NIMROD

FROM THE
CUSTOMER'S PERSPECTIVE

MING CHU

General Atomics

Nimrod Project Review Meeting
July 21 – 22, 1997

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OUTLINE

I. Summary of β (MHD) Research

1. β Limit is Determined by Ideal MHD

   α. Troyon Scaling Law Verified

   β. Dependence on Global Profile

2. Nonideal MHD Modes Observed at the β Limit
   — Plasma Rotation and Kinetic Effects Important

   α. Resistive Plasma Modes

   β. Resistive Wall Modes

3. β Limit Dynamics Depend on 3-D Effects

   α. Nonlinear Free Boundary Modes
   — Vertical Displacement, External Kinks

   β. Nonlinear Development of Magnetic Field

OUTLINE (Continued)

II. Challenges in MHD for ITER and Large Tokamaks

1. β Limits of Steady-State Tokamaks
2. Disruption Dynamics
3. More 3-D MHD

III. Survey of Existent (Nonlinear) MHD Codes

IV. Desirable Features of NIMROD

V. Validation Issues

1. Internal Consistency
2. Check with Known Linear Codes
3. Check with Other Nonlinear Codes
   - α. Scenario Development
   - β. Quantitative Comparison

IDEAL MHD THEORY PREDICTS A SIMPLE BETA LIMIT SCALING

- **NUMERICAL CALCULATIONS (1982–1984)**
  - $\beta(\max) \propto \dfrac{I(MA)}{a(m)\ B(T)}$ "Troyon scaling." Define $\beta_N = \dfrac{\beta(\%)}{I/aB}$
  - $\beta_N(\max) = 2.8 - 3.2$ Ideal $n = 1$ kink mode (Troyon, Tuda).
  - $\beta_N(\max) = 3.7 - 4.4$ Ideal $n = \infty$ ballooning (Sykes, Bernard, Tuda).

- **EXPERIMENTS:**
  - $\beta_N(\max) \approx 3.5$ "Standard."
  - $\beta_N(\max) \leq 6$ With profile modification.

- **ANALYTIC CALCULATIONS:**
  - $\beta(\max) = 28\dfrac{\varepsilon}{q} = 5.6\dfrac{I}{aB}$ Troyon scaling derived for simplified profiles (Wesson).
  - High–n and low–n limits become the same for q >> 1. Asympototic scaling (Ramos).

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Courtesy E.J. Strait "Stability of High β Tokamak Plasmas"
Phys. Plasmas 1 (1994) 1415

