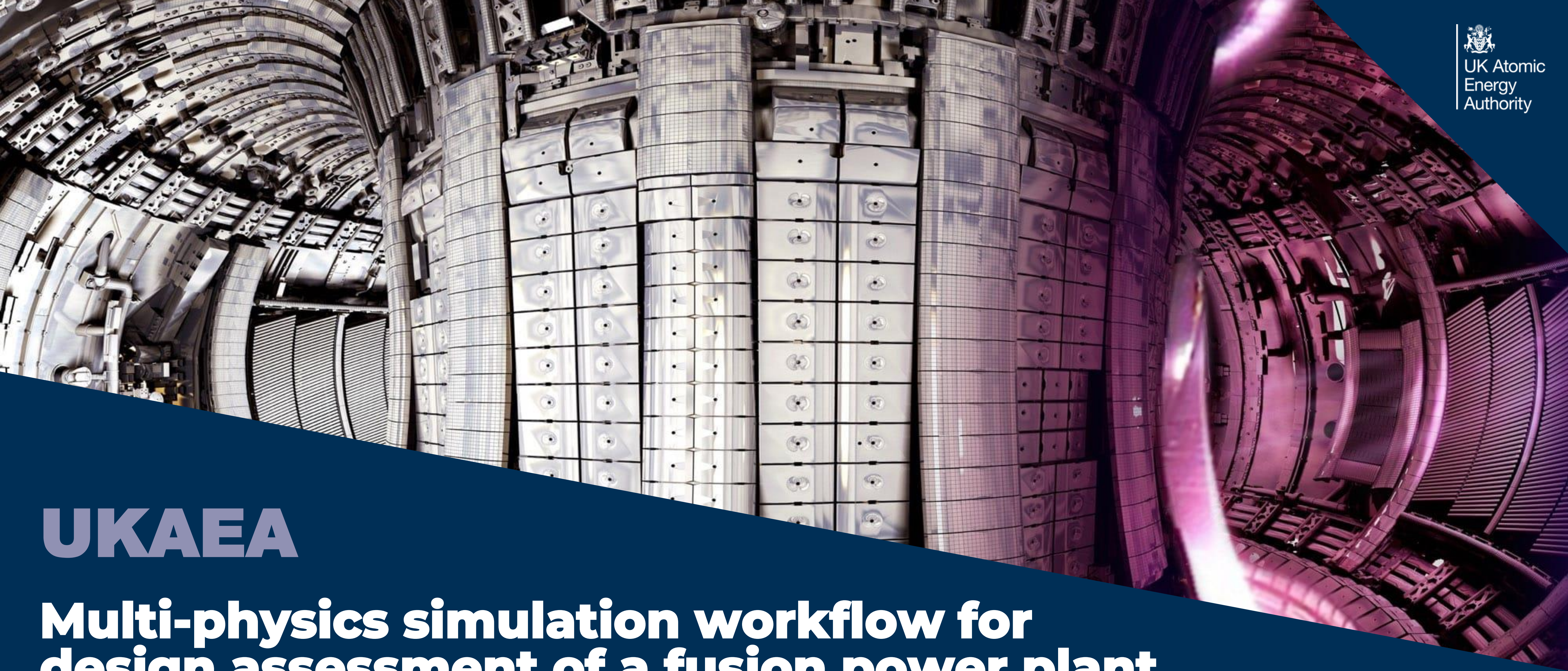


UK Atomic Energy Authority

UKAEA

Multi-physics simulation workflow for design assessment of a fusion power plant plasma-facing component

WOST-23, Weimar, 22nd June 2023

Sebastian Rosini, Tom Deighan

Agenda

UK Atomic Energy Authority

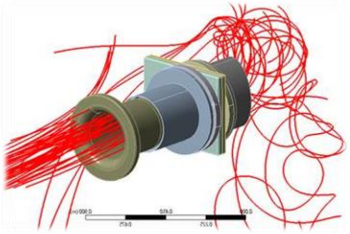
1. Fusion Simulations & Loading
2. Challenges for Fusion
3. Case Study: analysis of a plasma-facing component

Fusion Simulations & Loading

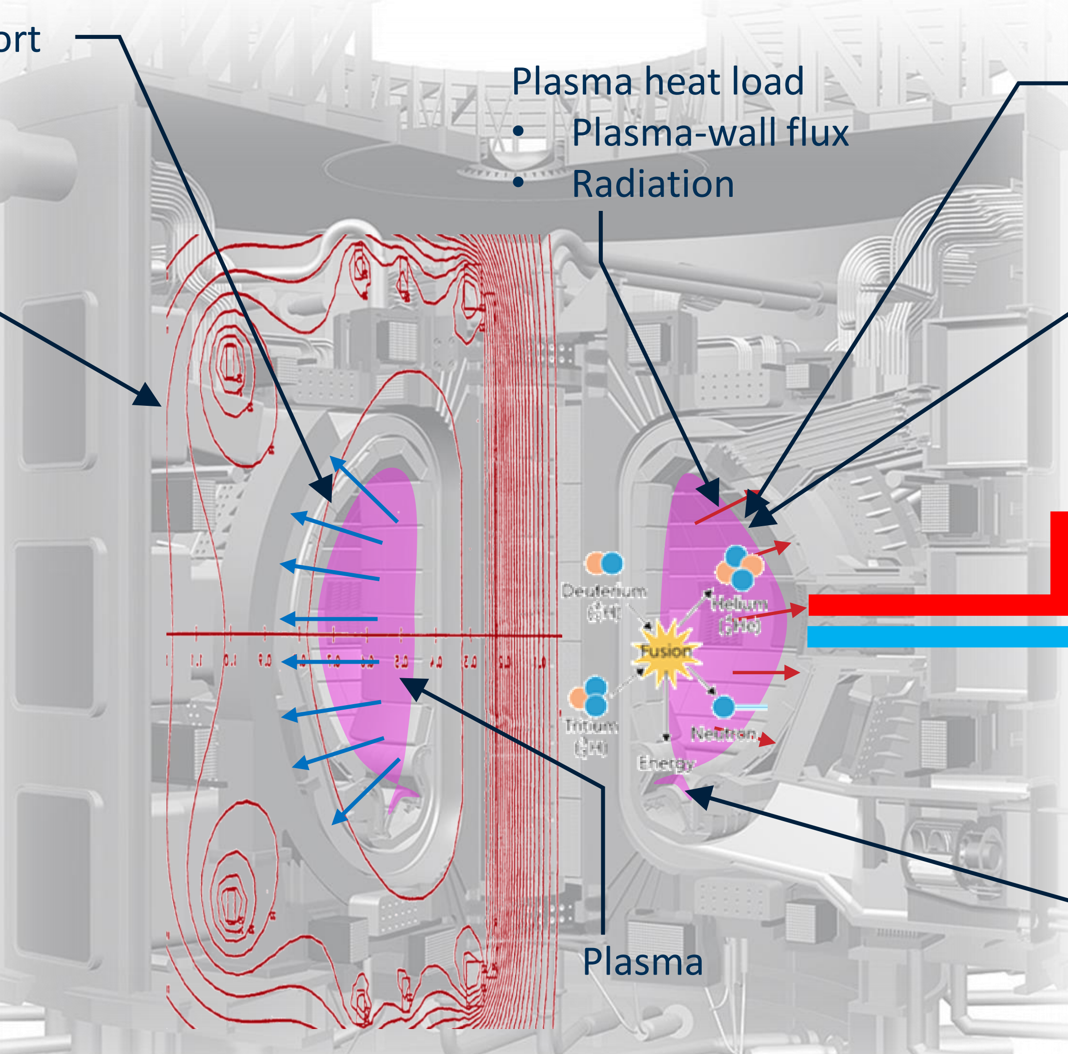
Neutron transport

EM field
- Static and transient
- Multi-axial

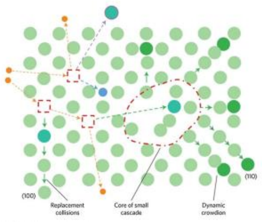
Plasma heating
- Beamline – particle tracking



