SOUL: A 1D SOL Module for CRONOS

Rajiv Goswami[1], Jean-François Artaud[2], Frédéric Imbeaux[2], Jerôme Bucalossi[2] & Christophe Guillemaut[2]

[1]Institute for Plasma Research, India.

[2]IRFM, CEA, France.

July 25, 2011

Outline

Introduction

Previous Work & Motivation
- How?
- Why SOUL?

Model(s)
- Physical
- Coupling mechanism
- Numerical

Results
- Subsonic solution:
- Supersonic solution:
- CRONOS+SOUL convergence:

Summary

Conclusion & Future Work

- Modelling of full tokamak (magnetic axis to walls).
- Integrate two distinct regions (Core & SOL).
- Core:
  - Closed field lines.
  - 1D (Flux surface averaged) transport equations on 2D shaped magnetic equilibria => (1.5D).
  - Long radial transport time scale (0.1 – 1 s).
- SOL:
  - Open field lines.
  - 2D (Braginskii-like) fluid equations.
  - Shorter time scale (few ms).
- Coupling schemes/Boundary conditions for Core + SOL ?

Two major approach

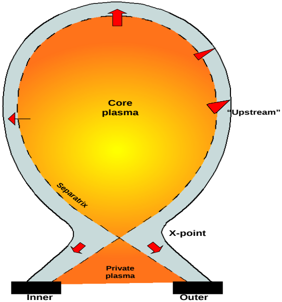
- Extend the 2D grid used for SOL upto the magnetic axis [1].
- Couple the Core to the SOL at the separatrix [2]-[4].

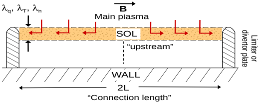
Issues

- Highly complex 2D SOL codes with many parameters.
- Full 2D SOL simulations are very time consuming even with current computer capabilities!
- Convergence issues (extremely slow or failure) for some parameter regimes?
- Applicability of present 2D SOL codes without a proper SOL turbulence model, in a predictive mode is unclear.

What to do?

Take a "middle path" between the highly simplistic two-point models and the complex and slow, 2D SOL codes!





Since the SOL has:

- a small radial extent.
- strong influence by the fast parallel transport.

The direction aligned along the plasma flow is crucial to particle & energy exhaust, through the generation of (large) flows, density & temperature gradients, etc.

Thus!
SOUL solves for this parallel dynamics, Braginskii-like plasma fluid equations. Assuming steady-state,

- Radial dynamics is incorporated through 0D arguments such as SOL widths, etc.
- The SOL is assumed to be "straightened-out".
- Information about parallel connection length & X-point position is provided by CRONOS.
- The parallel transport is assumed to be classical, without flux limits to simulate kinetic effects.

Particle balance:

$$\frac{d}{dx}(nv) = \mathbf{S}_{\perp}\theta(x_d - x) + nn_n\langle\sigma v\rangle_i - n^2\langle\sigma v\rangle_r \qquad (1)$$

Momentum balance (neglecting viscosity):

$$\frac{d}{dx}\left[mnv^2 + n(T_e + T_i)\right] = -mnv\left(n_n\langle\sigma v\rangle_{cx} + n\langle\sigma v\rangle_r\right) \qquad (2)$$

Electron energy balance:

$$\frac{d}{dx}\left(\frac{5}{2}nvT_e - \kappa_{\parallel e}\frac{dT_e}{dx}\right) = \mathbf{Q}_{\perp e}\theta(x_d - x) - n^2\xi_I L_z(T_e)$$
$$-E_i nn_n\langle\sigma v\rangle_i - \frac{3}{2}T_e n^2\langle\sigma v\rangle_r - n\nu_{ei}(T_e - T_i) + v\frac{d}{dx}(nT_e) \qquad (3)$$

Ion energy balance:

$$\frac{d}{dx}\left(\frac{5}{2}nvT_i + \frac{mnv^3}{2} - \kappa_{\|i}\frac{dT_i}{dx}\right) = \mathbf{Q}_{\perp\mathbf{i}}\theta(x_d - x)$$
$$-\left[\frac{3}{2}(T_i - T_n) + \frac{mv^2}{2}\right] n^2\langle\sigma v\rangle_{\mathrm{cx}} - \left(\frac{3}{2}T_i + \frac{mv^2}{2}\right) n^2\langle\sigma v\rangle_{\mathrm{r}}$$
$$+n\nu_{ei}(T_e - T_i) - v\frac{d}{dx}(nT_e) \qquad (4)$$

Neutral (diffusion) equation:

$$\frac{d}{dz}\left(-D_n\frac{dn_n}{dz}\right) = -nn_n\langle\sigma v\rangle_{\mathrm{i}} + n^2\langle\sigma v\rangle_{\mathrm{r}} \qquad (5)$$

$$D_n = \frac{T_i}{mn(\langle\sigma v\rangle_{\mathrm{i}} + \langle\sigma v\rangle_{\mathrm{cx}})}$$

Stagnation point bc's:

$$\mathbf{M}\ ,\ \mathbf{n}'\ ,\ \mathbf{T}_e'\ ,\ \mathbf{T}_i'\ ,\ \mathbf{n}_n' = 0$$

