities for increased collaboration scope abound.

The newest stellarator experiment in the world, W7-X, is under construction in Germany   (~$1.5B ready in 2014)
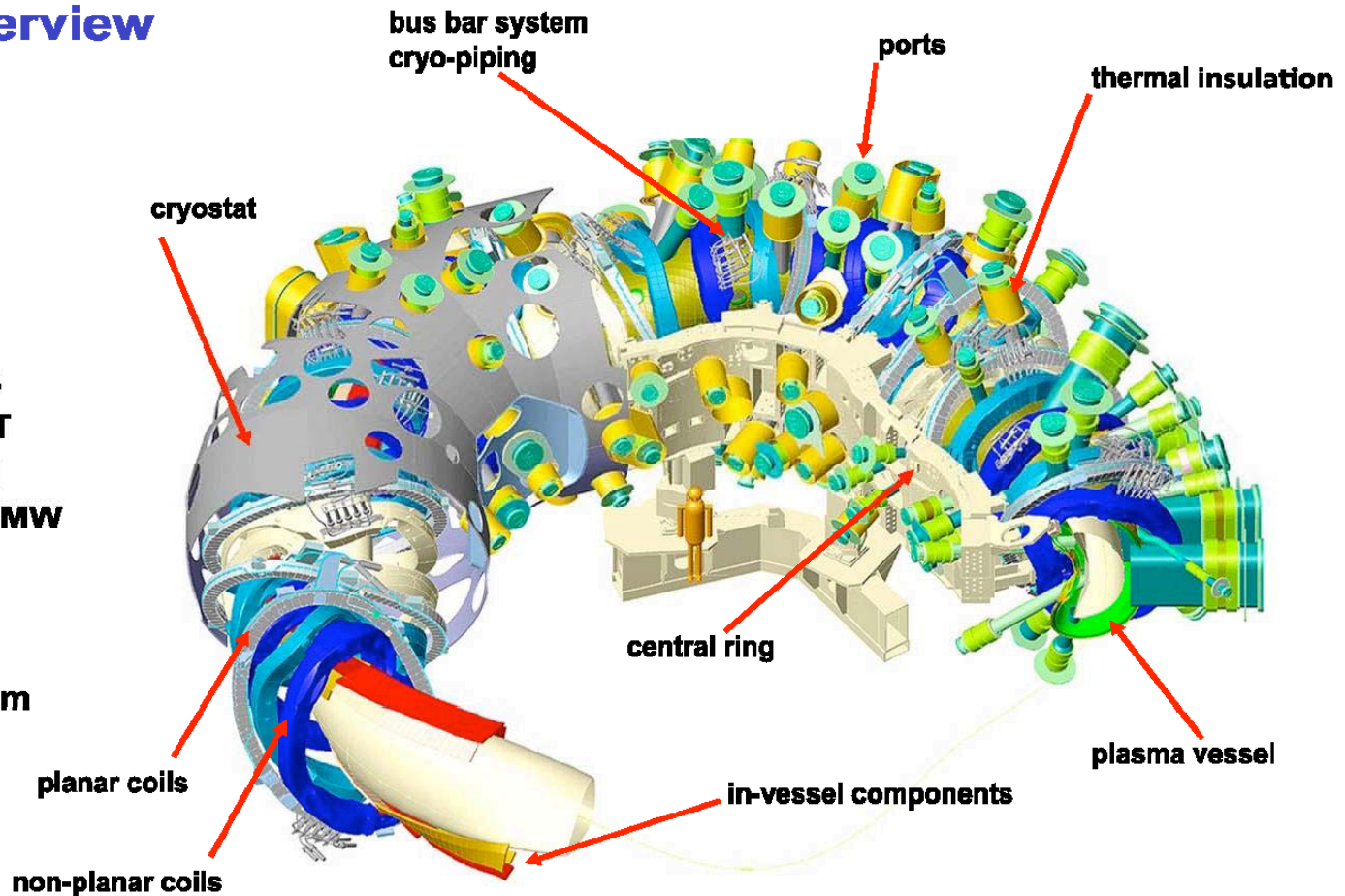
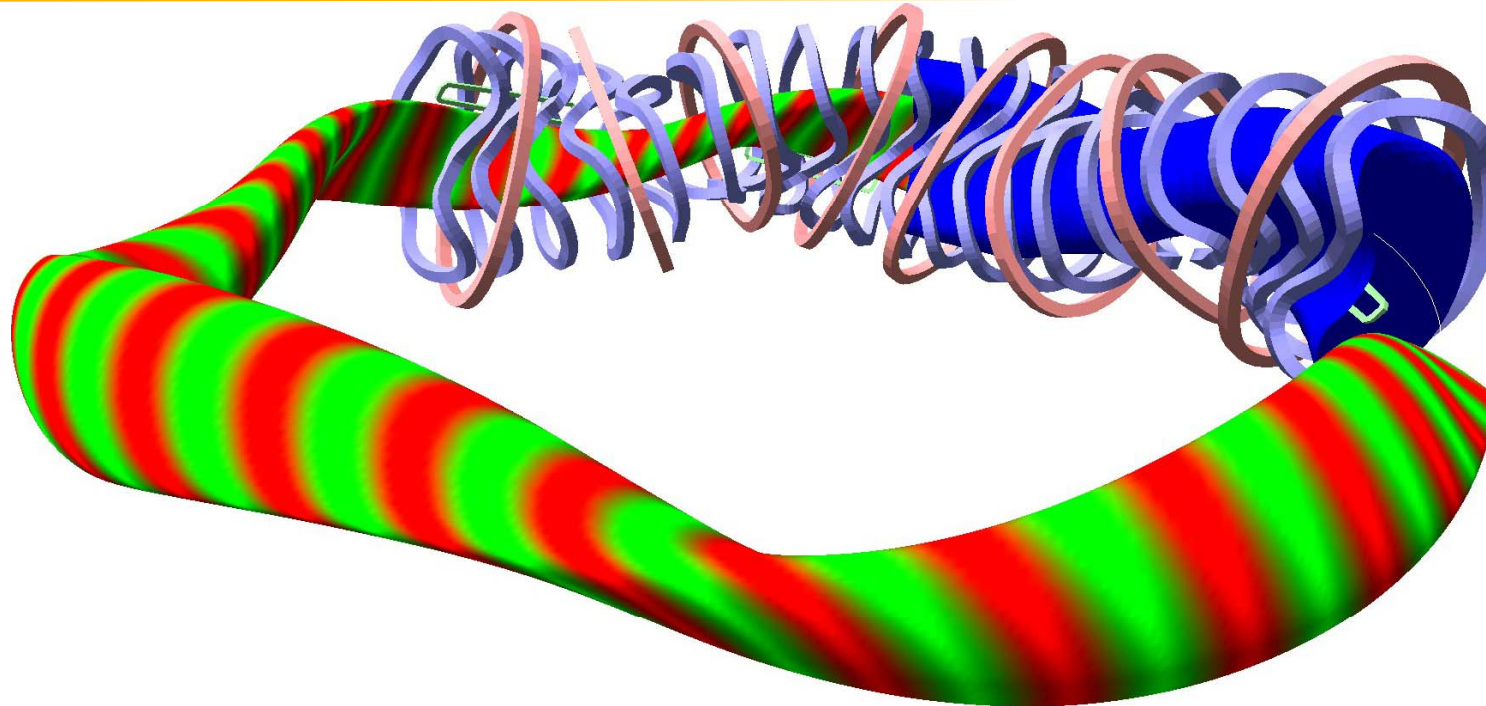## Schematic Overview

major radius: 5.5 m

minor radius: 0.53 m

plasma volume:30 m³

non-planar coils:50

planar coils:20

number of ports:254

rot. transform:5/6 -5/4

induction on axis:< 3T

stored energy:600 MJ

heating power:15 -30 MW

pulse length: 30 min

machine height:4.5 m

machine diameter:16 m

machine mass:725 t

cold mass:425 t

bus bar system
cryo-piping

ports

thermal insulation

cryostat

central ring

plasma vessel

planar coils

in-vessel components

non-planar coils

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3D Geometry of the W7-X Plasma

