BURNING PLASMA SCIENCE

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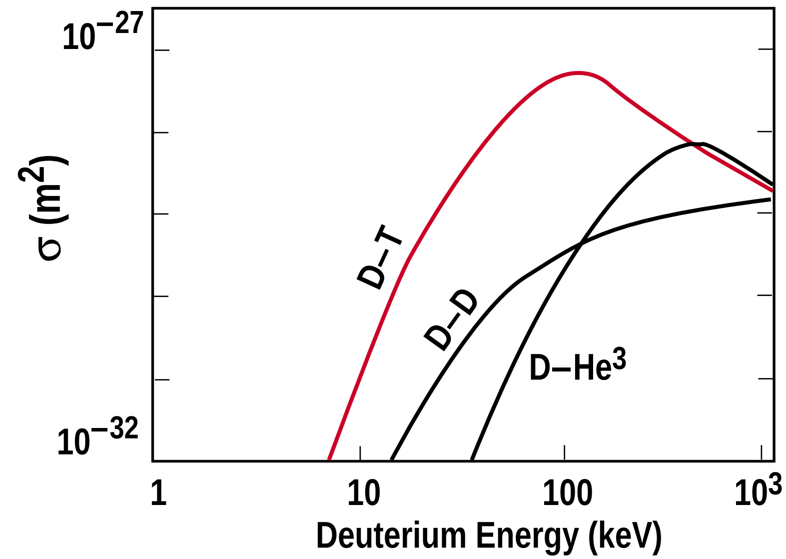
Producing and Understanding a Sustained Fusion Heated Plasma is a Grand Challenge Problem for Field of Plasma Physics...

... and we are ready to take this step!

DT FUSION

$$_1D^2 + {}_1T^3 \rightarrow {}_2\underbrace{He^4}_{(3.5\ \text{MeV})} + {}_0\underbrace{n^1}_{(14.1\ \text{MeV})}$$

Energy/Fusion: ε_f = 17.6 MeV

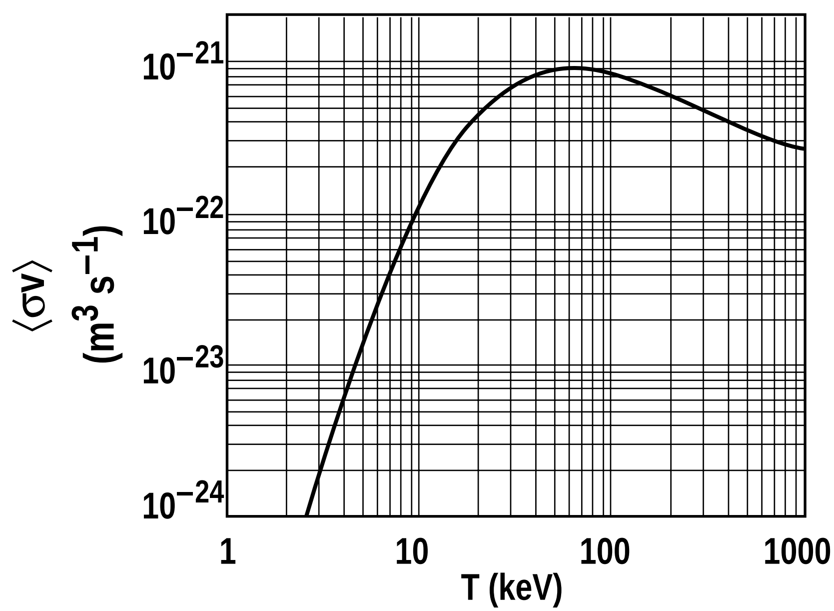


Fusion Reaction Rate, R for a Maxwellian

$$R = \iint \sigma(v')\, v' f_D(\vec{v}_D)\, f_T(\vec{v}_T)\, d^3\vec{v}_D\, d^3\vec{v}_T$$

where $\vec{v}' \equiv \vec{v}_D - \vec{v}_T$

$$R = n_D n_T \langle \sigma v \rangle$$



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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", $\tau_E \equiv \frac{W}{P_{loss}}$

ENERGY BALANCE

$$\frac{dW}{dT} = \left\{ \frac{1}{4} n^2 \langle\sigma v\rangle \varepsilon_\alpha V + P_{heat} \right\} - \frac{W}{\tau_E}$$

α-heating power

Additional heating input

loss rate

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STEADY-STATE FUSION POWER BALANCE

$$\frac{dW}{dt} \to 0 \implies P_\alpha + P_{heat} = \frac{W}{\tau_E}$$

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	$Q = 5$	$f_\alpha = 50\%$
	$Q = 10$	$f_\alpha = 60\%$
	$Q = 20$	$f_\alpha = 80\%$
	$Q = \infty$	$f_\alpha = 100\%$

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PARAMETERIZATION OF Q VERSUS $nT\tau_E$ OR $P\tau_E$

Recast power balance: $P_\alpha + P_{heat} = \dfrac{W}{\tau_E}$

$$nT\tau_E = p\tau_E = \frac{12T^2}{\langle\sigma v\rangle\, \varepsilon_\alpha \left(1 + \frac{5}{Q}\right)}$$

Useful since in 10–20 keV range

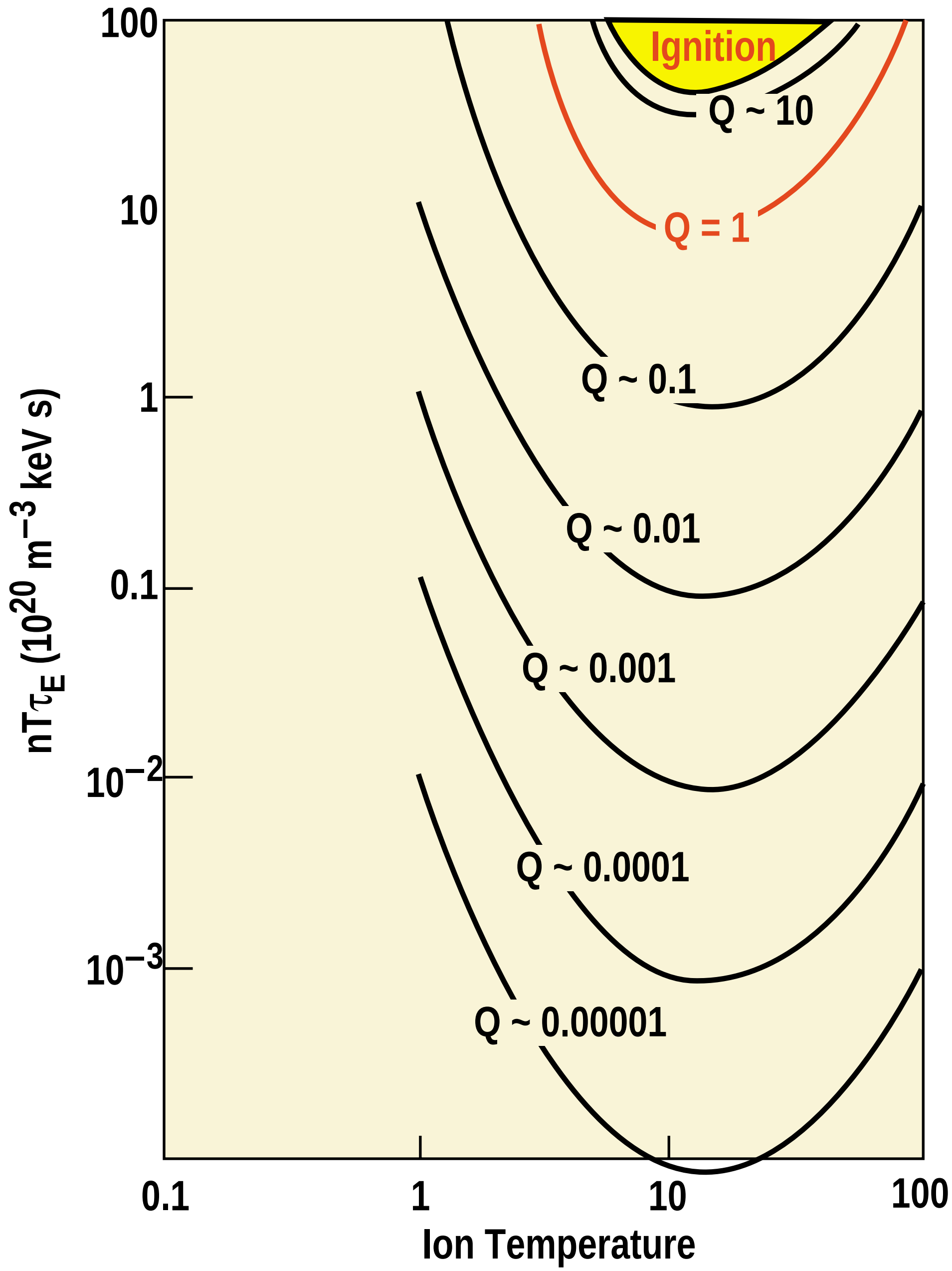
where $p\tau_E$ is minimum for given Q

$\langle\sigma v\rangle \propto T^2$

and p is limited by MHD stability in

magnetically confined plasmas

Ignition $Q = \infty \Rightarrow p\tau_E > \dfrac{12T^2}{\langle\sigma v\rangle\varepsilon_\alpha}$



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Outline

- Basic Requirements for a Burning Plasma
- Frontier Science Issues: What do we want to know?
- Q~1 Results: At the threshold
- Q~5: α-effects on TAE stability
- Q~10: Strong non-linear coupling
- Q≥20: Burn Control & Ignition
- Taking the "Next Step"

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

There are TWO Types of Burning Plasma Issues...

- Getting There & 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

IMPORTANT PHYSICAL PROPERTIES OF α-HEATING

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

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

- FOR TOKAMAK "TYPICAL" PARAMETERS AT Q ~ 10

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

- 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

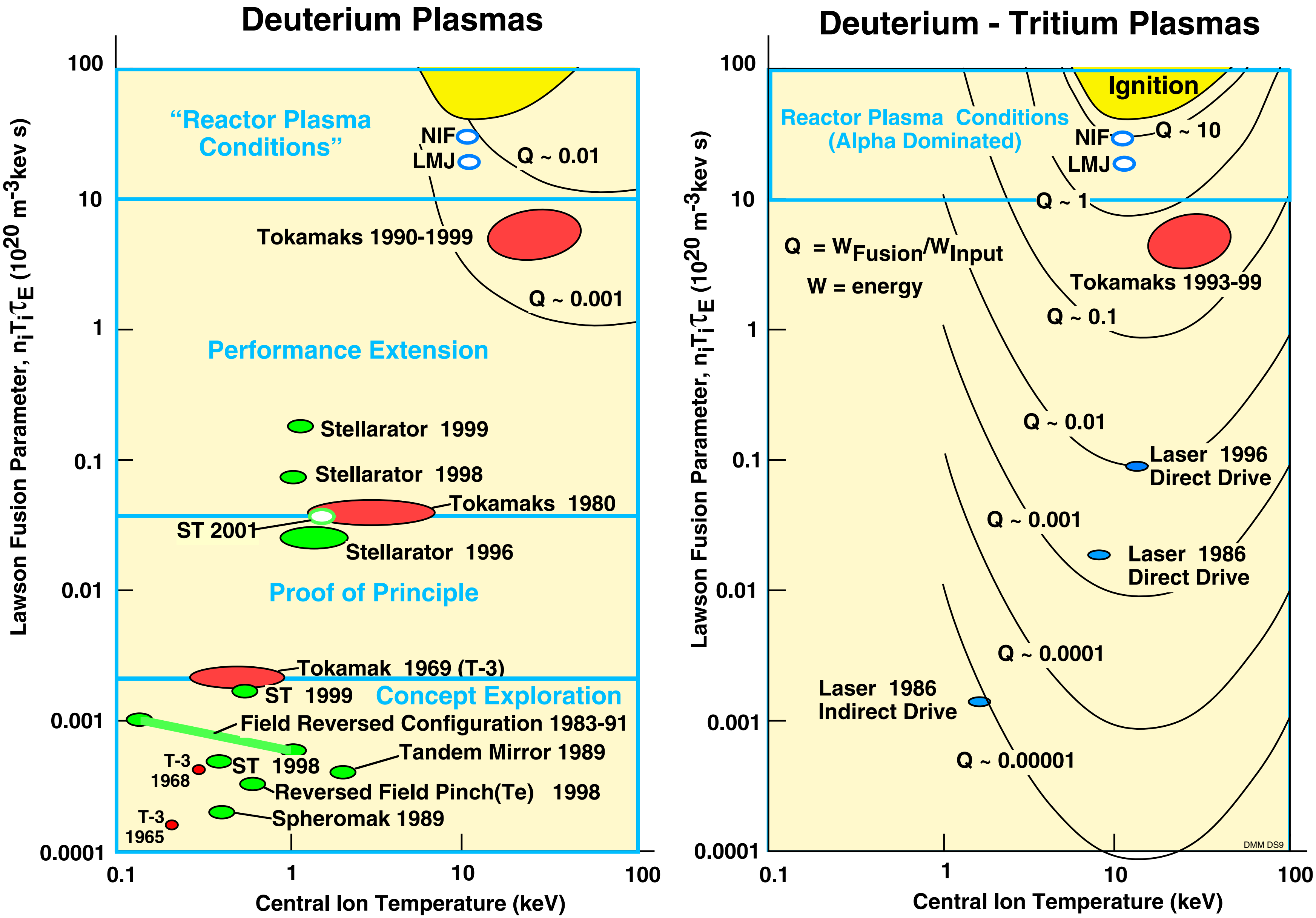
Note at B ~ 5 T: $v_{\text{Alfvén}} \sim 5 \times 10^6$ m/s $< v_\alpha$

- CAN IMMEDIATELY DEDUCE:

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

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

HOW CLOSE ARE WE TO BURNING PLASMA REGIME?



- Tokamak experiments have approached Q ~ 1 regime.

