Design and Analysis of Actively-cooled, Edge-transport Diagnostic for Long-pulsed Operation in WEST

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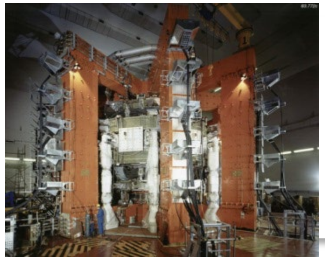
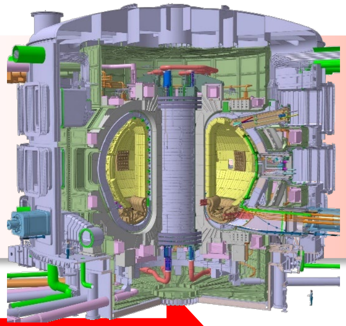
September 11, 2023

Plasma facing components – we have many orders of magnitude to go

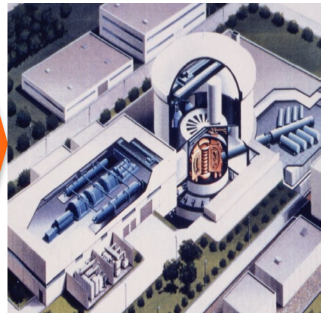
JET



ITER



Fusion DEMO



50 x divertor ion fluxes

5000 x divertor ion fluence

10^6 x neutron fluence (1dpa)

up to 5 x ion fluence

up to 100 x neutron fluence (150dpa)

Operates for seconds

Operates for an hour

Operates continuously

Components need to be developed and tested under fusion prototypic conditions:
High fluxes, high ion fluence, high neutron fluence

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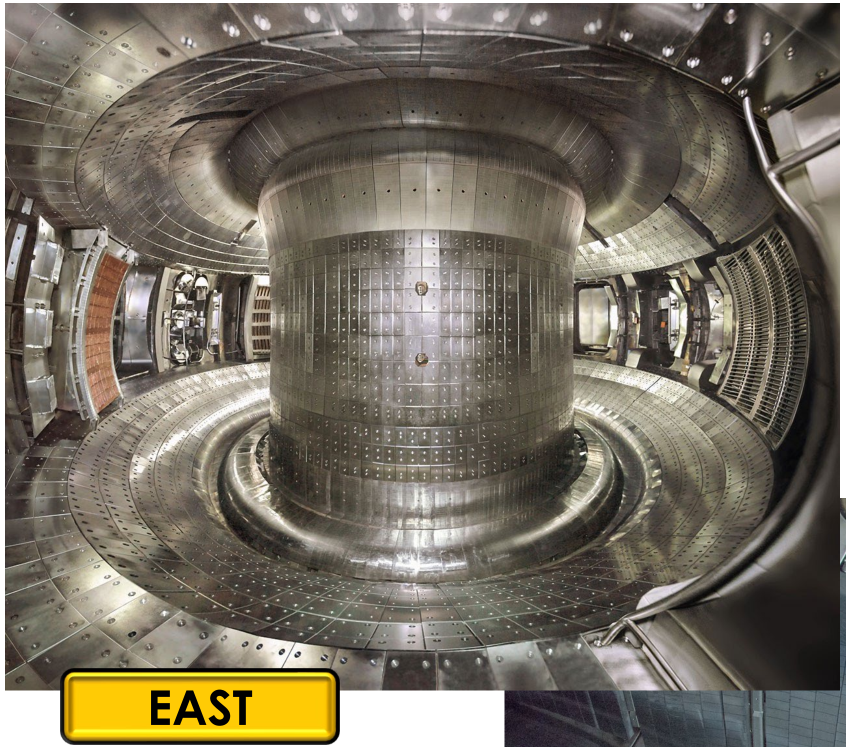
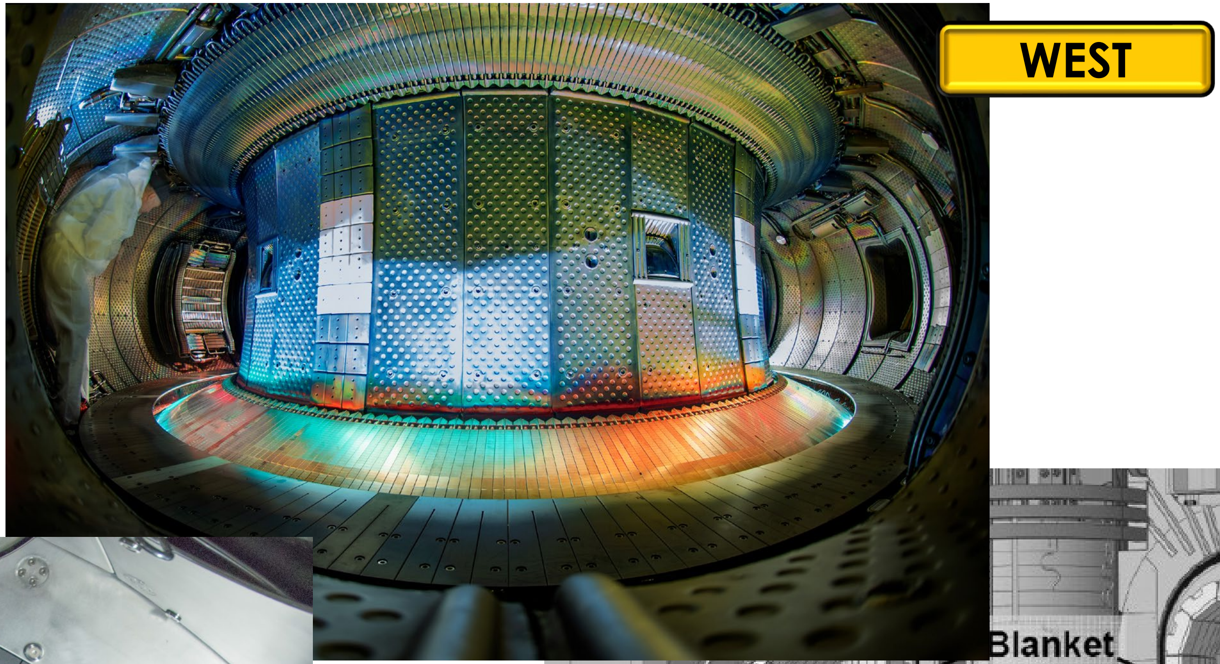
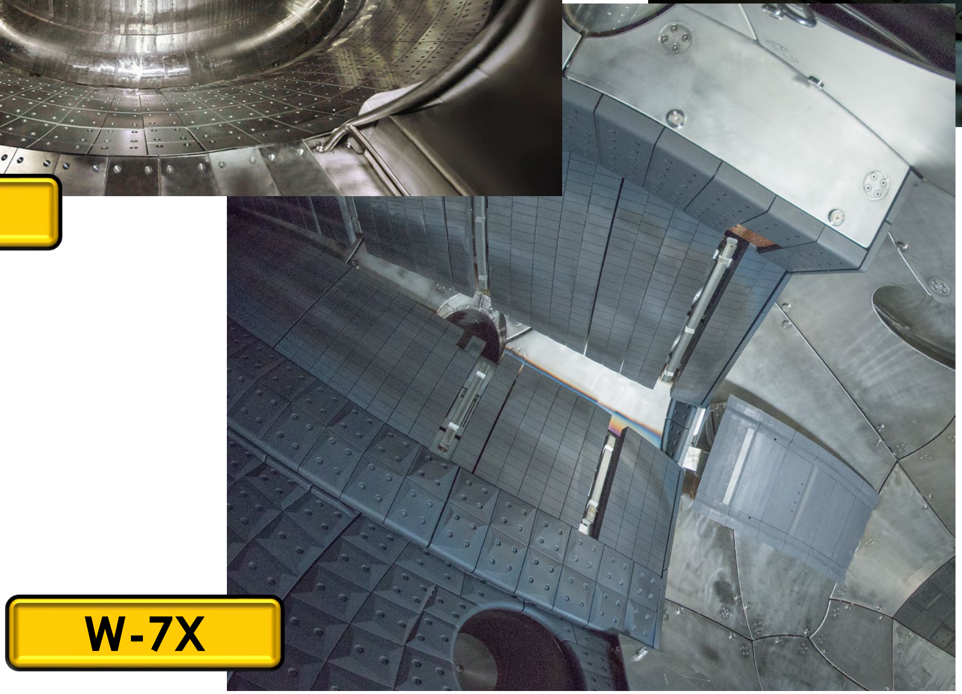
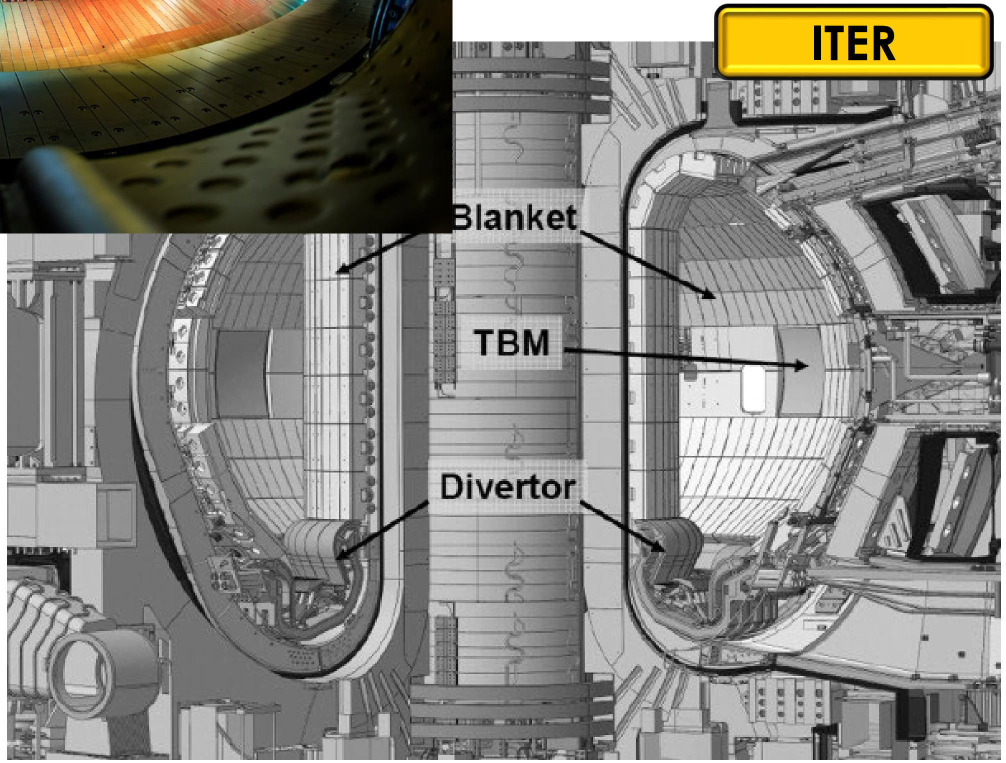
How do we design Plasma Facing Components for a reactor?









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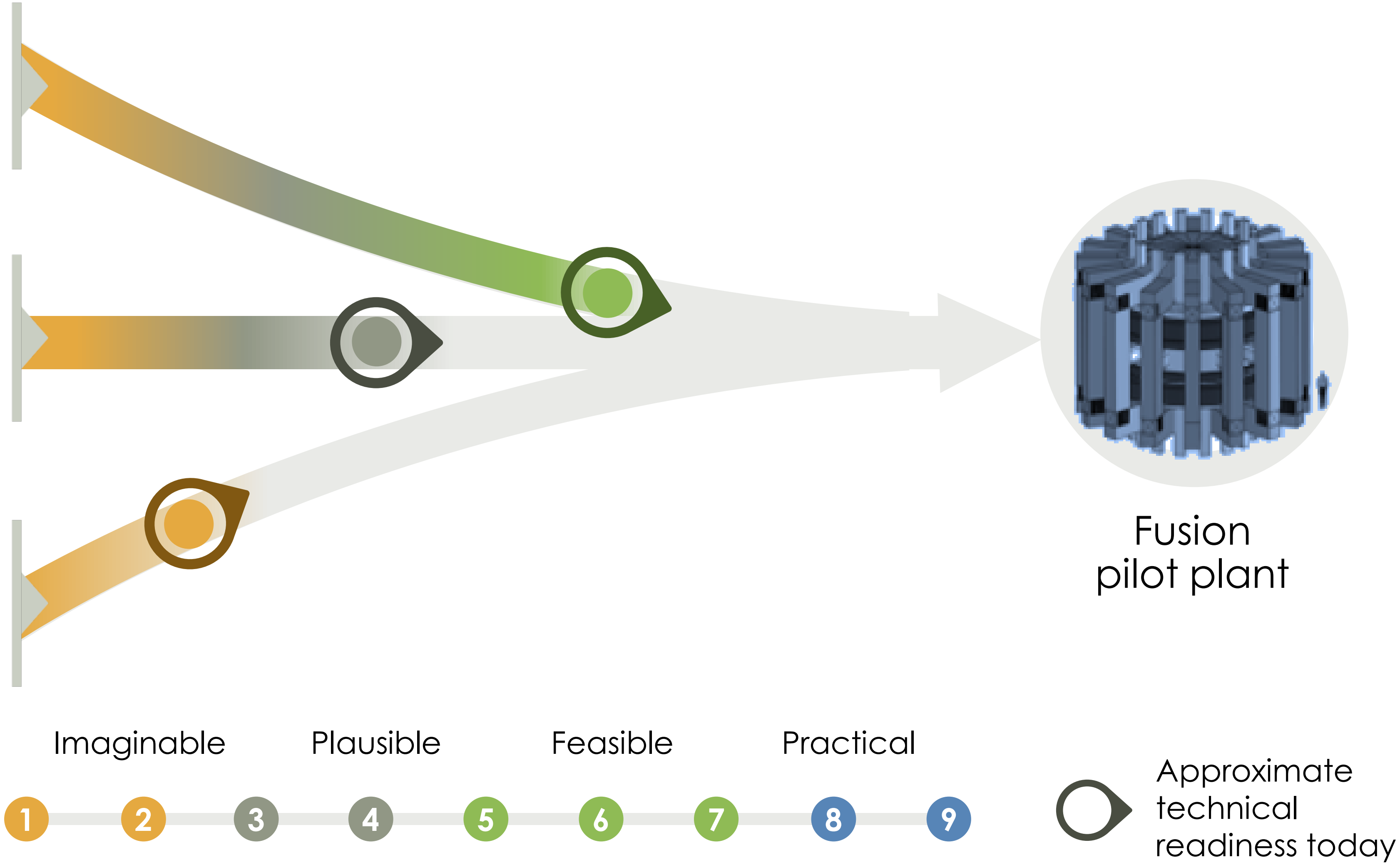
Technical readiness must be advanced rapidly to move towards the achievement of fusion power

Creating and sustaining a fusion power source

Materials to survive in the fusion environment

Fuel self-sufficiency and harnessing fusion power

Technical Readiness Level (TRL)



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WEST tokamak

- The W Environment in Steady-state Tokamak (WEST) tokamak in Cadarache, France is designed to support ITER operation and DEMO conceptual design activities.
- WEST has two missions:
  - Qualification of high heat flux PFCs
  - Integrated steady-state operation at high confinement, with a focus on power exhaust issues
- It is designed to operate long pulse, up to 1000 seconds, including:
  - 8.8 MW RF power
  - ITER divertor target technology (W water-cooled monoblocks)

