INTRODUCTION TO BURNING PLASMA PHYSICS

Gerald A. Navratil
Columbia University

American Physical Society - Division of Plasma Physics
2001 Annual Meeting, Long Beach, CA
1 November 2001

THANKS TO MANY PEOPLE WHO HELPED...

BILL DORLAND
BOB GROSS
RICH HAWRYLUK
ALI MAHDAVI
DALE MEADE
RIP PERKINS
TOM PETRIE
PETE POLITZER
STEW PRAGER
JIM STRACHAN
JIM VAN DAM
...AND OTHERS

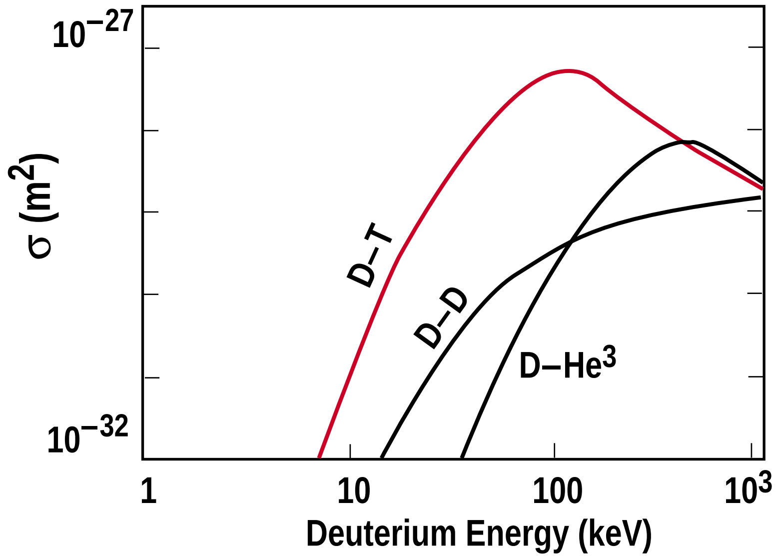
- + UFA BURNING PLASMA WORKSHOP - AUSTIN 2000
- + UFA BURNING PLASMA WORKSHOP - SAN DIEGO 2001
- + FESAC BURNING PLASMA PANEL & REPORT

PRODUCING AND UNDERSTANDING A SUSTAINED FUSION HEATED PLASMA IS A GRAND CHALLENGE PROBLEM FOR OUR FIELD

DT FUSION

$$ {}_1D^2 + {}_1T^3 \rightarrow \underbrace{\underset{(3.5\ \text{MeV})}{\underset{\uparrow}{{}_2He^4}} + \underset{(14.1\ \text{MeV})}{\underset{\uparrow}{{}_0n^1}}} $$

Energy/Fusion: $\varepsilon_f = 17.6$ **MeV**

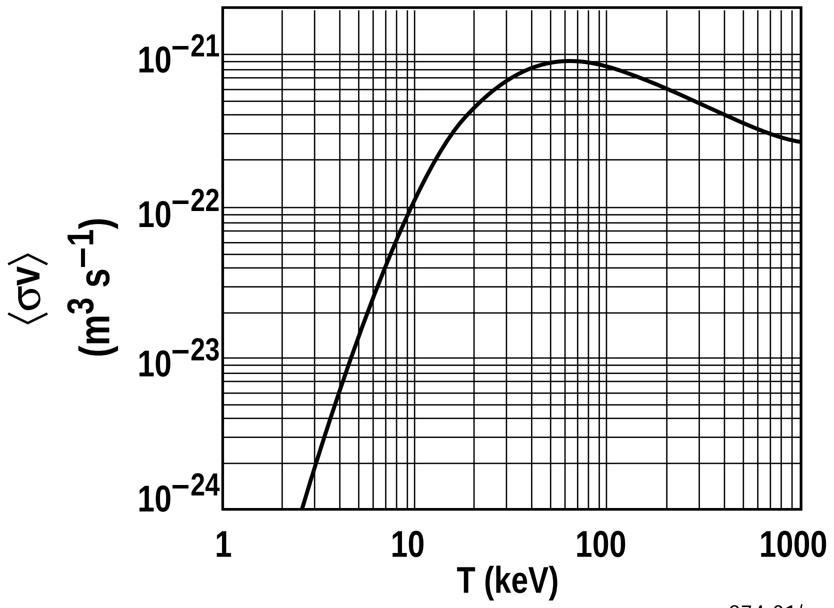


Fusion Reaction Rate, R
for a Maxwellian

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

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

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



274-01/rs

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

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

STEADY-STATE FUSION POWER BALANCE

$$\frac{dW}{dt} \rightarrow 0 \implies P_\alpha + P_{heat} = \frac{W}{\tau_E} \quad , P_{heat} = \text{ext. supplied heating}$$

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

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

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

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

Useful since in 10–20 keV range

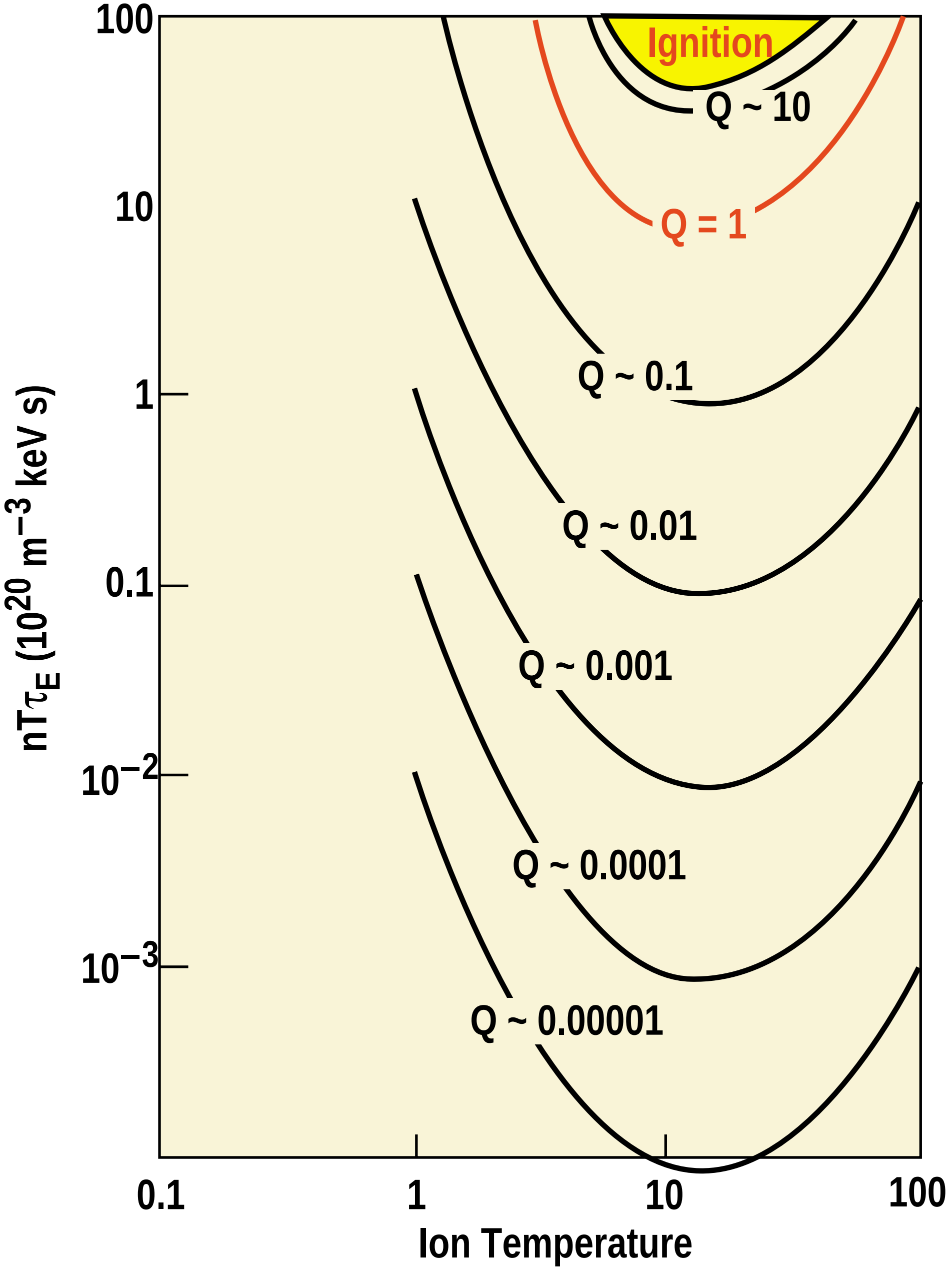
where $p\tau_E$ is minimum for given Q

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

and p is limited by MHD stability in

magnetically confined plasmas

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



274-01/rs

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

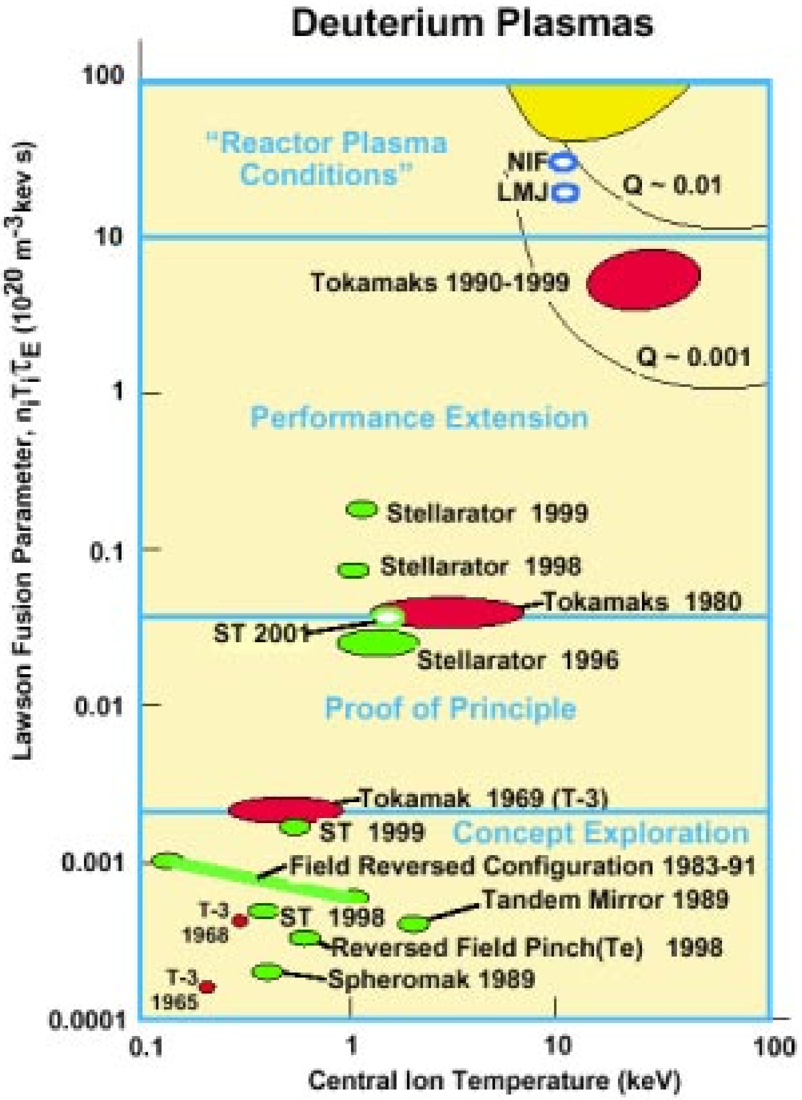
  Note at B ~ 5 T: $v_{\mathrm{Alfvén}} \sim 5 \times 10^6$ m/s $< v_\alpha$

