Center for Simulation of Wave Interactions with MHD (SWIM)

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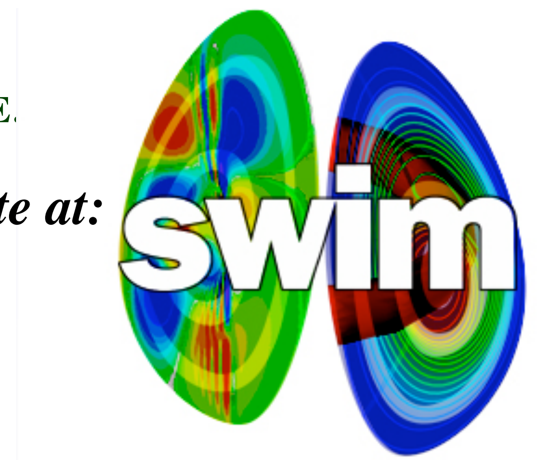
See our fun website at:
www.cswim.org



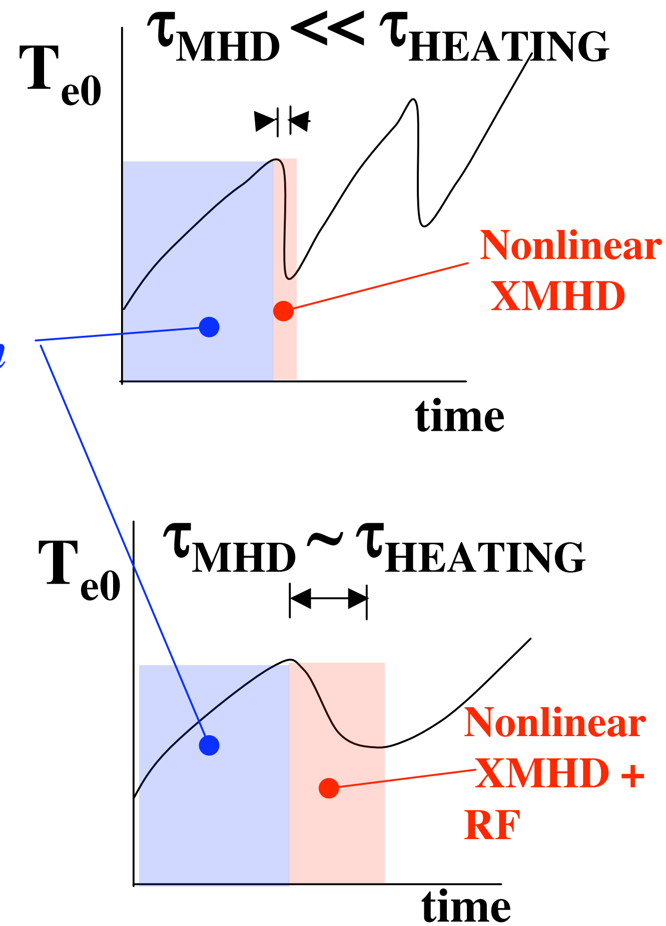
SciDAC
Scientific Discovery through Advanced Computing

The SWIM project is carried out in two physics campaigns distinguished by the time scale of unstable MHD motion

Fast MHD phenomena – separation of time scales

- **Response of plasma to RF much slower than fast MHD motion – transport time-scale**
- **RF drives slow plasma evolution, sets initial conditions for fast MHD event**
- **Example: sawtooth crash**

Slow plasma evolution



Slow MHD phenomena – no separation of time scales

- **RF affects dynamics of MHD events ⇔ MHD modifications affect RF drive plasma evolution**
- **Deals with multi-scale issue of parallel kinetic closure including RF (mainly ECRH)**
- **Example: Neoclassical Tearing Mode**