Sheath bc's @ target:

$$\mathbf{M_t} \geq 1\ ;\ \mathbf{q_e^{tot}} = \delta_e \mathbf{nvT_e}\ ;\ \mathbf{q_i^{tot}} = \delta_i \mathbf{nvT_i}\ ;\ -\mathbf{D_n}\frac{\mathbf{dn_n}}{\mathbf{dz}} = \mathbf{R} * \mathbf{nvsin}\alpha$$

At a given step in the time evolution of CRONOS, do:

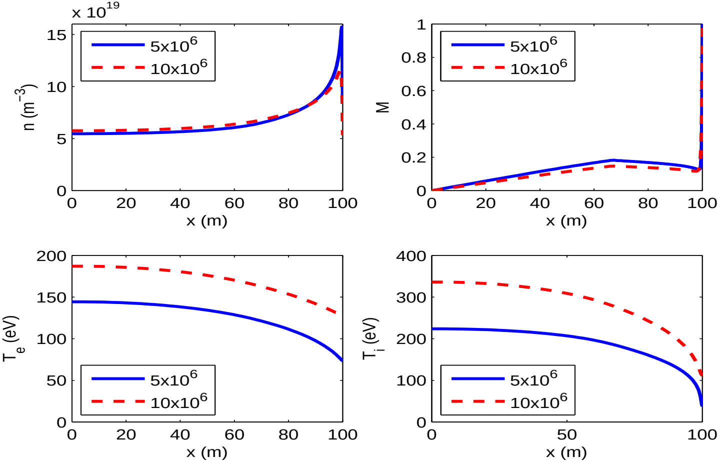
1. Use ($\mathbf{S}_{\perp}^{\text{init}}$ and $\mathbf{Q}_{\perp \mathbf{e(i)}}^{\text{init}}$) as input in SOUL to get $\mathbf{n}$ and $\mathbf{T}_{\mathbf{e(i)}}$ values.
2. Plug the stagnation point values $\mathbf{n}^{\text{st}}$ and $\mathbf{T}_{\mathbf{e(i)}}^{\text{st}}$ into CRONOS as separatrix boundary values.
3. Now use the $\mathbf{S}_{\perp}$ and $\mathbf{Q}_{\perp \mathbf{e(i)}}$ output from CRONOS as input in SOUL to obtain new $\mathbf{n}$ & $\mathbf{T}_{\mathbf{e(i)}}$.
4. Rerun CRONOS with the new separatrix boundary values and get updated values for $\mathbf{S}_{\perp}$ and $\mathbf{Q}_{\perp \mathbf{e(i)}}$.
5. Run loop (2 – 4) till convergence!

Advance CRONOS in time.

- Hybrid scheme for advection terms (upwinding when required).
- 2nd-order finite-difference for diffusion terms.
- Obtain a set of discrete nonlinear coupled equations on a nonuniform (exponential) grid.
- Use a globally-convergent Newton solver for these nonlinear systems of equations.

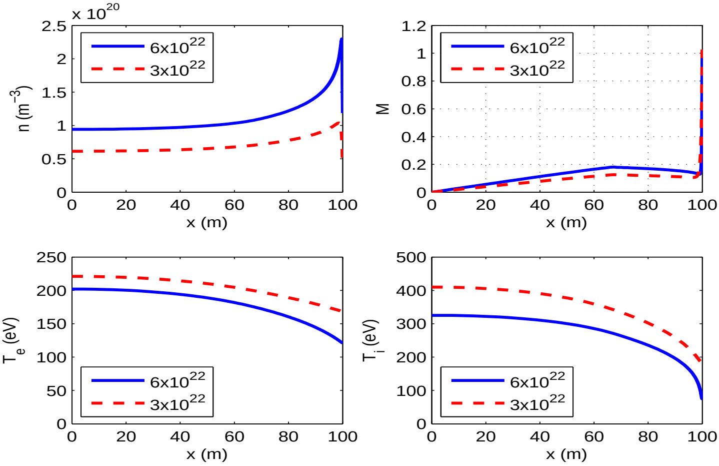
Variable $Q_{\perp e(i)}$ (W/m^3)

$$\mathbf{S}_\perp = \mathbf{3} \times \mathbf{10^{22}} \ /m^3/s$$

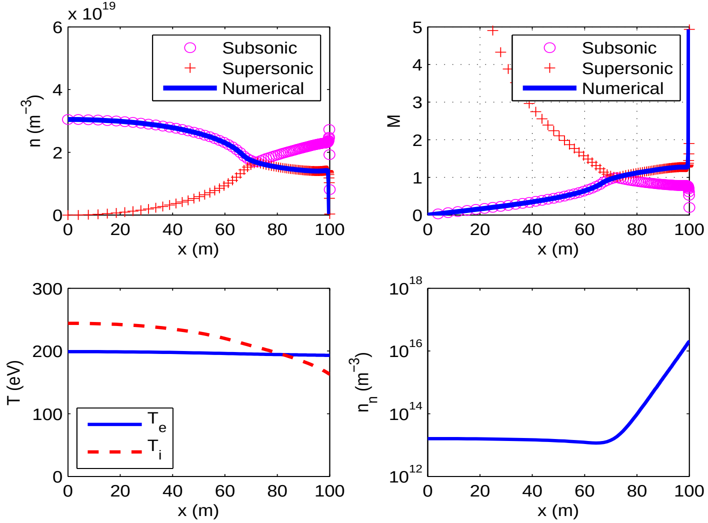


Variable $S_\perp$ ($/m^3/s$)