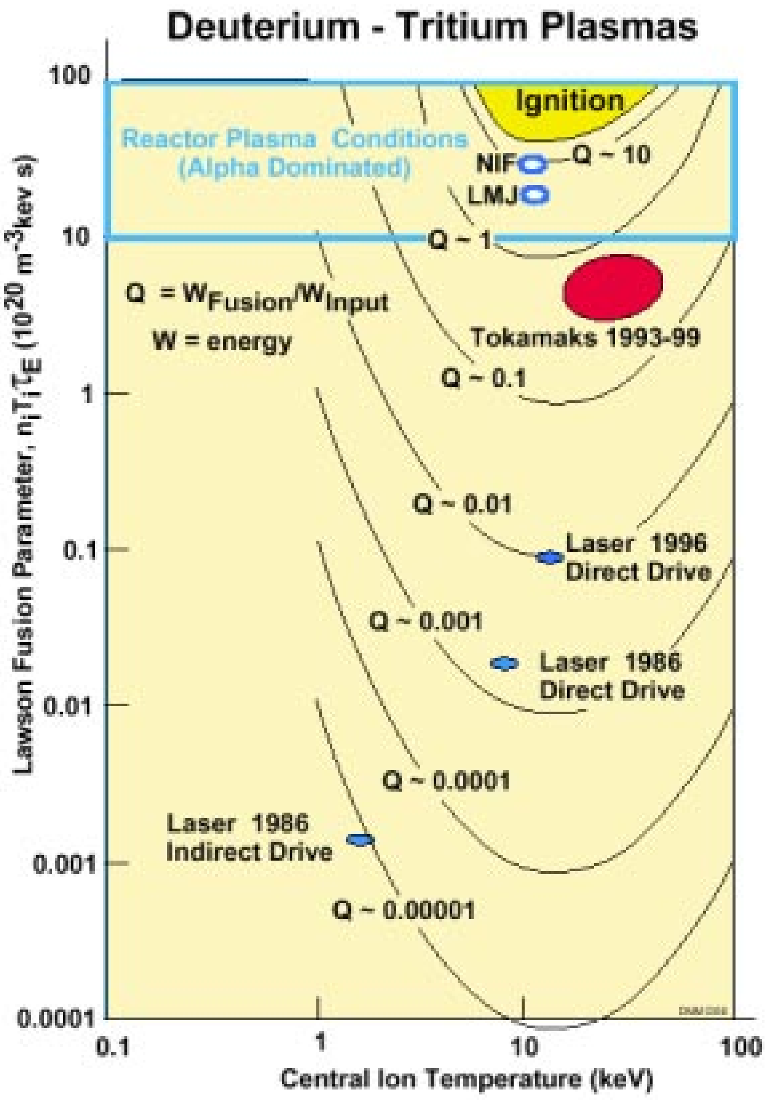
- CAN IMMEDIATELY DEDUCE:

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

  2) $T_i \sim T_e$ since $v_\alpha >> v_{Ti}$ AND $m_\alpha >> m_e$ 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

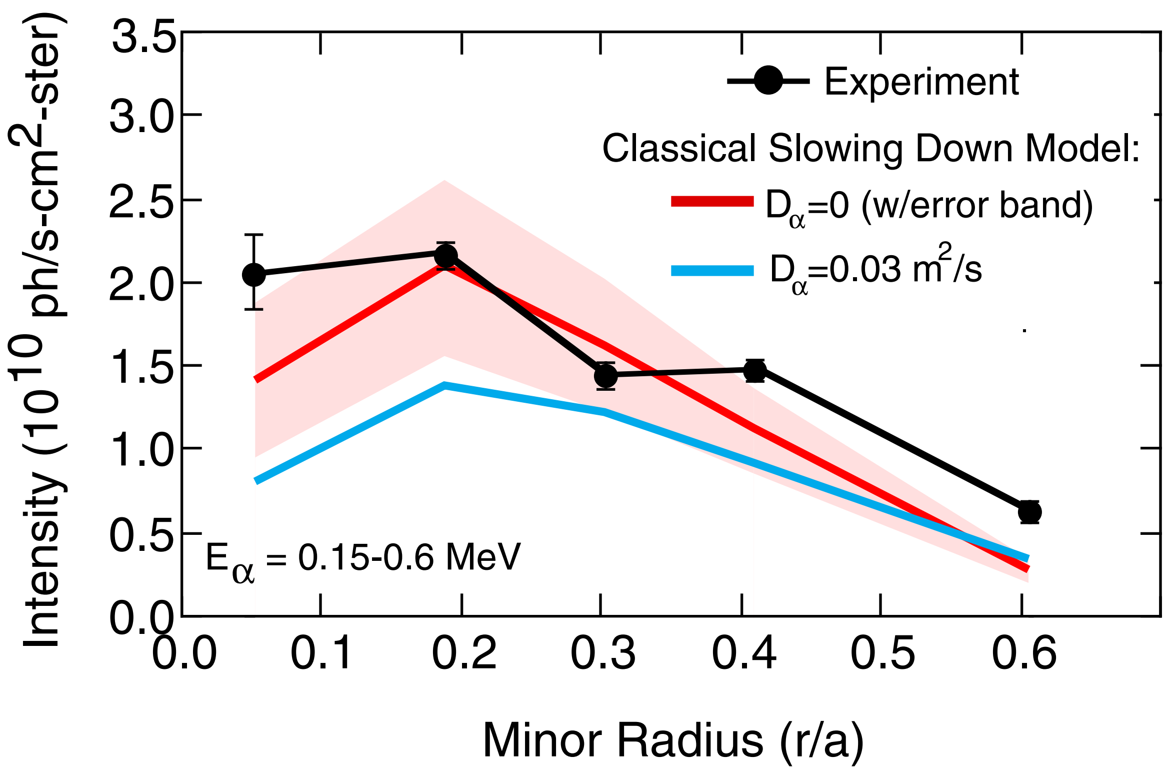
At the Burning Plasma Threshold

DT EXPERIMENTS ON TFTR AND JET

	TFTR	JET
Peak Transient Q	0.27	0.61
α Confinement	Classical	Classical
α Slowing Down	Classical	Classical
α Heating Observed	Yes, but weak	Yes
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]