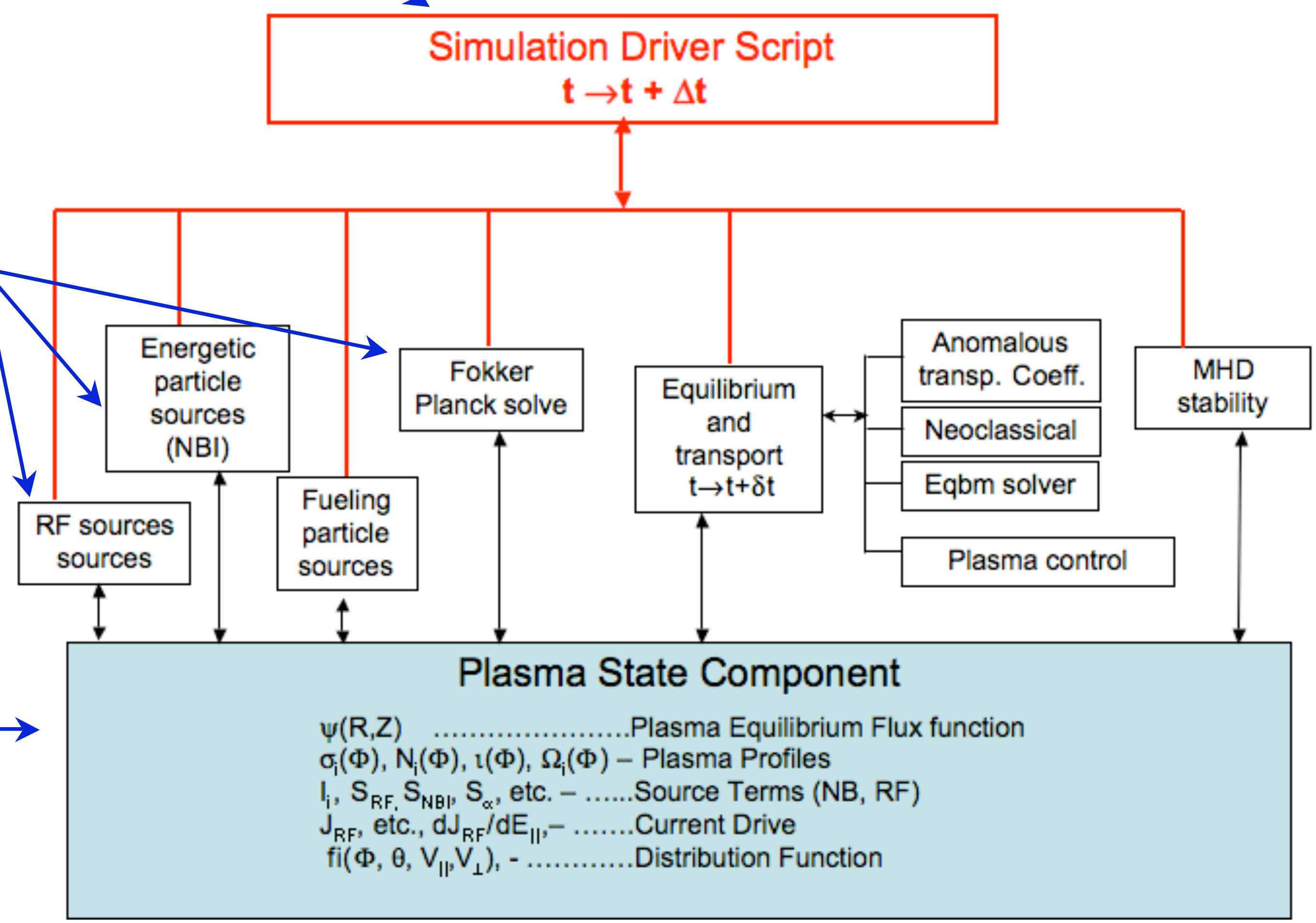
Software infrastructure: Integrated Plasma Simulator (IPS)

A flexible, extensible computational framework capable of coupling state-of-the-art models for energy and particle sources, transport, and stability for tokamak core plasma

Integrated Plasma Simulator design – component based architecture allows continued, independent development of physics

Physics layer Driver Script allows extensibility, flexibility in controlling simulation

Physics components drawn from existing code base – multiple code implementations for each component



Plasma State data component plays a central role:

D. McCune: GP9.00142 Tues. AM

Can incorporate composite, multi-physics, tightly coupled functionality as IPS components

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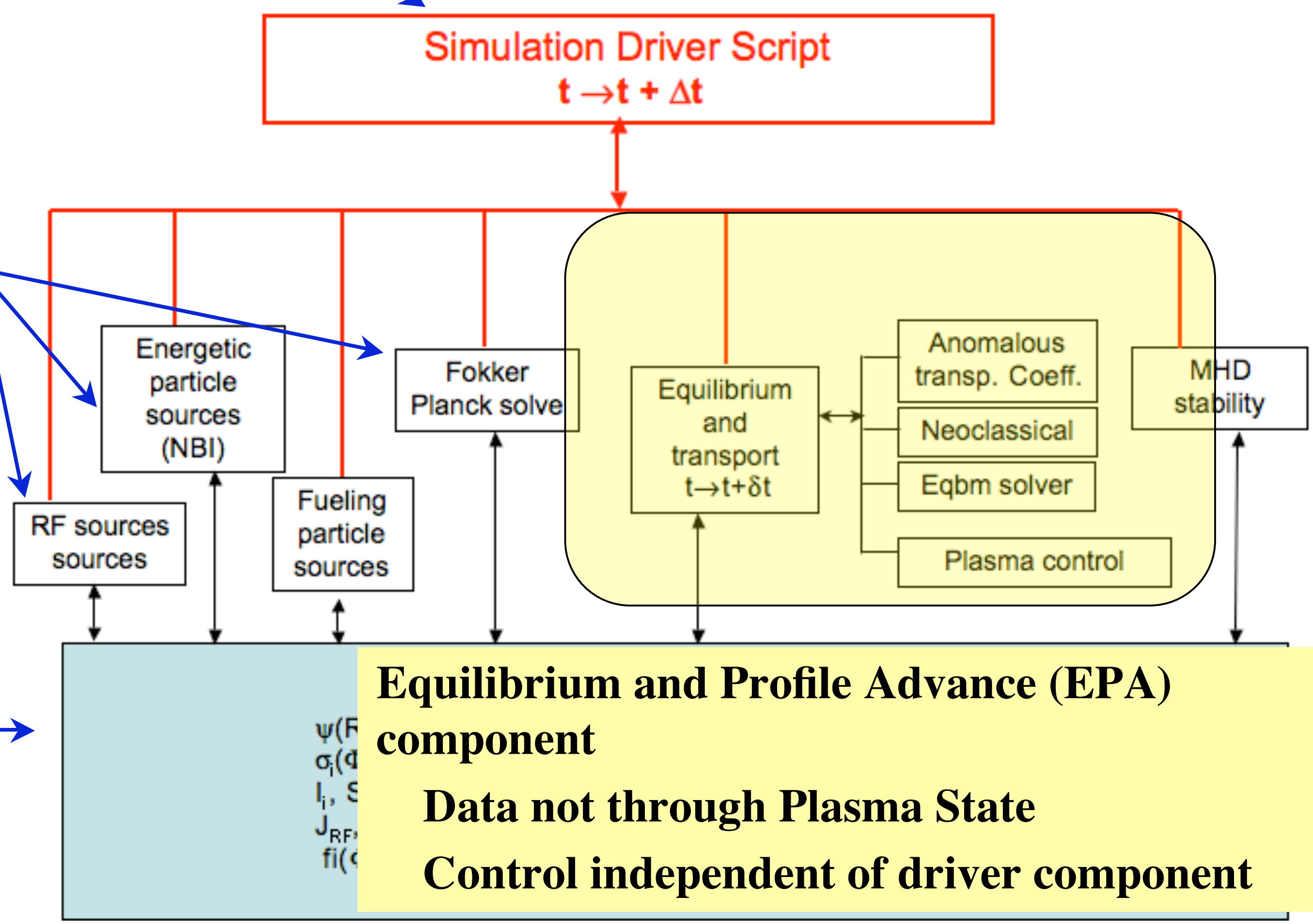


