Global MHD: Fusion Theory Needs

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Outline

General perspectives

- Immediate issues

  preparation for ITER

- Longer term: preparation for going beyond ITER

  tokamaks and stellarators

PPPL Strategic Initiatives

- Develop magnetic fusion energy
  - Advance the spherical tokamak for multiple fusion applications
  - Explore the physics and engineering science of plasmas producing fusion power (ITER & beyond)
  - Develop methods to control the plasma-material interface
  - Use 3D magnetic fields for steady-state, disruption-free plasma confinement
  - Develop integrated predictive models of burning plasmas

- Establish a center of excellence in plasma astrophysics

- Develop plasma science and related applications

US Program Priorities: ReNeW & FESAC

- ReNeW
  1. Burning Plasma in ITER
  2. Predictable High-performance, Steady-state Plasmas
  3. Taming the Plasma-Material Interface
  4. Harnessing Fusion Power
  5. Optimizing the Magnetic Configuration

- FESAC Priorities, Gaps, and Opportunities Report

  Plasma Facing Components

  Materials

  Off-normal events (disruptions & ELMs)

  Fuel-cycle

  Plasma-wall interactions

  Integrated high-performance

Immediate Issues: ITER

- ITER

  Need to control and mitigate Disruptions

  Need to minimize ELMs or minimize ELM energy loss

  ITER designed to withstand ~3000 disruptions

  and with relatively thick wall & divertor armor

- ITER issues continue: ELMs & Disruptions

  - Worse in DEMO: more energy, higher forces
  - PFC armor must be much thinner to achieve TBR > 1

    most reactor designs have 1-3 mm of W armor

    ITER has 1cm Be/W plus 2.5cm of Cu (ΔTBR 12%)

  Disruptions and ELMs must be reliably eliminated

ITER Disruptions

Needs well documented:

- Reliable prediction of coming disruption (earlier better)

  prediction of how to avoid disruptions (by control)

- Understanding of how to mitigate peak energy fluxes in thermal quench

- Understanding of how to mitigate high electromagnetic loads during current quench

- Understanding of how to suppress runaway electrons

➔ Need validated model of disruption process to extrapolate from present experiments

Disruption Modeling at PPPL?

- Bell committee report, April 2012
- Several activities by individuals or small groups
- Complex problem, many aspects
  - 3D, often involves locked mode
  - hybrid MHD & kinetic
  - has to include interaction with wall
- Will we take on this challenge?

ELM Mitigation & Avoidance

Needs well documented: Expect that ITER limit on ELM energy loss < 1%

Three approaches:

- Stimulate frequent tiny ELMs: small pellets; small motions; small shape change.

- 3D magnetic perturbation (RMP) of equilibrium

  DIIID, NSTX, JET, MAST, AUG, KSTAR

  Different behavior on different machines!

  Is transport affected or stability?

  No validated understanding or modeling

  What magnetic perturbations can be tolerated?

- Regimes without ELMs (QH, I-mode)