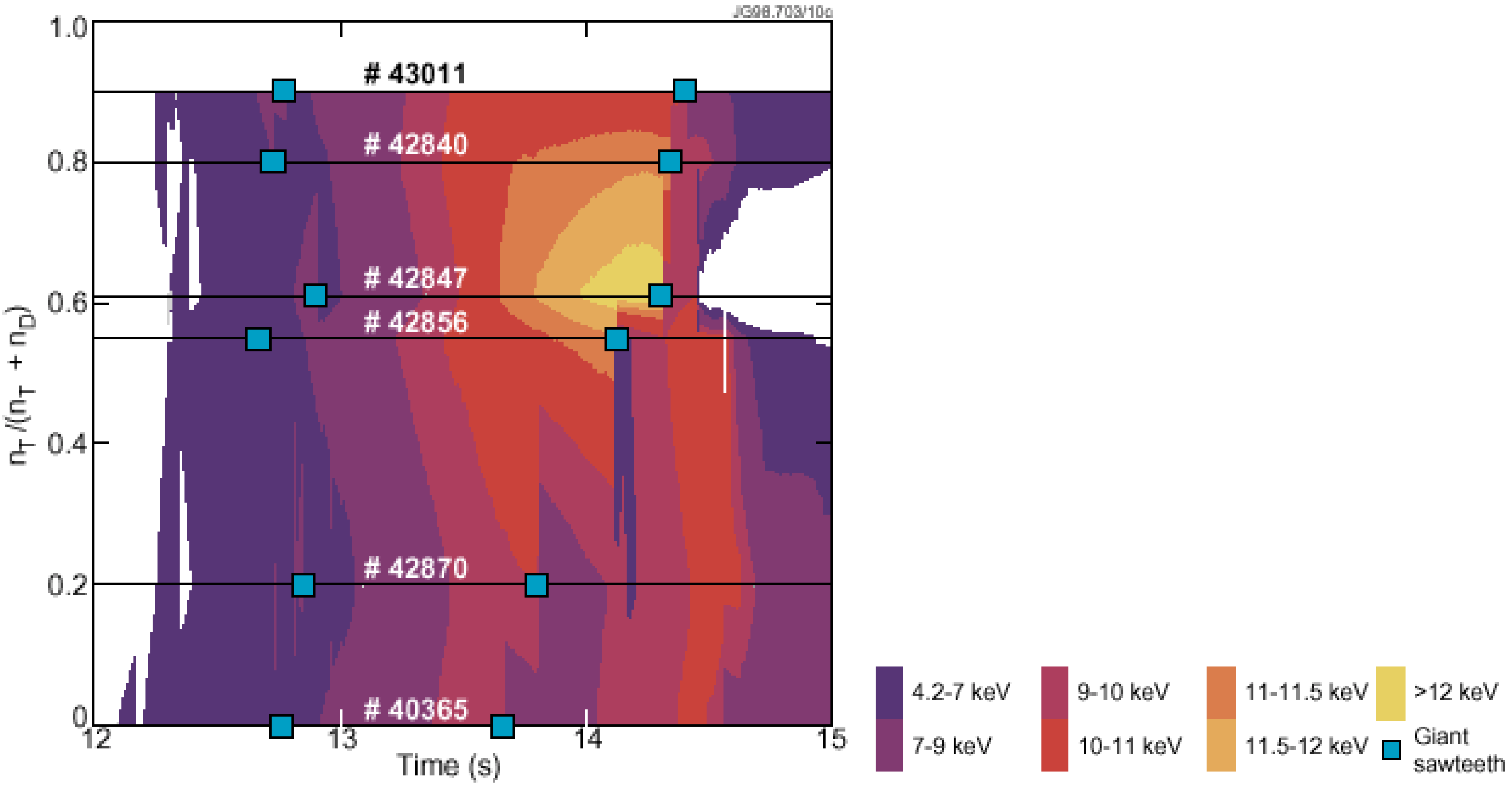
274-01/rs

FUSION ALPHAS ARE CONFINED AND SLOW DOWN CLASSICALLY IN TFTR



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

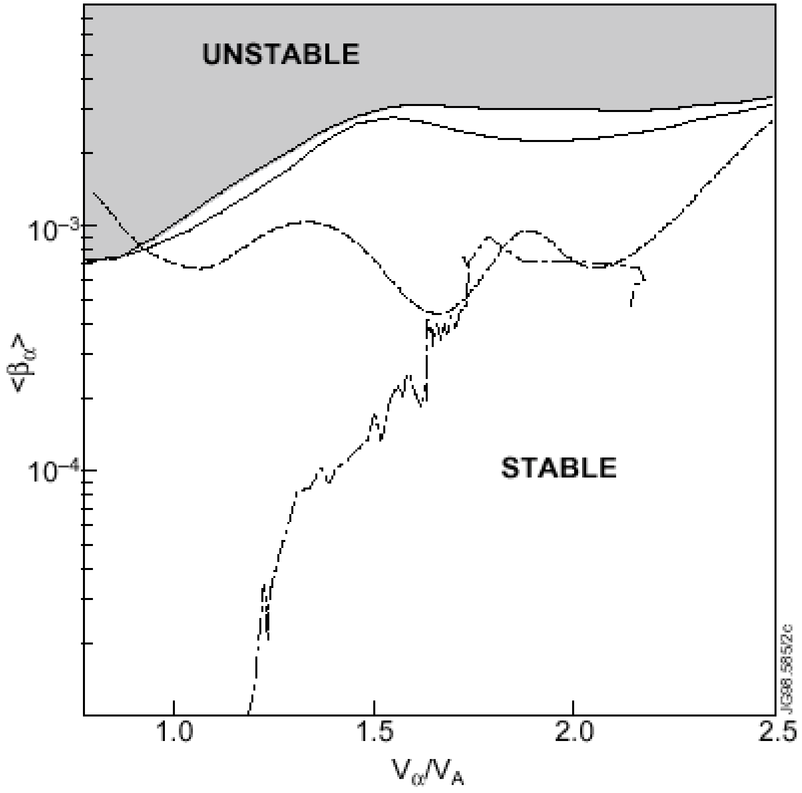
JET DT EXPERIMENTS SHOW α-HEATING OF CENTRAL ELECTRONS



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

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.



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 $R\nabla\beta_\alpha$

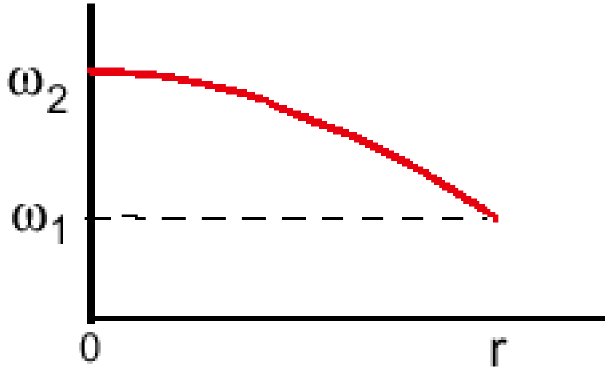
	Range of Interest (e.g. ARIES-RS/AT)	ITER-FEAT (reference)	FIRE (reference)	JET
$V_\alpha/V_A(0)$	≈ 2.0	1.9	2.2	1.6–1.9
ρ_α/a	≈ 0.02	0.016	0.028	~0.1
Max $R\nabla\beta_\alpha$	0.03–0.15*	0.05	0.035	0.02–0.037

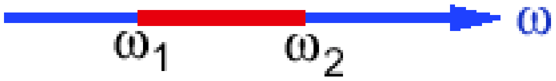
274-01/rs

GEOMETRIC EFFECTS ON ALFVEN WAVES

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

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

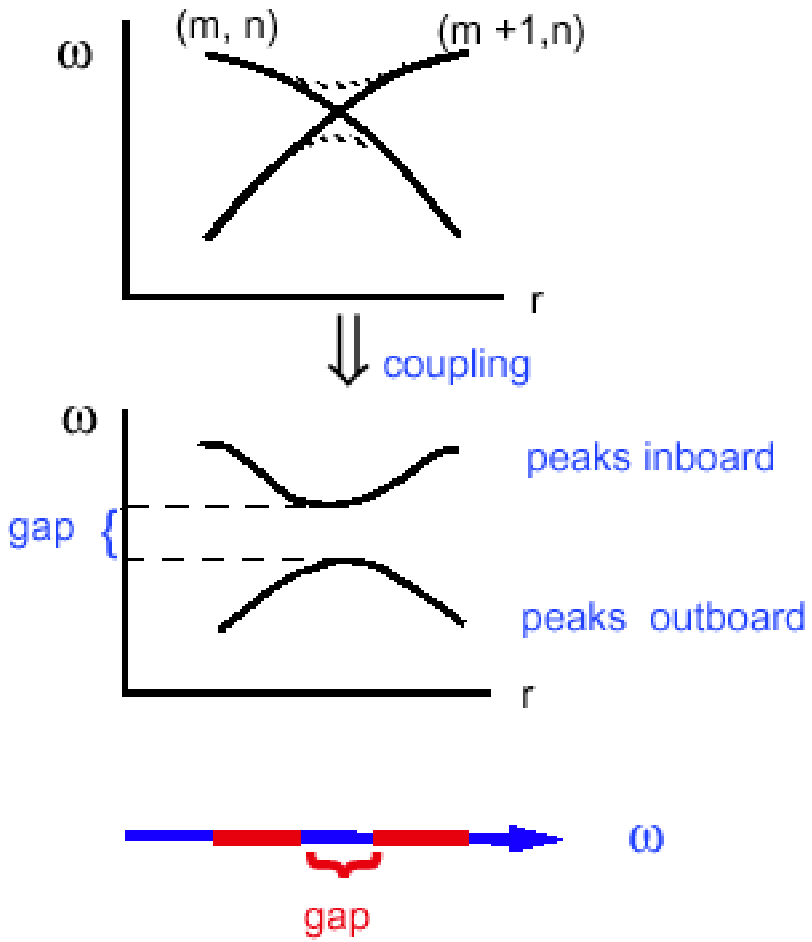




- Continuous spectrum, shear Alfvén resonance

GEOMETRIC EFFECTS ON ALFVEN WAVES

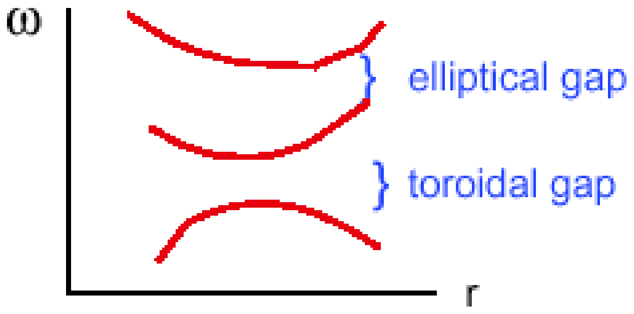
Add 2D toroidal effects:



- 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

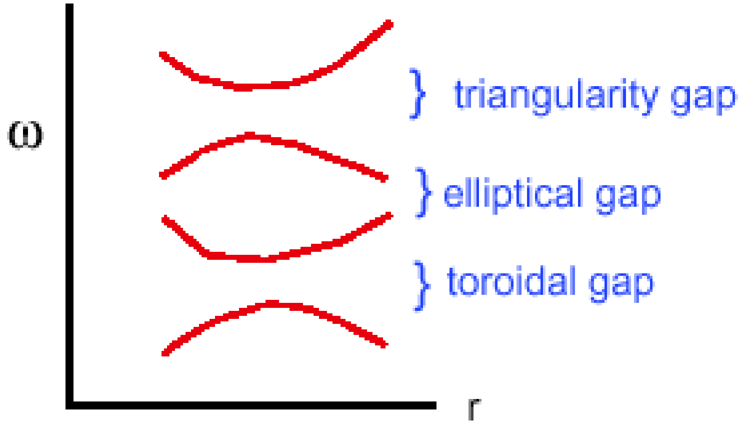
GEOMETRIC EFFECTS ON ALFVEN WAVES

Add elliptical cross-section effects:



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

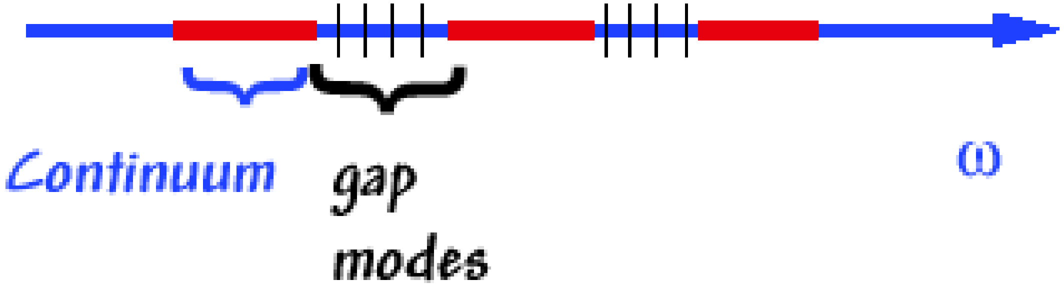
Add triangularity cross-section effects:



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

GEOMETRIC EFFECTS ON ALFVEN WAVES

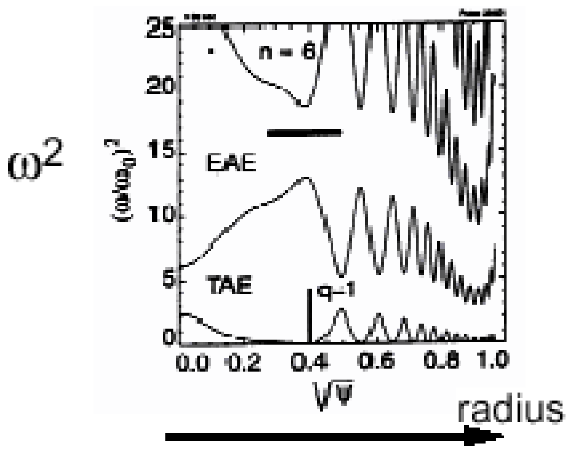
Discrete Modes Appear in Gaps in the Continuum:



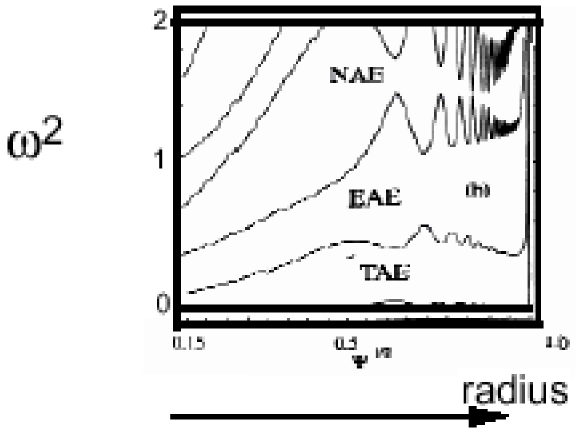
- **Alfvén wave continuum is strongly damped.**
- **TAE gap-modes are less damped: free energy from ∇p_{α} tapped by wave/particle resonance drive from α-particles may destabilize these modes.**

