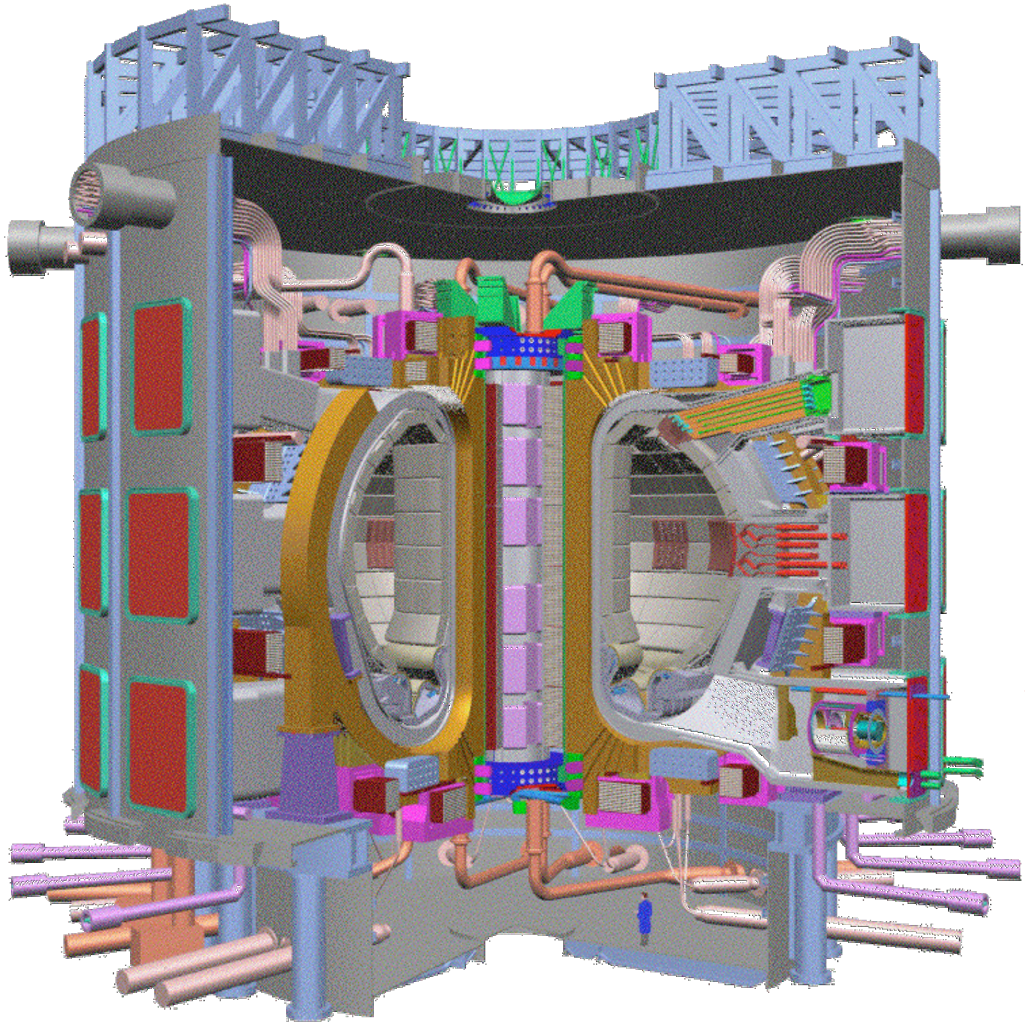
Burning Plasma Science:
The Challenge and Opportunity



Gerald A. Navratil

Columbia University

2004 AAAS Annual Meeting
Symposium on
Burning Plasma Physics
Seattle, WA
12-16 February 2004

OUTLINE

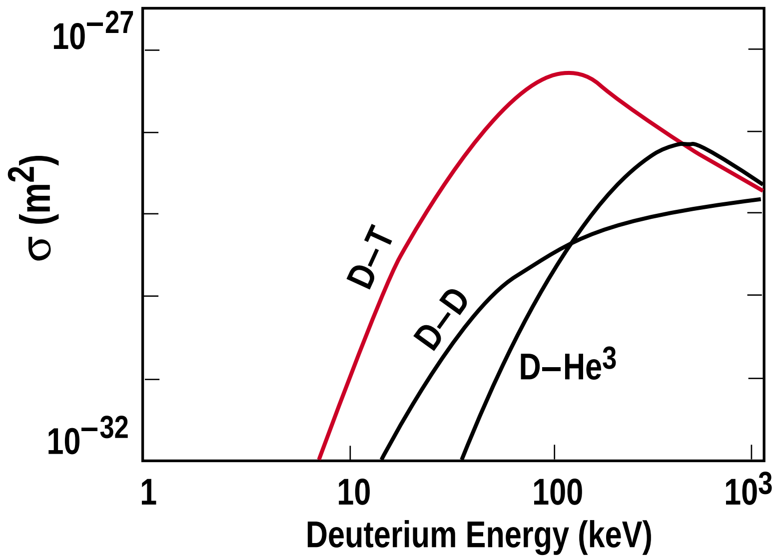
- BASIC REQUIREMENTS FOR A BURNING PLASMA
- FRONTIER SCIENCE ISSUES: WHAT DO WE WANT TO KNOW?
- Q~1 RESULTS: AT THE THRESHOLD
- Q~5: α-EFFECTS ON TAE STABILITY
- Q~10: STRONG NON-LINEAR COUPLING
- Q≥20: BURN CONTROL & IGNITION
- TAKING THE “NEXT STEP”: ITER

DT FUSION

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

$$ \underbrace{(3.5\ \text{MeV}) \quad (14.1\ \text{MeV})} $$

Energy/Fusion: $\varepsilon_f = 17.6$ MeV

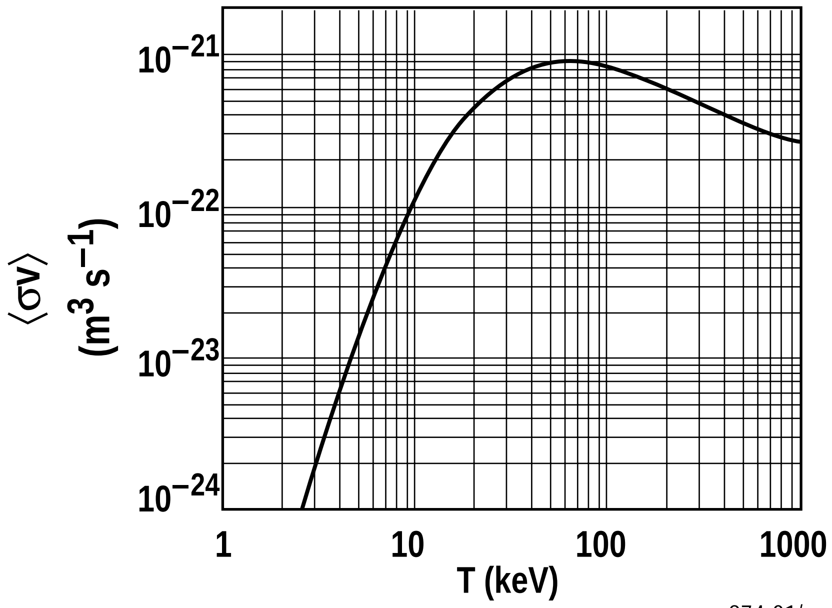


Fusion Reaction Rate, R
for a Maxwellian

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

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

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



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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, $W = \int \left\{ \frac{3}{2} n T_i + \frac{3}{2} n T_e \right\} d^3x = 3nTV$

