TSVV-14
Multi-Fidelity Systems Code for DEMO

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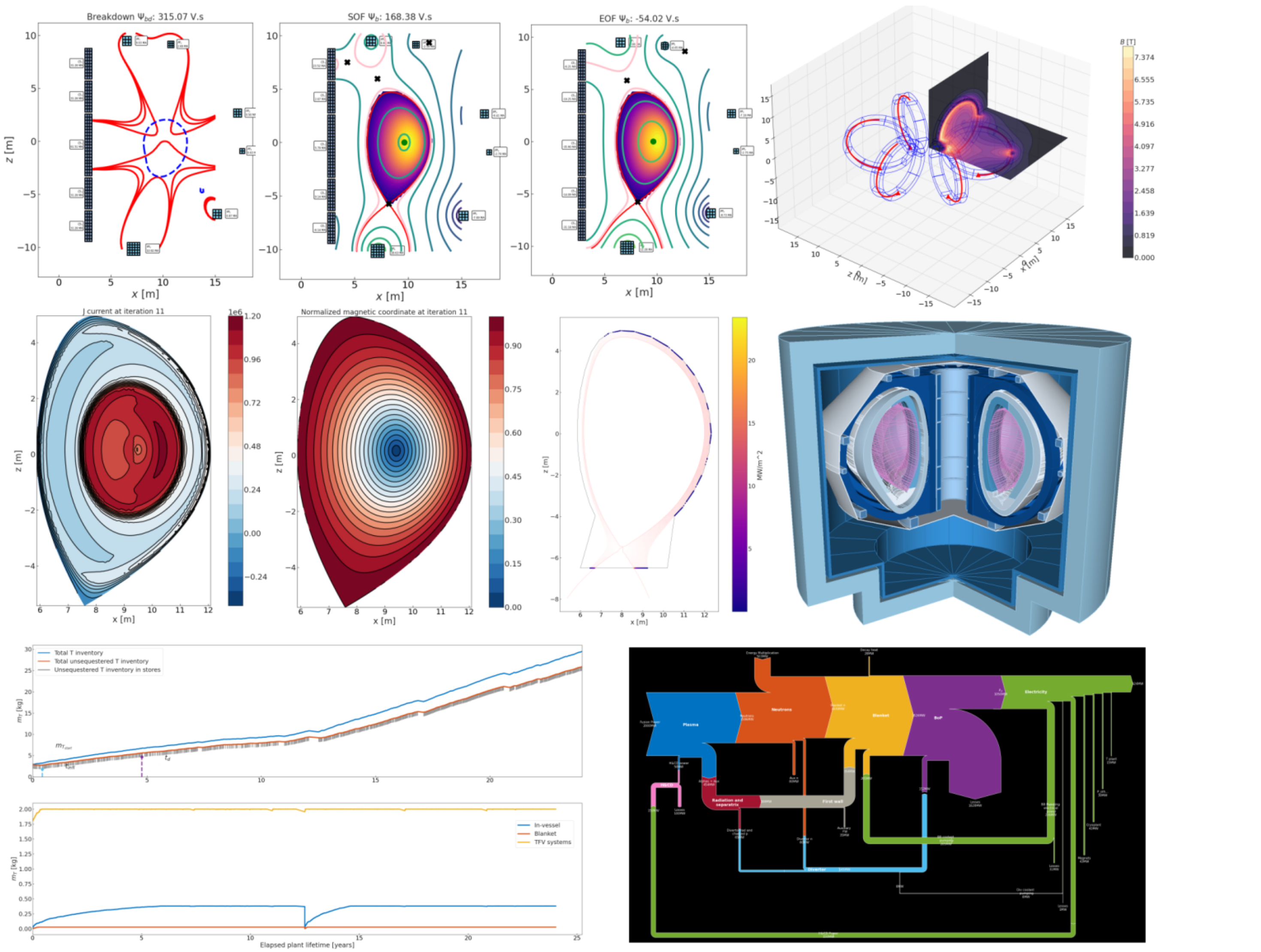
Outline

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



Bluemira GitHub

Introduction

What is TSVV-14?

Objective

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.

Participants and Acknowledgements

UKAEA:

M. Coleman, **J. Cook, O. Funk**, G. Graham, J. Matthews, J. Morris, C. Mould, H. Saunders, D. Vaccaro, **O. Wong**

KIT:

F. Franza**, I. Maione, T. Pomella-Lobo, G. Verma**

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

Outline

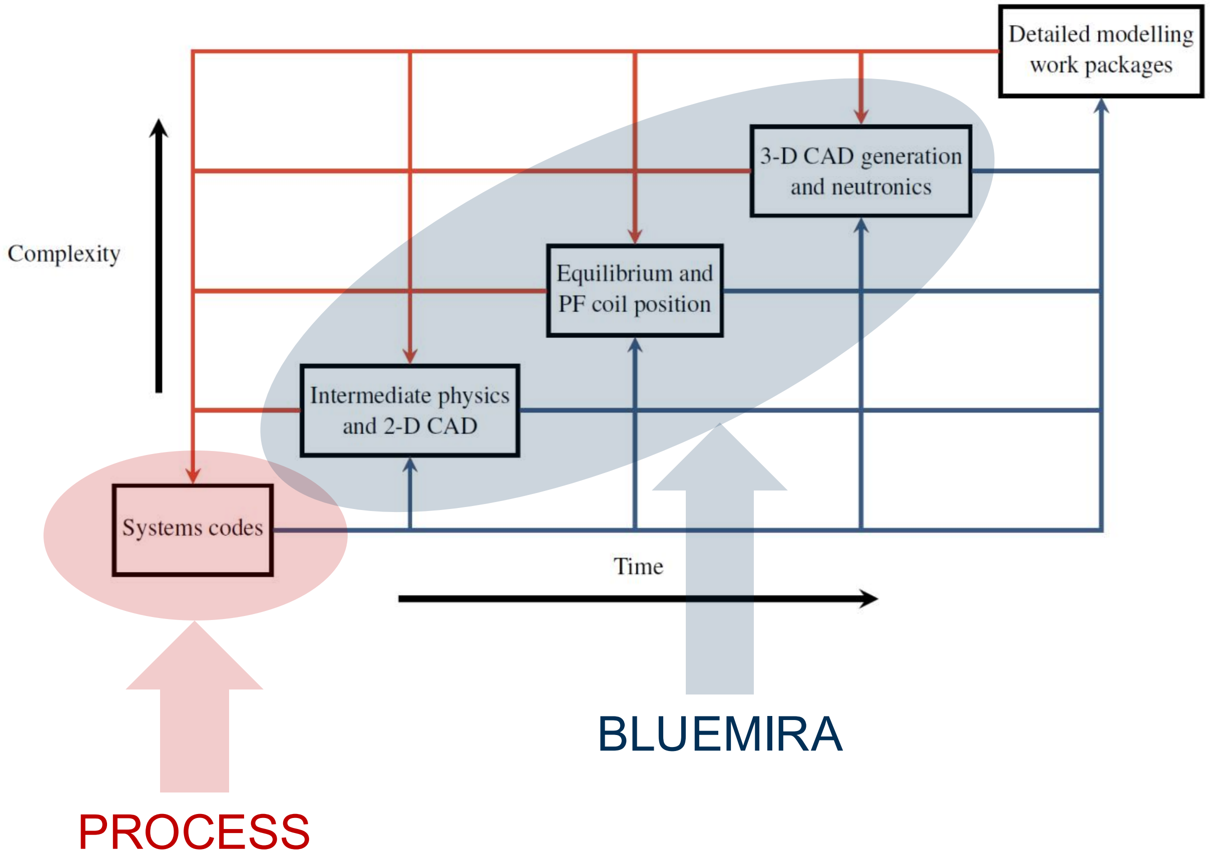
Rationale

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 and where sensible for what we are trying to achieve.



