Addressing Experimental Challenges of Fusion Energy with Computational Physics

By

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Presented at the workshop:

Computational Challenges in Magnetized Plasmas

UCLA Institute for Pure & Applied Mathematics

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DIII-D NATIONAL FUSION FACILITY

GENERAL ATOMICS

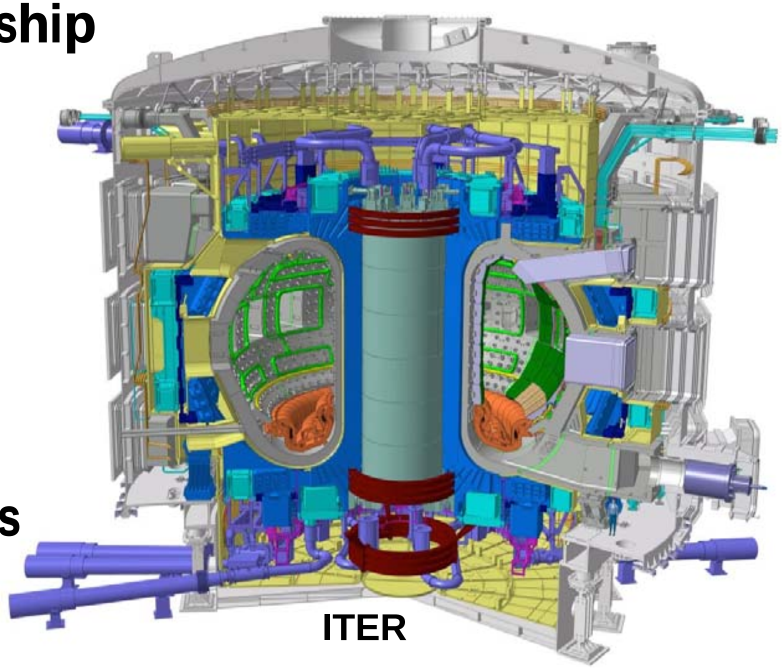
New Era in Fusion Energy Now Emerging

- **A burning plasma experiment is now being constructed under world-wide partnership**
  - *'**ITER**' – Latin for '**the way**'*

- **ITER's mission:**
  - "To Demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes"

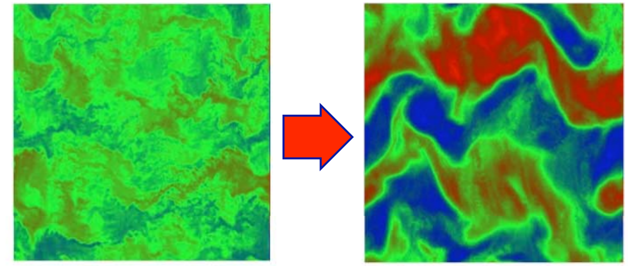
- **ITER will make hundreds of Mega-Watts of fusion power**
  - Energy gains of x10 or higher
  - Dominant self-heating from the fusion process
  - Steady state operation for thousands of seconds

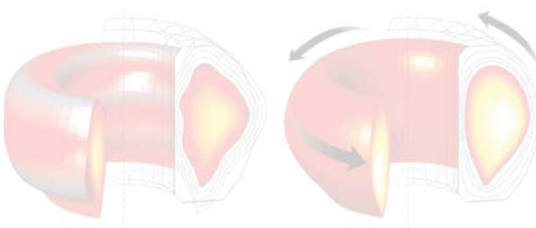
    → *Resolve plasma physics dynamics, test materials and tritium breeding blankets for a fusion power plant*



Burning Plasma Regime Poses New Physics Challenges

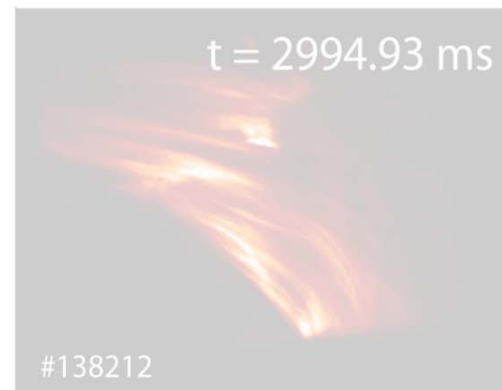
- **Self-heated fusing plasmas**
  - Energy transport & turbulence change





- **Self-sustaining 'bootstrap' driven currents**
  - Operate above present stability limits

- **Heal flux tearing instabilities**
  - Control current distribution



- **Avoid heat bursts that melt vessel walls**
  - Regulate the plasma edge behavior

- **Develop control over the plasma termination**
  - A complex multi-scale challenge

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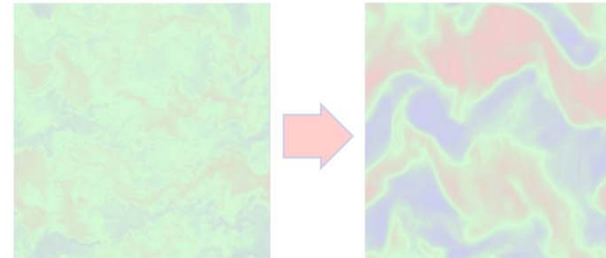

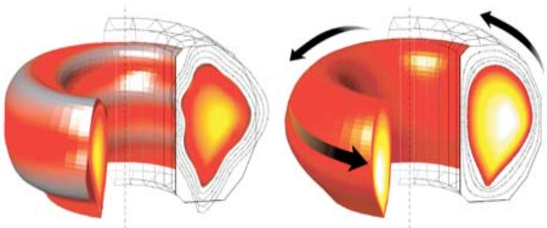

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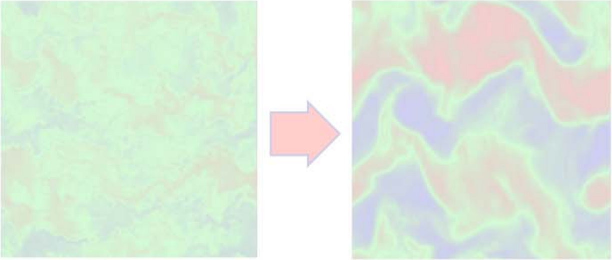

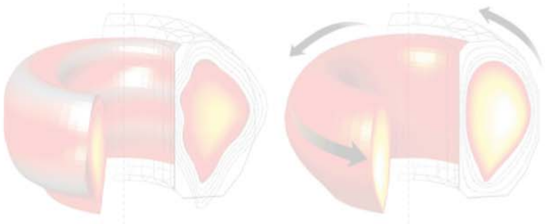

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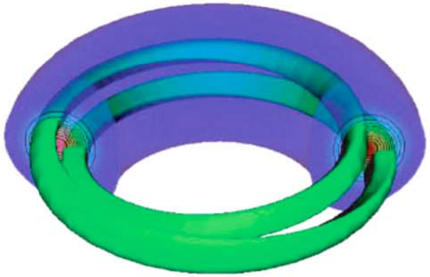

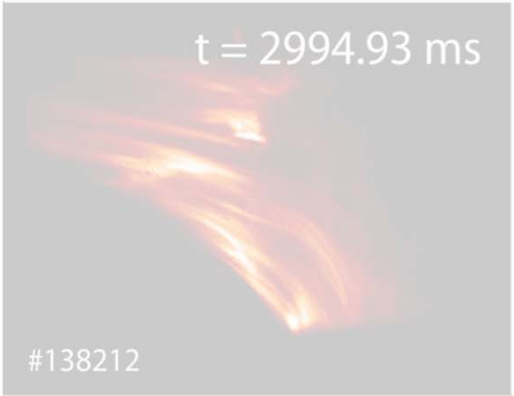

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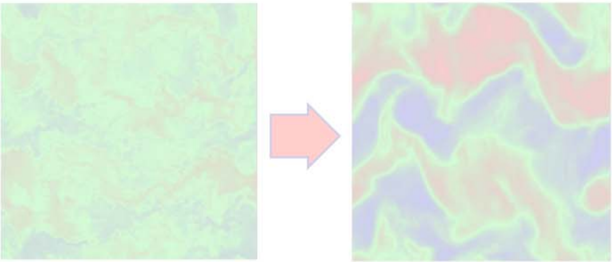

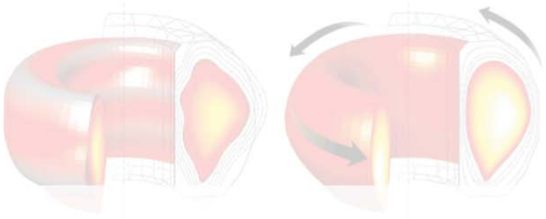

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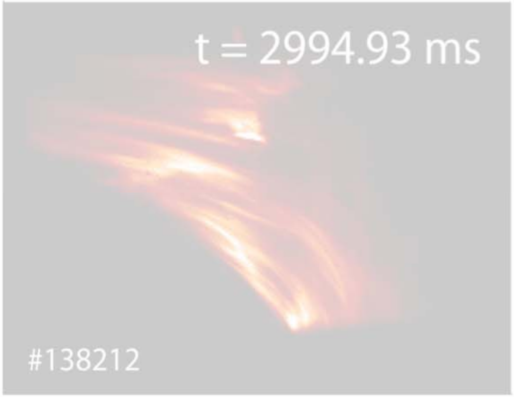

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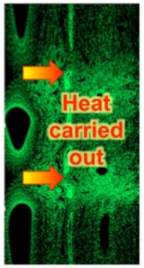

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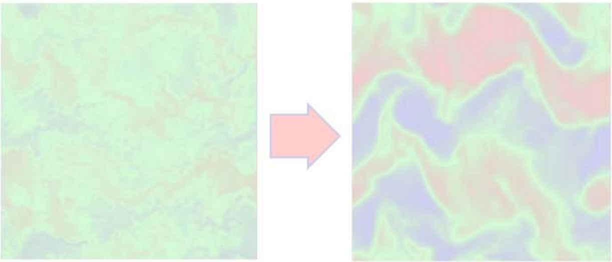

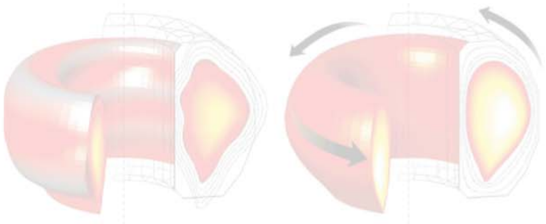

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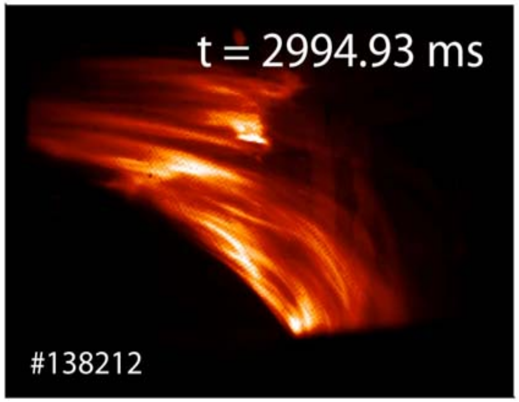

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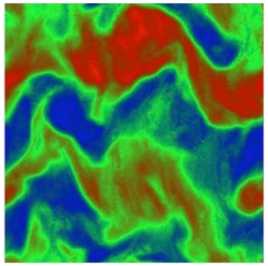
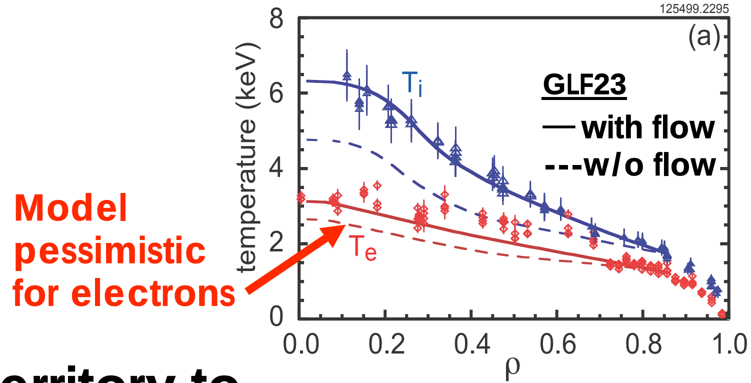
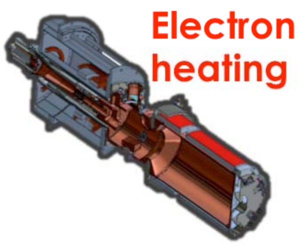
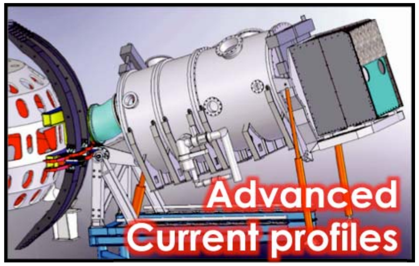
Computational Physics Plays a Key Role in the Interpretation of Experimental Phenomena

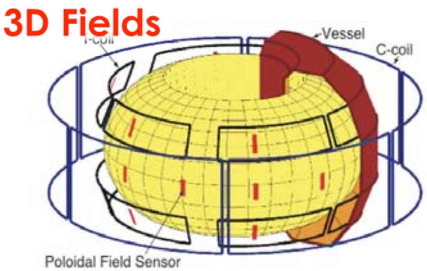
- **Computational physics enables us to understand what theory really looks like in reality**
  - Can predict and identify phenomena
- **Computational physics is the tool to predict future devices**
  - But models need experiments to determine & quantify physics
    - Process is a two-way partnership
    - Is perfect match the goal?
- **Experiments need to move into new territory to explore and resolve the physics of burning plasmas**

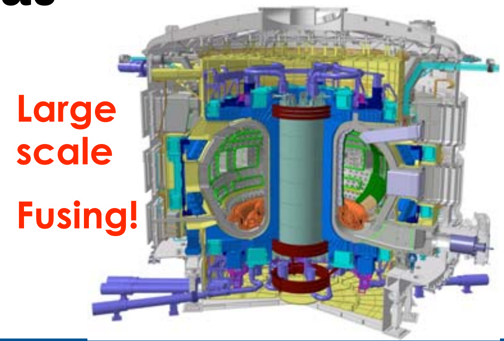




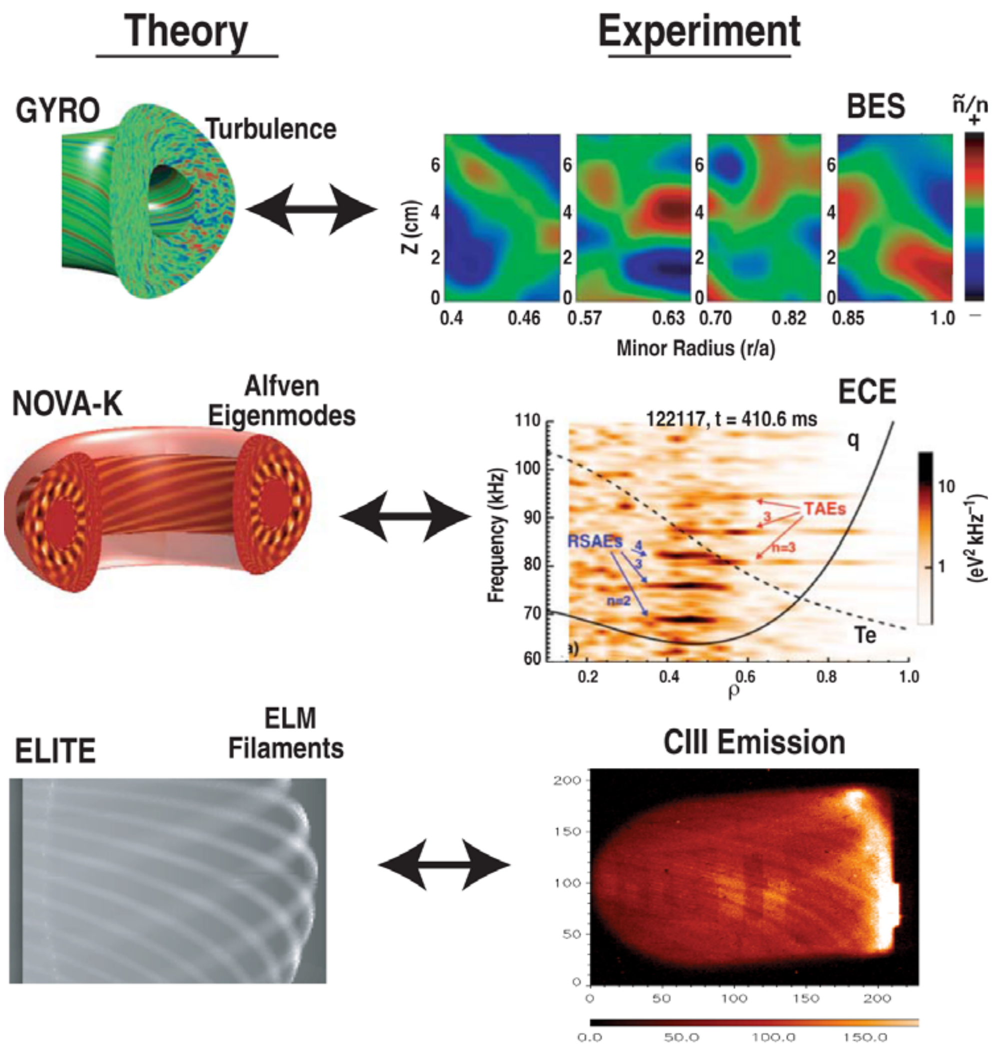








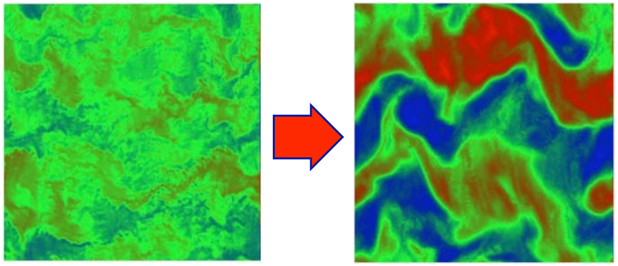
Validation of State-of-the-Art Models is a Central Theme of Fusion Science Research



