BSTING: global fluid turbulence simulations in W7-X

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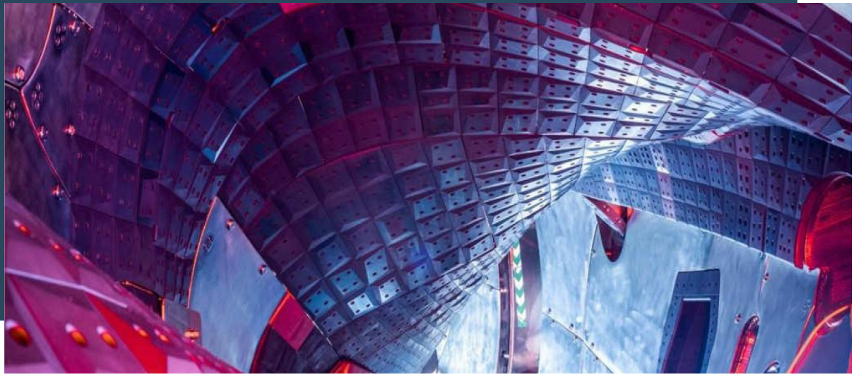

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BOUT++

BOUT++ is an open source framework for fluid (turbulence) simulations

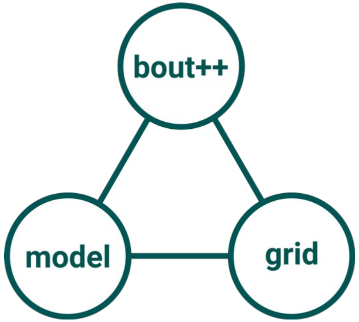
- **No set model, geometry or numerical methods**

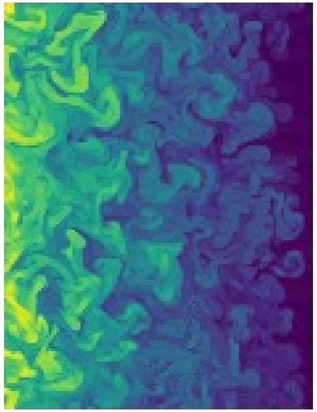
Many previous applications:

- **ELMs, edge turbulence/transport, divertor detachment, MHD, magnetic reconnection, waves on a beach, chocolate bubbles...**

Recent developments include multi-fluid model & adanced computational techniques

- **Hermes-3 3D- multifluid model for turbulence and transport**





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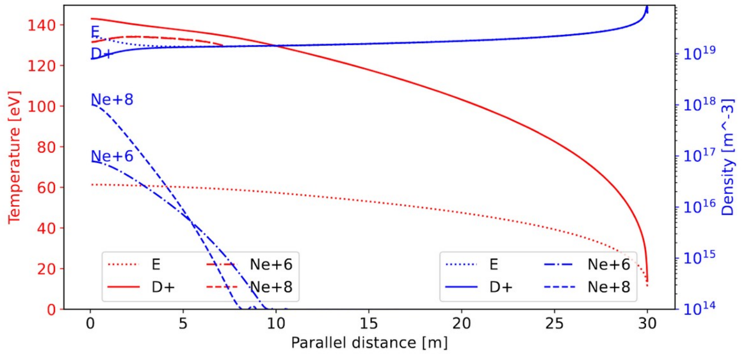


Figure 7: Steady state solution with 100% recycling, evolving all charge states of neon as separate fluids with their own densities, temperatures and flow velocities. A subset of species densities (blue lines) are shown on a logarithmic scale. Simulation inputs in `examples/1D-neon` of the Hermes-3 repository.