Features

Parameterised CAD

Reactor workflow

Coupling transport solver to FBE

Balance of plant

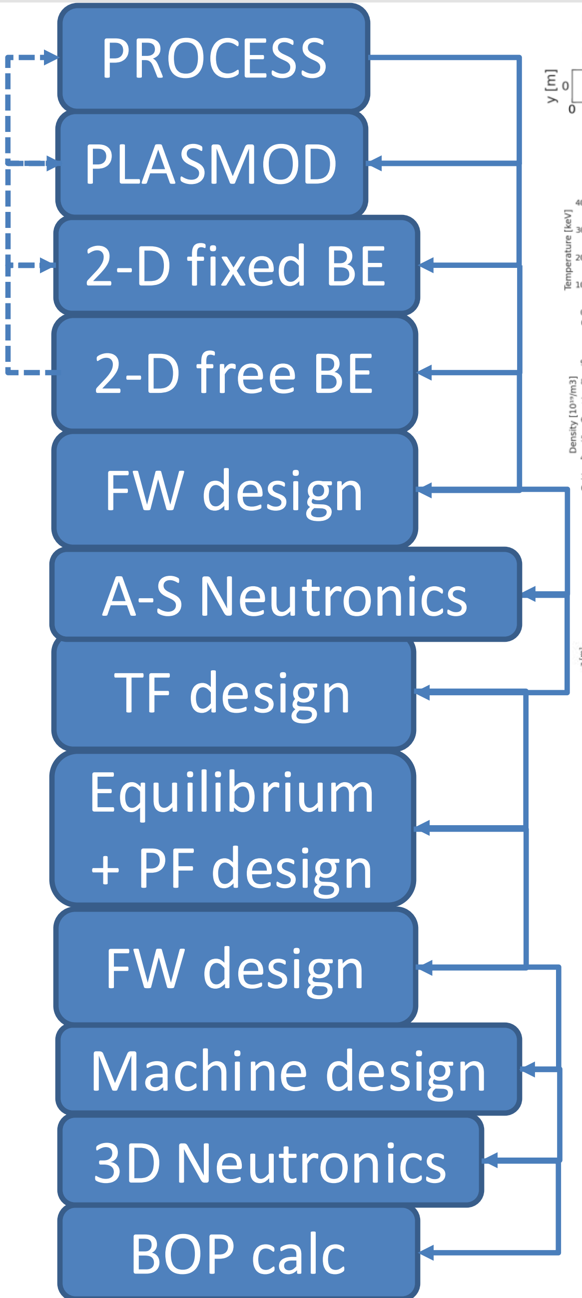
Systems code coupling

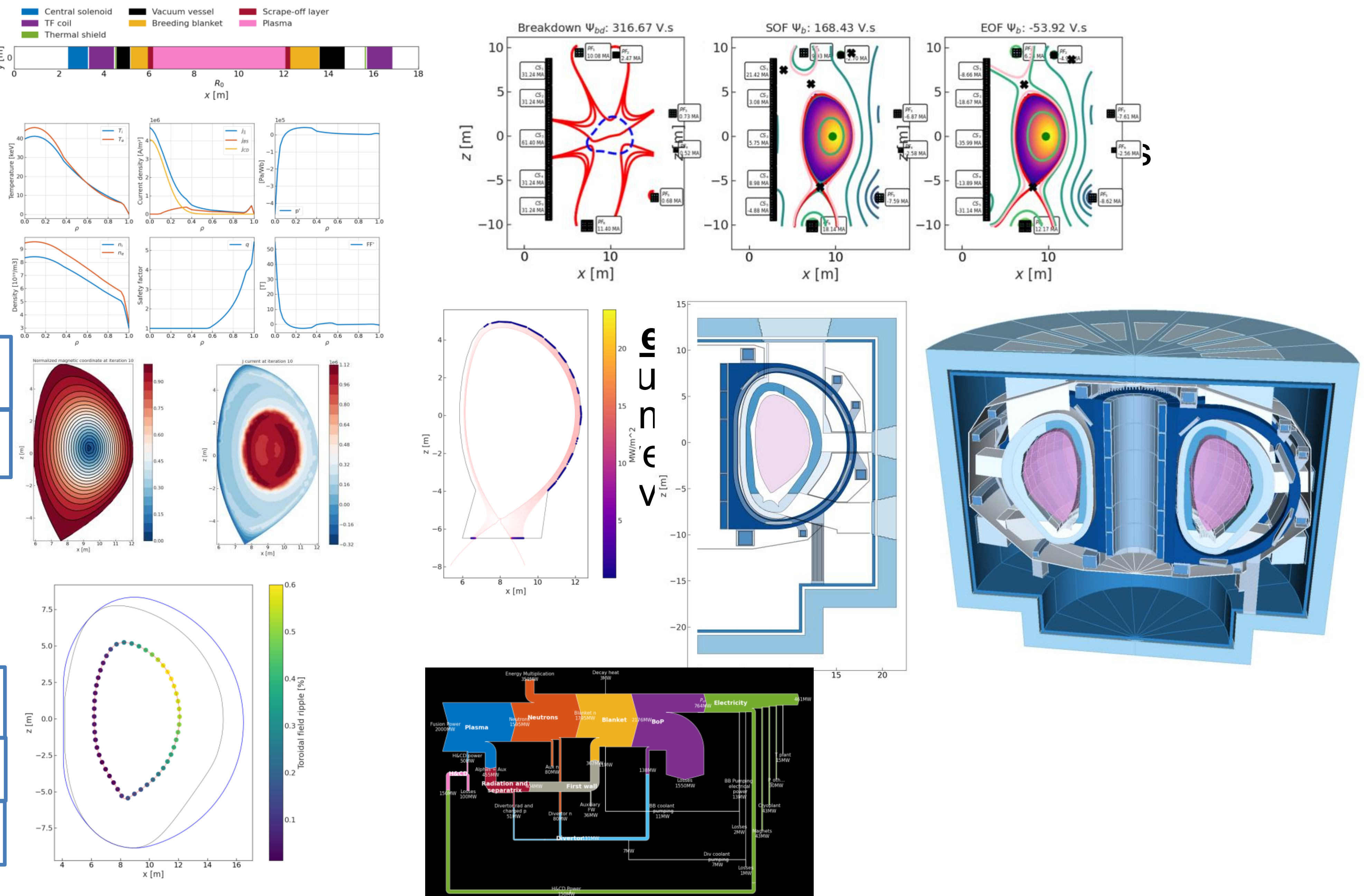
3-D CAD updates

3-D Neutronics

WP design

EU-DEMO workflow in BLUEMIRA





Outlook

Baseline

- BLUEMIRA not scheduled to be "officially" used to produce the baseline, but the baseline design was parameterised in BLUEMIRA as a use case.
- Used as part of the G2a EU-DEMO baseline in 2025 and subsequent design explorations (see e.g. [1]).
- Continuous interaction with EUROfusion regarding EU-DEMO:
  - Ensure the parameterisation in PROCESS and BLUEMIRA is as intended
  - Ensure input parameters and sub-models are up-to-date