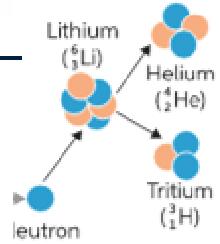
Plasma heat load
- Plasma-wall flux
- Radiation



Plasma

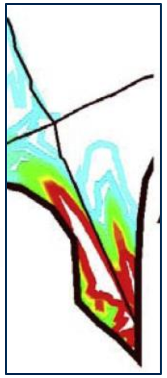


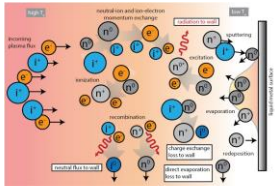
Material irradiation damage



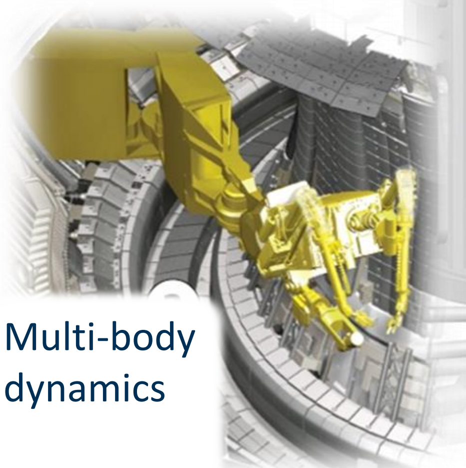
Tritium breeding, transport and recovery

Coolant fluid dynamics
- Water
- Helium
- Liquid metal
- …



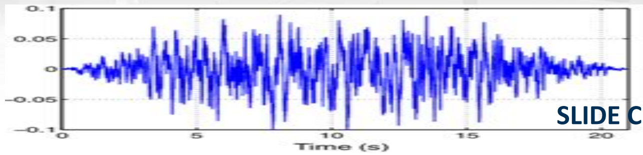


Plasma surface interaction
- High heat load
- Erosion



Multi-body dynamics

Seismic loading



SLIDE COURTESY: TOM DEIGHAN, ENGINEERING SIMULATION RESEARCH SECTION LEAD

Fusion Engineering Ultimate Goal

UK Atomic Energy Authority

- Engineering is responsible for the **Design**, **Qualification** and **Lifetime Operations** of Fusion reactor systems
- Analysis and simulation underpins all these stages – ultimately to support estimating the probability of achieving specified requirements
  - This can all be considered as what is often referred to as “Virtual Qualification” - and an extension of this
  - Better termed “**simulation-assisted reliability assessment**” as no such thing as pure “virtual” qualification

- The Mission of Engineering Simulation Research:
  - Applied research, development and deployment of analysis methods and processes to enable virtual design, qualification and lifetime operations of Fusion systems

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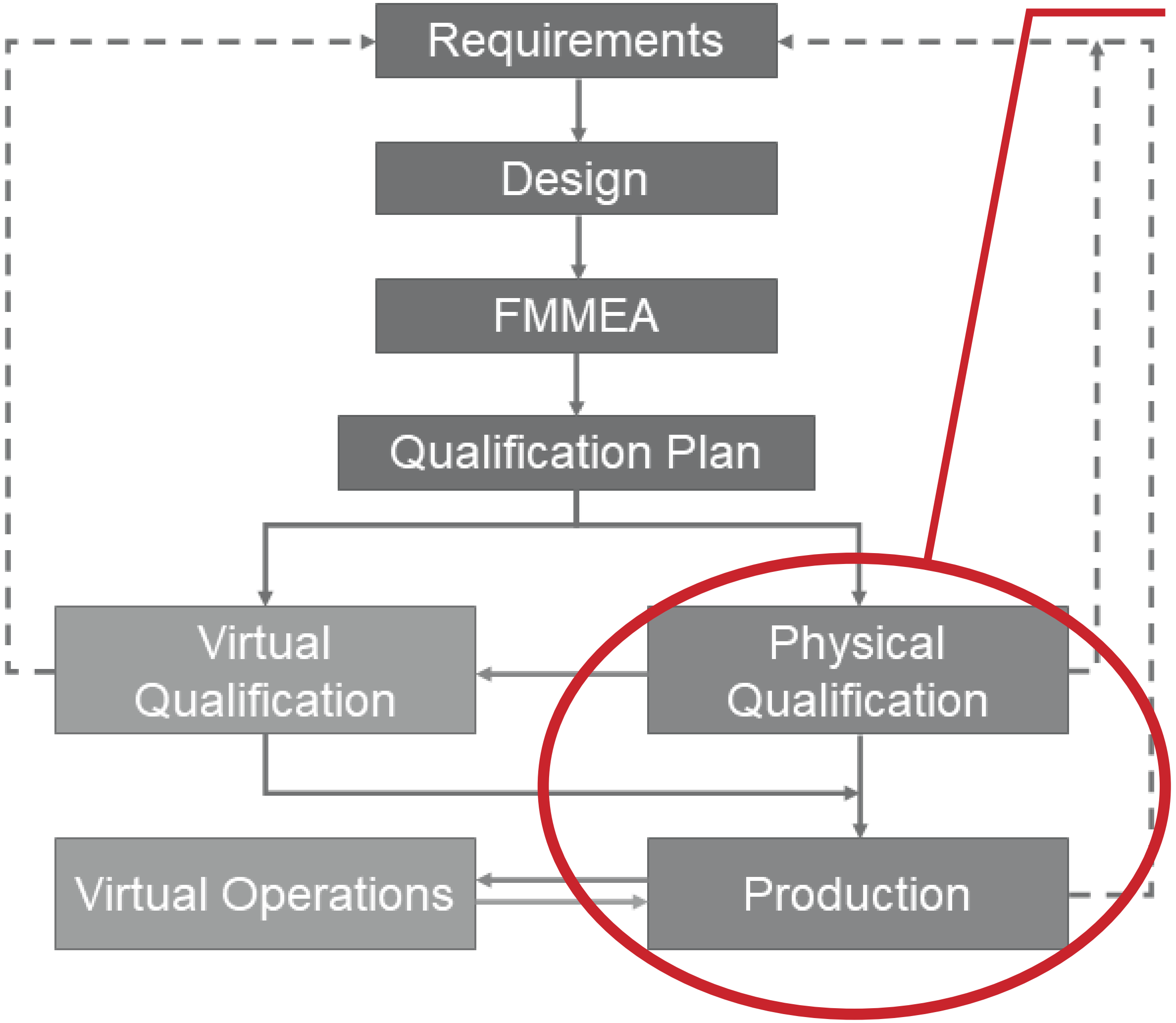
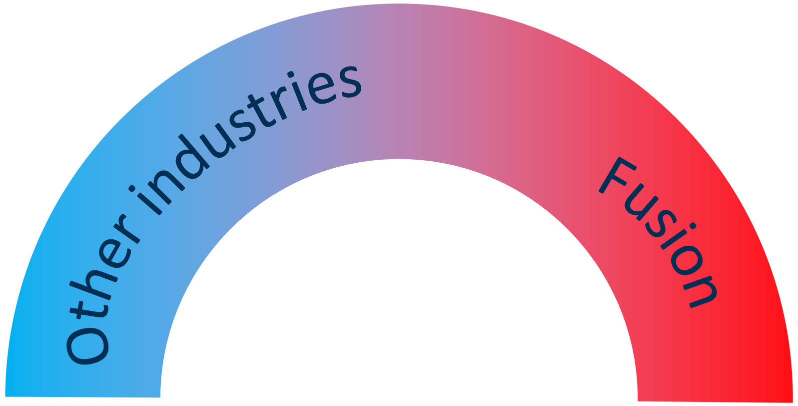
Challenges for Fusion