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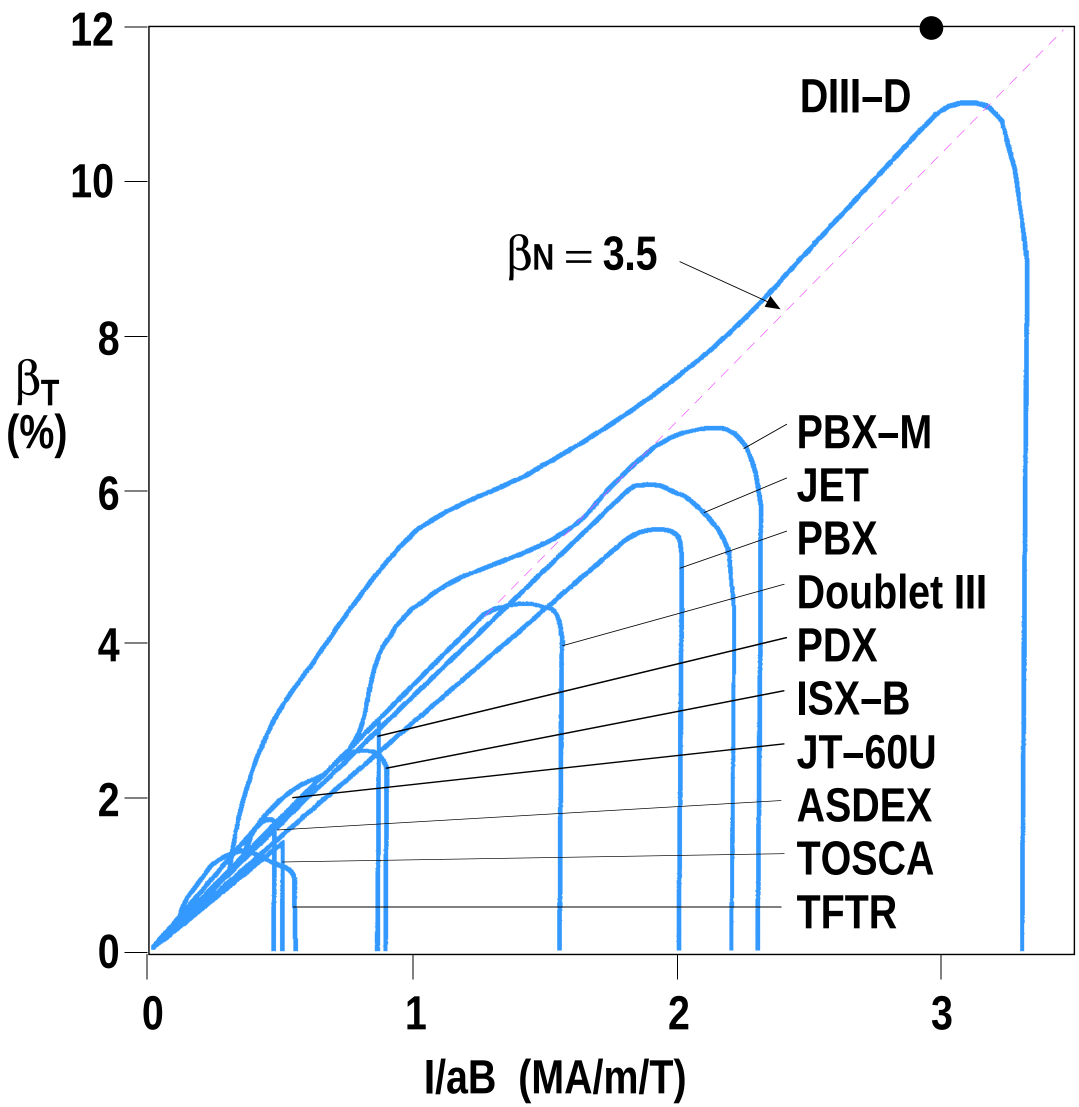
