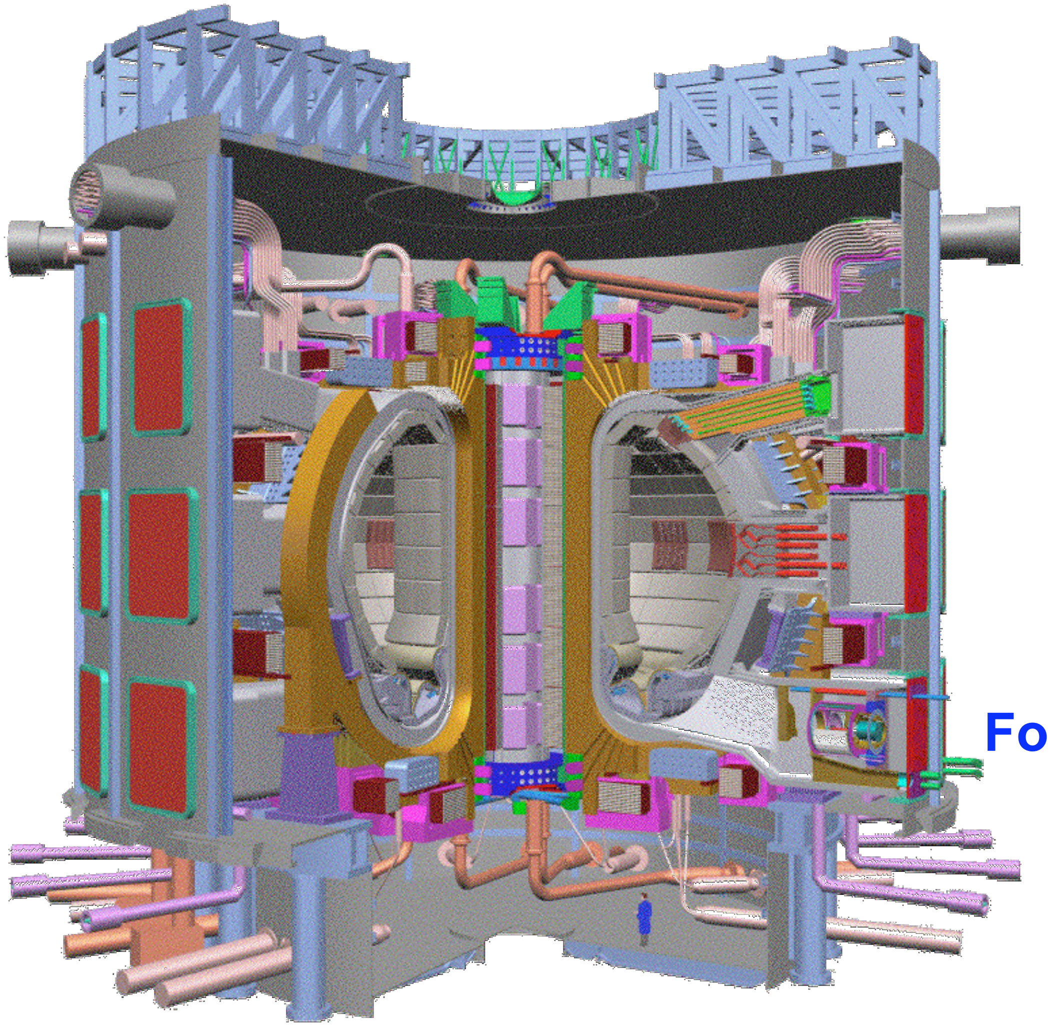
U. S. Science Interests in ITER



Gerald A. Navratil

Columbia University

Forum on the Future of Fusion
Fusion Power Associates
Washington, DC
19-21 November 2003

CONTEXT & REFERENCES

- US DOES NOT (YET) HAVE A BURNING PLASMA OR ITER PROGRAM ESTABLISHED: NO “OFFICIAL” LIST OF PRIMARY US SCIENCE INTERESTS

- VIEWS EXPRESED HERE ARE MY OWN, INFORMED BY PARTCIPATION IN US FUSION COMMUNITY BURNING PLASMA PLANNING ACTIVITY:
  - UFA BURNING PLASMA WORKSHOPS: AUSTIN 2000; SAN DIEGO 2001
  - SNOWMASS FUSION SUMMER STUDY 2002

AND

  - INTERNATIONAL TOKAMAK PHYSICS ACTIVITY (ITPA)

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OUTLINE

- BURNING PLASMA BASICS
- FRONTIER SCIENCE IN BURNING PLASMA:
  - + Q~5: □-EFFECTS ON TAE STABILITY
  - + Q~10: STRONG NON-LINEAR COUPLING
  - + Q≥20: BURN CONTROL & IGNITION

FUSION " SELF-HEATING" POWER BALANCE

FUSION POWER DENSITY: $p_f = \mathcal{R}\varepsilon_f = \frac{1}{4} n^2 \langle \sigma v \rangle \varepsilon_f$ for $n_D = n_T = \frac{1}{2} n$

TOTAL THERMAL ENERGY
IN FUSION FUEL, $W = \int \left\{ \frac{3}{2} nT_i + \frac{3}{2} nT_e \right\} d^3x = 3nTV$

DEFINE " ENERGY CONFINEMENT TIME" , $\tau_E \equiv \dfrac{W}{P_{loss}}$

ENERGY BALANCE

$$\frac{dW}{dT} = \left\{ \underbrace{\frac{1}{4} n^2 \langle \sigma v \rangle \varepsilon_\alpha V}_{\alpha\text{-heating power}} + \underbrace{P_{heat}}_{\text{Additional heating input}} \right\} - \underbrace{\frac{W}{\tau_E}}_{\text{loss rate}}$$

STEADY-STATE FUSION POWER BALANCE

$$\frac{dW}{dt} \rightarrow 0 \quad \Longrightarrow \quad P_\alpha + P_{heat} = \frac{W}{\tau_E}$$

Define fusion energy gain, $Q \equiv \dfrac{P_{fusion}}{P_{heat}} = \dfrac{5\,P_\alpha}{P_{heat}}$

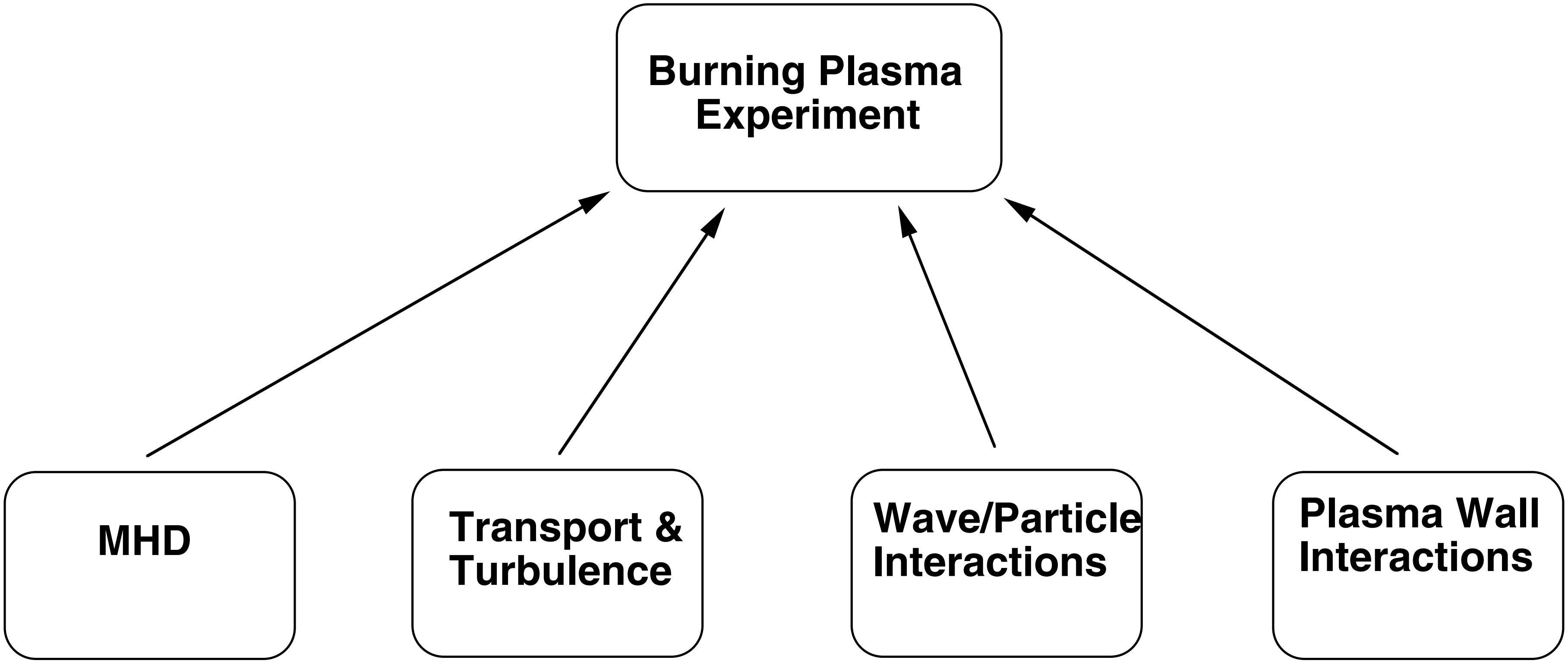
Define α-heating fraction, $f_\alpha \equiv \dfrac{P_\alpha}{P_\alpha + P_{heat}} = \dfrac{Q}{Q+5}$

