SCIENCE, INNOVATION AND COLLABORATION IN MAGNETIC FUSION ENERGY

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TO

1999 FUSION SUMMER STUDY

JULY 12, 1999

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CONTEXT

- There are exciting near-term opportunities for science and innovation in the areas of:
  - Turbulence and transport ⇒ Minimize power plant size
  - Macrostability ⇒ Maximize power density
  - Wave-particle interactions ⇒ Efficient sustainment
  - Plasma-wall interactions ⇒ Survivability
- To broaden ⇒ stabilize the base of fusion:
  - Strengthen the scientific basis for the Advanced Tokamak.
  - Investigate alternatives that resolve Tokamak issues and/or lead to more attractive development paths and products.
- To prepare for a major decision to move forward more aggressively in 2003-4.
  - When the "climate" may have changed.

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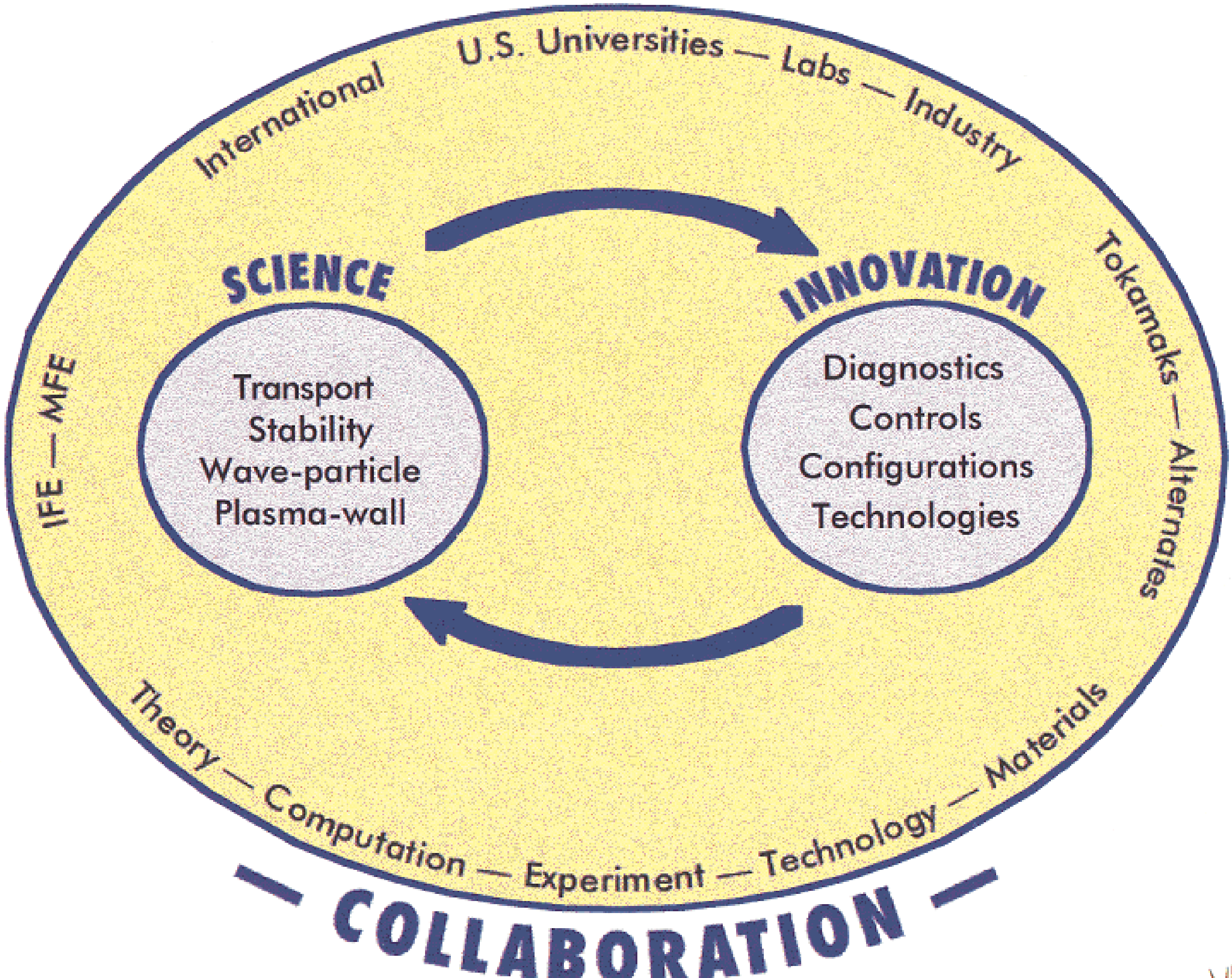

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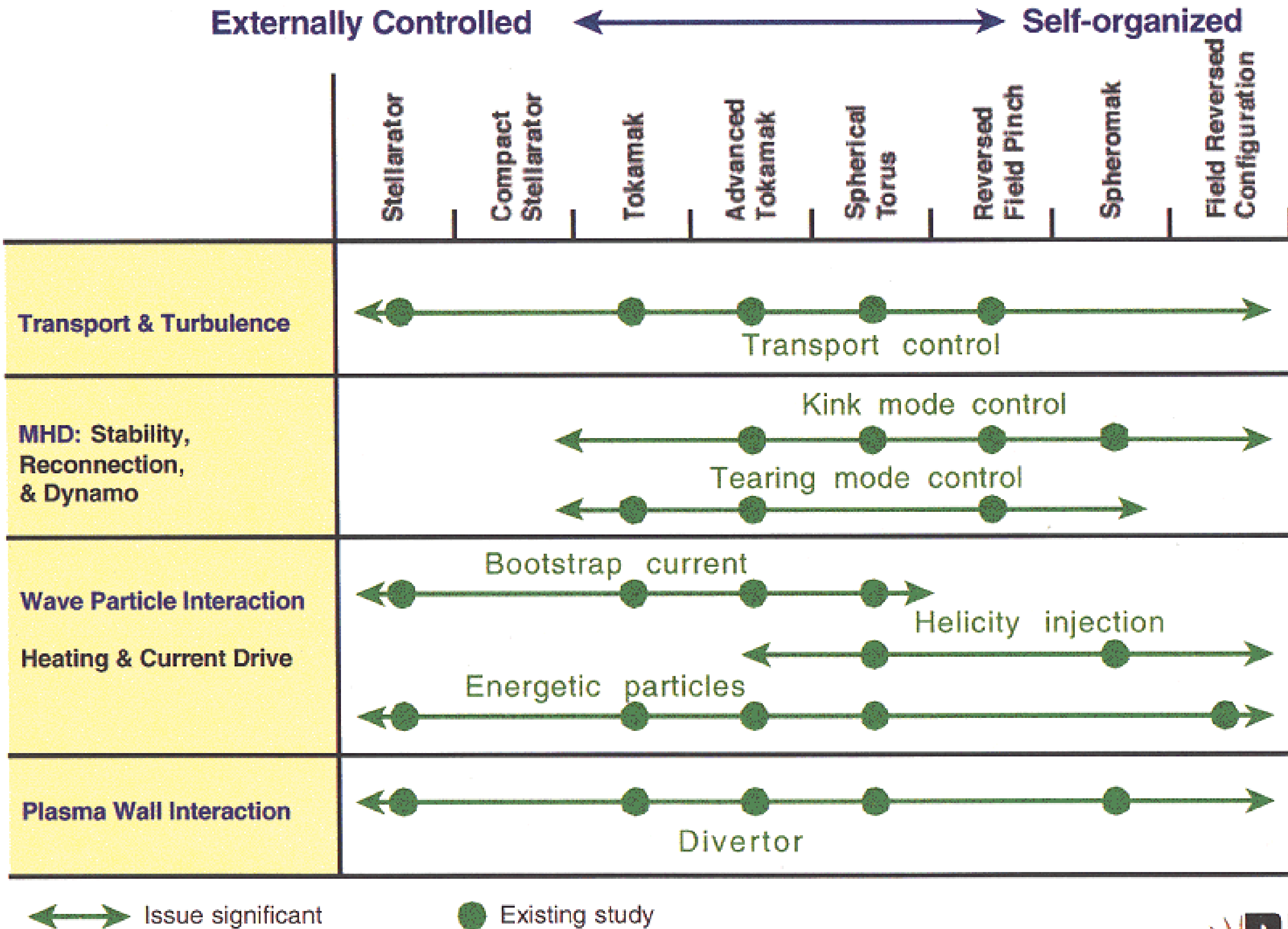
Science Topics vs. MFE Configurations



