PPPL Research Highlights FY08

Rob Goldston, PPPL

For PPPL and our Collaborators

Fusion Power Associates Meeting
December 4, 2008

Can Touch on Only a Few Highlights

- NCSX Project Closeout
- NSTX
  - ETG Mode Detection
  - Lithium Effects
  - Non-Axisymmetric Physics
- ITER
- Magneto-Rotational Instability

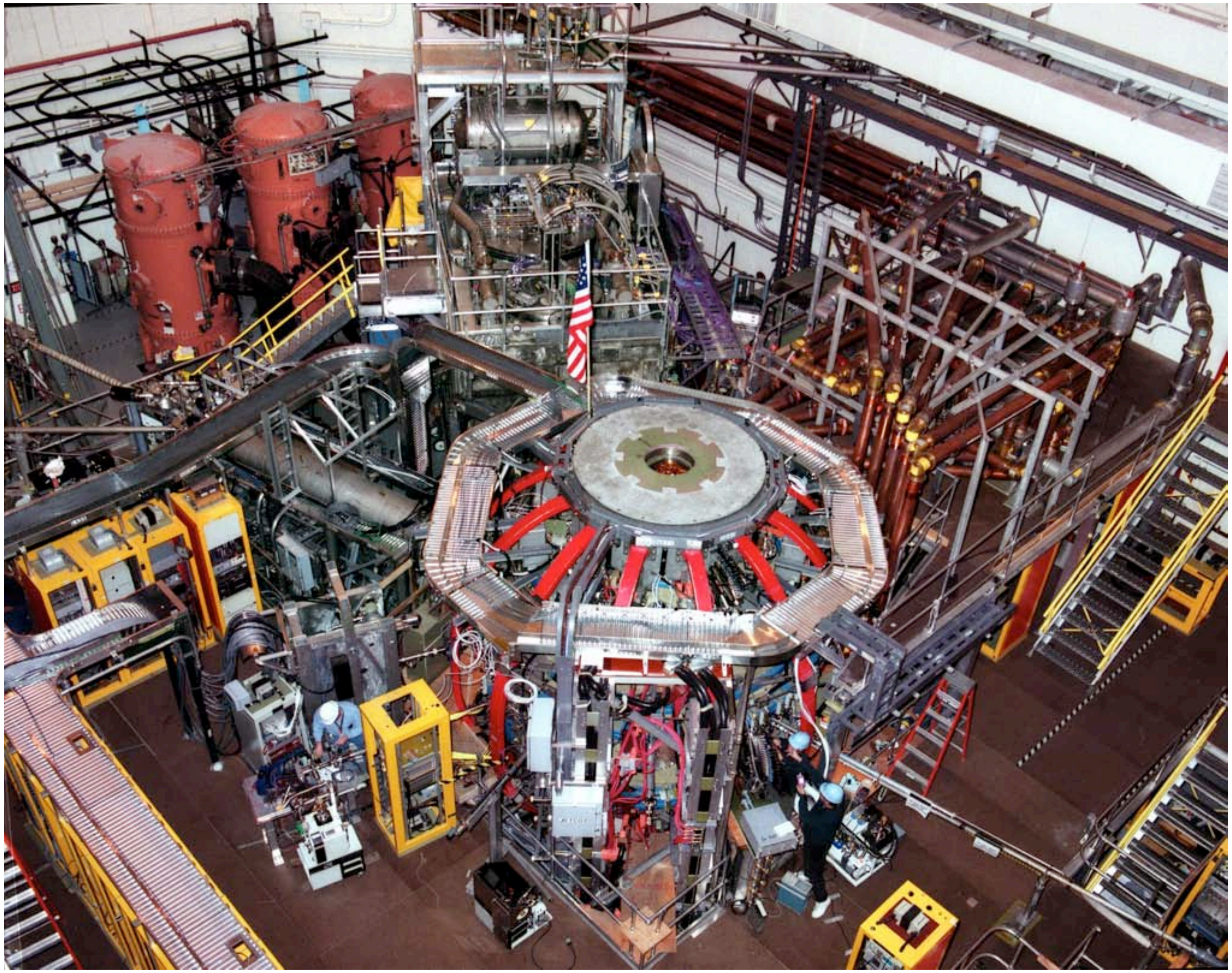
- How Should We Approach ReNeW?

NCSX Demonstrated Key Precision Assembly Step, Components Stored

- All modular coils completed to required accuracy
- 2 of 6 half-periods welded, required accuracy achieved
- All vacuum vessel subassemblies complete
- Half field period fit over vessel
- All TF Coils completed
- All components stored in NCSX Test Cell
- Full documentation this year

NSTX is Addressing Basic Toroidal Science For ST's, ITER and Fusion Development

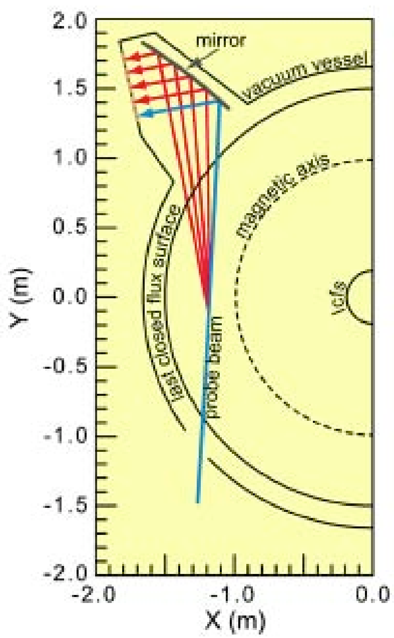
College W&M
Colorado Sch Mines
Columbia U
Comp-X
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Maryland
U Rochester
U Washington
U Wisconsin

