Introducing the BLUEMIRA fusion reactor design framework

M. Coleman[a,b,c,*], J. E. Cook[a], F. Franza[d], I. A. Maione[d], S. McIntosh[e], A. I. Blair[a], S. Desai[a], O. Funk[a], G. Graham[a], J. Matthews[a], J. Morris[a], C. Mould[a], A. Nilima[a], H. R. D. Saunders[a], D. Short[a], D. Vaccaro[a], O. Wong[a]

[a]United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon, OX14 3DB, United Kingdom
[b]EUROfusion, Boltzmannstr. 2, Garching, 85748, Germany
[c]Delta X Fusion S.L.U., Calle del Horno 2, Paracuellos de la Ribera, 50299, Spain
[d]Karlsruher Institut für Technologie, Hermann-von-Helmholtz-Platz 1, Eggenstein-Leopoldshafen, 76344, Germany
[e]ITER Organisation, Route de Vinon-sur-Verdon, 13067 St. Paul-lez-Durance, CS 90 046, France

UK Atomic Energy Authority

Outline

- Introduction

- Selected BLUEMIRA modules

- Case studies

- Next steps

Introduction

Dozens of organisations are presently designing fusion power reactors across the world.

Most of their concepts are MCF, many of which are tokamaks.

Introduction

The fact that many people are designing fusion power reactors is not new… but the nature of fusion research is changing.

Many organisations successfully use systems codes to inform their initial design stages, rapidly iterating low-fidelity design points.

When moving to higher fidelity concept designs, however, progress tends to slow down.

- A broad set of multi-disciplinary skills are required

- Different tools are used sequentially, passing assumptions, load cases, etc.

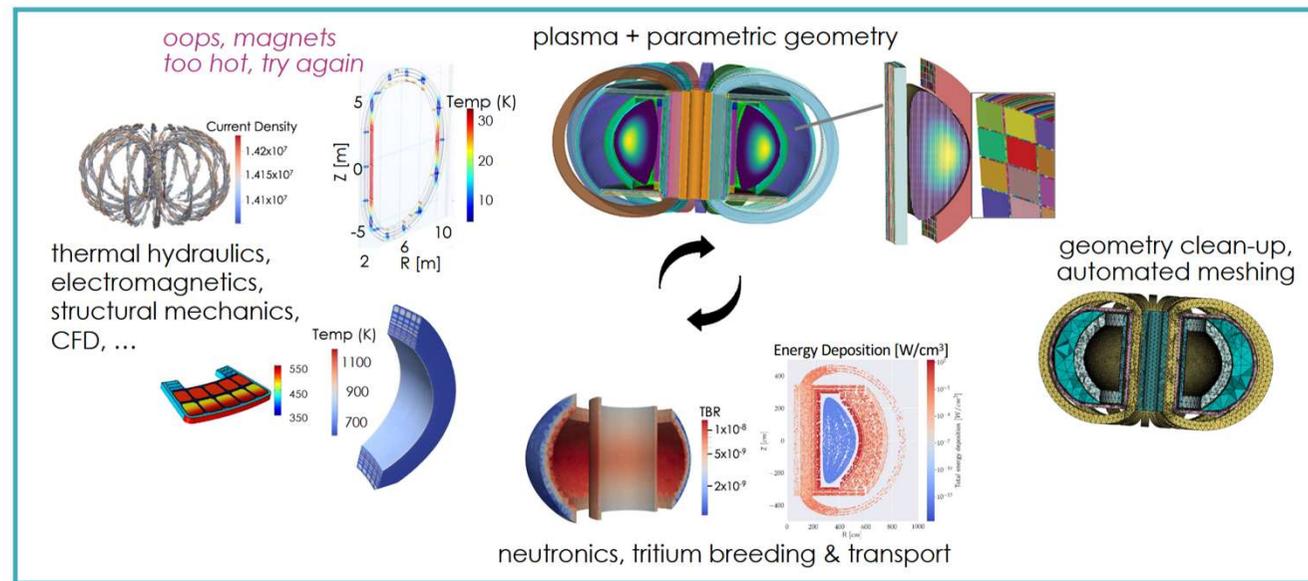- Reaching a concept design and changing that design can be a very slow exercise…
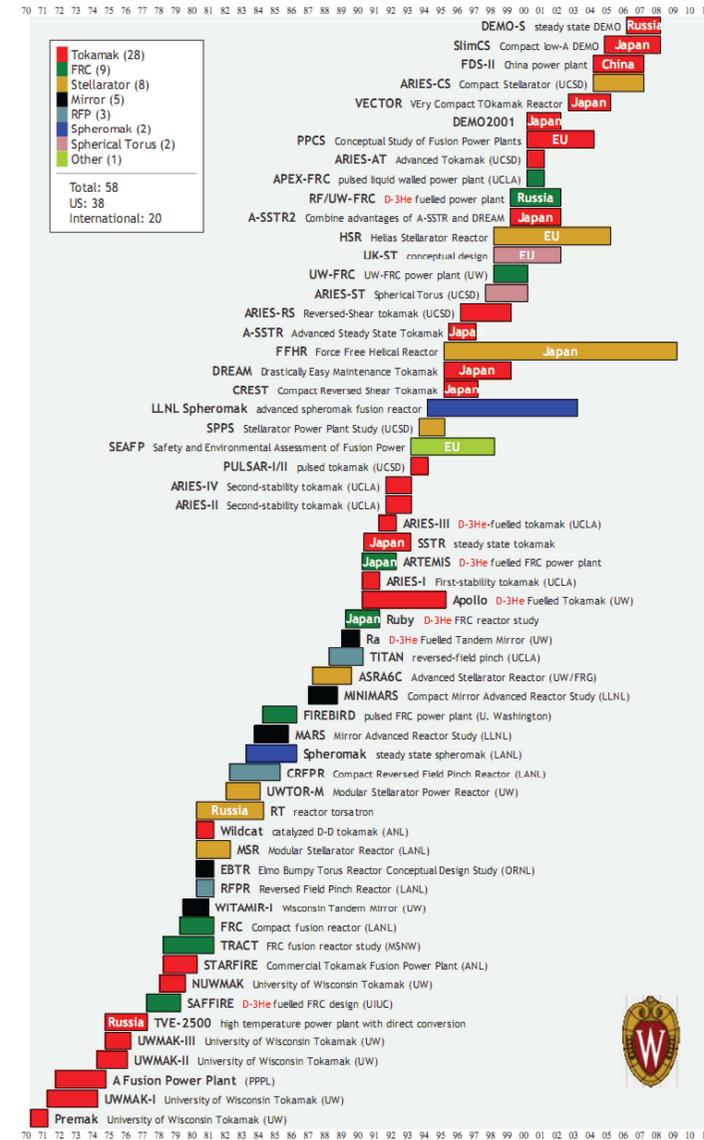
[1] El-Guebaly, Fifty Years of Magnetic Fusion Research (1958–2008)

Speeding up the design cycle

Several authors have noted the challenges that higher fidelity fusion reactor design cycles pose, and have proposed tools to address them:

- MIRA [2, 3]
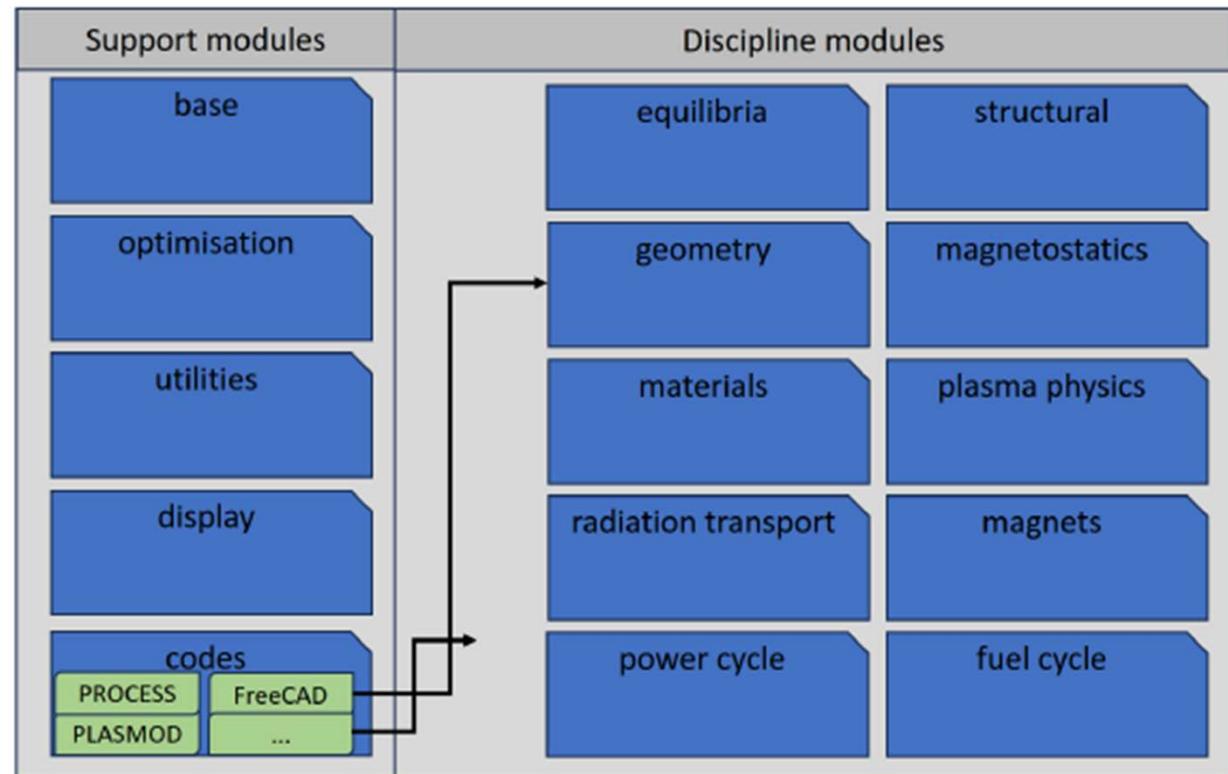- BLUEPRINT [4, 5]
- FUSE [6, 7]
- FREDA [8, 9]

[9]

Software, status, structure

BLUEMIRA:

- Collaboration between UKAEA and KIT
- Version: 2.11.0
- License: LGPLv2.1+
- Language: Python 3.11 - 3.12
- Platform: Linux // WSL2 // (MacOS WIP)
- Modular

Other associated software:

- eqdsk (v 0.8.0)
- matproplib (v 0.0.1)
- tokamak-neutron-source (v 0.1.4)
- fast-ctd (v 0.1.1)

BLUEMIRA modules

0/1-D radial build solver: PROCESS [10, 11]

BLUEMIRA has a generic interface to 0/1-D "systems codes". We actively maintain an interface to PROCESS (latest release).

PROCESS is a simple but sophisticated systems code which we typically use as the starting point for a design workflow. It solves a "full reactor" constrained design optimisation problem and produces a 0/1-D design point.

The radial build, plasma profiles, and 0-D parameters are extracted and used in subsequent activities.
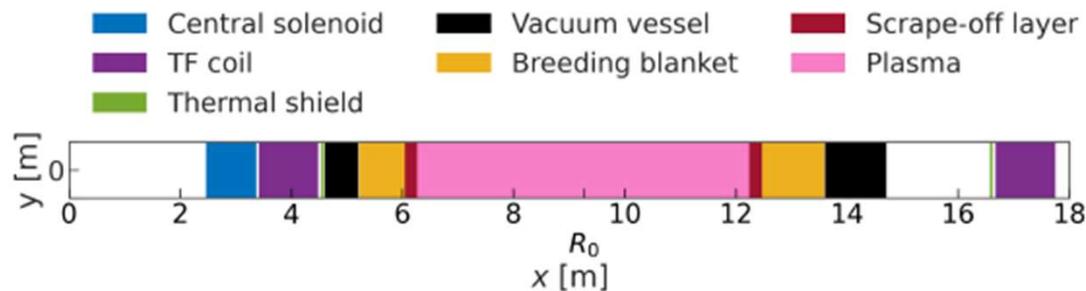
Magnetostatics – (1/2)

BLUEMIRA has a range of 2-D and 3-D analytic and semi-analytic uniform current density source terms:

- Green's functions (ψ, B_x, B_z, ..)
- Poloidal ring of rectangular cross-section
- Biot-Savart filaments
- Trapezoid of rectangular cross-section
- Circular arc of rectangular cross-section