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

ENERGY BALANCE

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

STEADY-STATE FUSION POWER BALANCE

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

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

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

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

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

Useful since in 10–20 keV range

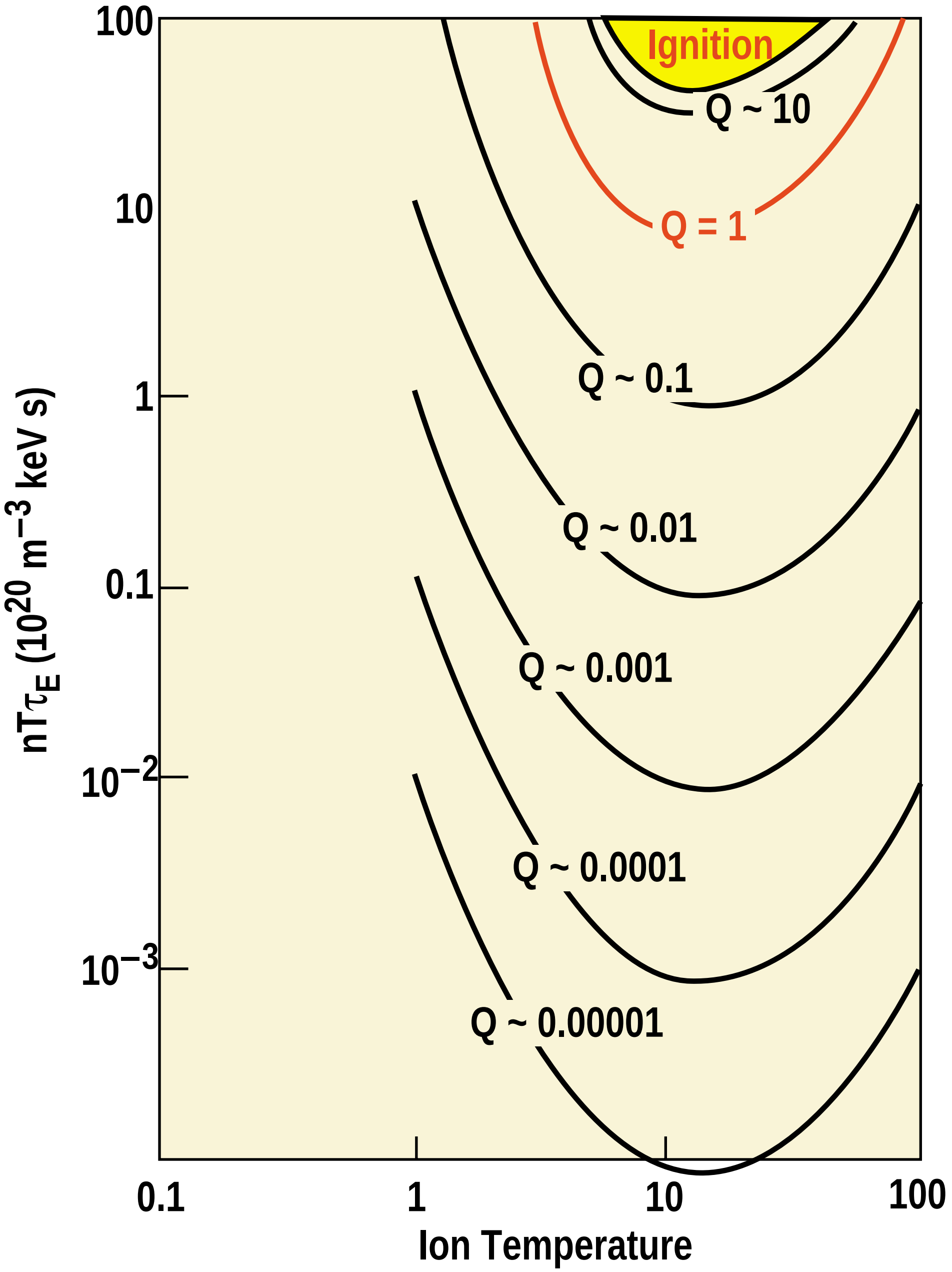
where $p\tau_E$ is minimum for given Q

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

and p is limited by MHD stability in

magnetically confined plasmas

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



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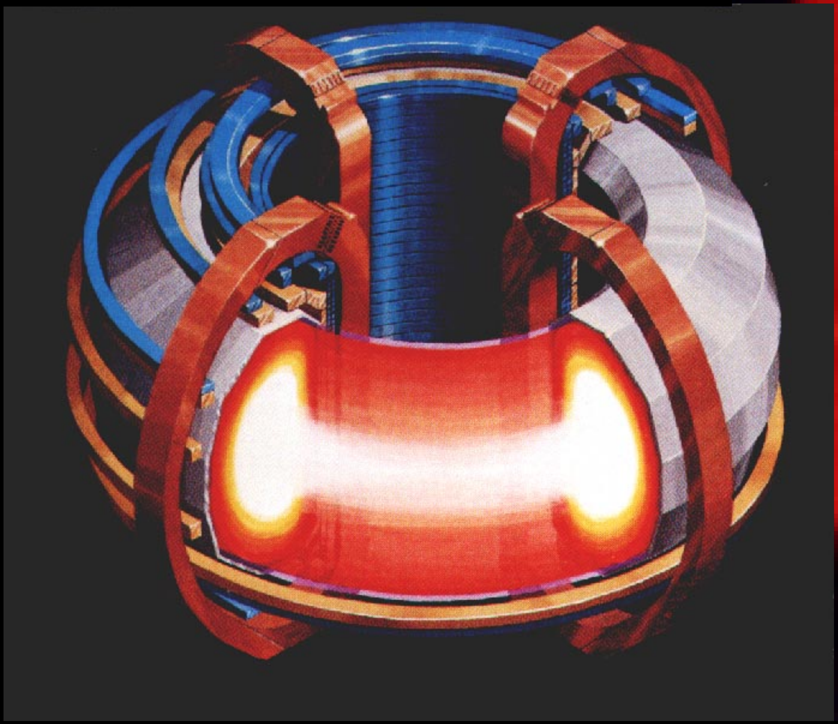
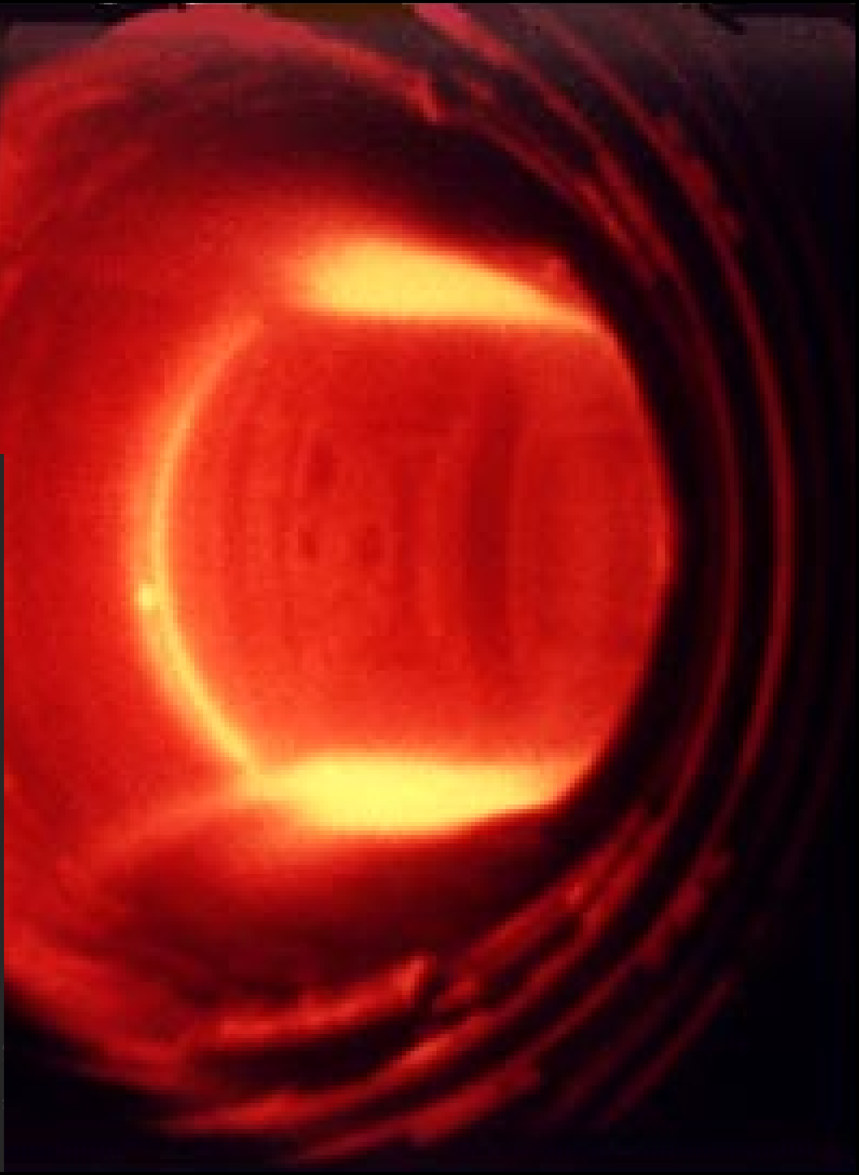
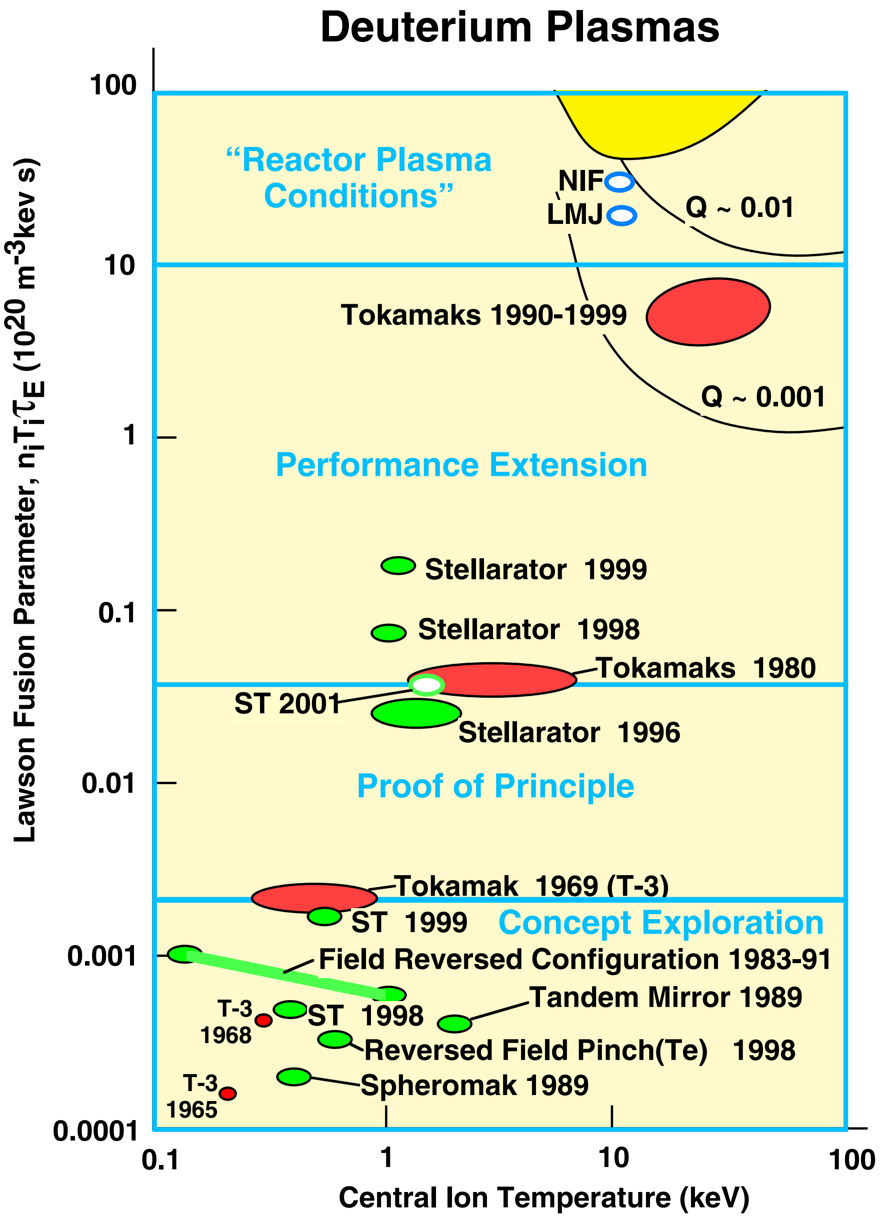
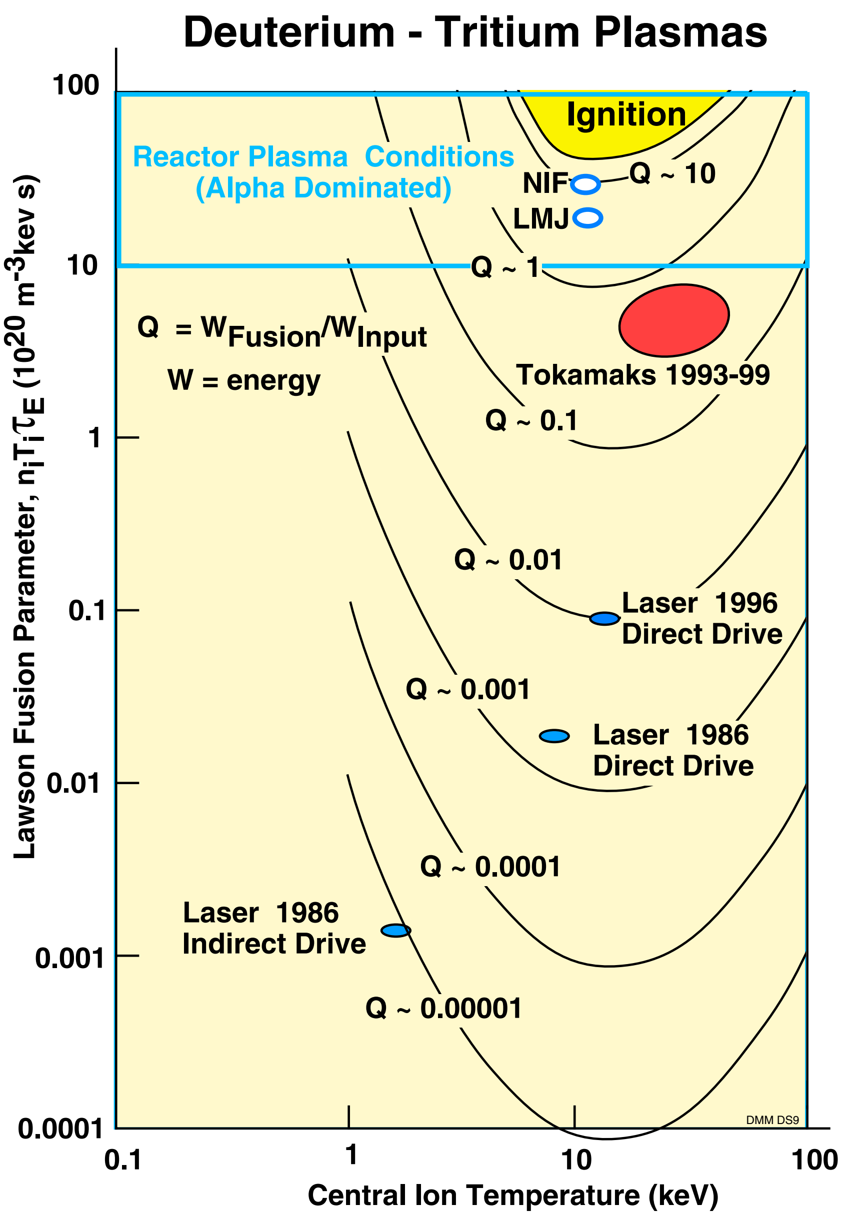
Toroidal Magnetic Confinement of Plasma