Q $\leq$ 1 Results from TFTR and JET

At the Burning
Plasma Threshold

DT EXPERIMENTS ON TFTR AND JET

	TFTR	JET
Peak Transient Q	0.27	0.61
α Confinement	Classical	Classical
α Slowing Down	Classical	Classical

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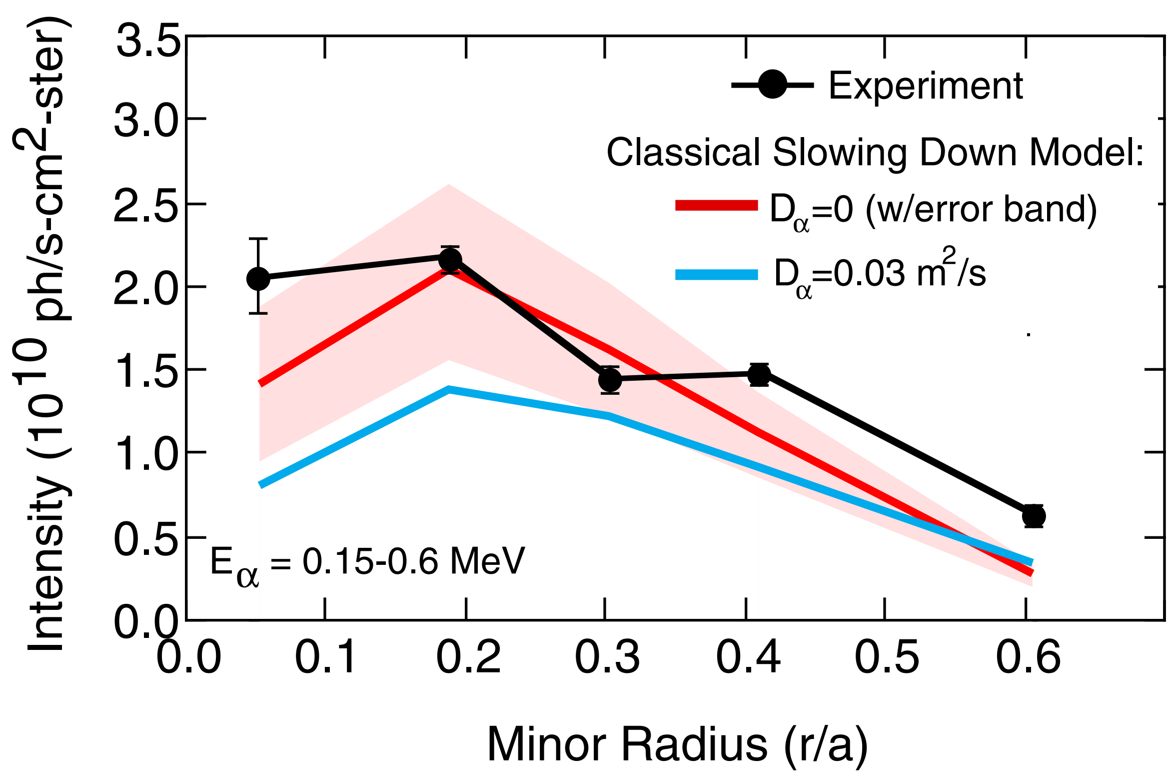
Fusion Alphas are Confined and Slow Down Classically in TFTR



- **JET reports same conclusion using detailed modeling of α-heating power balance.**

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α Heating Observed	Yes, but weak	Yes

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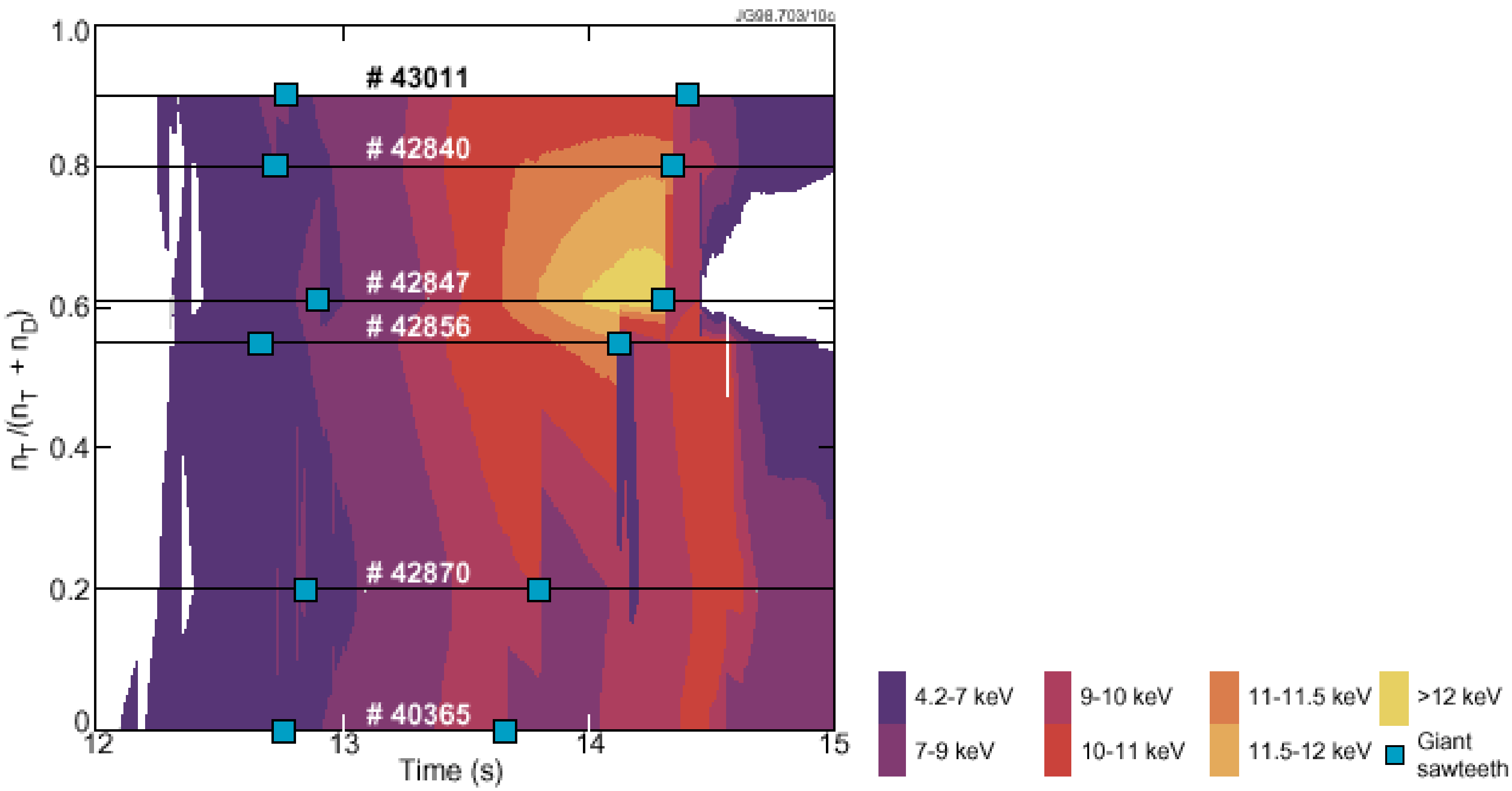
JET DT EXPERIMENTS SHOW α-HEATING OF CENTRAL ELECTRONS



- D/T ratio varied & maximum ΔT_e ~ 3 keV at 60% T

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α Heating Observed	Yes, but weak	Yes
α Driven Alfven Waves in Highest P_α Plasmas	No	No

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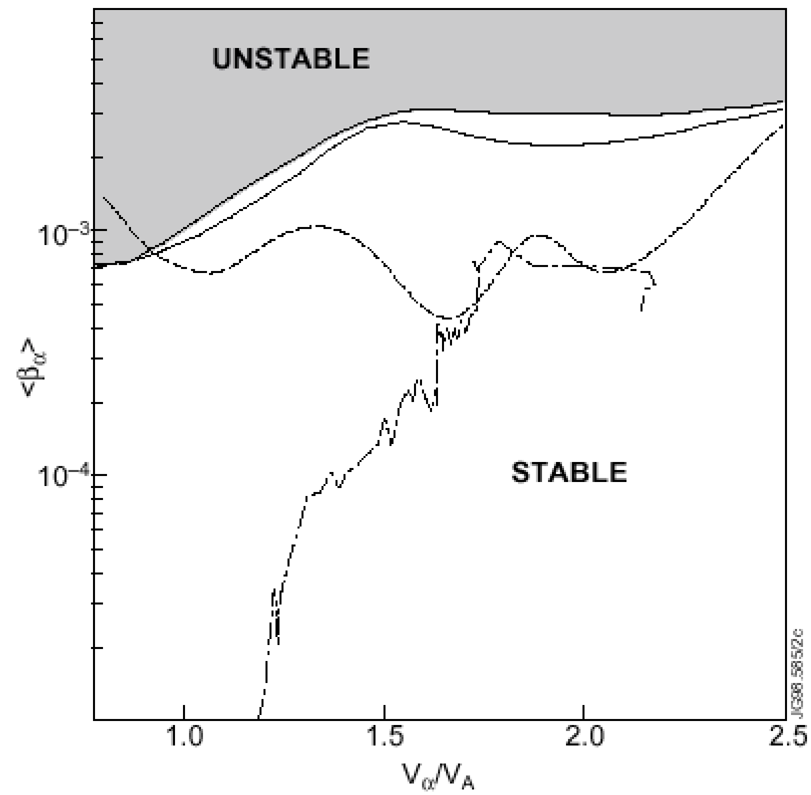
NO α-DRIVEN ALFVENIC INSTABILITIES SEEN IN TFTR AND JET IN HIGHEST FUSION POWER DT PLASMAS

- **AE stable due to strong damping by beam and plasma ions in NBI heated hot ion mode plasmas.**
- **AE modes were observed in equilibria with low shear and higher central q just after NBI turned off.**



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α Driven Alfven Waves in Highest P_α Plasmas	No	No
T_i	36 keV	28 keV
T_e	13 keV	14 keV
n	1×10^{20} m^{-3}	0.4×10^{20} m^{-3}
$nT\tau$	4.3×10^{20} m^{-3} keVs	8.3×10^{20} m^{-3} keVs
f_α	5% [~2MW]	12% [~3 MW]

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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-FEAT (reference)	FIRE (reference)	JET
$V_\alpha/V_A(0)$	≈ 2.0	1.9	2.2	1.6–1.9
ρ_α/a	≈ 0.02	0.016	0.028	~0.1
Max $R\nabla\beta_\alpha$	0.03–0.15*	0.05	0.035	0.02–0.037

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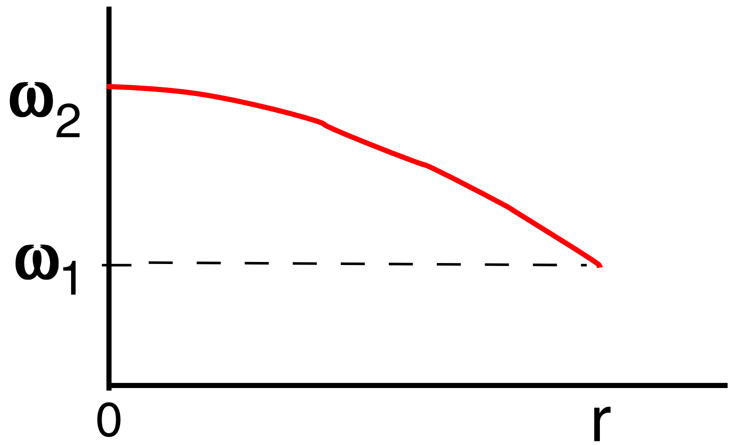
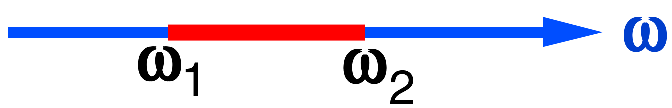
Geometric Effects on Alfven Waves

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

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

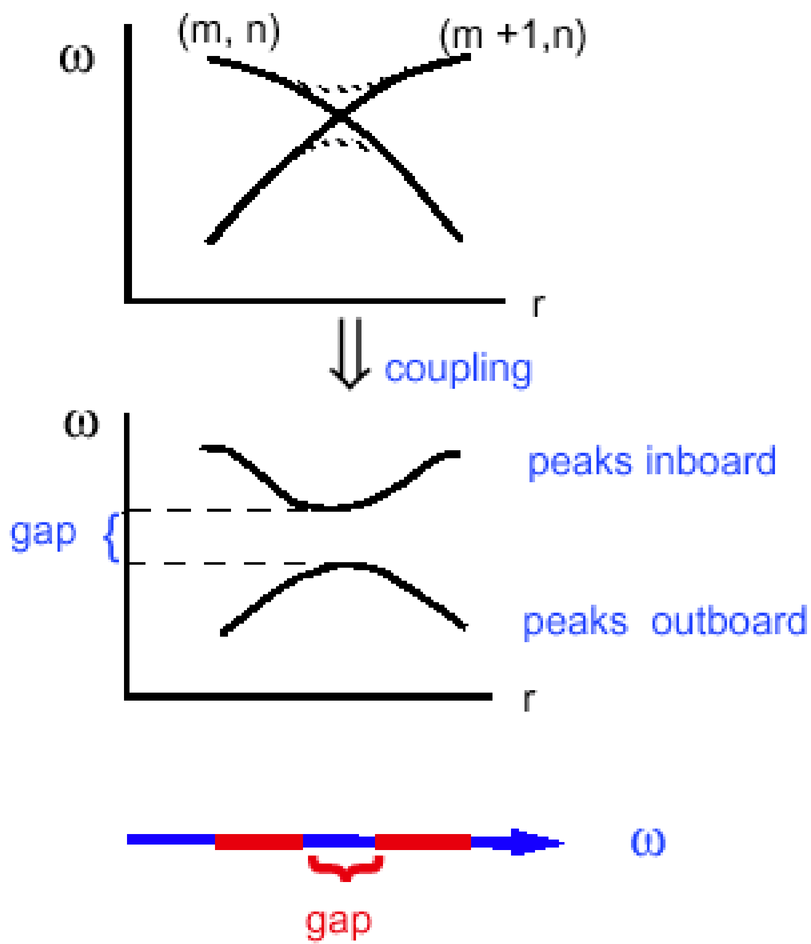




- Continuous spectrum, shear Alfvén resonance

GEOMETRIC EFFECTS ON ALFVEN WAVES

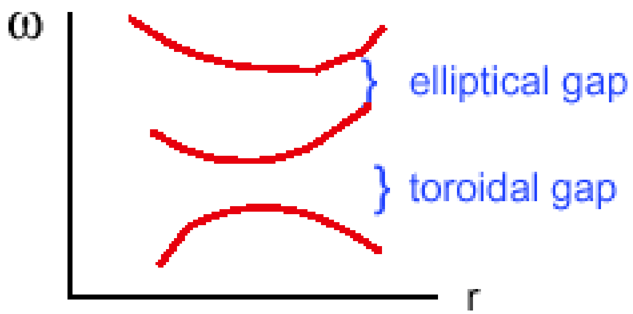
Add 2D toroidal effects:



