Integration of Customized MHD Modeling into a Digital Engineering Workflow for Advanced Liquid Metal Blankets

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Collaborators:

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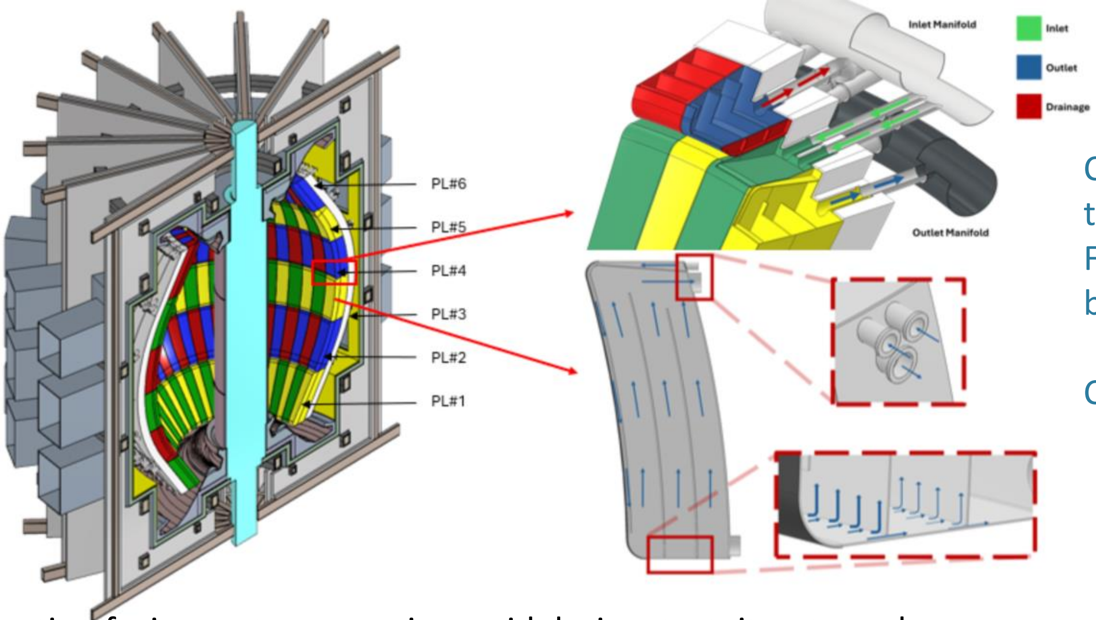
Colin Baus, Luigi Candido, Carli Smith, Jack Taylor, Bibake Uppal Kyoto Fusioneering

Work supported in part by the U.S. DOE INFUSE Program

IAEA-DEFER MIT Cambridge MA December 11, 2025

Motivation



Concept design of spherical tokamak integrating Kyoto Fusioneering SCYLLA breeding blanket.

Candido *et al.* FED 2026

- Next-generation fusion systems require rapid design–test–iterate cycles
- Digital engineering offers unified workflows for design, simulation, and validation
- Liquid metal (LM) blankets present complex multi-physics challenges:
  - Strong magnetic fields
  - Complex 3D geometries
  - Coupled thermal, structural, and neutronic loads
- Need for scalable, high-fidelity MHD modeling integrated into engineering platforms

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Outline

- Problem Set-up, Preparation and Meshing
- CFD Modeling at PPPL
- MHD
- Virtual Prototyping System
- Coupling
- Transient Flows
- Multiphysics Analysis

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Dear Andrei,

As discussed, please find attached the outboard equatorial module of SCYLLA BB.

I also attach a picture showing the LiPb flow path.

- Inlet temperature: 773.15 K
- Inlet flow rate: 80.46 kg/s
- Tungsten volumetric heating: 31 MW/m3
- Lithium Lead volumetric heating: 16.5119*exp(-0.0538*y) MW/m3, y in cm
- Tungsten surface heat flux: 0.5 MW/m2

You should have all the data related to material properties. It would be interesting to see how the results change using a thermal conductivity for SiCf/SiC in the range 10-20 W/m/K, and the usual comparison with 0T/4T magnetic field. We can discuss also other sensitivity analyses. Let me know if you have any questions.

Best regards,

One attachment • Scanned by Gmail

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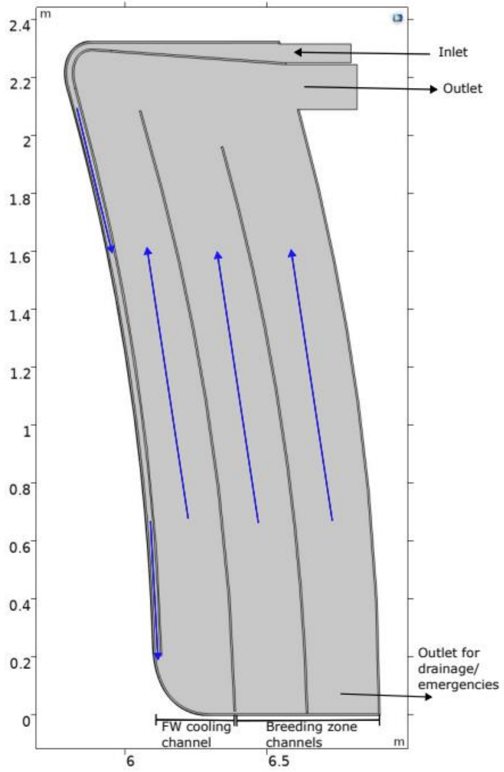
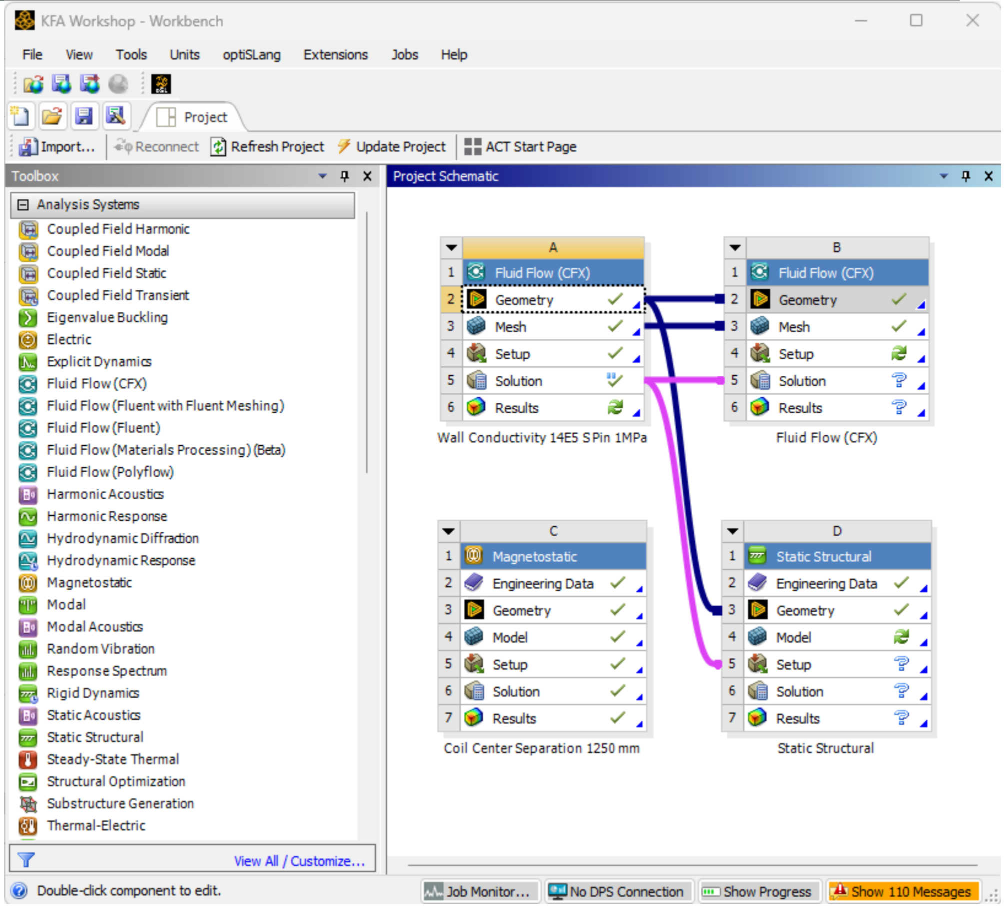


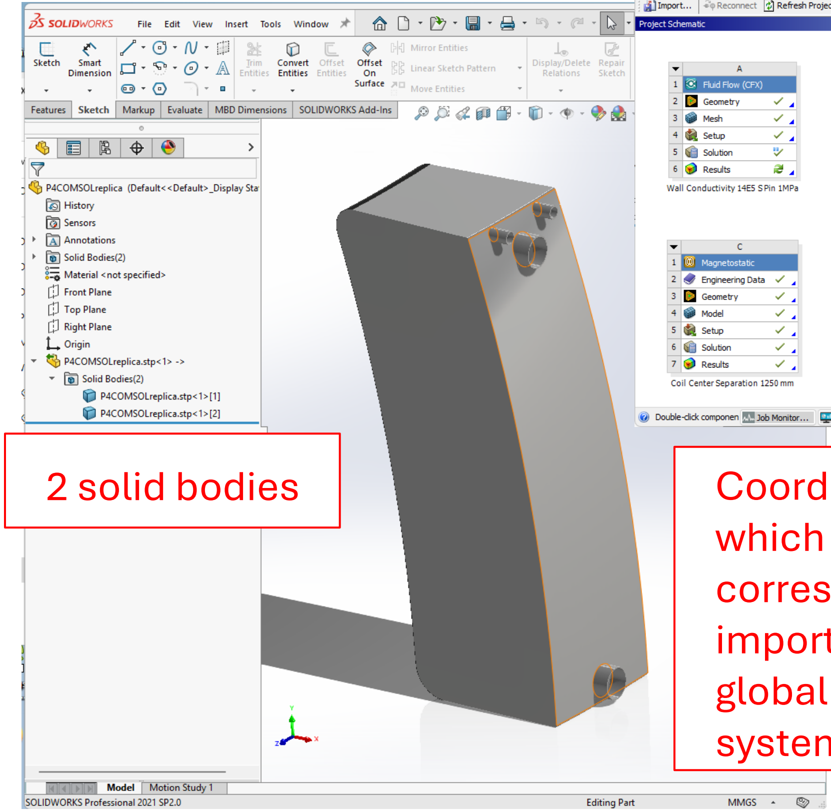
System Set-up

- Many problems can be coupled using drag and drop in Workbench
  - CFX geometry can be transferred directly to structural and another fluids problem
  - CFX mesh set-up can be transferred to another CFX problem
  - Temperature and pressure distribution can be transferred from CFX to static structural set-up
- Some couplings need to be done manually
- More info in ANSYS Workbench documentation

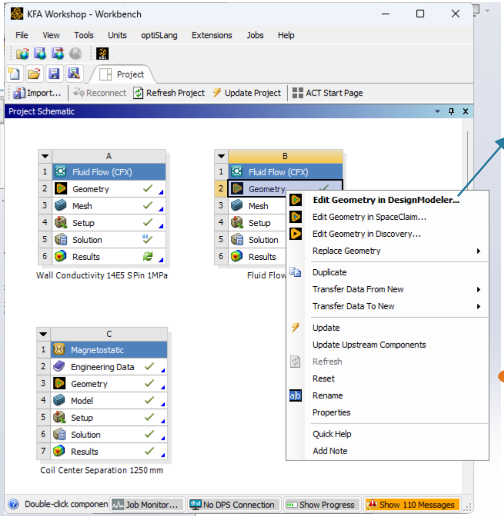


Geometry Input and Preparation

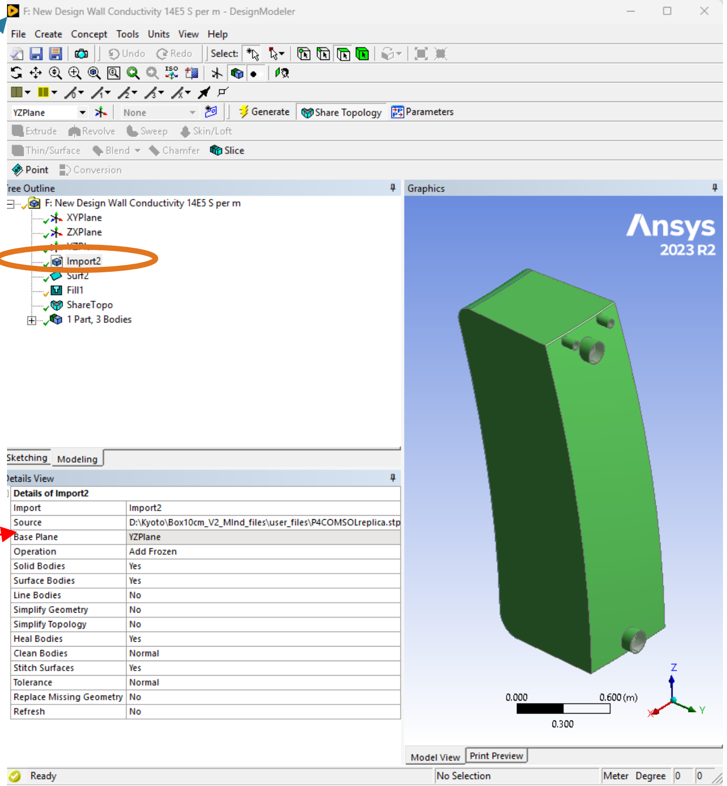
STEP file viewed in SolidWorks



2 solid bodies



STEP file directly imported in Design Modeler



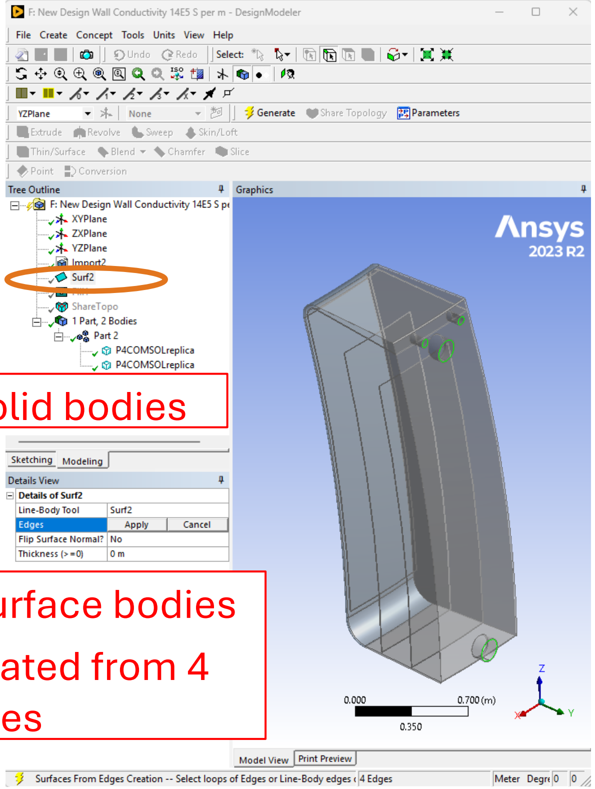
Coordinate system which will correspond to imported part global coordinate system

Geometry Input and Preparation

Lid surfaces created

Fluid volume is created by Fill operation

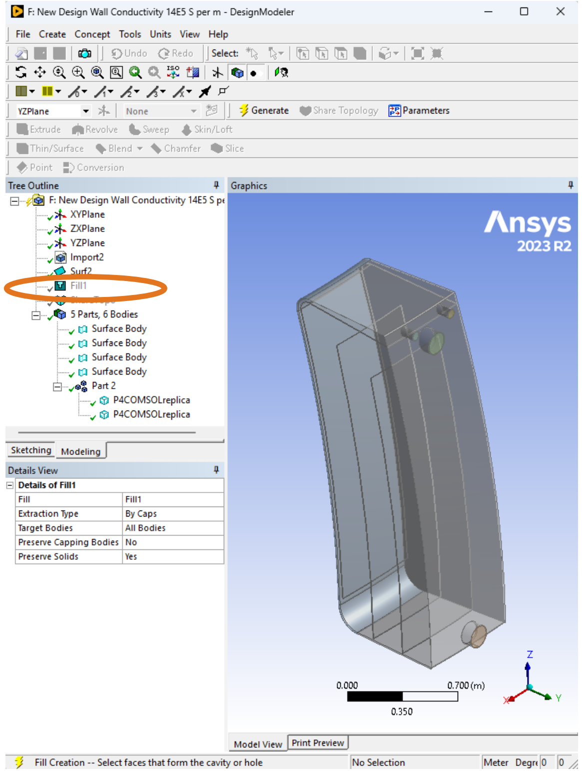
This operation also ensures that there are no leaks

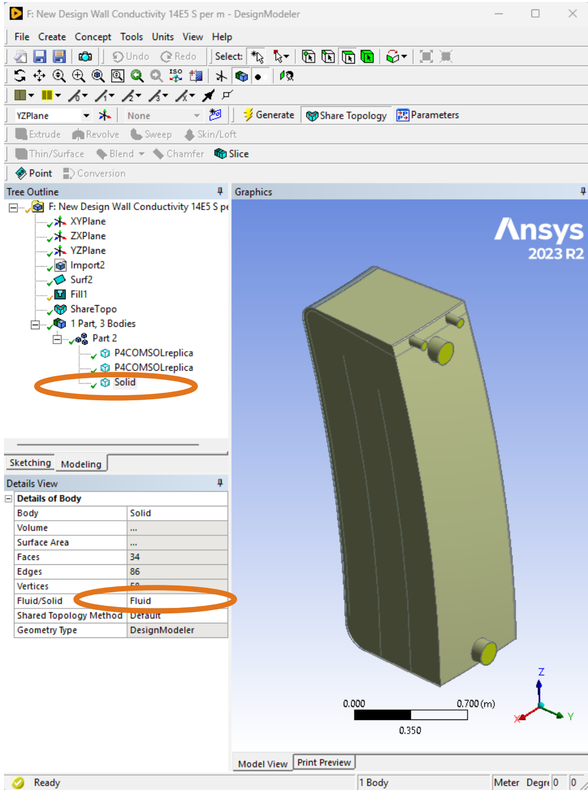


2 solid bodies

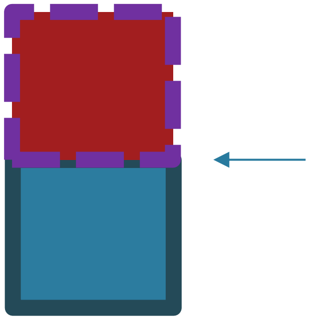
4 surface bodies

Created from 4 edges



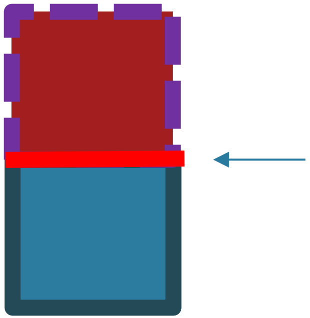


Share topology operation ensures that all bodies connected in one part will share the same surface



