Karlsruhe Institute of Technology

UK Atomic Energy Authority

TSVV-14: Multi-Fidelity Systems Code for DEMO

J. Morris, M. Coleman, J. Cook, O. Funk, I. Maione, T. Pomella-Lobo, H. Saunders, O. Wong

Thrust 5 meeting – 7th June 2023

European Commission | UKRI Engineering and Physical Sciences Research Council

Contract for the Operation of the JET Facilities Co-Funded by Euratom
This work was funded by the RCUK Energy Programme [Grant number EP/W006839/1]

Outline

Work 2022-2023

1. Features
2. Minor updates
3. Complementary work
4. Developers/users
5. Outlook
6. Summary

TSVV-14 - reactor design framework requirements

Carrying out a series of 0-D to 3-D design and analysis tasks in a self-consistent manner

Optimising a reactor design point and various sub-systems

Performing a range of whole-plant performance analyses and sub-system analyses, to varying degrees of fidelity

Creating 3-D CAD models and preparing inputs for neutronics, finite element, and other 3-D analyses

UKAEA + KIT – 2.4 PPY + 0.6 ACH

Features

Parameterised CAD

Reactor workflow

Coupling transport solver to FBE

Balance of plant

3-D CAD updates

Systems code coupling

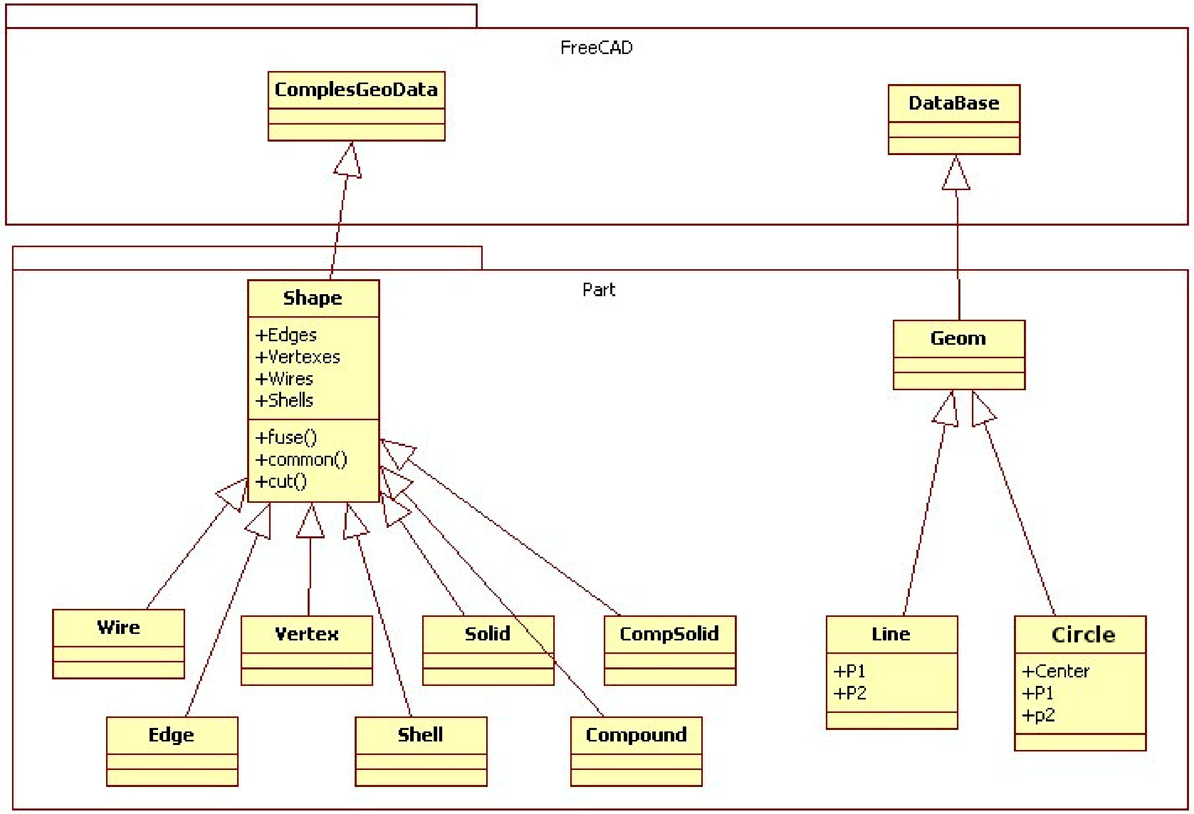
Features

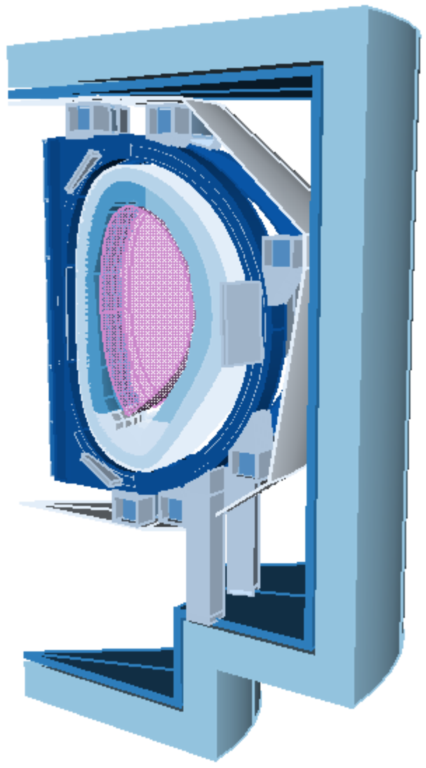
Parameterised CAD

The geometry module of bluemira is based on FreeCAD, an open-source parametric 3D modeler that mostly satisfies all the requirements identified for the creation of a FPP CAD. – Allows for move to parametric FEA.