- 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

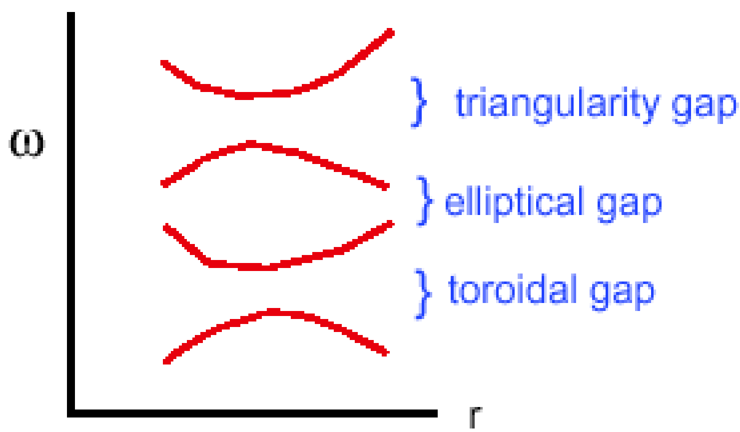
GEOMETRIC EFFECTS ON ALFVEN WAVES

Add elliptical cross-section effects:



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

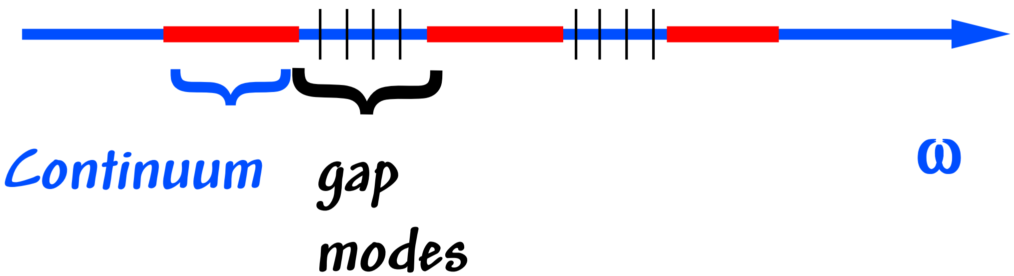
Add triangularity cross-section effects:



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

GEOMETRIC EFFECTS ON ALFVEN WAVES

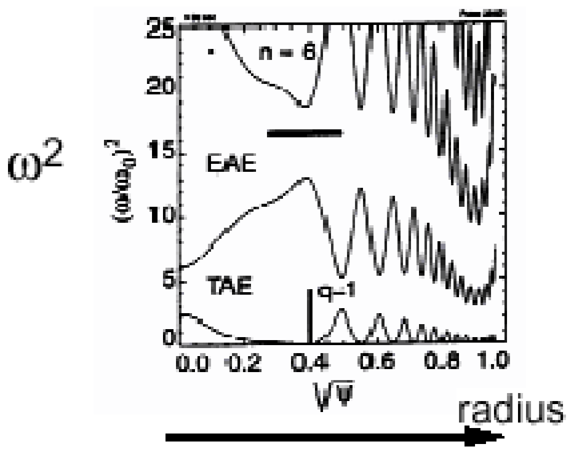
Discrete Modes Appear in Gaps in the Continuum:



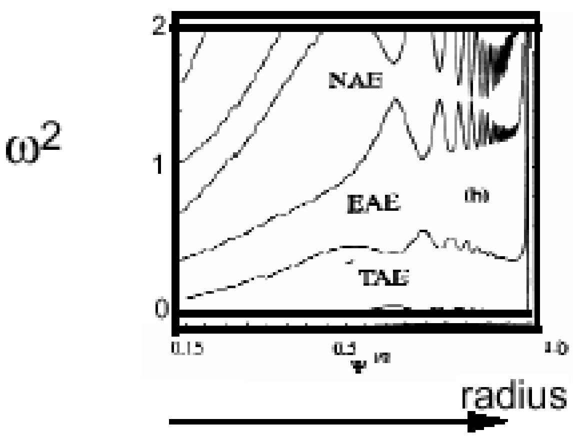
- **Alfvén wave continuum is strongly damped.**
- **TAE gap-modes are less damped: free energy from ∇p_α tapped by wave/particle resonance drive from α-particles may destabilize these modes.**

Basic Alfven Eigenmode Physics Extends to Range of Toroidal Configurations

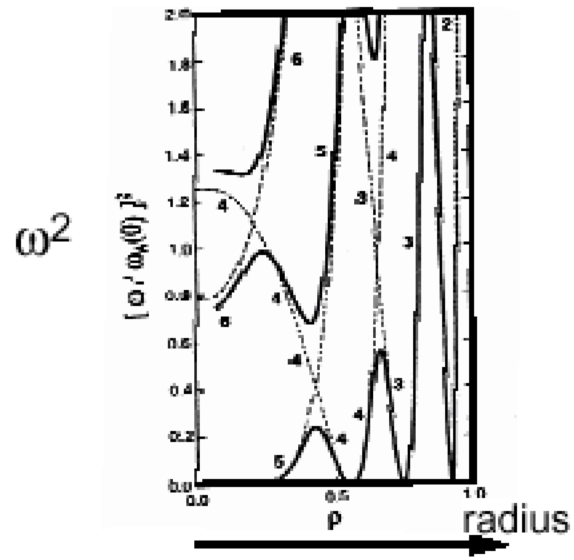
Tokamak:



Spherical Torus:



Stellarator:



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

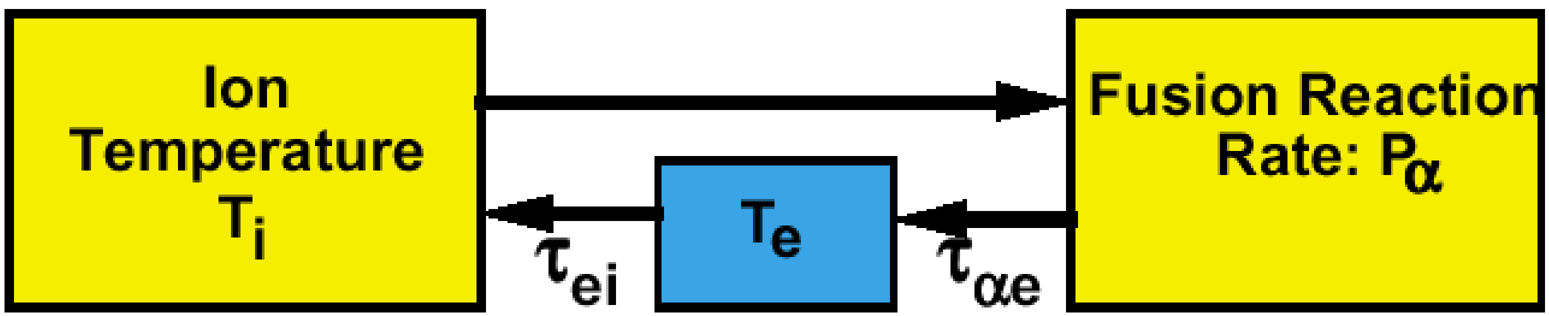
New Alpha Effects Expected on Scale of Burning Plasma

- 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.
- Reliable simulations not possible...needs experimental information in new BP regime.

Q ~ 10: Strong Non-Linear Coupling

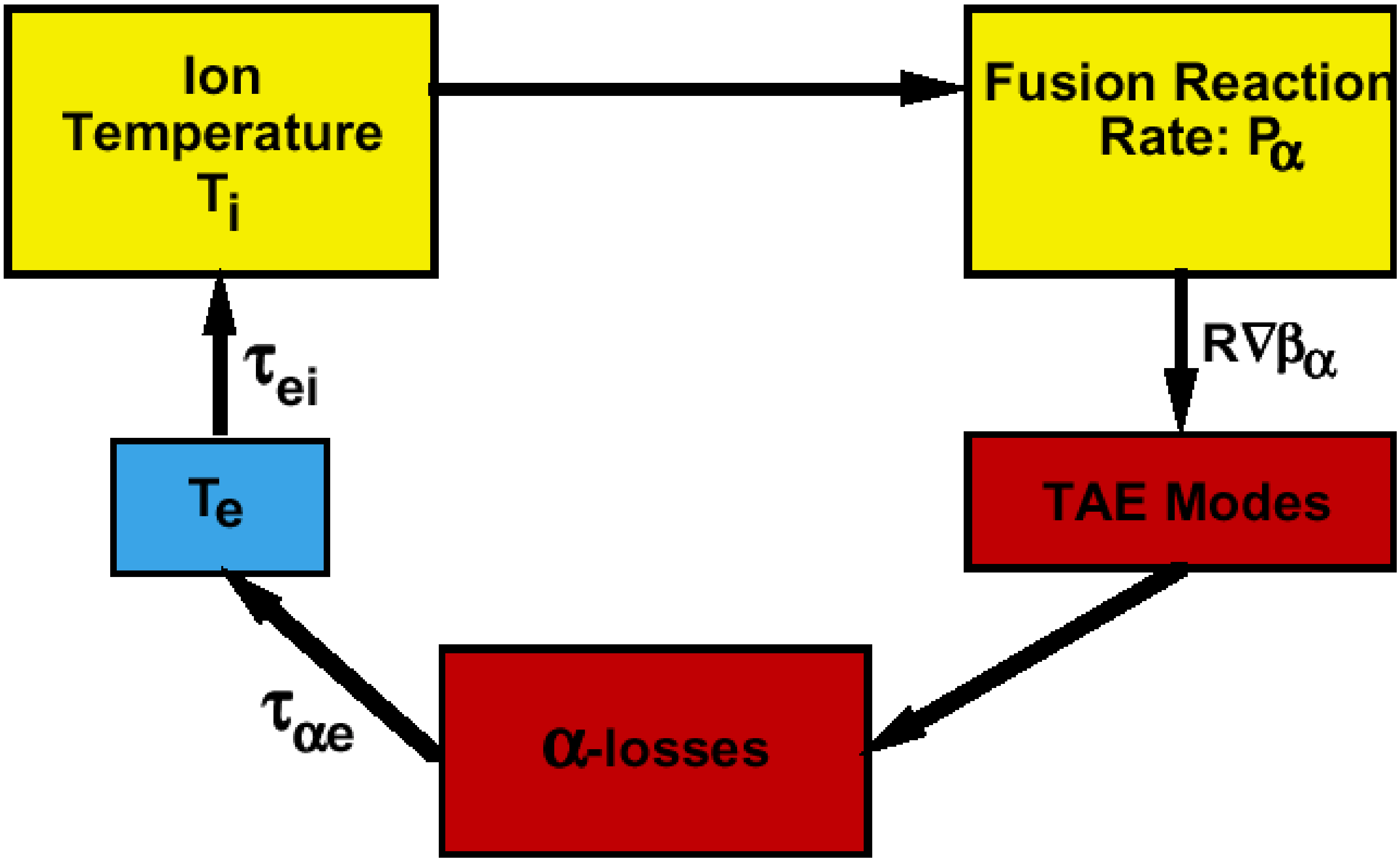
Burning Plasma System is Highly Non-Linear...