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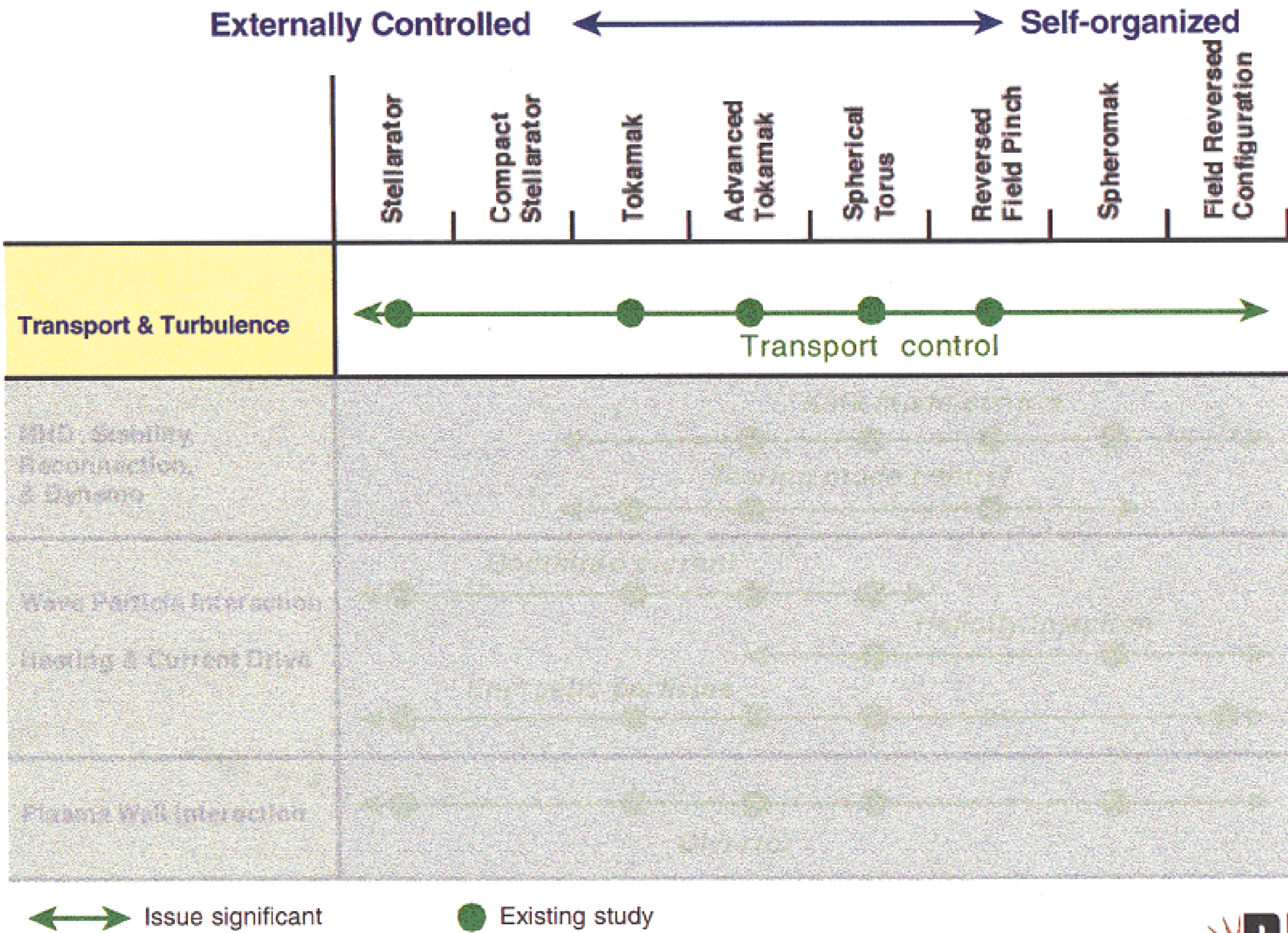
Science Topics vs. MFE Configurations



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Transport – Status & Opportunities

- New methods of profile modification and measure - ment allow study of Internal Transport Barriers.

- Massively Parallel Processor computers are allowing breakthroughs in quantitative understanding ⇒ SSI

- Further insights and capabilities are in the wings:
  - New diagnostics to image turbulence in at least two dimensions.
  - IBW for local rotation ⇒ transport & stability control.
  - ST's for higher β while MHD stable ⇒ E.M. effects. Predicted stability to μ-turbulence (!)
  - Stellarators for varying trapped particle effects.
  - RFP / Spheromak for multi-mode tearing effects.