HOW CLOSE ARE WE TO BURNING PLASMA REGIME?





- Tokamak experiments have approached Q ~ 1 regime.

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 **EXOTHERMIC** 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⇐

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: $v_{Alfvén} \sim 5 \times 10^6$ 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.

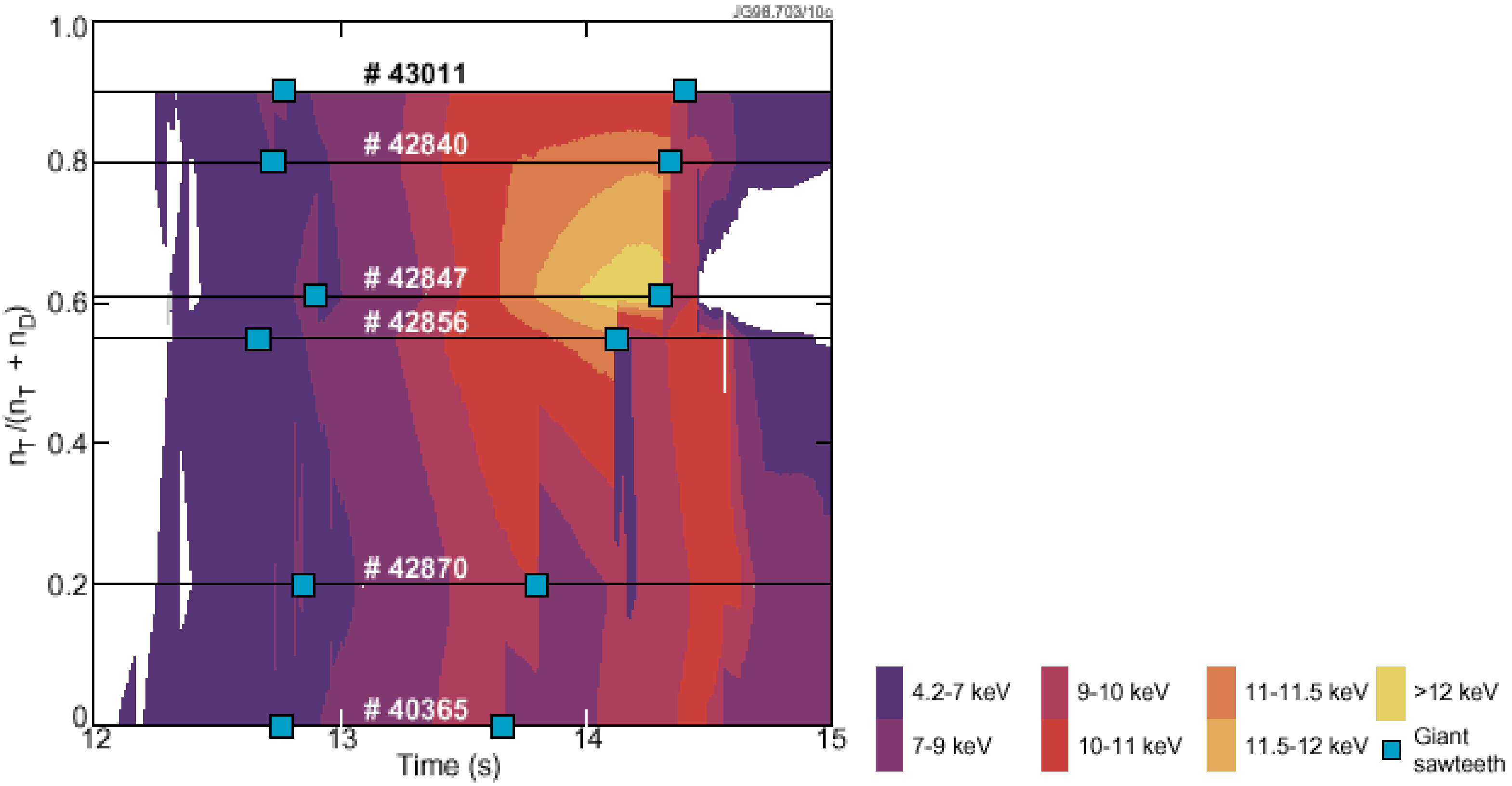
$Q \leq 1$ Results from TFTR and JET

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

JET DT EXPERIMENTS SHOW α-HEATING OF CENTRAL ELECTRONS



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

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]

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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 $R\nabla\beta_\alpha$

	Fusion Power Plant (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

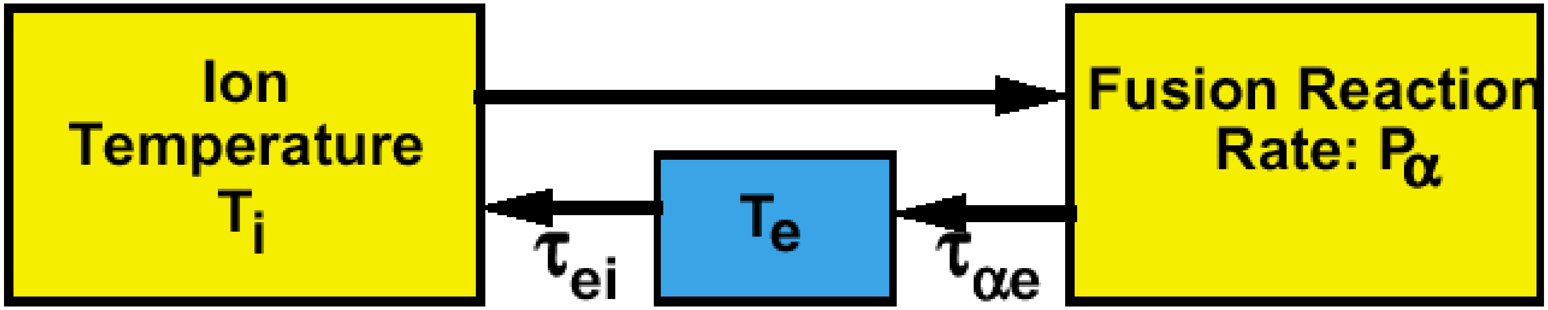
New Alpha Effects Expected on Scale of Burning Plasma

- Present experiments show alpha transport due to only a few global modes.
- Smaller value of $\square_{\square}$/<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.

$Q \sim 10$: Strong Non-Linear Coupling & Steady-State High □ Operation

BURNING PLASMA SYSTEM IS HIGHLY NON-LINEAR...