Basic Coupling of Fusion Alpha Heating:



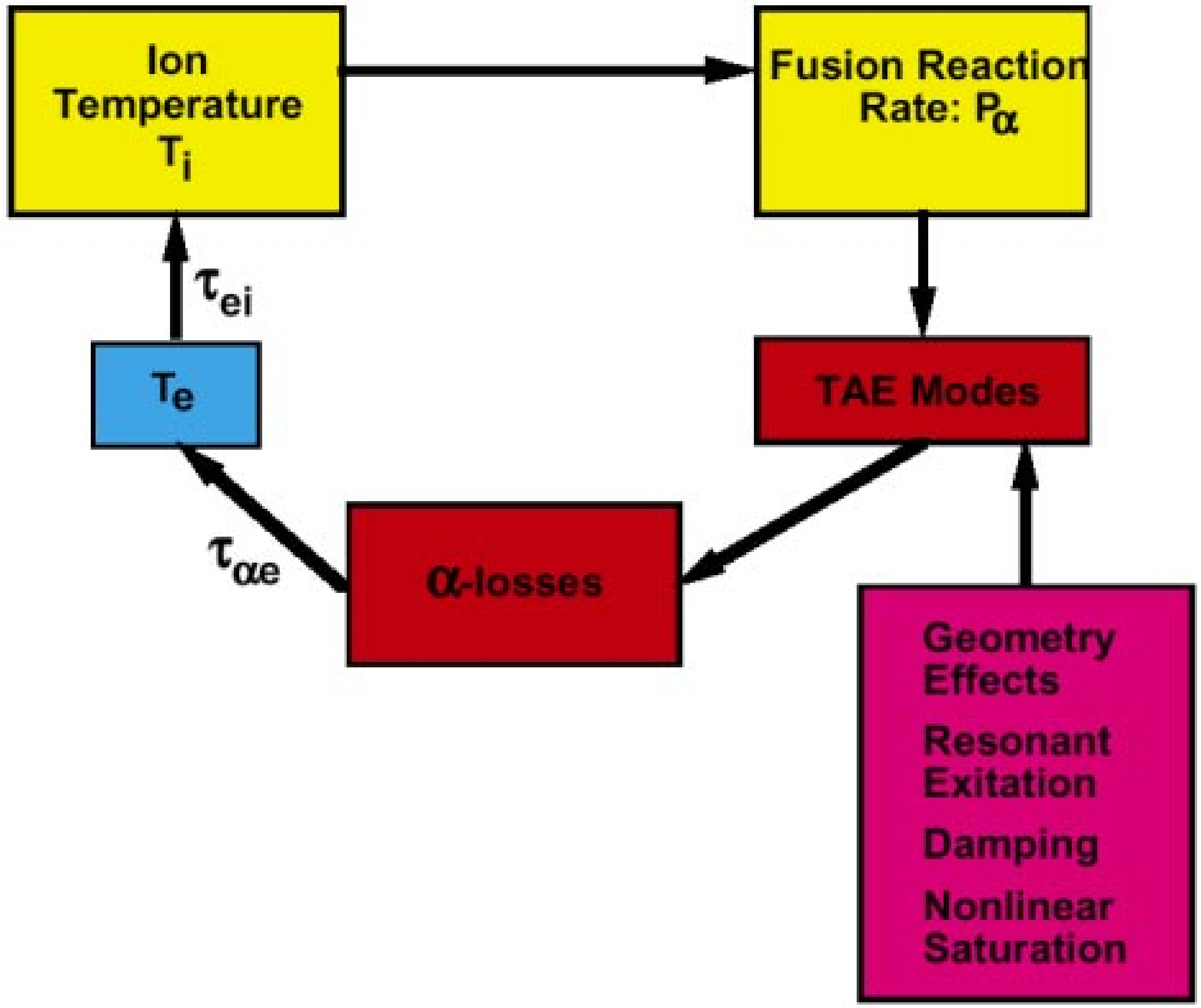
BURNING PLASMA SYSTEM IS HIGHLY NON-LINEAR...

ADD ALPHA DRIVEN TAE MODES:



Burning Plasma System is Highly Non-Linear...

Add Complex Physics of Alpha Driven TAE Modes:



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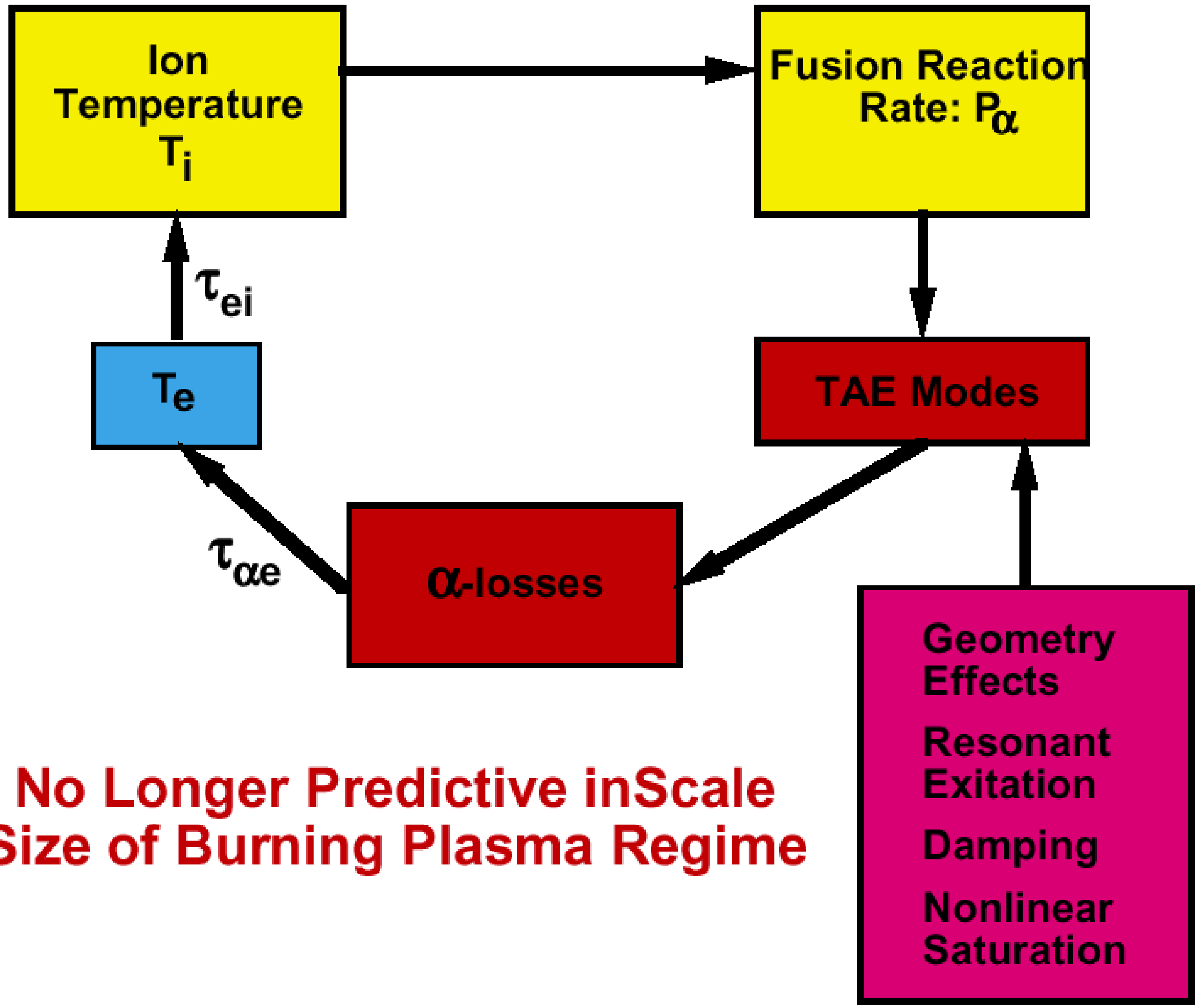
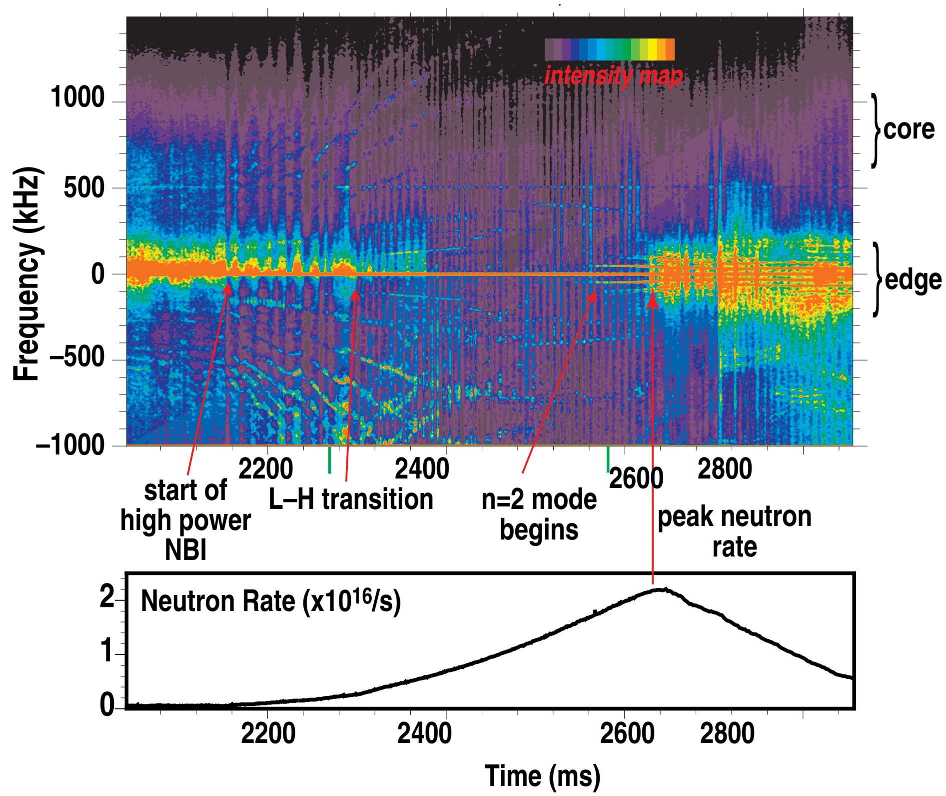


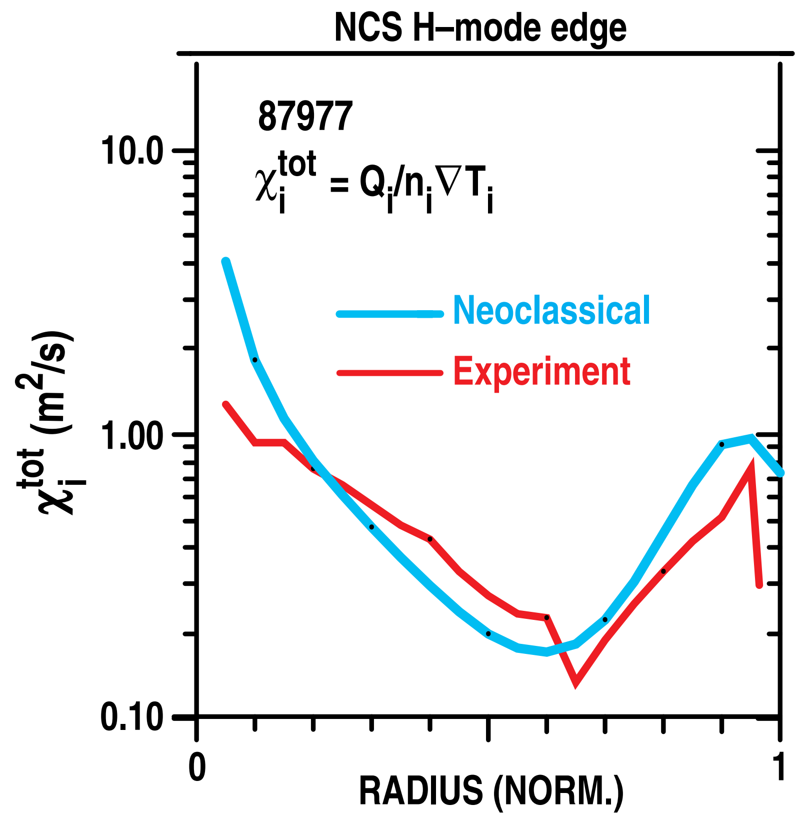
No Longer Predictive inScale
Size of Burning Plasma Regime

MAJOR DISCOVERY OF THE 1990's: ION TURBULENCE CAN BE ELIMINATED

- Color contour map of fluctuation intensity as function of time from FIR scattering data
  - Higher frequencies correspond to core, low to edge



- Total ion thermal diffusivity at time of peak performance
  - H = 4.5 W = 4.2 MJ
    β = 6.7% β_N = 4.0



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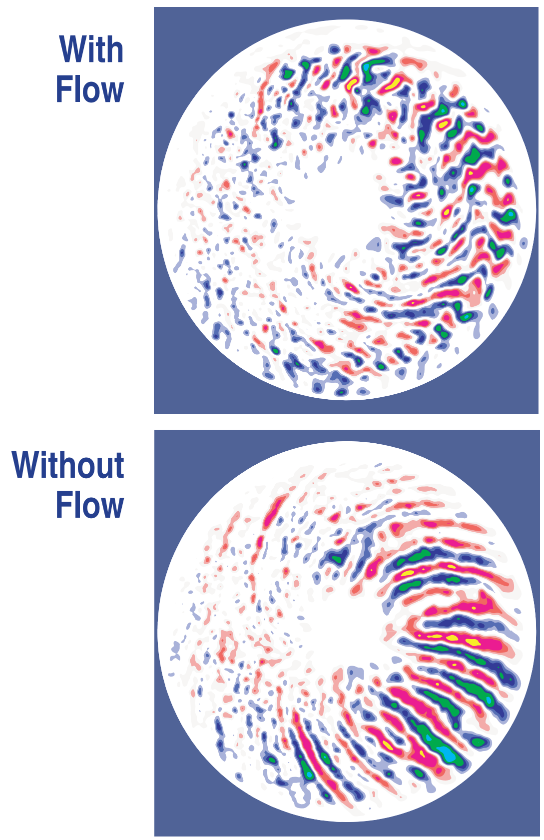
SHEARED FLOW CAUSES TRANSPORT SUPPRESSION