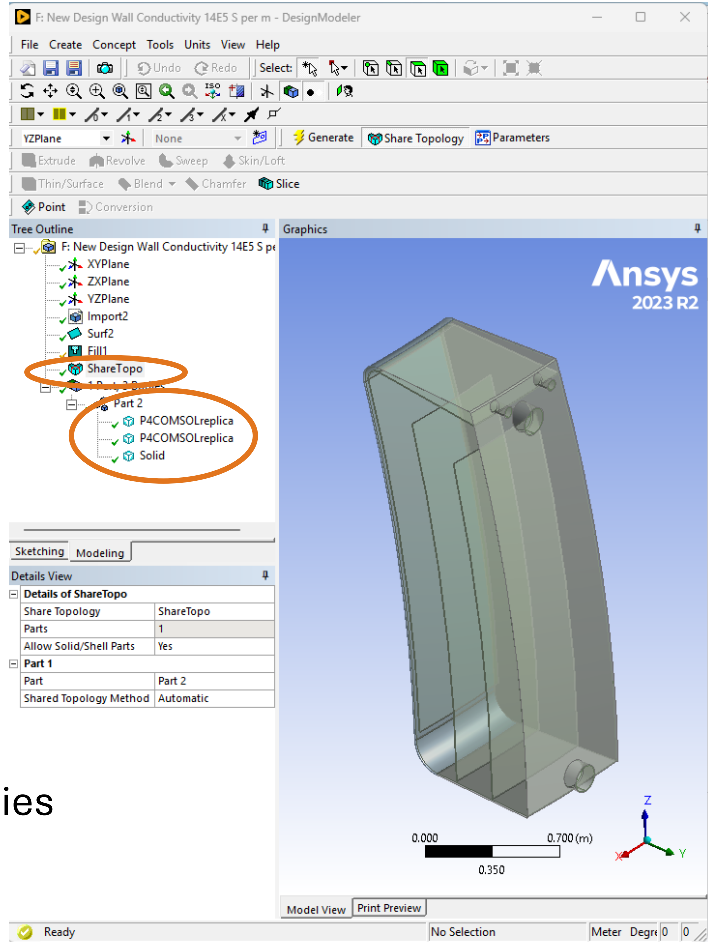
No share topology

Two coincident surface



Share topology

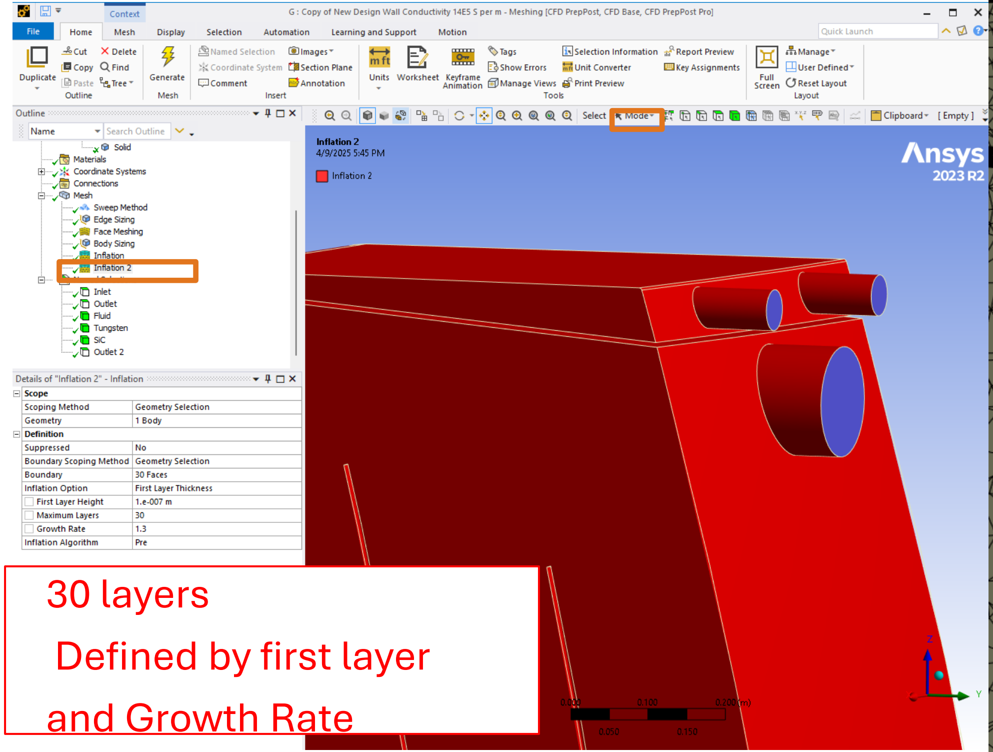
One surface mutual for both bodies



Meshing

Inflation on fluid domain is required for proper resolution of boundary layers

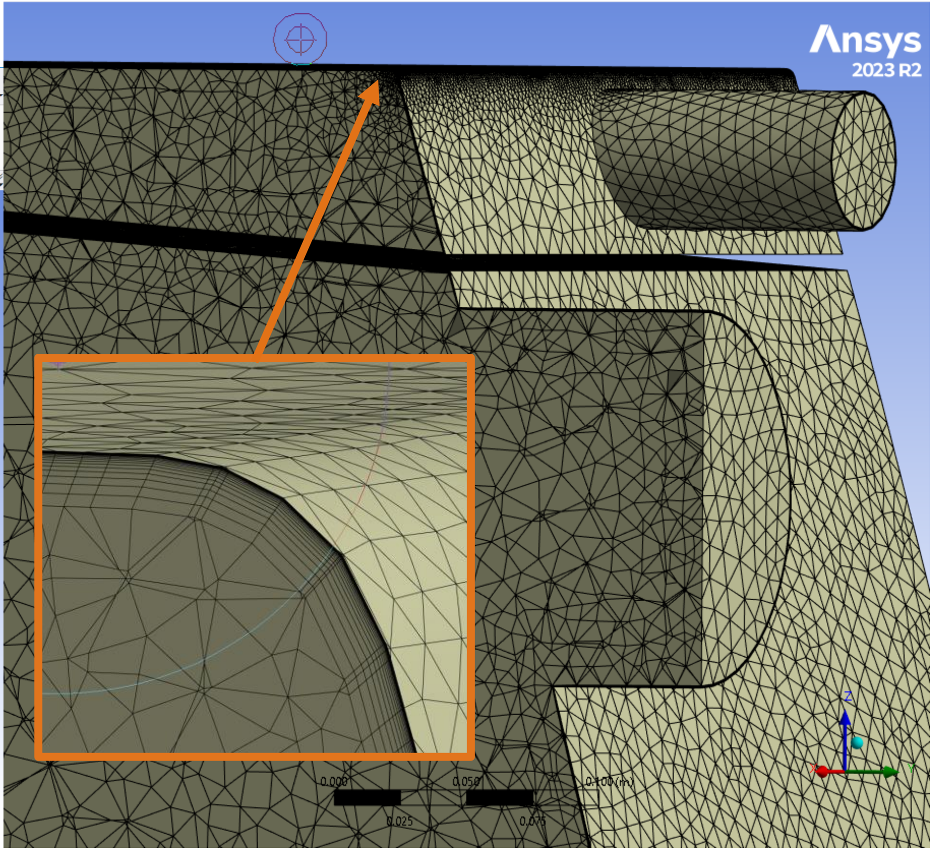
Box mode can be used to select all surfaces



30 layers

Defined by first layer

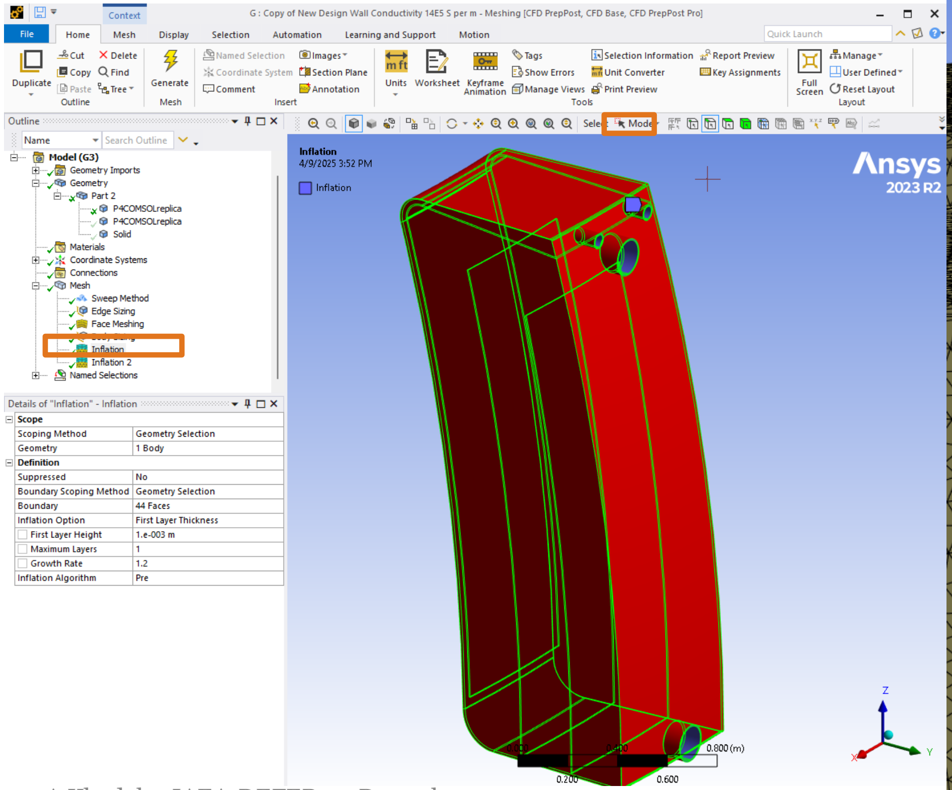
and Growth Rate

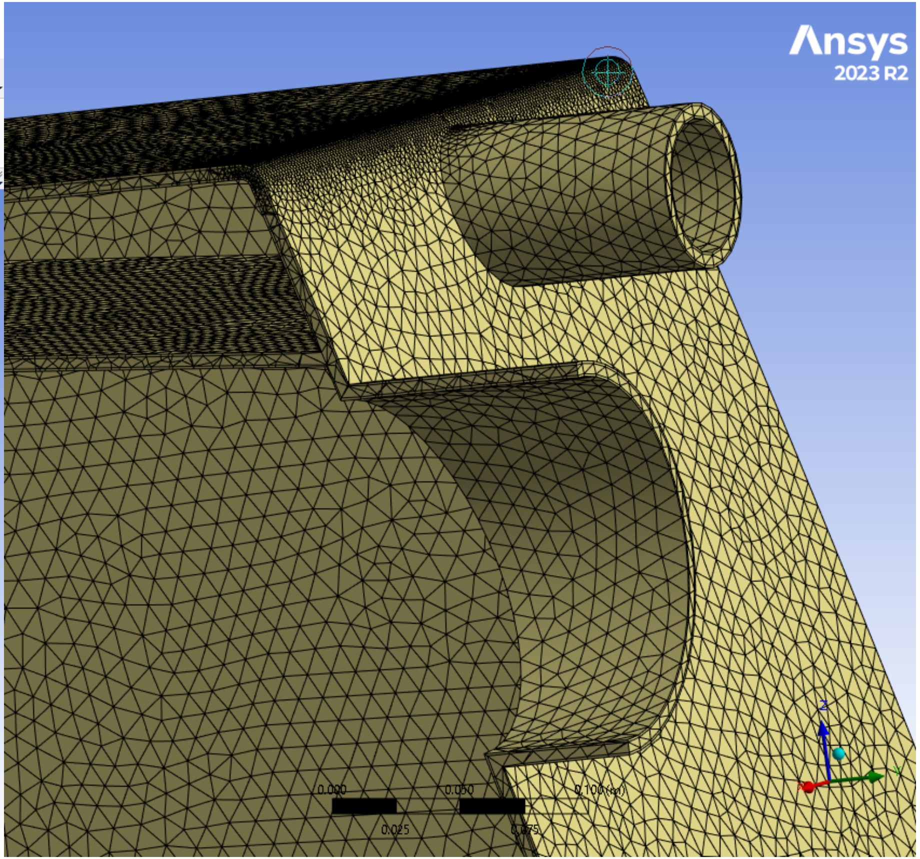


Meshing

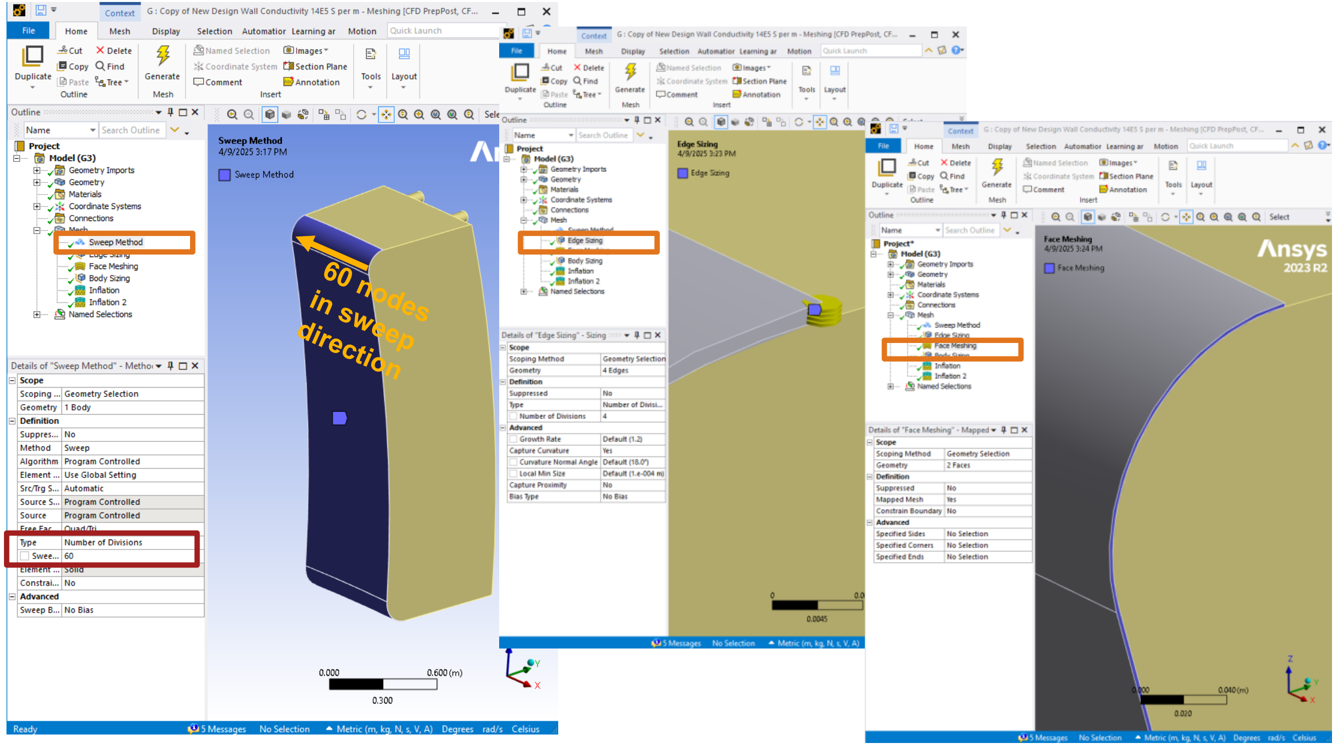
Inflation on solid bodies to make sure there are several elements through the thickness

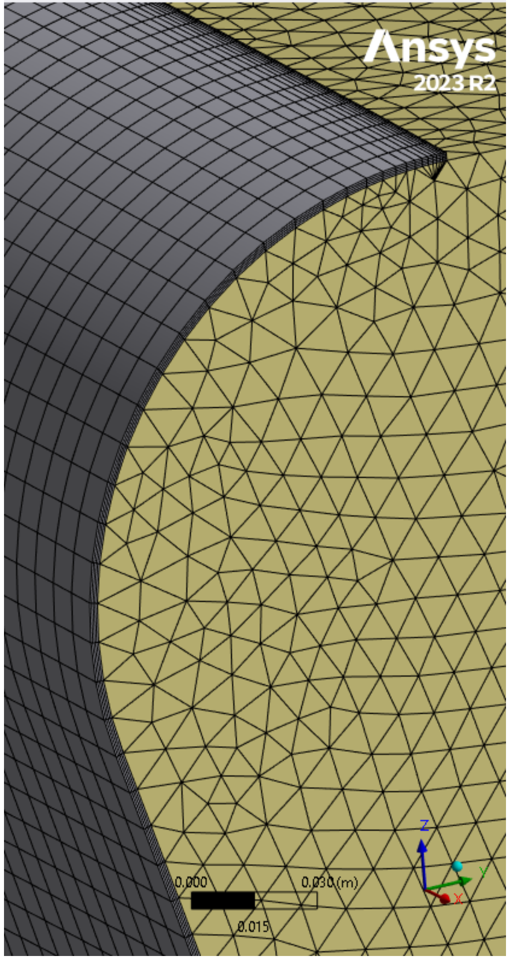
Box mode can be used to select all surfaces