BASIC COUPLING OF FUSION ALPHA HEATING:



Ion Temperature T_i

Fusion Reaction Rate: P_α

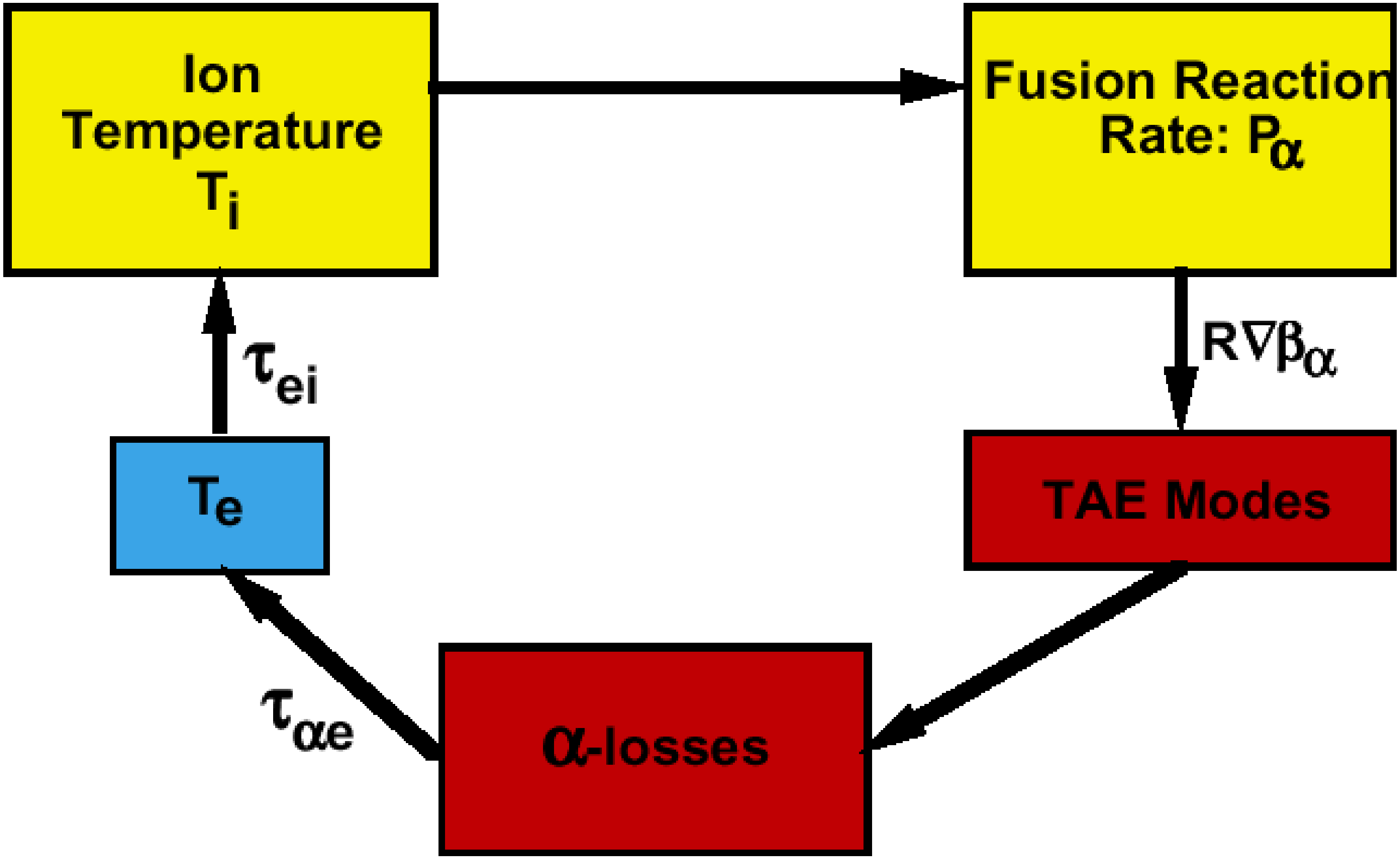
T_e

τ_{ei}

$\tau_{\alpha e}$

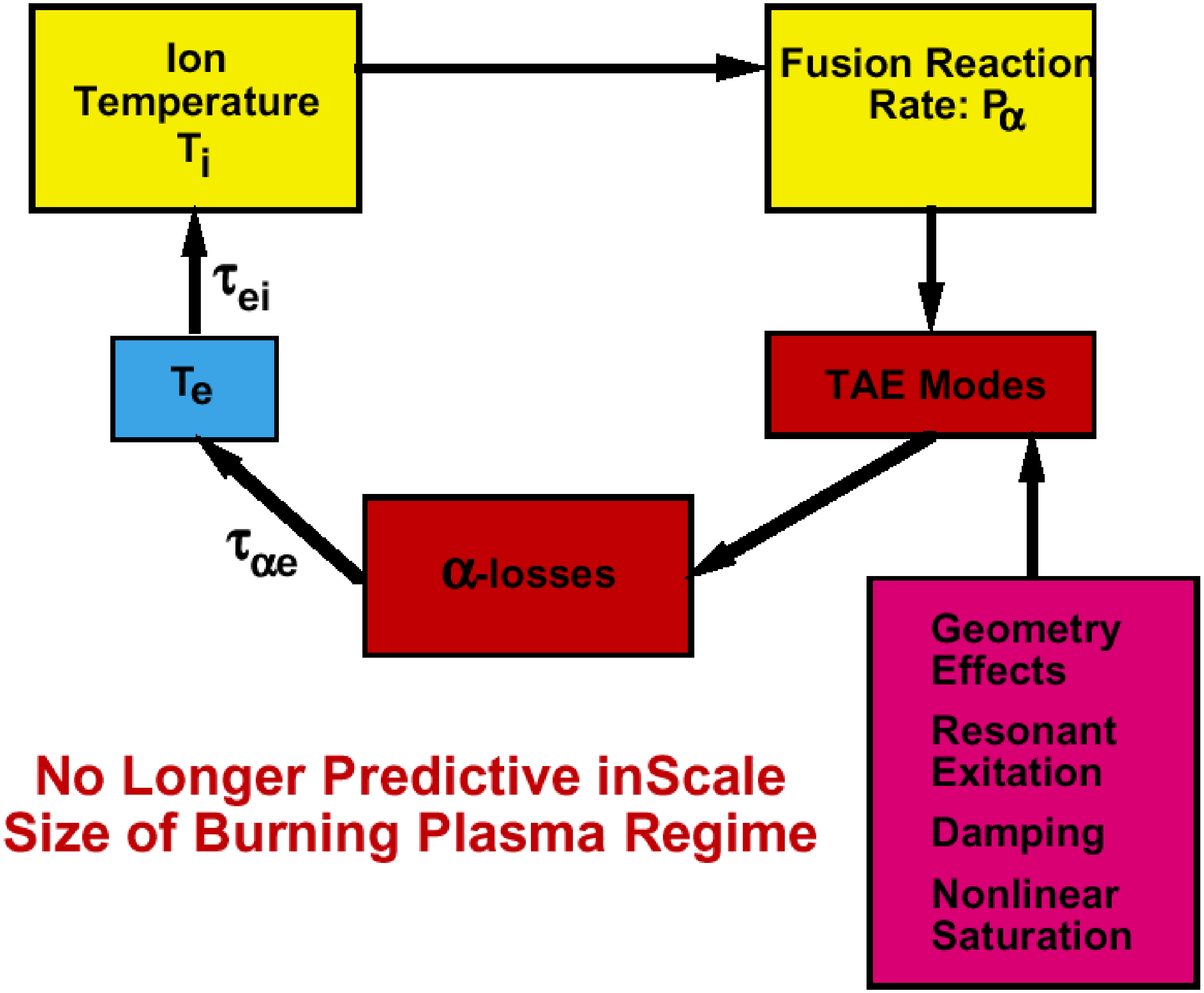
BURNING PLASMA SYSTEM IS HIGHLY NON-LINEAR...

ADD ALPHA DRIVEN TAE MODES:



BURNING PLASMA SYSTEM IS HIGHLY NON-LINEAR...

ADD COMPLEX PHYSICS OF ALPHA DRIVEN TAE MODES:



Ion Temperature T_i

Fusion Reaction Rate: P_α

TAE Modes

α-losses

T_e

τ_{ei}

$\tau_{\alpha e}$

Geometry Effects

Resonant Exitation

Damping

Nonlinear Saturation

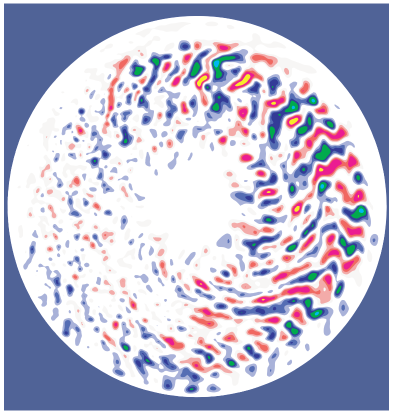
No Longer Predictive inScale Size of Burning Plasma Regime

