How Generic is Burning Plasma Physics?

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Are results from a tokamak BP experiment transferable to other mag configurations?

Does it matter?

A lower bound

zero transferability = zero utility

An upper bound

A tokamak BP expt will NOT pre-empt a non-tokamak BP expt

The intermediate reality

Tokamak BP exp't can have large influence on other, related concepts

Examine Key BP Issues

- **Classical behavior**
- **Alpha-generated instabilities**
- **Alpha effects on existing instabilities**
- **Fluctuation-driven alpha transport**
- **Burn control and integration**
- **The unknown**

Will not discuss non-burning issues studies in a BP expt:

- **Transport scaling (ρ^*, ν^* etc)**
- **Runaway electrons**
- **……**

Sample List of Configurations

- **q > 1 axisymmetric: tokamak family**
  AT, ST
- **q < 1 axisymmetric: RFP, spheromak**
- **q= 0 axisymmetric: FRC, dipole**
- **Nonaxisymmetric: stellarator family**

Classical Behavior

- **Collisional alpha slowing and heating**

  well-understood, entirely generic

- **Alpha losses from field ripple**

  first orbit losses
  ripple transport
  stochastic ripple transport (collisionless)

  well-understood, generic, details differ
  possibly simpler at q < 1 (smaller neoclassical effects)
  more complex in stellarator(+ Er effects)

Alpha-Generated Instabilities

- **Shear Alfvén waves**

  driven by ∇p_α
  guiding center resonance

- **Fast Alfvén/cyclotron waves**

  driven by non-Maxwellian f(v)
  cyclotron resonance

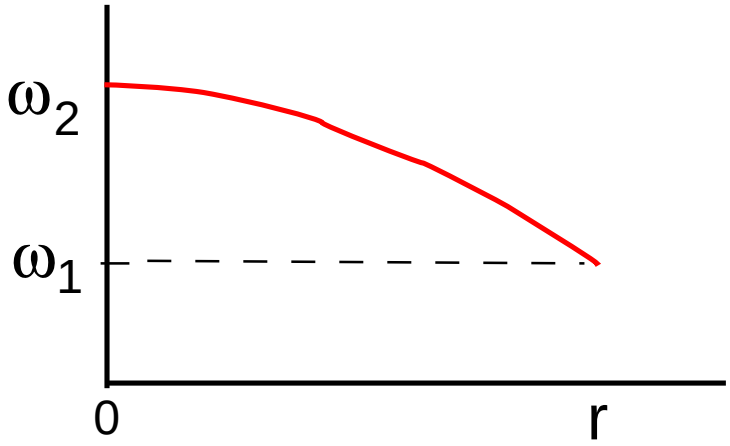
Alpha-Excited Alfvén Instabilities

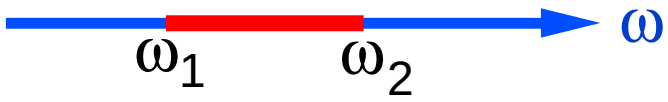
- **Geometric effects on Alfvén waves (and kinetic effects)**
- **Excitation mechanisms**
- **Damping mechanisms**
- **Nonlinear saturation (and alpha particle transport)**

