The Science Frontier of MFE Burning Plasma Physics

Gerald Navratil
Columbia University

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Outline

- Introduction to Burning Plasmas
- Examples of Frontier Science in Burning Plasmas
- Comments on How to Explore this Exciting New Regime

Has been extensive community effort to define BP Science

- 1999 Fusion Summer Study (Snowmass)
- 2000 UFA Burning Plasma Scince Workshop I (Austin)
- 2001 UFA Burning Plasma Scince Workshop II (San Diego)
- 2001 FESAC Burning Plasma Panel Report

Plasma Requirements for a Fusion-Dominated Plasma

Power Balance $D + T = n(14.1\text{MeV}) + He(3.5\text{MeV})$

$$P_{aux\text{-}heat} + n^2 \langle\sigma v\rangle U_\alpha V_p/4 - C_B T^{1/2} n_e^2 V_p = 3nkTV_p/\tau_E + d(3nkTV_p)/dt$$

where: $n_D = n_T = n_e/2 = n/2$, $n^2 \langle\sigma v\rangle U_\alpha V_p/4 = P_\alpha$ **is the alpha heating power,** $C_B T^{1/2} n_e^2 V_p$ **is the radiation loss,** $W_p = 3nkTV_p$ **and** $\tau_E = W_p/(P_{aux\text{-}heat} - dW_p/dt)$ **is the energy confinement time.**

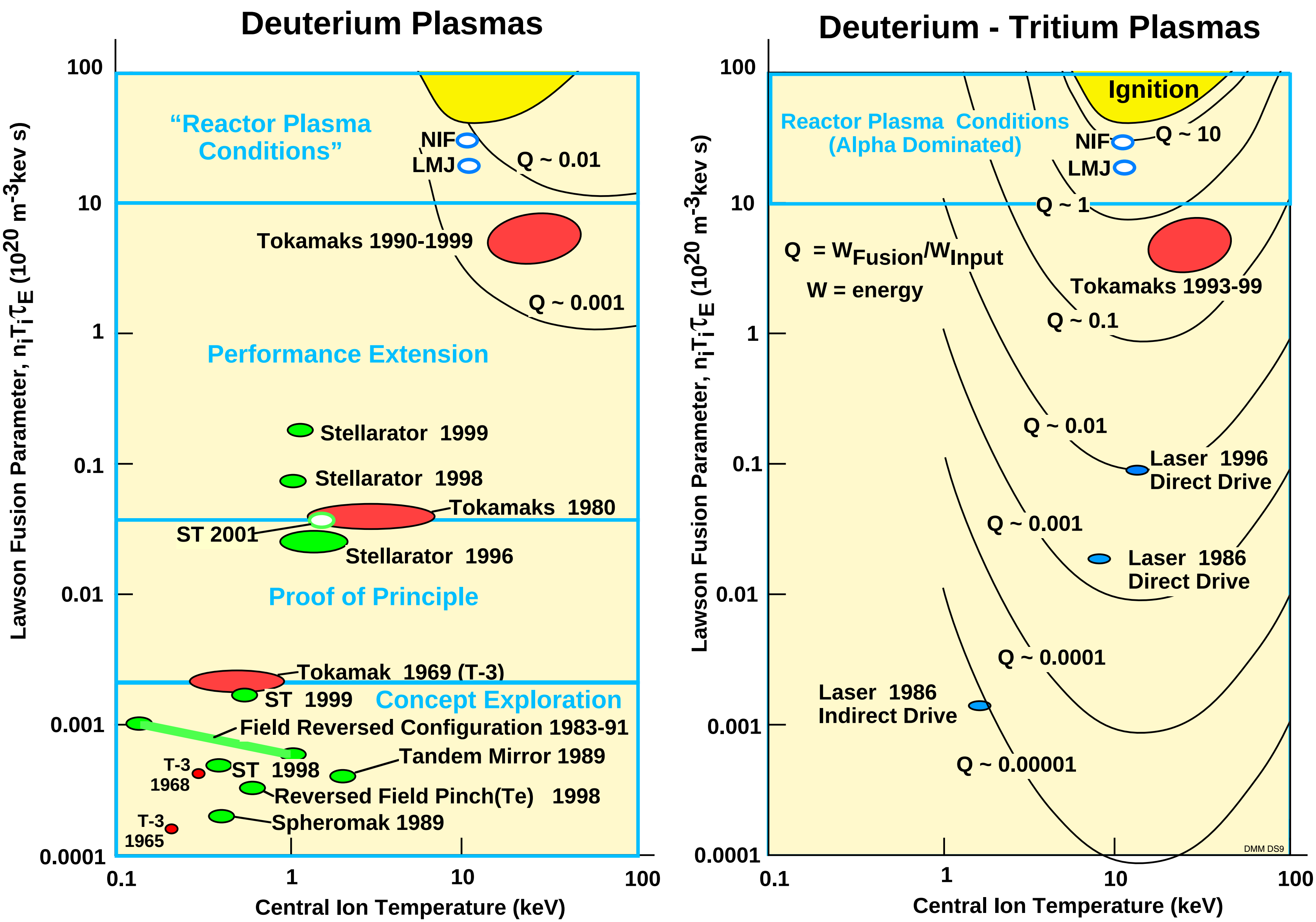
In Steady-state:

$$n\tau_E = \frac{3kT}{\langle\sigma v\rangle U_\alpha (Q+5)/4Q - C_B T^{1/2}}$$

where $Q = P_{fusion}/P_{aux\text{-}heat}$ **Palpha/(Palpha + Paux-heat) = Q / (Q + 5)**

$Q = 1$ **is Plasma Breakeven,** $Q = \infty$ **is Plasma Ignition**

How Close Are We to the Burning Plasma Regime?



The tokamak is sufficiently advanced to permit the design, construction and initiation of a next step burning plasma experiment within the next decade that could address the fusion plasma and self-heating issues for magnetic fusion.

THERE ARE TWO TYPES OF BURNING PLASMA ISSUES...