Scientific Breakeven	$Q = 1$	$f_\alpha = 17\%$
Burning Plasma Regime	$Q = 5$	$f_\alpha = 50\%$
	$Q = 10$	$f_\alpha = 60\%$
	$Q = 20$	$f_\alpha = 80\%$
	$Q = \infty$	$f_\alpha = 100\%$

THERE ARE TWO TYPES OF BURNING PLASMA ISSUES...

- GETTING & STAYING THERE:
  - + DENSITY, TEMPERATURE, AND τ_E REQUIRED FOR Q ≥ 5
  - + MHD STABILITY AT REQUIRED PRESSURE FOR Q ≥ 5
  - + PLASMA EQUILIBRIUM SUSTAINMENT ($\tau > \tau_{SKIN}$)
  - + POWER, FUELING, & REACTION PRODUCT CONTROL

Major Advances & Discoveries of 90's Are Foundation for ITER Burning Plasma Experiment



MHD

- q-profile control and measurement
- steady-state, bootstrap equilibria
- active mode control of kink & tearing

Transport & Turbulence

- shear-flow turbulence suppression
- gyro-kinetic theory based models
- extensive data-base models on transport using dimensionless scaling

Wave/Particle Interactions

- alpha heating in DT found to be classical for $Q \leq 1$
- "standard model" of Alfvén Eigenmodes
- LHCD & ECCD used for near SS & mode control

Plasma Wall Interactions

- detached divertor demonstrated
- large scale models developed
- high heat-flux metallic technology developed

THERE ARE TWO TYPES OF BURNING PLASMA ISSUES...

- GETTING & STAYING THERE:
  - + DENSITY, TEMPERATURE, AND τ_E REQUIRED FOR $Q \geq 5$
  - + MHD STABILITY AT REQUIRED PRESSURE FOR $Q \geq 5$
  - + PLASMA EQUILIBRIUM SUSTAINMENT ($\tau > \tau_{SKIN}$)
  - + POWER, FUELING, & REACTION PRODUCT CONTROL
- NEW SCIENCE PHENOMENA TO BE EXPLORED
  - + **$Q \geq 5$:** ALPHA EFFECTS ON STABILITY & TURBULENCE
  - + **$Q \geq 10$:** STRONG, NON-LINEAR COUPLING BETWEEN ALPHAS, PRESSURE DRIVEN CURRENT, TURBULENT TRANSPORT, MHD STABILITY, & BOUNDARY-PLASMA
  - + **$Q \geq 20$:** STABILITY, CONTROL, AND PROPAGATION OF THE FUSION BURN AND FUSION IGNITION TRANSIENT PHENOMENA

BURNING PLASMA IS A NEW REGIME:
FUNDAMENTALLY DIFFERENT PHYSICS

NEW ELEMENTS IN A BURNING PLASMAS:

SELF-HEATED BY FUSION ALPHAS

SIGNIFICANT ISOTROPIC ENERGETIC POPULATION OF 3.5 MEV ALPHAS

LARGER DEVICE SCALE SIZE

PLASMA IS NOW AN <u>EXOTHERMIC</u> MEDIUM & HIGHLY NON-LINEAR

COMBUSTION SCIENCE ≠ LOCALLY HEATED GAS DYNAMICS

FISSION REACTOR FUEL PHYSICS ≠ RESISTIVELY HEATED FUEL BUNDLES

⇒OPPORTUNITY FOR UNEXPECTED DISCOVERY IS VERY HIGH⇐

Snowmass: ITER Physics Interests

- Exploration of alpha particle-driven instabilities in a reactor-relevant range of temperatures.
- Capability to address the science of self-heated plasmas in reactor-relevant regimes of small $\square^*$ (many Larmor orbits) and high $\square_N$ (plasma pressure), and with the capability of full non-inductive current drive sustained in near steady state conditions.
- Exploration of high self-driven current regimes with a flexible array of heating, current drive, and rotational drive systems.
- Strongly-coupled physics issues of equilibrium, stability, transport, wave-particle interactions, fast ion physics, and boundary physics in the regime of dominant self-heating.
- Investigation of temperature control and removal of helium ash and impurities with strong exhaust pumping.

IMPORTANT PHYSICAL PROPERTIES OF α-HEATING

- FOR Q ~ 10: $nT\tau_E \sim 2 \times 10^{21}\ \mathrm{m^{-3}\ keV\ s}$ for $T \sim 10$ keV

  + WHEN NON-IDEAL EFFECTS (PROFILES, HE ACCUMULATION, IMPURITIES SOMEWHAT LARGER VALUE ~ $3 \times 10^{21}\ \mathrm{m^{-3}\ keV\ s}$

- FOR TOKAMAK “TYPICAL” PARAMETERS AT Q ~ 10

  $n \sim 2 \times 10^{20}\ \mathrm{m^{-3}}$ $T \sim 10$ keV $\tau_E \sim 1.5$ s

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- BASIC PARAMETERS OF DT PLASMA AND α

  $v_{Ti} \sim 6 \times 10^5$ m/s $v_\alpha \sim 1.3 \times 10^7$ m/s $v_{Te} \sim 6 \times 10^7$ m/s

  Note at B ~ 5 T: $v_{Alfvén} \sim 5 \times 10^6$ m/s $< v_\alpha$

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- CAN IMMEDIATELY DEDUCE:

  1) α-PARTICLES MAY HAVE STRONG RESONANT INTERACTION WITH ALFVEN WAVES.

  2) $T_i \sim T_e$ since $v_\alpha >> v_{Ti}$ AND $m_\alpha >> m_e$ THE α-PARTICLES SLOW PREDOMINANTLY ON ELECTRONS.

Q ~ 5: α-EFFECTS ON TAE STABILITY

ALPHA PARTICLE EFFECTS: KEY DIMENSIONSLESS PARAMETRS

- Three dimensionless parameters will characterize the physics of alpha-particle-driven instabilities:
  - Alfven Mach Number: $V_\alpha/V_A(0)$
  - Number of Alpha Lamor Radii (inverse): ρ_α/a
  - Maximum Alpha Pressure Gradient (scaled): Max $R\nabla\beta_\alpha$

	Range of Interest (e.g. ARIES-RS/AT)	ITER	JET
$V_\alpha/V_A(0)$	$\approx$ 2.0	1.9	1.6–1.9
ρ_α/a	$\approx$ 0.02	0.016	~0.1
Max $R\nabla\beta_\alpha$	0.03–0.15	0.05	0.02–0.037

