MHD Codes - Scalability

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MHD Codes

- Classification
  - *Toroidal vs. slab*
  - *Explicit, semi-implicit, implicit*
  - *Physics capability: resistive MHD, two-fluid MHD, extended MHD (including gyroviscous stress tensor)*
  - *Order of accuracy*
  - *Finite elements, finite difference, finite volume, spectral element*
- A variety of MHD codes exist within DOE labs
- Exercise: determine precisely the strengths and weaknesses of MHD codes vis-à-vis scalability on petascale platforms and beyond and physics capability so these codes can be effectively used within the FSP

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MHD Codes

Name	Geometry	Physics	Time stepping	Discretization	Accuracy	Comments
M3d	Torus	Extended	SI	FE/FD	2nd	Work-horse; Hodge decomp. Imp in FC
NIMROD	Torus	Extended	Implicit	FE/SE/FFT	Any? 4th	Work-horse; Implicit - supraLU
M3d-C1	Torus	Extended	SI	FE/FFT	4th/5th	C1; Formulation allows diff. MHD models
SEL	Slab	Two-fluid	Implicit	SE	Any?	JFNK; FETI-DP precon
AMR-MHD	Torus	Resistive	Explicit	FV	2nd	Used for pellet injection
JFNK-C	Torus	Two-fluid	Implicit	FD	2nd	JFNK- MG precond
JFNK-PS	Slab	Resistive	Implicit	FE	2nd	JFNK - black-box prec
JFNK-RSW	Torus	Resistive	Implicit	FV/FD	2nd/4th	JFNK- directional split; eigen-structure precon
MHD-Allspeed	Slab	Resistive	SI	FV	2nd	Analy. sep. of scales; a la low-M projection
LB	Slab	Resistive	Explicit	?	?	Unknown entity
DG MHD	Slab	Resistive	Explicit	FV	Any	C -1 cont; limiters

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MHD Physics

- Resitive MHD
  - *the smallest scale is determined by a single non-dimensional number, i.e., the Lundquist number (scales as $S^{-1/2}$)*
    - *Meaningless to talk in terms of “ITER sized plasmas”. Talk in term of S.*

- Incorporate lowest order FLR corrections to resistive MHD equations result in changes to the electron momentum equations (generalized Ohm’s law) and ion stress tensor
  - *WW: Whister waves arise from JxB term in Ohm’s law*
  - *KAW: Kinetic Alfven wave - due to parallel electron pressure gradient in Ohm’s law*
  - *GVW: GyroViscous waves - associated with ion response, due to divergence of off-diagonal terms in the Gyroviscous stress tensor*
- All these waves are DISPERSIVE ($\omega \propto k^2$)
  - *Require implicit treatment*

Model	Momentum	Ohm's Law	WW	KAW	GVW
General	$mn\frac{d\boldsymbol{v}}{dt} = -\nabla(p_e + p_i)$ $\boldsymbol{J}\times\boldsymbol{B} - \nabla\cdot(\Pi_{\|\|e} + \Pi_{\|\|i})$ $-\nabla\cdot\Pi_i^{gv}$	$\boldsymbol{E} = -\boldsymbol{v}\times\boldsymbol{B} + \eta\boldsymbol{J}$ $\frac{1}{n_e}(\boldsymbol{J}\times\boldsymbol{B} - \nabla p_e - \Pi_{\|\|e})$	Yes	Yes	Yes
Generalized Hall MHD	$mn\frac{d\boldsymbol{v}}{dt} = -\nabla(p_e + p_i)$ $\boldsymbol{J}\times\boldsymbol{B} - \nabla\cdot(\Pi_{\|\|e} + \Pi_{\|\|i})$	$\boldsymbol{E} = -\boldsymbol{v}\times\boldsymbol{B} + \eta\boldsymbol{J}$ $\frac{1}{n_e}(\boldsymbol{J}\times\boldsymbol{B} - \nabla p_e - \Pi_{\|\|e})$	Yes	Yes	No
Neoclassical MHD	$mn\frac{d\boldsymbol{v}}{dt} = -\nabla(p_e + p_i)$ $\boldsymbol{J}\times\boldsymbol{B} - \nabla\cdot(\Pi_{\|\|e} + \Pi_{\|\|i})$ $-\nabla\cdot\Pi_i^{gv}$	$\boldsymbol{E} = -\boldsymbol{v}\times\boldsymbol{B} + \eta\boldsymbol{J}$ $-\frac{1}{n_e}\Pi_{\|\|e}$	No	No	Yes
Generalized Resistive MHD	$mn\frac{d\boldsymbol{v}}{dt} = -\nabla p$ $\boldsymbol{J}\times\boldsymbol{B} - \nabla\cdot\Pi_{\|\|}$	$\boldsymbol{E} = -\boldsymbol{v}\times\boldsymbol{B} + \eta\boldsymbol{J}$	No	No	No

What is relevant for ITER?