Showing direction and magnitude of equilibrium diamagnetic and Pfirsh-Schlüter currents around the torus. There are straight sections with triangular shaped cross-section and low B, and curved sections with bean cross-section and high B.
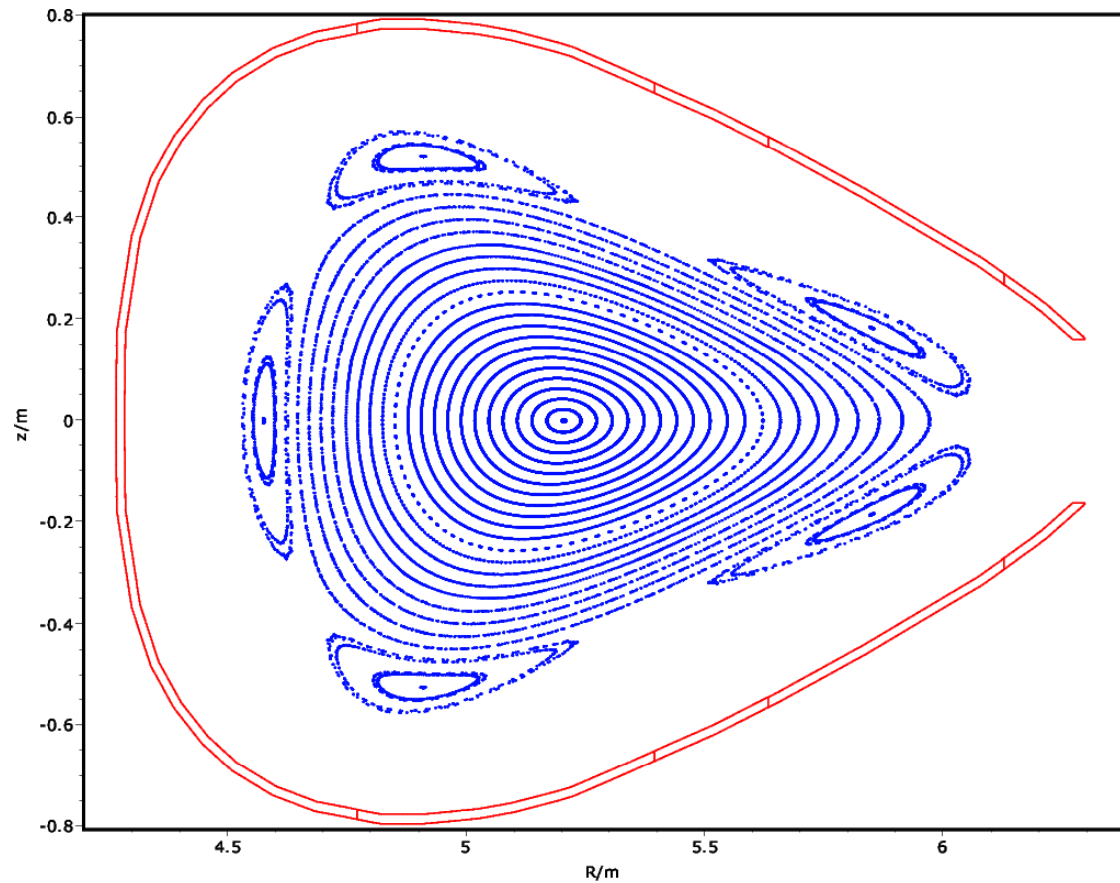
W7-X is quasi-omnigenous: The second adiabatic invariant, $J^*(\psi)$ isocontours for trapped particles, are aligned with flux surfaces , minimizing neoclassical transport.
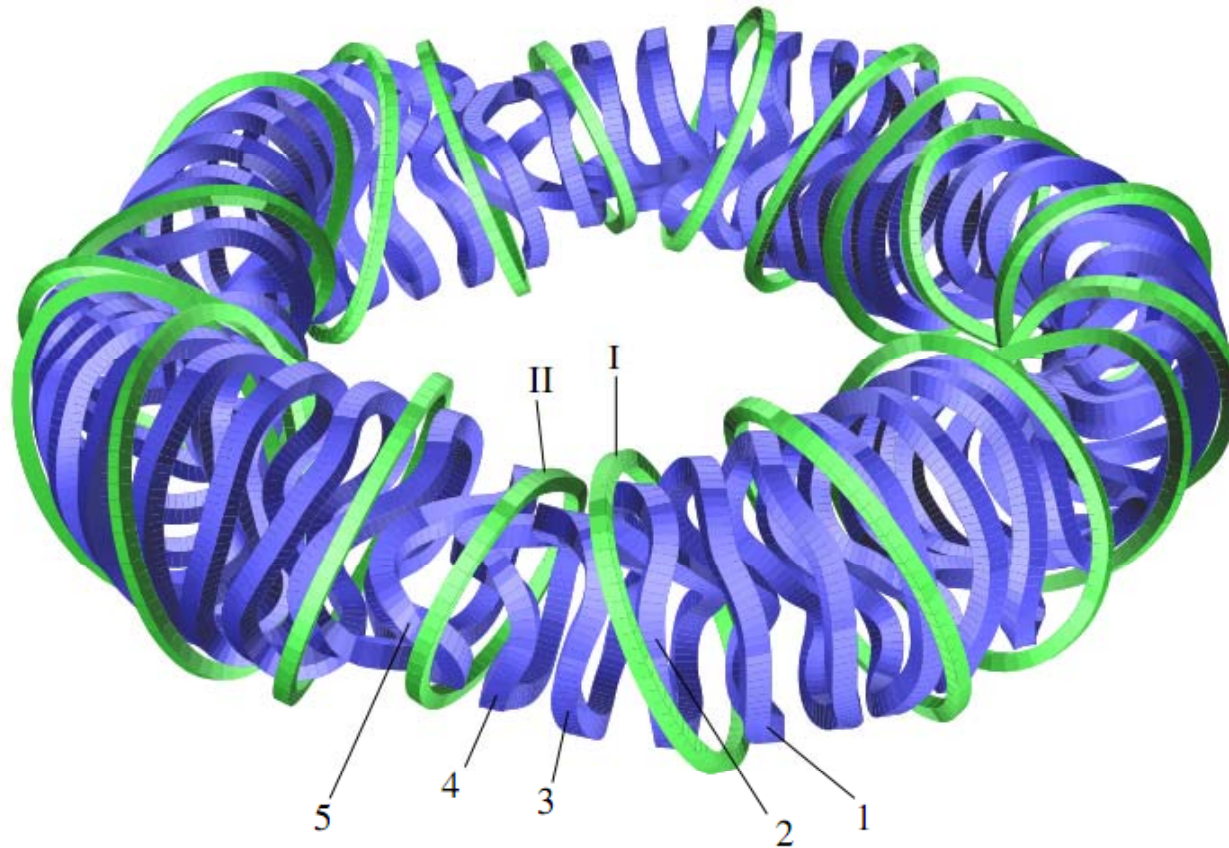
W7-X Magnetic Configuration at $\varphi = 0^\circ$
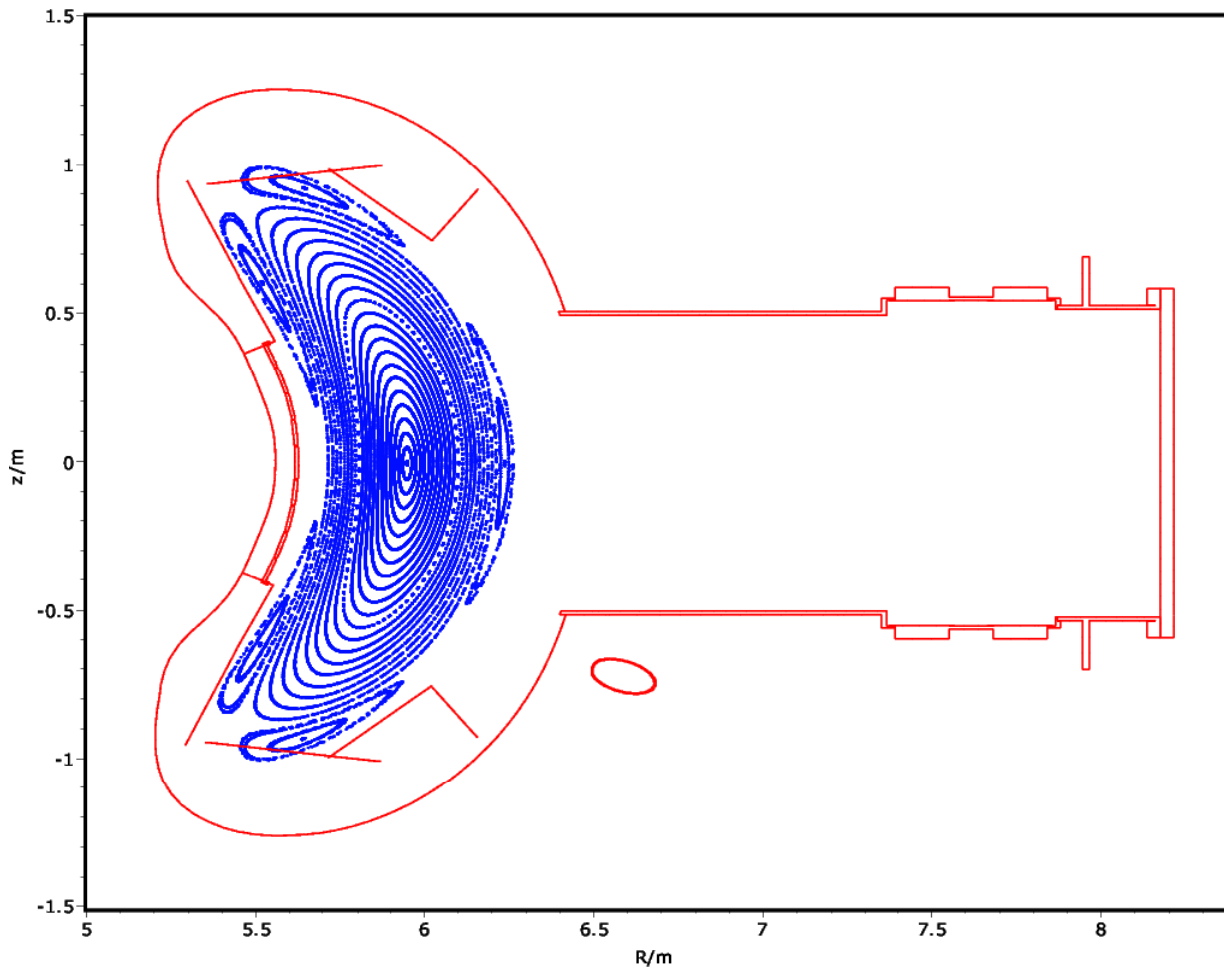
"Bean-shaped"