- GETTING THERE & STAYING THERE:
  - + ENERGY CONFINEMENT FOR Q ≥ 5
  - + STABILITY AT REQUIRED PRESSURE FOR Q ≥ 5
  - + MAINENANCE OF PLASMA EQUILBRIUM LONG ENOUGH
  - + POWER, FUELING, & REACTION PRODUCT CONTROL

- NEW SCIENCE PHENOMENA TO BE EXPLORED
  - + **Q ≥ 5:** ALPHA EFFECTS ON STABILITY & TURBULENCE
  - + **Q ≥ 10:** STRONG, NON-LINEAR COUPLING BETWEEN ALPHAS, PRESSURE DRIVEN CURRENT, TURBULENT TRANSPORT, MHD STABILITY, & BOUNDARY-PLASMA
  - + **Q ≥ 20:** STABILITY, CONTROL, AND PROPAGATION OF THE FUSION BURN AND FUSION IGNITION TRANSIENT PHENOMENA

Many New and Exciting Phenomena to Study in a BP

New Elements in a Burning Plasmas:

Self-Heated by Fusion Alphas

Significant Isotropic Energetic Population of 3.5 MeV alphas

Some key new physical effects expected:

- Alpha Effects:
  - + m=1 sawtooth for normal q-profile plasmas
  - + Alfvén eigenmodes driven by super-alfvénic alphas
- Highly Non-linear interaction of alpha self-heating with strongly coupled Advanced Tokamak Plasmas
- Plasma/Boundary Interaction - Edge Plasma Effects
- Burn Control and Transients at high $Q \geq 20$

ALPHA PARTICLE EFFECTS: KEY DIMENSIONLESS PARAMETERS

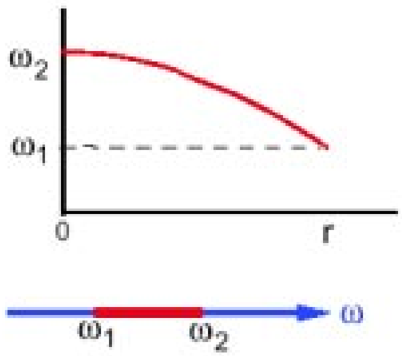
- Three dimensionless parameters will characterize the physics of alpha-particle-driven instabilities:
  - Alfven Mach Number: $v_\alpha/v_A(0)$
  - Number of Alpha Larmor Radii (inverse): ρ_α/a
  - Maximum Alpha Pressure Gradient (scaled): Max $R\nabla\beta_\alpha$

	Range of Interest (e.g. ARIES-RS/AT)	ITER-FEAT (reference)	FIRE (reference)
$v_\alpha/v_A(0)$	$\approx$ 2.0	1.9	2.2
$\rho_\alpha/\langle a\rangle$	$\approx$ 0.02	0.016	0.028
Max $R\nabla\beta_\alpha$	0.03-0.15 *	0.05	0.035