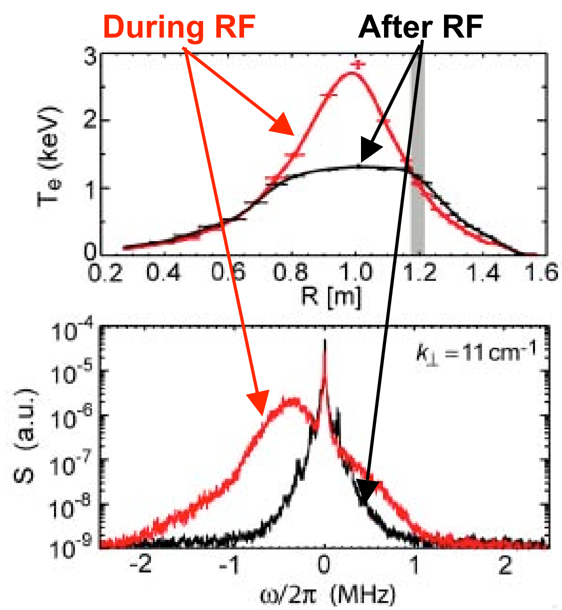


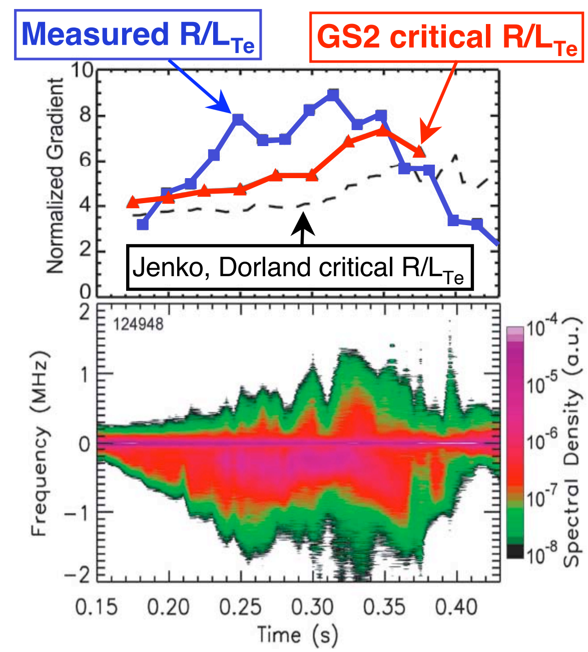
Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

Short-Wavelength Turbulence in Plasma Core has Clear Characteristics of ETG Modes

- **Fast waves at high harmonics of ion-cyclotron frequency (HHFW) heat electrons through electron Landau damping and TTMP**
- **Fluctuations measured by low-angle forward scattering of 280 GHz μ-waves**





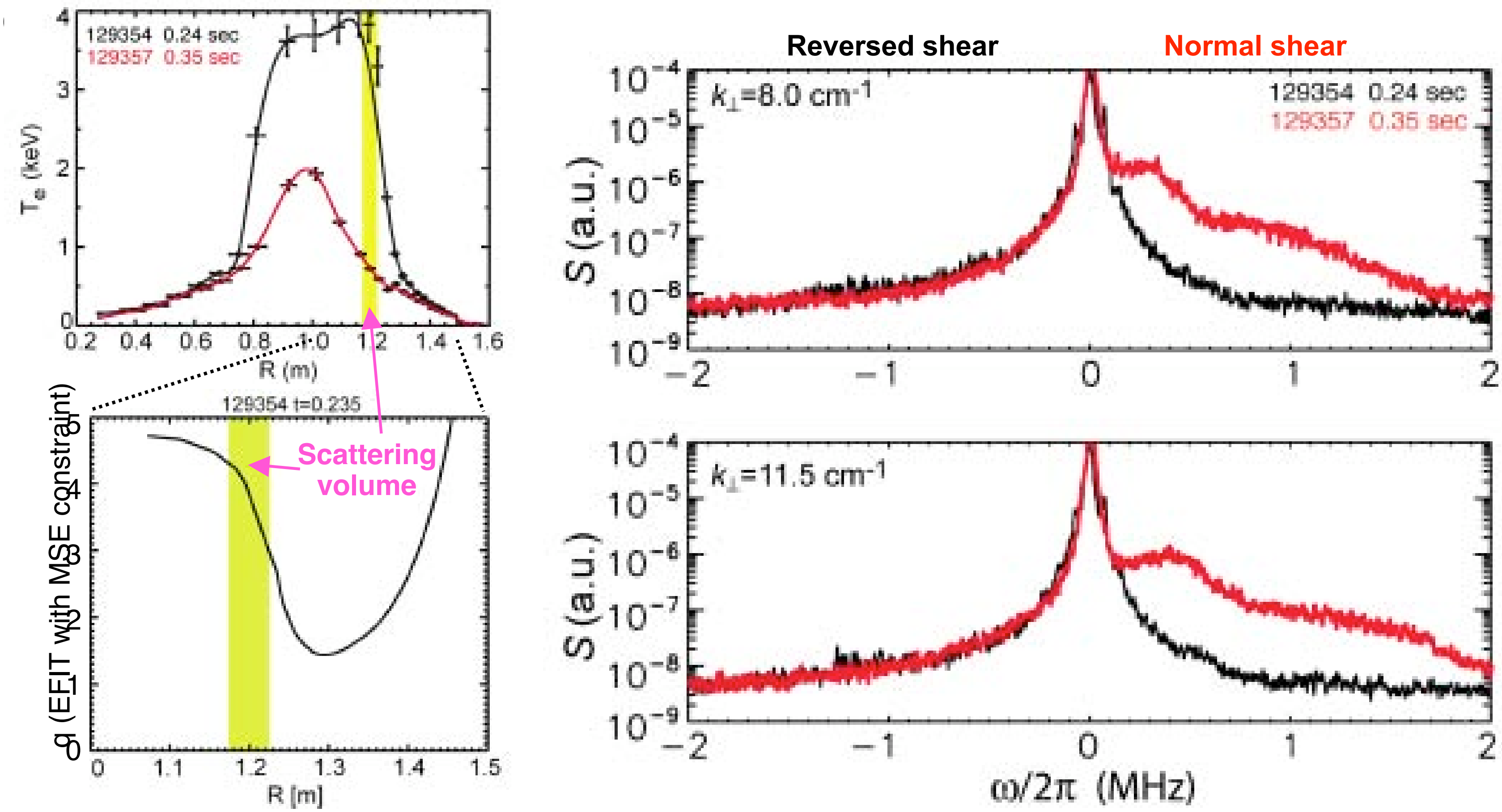


- **Detected fluctuations in range $k_\perp\rho_e$ = 0.1 – 0.4 propagating in electron diamagnetic drift direction**
  - Rules out ITG and TEM modes as source of this turbulence
  - Agreement with linear gyrokinetic code (GS2) for ETG onset