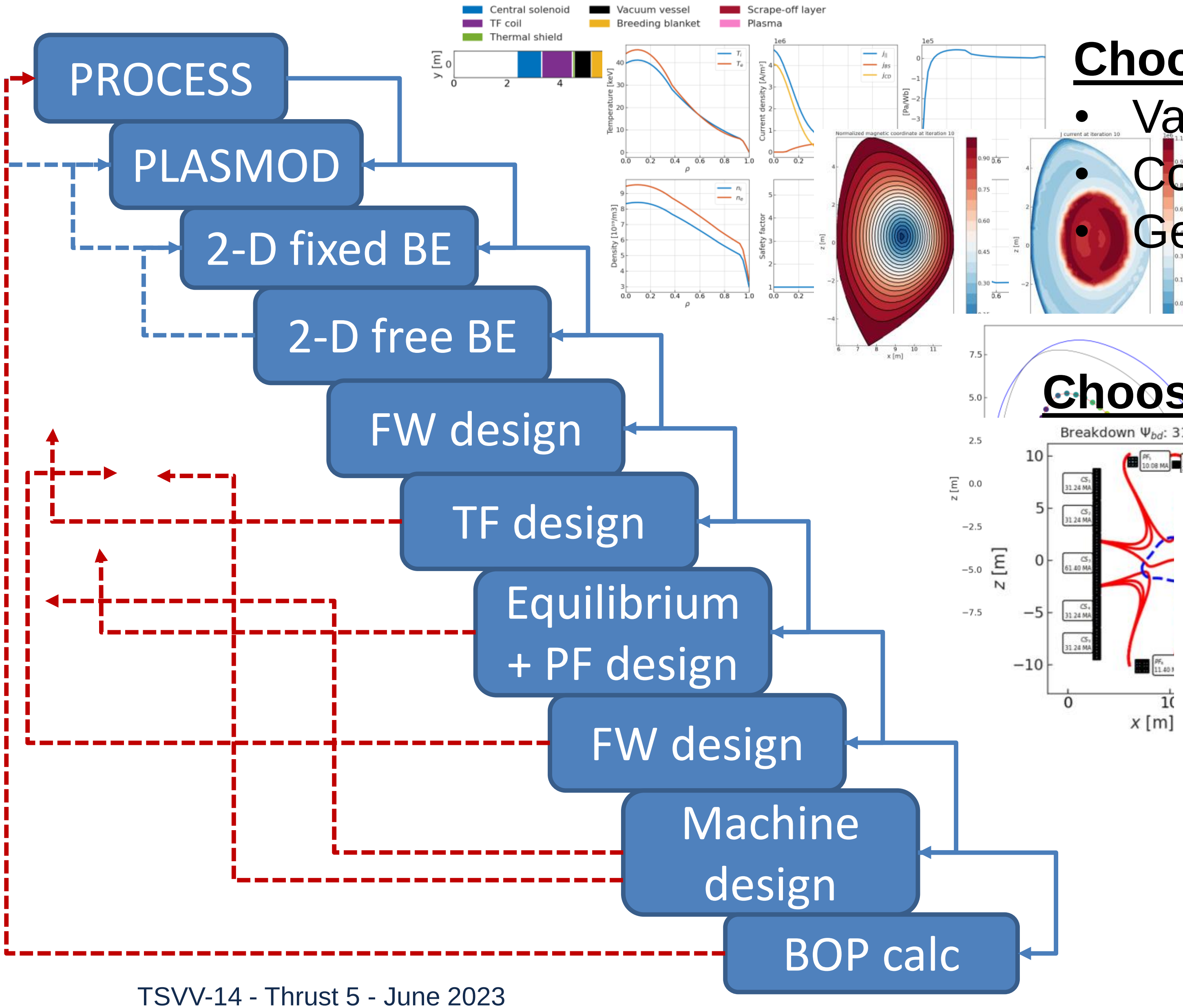
FreeCAD parametric objects (i.e. wire, face, shell, solid) have been wrapped into bluemira geo objects. A python FreeCAD api has been implemented to expose ….

- Arch
- Assembly
- Base
- Draft
- Expression
- FEM
- GCS
- Part →
- PartDesign
- Path
- Sketcher
- …