Previous work with BOUT++ in W7-X

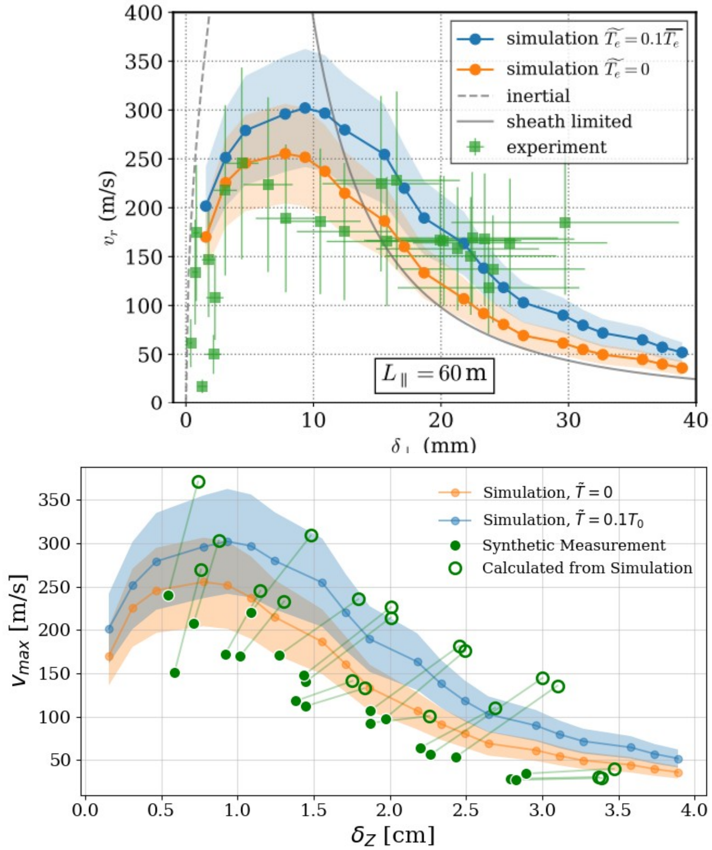
Fundamental understanding of filament propagation

- **Nonuniform curvature in slab geometry [1,2]**
- **Filament trajectories in regions of abrupt connection length transitions [3]**

Drift-plane (2D) simulations compared to MPM probe measurements [4]

Synthetic MPM probe [5]

- **Provided context for experimental measurements**



Top: Comparison of experiment and simulation
Bottom: Synthetic scaling with errors determined by the synthetic diagnostic.

[1] B Shanahan et al., *JP;CS* 2016
[2] P Huslage et al., *PPCF* 2024
[3] B Shanahan & P Huslage, *JPP* 2020
[4] C Killer & B Shanahan et al., *PPCF* 2020.
[5] B Shanahan et al., *PPCF* 2021

BSTING

BSTING is the code name for development of **B**OUT++ to **S**imulate **T**urbulence **I**n **N**onaxisymmetric **G**eometry

Previously simulated isothermal turbulence in the SOL of an analytic stellarator geometry*

W7-X geometries now possible, with an improved model

An elliptic grid is used

- **Inner surface (blue) provided by (0% β) VMEC**
- **Outer surface (red) is a description of the divertor (+extended outer surface)**

Grid generation interfaced with webservices

Simulated density snapshot in the SOL of W7-X.

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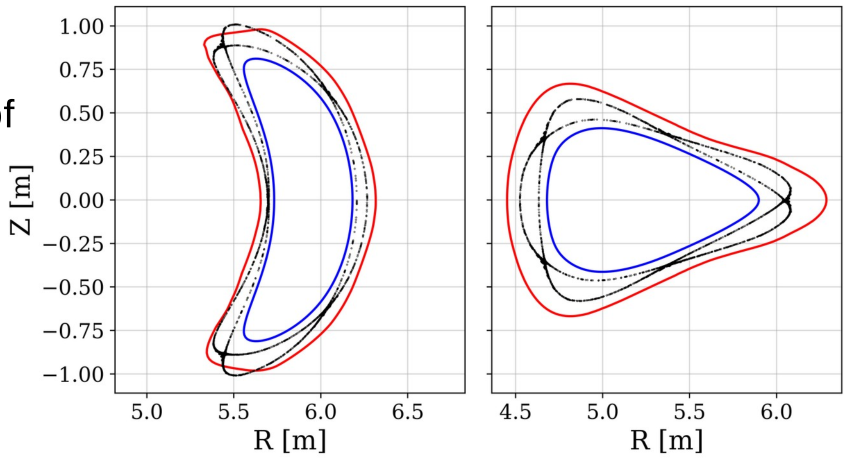