- **High speed computing is key element**
- **Comprehensive & excellent diagnostics**
- **Validation as collaborative effort,** eg for DIII-D:
  - Turbulence: GA, UCLA, Wisconsin, MIT, UCSD, etc.
  - Alfvén eigenmodes: UCI, PPPL, GA
  - Edge plasma instabilities: UCSD, LLNL, ORNL, SNL, GA

Experiments & diagnostics are key to the development of validated physics models

Contents



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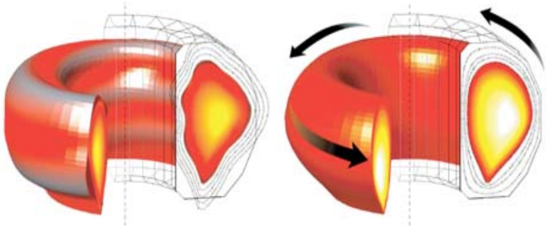

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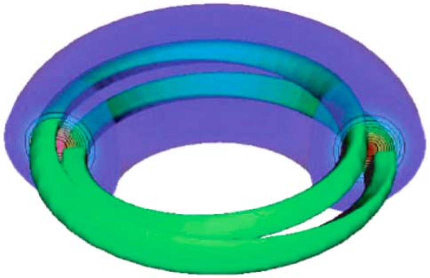

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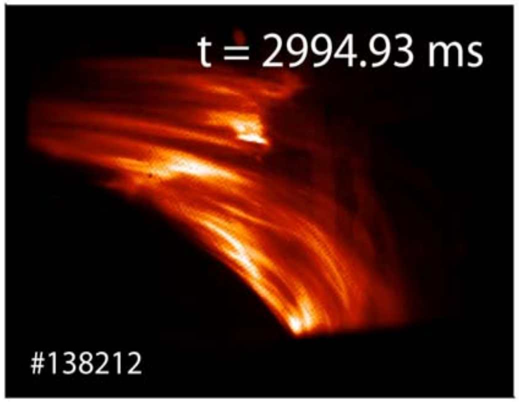

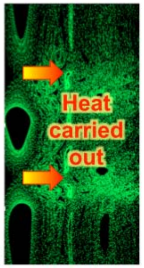

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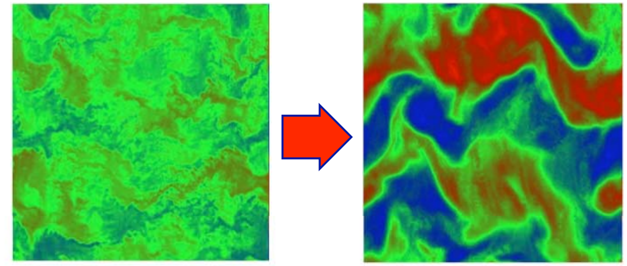

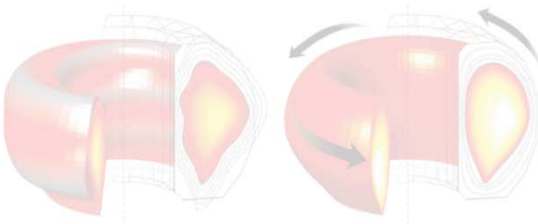

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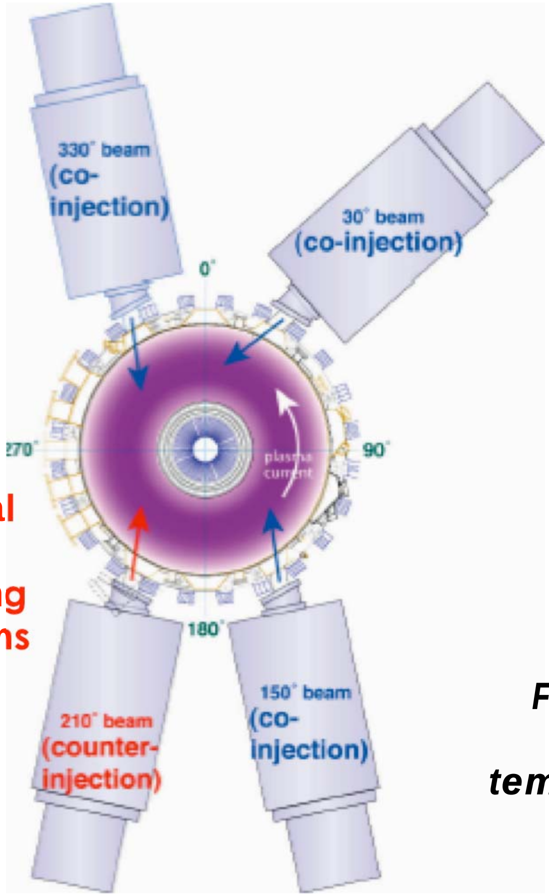
Behavior is Fundamentally Different in the Burning Plasma Regime

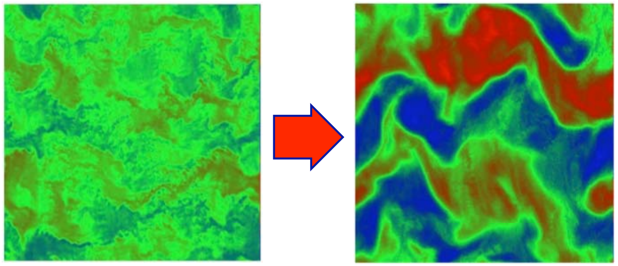
- **Most present tokamaks use neutral particle beam heating**



DIII-D neutral beam heating systems

  - Generally deposit on the ions and drive considerable rotation
- **Fusion devices are alpha particle heated**
  - Energetic alphas are super-Alfvenic and slowed down on electrons
  - Does not drive momentum
- **This changes the way heat and particles flow through the plasma**
  - These fluxes drive turbulent eddies
  - Scale of eddies change in burning regime

Fine scale electron temperature gradient modes



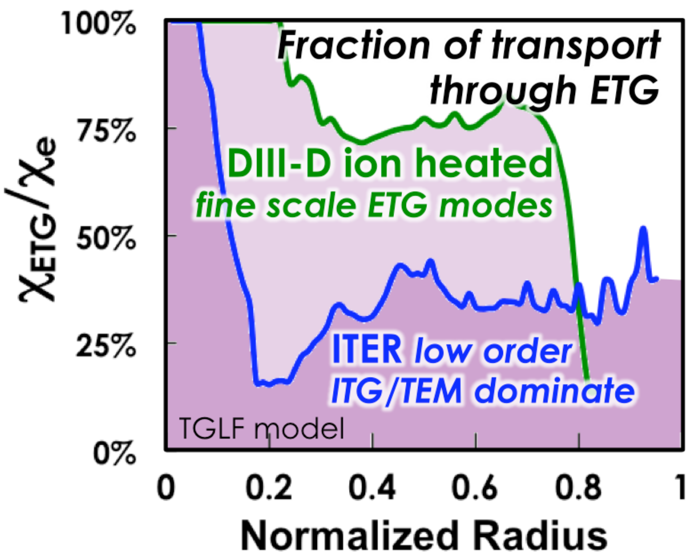
Larger scale trapped electron modes

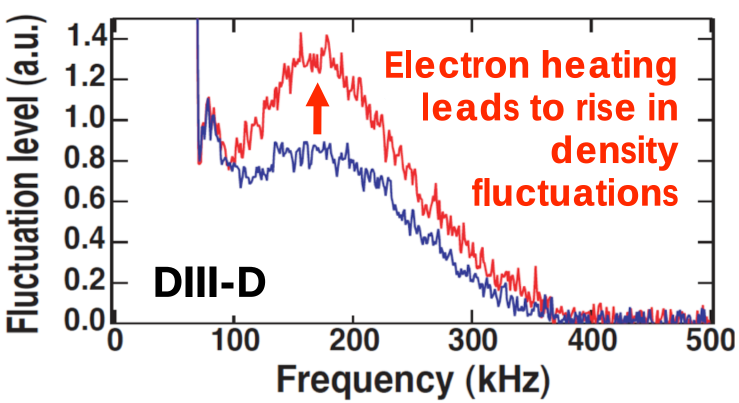
These are different transport instabilities!

Codes and Experiments Can Quantify Changes in Burning Plasma Relevant Regimes

- **Transport processes are different with dominant α heating of electrons**
  - **Nature & scale of turbulence change ➔**
  - *Because heat, momentum and particle throughput are very different*
- **Burning plasma regimes likely to be different optimization from present high torque ion heated devices**
  - *May need to change plasma current, pressure, density, or profile shapes*
    - *Enable ITER to succeed*
    - *Design of FNSF and power plant*

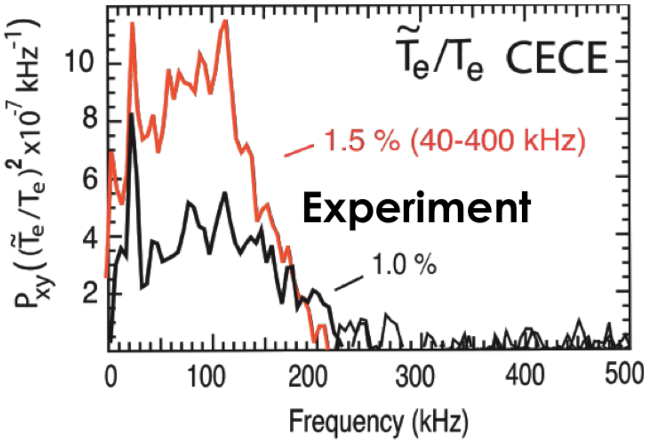
Vital to prepare for this – avoid lengthy re-optimizations in ITER and prepare tools to interpret behavior

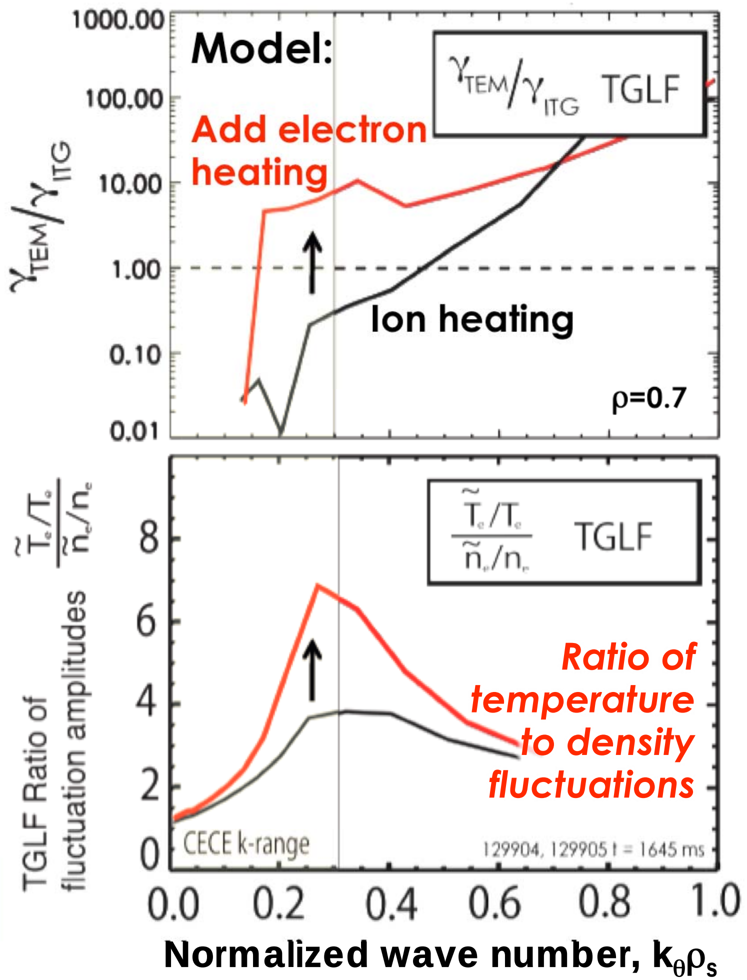




Transport Codes Provide Basis For Understanding

- **Codes can show changes in transport mechanisms and manifestation**
  - Example: low performance regime:
  - Fluctuations manifest more in temperature channel ➘
    - ***Validate experimentally:***

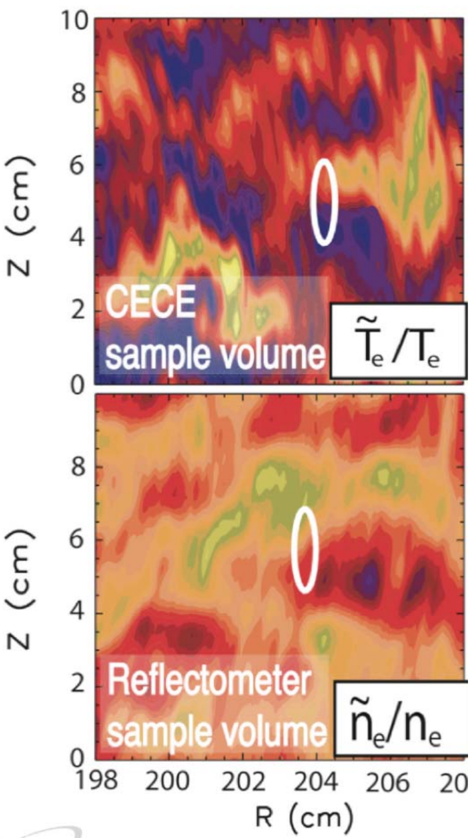


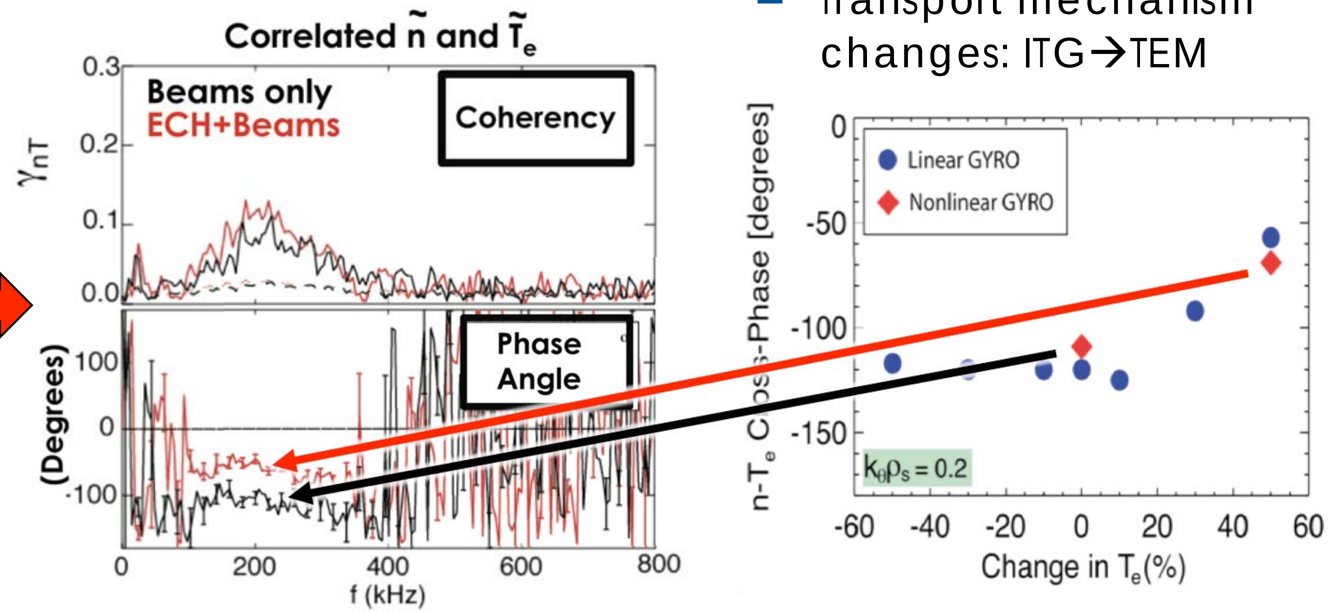


Codes vital to interpret and predict behavior
– explain why observed changes happen…

Experimental $\tilde{n}_e - \tilde{T}_e$ Cross-Phase Angle Provides Quantitative Test of Nonlinear Gyrokinetic Simulations

Measured $\tilde{n}_e - \tilde{T}_e$ fluctuation cross-phase angle increases with electron heating – as theory predicts:





- **GYRO simulation used to create synthetic diagnostic**
  - Transport mechanism changes: ITG→TEM

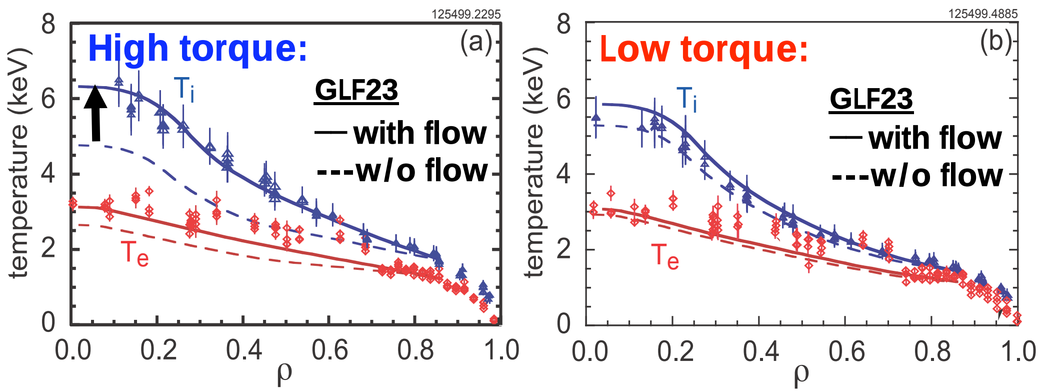
- **Data validates prediction of transport changes**