COMPLEX TAE MODE SPECTRUM IN BP ⇒ LARGE ALPHA TRANSPORT

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

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

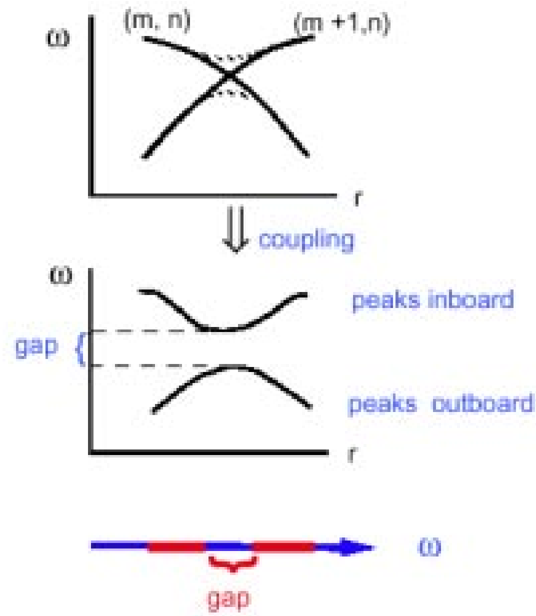


continuous spectrum,

shear Alfven resonance

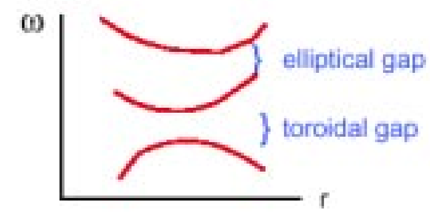
2D torus

Axisymmetric, circular



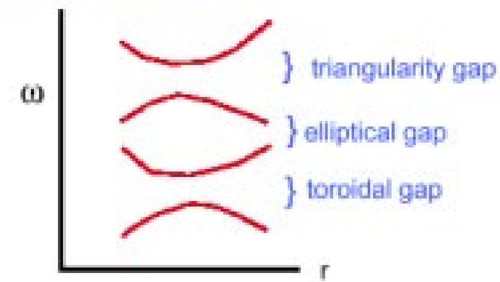
With elliptic cross-section

coupling of m, m + 2

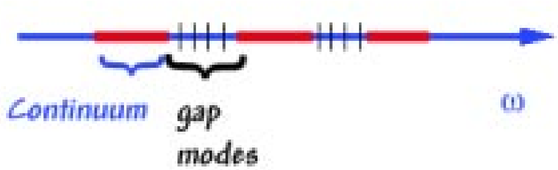


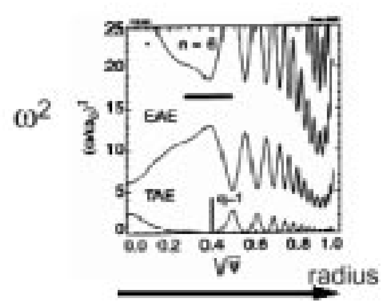
With triangularity

coupling of m, m + 3



Discrete Modes in Gaps

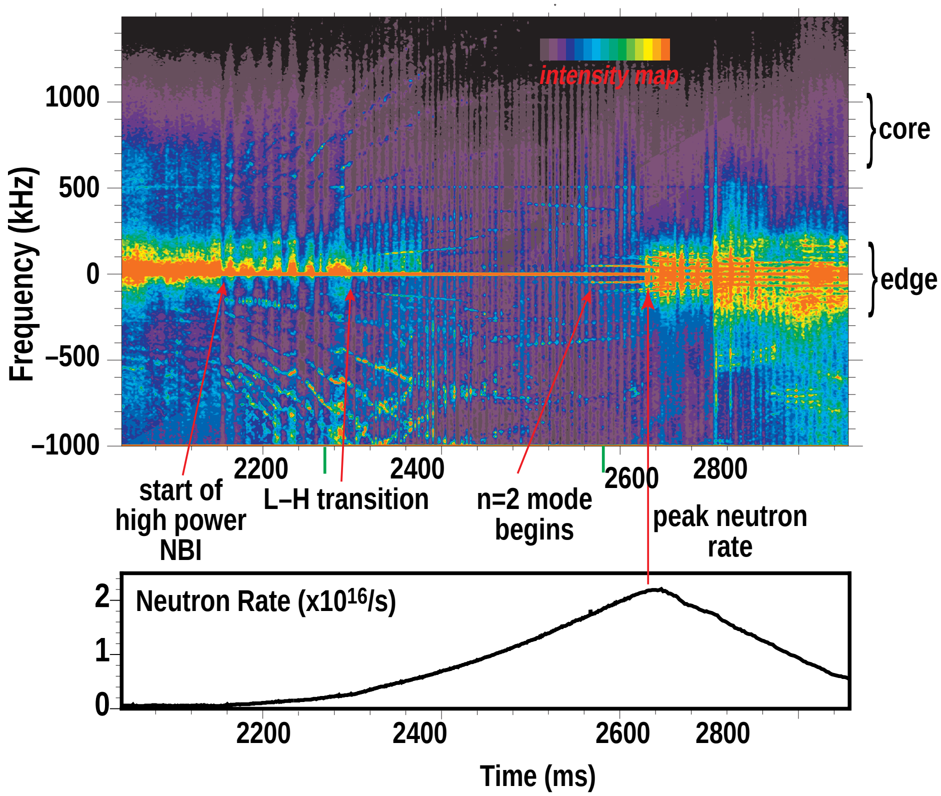




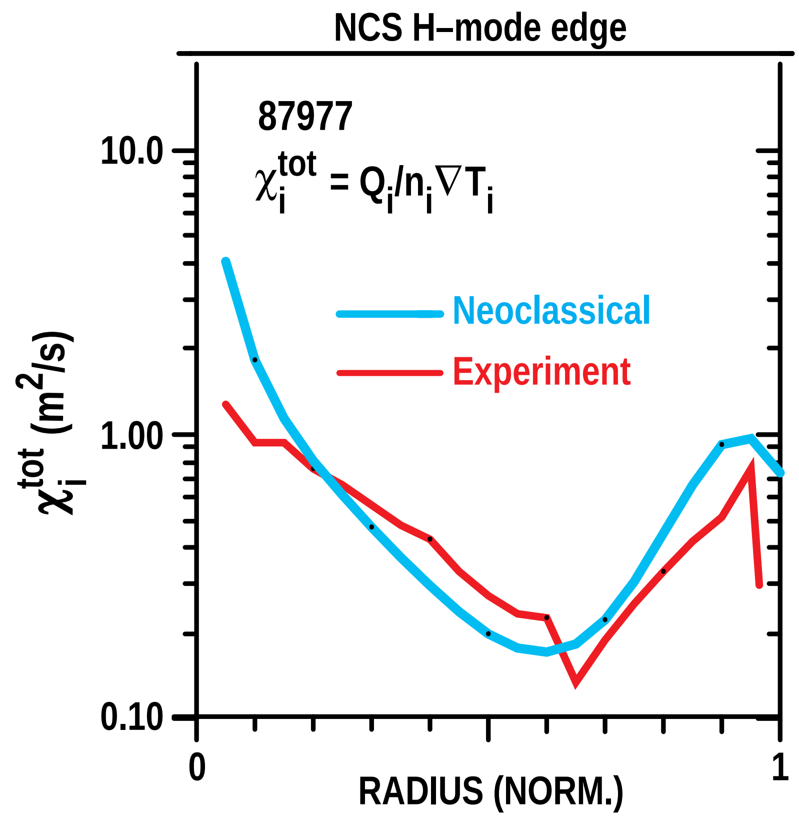
- Alfvén eigenmodes driven by free energy of expansion of alpha particles
- Present experiments show alpha transport due to few global modes
- Smaller value of $r_a/\langle a \rangle$ in a Burning Plasma may lead to "sea" of resonantly overlapping unstable modes & **large alpha transport**.

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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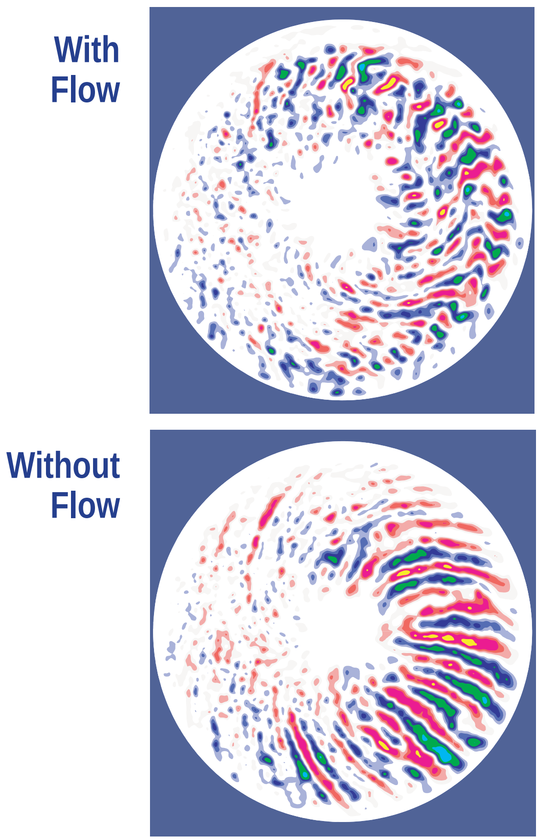
SHEARED FLOW CAUSES TRANSPORT SUPPRESSION