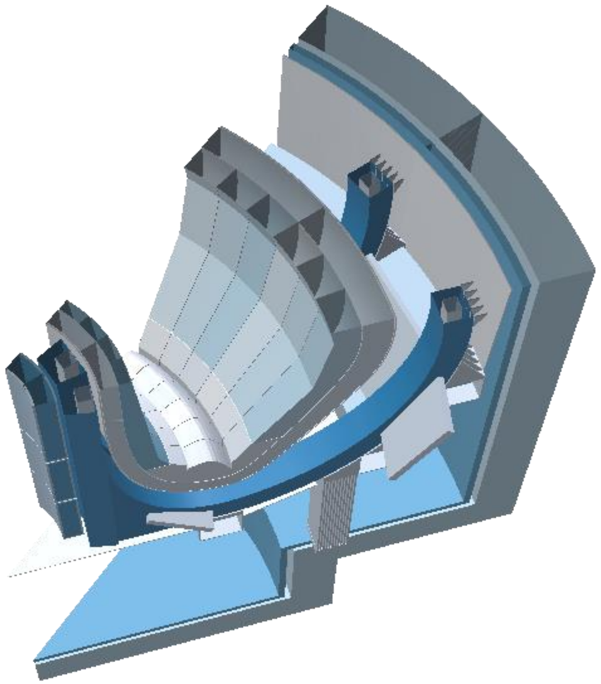
[1] Quartararo et al., "Systems codes", DEMO LAR Gate Review G2a, 17 November 2025

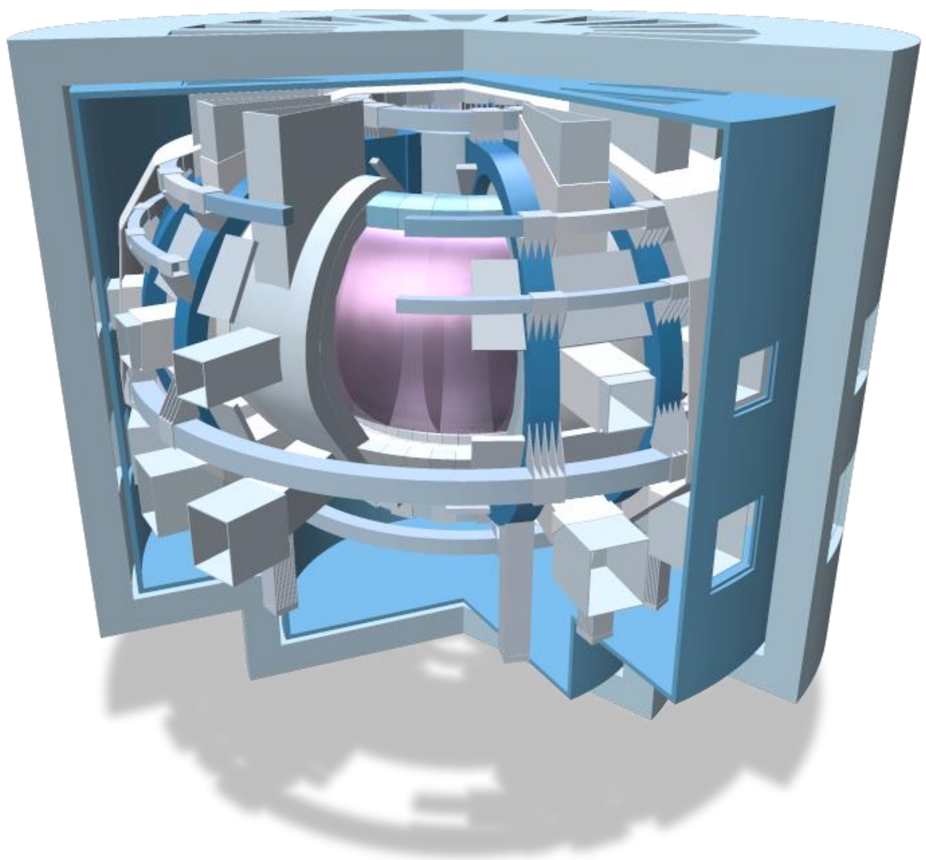
Features

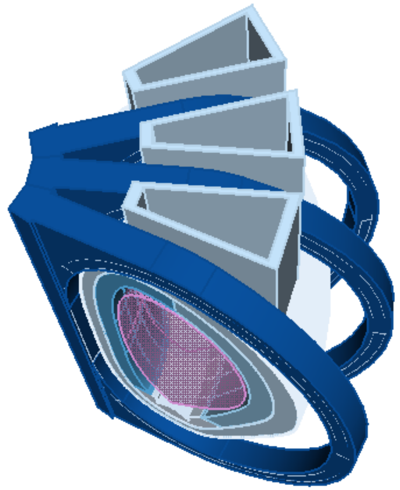
Parameterised CAD

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.