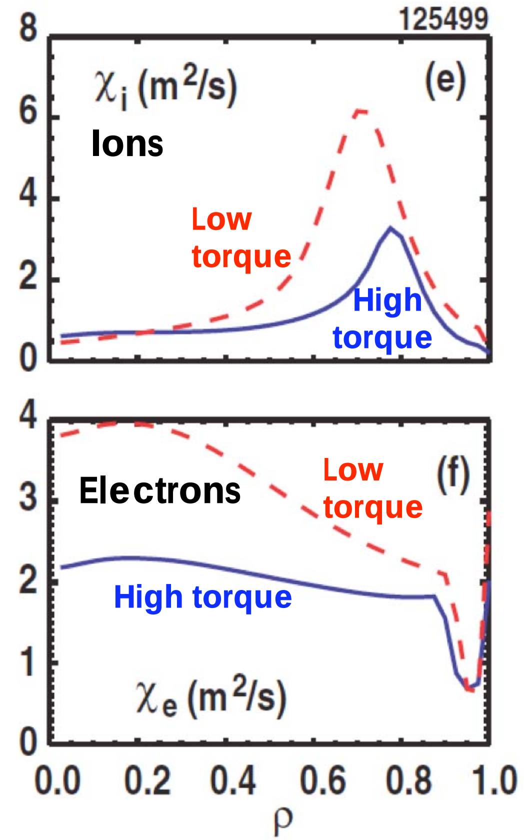
Innovative measurements coupled with state-of-the-art modeling provide confidence in physics models

[White, PoP 2009]

Codes Can Capture Trends…
But need data in right regimes to constrain them

- **Comparisons of low and high torque shows strong flow effect on transport**
- **But rotation effect manifests differently between ion and electron channels**
  - Model captures flow role in ion channel
  - But is pessimistic for electrons:



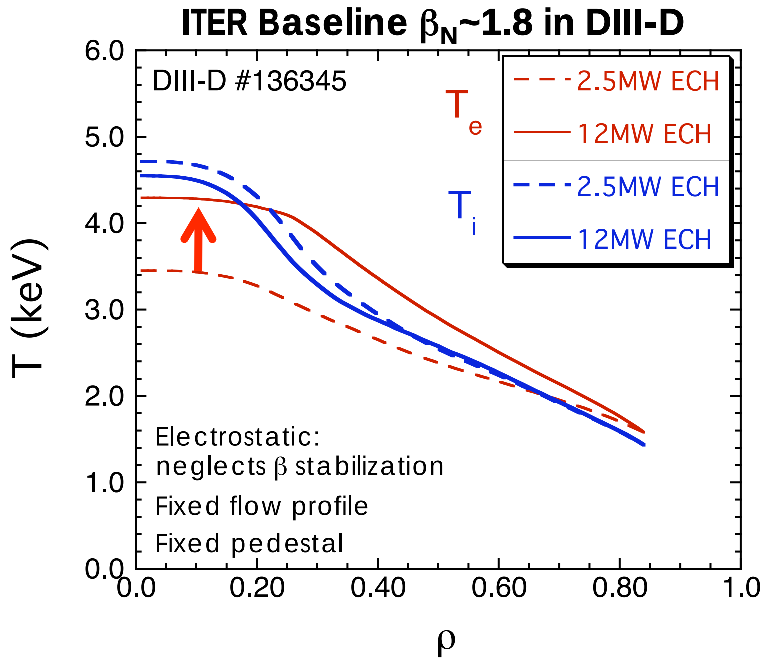


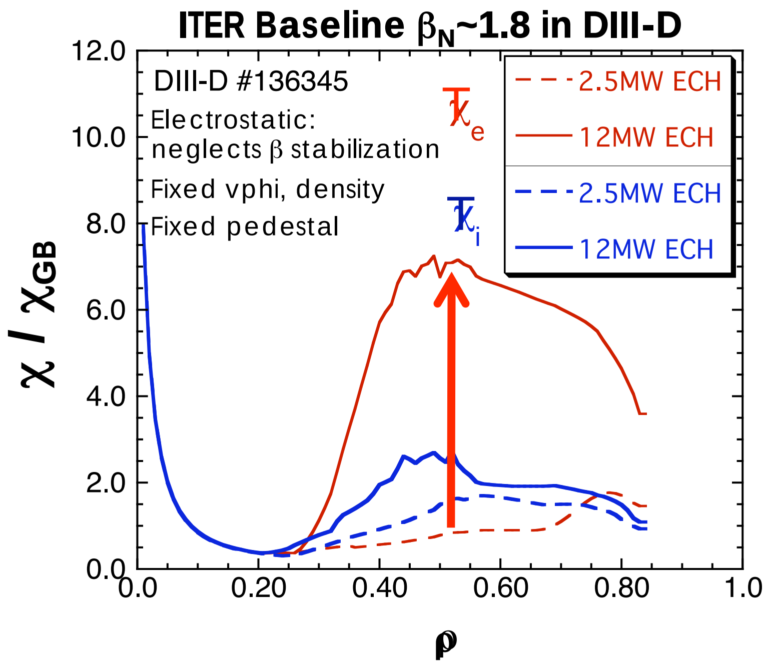
Need to investigate physics in relevant regimes to resolve models

– **Electron dominant heating at low rotation: explore match, trends, structures and phenomenology**

Codes Point the Way: TGLF Modeling Shows Rise in Transport as Electron Heating Increases

- **Electron heating raised from 2.5 MW to 12 MW (2.3 MW of ion heating fixed)**
- **Ion transport only slightly affected**
- **Electron energy transport increases dramatically → x8!**



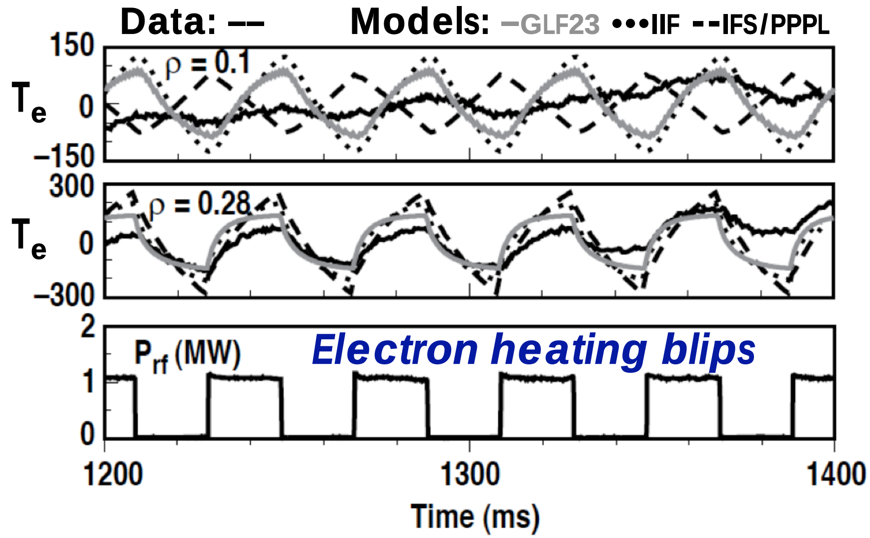


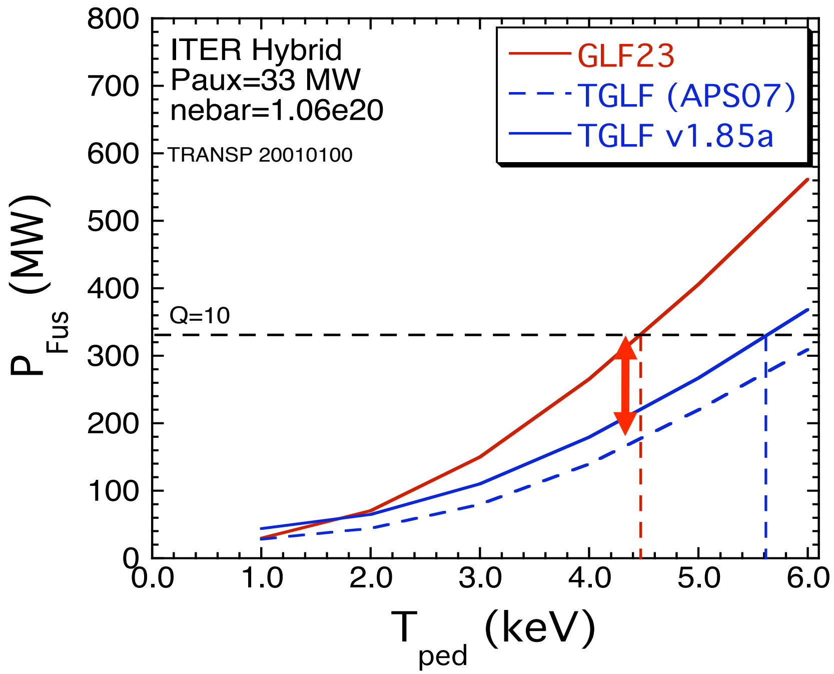
Property know as 'stiffness' (limiting gradient) – how is this affected, and can this be manipulated by modifying plasma conditions? (J, β, Ω)

[Kinsey, APS 2009]

Resolving Transport Models Is Central To Developing Effective Fusion Plasma Scenarios

- **Transport models disagree with ➔ each other and experiment:**
  - Do not capture core modulation in these low performance plasmas
  - Some do not even match phase!





- **Different models give wide range in ITER fusion power projection:**
  - Dictate / depends on pedestal

Predictability is key to understanding how to optimize regime for high fusion power

[Deboo, Nucl. Fus. 1998, Kinsey APS 2009]

Pause for thought:

What is Needed to Resolve Physics Models?

- **Codes make numeric predictions**
  - Right or wrong – how does this help?
  - Often codes aren't expected to make quantitative match
- **Predicting trends and phenomenology**
  - One of the main ways to convince that underlying model is right
- **Predicted structure/spectra of events can be clearer indicator**
  - Compare with detailed measurements in experiments to confirm the simulated and real processes agree
- **Comparisons must be extended to relevant regimes**
  - Where relevant mechanisms are dominant & can be best tested
  - Provides key tests as new parameters encountered

Resolving predictable behavior is an iterative process between modeling and experiment

  - *And requires in depth thought about the underlying physics*

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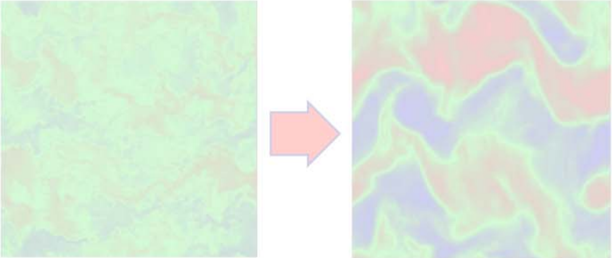

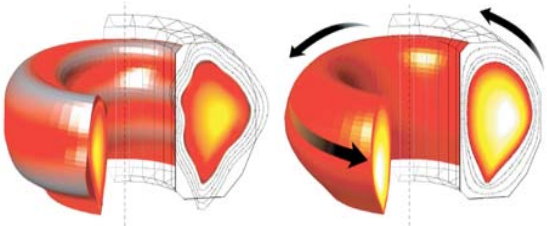

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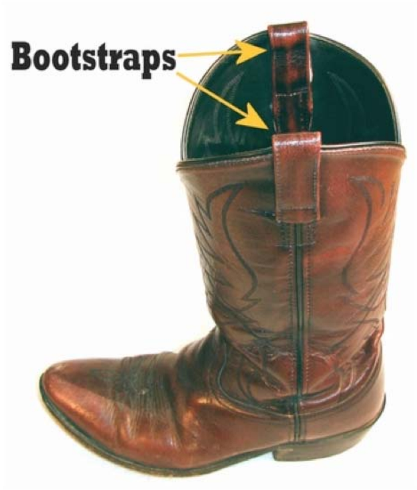
With Sufficient Plasma Pressure, Tokamaks Can Make Their Own ‘Bootstrap’ Current

With Sufficient Plasma Pressure, Tokamaks Can Make Their Own 'Bootstrap'* Current

***From the legend of Baron Von Munchausen**

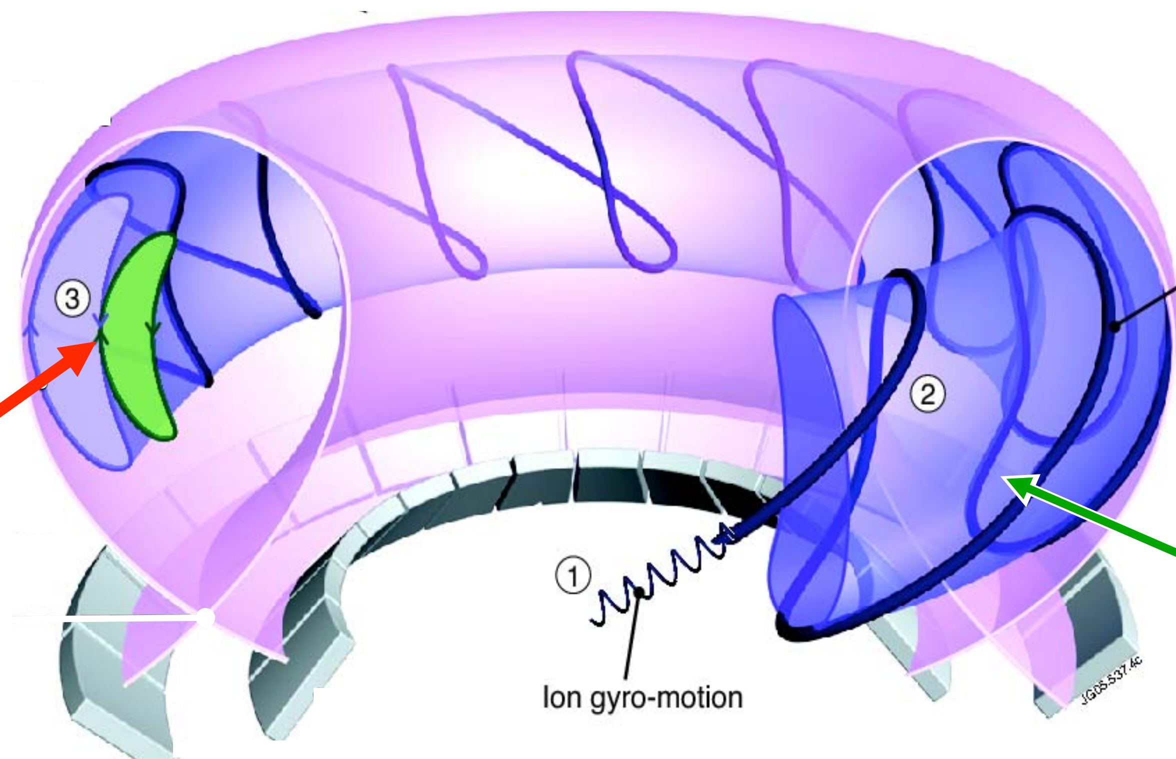
- Who succeeded in pulling himself, and his horse, out of a swamp up by his hair!

- Later retellings converted this to bootstraps



With Sufficient Plasma Pressure, Tokamaks Can Make Their Own ‘Bootstrap’ Current

1-2: Gyro-orbits drift due to non-uniform field ⇒ banana orbits



3: Density & temperature gradients mean <u>more</u> & <u>faster</u> particles on orbits nearer the core (green cf blue) leading to a net “banana current”

- *this is transferred to a helical **bootstrap current** via collisions*

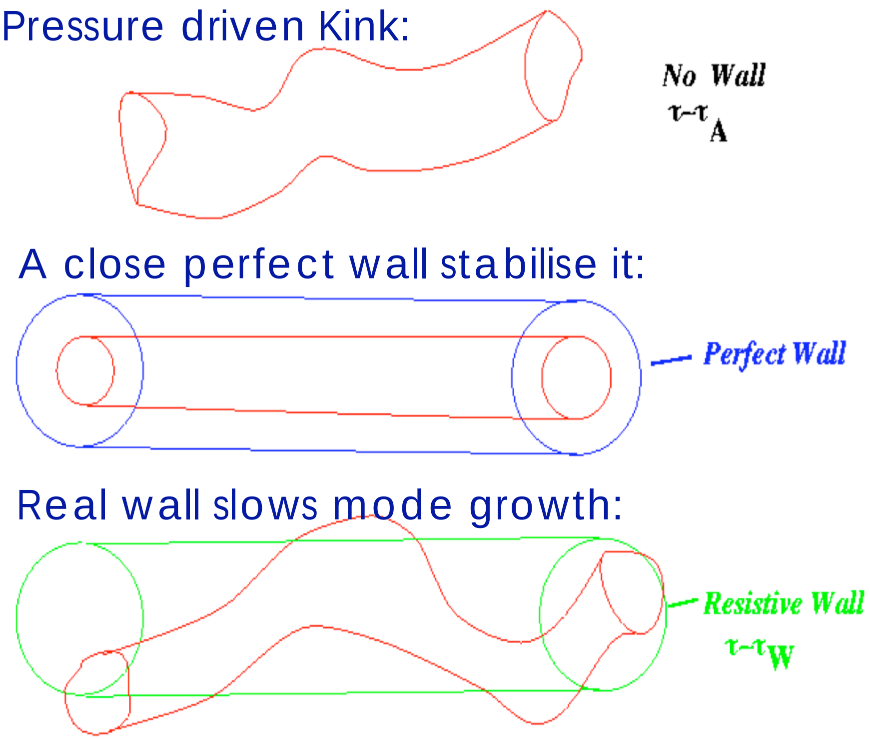
New Stability Challenges on Path to High Pressure Self-Sustaining Fusion Steady State