274-01/rs

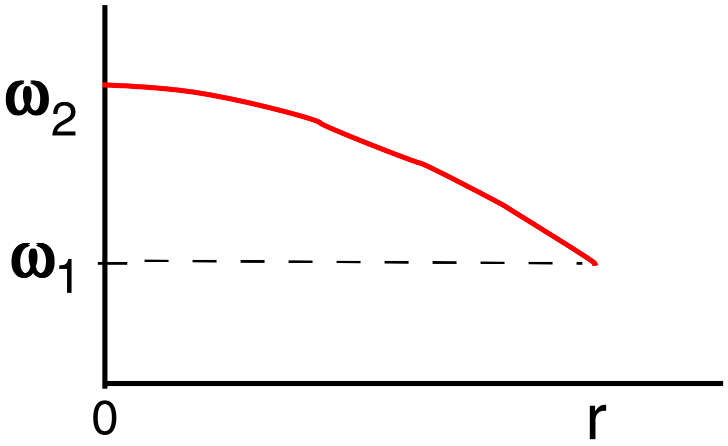
GEOMETRIC EFFECTS ON ALFVEN WAVES

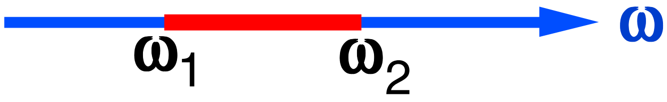
- Uniform Slab $\omega = k_{||} v_A$

Geometric Effects on Alfven Waves

- **Uniform Slab** $\omega = k_{||} v_A$

- **1D cylinder** $\omega = k_{||} v_A (r)$

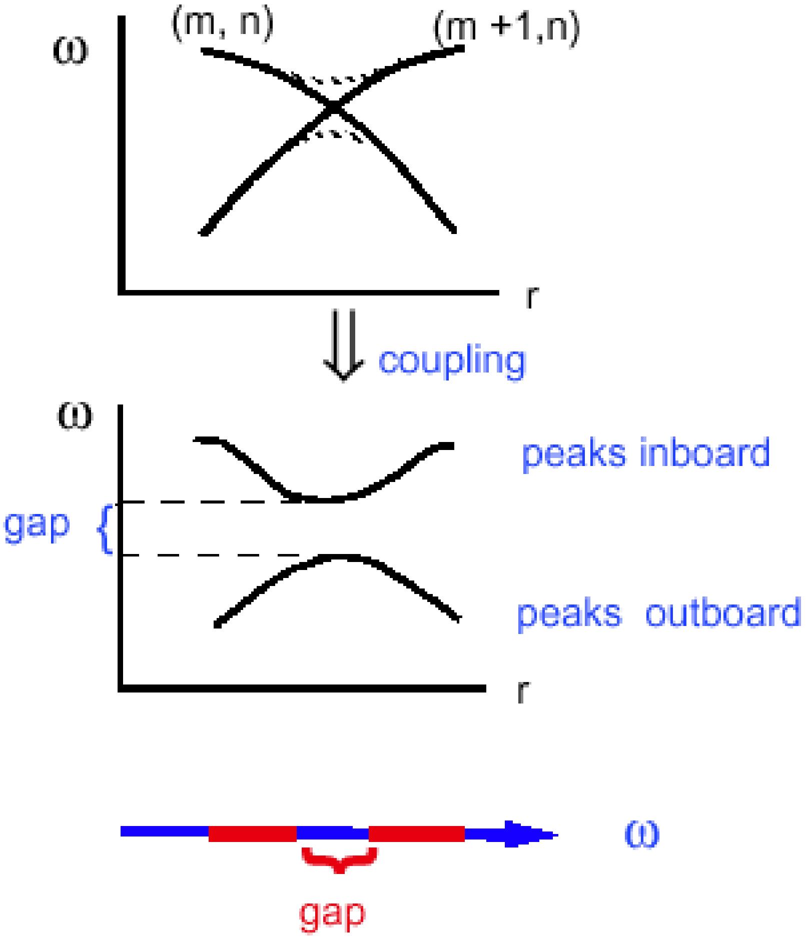




- Continuous spectrum, shear Alfvén resonance

GEOMETRIC EFFECTS ON ALFVEN WAVES

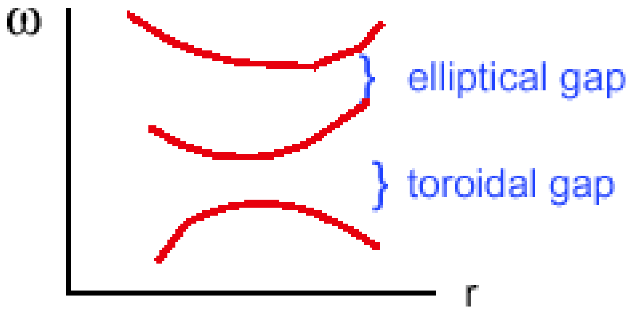
Add 2D toroidal effects:



- Periodic boundary conditions for toroidal mode number, n, and poloidal mode number, m
- m and m+1 are coupled and a “gap” is opened in the otherwise continuous spectrum

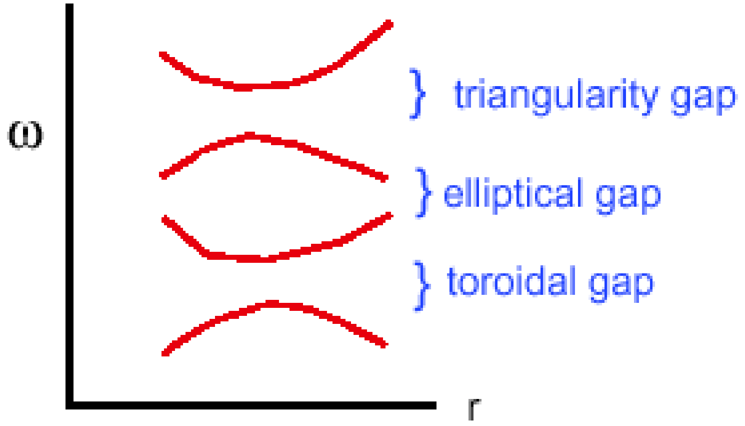
GEOMETRIC EFFECTS ON ALFVEN WAVES

Add elliptical cross-section effects:



- m and m+2 are now coupled and an elliptical “gap” is opened in the continuous spectrum

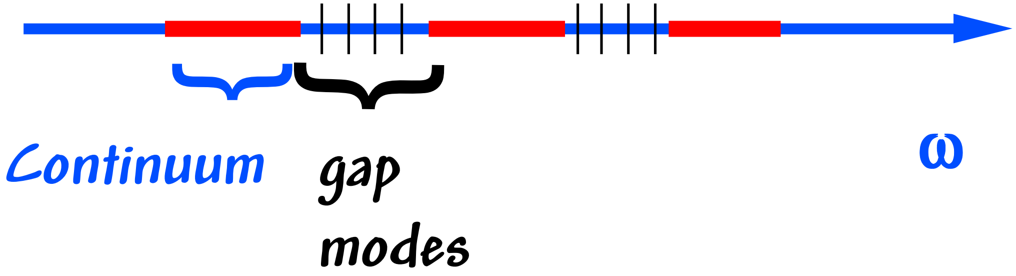
Add triangularity cross-section effects:



- m and m+3 are now coupled and an triangularity “gap” is opened in the continuous spectrum

GEOMETRIC EFFECTS ON ALFVEN WAVES

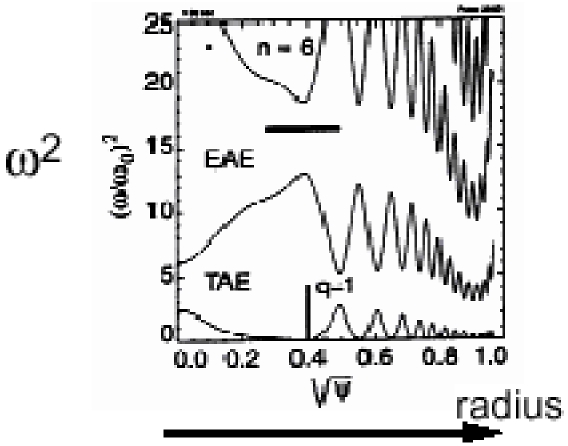
Discrete Modes Appear in Gaps in the Continuum:



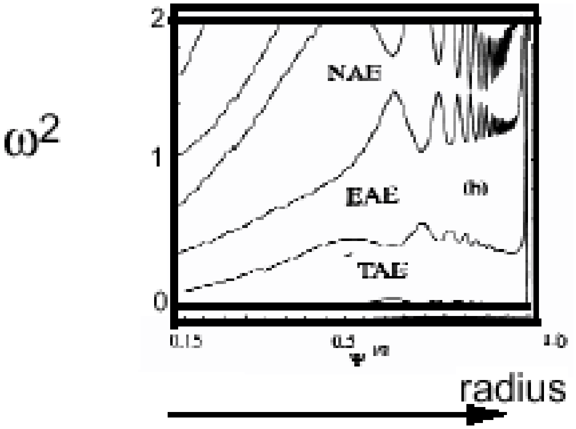
- **Alfvén wave continuum is strongly damped.**
- **TAE gap-modes are less damped: free energy from ∇p_α tapped by wave/particle resonance drive from α-particles may destabilize these modes.**

BASIC ALFVEN EIGENMODE PHYSICS EXTENDS TO RANGE OF TOROIDAL CONFIGURATIONS

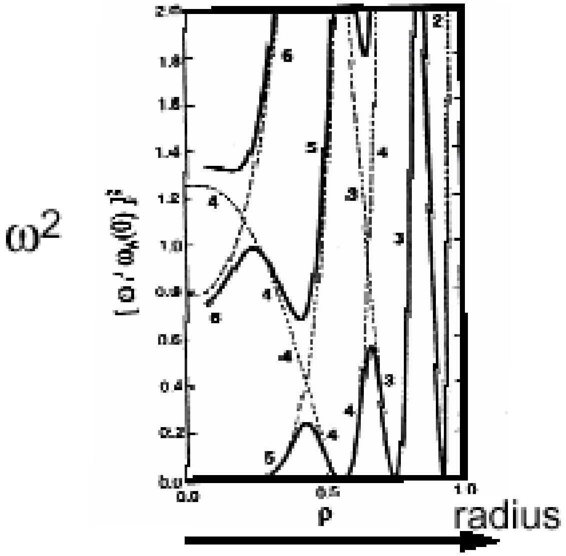
Tokamak:



Spherical Torus:



Stellarator:



- Details of spectra differ but underlying physics and modeling tools are common.