Fast and accurate calculations of magnetic fields without resorting to finite elements.
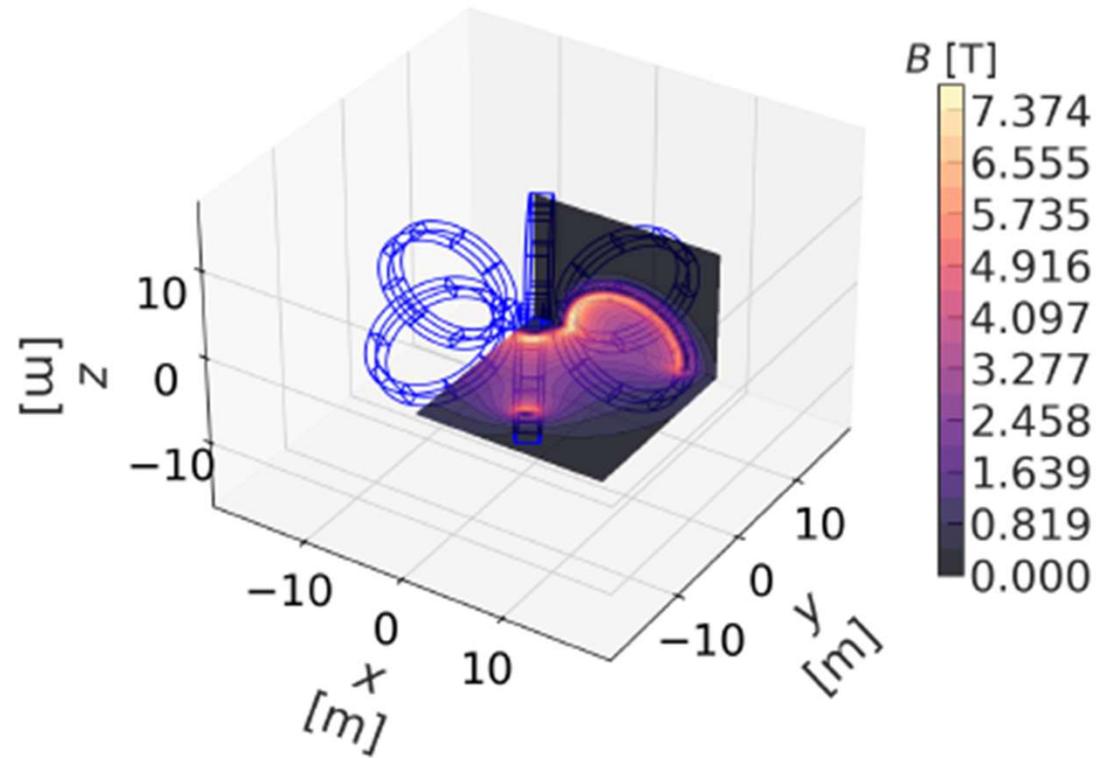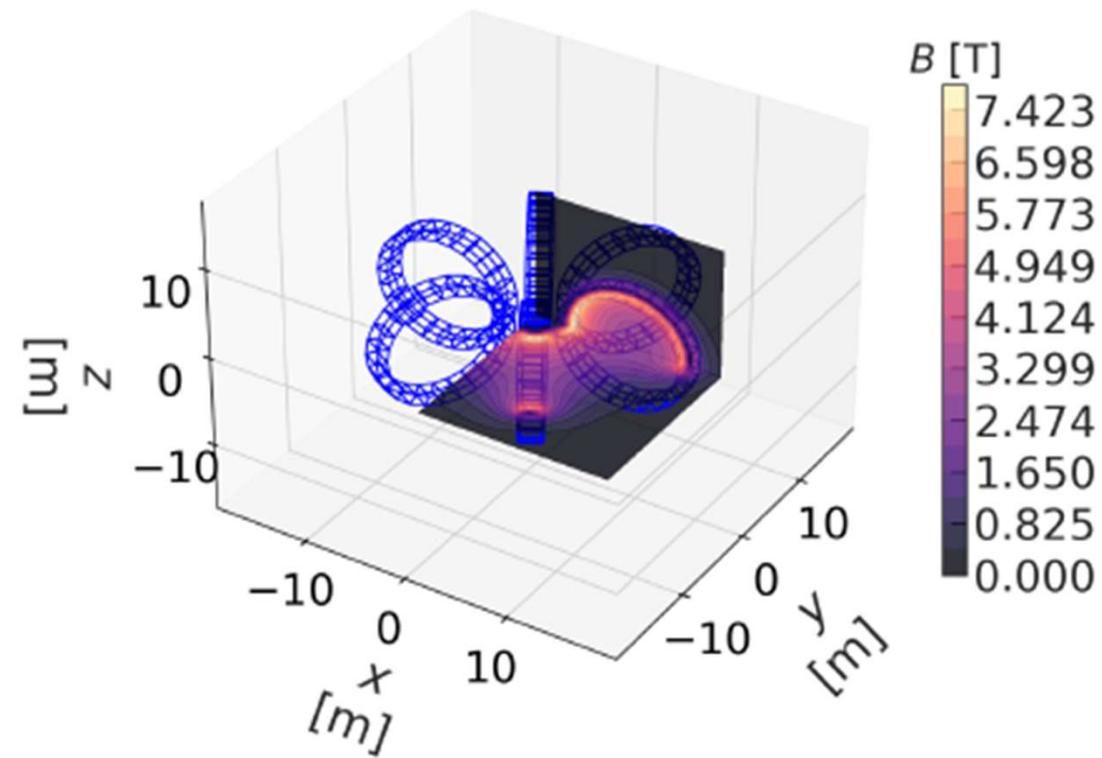
$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0 I}{4\pi} \int_{\mathcal{L}} \frac{d\mathbf{l} \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3}$$

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \iiint_{\mathcal{V}} \frac{\mathbf{J}(\mathbf{r}') \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} d\mathbf{r}'$$

where:

$d\mathbf{l}$ = differential vector of a current-carrying path

$\mathbf{r}$ = sink point $\{x, y, z\}$ at which the field is to be calculated

$\mathbf{r}'$ = source point $\{x', y', z'\}$ containing the centre of the current source

$\mathcal{L}$ = length domain where the current flows

$d\mathbf{r}'$ = differential volume of a current-carrying element

$\mathbf{J}$ = current density vector

$\mathcal{V}$ = volume domain where $\mathbf{J}$ is defined

Magnetostatics – (2/2)

| **M. Coleman – Introducing the BLUEMIRA fusion reactor design framework – OSSFE, 11/03/2026, Munich, Germany**

Equilibria – (1/2) free boundary solver

Free boundary solver:

- Static, inverse
- Finite difference
- Arbitrary profiles (incl. formulations to match $\{\beta_p, l_i, I_p\}$)
- Benchmarked with CREATE [12], FreeGSNKE [13]

Equilibrium constraints:

- Flux
- Isoflux
- Radial, vertical field
- ...

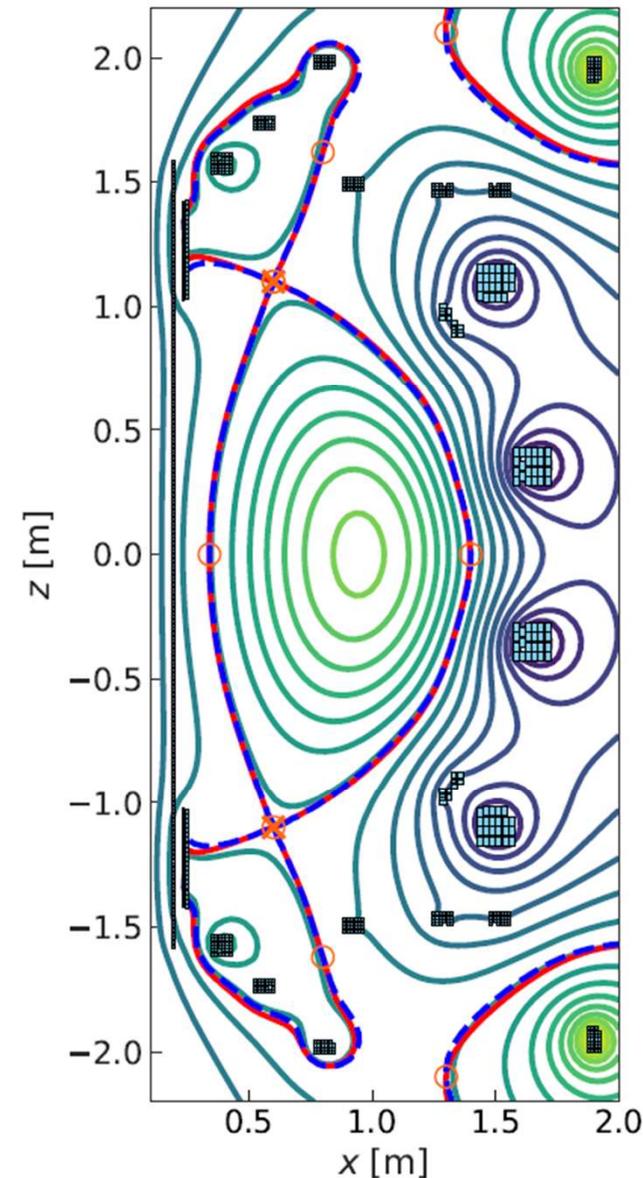$$\mathbf{GI} - \mathbf{b_t} + \mathbf{b_p} = 0$$

where:

$\mathbf{G} = n_t \times n_c$ matrix of unit current responses at the control points

$\mathbf{I} = n_c$ vector of coil currents

$\mathbf{b_t} = n_t$ vector of desired target values

$\mathbf{b_p} = n_t$ vector of passive current contributions (including the plasma)

Equilibria – (2/2) additional features

- Solve a variety of constrained optimisation problems, e.g:

- Routines for constrained coil position and current optimisation

- Up-down symmetric coils and equilibrium solve

- Spherical [15] and toroidal harmonic [16] constraints

- RZIp [17] implementation, benchmarked with FIESTA [18]
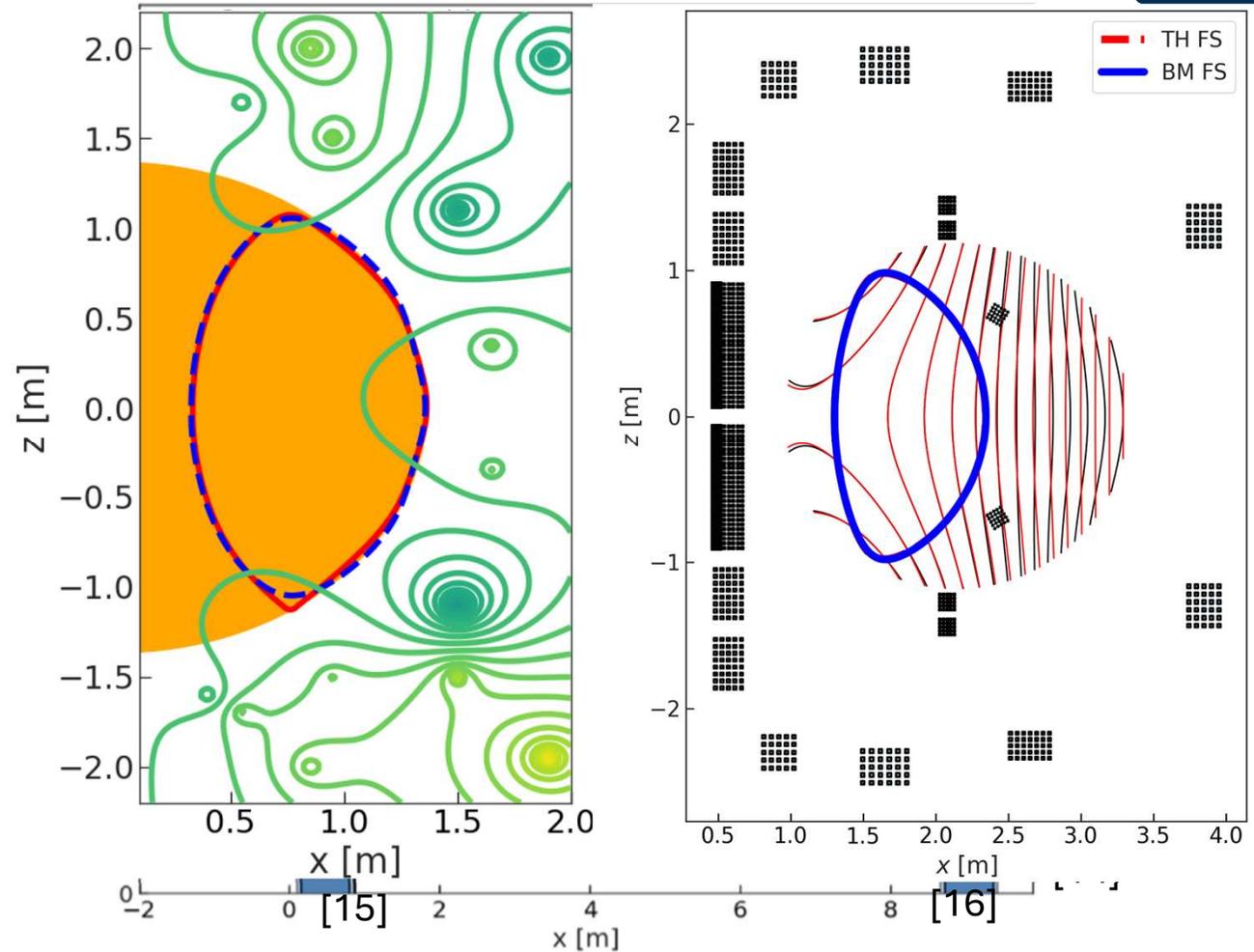
Geometry – (1/2)

Geometry in BLUEMIRA is provided in terms of native CAD "primitives" (boundary representations)

- OpenCASCADE is wrapped by FreeCAD, which is wrapped in BLUEMIRA. This is to protect users from API changes…

- Primitive geometry representation does away with some discretisation issues, and facilitates interfacing with meshing and finite element codes

- FreeCAD and Polyscope viewers

Geometry – (2/2)

Geometry parameterisations are provided to enable optimisation of geometry

- Built-in geometrical constraints (e.g. tangency)