NSTX

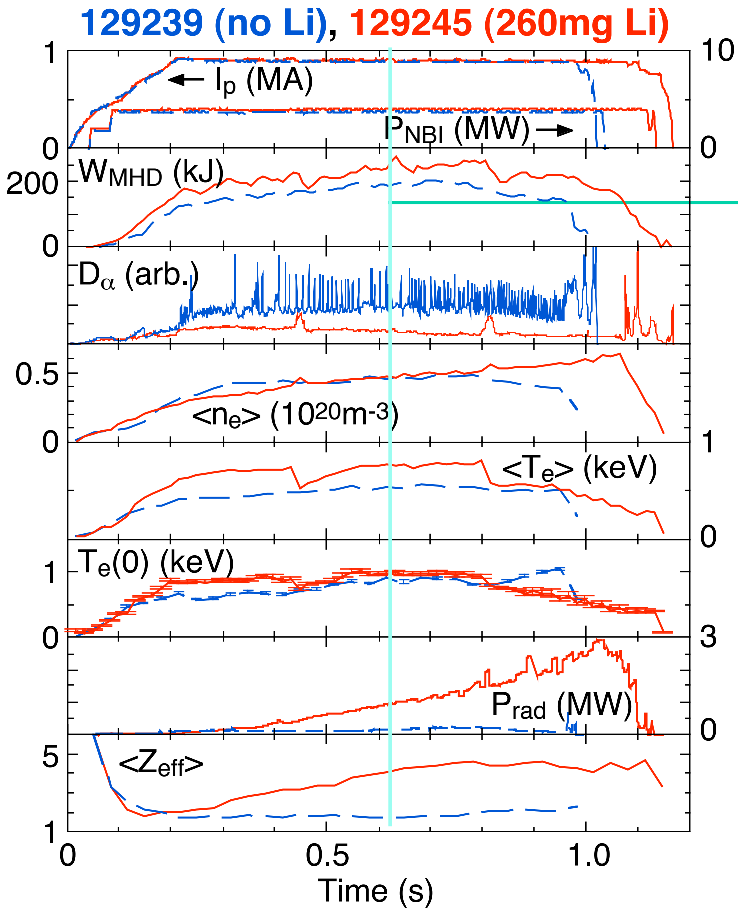
Electron Gyro-Scale Fluctuations Can Be Suppressed by Reversed Magnetic Shear in Plasma Core

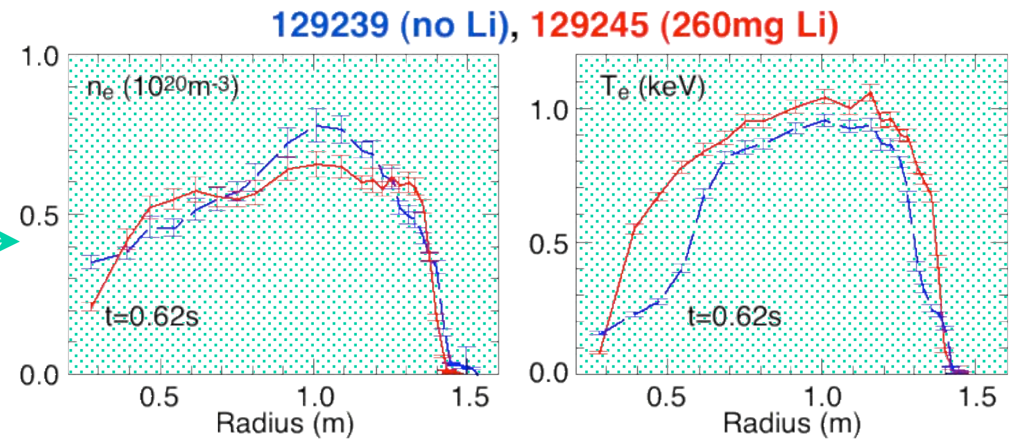
- Shear-reversal produced by early NB heating during plasma

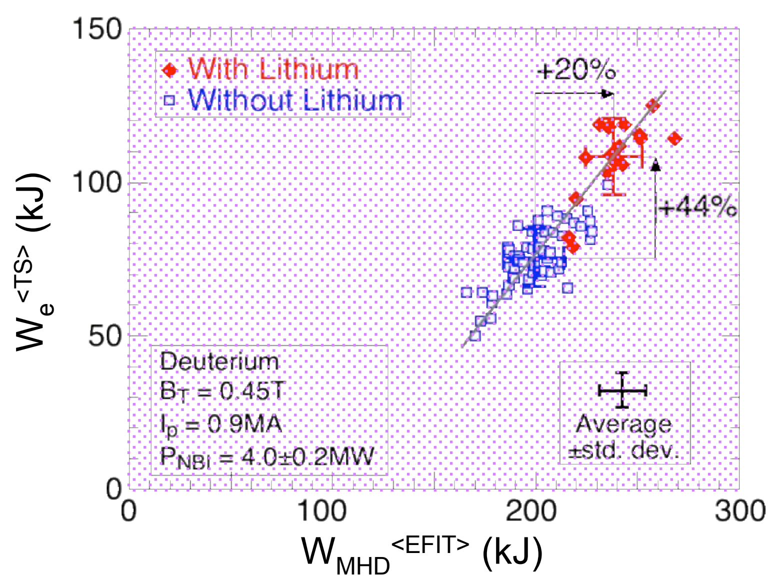


- **Suppression of Electron Temperature Gradient (ETG) mode by shear-reversal and high T_e/T_i predicted by Jenko and Dorland, Phys. Rev. Lett 89 (2002)**

Lithium Evaporative Coating Reduces Deuterium Recycling, Suppresses ELMs, Improves Confinement