New Alpha Effects Expected on Scale of Burning Plasma

- Present experiments show alpha transport due to only a few global modes.
- Smaller value of $\rho_\alpha/\langle a\rangle$ in a Burning Plasma may lead to a “sea” of resonantly overlapping unstable modes & possible large alpha transport.

New Alpha Effects Expected on Scale of Burning Plasma

- Present experiments show alpha transport due to only a few global modes.
- Smaller value of □□/<a> in a Burning Plasma should lead to a “sea” of resonantly overlapping unstable modes & possible large alpha transport.
- Reliable simulations not possible with our ‘standard model’...needs experimental information in new regime.

Q ~ 10: Strong Non-Linear Coupling & Steady-State High β Operation

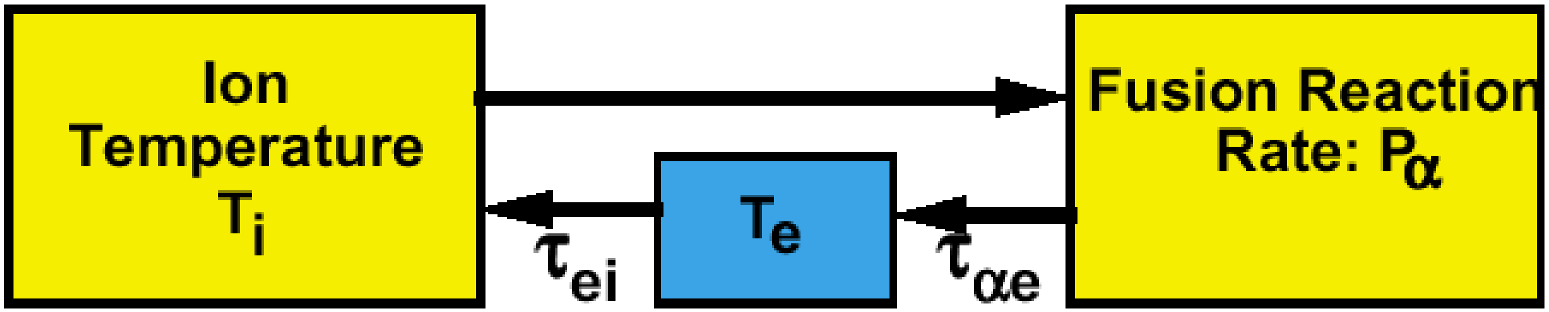
US ITER Science Interest Driven by Small Size/High Power Density

Fusion Reactors and Power Plants Design Studies

Parameter		ITER-ss	PULSAR-I	PPCS-C	ARIES-RS	A-SSTR2	STPP
B_ϕ	(T)	5.1	6.7	7.5	8.0	11	1.8
I_p	(MA)	9	14.2	6.4	11.3	12	31
R, a	(m)	6.35, 1.85	9.2, 2.3	7.5, 2.5	5.52, 1.38	6.2, 1.5	3.42, 2.44
A		3.4	4.0	3.0	4.0	4.1	1.4
V	(m^3)	800	1540	1750	350	470	1081
P_{fus}	(MW)	360	2030	3400	2170	4000	3300
P_{aux}	(MW)	72	0	112	81	85	76
Mode		ss	2.5 hr	ss	ss	ss	ss
$H_{98(y,2)}$		1.6	1.4	1.3	1.4	1.6	1.3
β_N		3.1	3.0	4.0	5.0	4.0	8.2
n_e/n_{GW}		0.81	1.4	1.5	1.1	1.2	0.82

BURNING PLASMA SYSTEM IS HIGHLY NON-LINEAR...

BASIC COUPLING OF FUSION ALPHA HEATING:



Ion Temperature T_i

τ_{ei}

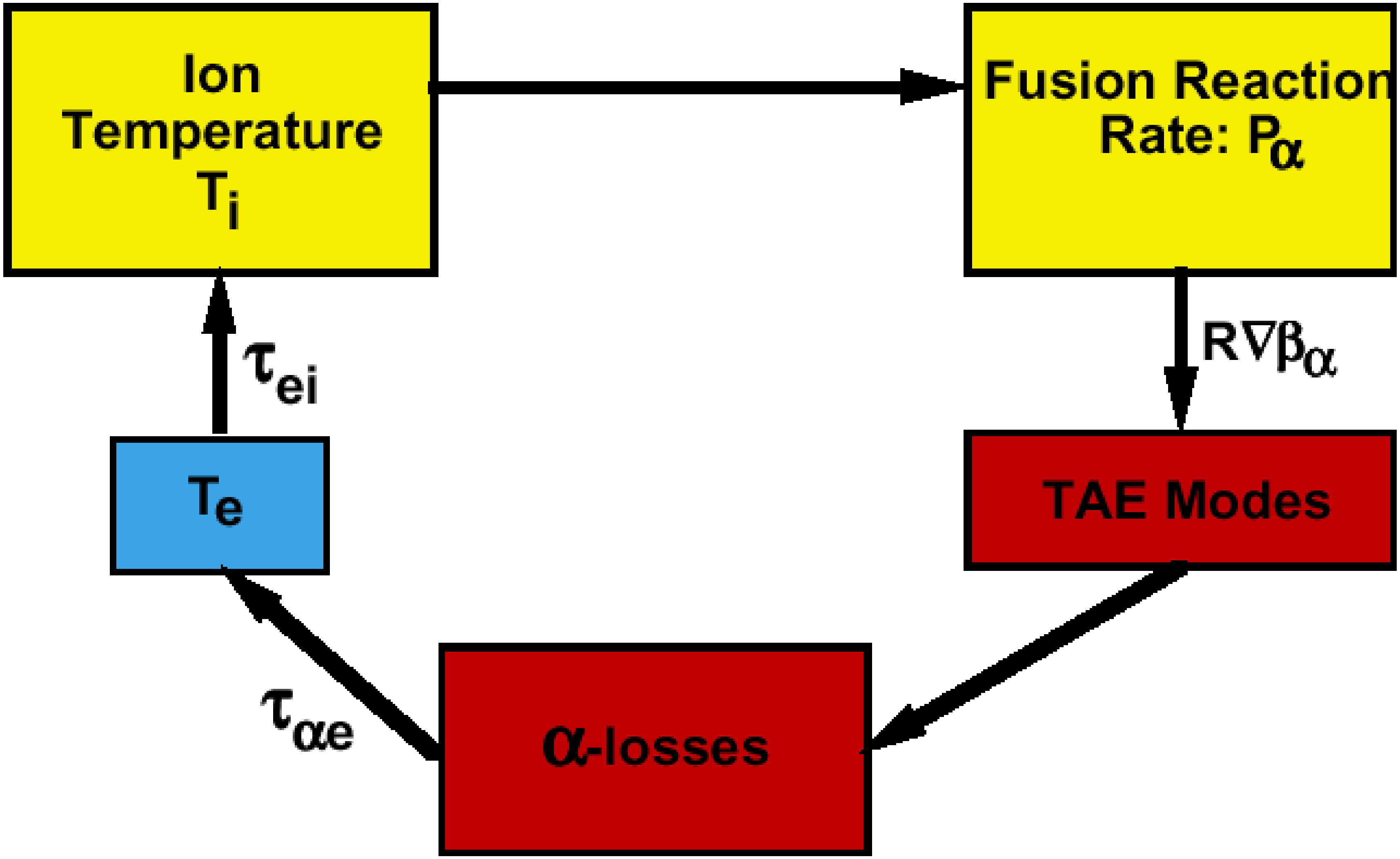
T_e

$\tau_{\alpha e}$

Fusion Reaction Rate: P_α

BURNING PLASMA SYSTEM IS HIGHLY NON-LINEAR...