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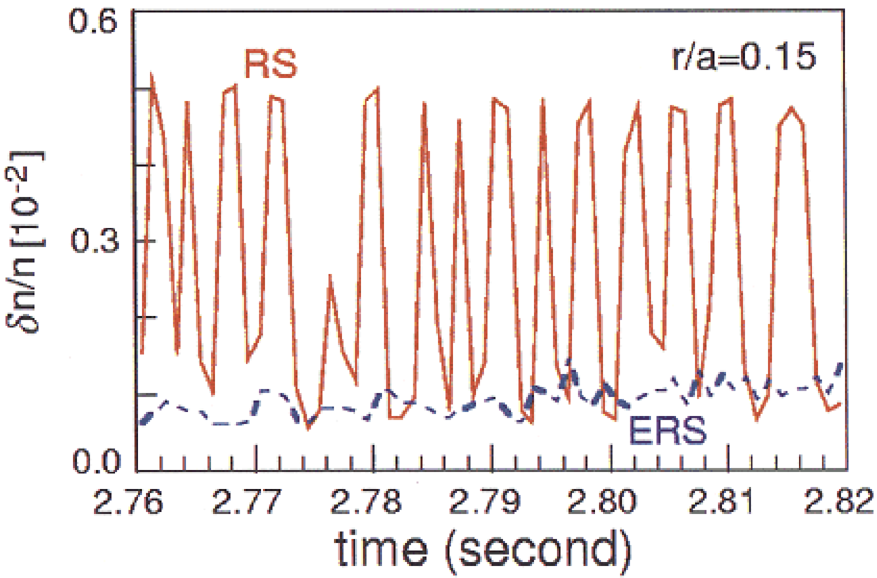
LOCAL TURBULENCE BURSTING MAY BE CAUSED BY FLUCTUATING ZONAL FLOWS

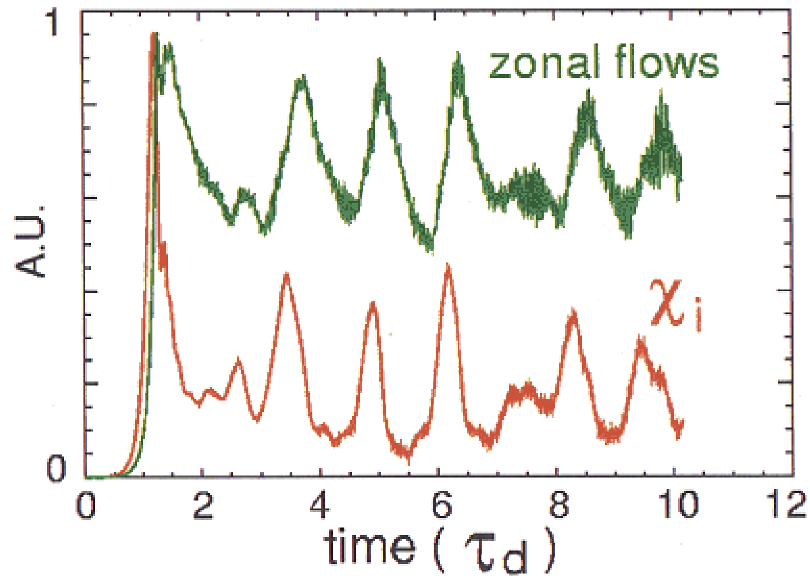
EXPERIMENT



[Mazzucato, et al., PRL, 1996]

large bursts of fluctuation in TFTR RS plasmas observed period ~ collisional flow damping time

SIMULATION



[Lin, et al., 1999]

collisional damping of zonal flows causes bursts of turbulent transport in gyrokinetic simulations

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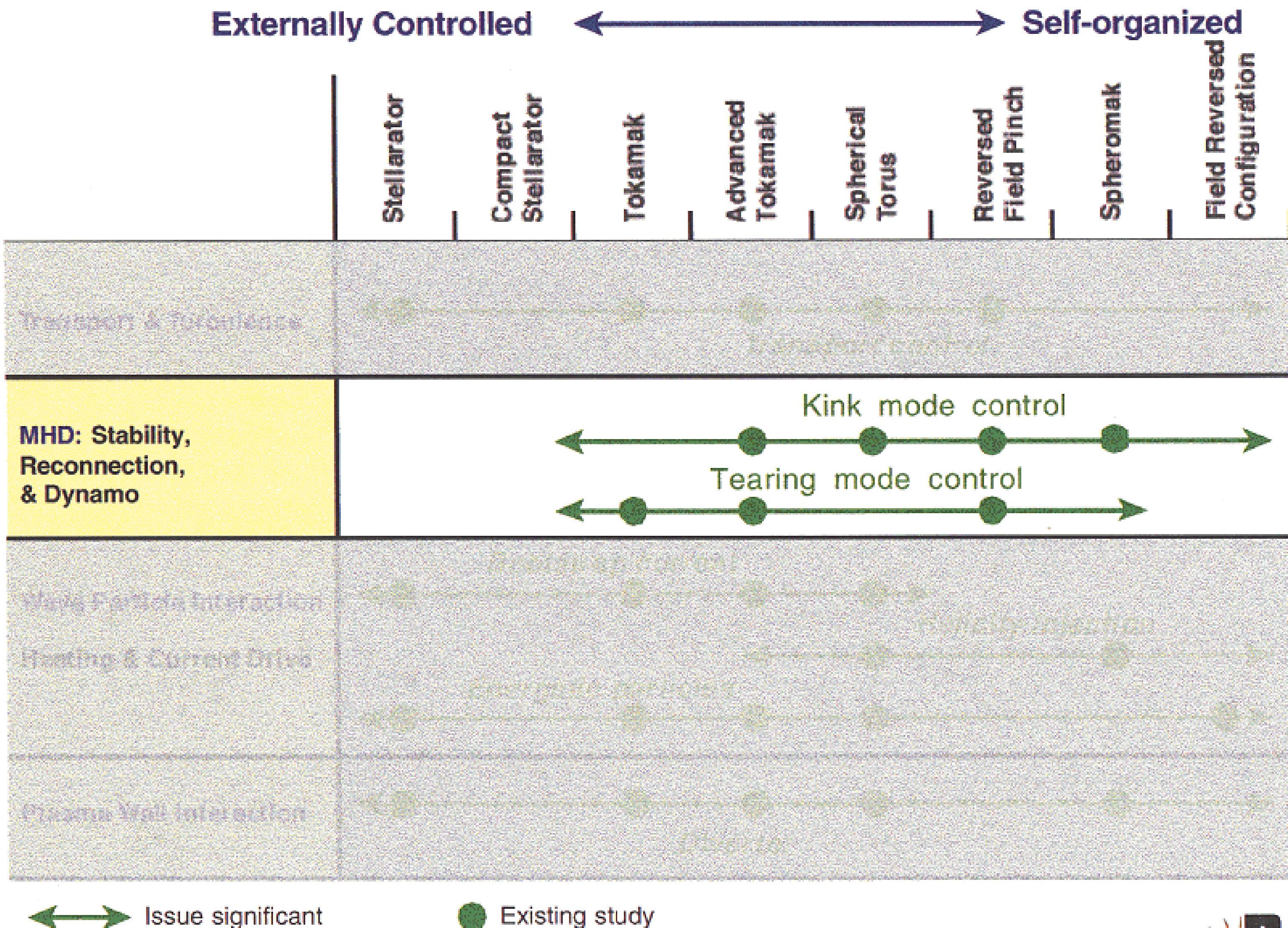

