TSVV-14
Multi-Fidelity Systems Code for DEMO

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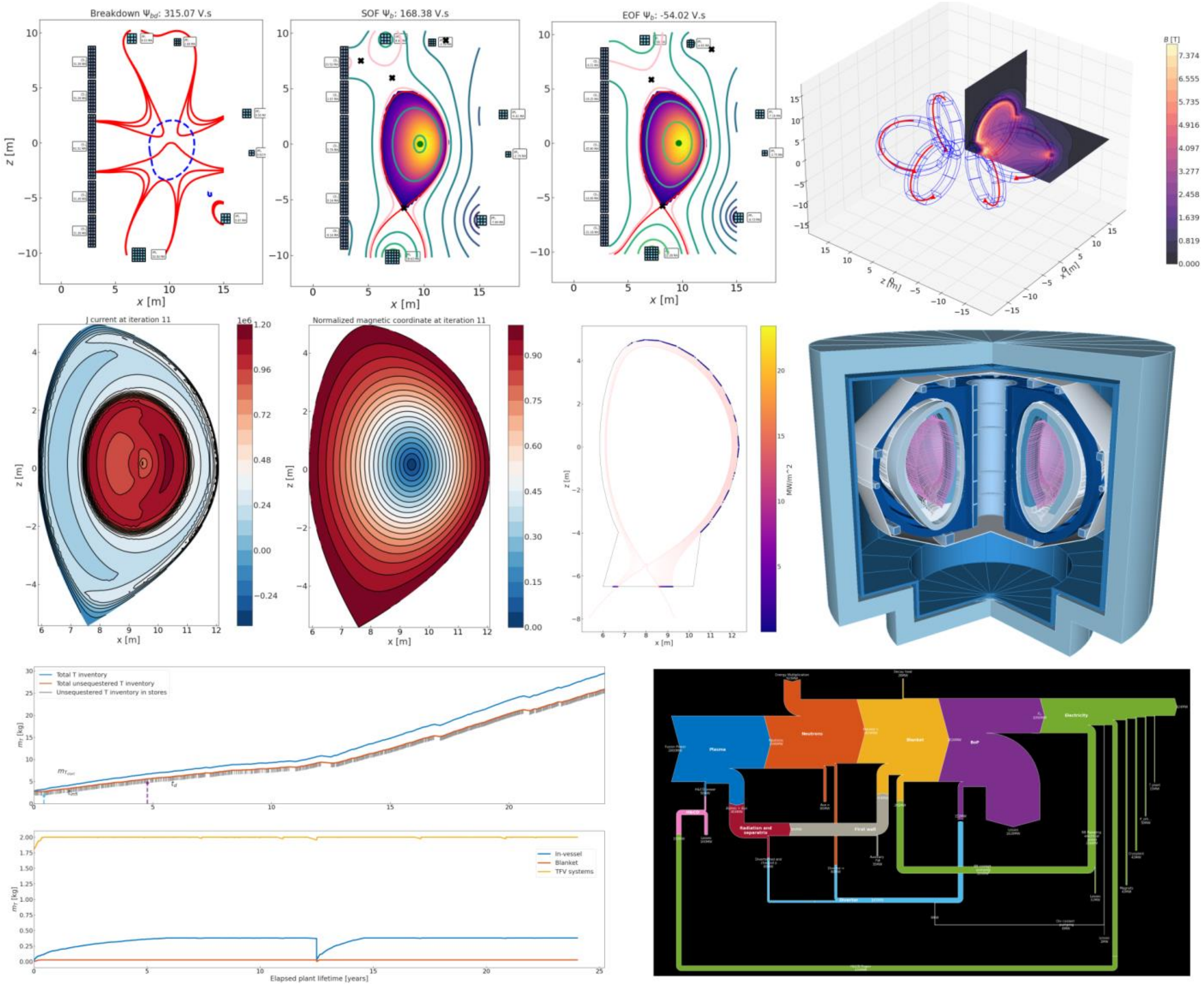
Outline

1. Intro
2. Features
3. General software dev
4. Developers/users
5. Complementary work
6. Outlook
7. Summary



Bluemira GitHub

Introduction

What is TSVV-14?

<u>Objective</u>

Aim is to create a supported and widely used open-source reactor design tool capable of integrated modelling at multiple levels of fidelity (0-D, 1-D, 2-D, 3-D).

Project team: UKAEA + KIT (2.4 ppy/year)

It isn’t a digital twin, “pulse design tool” or “flight simulator”.
It is a concept design tool.

Outline

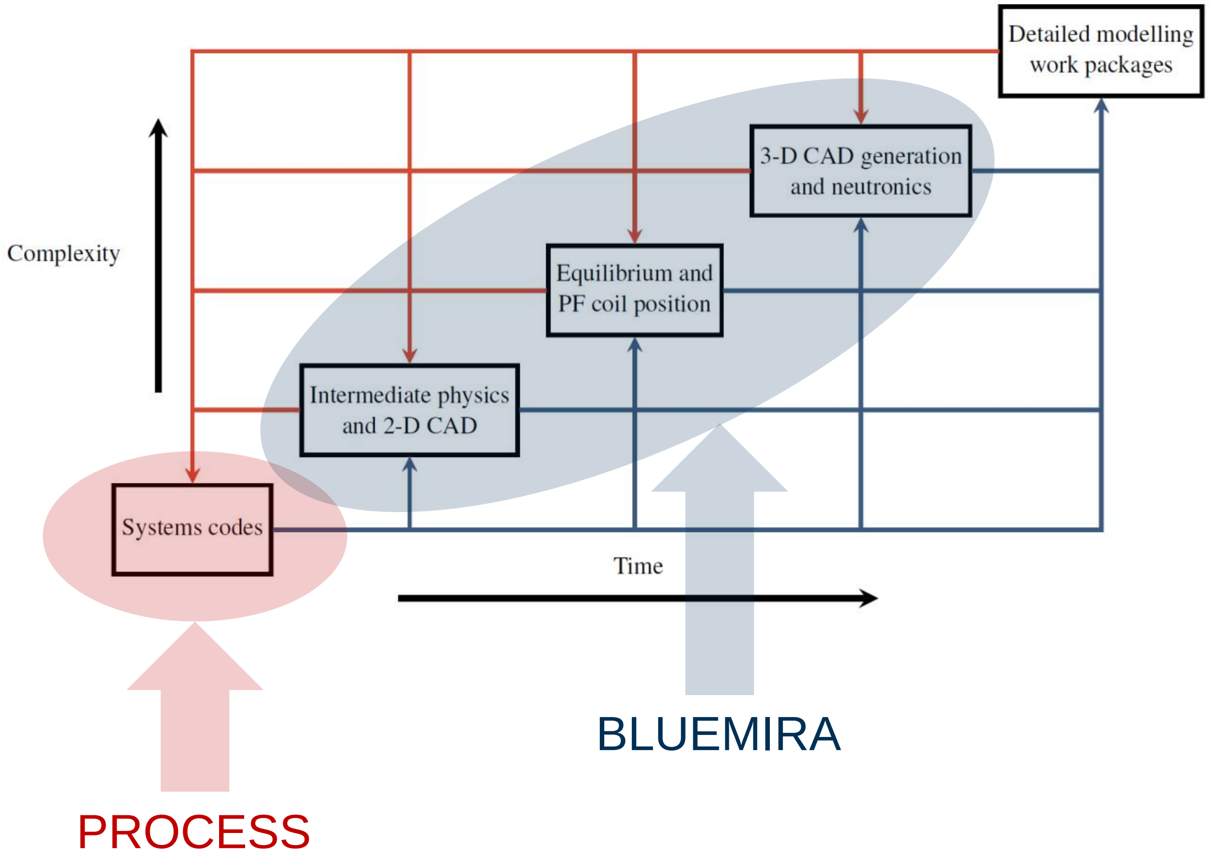
Rationale

Time saved allows for more optioneering in preconceptual and conceptual design phases

Can de-risk programme

Reduce human error

Attempt to make self-consistent automated workflow as far into top right as possible <u>and where sensible for what we are trying to achieve</u>.