Simulation domain. The inner boundary is shown in blue, the outer boundary is in red

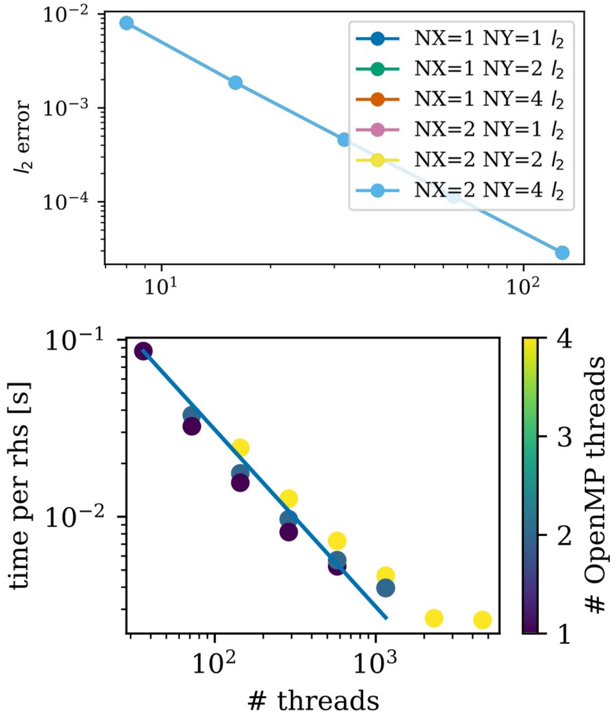
*** B Shanahan et al., *JPP* 2024.**

Numerical development* – D Bold

Extensive work has been done to improve code performance

Improved grid generation, numerical operators, and parallelization

- **~1 month for full-size W7-X**
  - (single field period)
- **~1 week for lower resolution**



TOP: MMS test of FCI operators
BOTTOM: Scaling of new operators in BSTING

*** D Bold & B Shanahan *in preparation*.**

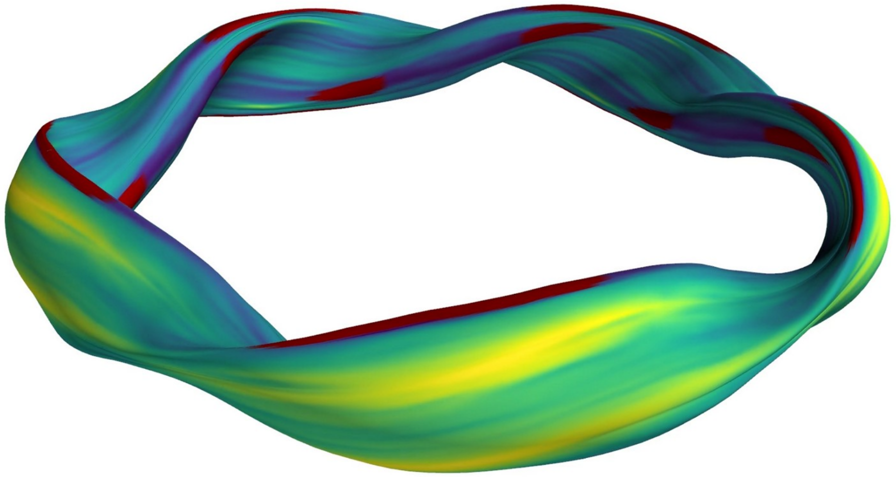
Hights plasma model – n, ω, $nv_{||}$, P_e, P_i, $J_{||}$