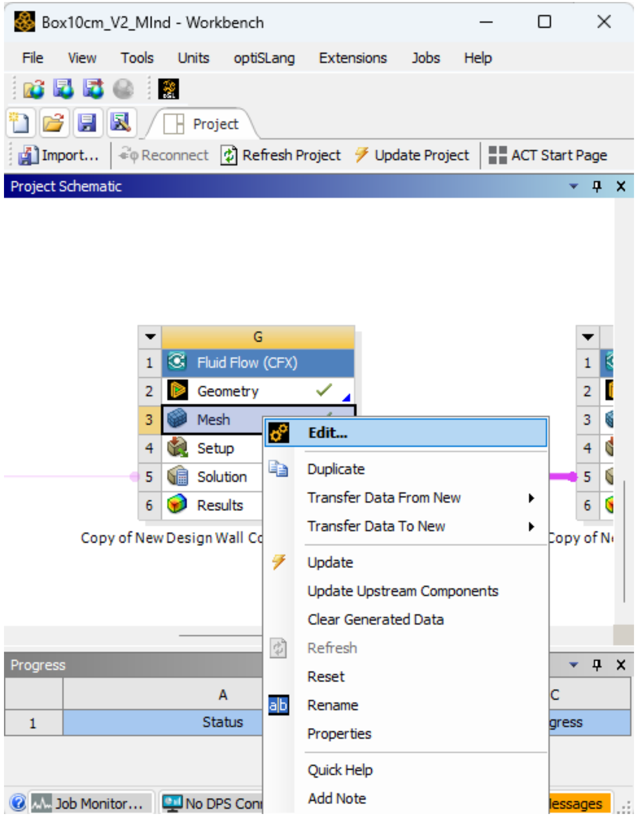


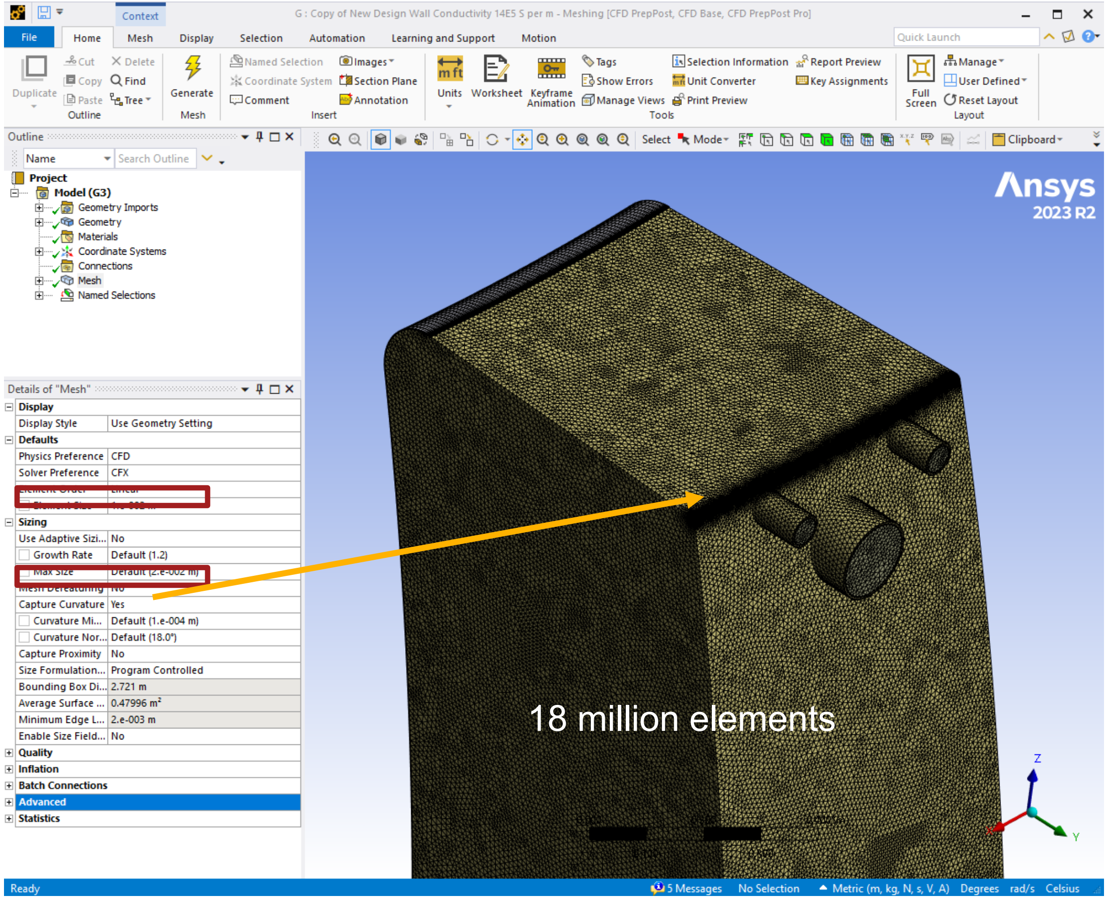
Sweep Meshing of Sweepable Geometry
Not necessary can be abandoned to make meshing automatic
Should be first meshing operation





Global Mesh Settings





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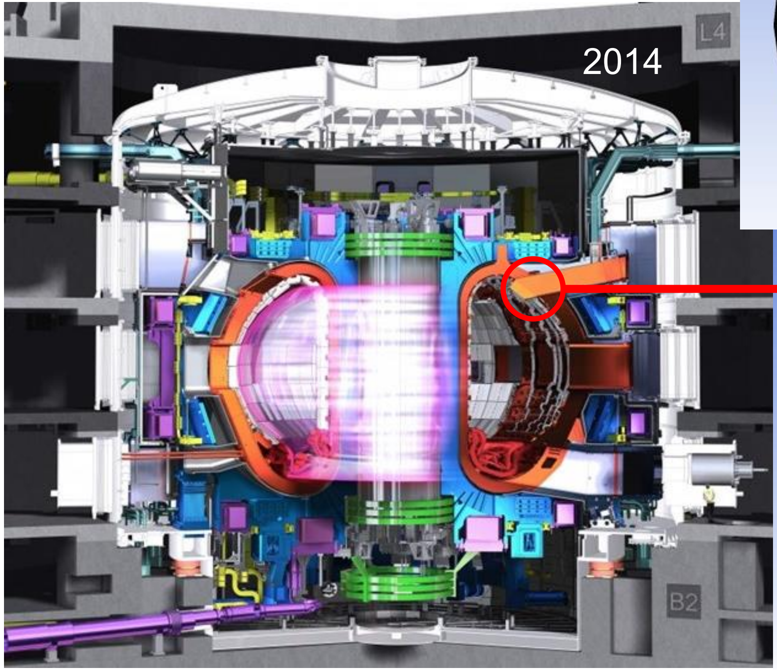
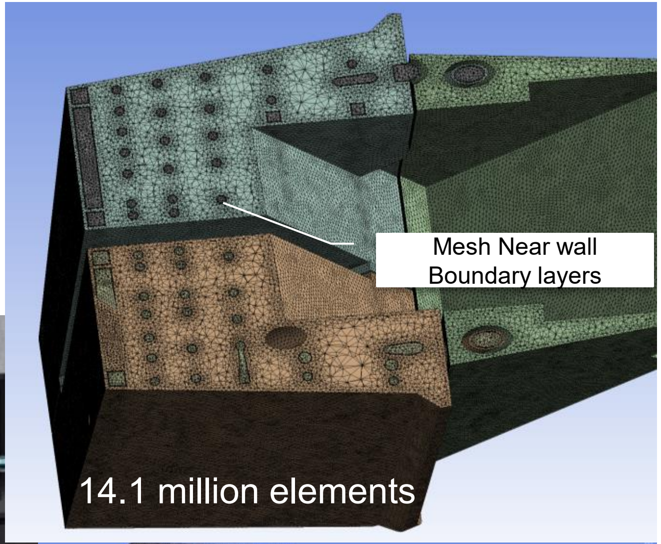
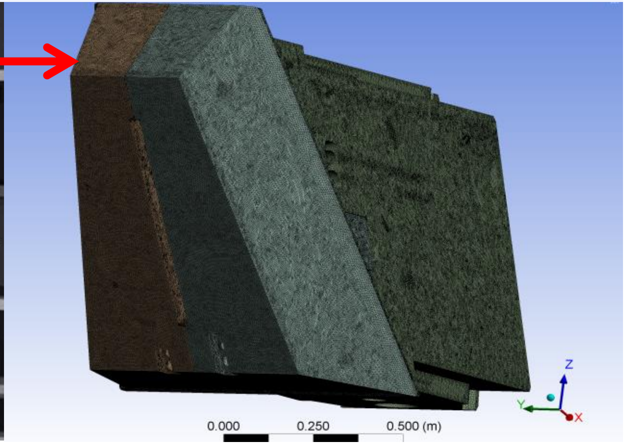
CFD analysis in PPPL

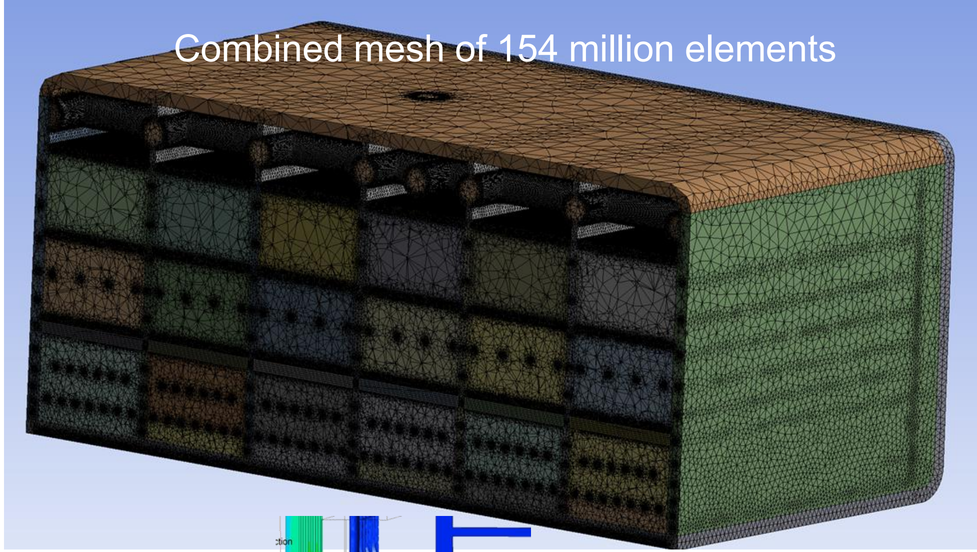
- The analysis of many fusion applications such as first wall blankets requires application of Computational Fluid Dynamics (CFD) methods.
- Highly customized version of ANSYS CFX is used at PPPL for thermal analysis of complex systems involving fluid flow and heat transfer in liquids and solids Virtual Prototyping of Liquid Metal Blanket Performance



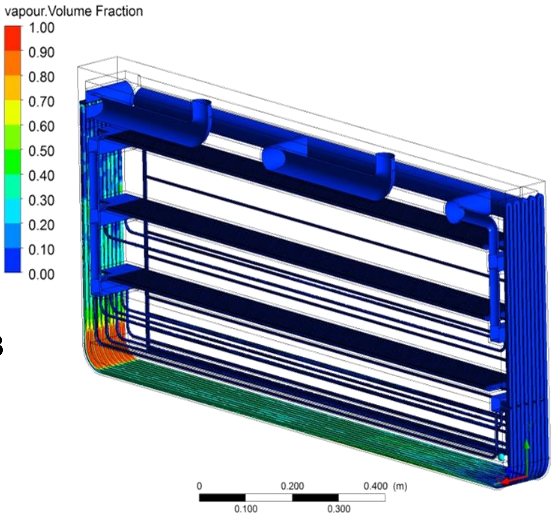


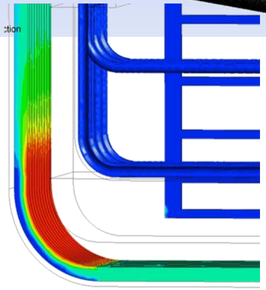


3D Two Phase Flow CFD



CFETR Pre-Superheated Blanket was performed using ANSYS CFX and included: 3D coolant flow analysis, external volumetric and surface heating effect, and two-phase wall boiling.





Khodak, et al. FST (2017).72(4), 628–633.
https://doi.org/10.1080/15361055.2017.1350478

Blanket coolant vapor volume fraction distribution.

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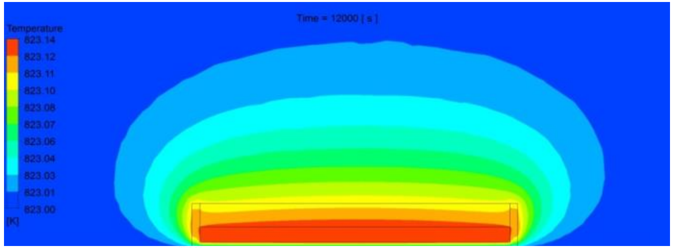
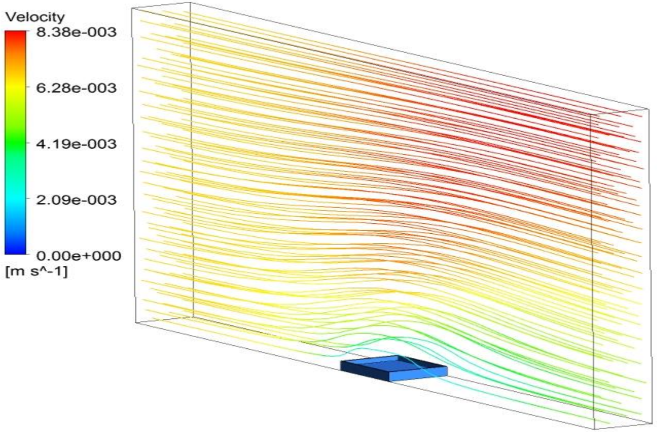
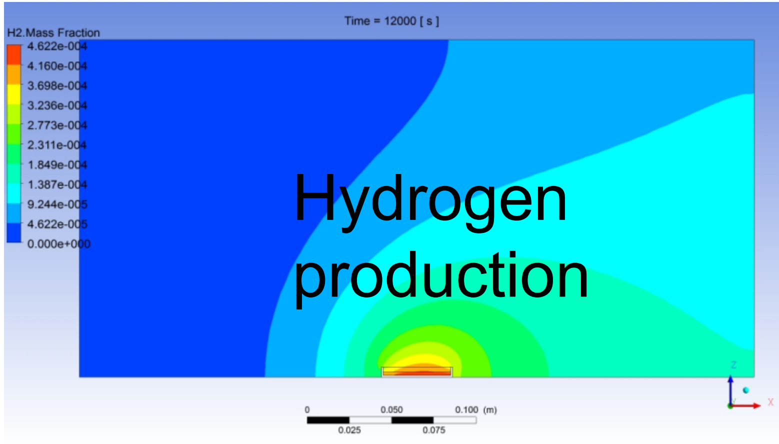
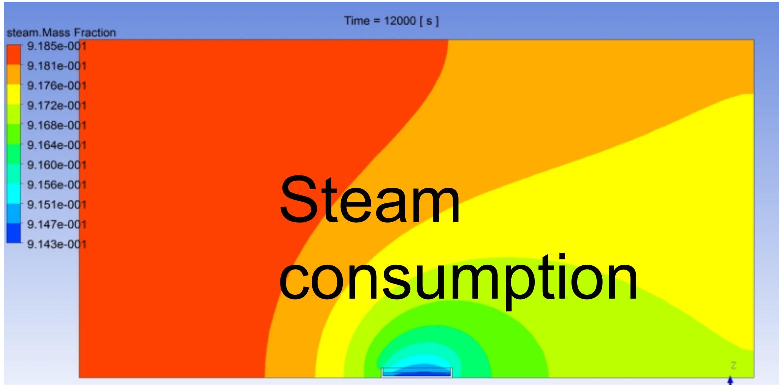
3D CFD with Chemical Reactions in Porous Media

Conjugated heat transfer approach is applied to calculate heat transfer in support structures as well as coolant flow, simultaneously with the porous medium steam flow in a blanket's granular beds.









A. Khodak, et al.
IEEE Trans. Plasma Sci, 46 (2018) 2332

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CFD

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot \left(\rho \vec{V}\right) = 0$$

$$\frac{\partial \rho \vec{V}}{\partial t} + \vec{\nabla} \cdot \left(\rho \vec{V} \vec{V}\right) = -\vec{\nabla} p + \vec{\nabla} \cdot (\boldsymbol{\tau}) + \rho \vec{g} + \vec{\boldsymbol{j}} \times \vec{\boldsymbol{B}}$$ ← Lorentz Force

$$\frac{\partial \rho c_p T}{\partial t} + \vec{\nabla} \cdot \left(\rho \vec{V} c_p T\right) = \vec{\nabla}\left(\lambda \vec{\nabla} T\right) + \boldsymbol{\tau} : \vec{\nabla} \vec{V} + \dot{h} + \vec{\boldsymbol{j}} \cdot \vec{\boldsymbol{E}}$$ ← Joule Heat

MHD

Electric Potential Formulation +1 PDE

Magnetic Induction Formulation +3 PDE
with Gauss law enforced +4 PDE

Magnetic Vector Potential Formulation +4 PDE
with gauge enforced +5 PDE

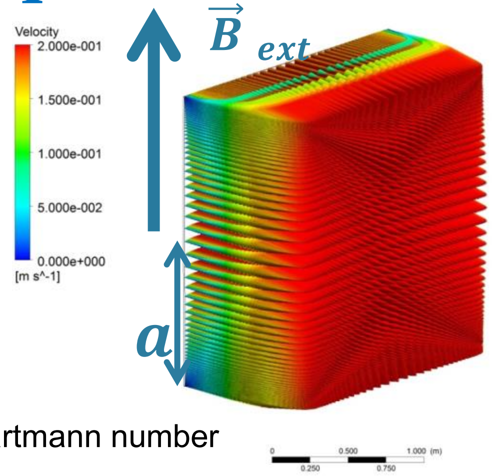
$$\frac{\partial \vec{\boldsymbol{B}}}{\partial \boldsymbol{t}} = -\vec{\boldsymbol{\nabla}} \times \vec{\boldsymbol{E}}$$ ← Maxwell-Faraday Equation

$$\left(\vec{\boldsymbol{E}} + \vec{\boldsymbol{V}} \times \vec{\boldsymbol{B}}\right) = \frac{\vec{\boldsymbol{j}}}{\boldsymbol{\sigma}}$$ ← Ohm's Law

$$\vec{\boldsymbol{\nabla}} \times \vec{\boldsymbol{H}} = \vec{\boldsymbol{j}} + \frac{\mathbf{1}}{\boldsymbol{c}^2} \frac{\partial \vec{\boldsymbol{E}}}{\partial \boldsymbol{t}}$$ ← Ampere's Law

$$\vec{\boldsymbol{\nabla}} \cdot \vec{\boldsymbol{B}} = \mathbf{0}$$ ← Gauss Law

Square Duct Flow Non-Conducting Wall



Hartmann number

$$Ha = B_0 a\sqrt{\sigma/\rho\nu}$$

$$\rho = const$$

Flow rate

$$\tilde{Q} = \int_{-1}^{1} d\tilde{y} \int_{-1}^{1} \tilde{V} d\tilde{x} \qquad \frac{\partial p}{\partial z} = const$$

$$\tilde{x} = \frac{x}{a} \qquad \tilde{y} = \frac{y}{a} \qquad \vec{V}_{wall} = 0$$

$$\vec{B}_{wall} = \vec{B}_{ext}$$

$$\tilde{V} = \frac{\rho\nu V}{a^2\left(-\frac{\partial p}{\partial z}\right)} \qquad \left(\frac{\partial\varphi}{\partial n}\right)_{wall} = 0$$

Fully developed flow of conducting Fluid subject to uniform transverse magnetic field