Introduction

Deliverables

Deliverables		
Software architecture review and merge of BLUEPRINT and MIRA		2-D magnet winding pack design module
Integration with existing 0-D/1-D systems codes (e.g. PROCESS)		Vertical stability model incorporated into equilibrium solver
Coupled 1.5-D transport solver and free-boundary equilibrium solver		Coupling to open-source 3-D multi-physics FEA tools for “post run” workflow
Automatic 3-D CAD generation		Plant power balance
2-D deterministic radiation transport		First wall design module taking advantage of integrated tools
3-D radiation transport model integration (e.g. OpenMC)		Implementation of global optimisation solver in BLUEMIRA

Features

Parameterised CAD

Reactor workflow

Coupling transport solver to FBE

Balance of plant

Systems code coupling

3-D CAD updates

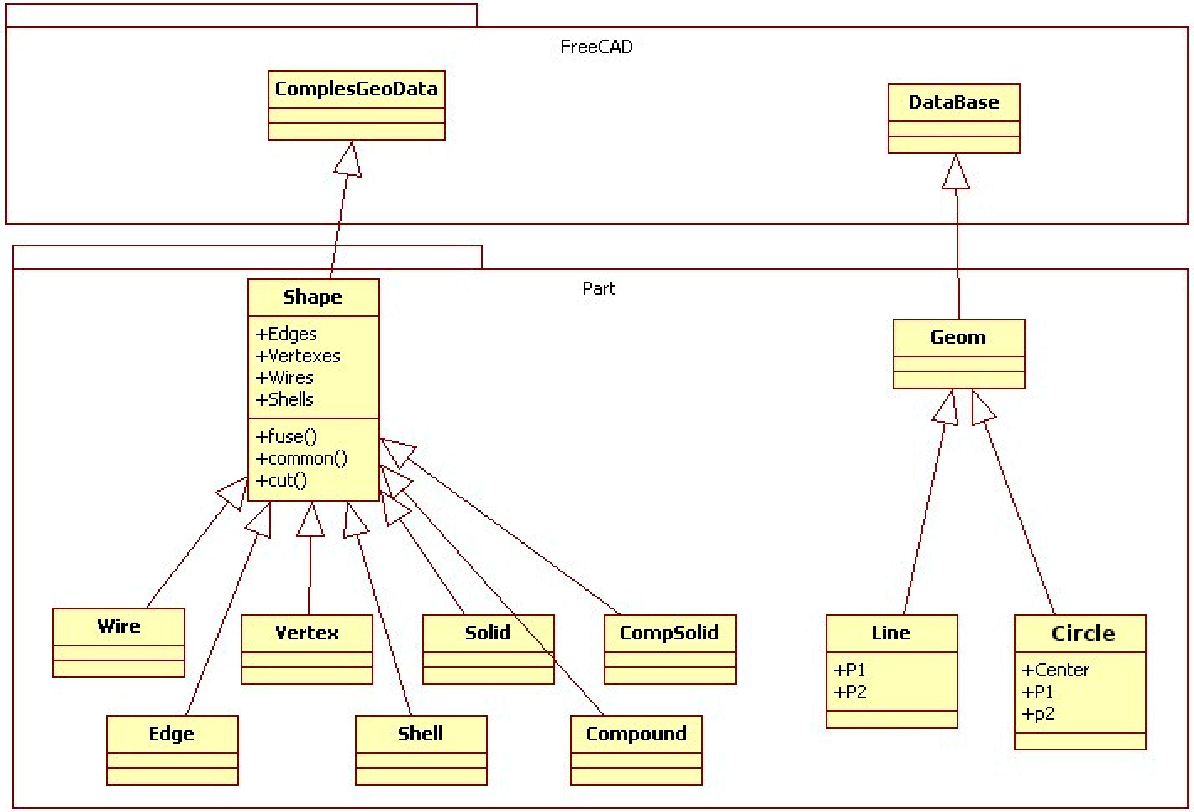
Features

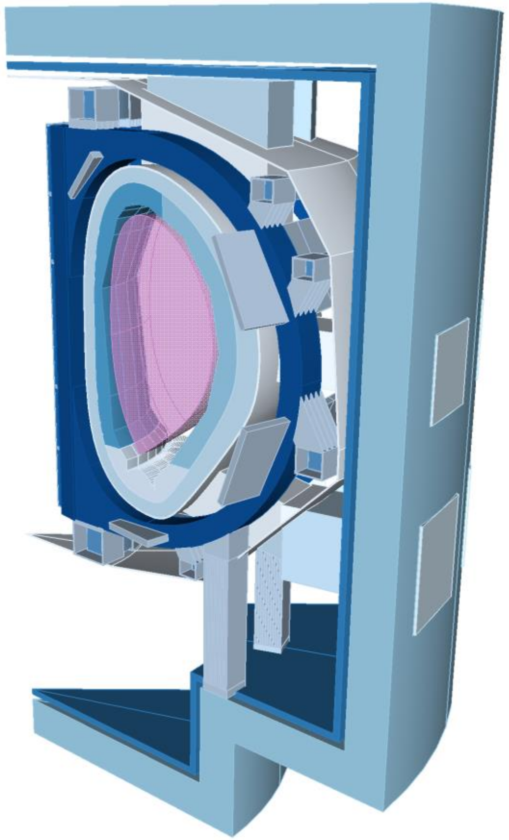
Parameterised CAD

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.

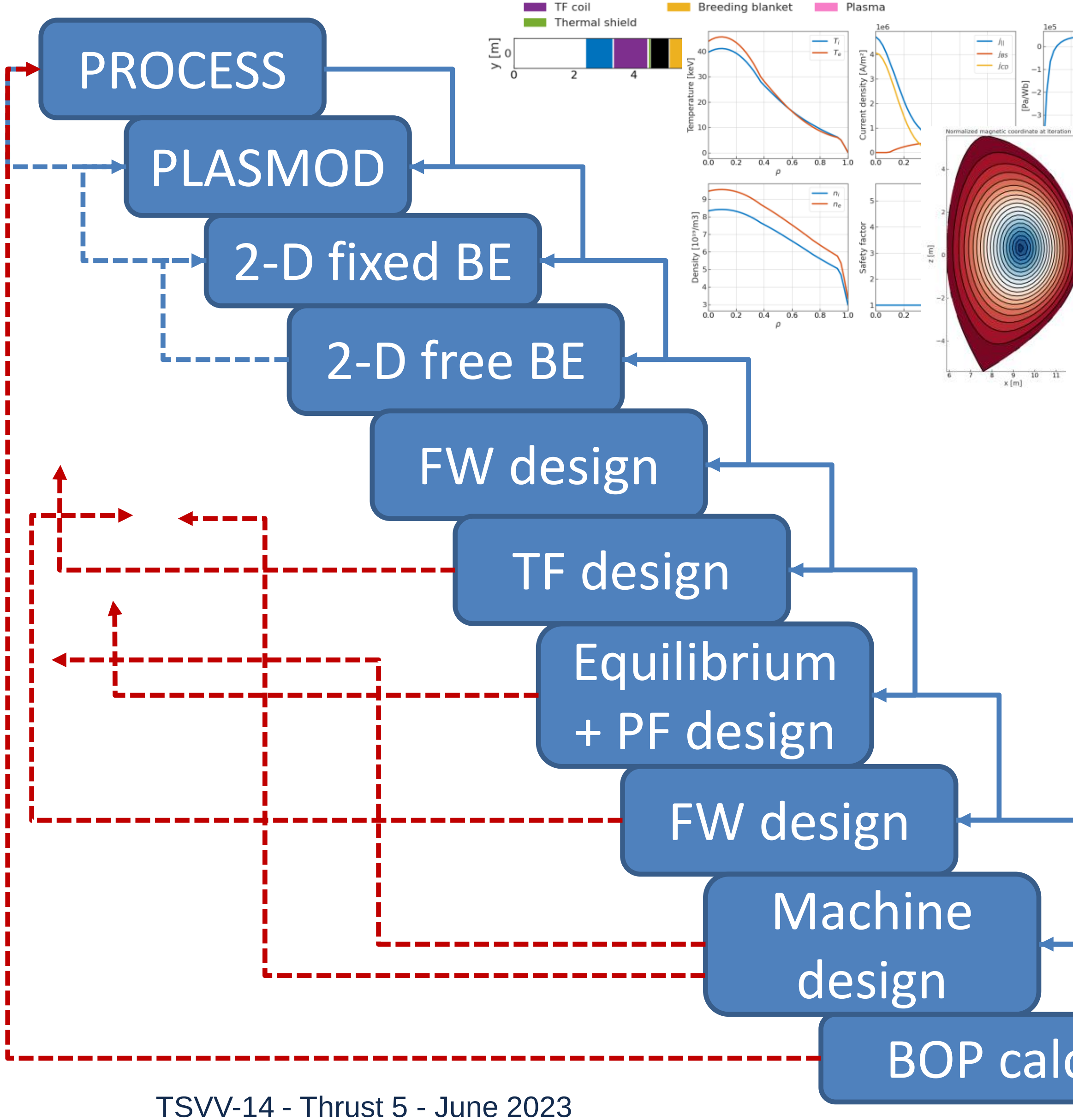
FreeCAD parametric objects (i.e. wire, face, shell, solid) have been wrapped into bluemira geo objects. A python FreeCAD api has been implemented to expose main CAD functionalities.