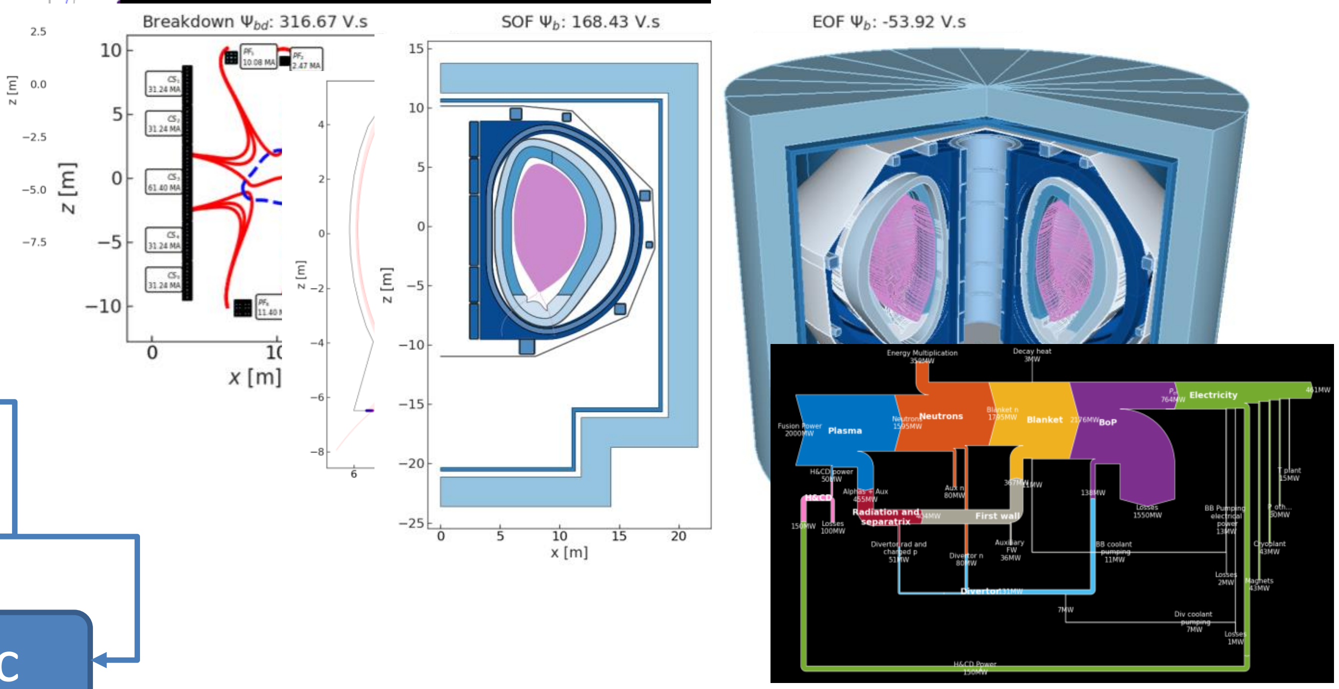
EU-DEMO workflow in BLUEMIRA



Choose inputs:

- Values, constraint values
- Constraints, objective functions
- Geometry parameterisations

Choose calculations:

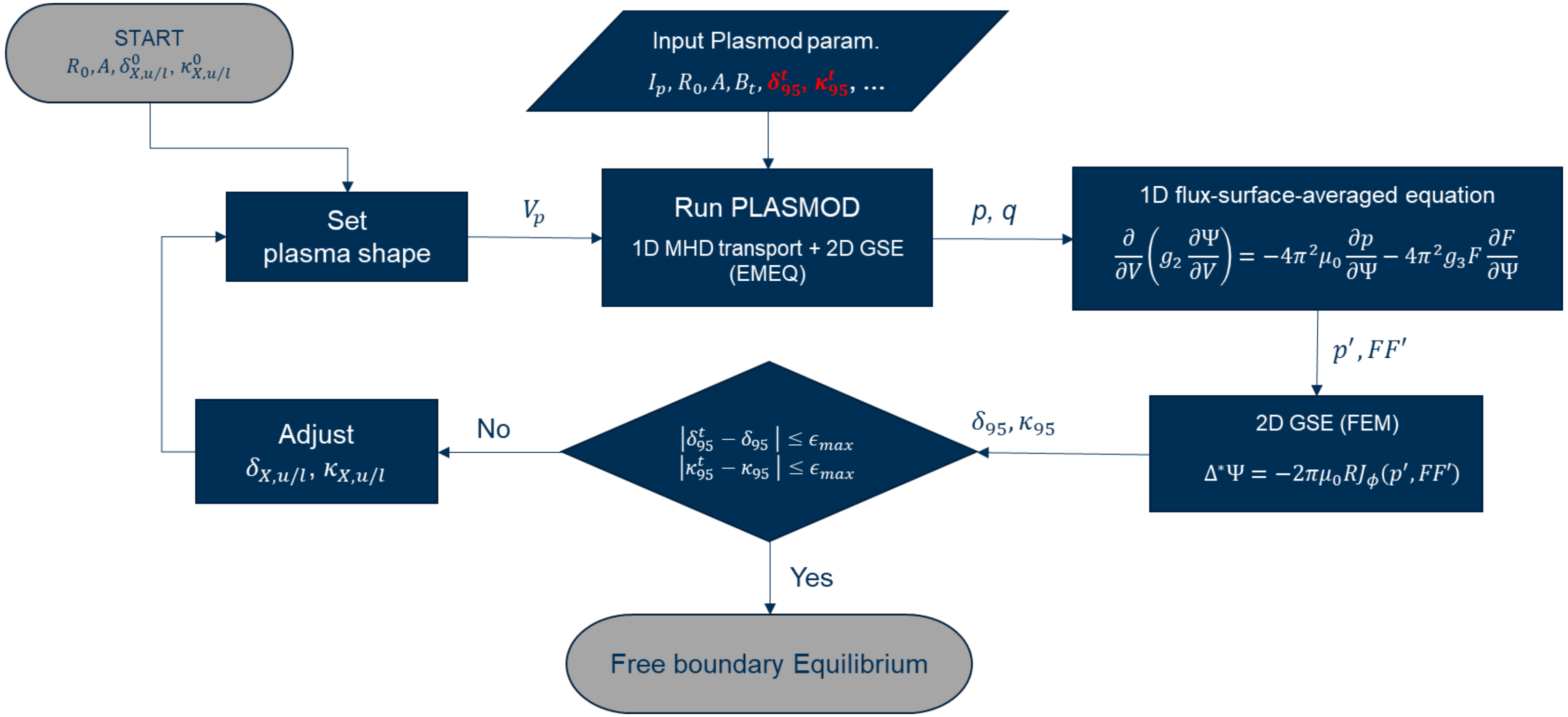


Features

Coupling transport solver to Fixed Boundary Equilibrium

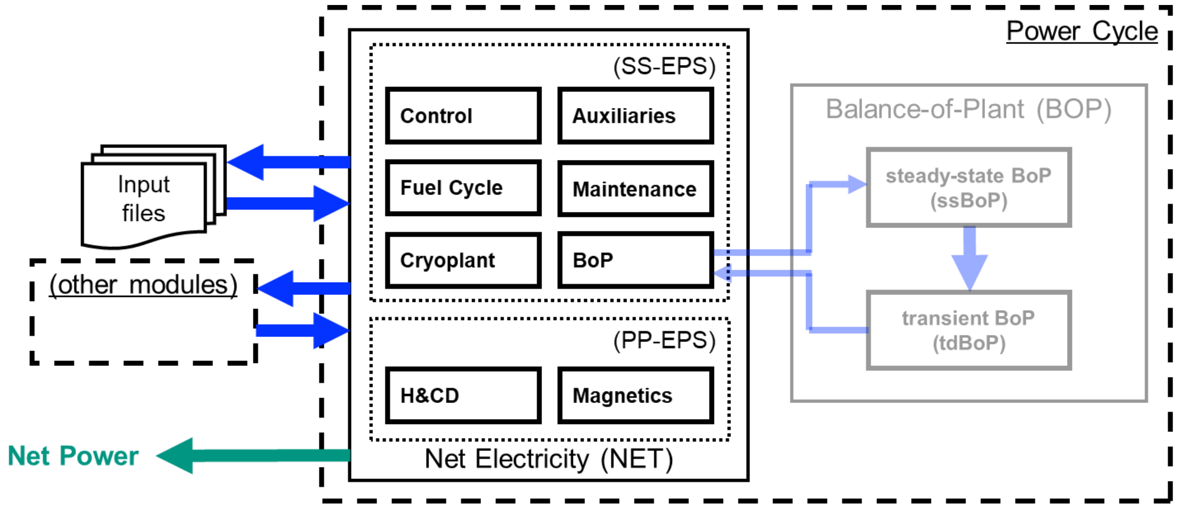
<u>Objective:</u> Use plasma profiles from a transport solver, matching target plasma shape parameters, in free boundary equilibrium.