- Different parameterisations can be used in the same optimisation problems

- Enables different topologies to be explored
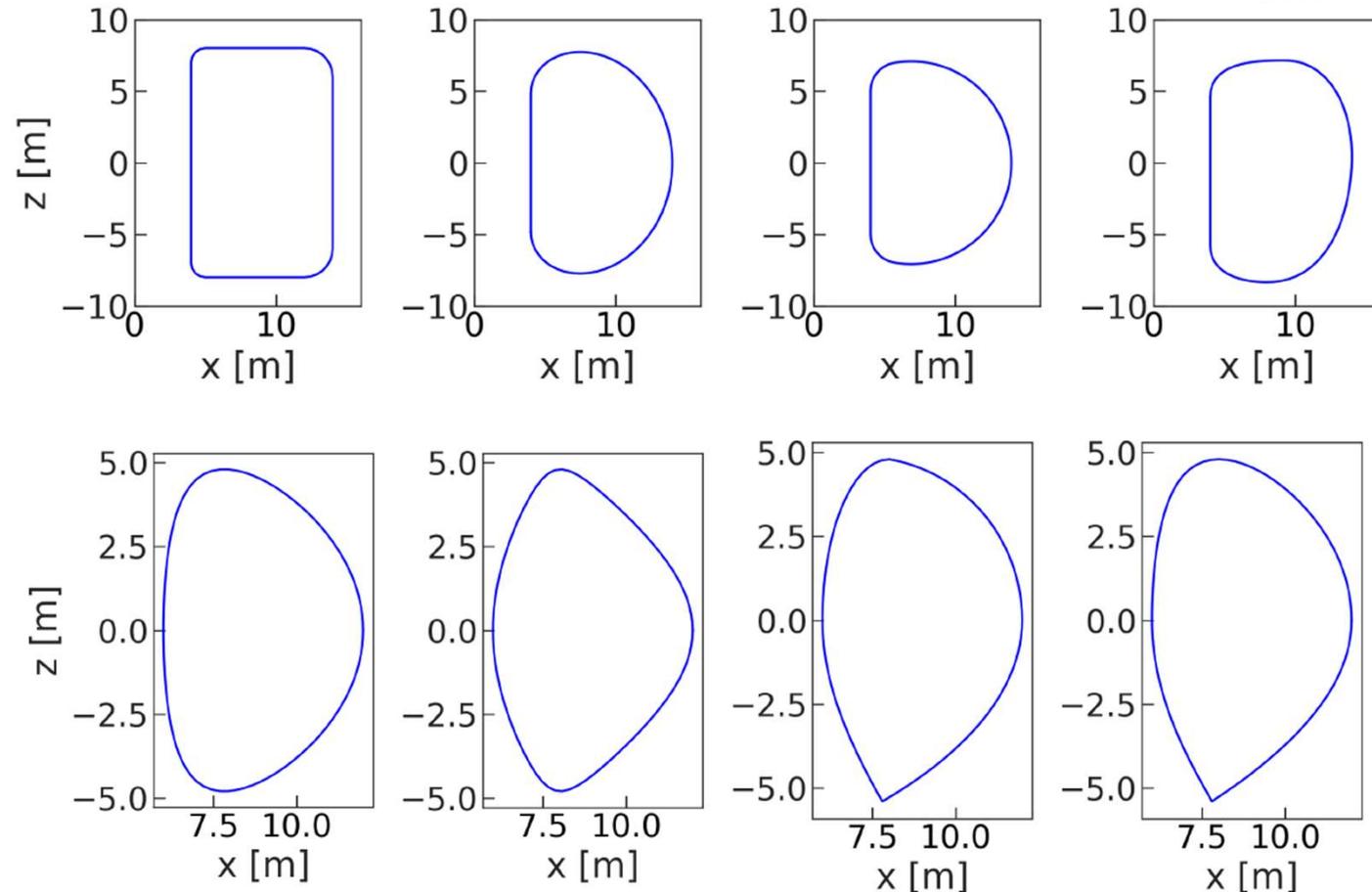
Materials

A materials property library package, <u>matproplib</u>, is used in BLUEMIRA.

- Create materials and mixtures of materials

- Define material composition

- Assign material properties that depend on operational conditions

- Interfaces to:
  - Neutronics codes (<u>OpenMC</u> [20], <u>MCNP</u>, …)
  - FE codes (work in progress)

- Set of publicly available materials

- Private materials (e.g. EUROfer97, CuCrZr, etc.) hosted separately
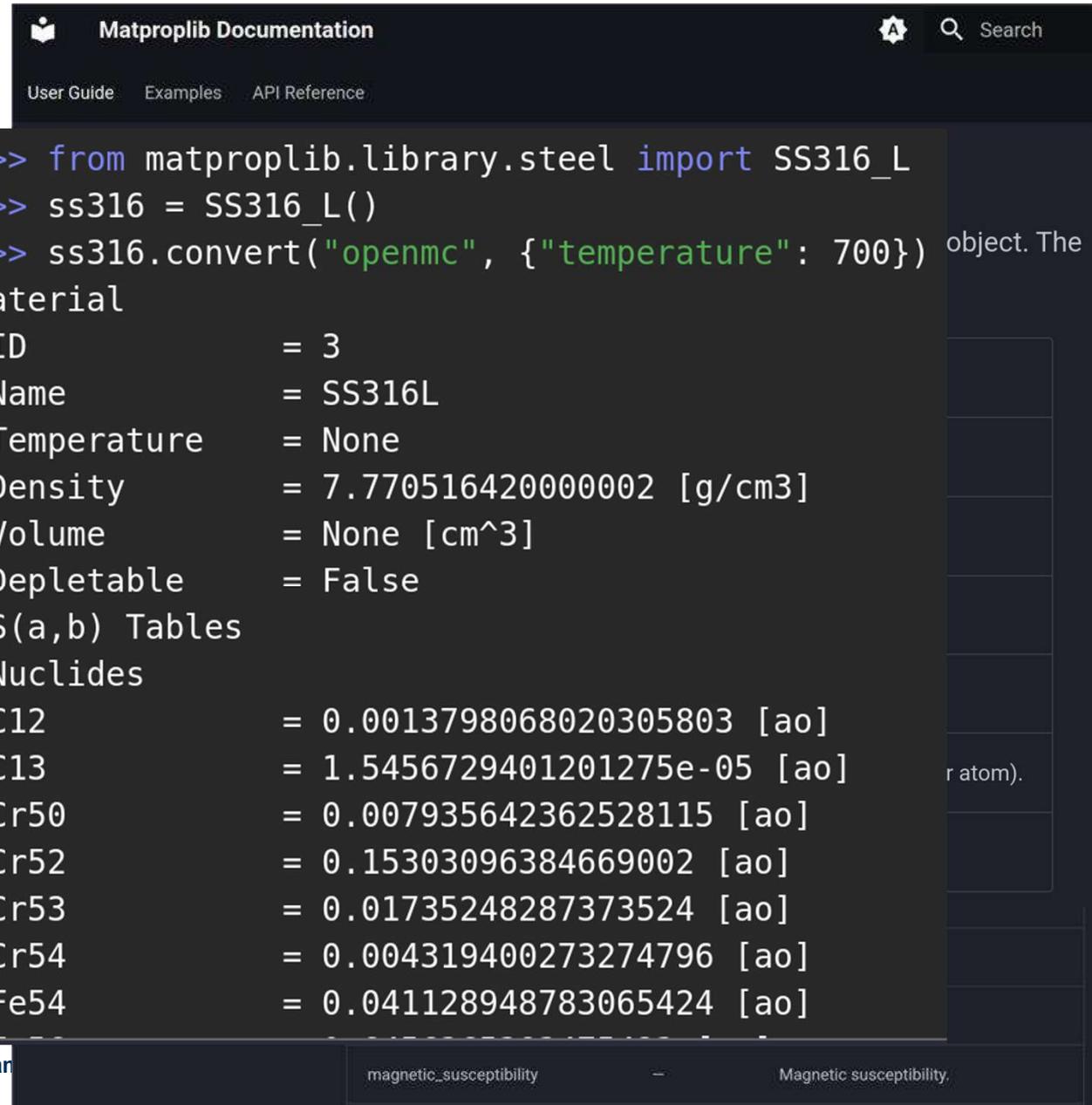
Matproplib Documentation

User Guide   Examples   API Reference

```
>>> from matproplib.library.steel import SS316_L
>>> ss316 = SS316_L()
>>> ss316.convert("openmc", {"temperature": 700})
Material
  ID             = 3
  Name           = SS316L
  Temperature    = None
  Density        = 7.770516420000002 [g/cm3]
  Volume         = None [cm^3]
  Depletable     = False
  S(a,b) Tables
  Nuclides
  C12            = 0.0013798068020305803 [ao]
  C13            = 1.5456729401201275e-05 [ao]
  Cr50           = 0.007935642362528115 [ao]
  Cr52           = 0.15303096384669002 [ao]
  Cr53           = 0.0173524828737373524 [ao]
  Cr54           = 0.00431940027327479 6 [ao]
  Fe54           = 0.041128948783065424 [ao]
```
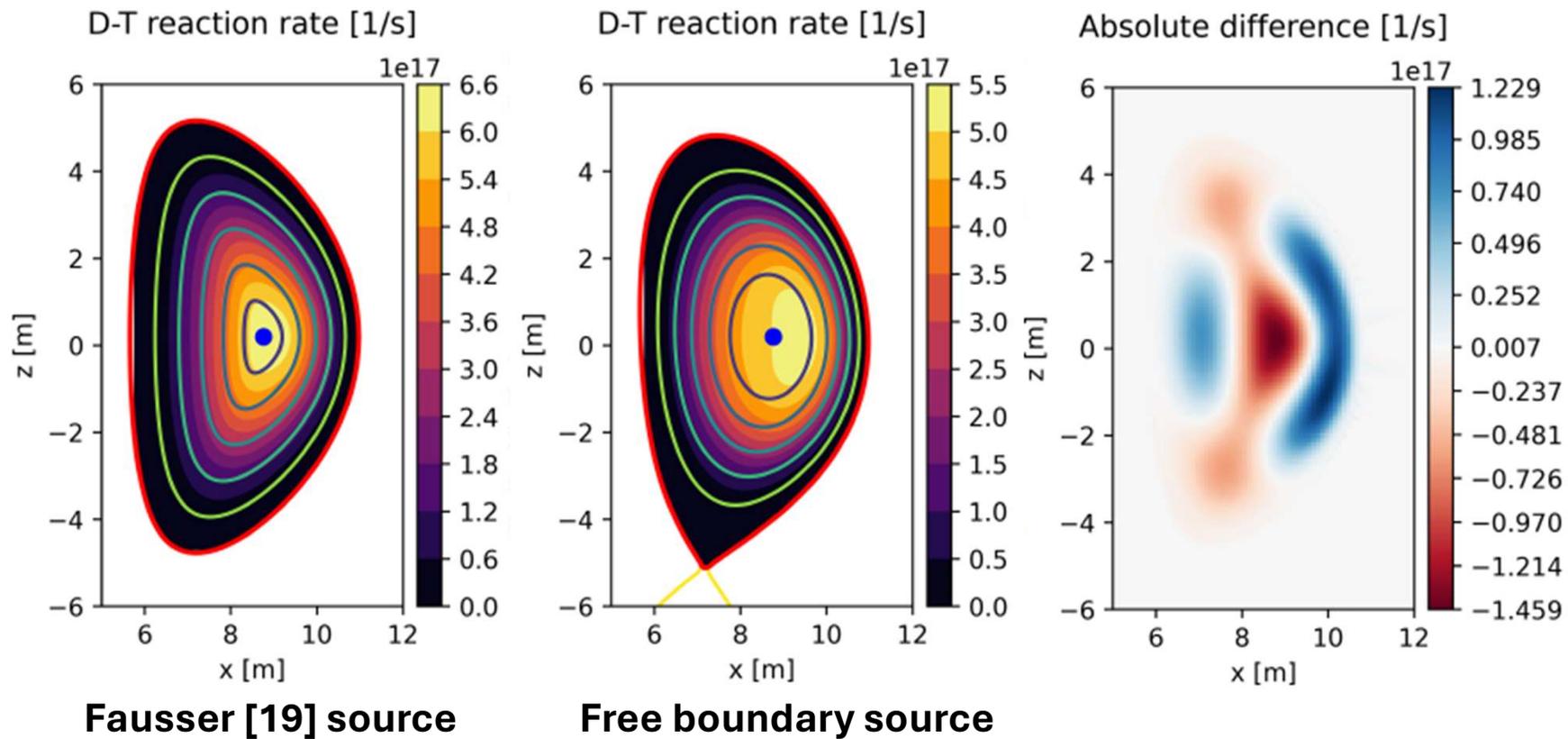
magnetic_susceptibility   —   Magnetic susceptibility.

Neutronics – (1/3) source term

tokamak-neutron-source can create a highly representative thermal fusion neutron source, which can take arbitrary plasma profiles and MHD equilibria as inputs.