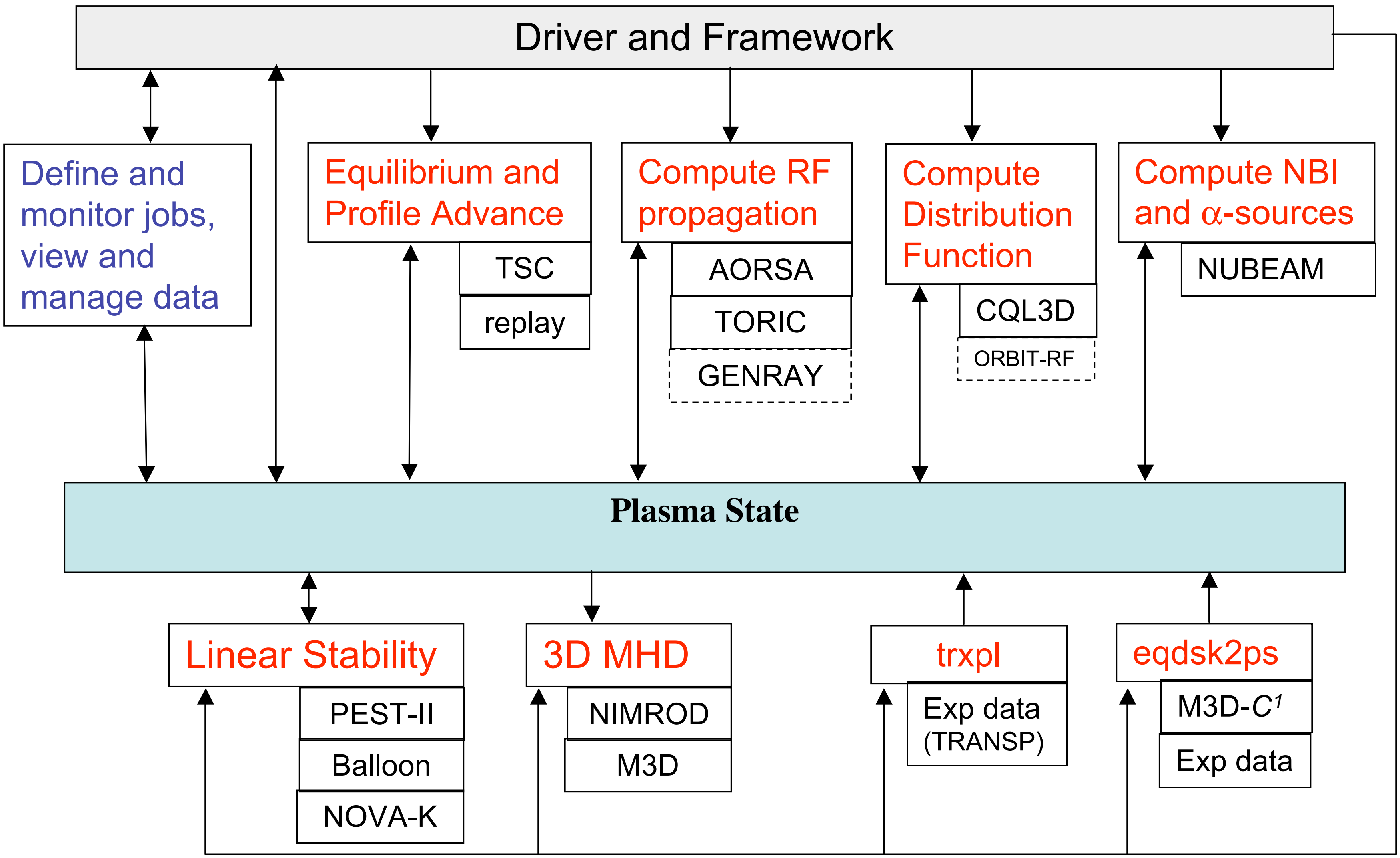
Plasma State data component plays a central role:

D. McCune: GP9.00142 Tues. AM

Equilibrium and Profile Advance (EPA) component

- **Data not through Plasma State**
- **Control independent of driver component**

A physicists view of the Integrated Plasma Simulator. Implemented with existing well tested and validated codes. Multiple code implementations



Physics studies with IPS

- **ITER discharge simulations with massively parallel RF and neutral beam components**
- **Use of IPS to study ECCD resistive tearing mode stabilization and motion of flux surfaces – coupling to GENRAY ECH ray tracing to NIMROD nonlinear MHD**
- **Use of IPS to study parallelization in time of DTEM turbulence *(parareal algorithm)***
- **Studies of RF driven energetic tail formation on Alcator C-mod**
- **Onset of saturated n = 1, m = 1,2 modes in NSTX – coupling of IPS to M3D**
- **Use of IPS to study control of sawtooth onset time with lower hybrid waves on C-mod**
- **Interface with FACETS for core-edge coupling**

IPS is supporting ITER simulations for International Tokamak Physics Activity (ITPA) and ITER Organization tasks

A planned operational scenario of ITER is the "*hybrid mode*" → achieve high fusion yield for long discharge time

Typical simulation with IPS

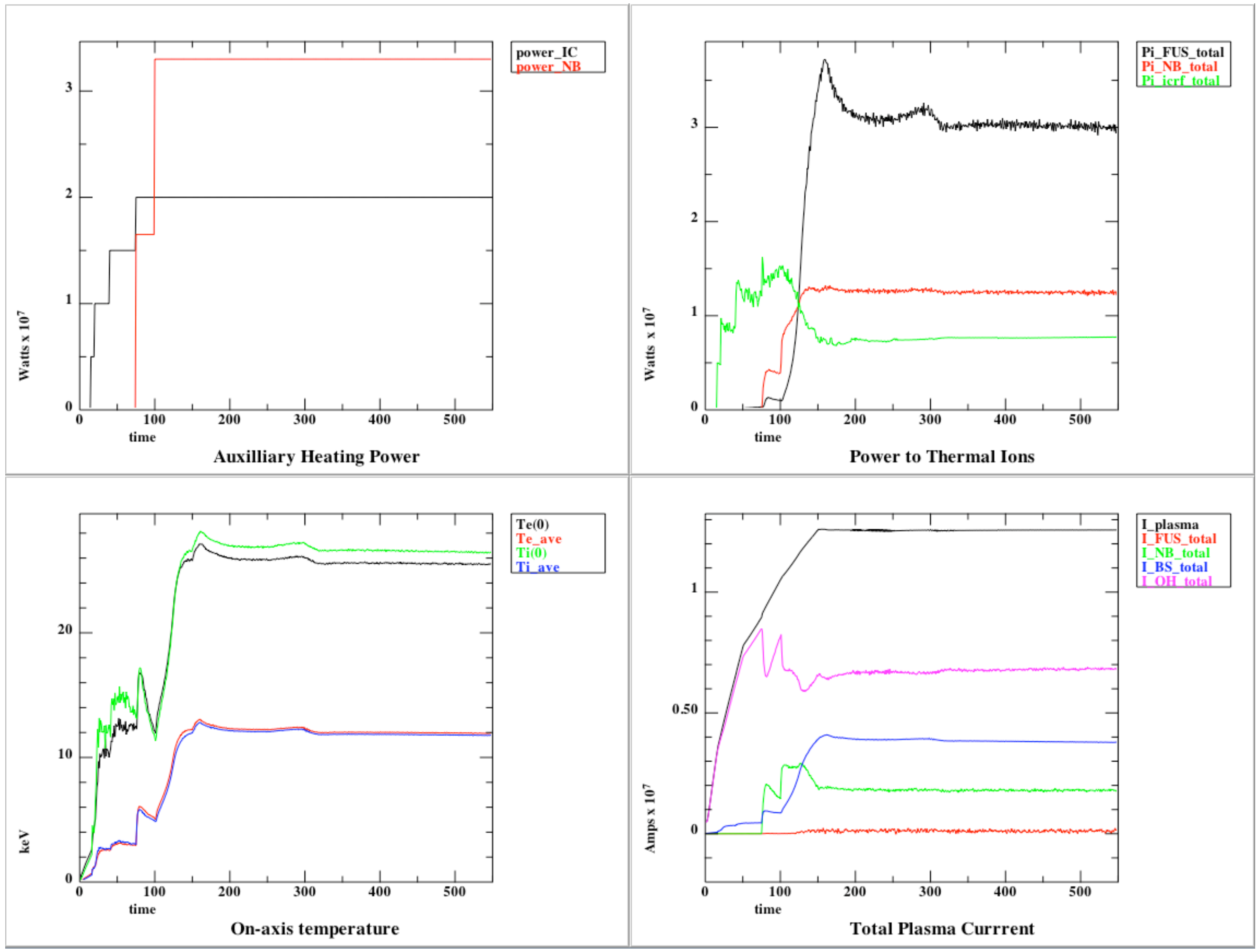
TSC - transport and eqbm.