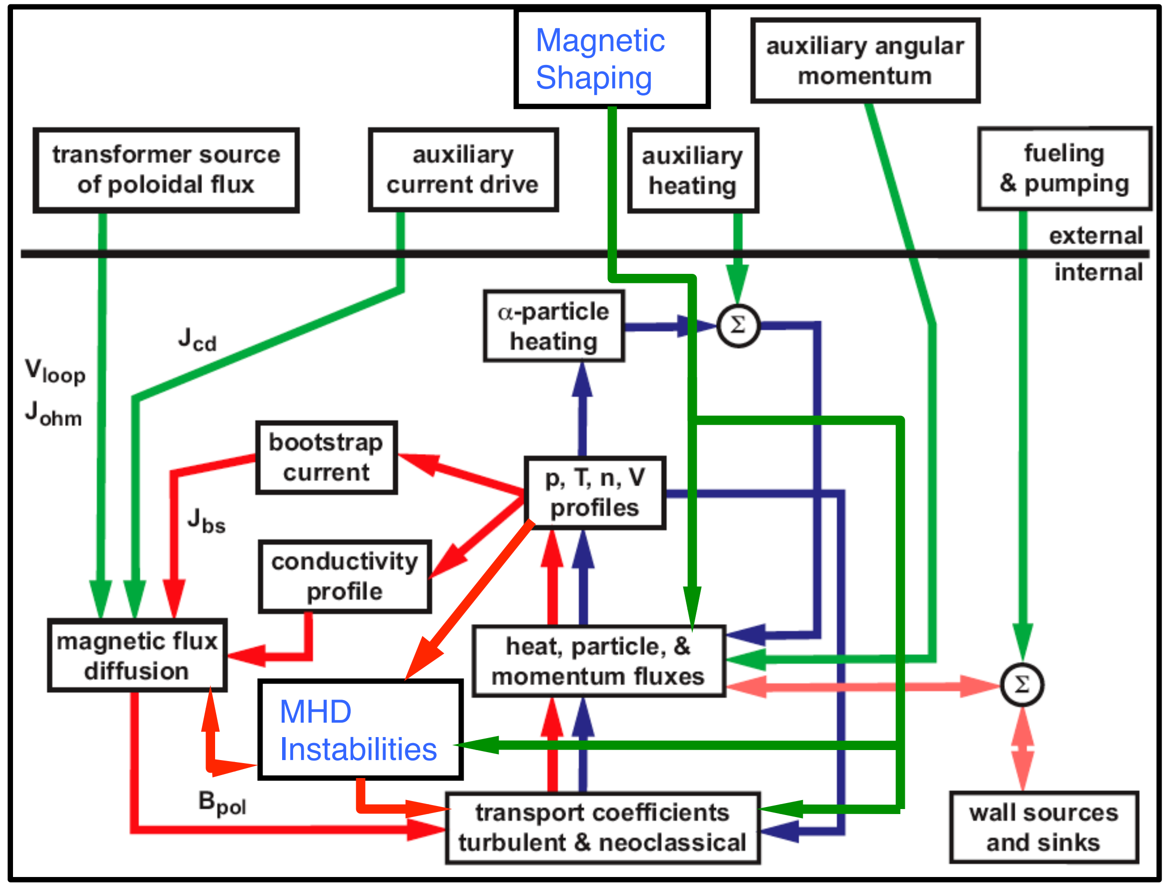
Burning tokamak plasmas: Very non-linear

MHD is central:

- Burning, steady-state
  => high beta

- Fast-alphas: strong kinetic-MHD interactions

- Evolution of current profile interaction with stability, transport



ala Politzer, 2005

- Shaping constrained by blankets, shielding

- Shaping is the easiest control knob

Preparation for ITER Operation

We must use our best understanding to obtain ITER's success.

$Q > 10$. $Q > 5$ long pulse.

We must use ITER to challenge and validate our understanding.

- We must have realistic models to guide ITER experiments and stay within limits

- We need our best predictions to compare with ITER observations.

- Diagnostics will be more limited than current experiments

Preparation for ITER Operation, cont'd

- General need for Integrated Modeling (SciDAC; FSP)

- Importance of Non-linear kinetic-MHD
  - $\beta_N > 2$: saturated MHD modes common
    Key part of plasma-state
  - fast-particle driven *AEs, EPMs from alphas and CD
  - fast-particle modifications of MHD tearing, kinks
  - rotation and rotation gradient effects on MHD
  - fast-particle transport due to MHD (all)
  - transport modifications and nonlinearity thru p', J
  - possible direct coupling between fast-particle & thermal spectra?

Importance of Non-linear kinetic-MHD

- At significant β, β_P MHD & kinetics seem inseparable…?

- Need routinely available tools to evaluate non-linear interactions: MHD with kinetic contributions & impact
  - MHD amplitudes
  - thermal transport
  - fast ion transport
  - disruptivity

- Will we provide these tools? Someone must.

RWM Interaction with Fast Ions

- Fast ion precession can stabilize RWMs, allowing operation above the no-wall limit even at low rotation. [Hu et al.]
- This has been observed experimentally on DIII-D, JT-60U, and NSTX.
- Analysis indicates that this may provide RWM stabilization in ITER, without external rotation drive [Berkery, Sabbagh]. Will it be strong enough?
- Experiments on DIII-D and JT-60U observe RWMs being triggered by fast-ion loss from fishbone-like instabilities, forcing the plasma below the no-wall β-limit.
- In future burning plasmas, fast ion instabilities and Alfvenic instabilities may cause alpha-transport, and destabilize the RWM. Could cause disruptions!