**Fausser [19] source**   **Free boundary source**

Neutronics – (2/3) axisymmetric CSG

An axisymmetric CSG neutronics pipeline in OpenMC [20] for tokamaks:

- Simplified geometry (blankets, divertors, vacuum vessel)

- Blanket split into 3 different materials

- CSG cells, predominantly polygons (cones and planes)

- Runs relatively fast (100,000 neutrons x 3 batches in ~3 minutes)
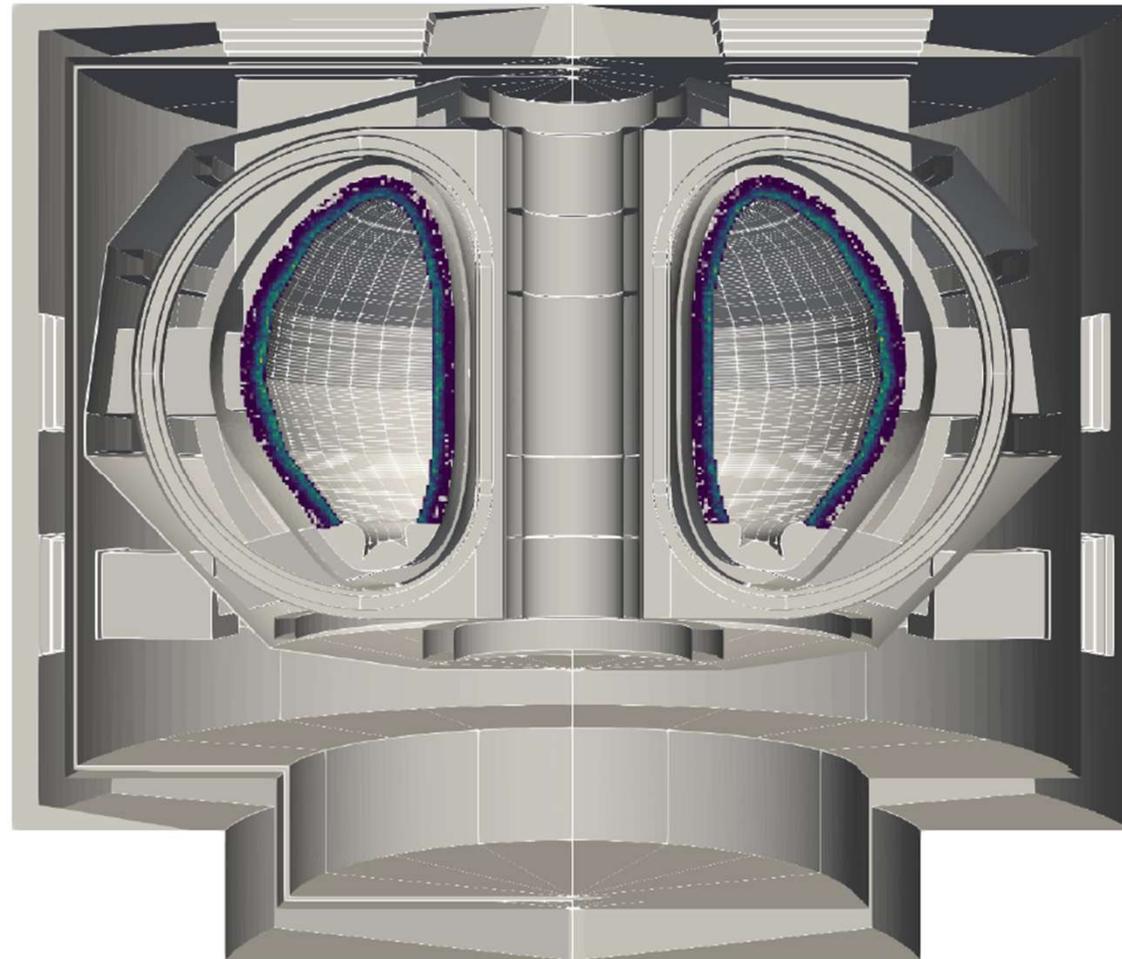
- Improvements planned!
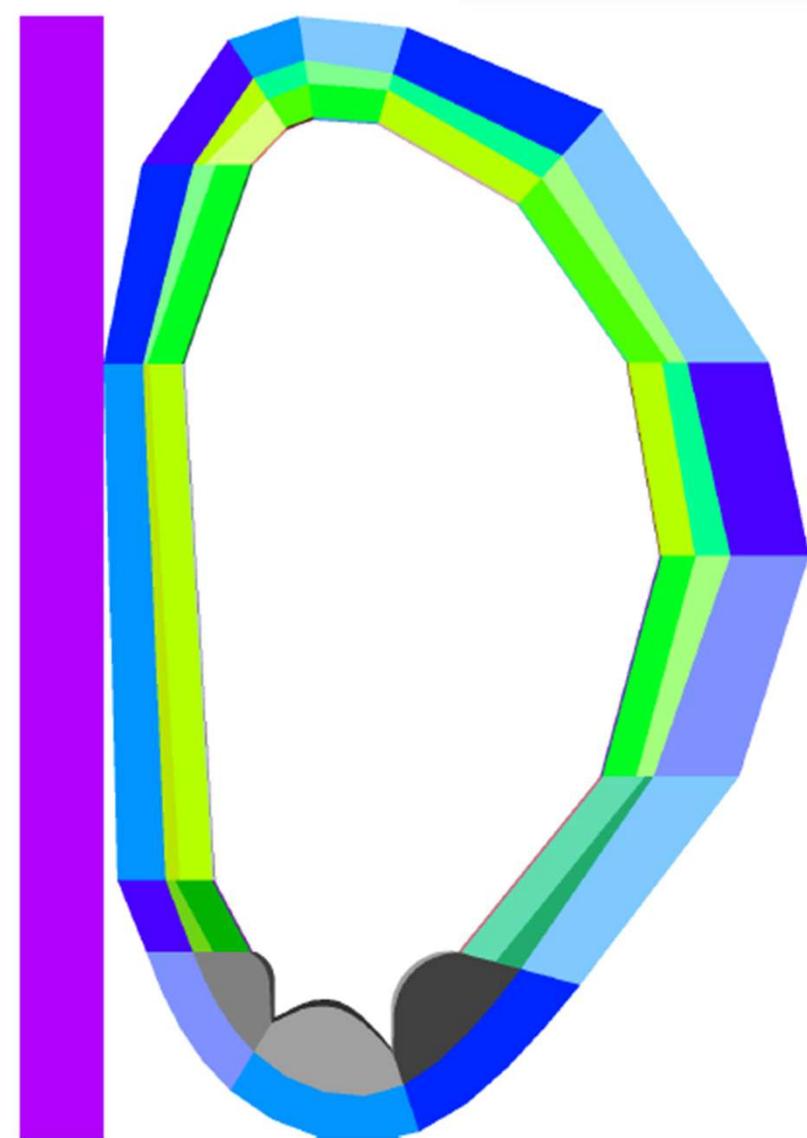
Neutronics – (3/3) CAD

CAD pre-processing pipeline (fast-ctd):

- Overlap checking
- Imprinting
- Merging
- Meshing + MOAB [21] + DAGMC [22]

Pre-processing runs in ~ 11 minutes for this geometry

OpenMC [20] runs 100,000 neutrons x 3 batches in ~11 minutes

TBR contribution per voxel

- 5.7e-09
- 4e-9
- 2e-9
- 1.0e-11

First wall heat loads – (1/2) charged particles [23]

- Simple field-line tracing in axisymmetry

- Calculate incident heat flux based on posited SOL physics model parameters $(\lambda_q, \ldots)$

At the mid-plane the parallel heat flux density is:

$$q_{\parallel,mp}(x_{mp}) = \frac{P_{SOL}}{2\pi f_x(x_{mp})}\left(\frac{f_{near}}{\lambda_{q_{near}}}e^{\frac{-x_{mp}}{\lambda_{q_{near}}}} + \frac{1-f_{near}}{\lambda_{q_{far}}}e^{\frac{-x_{mp}}{\lambda_{q_{far}}}}\right)$$

where:

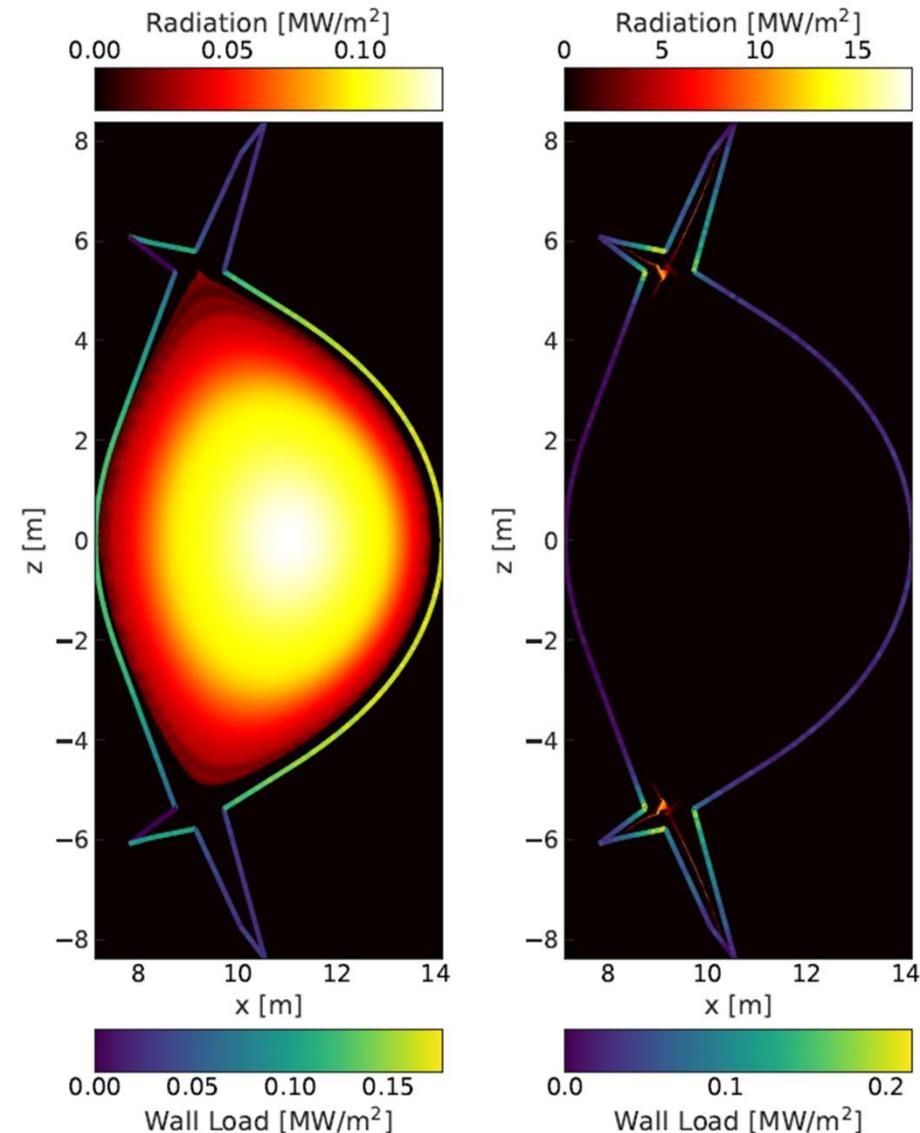|	
x_{mp}	= mid-plane radial coordinate of a flux tube
P_{SOL}	= total charged particle power crossing the separatrix into the scrape-off layer (SOL), (ignoring synchrotron losses)
$\lambda_{q,near}, \lambda_{q,far}$	= near and far SOL power decay length constants
f_{near}	= fraction of SOL power assumed to be deposited in the near SOL
$f_x(x_{mp})$	= local flux tube expansion factor
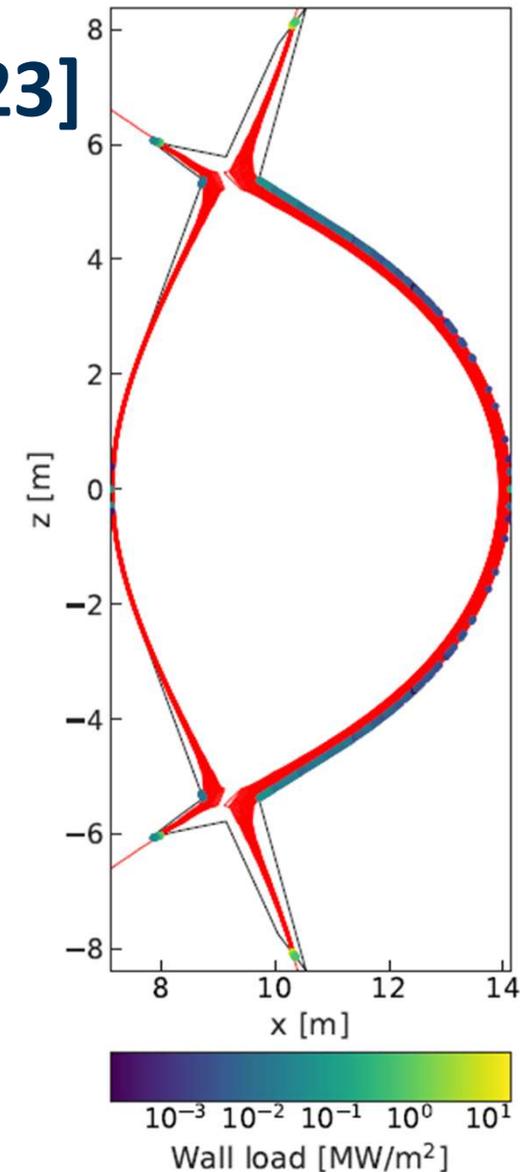
First wall heat loads – (2/2) radiation [23]

- Core and SOL radiation from plasma

- Calculate source term based on posited plasma profiles

- SOL temperature and density evolution modelled with two-point model

- Source term is used in CHERAB [24] with an axisymmetric FW

$$\frac{dP_{\text{rad}}}{dV} = \sum_k f_k \, n_e^2 \, L_k(T_i)$$

| **M. Coleman – Introducing the BLUEMIRA fusion reactor design framework – OSSFE, 11/03/2026, Munich, Germany**

And more...