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

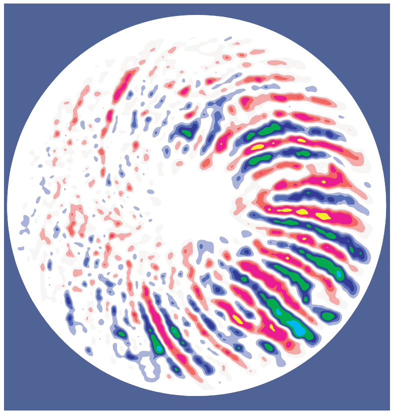
Gyrokinetic Theory

- Simulations show turbulent eddies disrupted by strongly sheared plasma flow

With Flow

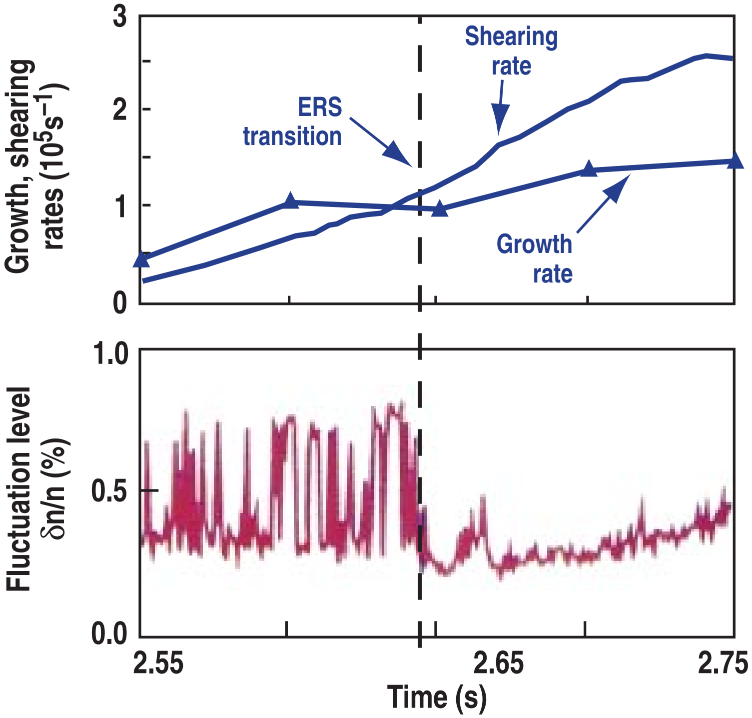


Without Flow



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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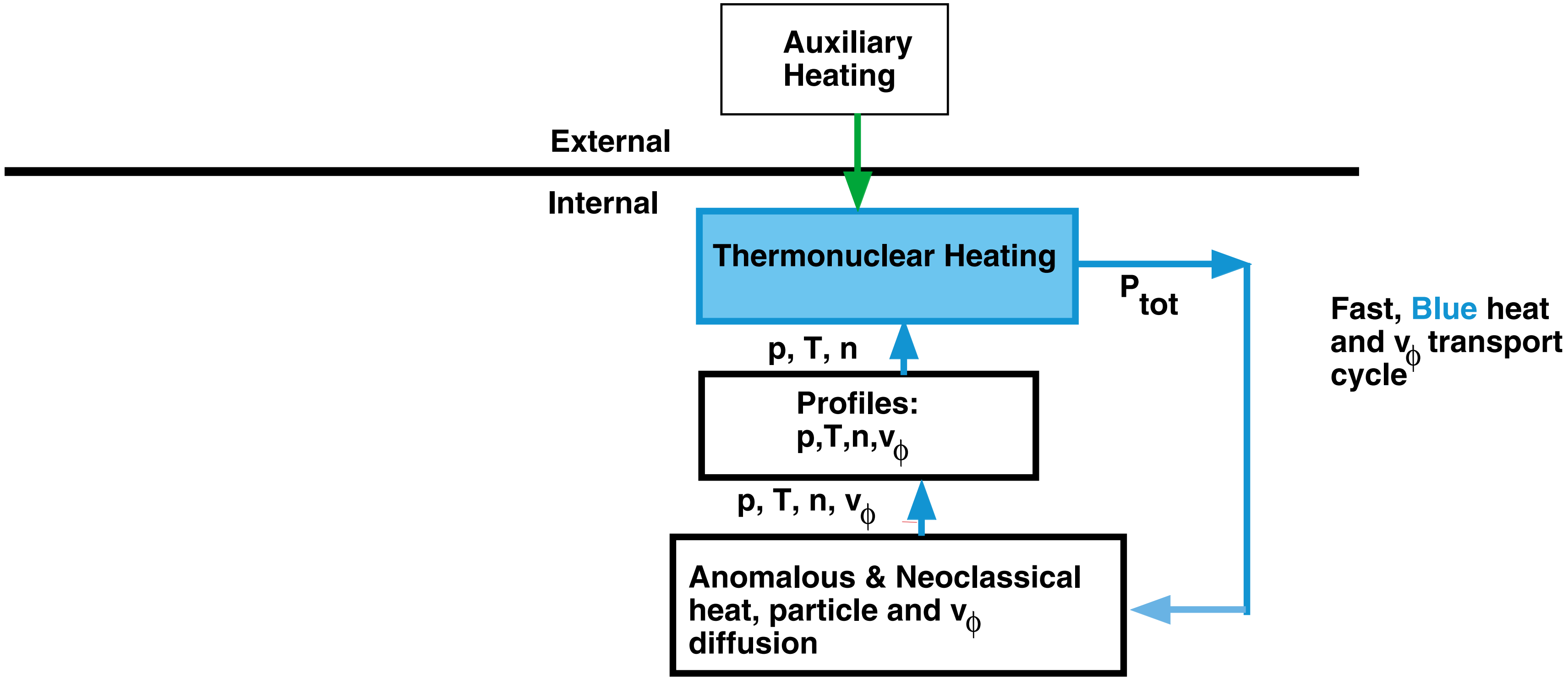
ADVANCED TOKAMAK NONLINEAR TRANSPORT COUPLINGS

