The SWIM Fast MHD Campaign

Presented by

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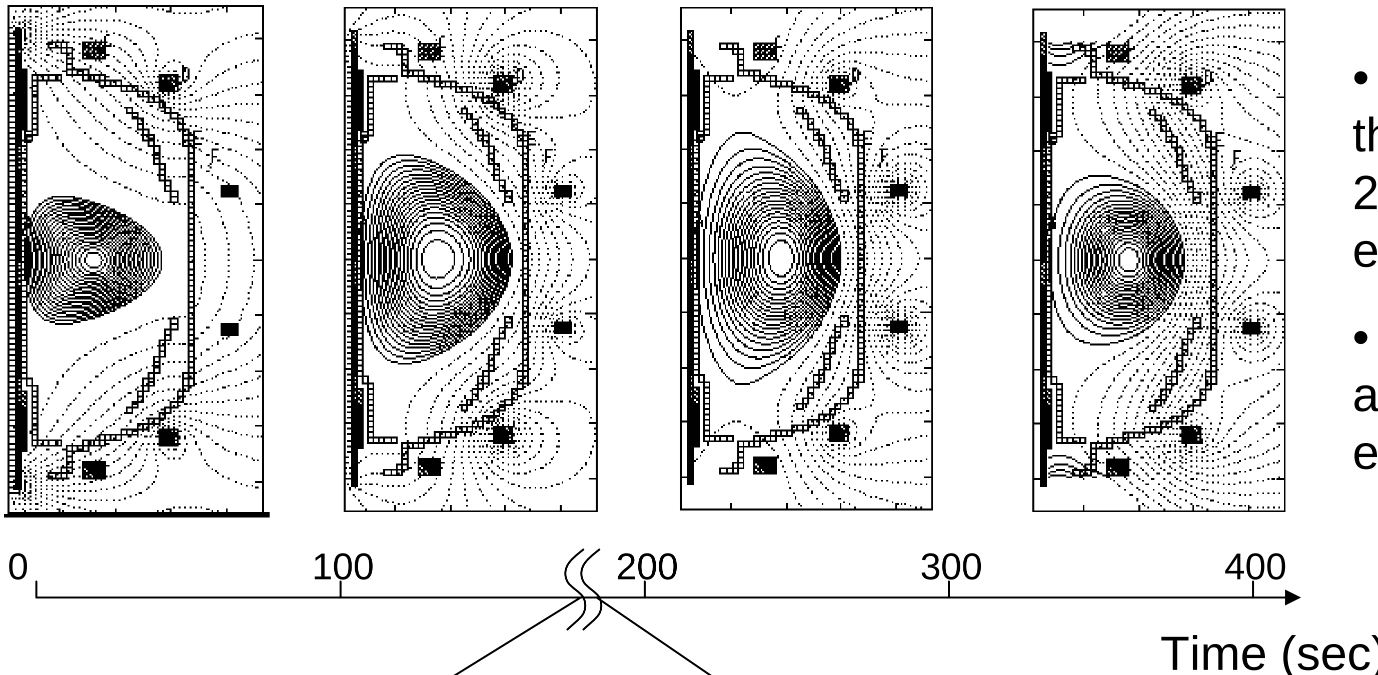
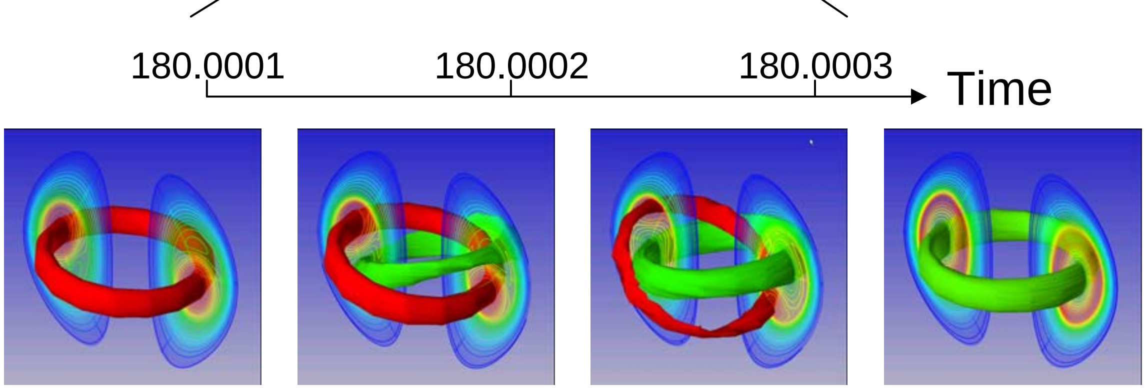
Outline