- Interface to 1.5-D transport and fixed boundary solver PLASMOD [25]

- Fixed boundary equilibrium solver

- Winding pack design module

- Fuel cycle model

- Power cycle model
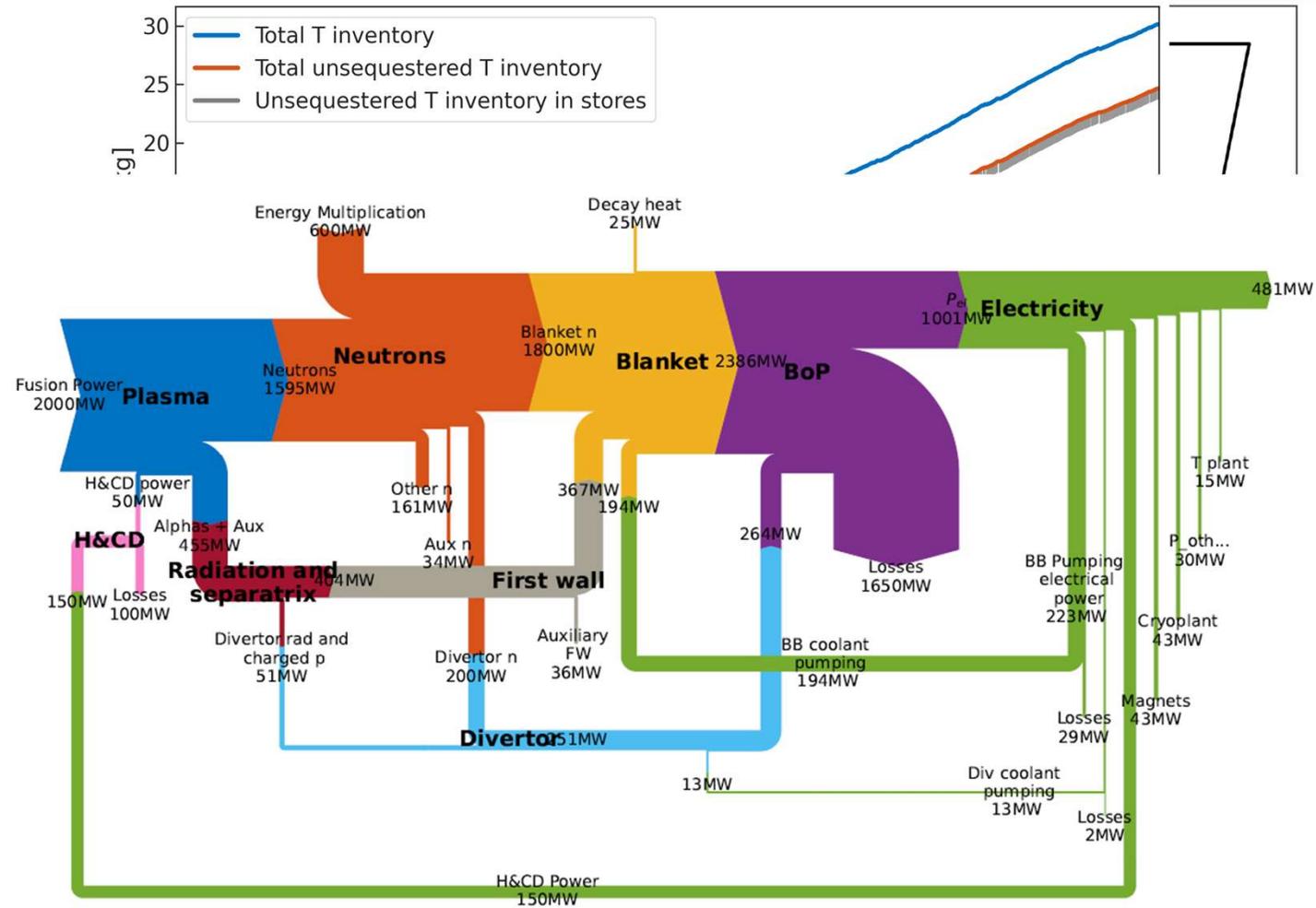
Case studies

Conventional A tokamak parameterisation

For the purposes of demonstration, a full-reactor design parameterisation is used with the following workflow:

- PROCESS run

- Initial "reference" equilibrium design

- Initial FW shape design

- TF coil poloidal shape optimisation

- PF system optimisation

- FW shape optimisation and panelling

- CAD component design (blankets, divertor, vessel, etc.)

- Axisymmetric CSG neutronics analysis

- CAD component design (PF coils, ports, thermal shields, etc.)

- Steady-state power balance model

A scan results (PROCESS and BLUEMIRA)

- 100 points in $A \in [2.6 - 3.6]$
- 7-8% failure rate (geometry -> CSG)

| **M. Coleman – Introducing the BLUEMIRA fusion reactor design framework – OSSFE, 11/03/2026, Munich, Germany**
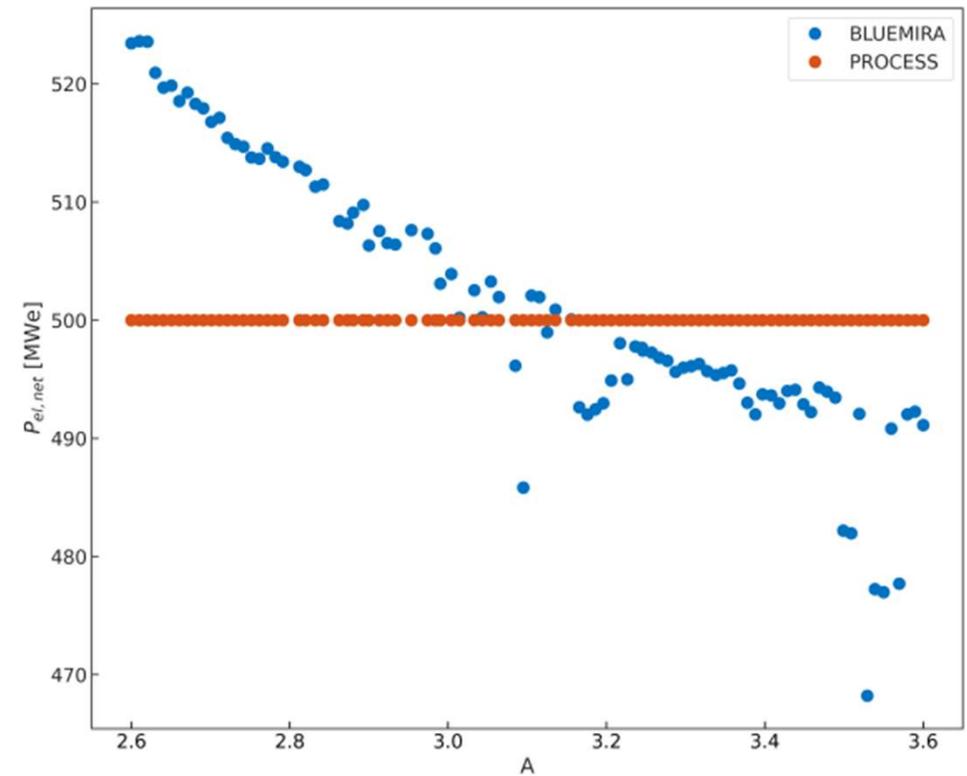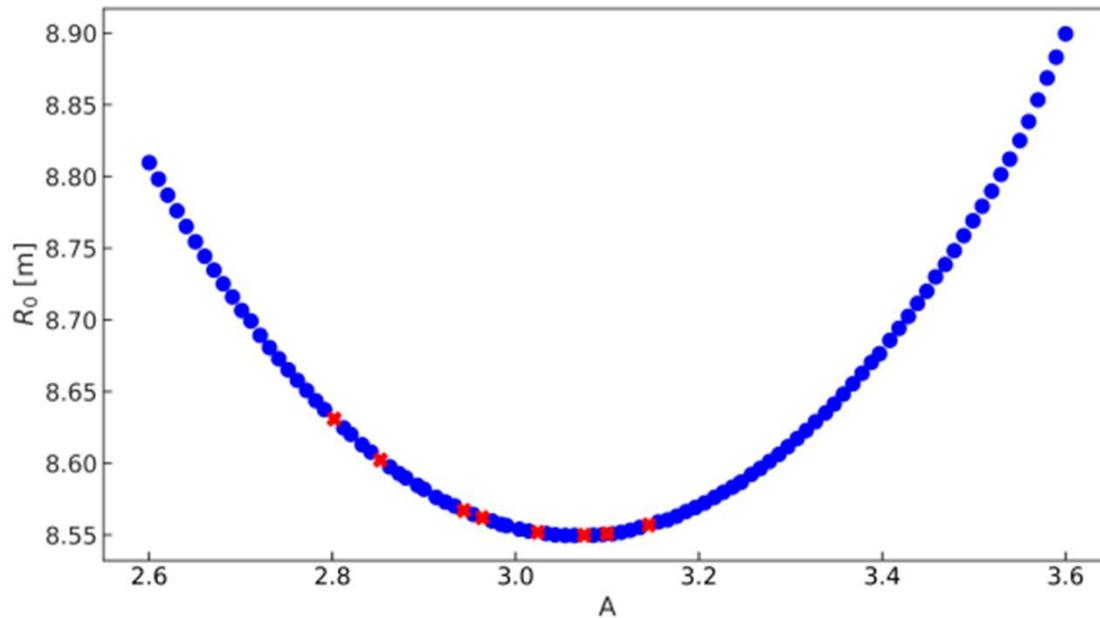
A scan results

- Average total (PROCESS + BLUEMIRA) runtime of 6.2 minutes

(a) $A = 2.6$ (b) $A = 3.1$ (c) $A = 3.6$

(d) $A = 2.6$ (e) $A = 3.1$ (f) $A = 3.6$
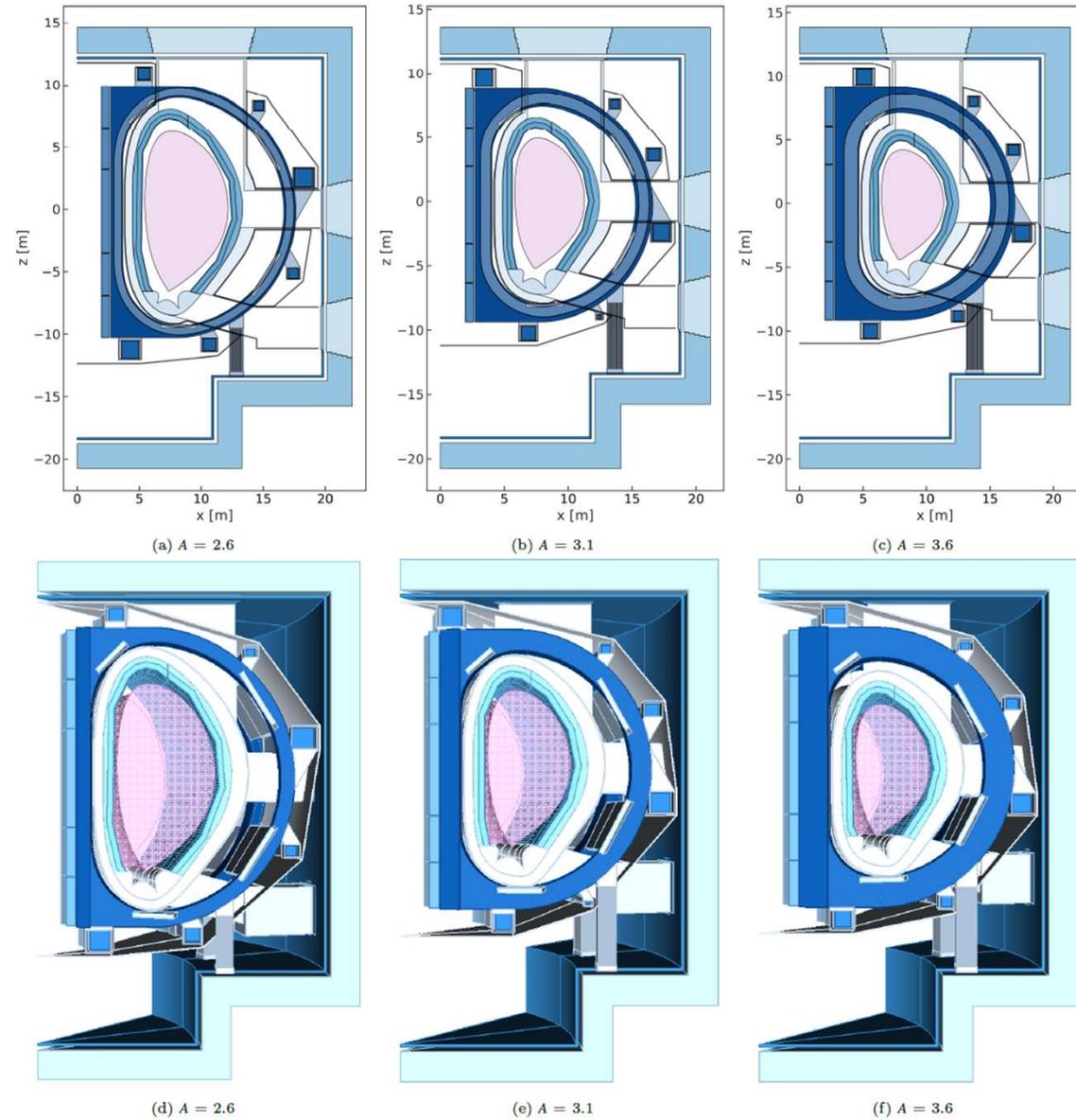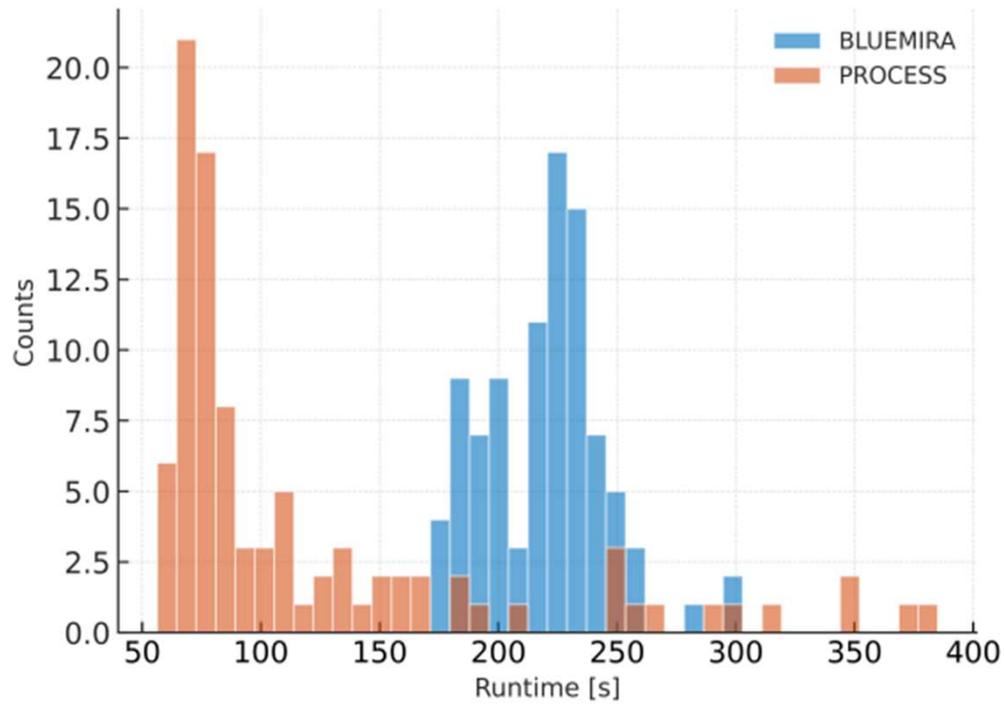
Present use of BLUEMIRA