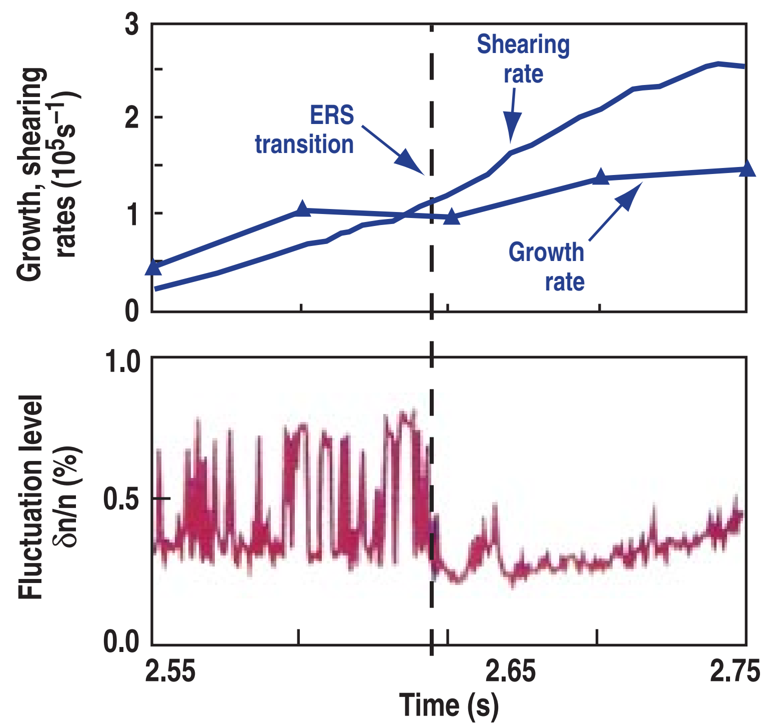
Gyrokinetic Theory

- 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



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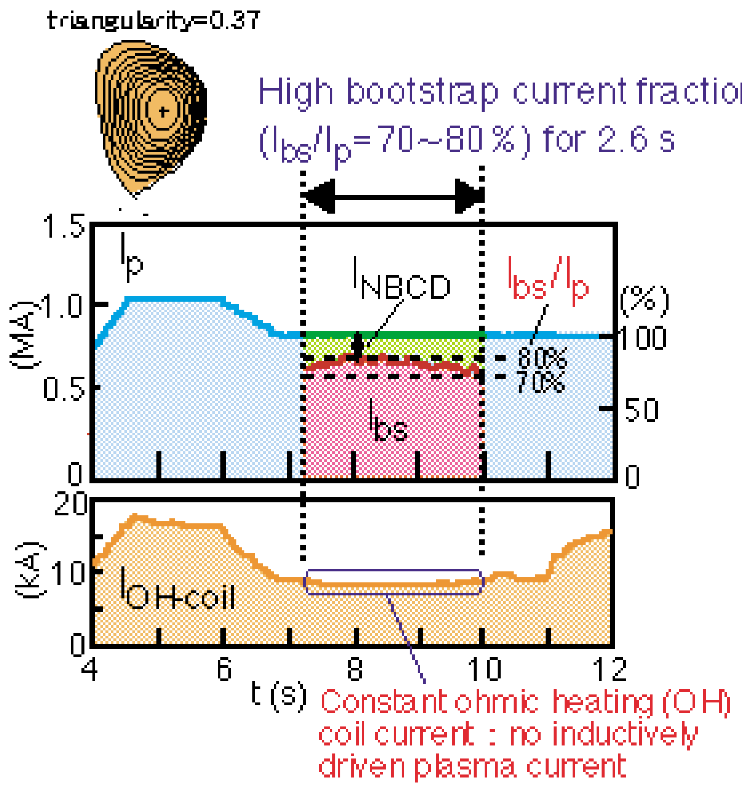
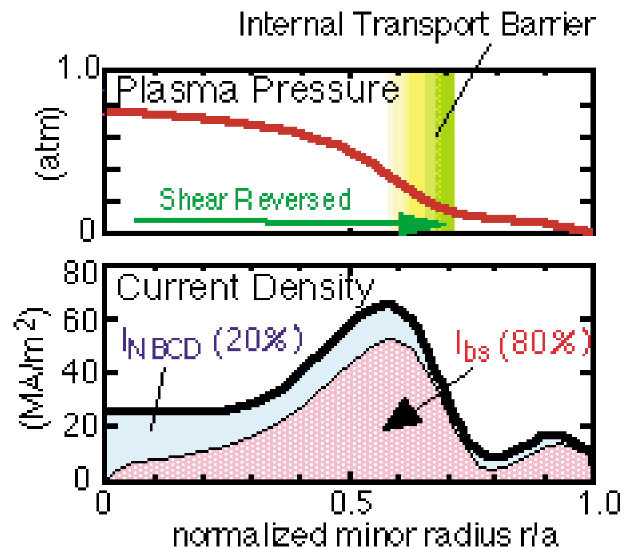
Combination of Turbulence Suppression & Bootstrap Current Leads to Steady-State Advanced Tokamak



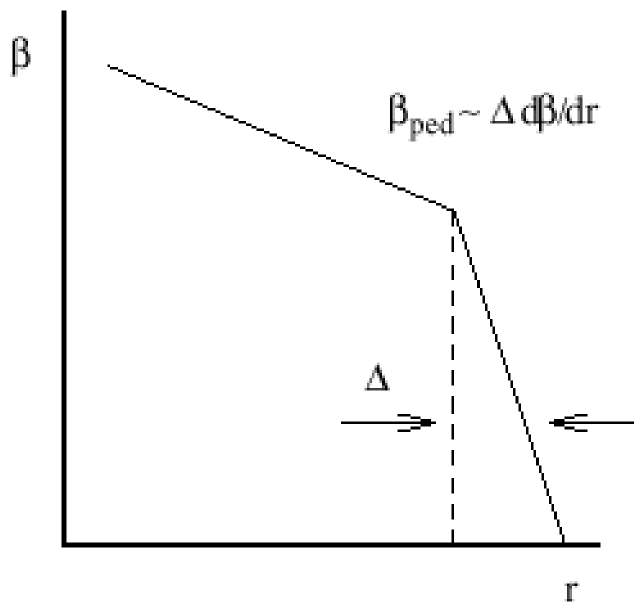


- Data from JT-60U shows sustained transport barrier and 100% non-inductive current drive

Plasma Boundary Physics: Heat Removal & Confinement

Edge Pedestal Strongly Coupled to Confinement: Internal ∇T limited by microturbulence so edge T controls central fusion reactivity:

$$P_{FUSION} \sim [T_{EDGE}]^7$$



Energetic ions modify Δ: coupling to α-particles.

Heat removal solutions trend to high edge density – but bootstrap current sustained steady-state plasmas trend towards lower edge density:

compatability an open issue in burning plasma regime

Pedestal Temperature Requirements for Q=10

Device	Flat ne◆	Peaked ne*	Peaked ne w/ reversed q
IGNITOR❖	5.1	5.0	5.1 keV
FIRE	4.1	4.0	3.4 keV
ITER-FEAT ✦	5.8	5.6	5.4 keV

◆ flat density cases have monotonic safety factor profile

* $n_{eo} / n_{ped} = 1.5$ with n_{ped} held fixed from flat density case

❖ 10 MW auxiliary heating

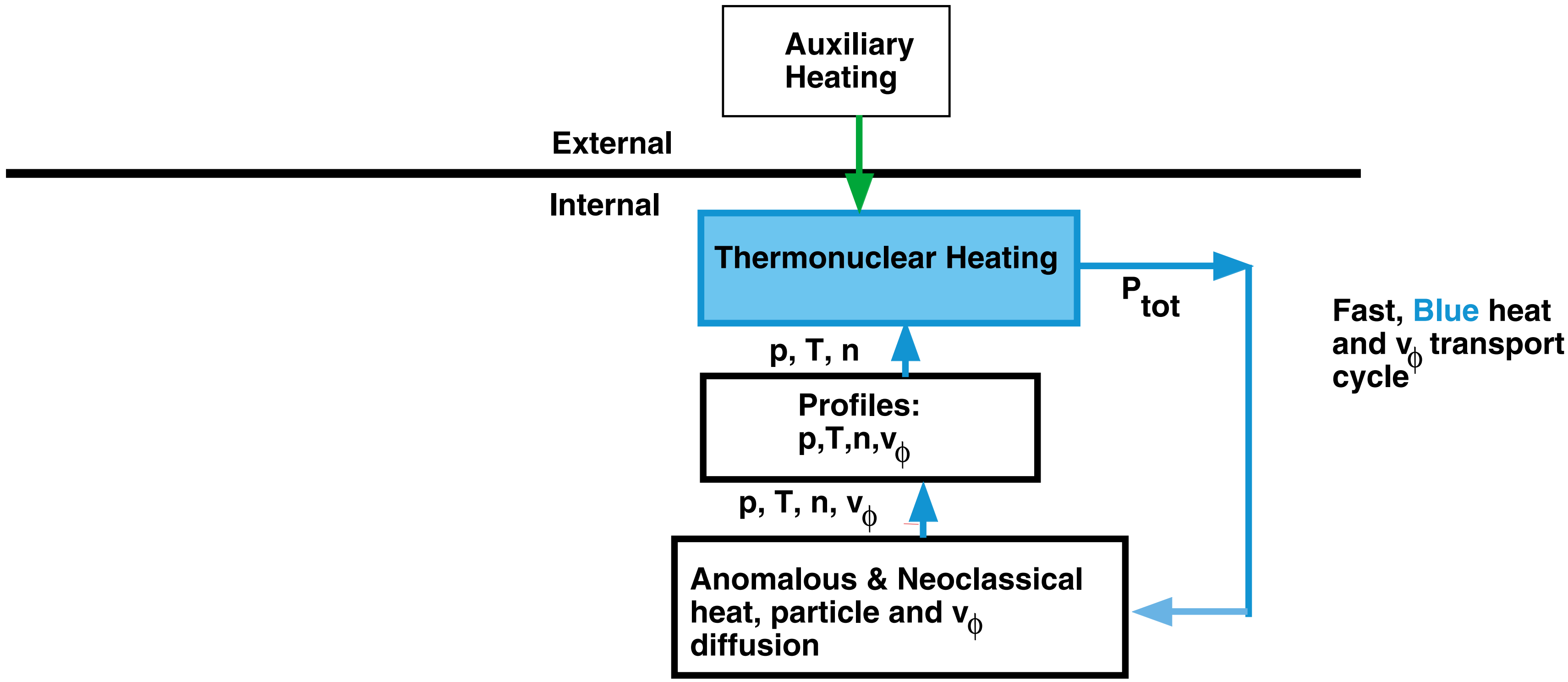
11.4 MW auxiliary heating

✦ 50 MW auxiliary heating

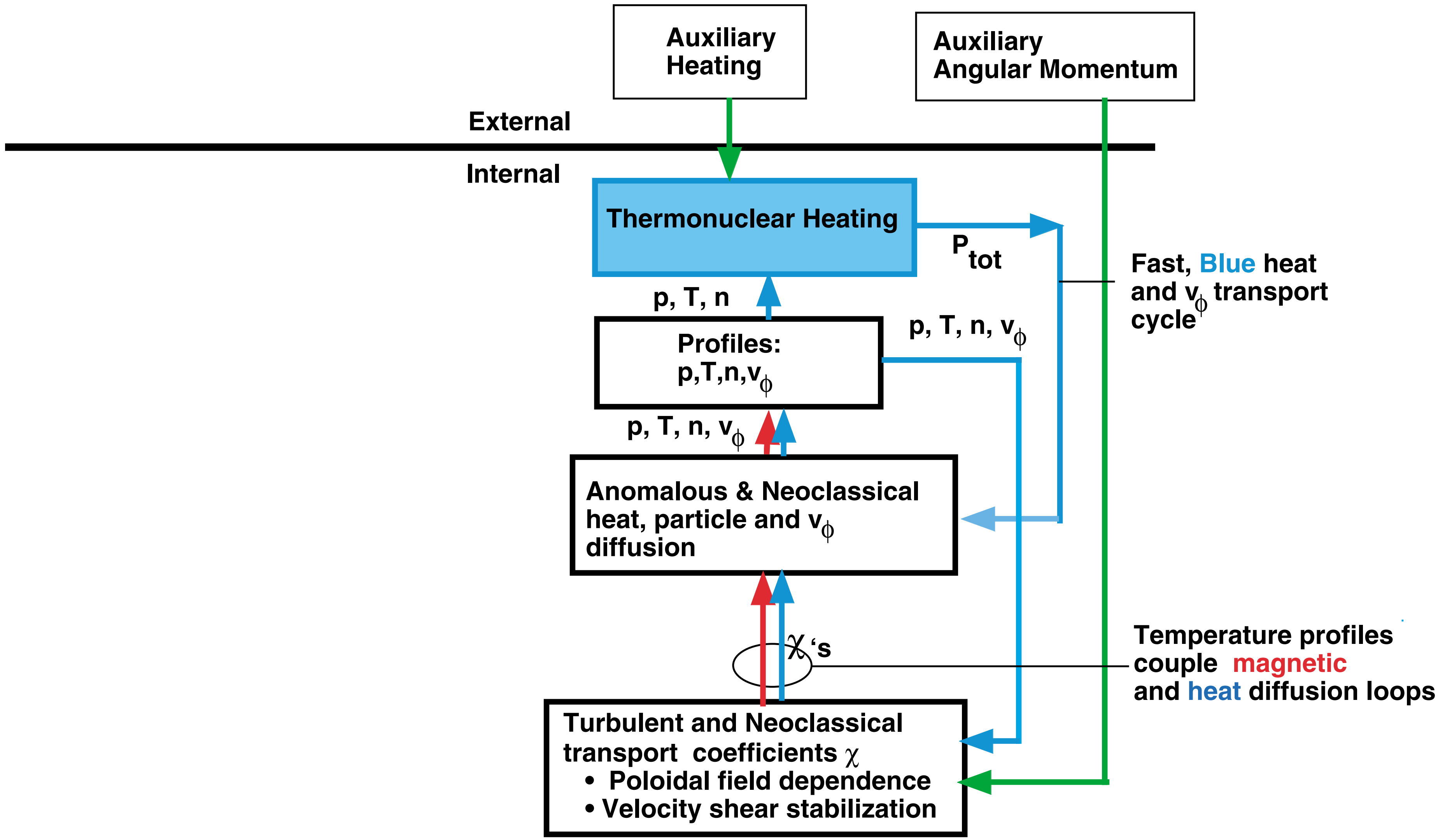
ADVANCED TOKAMAK NONLINEAR TRANSPORT COUPLINGS