Thermonuclear Heating

ADVANCED TOKAMAK NONLINEAR TRANSPORT COUPLINGS



Auxiliary Heating

External

Internal

Thermonuclear Heating

P_{tot}

Fast, Blue heat and v_ϕ transport cycle

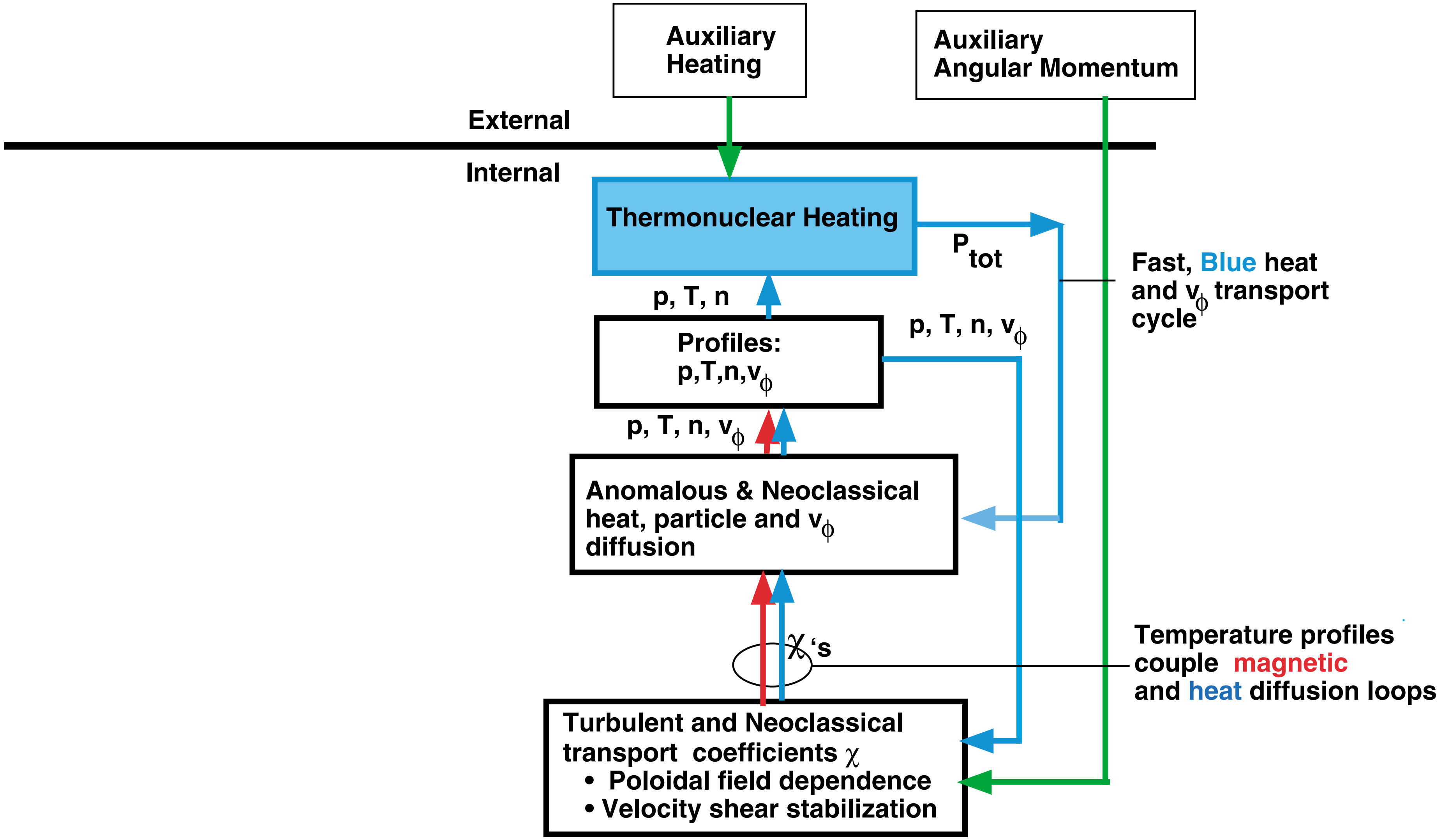
p, T, n

Profiles: p, T, n, v_ϕ

p, T, n, v_ϕ

Anomalous & Neoclassical heat, particle and v_ϕ diffusion

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

p, T, n, v_ϕ

Profiles: p,T,n,v_ϕ

p, T, n, v_ϕ

Anomalous & Neoclassical heat, particle and v_ϕ diffusion

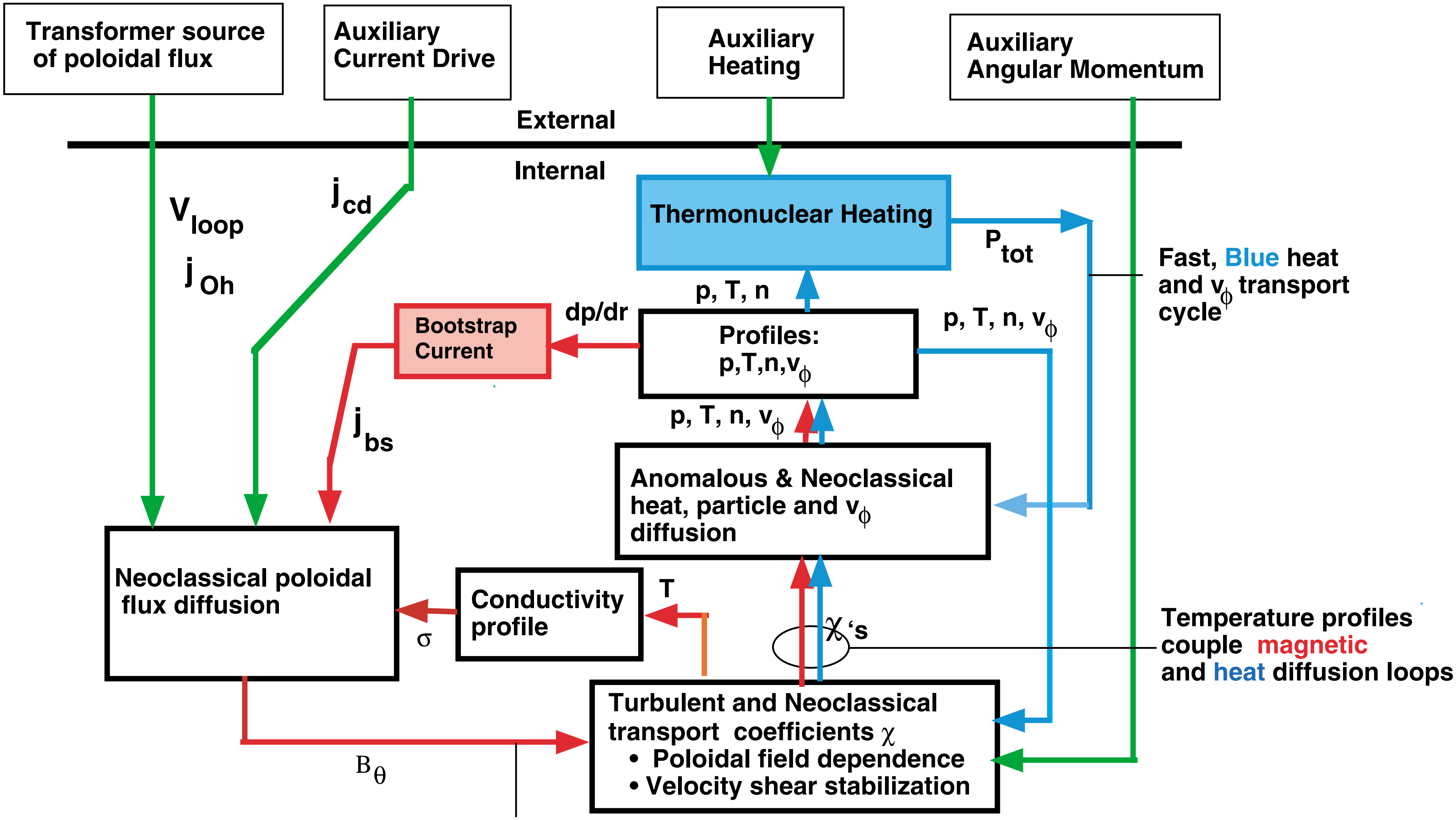
χ's

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}

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

Turbulent and Neoclassical transport coefficients χ

- Poloidal field dependence
- Velocity shear stabilization

B_θ

Fast, Blue heat and v_ϕ transport cycle

Temperature profiles couple magnetic and heat diffusion loops

Slow, red magnetic flux diffusion loop

$Q > 20$:

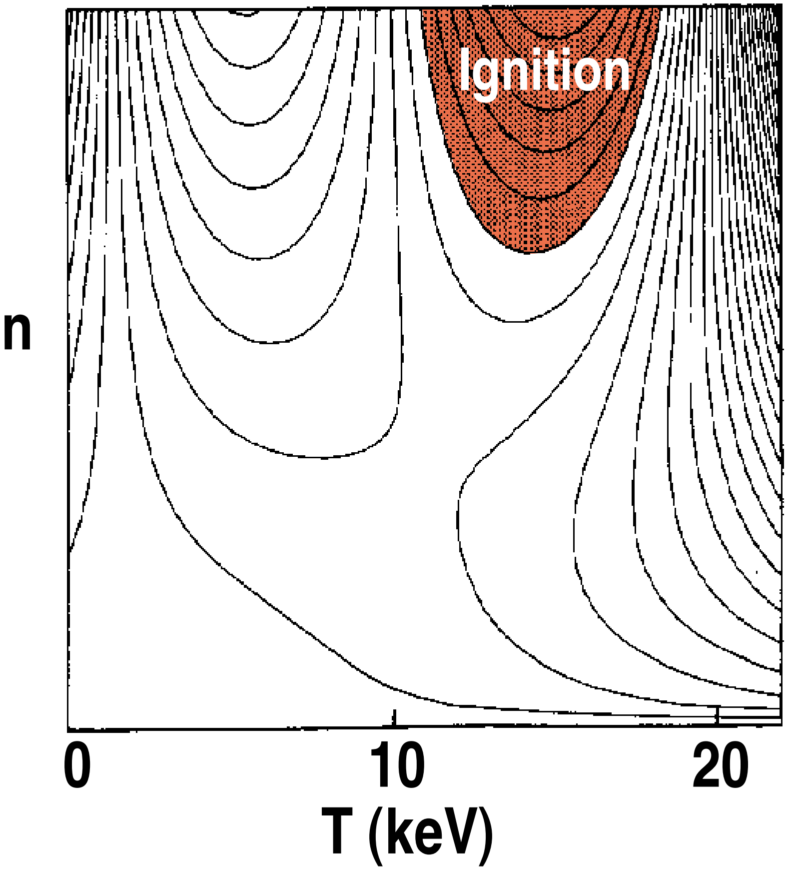
Burn Control & Ignition Transient Phenomena

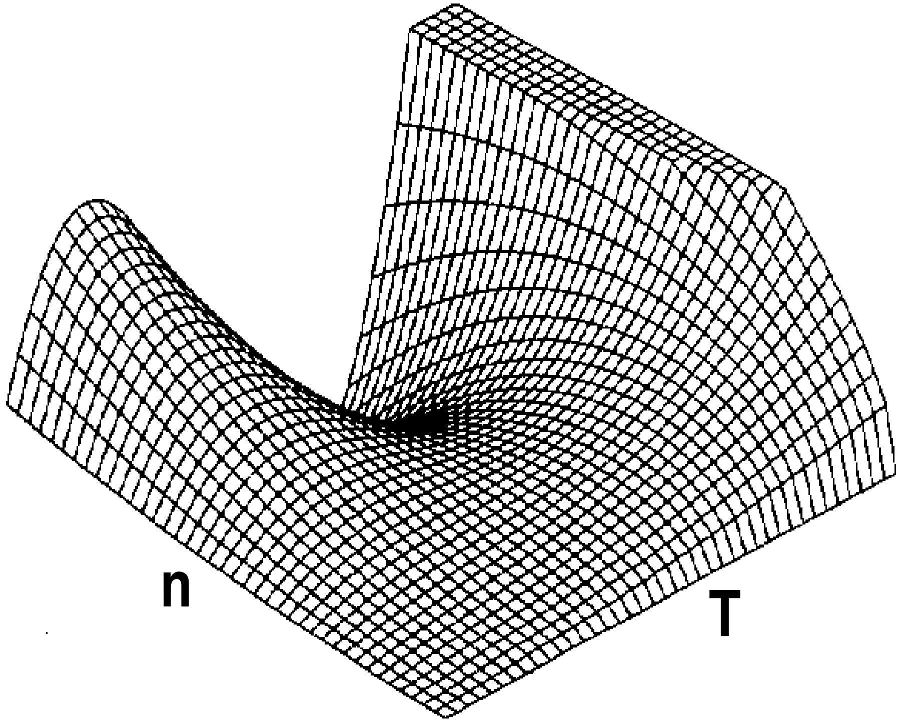
TRANSIENT BURN PHENOMENA WHEN Q $\gtrsim$ 20

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





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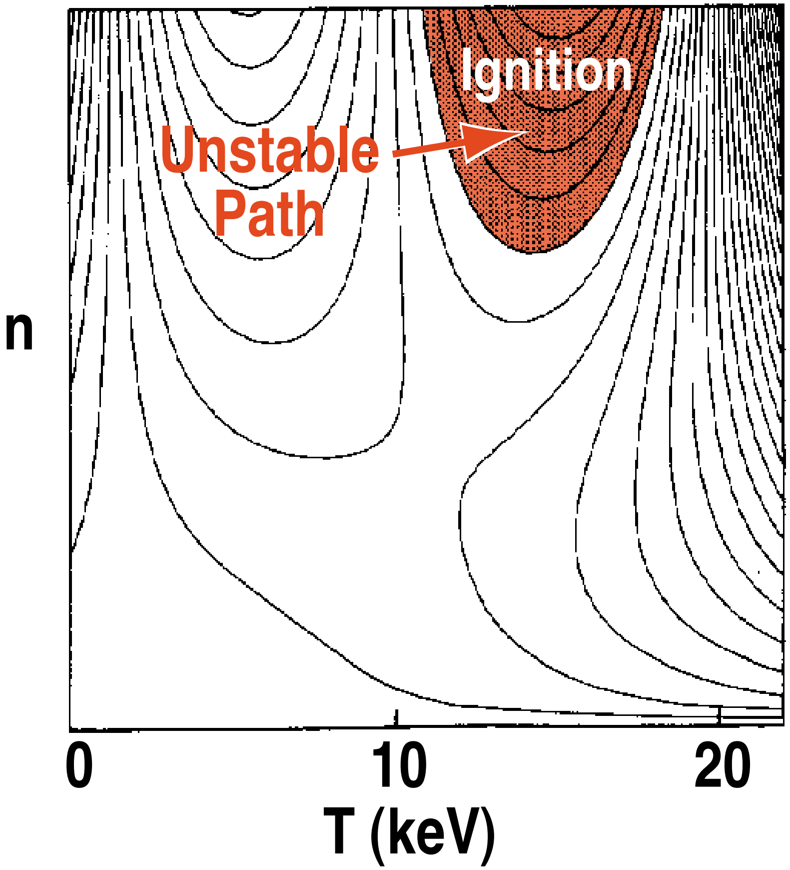