UKIFS: STEP reactor design, courtesy of A. Pearce (UKIFS), see also [14, 15, 23]
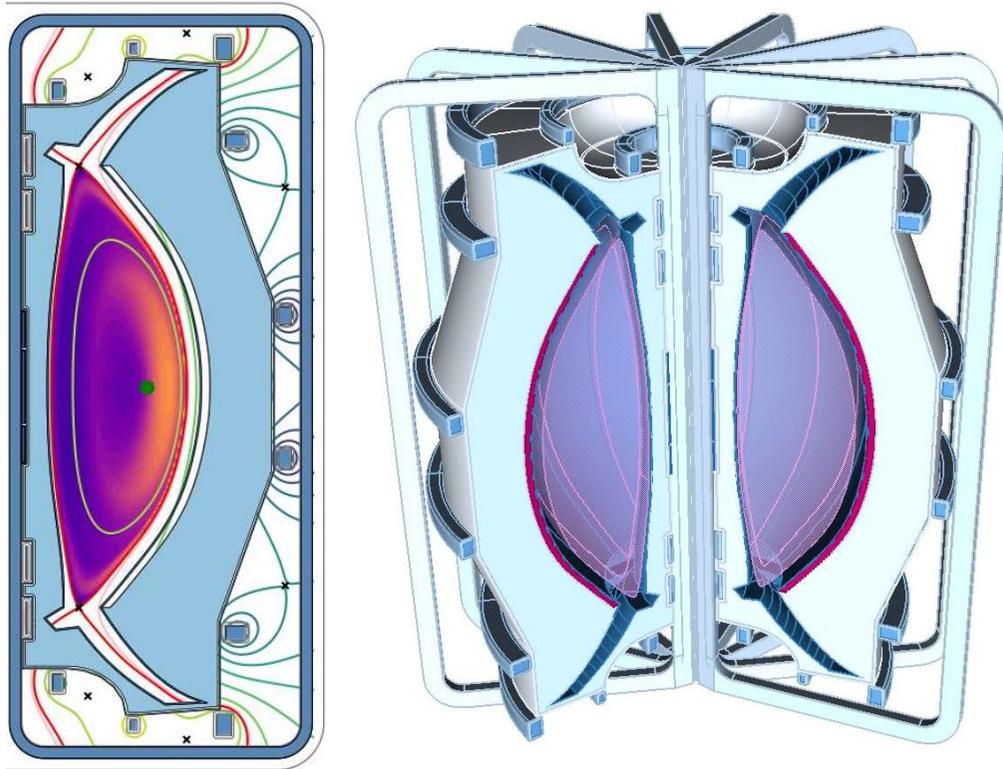
EUROfusion: EU-DEMO LAR reactor design
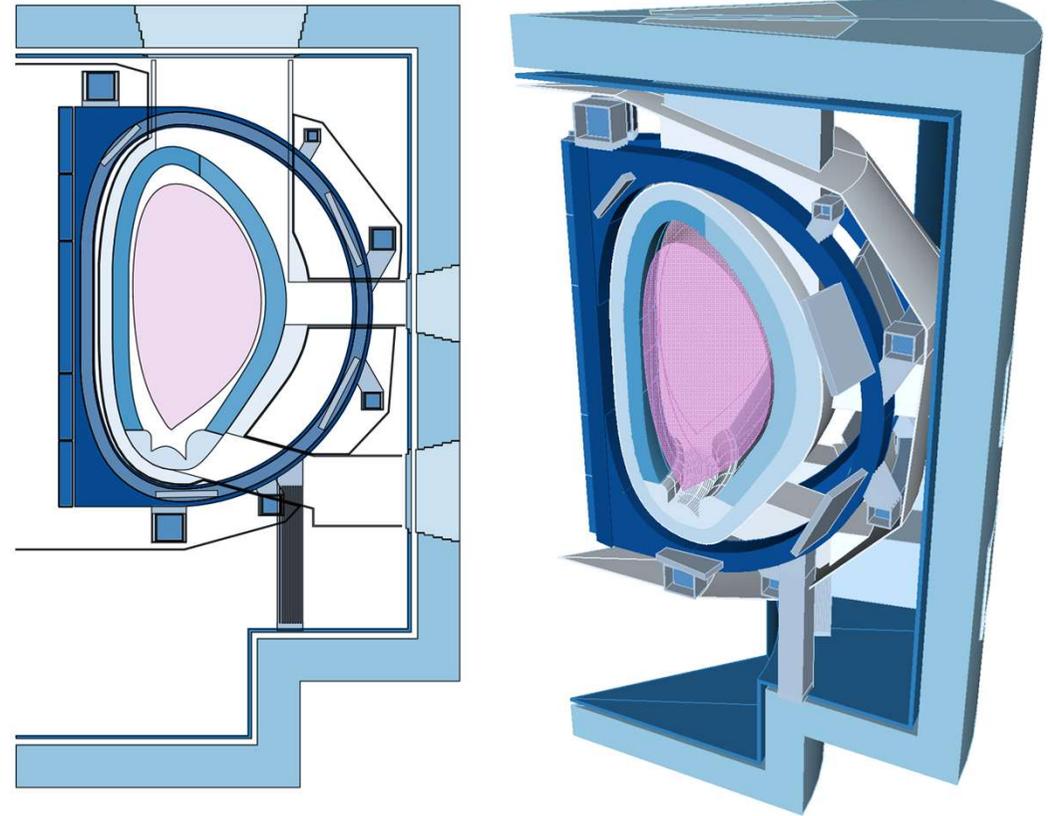
Other reactor parameterisations…

Make your own: bluemira-template-project
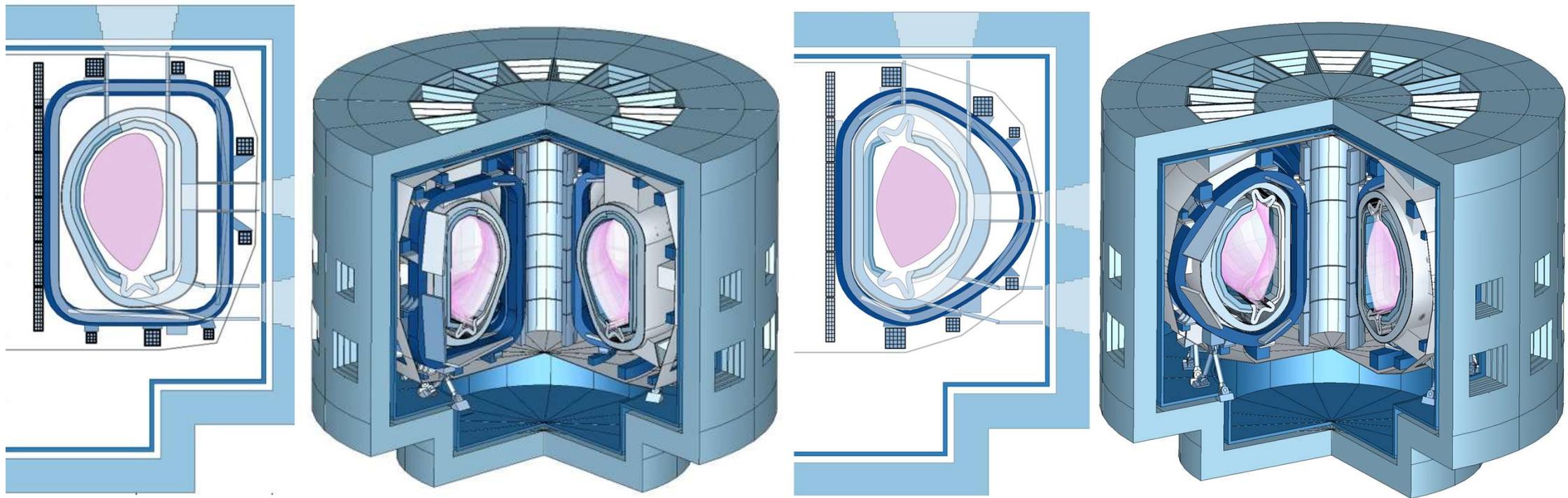
Next steps

- User experience and user interface improvements

- Explore alternative CAD engine options

- CSG + CAD neutronics pipeline improvements

- Couple to open-source 1.5-D transport + fixed boundary solver

- Full interface to 3-D finite element framework

- …

UK Atomic Energy Authority

Summary

- BLUEMIRA is a modular, open-source tokamak fusion reactor design framework.

- A wide variety of modules covering typical tokamak design activities ranging from systems code runs and plasma equilibrium design to 3-D CAD generation and neutronics analyses are included.

- Custom reactor design parameterisations and workflows can be assembled by sequentially combining a series of design stages.

- We invite those interested in using and/or contributing to this framework to get in touch via the online repository:
  - https://www.ukaea.org/service/bluemira
  - https://github.com/Fusion-Power-Plant-Framework/bluemira
  - https://bluemira.readthedocs.io/en/latest/
  - https://github.com/Fusion-Power-Plant-Framework/bluemira-template-project

Thank you

M. Coleman, J. E. Cook, F. Franza, I. A. Maione, S. McIntosh, A. I. Blair, S. Desai, O. Funk, G. Graham, J. Matthews, J. Morris, C. Mould, A. Nilima, H. Saunders, D. Short, D. Vaccaro, O. Wong

References – (1/3)

[1] El-Guebaly, Fifty Years of Magnetic Fusion Research (1958–2008): Brief Historical Overview and Discussion of Future Trends , Energies, 3(6), 2010

[2] Franza, F. (2019). *Development and validation of a computational tool for fusion reactors' system analysis* (Doctoral dissertation). Karlsruher Institut für Technologie.

[3] Franza, F., Boccaccini, L. V., Fable, E., Landman, I. S., Maione, I. A., Petschanyi, J., Stieglitz, R., & Zohm, H. (2022). MIRA: A multi-physics approach to designing a fusion power plant. *Nuclear Fusion, 62*, 076042.

[4] M. Coleman, S. McIntosh, BLUEPRINT: A novel approach to fusion reactor design, Fusion Engineering and Design 139 (2019) 6–38. doi:10.1016/j.fusengdes.2018.12.036.

[5] M. Coleman, An integrated design framework for future nuclear fusion power reactors, Thesis, University of Cambridge

[6] Meneghini, O., Slendebroek, T., Lyons, B. C., McLaughlin, K., McClenaghan, J., Stagner, L., Harvey, J., Neiser, T. F., Ghiozzi, A., Dose, G., Guterl, J., Zalzali, A., Cote, T., Shi, N., Weisberg, D., Smith, S. P., Grierson, B. A., & Candy, J. (2024). *FUSE (Fusion Synthesis Engine): A next generation framework for integrated design of fusion pilot plants*. arXiv.

[7] T. Slendebroek, A.O. Nelson, O.M. Meneghini, G. Dose, A.G. Ghiozzi, J. Harvey, B.C. Lyons, J. McClenaghan, T.F. Neiser, D.B. Weisberg, Exploring the fusion power plant design space: comparative analysis of positive and negative triangularity tokamaks through optimization, Nuclear Fusion 66 026032 (2026)

[8] C. Collins, J. M. Park, R. Barnett, K. Borowiec, E. Hassan, P. Humrickhouse, K. Kim, J. Lore, P. Snyder, V. Badalassi, The Freda Team Team, Introducing FREDA: an integrated physics and engineering tool for fusion reactor design, assessment, and optimization, in: APS Division of Plasma Physics Meeting Abstracts, Vol. 2023 of APS Meeting Abstracts, 2023,

[9] Dudson, B., on behalf of Collins, C. S., & the FREDA Team. (2024, August 7). *Fusion REactor Design & Assessment (FREDA) SciDAC Project* [Conference presentation]. ABOUND SciDAC Workshop.

[10] M. Kovari, R. Kemp, H. Lux, P. Knight, J. Morris, D. J.Ward, "PROCESS": A systems code for fusion power plants—Part 1: Physics, Fusion Engineering and Design 89 (12) (2014) 3054–3069.

[11] M. Kovari, F. Fox, C. Harrington, R. Kembleton, P. Knight, H. Lux, J. Morris, "PROCESS": A systems code for fusion power plants – Part 2: Engineering, Fusion Engineering and Design 104 (2016) 9-20

References – (2/3)

[12] R. Albanese, R. Ambrosino, A. Castaldo, and V. P. Loschiavo, "Optimization of the PF coil system in axisymmetric fusion devices," *Fusion Engineering and Design*, vol. 133, pp. 163–172, Aug. 2018

[13] N. C. Amorisco, A. Agnello, G. Holt, M. Mars, J. Buchanan, S. Pamela, FreeGSNKE: A Python-based dynamic free boundary toroidal plasma equilibrium solver, Physics of Plasmas 31 (4) (2024) 042517

[14] A. Nilima, M. Bluteau, J. Cook, O. Funk, G. Graham,J. Matthews, S. I. Muldrew, A. J. Pearce, D. Vaccaro, Optimisation of STEP poloidal field coils with superconducting coil constraints in STEP-Bluemira power plant design framework, Fusion Engineering and Design 220 (2025) 115357.

[15] G. Graham and O. Bardsley and S. Kahn and A. Pearce and M. Johnson}, Conceptual design of spherical tokamaks using spherical harmonic flux constraints in Bluemira, Proc. 30thIEEE Symp. on Fusion Engineering (2023)

[16] C. Mould et al., Constraining Equilibria with Toroidal Harmonics in the Bluemira Design Framework, this conference

[17] J. A. Leuer, Passive Vertical Stability in the Next Generation Tokamaks, Fusion Technology 15 (2P2A) (1989) 489–494

[18] G. Cunningham, "There is no FIESTA paper", personal communication, (2017).