Most complex model currently available:

- **electrostatic**
- **evolves ion and electron pressures**
- **full-profile evolution**

Developments ongoing for:

- **full ion viscosity (NC E_r)**
- **electromagnetic effects**
- **(fluid) neutrals & impurities**

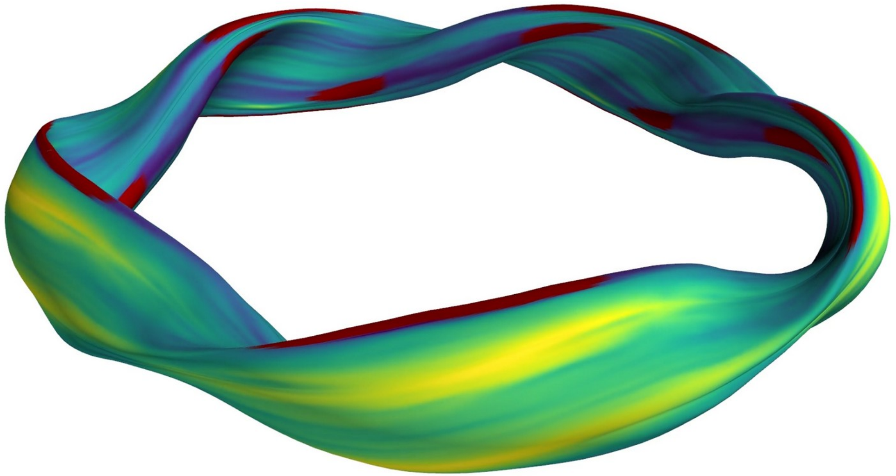


Simulated density snapshot in the SOL of W7-X.

Initial results: Fluctuation characteristics

Simulated perturbations reminiscent of experimental results*

- **density perturbations ~10%-40% above background**
- **$\delta_\perp \approx$ few cms**
- **higher transport near X-points**
- **0.8 < Ti/Te < 1.3**
- **low radial velocities**



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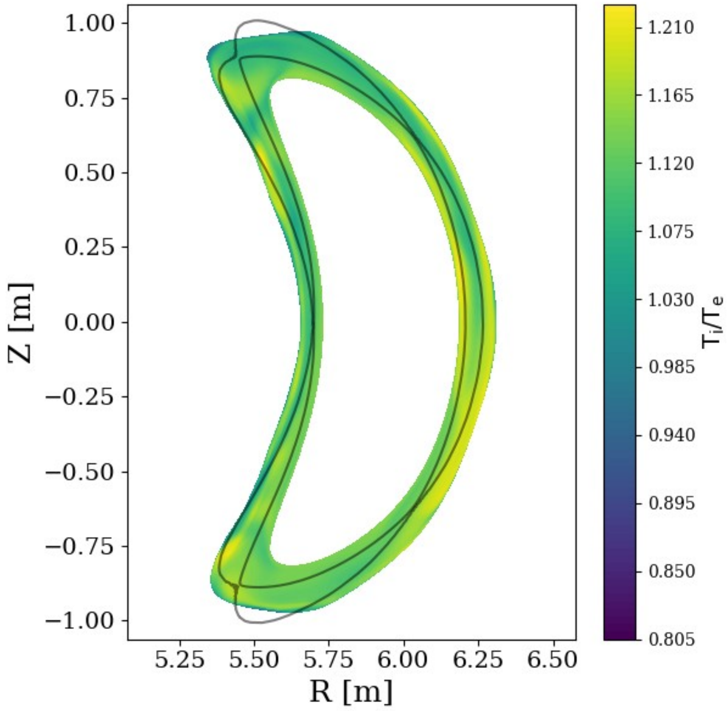