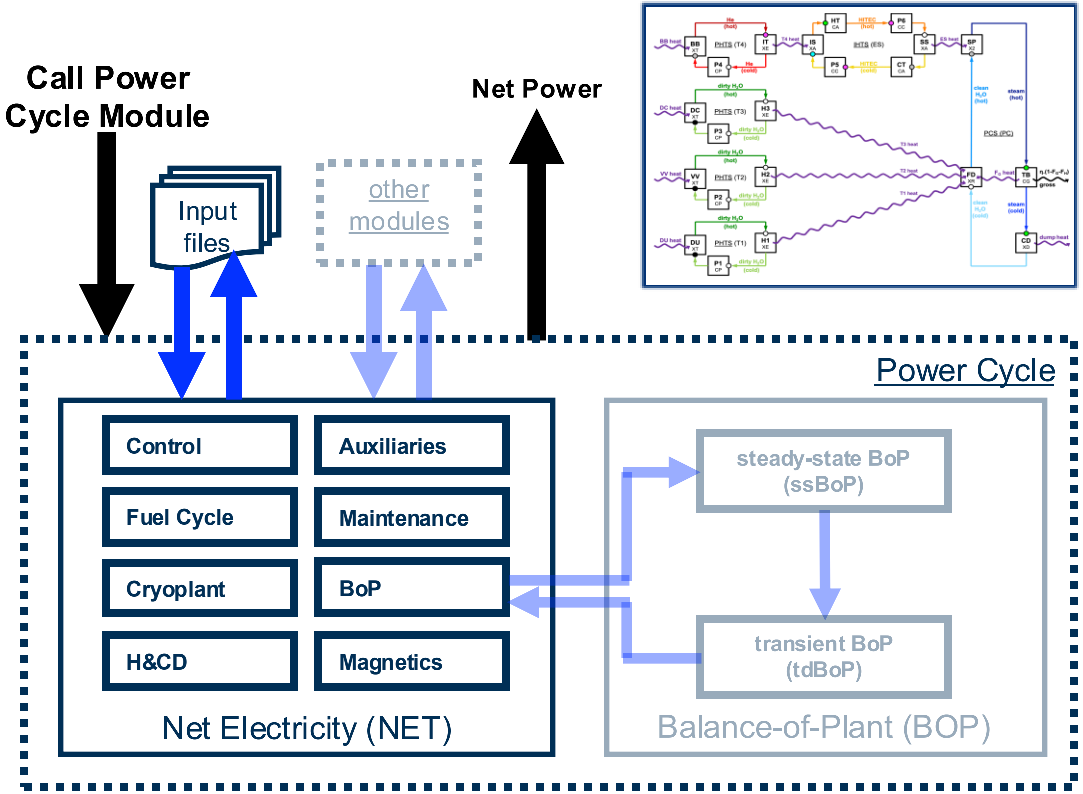
Features

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
  - Loads imported from other modules
  - 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
- Verified against:
  - Minucci et al Nuclear Fusion Project, Energies. 13 (2020)
  - Indirect-BOP HCPB EU-DEMO 2017 Baseline Model (E. Bubelis et al. Fus Eng Design 2018,2019)

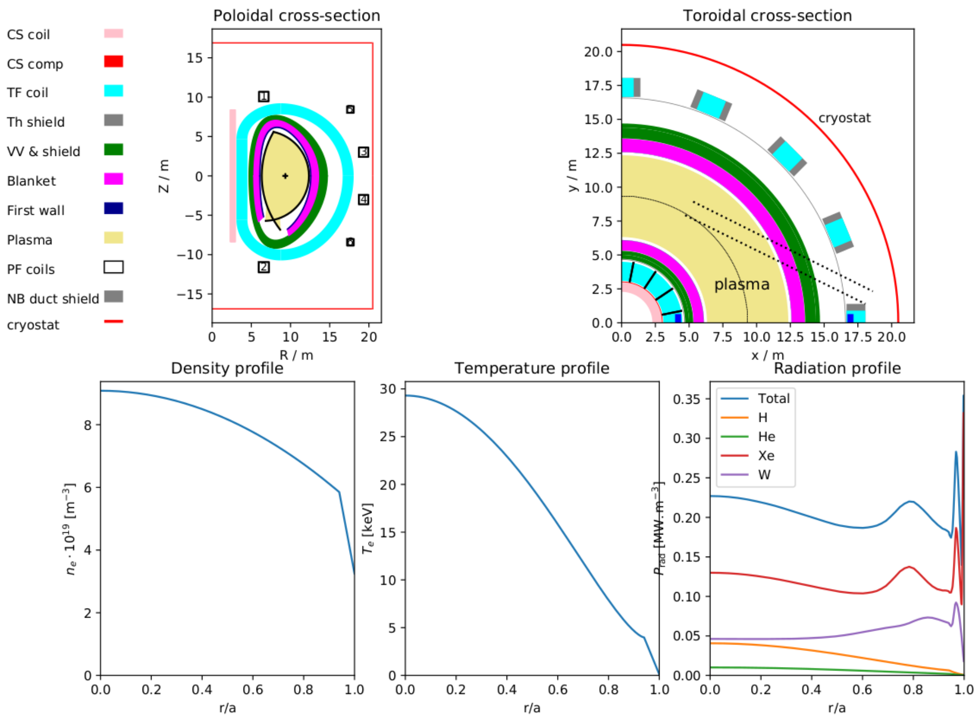


Features

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)

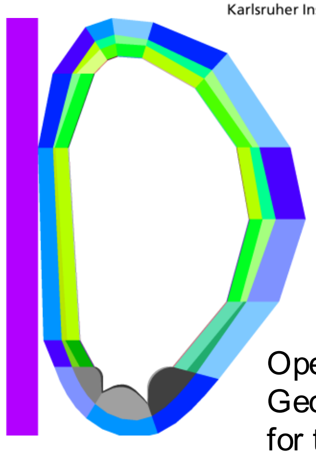
PROCESS is now open source under MIT licence and [available on GitHub]