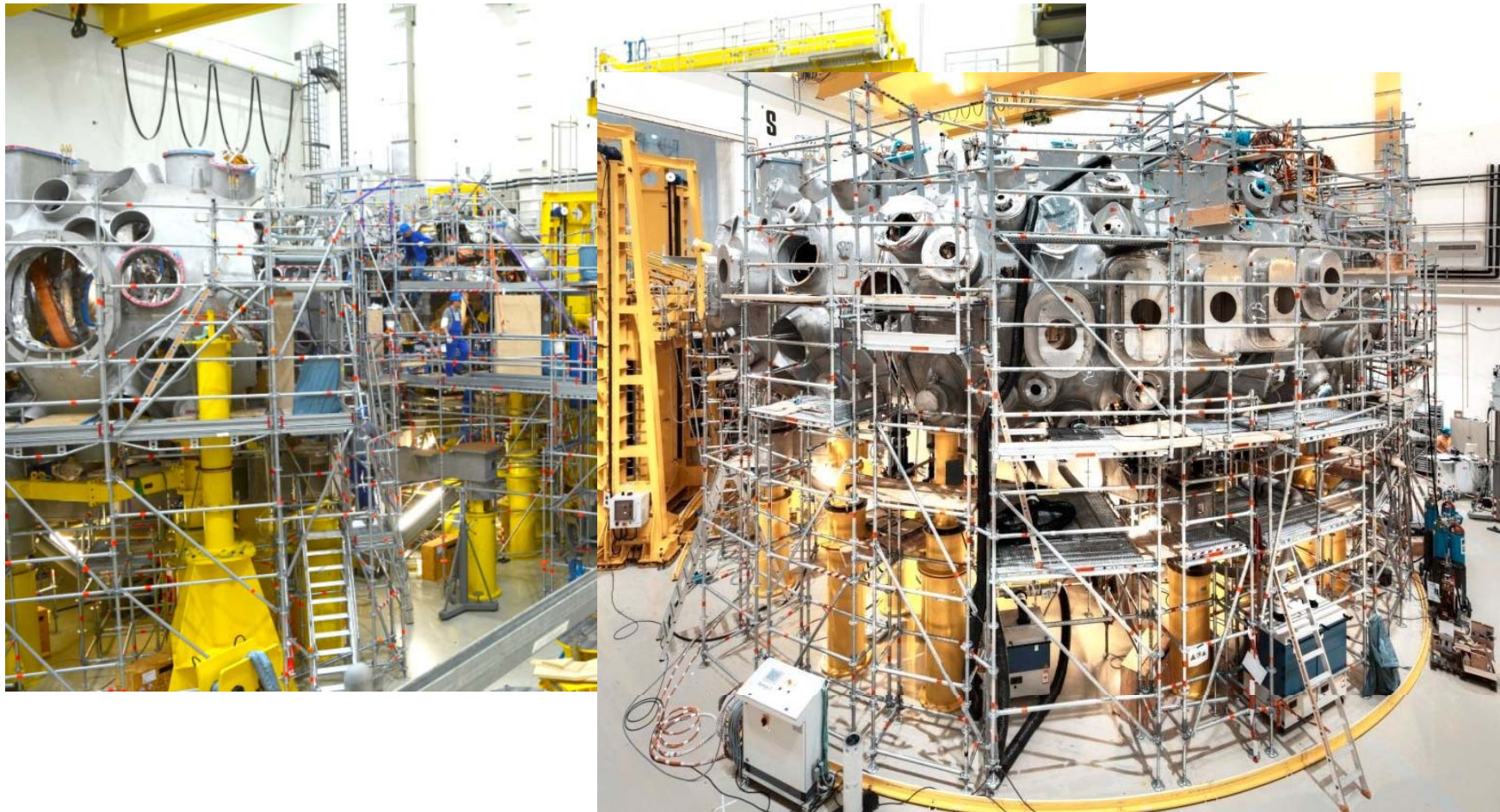# W7-X Magnetic Configuration at $\varphi = 36°$

"Triangular-shaped"

To make that plasma shape, the following coil set is chosen

Seven different coil types….5 nonplanar, and 2 planar

M. Drevlak et al. Nucl. Fusion 45, 731 (2005)

# View in the W7-X test cell

June 2011: Four out of five sections are in place

Our US-German collaboration has three elements

- Providing copper trim coils to be mounted externally on the W7-X cryostat (PPPL/ORNL)

- Developing a scraper element for the divertor (ORNL)

- Working on control issues under the theme of 3D Diverted Plasmas. (PPPL/ORNL/LANL)
    - PPPL is working on modifying codes to model the pressure-induced stocastization of flux surfaces, which then changes island divertor geometries.
    - The LANL effort involves theoretical modeling of whether the stellarator bootstrap current depends on the radial electric field, and an experimental investigation (IR imaging) of the heat loading and wall interactions in the W7-X divertor.

PPPL/ORNL Error correction coils
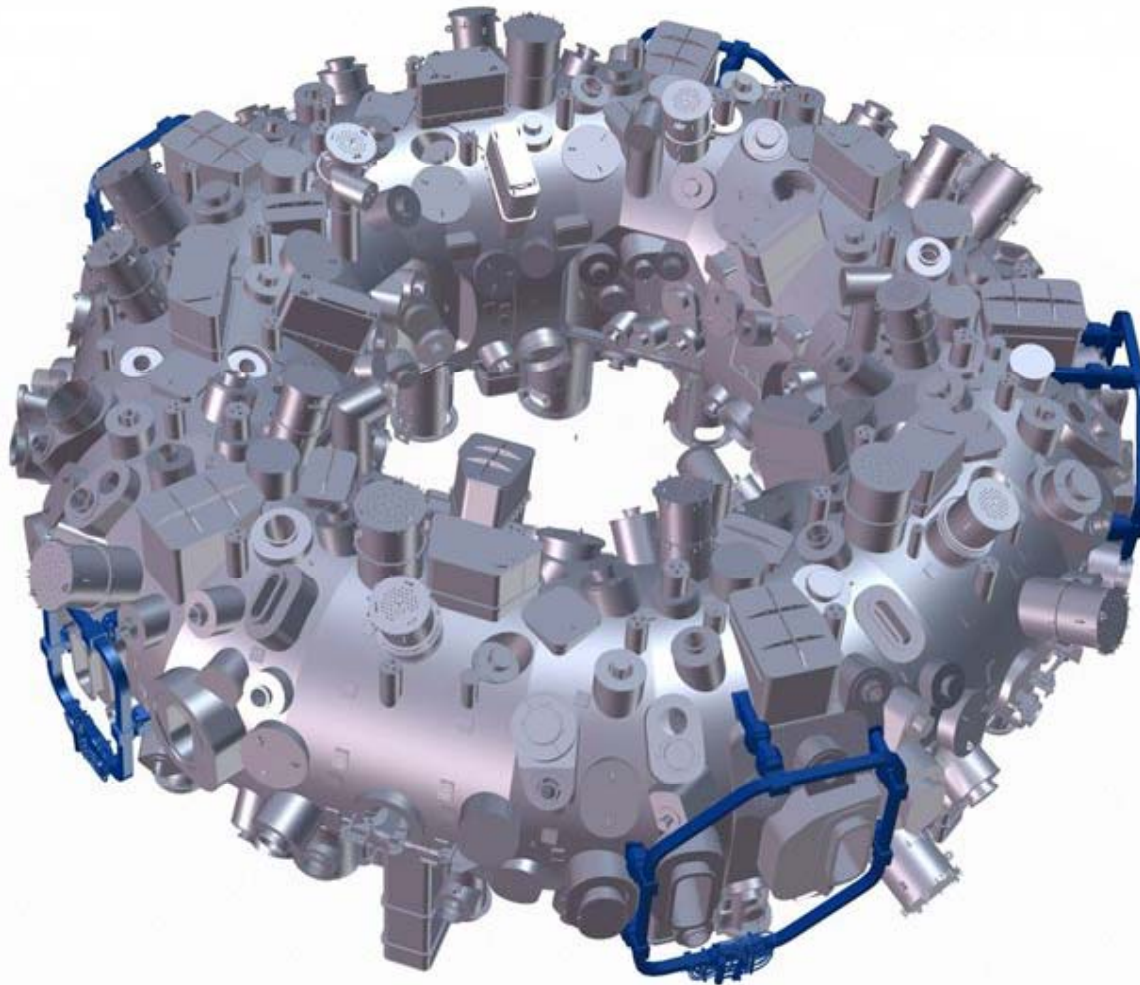
Note the number and variety of ports on this vessel.