- More than any other industry Fusion cannot rely on the full product qualification / confirmation testing
- Larger scale component / sub-assembly testing under full combined operating conditions prohibitively expensive or not possible (due to complexity of physics involved) without conducting full product test
- Reliance and confidence in operational measurements is reduced due to operating environment

Reliance on "Virtual Qualification"



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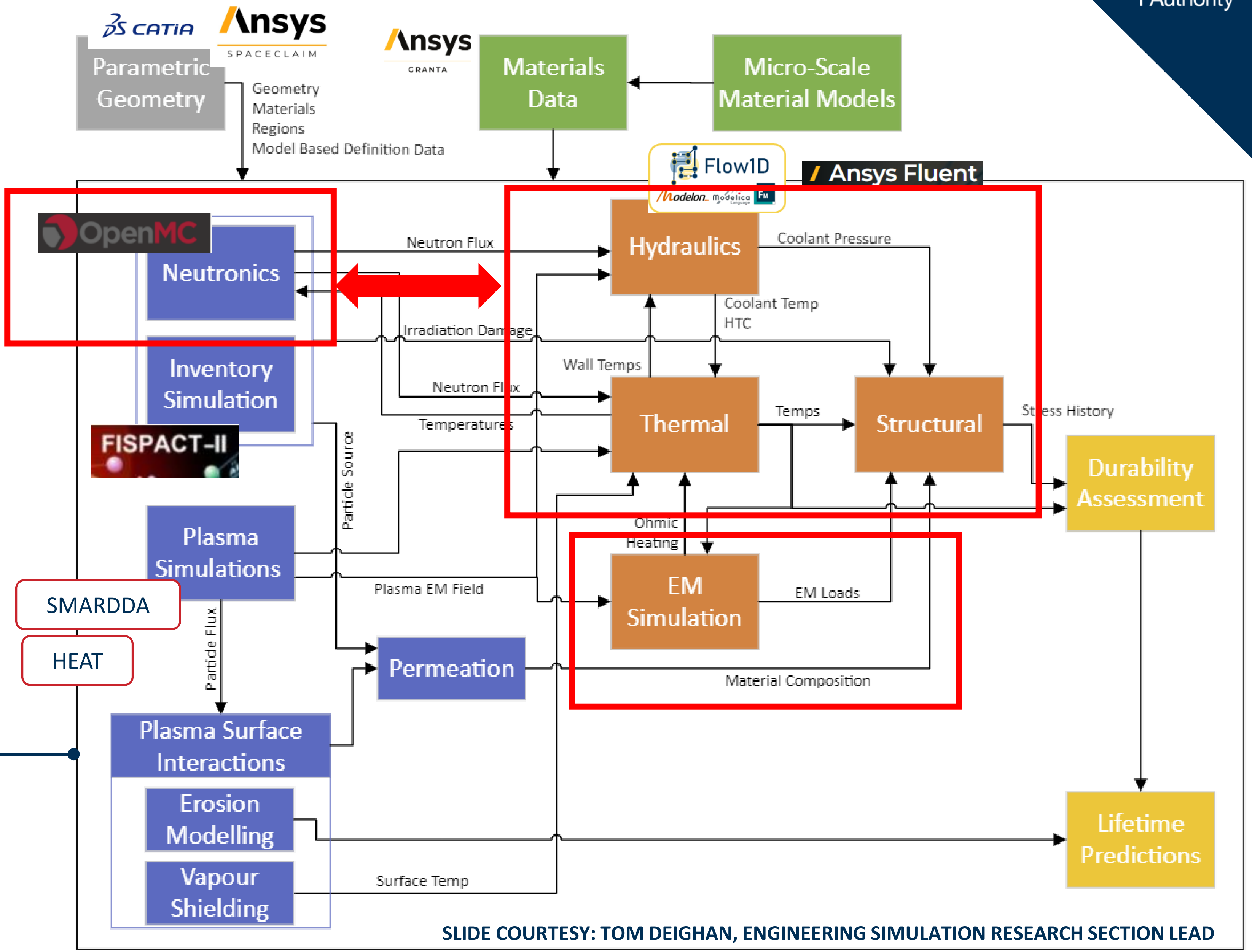
Workflow Integration with UQ

- Efficient parametric design exploration with metamodeling techniques
- Sensitivity analysis
- Uncertainty propagation and quantification for Robust design optimisation
- Model calibration

Ansys OPTISLANG



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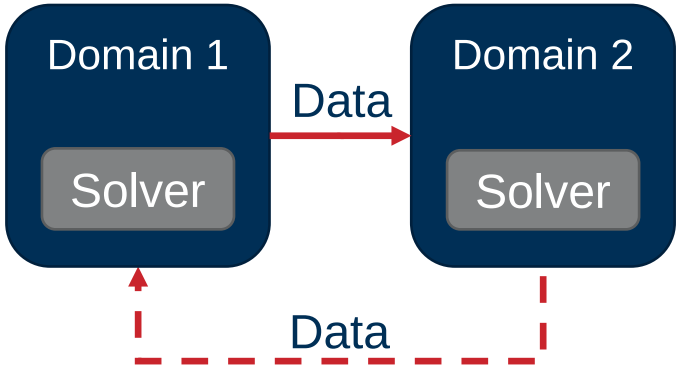
Multi-physics?

Workflow Integration

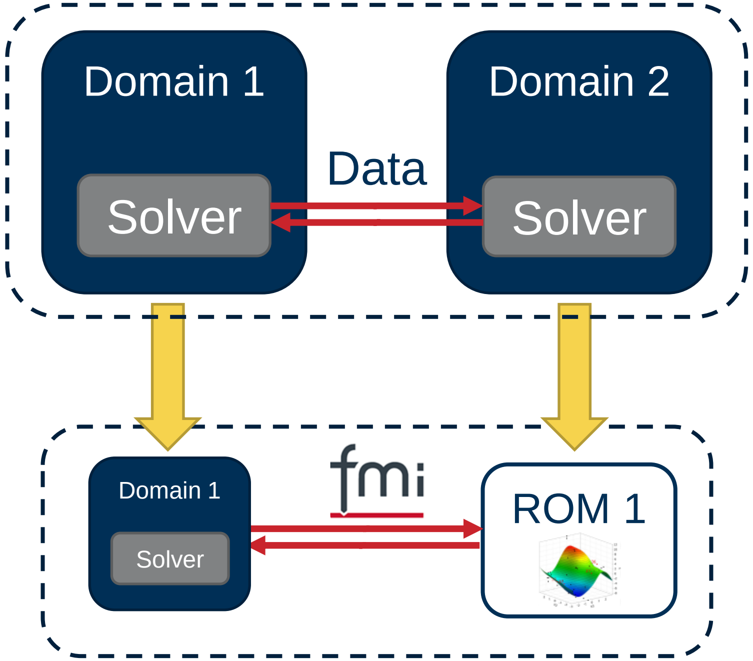


Iterative Workflow

- Quicker to setup, allows in-progress models to be tested
- Easy integration to UQ, calibration, robustness analyses, etc.