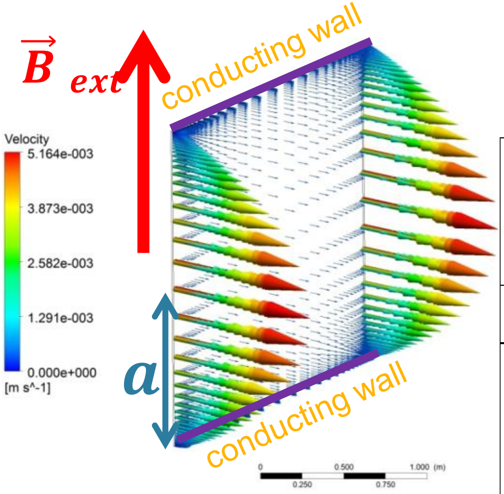
Smolentsev *et al. (2014)* case A1

	Analytical Solution	Current Density in from Ampere's Law			Current Density from Ohm's Law		Size	Ratio
		Magnetic Induction Formulation	CFX Magnetic Vector Potential Formulation Modified	CFX Electric Potential Formulation Modified	CFX Magnetic Vector Potential Formulation	CFX Electric Potential Formulation		
Ha	Shercliff [7]	Equations (1,2,3,5,10)	Equations (1,2,3,15,18)	Equations (1,2,3,15,26)	Equations (1,2,3,15,18)	Equations (1,2,3,15)	N∥ N⊥	R∥ R⊥
500	7.679892E-03	0.0076799	0.0082639	0.0082697	0.0082172	0.0082166	100	100
		-0.00010%	**-7.60437%**	**-7.67989%**	**-6.99629%**	**-6.98848%**	100	100
			0.0076807	0.0076797	0.0076259	0.0076259	100	1000
			-0.01052%	**0.00251%**	**0.70304%**	**0.70304%**	100	1000
5000	7.902124E-04	0.00079031					100	100
		-0.01236%					100	100
			0.00078897	0.00078996	0.0007733	0.0007733	100	10000
			0.15722%	**0.03194%**	**2.14023%**	**2.14023%**	100	10000
50000	7.969391E-05	0.000079689	0.0000815				400	10000
		0.00616%	**-2.26628%**				400	10000
		0.00007969	0.000080431				800	10000
		0.00491%	**-0.92490%**				800	10000

Analytical solution from Shercliff *(1953) Proc. Camb Phi. Soc. 49, pp 136-144*

Square Duct Flow with Conducting Walls

Two conducting walls perpendicular to the magnetic field direction.



$$\vec{B}_{wall} = \vec{B}_{ext} \qquad \rho = const$$

$$\vec{V}_{wall} = 0 \qquad \frac{\partial p}{\partial z} = const$$

wall conductance

$$\left(\frac{\partial \varphi}{\partial n}\right)_{wall} = 0 \qquad c_w = 0.01$$

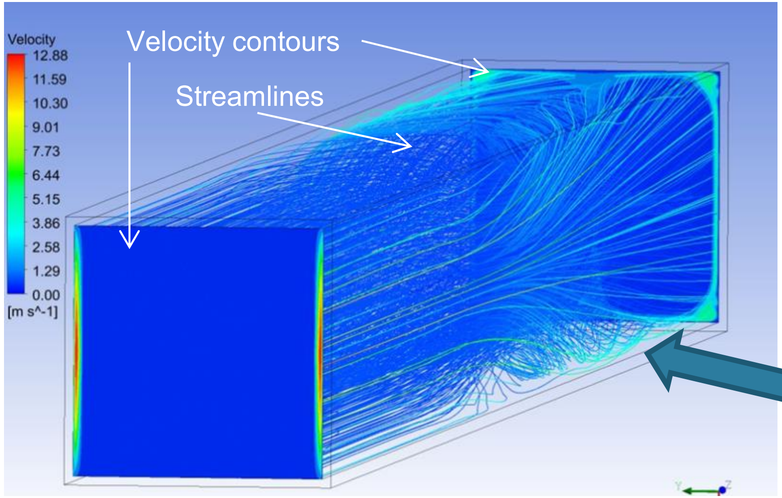
Fully developed flow of conducting Fluid subject to uniform transverse magnetic field

Smolentsev *et al. (2014)* case A2

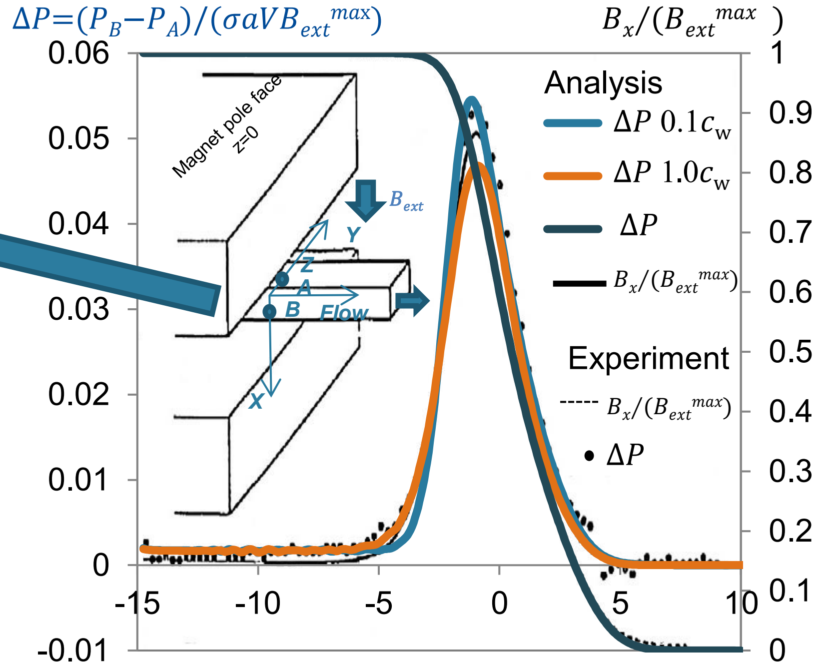
	Analytical Solution	Current Density in from Ampere's Law			Current Density from Ohm's Law		Size	Ratio
		Magnetic Induction Formulation	CFX Magnetic Vector Potential Formulation Modified	CFX Electric Potential Formulation Modified	CFX Magnetic Vector Potential Formulation	CFX Electric Potential Formulation		
Ha	Hunt [8]	Equations (1,2,3,5,10)	Equations (1,2,3,15,18)	Equations (1,2,3,15,26)	Equations (1,2,3,15,18)	Equations (1,2,3,15)	N∥ N⊥	R∥ R⊥
500	1.405351E-03	0.0014063	0.0082639	0.0082697	0.0082172	0.0082166	100	10000
		-0.06751%	**-7.60437%**	**-7.67989%**	**-6.99629%**	**-6.98848%**	100	10000
		0.0014063	0.0076807	0.0076797	0.0076259	0.0076259	200	10000
		-0.06751%	**-0.01052%**	**0.00251%**	**0.70304%**	**0.70304%**	200	10000
5000	1.907361E-05	0.00079031					100	100
		-0.01236%					100	100
			0.00078897	0.00078996	0.0007733	0.0007733	100	10000
			0.15722%	**0.03194%**	**2.14023%**	**2.14023%**	100	10000
50000	2.677874E-07	2.7223E-07	2.677E-07	2.6761E-07		2.2170E-07	400	10000
		-1.65899%	**0.03265%**	**0.06626%**		**17.21046%**	400	10000
		2.6942E-07	2.68346E-07	2.68363E-07		2.4338E-07	800	10000
		-0.60965%	**-0.20858%**	**-0.21493%**		**9.11448%**	800	10000

Analytical solution from Hunt *(1965) J. Fluid Mech. 21, pp 577-590*

3D MHD Analysis Channel with Fringe Field



3D Square Duct flow with Change in External Field
Cross-section pressure drop and magnetic field distribution along the square duct
Ha=2900, $N=Ha^2/Re=540$, $c_w=0.07$



B.F. Picologlou C.B. Reed, in: IUTAM Symposium on liquid metal MHD, Riga, USSR, May 16, 1988

- ANSYS CFX adapted at PPPL for MHD problems using a magnetic induction approach[1]
- Modified code tested against benchmarks relevant for fusion applications[1]

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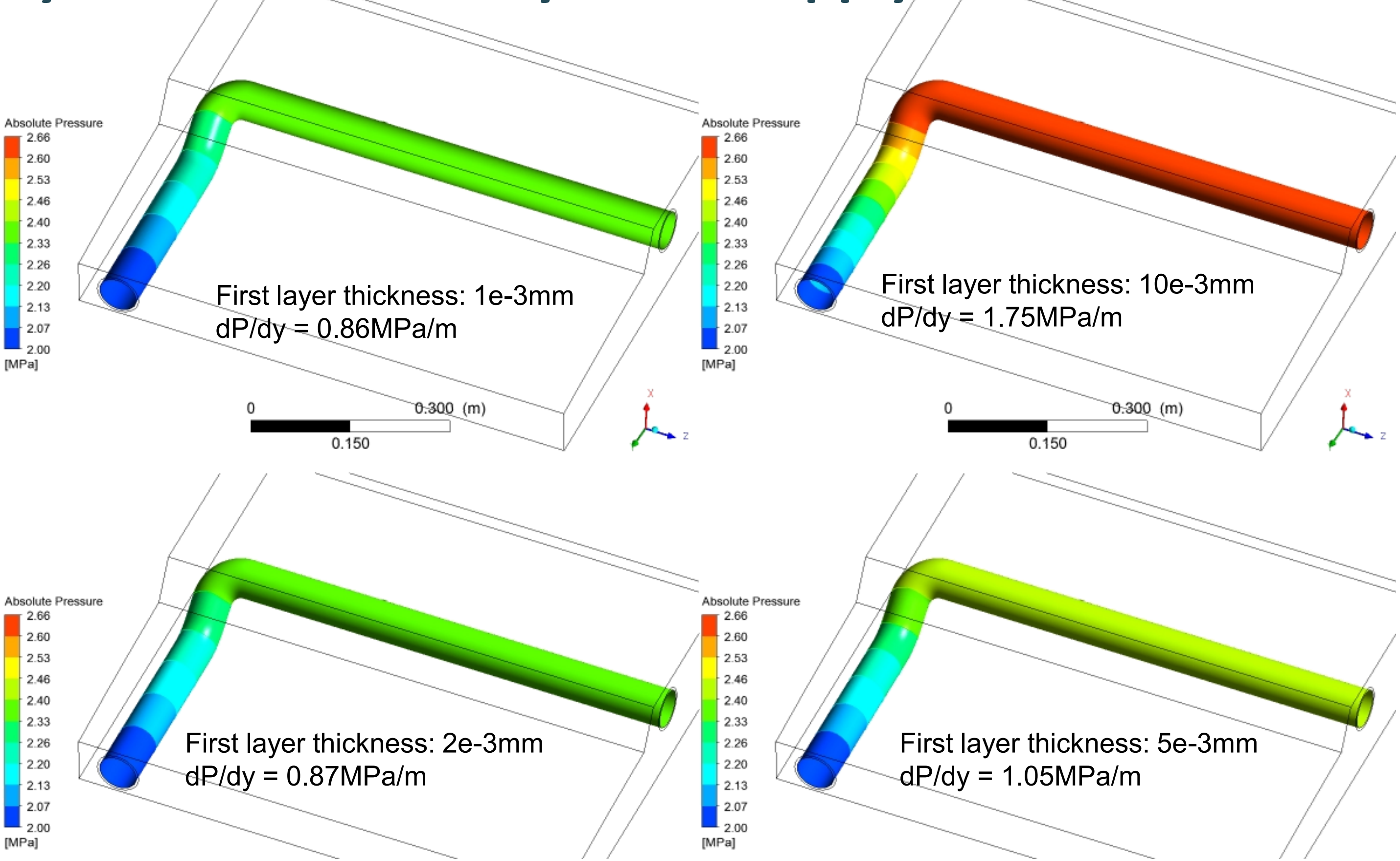
A. Khodak IEEE TPS 2017

DCLL blanket analysis mesh sensitivity at the supply channel

Bz =4 T
Diameter 60 mm
Wall Thickness 4mm
Flow 10 kg/s
Analytical Solution
dP/dy =0.85 MPa/m



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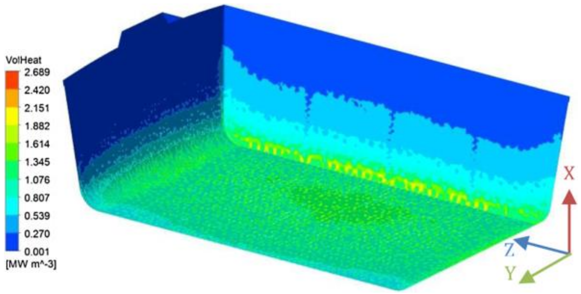
Khodak et al FED 2018

Virtual Prototyping of Liquid Metal Blanket Performance

- LM Blanket is a crucial element of the next step fusion device:
  - harvesting energy from fusion reaction
  - producing fuel for fusion reaction through tritium breeding
- PPPL possesses unique expertise in modeling of liquid metal blankets, including transient, electromagnetic, fluid, thermal and structural analysis, with three-dimensional nuclear loading
- Unique Features:

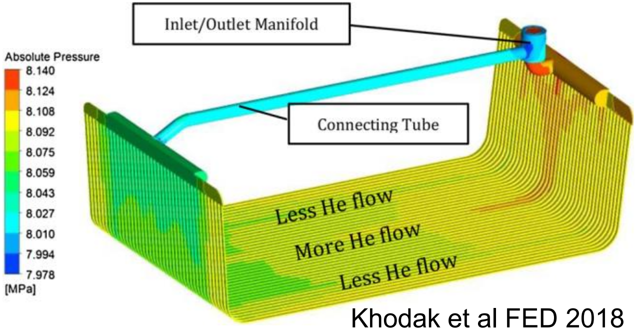
Neutronics code connection



Volumetric heat source imported from Attila.

Two Fluid CFD analysis

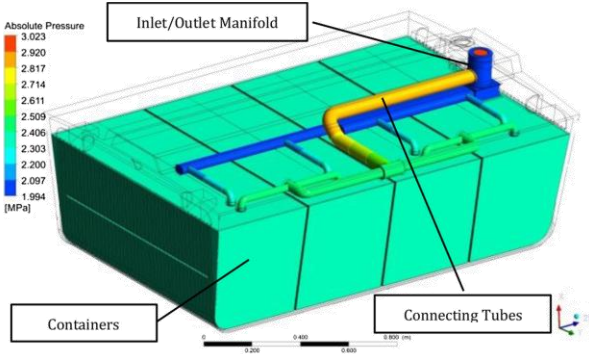
He coolant pressure distribution



Khodak et al FED 2018

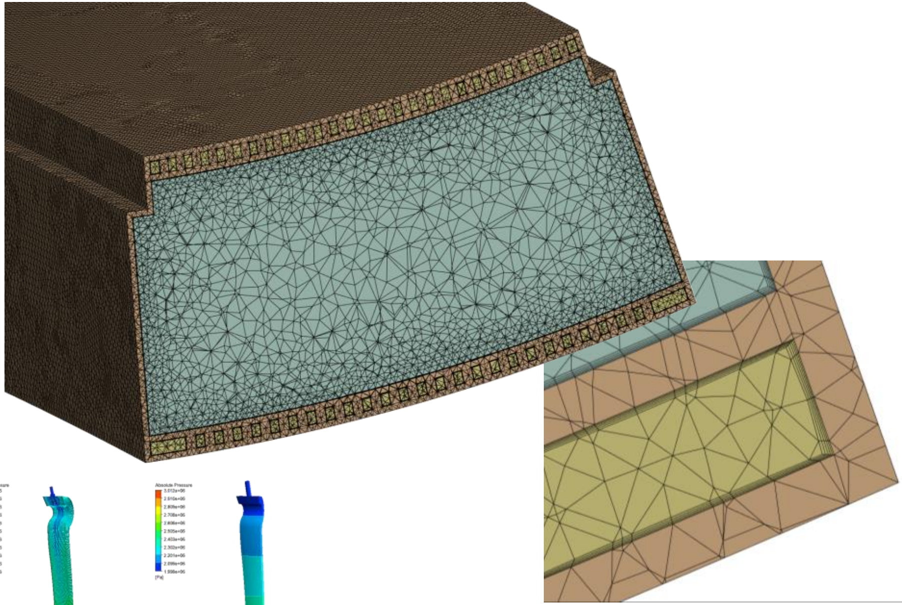
Conjugate Heat Transfer

Pressure distribution in Li17PB

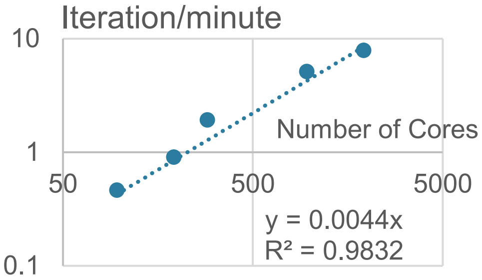


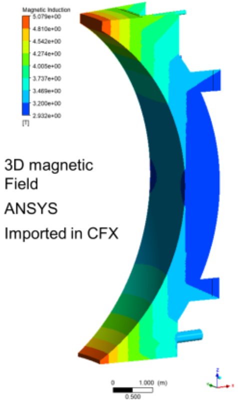
PPPL 3D MHD CFD analysis of STAR blanket using ANSIS CFX

- 3D CFD MHD Analysis
- Coupling with M3D-C1
- Automatic mesh Generation
- Massive parallel processing analysis on NERSC

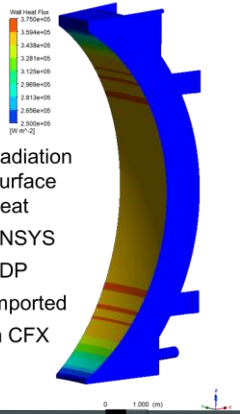


- Parallelization study was performed using PPPL Stellar cluster
- The queue time increases for higher number of cores requested
- Study continues with higher number of cores, using exponential licensing structure of ANSYS



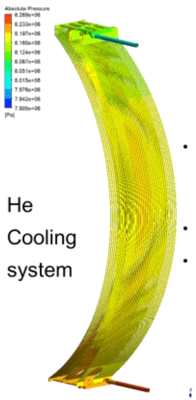


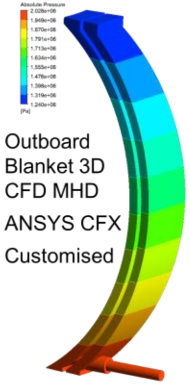
- 3D magnetic Field
- ANSYS
- Imported in CFX