Five normal copper EC coils (& eventually power supplies) will be provided by the USA

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# W7-X will use an island divertor for power exhaust

- Island chain at edge defines last closed flux surface

- Helical X-point, qualitatively similar to poloidal divertor in tokamak

- Concept validated in W7-AS

- Restricts edge transform value allowable
  - $\iota_b \sim 1$ in W7-X (5/5 islands)

Magnetic surface

Baffle plates

R
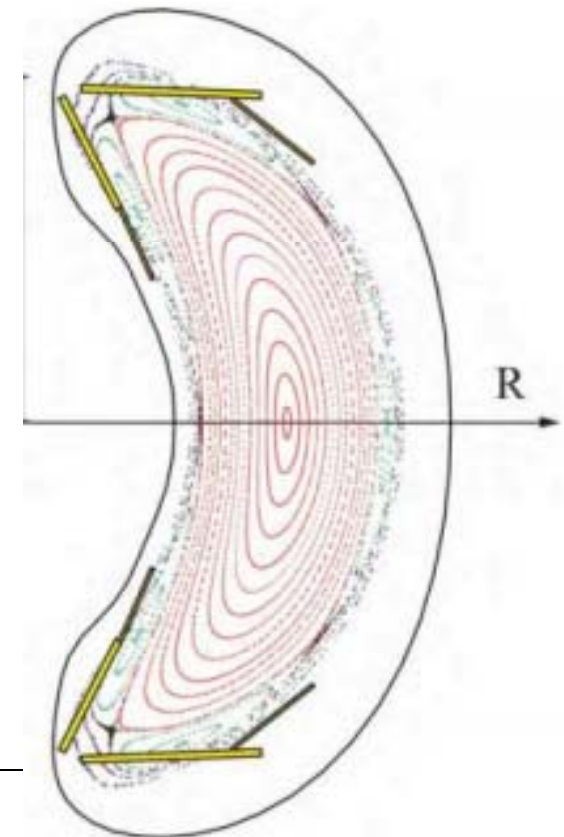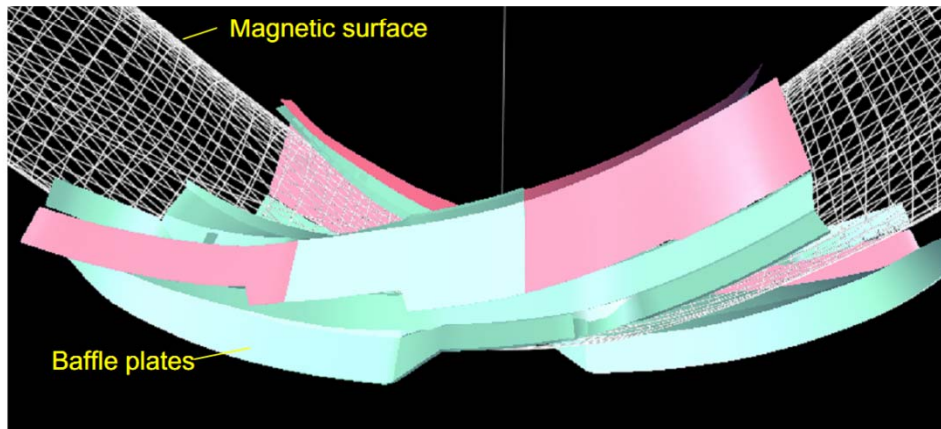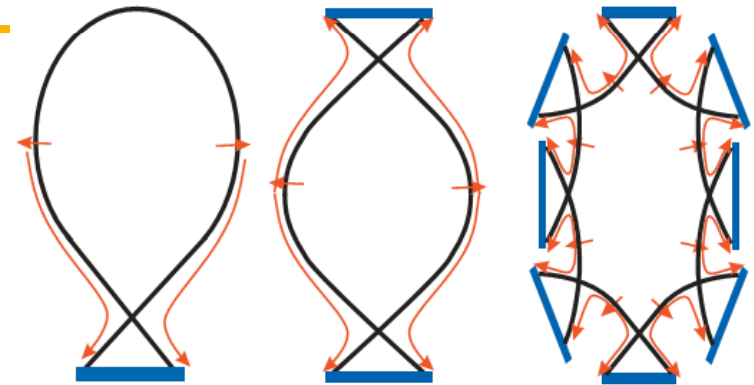
ORNL is designing a "divertor scraper element"

Divertor scraper element:
Protects against Transients during β evolution
Max. flux > 10 MW/m^2, 30 s
ITER monoblock technology IPP/ORNL

Cross-section of island divertor
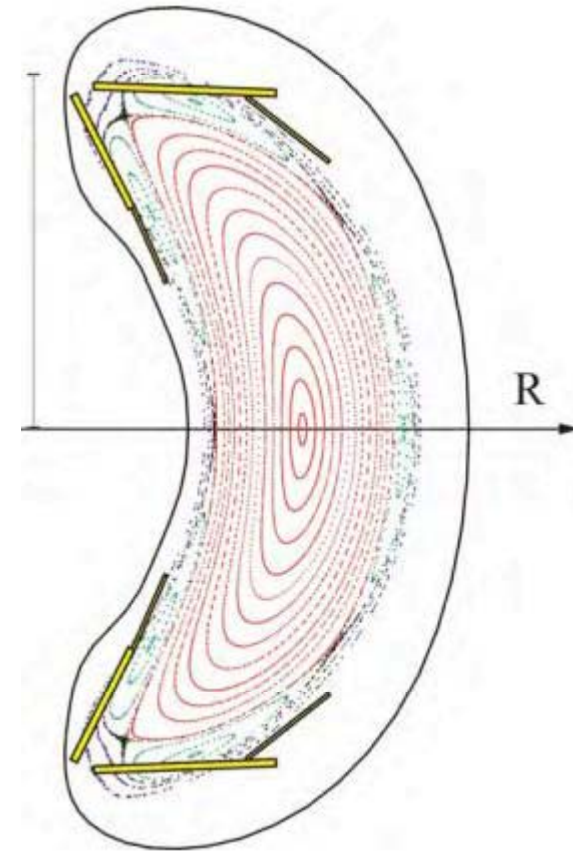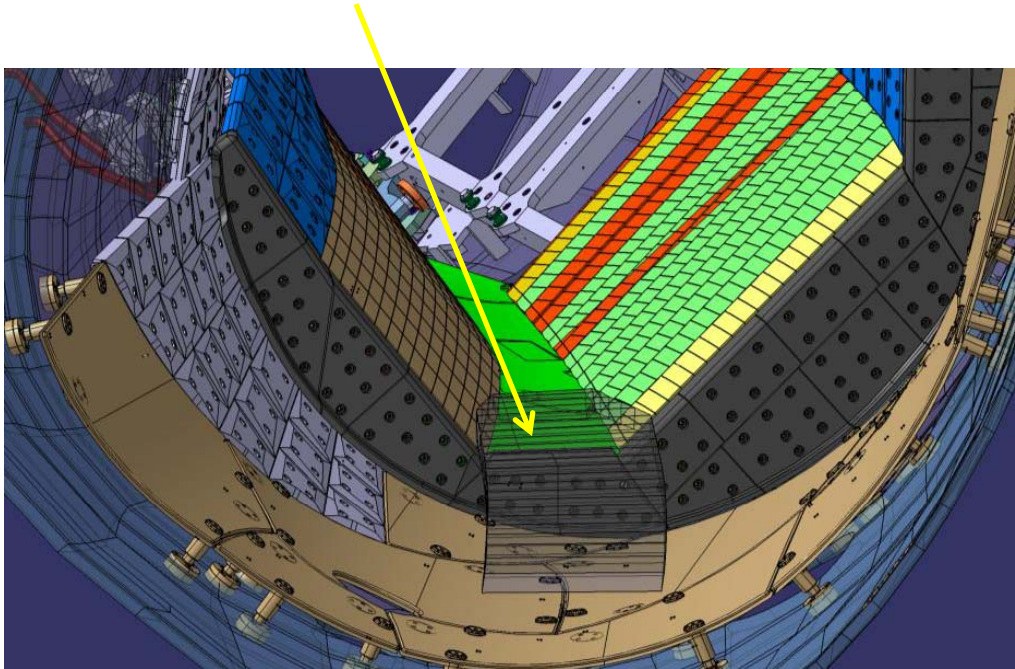
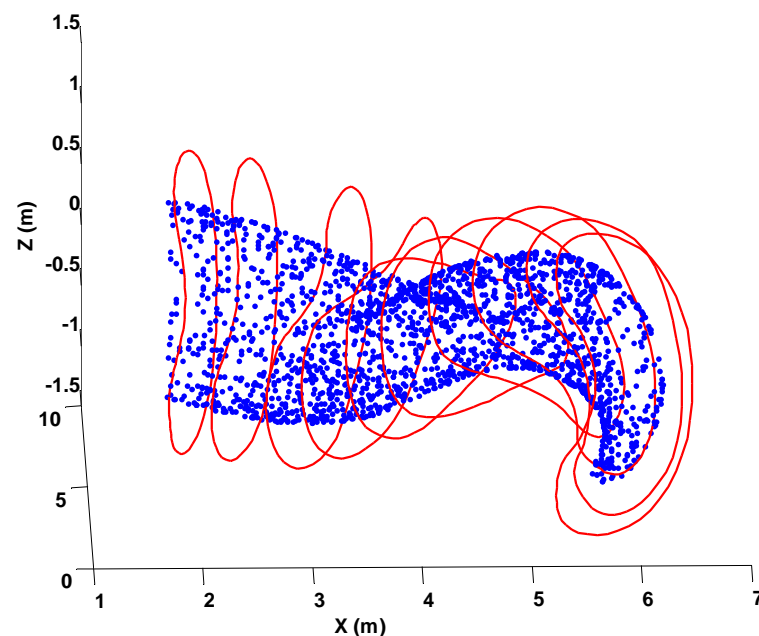# In particular, the scraper element is added to protect tile edges during intermediate I_{BS} phase

- During bootstrap current build-up, field line footprints focus excessive heat flux on divertor tile edges