Multiple tool/solver co-simulation

Full physics solver coupling



Systems simulation coupling

Single tool/solver coupled physics

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Case Study: Analysis of a plasma-facing component

The Case Study

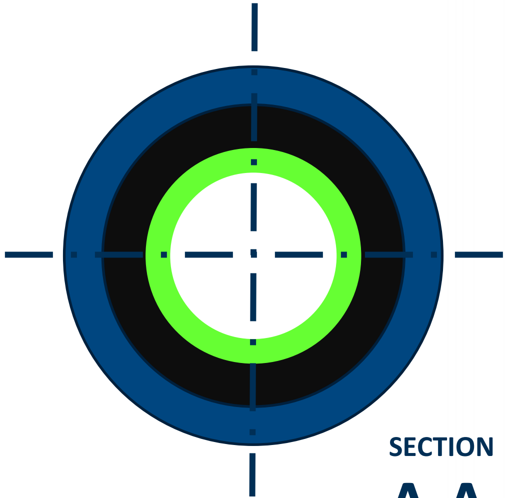
- It looks at creating a workflow that connects:
  - Neutronics analysis → OpenMC
  - Quasi-1D fluid analysis → Siemens Flomaster/OpenModelica
  - Thermal-Structural analysis → Ansys Workbench

- **Not** based on a real design

- Created to capture the challenges that can arise in connecting the different physics and provide guidance to the analysts

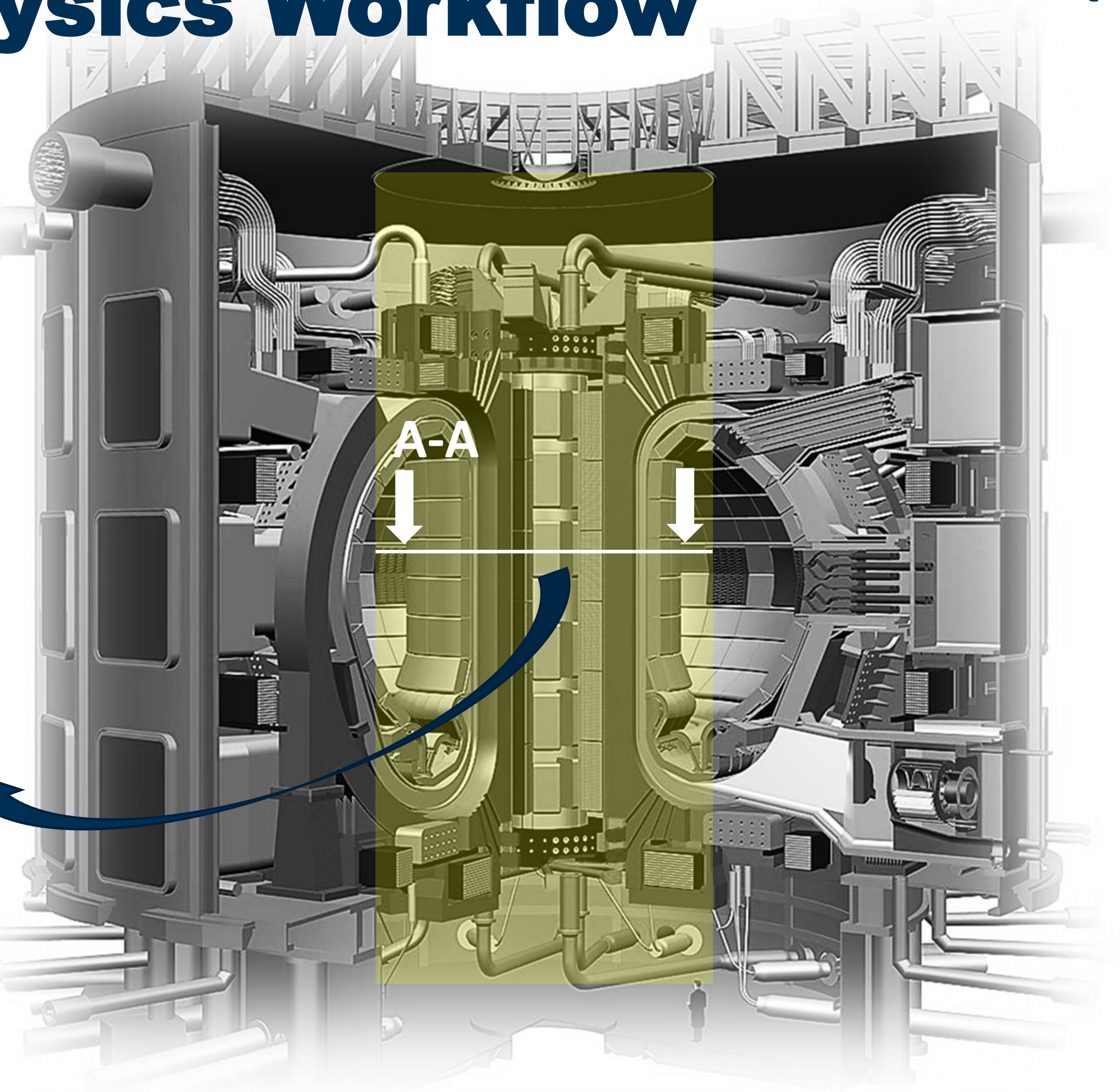
Multi-Physics Workflow

Neutronics Model



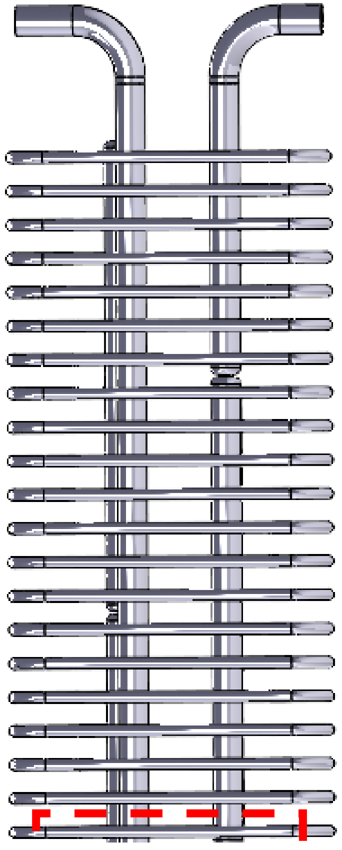
SECTION A-A

- In-board column
- Homogenised materials
- Neutrons propagating through different components



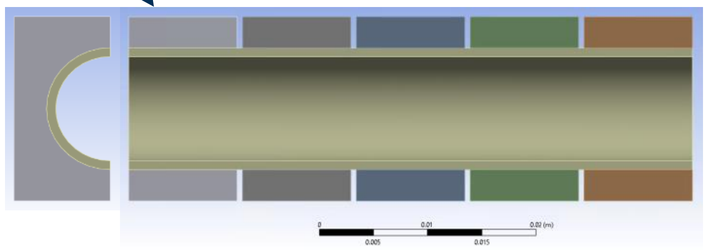
Schematic layout of the ITER fusion reactor