Temperature ratio snapshot

*** C Killer & B Shanahan et al., *PPCF* 2020.**

Initial results: Global flows

Dominant poloidal flows, as seen previously*

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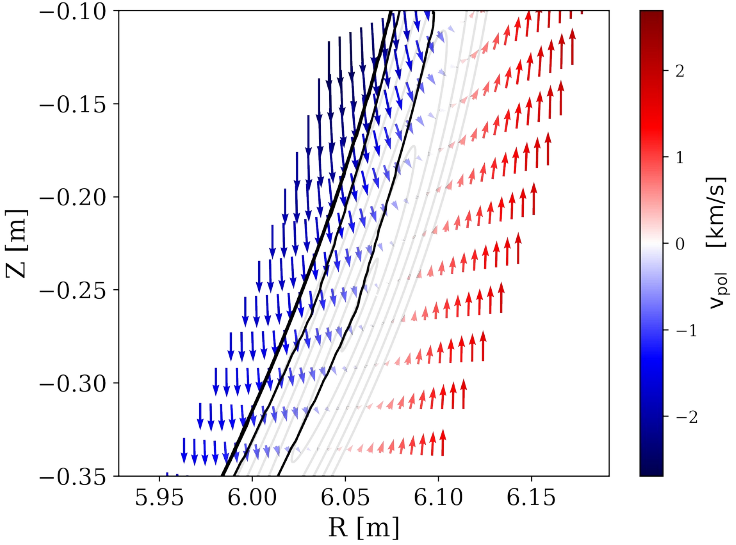
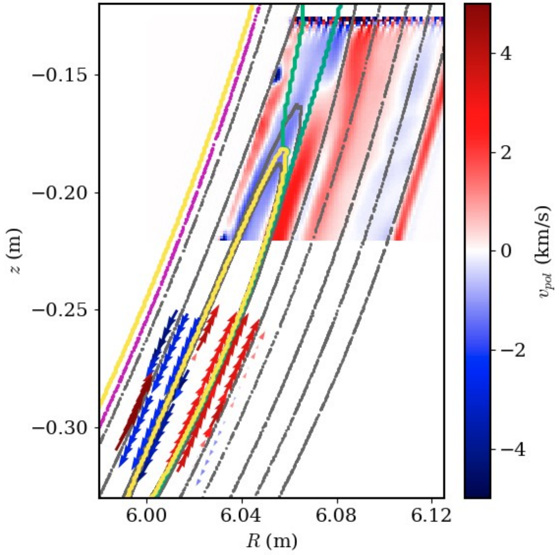
Simulated flows similar to MPM & GPI measurements

- **Shear layers in MPM path and GPI view**



Simulated flow trajectories



MPM and GPI measurements of poloidal flows in the SOL (Thanks C Killer, S Ballinger)