BASIC ALFVEN EIGENMODE PHYSICS EXTENDS TO RANGE OF TOROIDAL CONFIGURATIONS

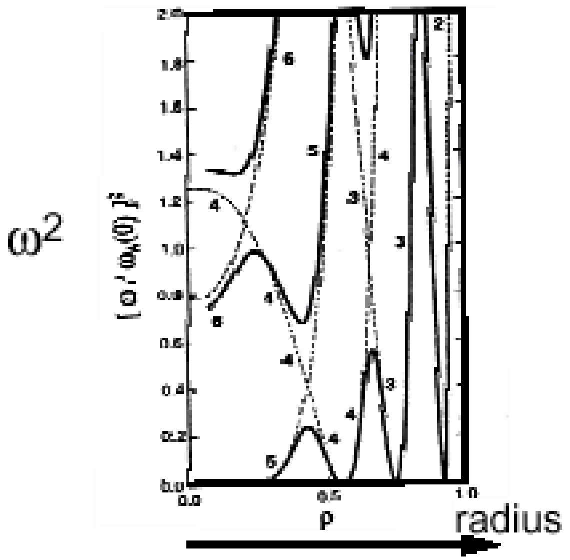
Tokamak:



Spherical Torus:



Stellarator:



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

New Alpha Effects Expected on Scale of Burning Plasma

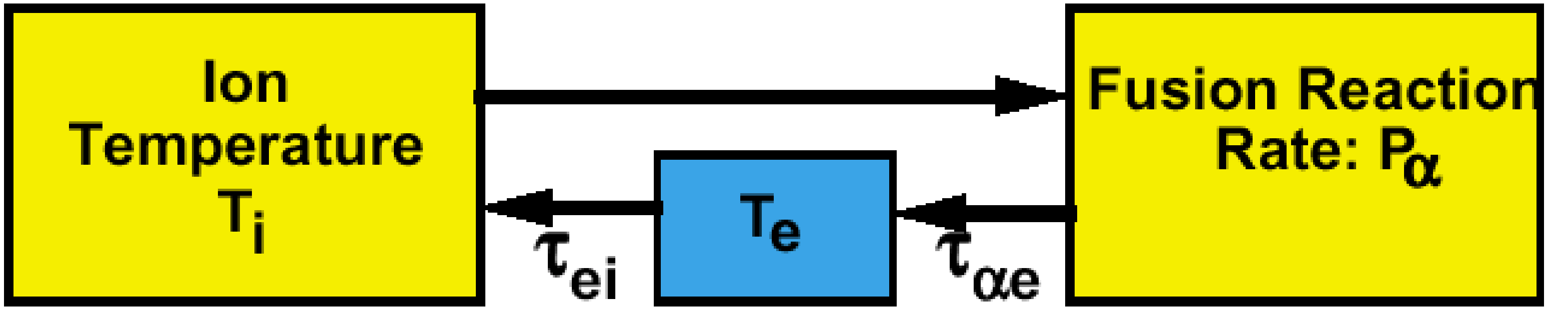
- **Present experiments show alpha transport due to only a few global modes.**
- **Smaller value of $\rho_\alpha/\langle a \rangle$ in a Burning Plasma may lead to a "sea" of resonantly overlapping unstable modes & possible large alpha transport.**
- **Reliable simulations not possible...needs experimental information in new regime.**

This and other alpha physics will be discussed in more detail in next talk by Bill Heidbrink...

Q ~ 10: Strong Non-Linear Coupling

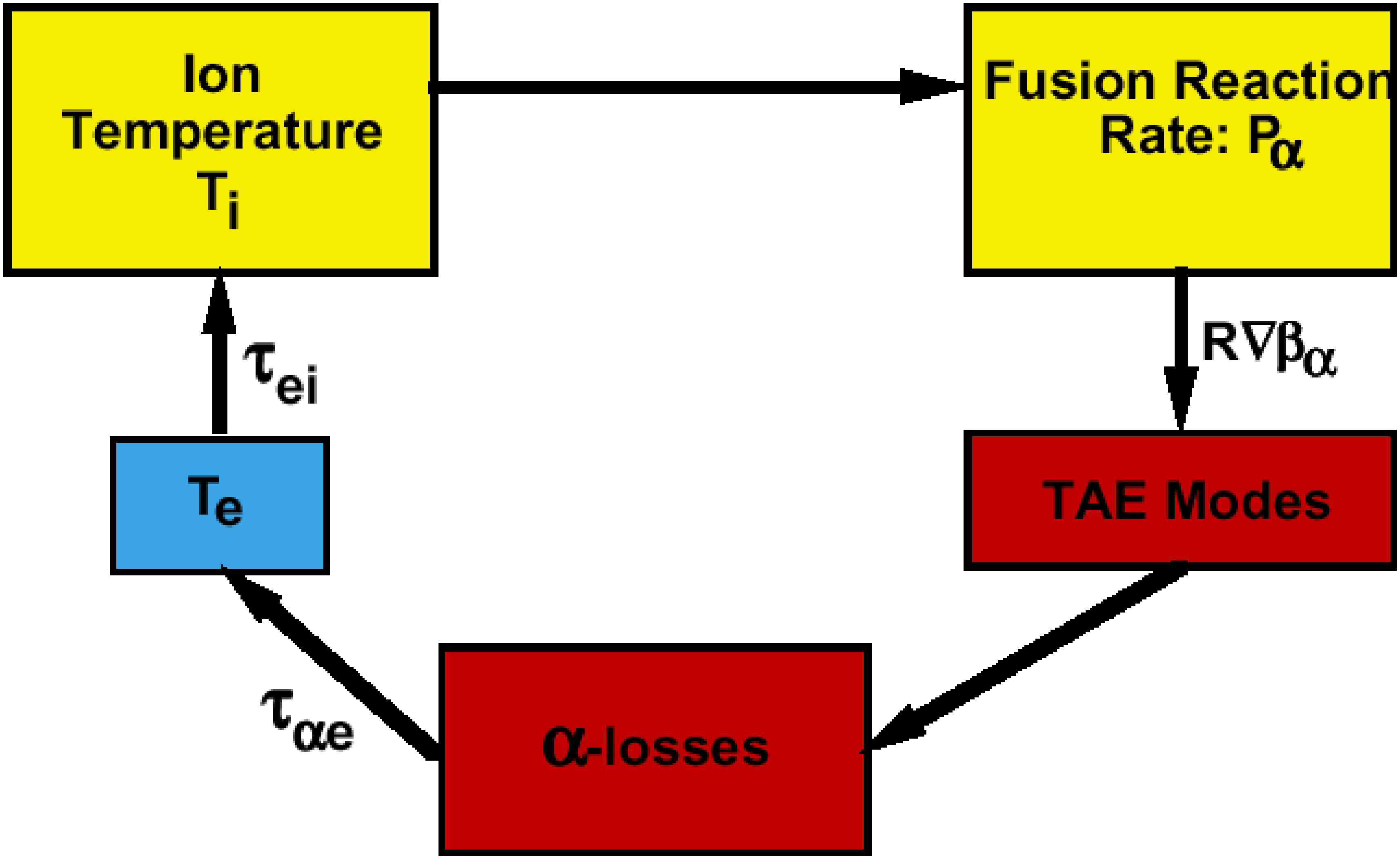
BURNING PLASMA SYSTEM IS HIGHLY NON-LINEAR…

BASIC COUPLING OF FUSION ALPHA HEATING:



BURNING PLASMA SYSTEM IS HIGHLY NON-LINEAR...

ADD ALPHA DRIVEN TAE MODES:



Ion Temperature T_i

Fusion Reaction Rate: P_α

$R\nabla\beta_\alpha$

TAE Modes

α-losses

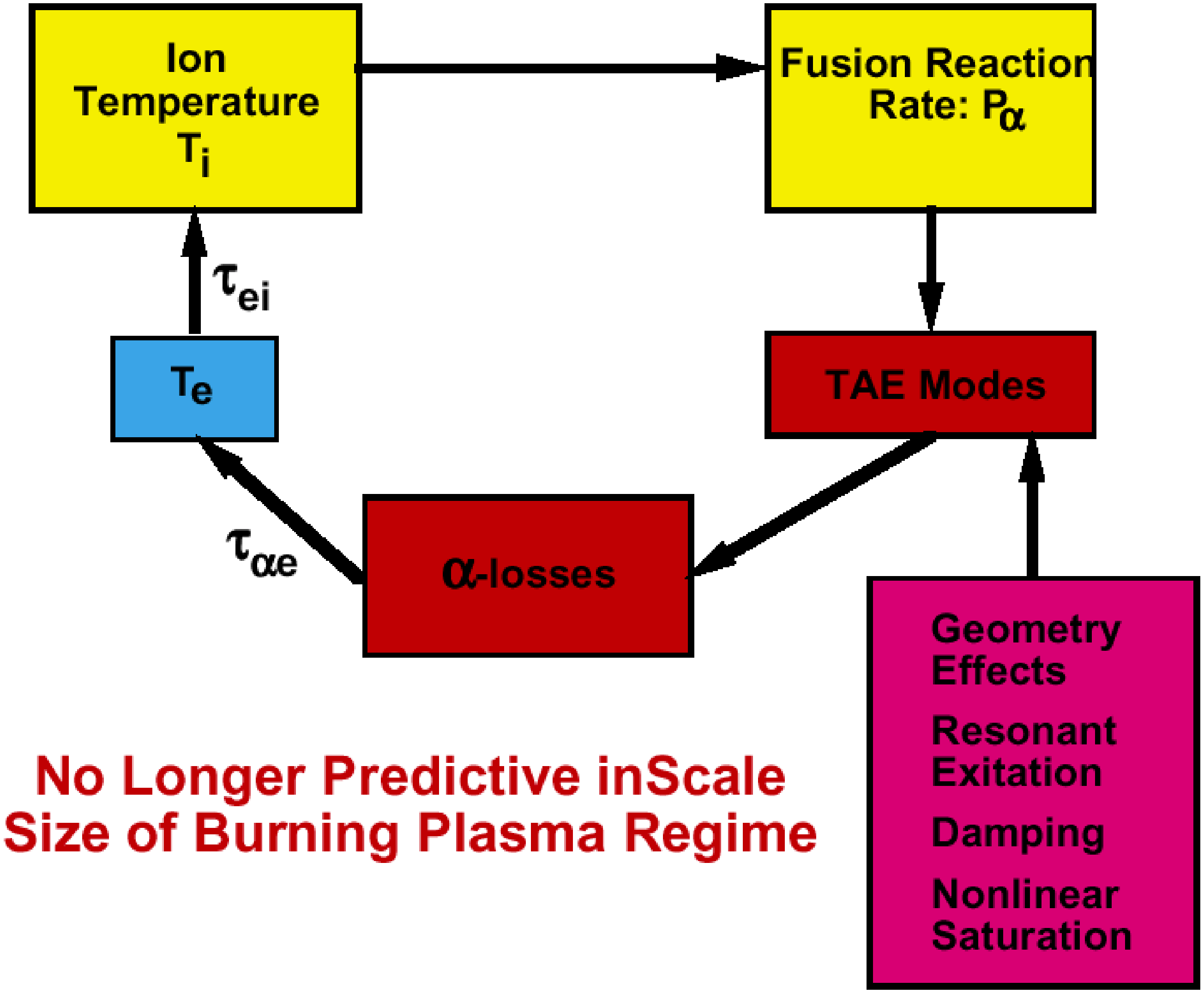
$\tau_{\alpha e}$

T_e

τ_{ei}

BURNING PLASMA SYSTEM IS HIGHLY NON-LINEAR...