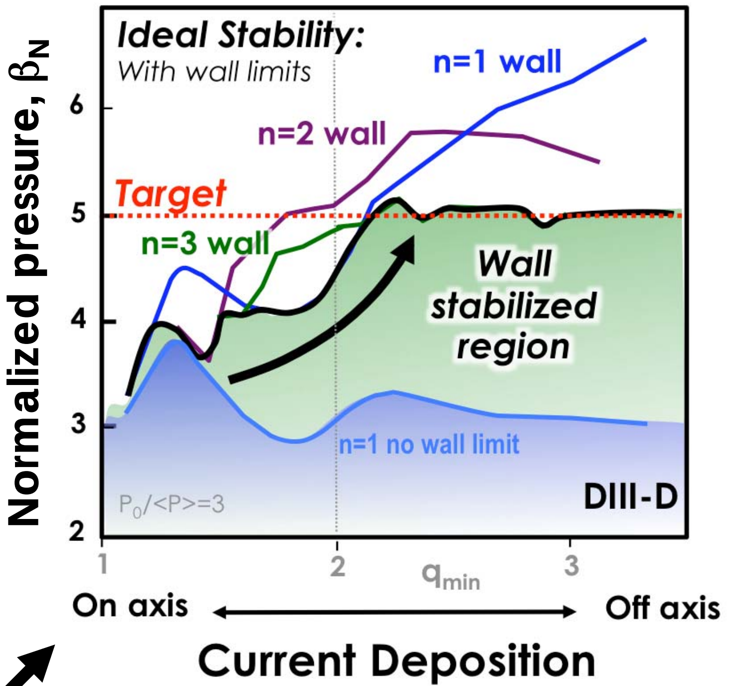
High pressure requires operation above the 'kink mode' limit:

Pressure driven Kink:

A close perfect wall stabilise it:

Real wall slows mode growth:

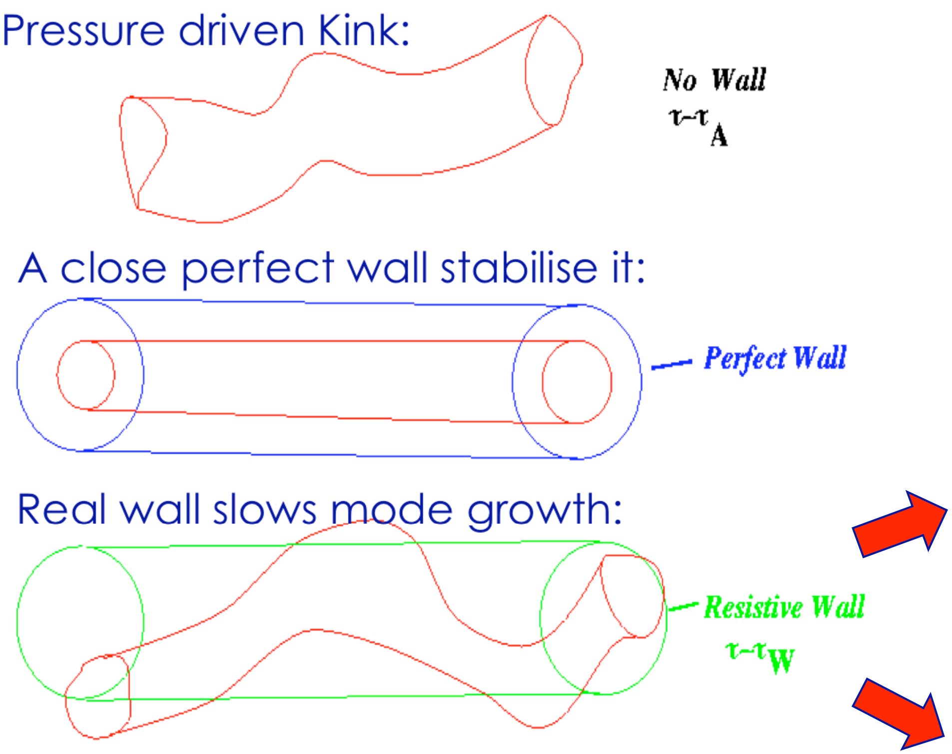




- **Codes guide development of profiles**
  - ***But what are requirements of operation in the wall stabilized regime?***

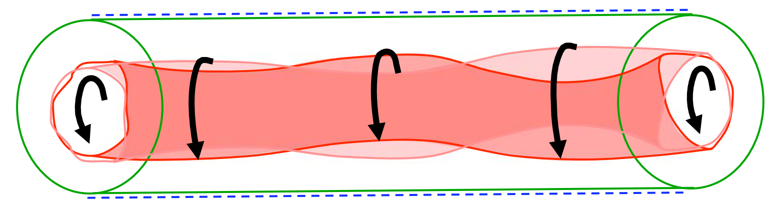
New Stability Challenges on Path to High Pressure Self-Sustaining Fusion Steady State

High pressure requires operation above the 'kink mode' limit:

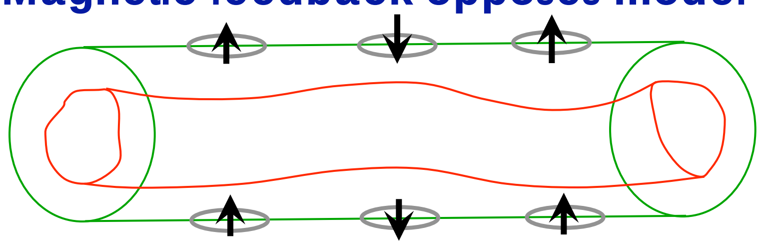


Solutions:

Rotation causes dissipation in the wall and the plasma:



Magnetic feedback opposes mode:



- **Codes guide development of profiles**
  - ***But what are requirements of operation in the wall stabilized regime?***

MISK Code Explains Apparent High Pressure Stability in DIII-D

- **Wave-particle resonances of fast ions extract energy from the mode:**

$$\delta W_K^T \propto \sum_{l=-\infty}^{+\infty} \frac{\omega_{*N} + \left(\hat{\varepsilon} - 3/2\right)\omega_{*T} + \omega_E - \omega_{RWM}}{\left\langle \omega_D \right\rangle + l\omega_b + \omega_E - \omega_{RWM}}$$

Precession drift

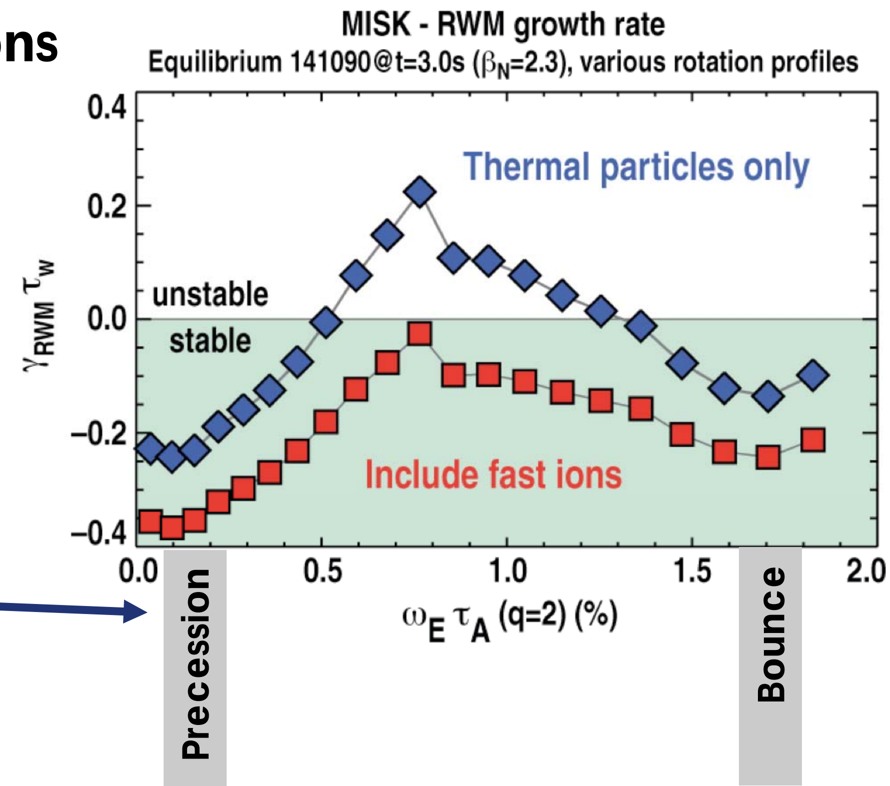
Bounce frequency

∝ Plasma rotation

Mode rotation

  - When **plasma rotation** matches other resonances in plasma

- **Promising model but is damping correct?**



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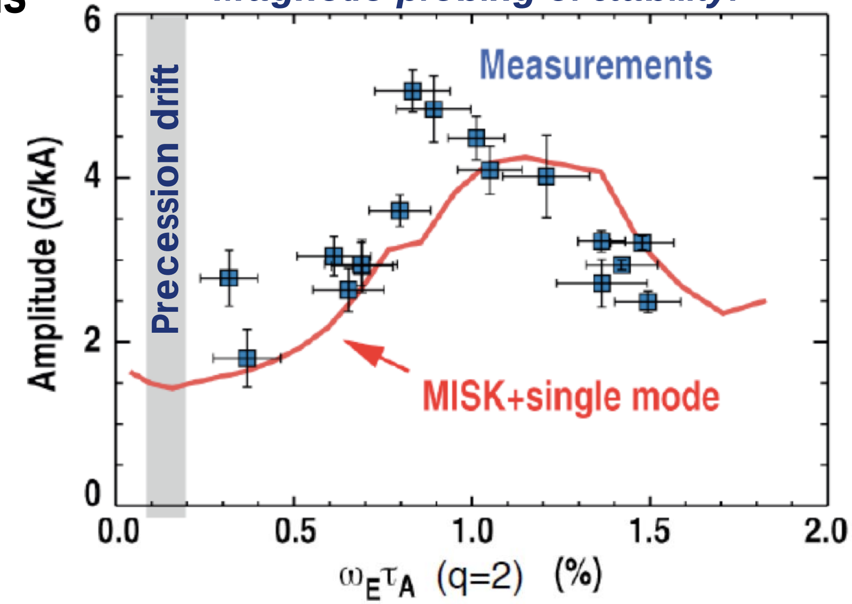
Magnetic probing of stability:



- **Promising model but is damping correct?**
  - Magnetic probing of plasma stability picks up trend
    - Plasma remains stable but responds more strongly between resonances
  - **But for true test:** predict where plasma goes unstable – where to look
    - Maximum quantification of damping terms

➔ Good comparisons need to be informed by physics understanding

[Lanctot APS 2010, Berkery PoP 2010]

Contents

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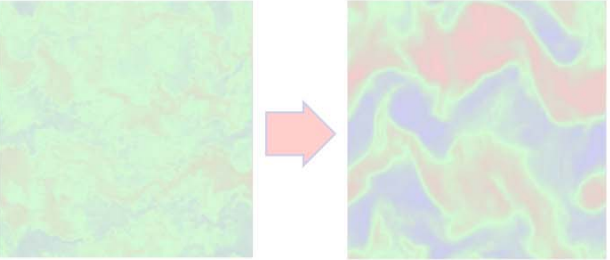
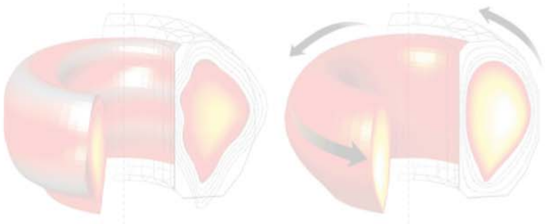
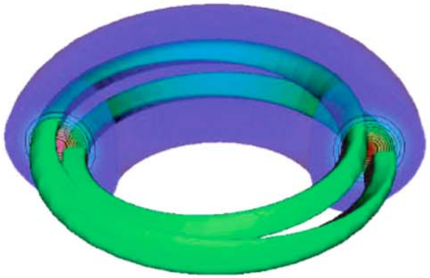
  - Energy transport & turbulence change





- Self-sustaining fusion steady state
  - Operate above present stability limits
- **Heal flux tearing instabilities**
  - Control current distribution

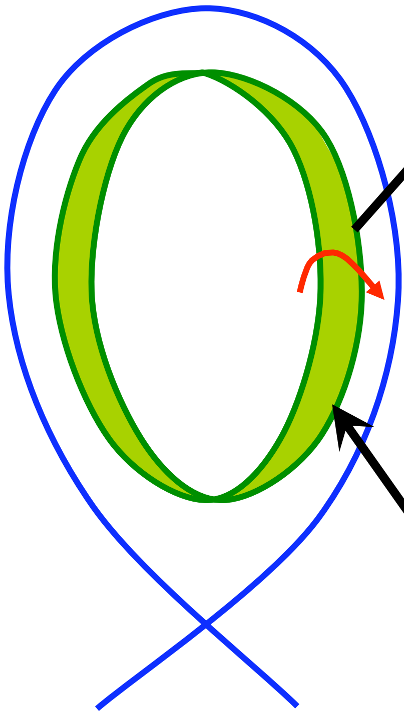


- Avoid heat bursts that melt vessel walls
  - Regulate the plasma edge behavior

- Develop control over the plasma termination
  - A complex multi-scale challenge

Magnetic Islands Can be Driven by a Bootstrap Effect

- Rational q surfaces are subject to resonant tearing

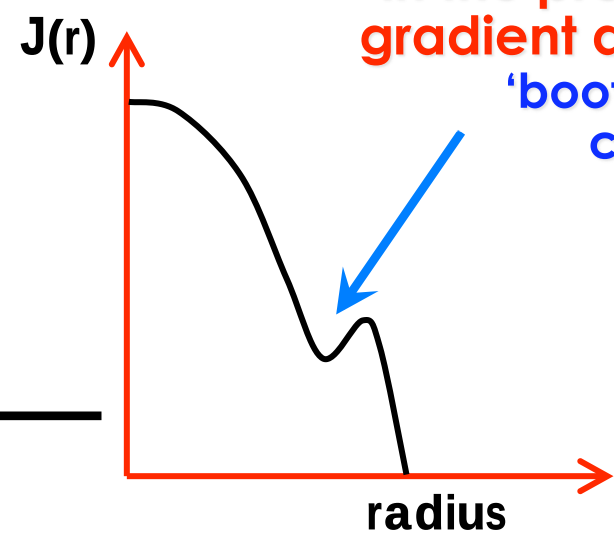


good conduction about island

flattens pressure gradients across the island

leaves a helical hole in the pressure gradient driven ‘bootstrap’ current

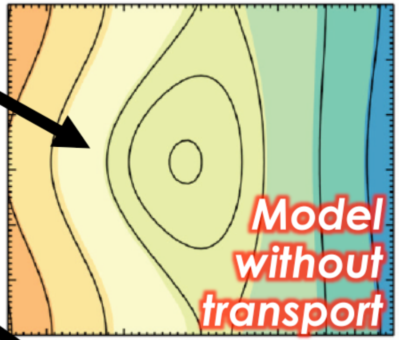
Needs a trigger to kick the whole process off (?)

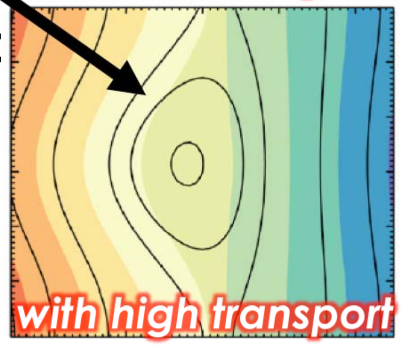


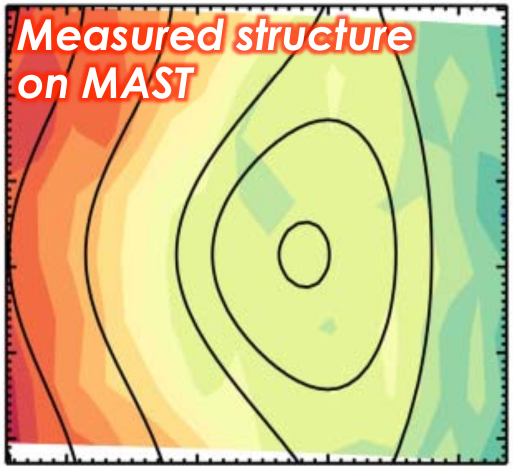
current perturbation drives island growth

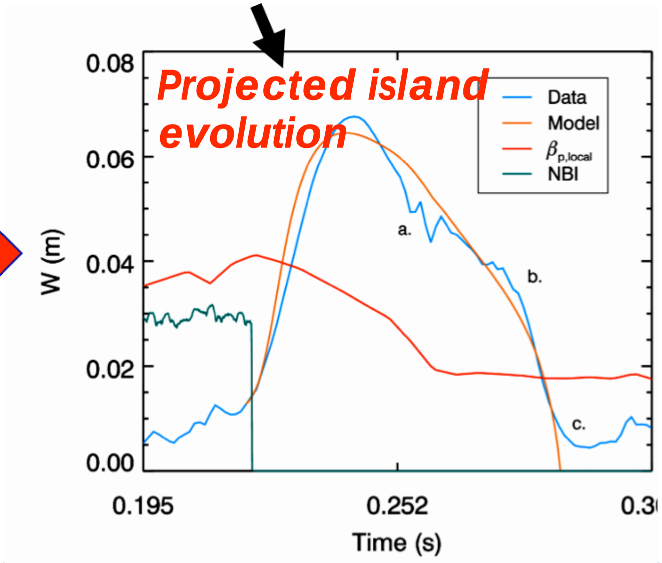
Measuring Structure of an Island Can Constrain the Model of its Evolution

- **Magnetic island expected to flatten pressure gradients**
  - Removes bootstrap drive for island growth
- **But cross field transport can re-establish gradients**
  - Prevents flattening, reduces mode drive
- **MAST 8 laser Thomson scattering system resolves effect**
  - Provides estimate of cross field transport term to calculate island size evolution