Experiments are 3D

- 3D deviations from axisymmetry are important
- Imposed from field-error compensation & RWM control
  Imposed for ELM control
- Also from field errors, assembly tolerances, magnetic materials

- Effects similar to 3D shaping in stellarators
- Flux surfaces can have islands, stochastic regions
  - Impact on core and edge transport, thermal and fast-particle

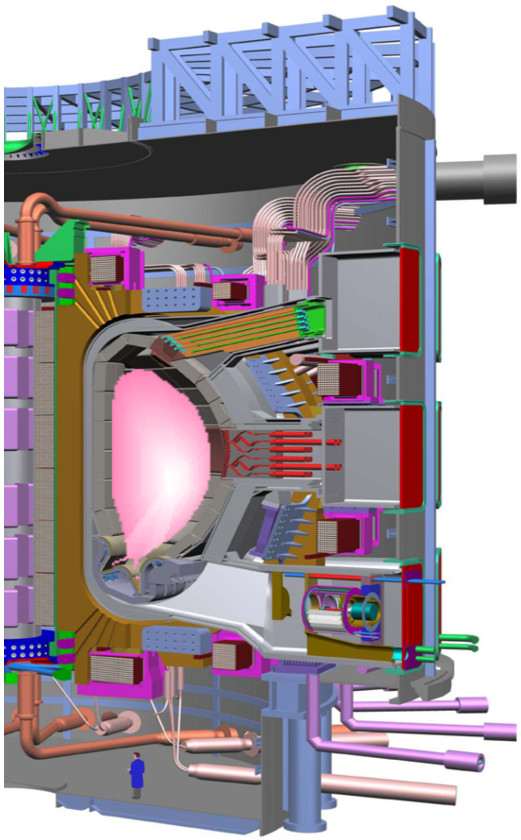
- Kinetic effects important on equilibrium!
  physics same as with finite frequency MHD
  - e.g. rotational shielding of 3d magnetic perturbations

Need reliable understanding and models of 3D equilibria and physics

Beyond ITER: Need β higher

Need

- Higher fusion power & Q at ~same size
- Steady state with less CD, more bootstrap current
- Disruption free, reliable
- Robust divertor
- TBR > 1



But, must be simpler, more cost effective.

β higher, β_P higher

MHD & kinetic effects stronger, more important.

Substantial advances in Steady-State Tokamak Regimes

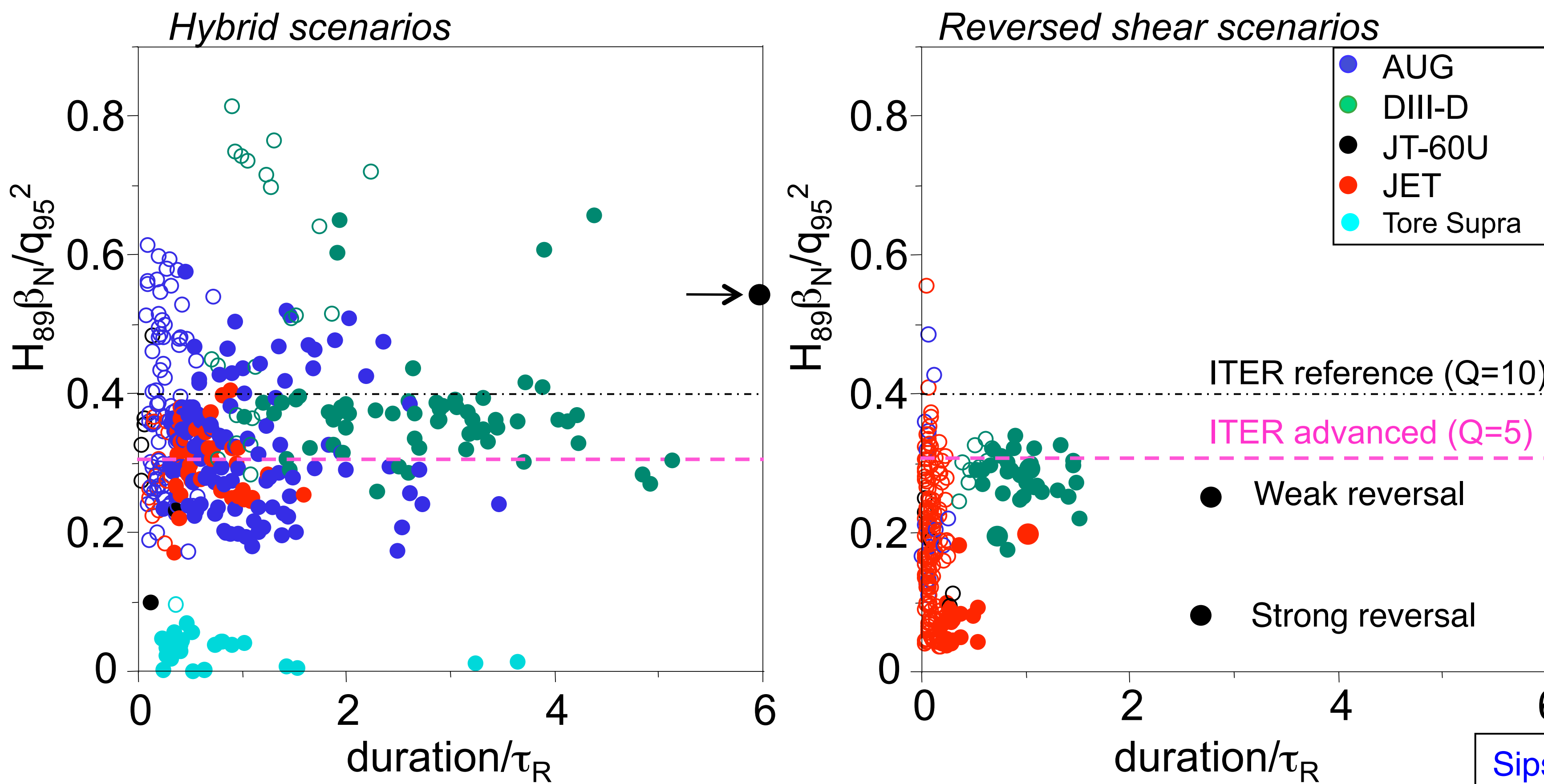
- Lots of significant work by AUG, DIII-D, JET, JT-60U
  in part to prepare for ITER. NSTX for ST parameters for FNSF.