- Iterate between PLASMOD and fixed boundary equilibrium solver
  - Match plasma volume
  - Adjusting boundary shape parameters
  - Reach target 95th flux surface shape parameters
- Pass from fixed boundary equilibrium to free boundary equilibrium



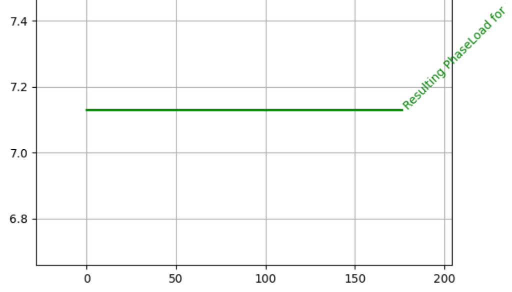
Features

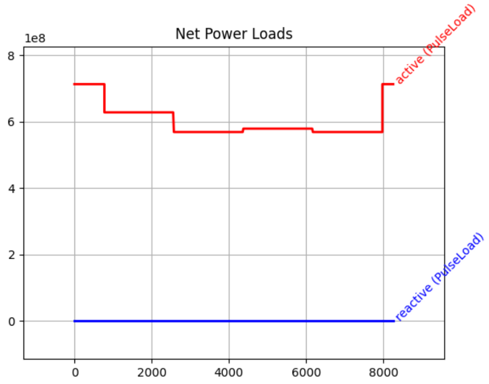
Balance of plant

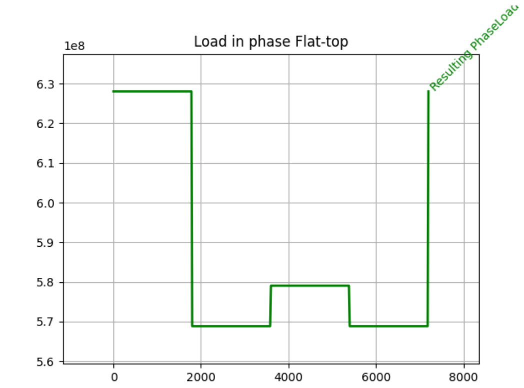


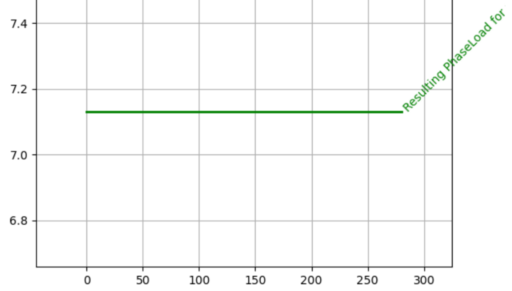
Simple example

Inputs: ECH, "All Field Coils" & "CS recharge", simplified BOP, no reactive powers.