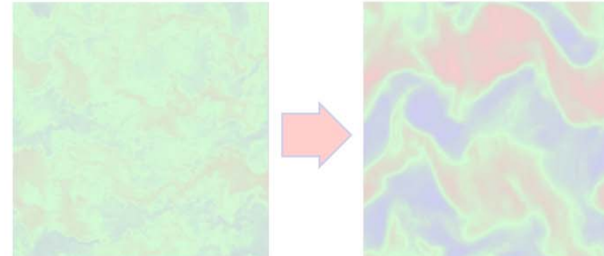


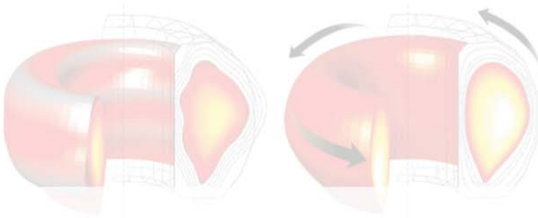


Structure of a process is intimately related to projecting its behavior

Contents

- Self-heated fusing plasmas
  - Energy transport & turbulence change





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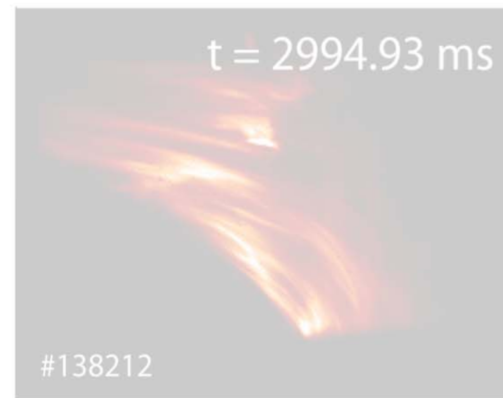
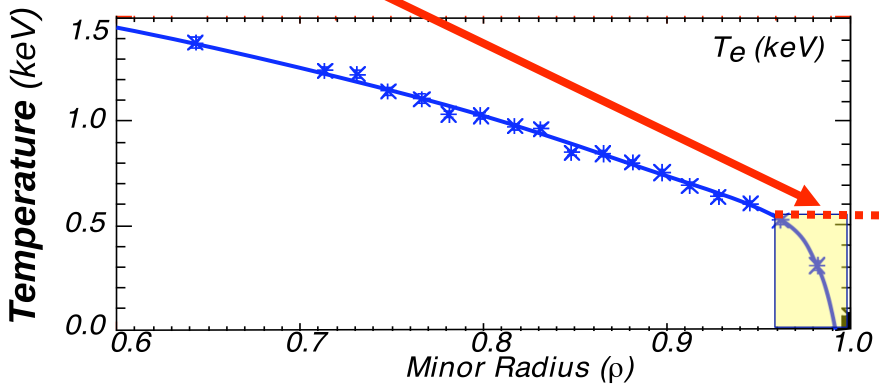


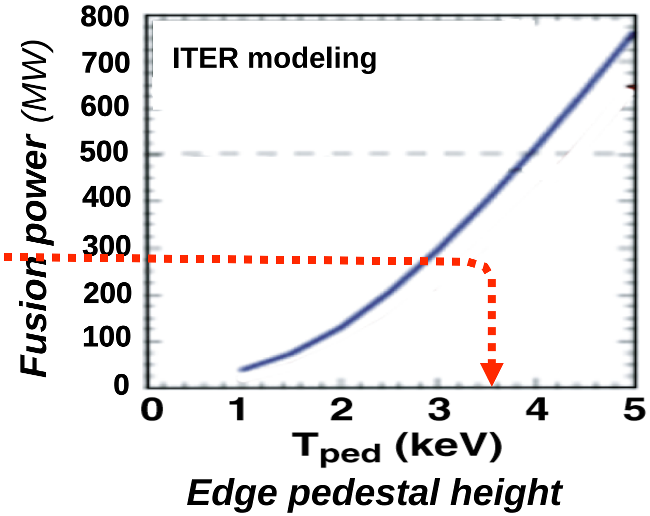
- **Avoid heat bursts that melt vessel walls**
  - Regulate the plasma edge behavior

- Develop control over the plasma termination
  - A complex multi-scale challenge

Modeling-Experiment Comparisons are Improving Physics Understanding of Plasma Edge Dynamic

- High **'pedestal'** pressure is important for fusion performance





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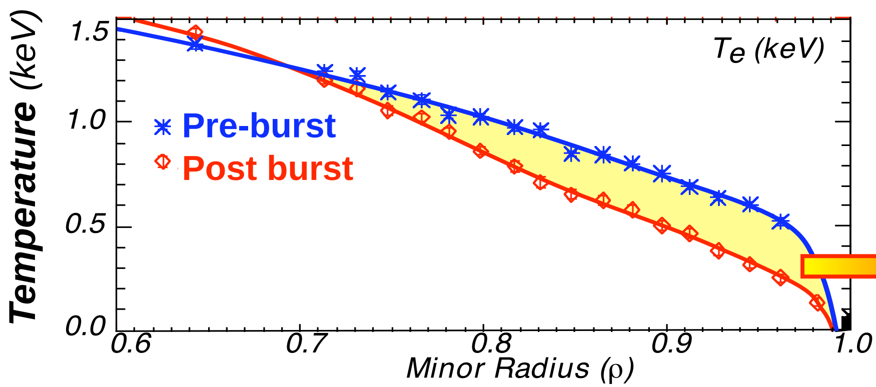
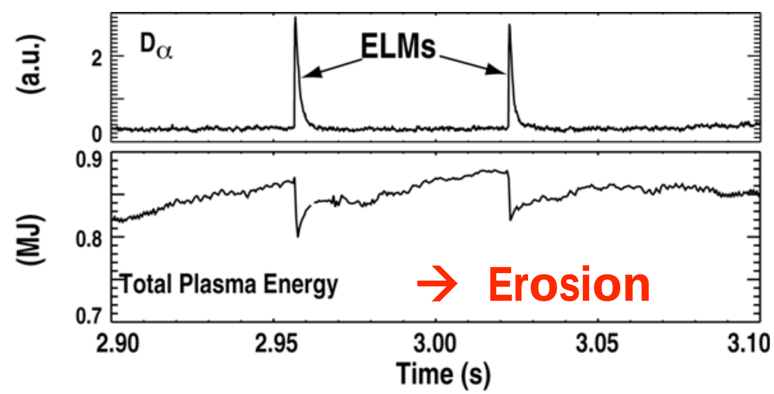


- **But excess pressure can overcome magnetic field**

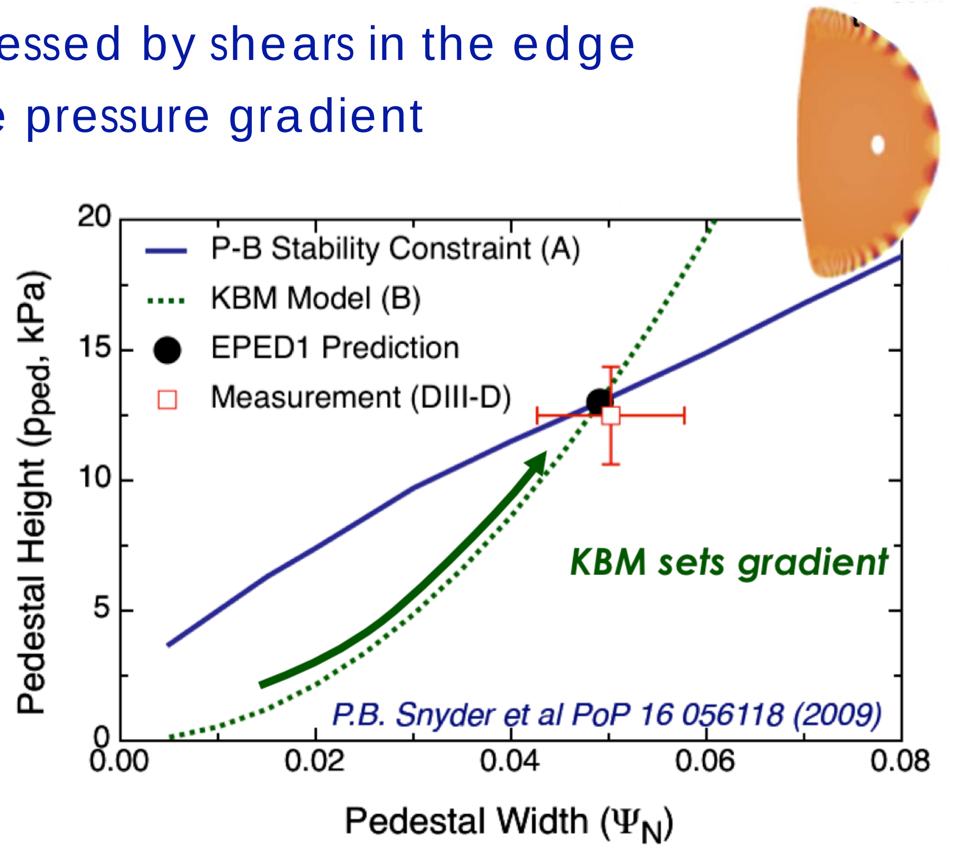
Energy Bursts



- **These events can erode wall materials**
  - One of the most serious challenges for future fusion devices

Modeling-Experiment Comparisons are Improving Physics Understanding of Plasma Edge Dynamic

- **Stability modeling explains behavior of the edge**
  - Usual turbulent transport is suppressed by shears in the edge
  - **Kinetic ballooning** mode sets the pressure gradient



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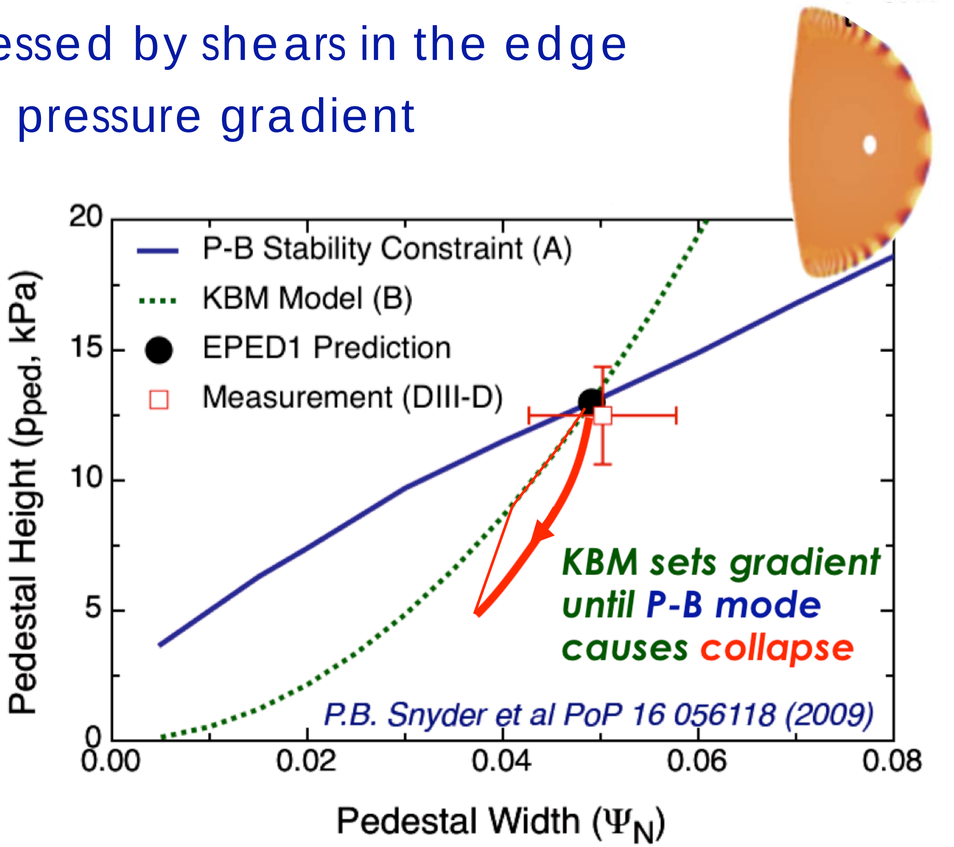

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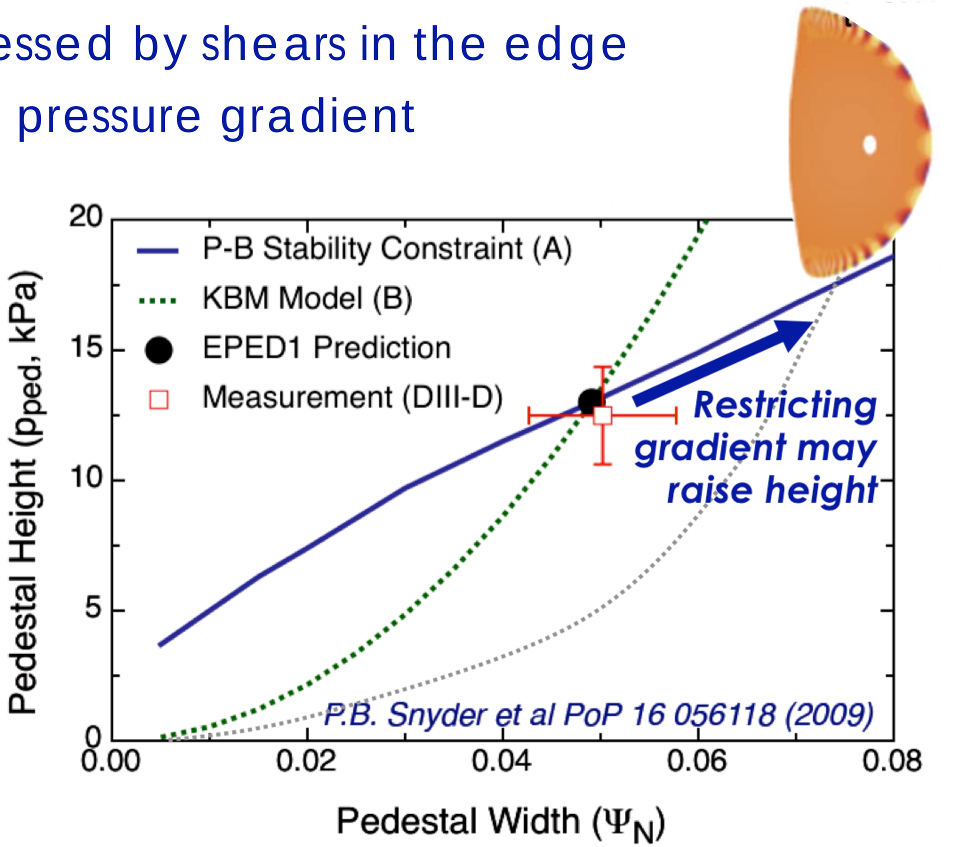

- **Raises intriguing possibilities**
  - Restricting gradients in the edge may allow wider and higher pedestal

Modeling-Experiment Comparisons are Improving Physics Understanding of Plasma Edge Dynamic

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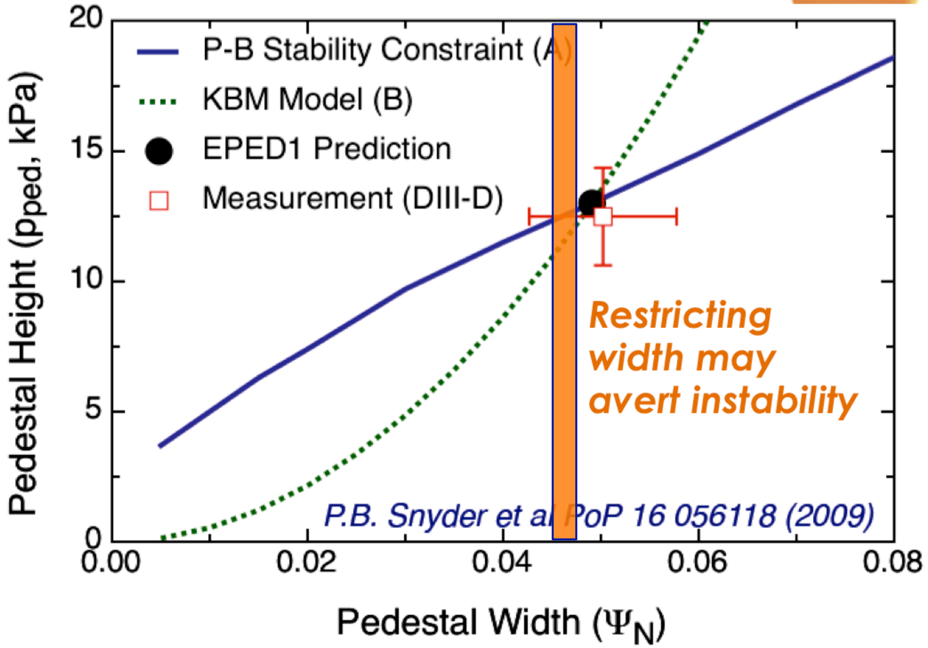
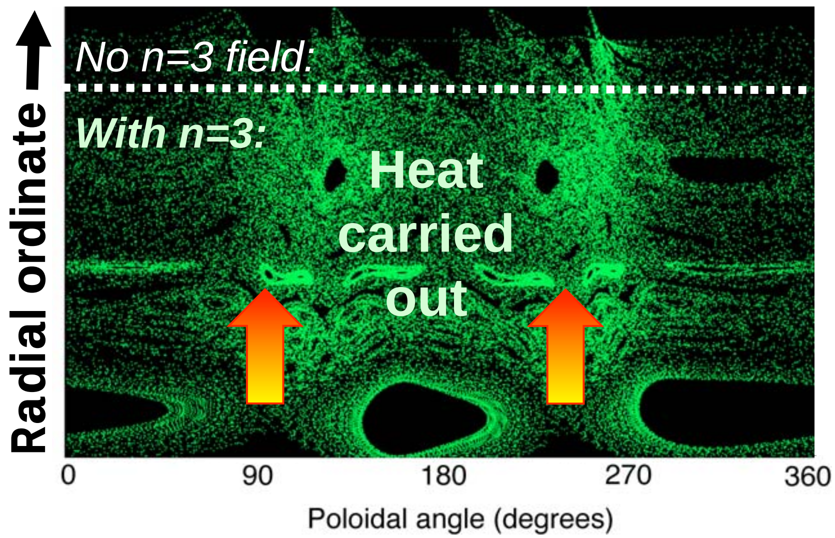


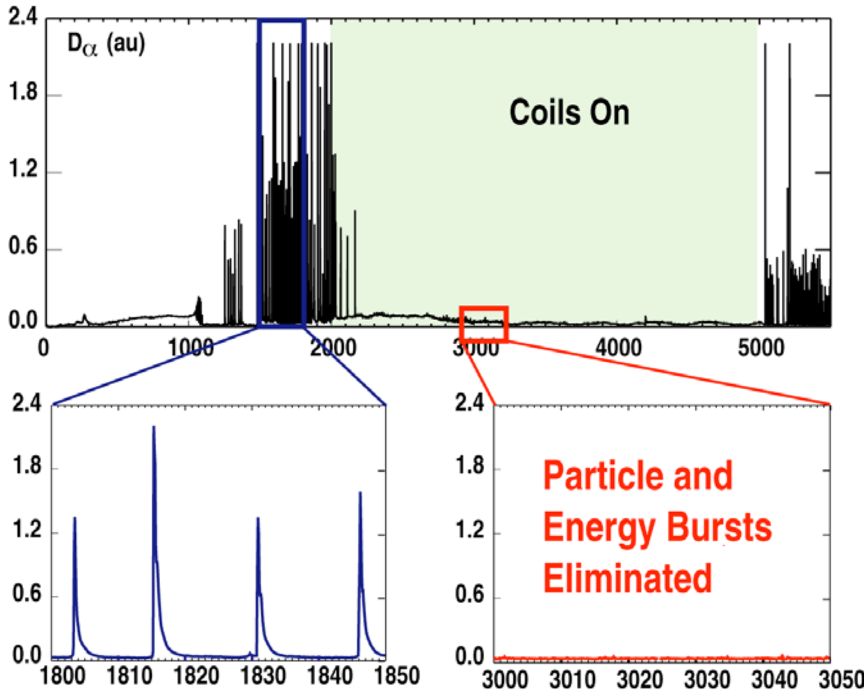
- **Raises intriguing possibilities**
  - Restricting gradients in the edge may allow wider and higher pedestal
  - Restricting width may avert edge mode
    - Magnetic islands might cause the required barrier

Computational models can lead to transformational improvements!