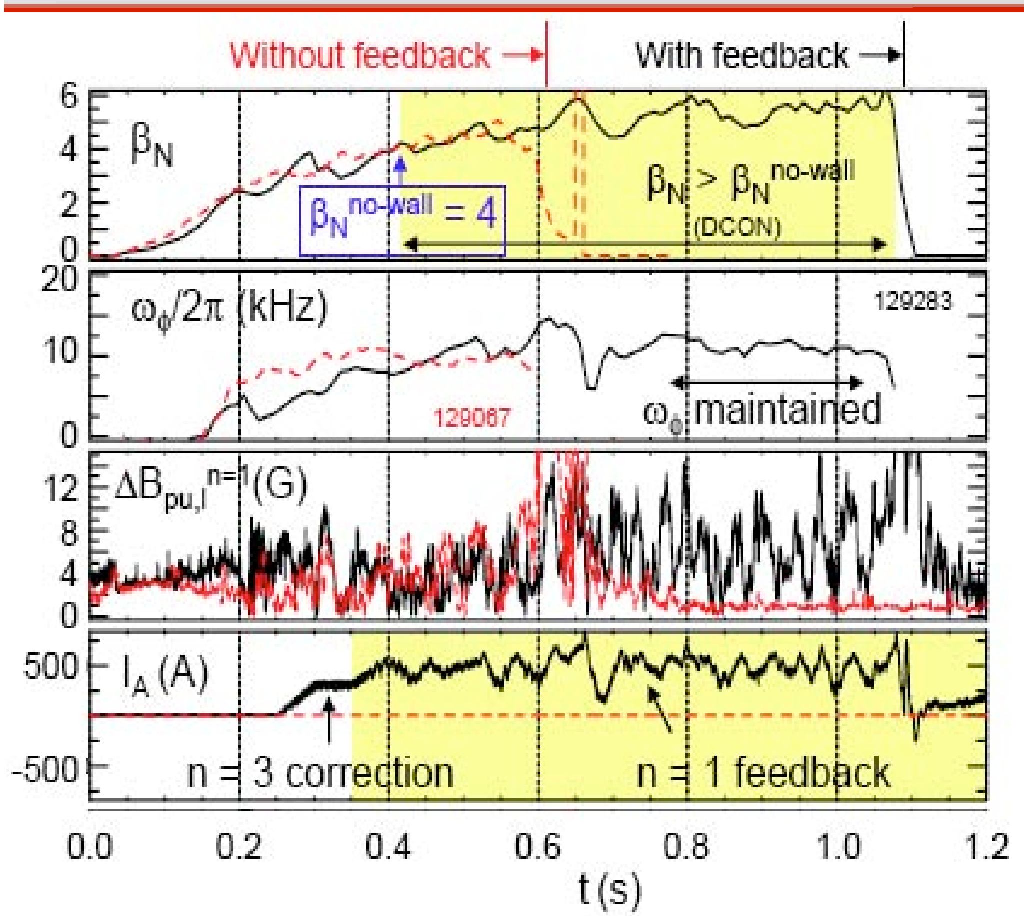




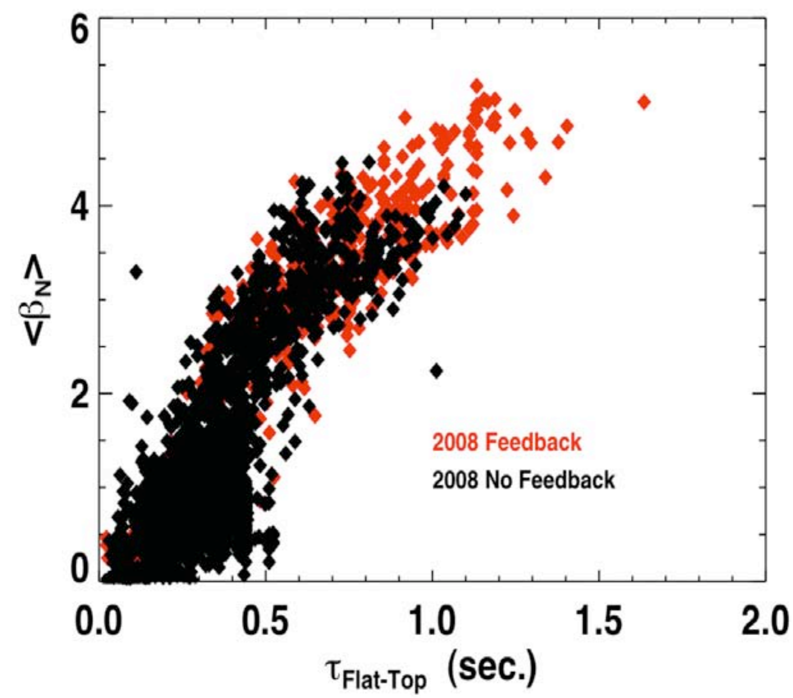
Pulsed RMP coils induce ELMs, reduce density and Z_{eff}

NSTX

Correction of n = 3 Error Field Plus Feedback Control of n = 1 Mode Reliably Extends Duration of High-β_N Plasmas



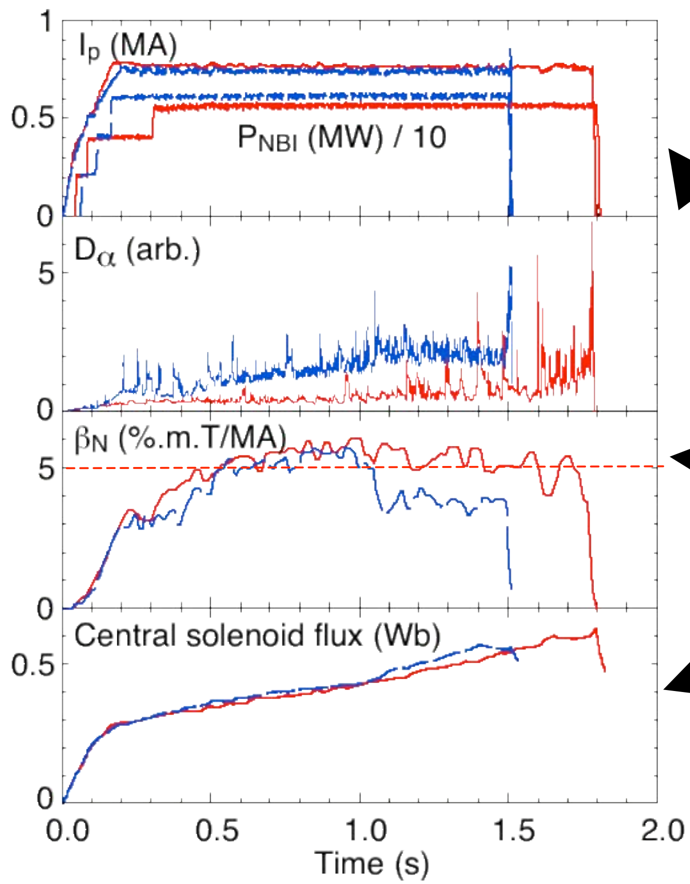
Optimized feedback scheme
applied routinely in 2008