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

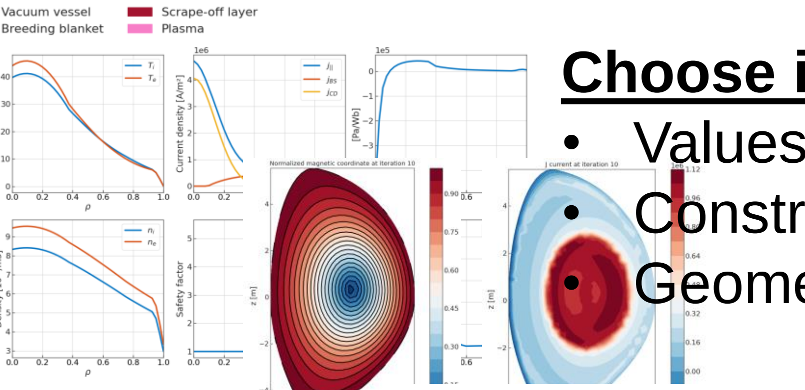




EU-DEMO workflow in BLUEMIRA



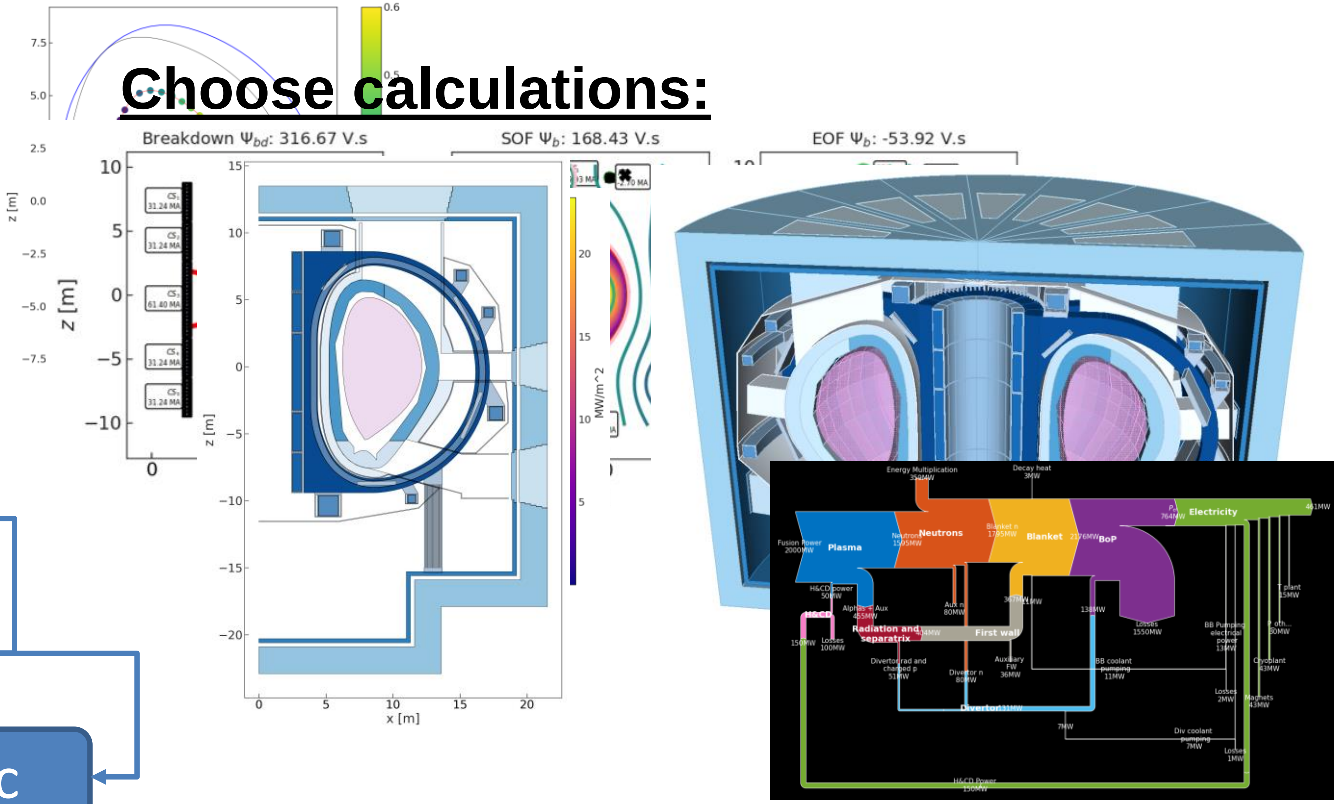
TSVV-14 - Thrust 5 - June 2023



Choose inputs:

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

Choose calculations:

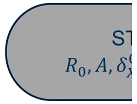


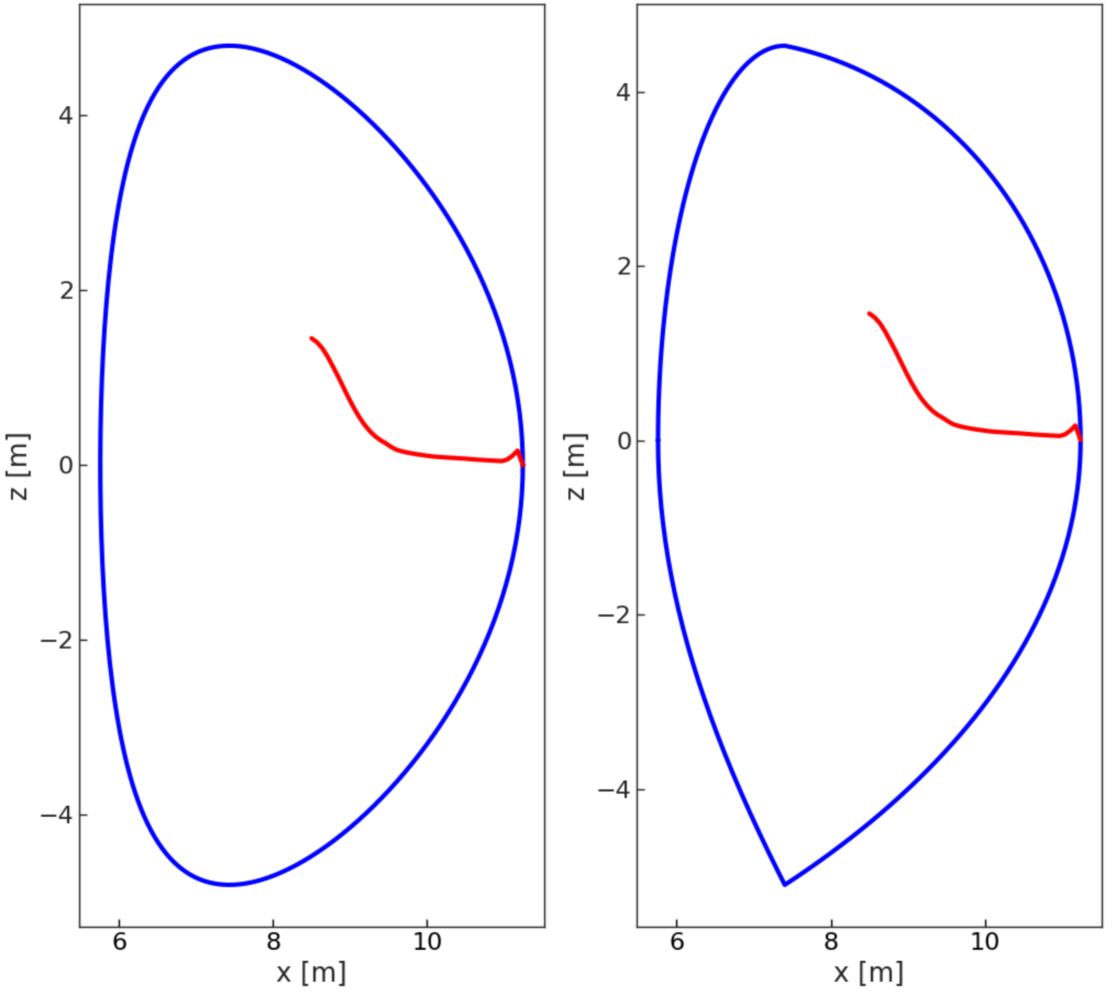
Features

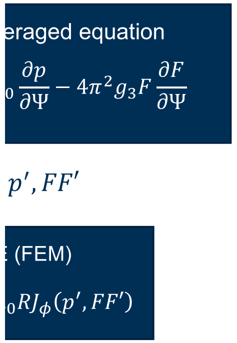
Coupling transport solver to Fixed B

Objective: 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







[14] F. Franza | PSDD & PSD End-of-Year Technical Workshop | 25.11.2021

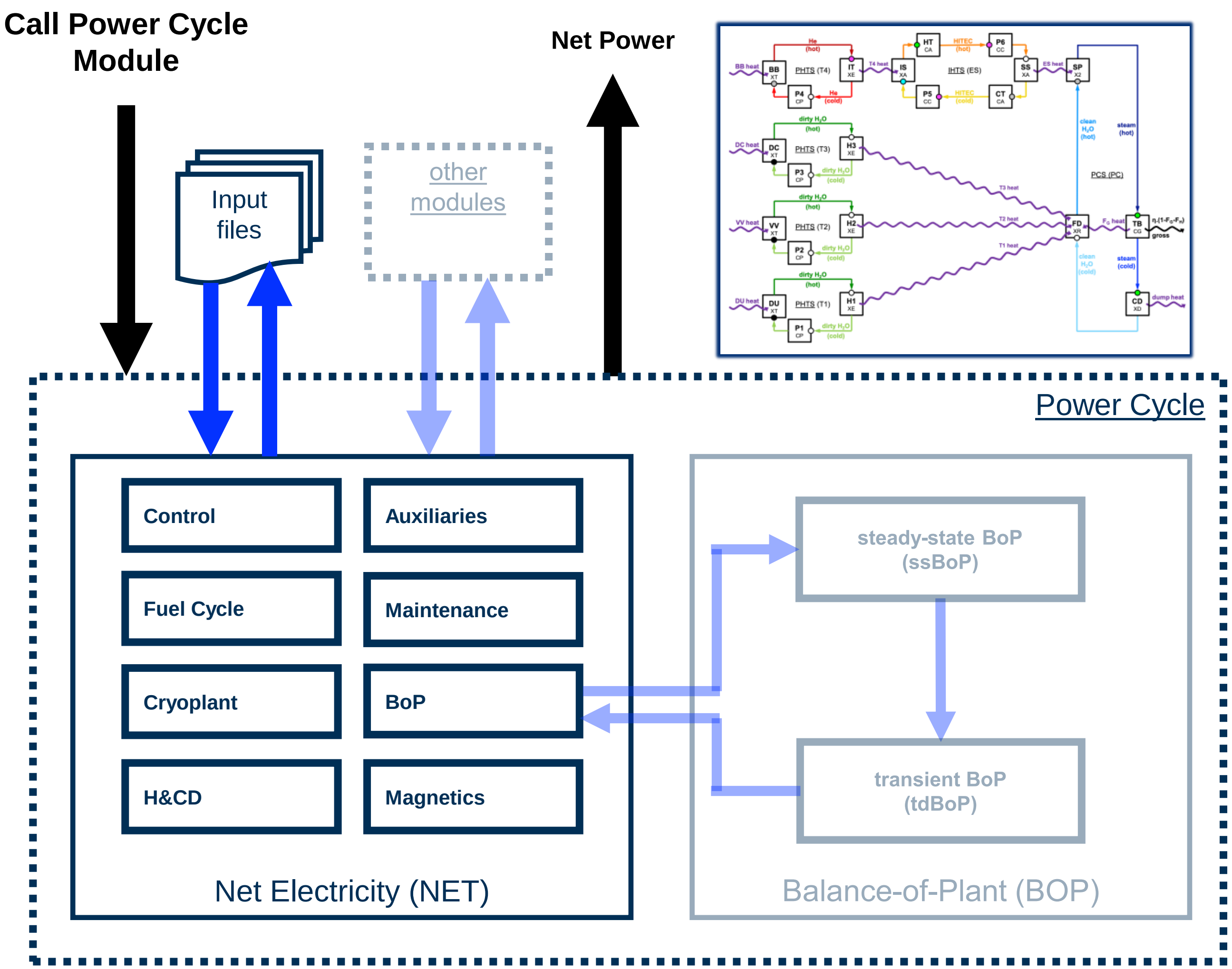
Features

Balance of plant

Pulse dynamics in only 4 phases (flat, dwell, transitions)

Module divided in 2 sub-modules

- A NET (net electricity calculator)
  - Accounting tool for all power plant loads (active & reactive)
  - Very generic description for individual loads: flexibility/versatility in power plant design
  - Automatic tools for plotting selected sub-sets of loads
  - Designed to import loads from other modules
  - First implementation under review
  - Planned: load tags, interfaces with plasma & coil models
- BOP (balance-of-plant calculator)
  - Thermodynamical model with both power & mass balances
  - Produces technological descriptions of major BoP systems
  - Plots simplified thermodynamical cycle diagrams
  - Steady-state model complete, implementation to start
  - Transient model under development
  - Planned: import Sankey diagram tools from BLUEPRINT



Features

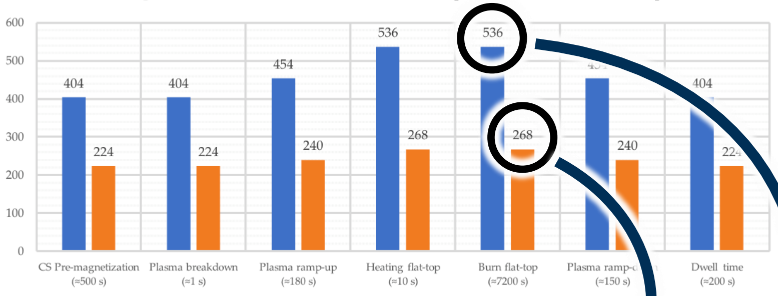
Balance of plant

Against published load list for HCPB-DEMO

S. Minucci, S. Panella, S. Ciattaglia, M.C. Falvo, A. Lampasi, Electrical Loads and Power Systems for the DEMO Nuclear Fusion Project, Energies. 13 (2020) 2269. https://doi.org/10.3390/en13092269.