Geometric Effects on Alfven Waves

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

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





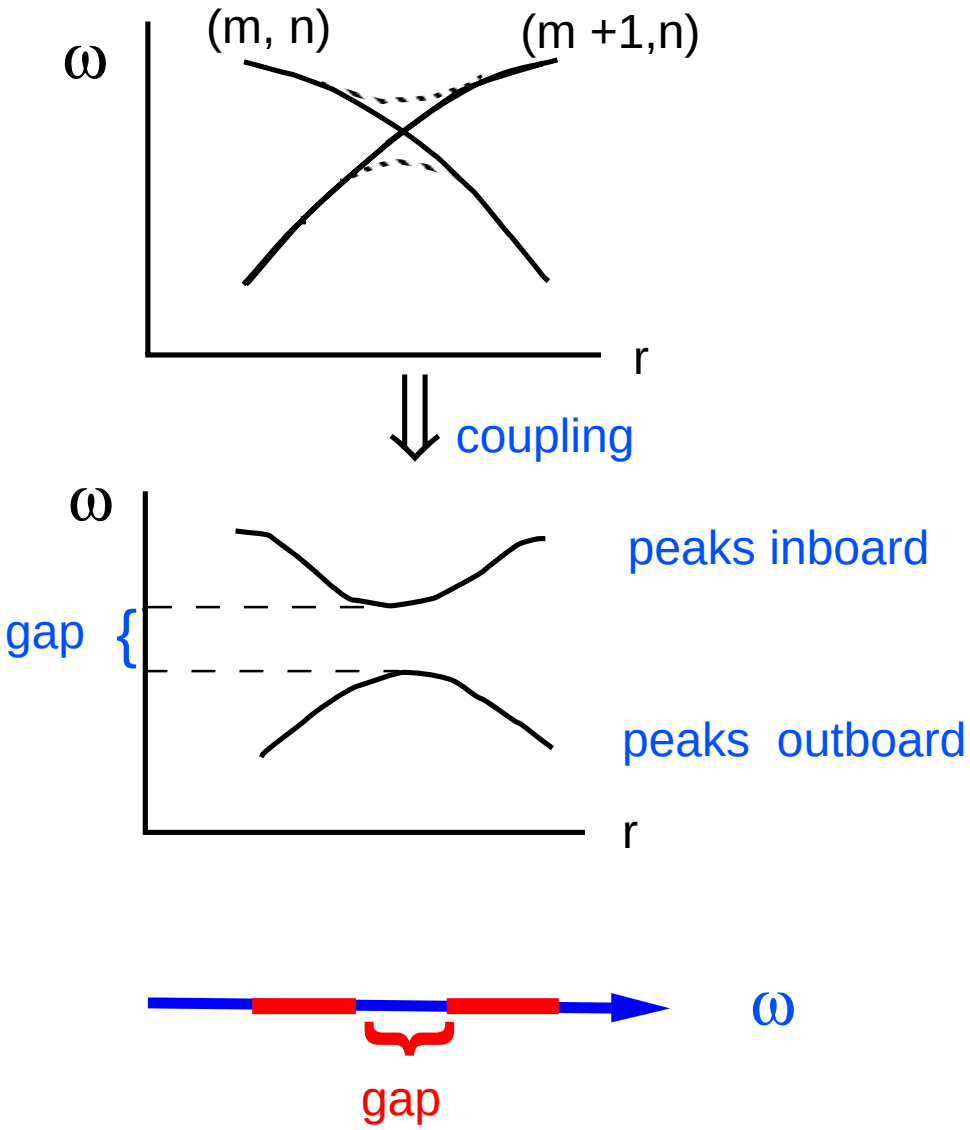
continuous spectrum,

shear Alfven resonance

not applicable to any concept

2D torus

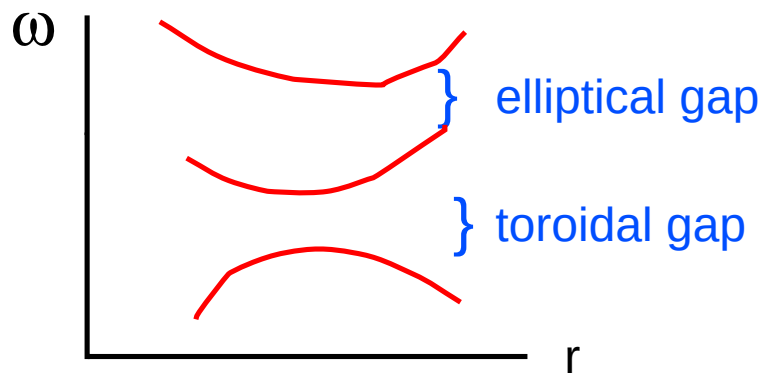
Axisymmetric, circular



- **similar in all circular tori, details vary**
- **other concepts are extensions of the above (except FRC with B = 0)**