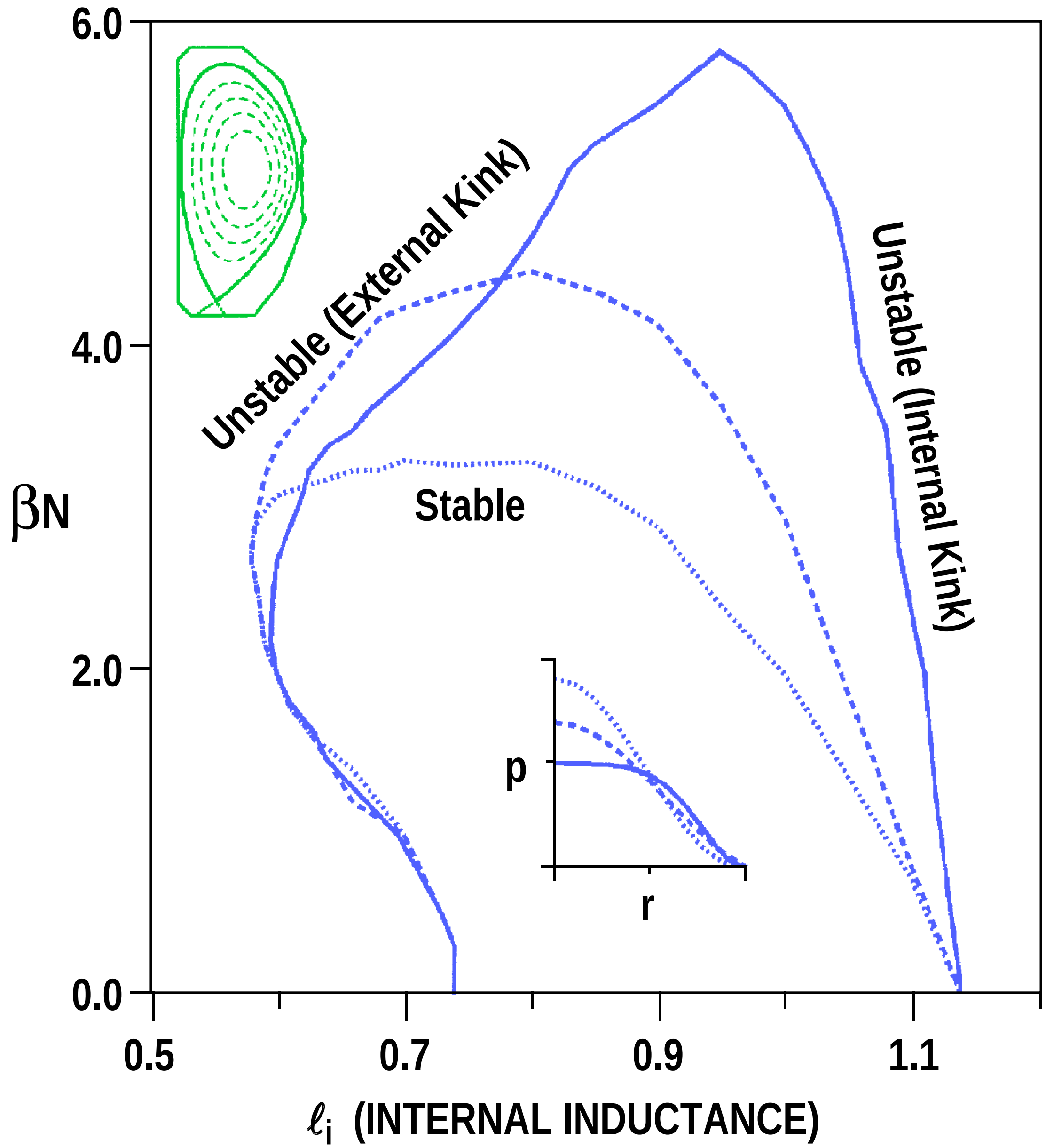
EXPERIMENTS CONFIRM BETA LIMIT SCALING