- Radiation Surface Heat
- ANSYS
- ADP
- Imported
- In CFX

He Cooling system



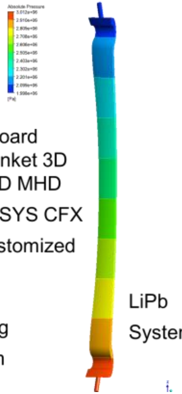


- Outboard Blanket 3D CFD MHD
- ANSYS CFX
- Customised

LiPb System

- Inboard Blanket 3D CFD MHD
- ANSYS CFX
- Customized

He Cooling system



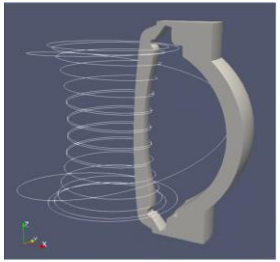
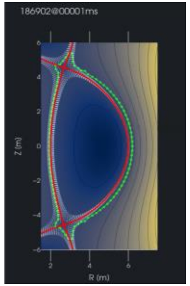
LiPb System

- Turbulent He flow analysis
- MHD Li Pb flow analysis
- Conjugate Heat Transfer

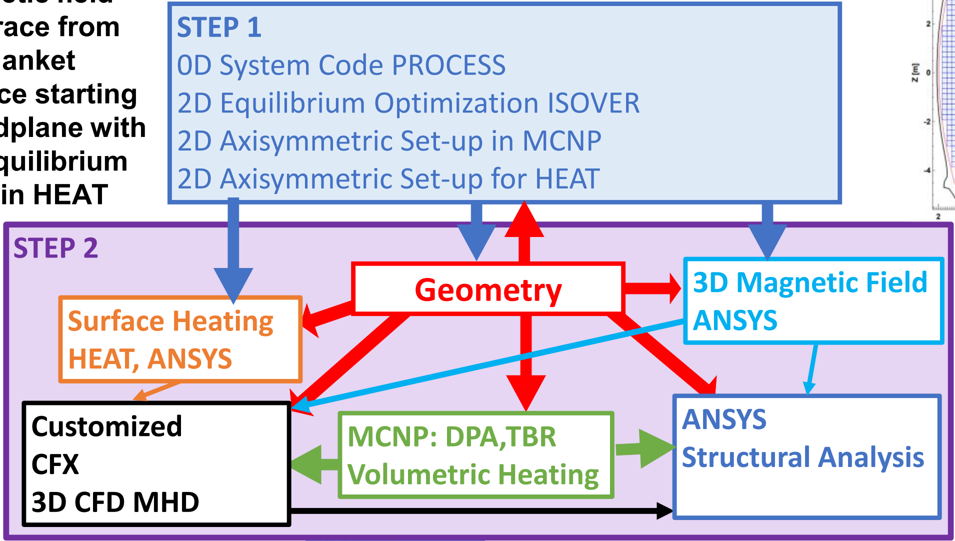
Outline

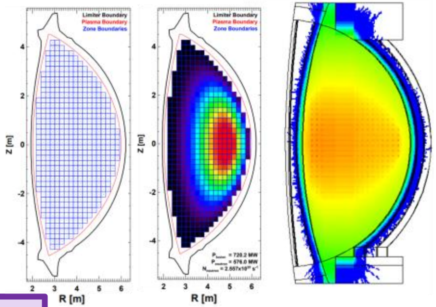
- Problem Set-up, Preparation and Meshing
- CFD Modeling at PPPL
- MHD
- Virtual Prototyping System
- Coupling
- Transient Flows
- Multiphysics Analysis

Virtual Prototyping System

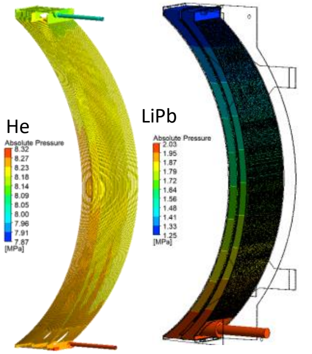



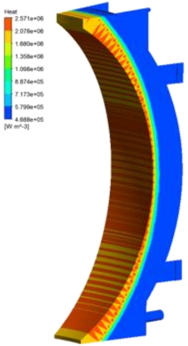
Magnetic field line trace from the blanket surface starting at midplane with the equilibrium used in HEAT





Neutron Source from ISOLVER Interpolated into MCNP

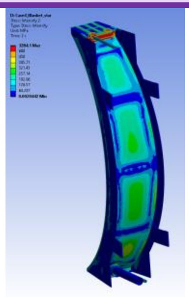




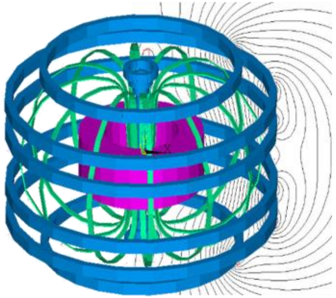
Absolute pressure in He coolant (left) and Li-Pb (right) fluid zones of the Out-Board blanket

Volumetric heating from MCNP imported in CFX

Stress Result under Pressure Load



Axisymmetric magnetic field obtained using ISOLVER and PF and TF coils geometry used for 3D interpretation in ANSYS

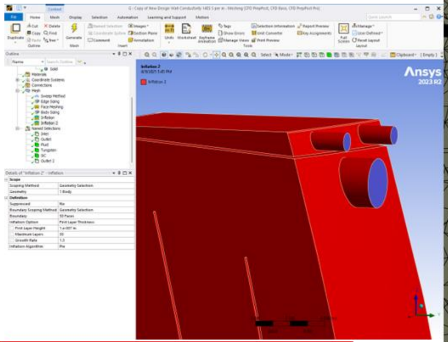


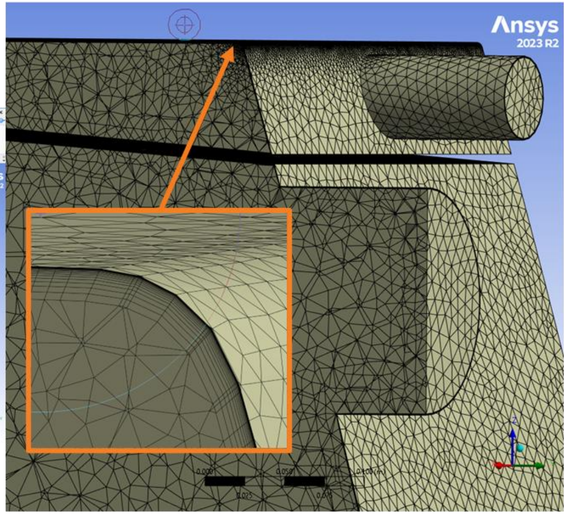
PPPL PRINCETON PLASMA PHYSICS LABORATORY

Khodak et al. FED 2023 https://doi.org/10.1016/j.fusengdes.2023.113692

Automatic Meshing Procedure

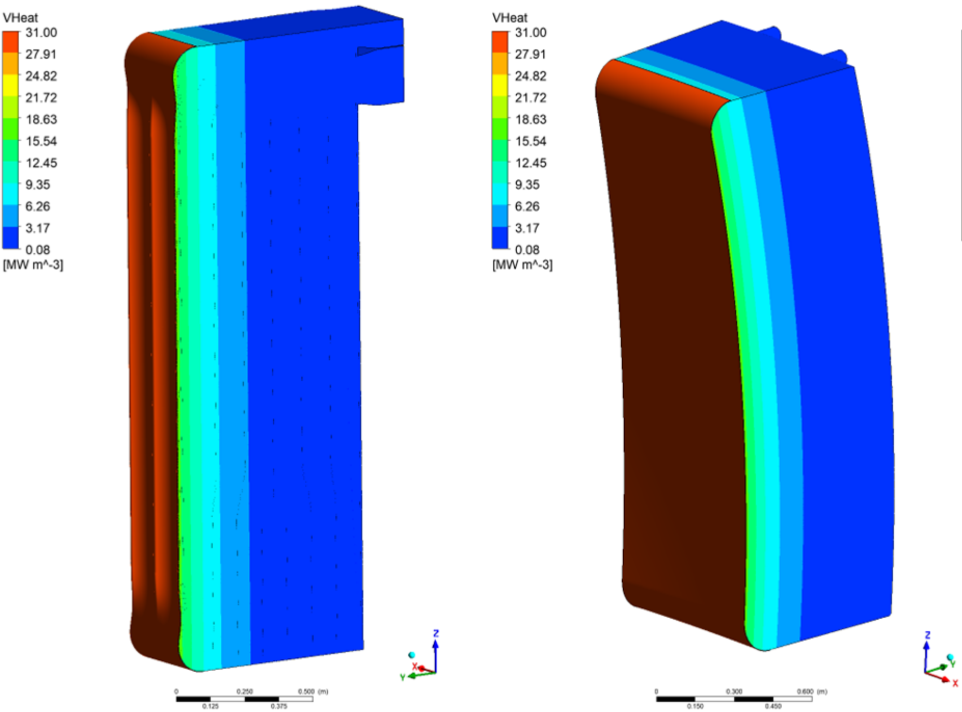
Inflation on fluid domain is required for proper resolution of boundary layers
Box mode can be used to select all surfaces



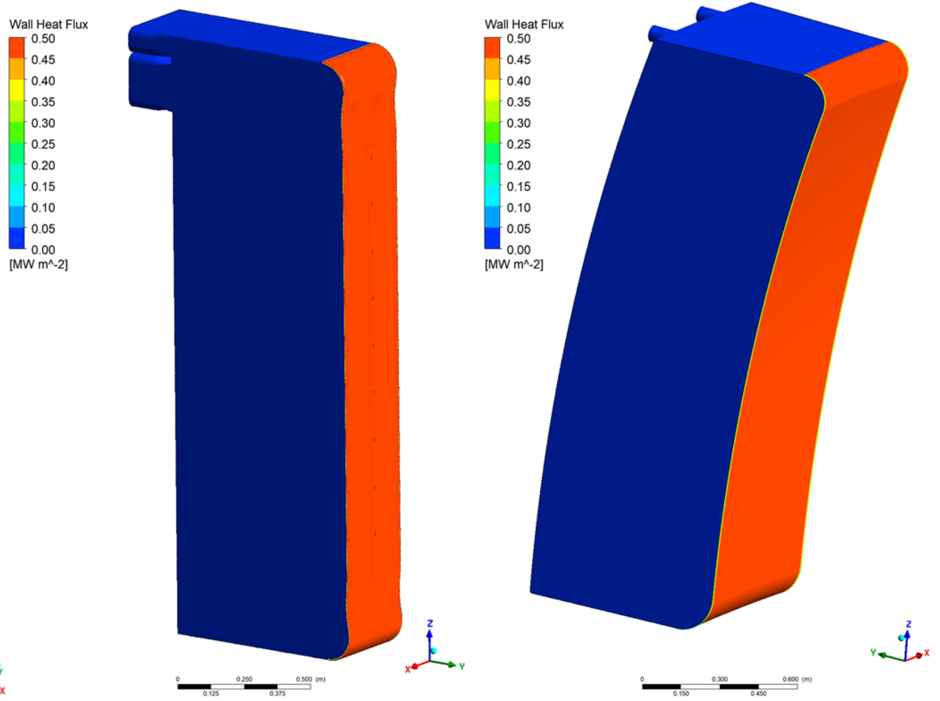


30 layers
Defined by first layer and Growth Rate

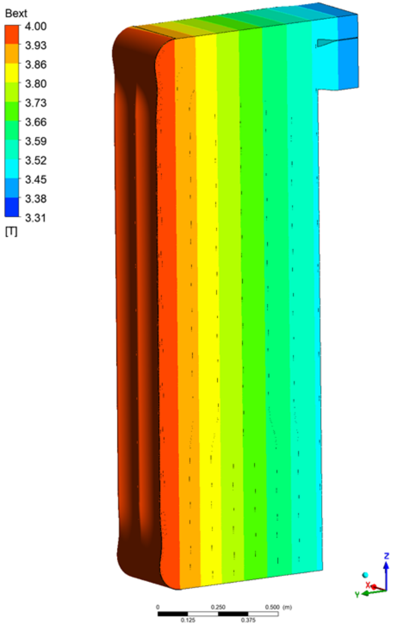
Volumetric Heating

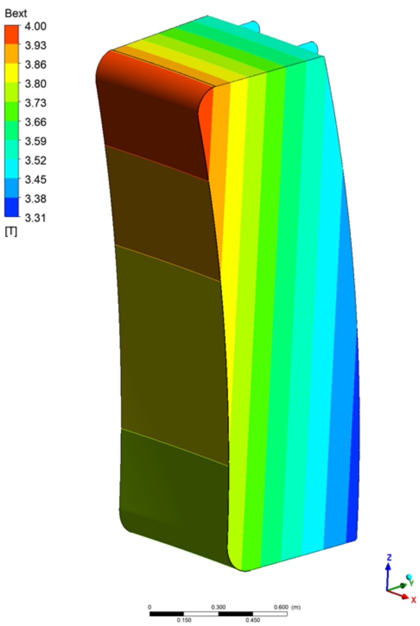


Surface Heating

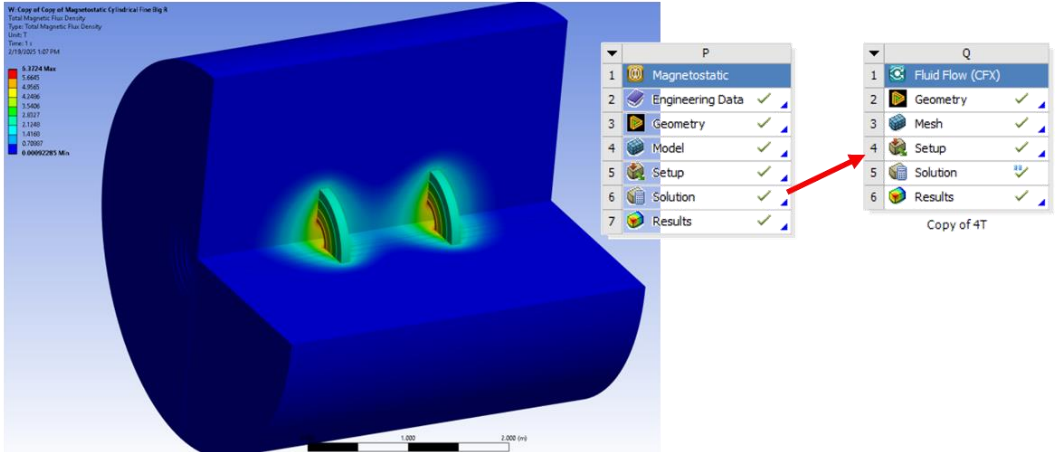


Magnetic Field

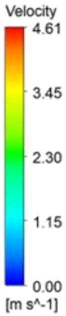


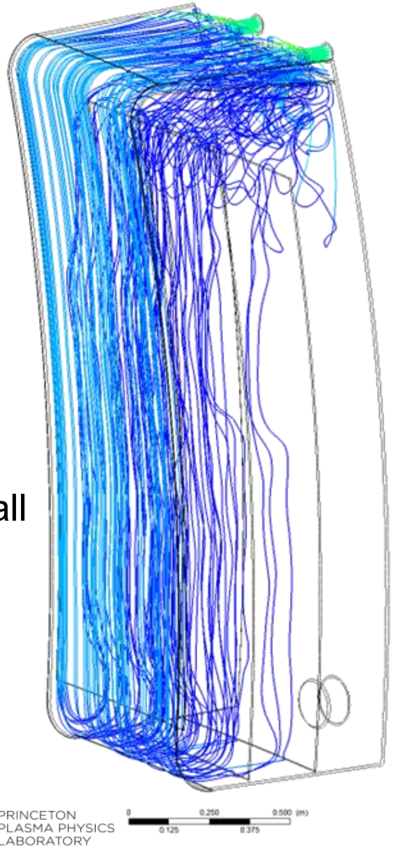


3D external magnetic field
Coupling with Magnetostatic analysis
Coil Center Separation 1250 mm