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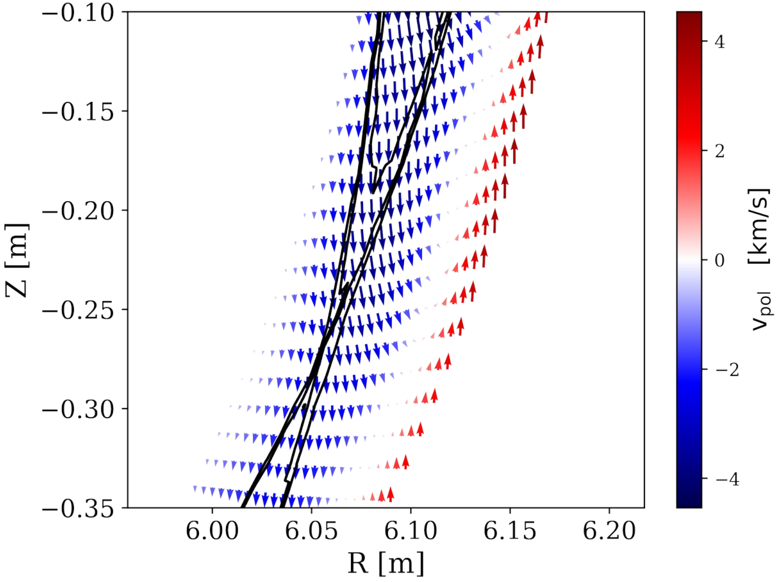
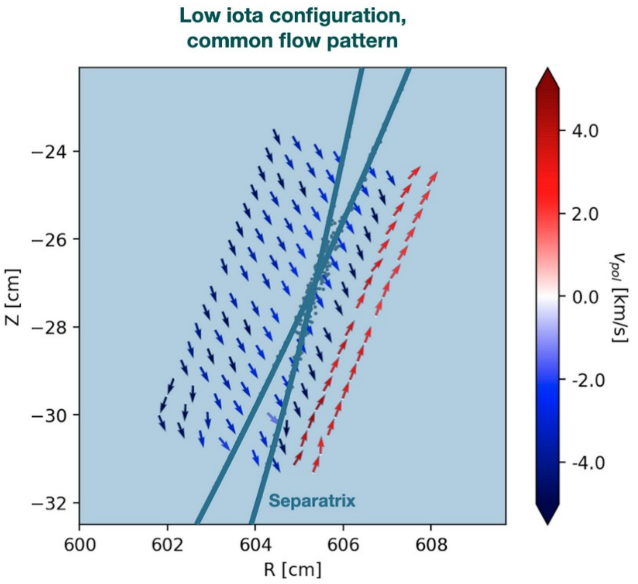


Simulated poloidal velocity profile



Experimental measurements of filament velocity. GPI diagnostic
(Thanks S Ballinger)

Summary and outlook

BSTING has provided a tool for nonlinear fluid simulations, including the SOL.

- **Recent devlopments have allowed for full W7-X geometry**
- **Initial results in W7-X consistent with experimental characteristics**

Lots of physics to explore

- **Island region in FMM configuration (M Madeira)**
- **convective cells near X-points, filament generation mechanism, mode analysis, heat fluxes, ...**

Excited for collaboration

Simulated density snapshot in the SOL of W7-X.

backup slides

Hermes-3

Hermes-3 is a new model using BOUT++ for edge applications **[B Dudson *CPC* 2023]**

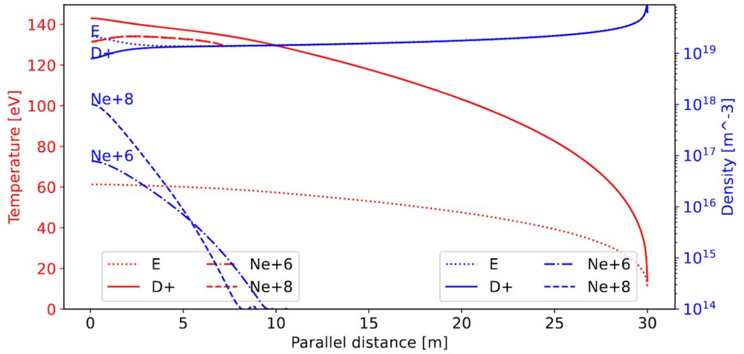
- **Multifluid, 1D, 2D or 3D(ish) for transport or turbulence**
- **Arbitrary number of ion and neutral species (determined at runtime)**
- **Uses ADAS & AMJUEL, fluid neutral models**
- **"relax_potential" option for steady-state potential**

Actively developed, online manual.

No development needed for 1D/2D applications.