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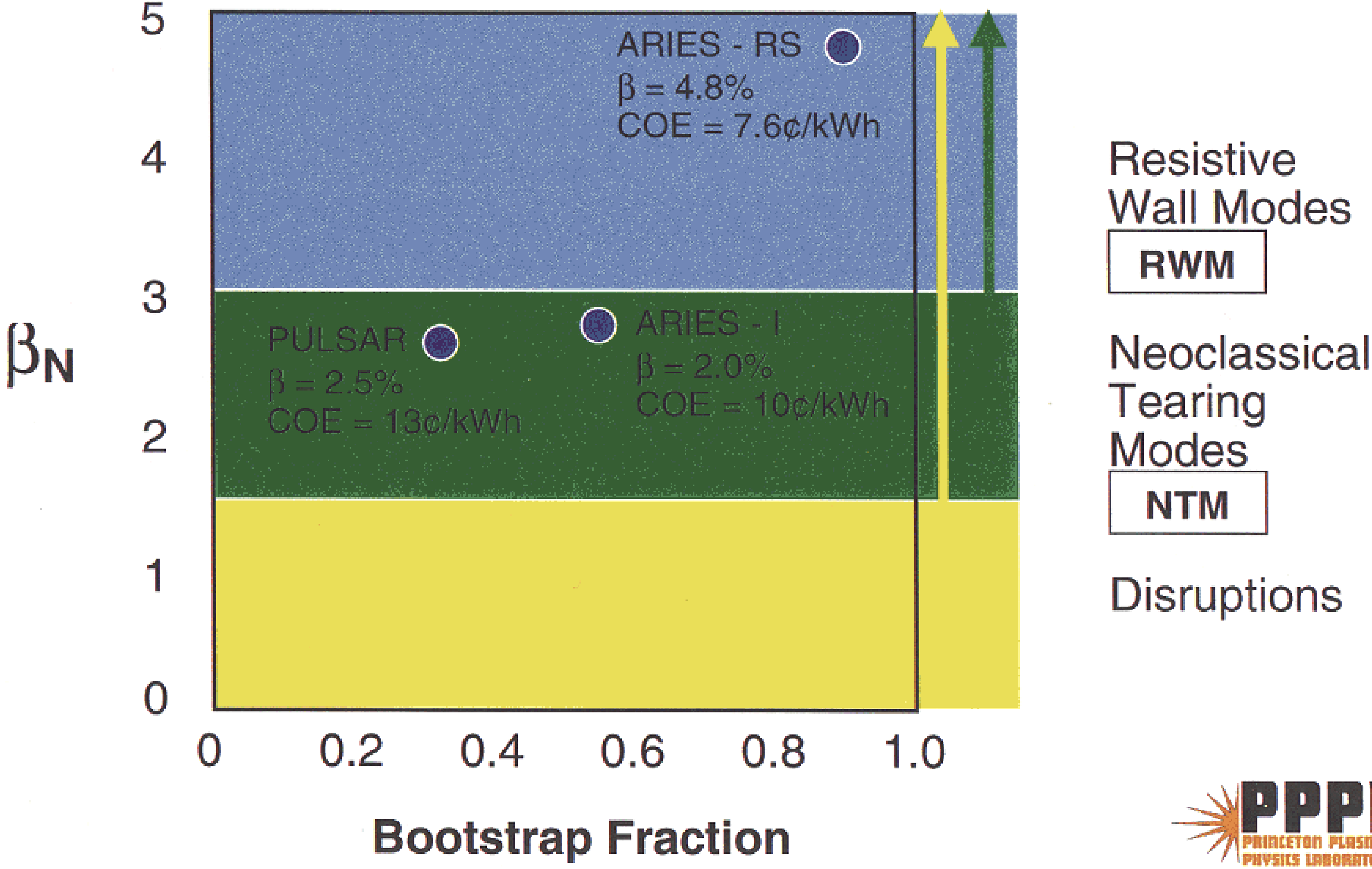
TOKAMAK MHD STABILITY CHALLENGE

Power Plant Studies Help Set Research Goals



Disruption Issues and Innovations

- **Issues:**
  - Thermal quench ⇒ divertor damage ⇒
    ⇒ graphite ⇒ tritium inventory
  - Vertical displacement ⇒ severe E.M. loads.
  - Loss of control ⇒ erosion of thin first wall.
- **Innovations:**
  - Killer pellets / liquid hydrogen injection.
  - Operate near vertical - displacment null point *vs.* $\Delta\beta$.
  - Profile control.
  - Operate at higher q, w/o shear reversal point (ST's) ?
  - Use stellarator fields for flux-surface, kink, and positional stability.
- **Science: do we really understand disruptions?**

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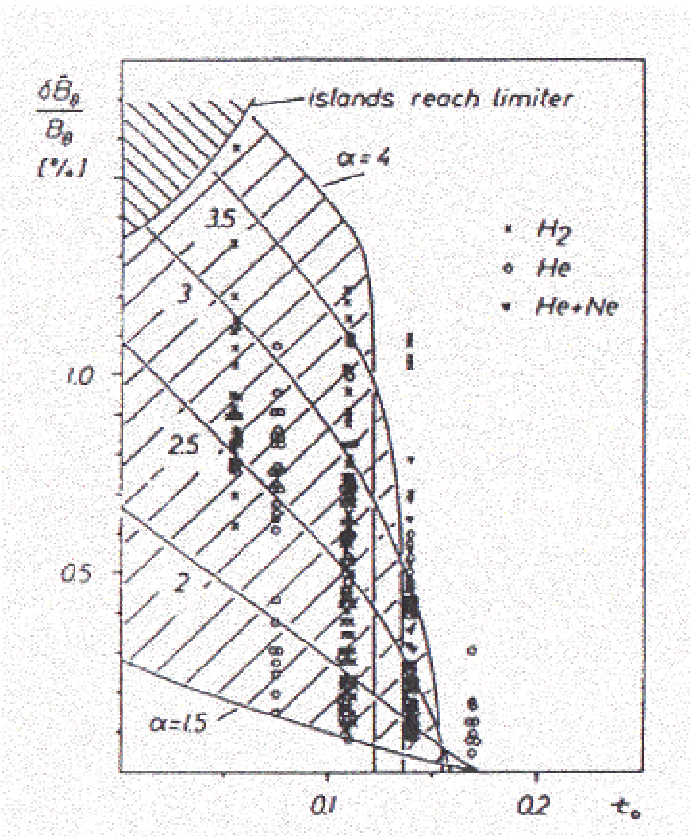
Stellarator Fields Suppress Disruptions for $\iota_{EXT} > 0.15$



With small external transform:

- No disruptions, even for $q_a < 2$! (W7A, Cleo)
- Murakami-normalized density limit increased x3. (W7A)

Current-free:

- No disruptions as ballooning limit is approached. (CHS, W7AS)

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NTM Issues and Innovations

- **Issues:**

  Threshold $\beta_N \sim \rho^* \sim (m_i T_i)^{1/2}/RB$

  DIII-D / JET / ARIES-RS $\Rightarrow$ β_N = 4.5 / 1.7 / 0.34

  A new "ubiquitous mode" for positive shear
  – seen in the edge of reversed-shear tokamaks.
  Seed islands reduced relative to a, in larger devices?