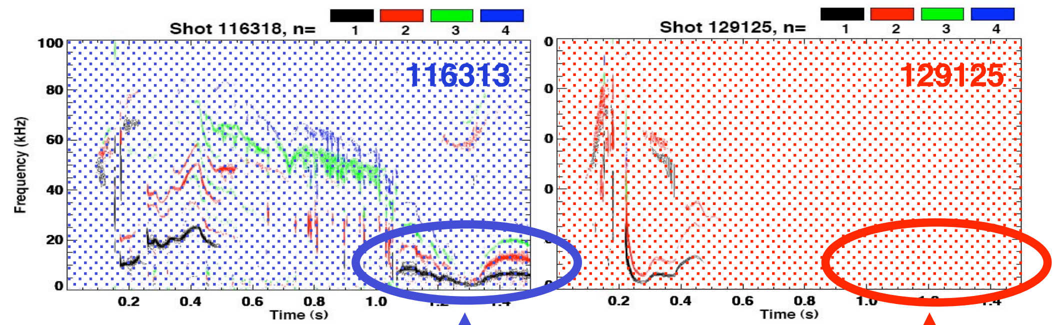


- **Correction of n = 3 intrinsic error field maintains toroidal rotation**
- **Resistive Wall Mode can develop at high normalized-β: terminates discharge**
- **Feedback on measured n = 1 mode reliably suppresses RWM growth**
  - **Limitations on time response and applied mode purity explored for ITER**

n=3 Error Field Correction With n=1 RWM Feedback and Lithium Coating Extends High-β_N Discharges

116313 – no mode control or Li
129125 – with mode control + Li





Onset of n=1 rotating modes avoided

NSTX pulse length limited by TF

NSTX power input limited by TF

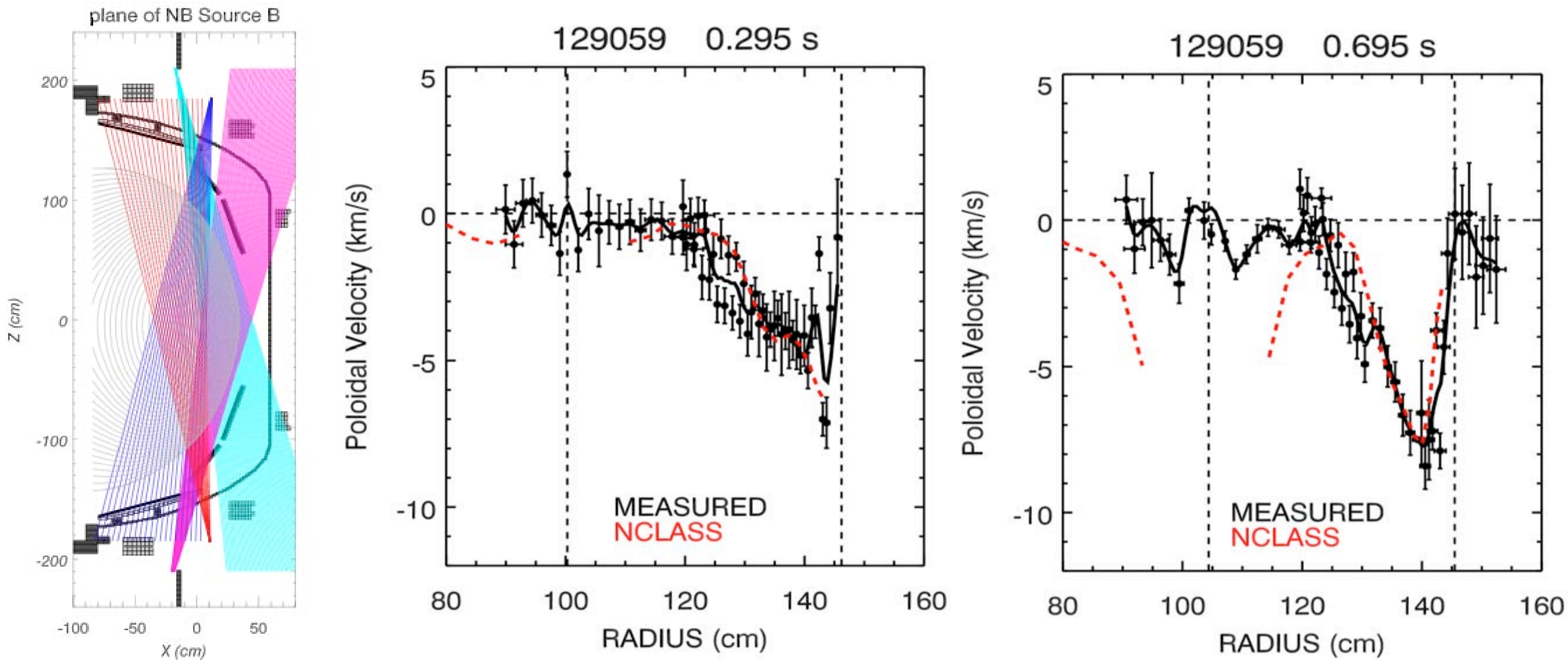
$\beta_N \geq 5$ sustained for 3-4 τ_{CR}