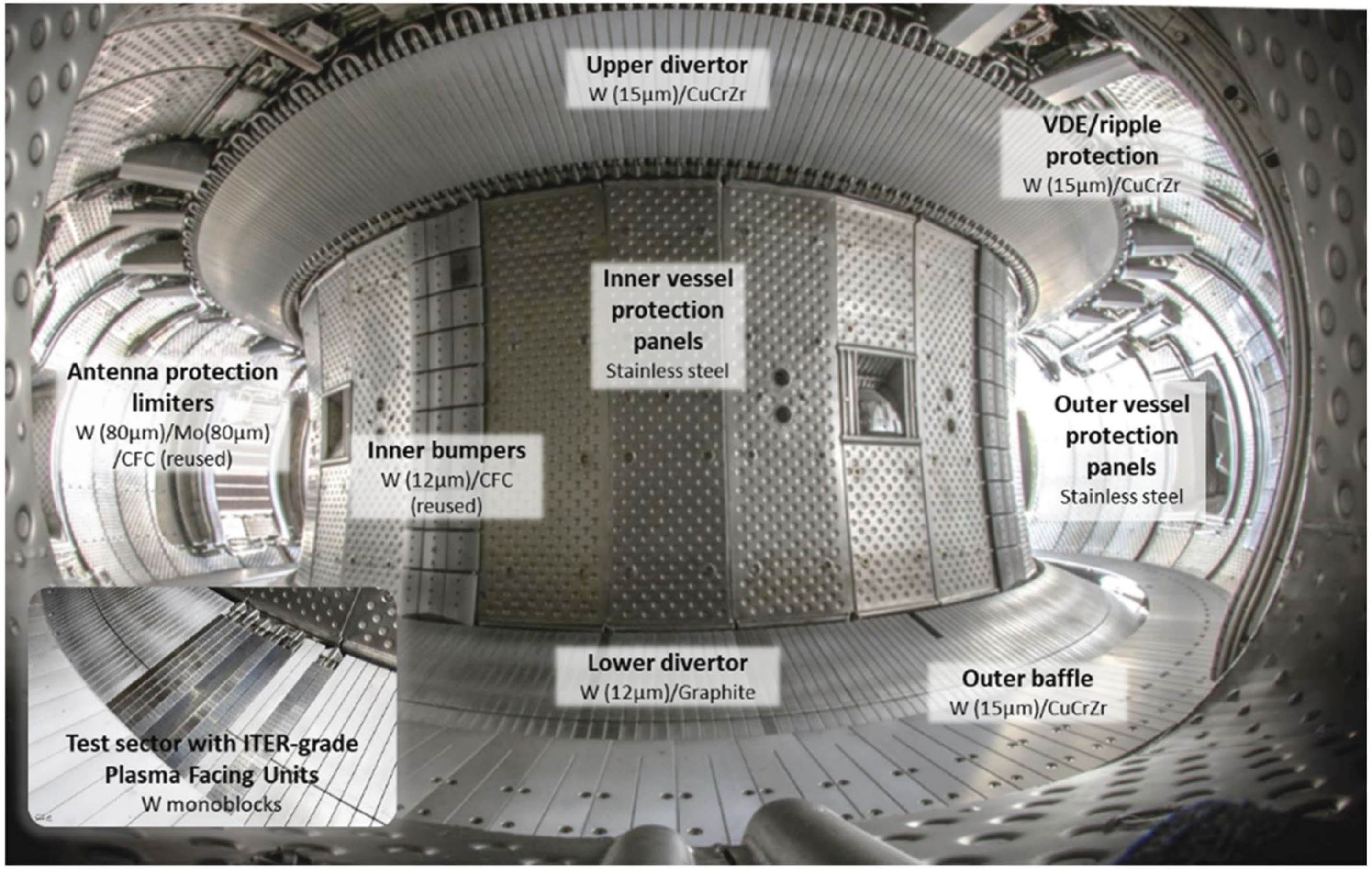
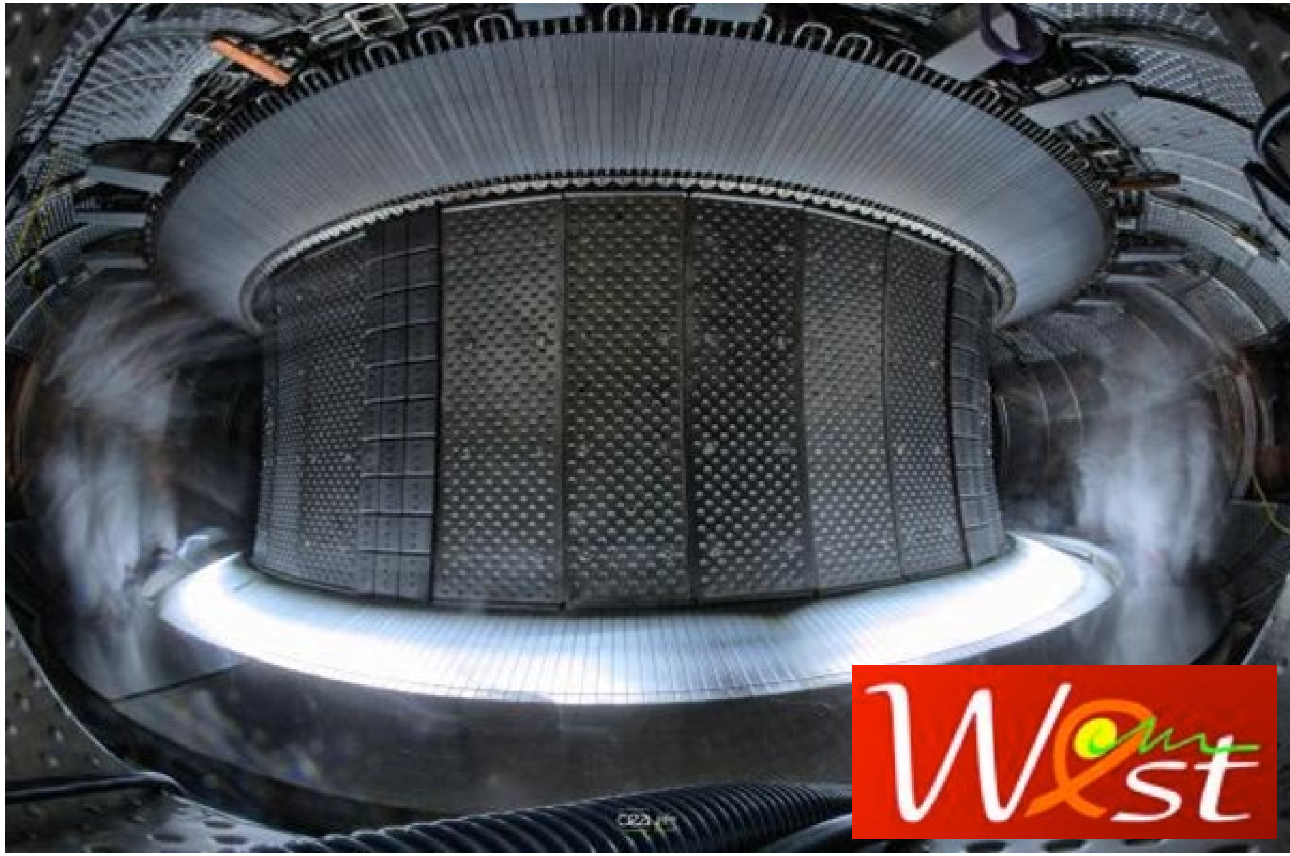


Figure from J. Bucalossi et al (2022) *Nucl. Fusion* **62** 042007

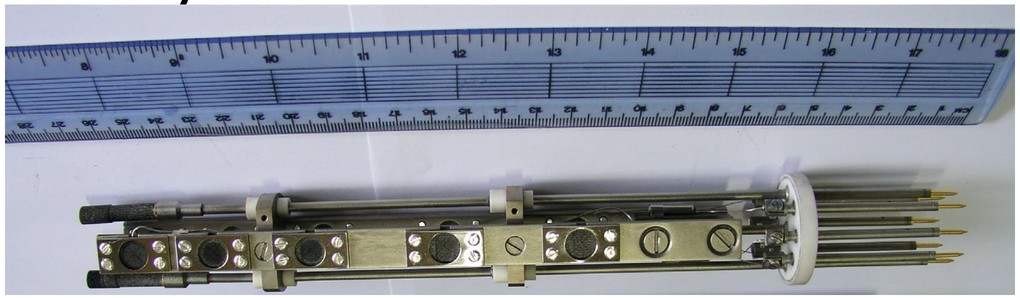
WEST - US collaboration

- Multi-institutional collaboration, involving ORNL, PPPL, University of Illinois, Urbana-Champaign, University of Tennessee, Knoxville, Massachusetts Institute of Technology, and Penn State University.
- The collaboration focusses on integrated analysis to predict and optimize plasma material interactions (PMI) and edge plasma conditions, as well as to investigate approaches to sustain long pulse operations.

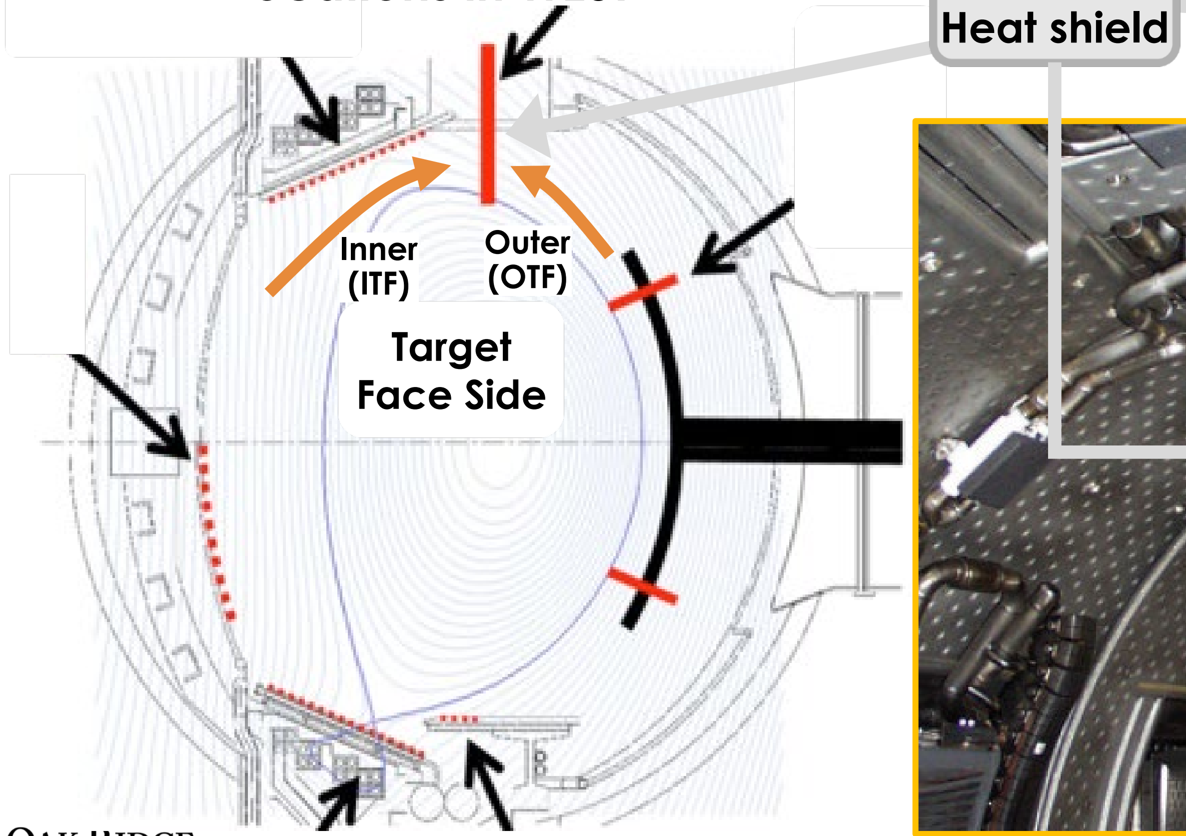


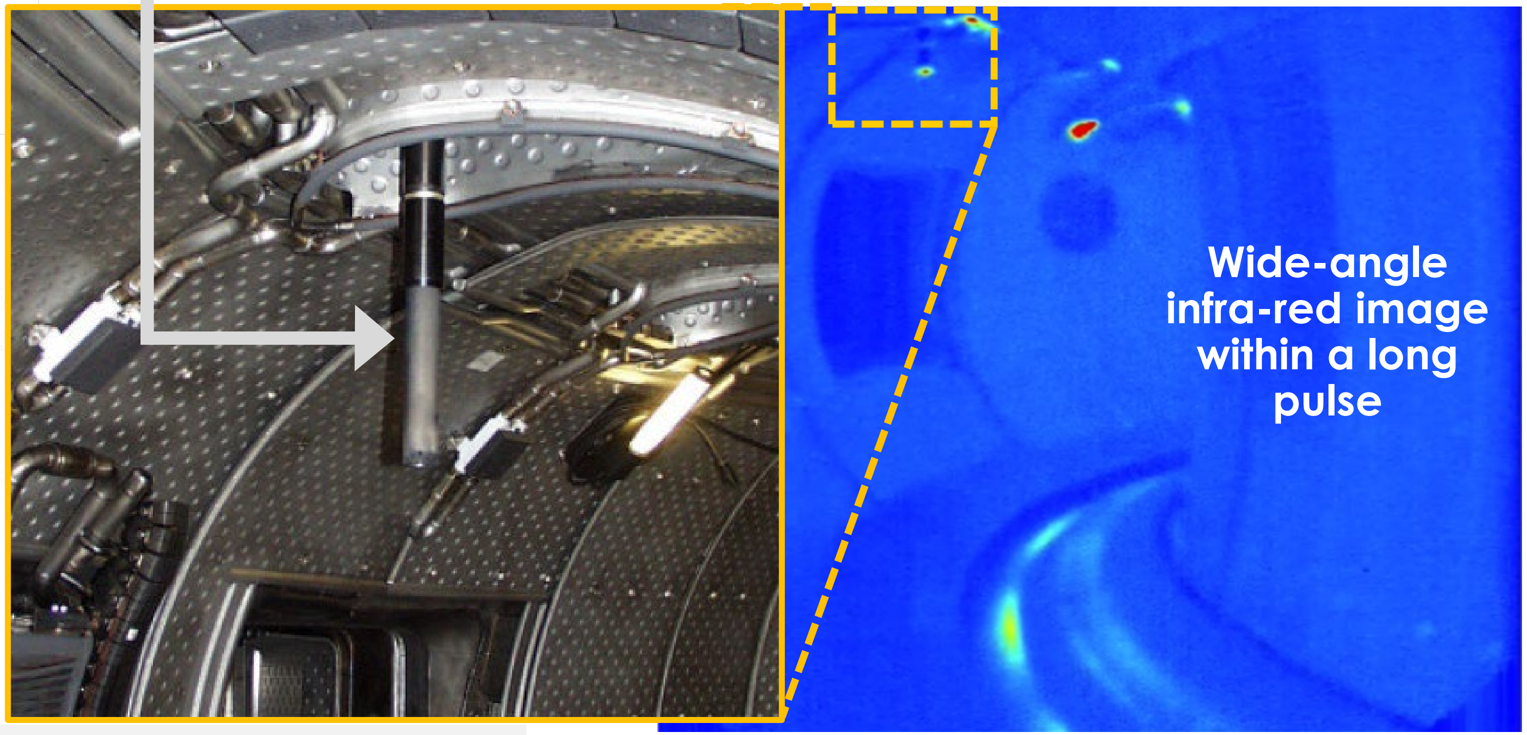
Collector probe for W transport analysis

- Used a reciprocating probe in upper divertor area of WEST.
- Probe drive also has Langmuir probe for background plasma measurements.



Surface & plunging probe locations in WEST

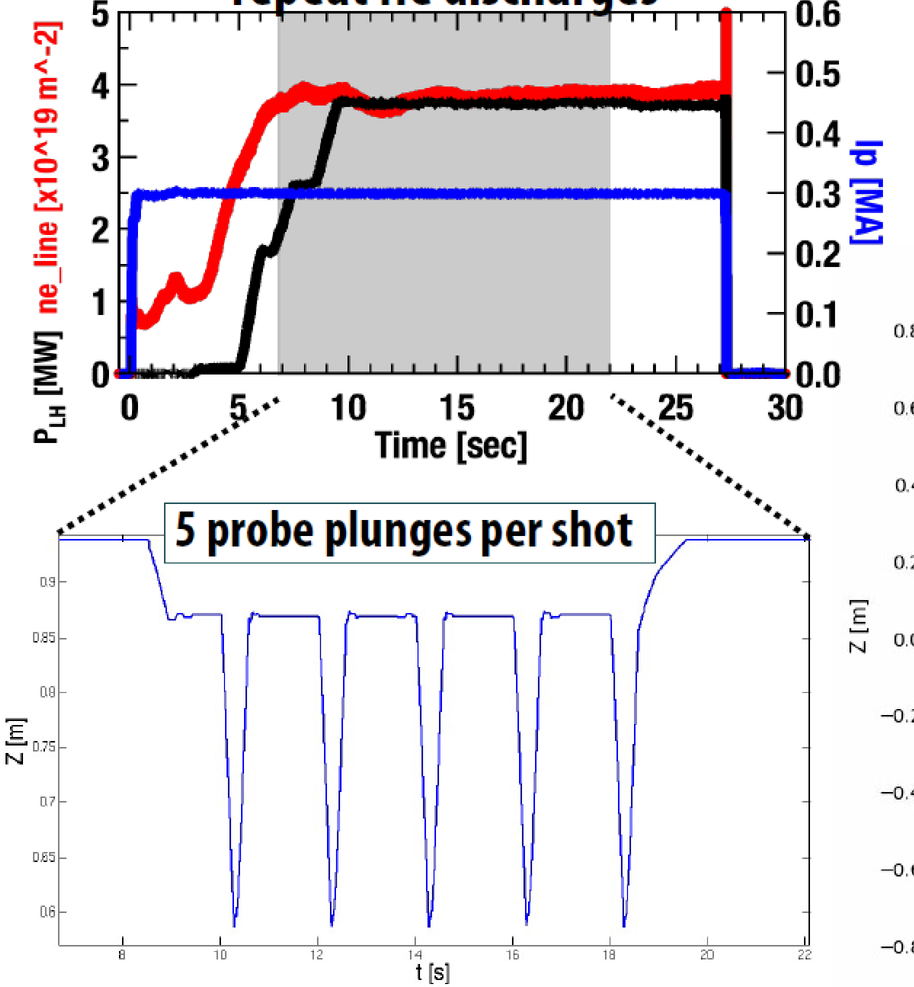




*J.P. Gunn et al., 2005 JNM

2020-1A: Samples adapted into upper CP & progressively plunged into far-SOL

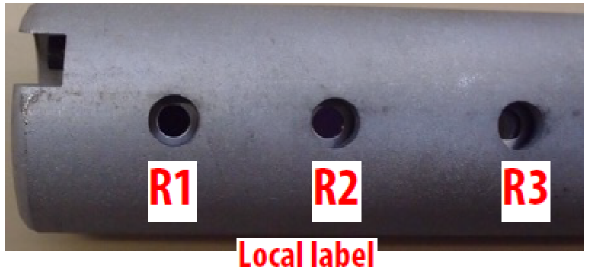
Samples exposed in multiple repeat He discharges