- **Innovations:**

  ECCD or LHCD feedback stabilization.
  High Glasser effect, hiqh q ($\Rightarrow$ high m), high ρ^* (ST).
  Negative shear to the edge (Compact Stellarator).

- **Science: do we fully understand NTM's?**

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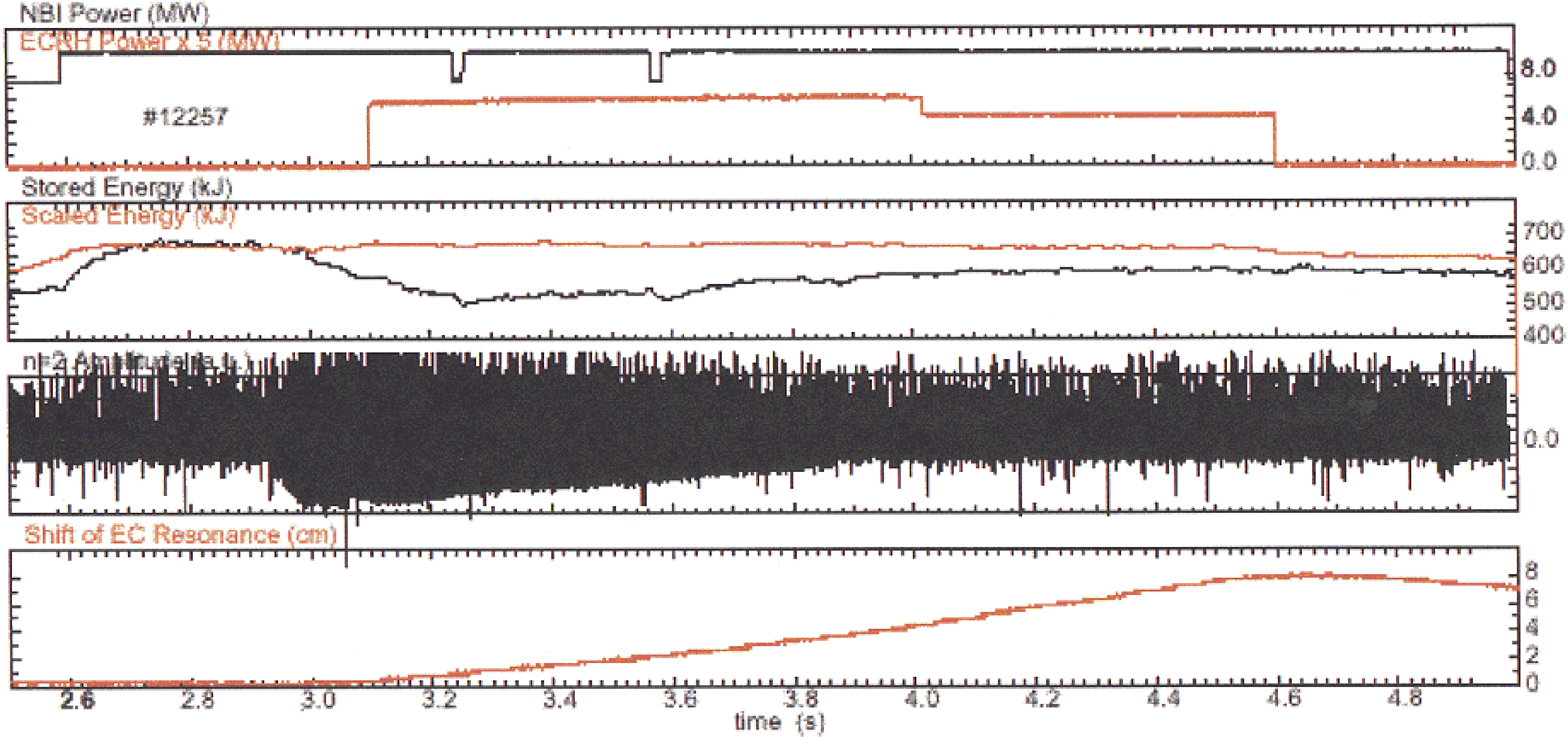
Progess on NTM Feedback Control