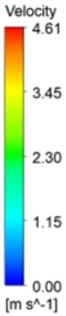
Velocity Streamlines





Electric
Potential
Model
SiCf/SiC wall
Laminar

Max V_{LiPb}
4.57 m/s

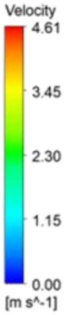


Magnetic
Induction
Model
SiCf/SiC wall
Laminar

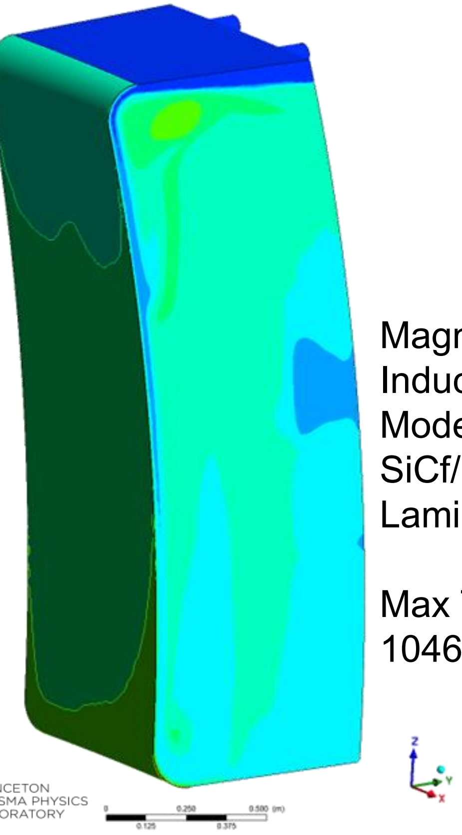
Max V_{LiPb}
4.61 m/s

No MHD
Turbulent
Buoyancy

Max V_{LiPb}
2.15 m/s

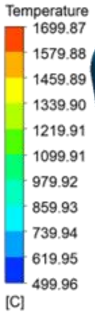


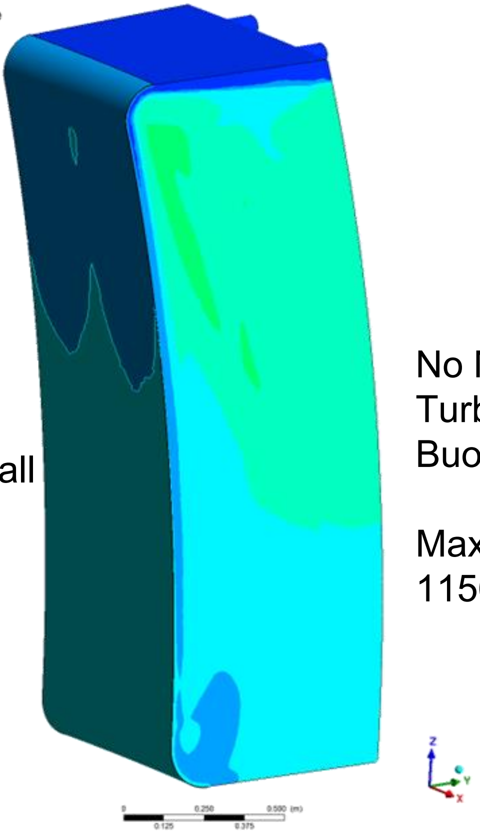
Temperature Distribution



Electric Potential Model
SiCf/SiC wall
Laminar

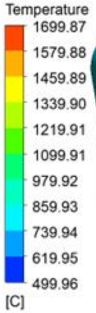
Max T
1270.42 C

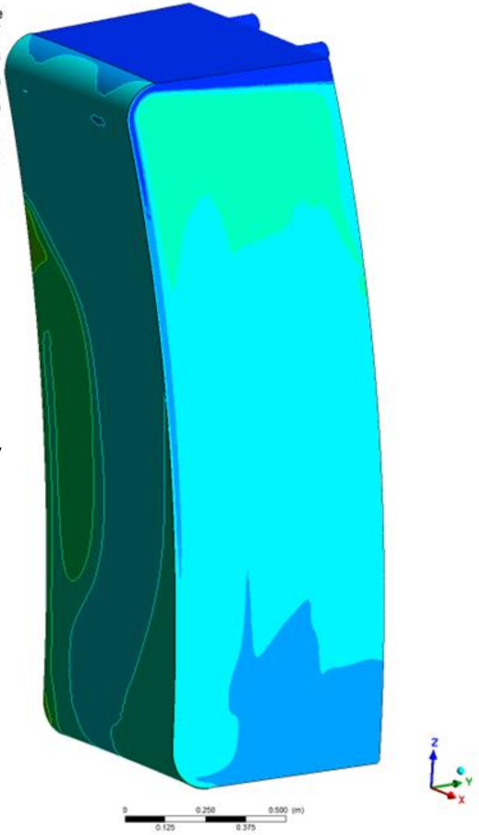




Magnetic Induction Model
SiCf/SiC wall
Laminar

Max T
1046.78 C





No MHD
Turbulent
Buoyancy

Max T
1156.2 C

PRINCETON PLASMA PHYSICS LABORATORY

Outline

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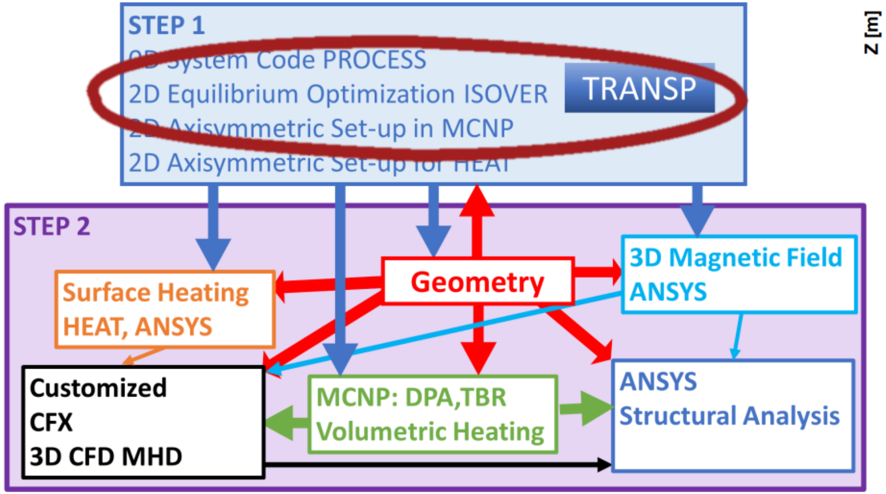
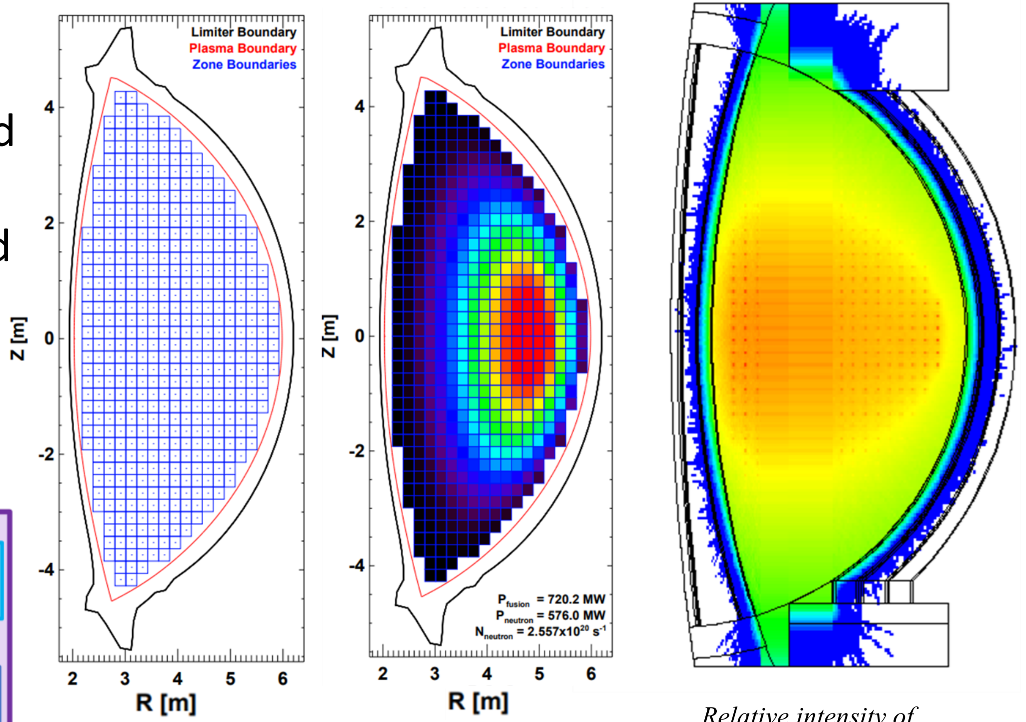
Neutron Source Interpolation for Neutronics Code MCNP

- Automatic spatial NS distribution transfer from ISOLVER to MCNP
- Connection to TRANSP can be achieved in a similar manner
- IMAS interface connection can be used





R,Z grid and plasma zone boundaries defined in iSOLVER

Neutron power density profile mapped onto the R,Z grid for import into MCNP

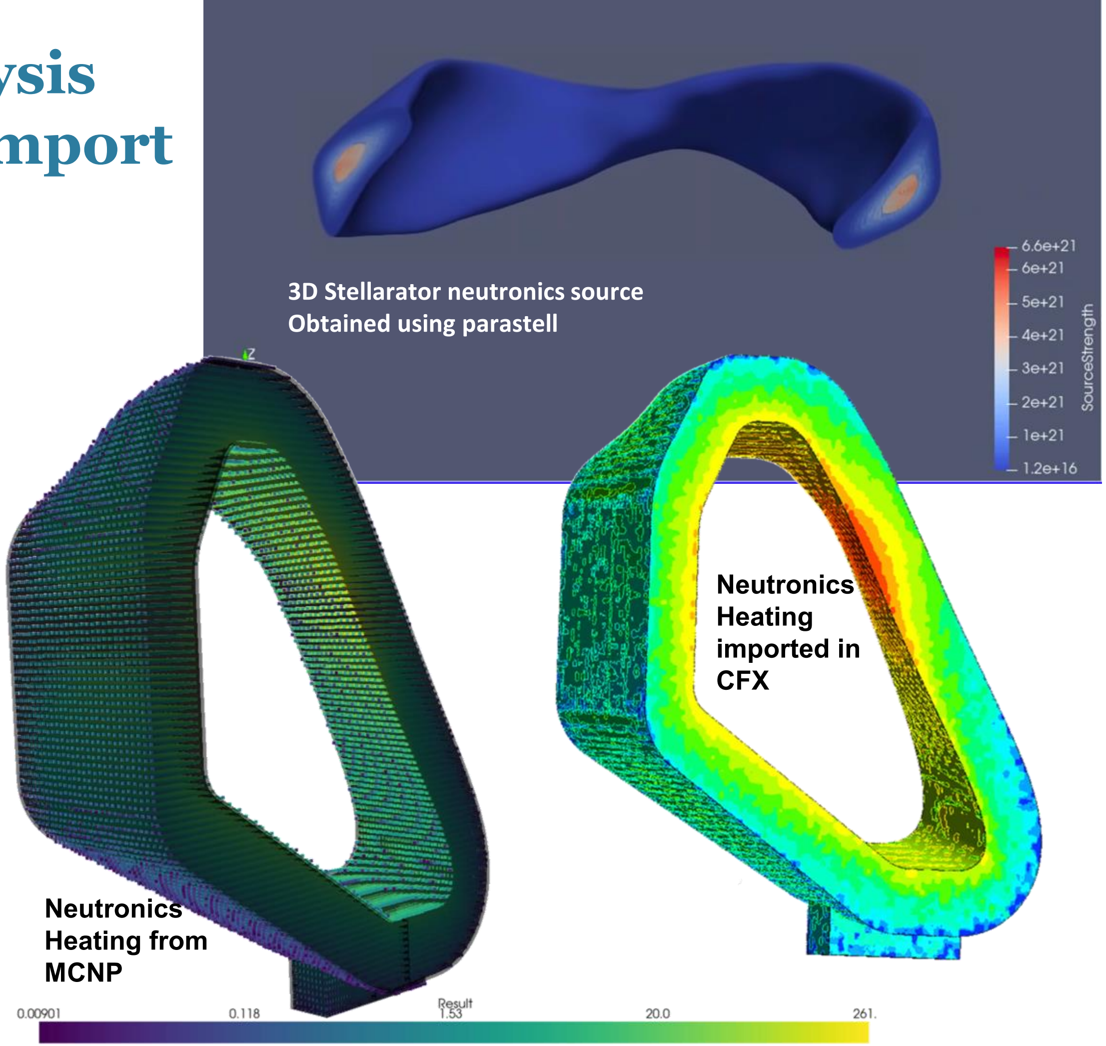
Relative intensity of neutrons born in MCNP model visualized by plotting neutron flux (E>13.99 MeV)

Linn et al. SOFE 2023

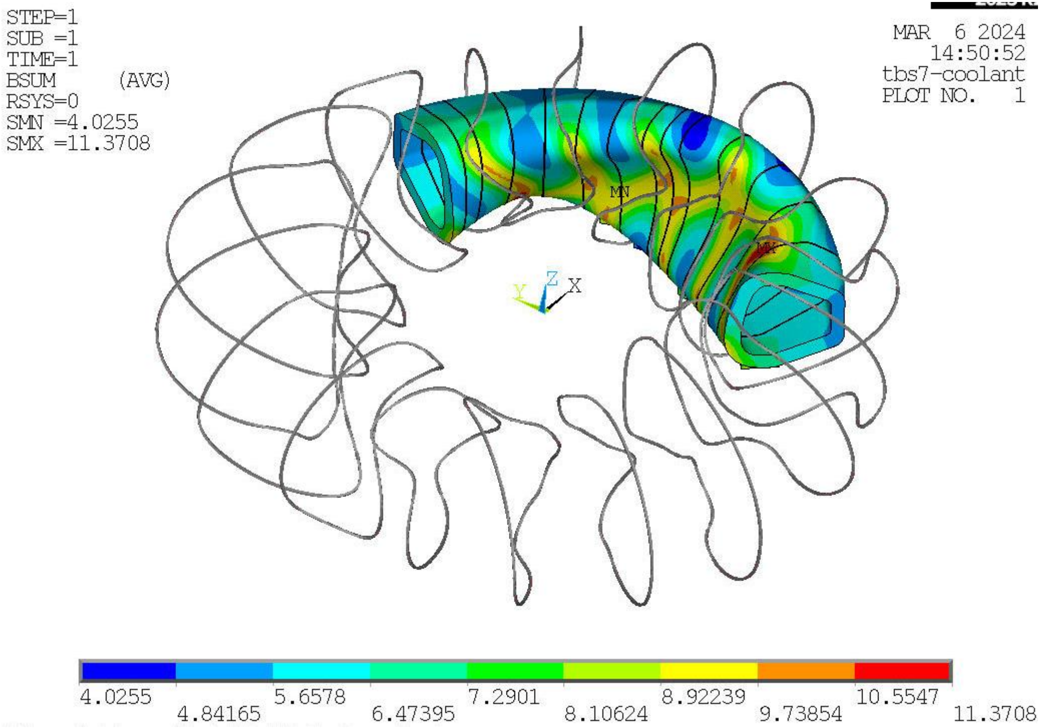
Stellarator Blanket Analysis
3D Neutronics Heating Import

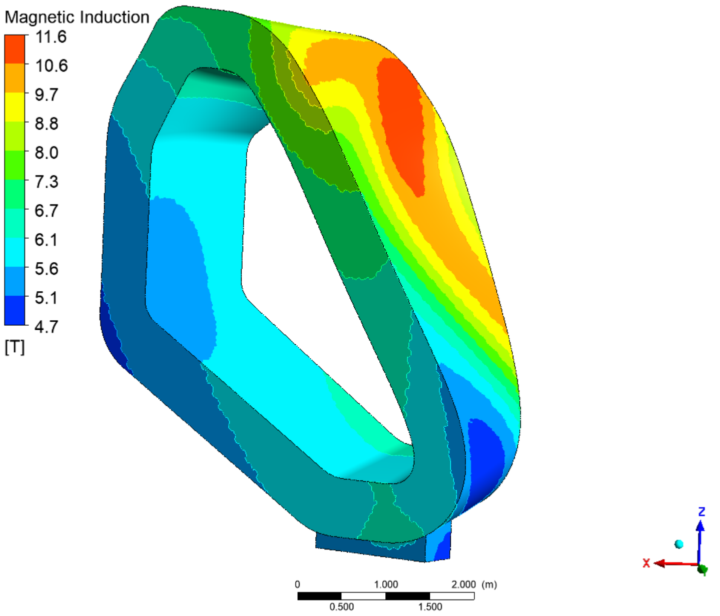
- Nuclear Analysis is completed using MCNP6.2
- Python scripts used to convert MCNP output to importable mesh tallies

- MCNP Cylindrical Mesh tally was used to acquire the nuclear heating
- Multiplication factor for heating was calculated per unit volume for a 2800MW plasma



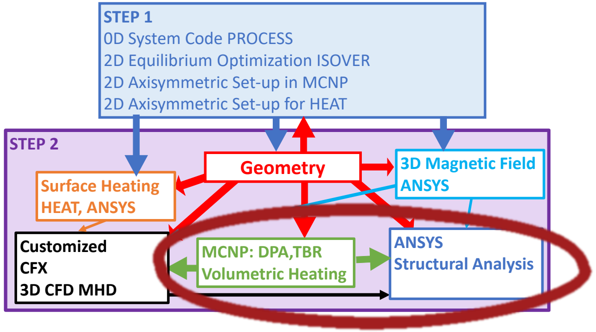
Stellarator Blanket Analysis
3D Magnetic Field





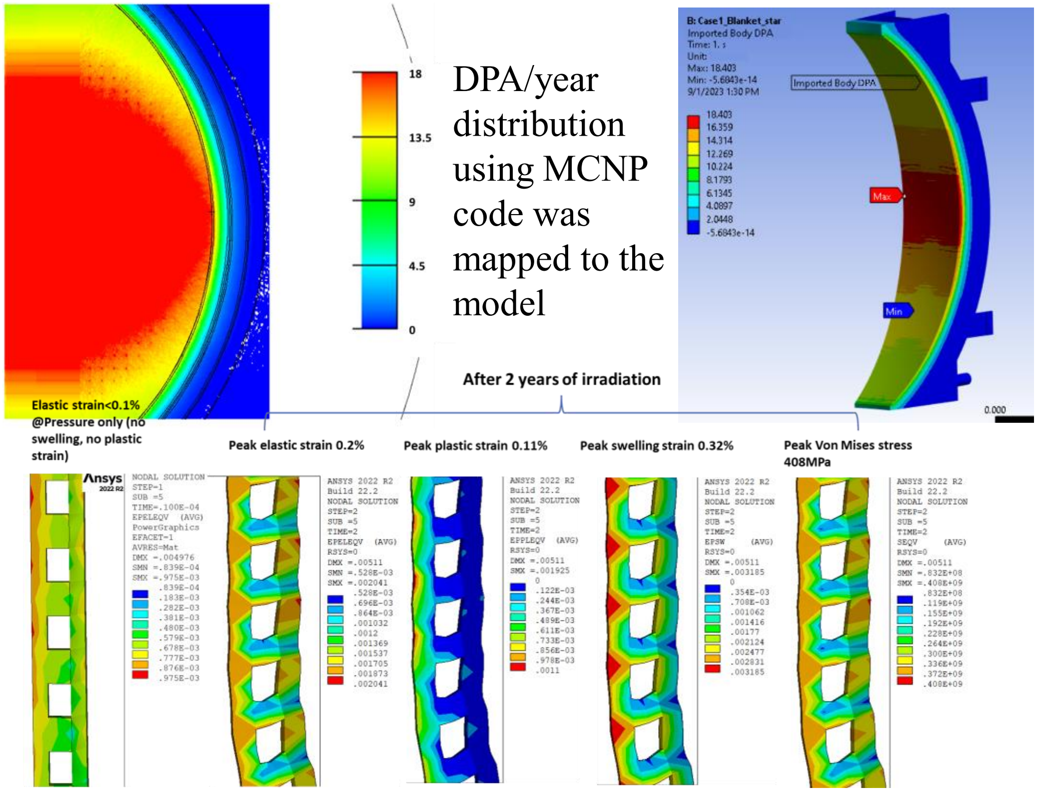
Magnetic Field

Structural Analysis 3D Neutronic Swelling Model



- Neutronics Swelling and Hardening are introduced in ANSYS ADPL using User Defined Functions for Properties
- DPA values are imported from MCNP

H.Zhang et al. IEEE TPS 2024



After 2 years, close look (500x) at the strains of first wall shows a complex strain-stress state which may initiate microcrack