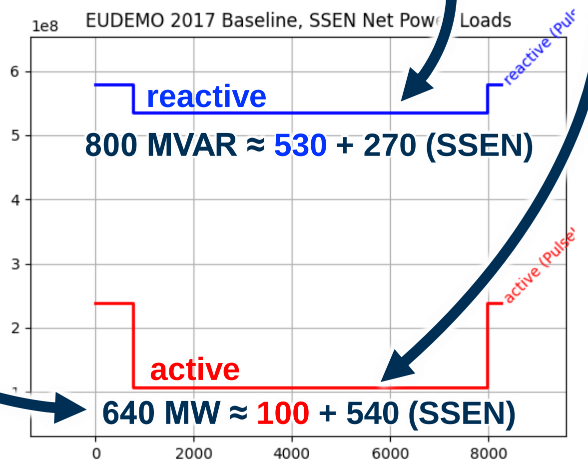
PBS	PBS Description	Power		Distribution
		Active (MW)	Reactive (MVAR)	
11	Magnet System	0	0	Passive
12	Vacuum Vessel (VV)	0	0	Passive
13	Divertor System	0	0	Passive
14	Blanket (HCPB) [1]	0	0	Passive
16	Blanket (WCLL) [1]	0	0	Passive
18	Limiter	0	0	Passive
20	Cryostat	0	0	Passive
21	Thermal Shields	0	0	Passive
22	Tritium, Fueling, Vacuum	12.2	7.7	SSEN
25	Tritium Extraction and Removal (HCPB) [1]	3.0	1.9	SSEN
27	Tritium Extraction and Removal (WCLL) [1]	3.0	1.9	SSEN
30	ECRH System (main power) [2,3]	125.0	60.5	PPEN
30	ECRH System (auxiliary power) [2]	6.0	2.9	SSEN
31	NBI System (main power) [2,3]	125.0	60.5	PPEN
31	NBI System (auxiliary power) [2]	6.0	2.9	SSEN
32	ICRH System (main power) [2,3]	125.0	60.5	PPEN
32	ICRH System (auxiliary power) [2]	6.0	2.9	SSEN
40	Plasma Diagnostic & Control System	6.1	3.0	SSEN
49	VV PHTS	9.7	4.7	SSEN
50	Breeding Blanket PHTS (HCPB) [1,3]	165.6	54.4	SSEN
52	Breeding Blanket PHTS (WCLL) [1]	59.4	19.5	SSEN
54	VV Pressure Suppression System (HCPB) [1]	2.3	0.0	SSEN
56	VV Pressure Suppression System (WCLL) [1]	4.6	2.9	SSEN
58	Divertor & Limiter PHTS (HCPB) [1]	19.5	12.1	SSEN
59	Divertor & Limiter PHTS (WCLL) [1]	10.0	6.2	SSEN
60	Remote Maintenance (RM) System [4]	5.0	3.1	SSEN
61	Assembly	4.6	2.2	SSEN
63	Radwaste Treatment and Storage	3.0	1.5	SSEN
70	Balance of Plant (HCPB) [1]	12.0	5.8	SSEN
72	Balance of Plant (WCLL) [1]	12.0	5.8	SSEN
80	Site Utilities	3.1	1.9	SSEN
81	Cryoplant & Cryodistribution	101.8	63.1	SSEN
82	Electrical Power Supply (main power) [3]	300.0	300.0	PPEN
82	Electrical Power Supply (auxiliary power)	21.0	10.2	SSEN
83	Buildings	54.8	26.6	SSEN
85	Plant Control System	3.6	1.7	SSEN
87	Auxiliaries	90.9	56.4	SSEN

Figure 7. Nominal SSEN active and reactive powers in each plasma phase, considering the two different PHTS-PCS options: **(a)** HCPB and **(b)** WCLL. ■ Active power (MW) ■ Reactive power (MVAR)



generator ranges around 800 MVA.

active power of around 640 MW.

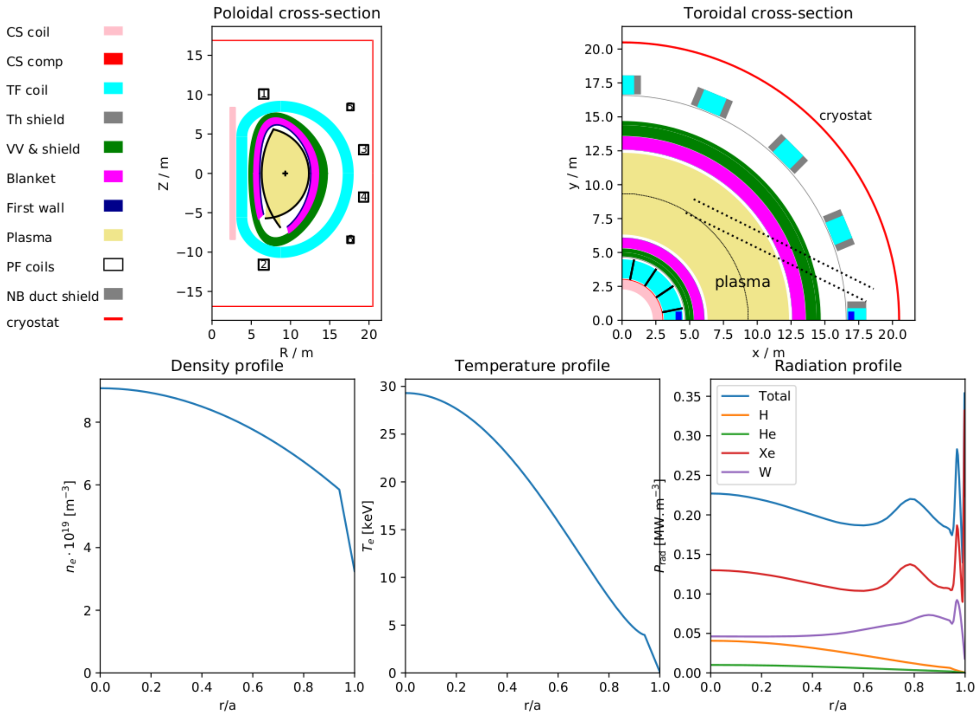


Features

Systems code coupling

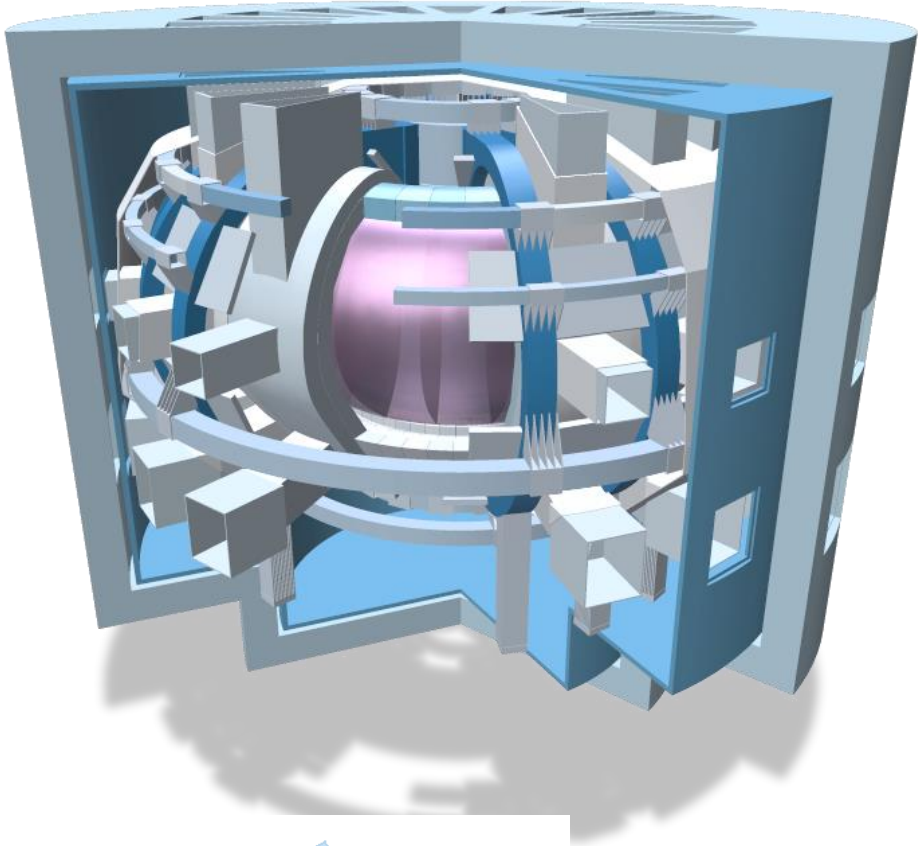
- Generic "Solver" API to Interface with external systems codes
  - PROCESS interface implemented
- Encapsulates 3 stages of running a program
  - Setup – transfer data from bluemira and create input
  - Run – execute systems code
  - Teardown – process output of systems code and transfer data to Bluemira 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)