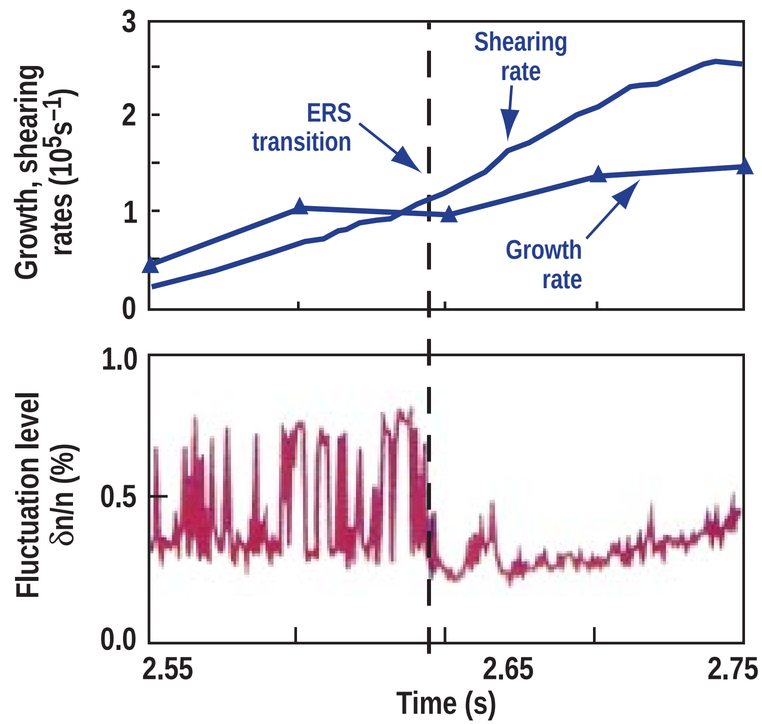
Gyrokinetic Theory

- 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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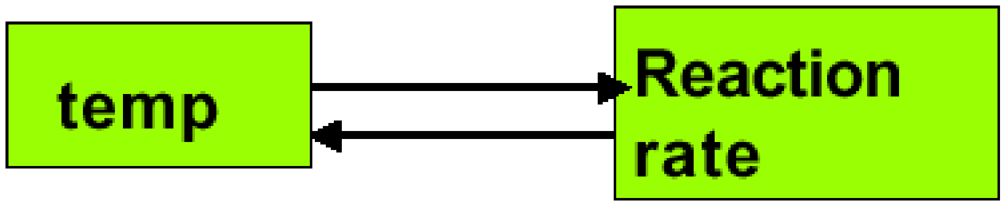
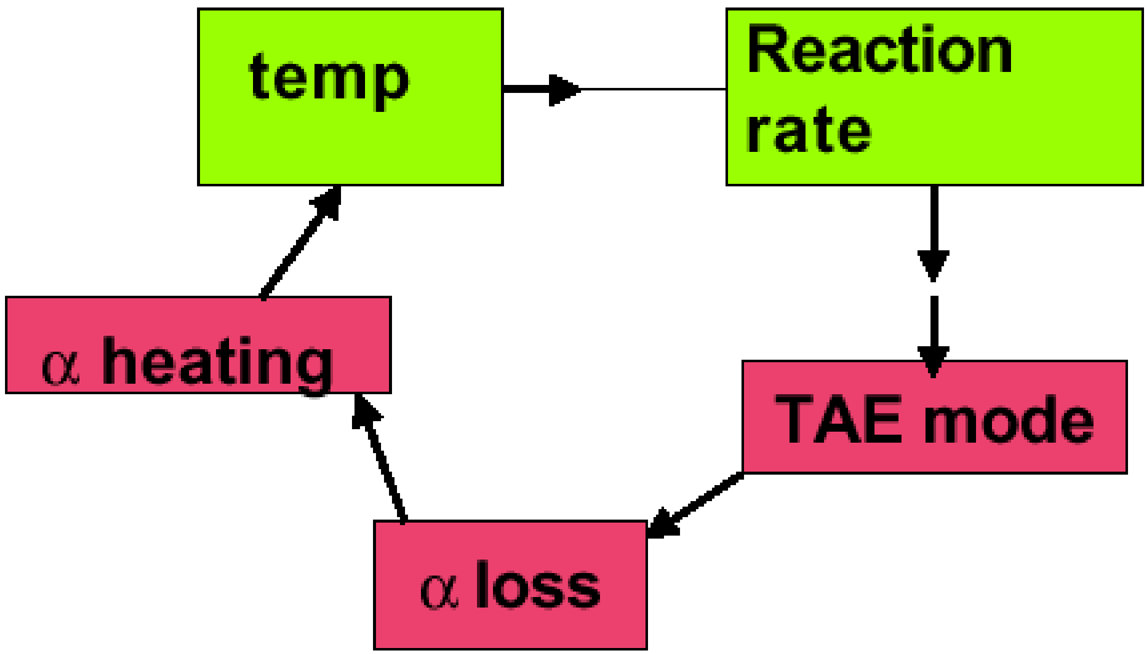
Burning Plasma System is Highly Non-Linear...

Basic Coupling of Fusion Alpha Heating:



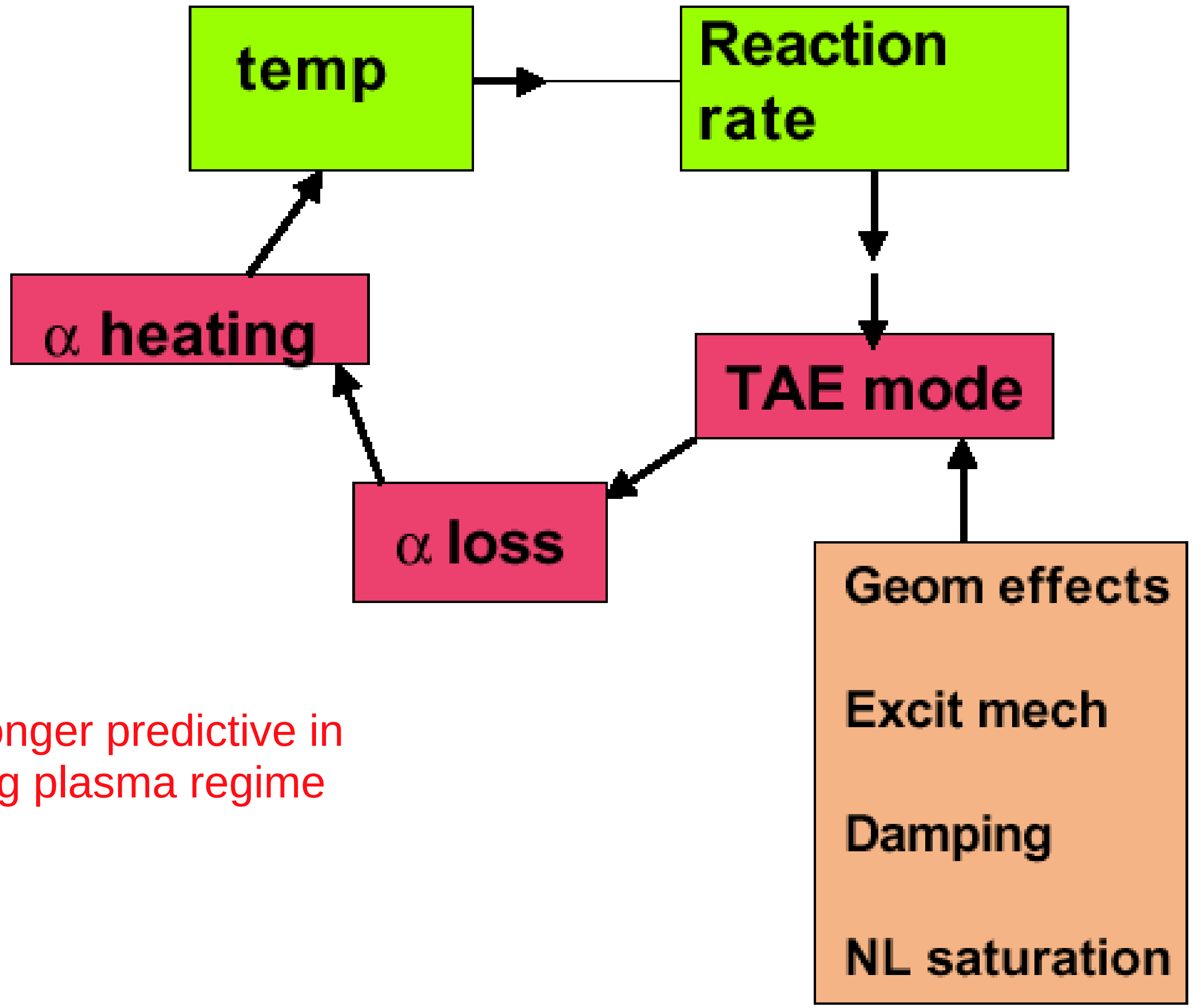
Burning Plasma System is Highly Non-Linear...

Add Alpha Driven TAE Modes:



Burning Plasma System is Highly Non-Linear…

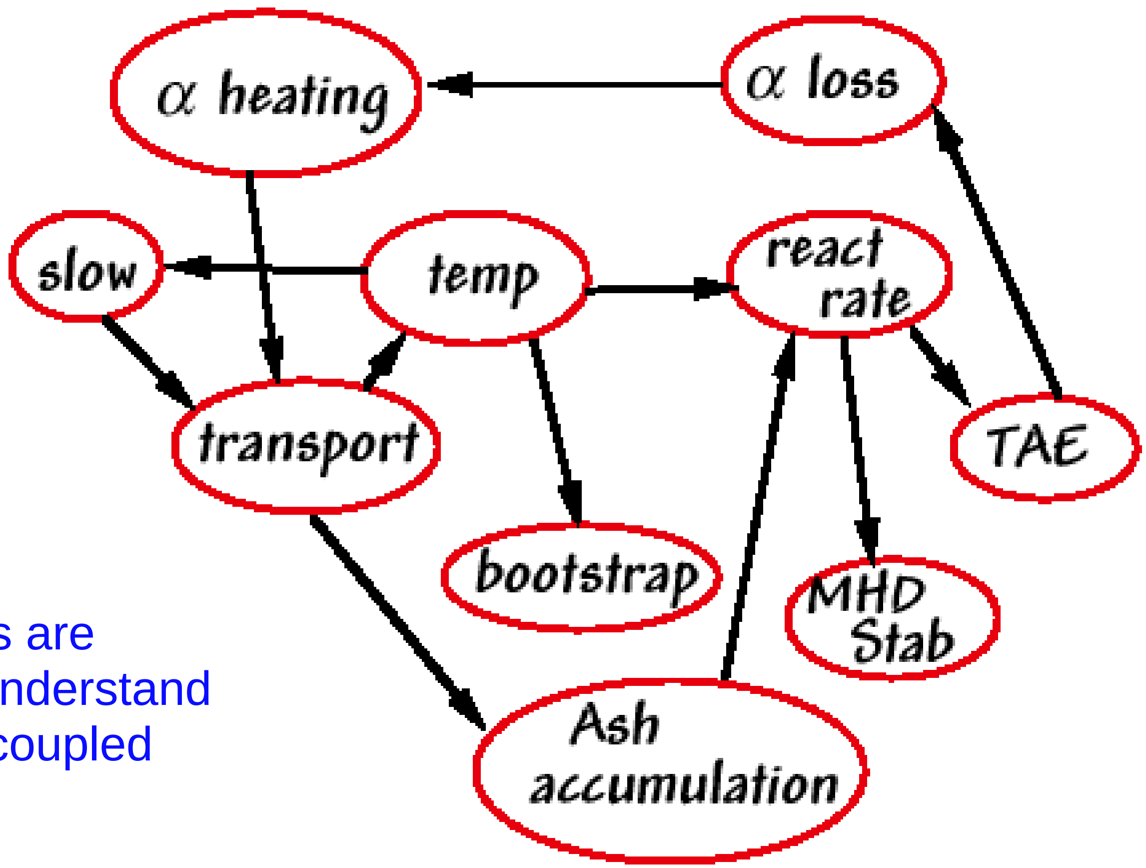
Add Complex Physics of Alpha Driven TAE Modes:



- No longer predictive in burning plasma regime

Burning Plasma System is Highly Non-Linear...