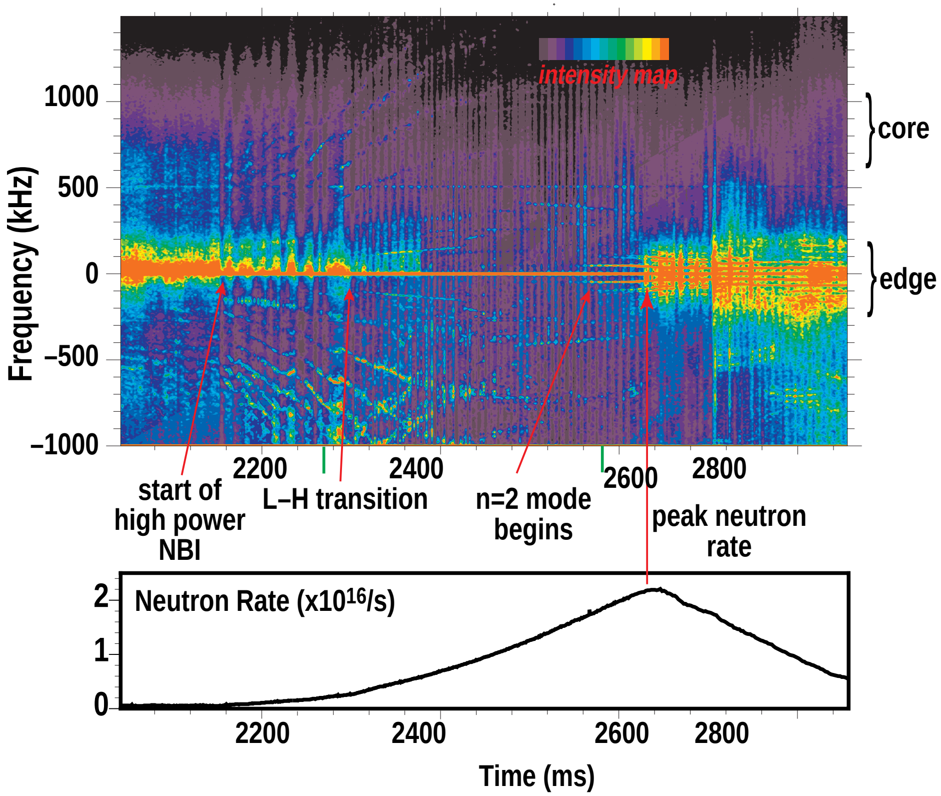
ADD COMPLEX PHYSICS OF ALPHA DRIVEN TAE MODES:



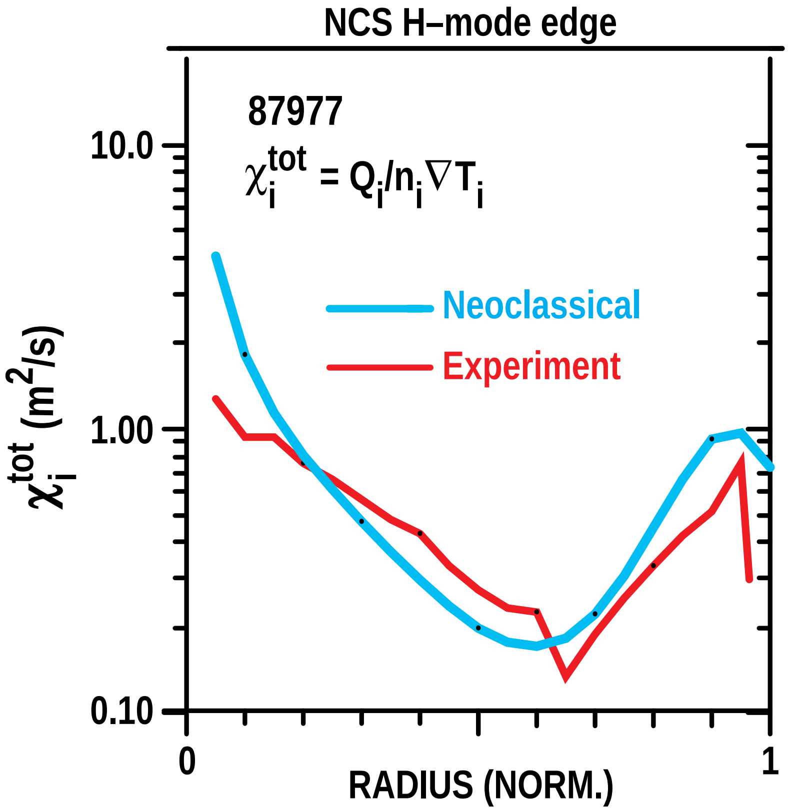
No Longer Predictive inScale Size of Burning Plasma Regime

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

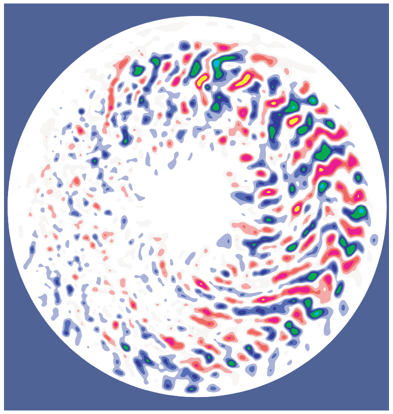


SHEARED FLOW CAUSES TRANSPORT SUPPRESSION

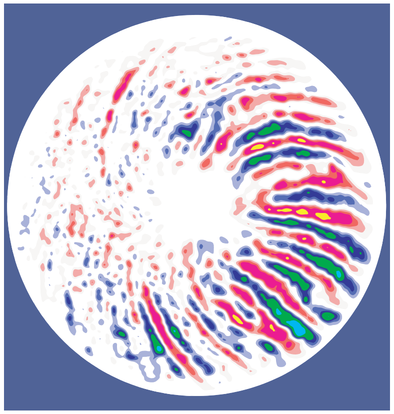
Gyrokinetic Theory

- Simulations show turbulent eddies disrupted by strongly sheared plasma flow

With Flow

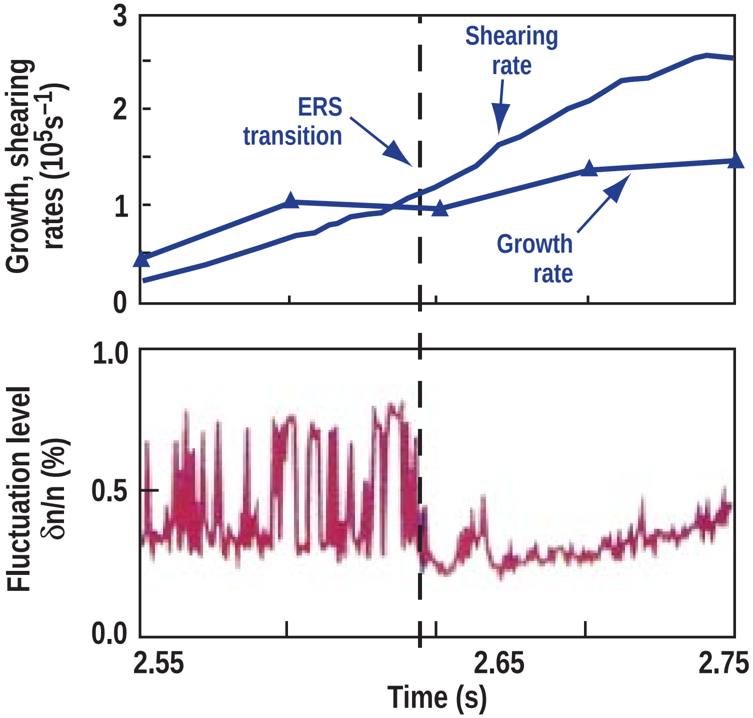


Without Flow



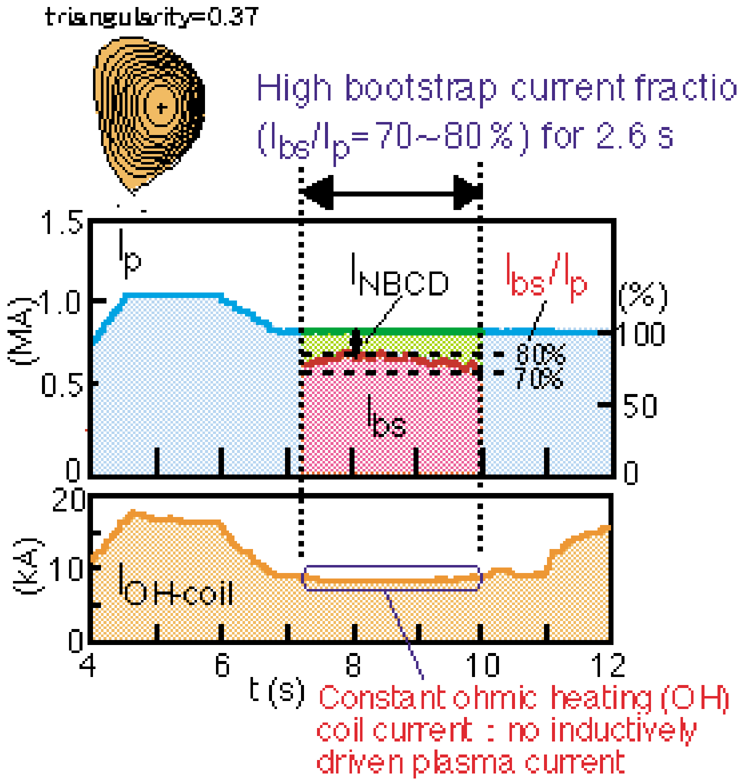
Experiment

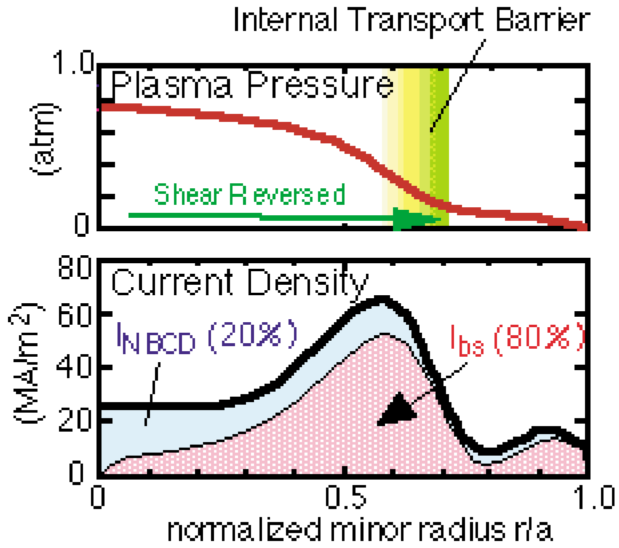
- Turbulent fluctuations are suppressed when shearing rate exceeds growth rate of most unstable mode



y

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



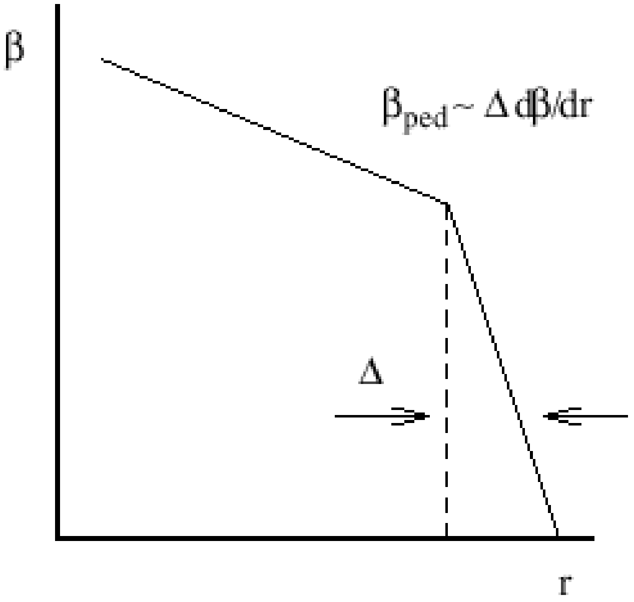


- Data from JT-60U shows sustained transport barrier and 100% non-inductive current drive