- New 'scraper element' is being designed to block field lines from reaching divertor edges in intermediate I_{BS} configurations

foot prints at I_{BS} =22kA

horizontal target

vertical target
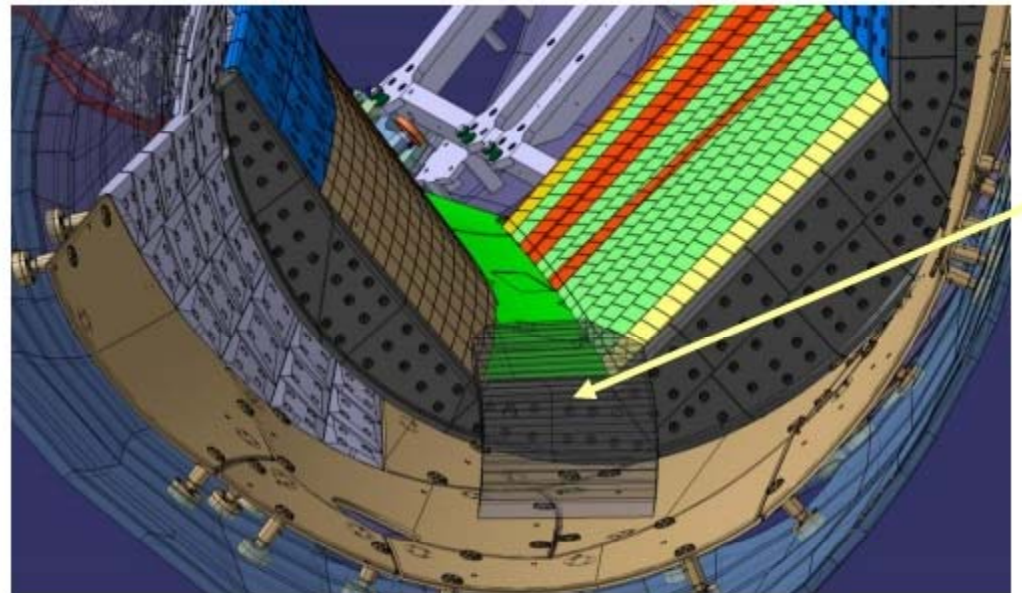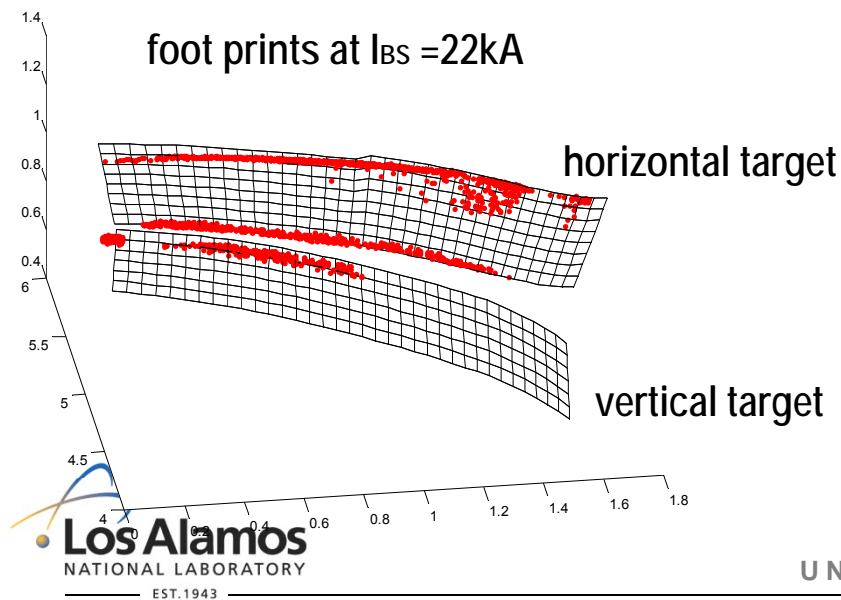
Field line tracing is used to estimate heat flux

- Field lines are followed in 3D including plasma contribution
  - VMEC[1] for 3D equilibrium (only gives field inside LCFS)
  - Extender[2] for plasma+coil fields outside LCFS

- Lines are initialized randomly along a field line that traces out a closed surface
  - Lines are then diffused with a given D_m
  - Example: 2000 lines, 10000 transits, $D_m = 1e\text{-}6$ m^2/m
  - For 50eV electrons this corresponds to $\chi_e = 4.2$ m^2/s
  - Sensitivity studies to be performed with respect to these parameters
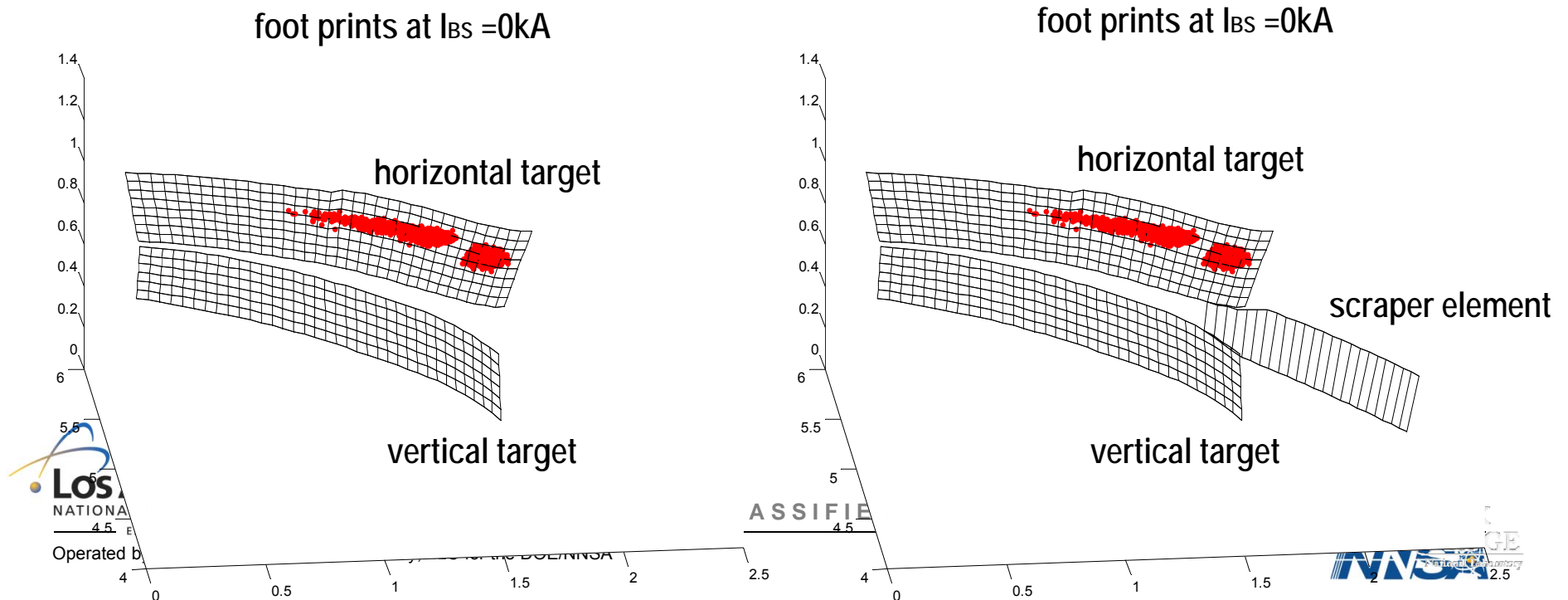
- Intersections of field lines with targets used to estimate plasma fluxes

[1] S.P. Hirshman, et al, Comp. Phys. Commun. 43, 143 (1986).
[2] M. Drevlak, et al, Nucl. Fusion, 45, 731 (2005).

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Field line tracing shows function of divertor scraper element

- **Intersections are found both with and without the scraper element**

- **0kA: Load is near middle of horizontal target, no load on scraper**

foot prints at I_{BS} =0kA

horizontal target

vertical target

foot prints at I_{BS} =0kA

horizontal target
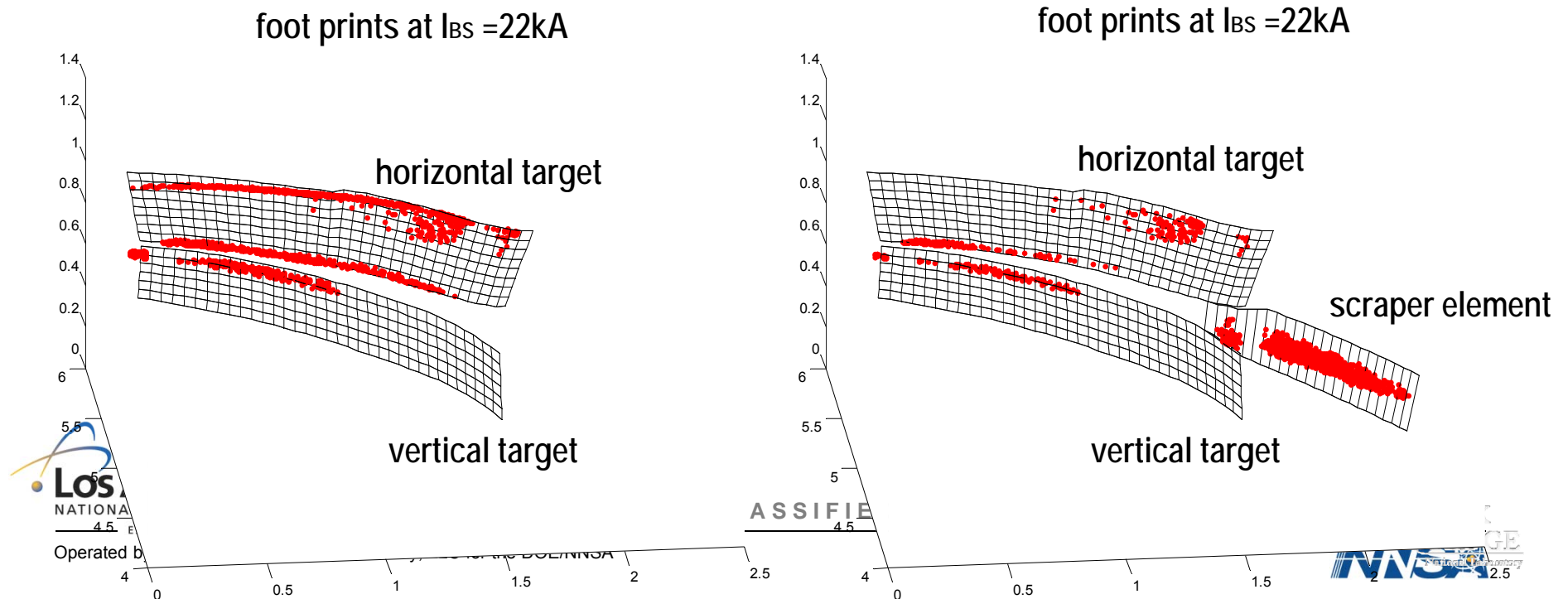
scraper element

vertical target

Field line tracing shows function of divertor scraper element

- **Intersections are found both with and without the scraper element**

- **0kA: Load is near middle of horizontal target, no load on scraper**

- **22kA: Without scraper edges of target are loaded; scraper catches most of this flux**