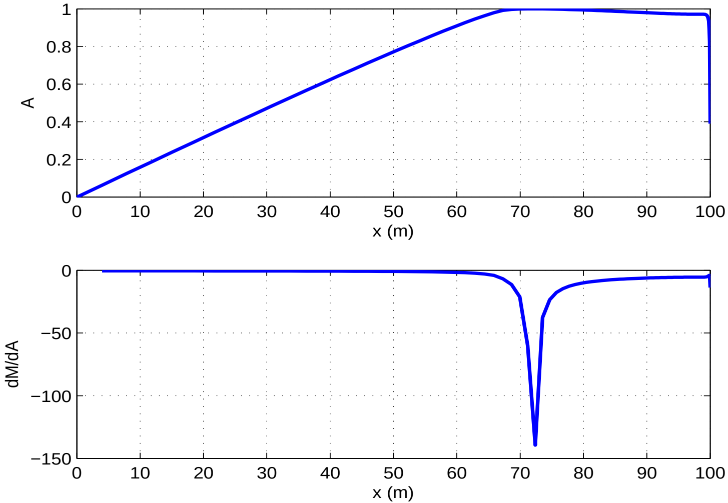
$$\mathbf{Q}_{\perp \mathbf{e(i)}} = \mathbf{15} \times \mathbf{10^6}\ \mathrm{W/m^3}$$

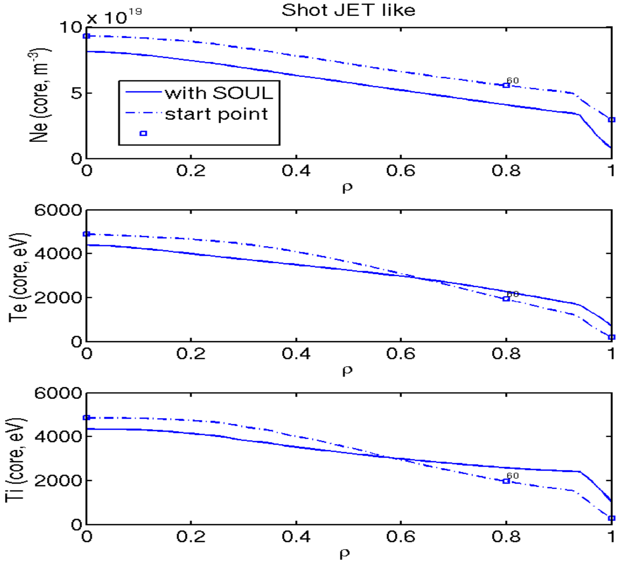


$$\mathbf{S}_{\perp} = \mathbf{5} \times \mathbf{10^{22}} \ /m^3/s \ , \ \mathbf{Q}_{\perp \mathbf{e(i)}} = \mathbf{6} \times \mathbf{10^6} \ W/m^3.$$



$$\mathbf{S}_{\perp} = \mathbf{5} \times \mathbf{10^{22}}\ /\mathrm{m}^3/\mathrm{s}\ ,\ \mathbf{Q}_{\perp \mathbf{e(i)}} = \mathbf{6} \times \mathbf{10^{6}}\ \mathrm{W}/\mathrm{m}^3.$$




Shot JET like
x 10^19
Ne (core, m^-3)
with SOUL
start point
60
ρ
Te (core, eV)
Ti (core, eV)

- SOUL is a 1D fluid code for modelling plasma transport in the SOL along magnetic field lines.
- It solves a set of Braginskii-like equations for electron and ions, assuming ambipolarity & no net current.
- Cross-field transport constitutes a source of mass and energy.
- Plasma-neutral collisions are considered through a separate fluid model for neutrals.
- Realistic bc's are employed.
- Use of nonuniform grids and direct matrix solver MUMPS enable very rapid simulation (~ 1 s).
- We also obtain a natural transition to "supersonic flows", which is in agreement with recent theoretical arguments [5].

- SOUL has now been integrated with CRONOS for providing reasonable separatrix bc's, and convergence of the coupling mechanism has been established.
- Benchmarking with well-diagnosed JET shots is ongoing.
- Communication to a journal.
- Inclusion of additional physics.

- D. Coster *et al.*, J. Nucl. Mater. **241-243**, 690 (1997).
- M. Fichtmüller *et al.*, Czech. J. Phys. **48/S2**, 25 (1998).
- A. Tarditi *et al.*, Contrib. Plasma Phys. **36**, 132 (1996).
- R. Stankiewicz *et al.*, J. Nucl. Mater. **313-316**, 899 (2003).
- Ph. Ghendrih *et al.*, Plasma Phys. Control. Fusion **53**, 054019 (2011).