# Status and Plans for the NIMROD Code Development Project

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# OUTLINE

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   B. Development status
   C. Linear solver

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IV. Graphical User Interface

V. Preprocessing

VI. Postprocessing
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   B. IBM Data Explorer

## OBJECTIVES

1. Model low-frequency phenomena in high-performance tokamaks.

2. Provide a flexible computational tool for alternates.

3. Explore the use of *concurrent engineering* and *quality function deployment* in large-scale code development.

## PRODUCT

**N**on-**I**deal **M**HD with **R**otation: **O**pen **D**iscussion

- Time-dependent, time-split, implicit fluid simulation code.

- Realistic, flexible geometry via finite element discretization of the poloidal plane.

- Pseudospectral representation of the periodic direction.

- Block decomposition of the computational domain for parallel computing on message passing architectures.

- Graphical User Interface for easy use.

- Multi-level graphics for routine and publication quality output.

# PHYSICS KERNEL

Original numerical formulation:

$\mathbf{J}_S$ equations->Ampere's law->implicit **E** equation.

Unacceptable coupling of shear and compressional Alfven waves.

Revised formulation:

Generalized Ohm's law->Faraday's law->implicit **B** equation.

Better numerical properties (see Glasser, et al.)

# Time-discrete Equations (Cold Plasma)

$Z_e=-q_i/q_e$
$\upsilon=Z_e m_e/m_i$
$m=m_i/Z_e+m_e$
$n=n_e$, electron number density
$\rho=mn=m_i n(1+\upsilon)/Z_e$, mass density
$\mathbf{M}=m_i\mathbf{J}_i/q_i+m_e\mathbf{J}_e/q_e$, momentum density
$f_\Omega$=numerical time-centering parameter

$$\frac{\Delta \mathbf{J}_s}{\Delta t}+\frac{f_\Omega q_s}{m_s}\mathbf{B}^*\times\mathbf{J}_s^{n+1}=\frac{n_s q_s^2}{m_s}\mathbf{E}+\frac{(f_\Omega-1)q_s}{m_s}\mathbf{B}^*\times\mathbf{J}_s^n$$

$$\mathbf{E}=\frac{1}{\varepsilon_0\omega_p^2}\frac{\Delta\mathbf{J}}{\Delta t}+f_\Omega\mathbf{B}^*\times\left(\frac{1}{\rho}\mathbf{M}^{n+1}-\frac{(\mathbf{1}-\upsilon)}{(\mathbf{1}+\upsilon)}\frac{1}{en}\mathbf{J}^{n+1}\right)$$
$$+(1-f_\Omega)\mathbf{B}^*\times\left(\frac{1}{\rho}\mathbf{M}^n-\frac{(\mathbf{1}-\upsilon)}{(\mathbf{1}+\upsilon)}\frac{1}{en}\mathbf{J}^n\right)$$

$$\mathbf{M}^{n+1}=\mathbf{M}^n+\Delta t\left(f_\Omega\Delta\mathbf{J}+\mathbf{J}^n\right)\times\mathbf{B}^*$$

$$\mathbf{E}_{imp}=\frac{1}{\varepsilon_0\omega_p^2}\frac{\Delta\mathbf{J}}{\Delta t}+\frac{f_\Omega^2\Delta t}{\rho}\left(B^{*2}-\mathbf{B}^*\mathbf{B}^*\right)\cdot\Delta\mathbf{J}-\frac{(\mathbf{1}-\upsilon)}{(\mathbf{1}+\upsilon)}\frac{f_\Omega}{en}\mathbf{B}^*\times\Delta\mathbf{J}$$
$$\mathbf{E}_{exp}=\frac{1}{\rho}\left[\mathbf{B}^*\times\mathbf{M}^n+f_\Omega\Delta t\left(B^{*2}-\mathbf{B}^*\mathbf{B}^*\right)\cdot\mathbf{J}^n\right]-\frac{(\mathbf{1}-\upsilon)}{(\mathbf{1}+\upsilon)}\frac{1}{en}\mathbf{B}^*\times\mathbf{J}^n$$

$$\Delta\mathbf{B}+\nabla\times\mathbf{Z}\cdot\nabla\times\Delta\mathbf{B}=-\Delta t\nabla\times\mathbf{E}_{exp}$$