Quasi-1D Fluid Model



Generic manifold design

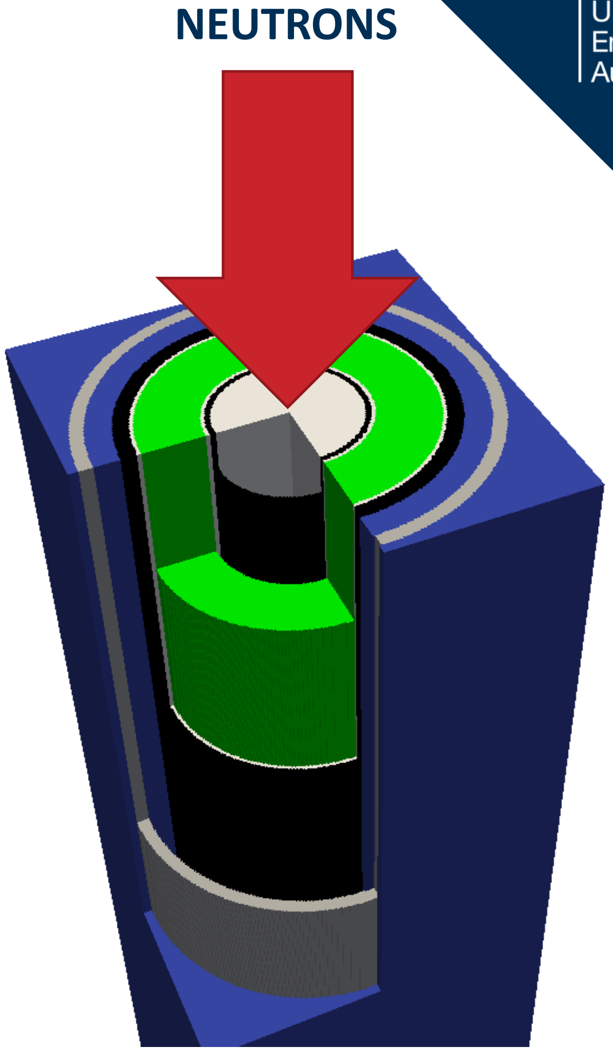
Thermal-Structural Model



Generic monoblock design

The Neutronics Model

- **Particles' behaviour is unpredictable** but the average behaviour of a large population of particles originating from the same source is better defined
- The process of single particles randomly streaming and colliding with nuclei can be simulated directly with computers **using Monte Carlo simulations**
- OpenMC performs a Monte Carlo simulation one particle at a time. **Before any particles are tracked, the problem must be initialised**. This involves:
  - reading input files and **building data structures** for the geometry, materials, tallies, and other associated variables
  - The continuous-energy or multi-group **cross section data** specified in the problem is read
  - The **source sites** consisting of coordinates, a direction, and an energy are sampled from the specified source

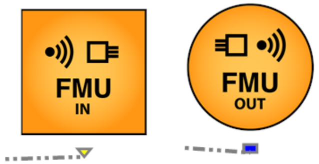


OpenMC User Guide

https://docs.openmc.org/en/v0.8.0/methods/introduction.html

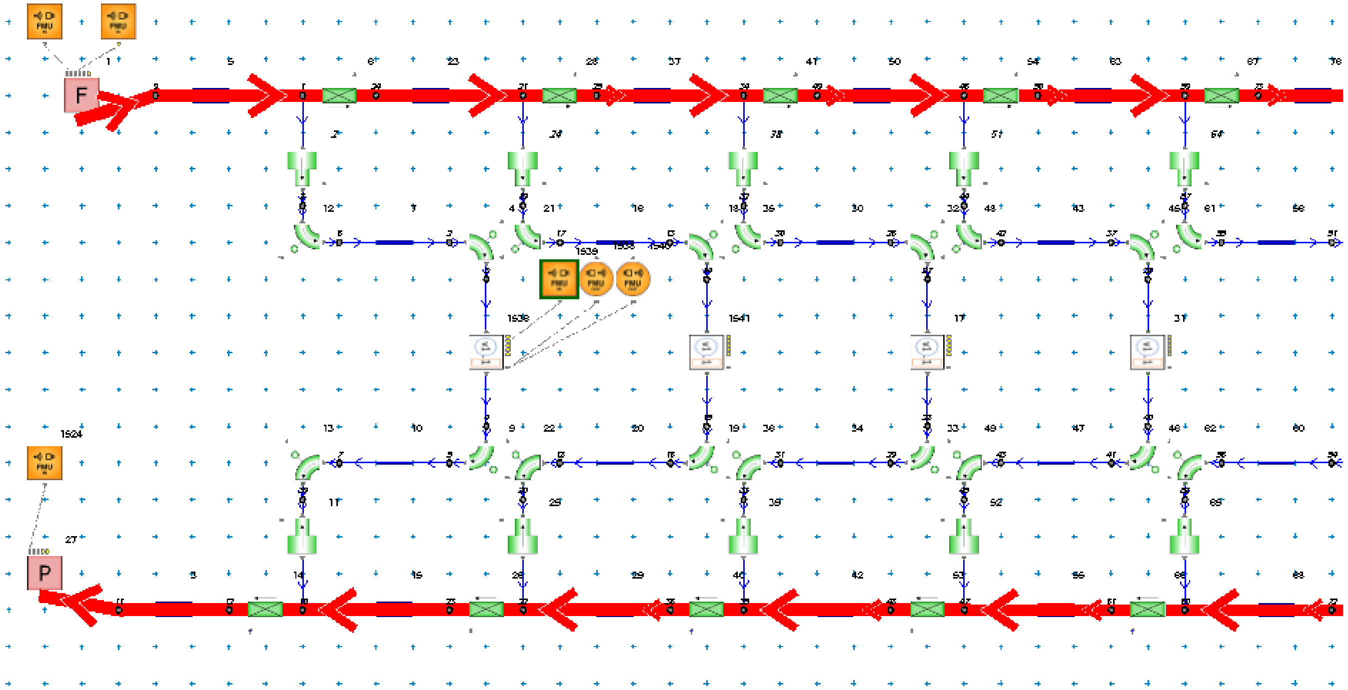
The Quasi-1D Fluid Model

- The Dittus-Boelter approximation is adopted to calculate the Nusselt Number for the HTC in each branch
- Model run as heat transfer to allow HTC calculation



Inputs	Outputs
Mass flow rate	HTC at each branch (Only HTC of branch 1 is passed to the thermal model)
Fluid temperature	
Fluid pressure	Fluid temperature at each branch (Only temperature of branch 1 is passed to the thermal model)
Wall temperature (at branches)	