Add Coupling to Energy Transport, Bootstrap Current, MHD Equilibrium & Stability, and Turbulence Suppression:

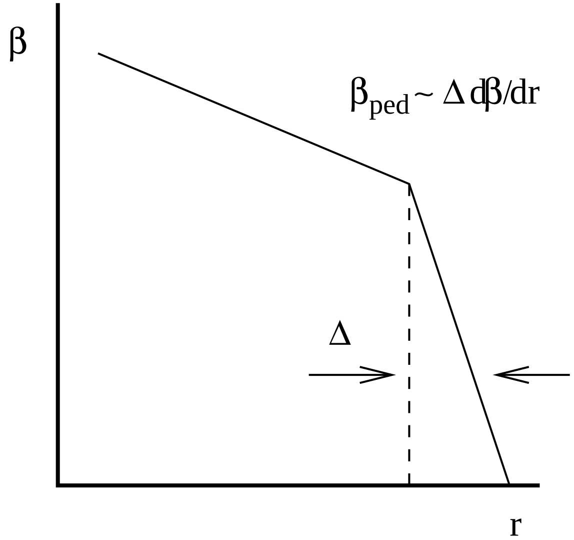


• Experiments are essential to understand this strongly coupled regime

Edge pedestal scalings very uncertain...

- **Wide range of theory & expt. evidence:** $\Delta/R \propto \rho_{*\theta}$ **(JT-60U, JET),** $\rho_{*\theta}^{2/3-1/2}$, $\beta_{pol}^{1/2}\rho_{*}^{0}$

Hammett, Dorland presented at UFA BPS - Workshop1



- **Making two assumptions (and use Uckan formula for** $q_{95}RI_p/(Ba^2)$**):**

  1. **Width** $\Delta \propto \sqrt{\epsilon}\rho_\theta \propto \rho q/(\kappa\sqrt{\epsilon})$ **(scaling preferred by two largest tokamaks)**
  2. **stability limit** $\partial\beta/\partial r \propto [1+\kappa^2(1+10\delta^2)]/Rq^2$ **(rough fit to JT-60U, Koide et.al., Phys. Plasmas 4, 1623 (1997), other expts.), get:**

$$T_{ped} = C_0 \left(\frac{n_{Gr}}{n_{ped}}\right)^2 \left[\frac{1+\kappa^2(1+10\delta^2)}{[1+\kappa^2(1+2\delta^2-1.2\delta^3)]}\frac{(1-(a/R)^2)^2}{(1.17-0.65a/R)}\right]^2 \frac{A_i R}{\kappa^2 a}$$

(Hammett, Dorland, Kotschenreuther, Beer, PPPL-3360 (1999))

Pedestal Temperature Requirements for Q=10

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

◆ flat density cases have monotonic safety factor profile

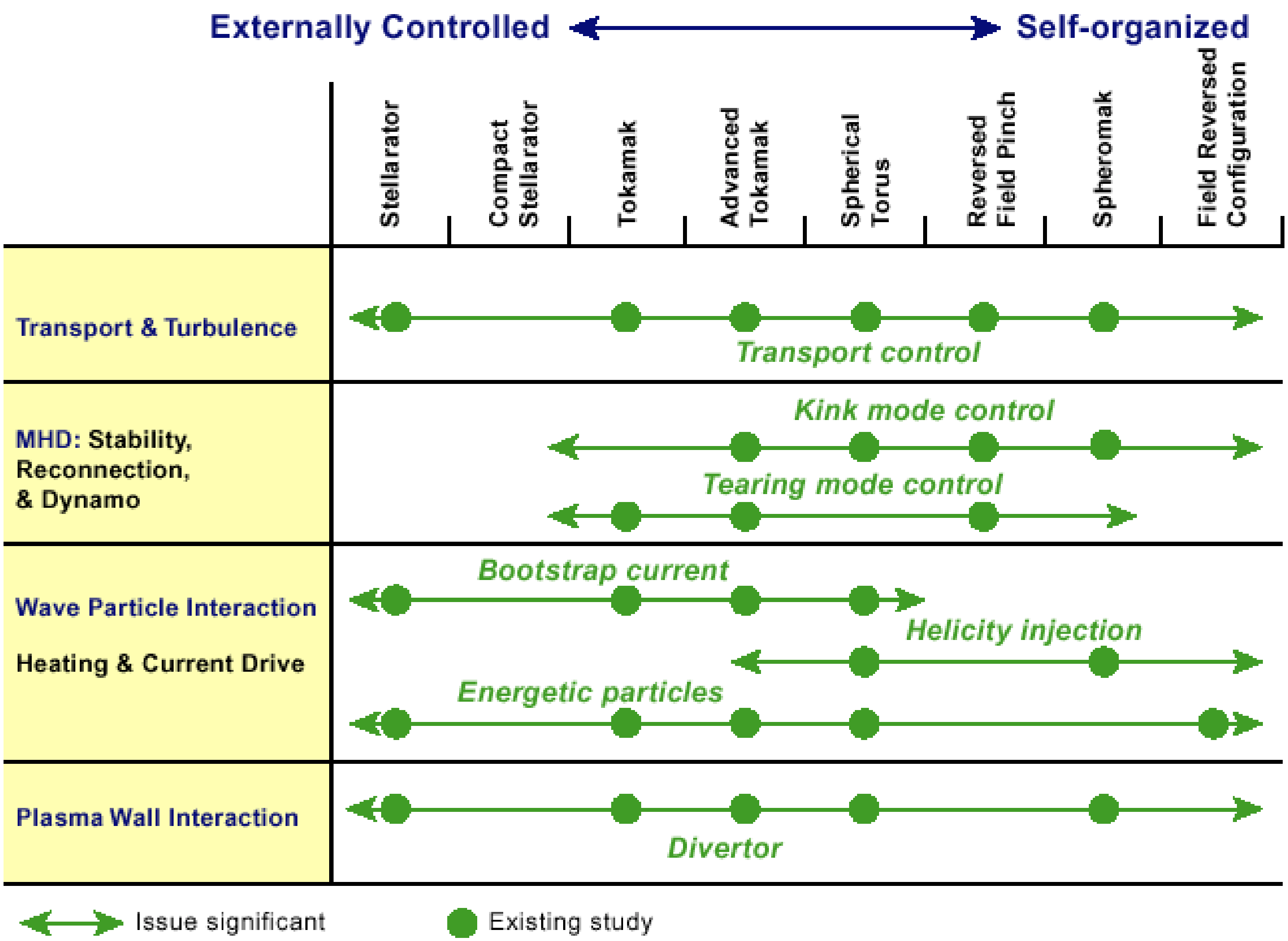
* $n_{eo} / n_{ped} = 1.5$ with n_{ped} held fixed from flat density case