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

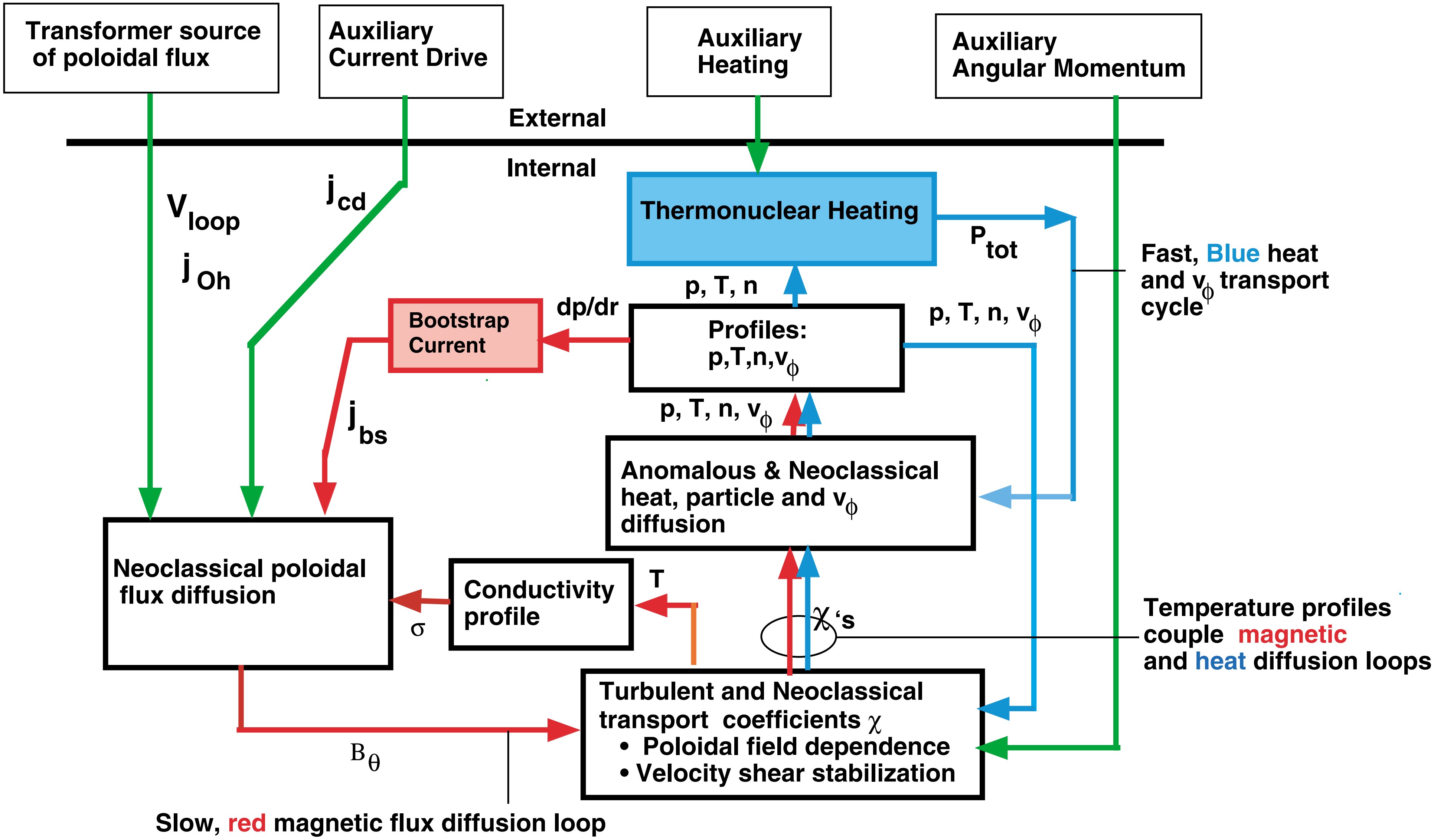
* $n_{eo} / n_{ped} = 1.5$ with n_{ped} held fixed from flat density case

❖ 10 MW auxiliary heating

11.4 MW auxiliary heating

✦ 50 MW auxiliary heating

ADVANCED TOKAMAK NONLINEAR TRANSPORT COUPLINGS



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

Bootstrap Current

dp/dr

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

$Q > 20$:

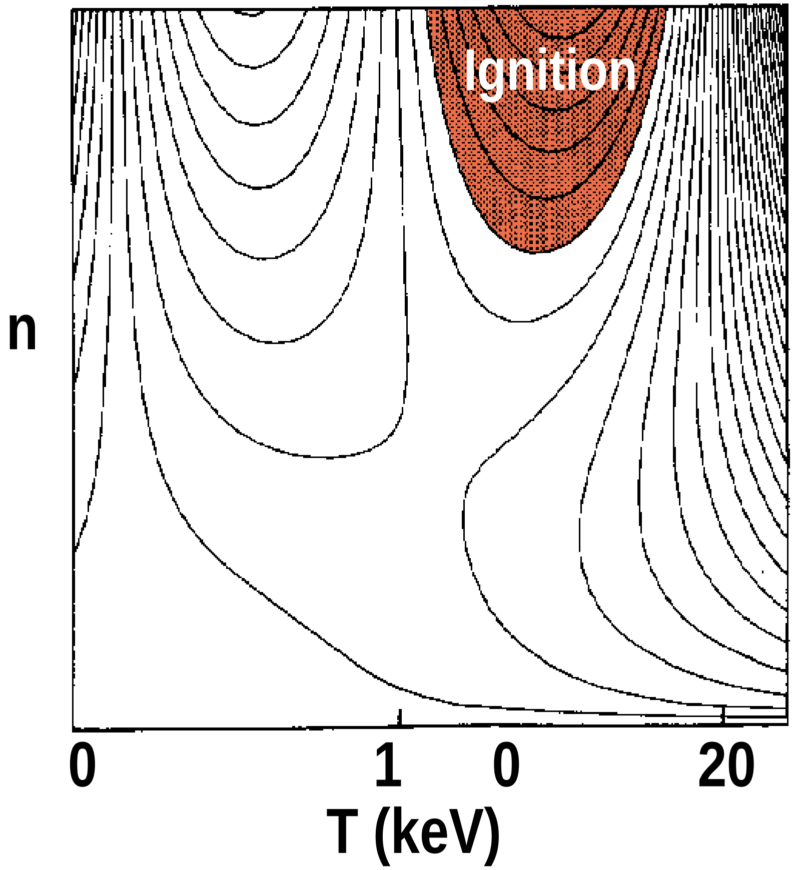
Burn Control &
Ignition Transient Phenomena