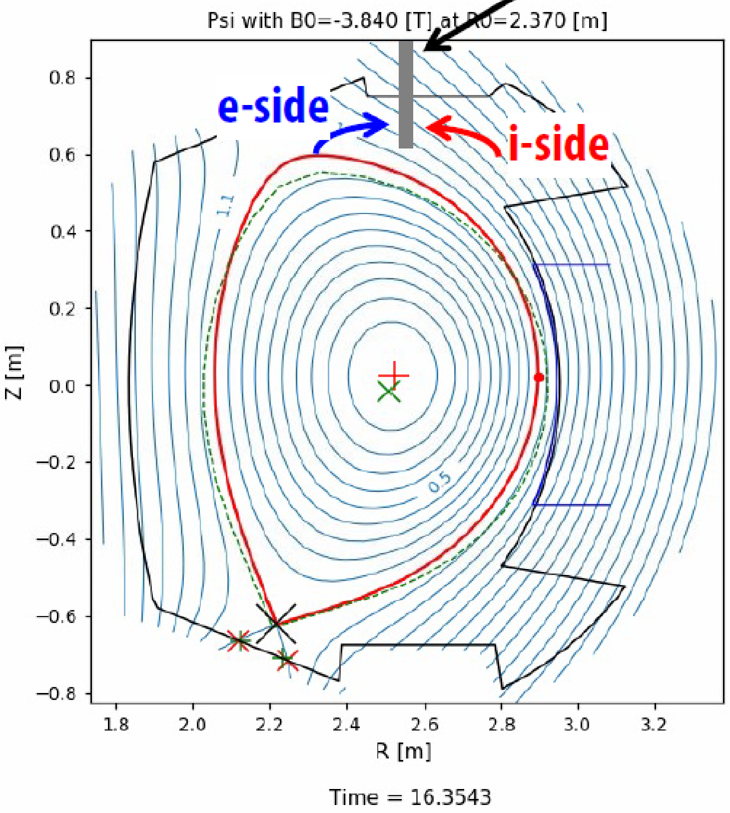


CP Sample holder with 5 samples

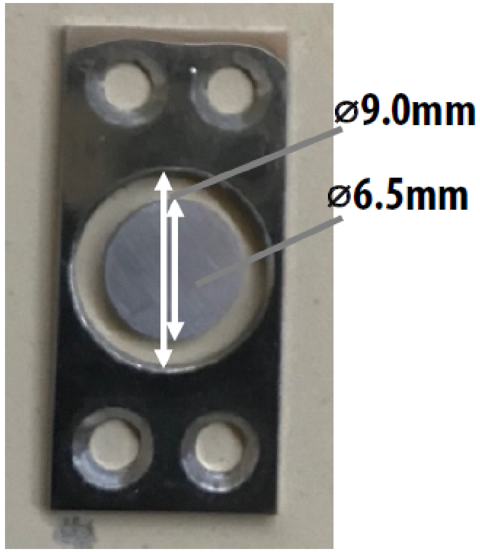
probe

CP heat shield with 3 W samples





W sample + old cover (redesigned for smaller dia.)



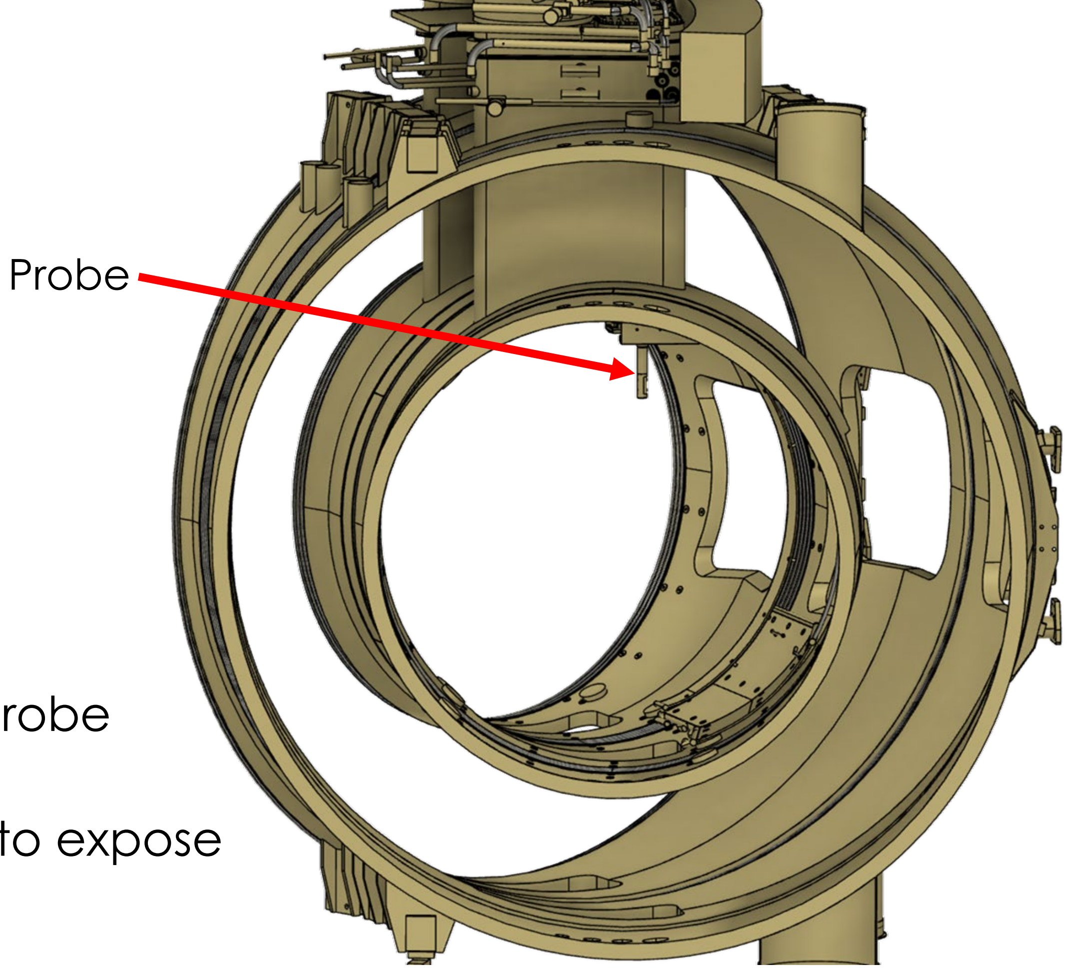
Water-cooled probe mission

- Characterization of samples, beginning with tungsten (W) single crystal samples, during long pulse plasma exposure in the WEST Scrape Off Layer (SOL) plasma.
- High fluence exposure to ITER-relevant conditions.
- Improved validation of PMI modeling of impurity and gas species, transport, implantation, and surface morphology of the sample.
- Mission need:
  1) Reach ITER-relevant exposure fluences → ~$5x10^{25}$ to 10^{26} ions/m^2, peak
  2) Langmuir Probe → T_e, N_e, Ion saturation
  3) Measure (or infer) exposed surface temperature of sample within +-20°C
  4) Impurity and gas species transport and implantation → ex-situ sample analysis, surface morphology, desorption, implantation

Probe retraction during discharge via IRTV (Special thanks to A. Grosjean for IR images & movie)

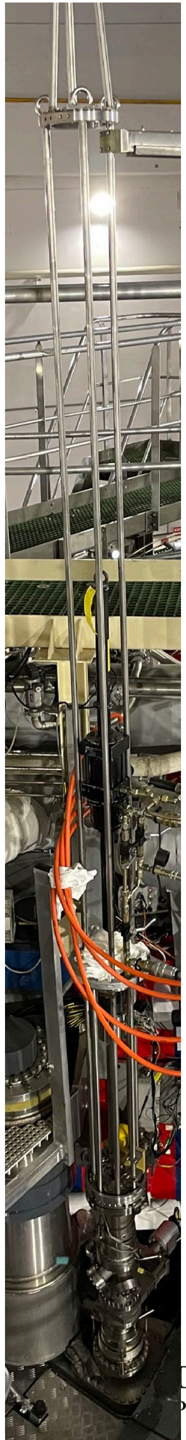
Probe design requirements

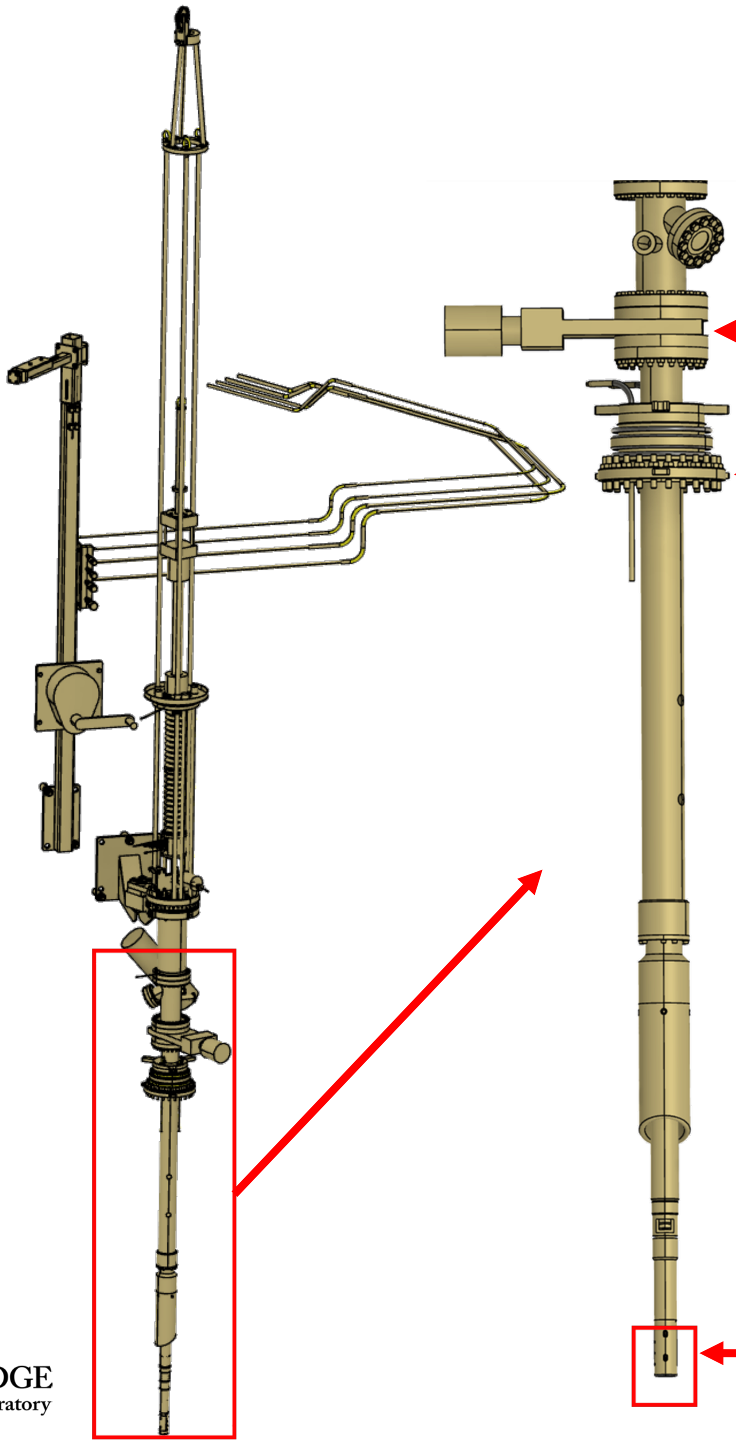
- Samples
  - Tungsten single crystal samples will be exposed
  - Both upstream and downstream exposure
  - Several samples along the Z axis
  - Temperature monitoring will be available
- Location
  - The samples will be exposed to the SOL through a probe inserted at the top of the WEST tokamak
  - The probe will have the ability to move in the Z axis to expose samples to different parts of the SOL
- Sampling time
  - The probe will be exposed for long pules in different parts of the SOL
  - Pulse time will be up to 1000 seconds
  - Water connections will be made to an existing WEST water feed, with 3 MPa inlet pressure and 70°C inlet temperature.

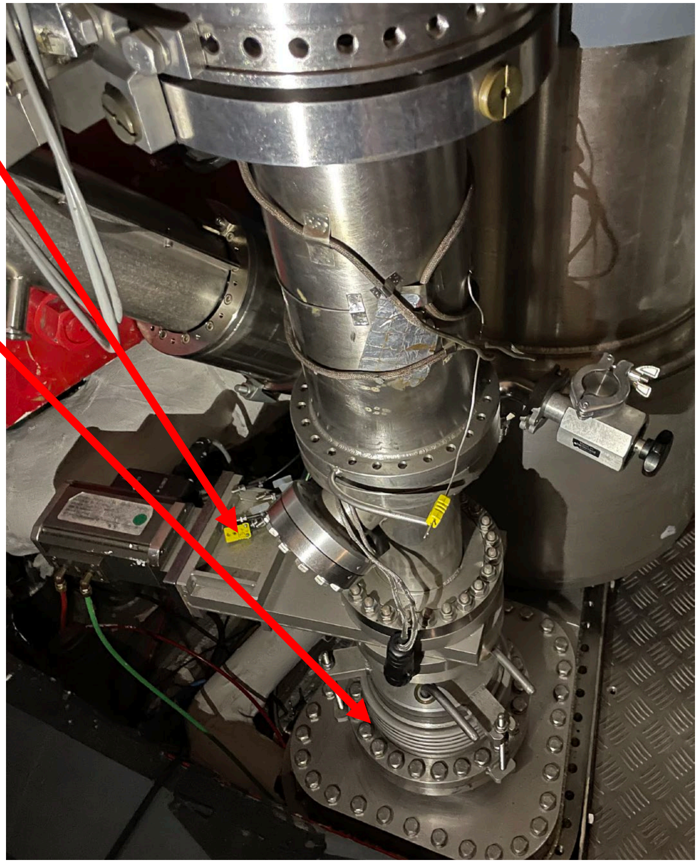


Z-direction

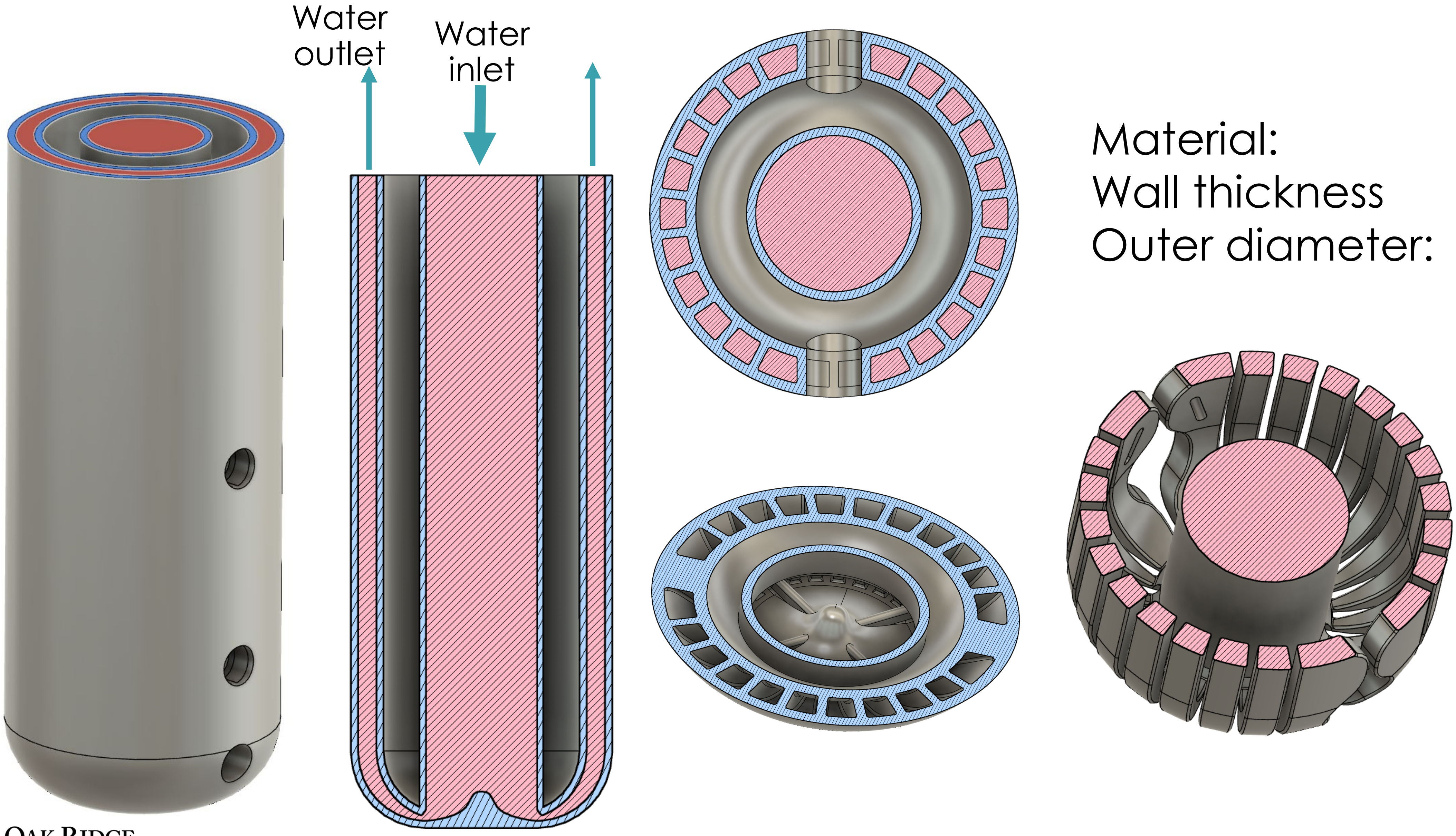
Probe design







Probe tip design concept



Material:	TZM
Wall thickness	1.5 mm
Outer diameter:	40 mm

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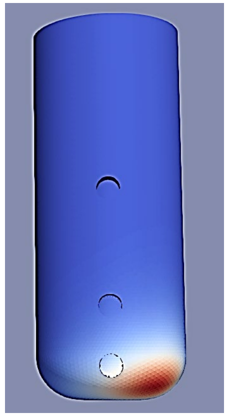
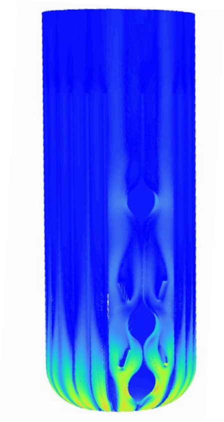
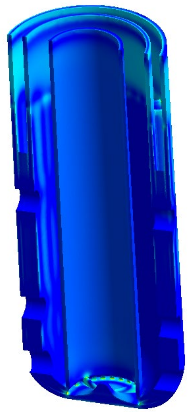
Simulation workflow