foot prints at I_{BS} =22kA

horizontal target

vertical target

foot prints at I_{BS} =22kA

horizontal target

scraper element

vertical target

Field line tracing shows function of divertor scraper element

- **Intersections are found both with and without the scraper element**

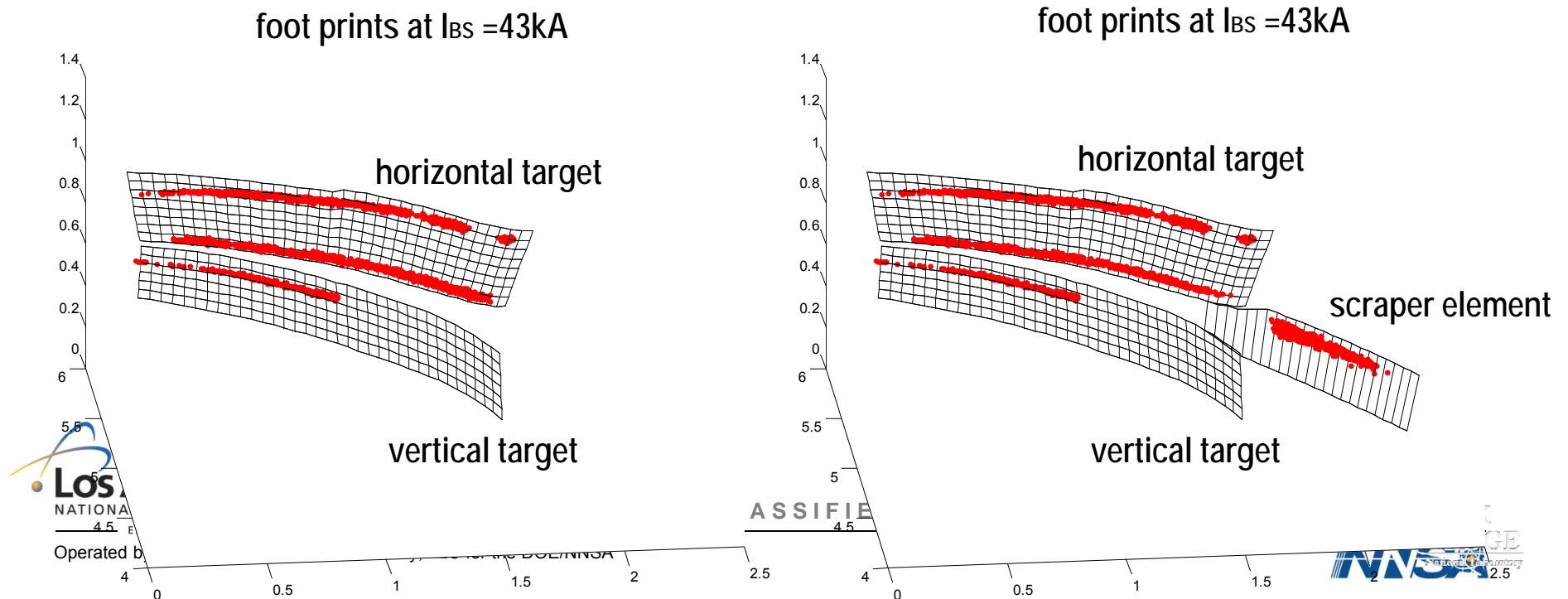- **0kA: Load is near middle of horizontal target, no load on scraper**

- **22kA: Without scraper edges of target are loaded; scraper catches most of this flux**
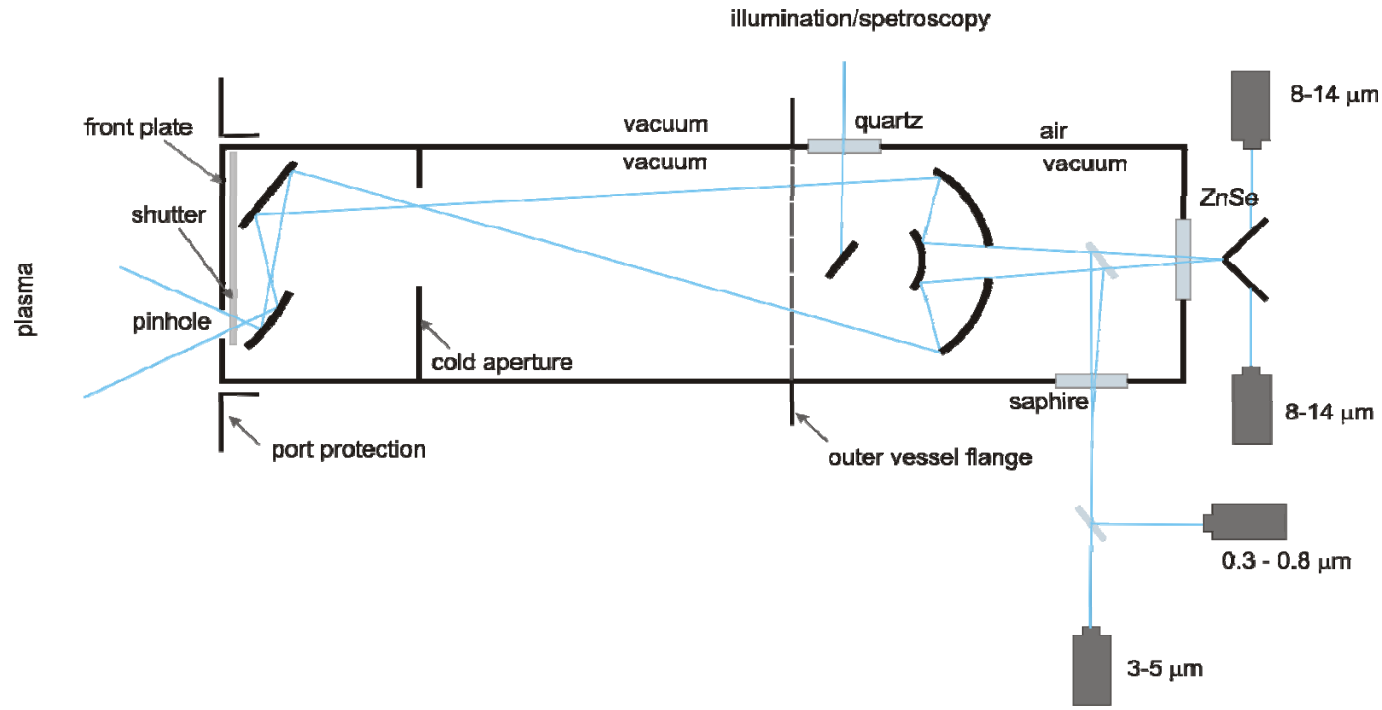
- **43kA: Footprint has moved away slightly from the target edge, scraper load reduced**

foot prints at I_{BS} =43kA

foot prints at I_{BS} =43kA

Measure the heat loads:
# IR-VIS access through 10 periscope systems

Schematic picture of the divertor endoscope: Main elements are: observation and Cassegrain optics enclosed in high-vacuum compatible tube, two 8-14 μm infrared cameras for monitoring of the temperature on the divertor surface; visible (0.3 – 0.8 μm) and fast infra-red camera (3-5 μm) for experimental observations and optional system for illumination of the divertor surface and spectroscopic observation of the divertor area. LANL will eventually provide 2 high resolution, high speed IR imaging science cameras, and develop real-time analysis tools.