TORIC - ICRF

NUBEAM – NBI, fusion

Initial scenario from C. Kessel

See A. Kritz, XO4, Friday AM



Summary of ITER simulations with IPS

Simulations at very high resolutions to show capability of massive parallelism

- TSC +AORSA + NUBEAM (1,000,000 particles/species)
- TSC + TORIC (255 poloidal modes) + NUBEAM (1,000,000 particles/species)
- *running times ~ 30 hr on 1600 cores*

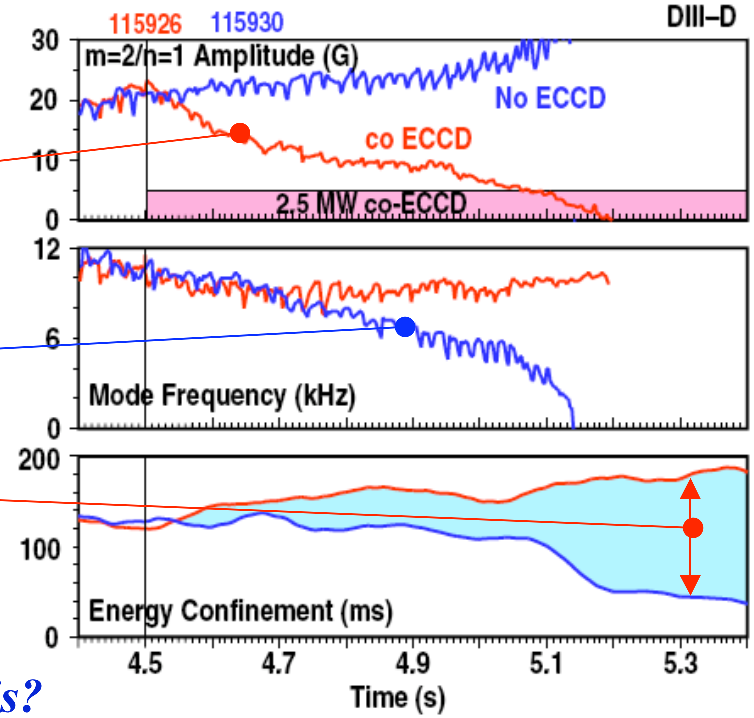
Simulations at resolutions more typical of present practice for comparison

- ITER hybrid scenario
- TSC (1 core), TORIC (31 poloidal modes, 4 cores), NUBEAM (5,000 particles/species, 16 cores)
- Typically ramp-up from 1.5 sec into flattop 550 sec

- **TSC alone – using TSC internal (analytic) models for NBI and ICRF**
  - *No parallelism, 1 core, running time ~ 11 hr*
- **TORIC + NUBEAM + TSC – sequential execution of parallel components**
  - *One level of parallelism, 16 cores, running time ~ 28 hr*
- **TORIC + NUBEAM + TSC – concurrent execution of parallel components**
  - *Two levels of parallelism, 24 cores, running time ~ 12 hr*
- **Parameter study – pedestal location, pedestal height (chi pedestal)**
  - Nine concurrent simulations run simultaneously
  - *Three levels of parallelism, 128 cores, running time ~ 16 hr*

Electron cyclotron current drive (ECCD) has been successful in controlling neoclassical tearing modes

- Electron cyclotron current drive drives down mode amplitude
- keeps mode rotating (no drop in frequency)
- improves energy confinement

