BOUT++

PDE Solver Framework for Plasma Models

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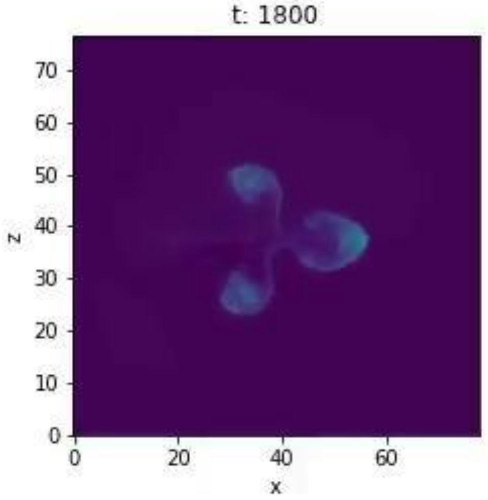
BOUT++

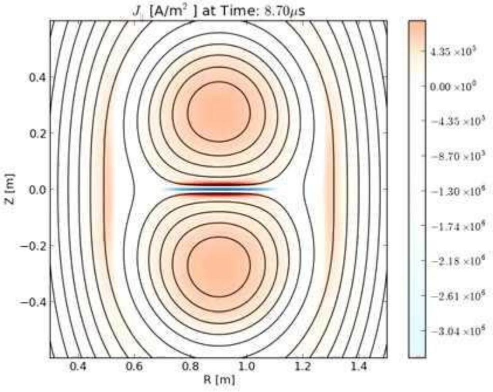
- Internationally used framework for solving PDEs in curvilinear geometry
- Specialised operators for plasma applications
- Domain-specific language in C++

```
phi = laplacian->solve(omega);
ddt(n) = -bracket(phi, n)
         + 2 * DDZ(n) * rho_s
         + D_n * Delp2(n);
ddt(omega) = -bracket(phi, omega)
              + 2 * DDZ(n) * rho_s / n
              + D_vort * Delp2(omega) / n;
```

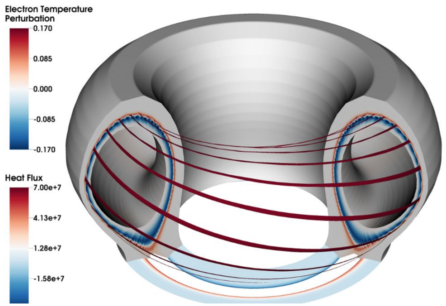


BOUT++ Capabilities

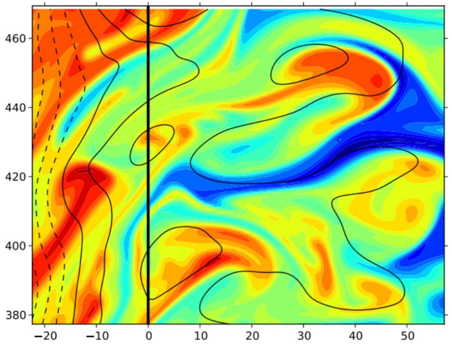
- Finite difference/volume in 3D mapped multi-block geometry
- Solves nonlinearly coupled hyperbolic, parabolic and elliptic equations
- MPI-parallelised, scales to ~4,000 cores, depending on problem
- Turbulence ~10^6—10^8 unknowns, ~10^5 core-hours



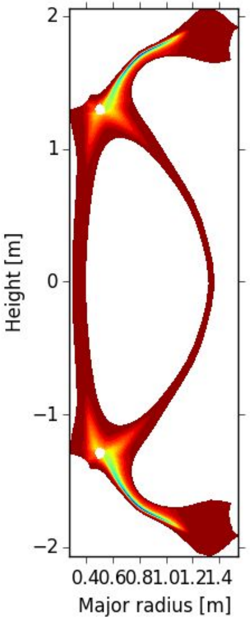
Magnetic reconnection



Edge Localised Modes



Turbulence



Transport

BOUT++ Applications

Many different models have been built on BOUT++

Different sets of equations, different geometries

<u>Topics</u>

- Edge Localised Modes
- Pedestal transport
- Filaments / blobs
- SOL turbulence
- Pellet injection
- RF interactions
- Magnetic Perturbations