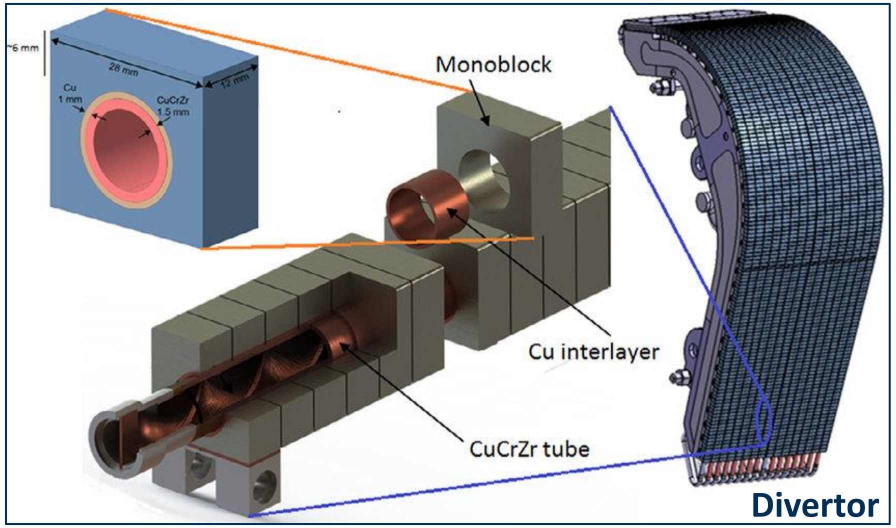
Fluid model inputs and outputs



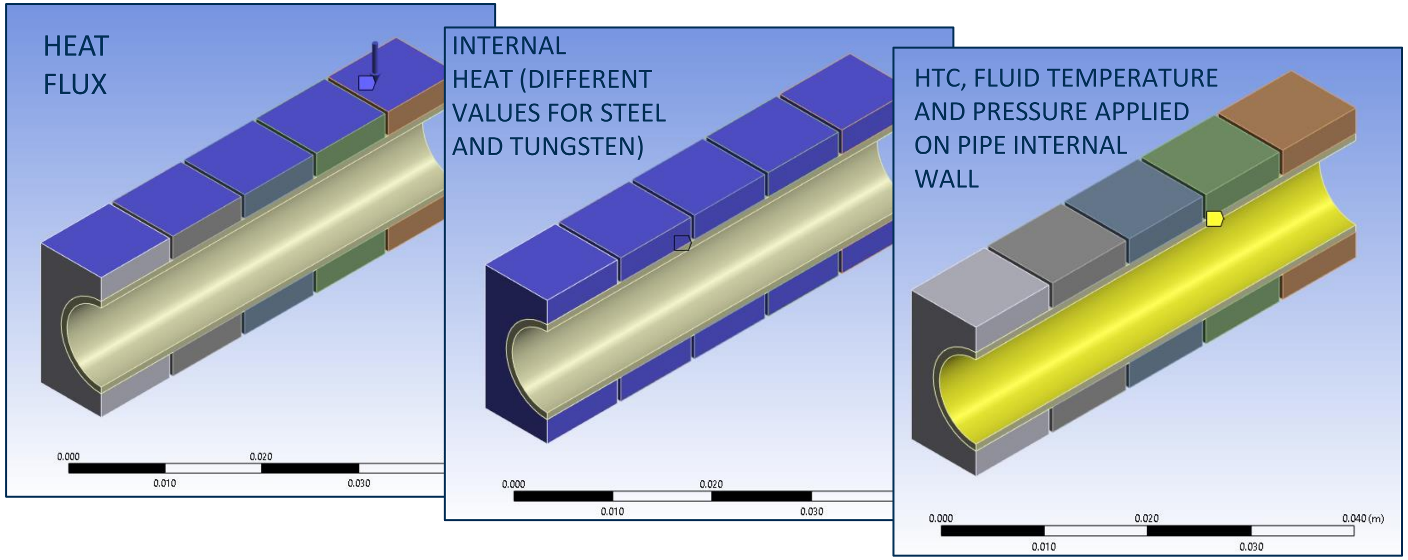
Mass flow rate distribution in a fluid network

The Thermal-Structural Model

- For symmetry reasons, only half of the monoblock is modelled
- Simple monoblock geometry with no interlayer
- CAD parametrically produced in ANSYS SpaceClaim
- **Heat Flux**: applied as a ramp from 0 W/m^2 at 0 s to 1 W/m^2 at 1 s
- **Internal Heat** ramp: neutron heating, 0 W/m^3 at 0 s, assigned W/m^3 in Steel and assigned W/m^3 in Tungsten at 1 s (from neutronics)
- **Convection ambient temperature**: 20ºC initial value at 0 s, ramps up to the assigned value (*Conv. Amb. Temp.* is a variable)



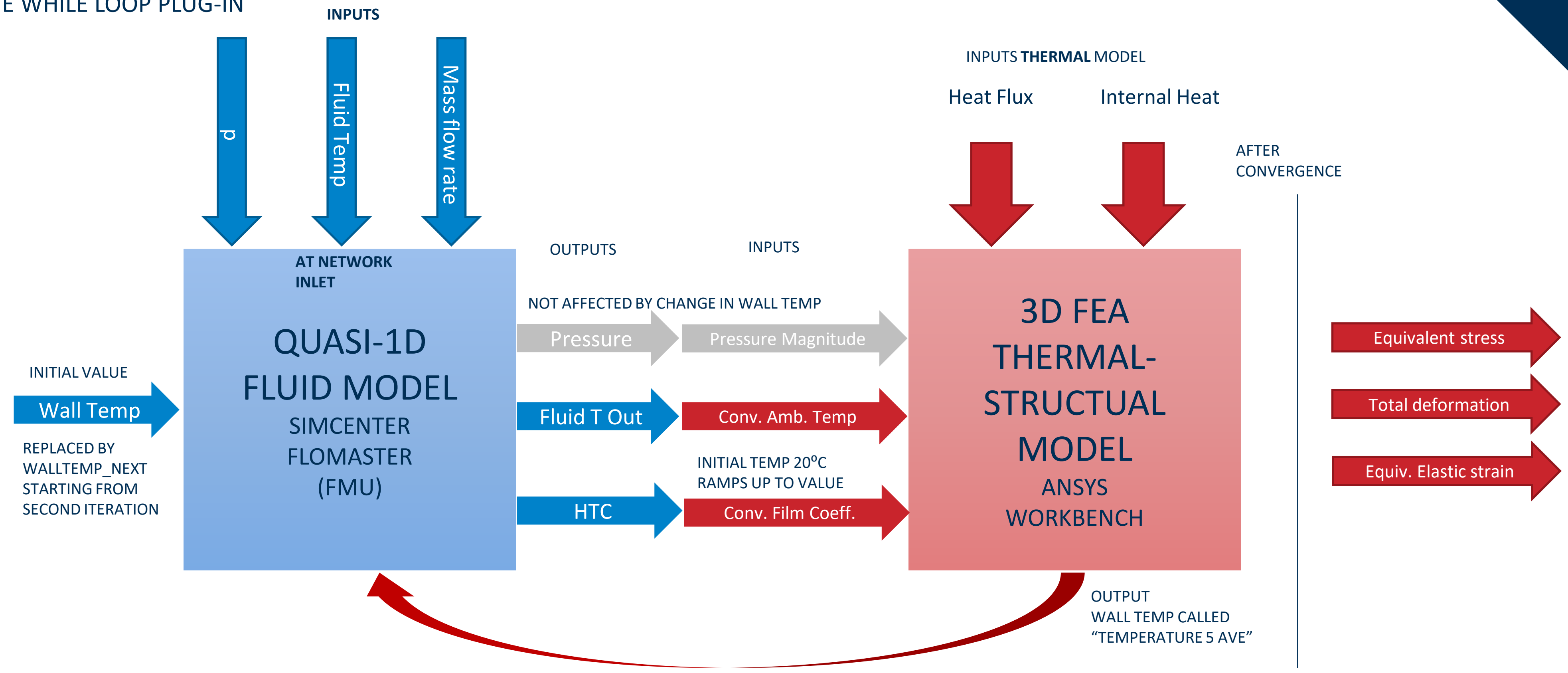
Bonnin X et al., “ITER divertor plasma response to time-dependent impurity” injection, Nuclear Materials And Energy, 12(C), March 2017



While Loop for Wall Temperature fed back to the fluid model

THANKS TO **BERND BUETTNER** FOR THE WHILE LOOP PLUG-IN

- The wall temperature was initially imposed in the fluid model
- However, this value would differ from the wall temperature calculated in the thermal-structural model
- In reality, the two are the same. Hence, a while loop is needed and the correct results to adopt are those obtained after convergence of the two wall temperatures



INPUTS

p

Fluid Temp

Mass flow rate

AT NETWORK INLET

QUASI-1D FLUID MODEL

SIMCENTER FLOMASTER (FMU)

INITIAL VALUE

Wall Temp

REPLACED BY WALLTEMP_NEXT STARTING FROM SECOND ITERATION

OUTPUTS

INPUTS

NOT AFFECTED BY CHANGE IN WALL TEMP

Pressure → Pressure Magnitude

Fluid T Out → Conv. Amb. Temp

INITIAL TEMP 20°C RAMPS UP TO VALUE

HTC → Conv. Film Coeff.