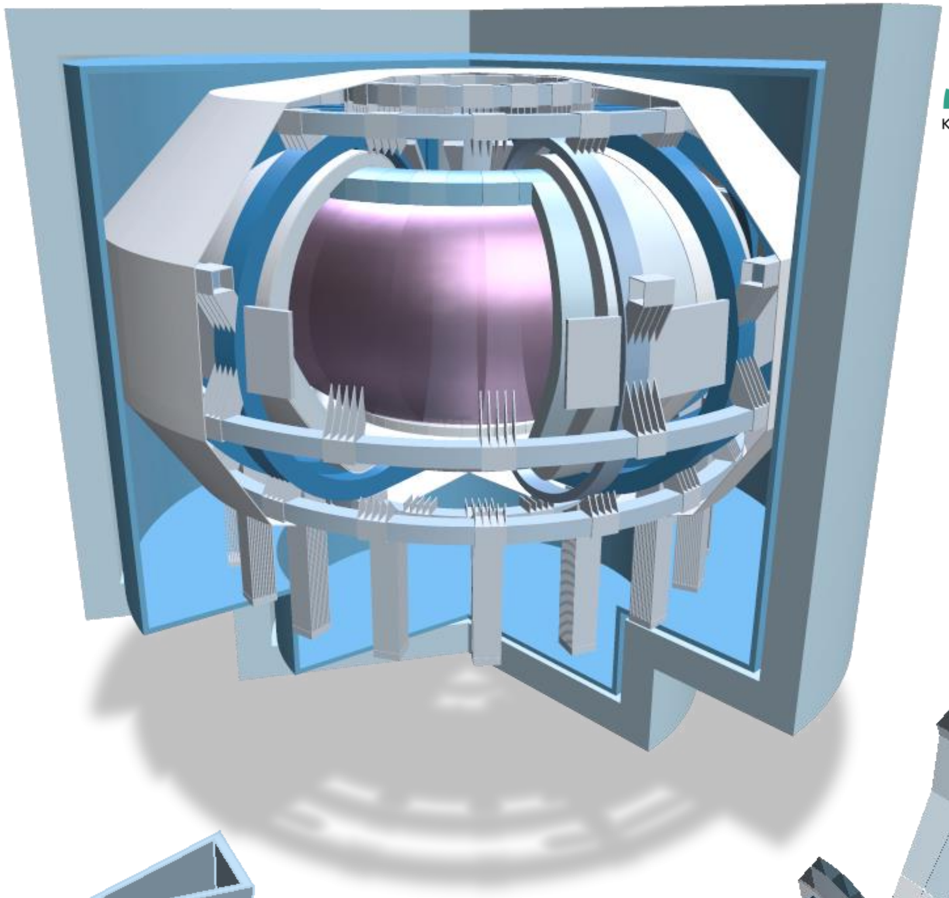


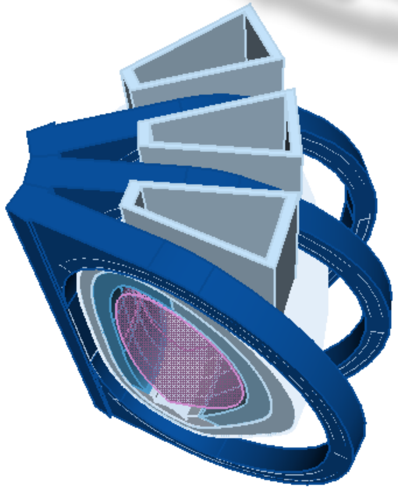


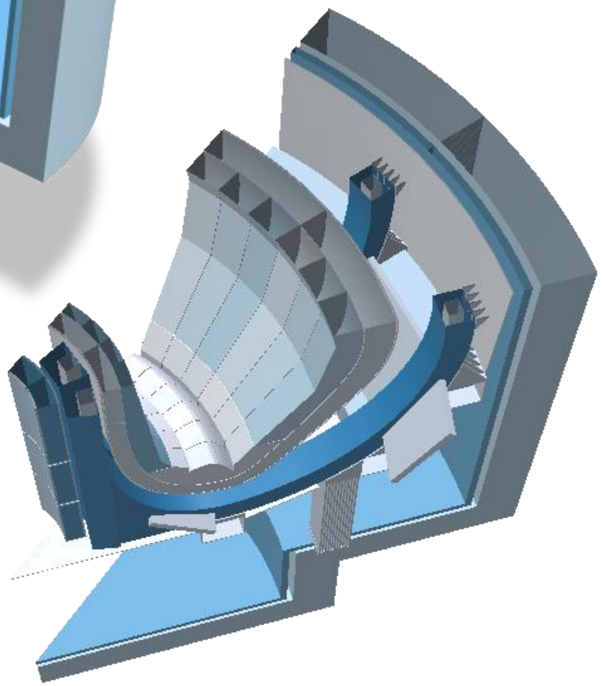
Features

3-D CAD updates

- From EUDEMO: Added ports, optimised blanket panelling, inter-coil support structures
- CAD sectoring, component level filtering (void space) and selection
- Polyscope viewer
- Expanded set of FreeCAD API's







Features

Systems code coupling

- Generic "Solver" API to Interface with external systems codes
  - PROCESS interface implemented

- Encapsulates 3 stages of running a program
  - Setup – transfer data from bluemira and create input
  - Run – execute systems code
  - Teardown – process output of systems code and transfer data to Bluemira objects

- High level interface completely abstracted (eg variable I/O, high level configuration)
- Low level interface available to expert users (eg. Low level configuration, direct interaction with code I/O)

Minor updates

Minor updates

QoL, minor features, performance, …

- Object orientated reactor design
    - Reactor objects hold various component managers
    - Component managers hold CAD and functions that
- Split between "Designers" and "Builders"
    - Designers solve optimisation problems and produce minimal geometry
    - Builders produce the final geometry based on designers output
- Efficient CI pipelines scale contributors to the project. PR's are tested for code quality and test coverage. All tests must pass and code owners must review and approve
- CAD outputs are tested on the domain on of their parameterisations, improving their robustness
- Bluemira can be access through a Docker image and in the future will be available on PyPi

Complementary work

STEP – Spherical harmonics for equilibrium solving

STEP – Arbitrary cross-section analytical magnetic source

Complementary work

STEP – Spherical harmonics for equilibrium solving

- Spherical Harmonics can be used as a constraint when positioning PF coils
  - Constraint used on vacuum psi with the plasma psi isolated
  - Keeping the vacuum psi constant within orange zone avoids equilibrium psi recalculation
  - Optimising coil positions aims to reproduce original vacuum psi
  - Possible secondary use case as a divertor constraint