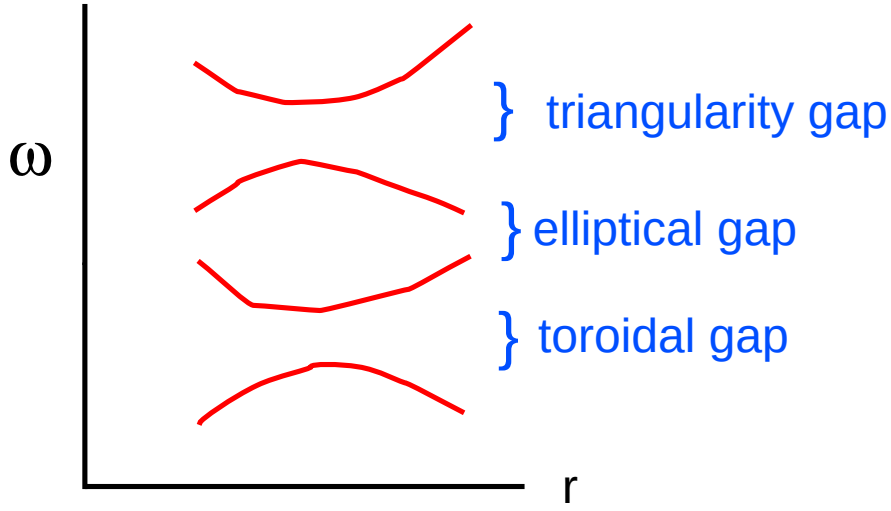
With elliptic cross-section

coupling of m, m + 2

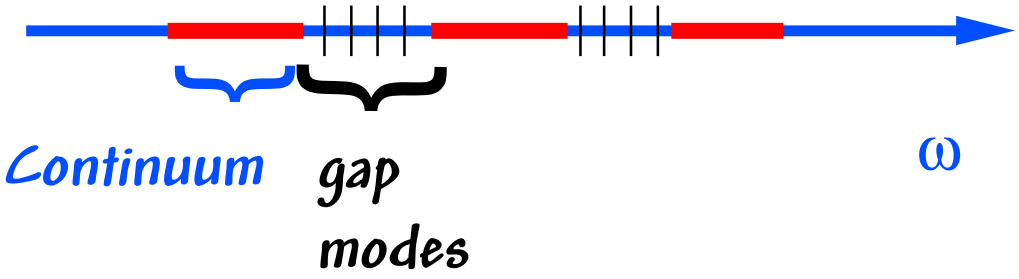


With triangularity

coupling of m, m + 3

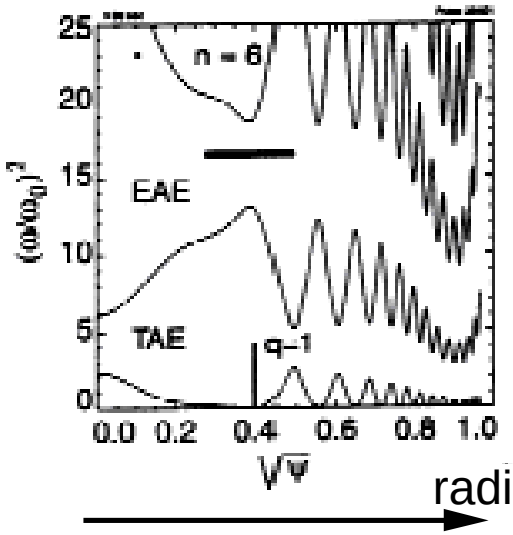


Discrete Modes in Gaps



- Basic physics extends to other concepts $\Longrightarrow$

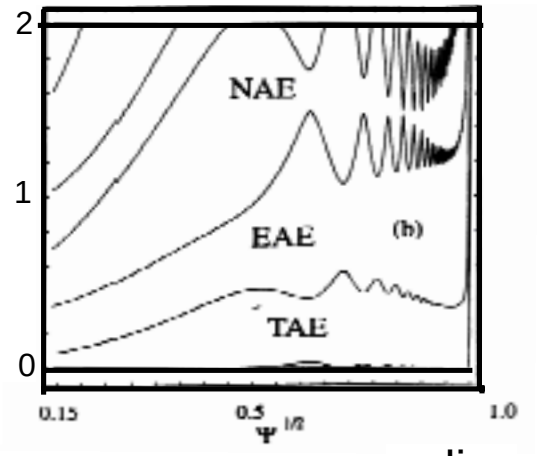
ω^2



radius

Tokamak

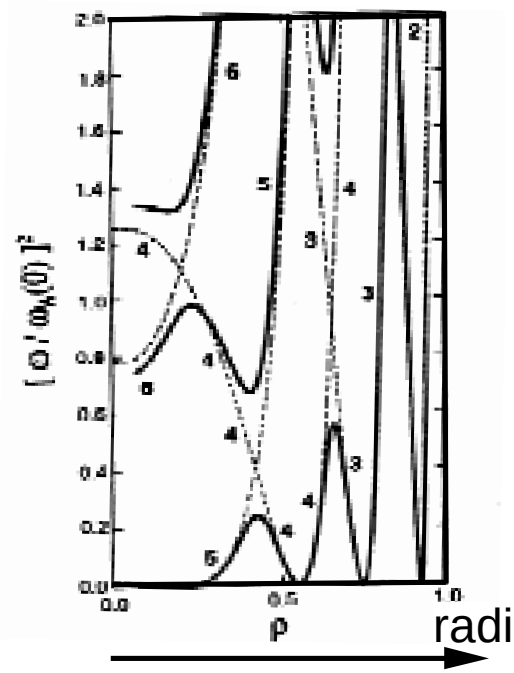
ω^2



radius

ST

ω^2



radius

Stellarator

Kinetic effects can discretize the continuum.