- WEST Parameters
- MHD-Poloidal Flux
- SOL flux profiles

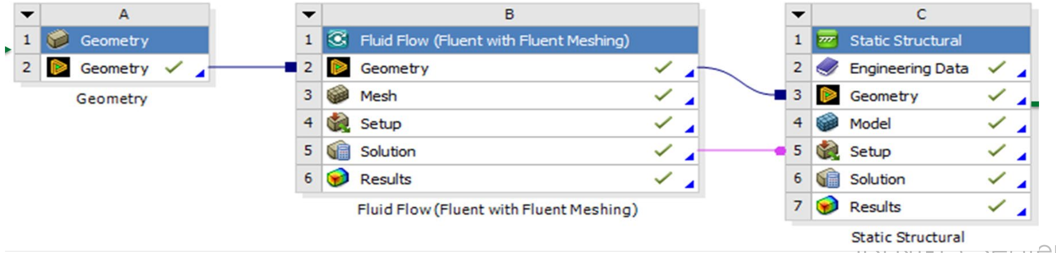
HEAT
Heat flux Engineering Analysis Toolkit

- Probe Tip Heat Fluxes
- Point Cloud
- FLUENT UDF Import

FLUENT
CFD/Heat Transfer

- Body Temperatures
- Dynamic Pressures

ANSYS MECHANICAL
Static Structural



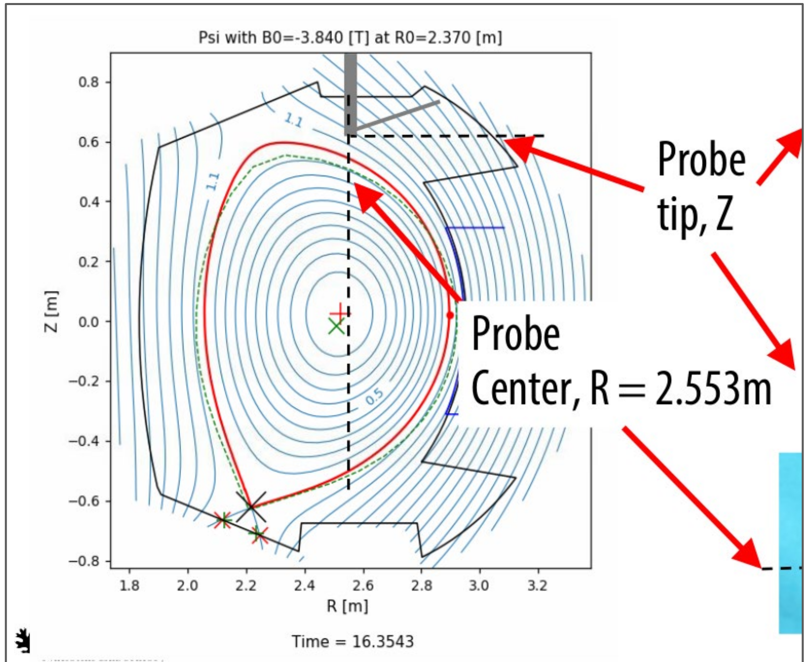
Simulation – HEAT results

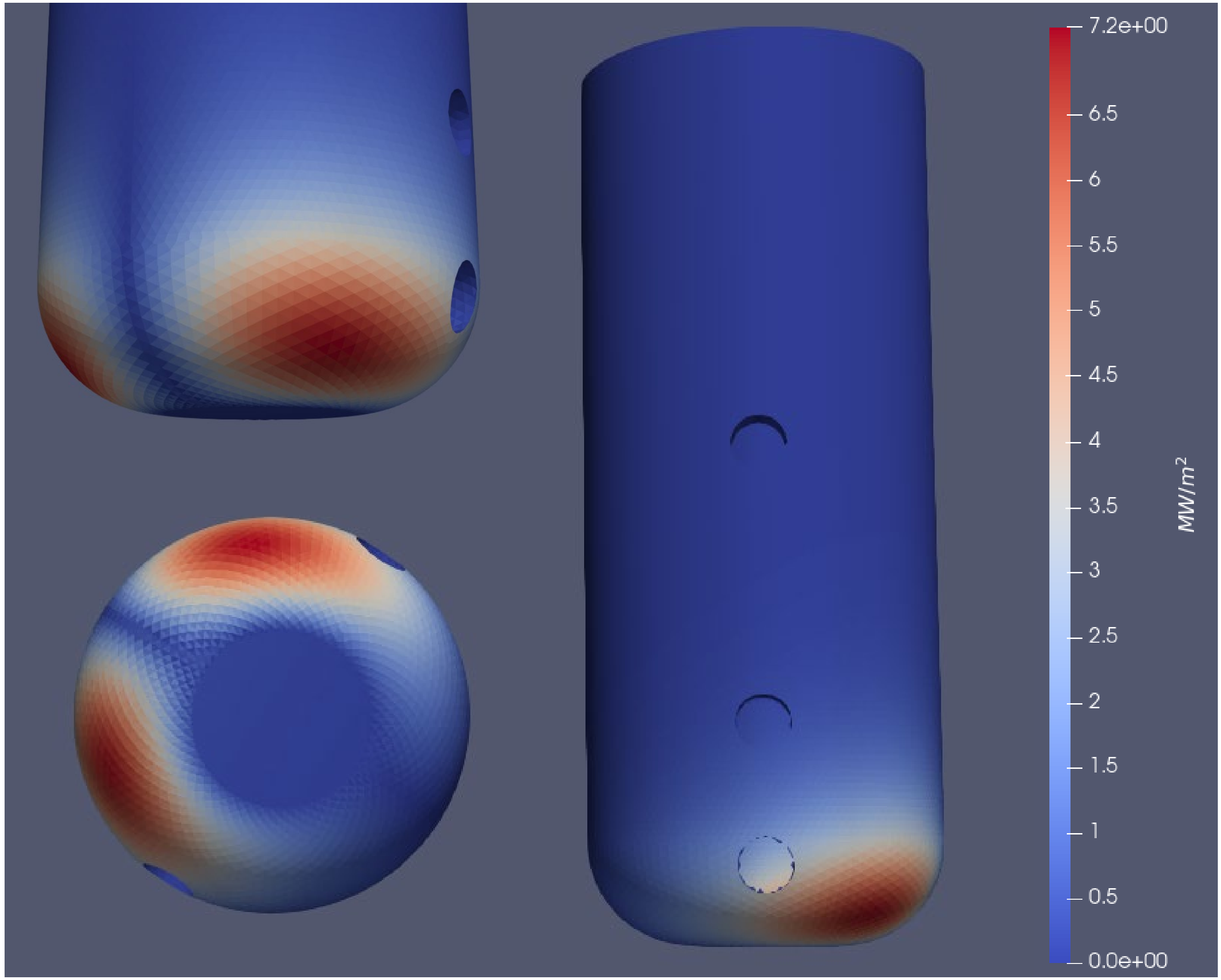
Heat flux Engineering Analysis Toolkit (HEAT)

- Suite of tools developed at ORNL* for predicting the heat flux incident upon PFCs in tokamaks.
- 3D heat loads from 2D plasmas for limited and diverted discharges.

HEAT Results

- 7.19 MW/m^2 Peak Heat Flux
- 5821 Watt Total Power to Probe Tip





*T. Looby, et al (2022), Fusion *Science and Technology* **78** *(1)* 10-27

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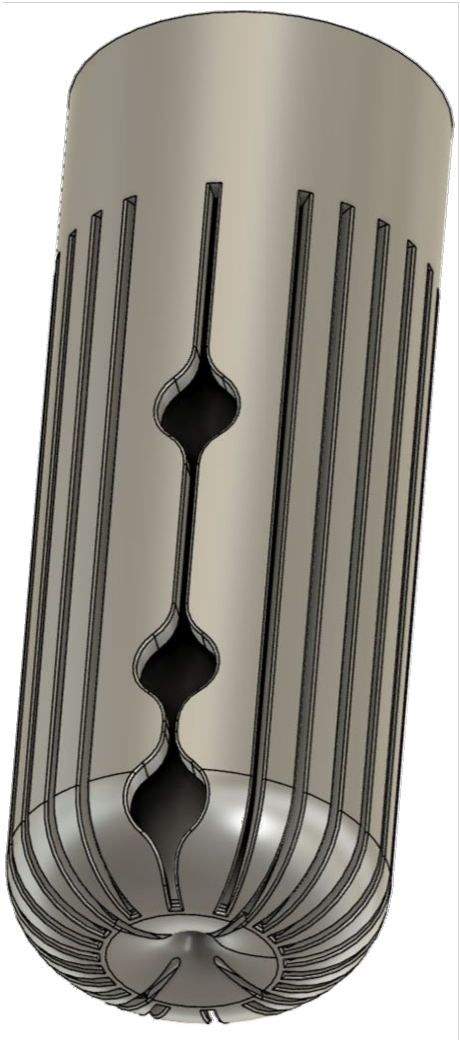
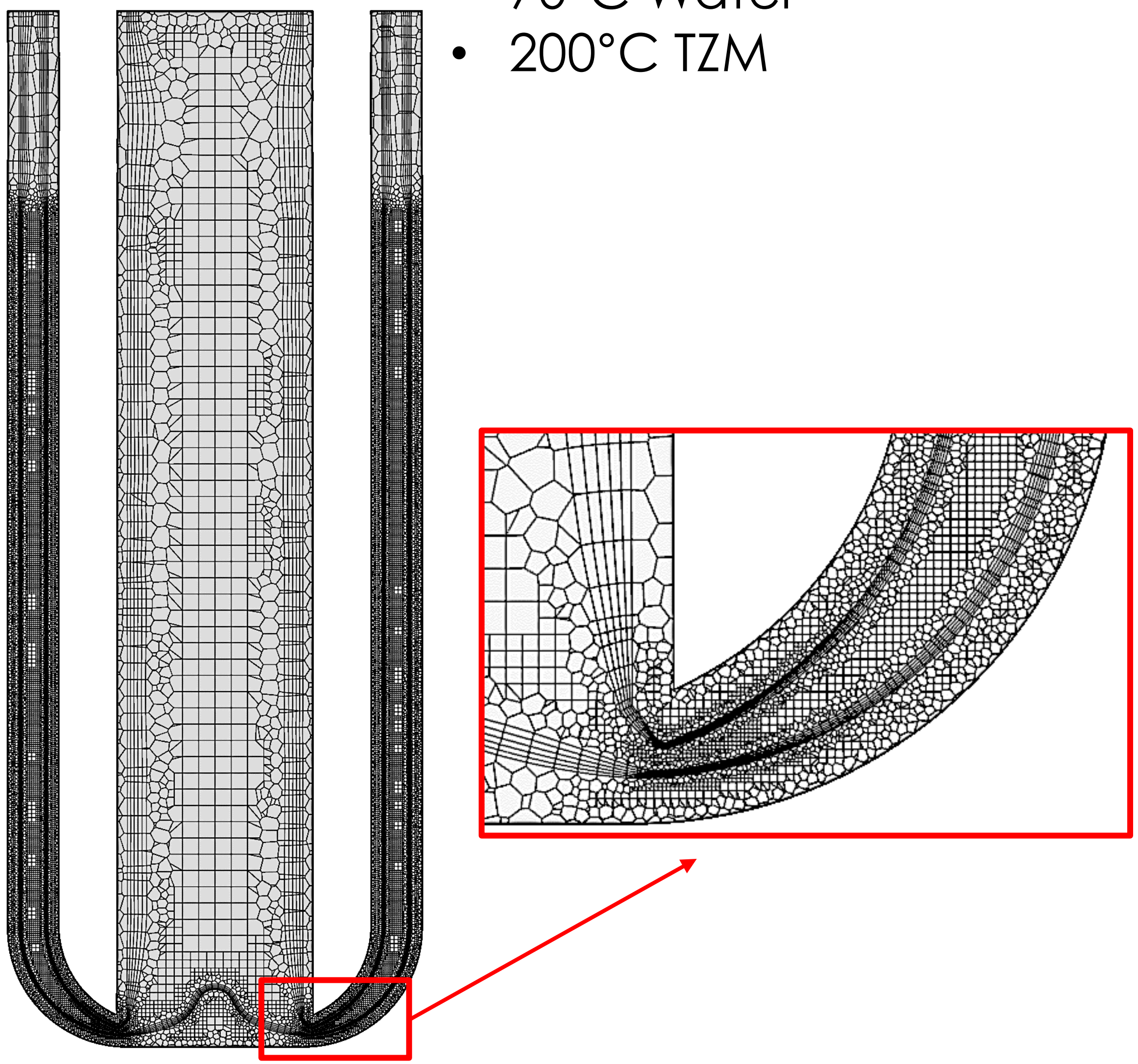
Simulation – FLUENT setup



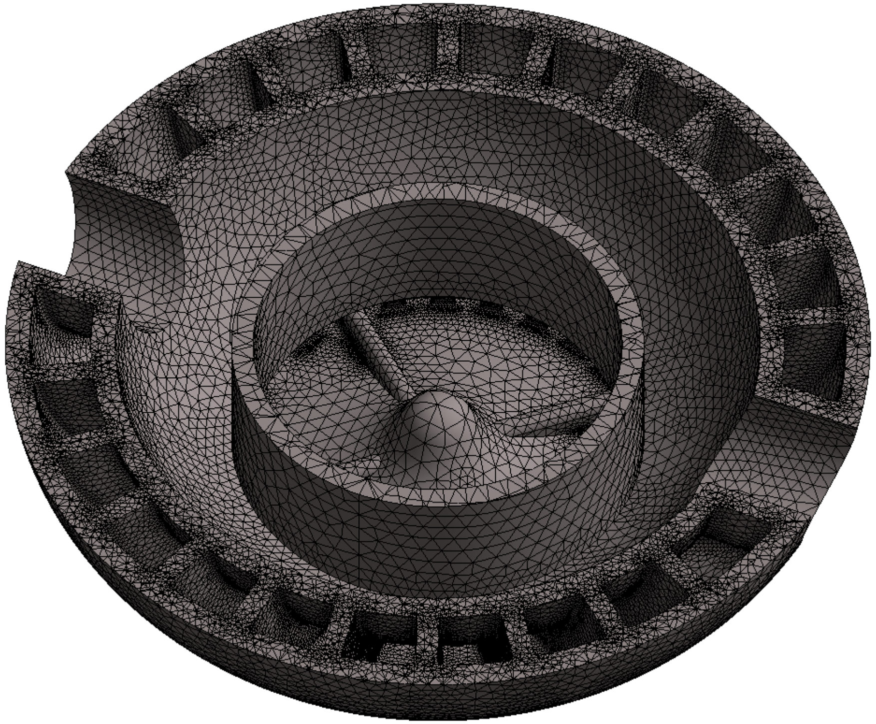


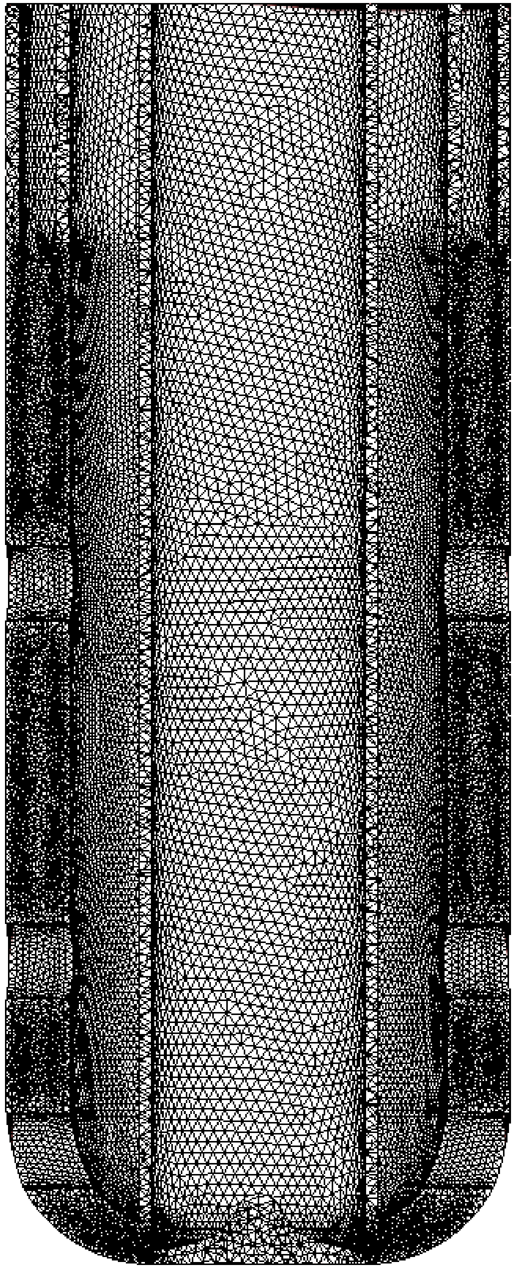
Constant material properties
- 70°C Water
- 200°C TZM