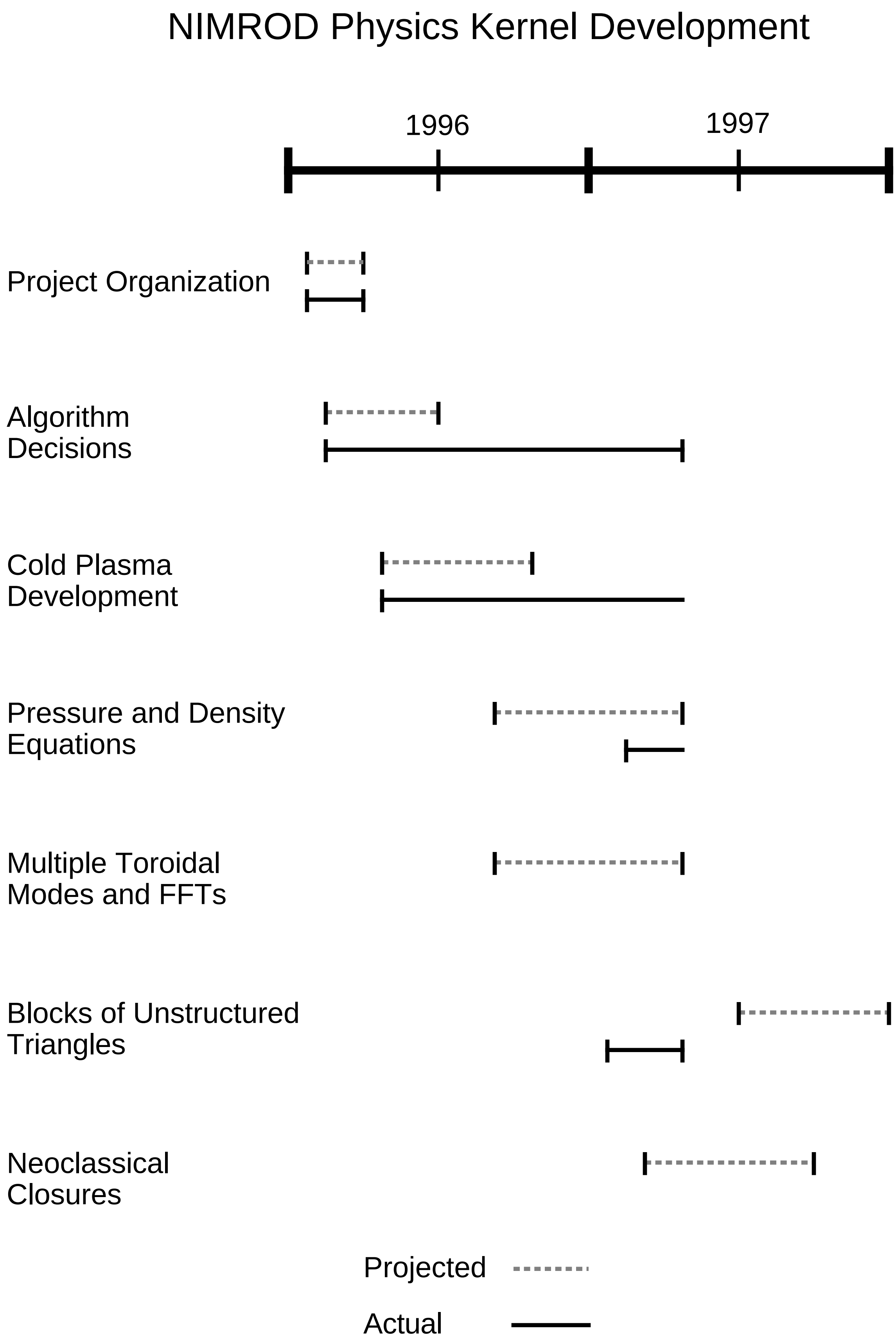
$$\mathbf{Z}=\frac{c^2}{\omega_p^2}\mathbf{I}+\frac{f_\Omega^2\Delta t^2}{\mu_0\rho}\left(B^{*2}-\mathbf{B}^*\mathbf{B}^*\right)-\frac{(\mathbf{1}-\upsilon)}{(\mathbf{1}+\upsilon)}\frac{f_\Omega\Delta t}{\mu_0 en}\mathbf{B}^*\times\mathbf{I}$$