<u>Formulation</u>

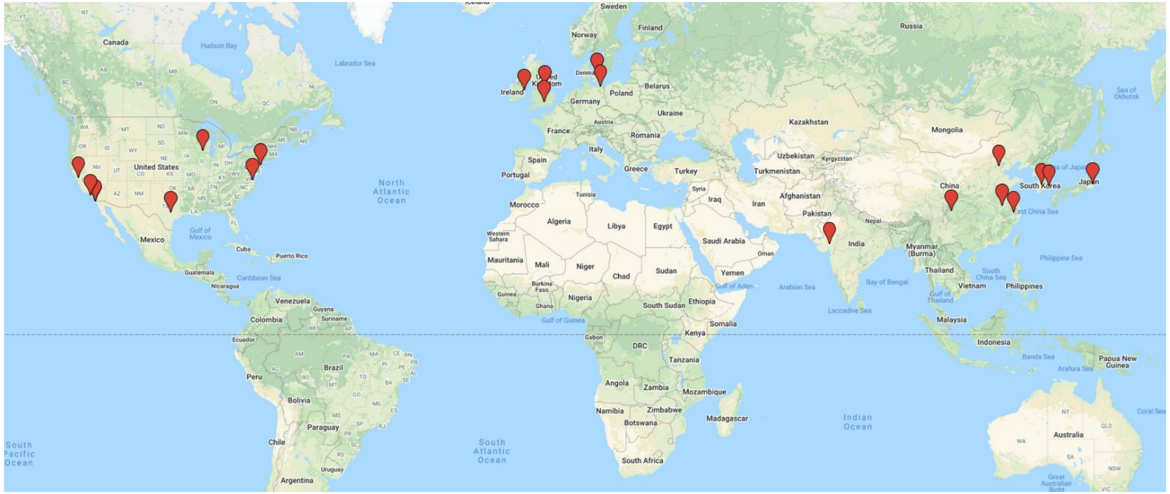
- Drift-reduced fluid
- Gyro-fluid
- Landau fluid closures
- Zonal flows
- Neutral interactions
- Impurity species

<u>Models</u>

- elm-pb/3f/5f/6f
- STORM
- Hermes
- SD1D
- CYTO
- Trans-neut
- BOUT++ GEM

BOUT++ Is Open Source

- Open source, users/developers worldwide
- Strong community, and investment in building capabilities to underpin research



<u>Top contributors</u>

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George Breyiannis
Brendan Shanahan
Ilon Joseph
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+ ~35 others

https://github.com/boutproject/

http://boutproject.github.io/

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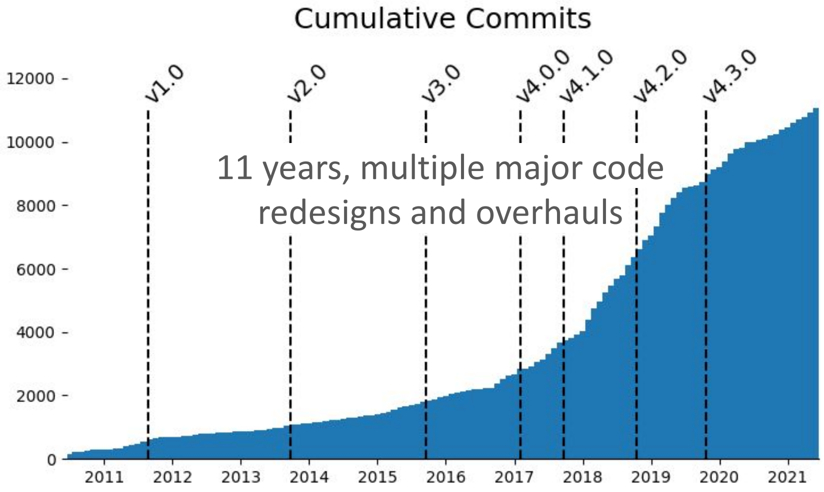