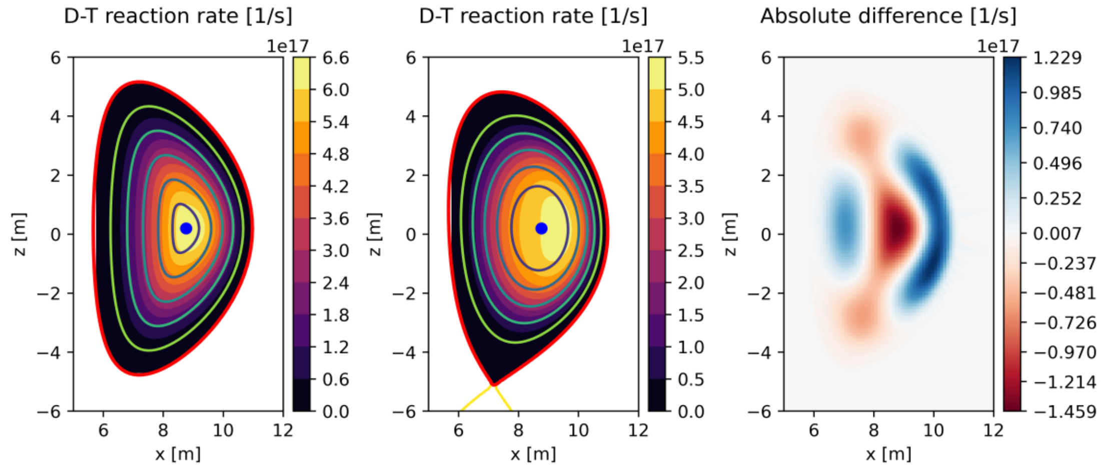
Features

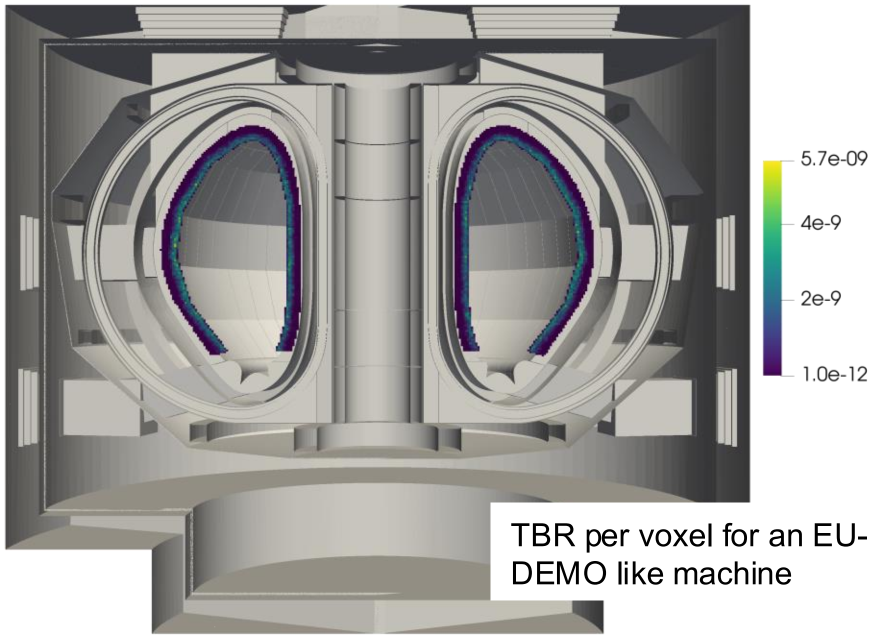
Neutronics

- Using OpenMC to calculate the neutronics quantities
  - TBR, heating, wall loads, etc.
- Creation of representative neutronics source python package *tokamak-neutron-source*[1]
- <u>Axis-symmetric 3-D case </u>to enable fast optimisation use in bluemira
- Non-axis symmetric case, handle more complex geometries



OpenMC Axis-symmetric Geometry divided into cells for tallying





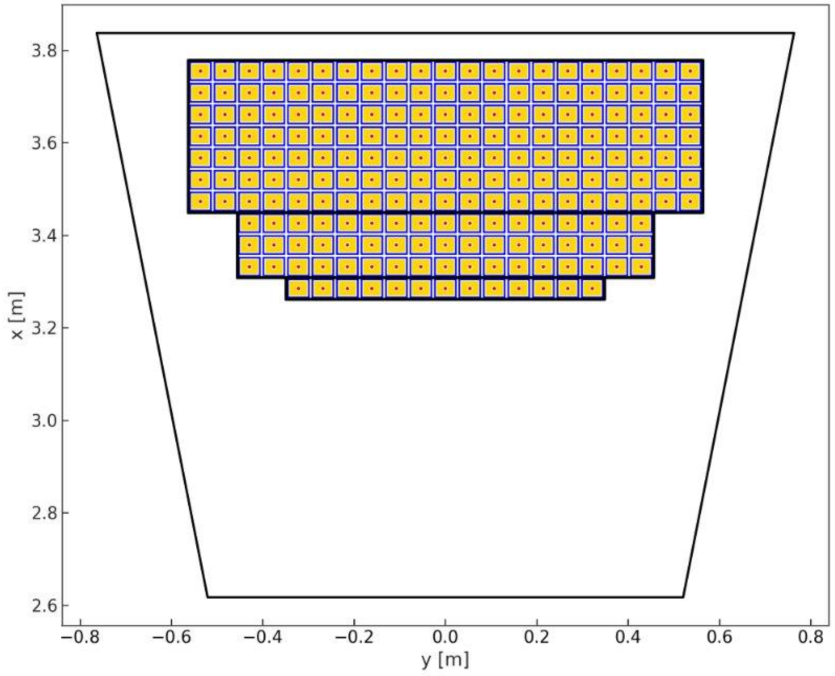
TBR per voxel for an EU-DEMO like machine

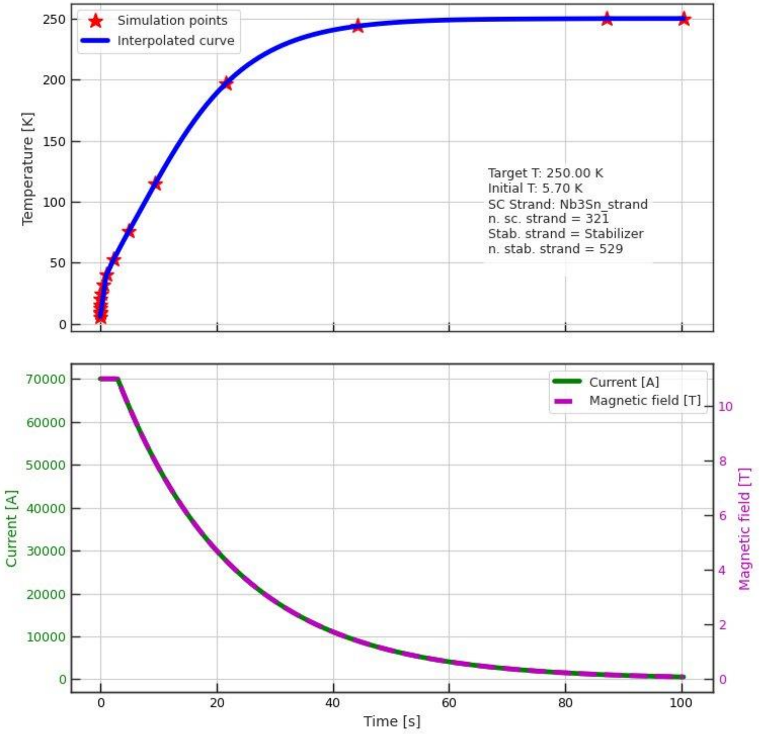
[1] github.com/Fusion-power-plant-framework/tokamak-neutron-source/

Features

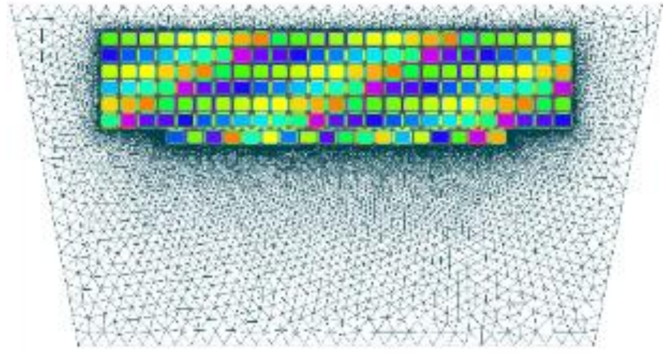
Winding pack design

- Winding pack design tool based on the MADE [1] methodology
- Simplified "spring analog" stress model
- Simplified quench model
- Minimal width TF design