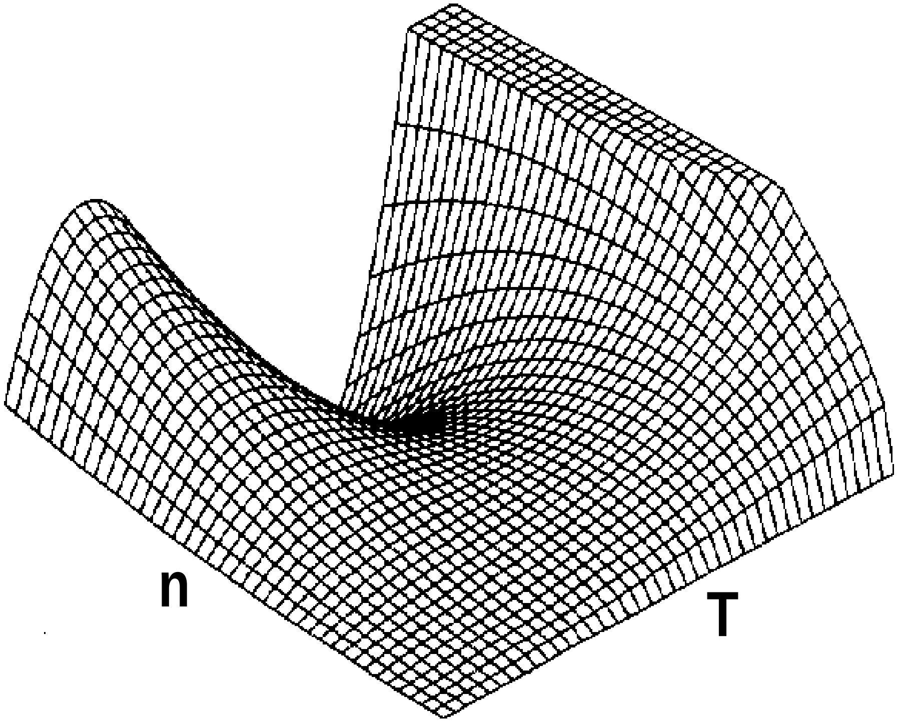
TRANSIENT BURN PHENOMENA WHEN Q ≳ 20

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

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

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





Surface of Constant P_{heat}

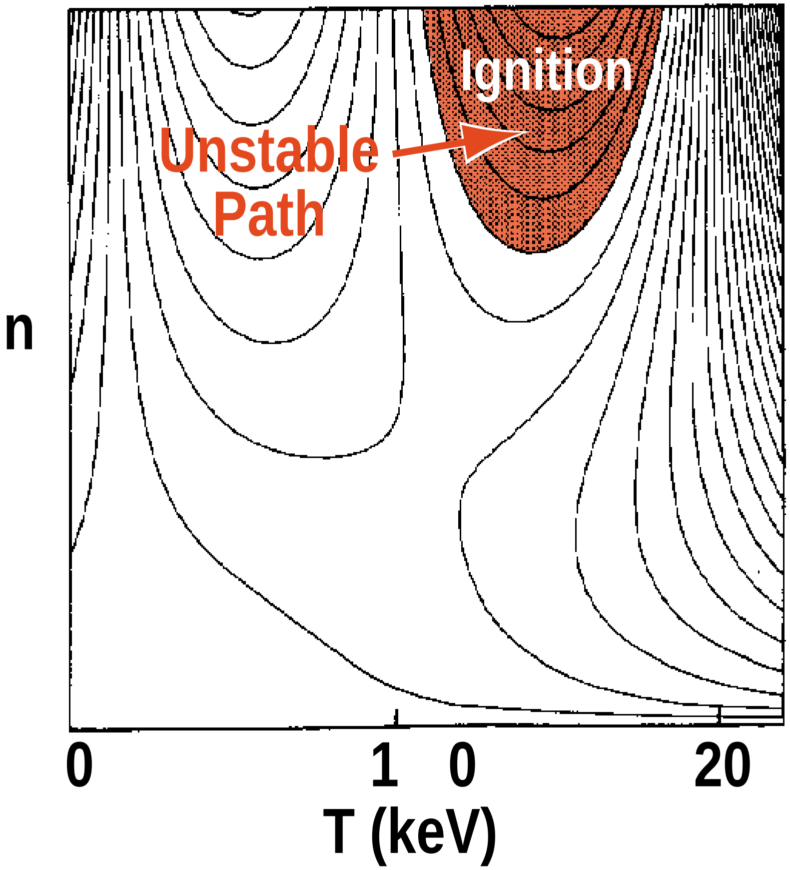
274-01/rs

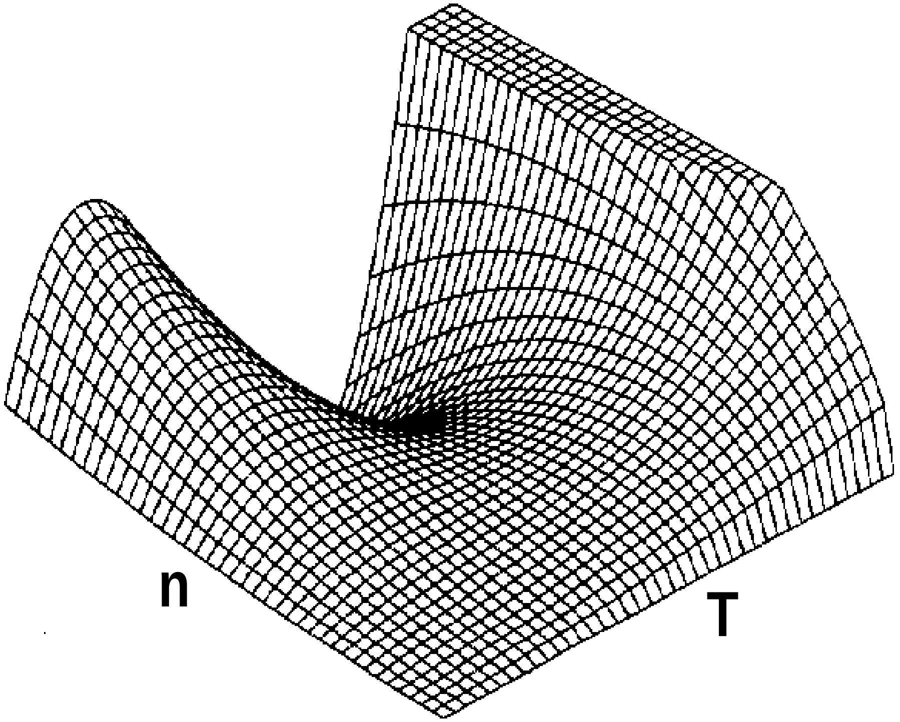
TRANSIENT BURN PHENOMENA WHEN Q ≳ 20

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

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

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





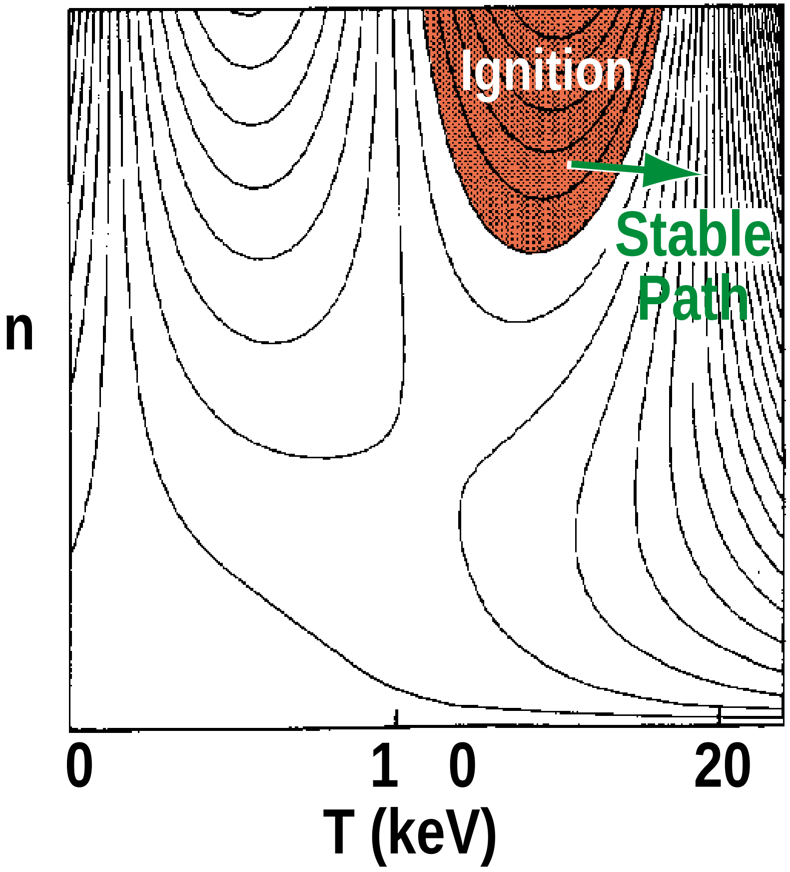
Surface of Constant P_{heat}

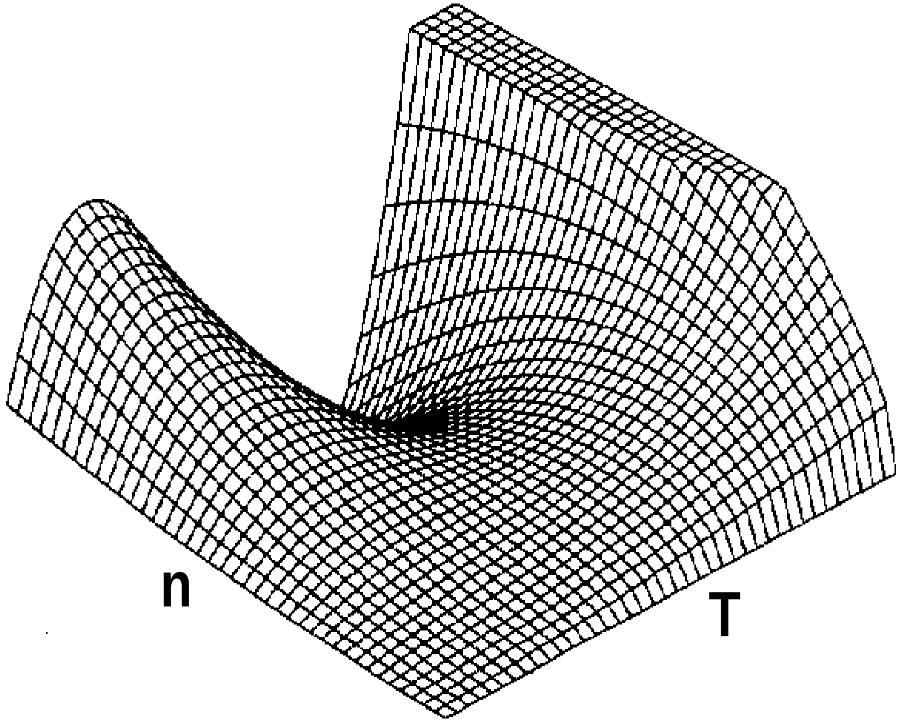
TRANSIENT BURN PHENOMENA WHEN Q ≳ 20

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

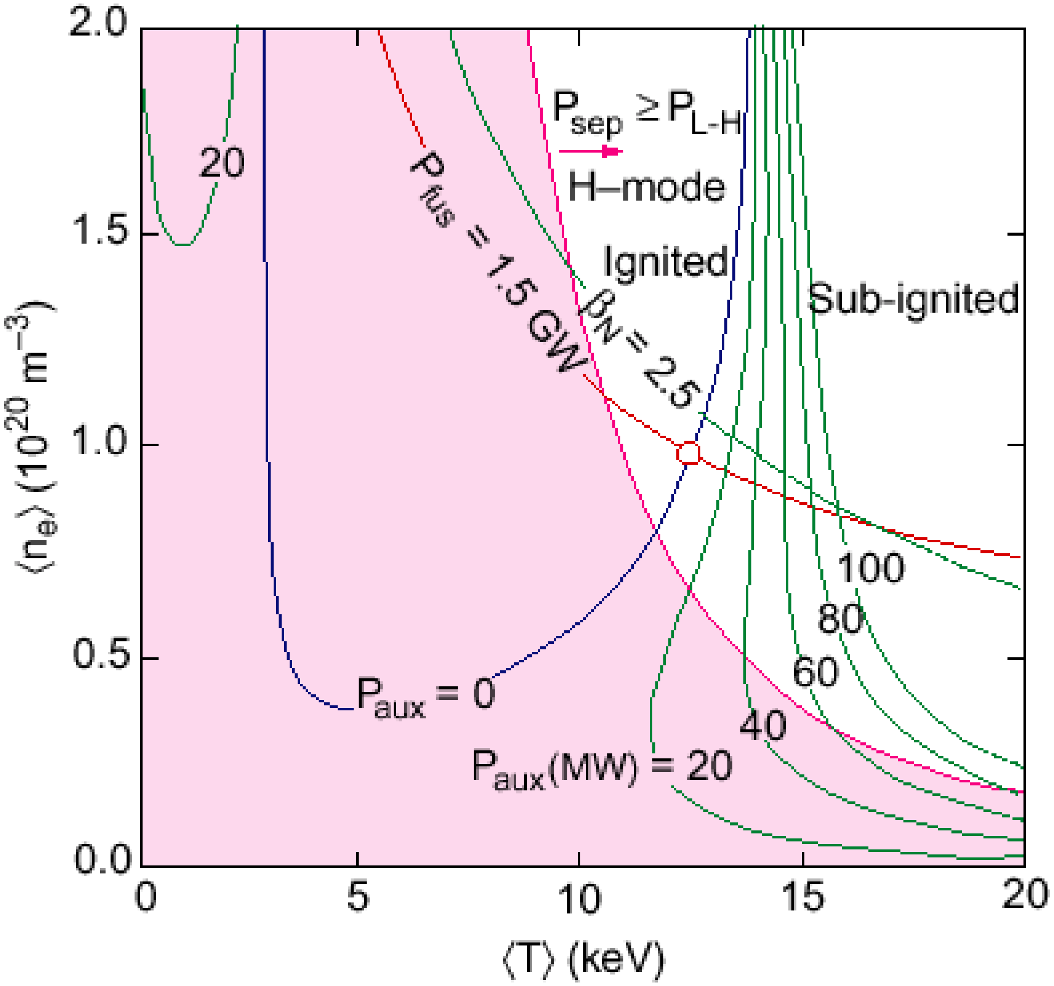




Surface of Constant P_{heat}

MORE "REALISTIC" POWER BALANCE

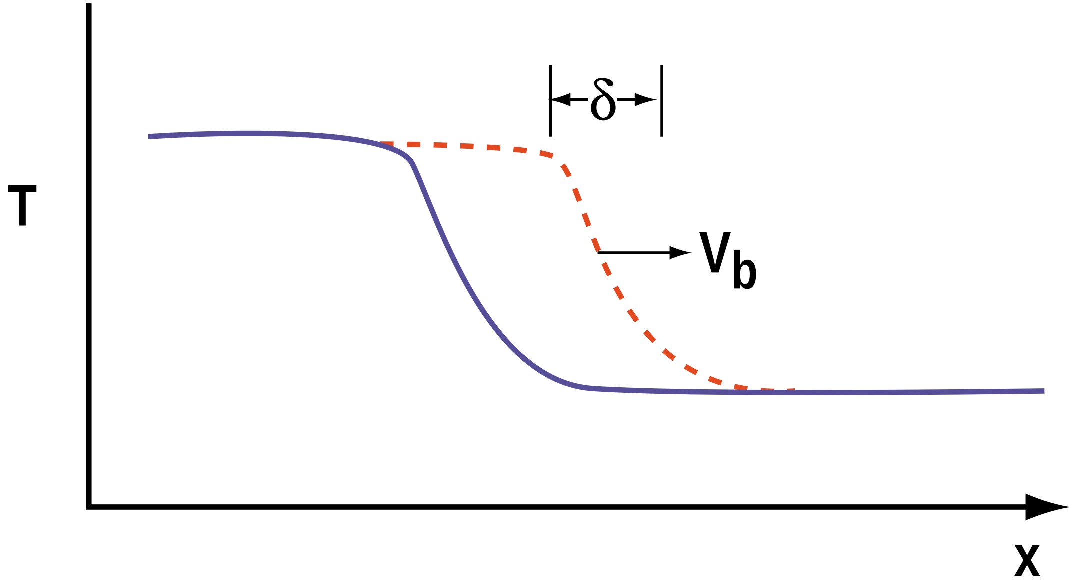
- **ITER POPCON Power Balance Analysis**



- **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 $\tau_d \sim \tau_{burn}$