PROCESS is now open source under MIT licence and available on GitHub

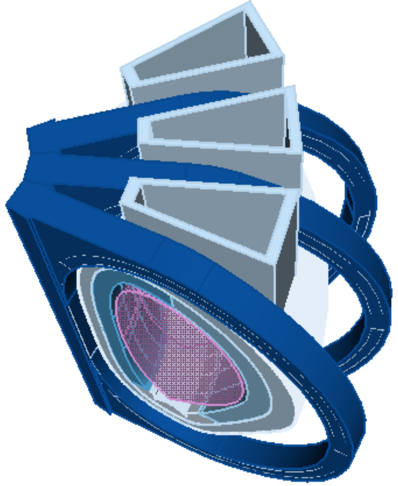


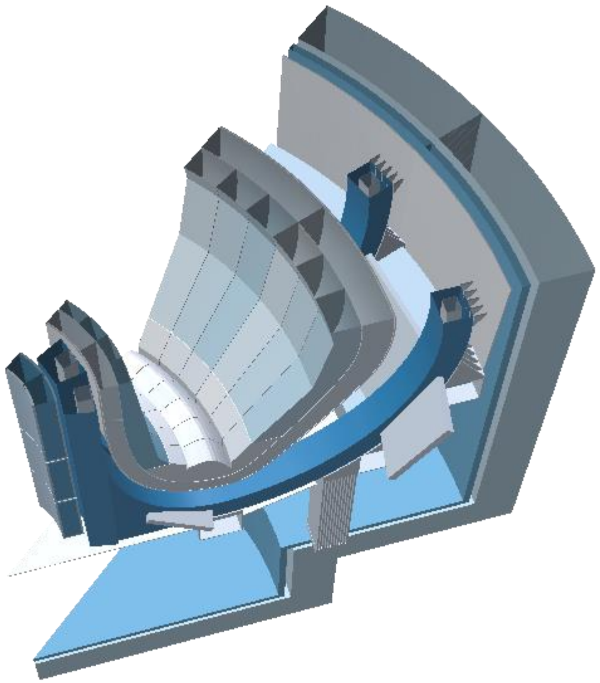
Features

3-D CAD updates



- From EUDEMO: Added ports, optimised blanket panelling, inter-coil support structures
- CAD sectoring
    - Exploited reactor symmetries to reduce build times by a factor of 2
- Component level filtering (void space) and selection
- Polyscope viewer
- Expanded set of FreeCAD API's



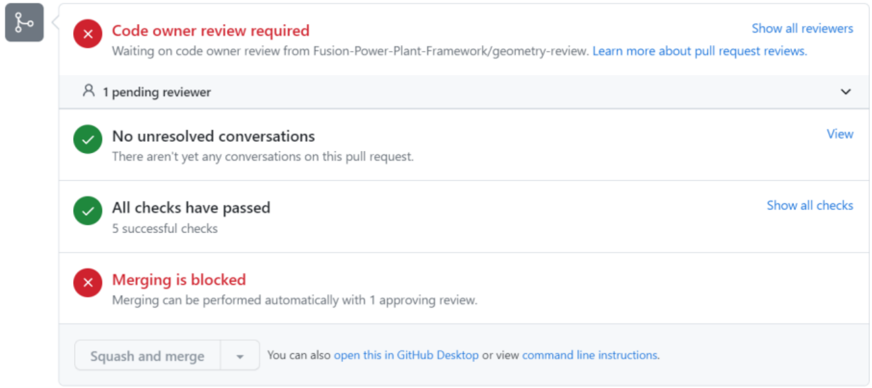


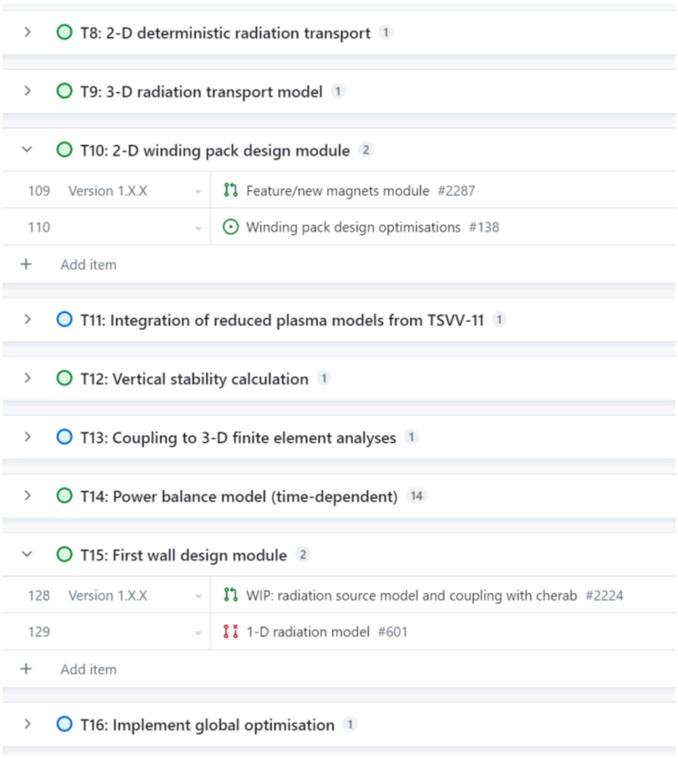
General software development

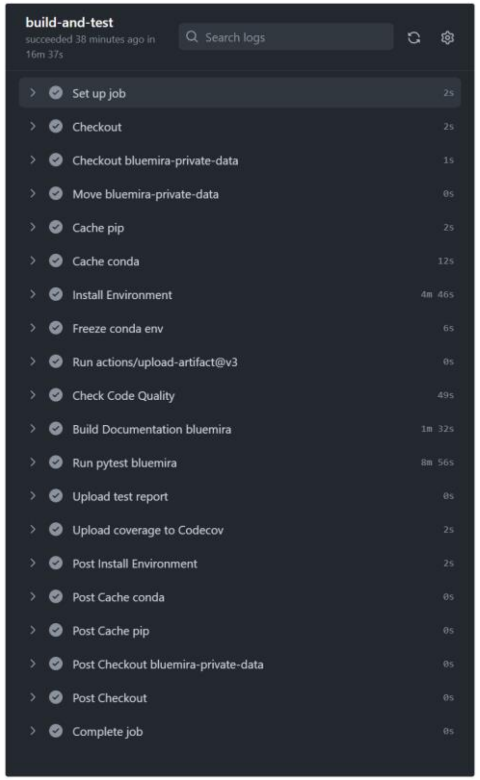
General software development

QoL, minor features, performance, …

- Object orientated reactor design
    - Reactor objects hold various component managers
    - Component managers hold CAD and functions
- 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.
- Designer/builder CAD outputs are robustly tested on the full range of their parameterisations
- Bluemira can be accessed through a Docker image and, in the near future, available on PyPi







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 a campaign of usability improvements to reduce the onboarding learning curve where possible. This includes:

- Writing clear documentation
- 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 problems.
- Refactoring the code to make it more maintainable and easier to use.
- Versioning of Bluemira to provide referenceable and stable points for users to build tools from.