Outline

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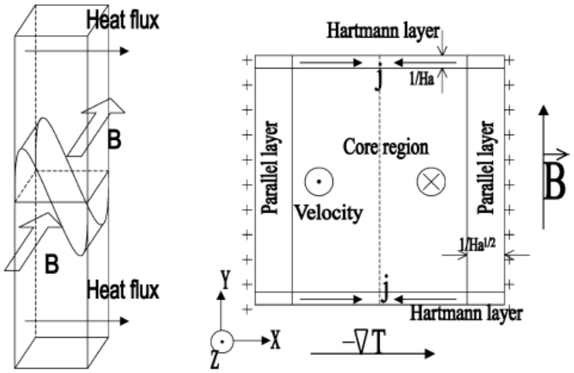
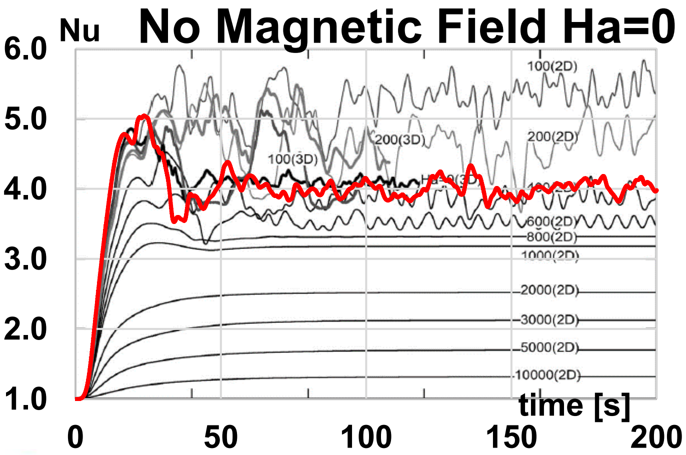
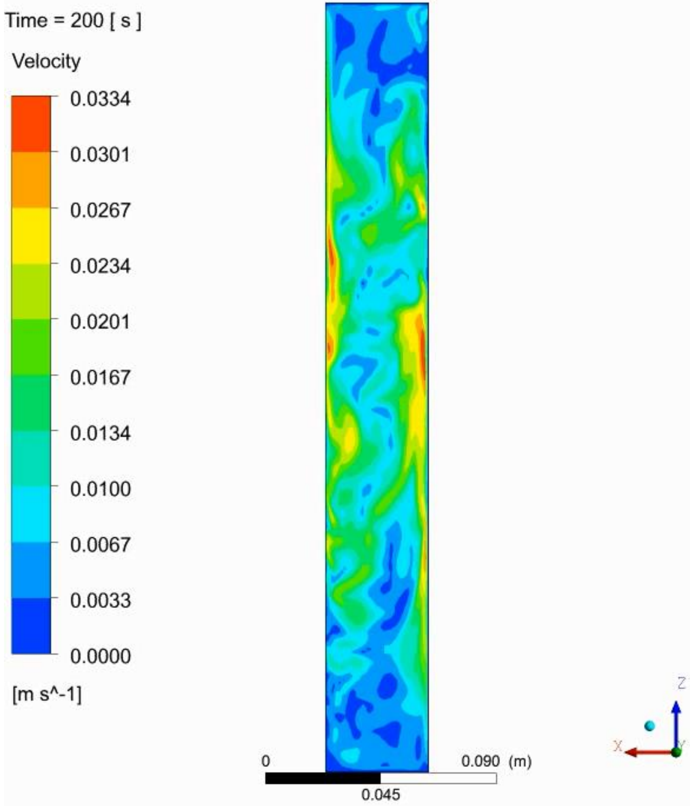
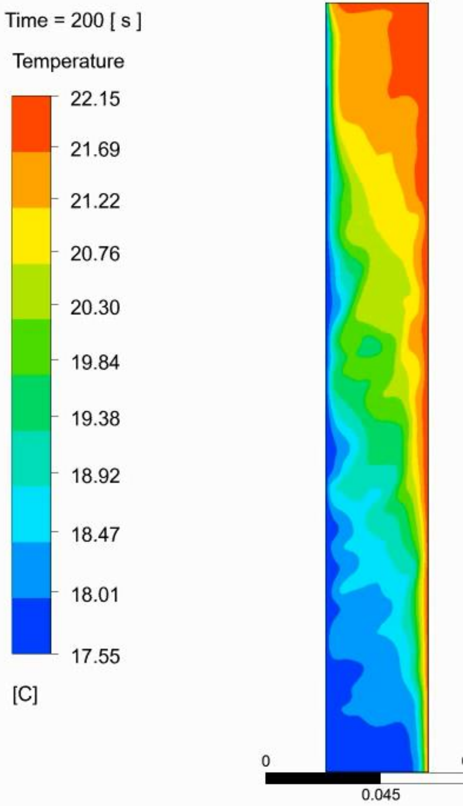
Natural Convection



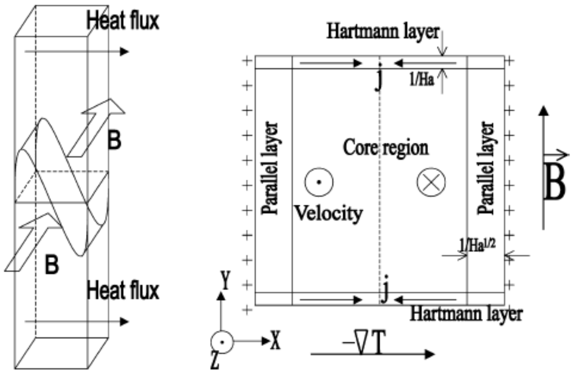


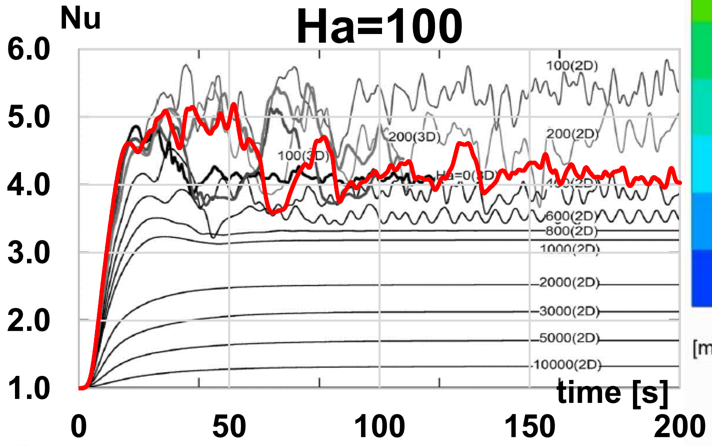


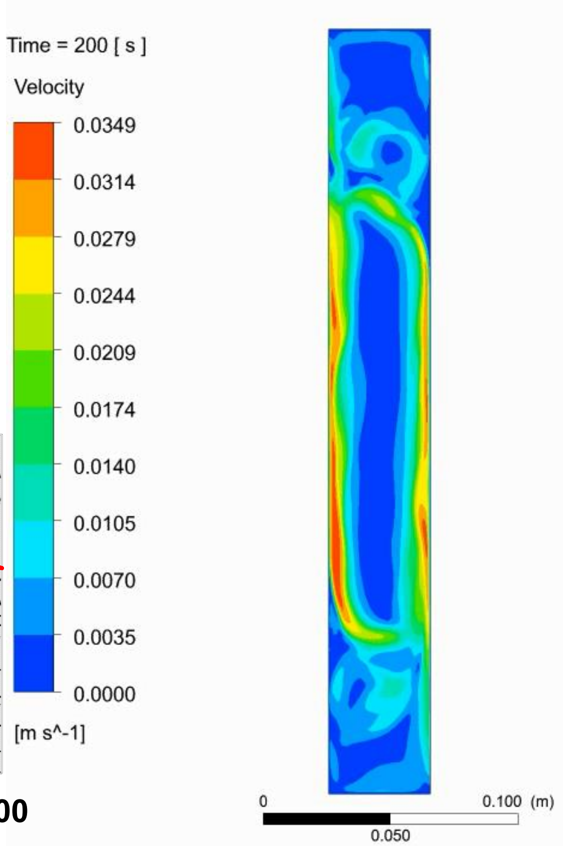


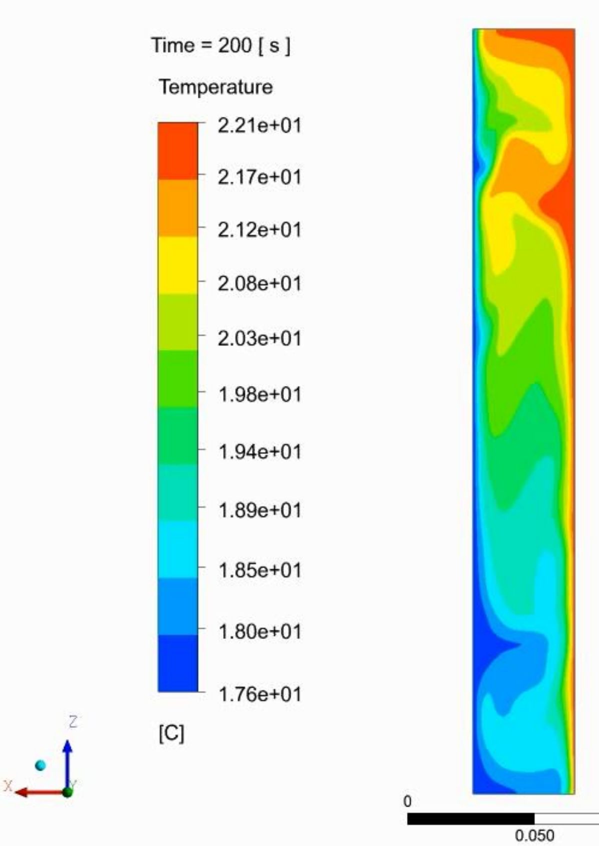
Experimental and Numerical Data Authie et al 2003

Natural Convection with MHD



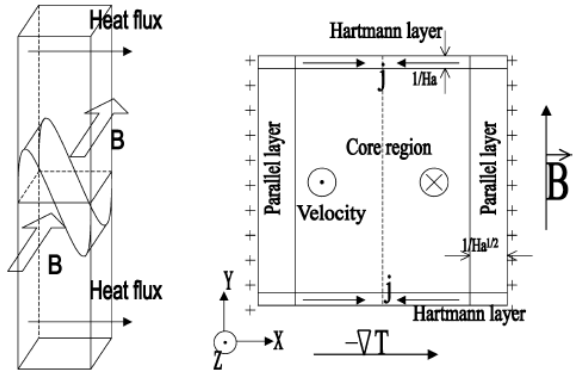


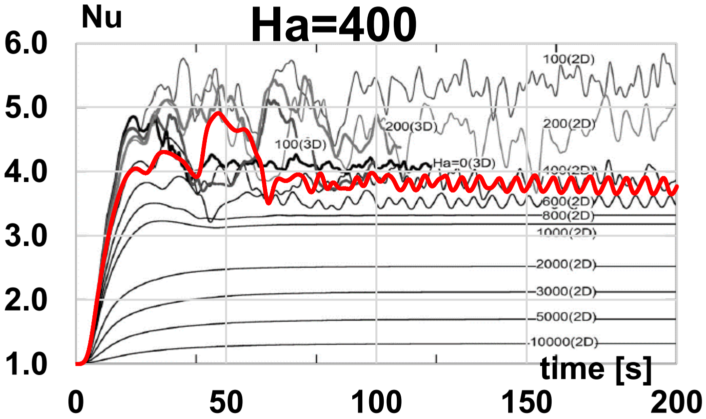


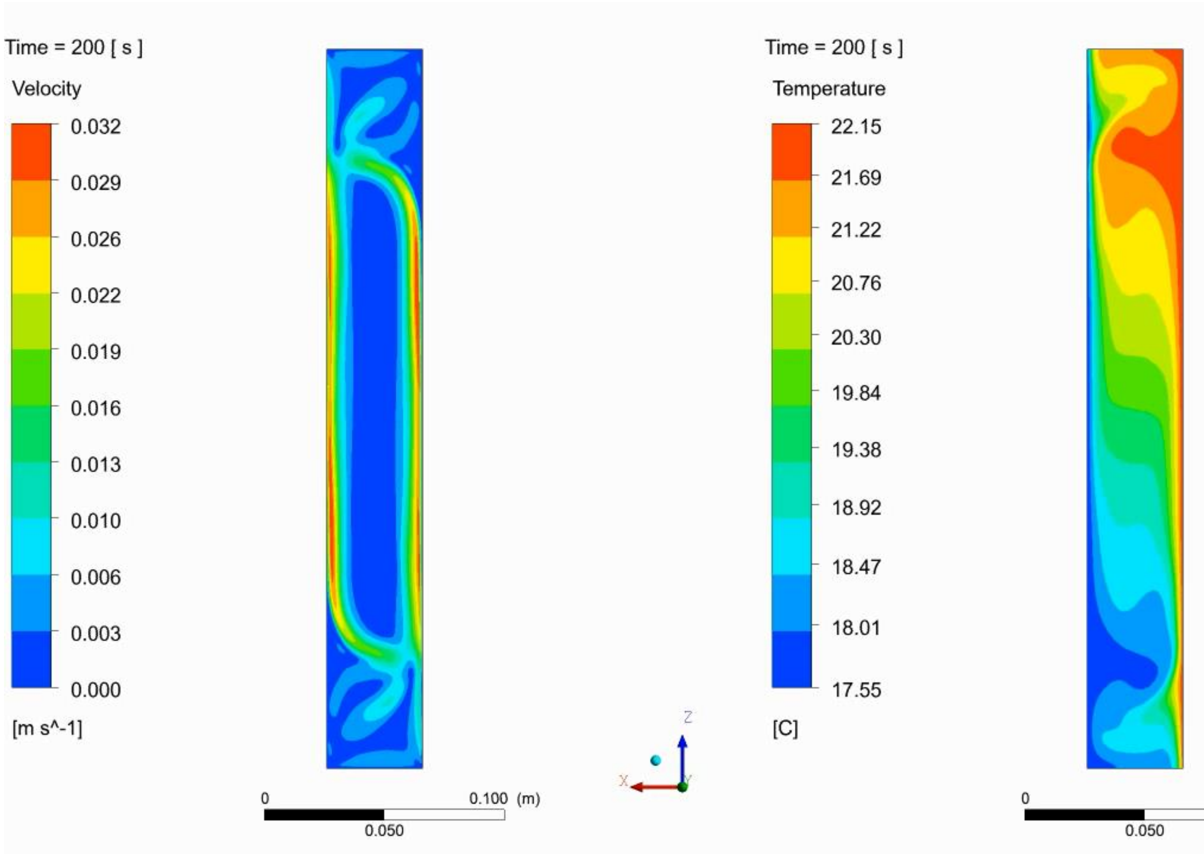


Experimental and Numerical Data Authie et al 2003

Natural Convection with MHD

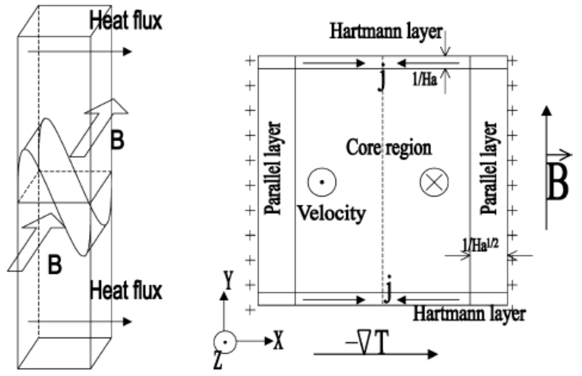


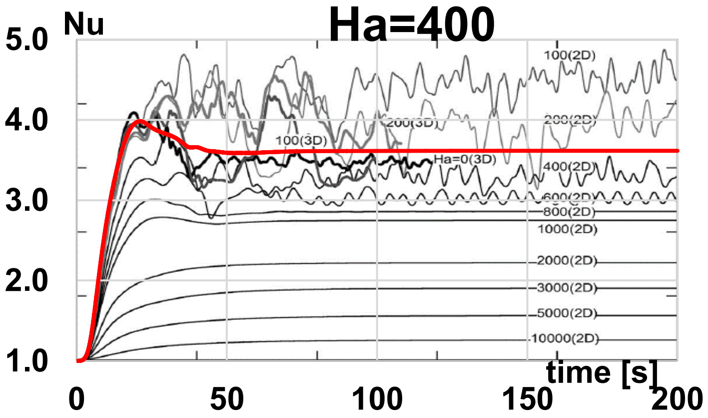


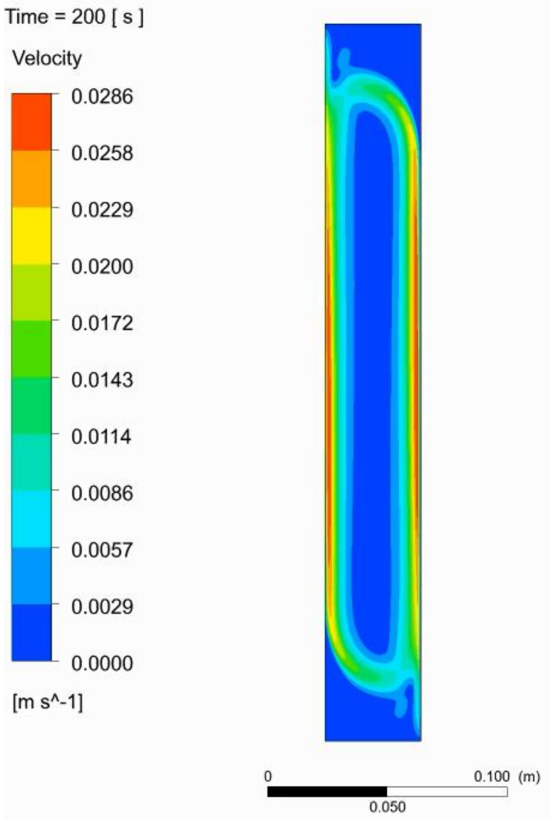


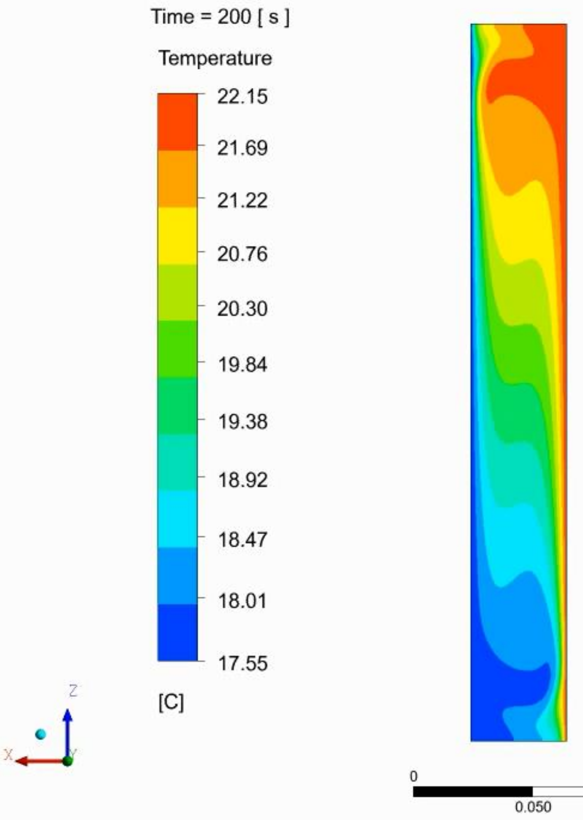
Experimental and Numerical Data Authie et al 2003