INPUTS **THERMAL** MODEL

Heat Flux

Internal Heat

3D FEA THERMAL-STRUCTUAL MODEL

ANSYS WORKBENCH

AFTER CONVERGENCE

Equivalent stress

Total deformation

Equiv. Elastic strain

OUTPUT WALL TEMP CALLED "TEMPERATURE 5 AVE"

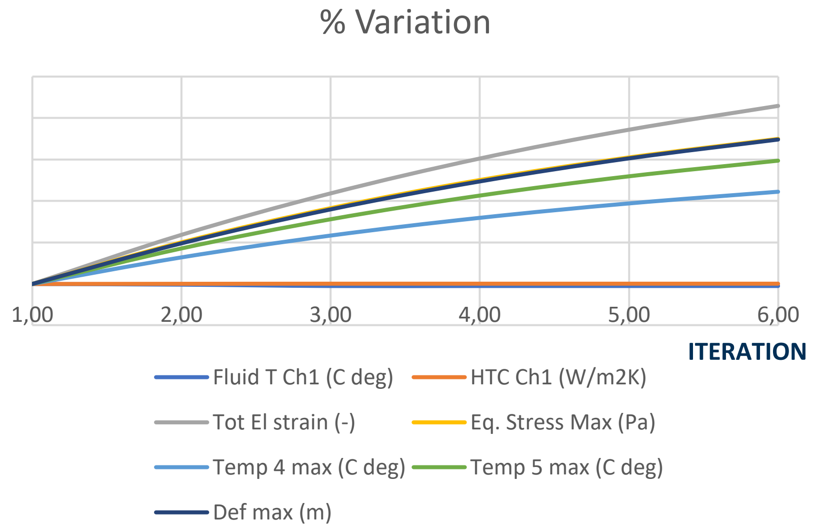
WALLTEMP_NEXT = TEMP 5 AVE

At the end of each while loop, the wall temperature difference parameter is calculated:

WALLTEMP_DIFF = abs((WallTemp_next-WallTemp)/WallTemp)*100

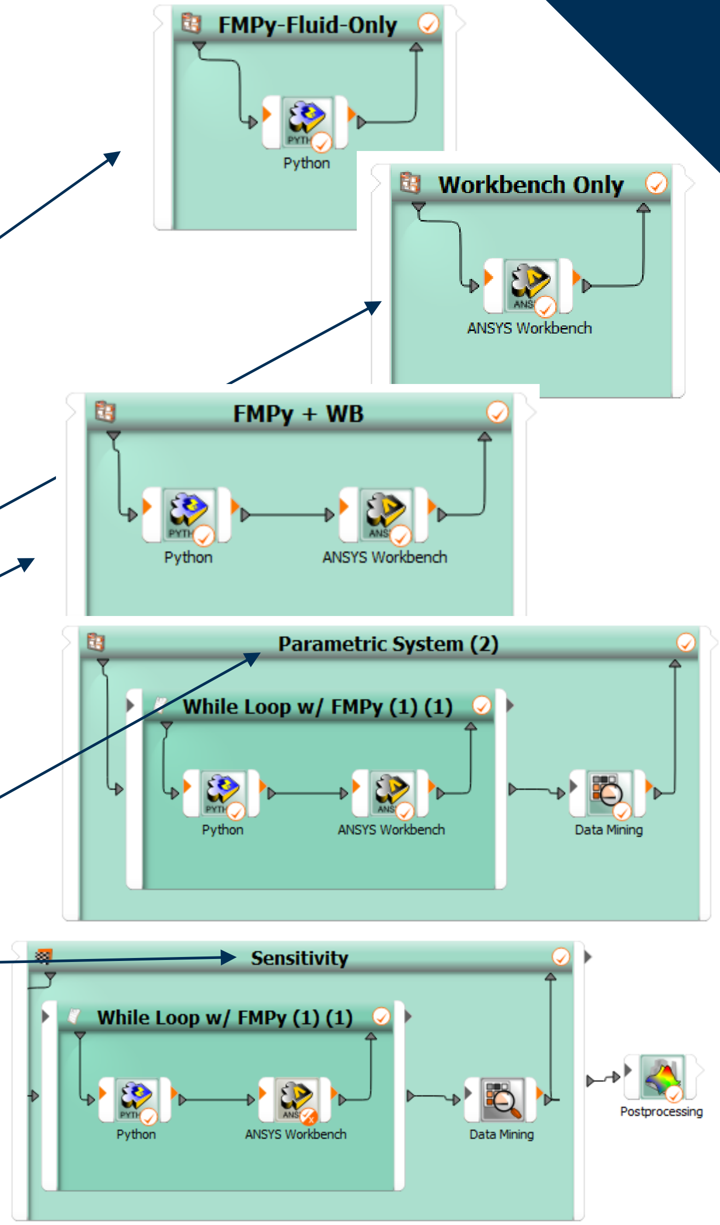
If this difference is larger than 2%, the loop continues

Convergence and Speed Checks



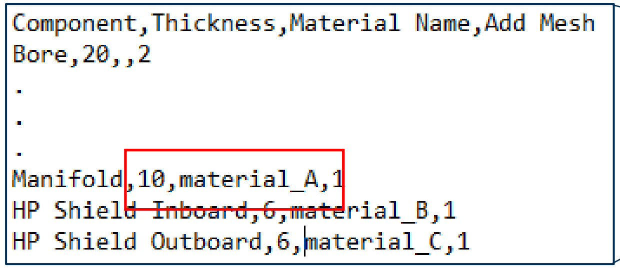
Model	Running times
Fluid model in Flomaster	160 s
FMU fluid model with FMPy in Spyder	210 s
FMU fluid model alone in optiSLang	217 s
Thermal-mechanical model in Workbench (note: GUI)	220 s (GUI)
T-M model alone in optiSLang	32 s
Fluid + T-M workflow in optiSLang	365 s The FMU still runs in 217s – the exchange of info might be the reason for 365 s > 217s + 32s
While loop for Wall Temp: Fluid + T-M workflow in optiSLang	1101 s for 3 steps for convergence: **367 s** per step
While loop in sensitivity analysis (50 design points)	888 min

SYSTEM: Intel(R) Core(TM) i5-8500 CPU @ 3.00GHz
4 GB GDDR5 NVIDIA Quadro P1000

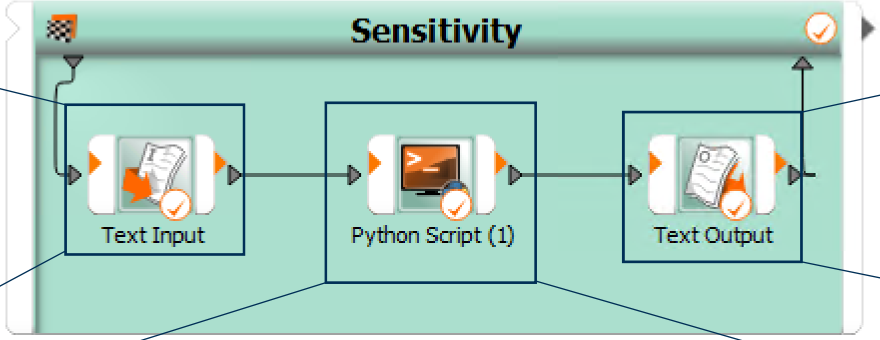


Neutronics Model optiSLang System

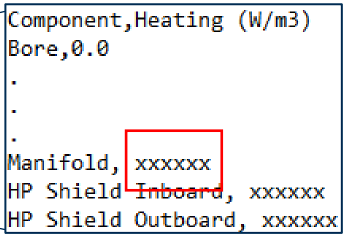
DIMENSIONS ARE READ



```
Component,Thickness,Material Name,Add Mesh
Bore,20,,2
.
.
.
Manifold,10,material_A,1
HP Shield Inboard,6,material_B,1
HP Shield Outboard,6,material_C,1
```