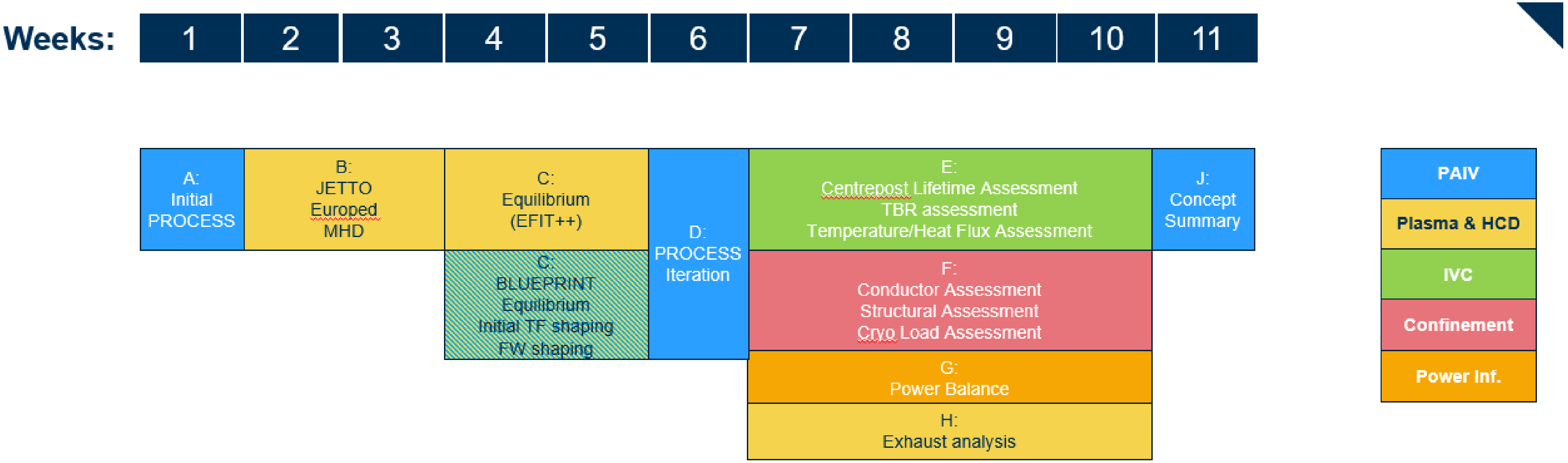
Complementary work

STEP Concept design

Spherical harmonics for equilibrium solving

Complementary work

STEP – Programme use

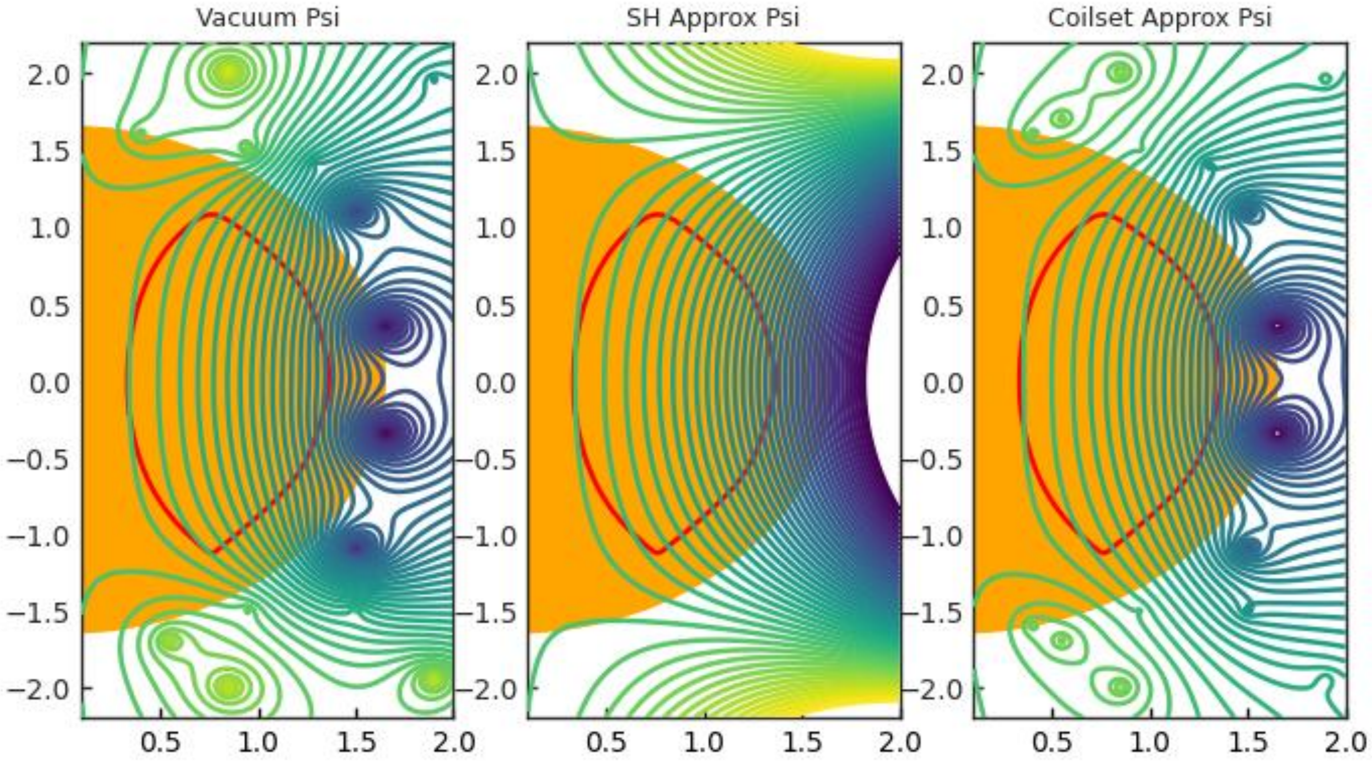


Active userbase using bluemira on a reactor design programme was generally beneficial for reviewing our workflow, user experience, coupling to other codes, and bug finding etc.

Complementary work

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



Working on expanding method with toroidal harmonics for conventional aspect ratio tokamaks

Figure created by G. Graham

Outlook

Neutronics

TF winding pack

Vertical stability

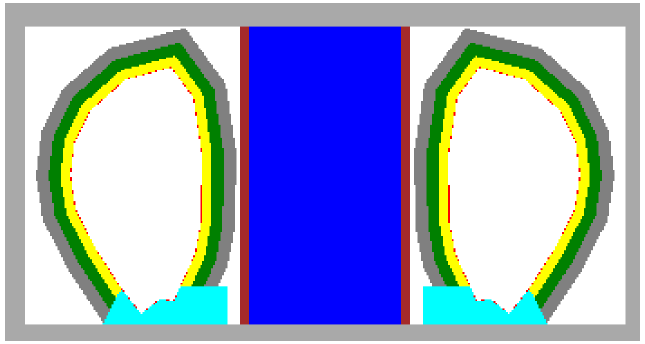
Radiation

Baseline

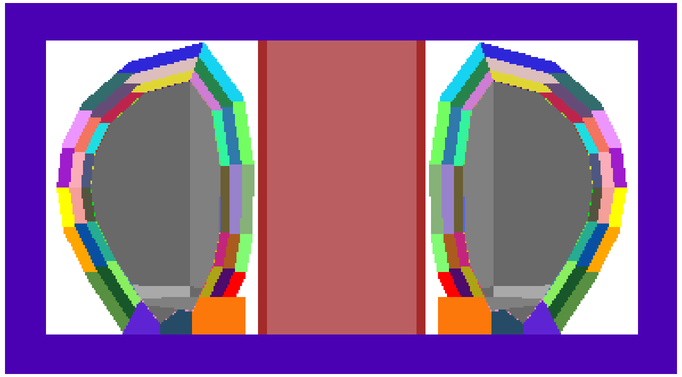
Outlook

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 already available to enable fast optimisation use in bluemira:



OpenMC Geometry



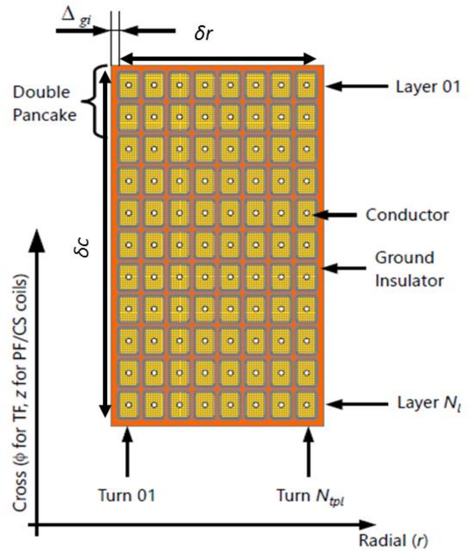
Divided into cells for tallying

- Future:
  - Non-axis symmetric case, handle more complex geometries, using pluggable parametric plasma source

Outlook

Coils Winding pack

The 2-D Winding Pack module to be implemented in bluemira will follow the approach in [1] and address both direct and indirect problems. It shall be applicable to the central solenoid, poloidal, and toroidal field coils and consider both geometrical, electromagnetic and structural constraints in a formulation suitable for bluemira.

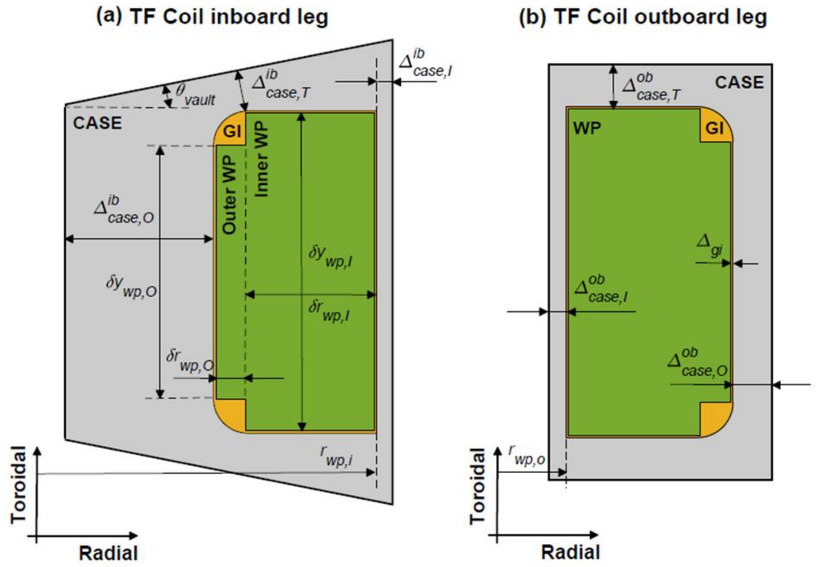


$$- I_{c,i}^{\max} \le (\mathbf{I_c})_i \le I_{c,i}^{\max}, \ \text{with } i = 1,2,...,N_c$$ currents

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

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

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



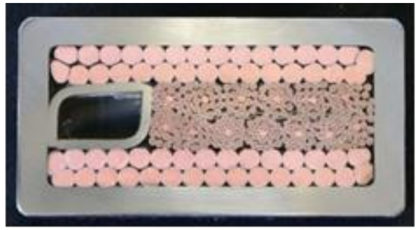
[1] F. FRANZA et al., "MIRA: A Multi-physics Approach to Designing a Fusion Power Plant," *Nucl. Fusion*, 62, 7, 076042 (2022)

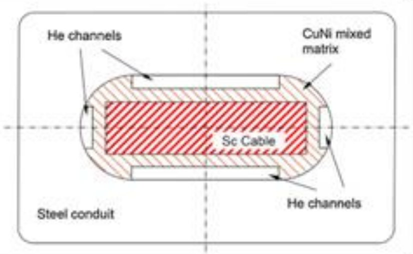
Outlook

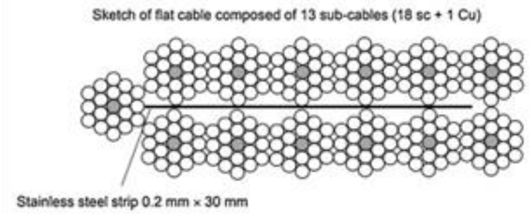
Coils Winding pack

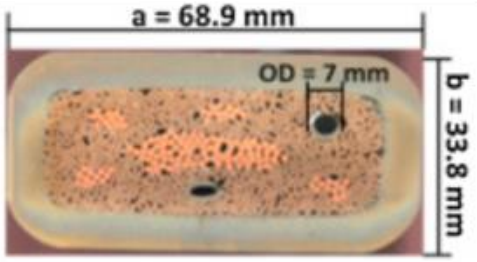
The code will be capable of accommodating various superconducting cable options, based on the technological solutions explored for ITER and DEMO.

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]	$\delta_{turn,ins}$







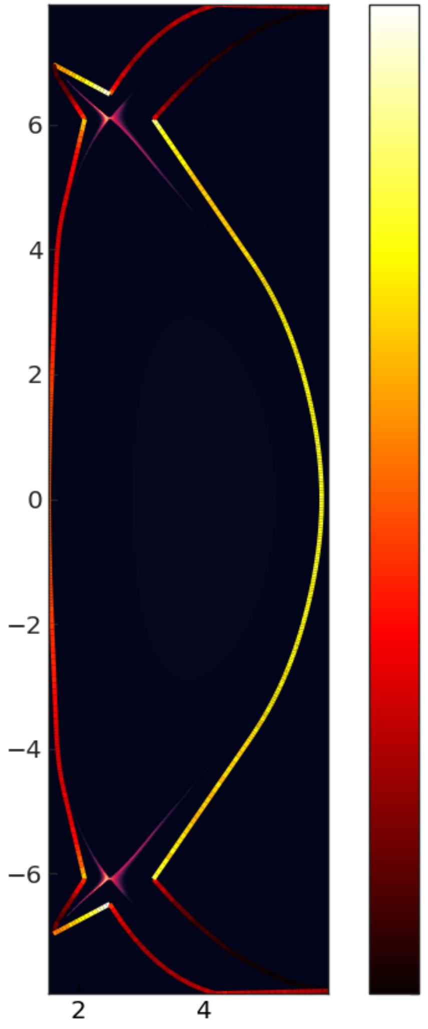


[1] V. Corato et al. The DEMO magnet system – Status and future challenges, Fusion Engineering and Design, Volume 174, 2022

Outlook

Radiation

- Calculation of
  - The line radiation source
  - first wall radiation heat flux
  - Uses CHERAB
- Improve first wall design problem
  - Starting point for first wall shaping algorithms
  - Directly account for radiation and particle heat loads.



Courtesy of D. Vaccaro

Outlook

Baseline

- Next EU-DEMO baseline to be issued by end of 2023
- BLUEMIRA not scheduled to be "officially" used to produce the baseline, but we will produce the baseline design point in BLUEMIRA as a use case.
- 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

Lessons learned

Merging code bases had significant overhead

Discretised → parametric CAD much more involved than first estimated

Overhead in getting started with bluemira for new machine types is mostly around creating “builders”

Deliverables

Progress

Deliverables		
Software architecture review and merge of BLUEPRINT and MIRA		2-D magnet winding pack design module
Integration with existing 0-D/1-D systems codes (e.g. PROCESS)		Vertical stability model incorporated into equilibrium solver
Coupled 1.5-D transport solver and free-boundary equilibrium solver		Coupling to open-source 3-D multi-physics FEA tools for “post run” workflow
Automatic 3-D CAD generation		Plant power balance
2-D deterministic radiation transport		First wall design module taking advantage of integrated tools
3-D radiation transport model integration (e.g. OpenMC)		Implementation of global optimisation solver in BLUEMIRA

Summary

Progress and outlook

- Move to parameterised CAD completed and CAD component builders complete
    - 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.
    - Workflow for general case needed
- 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.