Thermonuclear Heating

ADVANCED TOKAMAK NONLINEAR TRANSPORT COUPLINGS



ADVANCED TOKAMAK NONLINEAR TRANSPORT COUPLINGS



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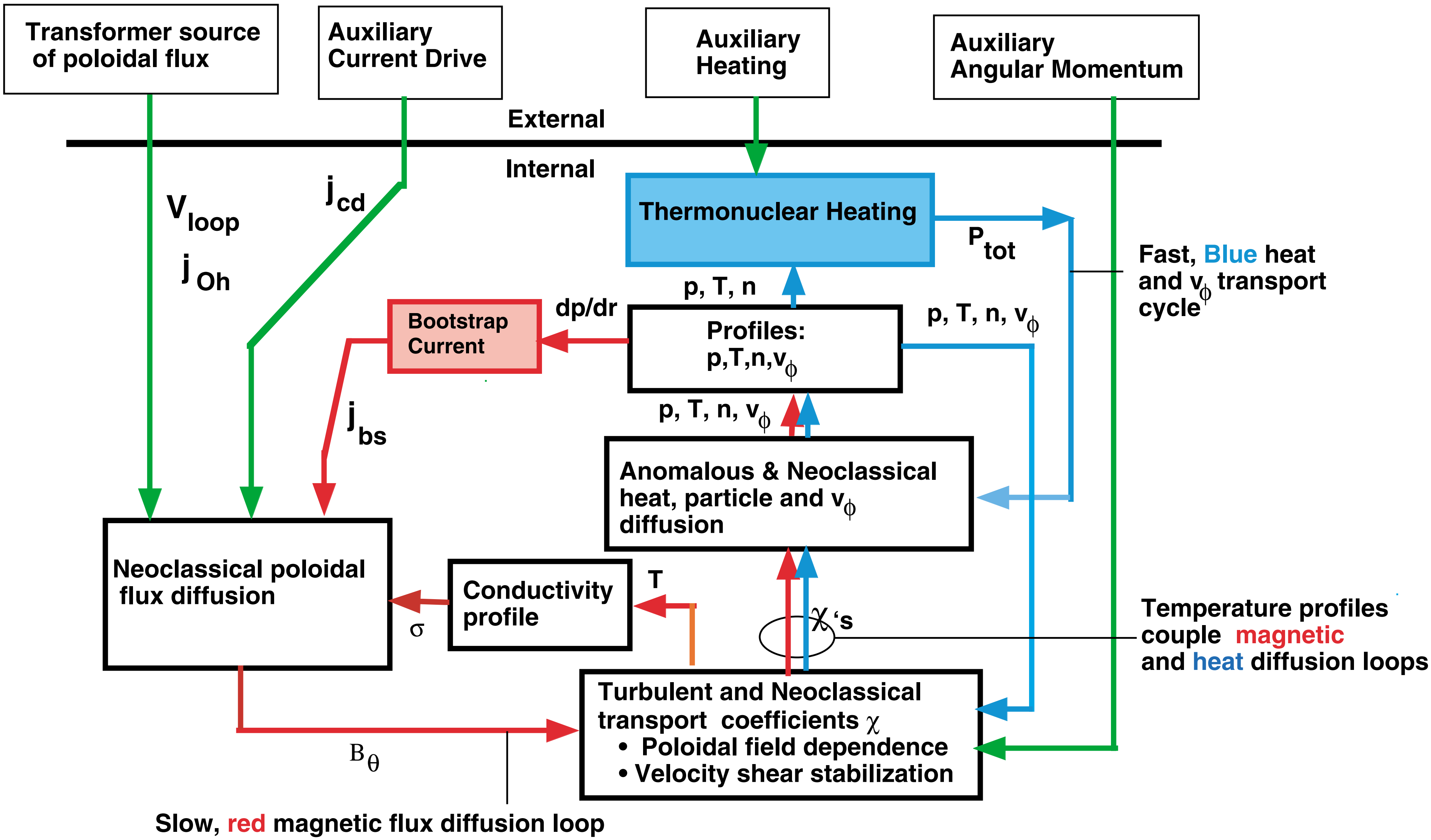


Q > 20:

Burn Control &
Ignition Transient Phenomena

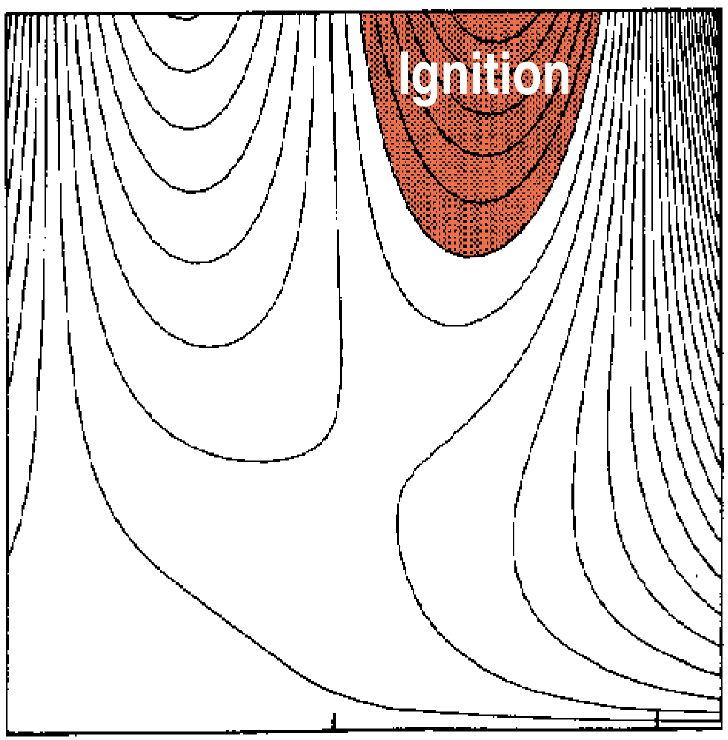
TRANSIENT BURN PHENOMENA WHEN Q $\gtrsim$ 20

Time dependent energy balance: $\frac{d}{dt}[3\,nT] = \frac{1}{4}\,n^2\varepsilon_\alpha V\,\langle\sigma v\rangle + P_{heat} - \frac{3\,nT}{\tau_E\,(n,T)}$

- At fixed n and high Q system can be thermally unstable

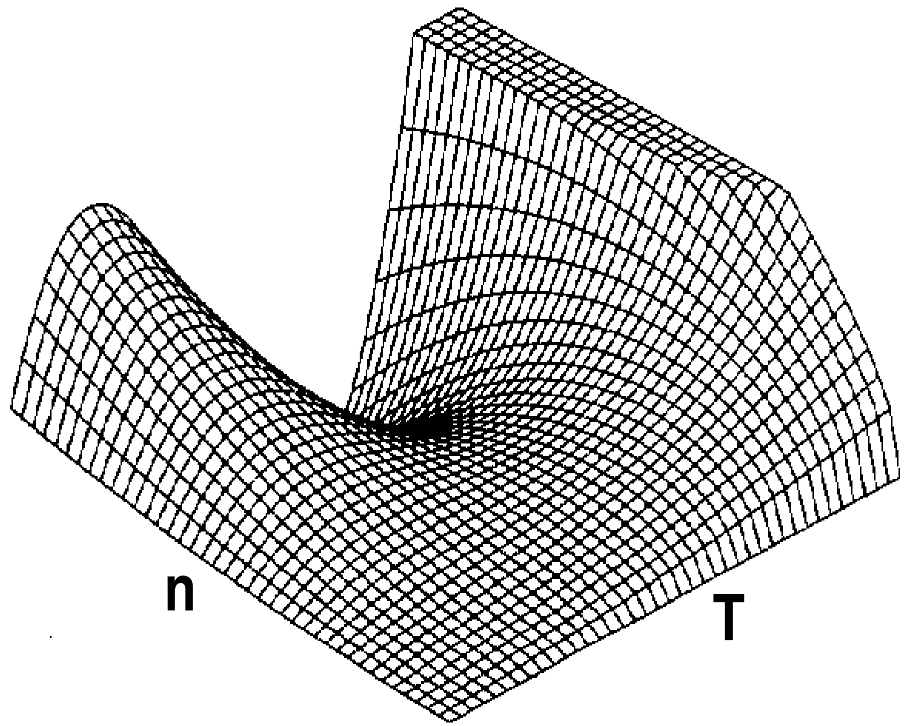
Solve for P_{heat} in steady-state: $P_{heat} = \frac{3\,nT}{\tau_E\,(n,T)} - \frac{1}{4}\,n^2\varepsilon_\alpha V\,\langle\sigma v\rangle$

n



0 10 20

T (keV)



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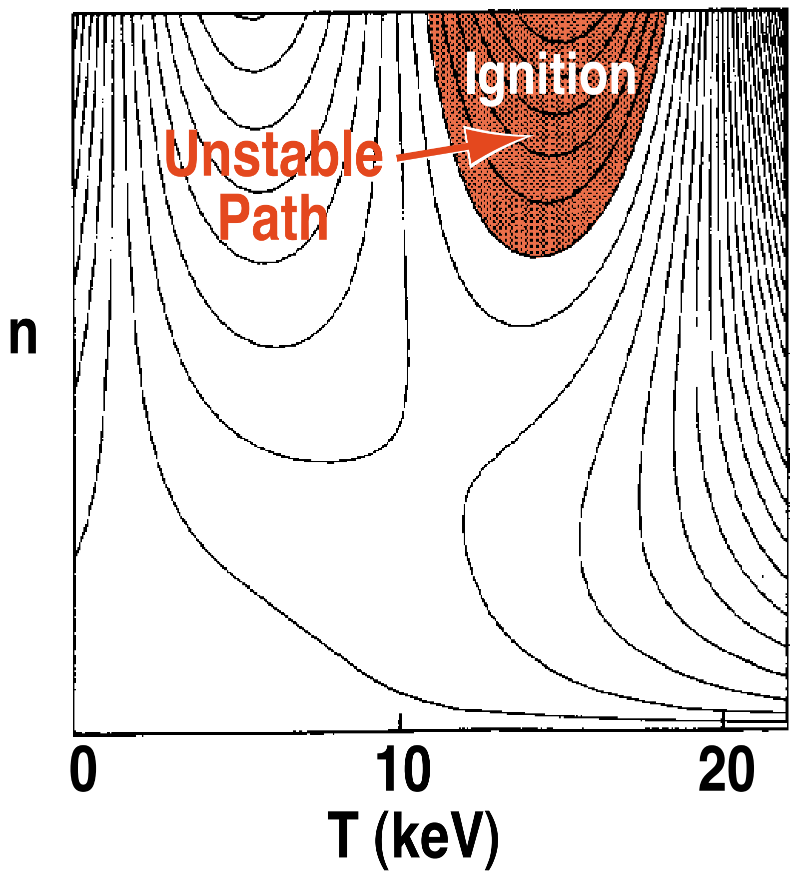

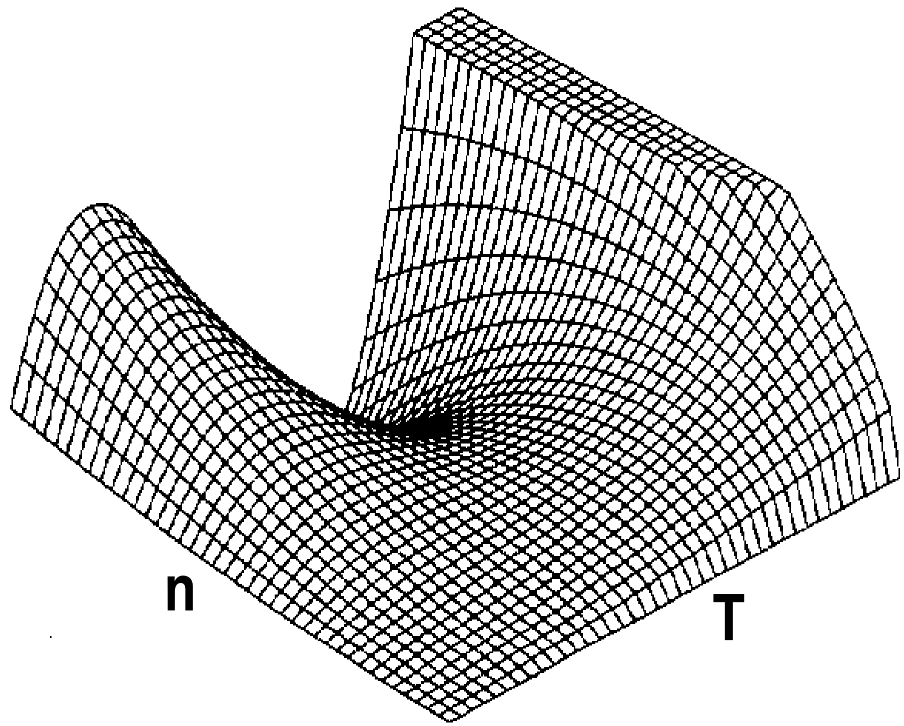

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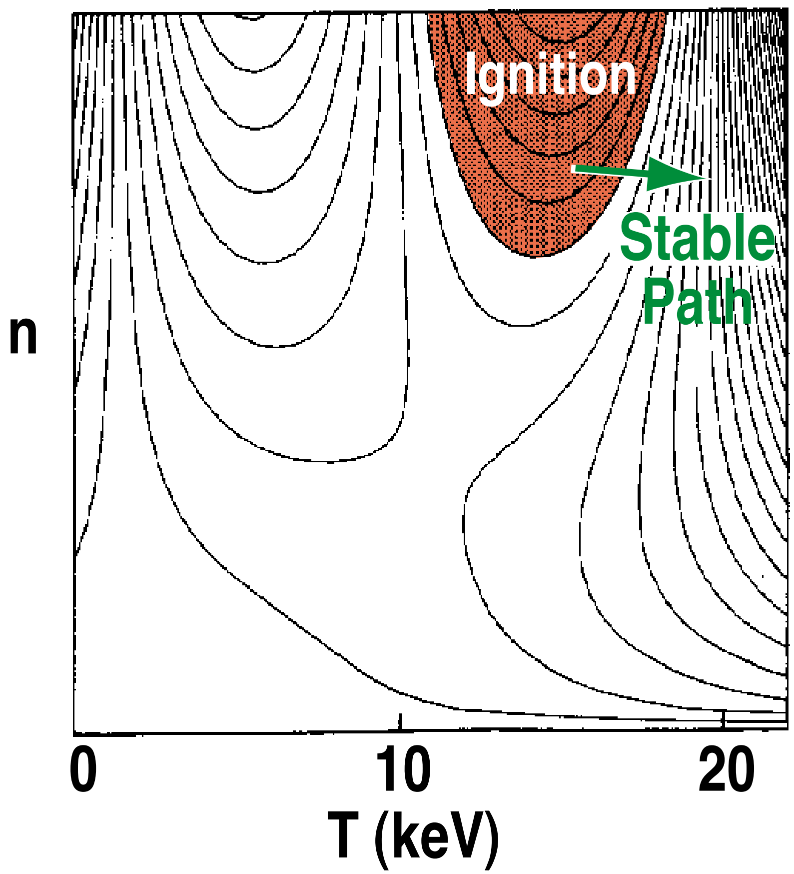