- What is the Fast MHD Campaign ?
- The IPS and the 1 1/2D approximation
- The Time Loop and the Plasma State
- The 3D post-processor
- Goals for the Fast MHD Campaign

Fast MHD Campaign:



- Plasma evolves through a series of 2D axisymmetric equilibrium states
- Instabilities occur as instantaneous events



- 3D Extended MHD simulation starts and ends in axisymmetric state

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Extended MHD Equations:

Evolving Equilibrium Description:

(Alfven waves removed from system)

$$\rho\left(\frac{\partial \vec{V}}{\partial t} + \cancel{\vec{V} \bullet \nabla \vec{V}}\right) + \nabla \bullet \overleftrightarrow{P} = \vec{J} \times \vec{B}$$

$$\frac{\partial n}{\partial t} + \nabla \bullet (n\vec{V}) = S_M$$

$$\frac{3}{2}\frac{\partial p}{\partial t} + \nabla \bullet \left(\vec{q} + \frac{5}{2}\overleftrightarrow{P} \bullet \vec{V} \right) = \vec{J} \bullet \vec{E} + S_{iE} + S_{eE}$$

$$\frac{3}{2}\frac{\partial p_e}{\partial t} + \nabla \bullet \left(\vec{q}_e + \frac{5}{2}\overleftrightarrow{P}_e \bullet \vec{V}_e \right) = \vec{J} \bullet \vec{E} - Q_\Delta + S_{eE}$$

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}, \qquad \vec{E} + \vec{V} \times \vec{B} = \eta \vec{J} + \frac{1}{ne}\left[\vec{J} \times \vec{B} - \nabla \bullet \overleftrightarrow{P}_e \right]$$

$$\mu_0 \vec{J} = \nabla \times \vec{B}$$

$$\overleftrightarrow{P} = p\overleftrightarrow{I} + \overleftrightarrow{\Pi}$$

$$p = p_e + p_i$$

$$n = n_e = \sum_i Z_i n_i \quad \text{charge neutrality}$$

$$\vec{V}_e = \vec{V} - \frac{1}{ne}\vec{J}$$

It was shown in the 70's (H. Grad) that <u>if the system is MHD stable</u>, the <u>inertial term can be deleted</u>, <u>equations can be averaged over flux surfaces</u>, and the <u>velocity field is uniquely determined.</u>

Requires transport coefficients to provide <u>closure</u> relations for:

$$\langle \vec{q}_e \bullet \nabla \psi \rangle, \langle \vec{q}_i \bullet \nabla \psi \rangle, \langle \vec{B} \bullet \overleftrightarrow{\Pi} \bullet \nabla \theta \rangle$$

Source terms S_E, S_M, …, very important

References for Evolving Equilibrium Description

- H. Grad and J. Hogan, Phys. Rev. Lett. 24 1337 (1970)
- J. B. Taylor, unpublished Culham report ~ 1972
- Y.P. Pao, Phys. Fluids 19 1177 (1976)
- Y.P. Pao, Phys. Fluids 21 1120 (1978)
- S. Hirshman and S. Jardin, Phys. Fluids 22 731 (1979)
- S. Jardin, J. Comput. Phys. 43 31 (1981)

Mathematical Basis for Evolving Equilibrium Description

If the system is axisymmetric and possesses good flux surfaces, then the equations for the pressures, densities, and magnetic field evolution can be averaged over flux surfaces to give 1-D evolution equations for the adiabatic field and fluid variables and a 2D elliptic equation that uniquely determines the shape of the flux surfaces:

$$\frac{\partial}{\partial t}\vec{Y} = \frac{\partial}{\partial \psi}\left[\overleftrightarrow{K}\bullet\frac{\partial}{\partial \psi}\vec{Y} + \vec{\Gamma}\right] + \vec{S}$$

$$\vec{Y}(\psi) = \begin{bmatrix} \iota \\ N \\ \sigma_e \\ \sigma_i \end{bmatrix}$$