Natural Convection MHD Original Electric Potential Formulation





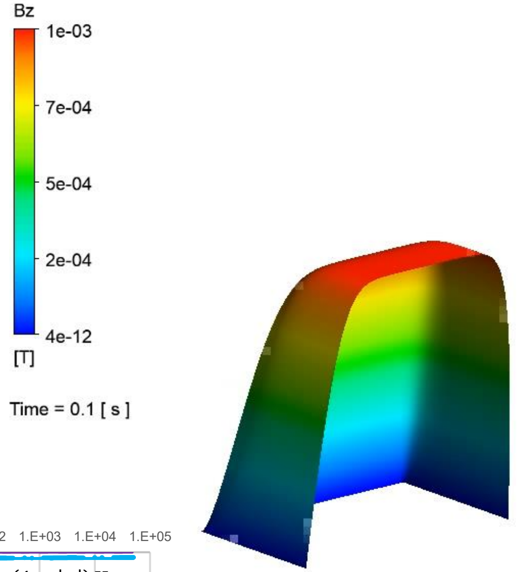




Experimental and Numerical Data Authie et al 2003

PPPL Magnetic Induction Formulation in ANSYS CFX

- Magnetic Induction MHD formulation was introduced in customized version of CFD code
- Transient MHD model was validated using analytical solution
- Customized code allows transient 3D MHD analysis in complex geometries



CFD
User Defined Sources

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}\cdot\left(\rho\vec{V}\right) = 0$$

$$\frac{\partial \rho\vec{V}}{\partial t} + \vec{\nabla}\cdot\left(\rho\vec{V}\vec{V}\right) = -\vec{\nabla}p + \vec{\nabla}\cdot(\boldsymbol{\tau}) + \rho\vec{g} + \vec{j}\times\vec{B}$$

Lorentz Force

$$\frac{\partial \rho c_p T}{\partial t} + \vec{\nabla}\cdot\left(\rho\vec{V}c_p T\right) = \vec{\nabla}\left(\lambda\vec{\nabla}T\right) + \boldsymbol{\tau}:\vec{\nabla}\vec{V} + \dot{h} + \vec{j}\cdot\vec{E}$$

Joule Heat

MHD
Magnetic Induction Equation

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla}\times\left(\vec{V}\times\vec{B}\right) - \vec{\nabla}\times\left(\frac{\vec{\nabla}\times\vec{B}}{\mu\sigma}\right)$$

$$\frac{\partial \vec{B}}{\partial t} = -\vec{\nabla}\times\vec{E}$$ Maxwell-Faraday Equation

$$\left(\vec{E} + \vec{V}\times\vec{B}\right) = \frac{\vec{j}}{\sigma}$$ Ohm's Law

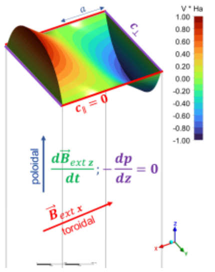
$$\vec{\nabla}\times\vec{B} = \mu\vec{j} + \frac{\mu}{\mu_0}\frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$ Ampere's Law

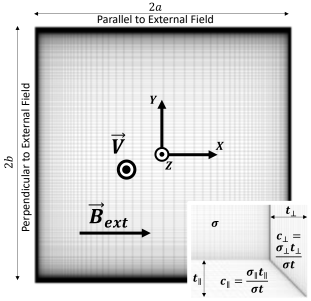
Linear Magnetic   Low Frequency

Introduced using:
User defined scalars
User defined transport equations
Gauss law enforced using additional $\vec{\nabla}\cdot\vec{B}$ cleaning procedure

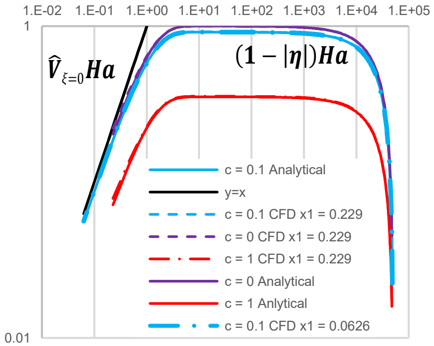
Validation

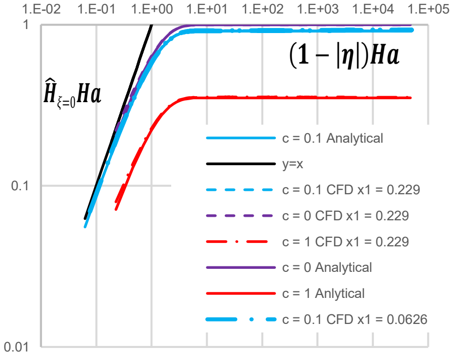
Analytical solution by Khodak (PAMIR 2024)
Problem proposed by Smolentsev (FED 2024)
Steady state insulated walls parallel to magnetic field





Velocity and induced field profiles at Ha =50000





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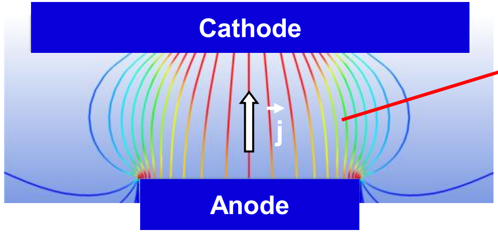
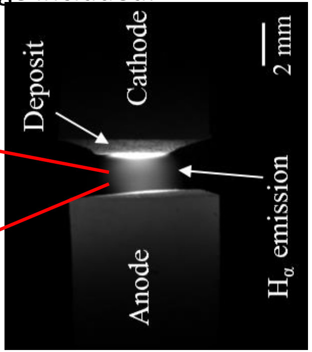
Universal computational platform for simulation of interacting solids, fluids, gases, and highly collisional plasma

- Customized 3D CFD code from ANSYS
- MHD simulations for high Hartman numbers
- Self-Consistent model of atmospheric arc discharge included.

Electric current streamlines:

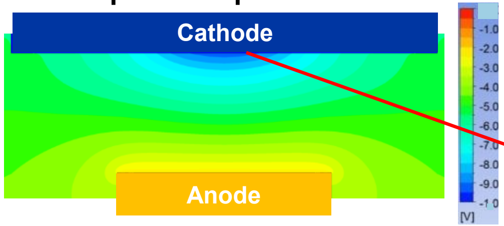


Arc contraction



Arc channel

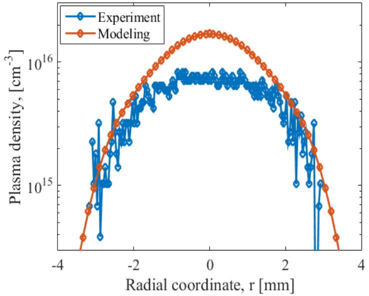
Electric potential profile:



Non-uniform potential distribution along the cathode tip

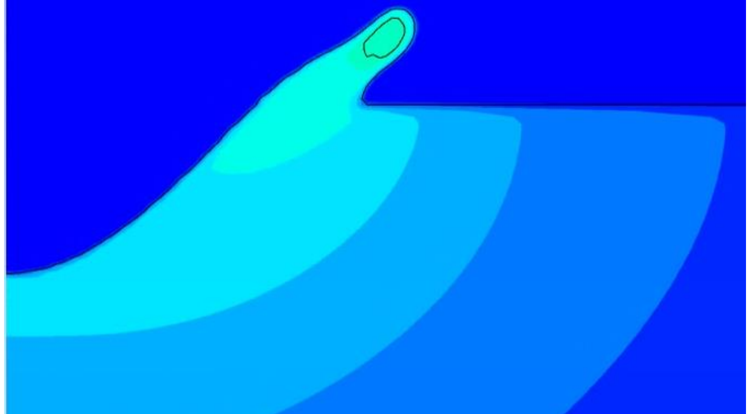
J. Chen, et al, Physics of Plasmas 2020

Middle plane plasma density profile:

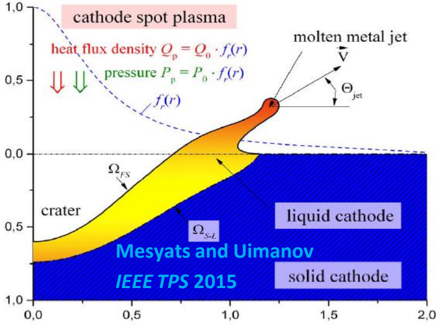


3-phase transient analysis

Unipolar act impact cavity development

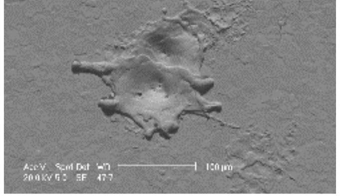


Vignitchuk, Khodak et al NME 2020



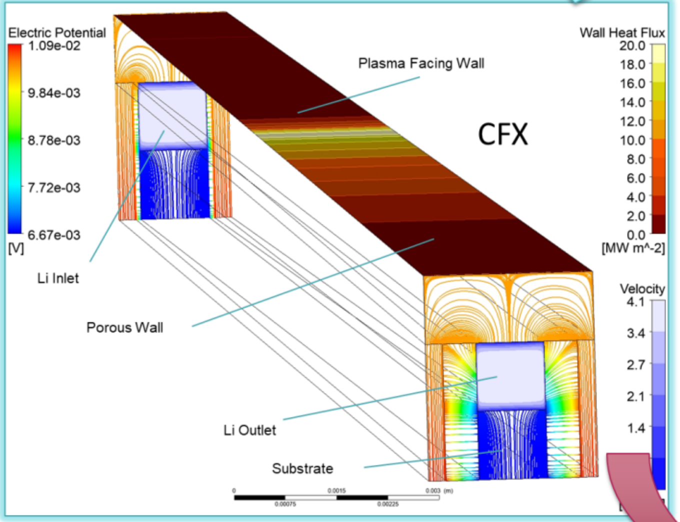
Mesyats and Uimanov *IEEE TPS 2015*

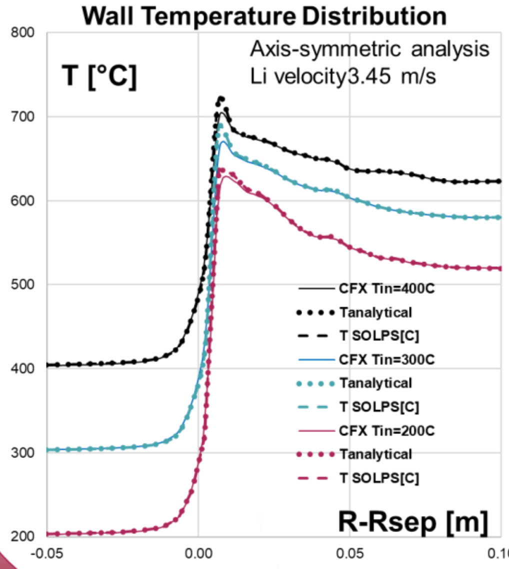
Khimchenko ITER 2019



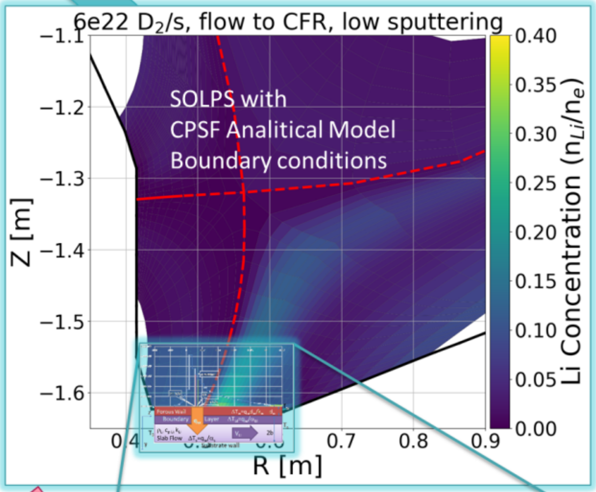
Coupled SOLPS 3D CFD MHD model

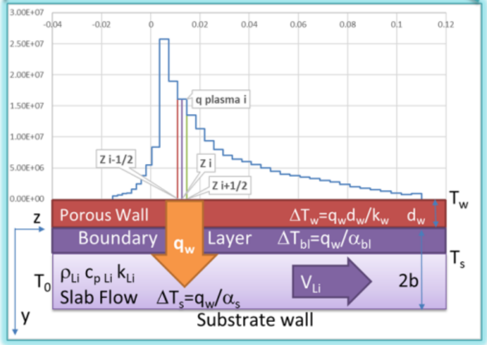
Heat and Species Flux profile from SOLPS





Temperature Distribution from CFX

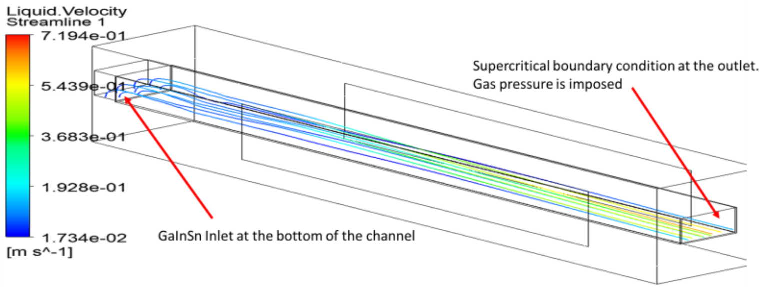




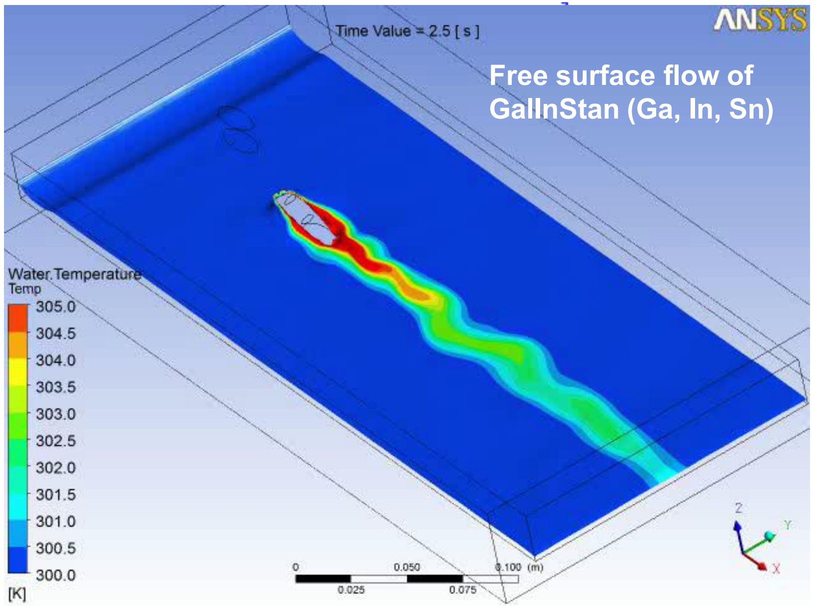
- Computational Fluid Dynamics analysis using ANSYS CFX code
- Lithium channel with porous first wall
- Heat and Species Flux profile from SOLPS is imposed.

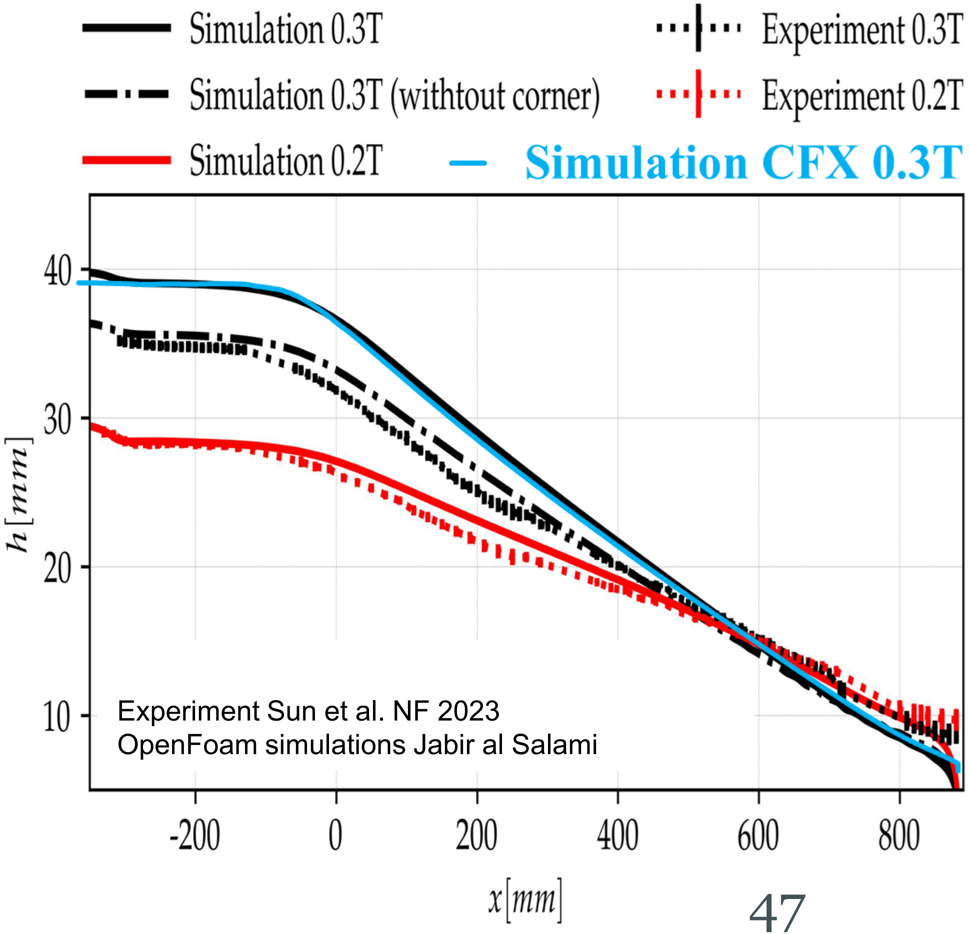
Khodak et al. IEEE TPS 2024 Khodak *et al.* FED 2024

Validation of the free surface MHD codes



CFX Simulation GaInSn level is not imposed both at the inlet at at the outlet





PRINCETON PLASMA PHYSICS LABORATORY

Summary

High-field MHD capabilities were implemented in the ANSYS CFX code and validated using a variety of steady-state and transient test cases.

The code forms the foundation of a Virtual Prototyping System for fusion device components, enabling fully multi-physics modeling and coupling with plasma-edge simulation tools.

This system has been successfully applied to the analysis and design optimization of liquid-metal blankets.