## Present Status

- Revised formulation including conforming/nonconforming approximation options.
- Two types of grid blocks:  1) rectangular blocks of structured quadrilateral cells, 2) blocks of unstructured triangles.
- Cold plasma equations (except semi-implicit term for Hall dynamics).
- Nonzero electrical resistivity (implicit).
- F90 conjugate gradient solver with diagonal preconditioning for blocks of triangles and either diagonal or direct, domain-decomposition preconditioning on rectangular blocks.
- Message passing for parallel computing (see Plimpton, et al.).

## In-progress and Planned Development

- Multiple toroidal modes and FFTs for pseudospectral operations.
- Pressure evolution equation including anisotropic thermal conduction.
- Explicit advection terms.
- Neoclassical closure terms.
- Arbitrary unit vectors.
- $\nabla \cdot \mathbf{B}$ cleaning.
- Multi-grid preconditioning for cg solver.


NIMROD Physics Kernel Development
1996
1997
Project Organization
Algorithm Decisions
Cold Plasma Development
Pressure and Density Equations
Multiple Toroidal Modes and FFTs
Blocks of Unstructured Triangles
Neoclassical Closures
Projected
Actual

Force-free, Ideal Linear Results for Comparison
(Computed by S. A. Galkin, Keldysh Institute of Applied Mathematics with the TWIST-R and RESTOR codes.)

# BENCHMARKING

NIMROD VALIDATION PLAN (DRAFT 9/20/96 Rev. 1)

I. Stable linear oscillations (MHD limit only)

A. Uniform Bphi, no current

1. Zero beta, 2-D

a. Compressional Alfven waves, plasma oscillations, whistler waves, all cases have perfectly conducting plasma

i) Rectangular region - frequency known analytically * Uniform grid

- Explicit
- Implicit

* Non uniform grid

- Explicit
- Implicit

ii) Cylindrical region

* Multiple blocks with seams

2. Zero beta, 3-D

a. Compressional Alfven waves, plasma oscillations, whistler waves - n=0 - Repeat the above test to assure there are no surprises.

b. Torsional Alfven waves, n > 0 - Compare frequency with analytic (?) solutions and with GATO. (Initialize with GATO eigenfunction?) Both explicit and implicit cases. i) Single block grid ii) Multiple block grid with seams

3. Finite beta, 2-D

a. Electron sound waves (turn off ions)

b. Ion sound waves (both species on)

c. Drift waves 4. Finite beta, 3-D redo 2-D cases

B. Force-free toroidal equilibria - Comparision with GATO frequencies and eigenfunctions. (Are there any analytic equilibria of this sort?)

II. Linear unstable modes, 3D (Ideal MHD limit)

A. Internal modes (perfectly conducting boundary at separatrix).

1. Force-free toroidal equilibria (are there any that we understand?)

2. Finite beta

a. Solov'ev equilibrium - Internal kink modes

i) Berger, et al, paper (growth rates and eigenfunctions)

ii) comparison of marginal points withBerger, et al., and DCON

b. Numerical equilibria - Compare growth rates and eigenfunctions with GATO, Keldish codes, marginal points with DCON i) DIIID

ii) TFTR

iii) ITER

iv) etc, etc, etc........