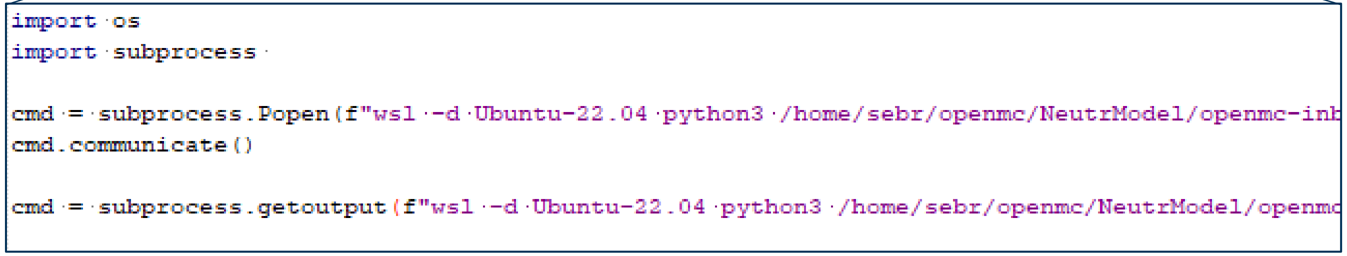


SCRIPT OUTPUT RECEIVED FROM LINUX



```
Component,Heating (W/m3)
Bore,0.0
.
.
.
Manifold, xxxxxx
HP Shield Inboard, xxxxxx
HP Shield Outboard, xxxxxx
```

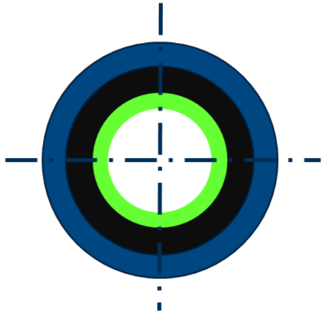
WINDOWS PYTHON TO RUN SCRIPT WITH LINUX PYTHON



```
import os
import subprocess 

cmd = subprocess.Popen(f"wsl -d Ubuntu-22.04 python3 /home/sebr/openmc/NeutrModel/openmc-inb
cmd.communicate()

cmd = subprocess.getoutput(f"wsl -d Ubuntu-22.04 python3 /home/sebr/openmc/NeutrModel/openmc
```



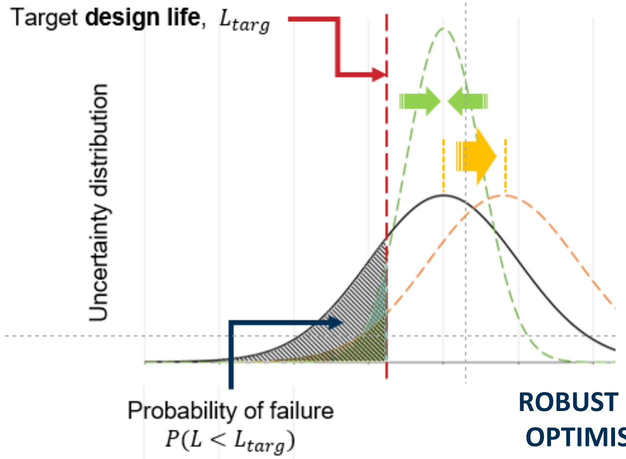
HOMOGENISED MATERIALS

Material A = 60% tungsten, 30% fluid, 10% pipe wall material

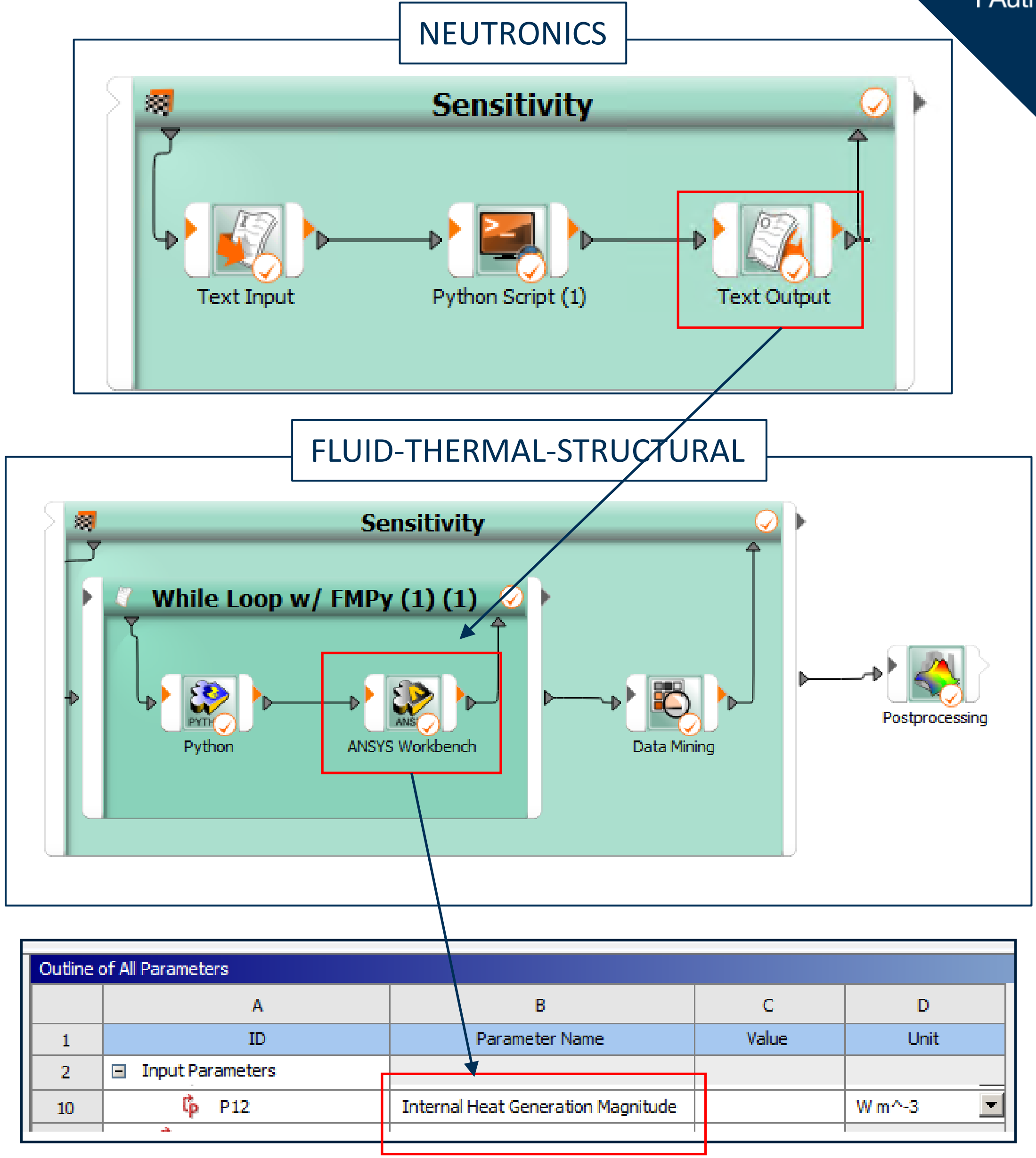
Current Work

Next steps:

- **Tie geometric parameters**
    - E.g. Pipe diameter in fluid and thermal-structural model to be tied to homogenised material in neutronics model cylinder
- **Connect workflows**
- **Add stochastic distributions** to parameters of interest and move to probabilistic assessments/reliability analyses



ROBUST DESIGN OPTIMISATION



Outline of All Parameters

	A	B	C	D
1	ID	Parameter Name	Value	Unit
2	⊟ Input Parameters			
10	P12	Internal Heat Generation Magnitude		W m^-3

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End of Presentation
Any Questions?

Thank you to Bernd Buettner, Andreas Grosche, Thomas Kranz and colleagues for the support