- EF/RWM control sustains rotation, high β

Flux consumption reduced by sustained high β + Li conditioning

- High elongation κ = 2.4 increases bootstrap current fraction

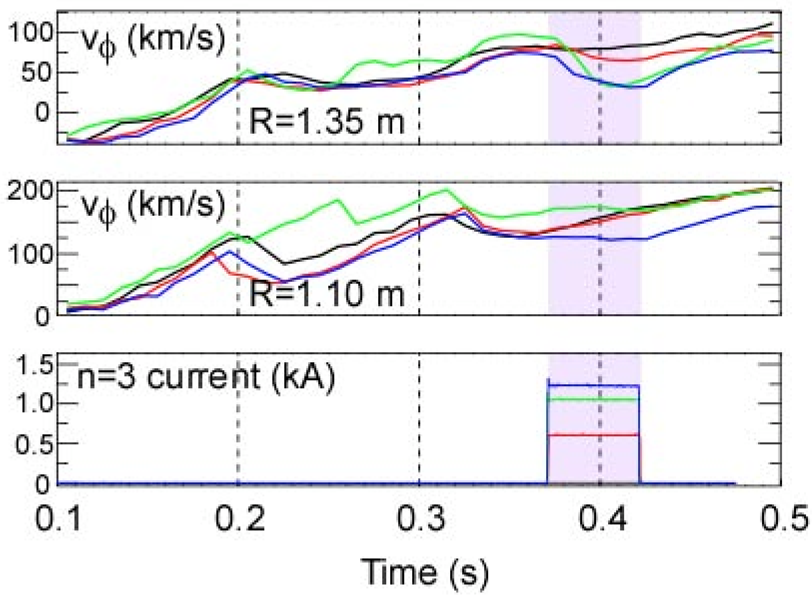
NSTX poloidal flow measurements are consistent with neoclassical theory computed with NCLASS/TRANSP



- Pseudo-velocity due to gyro-orbit finite lifetime effect is small in NSTX (≤ 0.5 km/s) compared to that apparent in TFTR (≤ 50 km/s).
  - In NSTX, this significantly reduces the uncertainty in comparing poloidal flow measurements to neoclassical theory.
- Higher-A tokamaks (DIII-D, JET) have reported v_θ inconsistent with neoclassical theory – aspect ratio difference?

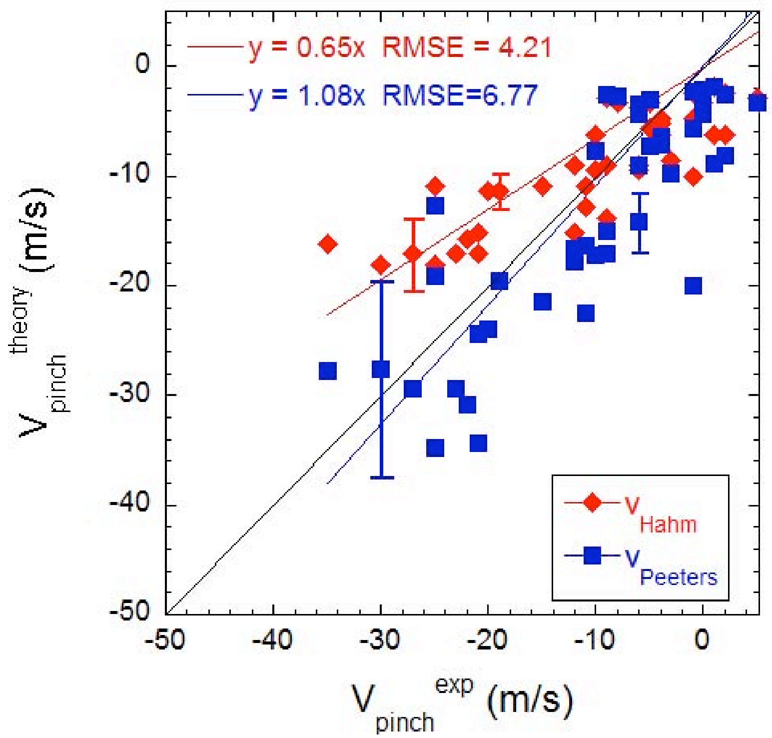
Investigated Momentum Transport Using Transient Perturbations to Separate Diffusivity and Pinch Terms

- **n = 3 braking pulses perturb rotation in outer region**



- **Determine χ_ϕ, v_{pinch} after turn-off of n=3 pulse**
  - NBI provides only known torque (calculated by TRANSP)

- **Inferred pinch velocities in outer region agree reasonably well with theories based on low-k turbulence**



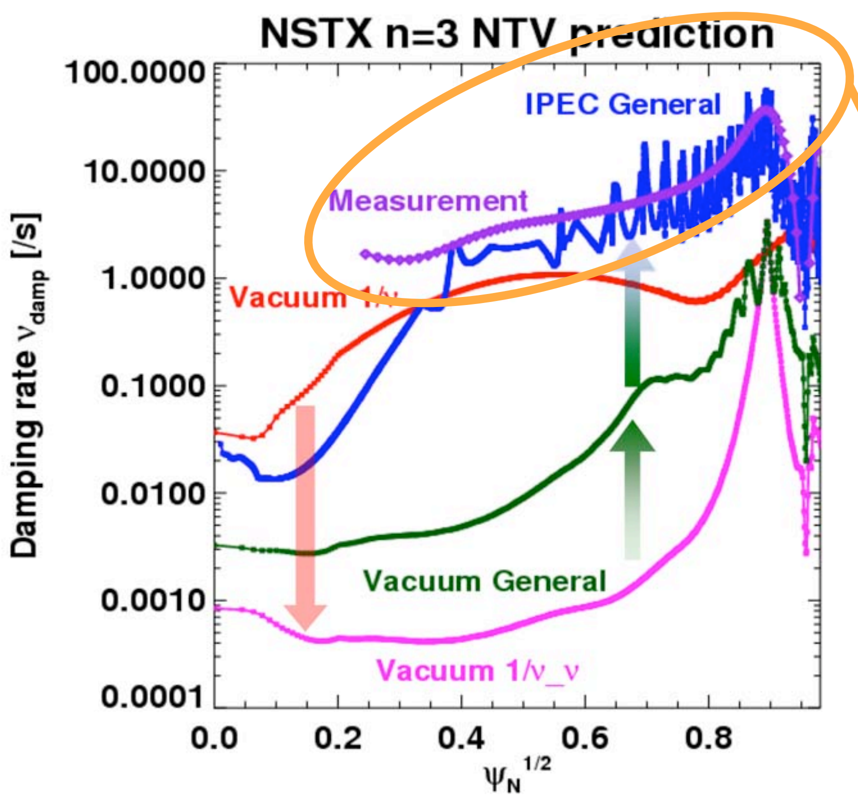
Peeters *et al.* (PRL, 2007)
Hahm *et al.* (PoP, 2007)