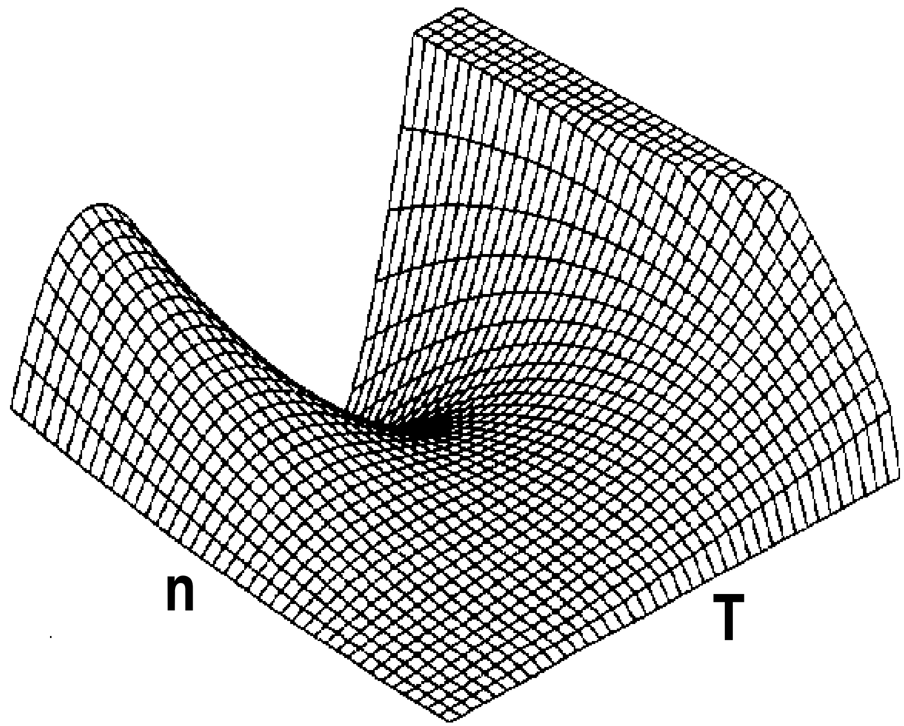

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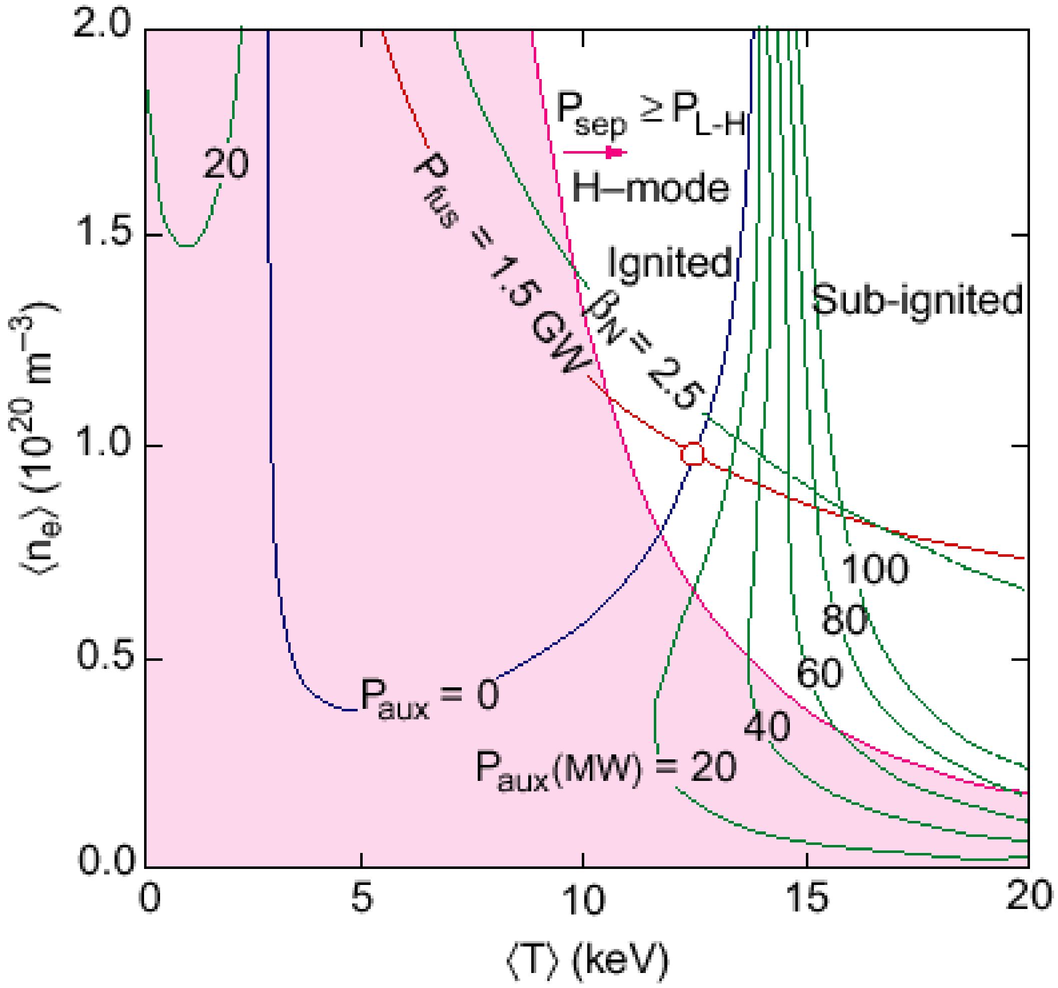
MORE "REALISTIC" POWER BALANCE

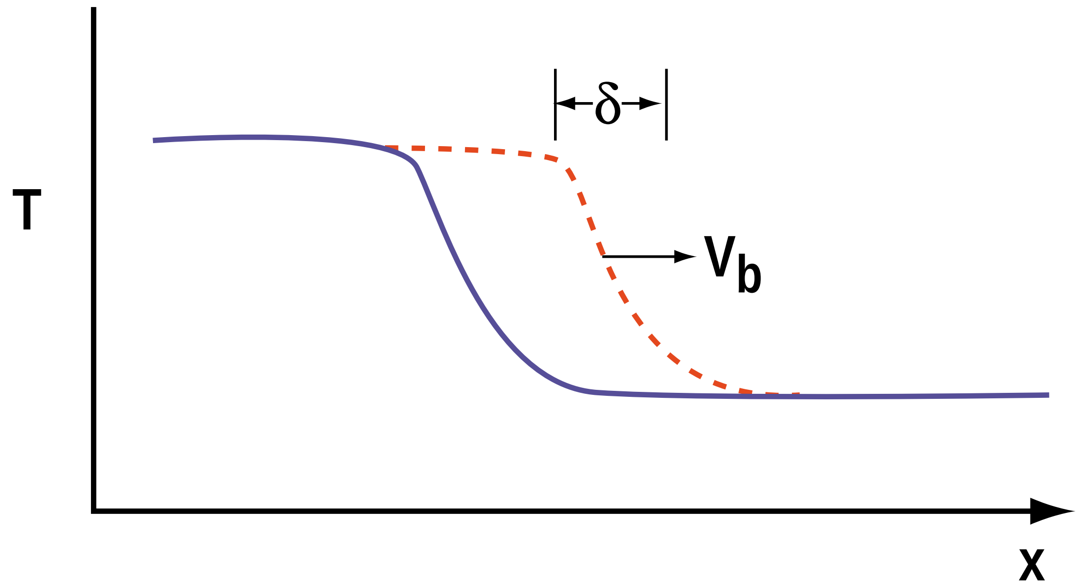
- **ITER POPCON Power Balance Analysis**



- **Additional limits on density, pressure, & power thresholds constrain operating space.**

FUSION " BURN" PROPAGATION AT HIGH Q

- **Deflagration – sub-sonic**
  - Mediated by diffusive thermal conductivity, χ



Diffusive Time Scale $\tau_d \sim \dfrac{\delta^2}{\chi}$

Fusion Burn Time Scale $\tau_{burn} \sim \dfrac{W}{P_f}$

In steady-state $\tau_d \sim \tau_{burn}$

$$\delta \sim \sqrt{\frac{\chi W}{P_f}}$$

$$V_b \sim \frac{\delta}{\tau_{burn}} \sim \sqrt{\frac{\chi P_f}{W}}$$

FUSION BURN PROPAGATION AT HIGH Q

- EXAMPLE PARAMETERS

$n \sim 4 \times 10^{20}\ m^{-3}$

$T \sim 20$ keV

$P_\alpha \sim 10\ MW/m^3$

$W = 3nT \sim 3.8\ MJ/m^3$

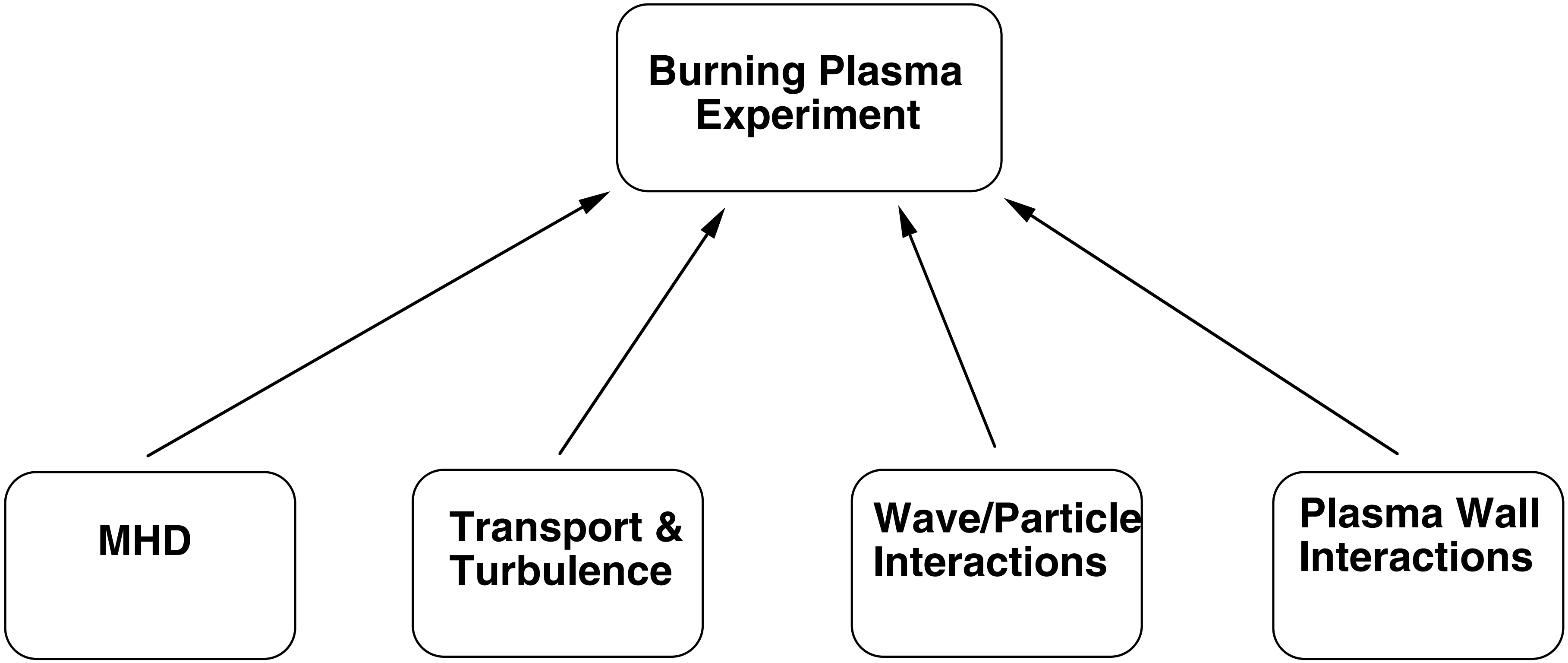
$\chi \sim 0.1\ m^2/s$

$\delta \sim 0.2$ m

$V_b \sim 0.5$ m/s

Comments on “Next Steps” for Study of Burning Plasmas

Major Advances & Discoveries of 90's Lay Foundation for Next Step Burning Plasma Experiments