- What can or must (at first order) be modeled with MHD?
  - *When is two-fluid/extended MHD important?*

- Edge localized modes (ELMs)
  - *Type I most detrimental. Triggers known*
  - *Other types: not so well-understood*
  - *ELM mitigation: pellet-induced, resonant magnetic perturbations*

- Sawteeth

- Vertical displacement events (VDEs)
  - *Needs coupling with other codes to model eddy currents*

- Disruption mitigation
  - *Noble gas injection is the preferred method*

- Energetic particles
  - *Coupling with gyrokinetic codes*

Benchmark Case

- Sawtooth cycle: accurate prediction is an important test for nonlinear MHD codes
- Stresses the nonlinear codes
  - *Long runs (~ 500-1000 τ_A)*
  - *Runs need to be well-resolved for reconnection, and to get the period correct*
- M3d and NIMROD have already done this benchmark test case
  - *For CDX-U (Details in Breslau, Sovinec, Jardin, Comp. Phys. Comm. 2008)*
  - *Analytical equilibrium and all other parameters clearly specified which makes it easier to get started*
  - $\kappa_{\parallel}$ *!=* $\kappa_{\perp}$ *(parallel heat conduction turned on)*

Table 1: Parameters for the next equilibrium for the CDX-U sawtooth benchmark.

Quantity	Value
Major radius R_0	0.341 m
Minor radius a	0.247 m (aspect ratio $=1.38$)
Ellipticity κ	1.35
Triangularity δ	0.25
Central temperature ($T_e = T_i$)	100 eV
Normalized central pressure $\mu_0 p_0$	7.5×10^{-4} (implies $n_{e0}=n_{i0}=1.863\times10^{19}\mathrm{m}^{-3}$)
α Parameter in pressure equation*	0.1
Vacuum value g_0 of $\mathrm{R}\cdot\mathrm{B}_\mathrm{T}$	$0.04252\ \mathrm{T}\cdot\mathrm{m}$
Effective ion charge Z_EFF	2.0
Loop voltage V_L	3.1741 V (implies $q_0\approx0.82$)

*$p(\psi)=p_0[\alpha\bar{\psi}+(1-\alpha)\bar{\psi}^2]$, where $\bar{\psi}\equiv(\psi-\psi_{\mathrm{limiter}})/(\psi_{\mathrm{axis}}-\psi_{\mathrm{limiter}})$.

Benchmark Case - Two Phases

- Phase I: Correctness
  - *Compare against M3d/NIMROD results*
  - *Time history of normalized kinetic energy for various toroidal mode numbers*
  - *Convergence: demonstrate that your code converges with the advertised order of accuracy*

- Phase II: Scalability
  - *This is a difficult issue because a code may be able to get the "correct" answer at a lower resolution than others*
  - *Should we test strong or weak scaling?*
    - *I prefer strong scaling - for resistive MHD for a given S, the resolution requirements to resolve the internal layers can be estimated well. Then for a given resolution a code which exhibits strong scalability is better than a code which doesn't*
  - *Code comparison metrics*
    - *Wall-clock time; FLOPS; Work units*

- Which codes are flexible to be easily adapted to the emerging (many-core multicore) architectures?
  - *Adaptability to migrate to hybrid programming models (MPI + OpenMP, beyond MPI) will be very important*

Remarks

- Code comparison exercises are useful but thankless tasks
  - *Need real commitment (funding?) to do this*
  - *Recall that the M3D-NIMROD benchmark took > 1 year to accomplish*
    - *Jardin (email 07/15/09) "That sounds like a good idea. But, the nonlinear benchmarking exercises are time consuming and require resources. I would think they are better carried out under our SciDAC (where they are actually funded) rather than in the FSP planning program.*
- Within the FSP, it is envisioned that there will be several opportunities for MHD
  - *Coupling with several other codes in the context of ELMs, VDEs, mitigation disruption*
- Need to identify strengths/weaknesses of existing codes to better utilize them within the FSP
- Scalability on extreme scale platforms will be essential
- The sawtooth benchmark test case is a good starting point
- Need to identify clear quantifiable metrics to compare MHD codes
  - *Work units: number of times the nonlinear function gets called (useful, for example, to measure amount of work in nonlinear FAS MG codes, or JFNK codes)*
  - *FLOPS*

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