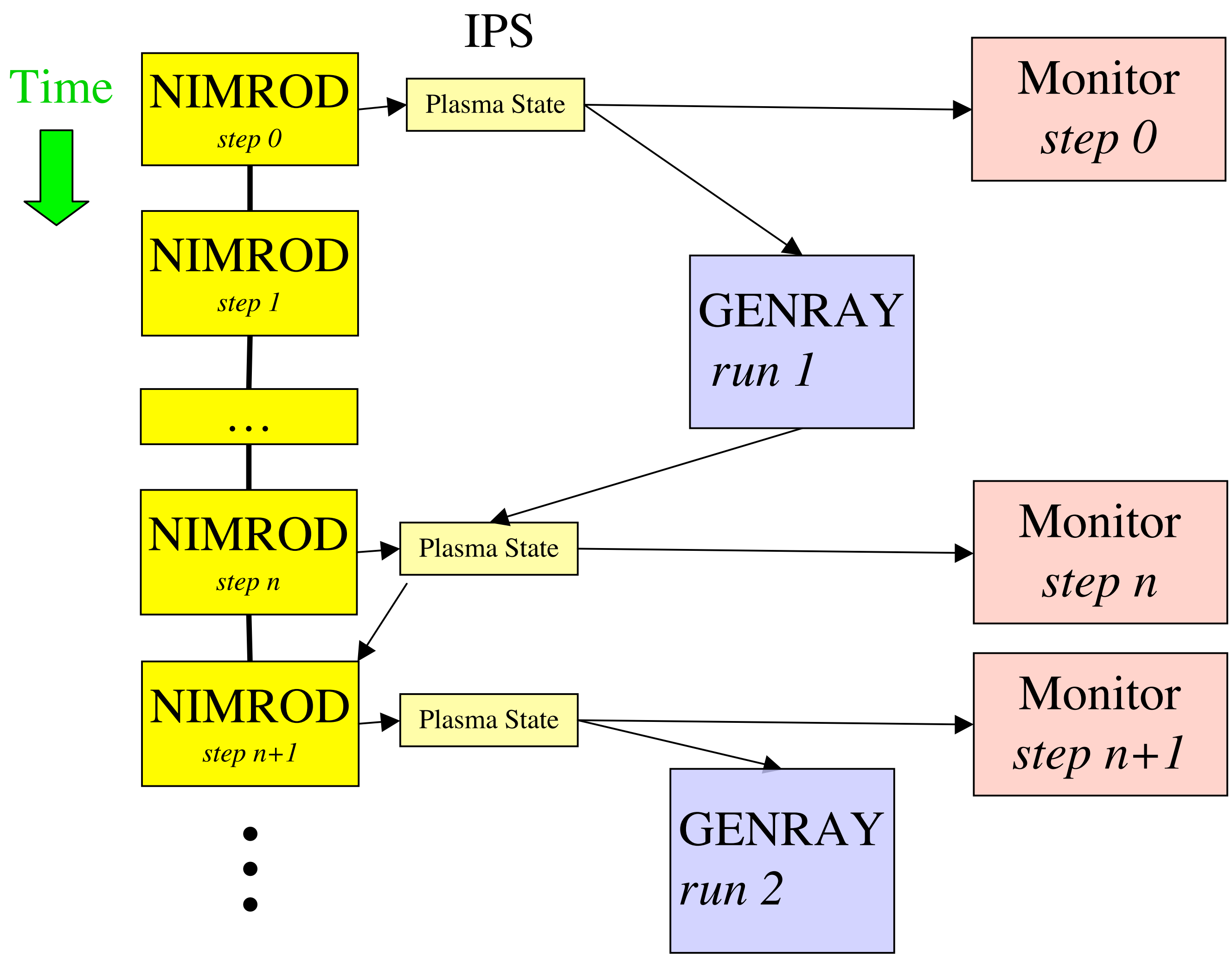


R. Prater
APS 2003

What do we have to do to model this?

- Slow response describing tearing modes → extended MHD (NIMROD)
- Modeling of ECRF propagation and absorption → RF (GENRAY)
- Couple extended MHD to RF component:
  – Give *n=0* modification of tearing mode and RF current back to RF code
- Couple RF component to extended MHD component:
  – Provide RF driven velocity-space flux, or moments thereof

NIMROD/GENRAY coupling in IPS – NIMROD is run as a service, but controls time loop via simulation *event handling*



- **For RF/MHD problem, NIMROD exports magnetic geometry and n,T profiles to Plasma State**
- **Using NIMROD's profiles, GENRAY then calculates RF propagation and power deposition; exporting these quantities to the Plasma State**
- **NIMROD converts GENRAY data into momentum and energy source terms.**
- **Coupling not yet fully completed**

Two levels of parallelism – parallel NIMROD run concurrently with GENRAY

Tales from the *parareal* – simple algorithm that allows parallelization in time *sometimes* (J. Lyons, Y. Mayday, G. Turinici, CR Acad. Sci. I – Math 332, (2001), 661-668)

Consider time evolution problem: $\frac{du}{dt} = F(u), \quad u(0) = u_0$

Define: $T_n = n\Delta T, \quad u_n = u(T_n)$

Assume have two time advance operators:

$F_{n,\Delta T}$ **fine – accurate but takes a long time to run** $u_{n+1} = F_{n,\Delta T}(u_n)$

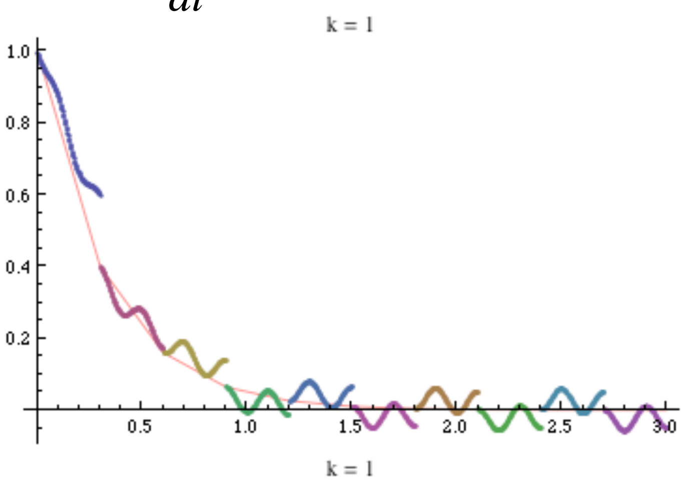
$G_{n,\Delta T}$ **coarse – inaccurate but runs very quickly** $u_{n+1} \sim G_{n,\Delta T}(u_n)$