Neoclassical Toroidal Viscosity Theory Generalized

- Generalized treatment for NTV transport describes dynamics of bouncing (ω_b) trapped particles subjected to magnetic + electric toroidal precession ($\omega_p = \omega_B + \omega_E$) and collisions ($\nu$) in a combined form:

$$\nu_{damp} \simeq \frac{F_{NTV}}{2\pi f_\varphi R_0 M n_e} \quad \text{and} \quad F_{NTV} \propto \frac{\nu_{eff}}{\left(\left(\ell\omega_b - n(\omega_B + \omega_E)\right)^2 + \nu_{eff}^2\right)} (\delta B / B)_w^2$$

NSTX
n=3 rotation braking experiment



- Key to include plasma response to external perturbation!
- The plasma is stable - but not as stable as a vacuum!
- IPEC code applied to NSTX and ITER

Generalized NTV theory more consistent with NSTX flow damping results

PPPL is Strongly Engaged in ITER

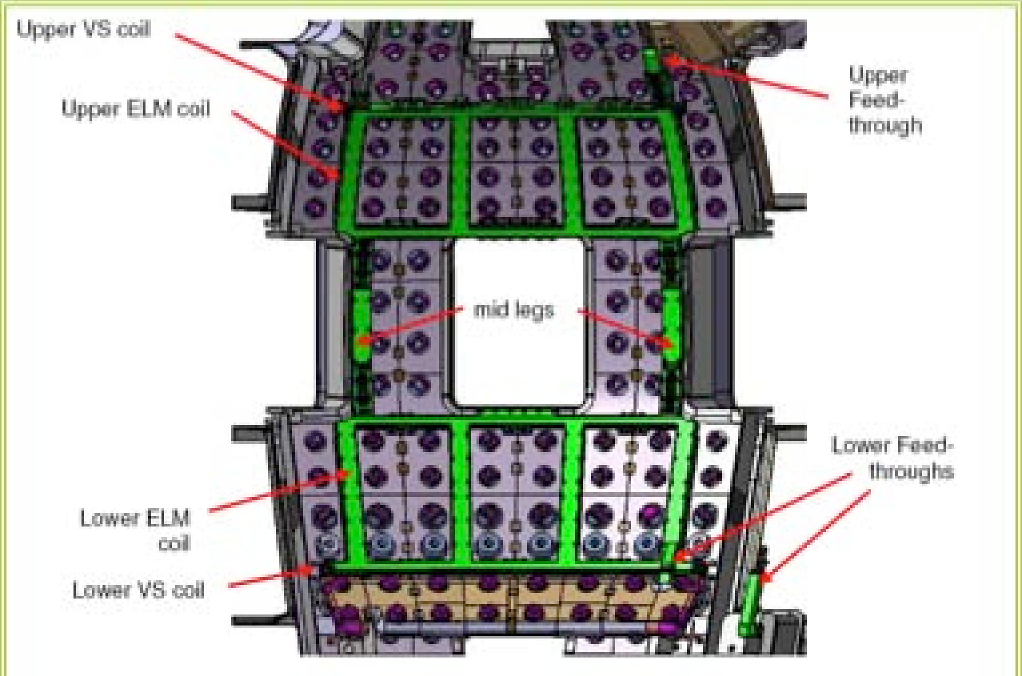
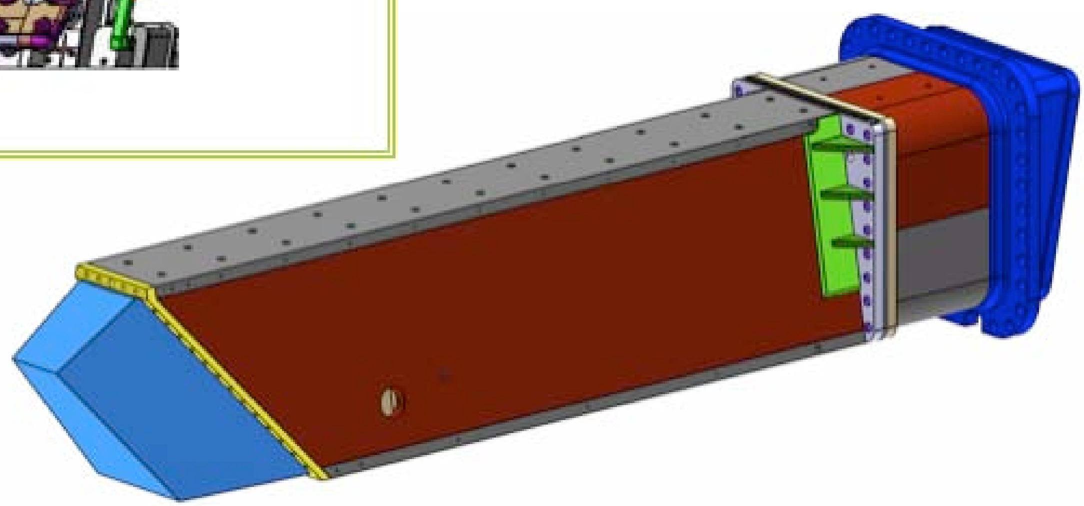