3-D Fields Can Eliminate Edge Heat Bursts

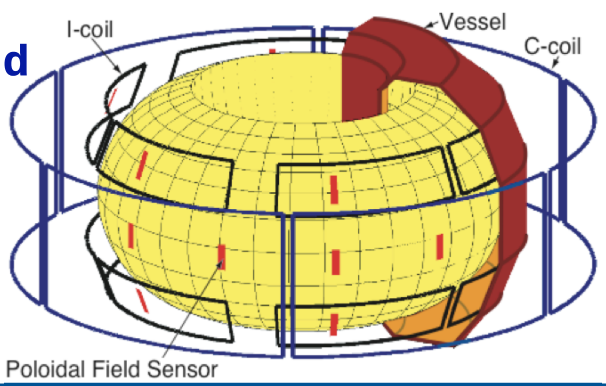
- **Early 'vacuum' modeling showed edge resonant fields ergodized flux surface structure:**





- ***But does this really hold up?***
  - What stops edge mode happening?
  - Does not explain narrow operational windows

3D Field Coils:



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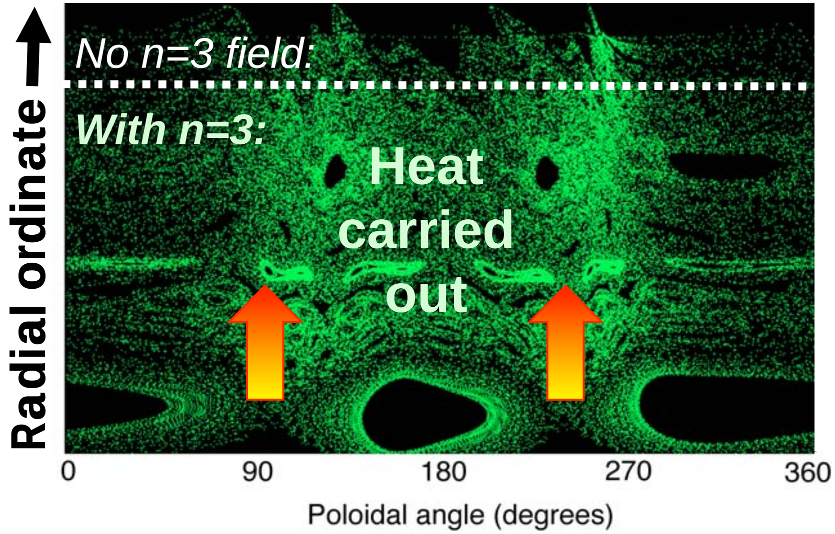
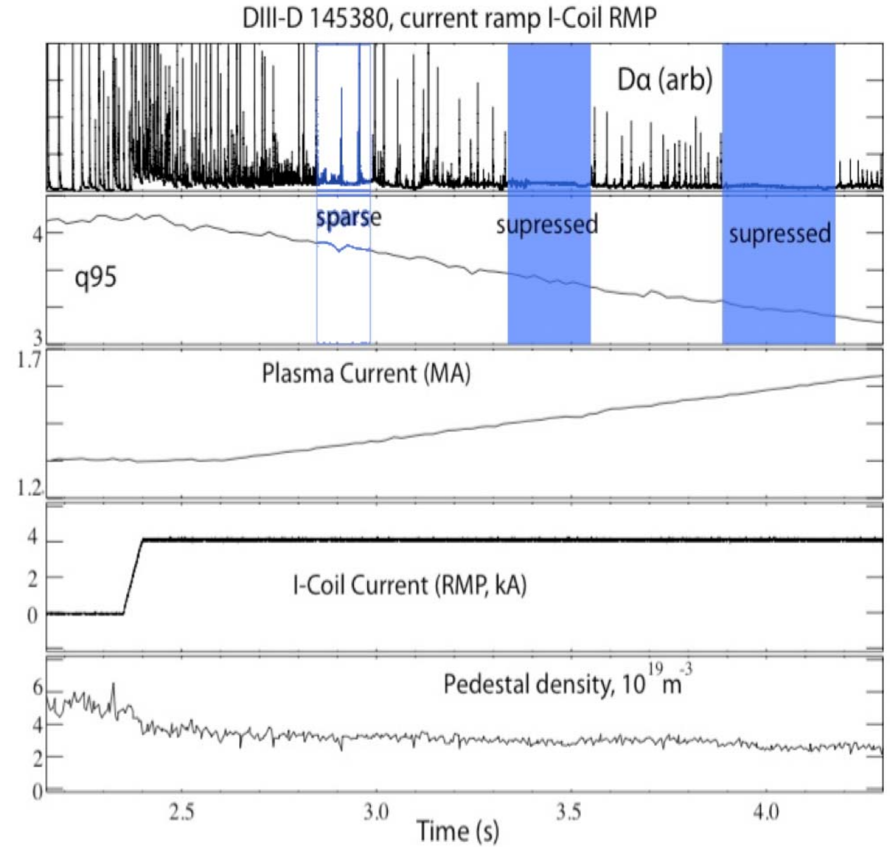


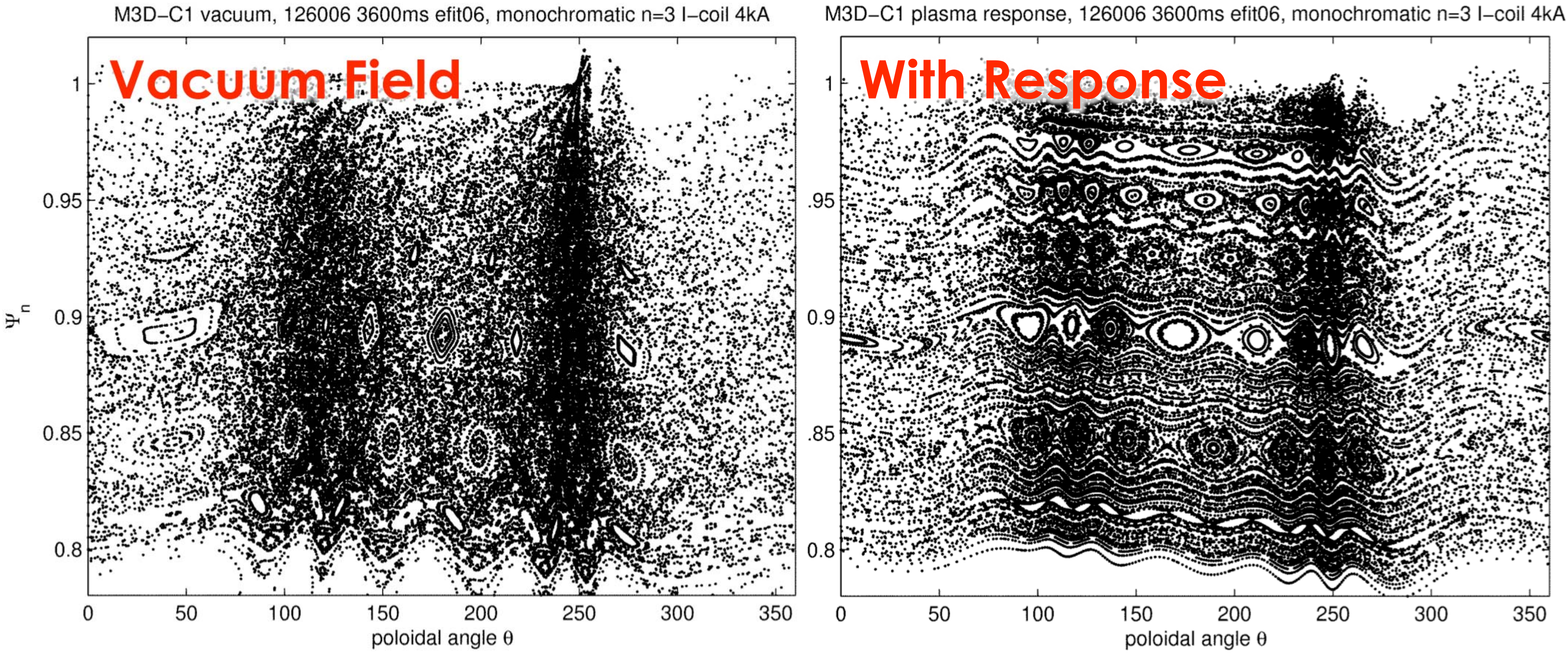


- ***But does this really hold up?***
  - What stops edge mode happening?
  - **Does not explain narrow operational windows**

[Snyder, APS 2011]

Proper Treatment of 3D Field Explains Behavior

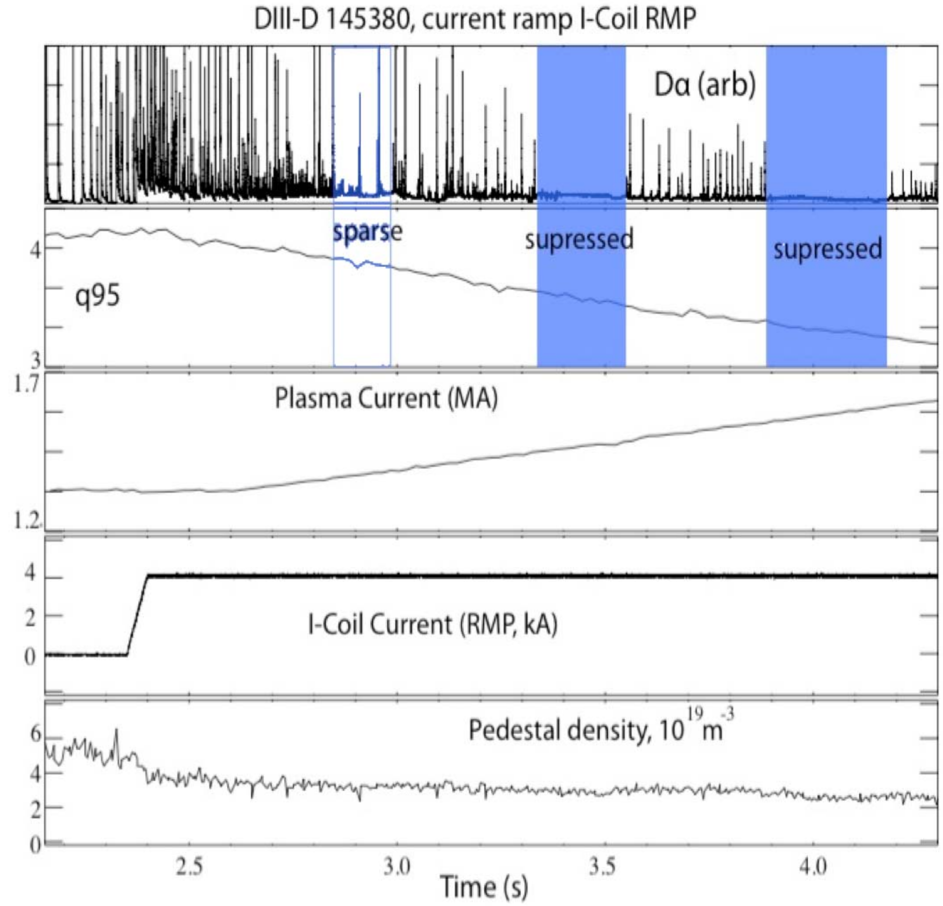
- **Plasma responds to 3D field:**
  - Driven distortion + rotational shielding ➔ transforms edge field:
  - **Island chains are key…**



[Ferraro, DIII-D PAC 2012]

Proper Treatment of 3D Field Explains Behavior

- **Windows in operational space…**



[Snyder, APS 2011]

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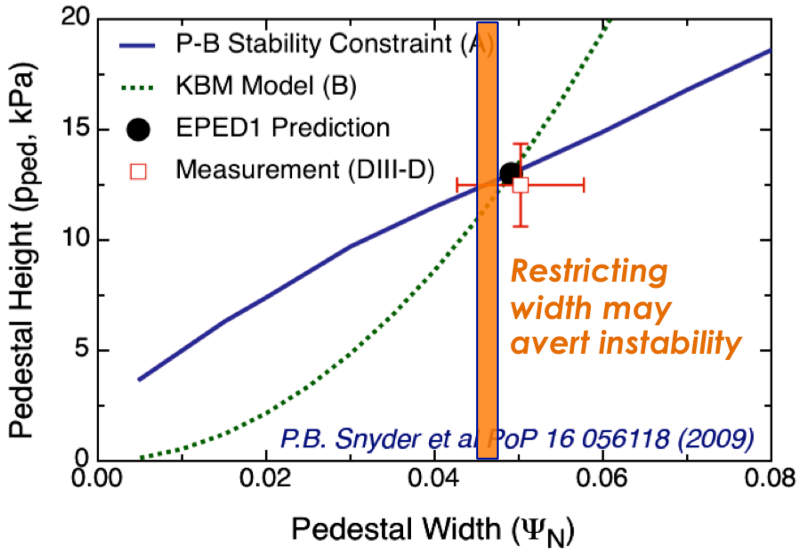
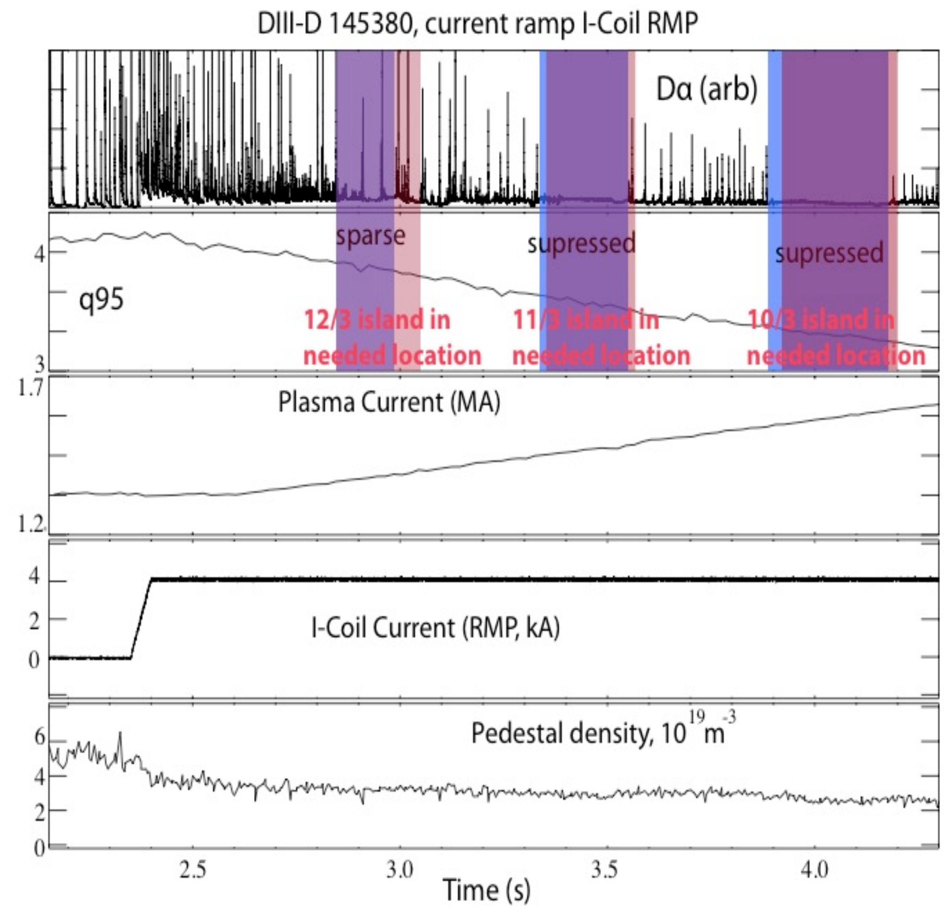
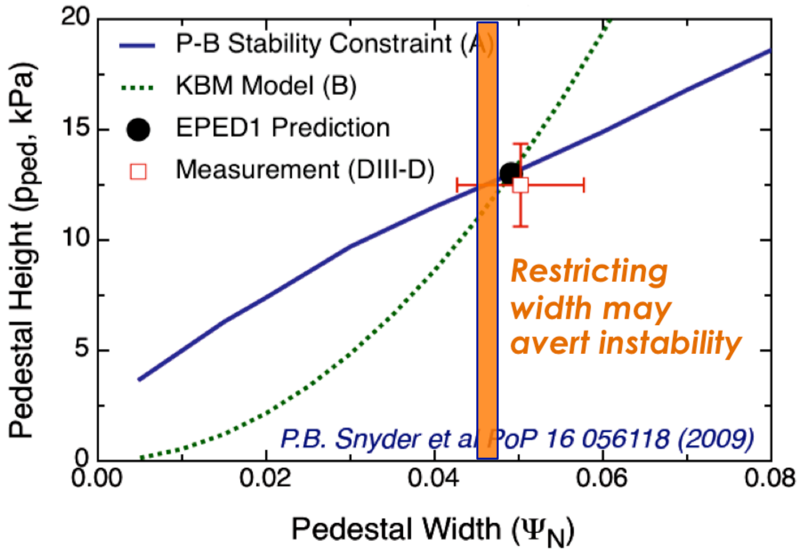
- **…Coincide with island location that would restrict pedestal width**