❖ 10 MW auxiliary heating

11.4 MW auxiliary heating

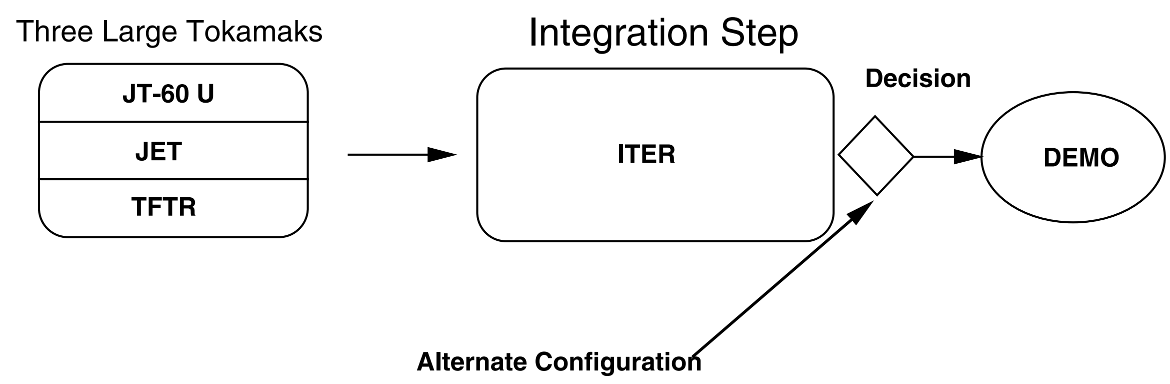
✦ 50 MW auxiliary heating

Generic Scope of Tokamak Burning Plasma Science

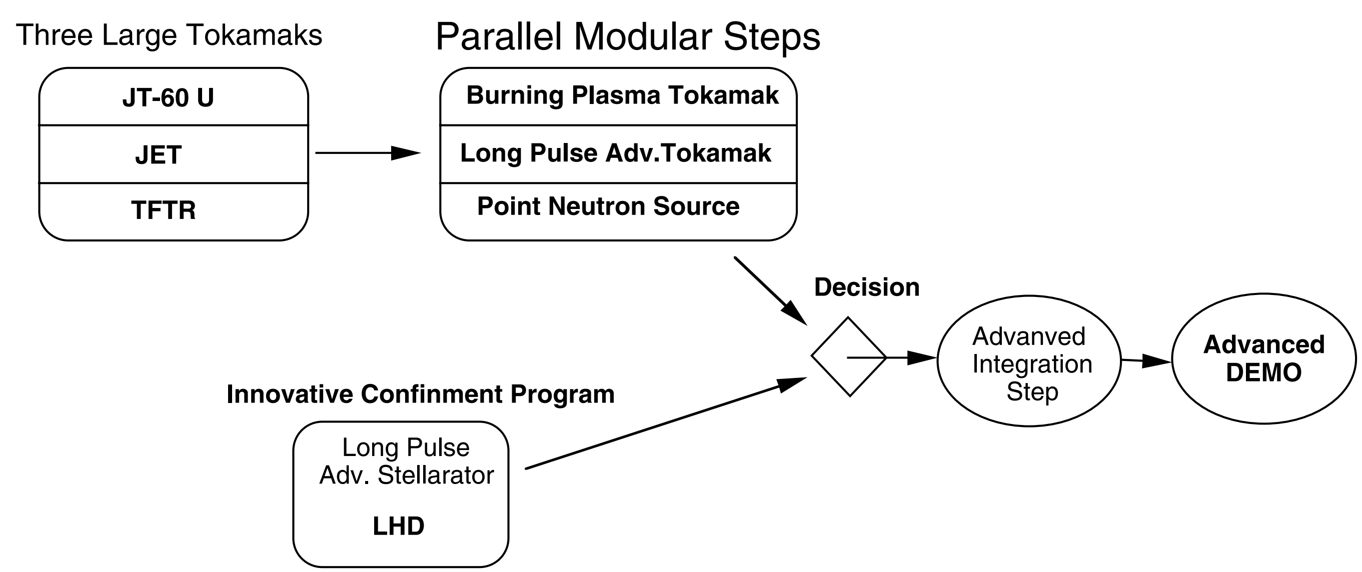


How to Proceed with BP: Two Paradigms

One Step to DEMO: Engineering Driven



Modular Strategy: Science Drives Next Steps



Panel Recommendation Fully Endorsed by FESAC August 2, 2001

3. *The US Fusion Energy Sciences Program should establish a proactive US 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 US should be ready to act and take advantage of it, but should not be dependent upon it. The US should implement a plan as follows to proceed towards construction of a burning plasma experiment:*

- Hold a "Snowmass" workshop in the summer, 2002 for the critical scientific and technological examination of proposed burning plasma experimental designs and to provide crucial community input and endorsement to the planning activities undertaken by FESAC. Specifically, the workshop should determine which of the specific burning plasma options are technically viable, but should not select among them. The workshop would further confirm that a critical mass of fusion scientists believe that *the time to proceed is now* and not some undefined time in the future.

- Carry out a uniform technical assessment led by the NSO program of each of the burning plasma experimental options for input into the Snowmass summer study.