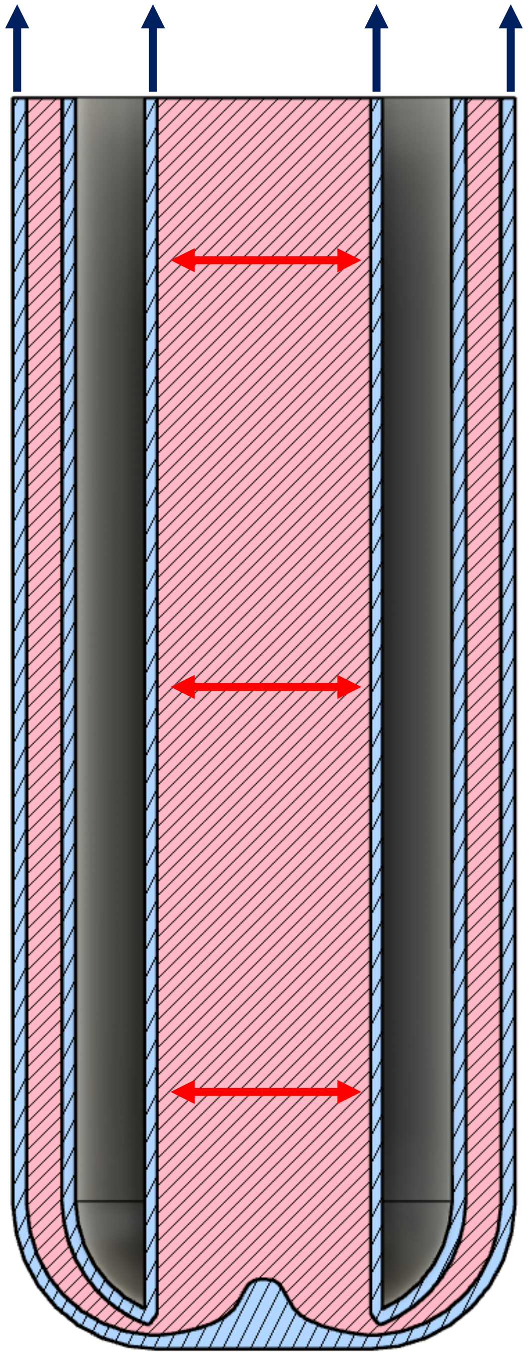
Simulation – ANSYS mechanical

Mechanical Set Up

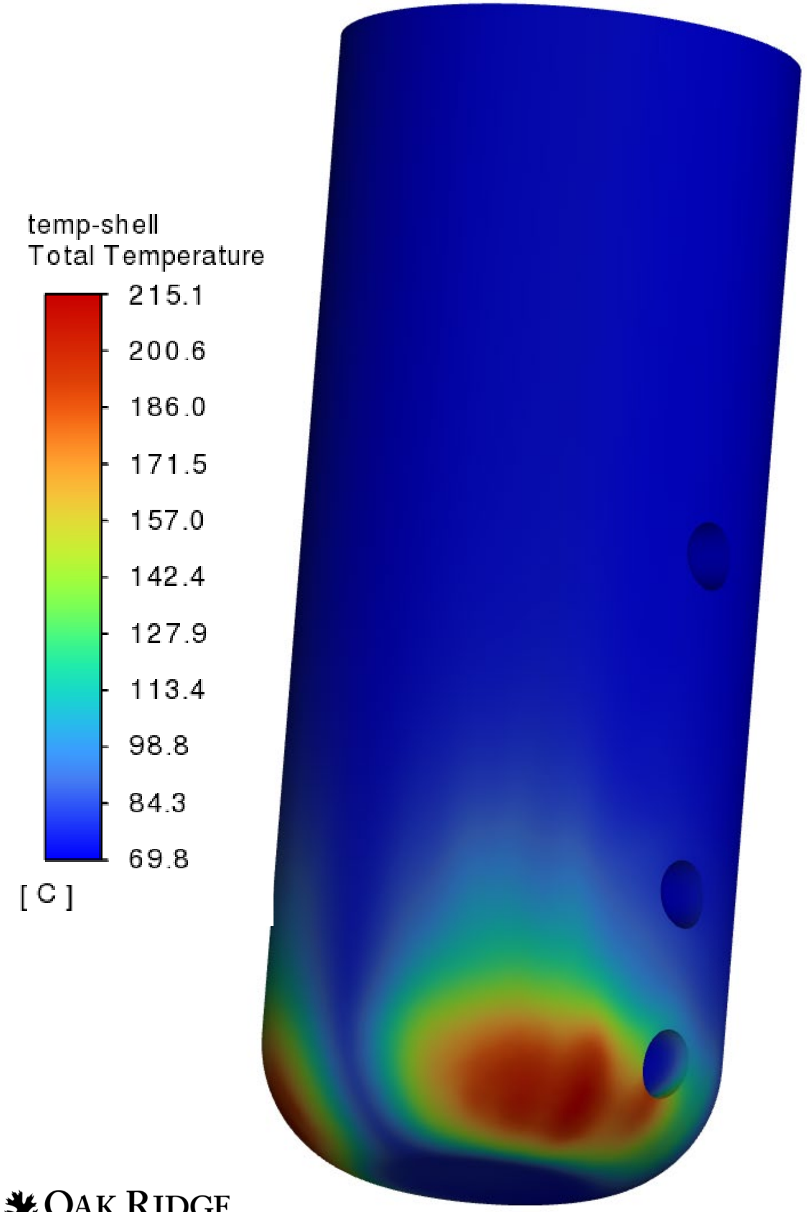
- Fixed Support on concentric top surfaces
- 30 Bar pressure on all wetted surfaces
- Temperature Dependent CTE, Youngs Modulus
- Imported Body Temperature from FLUENT

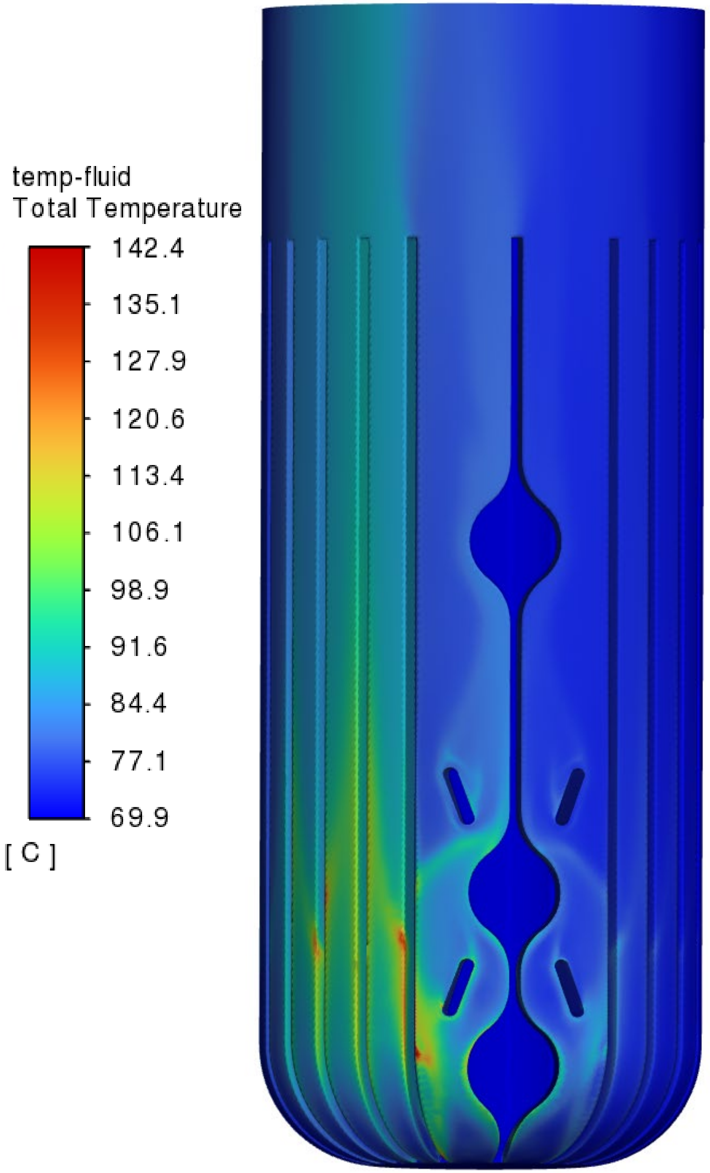






Results – FLUENT thermal-fluid analysis





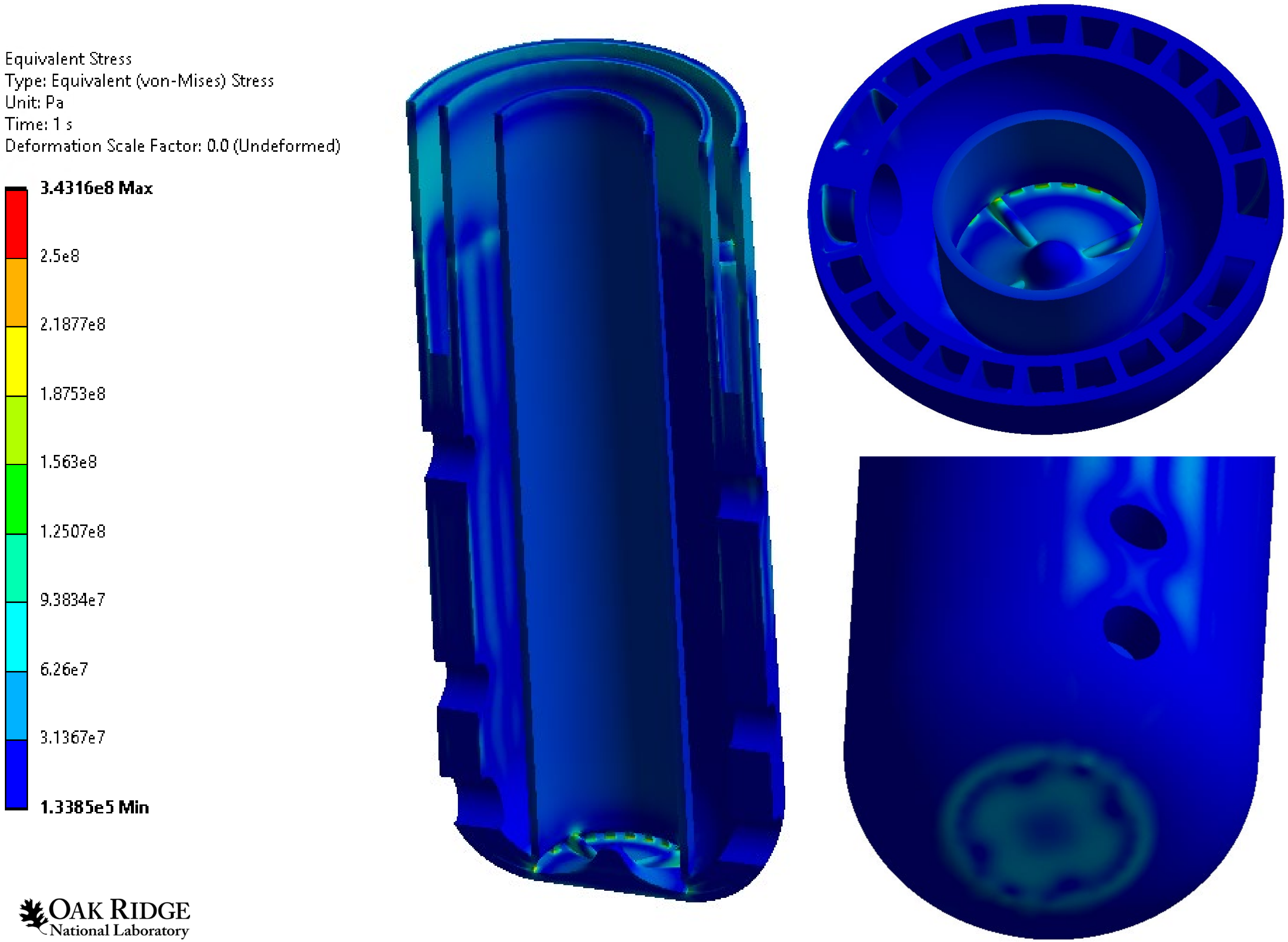
Peak temperature of TZM = 215 °C

Peak temperature of water = 142 °C

Total pressure drop of water = 330 kPa (47 psi)

Water temperature increase = 2.1 °C

Results – Von Mises stress



Localized peak Von Mises stress = 343 MPa

Yield strength of TZM
- 848 MPa at 70 °C
- 815 MPa at 200 °C

Ultimate strength of TZM
- 951 MPa at 70 °C
- 914 MPa at 200 °C

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Next steps

- Probe tip design
  - Optimize design concept (topology, materials, etc.)
  - Perform manufacturing qualification
  - Perform high heat-flux testing
- Finalize probe assembly design
- Manufacture probe assembly
- Testing / qualification for use on WEST
- Deploy by end of 2025

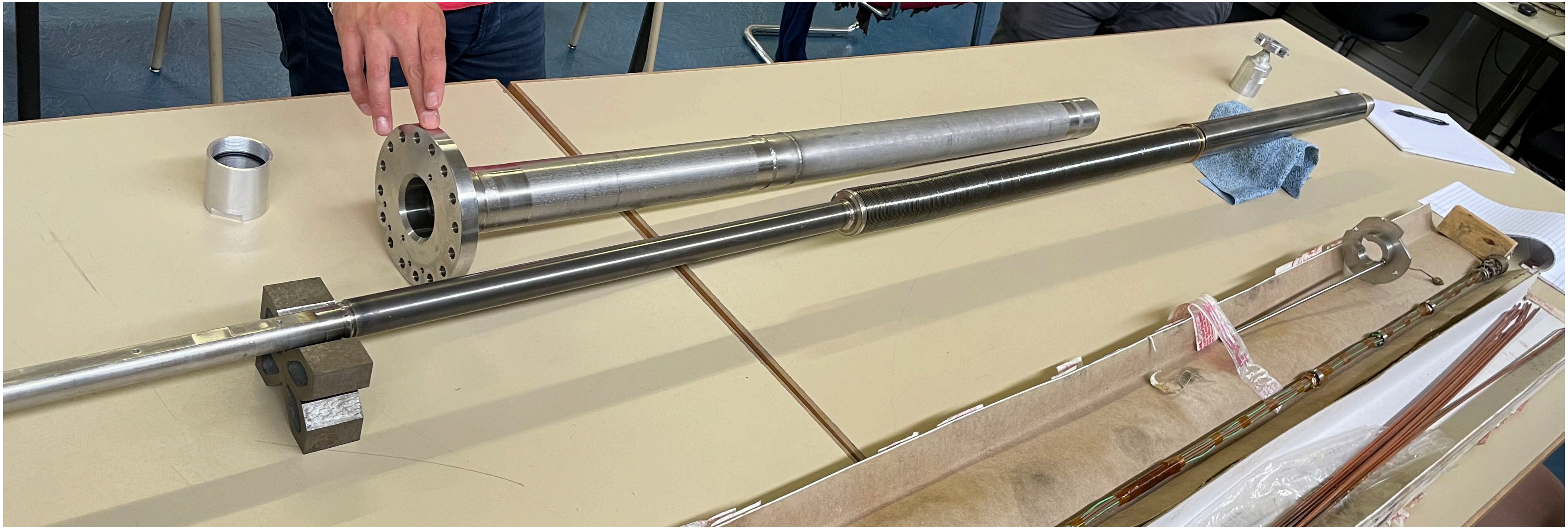
Summary and Conclusions

- The development of actively cooled Plasma Facing Components (PFCs) is a critical need for the development of long-pulse and steady-state fusion devices.
- A US-CEA collaboration to predict and optimize PMI and edge plasma conditions is also exploring design of a PFC for long pulse conditions.
- A design concept is presented for a water cooled diagnostic probe tip for WEST.
- Results indicate a TZM design is feasible to meet scientific requirements.
- Probe details need to be refined, tested, and qualified, and the design of entire reciprocating system needs to be completed.
- Installation and operation expected in 2025.