ASDEX-Upgrade



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RWM Issues and Innovations

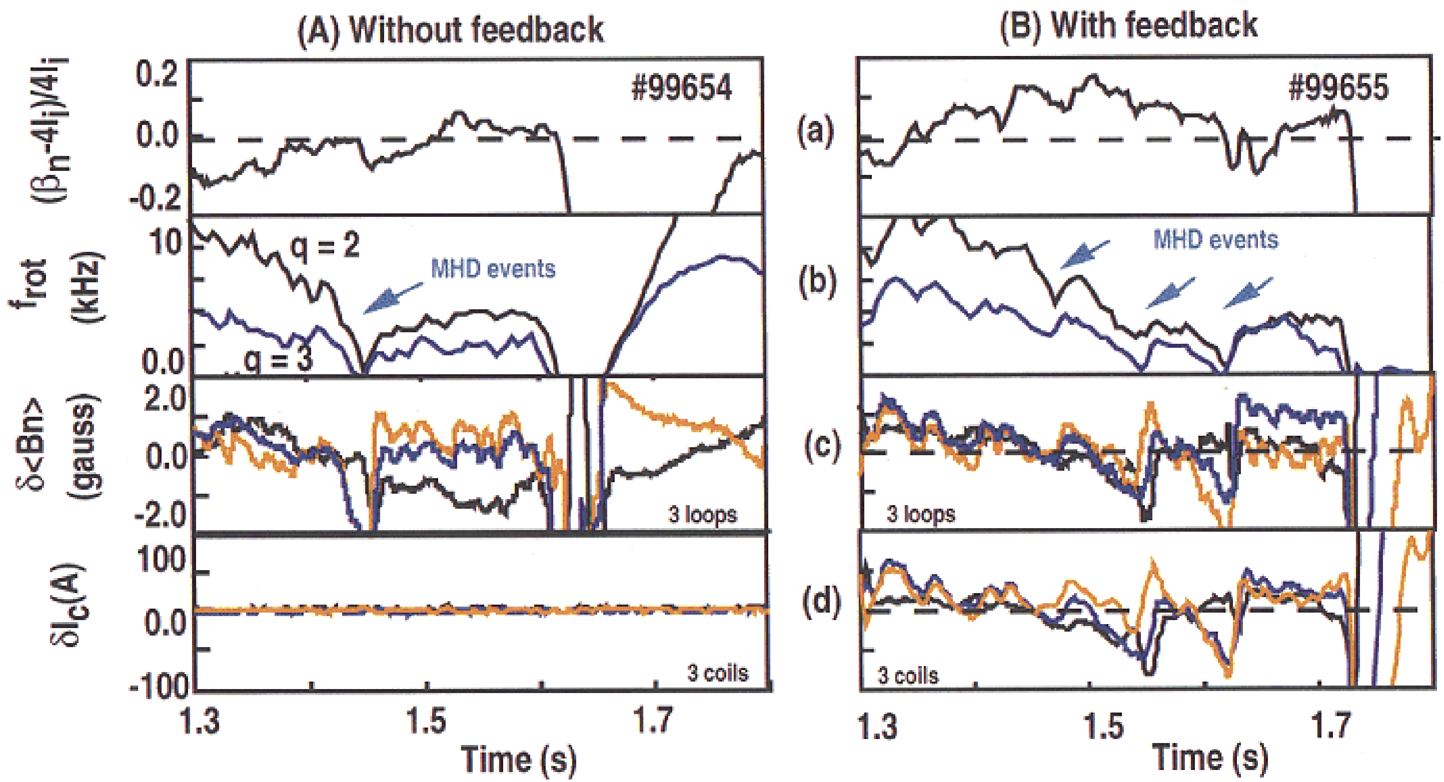
- **Issues:**
  - $n = 1 \Rightarrow 3$ kink mode stabilization a challenge.
  - Cannot sustain much plasma rotation in power plant.
  - How close to ideal-wall limit can you go?

- **Innovations:**
  - Multimode feedback stabilization
    - – synergy between Adv. Tokmak, RFP, Spheromak
  - Reduced v_ϕ/v_A, higher $\beta \Rightarrow$ more affordable in ST?
  - Compact Stellarator shape $\Rightarrow$ kink stable w/o a wall.
  - Why is the FRC stable on ideal timescale?

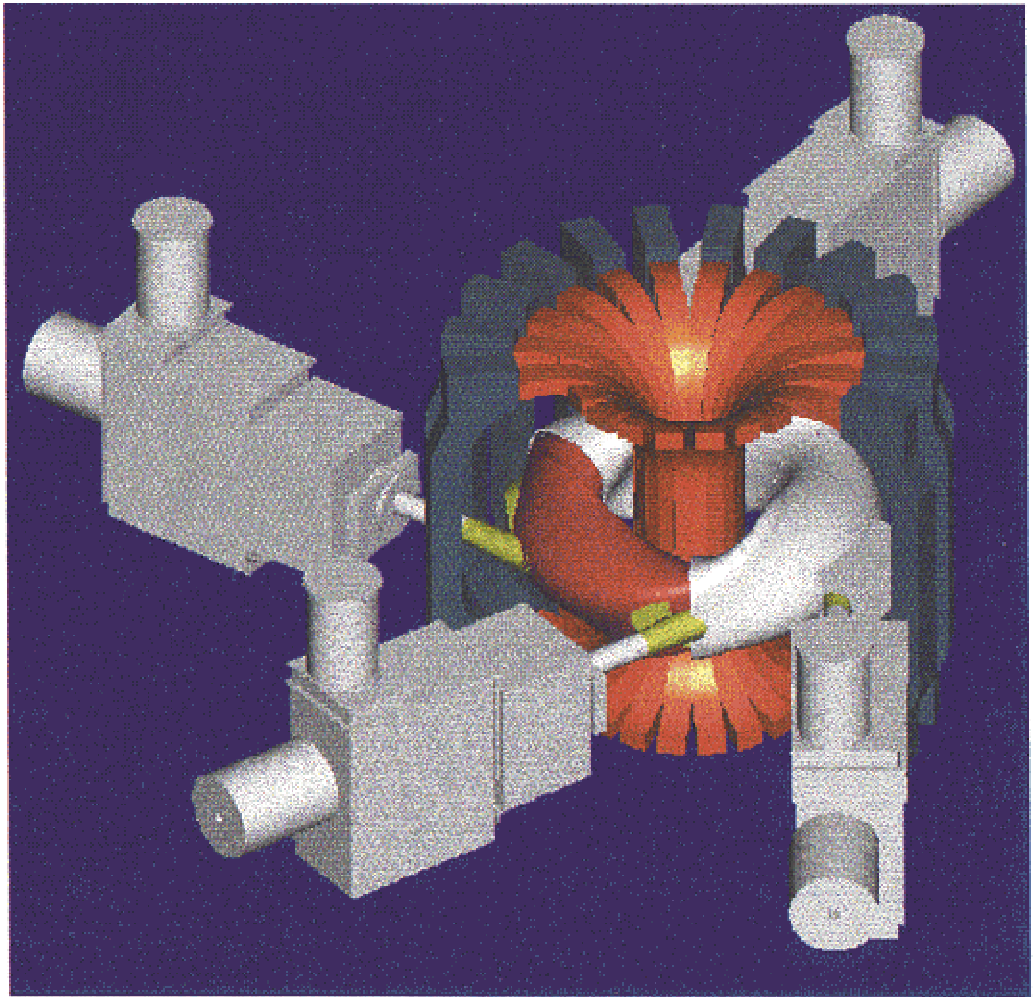
- **Science: do we fully understand kink modes?**

Initial Results for Feedback Control of RWM are Promising

DIII-D, Columbia U., PPPL



THE NATIONAL COMPACT STELLARATOR EXPERIMENT



Stellarator
⇒ steady state config.
⇒ complex coils

Quasi-axisymmetric
⇒ good confinement

Low aspect ratio
⇒ R=1.45 m, ⟨a⟩=0.42 m

Passively stable
at $\beta = 4\%$ (or more) to:

- Ballooning
- Vertical Displacement
- Neoclassical Tearing
- Kink, with no wall

Auburn U., Columbia U., ORNL, PPPL, U. Texas-Austin, U. Wisconsin

Australia, JA, Germany, Russia, Switzerland

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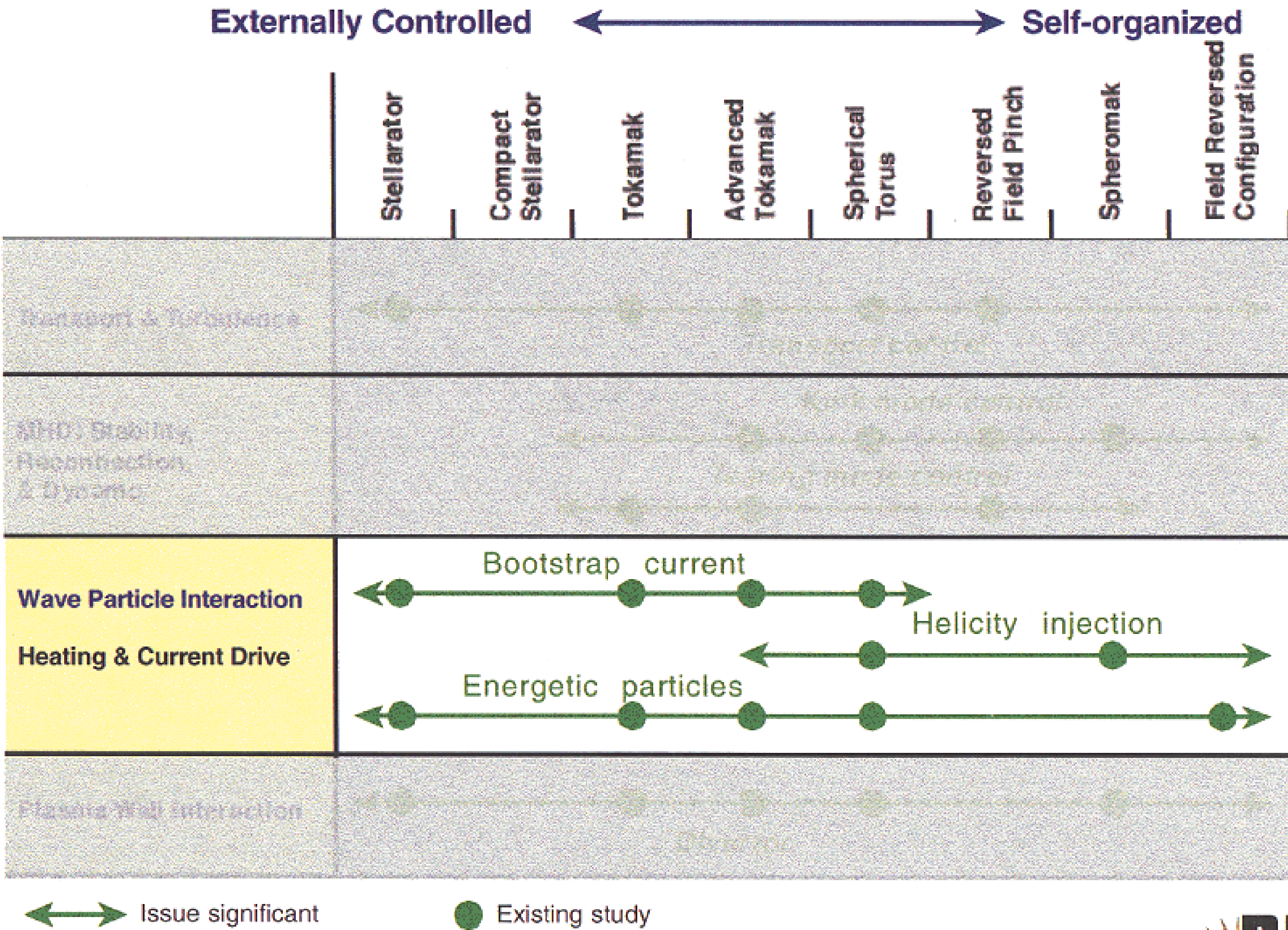

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Plasma Current Sustainment

- RF and NB current drive are fairly well understood, but not very efficient ⇒ Stellarators w/o current drive.
- Bootstrap current is a revolutionary discovery.
- Helicity injection or Rotamak current drive may be means to drive edge current efficiently.
  - ELM control – or spoiled H-mode?
  - Good synergy with Spheromak, FRC
- Current profile control hard in an RFP or Spheromak:

$$\frac{P_{cd}}{P_{fus}} \propto \frac{n(1-f_{bs})}{\beta_p^2 B_p^2 I_p} \quad \frac{\beta}{\beta_T}$$

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Energetic Particle Physics

- Excellent results to date:
  - Energetic particles are usually well confined.
  - Electron heating with alpha particles demonstrated.
- Key near-term tests are still needed:
  - What happens with heating ~ n^2T^2?
  - Need more understanding of effects of *AE's (ST).
- Innovations:
  - Alpha channeling, FRC stability.
- RFP's and Spheromaks may differ from Tokamaks, ST's, Stellarators.
  - Parallel losses along field lines could dominate!

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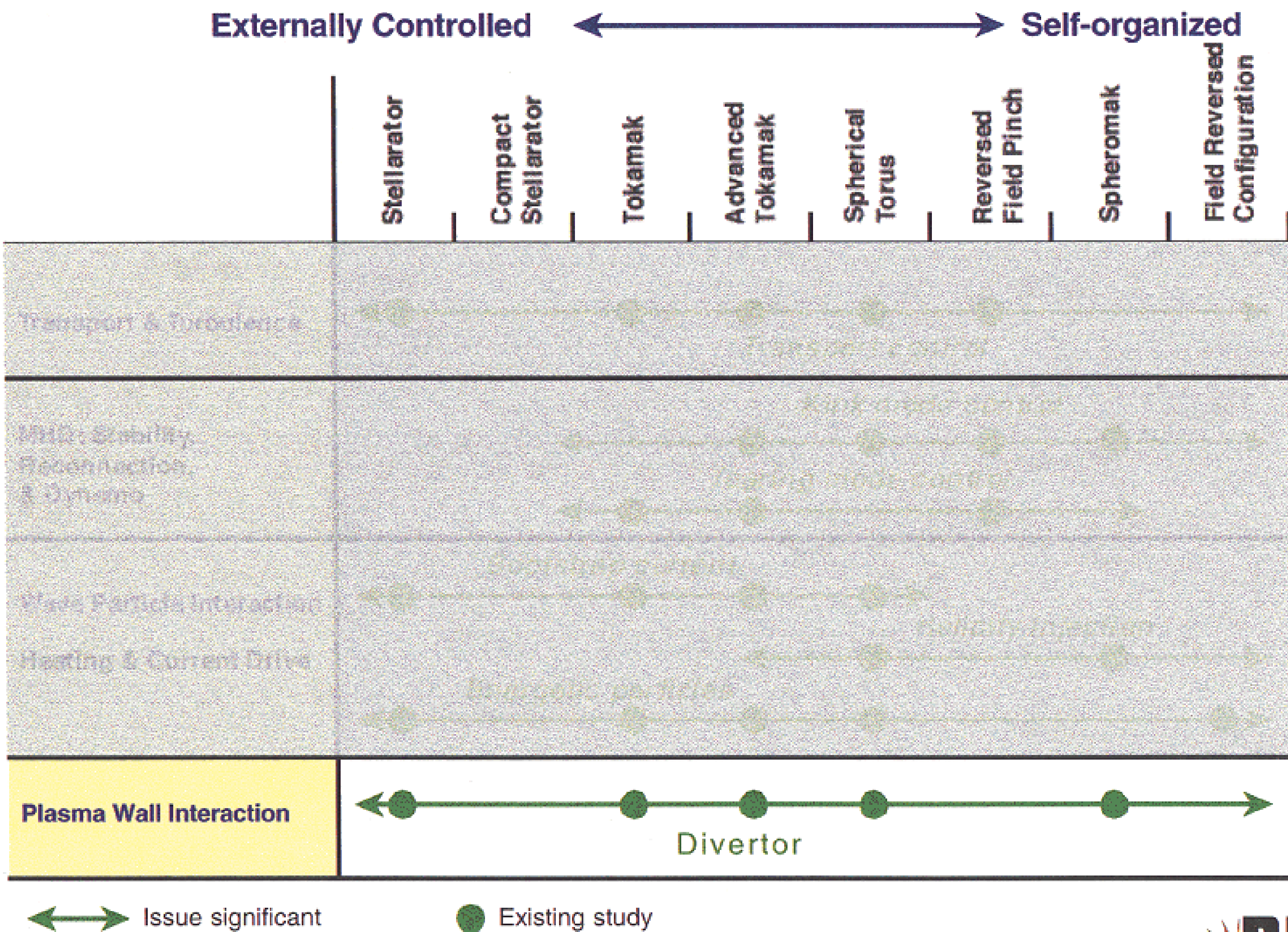
Science Topics vs. MFE Configurations