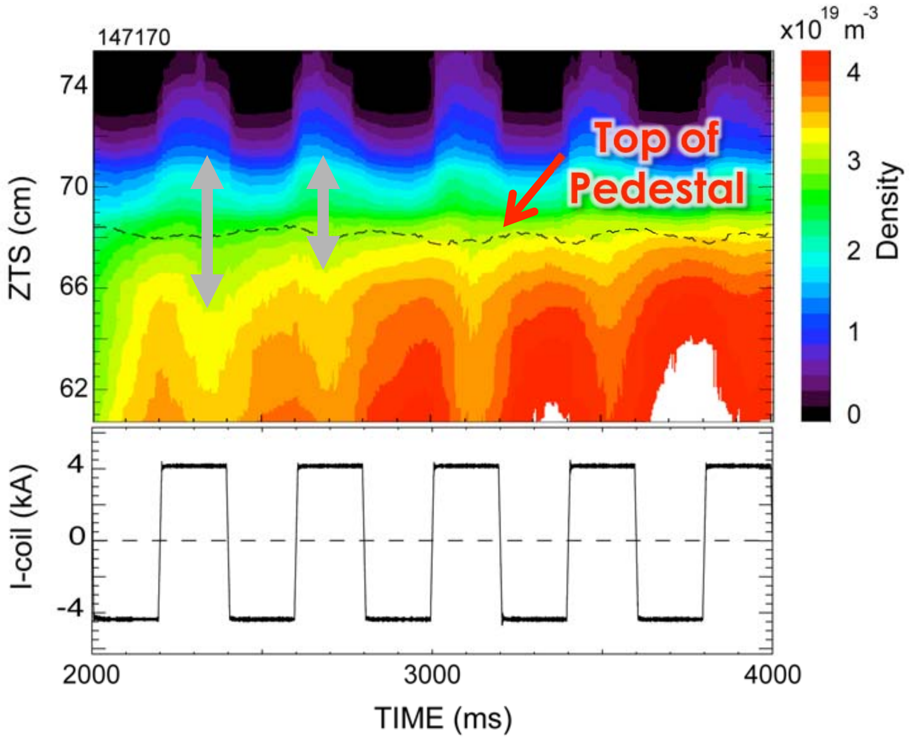




Proper Treatment of 3D Field Explains Behavior

- **Windows in operational space…**
- **…Coincide with island location that would restrict pedestal width**
- **Matches observation of island at the right location**
  - ***Basis for prediction!***





- **Computational MHD can identify hidden processes in experiments**
- **Sometimes needs number of steps and high accuracy to reconstruct**

[Snyder, APS 2011]

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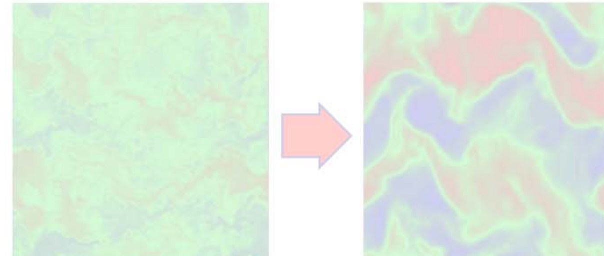

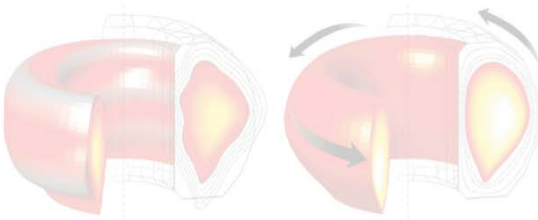

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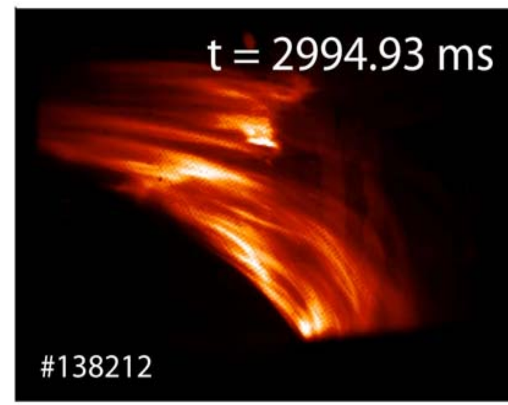

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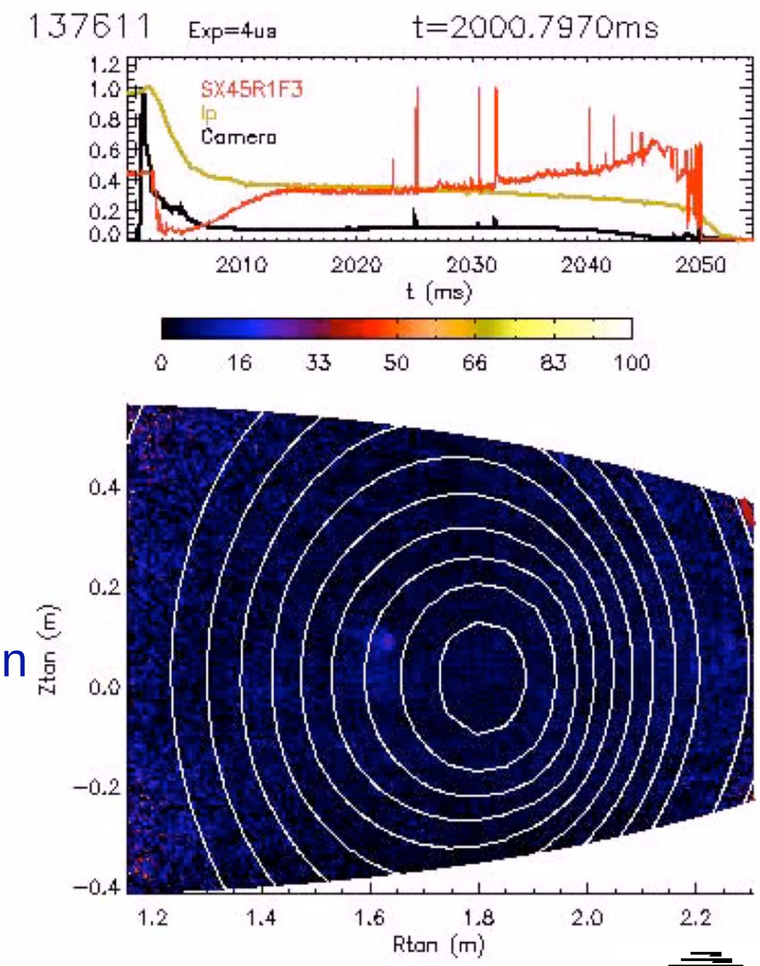
- **Develop control over the plasma termination**
  - A complex multi-scale challenge

Rapid Plasma Terminations Represent One of the Greatest Challenges to Tokamak Fusion

- **High thermal energies & induced forces**
  - Can be mitigated by gas injection
- **But remaining magnetic energy can drive a beam of 'runaway' electrons**
  - Potential for highly localized melting if beam control lost & it collides with wall
  - **Vital to develop a strategy**
- **Means of mitigation need modeling to understand viability & extrapolation**
  - Dynamics & influence on beam formation
  - Can gas jet quench the beam?
  - Understand beam dissipation
- ***These are often multi-scale fully 3D problems requiring sophisticated codes***



UC San Diego

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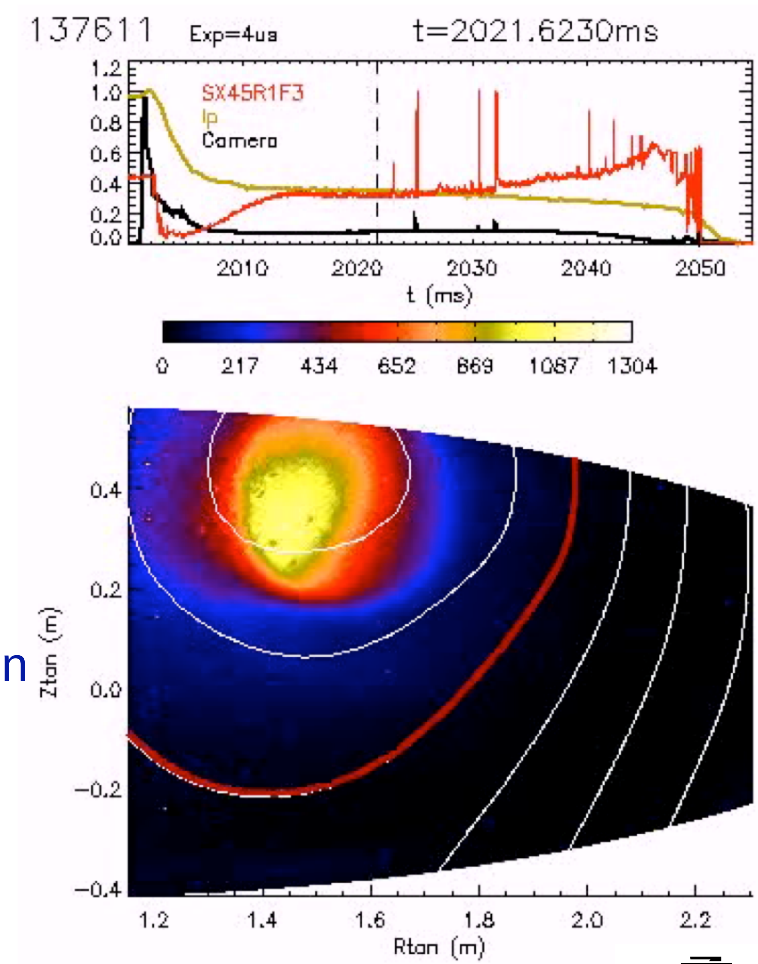

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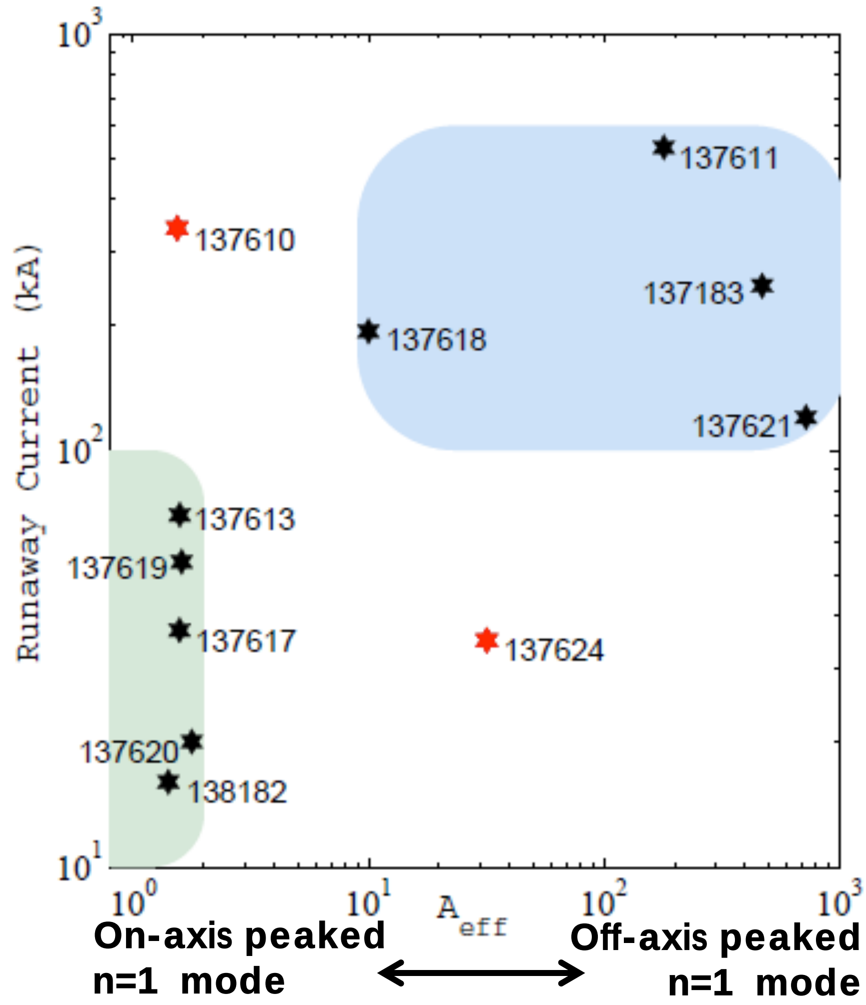
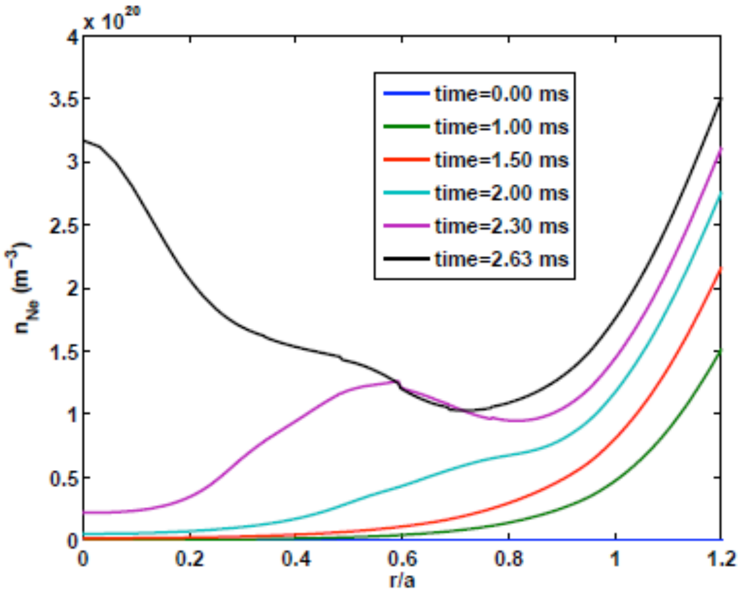
Formation of Runway Beam Influenced by Core Stability

- **Analyse linear stability of plasma 0.6ms after pellet quenches plasma**
- **Find core modes in all cases**
  - But some modes further off axis than others
  - Correlates well with incidence of RE beam formation
- **Provides key insight into physics of RE beam**



[GATO analysis by M. Kornbluth and D.A. Humphreys]

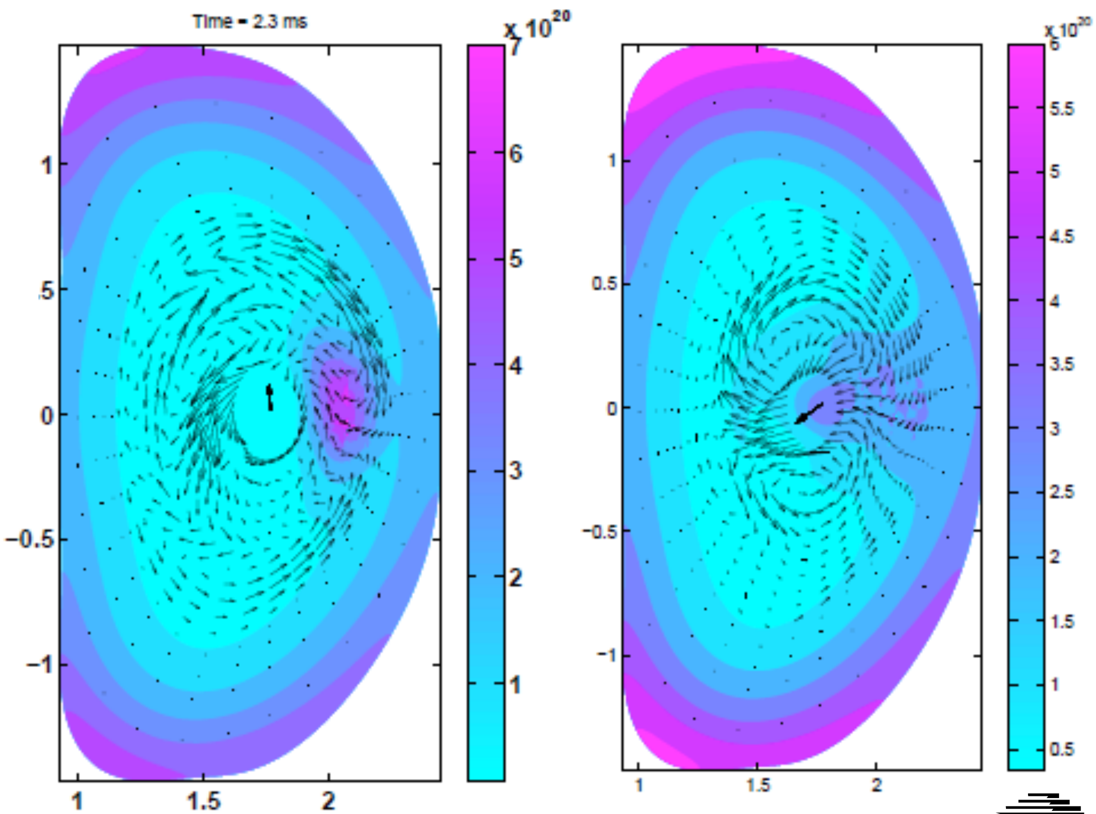
Mixing of Injected Neon Gas into the Core is Much More Efficient with 3D flow from 1/1 mode



Rapid increase in core Ne density associated with 1/1 mode.