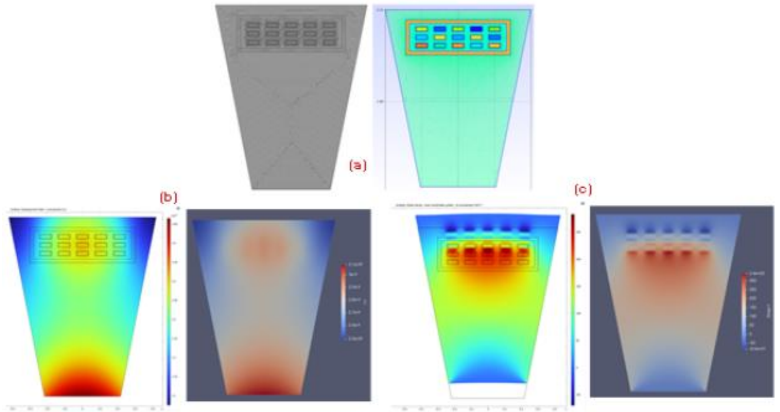




WIP: 2-D FE stress model



Benchmark with ANSYS and COMSOL

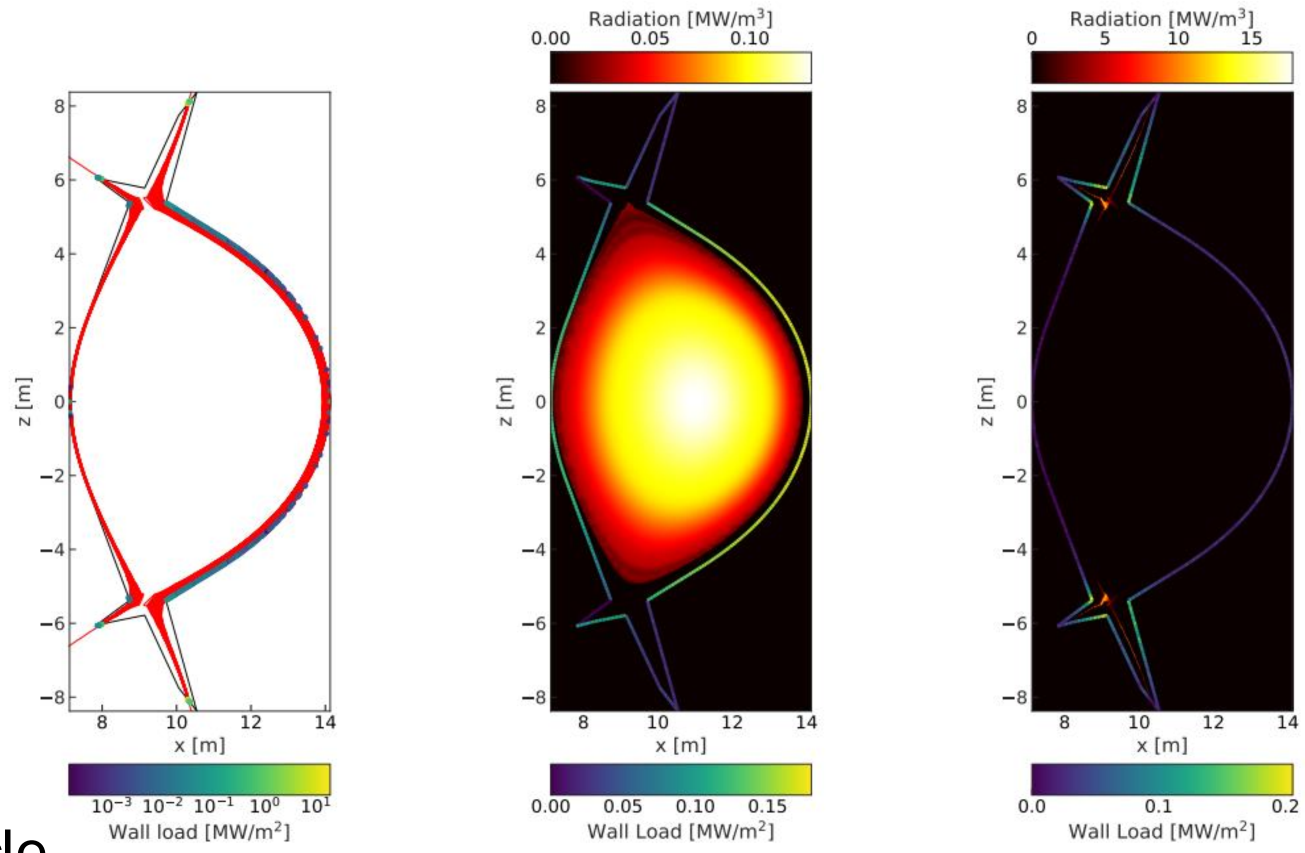


[1] Giannini et al., "The MAgnet Design Explorer algorithm (MADE) for LTS, Hybrid or HTS toroidal and poloidal systems of a tokamak with a view to DEMO", Fus. Eng. Des., **193**, 2023

Features

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.

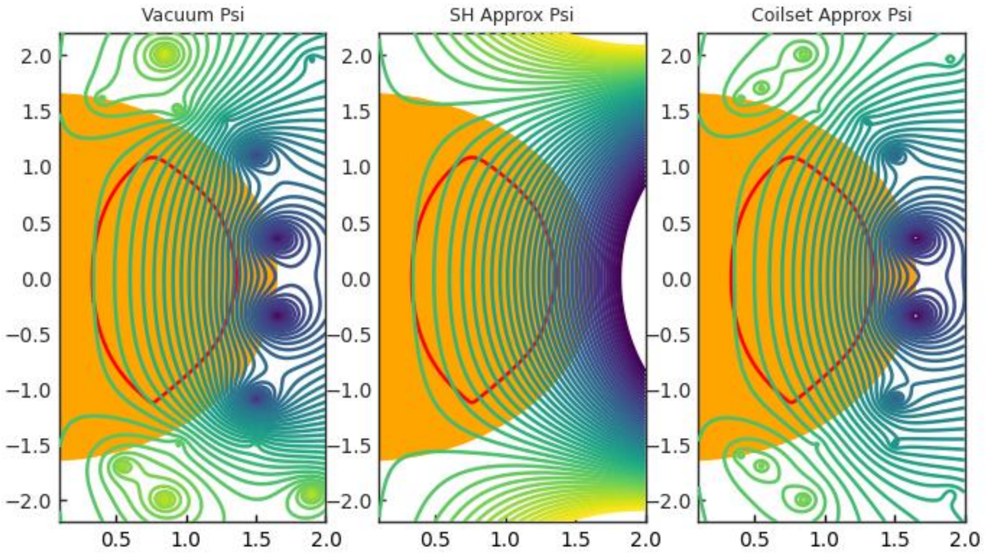


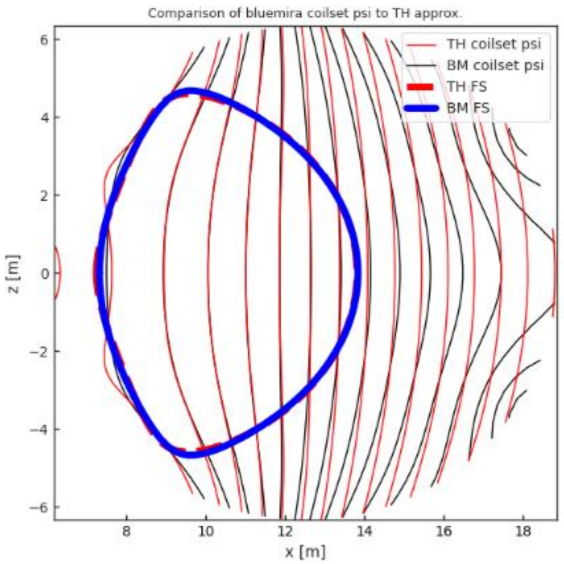
(a) Charged particle heat loads on the main chamber first wall. The red lines show the open flux surfaces carrying charged particles. (b) Core radiation source term and heat flux density on the first wall, as calculated by CHERAB. (c) SOL radiation source term and heat flux density on the first wall, as calculated by CHERAB