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PLASMA-WALL INTERACTIONS

- Tremendous progress has been made in plasma-wall interactions.
  - Achievement of recombining plasmas.
  - Excellent results on ash removal.
  - Understanding of mechanisms of parallel transport.
  - Strong reduction in heat flux.

- The distance to a power plant is still large...
  - Need lower Zeff – at higher heat flux.
  - Tritium retention must be reduced.
  - Major issues remain with handling off-normal events:
    - – disruptions, ELM's.
  - Consistency with core regimes.

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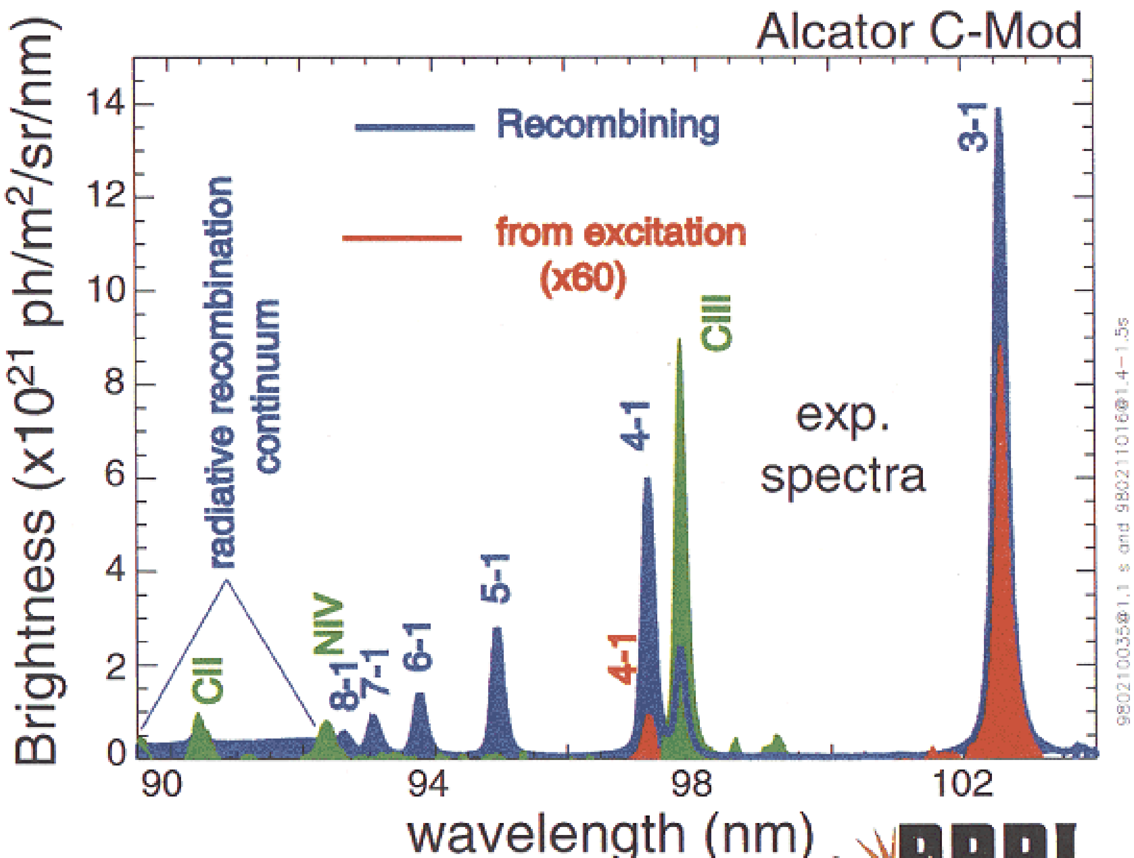
Neutral Particle Concentration Aids Ash Removal & Heat Reduction

- Plasma is extinguished by recom-bination.
- Heat flux is greatly reduced.



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Princeton Plasma Physics Laboratory

Liquid Walls are Revolutionary!

- TFTR showed highly enhanced confinement with low-recycling, lithium-dominated edge.
- Magnetically propelled, conductive liquid wall could stabilize resistive wall modes.
- Liquid walls should be resistant to off-normal events, such as ELM's and disruptions.
- Liquid walls may allow much lower activation.

KEY POINTS

- There are tremendous opportunities for science and innovation to resolve critical fusion issues.

- To exploit these opportunities requires collaboration across traditional lines of:

  Confinement Configurations (Ext. Cont. – Self-Org.)
  Disciplines (Theory/Comp. – Exp't – Technology)
  Institutions (Universities – Labs – Industry)

- This meeting provides a unique cross-cutting forum to identify opportunities – for science, for innovation, and for collaboration.

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Recommendations for this Meeting

- Talk with people you don't normally talk with.
- Listen carefully to everyone.
- Look for win-win collaboration opportunities.
- Create some exciting new insights and innovations to resolve critical issues for fusion.