- **Already implemented Stellarator 2-pt model**

Easy syntax in input files



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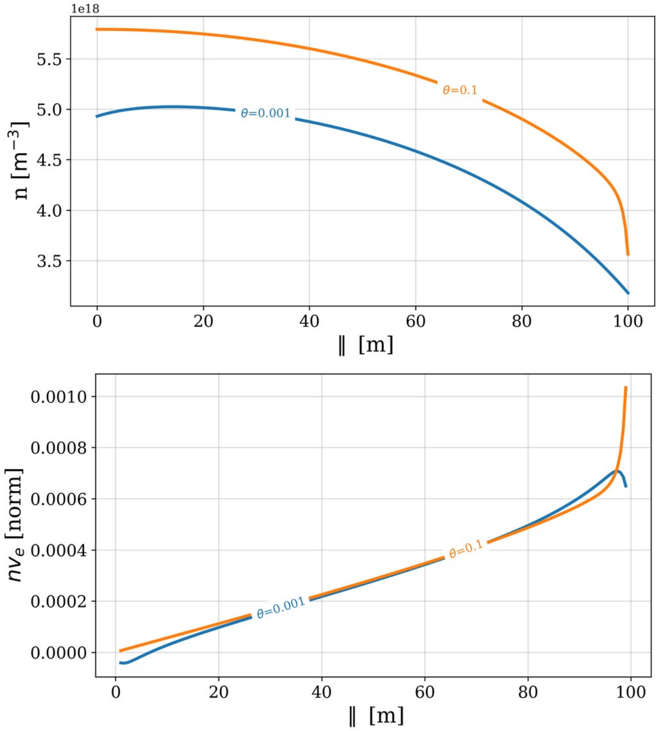

Density (top) and parallel momentum (bottom) in two cases within the Stellarator 2pt model implementation of Hermes-3

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Easy syntax in input files

```
[hermes]
components = d+, d, t+, t, he+, he, ne+, ne, e,
           collisions, sheath_boundary, recycling, reactions
[recycling]

species = d+, t+, he+, ne+

[reactions]
type = (
        d + e -> d+ + 2e,   # Deuterium ionisation
        t + e -> t+ + 2e,   # Tritium ionisation
        he + e -> he+ + 2e, # Helium ionisation
        he+ + e -> he,      # Helium+ recombination
        ne + e -> ne+ + 2e, # Neon ionisation
        ne+ + e -> ne,      # Neon+ recombination
       )
```

Example input from a Hermes-3 simulation with cross-field diffusion, collisions between species, sheath boundary conditions, and recycling

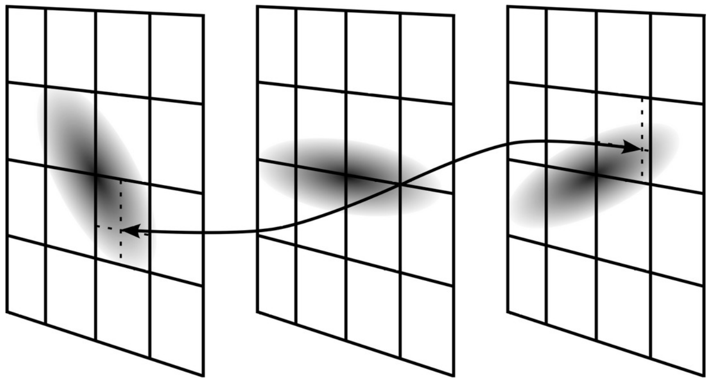
Stellarator stimulations in BOUT++ require lateral thinking

BOUT++ assumes a field-aligned model

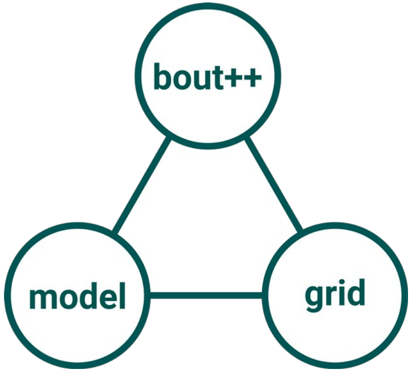
- **radial, toroidal, and ||**
  - At X-points, this breaks down as two coordinates are parallel.
    - Stellarators have lots of X-points…

Instead, use a method which is not aligned to the field

- **Flux Coordinate Independent (FCI) method for parallel derivates**
- **Requires changing all three BOUT++ "ingredients"**



A schematic of the FCI method



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- **finite difference / finite volume**