$\beta_N(\max) = 3.5 \pm 0.5$

I/aB is limited by current-driven kink instabilities at $q \approx 2$.

BETA LIMIT INCREASES WITH OPTIMIZATION OF PROFILES



- Theoretical calculations predict n = 1 kink stability improves with broad p(r) and peaked J(r) (high ℓ_i).
- High ℓ_i increases magnetic shear near the plasma edge, improves stability for larger edge pressure gradient.
- Experimentally confirmed in DIII–D, TFTR, JET, JT–60U.

NONIDEAL MHD MODES OBSERVED AT THE β LIMIT
PLASMA ROTATION AND KINETIC EFFECTS IMPORTANT

— Resistive Plasma Modes

— Locked Modes

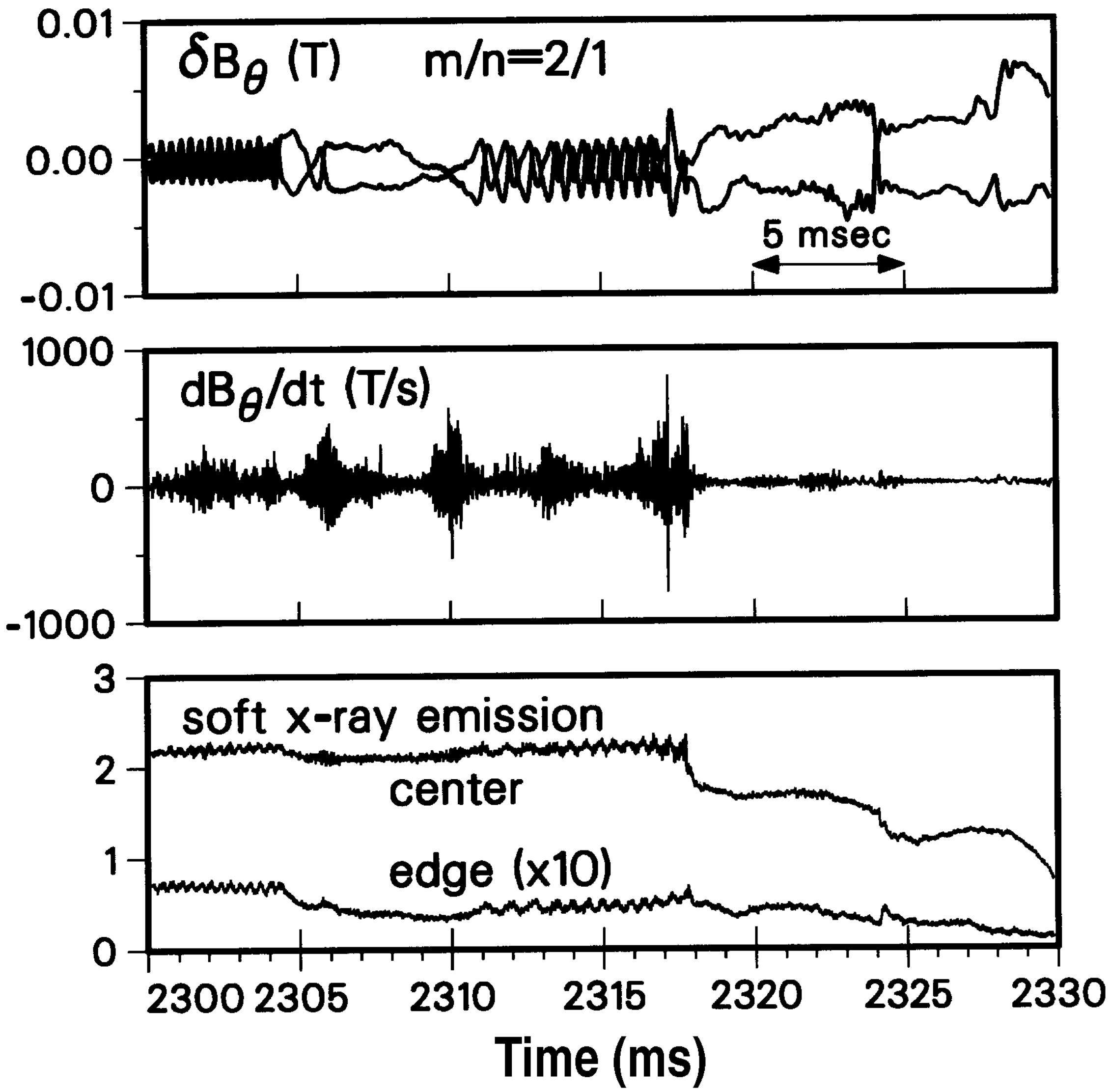
— Sawtooth

— Edge Localized Modes (ELMs)