ADD ALPHA DRIVEN TAE MODES:



Ion Temperature T_i

Fusion Reaction Rate: P_α

$R\nabla\beta_\alpha$

TAE Modes

α-losses

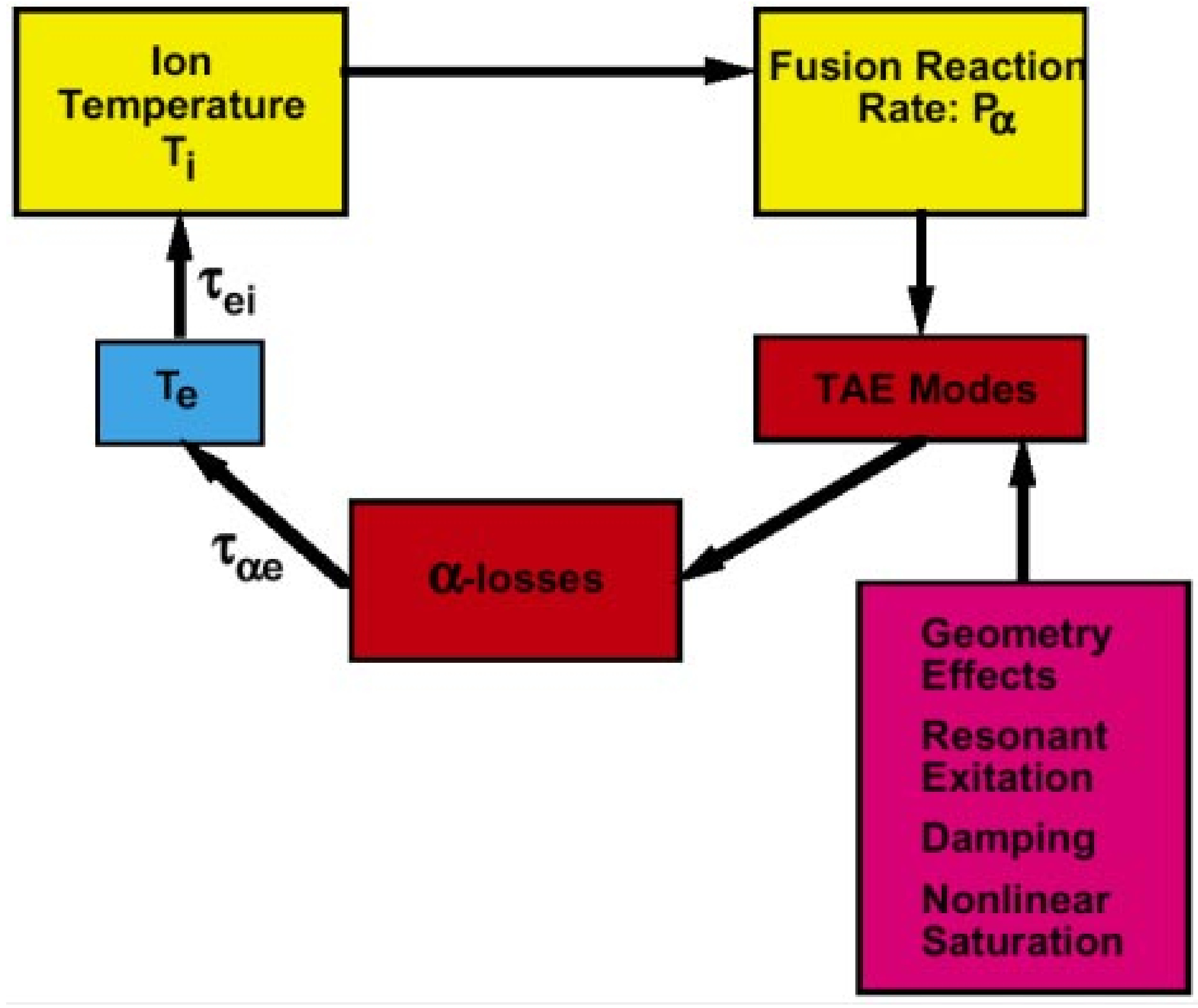
$\tau_{\alpha e}$

T_e

τ_{ei}

BURNING PLASMA SYSTEM IS HIGHLY NON-LINEAR...

ADD COMPLEX PHYSICS OF ALPHA DRIVEN TAE MODES:



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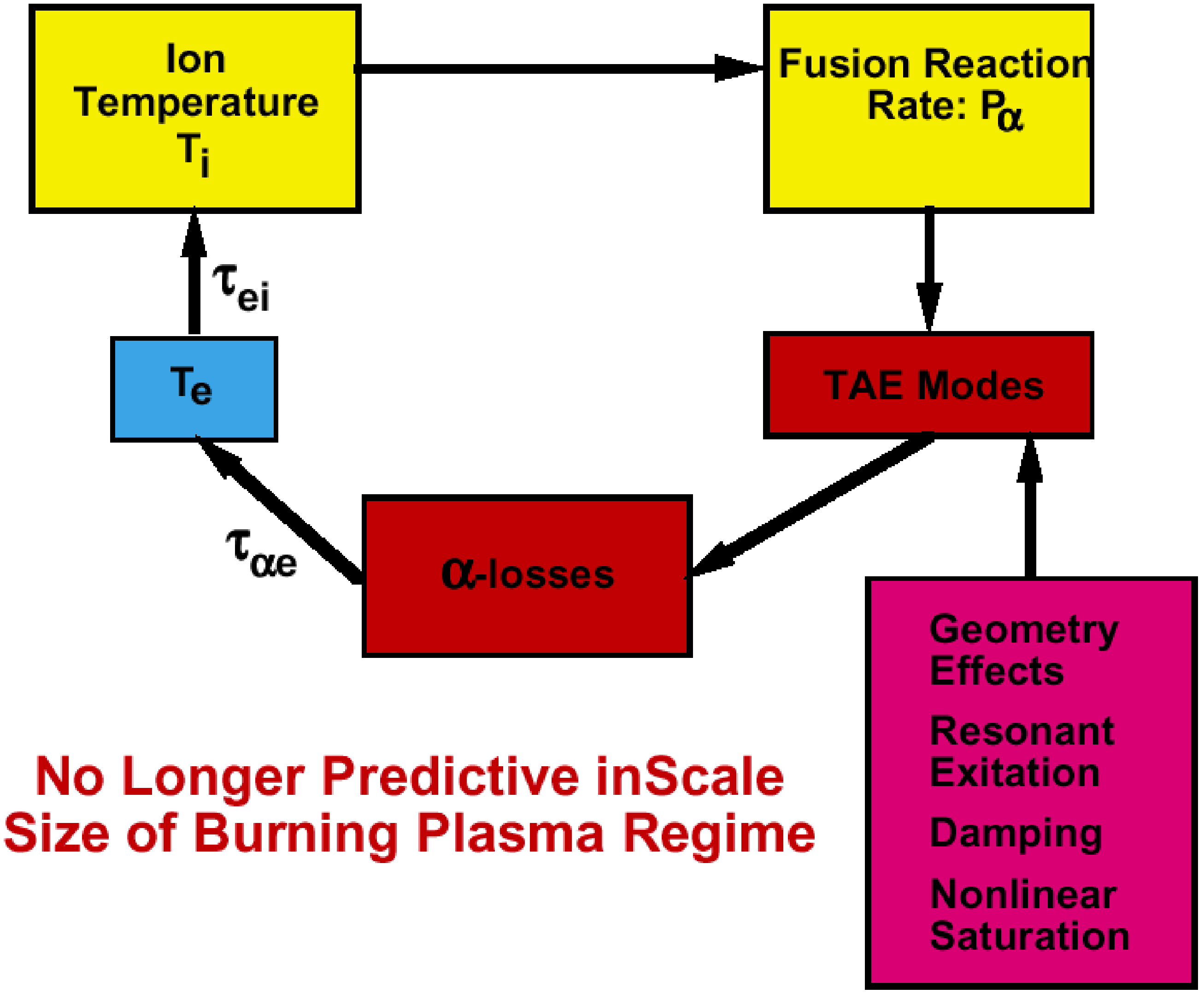