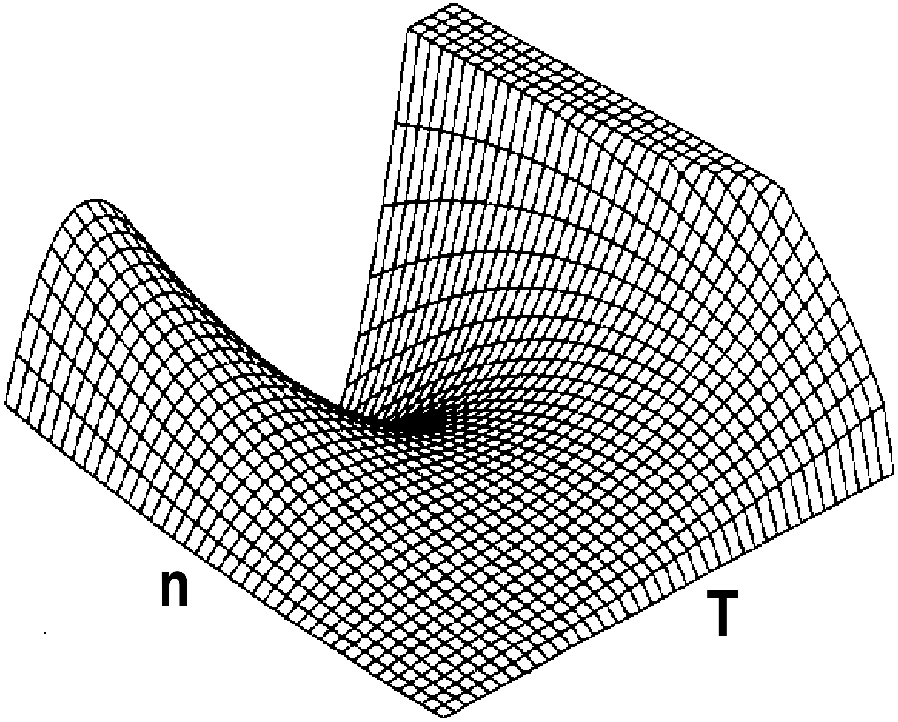

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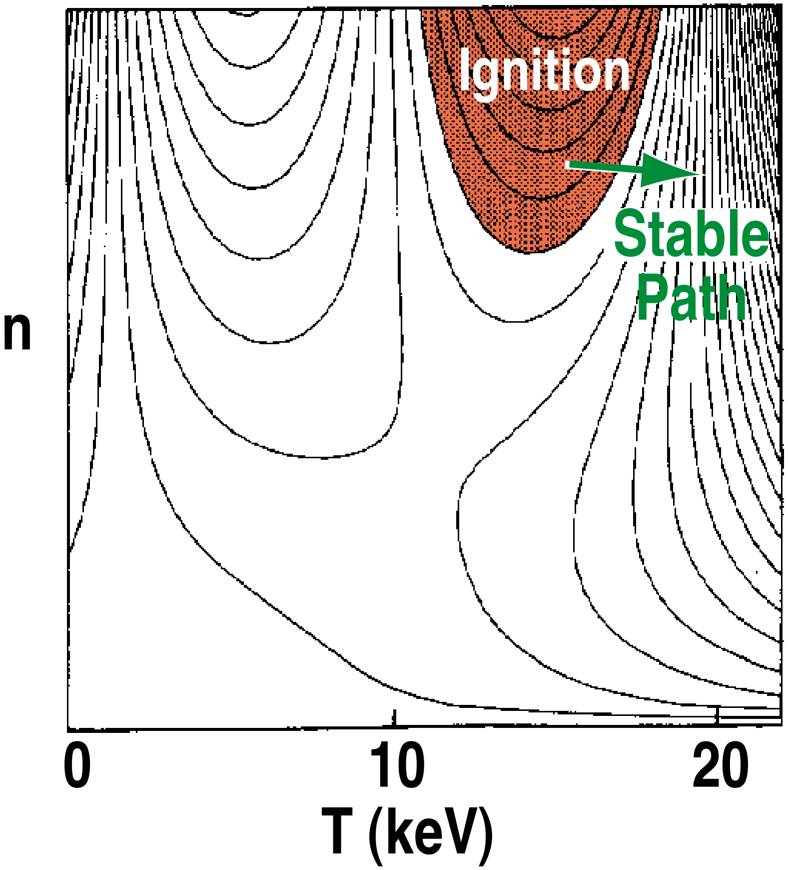

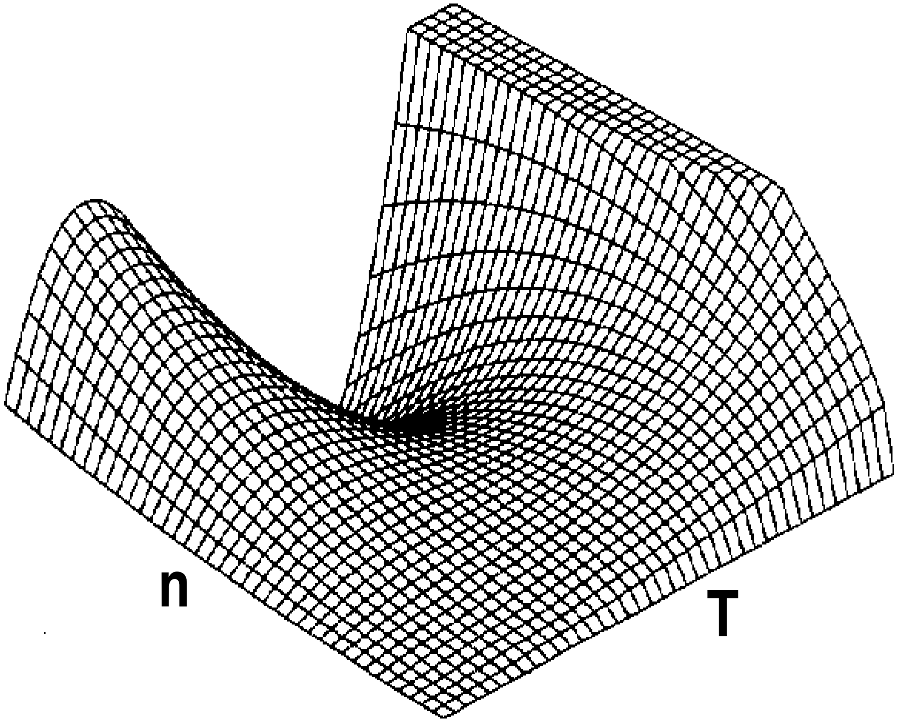

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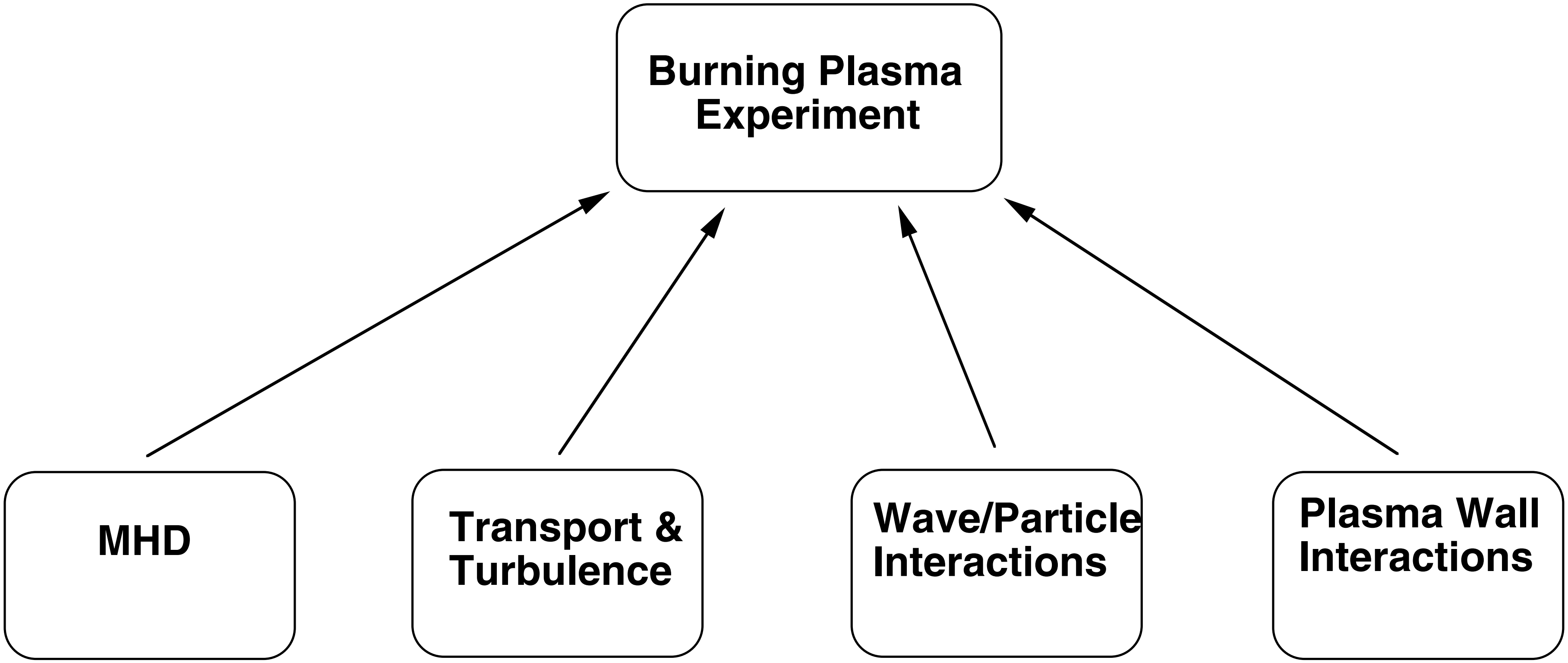
Taking the Next Step in Burning Plasmas: ITER

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



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 ≤ 1
- "standard model" of Alfvén Eigenmodes
- LHCD & ECCD used for near SS & mode control