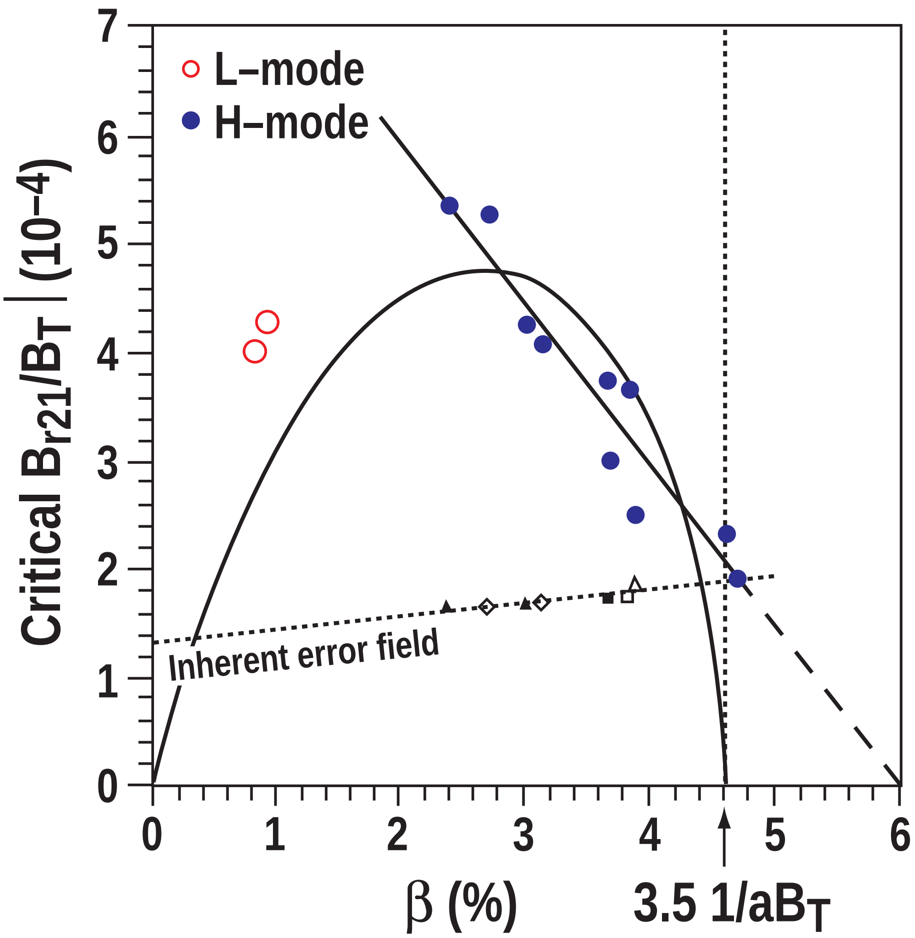
— Resistive Wall Modes

DISRUPTION AT HIGH β SHOWS STABILIZING EFFECT OF ROTATION

- Rotating m/n = 2/1 locks after a sawtooth, then grows to disruption.
- Consistent with stabilization by a resistive wall:
  - 2/1 mode is saturated while $\omega_{rot} \tau_W >> 1$
  - 2/1 mode grows after it stops rotating, $\gamma \lesssim \tau_w^{-1}$



THE CRITICAL m = 2, n = 1 RELATIVE ERROR FIELD FOR A LOCKED MODE DECREASES AS THE β LIMIT IS APPROACHED. THE INHERENT ERROR FIELD DUE TO F–COILS IS ALSO SHOWN



- DIII–D H–mode, SND, q_{95} = 3.5, κ = 1.8, 1 MA, 1.2 T, 5×10^{19} m^{-3}
- Error fields can
  - Reduce β limit
  - Decrease reliability
  - Increase disruptivity

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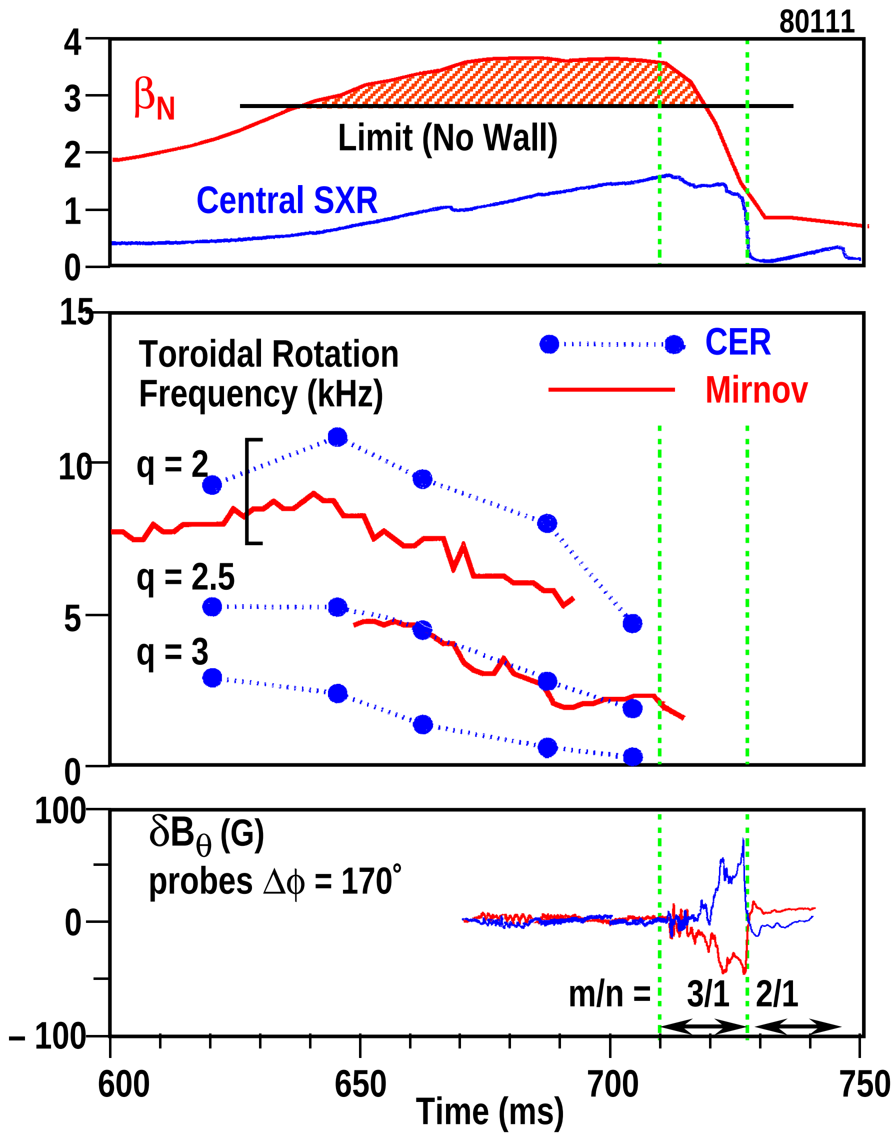
COLLAPSE AT HIGH β_N SHOWS IMPORTANCE OF ROTATION