Excitation Mechanism

- **Energy source ∇p_α**

- **Tapped through wave-particle resonance**

$$\omega - k_{||} v_{||} - \omega_d = 0$$

at high $\omega >> \omega_d$, resonance at $v_\alpha = v_A$

these mechanisms are generic

Damping Mechanisms

- **Continuum damping**
- **Radiative damping**
- **Orbit averaging**
- **Landau damping**
- **Trapped particle collisions**

mechanisms are generic,
and partly introduced by these modes

Nonlinear Saturation and Transport

- **Particles move resonantly in (r,v) space and form drift orbit island**

- **Multiple modes can yield island overlap and stochastic transport**

Alpha Effects on Low frequency Instabilities

- **Can destabilize if $\omega = \omega_d$ ($v_{ph} = v_d$)**
  (internal kink, ballooning …..)
  all concepts can have trapped particle toroidal drift precession

- **Can stabilize if $\omega << \omega_d$**
  toroidal flux (3rd) invariant constrains (int. kink, balloon, sawteeth)
  ω_d can be high for low field concepts

- **Energetic ion FLR can stabilize interchange**
  (could be significant for all q < 1 concepts)

Effect of Existing Modes on Alpha Transport

- **Orbit averaging of electrostatic turbulence by precessing ions,**
  may apply to ST, stell, RFP edge, improved q < 1 concepts

- **Sawtooth/island redistribution of alpha particles,**
  important in ST, RFP, spheromak

- **Internal kink, KBM - loss of resonant alphas**

Have past tokamak expt's been generic?

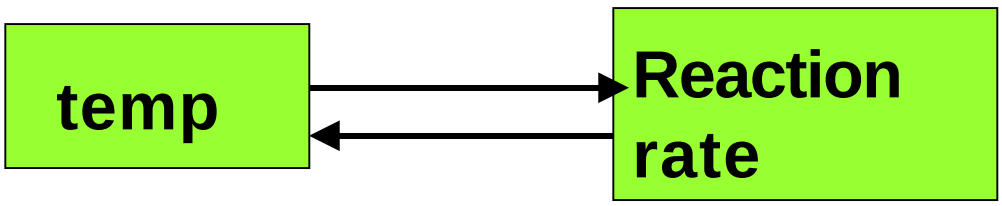
- **Nearly all tokamak research has influenced other concepts**

- **Neoclassical theory, MHD stability, sawteeth and islands, electrostatic turbulence, plasma-wall interactions…**

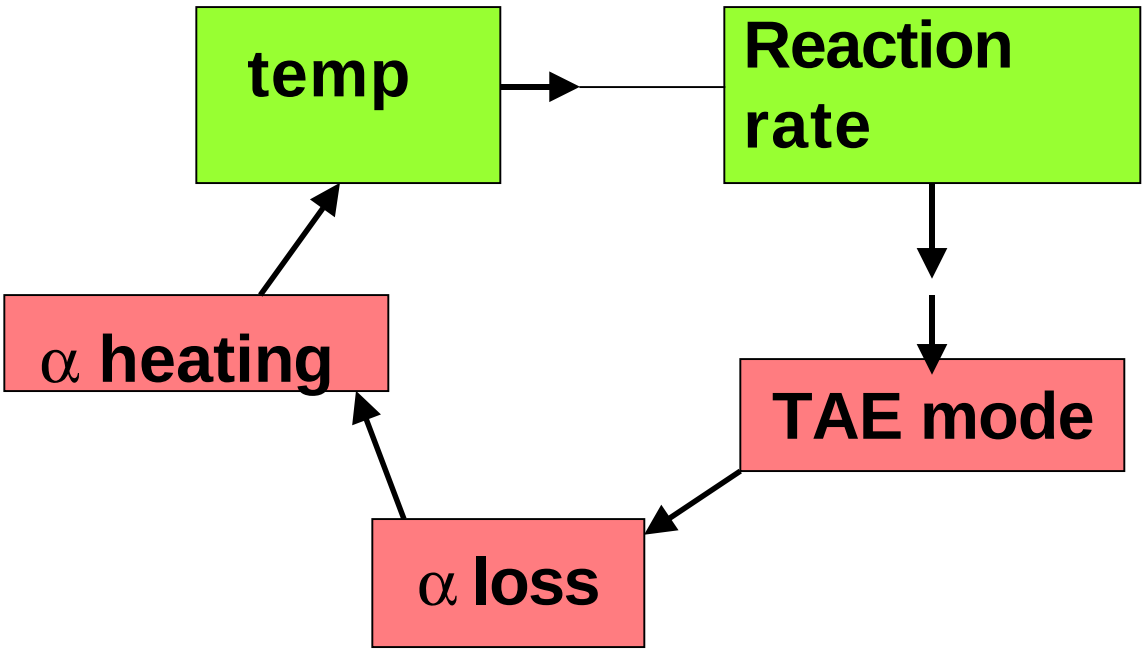
- **Control and integration techniques (profile control and fluctuations, heating and current drive, discharge cleaning……)**