Ion Temperature T_i

Fusion Reaction Rate: P_α

τ_{ei}

T_e

TAE Modes

$\tau_{\alpha e}$

α-losses

Geometry Effects

Resonant Exitation

Damping

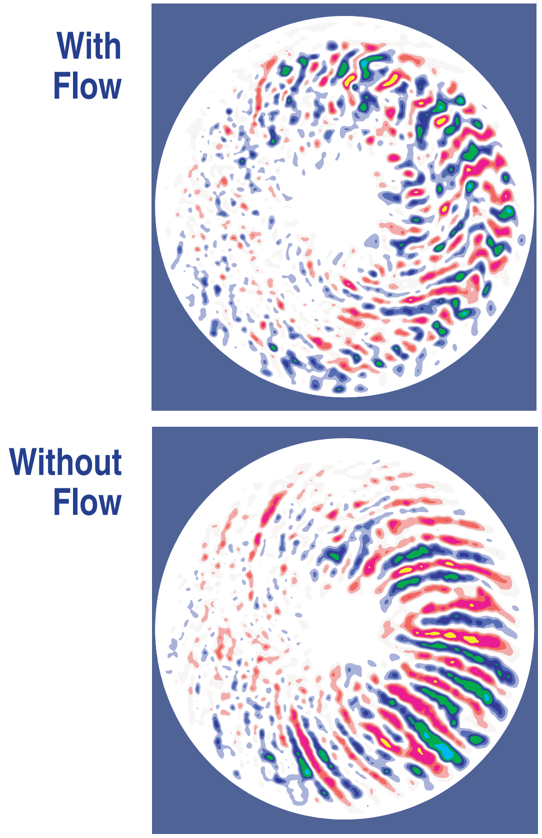
Nonlinear Saturation

No Longer Predictive inScale Size of Burning Plasma Regime

MAJOR DISCOVERY OF THE 1990's:
SHEARED FLOW CAUSES TRANSPORT SUPPRESSION

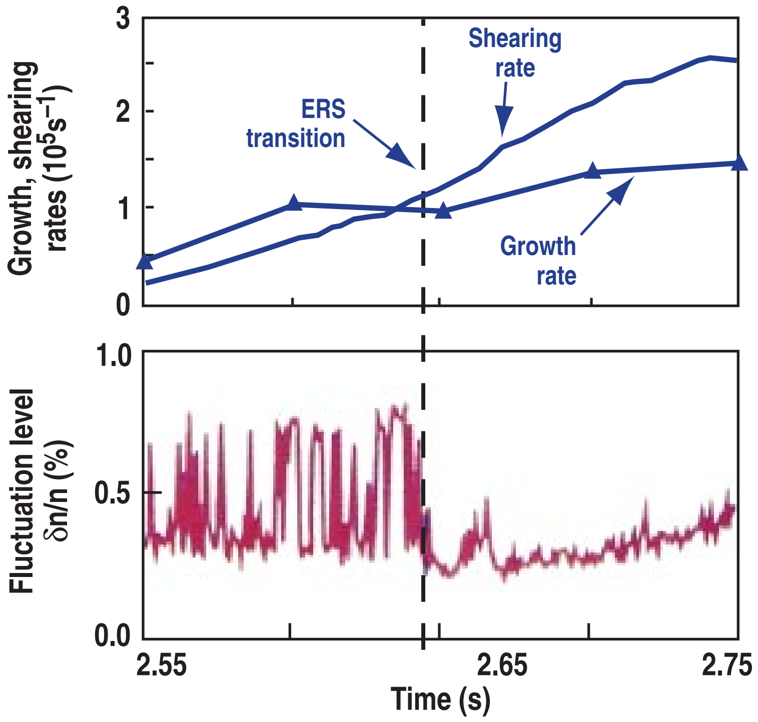
Gyrokinetic Theory

- Simulations show turbulent eddies disrupted by strongly sheared plasma flow



Experiment

- Turbulent fluctuations are suppressed when shearing rate exceeds growth rate of most unstable mode



Verified Prediction of Biglari, Diamond,Terry, Phys. Fluids B 2 1 (1990)

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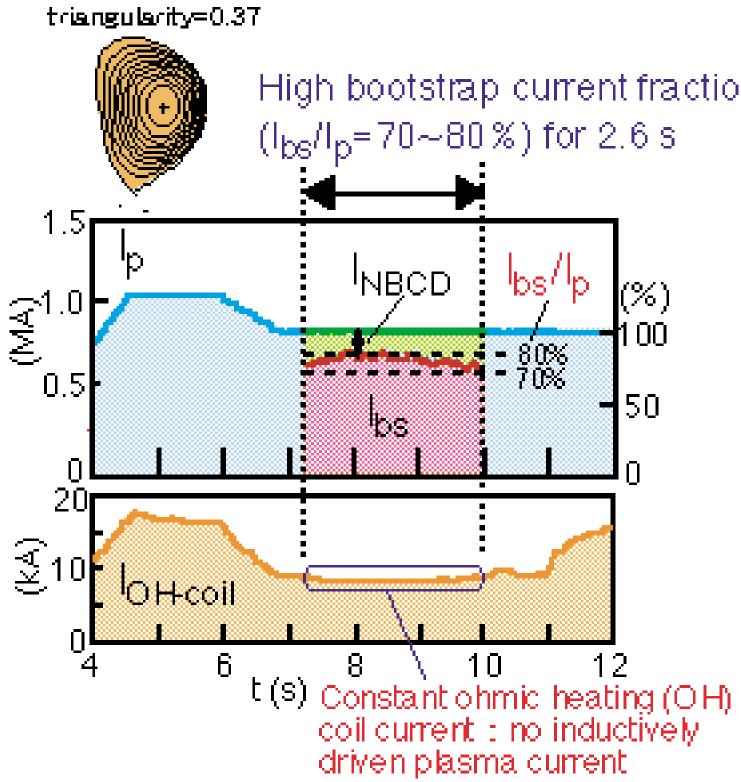
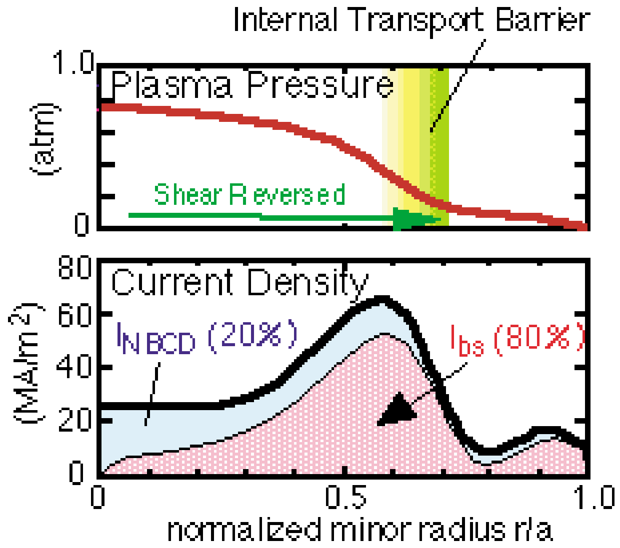
Combination of Turbulence Suppression & Bootstrap Current Leads to Steady-State Advanced Tokamak





- Data from JT-60U shows sustained transport barrier and 100% non-inductive current drive