$\iota(\psi) = q^{-1}$ is transform

$V'(\psi) = \oint \frac{dl}{B}$ is differential volume

$N(\psi) = n(\psi)V' = \oint \frac{dl}{B} n(R,Z)$ is particle number

$p(\psi) = \frac{1}{V'}\oint \frac{dl}{B} p(R,Z)$ is surface averaged pressure

$\sigma(\psi) = p(\psi)V'^{5/3}$ is entropy density

$\vec{S}(\psi) = \oint \frac{dl}{B} S(R,Z)$ are source terms

$\psi(\Psi)$ is magnetic flux coordinate

$$R^2\nabla\bullet R^{-2}\nabla\Psi + R^2\frac{d}{d\Psi}\left[\frac{\sigma(\Psi)}{V'^{5/3}}\right] + \frac{(2\pi)^{-2}}{\iota(\Psi)V'\langle R^{-2}\rangle}\frac{d}{d\Psi}\left[\frac{1}{\iota(\Psi)V'\langle R^{-2}\rangle}\right] = 0$$

This system is mathematically exact in this limit, and is totally free of all Alfven time-scale phenomena. It requires transport fluxes, surface averaged sources/sinks, and boundary conditions.

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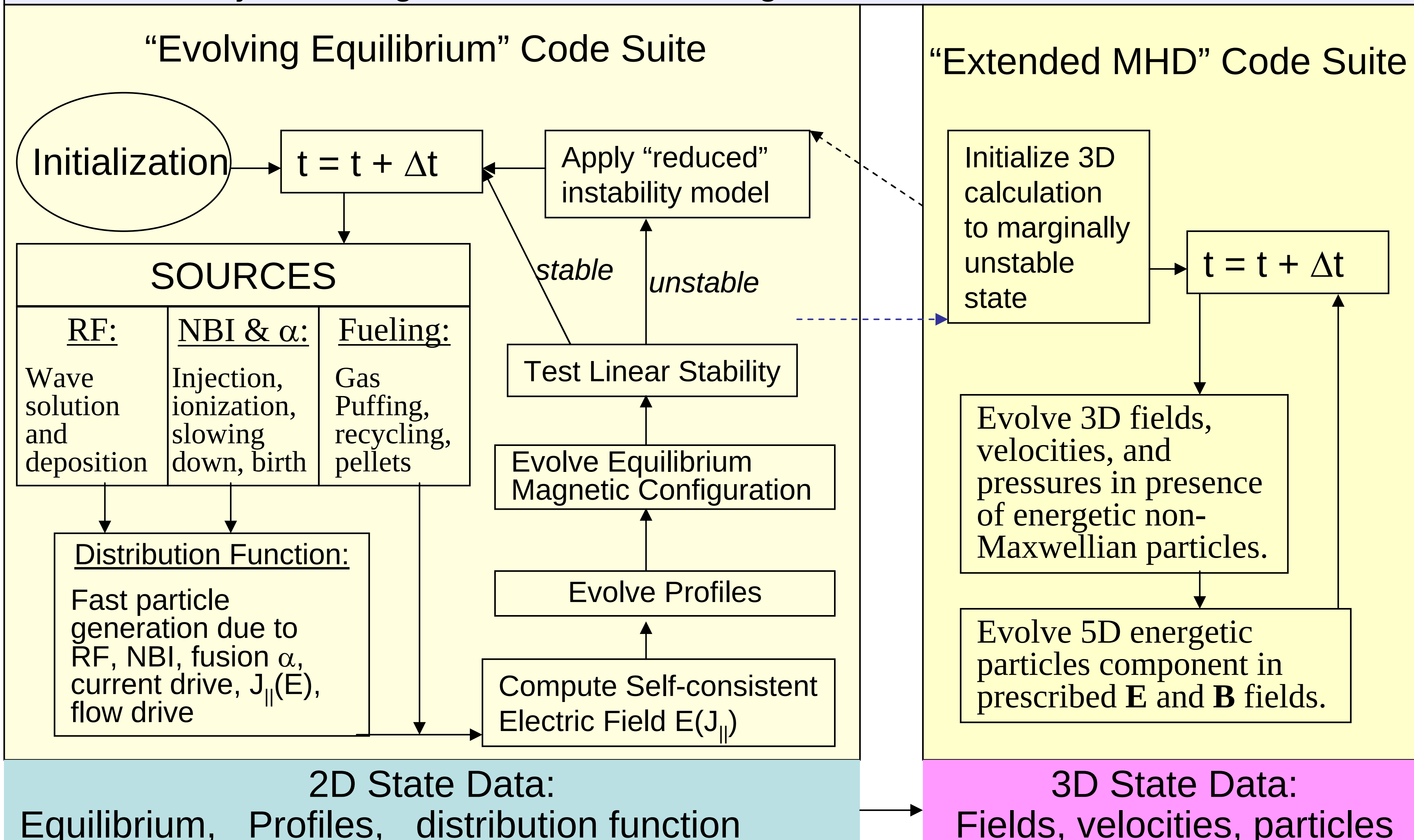
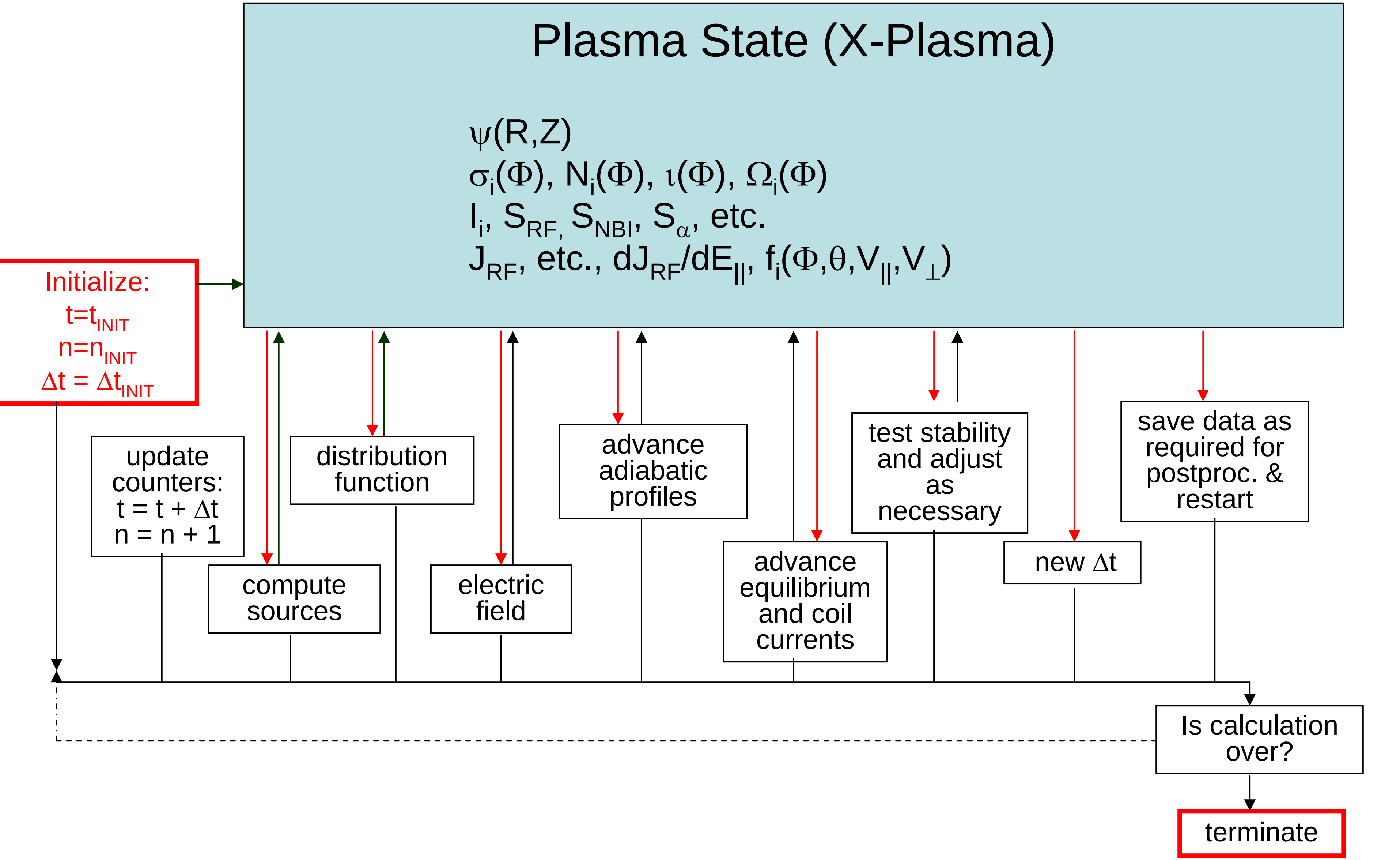
Common superstructure: Component orchestration and workflow tools, job launch, and job management and monitoring tools.