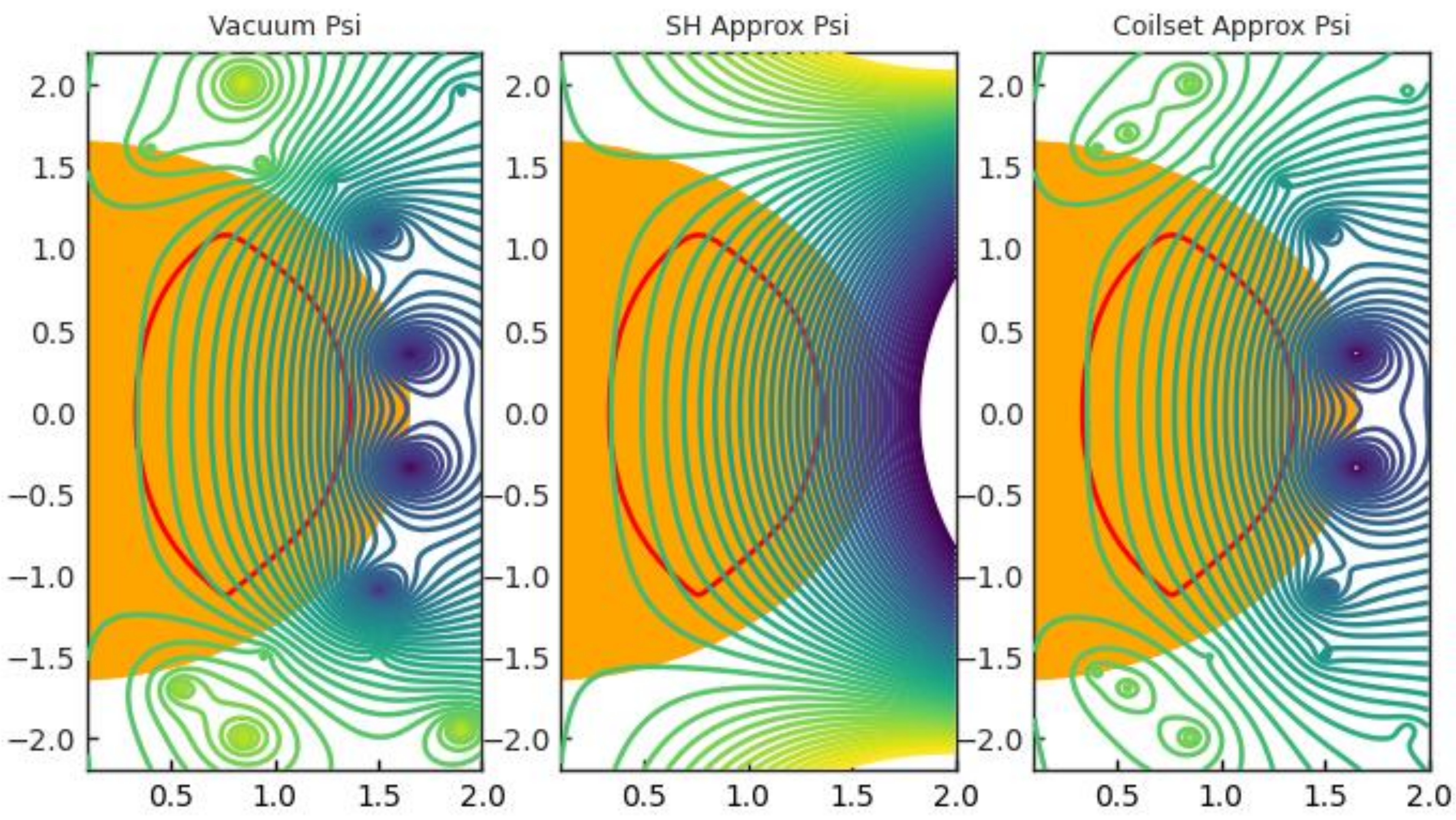
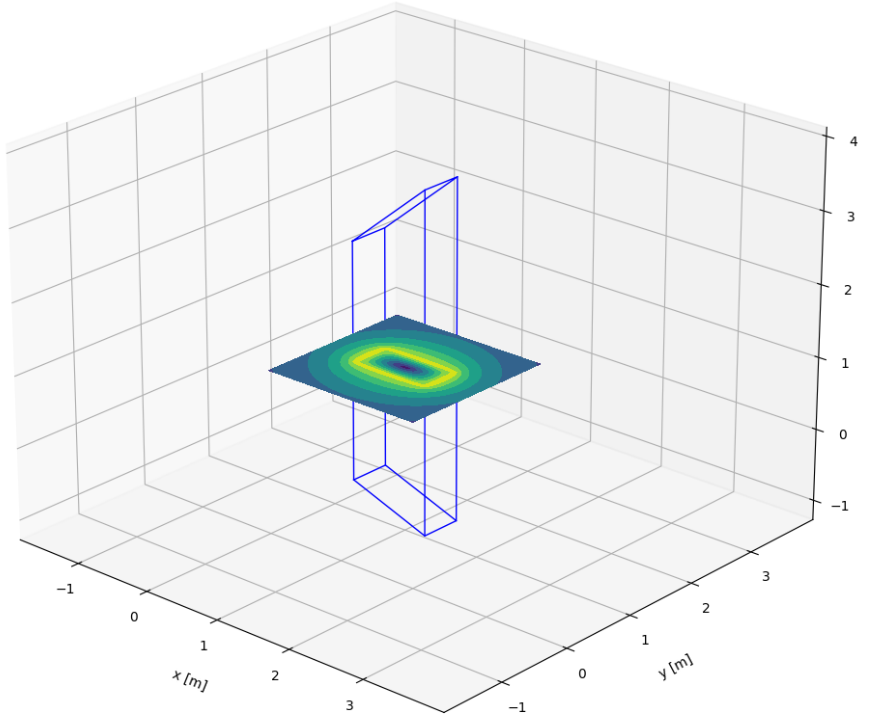


Figure created by G. Graham

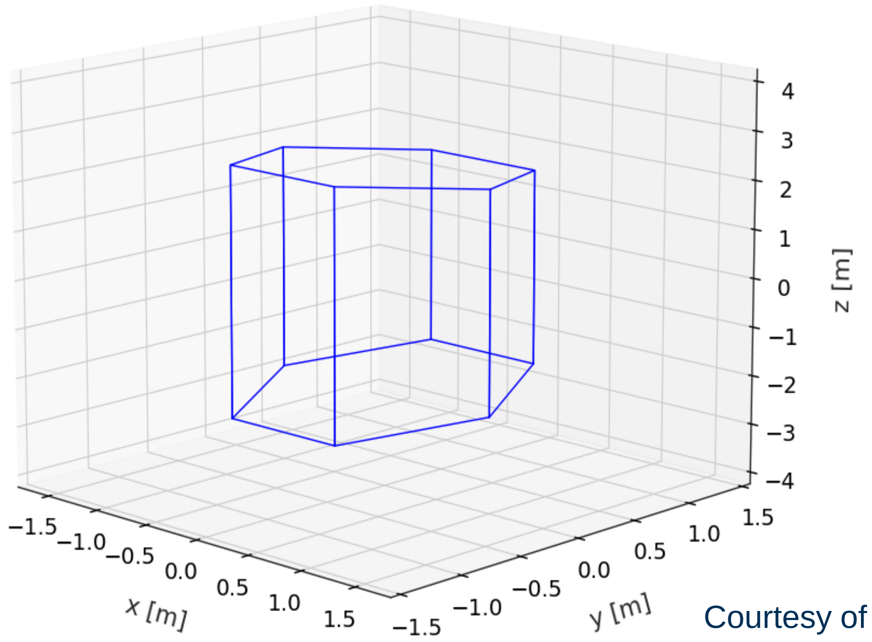
Complementary work

STEP – Arbitrary cross-section analytical magnetic source

- Generalising the existing rectangular analytical current sources for any cross-section magnets (work ongoing)