[19] C. Fausser, A. L. Puma, F. Gabriel, R. Villari, Tokamak D-T neutron source models for different plasma physics confinement modes, Fusion Engineering and Design 87 (5-6) (2012) 787–792.

[20] P. K. Romano, N. E. Horelik, B. R. Herman, A. G. Nelson B. Forget, K. Smith, OpenMC: A state-of-the-art Monte Carlo code for research and development, Annals of Nuclear Energy 82 (2015) 90–97.

[21] T. J. Tautges, C. Ernst, C. Stimpson, R. J. Meyers, K. Merkley, MOAB : a mesh-oriented database., Tech. Rep. SAND2004-1592, Sandia National Laboratories (SNL), Albuquerque, NM, and Livermore, CA (United States) (Apr. 2004).

[22] https://svalinn.github.io/DAGMC/

References – (3/3)

[23] D. Vaccaro, J. Cook, S. Kahn, T. Barrett, M. Bluteau, M. Coleman, F. Federici, S. Henderson, D. Horsley, A. Hudoba, M. Kovari, R. Osawa, A. Pearce, M. L. Richiusa, D. Short, M. Subramani, K. Verhaegh, Z. Vizvary, F. Bagnato, D. Galassi, S. Minucci, Models implemented in the methodological approach to design the initial STEP first wall contour, Fusion Engineering and Design 204 (2024) 114479.

[24] D. C. Giroud, D. A. Meakins, D. M. Carr, D. A. Baciero, M. C. Bertrand, CHERAB Spectroscopy Modelling Framework (Mar. 2018). doi:10.5281/zenodo.1206142

[25] E. Fable, C. Angioni, M. Siccinio, H. Zohm, Plasma physics for fusion reactor system codes: Framework and model code, Fusion Engineering and Design 130, (2018) 131-136

Back-up slides

The BLUEMIRA project

In 2020, Fabrizio Franza and I agreed to combine BLUEPRINT and MIRA in a collaboration between UKAEA and KIT in EUROfusion's TSVV-14: Multi-fidelity systems codes.

Over the past five years ~ 2.4 ppy / yr:

- 2 full-time, 4 part-time, 6-10 occasional collaborators

Used on:

- EUROfusion's EU-DEMO
- UKIFS' STEP

BLUEMIRA paper submitted to Nuclear Fusion (excerpts shown here), with some modules already partially described in [10, 11] (and shown here).

Use cases and requirements for a tokamak design framework

Based on observations of fusion reactor design efforts, we foresee the following use cases:

(i) Generation of concept
(ii) Modification of an ex
(iii) Exploration of the des concept
(iv) Comparison of alter concepts

For any design framework to be as useful as possible, to as many people as possible, the following aspects are important:

(i) Ease of access (licence, installati dency, etc.)
(ii) Ease of use (application progran sign, language, etc.)
(iii) Ease of understanding (document amples, training, etc.)
(iv) Ease of interoperability (file I/C visualisation, etc.)
(v) Robustness
(vi) Verification and validation

For tokamak design in particular, we consider the following features as necessary components of a framework:

(i) 0/1-D systems code solver
(ii) 1.5-D plasma transport and equilibrium solver
(iii) 2-D free boundary equilibrium solver(s)
(iv) 3-D magnetostatics solver(s)
(v) 2-D and 3-D geometry creation and manipulation
(vi) 2-D and 3-D radiation transport solver(s)
(vii) 2-D and 3-D finite element solver(s)
(viii) Material properties
(ix) Fuel cycle model
(x) Power balance model
(xi) Cost model

Equilibria – fixed boundary

BLUEMIRA has fixed and free boundary MHD equilibrium solvers (ideal MHD, static).

Fixed boundary solver:

- Finite element
- Arbitrary (fixed) boundary and profiles
- Used for coupling to PLASMOD
- Verified with Solov'ev
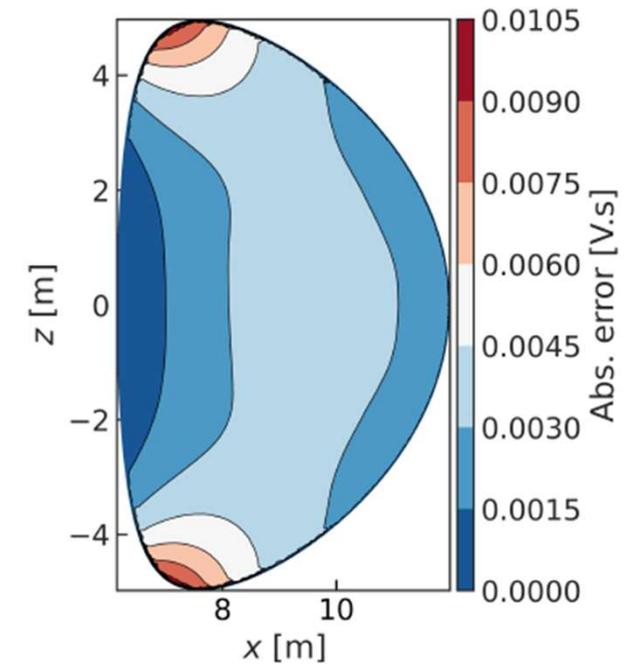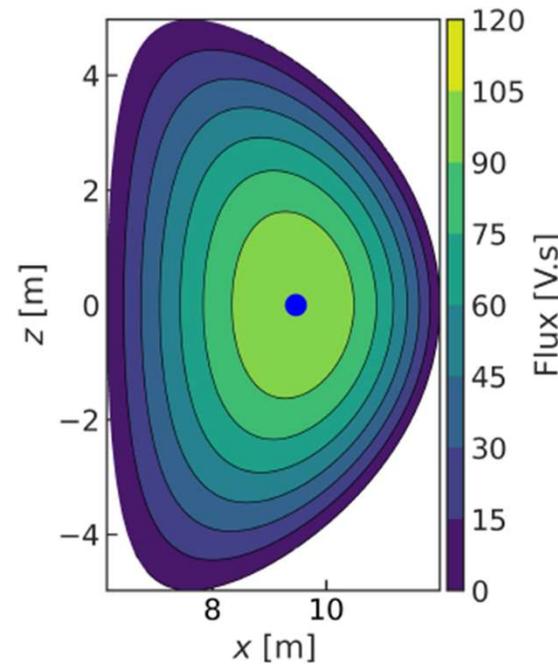
Comparison of source spatial distribution in a simple tokamak geometry
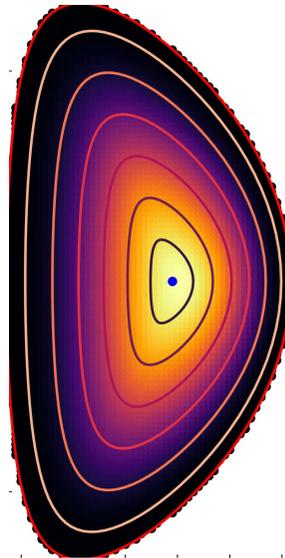
Experiment on a typical EU-DEMO like machine in BLUEMIRA (tns v0.1.2):

- OpenMC 0.15.2, 2 batches, same seed
- Simplified CSG geometry and materials
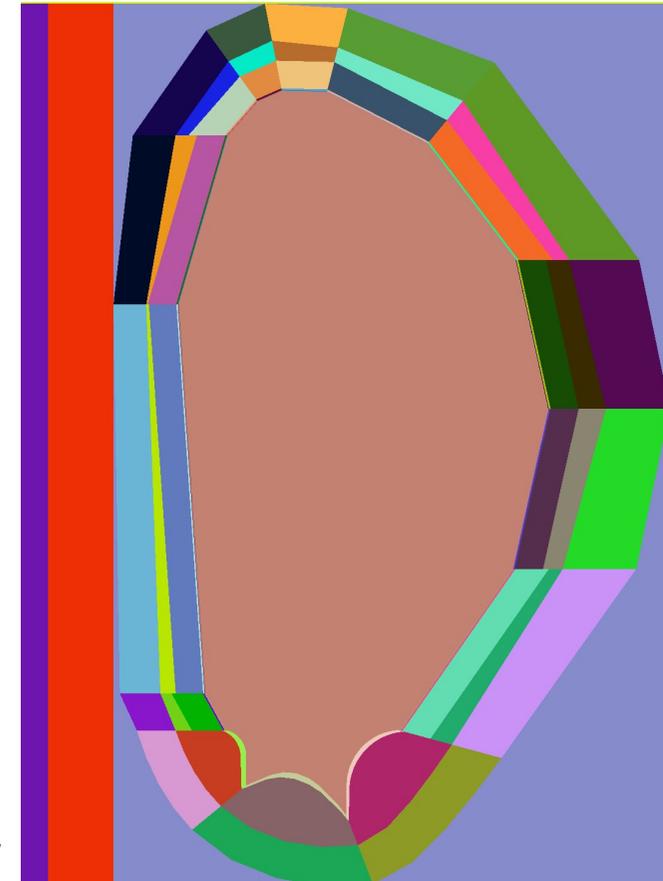- Parabolic-pedestal profiles, same fusion power
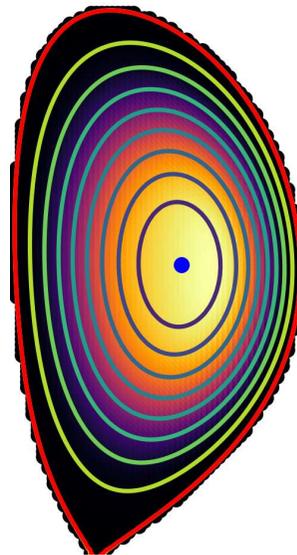- 0.1 x 0.1 m source discretisation
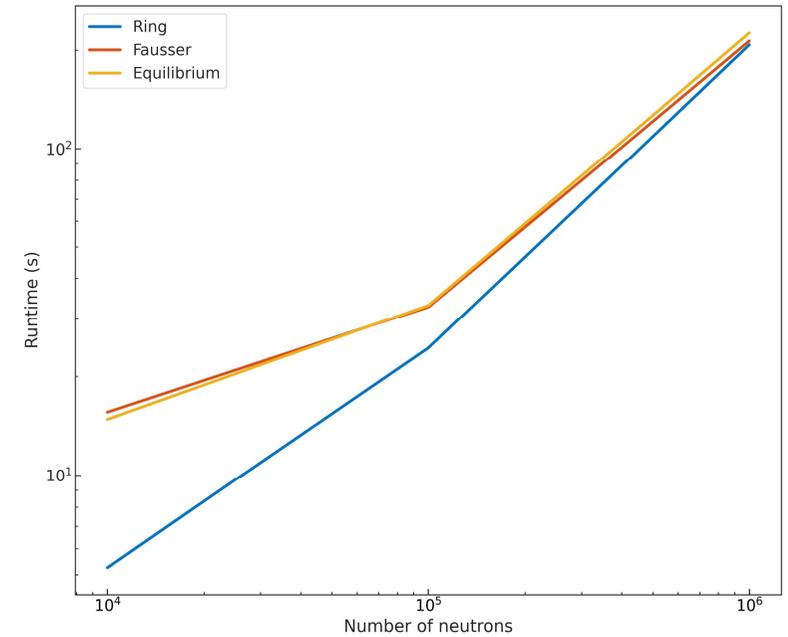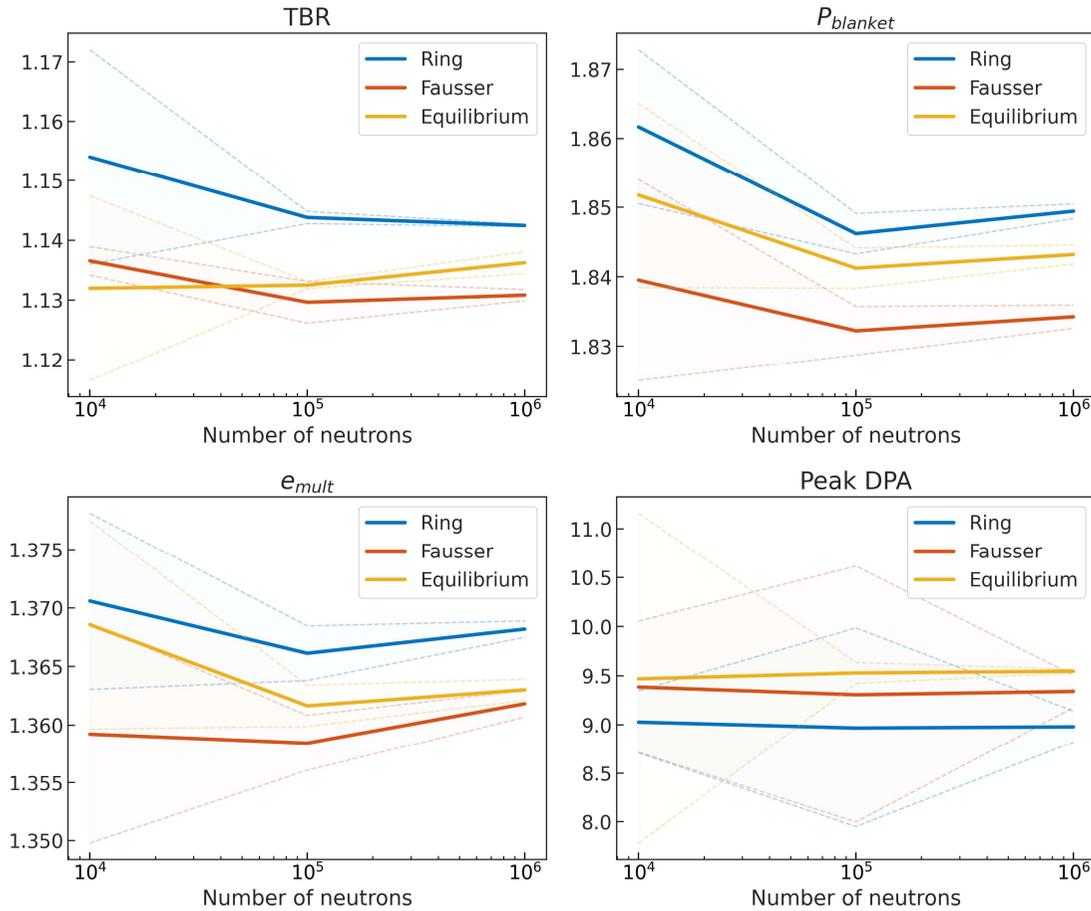
Ring (mono-energetic)   **Fausser**   **Equilibrium**