ADVANCED TOKAMAK NONLINEAR TRANSPORT COUPLINGS

Thermonuclear Heating

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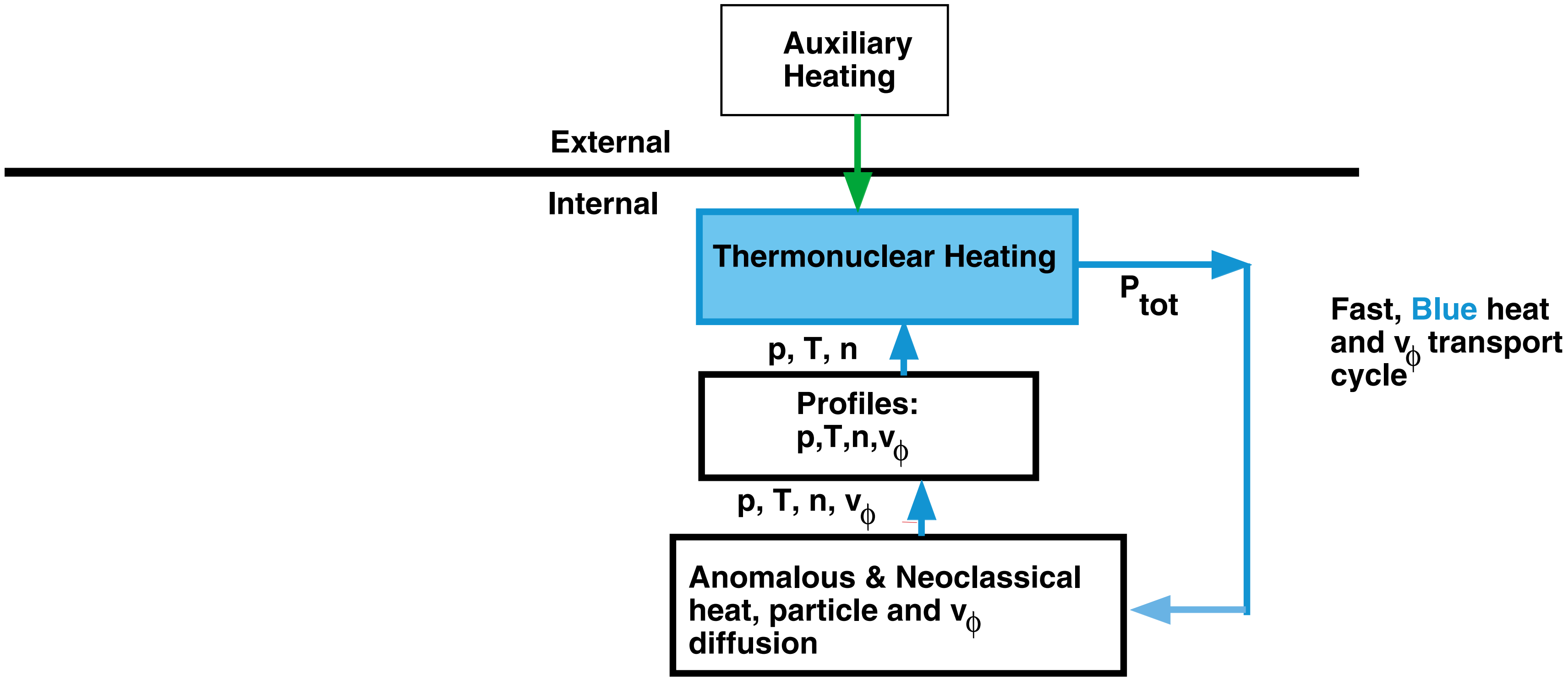