Discussion

Overview

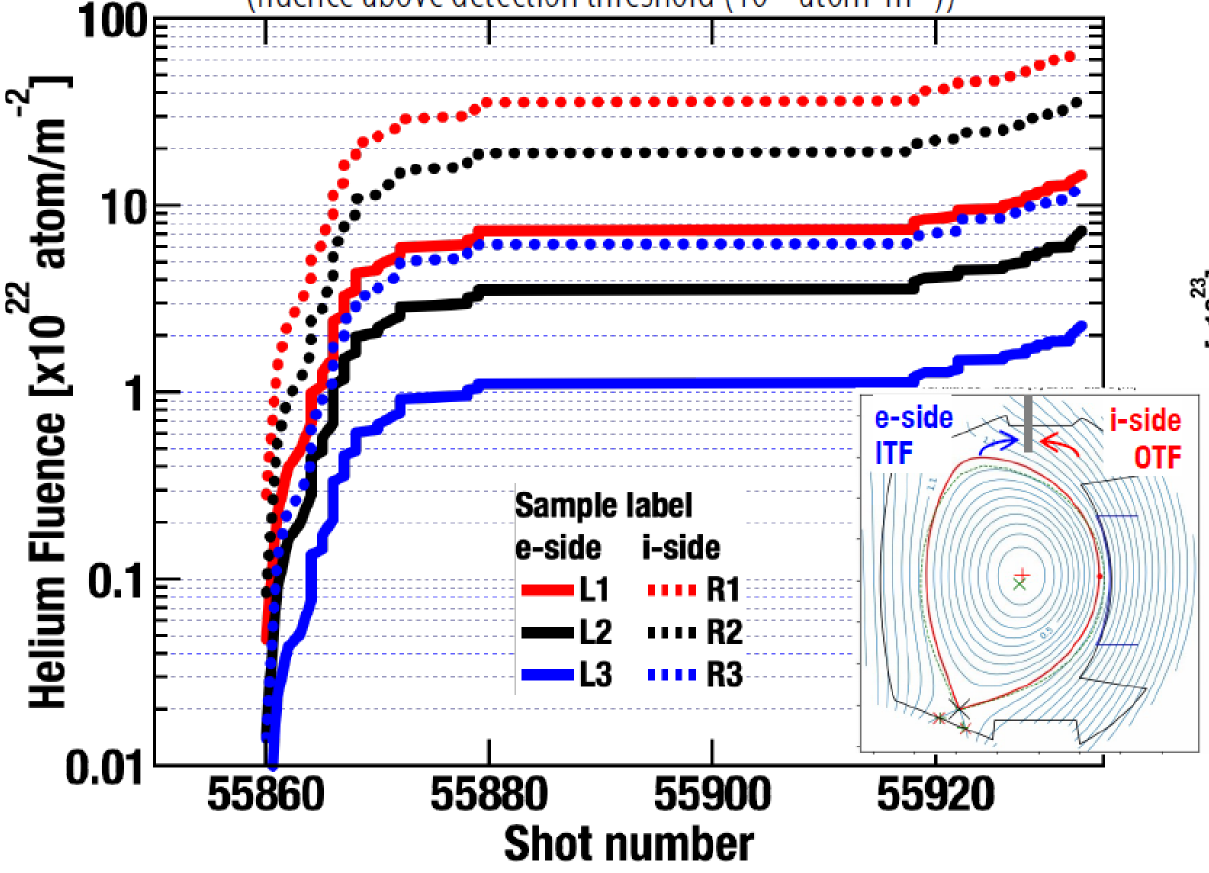
- Motivation
  - Actively cooled PFC's
  - CEA / ORNL collaboration
- Background
- Design and Simulation
- Summary and Conclusions



2020-1A: Good He fluence achieved with ~250 plunges in 50 shots; SOL profiles measured by companion upper vertical reciprocating probe

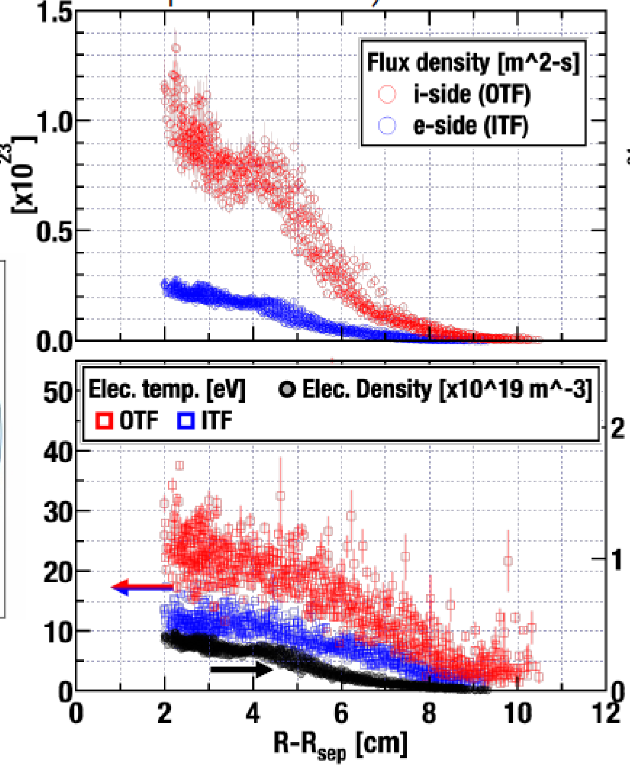
Asymmetry in total fluence per side

(fluence above detection threshold (10^{22} atom-m^{-2}))

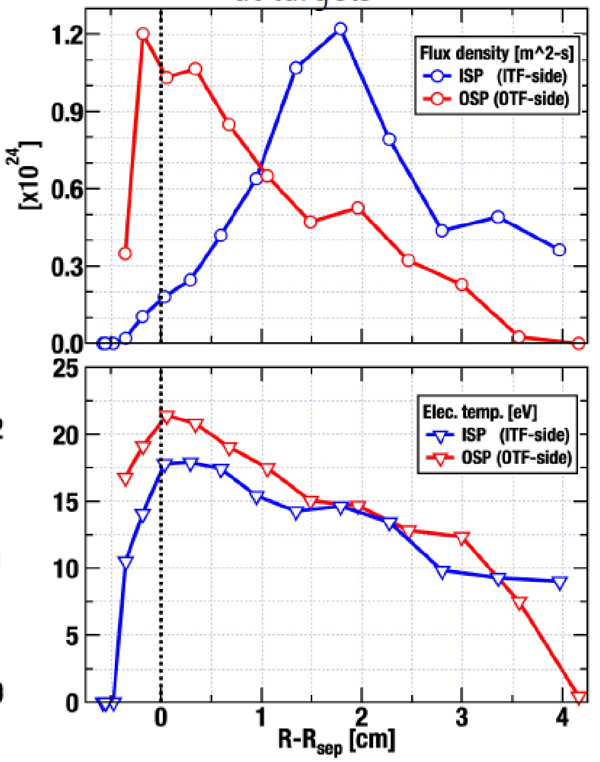


Measured upstream & target plasma profiles → modeling input

ITF/OTF upstream profiles are asymmetric



No asymmetry (in mag.) at targets

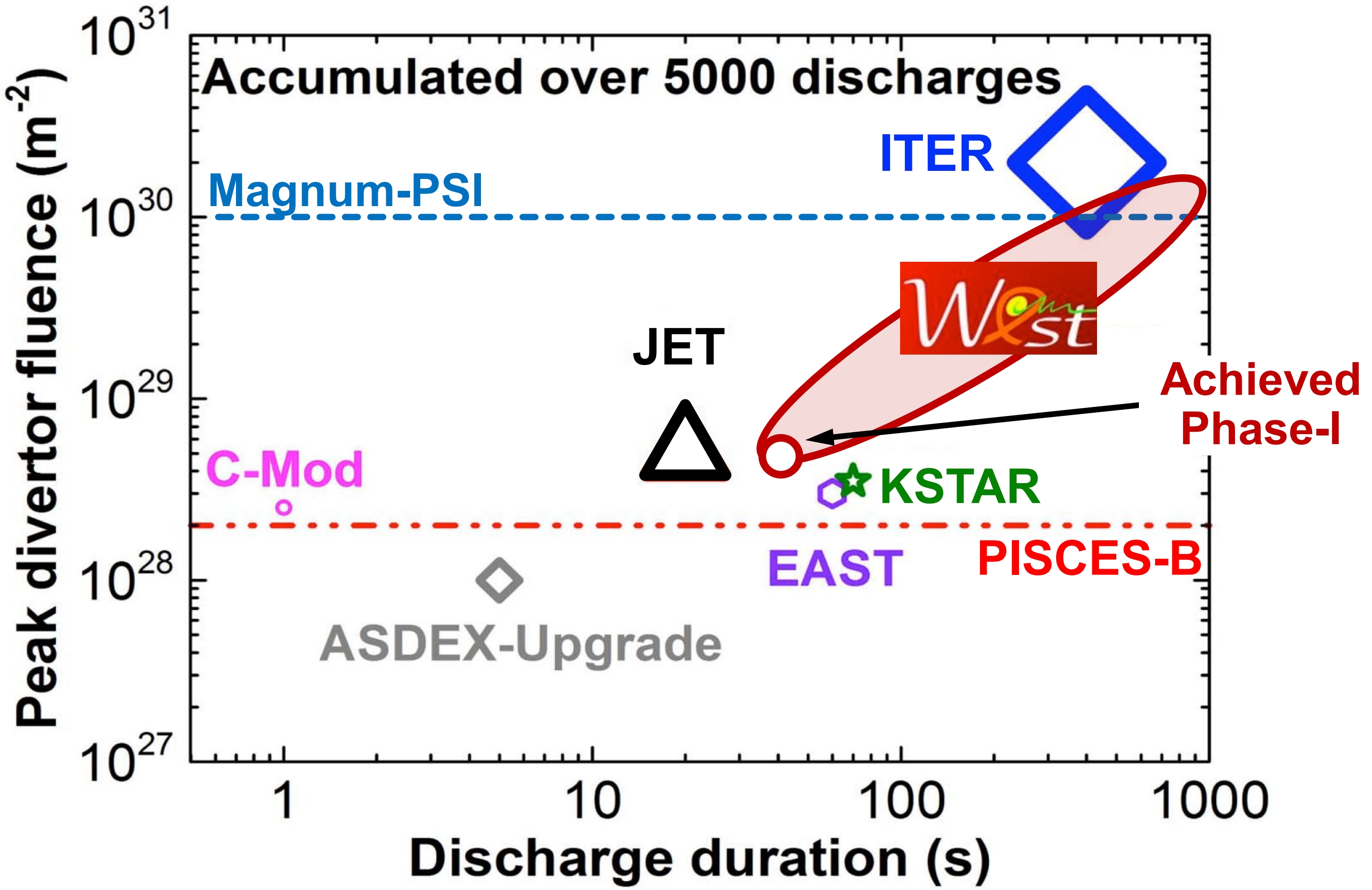


Why WEST (W Environment in a Steady-state Tokamak)? A Fully Tungsten PFC Device

- **Long-pulsed → actively cooled plasma-facing components (PFCs)**
  - *Modified ToreSupra facility*

- **Optimization of industrial-scale production / qualification processes ahead of ITER divertor procurement**

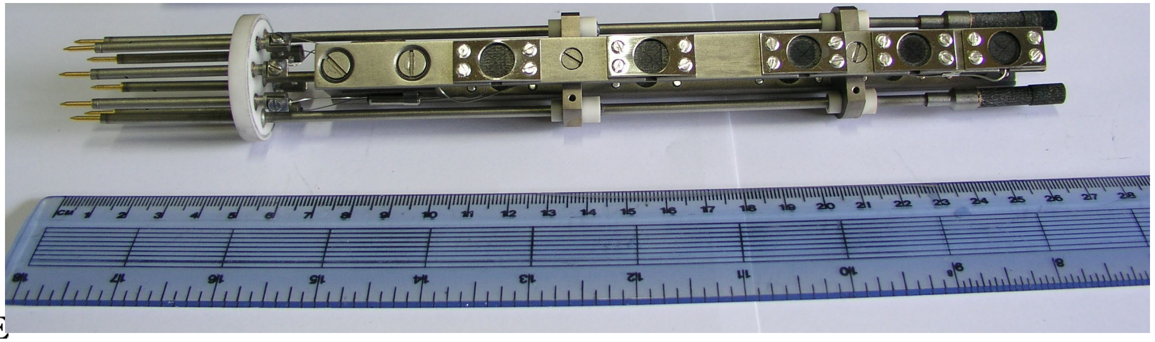
- **Integrated plasma scenario over relevant plasma wall equilibrium time scales**
  - *eventually 1000 sec pulses*
  - *~10^{30} PFC fluence*

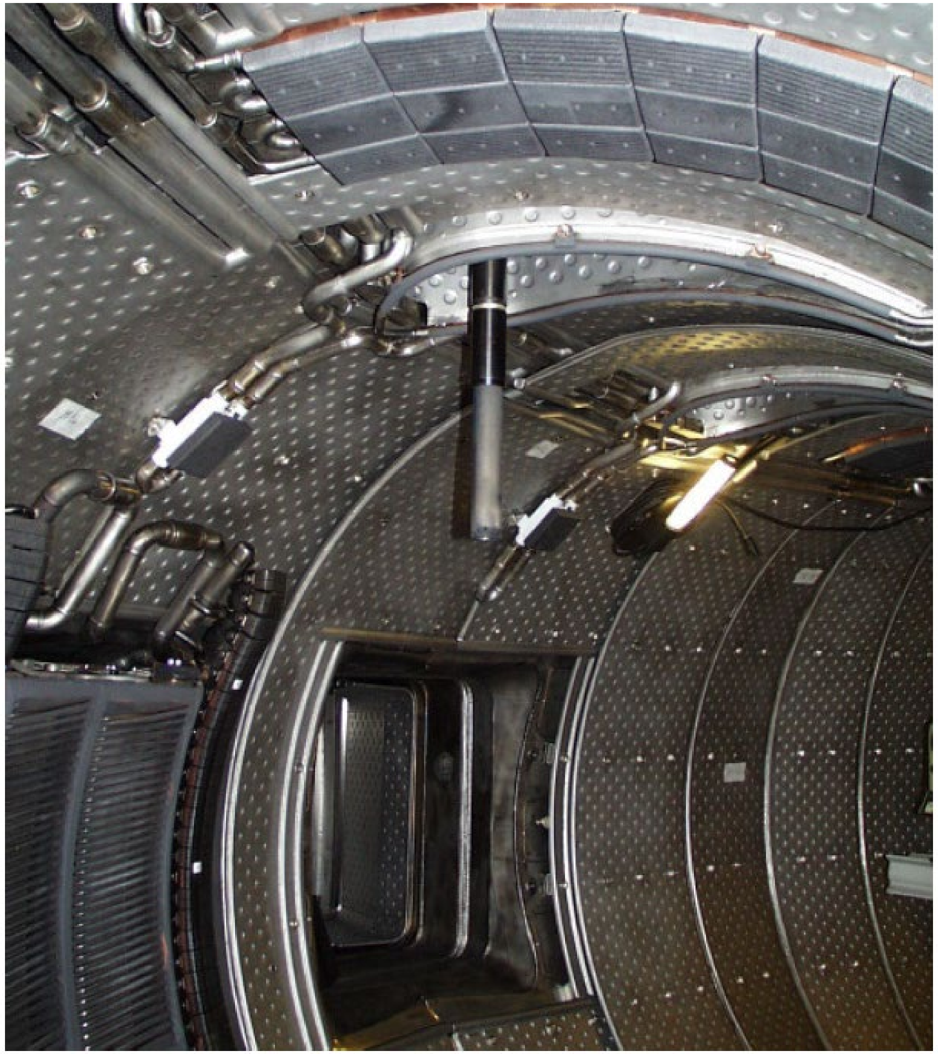


Adapted from: deTemmerman et al., (2018) PPCF

Probe impurity measurements

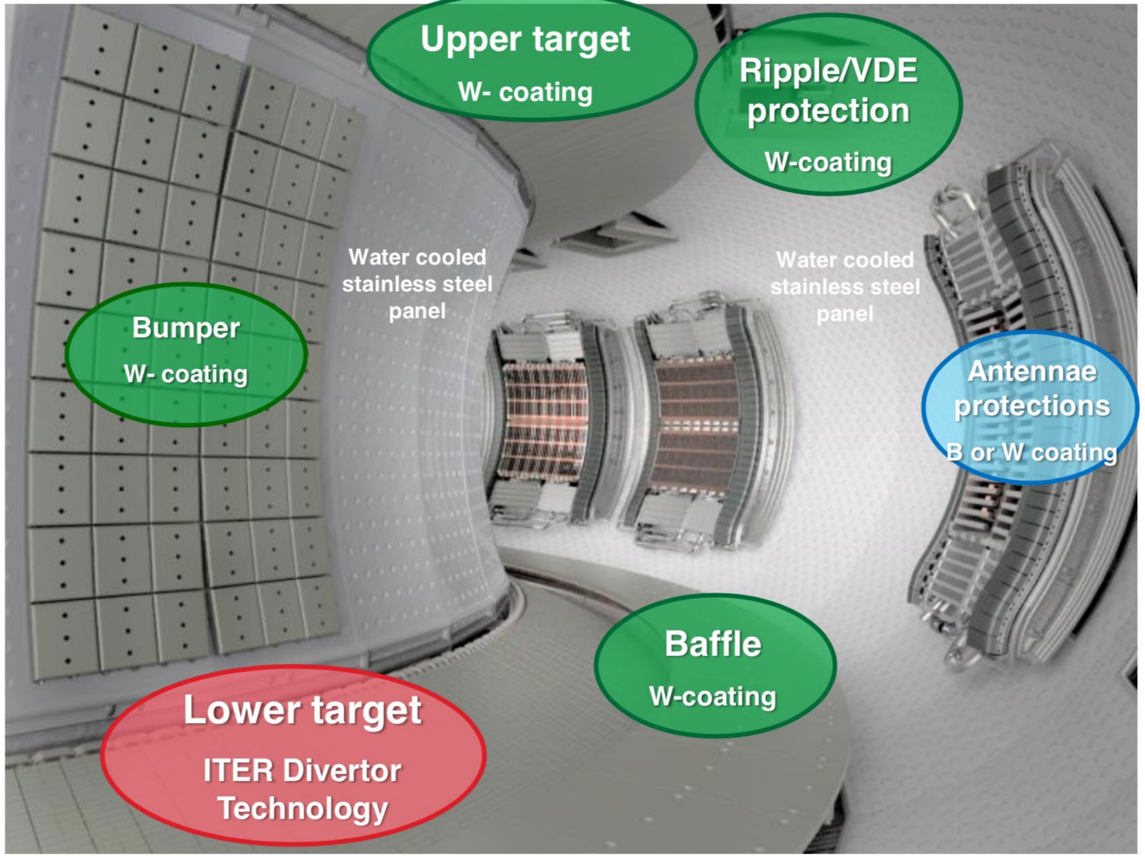
- WEST has previously deployed a Scrape-Off Layer Collector Probe to provide W transport analysis.
- In order to achieve high fluence data, an actively cooled probe is needed.