B. External modes - vacuum region - Comparisons with GATO.

III. Linear unstable modes (Resistive MHD)

A. Compare with Carreras, et al (n = 2 tearing mode in a circular cross section torus) - Growth rate and eigenfunction

B. Any other known toroidal solutions (Keldish codes?)

C. Marginal points (DCON?)

IV. Linear unstable modes with 2-Fluid effects

A. Cylindrical case (Pic3d comparison) 1. Ideal (1,1) mode

2. Resistive (2,1) mode

B. Toroidal case (QIP3D comparison)

1. Resistive (1,1) mode

2. Resistive (2,1) mode

V. Nonlinear evolution (Ideal and resistive MHD) - We need to identify a D nonlinear codes.

A. Internal modes???

B. External modes (requires moving separatrix)???

VI. Thermal Conductivity - Test pollution of perpindicular transport in highly anisotropic cases. Impose islands and see how well temperature conforms to the flux surfaces.

VII. Nonlinear evolution with 2-Fluid effects

A. Cylindrical case (Pic3d comparison)

1. Ideal (1,1) mode

2. Resistive (2,1) mode

B. Toroidal case (QIP3D comparison)

1. Resistive (1,1) mode

2. Resistive (2,1) mode

VIII. Neo-Classical effects - We need to define a suite of test problems here, too.

IX. Comparison with experiment - We need help here, too.

# Shear Alfven Wave Tests

- Uniform rectangular grid, doubly periodic, 1m on a side.
- Neither **k** nor **B** are aligned with the grid ($k_x$=$k_y$=2π, $k_z$=$2^{3/2}$π).

| formulation | conform | k-par/k | grid | $v_{phase}/v_A$ |
|---|---|---|---|---|
| E | y | 10% | 9x9 | 1.67 |
| E | y | 10% | 17x17 | 1.22 |
| E | n | 10% | 9x9 | 1.25 |
| E | n | 10% | 17x17 | 1.07 |
| E | y | 5% | 9x9 | 2.81 |
| E | y | 5% | 17x17 | 1.69 |
| E | n | 5% | 9x9 | 1.47 |
| E | n | 5% | 17x17 | 1.14 |
| E | y | 2.5% | 9x9 | 5.35 |
| E | y | 2.5% | 17x17 | 2.91 |
| E | n | 2.5% | 9x9 | 1.89 |
| E | n | 2.5% | 17x17 | 1.25 |
| B | y | 10% | 8x8 | 0.984 |
| B | y | 10% | 16x16 | 1.00 |
| B | n | 10% | 8x8 | 1.10 |
| B | n | 10% | 16x16 | 1.02 |
| B | y | 5% | 8x8 | 0.974 |
| B | y | 5% | 16x16 | 1.00 |
| B | n | 5% | 8x8 | 1.36 |
| B | n | 5% | 16x16 | 1.09 |
| B | y | 2.5% | 8x8 | 0.95 |
| B | y | 2.5% | 16x16 | 1.00 |
| B | n | 2.5% | 8x8 | 1.83 |
| B | n | 2.5% | 16x16 | 1.22 |

## GRAPHICAL USER INTERFACE

(NIMEXEC and supporting scripts)

Tcl scripts presently provide:

- job status information and control
- convenient input file editing
- links to preprocessing and postprocessing codes

Future developments will allow remote job control.

See demonstration.

## PREPROCESSING

(NIMSET & FLUXGRID)

- Read equilibrium code output.
- Generate grid based on flux surfaces.
- Generate block connections and vertex connections within blocks of unstructured triangles.
- Initialize physical fields such as $\mathbf{B}_0$ and momentum density perturbations.
- Write an initial dump file.

# POSTPROCESSING

Routine graphics (XDRAW):

- Grid plots
- Spatial slicing
- Slices showing temporal dependence
- Time-history traces
- Contour plotting of multi-block problems is being developed by N. Popova

IBM Data Explorer

- Multi-dimensional movies
- Sophisticated, 3D data rendering available

See demonstration.