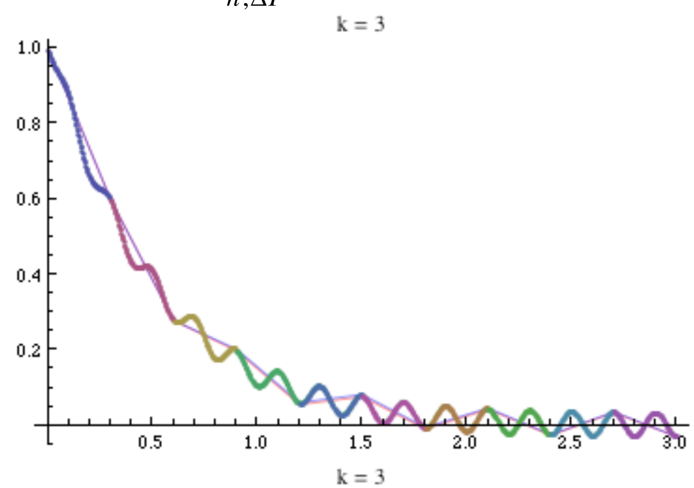
The method is based on the iteration scheme:

$$u_{n+1}^0 = G_{n,\Delta T}(u_n^0)$$

$$u_{n+1}^{k+1} = G_{n,\Delta T}(u_n^{k+1}) + F_{n,\Delta T}(u_n^k) - G_{n,\Delta T}(u_n^k)$$

Example: $\frac{du}{dt} - \lambda u = \sin(5\pi t) \equiv F_{n,\Delta T} \qquad \frac{du}{dt} - \lambda u = 0 \equiv G_{n,\Delta T}$





Can parareal be used to accelerate real physics calculations (e.g evolution of fully developed turbulence)? → BETA a pseudo-spectral solver for model DTEM physics

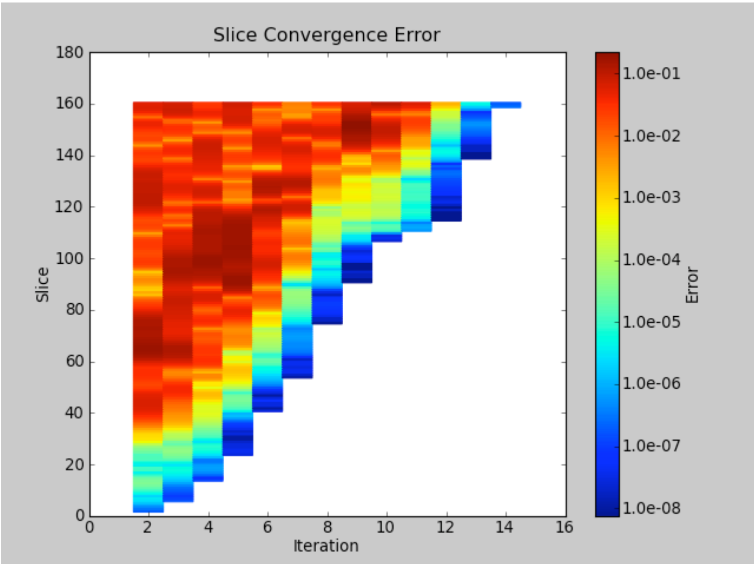
- **Fine solver based on Hasagawa-Mima:**

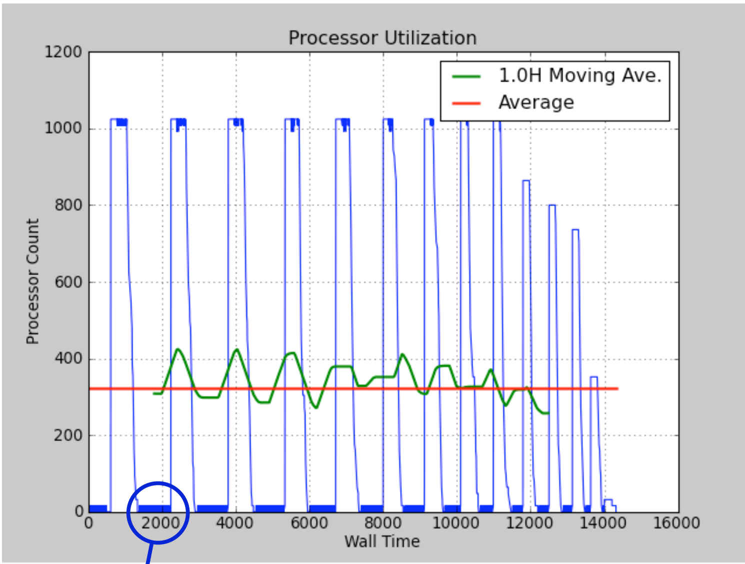
$$\frac{\partial}{\partial t}\left(1-\rho_s^2\nabla_\perp^2\right)\phi + D\frac{\partial^2\phi}{\partial y^2} + \frac{V_D}{2}\frac{\partial\phi}{\partial y} - \frac{4L_n}{\varepsilon^{1/2}}\left[\nabla_\perp\left(\frac{\partial\phi}{\partial y}\right)\times\hat{z}\right]\bullet\nabla_\perp\phi = Sources - Sinks$$