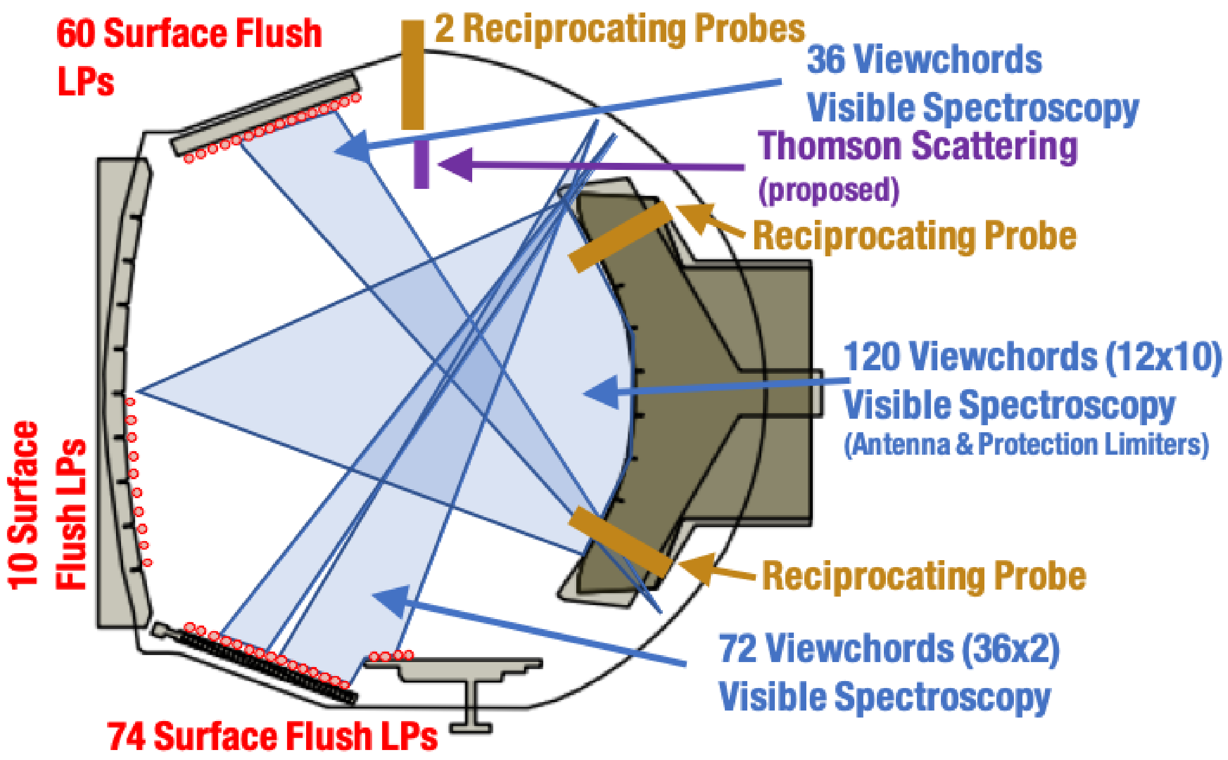


WEST HAS EXTENSIVE SET OF DIAGNOSTICS TO CHARACTERIZE PLASMA NEAR ALL KEY PFCs

Key PFCs in WEST*



WEST Edge Diagnostics**



*Bucalossi et al. (2011) Fusion Eng. Des. **Meyer et al. (2018) Rev. Sci. Intrum.

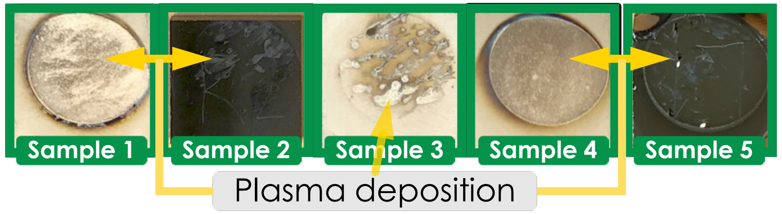
SAMPLING DEVICE CONSISTS OF MOLYBDENUM (MO) HEAT SHIELD & 10 CARBON-BASED SAMPLES

- **Demonstrates ability to sample W within tokamak edge but limited to ~12 seconds of exposure**
  - *On-going analysis to potentially realize minutes of exposure*

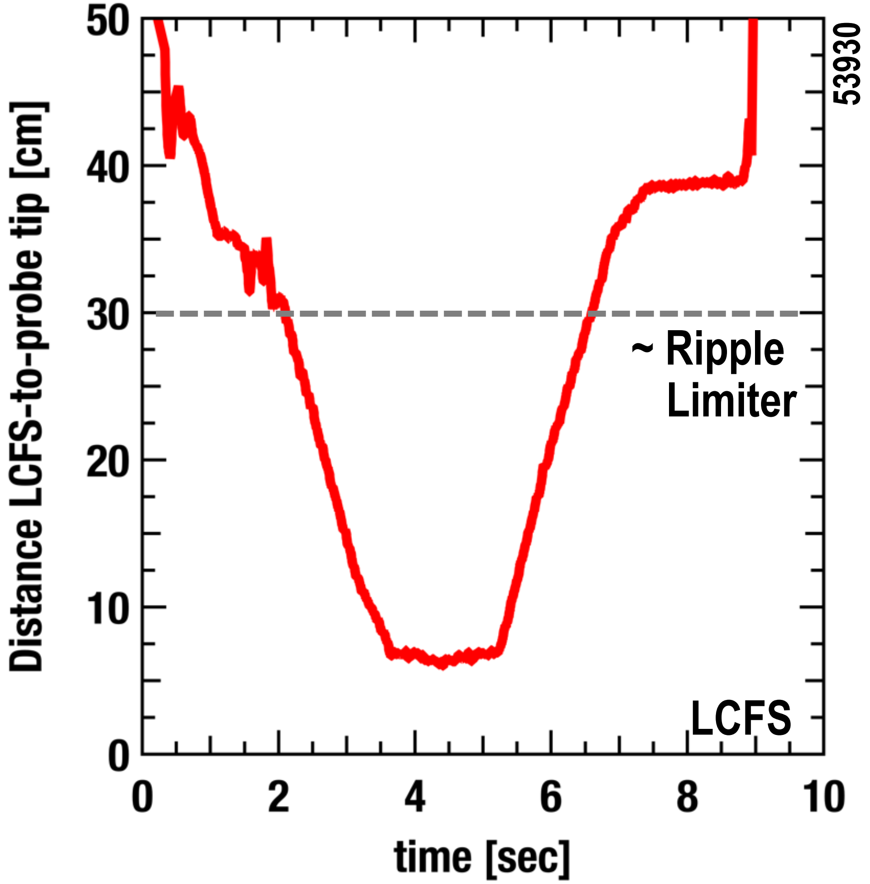
Mo-coated CFC heat shielding showing sample exposure holes

Sample-holder Tray/Insert

Samples show surface deposition due to exposure



Time trace of CP insertion (repeated in 12 discharges)



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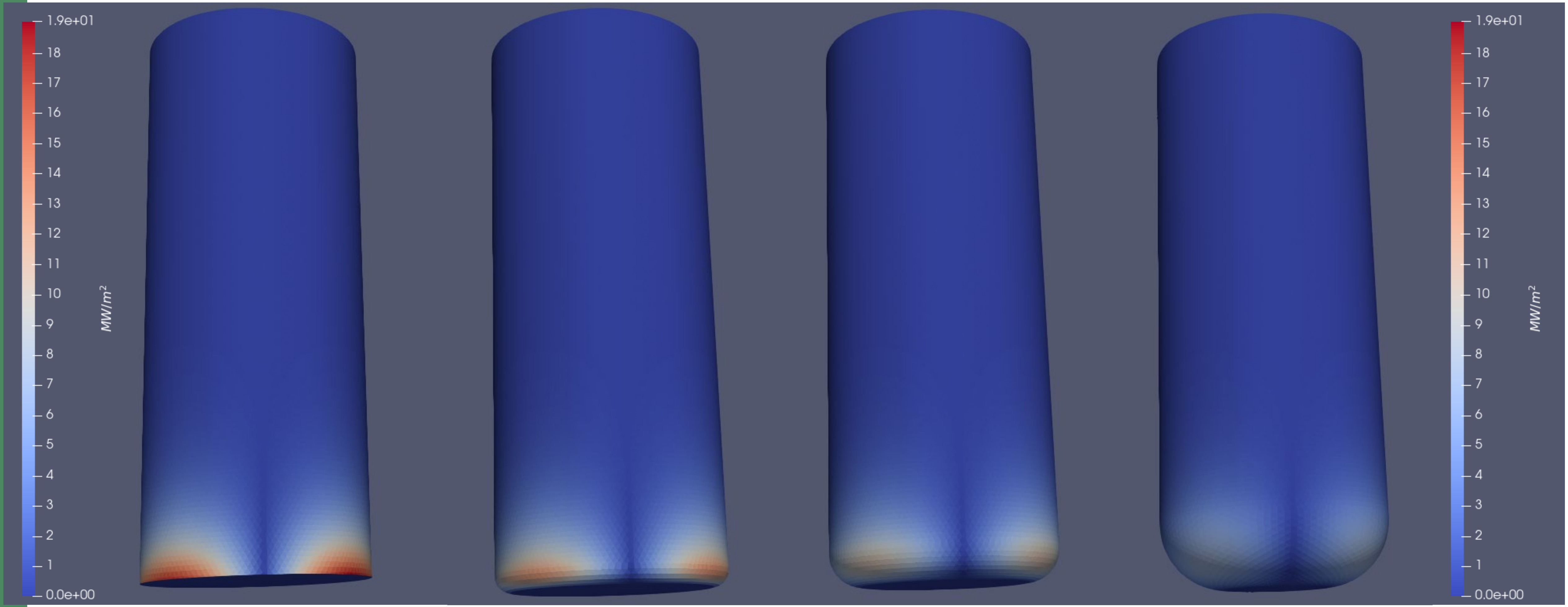
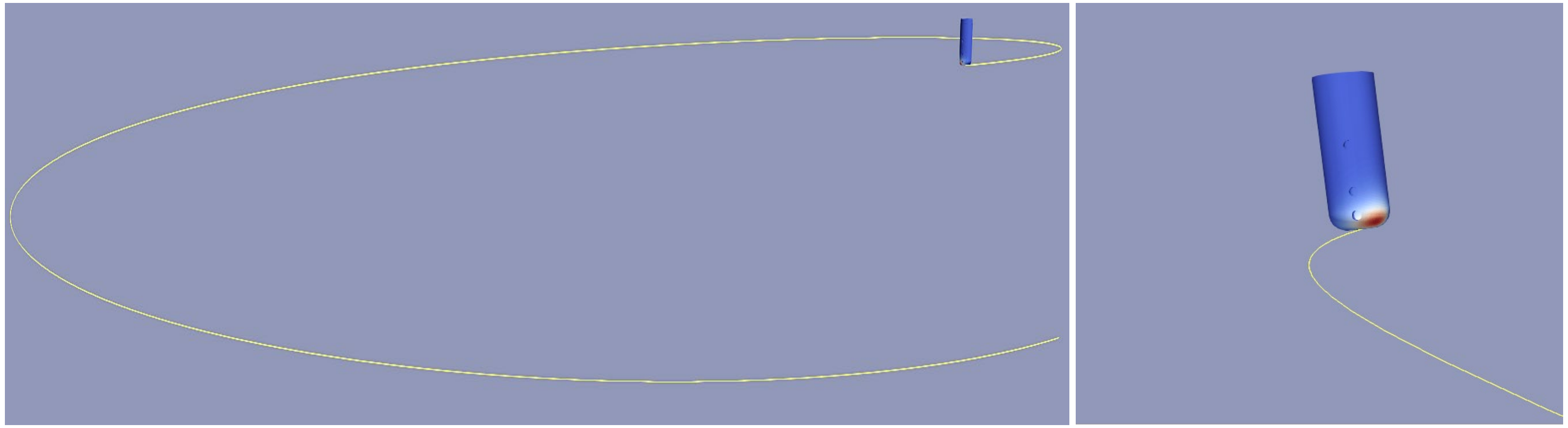
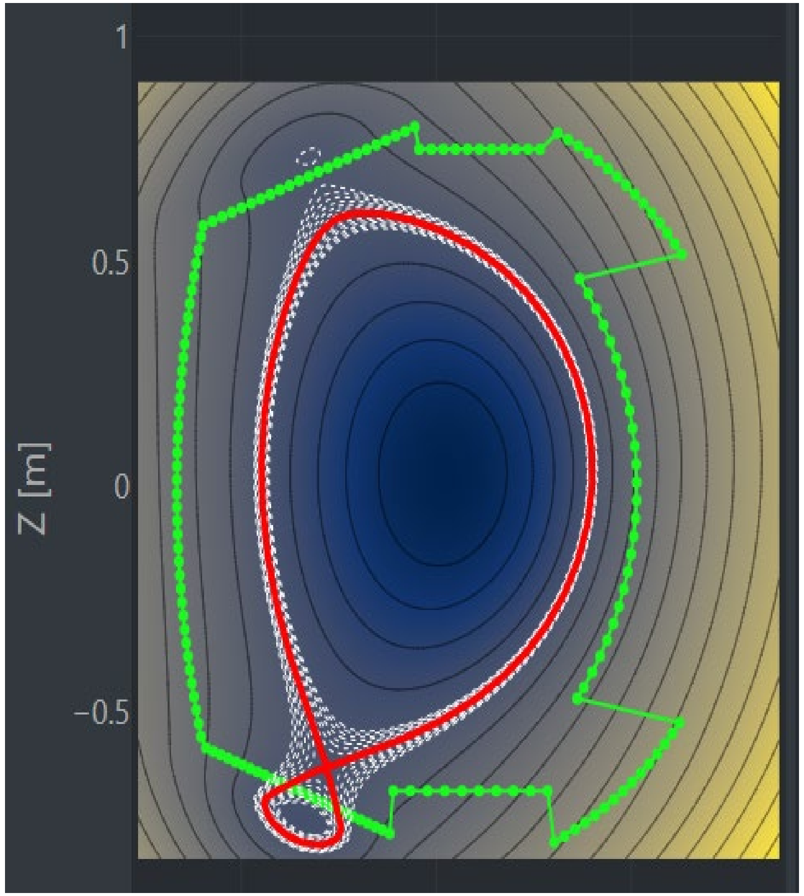
$\hat{b} \cdot \hat{n}$ Magnetic and Surface-Normal Incident Angle Effect



No Radius	2.88 mm Radius	5.75 mm Radius	11. 5 mm Radius
19 MW/m^2	**14 MW/m^2**	**11 MW/m^2**	**7.2 MW/m^2**