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

FUSION BURN PROPAGATION AT HIGH Q

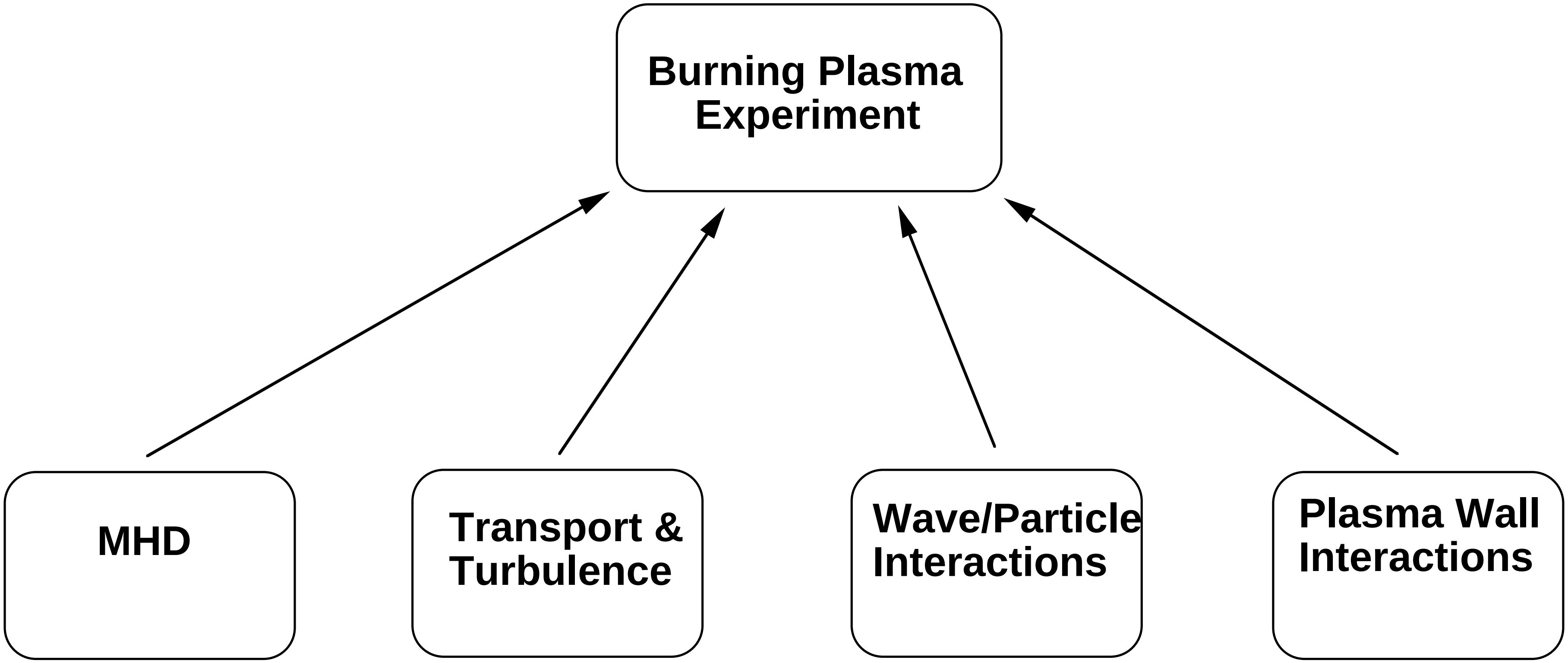
- EXAMPLE PARAMETERS
  - $n \sim 4 \times 10^{20}\ m^{-3}$
  - $T \sim 20$ keV
  - $P\alpha \sim 10\ MW/m^3$
  - $W = 3nT \sim 3.8\ MJ/m^3$
  - $\chi \sim 0.1\ m^2/s$

$\delta \sim 0.2$ 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



Burning Plasma Experiment

MHD

Transport & Turbulence

Wave/Particle Interactions

Plasma Wall Interactions

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 ≤ 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

$\omega_c \tau$

$\rho^* = \rho / \mathbf{a}$

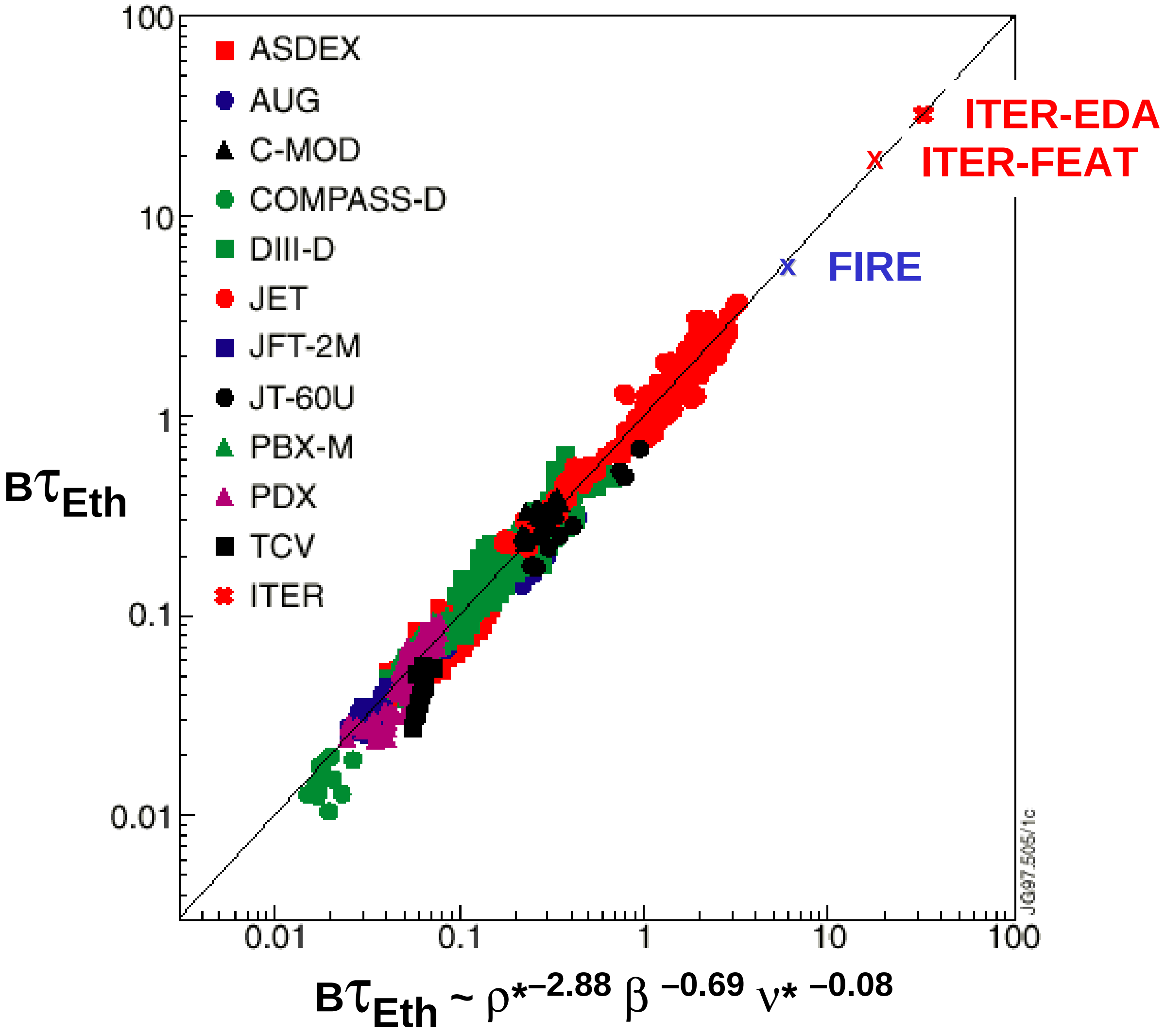
$\nu^* = \nu_c / \nu_b$

β

Similarity Parameter

$\mathbf{B\ R^{5/4}}$

Kadomtsev, 1975



Concluding Comments & Discussion

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

  is THE GRAND CHALLENGE problem in our field.

- 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.
- We must work together NOW to take this important Burning Plasma step.