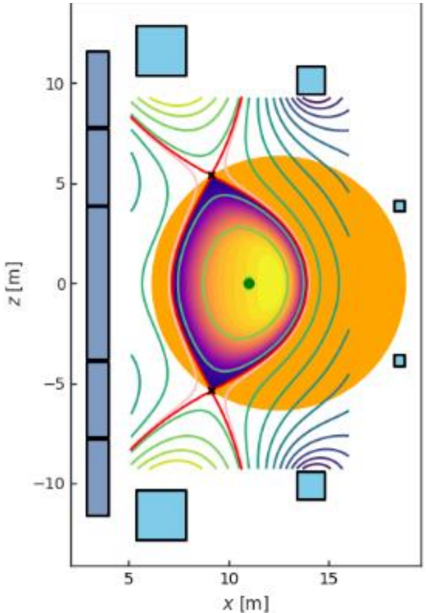
Features

Harmonics for equilibrium solving

- Harmonic constraints 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







General software development

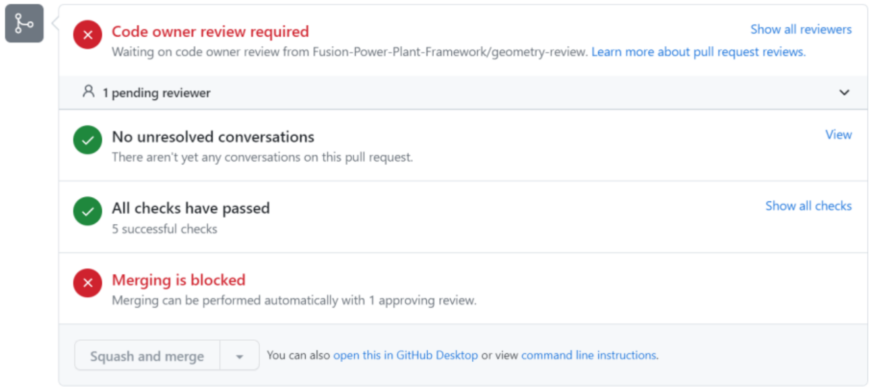
General software development

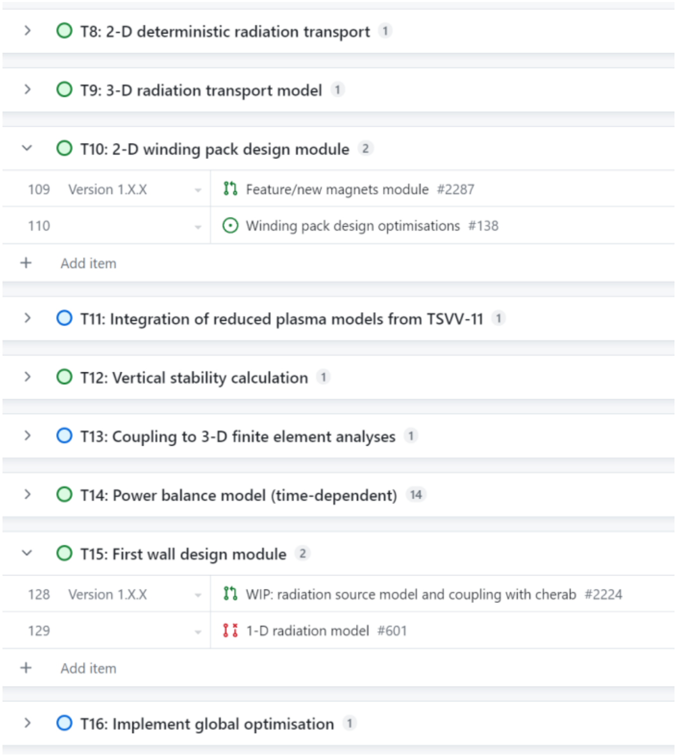
QoL, minor features, performance, …

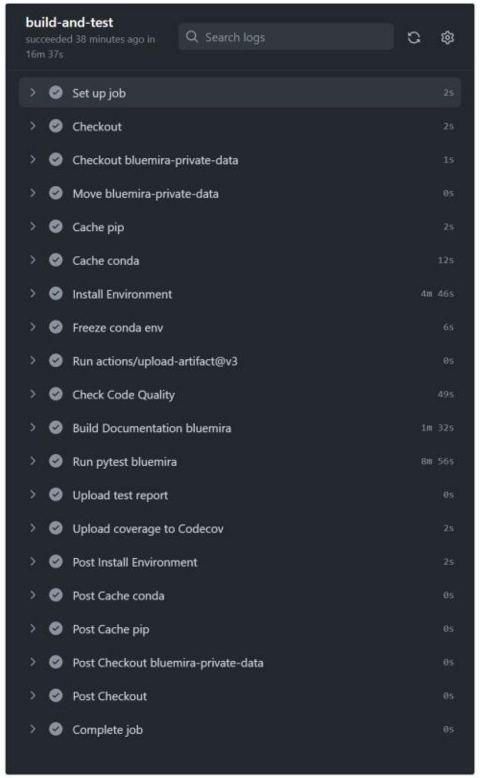
KIT Karlsruher Institut für Technologie

UK Atomic Energy Authority

- 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 the repository, and in the near future, available on PyPi
- Releases ~6 week since mid 2021







Packages and "Middleware"

github.com/Fusion-Power-Plant-Framework

- BLUEMIRA
- EQDSK – interface to g-eqdsk (with COCOS) and conversion to imas-ids
- tokamak-neutron-source – Representative neutron source
- matproplib – Bulk Materials Property Library dependent on conditions (temperature, pressure, magnetic field, strain...)
- fast-ctd – A fast converter from CAD to DAGMC neutronics compatible mesh

github.com/ukaea

- PROCESS

Users and developers

Users and developers

BLUEMIRA community

Core development team – 8 Members (UKAEA – 5, KIT – 3)

Users/followers/contributors – UKAEA ~50 (RACE, STEP, Digital, IED), External ~30 (VTT, STEP EDP, TE, PPPL, GA), Github Stars - 93

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.