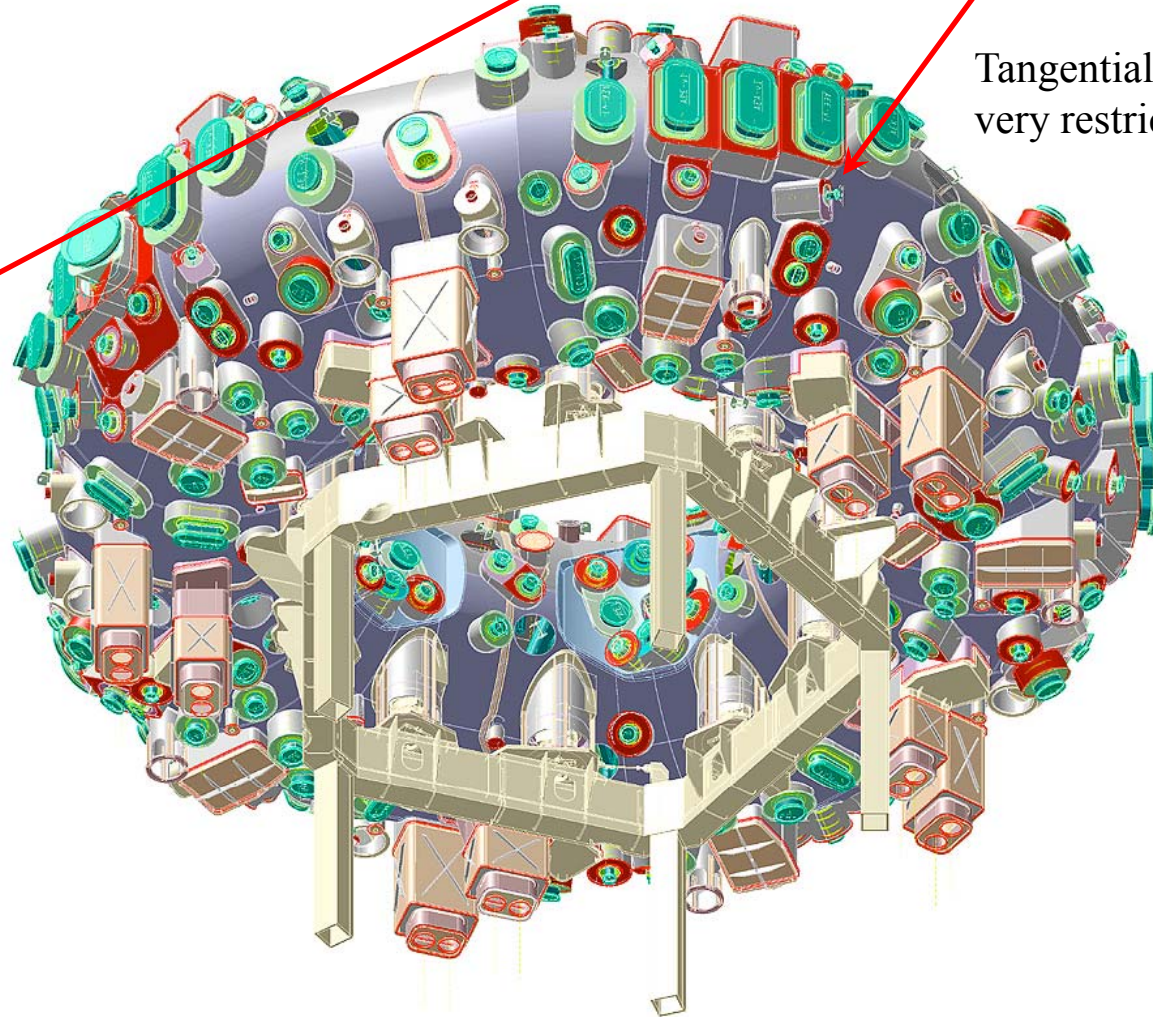# An example of the type of port access on W7-X
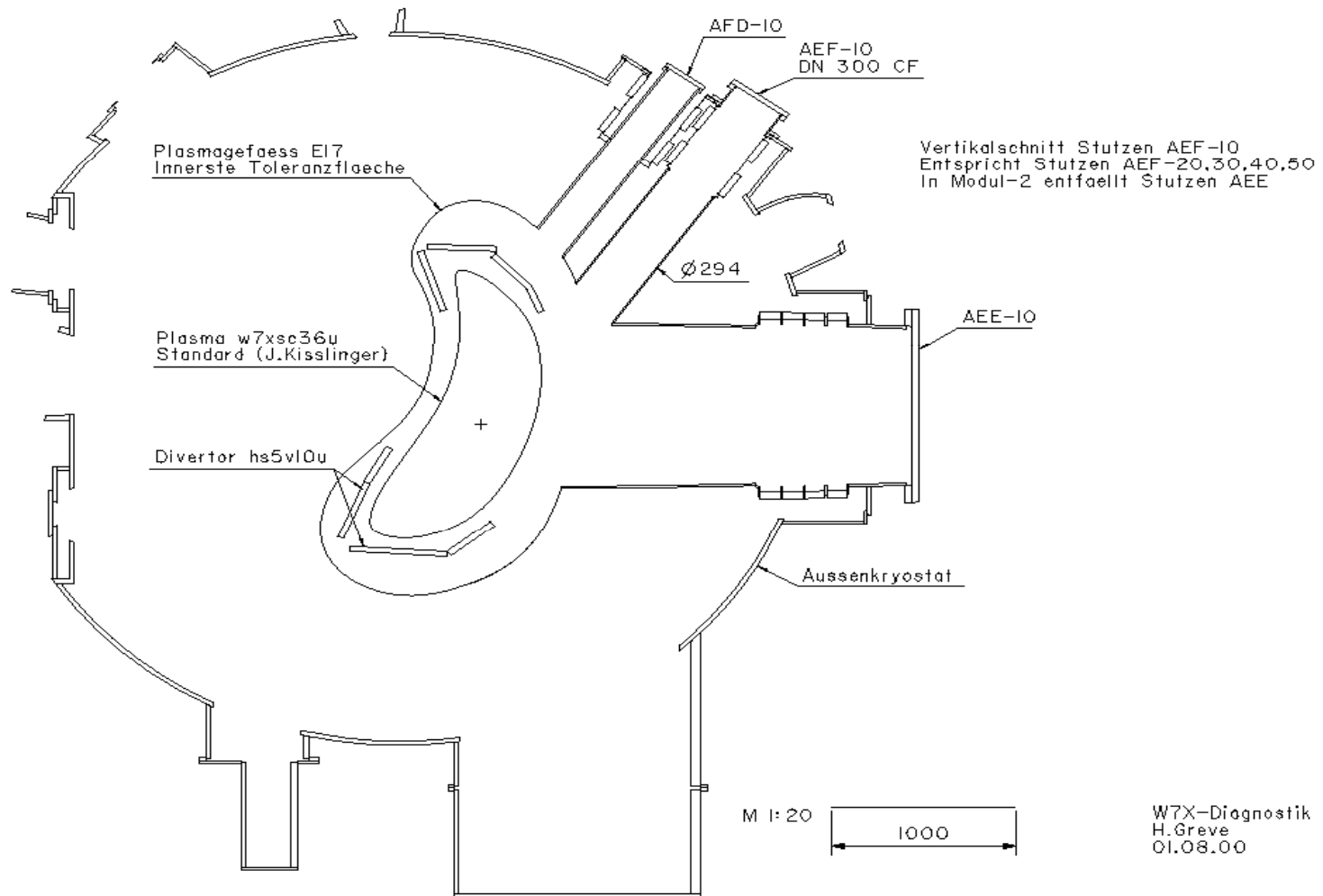
IR systems need to view the entire divertor

Since the machine has 5-fold symmetry, and each sector has an upper and lower divertor, then ultimately 10 views are required for machine (tile) protection.
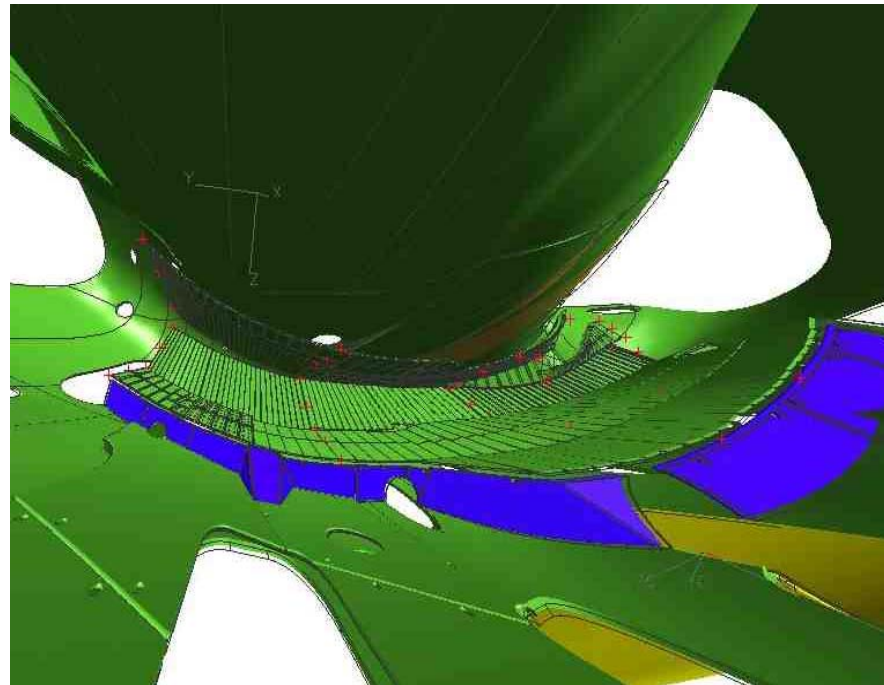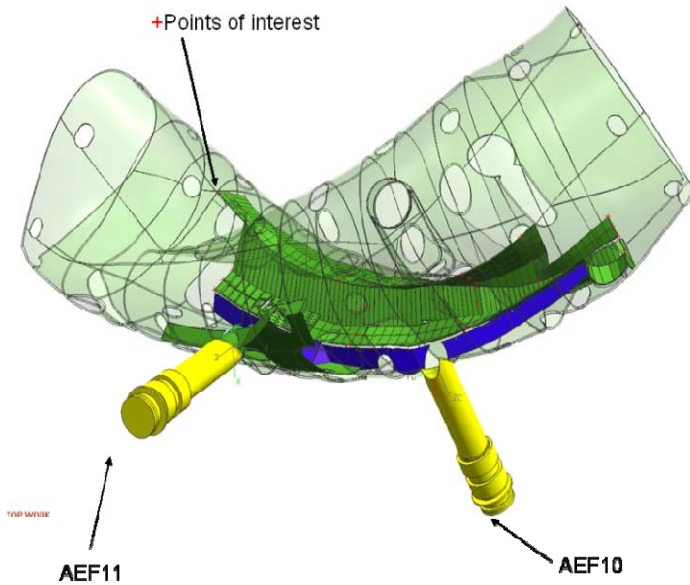
View from the AEF port onto divertor surface with reference points.