Physics models have straightforward syntax:

- **ddt(var) = Grad_par(var);**

Most user-interfacing is done through simple input files at run-time:

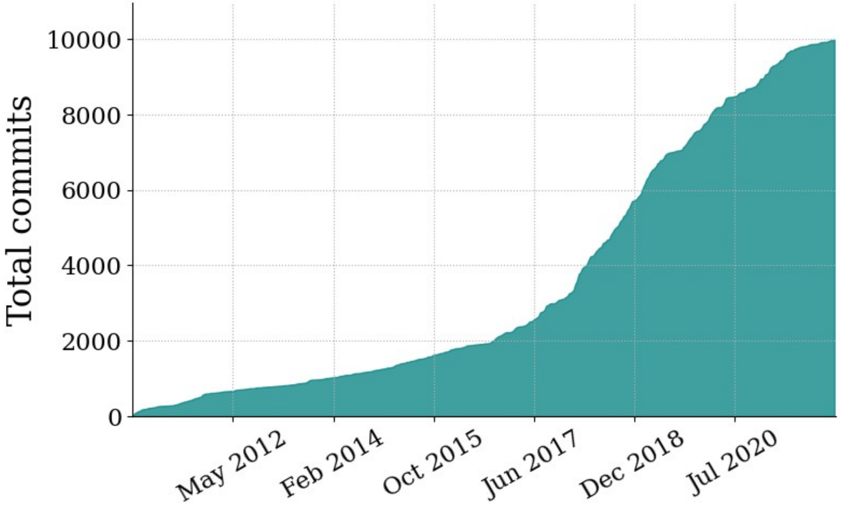
evolve_var = True
sheath_bndry = True

[var]

function = sin(X)

bndry_all = dirichlet(0.0)

source = gauss(x,0.21)



EMC3-lite in BOUT++

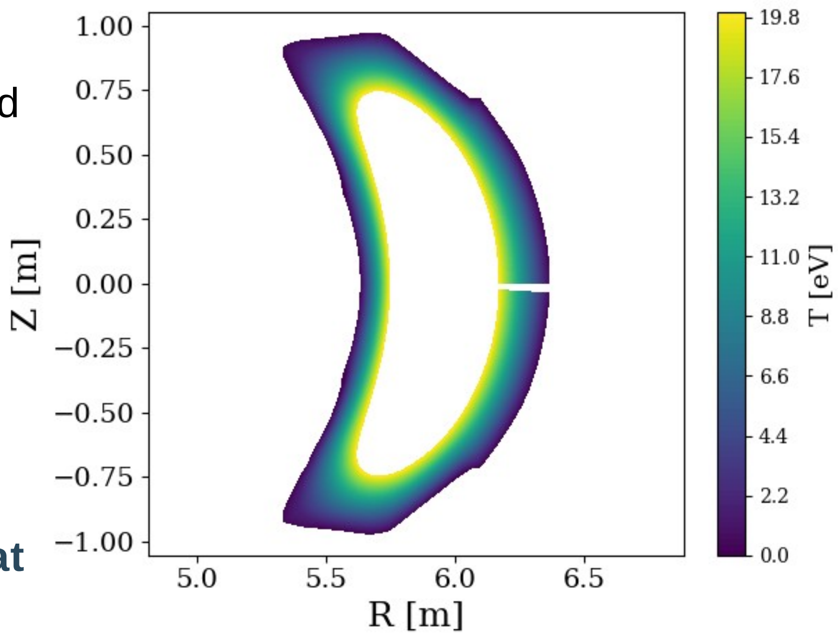
The equations for EMC3-lite have been implemented using BOUT++ FCI operators

- **available at: github.com/bshanahan/bsting-models**

Steady-state reached relatively quickly.

Pre- and post-processing work are underway.

- **Biggest limitation is grid generation and heat flux visualization**



Steady-state "T" profile in BOUT++ with the EMC3-lite model