- m/n = 3/1 mode becomes unstable when q = 3 surface ceases to rotate
- 3/1 mode has predicted features of "Resistive Wall Mode"

[1] E.J. Strait et al., Phys. Rev. Lett. 74 (1995) 2483; [2] T.S. Taylor et al., Phys. Plasmas 2 (1995) 2390.

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β LIMIT DYNAMICS DEPEND ON 3-D EFFECTS

α. **Nonlinear free boundary modes**

- **Vertical displacement**
- **External kinks**

β. **Nonlinear development of magnetic field**

- **Island topology**
- **Field line stochasticity**

CHALLENGES IN β LIMITS OF STEADY-STATE TOKAMAKS
MHD FOR ITER AND LARGE TOKAMAKS

— **Steady state equilibrium profiles**

— **Advanced tokamak equilibrium profiles**

— **Resistive wall boundary conditions (smart wall, rotating wall)**

— **Neoclassical resistive MHD**

— **Effect of energetic particles**

DISRUPTION DYNAMICS

— Vertical displacement halo currents

— Avoidance of locked modes by rotation, error field control, and plasma profile control?

— Identification of disruption precursors

— Plasma dynamics during a disruption: heat, particle, and flux transport, and effect on production of energetic particles

— Disruption amelioration scenarios

MORE 3-D MHD

1. Bootstrap current phenomena — slow compared to collision frequencies
   - Development of 3-D neoclassical MHD islands
   - Bootstrap current associated with H–mode transport barrier gradients
     - Extent and geometry of ELMs (energy goes to *inside* divertor plate!!)
     - Separatrix geometry leads to avalanche (self-organized critically)
     - Instability → magnetic stochasticity → parallel heat loss → big ∇P → Instability
     - Feedback, smart walls; fast particles
2. Effect of plasma rotation and resistive walls on evolution pressure-driven resistive wall modes
   - High-bootstrap-fraction, "advanced" discharges rely on walls for stabilization of ideal MHD kinks (low-n) modes
3. Error field criteria (possibly neoclassical)
4. Sawteeth reconnection (deviations from Kadomtsev)

Courtesy F. Perkins

DESIRABLE FEATURES OF NIMROD

- ❋ Two Fluid Formulation
- ❋ Readily Available
- ❋ User Friendly
- ❋ Easy to Maintain
- ❋ Fast Turnaround

CHARACTERISTICS OF MHD CODES

	MH3D	NFTC	MARS	FAR	XTOR	PIES	ARES	CTD	NIMROD
N.L. Res. MHD	X	X		X	X	X		X	X
Free Boundary N.L.									?
Neoclassical Tearing				X		X			X
Scrape-off Layer									?
Resistive Wall	X	X	X				X	X	X
q < 1	X	X	X	X	X		X	X	X
Two Fluid	X							X	X
Rotation		X	X					X	X
Predict Diagnostics	X								X
Fast Particles	X								?
Radial Element	General	F.D.	F.E.	F.D.	F.D.	F.D.	F.D.	F.D.	General
Fourier in Poloidal	X	X	X	X	X	X	X	X	novel
Fourier in Toroidal	X	X	X	X	X	X	X	X	X
Linear Regime	q. Imp	s. Imp	eig.	Imp.	s. Imp		eig.	s. Imp	General
Nonlinear Regime	q. Imp	s. Imp		exp.	s. Imp	iter.		s. Imp	General

VALIDATION ISSUES

1. Internal self-consistency of the code
2. Check with known linear codes
   - GATO
   - DCON
   - MARS
3. Check with known nonlinear codes
   - MH3D
   - XTOR
   - CTD
   - NEOFAR

   α. Scenario development
      - Halo current
      - Disruption

   β. Quantitative comparison
      - Nonlinear stability boundary