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

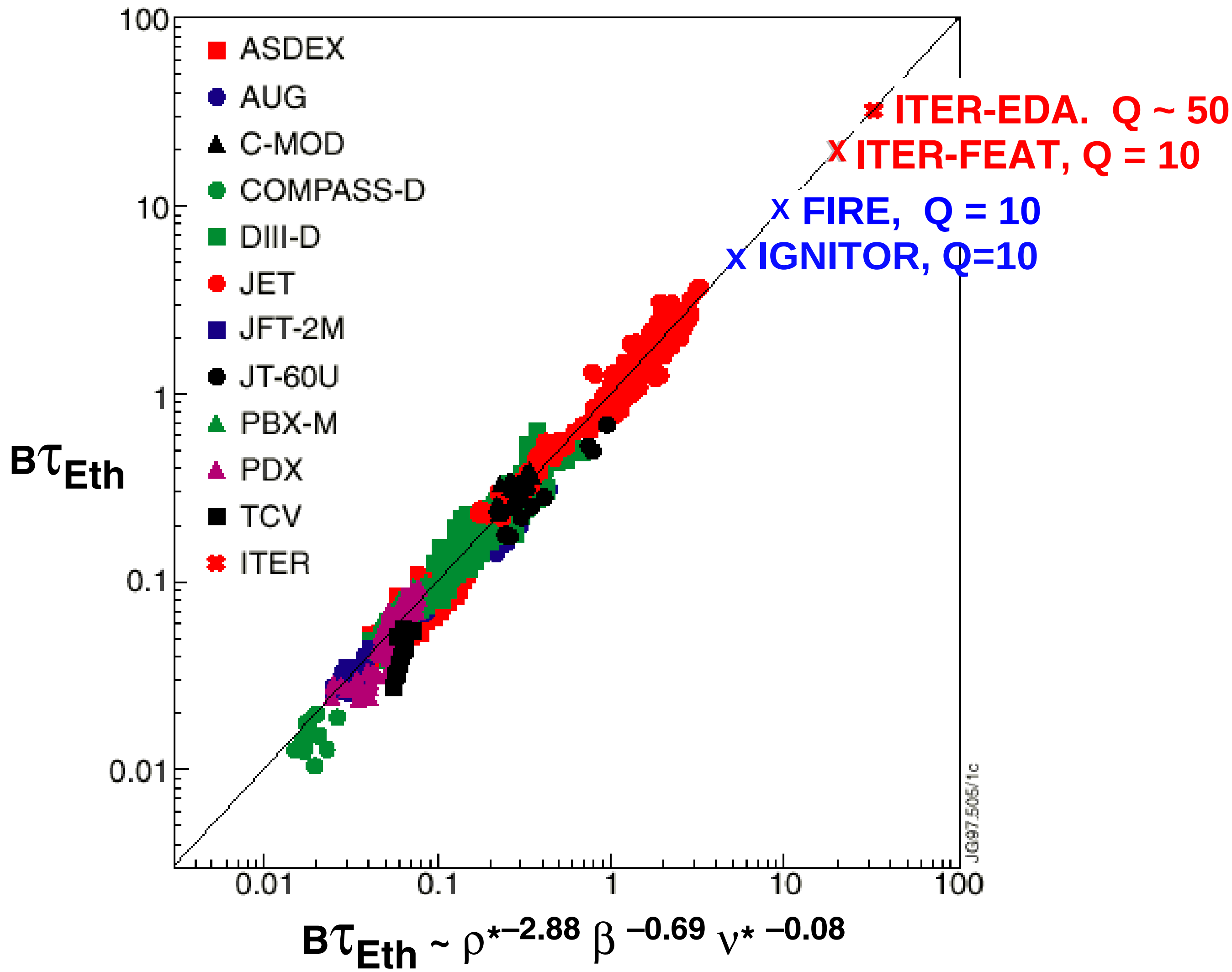
- detached divertor demonstrated
- large scale models developed
- high heat-flux metallic technology developed

Modest Confinement Extrapolation Needed for BP

Dimensionless Parameters
$\omega_c \tau = B\,\tau$
$\rho^* = \rho/a$
$\nu^* = \nu_c/\nu_b$
β

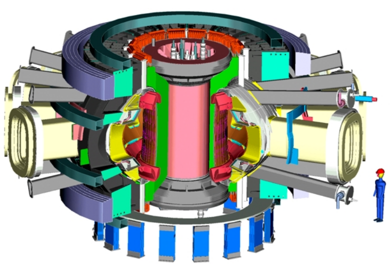
Similarity Parameter
$B\,R^{5/4}$

Kadomtsev, 1975



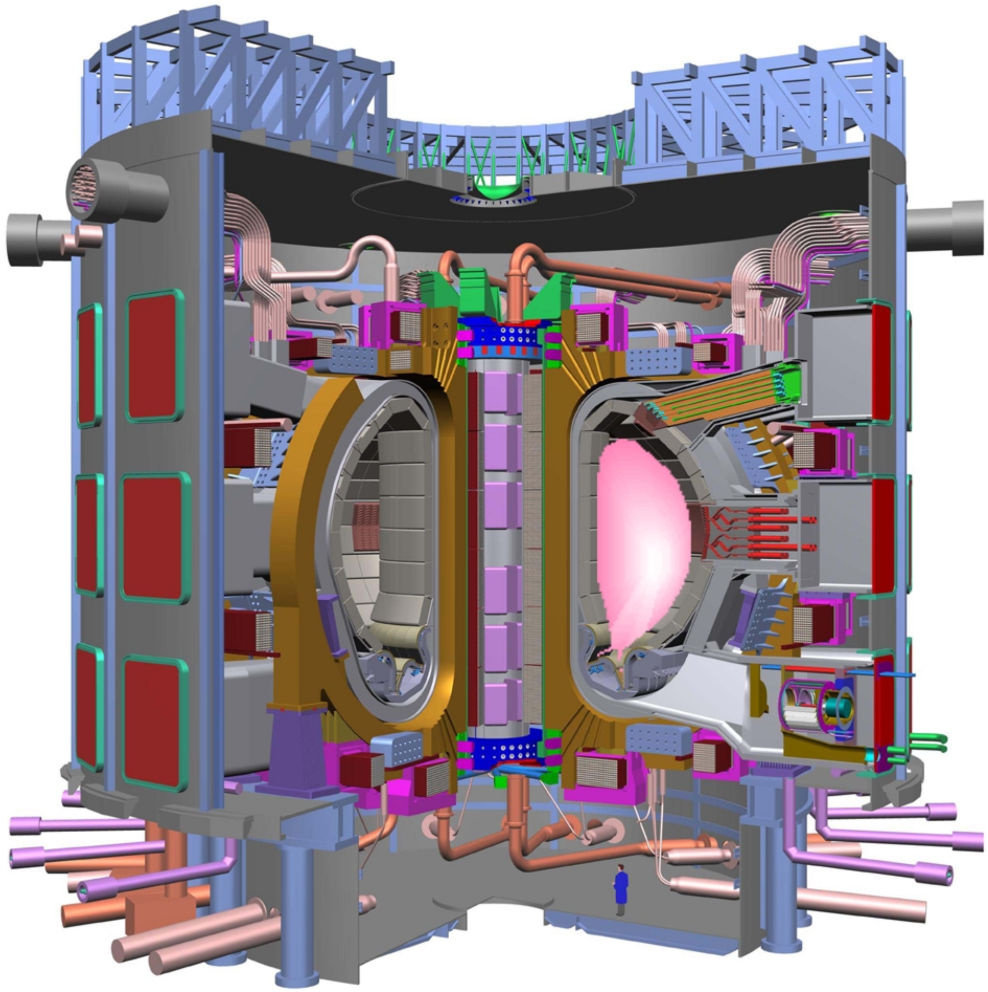
Burning Plasma Physics - The Next Frontier

Three Options
(same scale)



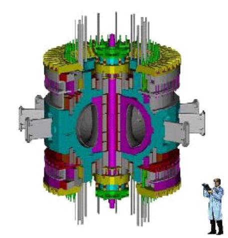
FIRE

US Based
International Modular Strategy



ITER-FEAT

JA, EU or CA Based
International Partnership



IGNITOR

Italian Based
International Collaboration

FESAC BP Report Recommendation 3

The U.S. Fusion Energy Sciences Program should establish a proactive U.S. plan on burning plasma experiments and should not assume a default position of waiting to see what the international community may or may not do regarding the construction of a burning plasma experiment. If the opportunity for international collaboration occurs, the U.S. should be ready to act and take advantage of it but should not be dependent upon it. The U.S. should implement a plan as follows to proceed towards construction of a burning plasma experiment:

- Hold “Snowmass-style” community meeting
- Carry out uniform technical assessment by NSO activity
- Request FESAC “action panel” to select preferred BP option
- National Research Council review of BP plans

Plan Prescribed in HR4

a) PLAN FOR UNITED STATES FUSION EXPERIMENT- The Secretary, on the basis of full consultation with the Fusion Energy Sciences Advisory Committee and the Secretary of Energy Advisory Board, as appropriate, shall develop a plan for United States construction of a magnetic fusion burning plasma experiment for the purpose of accelerating scientific understanding of fusion plasmas. The Secretary shall request a review of the plan by the National Academy of Sciences, and shall transmit the plan and the review to the Congress by July 1, 2004.

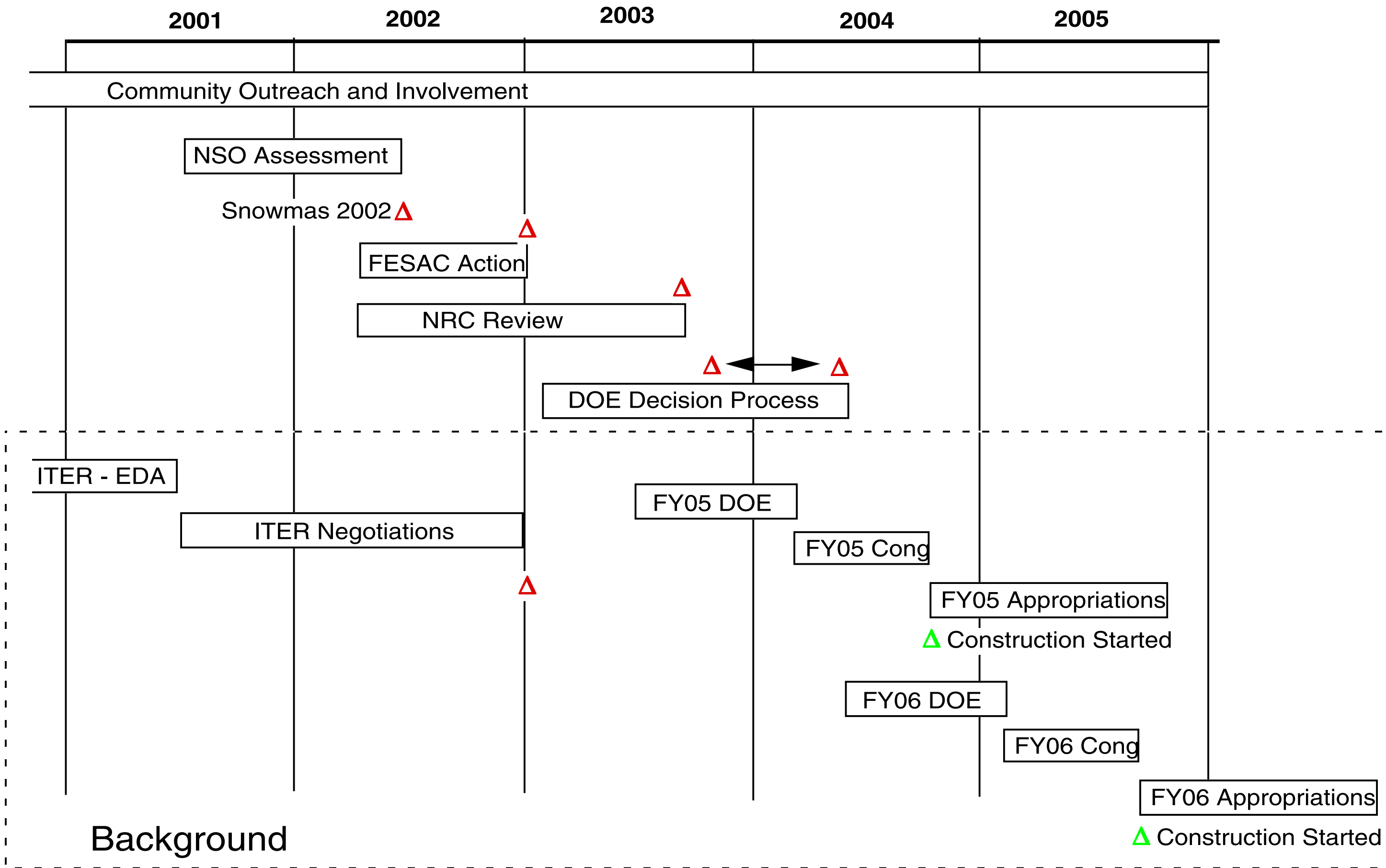
(b) REQUIREMENTS OF PLAN- The plan described in subsection (a) shall--

(1) address key burning plasma physics issues; and

(2) include specific information on the scientific capabilities of the proposed experiment, the relevance of these capabilities to the goal of practical fusion energy, and the overall design of the experiment including its estimated cost and potential construction sites.

(c) UNITED STATES PARTICIPATION IN AN INTERNATIONAL EXPERIMENT- In addition to the plan described in subsection (a), the Secretary, on the basis of full consultation with the Fusion Energy Sciences Advisory Committee and the Secretary of Energy Advisory Board, as appropriate, may also develop a plan for United States participation in an international burning plasma experiment for the same purpose, whose construction is found by the Secretary to be highly likely and where United States participation is cost effective relative to the cost and scientific benefits of a domestic experiment described in subsection (a). If the Secretary elects to develop a plan under this subsection, he shall include the information described in subsection (b), and an estimate of the cost of United States participation in such an international experiment. The Secretary shall request a review by the National Academies of Sciences and Engineering of a plan developed under this subsection, and shall transmit the plan and the review to the Congress not later than July 1, 2004.

Recommended US Plan for Burning Plasmas



The 2002 Fusion Summer Study will be a forum for the critical assessment of major next-steps in the fusion energy sciences program, and will provide crucial community input to the long range planning activities undertaken by the DOE and the FESAC. It will be an ideal place for a broad community of scientists to examine goals and proposed initiatives in burning plasma science in magnetic fusion energy and integrated research experiments in inertial fusion energy.

This meeting is open to every member of the fusion energy science community and significant international participation is encouraged.

Program Committee Co-Chairs:

Roger Bangerter, Lawrence Berkeley National Laboratory
Gerald Navratil, Columbia University
Ned Sauthoff, Princeton University

Endorsed by: US Department of Energy and The American Physical Society

For More Information: http://web.gat.com/snowmass

Concluding Comments

- Burning Plasma Studies open a new regime of plasma physics of an exothermic medium:

  ... is THE GRAND CHALLENGE problem
  in field of plasma physics.

- Physics basis for burning plasma step was nearly in hand in 1986 with proposals for CIT & later BPX : if built we now know it would have reached Q > 5.

- Dramatic progress in 1990's has established a sound basis for exploration of the Burning Plasma regime.

- Fusion Community meeting at Snowmass in July 2002 to prepare input for FESAC plan for a Burning Plasma Experiment to be reviewed by the National Academy.