- **For the coarse solver use same equation as fine solver, but:**
  - **Reduce spatial resolution: ~half**
  - **Faster, less precise time integrator: 4th order RK instead of VODPK**
  - **Change dissipation scale**
- **For projection from fine to coarse solution → truncation**
- **For lifting from coarse to fine solution → match spectral slope, use random phase; other wise, keep high order coefficients from previous iteration**
- **For convergence → total mode energy was shown to be a good proxy for convergence of low k modes. Thus only one convergence measure was needed.**
- **Initially implemented entirely in MPI (very complicated) – *Samaddar, Newman, Sanchez, J. Comp Phys 229 (2010) 6558-6573***

The parareal algorithm was re-implemented in the IPS without modification to the IPS → much more straightforward implementation

- **IPS implementation:**
  - **Three IPS components (no plasma state) – fine solver, coarse solver, convergence test**
  - **Task pool manager – efficiently handles parallel executions of fine solver**
  - ***Traditional* loop control – iteration loop, not time loop**
  - ***Two levels of parallelism – MPI coarse and fine solver codes, multiple instances of fine solver component***
- **Dividing the simulation time interval into 160 slices, convergence was obtained in 14 iterations for a reduction of simulation time of about ×6**





L. Berry (GP9, Tues. AM)

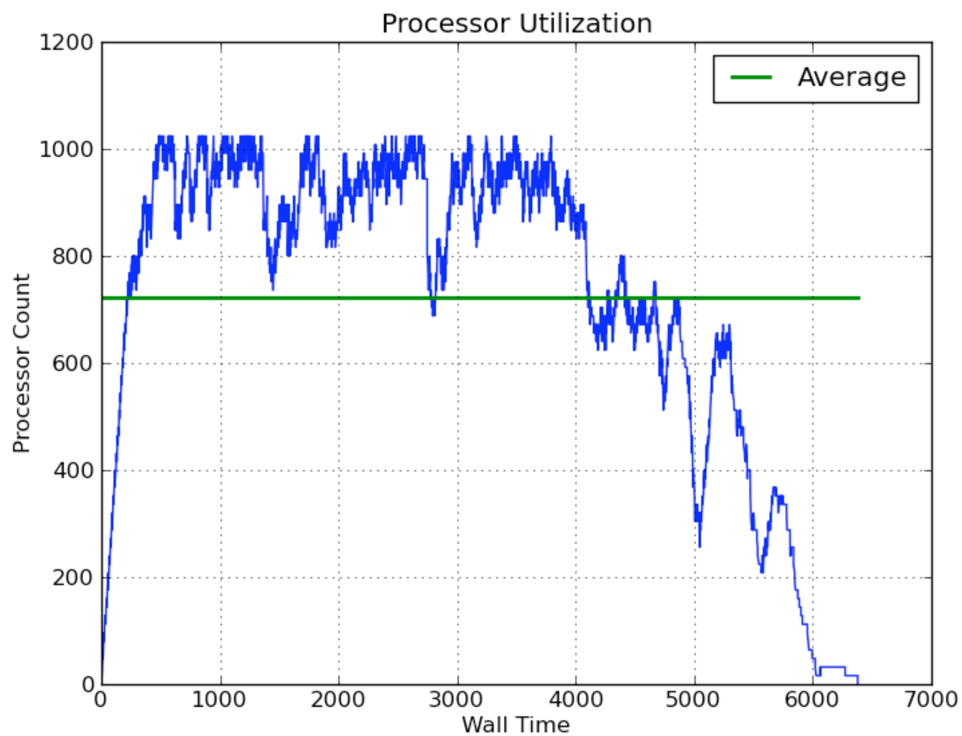
Suffers from inefficiency during long run of coarse solver

An innovative modification of the parareal workflow using IPS results an improvement in efficiency and run time, factor of 2

- **Obvious observation (but for years nobody observed it) – You don't have to wait for all coarse solves to complete before starting the iteration and the next round of fine solves.** → *You can interleave them*
- *Three levels of parallelism – MPI coarse and fine solver codes, multiple instances of coarse and fine solver components, concurrent execution of coarse solver, fine solver and convergence components*
- **Completely event driven** → *No traditional loop*

W. Elwasif (CM11, later this session)

Is this the route to turbulence modeling on the transport time scale or extended MHD studies at ITER relevant Lundquist numbers? Might be.



Other highlights

- **Interface with FACETS for core-edge coupling**
  - Use FACETS as another tightly coupled, multi-physics composite component
  - Project synergy: FACETS gets access to SWIM source components alternate work-flow. SWIM gets access to edge and core/edge models, alternative EPA model. Together we get earlier capability for higher fidelity coupled core/edge studies
- **Onset of saturated n = 1, m = 1, 2 modes in NSTX – coupling of IPS to M3D**
  - Developed TSC experimental data access capability $\rightarrow$ experimental profiles
  - Generalizing to an experimental data access component useable by other components
- **Theoretical development of RF/MHD equations consistent for Slow MHD studies, kinetic closures for extended MHD with RF**
- **Studies of RF driven energetic tail formation on Alcator C-mod**
  - Time dependent RF/Fokker Planck calculations with AORSA and CQL3D components
  - Exploring JFNK for tight coupling of AORSA/CQL3D
- **Use of IPS to study control of sawtooth onset time with lower hybrid waves on C-mod – Adds ray tracing component (GENRAY) also used in ITER scenario studies**