Burn Control and Integration

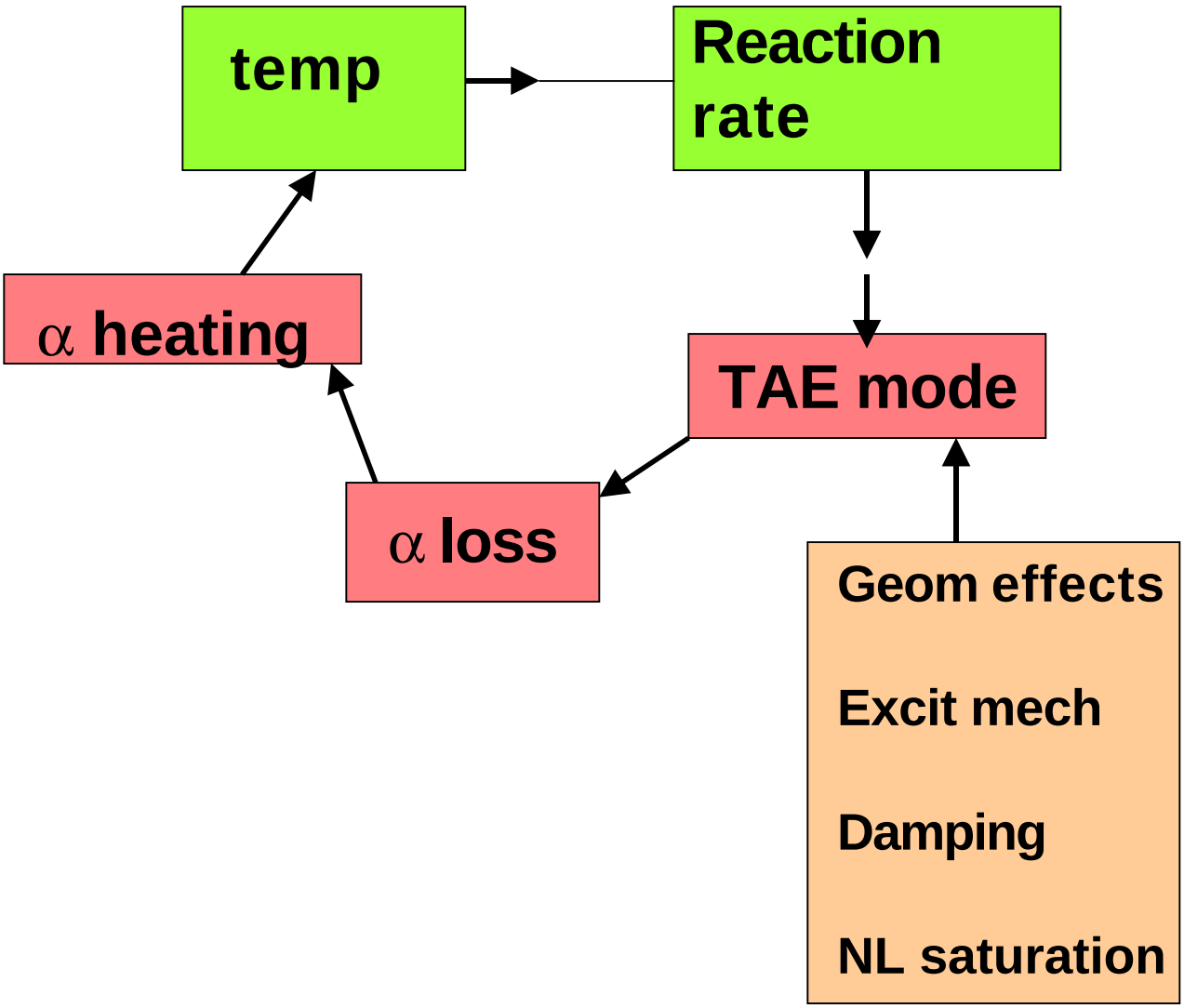
- Burning plasma > Σ(individual phenomena)
- Coupling is critical
- a “theory of integration” is not available
- thermal stability