Heat flux Engineering Analysis Toolkit (HEAT)
-a suite of tools for predicting the heat flux incident upon PFCs in tokamaks
-3D heat loads from 2D plasmas for limited and diverted discharges





Magnetic Flux expansion effect

Scaling Coefficient

$$q_{probe} = q_{||0} \cdot \hat{q}_{||}(\varphi) \cdot \frac{B_{probe}}{B_{omp}} \cdot (\hat{b} \cdot \hat{n})$$

Probe Heat Flux (point cloud)

WEST Specific Poloidal flux

Magnetic and Surface Normal Incident Angle effect

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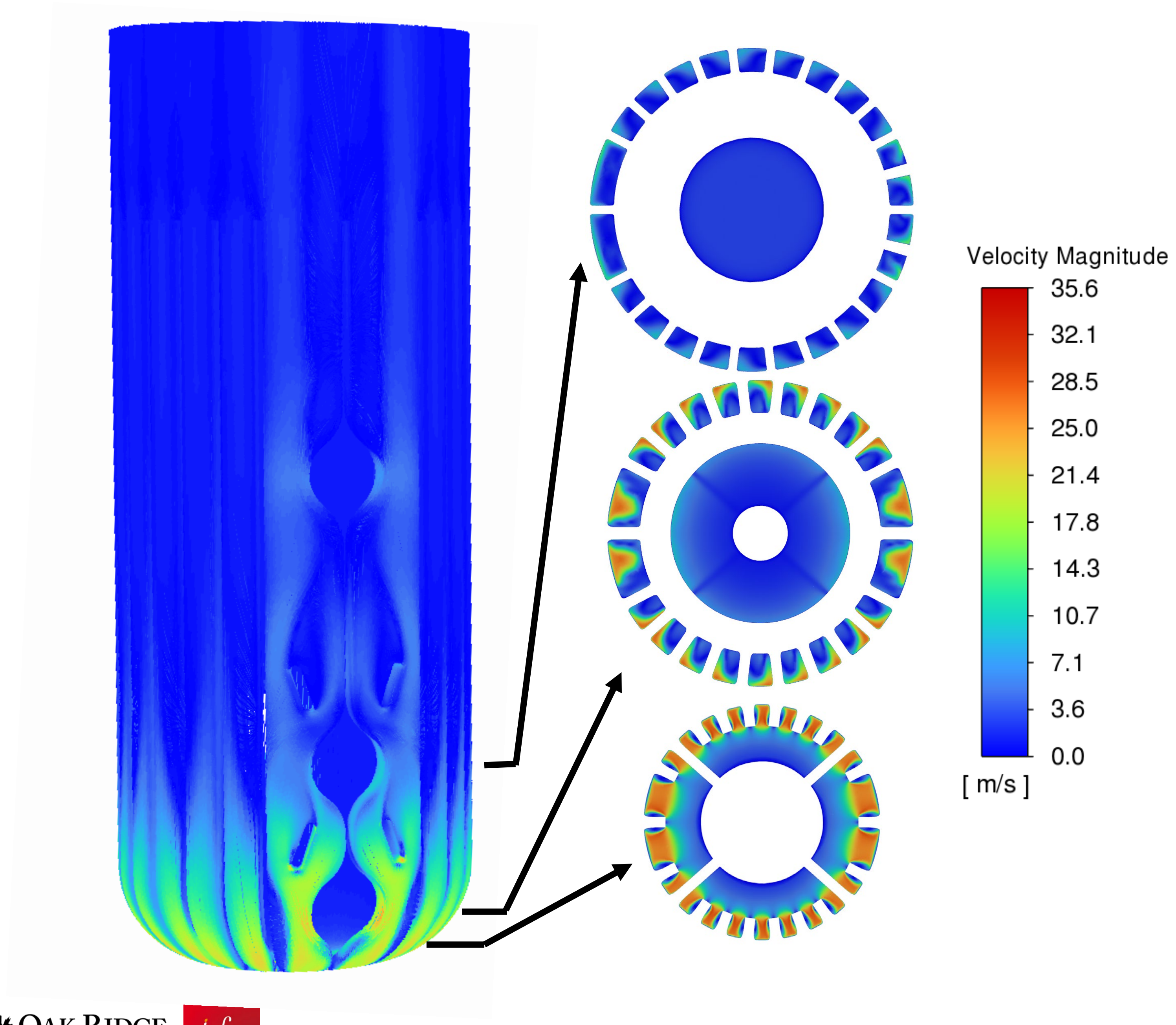
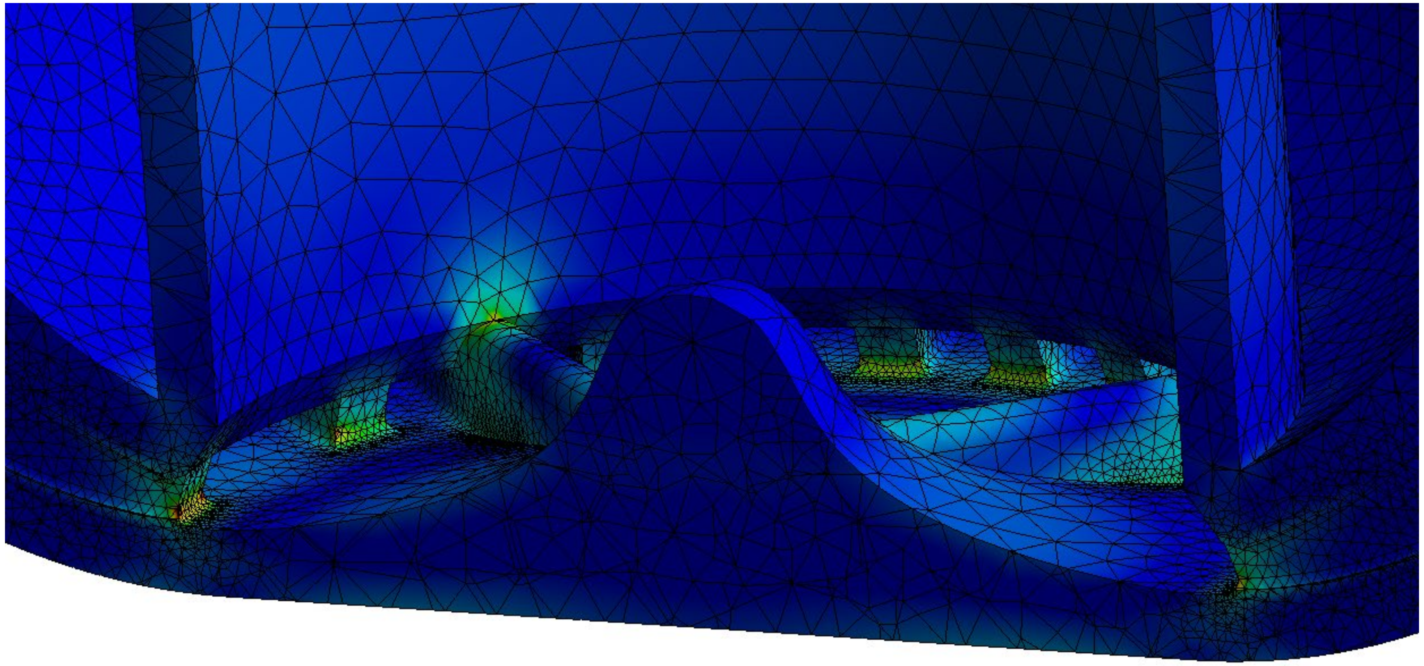


Total Pressure Drop 3.3bar - 47 psi
35.6 m/s Max Velocity



TZM at 70C

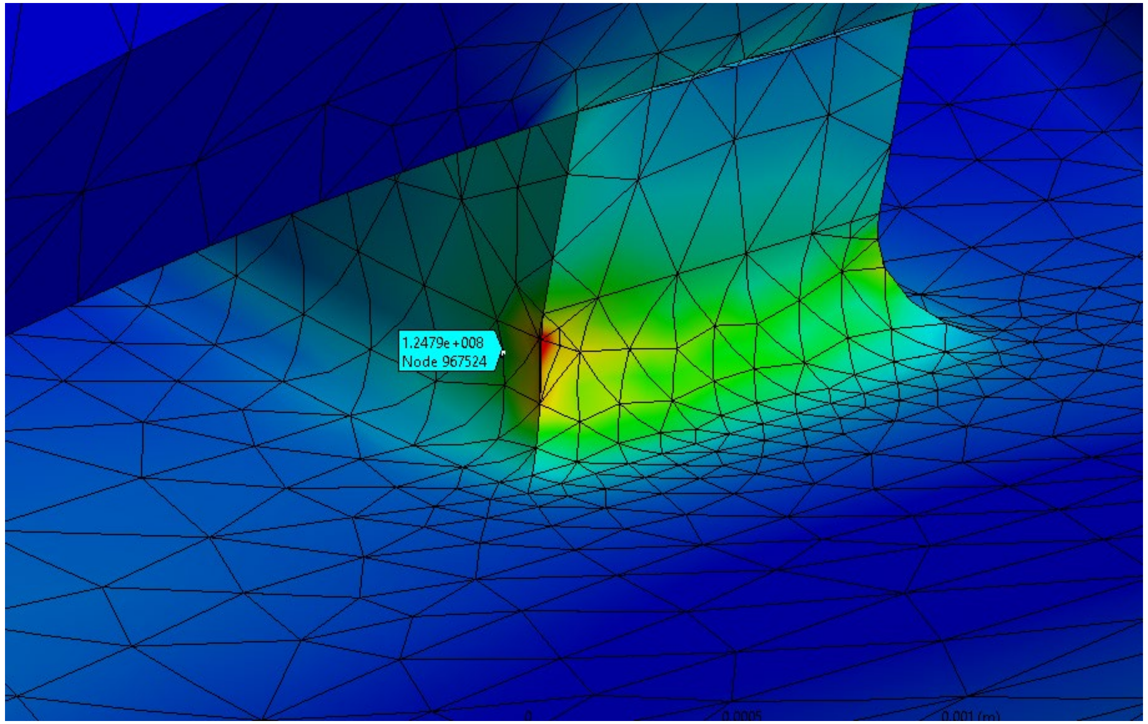
Yield Strength 848 MPa

Ultimate Strength 951 MPa

TZM at 200C

Yield Strength 815 MPa

Ultimate Strength 914 MPa



Comparison of material choices

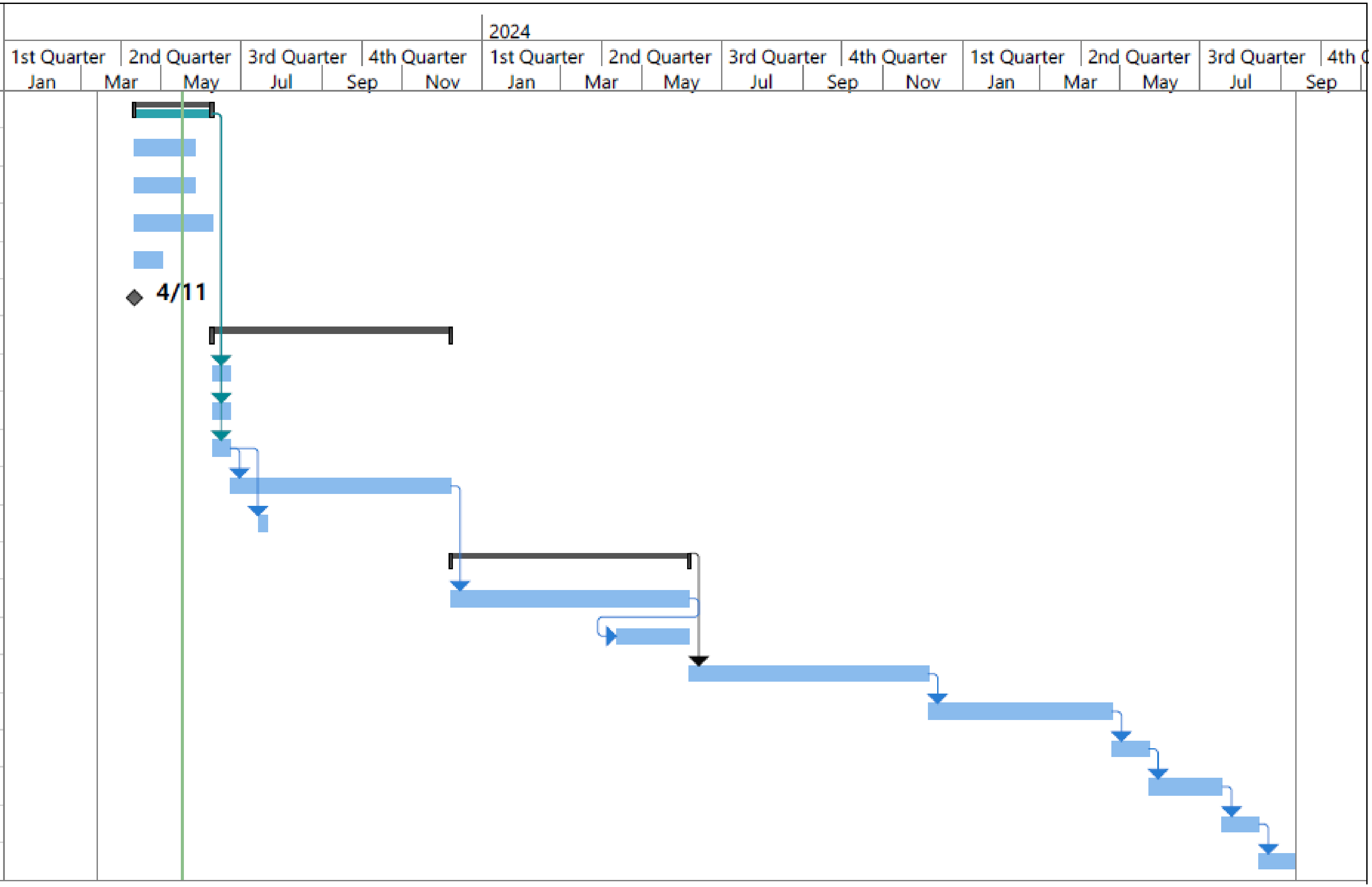
Properties @ 200C	**TZM**	**GRCop-42**
Thermal conductivity (W/m-K)	118	320
Tensile strength (MPa)	815	185
Thermal expansion coefficient ($x10^{-6}$ K^{-1})	5.1	15
Elastic modulus (GPa)	325	130
Melting point (°C)	2620	~800
Thermal shock resistance (K)	334.4	62.6
Additive manufacturing experience	Low	High
WEST colling system experience	Low	Med
Ductility / toughness	Med	High

Design deliverables

Maturity of System Design Documents at the End of the Design Phases	Design Phases		
	Conceptual	Preliminary	Final
Functional Requirements (thermal, mechanical, I&C, safety, etc.)	Complete		
Interface Definition	Preliminary	Complete	
System Design Description – design report	Preliminary	Updated	Complete
Configuration Model (CAD model)	Feasible	Preliminary	Complete
Load Specifications	Preliminary	Complete	
Diagrams (P&ID, C&ID, SLD, routing/cabling)		Preliminary	Complete
Mechanical Engineering Drawings			Complete
Bill of Material (BOM)	Preliminary	Consolidated	Complete
Design Compliance Matrix (DCM)		Preliminary	Complete
Test Plan	Preliminary	Updated	Complete
Assembly Plan		Preliminary	Complete
Engineering Analysis Reports and Calculation Notes	At any stage to support design justification		

Notional project schedule

ID		Task Mode	Task Name	Duration	Start	Finish
1			**Pre-conceptual design**	**43 days**	**Tue 4/11/23**	**Thu 6/8/23**
2			Collect requirements	34 days	Tue 4/11/23	Fri 5/26/23
3			Define scope and schedu	34 days	Tue 4/11/23	Fri 5/26/23
4			AM definition	43 days	Tue 4/11/23	Thu 6/8/23
5			Initiate CAD model	15 days	Tue 4/11/23	Mon 5/1/23
6			Kick-off meeting	0 days	Tue 4/11/23	Tue 4/11/23
7			**Conceptual design**	**130 days**	**Fri 6/9/23**	**Thu 12/7/23**
8			Define requirements	10 days	Fri 6/9/23	Thu 6/22/23
9			Define interfaces	10 days	Fri 6/9/23	Thu 6/22/23
10			Develop load spec	10 days	Fri 6/9/23	Thu 6/22/23
11			Engineering design	120 days	Fri 6/23/23	Thu 12/7/23
12			AM quick prototype	5 days	Fri 7/14/23	Thu 7/20/23
13			**Preliminary design**	**130 days**	**Fri 12/8/23**	**Thu 6/6/24**
14			Engineering design	130 days	Fri 12/8/23	Thu 6/6/24
15			AM prototype	40 days	Fri 4/12/24	Thu 6/6/24
16			Final design	130 days	Fri 6/7/24	Thu 12/5/24
17			Procurement	100 days	Fri 12/6/24	Thu 4/24/25
18			Assembly	20 days	Fri 4/25/25	Thu 5/22/25
19			Testing	40 days	Fri 5/23/25	Thu 7/17/25
20			Commissioning	20 days	Fri 7/18/25	Thu 8/14/25
21			Deliver to WEST	20 days	Fri 8/15/25	Thu 9/11/25



Oak Ridge National Laboratory