Impacts massive gas mitigation efficiency → # of injectors needed

Poloidal Flow pattern produces localized blob that gets pushed into core:



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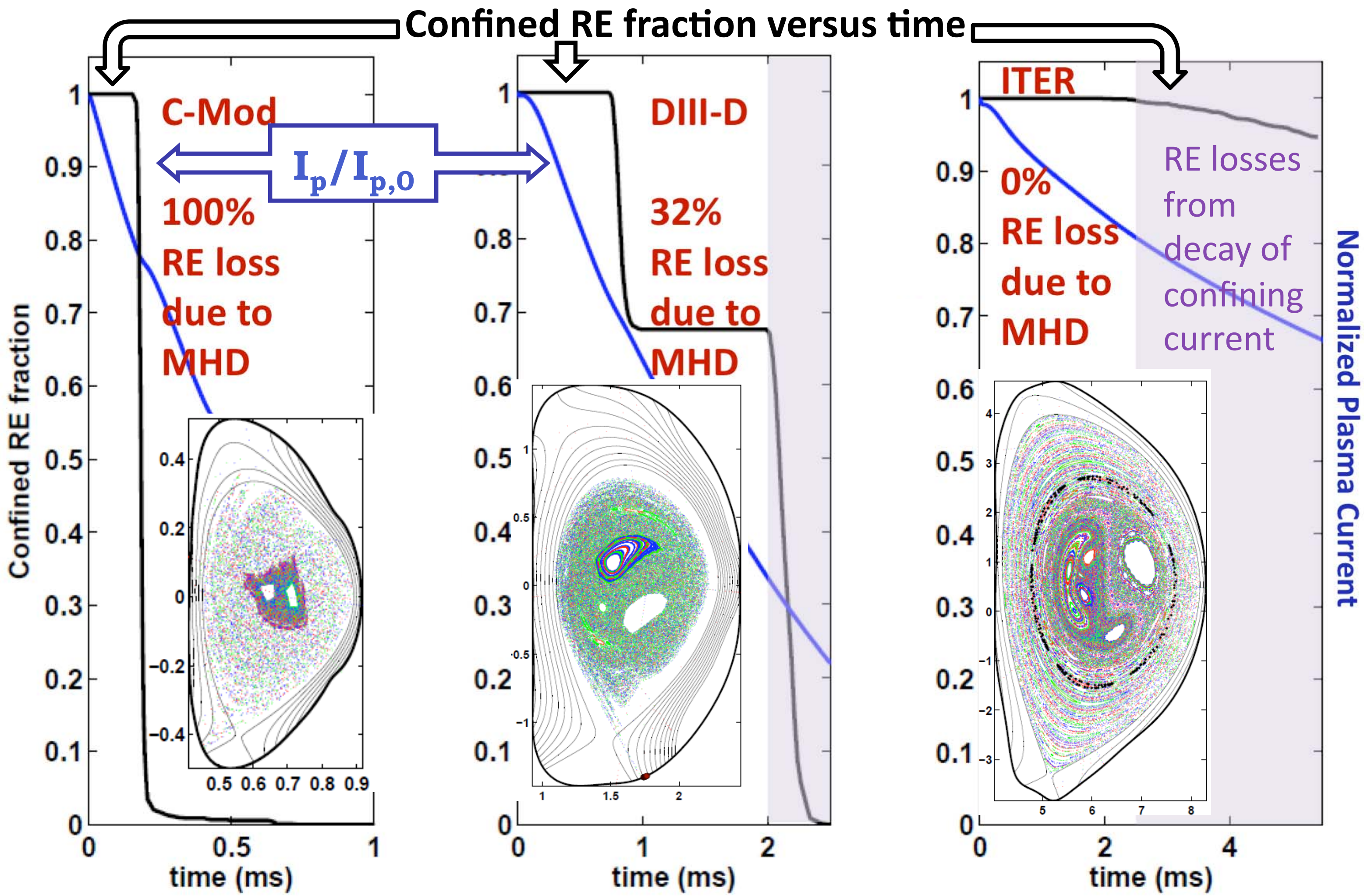
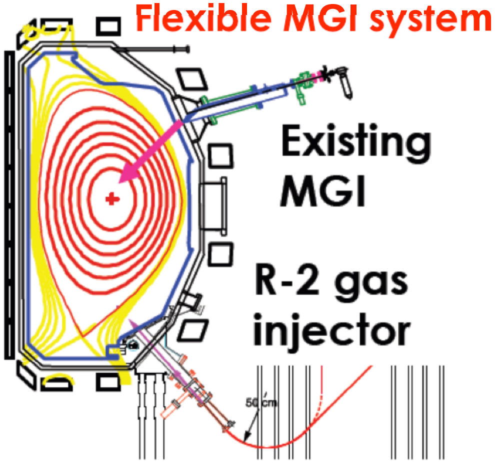
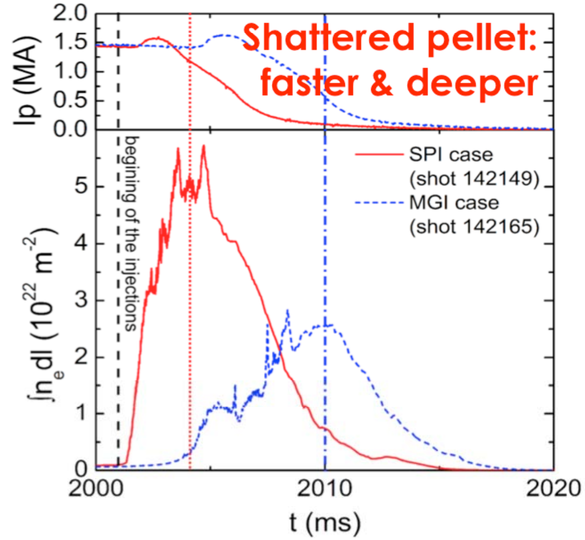
Promising Concept That Internal MHD Might Dissipate Beam Scales Unfavorably to Larger Devices

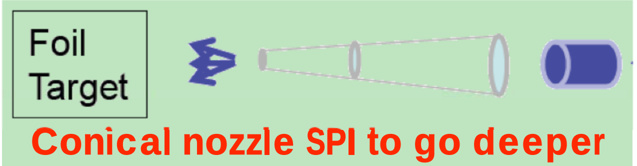


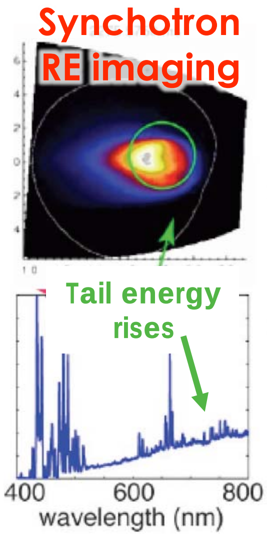
[Izzo, ITPA 2011]

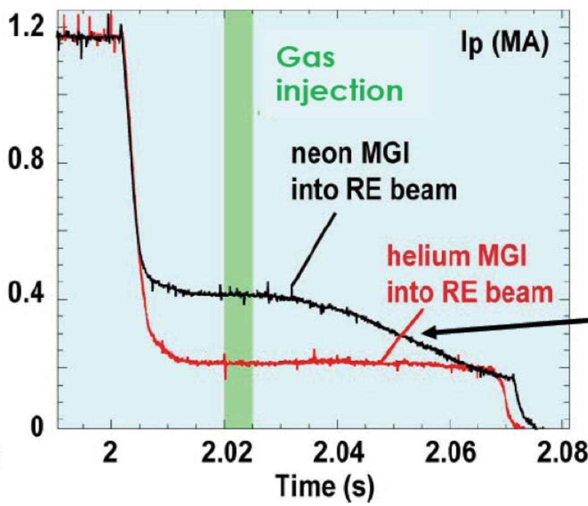
A Rich Experimental Program is Underway to Develop Disruption Mitigation for ITER







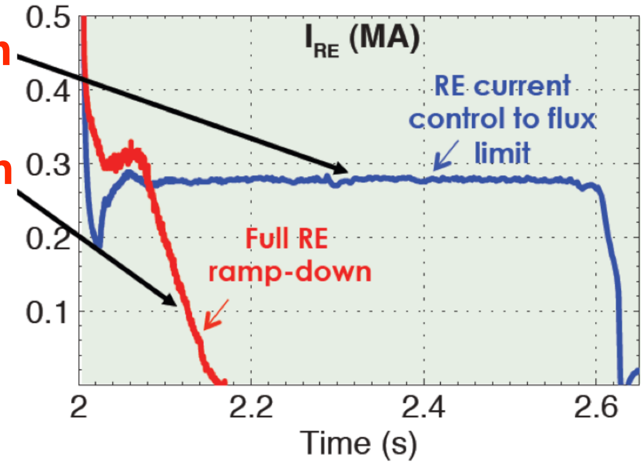




- **Runaway beam control**

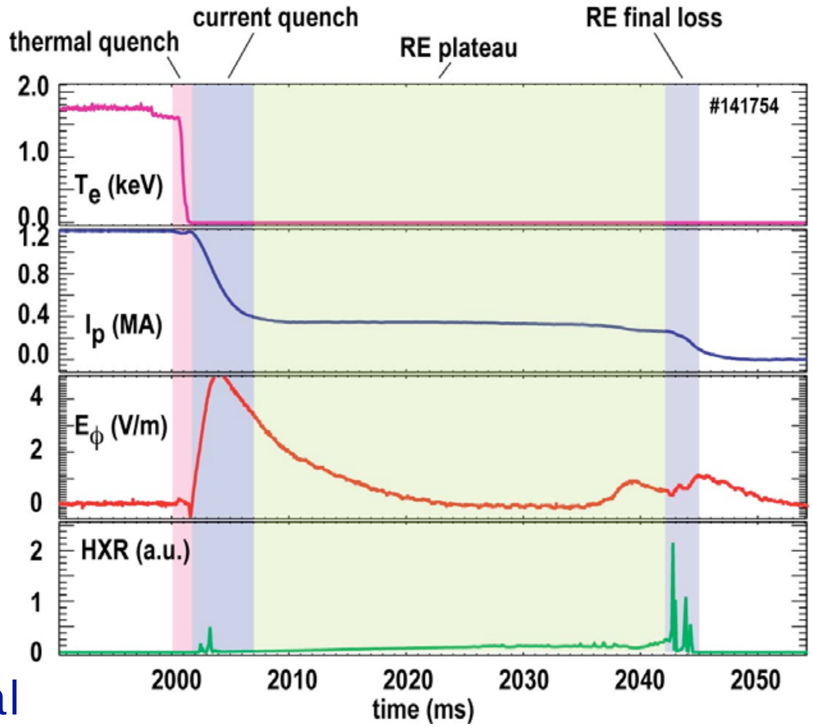
...or ramp-down

& dissipate with high Z gas



Emergent Strategy on Disruption Mitigation Needs to be Guided by Computational Physics

- **Prevent runaway beam in thermal quench**
    - Needs high density from gas injection
  - Understand how gas is assimilated
  - And consequences for thermal radiation & runaway beam
- **...or in current quench**
  - Understand formation conditions of runaway beam
- **...or in plateau phase**
  - Requires good control & understanding of RE beam stability
  - Resolve degree of dissipation of runaway beam & action of additional mitigators (high Z gas, 3D fields, dust, etc.)



The potential of any technique is only understood through interpretation by computational modeling

Conclusions: Computational Physics Plays a Key Role in The Interpretation of Experimental Phenomena

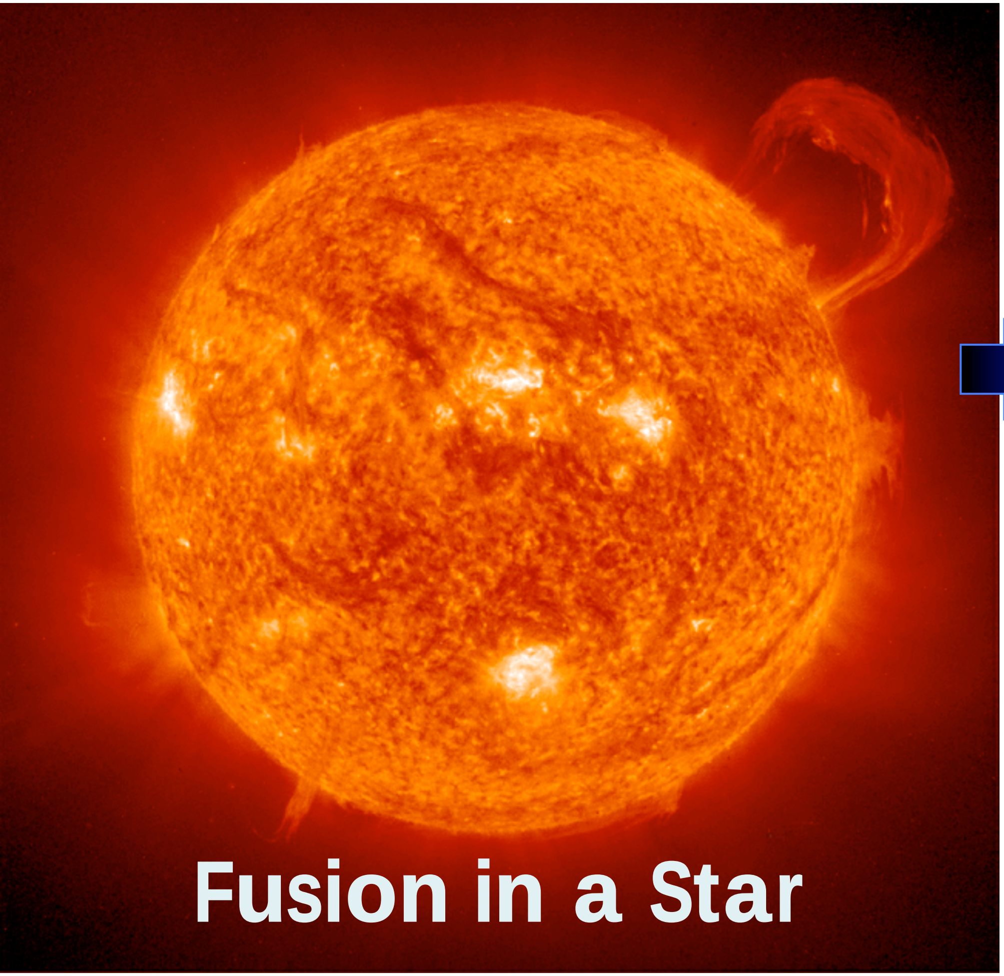
- **Computational physics enables us to understand how theory really looks like in reality**
  - Can predict and identify phenomena
- **Computational physics is the tool predict future devices**
  - But models need experiments to determine & quantify physics
    - Process is a two-way partnership
- **Experiments are moving into new territory to explore and resolve the physics of burning plasmas**

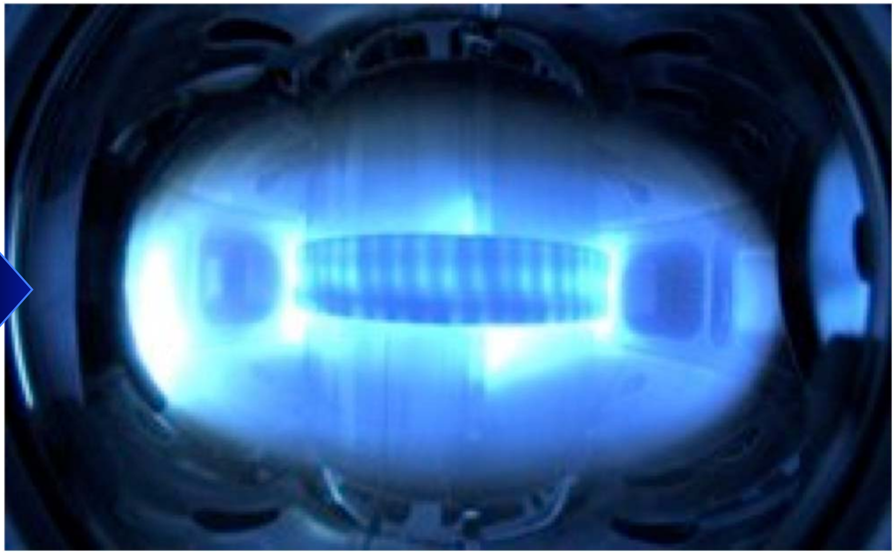
This is perhaps the most exciting time for burning plasma science:

- *Computational techniques capturing physics in realistic simulations*
- *Best experimental tools we've ever had*
  - *High flexibility, perturbative, probing, relevant conditions*
- *Best diagnostics we will ever have*

Now is the time to resolve the physics of fusion plasmas

The Goal





A Star on Earth

How do we make this work?

Reserves

Off-Axis Current Enables Access to Higher Pressure

- **Current generates twist in magnetic field**
  - Too much twist leads to instability – ‘kink’
  - Pressure also help push out kink distortion
- **Kink distortion in field peaks outside main current channel**
  - Displaces contours further out
- **Wall acts like a superconductor**
  - Stops field penetration
  - Pushes back on kink
- **If current off axis, kink distortion much further out**
  - More field tries to get through wall
  - Wall pushes back harder
  - Energetics: Kink distortion has to compress field more to grow
- **Need more energy to drive kink**
  - Either higher twist (current) or higher pressure can be achieved