Shared infrastructure components: high level numerical libraries, job monitoring and tracking, file I/O and staging, metadata management, collaboration, graphics

Possible Time Loop and Role of Plasma State:



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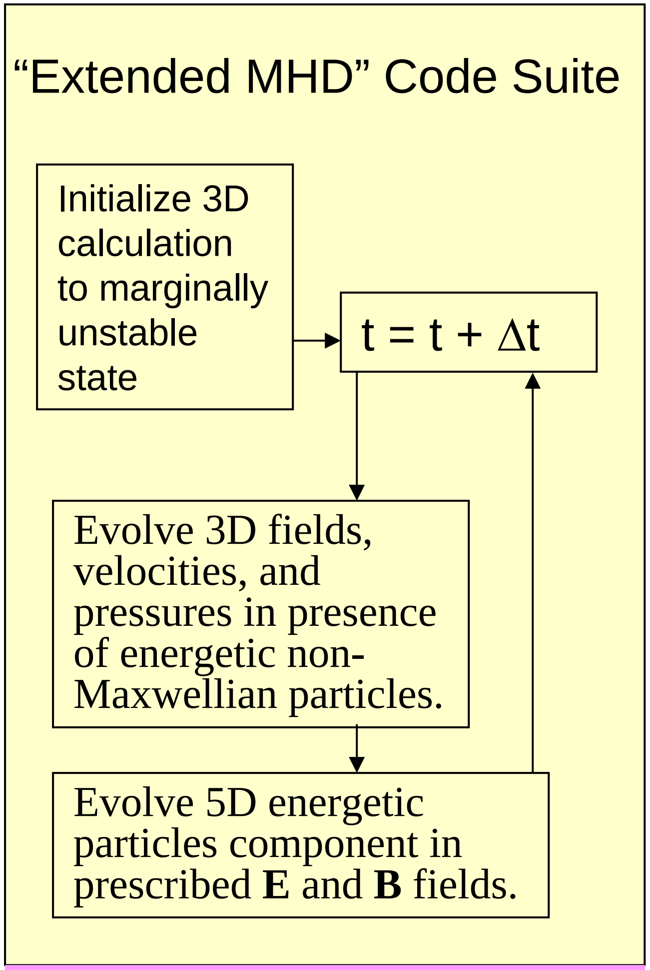
The 3D Post-Processor

- Initially we will use M3D and NIMROD
- Need to transfer 2D state data to 3D state data
- Need to convert distribution function into equivalent particle distribution
- These codes need to be optimized on the ORNL machines
- Can we start with linear stability codes rather than nonlinear codes (for speed)?



2D State Data:
Equilibrium, Profiles, distribution function

3D State Data:
Fields, velocities, particles

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From Call-for-Proposals:

General Goal:

Develop an integrated predictive modeling capability for a specific topical area (RF+MHD) while, at the same time, dealing with the integration issues that will be faced by the FSP.

Specific Goal:

Understand how electromagnetic waves affect MHD stability of a fusion plasma and how these effects can be used to optimize the performance of a burning plasma.

Specific product:

A suite of simulation codes that self-consistently couples the time evolution of the plasma equilibrium with the wave-driven modifications of the current, temperature, and flow profiles and includes the analysis of stability limits.

- It is expected that the software and algorithm development environment and the code framework will be flexible enough to facilitate recombining of software components into new code capabilities as additional physics is added to the mathematical models.

- This code suite should be benchmarked against profile control experiments with pulse lengths that are long compared to the magnetic field diffusion times. Such an integrated simulation capability will allow the development of optimized burning plasma scenarios.

Final Comments:

- We should strive to include the best (state-of-the-art) code module within each module category…at least as an option. This will make this software the code-of-choice for serious ITER applications.
- We need to calculate the self-consistent distribution function under the actions of RF, NBI, and fusion heating, and the effect of this on MHD stability. This will be the unique feature of this campaign.
- Need to follow good coding practices so system does not become unwieldy as it grows
- Need to have ease-of-use and publication-quality graphics capability
- Let us not shy-away from parallelism

Final, Final Comments (on units)

- Code modules can use any internal units they want, but all input/output should be in MKS units (SI) + eV

- Meters, kilograms, seconds, amperes, joules, watts, volts, ohms, tesla, etc.

- p = n k_B T(ev) k_B=1.60x10^{-19} J/eV

$$e = \frac{3}{2} p$$