Are there a lot of ports?   Yes and No

Tangential views are small & very restricted

254 port penetrations, of which 150 are available to diagnostics

So, basically 30 ports per sector

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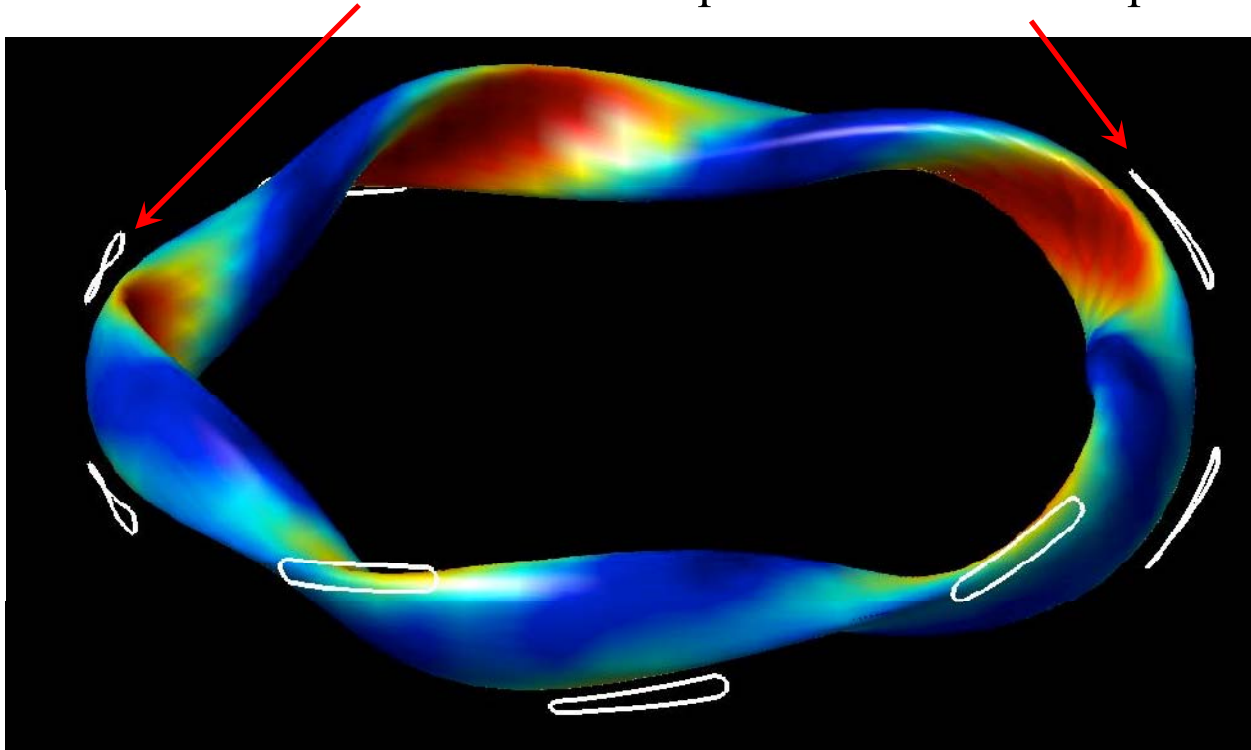# View from quasi-tangential ports (visible and some IR)

View from AEQ port

Opposite AEQ port
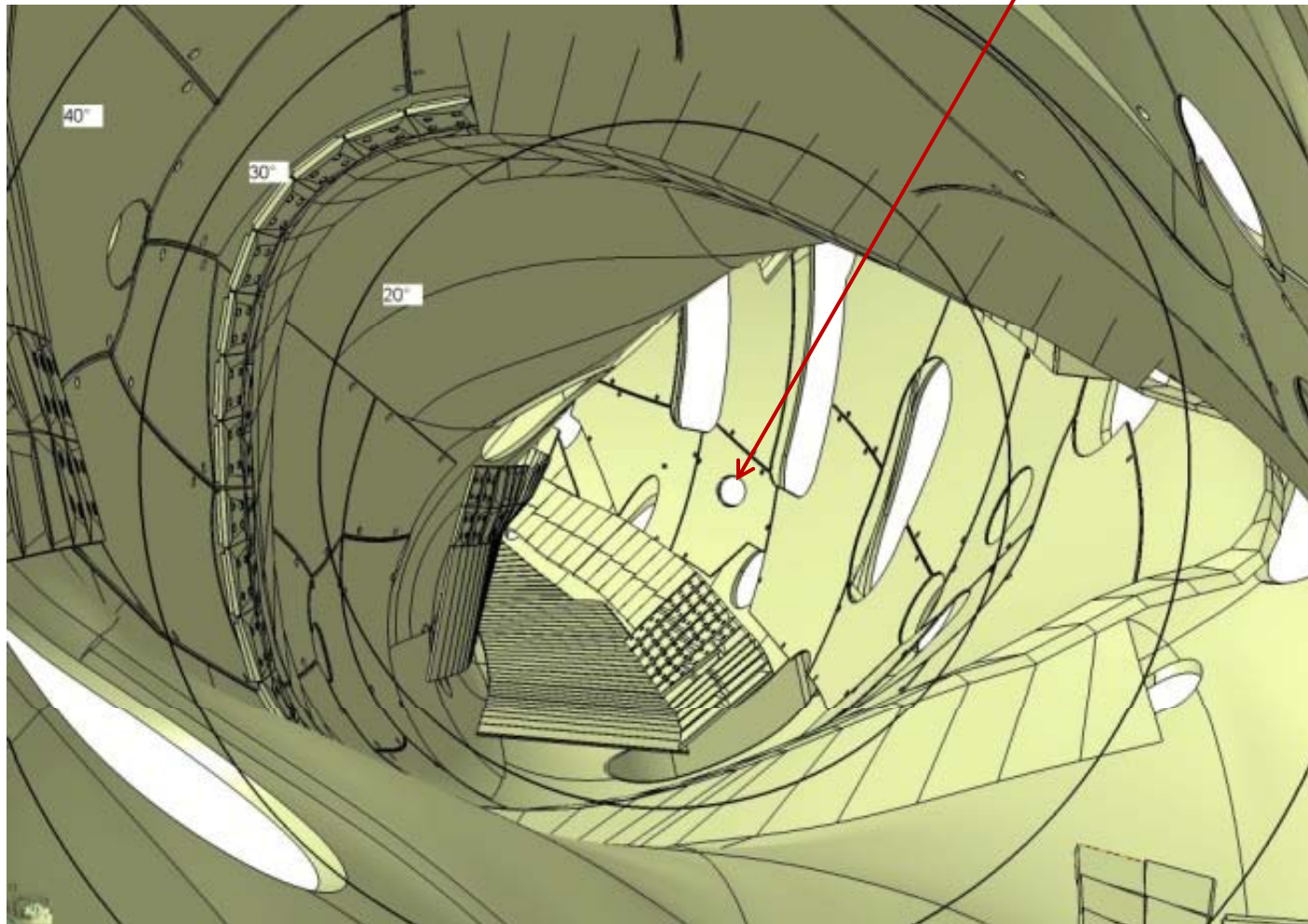
STELLOPT/PIES W7-X reconstruction capability

- Will provide reconstruction tools with/without islands and stochastic regions
  - Essential to the prediction of divertor strike points for control
- Will model effects of divertor sweep coils on the strike points

*Plotting the mod-B surfaces. White loops are the sweep coils

Bootstrap current in W7-X

- Plasma current influences rotational transform profile and can modify X-points and magnetic islands near plasma edge

- W7-X uses an island divertor, so particle and energy deposition on divertor plates depend strongly on the island geometry

- Estimates of tolerable plasma current indicate that it should be controlled within a range of ~10kA

- W7-X has been optimized for zero bootstrap current J_{bs}

- Coil imperfections can result in J_{bs} up to 100kA even in the standard configuration ($<\beta> \sim 4\%$)

LANL effort on understanding stellarator bootstrap current

- For island divertor to operate in W7-X have to be able to compensate for J_{bs}, and so to understand it.

- Some most fundamental features of stellarator J_{bs} are still poorly understood.

- Andrei Simkov (XCP-6) is collaborating with IPP Greifswald's Prof. P. Helander, H. Maassberg, and C. Beidler to understand J_{bs} dependence on the radial electric field, which is not predicted by the standard analytic theory.

Summary of the present W7-X collaboration

- Looking a pressure-induced stochastization of equilibrium flux surfaces.

- Providing a Trim coil system (coils and power supplies)

- Looking at divertors (science & technology aspects) in a 3D geometry, providing specialized divertor hardware.

- Developing long-pulse plasma control capabilities, through modeling (bootstrap issues), controllers, and edge (IR) diagnostics.

These elements are highly constrained by present budgets, but in the future, as operation draws closer, we hope to expand them, and grow US research on W7-X into other related areas (such as long-pulse fueling).