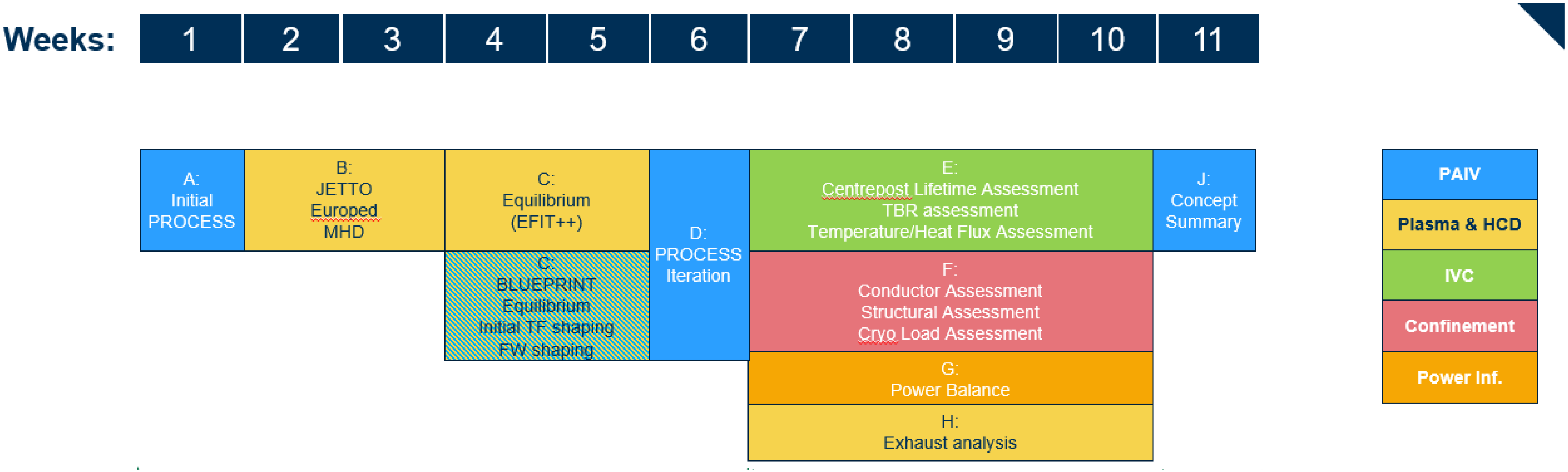
Complementary work

STEP Concept design

ROBUST Blanket design workflow

Complementary work

STEP – Programme use

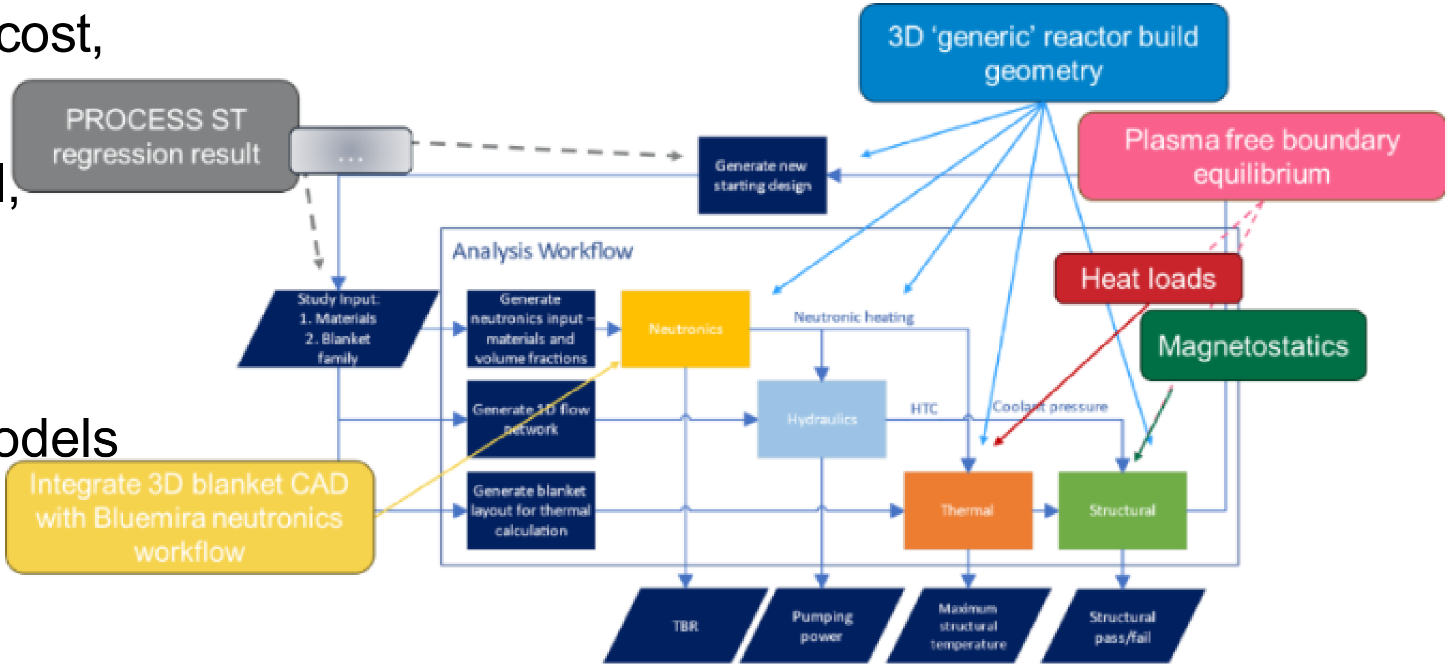


Active userbase using bluemira on a reactor design programme was generally beneficial for reviewing our workflow, user experience, coupling to other codes, and bug finding etc.

Complementary work

ROBUST (Reliability Optimised Blankets under Simulation and Test)

- Using PROCESS and Bluemira as part of (and a starting point for) a high fidelity blanket design pipeline
  - Outputs from PROCESS for duty cycle, cost, some plasma properties
  - Ouputs from BLUEMIRA used for spatial, thermal and magnetostatic data
  - Enable comprehensive reactor systems integration and improve breeder-blanket down-selection through higher fidelity models and plant-level data.



Summary

Deliverables

Karlsruher Institut für Technologie

UK Atomic Energy Authority

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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

Lessons learned

- Merging code bases had significant overhead
- Transition from discretised to primitive CAD much more involved than first estimated
- Overhead in getting started with bluemira for new machine types is mostly around creating “builders”
- Securing buy-in from end-users is challenging

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.
- EU-DEMO workflow constructed and used as part of the 2025 baseline design workflow.
- Balance of plant model implemented.
- Winding pack tool completed with initial set of features
  - 2-D FE stress model in progress
- Neutronics workflows completed (including high-fidelity neutron source term)
  - Fast axisymmetric CSG model
  - Slower CAD-based model
- Bluemira overview paper submitted and available on pinboard (Coleman et al. 2025)