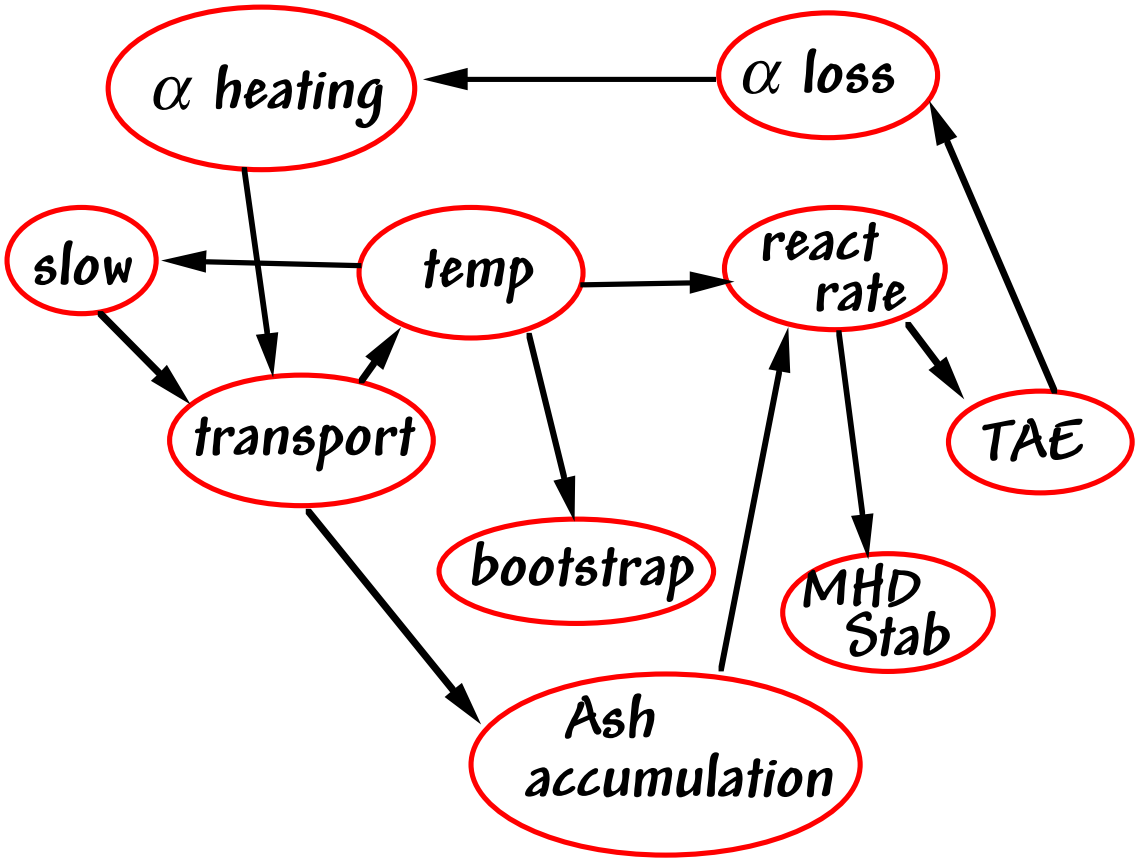
Add a little alpha physics



Add a little more alpha physics



can add more



etc

Control tools may be transferable

(ash control, temp. control, profile control, ...)

Main reasons for a burning plasma experiment:

- **Physics elements and integration are basic scientific challenges**

- **Constitutes a remarkable scientific feat**
  (integration or application of known physics elements : VLSI, laser atom control, production of anti-matter atoms…..)

- **Key step for fusion power**

and,

- **There is no need to separate burning plasma physics from fusion power (even in a science program)**

- **We should not become too reductionist or blasé (or cynical)**

- **There is no need to separate burning plasma physics from fusion power**

- **A burning plasma physics experiment would make the fusion program whole (if the base program is not jeopardized)**

Summary

A burning plasma experiment would have large scientific impact on many confinement configurations.