- 100% Non-inductive plasmas achieved in three strategies
  ~ stationary for at least ~3 relaxation times for the current profile
  hybrid; weak reversed shear; strongly reversed shear

- DIIID : extensive shape optimization. DN, κ~1.9, δ~0.6, ζ~ -0.25
- JT-60U : extended to almost 30 sec.
- DIII-D, JT-60U, NSTX : above the no-wall limit

Use $G = \beta_N H / q_{95}^2$ as a dimensionless metric for $nT\tau \sim Q$
using either $H_{89} = \tau_E$ / ITER-89P or $H_{98} = \tau_E$ / ITER-98(y,2)

Need route to high performance at high-bootstrap



Sips 2005
+ new data

- JT-60U Hybrid sustained for 16 τ_R
- All three regimes sustained to ~ 3 τ_R or longer, stationary.
- Bootstrap current fractions differ systematically

Hybrid $f_{boot} < 0.5$; Weak reversal $f_{boot} \sim 0.6$; Strong rev. $f_{boot} > 0.7$

Reactor Designs are Not Consistent with Sustained AT Characteristics

	Hybrid	Weak Rever	Strong Rever	Slim CS	CREST	EU AB	EU C	Aries-AT
	DIII-D	DIII-D	JT-60		Weak rev			Strong rev.
q_{95}	3.3	6.3	8.3	5.4	4.3	3.0	4.3	3.2
H_{98}	1.5	1.5	1.8	1.3	1.3	1.2	1.3	1.7
β_N	2.8	3.7	1.7	4.3	5.5	3.5	4	5.4
G_{98}	0.38	0.14	0.044	0.19	0.39	0.47	0.28	0.90
$f_{bootstrap}$	~0.4	0.65	0.75	0.77	0.83	0.45	0.63	0.91
n / n_{GW}	0.4	0.5		0.98	1.3	1.2	1.5	0.9

- Need to iterate designs using more realistic parameters

Stellarators Provide Different Approach

- Steady state and disruptions avoidance from 3D shaping
- Sustained high-beta, quiescent confinement already achieved.

Physics Issue:

Soft Beta limit from changes in confinement.

Due to change in MHD equilibrium?

How to predict & validate accurately?

Same physics as high-beta tokamaks, including 3D perturbations.

Stellarators Priority Issues
Need MHD advances

US Assessment (ReNeW & FESAC):

1. Simplify coil designs to achieve attractive physics

2. Demonstrate integrated high performance: high-(β H) at low collisionality

3. Confinement predictability

4. Effective 3D divertor design

PPPL has key elements of 3D design & equilibrium.

Will we pursue them?