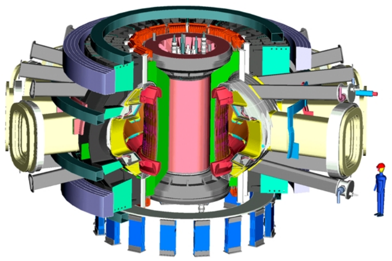
Plasma Wall Interactions

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

Burning Plasma Physics - The Next Frontier

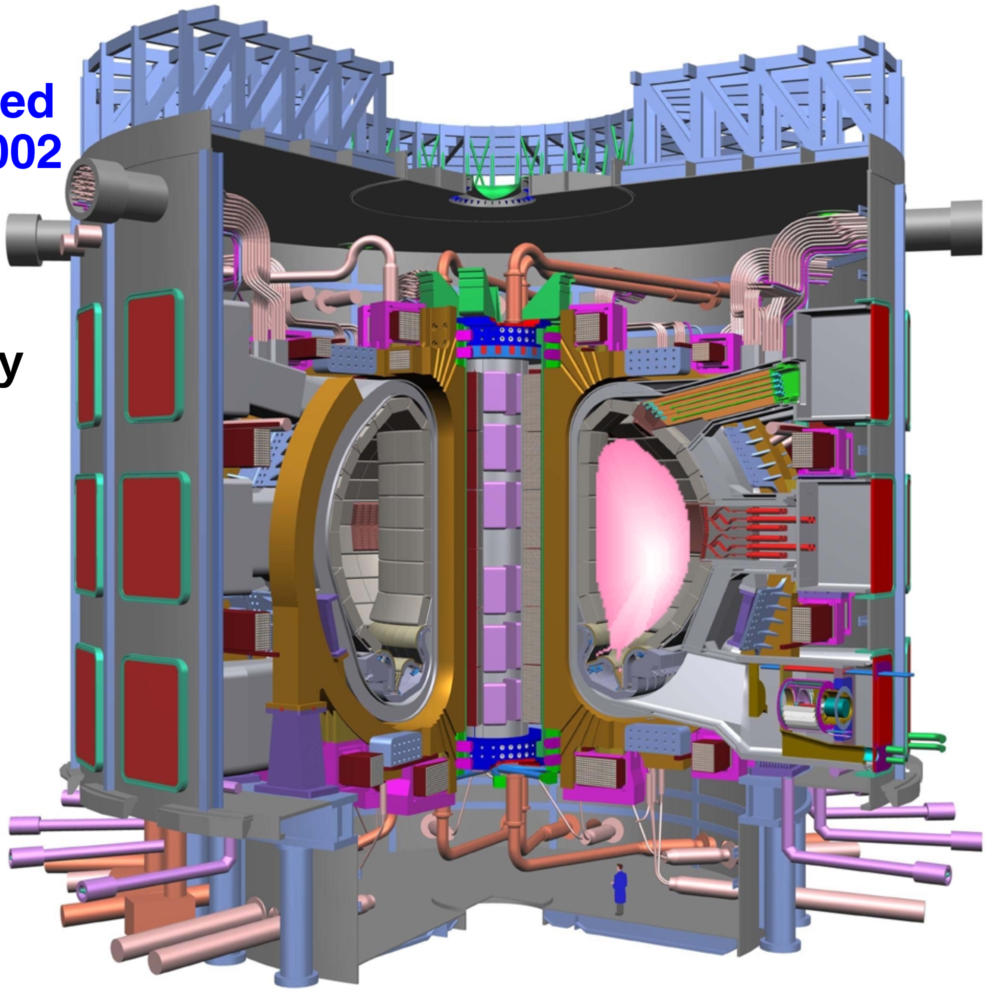
Three Options Examined by US at Snowmass 2002

FESAC & Nat'l Academy endorsed US try to procede with ITER



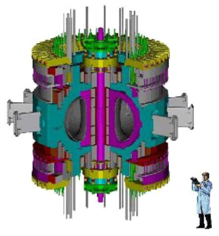
FIRE

US Based
International Modular Strategy



ITER

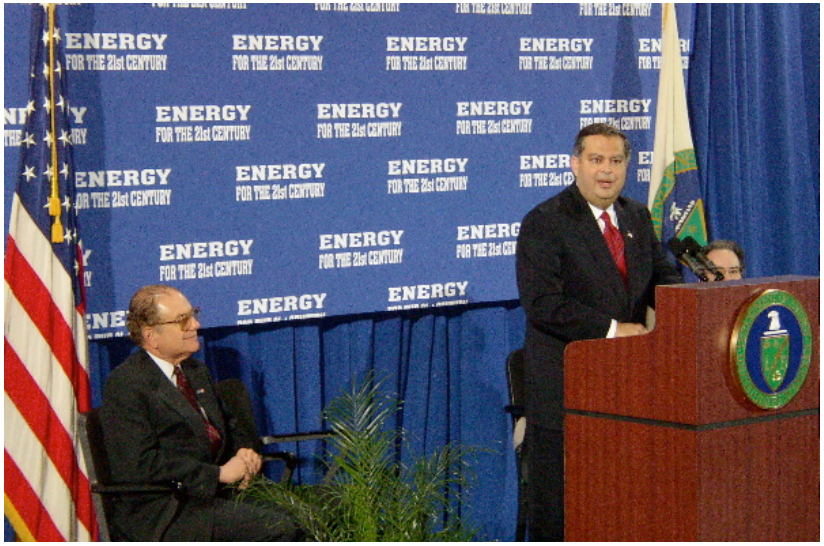
JA, EU or CA Based
International Partnership



IGNITOR

Italian Based
International Collaboration

“I am pleased to announce today, that President Bush has decided that the United States will join the international negotiations on ITER.”



Secretary of Energy Spencer Abraham
30 January 2003

…we know that this experiment is a crucial element in the path forward to satisfying global energy demand.

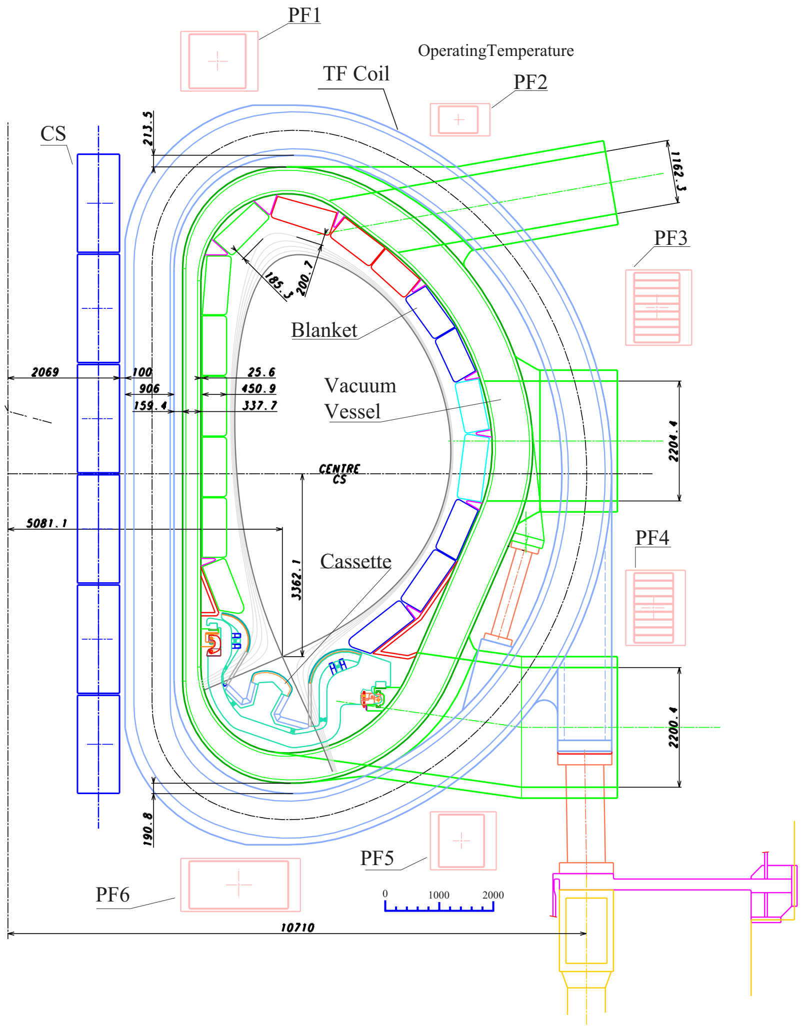
President Bush has faith in American science. And he knows the huge energy challenges for the United States and for the world that fusion science seeks to tackle.

And let me tell you, he is not one for taking baby steps when leaps are called for.

By the time our young children reach middle age, fusion may begin to deliver energy independence and energy abundance to all nations rich and poor. Fusion is a promise for the future we must not ignore.

But let me be clear, our decision to join ITER in no way means a lesser role for the fusion programs we undertake here at home. It is imperative that we maintain and enhance our strong domestic research program … at the universities and at our other labs.

The ITER Design: Poloidal Elevation



	ITER
Major radius	6.2 m
Minor radius	2.0 m
Plasma current	15 MA
Toroidal magnetic field	5.3T
Elongation / triangularity	1.85 / 0.49
Fusion power amplification	≥ 10
Fusion power	~400 MW
Plasma burn duration	~400 s

ITER parameters in Q = 10 reference inductive scenario

ITER Design Goals

Physics:

- ITER is designed to produce a plasma dominated by α-particle heating
- produce a significant fusion power amplification factor ($Q \geq 10$) in long-pulse operation
- aim to achieve steady-state operation of a tokamak ($Q = 5$)
- retain the possibility of exploring ‘controlled ignition’ ($Q \geq 30$)

Technology:

- demonstrate integrated operation of technologies for a fusion power plant
- test components required for a fusion power plant
- test concepts for a tritium breeding module

ITER PLANS & STATUS

AIMS AT CONSTRUCTION START IN 2006 – FIRST PLASMA 2015:

SIX PARTNERS NEGOTIATING TO CONSTRUCT

CHINA	JAPAN
EU	RUSSIA
KOREA	USA

INTERNATIONAL NEGOTIATIONS MUST CHOOSE SITE

JAPAN	OFFERED SITE IN ROKKASHO
EU	OFFERED SITE IN CADARACHE

⇒ CONSENSUS DECISION REQUIRED: SPRING 2004?⇐

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.

- DRAMATIC PROGRESS IN 1990'S HAS ESTABLISHED A SOUND BASIS FOR EXPLORATION OF THE BURNING PLASMA REGIME.
- US WORKING WITH INTERNATIONAL COMMUNITY TO BUILD FIRST MAGNETICALLY CONFINED BURNING PLASMA: ITER
- HIGH LEVEL OF EXCITEMENT IN THE PLASMA PHYSICS COMMUNITY AS WE (HOPEFULLY) SOON START CONSTRUCTION OF LONG ANTICIPATED BURNING PLASMA EXPERIMENT.