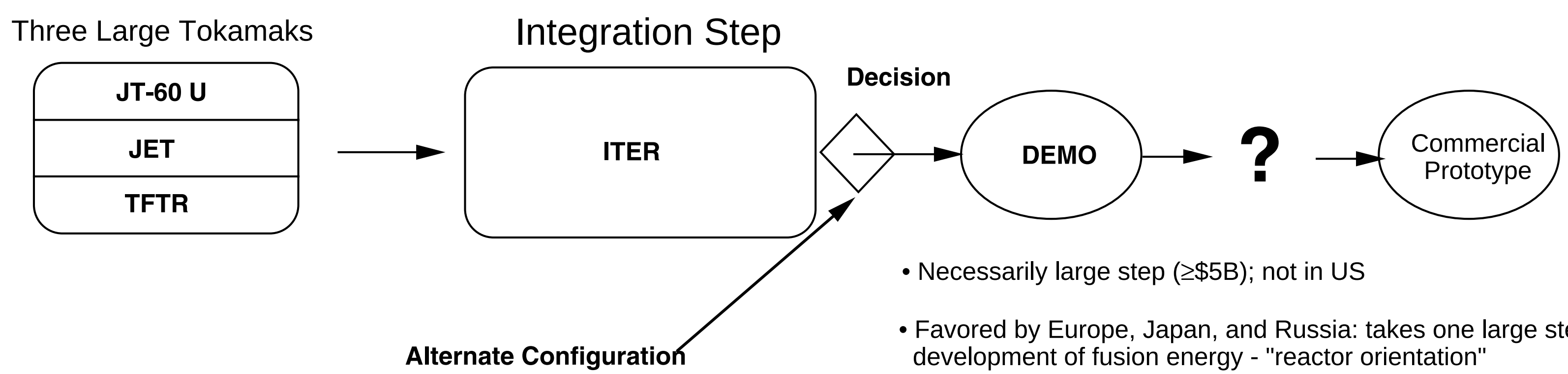
- Request the Director of the Office of Energy Sciences to charge FESAC with the mission of forming an "action" panel in Spring, 2002 to select among the technically viable burning plasma experimental options. The selected option should be communicated to the Director of the Office of Science by January, 2003.

- Initiate a review by a National Research Council panel in Spring, 2002, with the goal of determining the desirability as well as the scientific and technological credibility of the burning plasma experiment design by Fall, 2003. This is consistent with a submission of a report by DOE to congress no later than July, 2004.

- Initiate an outreach effort coordinated by FESAC (or an ad-hoc body) to establish an appreciation and support for a burning plasma experiment from science and energy policy makers, the broader scientific community, environmentalists and the general public. This effort should begin now.

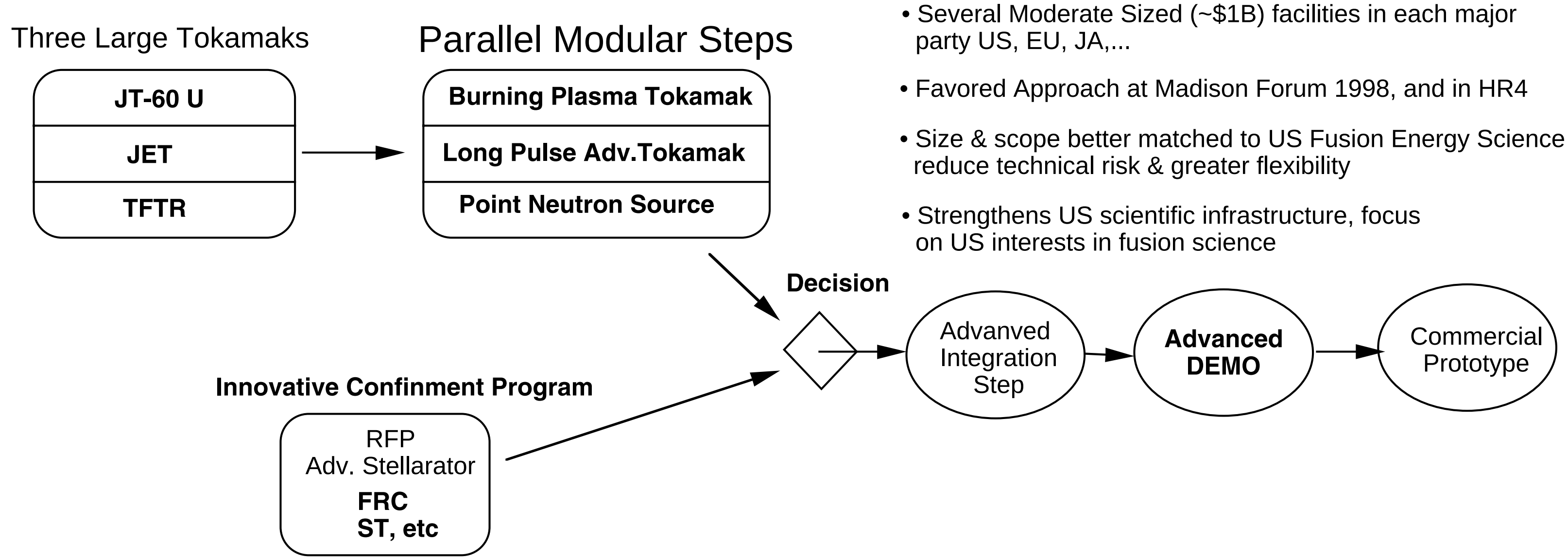
How to Proceed with BP Experiment: Two Paradigms

One Step to DEMO: Engineering Driven



- Necessarily large step (≥$5B); not in US
- Favored by Europe, Japan, and Russia: takes one large step towards development of fusion energy - "reactor orientation"
- International financing & organization have æ "deferred" construction several times.

Modular Strategy: Science Drives Next Steps



- Several Moderate Sized (~$1B) facilities in each major party US, EU, JA,...
- Favored Approach at Madison Forum 1998, and in HR4
- Size & scope better matched to US Fusion Energy Science Program: reduce technical risk & greater flexibility
- Strengthens US scientific infrastructure, focus on US interests in fusion science

Comments & Discussion Points

- Two Paradigms are both based on a genuine desire by their proponents to develop fusion energy.
- Reviewing 1996 Physics Today article by Stix and Sessler, ITER redesign and progress in field have addressed some of their specific technical concerns, but core concern remains: integrated "ITER-like" step is premature and ill-sized.
- Wish my colleagues in the fusion program will listen to each other and participate in the FESAC process to reach community consensus on best way for US proceed:

  Then work together take this important Burning Plasma step.