Existing functionality - rectangular prism



Courtesy of J. Matthews

Work in progress – hexagonal prism

Users and developers

Users and developers

BLUEMIRA community

Core development team – 8 Members (UKAEA – 5, KIT – 2, IPP – 1)

Users/followers/contributors – UKAEA – 11 (RACE, STEP, Digital), External – 21 (VTT, STEP EDP, TE, PPPL, GA)

To drive usage and community engagement with Bluemira we have undertaken several usability improvements to reduce the onboarding learning curve where possible. This includes:

- Providing examples explaining how to use certain aspects of the code
- Creation of training material to enable a wider dissemination of knowledge
- Training individual users on Bluemira enabling them to contribute back to the code
- Interacting with users on the repository, helping solve user's problems.
- Maintaining and improving test coverage
- Versioning of Bluemira to provide referenceable and stable points for users to build tools from

Outlook

Neutronics

TF winding pack

Vertical stability

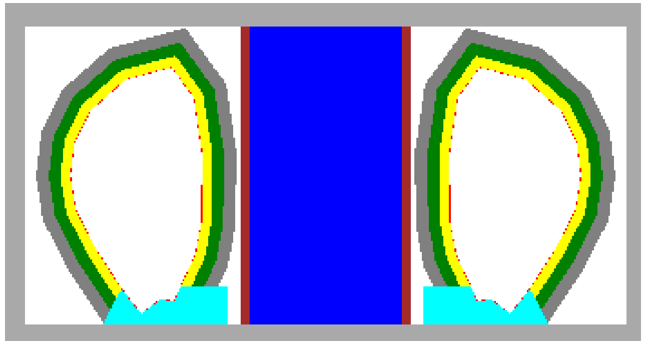
Radiation

Baseline

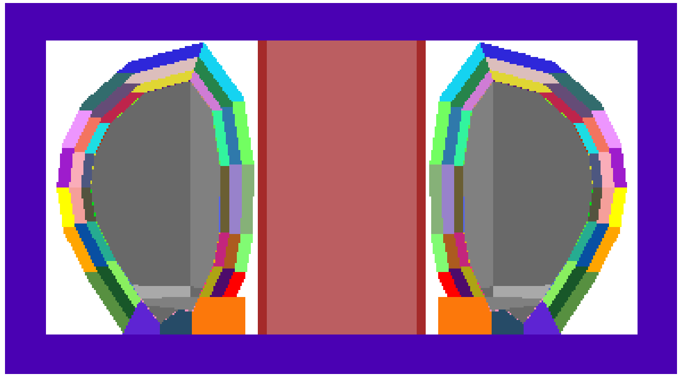
Outlook

Neutronics

- Using OpenMC to calculate the neutronics quantities
  - TBR, heating, wall loads, etc.
  - Integrated into the optimisation and design of the first wall.
- Axis-symmetric 3-D case to enable fast optimisation use in bluemira:



OpenMC Geometry



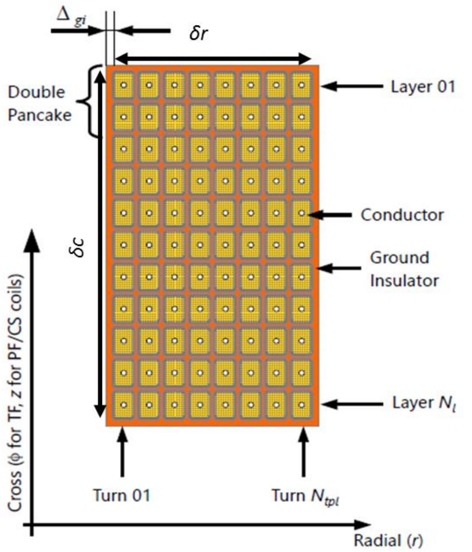
Divided into cells for tallying

- Future:
  - Handle more complex geometries, using pluggable parametric plasma source

Outlook

Coils Winding pack

The 2-D Winding Pack module to be implemented in bluemira shall address both direct and indirect problems and be applicable to the central solenoid, poloidal, and toroidal field coils. It shall consider both geometrical, electromagnetic and structural constraints in a formulation suitable for bluemira.

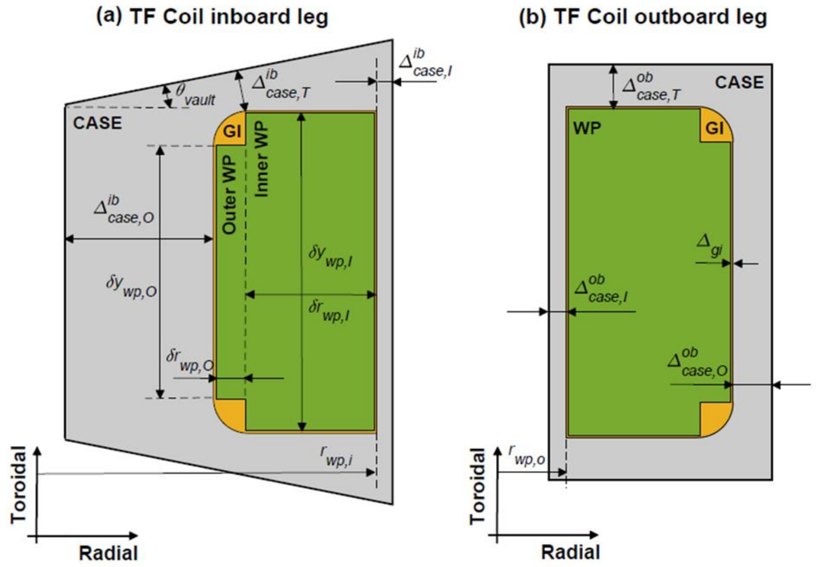


$$- I_{c,i}^{max} \leq (\mathbf{I_c})_i \leq I_{c,i}^{max}, \text{ with } i = 1, 2, ..., N_c$$ currents