Auxiliary Heating

External

Internal

Thermonuclear Heating

P_{tot}

p, T, n

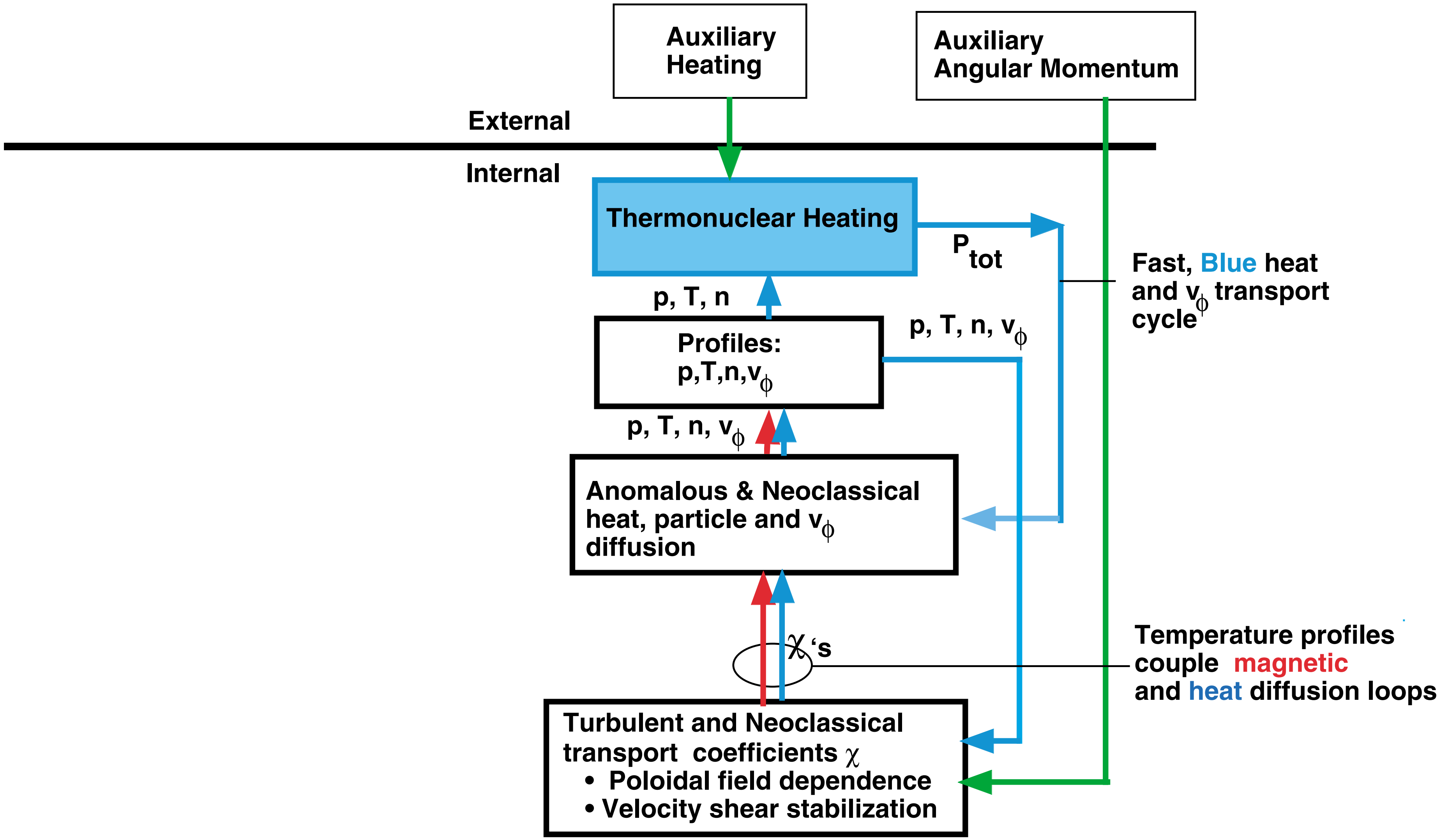
Profiles:
p, T, n, v_ϕ

p, T, n, v_ϕ

Anomalous & Neoclassical heat, particle and v_ϕ diffusion

Fast, Blue heat and v_ϕ transport cycle

ADVANCED TOKAMAK NONLINEAR TRANSPORT COUPLINGS



Auxiliary Heating

Auxiliary Angular Momentum

External

Internal

Thermonuclear Heating

P_{tot}

Fast, Blue heat and v_ϕ transport cycle

p, T, n

Profiles: p,T,n,v_ϕ

p, T, n, v_ϕ

p, T, n, v_ϕ

Anomalous & Neoclassical heat, particle and v_ϕ diffusion

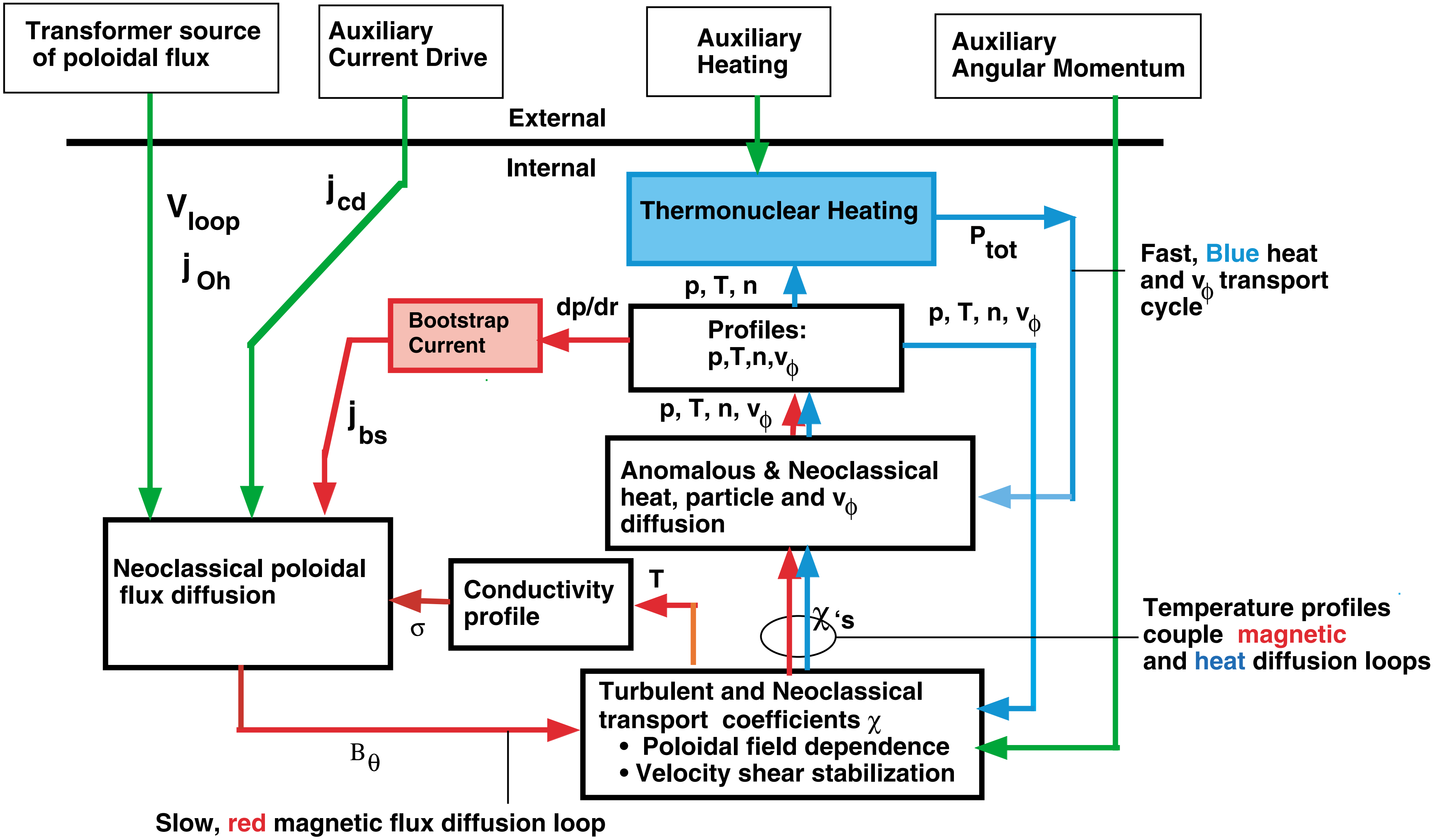
χ's

Temperature profiles couple magnetic and heat diffusion loops

Turbulent and Neoclassical transport coefficients χ

- Poloidal field dependence
- Velocity shear stabilization

ADVANCED TOKAMAK NONLINEAR TRANSPORT COUPLINGS



Transformer source of poloidal flux

Auxiliary Current Drive

Auxiliary Heating

Auxiliary Angular Momentum

External

Internal

V_{loop}

j_{Oh}

j_{cd}

Thermonuclear Heating

P_{tot}

Fast, Blue heat and v_{ϕ} transport cycle

p, T, n

dp/dr

Bootstrap Current

Profiles: p, T, n, v_{ϕ}

p, T, n, v_{ϕ}

j_{bs}

p, T, n, v_{ϕ}

Anomalous & Neoclassical heat, particle and v_{ϕ} diffusion

Neoclassical poloidal flux diffusion

Conductivity profile

σ

T

χ's

Temperature profiles couple magnetic and heat diffusion loops

Turbulent and Neoclassical transport coefficients χ

- Poloidal field dependence
- Velocity shear stabilization

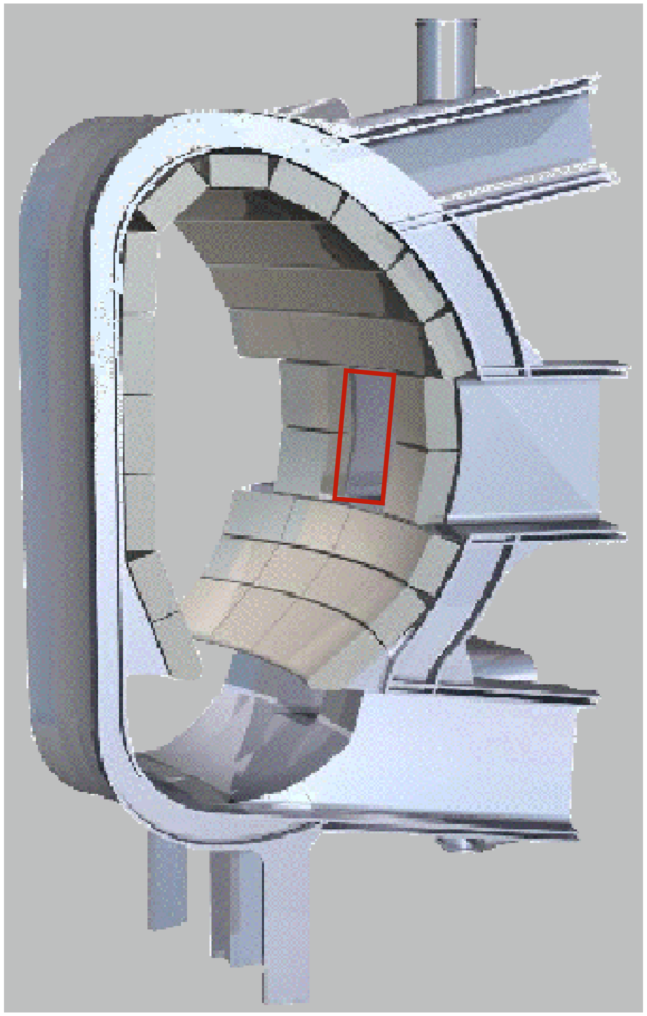
B_{θ}

Slow, red magnetic flux diffusion loop

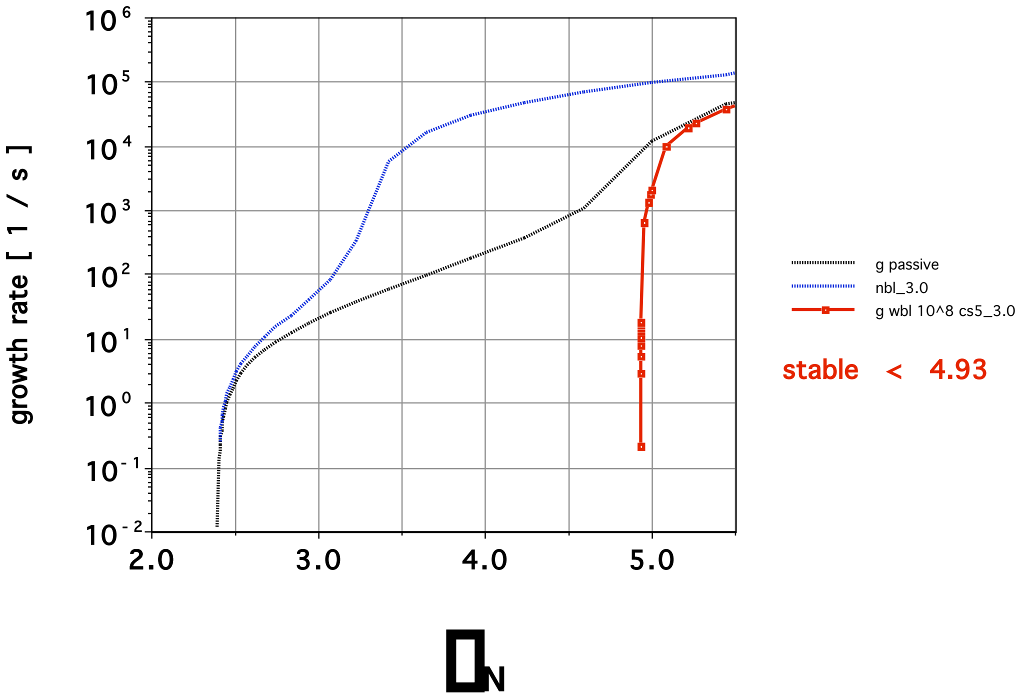
MHD Stability in ITER Burning Plasma

- Requirement for high $\beta_N > 3$ set by two critical effects:
  - High fusion power density for small size/lower cost
  - High bootstrap current fraction for efficient current drive in steady-state operation
- Two principal β-limiting MHD modes:
  - Neoclassical Tearing Modes – stabilized by local ECCD and/or current profile control
  - Resistive Wall Modes – stabilized by plasma rotation and/or active feedback control

New Results Driving AT Interests in ITER: Internal RWM Control Coils May Allow β_N~5



RWM Growth Rate With Feedback



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SUMMARY OF US SCIENCE INTERESTS IN ITER

- **Exploration of alpha particle-driven instabilities.**
- **Self-heated plasmas in reactor-relevant regimes of small ρ^* (many Larmor orbits) and high β_N (plasma pressure), sustained in near steady state conditions.**
- **Exploration of high self-driven current regimes.**
- **Strongly-coupled physics issues.**
- **Temperature control and strong exhaust pumping.**

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Flexibility of ITER to explore advances we will make in fusion science, including diagnostic systems essential for understanding.