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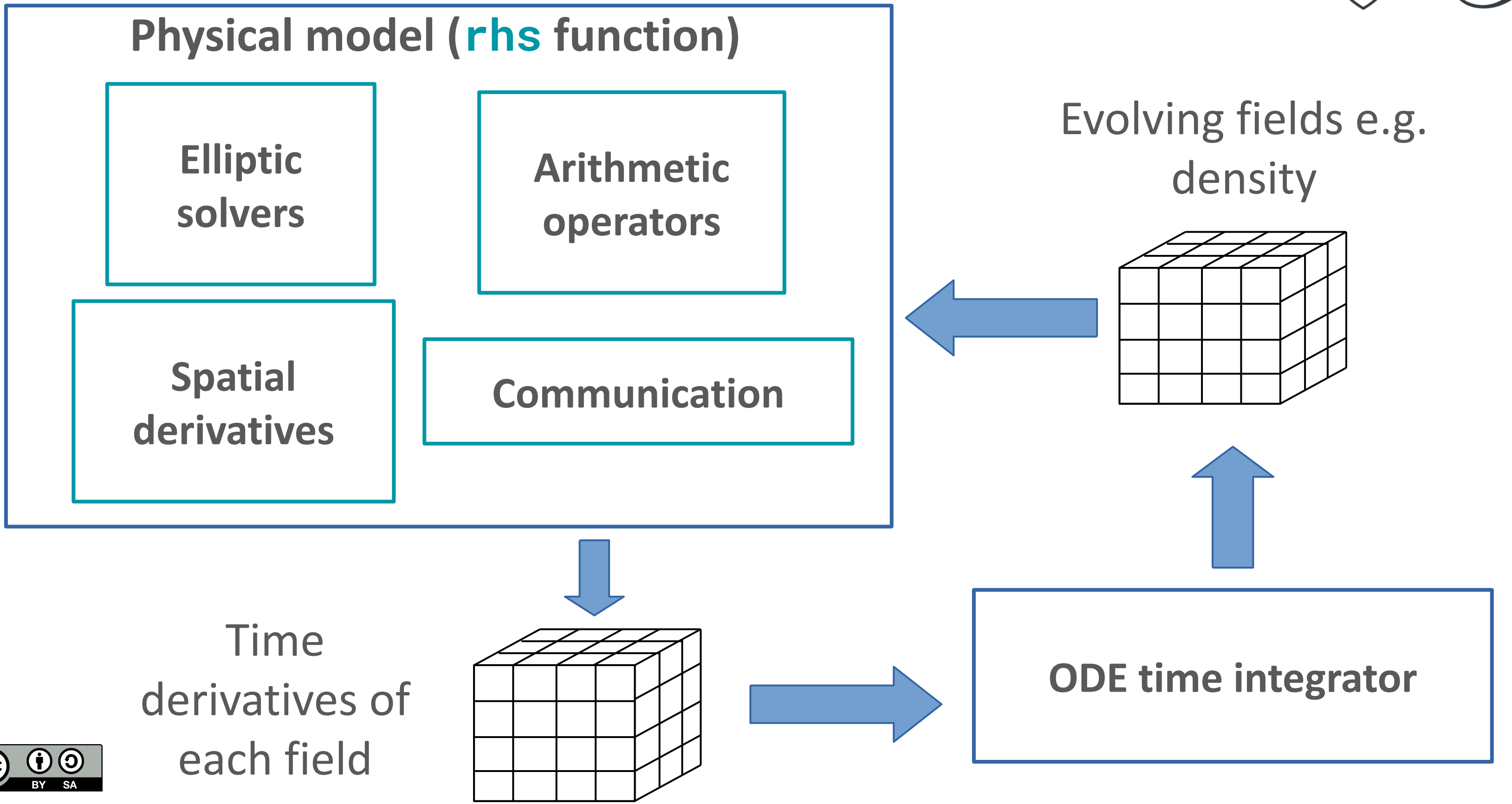
Matrix-free Method of Lines



BOUT++ Framework

UNIVERSITY of York

```
class Blob2D : public PhysicsModel {
private:
  // Evolving variables
  Field3D n, omega;
  …
public:
  int init(bool restarting);
  int rhs(BoutReal time);
};

BOUTMAIN(Blob2D);
```

Class inheriting from `PhysicsModel`

Model variables, input parameters

Model setup and initialisation

Calculation of time derivatives

Macro creating `main` entry point

BOUT++ Example Model

https://github.com/boutproject/BOUT-dev/tree/master/examples/blob2d

$$\frac{\partial n}{\partial t} = -\frac{1}{B}\underline{b} \times \nabla\phi \cdot \nabla n + 2\rho_s \frac{\partial n}{\partial z} + D_n \nabla_\perp^2 n$$

```
ddt(n) = -bracket(phi, n)
         + 2 * rho_s * DDZ(n)
         + D_n * Delp2(n);
```

$$\frac{\partial \omega}{\partial t} = -\frac{1}{B}\underline{b} \times \nabla\phi \cdot \nabla \omega + \frac{2\rho_s}{n} \frac{\partial n}{\partial z} + \frac{D_{vort}}{n} \nabla_\perp^2 \omega$$

```
ddt(omega) = -bracket(phi, omega)
             + (2 * rho_s / n) * DDZ(n)
             + D_vort * Delp2(omega) / n;
```

$$\omega = \nabla_\perp^2 \phi$$

```
phi = laplacian->solve(omega);
```

BOUT++ Flexibility

- Guiding principle of BOUT++ is flexibility
- Choice of numerical method for each operator
- Can be specified at runtime or compile time

BOUT.inp input file:

```
[mesh]
nx = 64
ny = 1
nz = 64

[mesh:ddx]
first = C4
second = C2
[mesh:ddz]
first = U2
```

blob2d.cxx source code:

```
ddt(n) = -bracket(phi, n, BRACKET_ARAKAWA)
         + 2 * DDZ(n, CELL_CENTRE, "FFT") * rho_s
         + D_n * Delp2(n);
```

Command line:

```
./blob2d solver:type=rk4 laplace:type=petsc
    mesh:nx=128 mesh:ddx:first=C2
```

BOUT++ Python Interface

- Cython wrapper around C++ interface
- Useful for post-processing and term decomposition

https://github.com/boutproject/boutcore-examples/blob/main/blob2d.py

```
class Blob2D(PhysicsModel):
  def init(self, restart):
    …
  def rhs(self, time):
    …
    ddt_n = self.n.ddt() # Limitation of Python
    ddt_n.set(0)         # interface
    ddt_n += -bracket(self.phi, self.n)
             + 2 * DDZ(self.n) * self.rho_s
             + self.D_n * Delp2(self.n)
    self.phi = self.laplacian.solve(self.omega,
                                    self.phi)
```

```
# Create an instance
blob2d = Blob2D()
# Start the simulation
blob2d.solve()
```