Magnetic field $$B(\mathbf{p_{j,i}}; \mathbf{I_c}) \leq B_{max,i}, \text{ with } \begin{cases} i = 1, 2, ..., N_c \\ j = 1, 2, ..., N_{\partial\mathcal{D},i} \end{cases}$$

$$F_{z,PF}^{g}(\mathbf{I_c}, J_{\phi,p}) \leq F_{z,PF}^{max}, \text{ with } g = 1, 2, ... N_c^{PF}$$ EM loads

Temperature margin $$\Delta T_{cs} = T_{cs} - T_{op} \geq \Delta T_{cs}^{min}$$

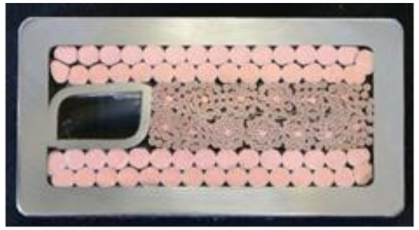


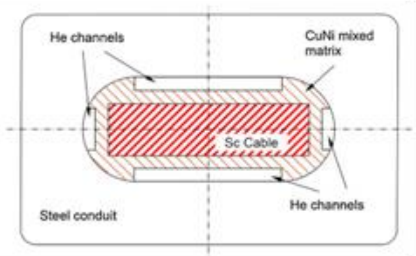
Outlook

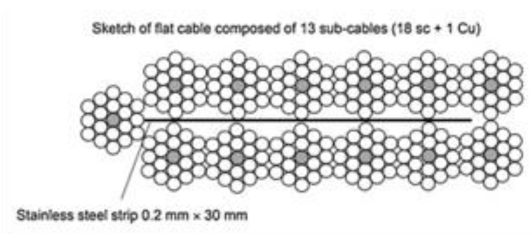
Coils Winding pack

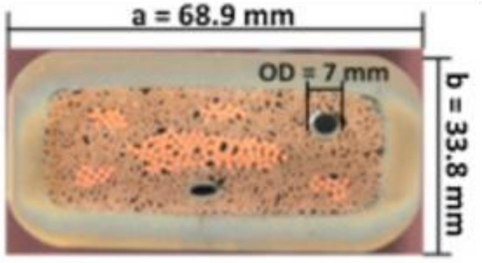
The code shall be capable of accommodating various superconducting cable options, based on the technological solutions explored for ITER and DEMO.

Parameter	[Unit]	Variable
Maximum allowable magnetic field	[T]	B_{max}
Maximum operating temperature at field peak	[K]	T_{op}
Maximum operating strain	[%]	ϵ_{op}
Minimum temperature margin	[K]	ΔT_{cs}^{min}
Helium (coolant) fraction in conductor	[%]	f_{He}
Copper to superconducting ratio in strand	[%]	f_{Cu2sc}
Strand diameter	[mm]	d_{strand}
Number of superconducting strands in conductor	[-]	N_{strand}^{SC}
Number of Copper stabilizer strands in conductor	[-]	N_{strand}^{Cu}
Helium coolant channel diameter	[mm]	d_{ch}
Radial/cross width of cable space	[mm]	$\delta r_{turn,c} / \delta c_{turn,c}$
Steel jacket thickness	[mm]	$\delta_{turn,j}$
Turn insulator thickness	[mm]	$\delta_{turn,ins}$





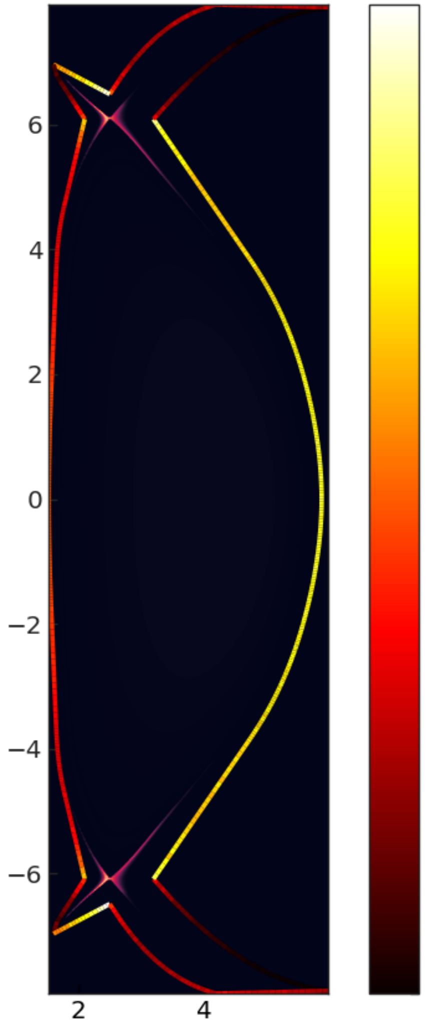




Outlook

Radiation

- Calculation of
  - The line radiation source
  - First wall radiation heat flux
- Improve first wall design problem
  - Starting point for first wall shaping algorithms
  - Directly account for radiation and particle heat loads.
- Feature implemented in branch and under initial review



Courtesy of D. Vaccaro

Outlook

Baseline

- Next EU-DEMO baseline to be issued in Q3 2023
- BLUEMIRA not scheduled to be "officially" used to produce the baseline, but we will produce a baseline design point once the input parameters have been decided
- Continuous interaction with EUROfusion regarding EU-DEMO:
  - Ensure the parameterisation in BLUEMIRA is as intended
  - Ensure input parameters and sub-models are up-to-date

Summary

Summary

Progress and outlook

- Move to parameterised CAD completed and most of CAD component builders done – some port/shield interaction still to be done
  - Remote maintenance considerations – some already but would like to expand to more detailed allowances for support structure and space needed for ports.
- Coupled transport solver (PLASMOD) to fixed boundary equilibrium solver.
- EU-DEMO workflow constructed and will attempt to use to create equivalent of 2023 baseline as a test.
- Balance of plant model implemented.
- Winding pack tool and neutronics coupling key features for rest of this year/early next year.