Comparison of source spatial distribution in a simple tokamak geometry

M. Coleman – Introducing the BLUEMIRA fusion reactor design framework – OSSFE, 11/03/2026, Munich, Germany
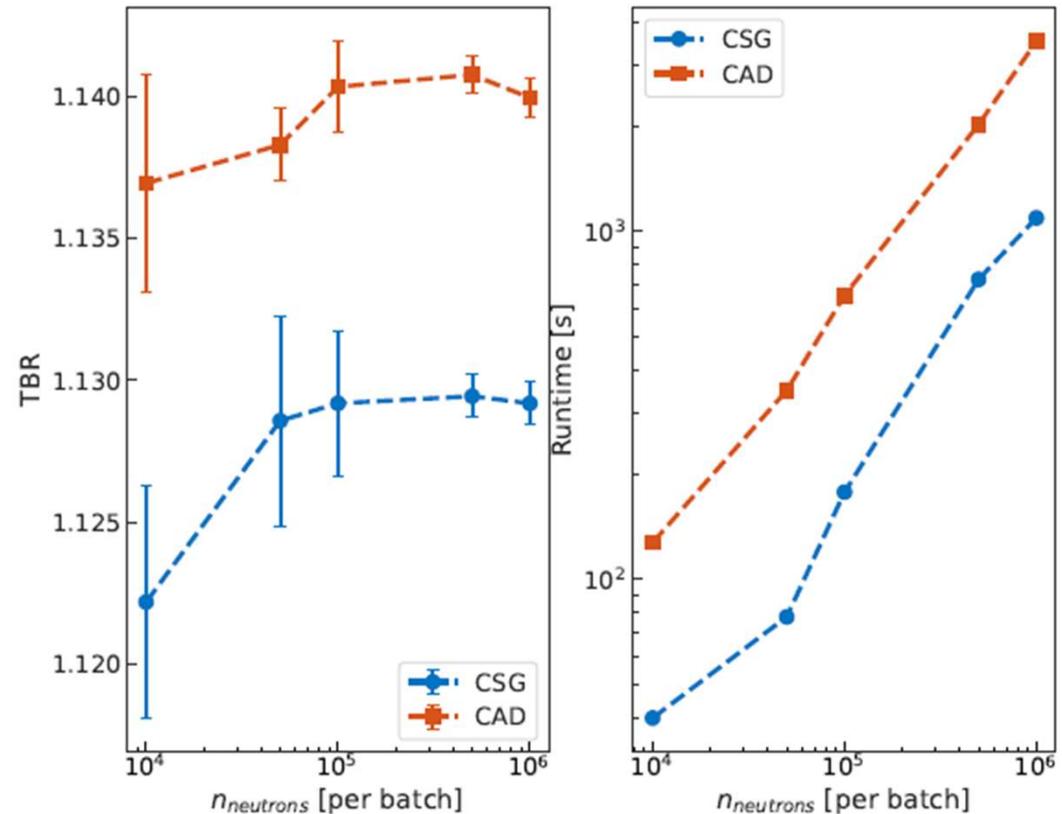
Neutronics – (4/4) comparison

Here we compare the CSG and CAD neutronics pipelines on the same tokamak design point:

- Same (base) geometry
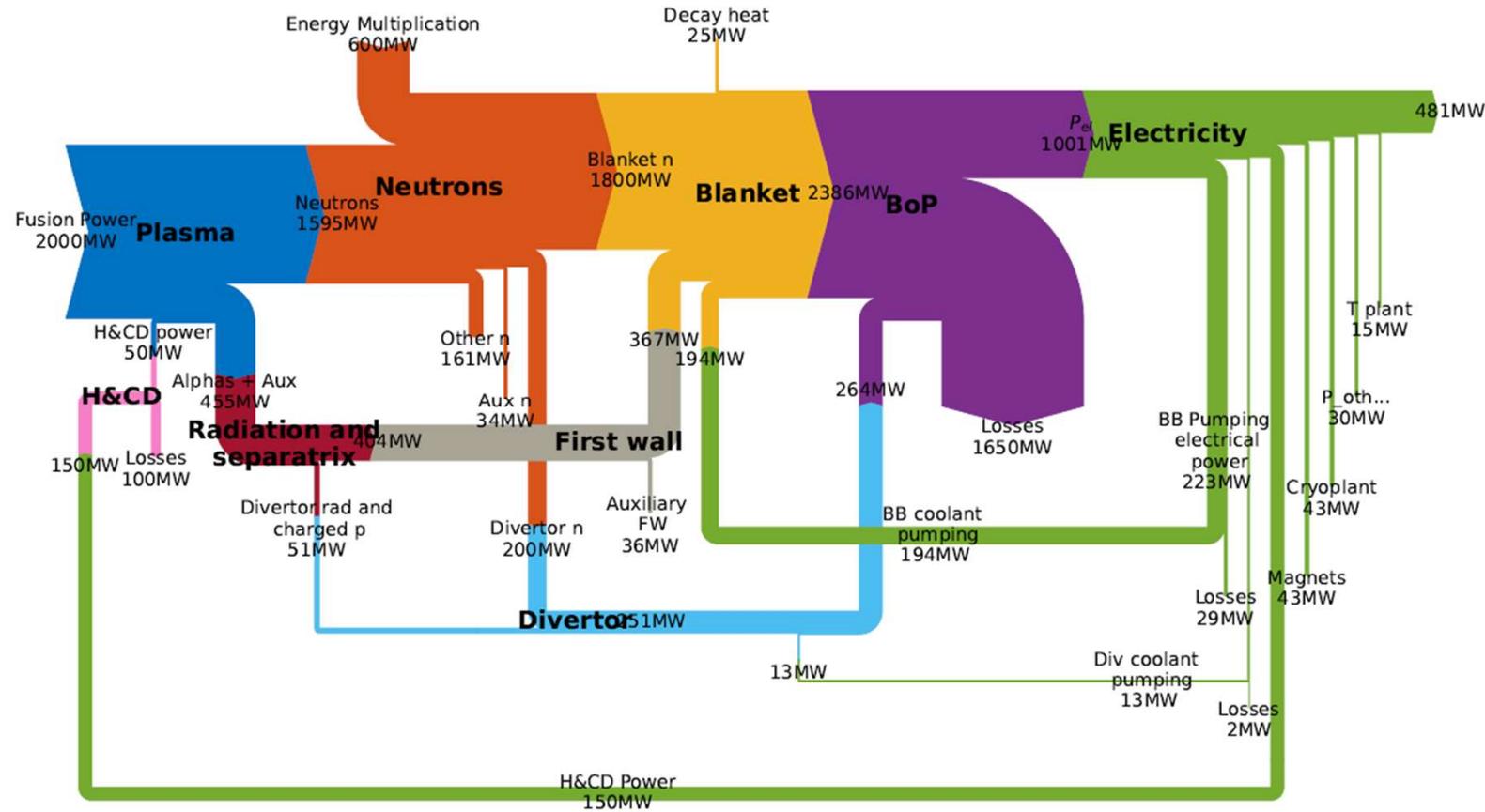- Same materials
- Same neutron source

We would expect to see lower TBR in the CAD pipeline, because of gaps in the blanket, but we don't. This is due the how CAD is meshed and is a problem we will address in future work.

Power cycle

Steady-state power cycle model

- Same parasitic loads as PROCESS
- Slightly more detailed
- Power deposition in IVCs from neutronics models

Conventional A tokamak parameterisation

PROCESS problem

$$\mathbf{x}^* = \underset{\mathbf{x}}{\text{minimise}}: \quad R_0$$

$$\text{subject to}:$$

$$\mathbf{x} \geqslant \mathbf{x}_{min}$$

$$\mathbf{x} \leqslant \mathbf{x}_{max}$$

$$P_{el,net} = P_{el,net_{target}}$$

$$\tau_{flattop} \geq \tau_{flattop_{min}}$$

$$P_{sep}B_T/q_{95}AR_0 \leq (P_{sep}B_T/q_{95}AR_0)_{max}$$

$$f_{LH_{min}} \leq f_{LH} \leq f_{LH_{max}}$$

$$\overline{n_e} \leq f_{GW}n_{GW}$$

$$n_{e,core} \geq n_{e,ped}$$

$$\beta \leq \beta_{max}$$

$$\sigma_{TF,case,peak} \leq \sigma_{TF,case,max}$$

$$\sigma_{TF,WP,peak} \leq \sigma_{TF,WP,max}$$

$$J_{TF} \leq J_{TF_{max}}$$

$$\Delta_{T,TF} \geq \Delta_{T,TF_{min}}$$

$$\sigma_{CS,peak} \leq \sigma_{CS_{max}}$$

$$\Delta_{T,CS} \geq \Delta_{T,CS_{min}}$$

$$\sigma_{VV,TFCFD} \leq \sigma_{VV_{max}}$$

$$\dots$$

TF coil shape problem

$$\boldsymbol{\alpha}^* = \underset{\boldsymbol{\alpha}}{\text{minimise}}: \quad \int_0^1 \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dz}{dt}\right)^2}\, dt$$
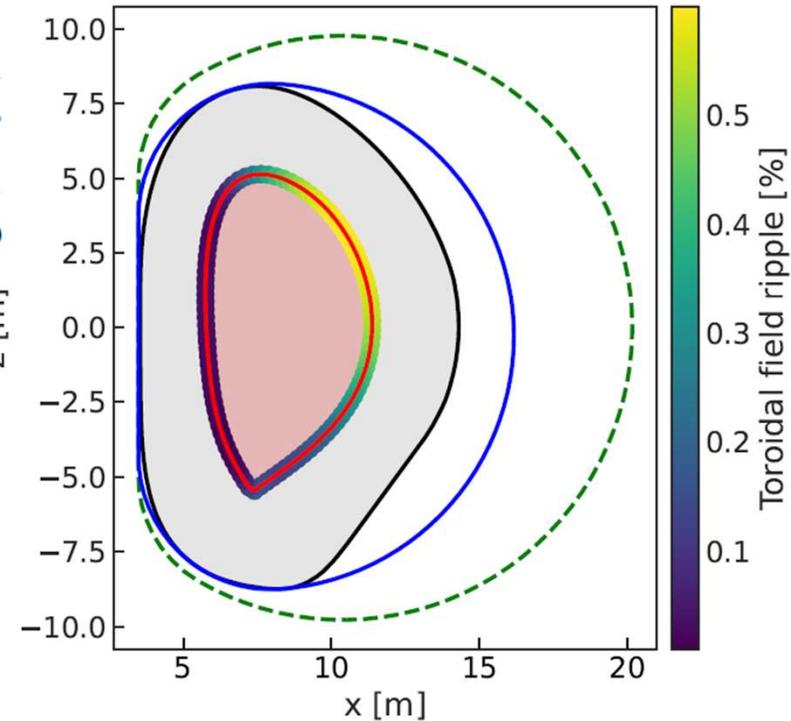
$$\text{subject to}:$$

$$\{r_1, r_2, r_3\} \geqslant r_{TF,min}\mathbf{1}$$

$$\theta_1 + \theta_2 + \theta_3 \leq 180°$$

$$\delta_\phi|\partial\Omega_p \leqslant \delta_{\phi,max}\mathbf{1}$$

$$d^\pm(\mathcal{S}_{CCL}(\boldsymbol{\alpha}, n), \Omega_{Koz}) \leqslant \mathbf{0}$$

Conventional A tokamak parameterisation

Upper port problem

$$\mathbf{x}^* = \underset{\mathbf{x}}{\text{minimise}} : \qquad x_{ob} - x_{ib}$$

subject to :

$$x_{ob} - x_{cut_{BSS}} - \Delta_{RM} \leq x_{BB_{max}} - x_{cut_{BSS}}$$

$$x_{cut_{FW}} - x_{BB_{max}} \leq x_{ob} - x_{cut_{FW}} + \Delta_{RM}$$

$$x_{ib} + \frac{|x_{cut_{FW}} - x_{BB_{min}}|}{2} \leq x_{cut_{FW}}$$

$$\gamma_{min} \leq \gamma \leq \gamma_{max} \tag{27}$$

PF coil position and current problems

$$\mathbf{L}^* = \underset{\mathbf{L}}{\text{minimise}} : \qquad \|\mathbf{I}^*\|_2^2$$

subject to :

$$\mathbf{L}_{min} \leq \mathbf{L} \leq \mathbf{L}_{max} \tag{28}$$

where $\mathbf{I}^*$ is the vector of optimal currents for a given set of positions, $\mathbf{L}$, which is the result of a current optimisation problem, discussed in the next section.

5.4.3. PF coil current optimisation problem

For the PF coil current optimisation, a similar optimisation problem to the one described by Albanese et al. in [107] for EU-DEMO is solved, as detailed in [53], see Eq. 29.

$$\mathbf{I}^* = \underset{\mathbf{I}}{\text{minimise}} : \qquad \|\mathbf{GI} - \mathbf{b_t} + \mathbf{b_p}\|_2^2 + \|\mathbf{\Gamma I}\|_2^2$$

subject to :

$$|\mathbf{I}| \leq \mathbf{I}_{max}$$
$$B_p|_{X_{point}} \leq 0 + \epsilon \tag{29}$$
$$\mathbf{B}_{p,coils} \leq \mathbf{B}_{p,max}$$
$$|\mathbf{F}_{z,coils}| \leq \mathbf{F}_{z,max}$$