Figure 1: ELM Coil Assembly

Leading design effort of RMP coils for ITER

Managing broad US design effort on ITER diagnostics

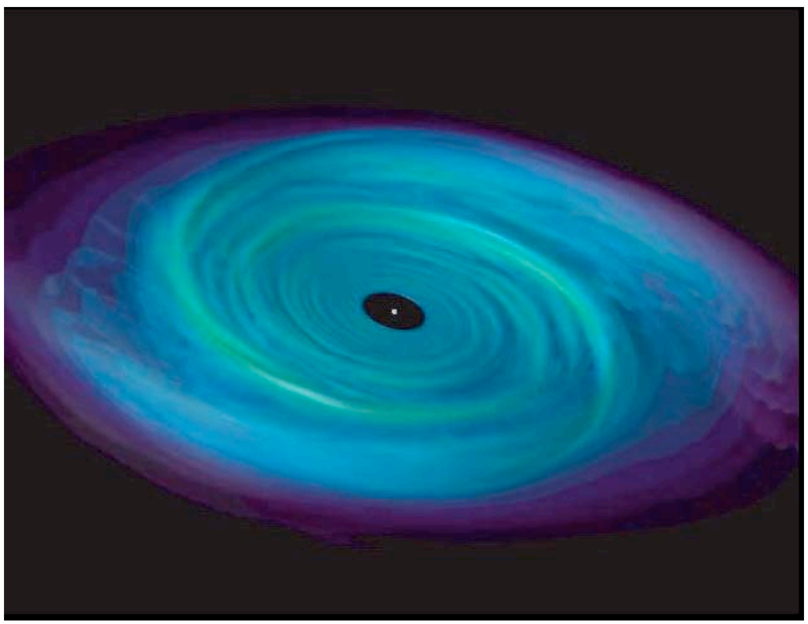
Leading generic design of upper port plugs



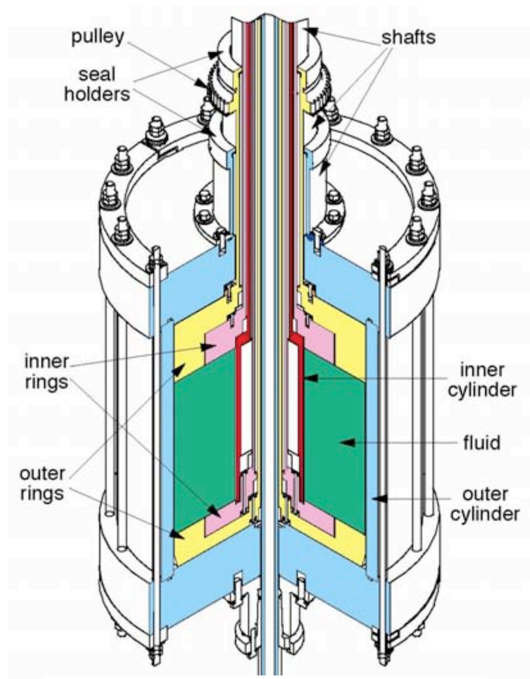
Responsibiity for steady state electrical power network

Magnetorotational Instability Experiment

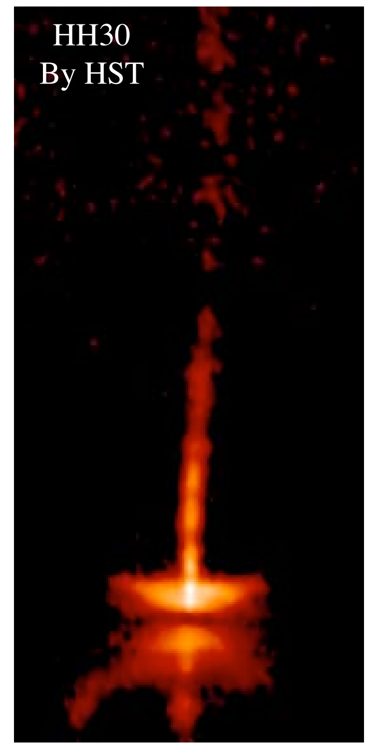
- To study fundamental physics of fast angular momentum transport in accretion disks
  - Can hydrodynamic turbulence support fast accretion? No!
  - Does MRI exist in the pure MHD form transporting angular momentum? We found its precursors!



Accretion Disks



MRI Experiment



Protostellar Disk

What are the Key Questions to Answer, *e.g.,* in an Initiative to Tame the Plasma-Material Interface ?

Q1 Can high-performance, fully steady-state plasma operation avoid high-energy ELMs and damaging disruptions?

Q2 Can extremely high radiated-power fraction be consistent with high confinement and acceptable (nD+nT)/ne?

Q3 Can magnetic flux expansion and/or stellarator-like edge ergodization reduce heat loads sufficiently, consistent with adequate He pumping?

Q4 Can tungsten or other solid materials provide acceptable erosion rates, core radiation and tritium retention?

Q5 Can dust production be limited, and can dust be removed?

Q6 Can liquid surfaces effectively handle high heat flux and provide adequate tritium exhaust, while limiting dust production?

Q7 Can plasma-material interface solutions developed at low neutron fluence be made compatible with the high neutron fluence of Demo?

What are the Program Elements Needed to Support, *e.g.*, an Initiative to Tame the Plasma-Material Interface ?

	Materials and Technology Development
A1	Develop new refractory PFC materials and test in both powerful PMI machine and under neutron irradiation
A2	Develop and test PFC technologies for solid systems, including PFM to heat sink joining and He cooling with O and T removal
A3	Develop and test liquid PFC technologies, including modeling and experimental validation, and techniques for recycling evaporated lithium
A4	Develop technologies for real-time dust removal
A5	Develop long-pulse heating and current drive systems
	Existing Confinement Experiments
A6	Develop predictive understanding of power scrape-off
A7	Develop non-inductive scenarios without ELMs and disruptions
A8	Test innovative divertor configurations and PFC materials ☐(both solid and liquid)
A9	Develop extensive diagnostics for plasma material interaction
	Theory and Computation
A10	Increase theory and computation focus on edge and SOL physics
A11	Advance theory of plasma-material interaction, including surface properties under erosion and redeposition
A12	Design new plasma-facing alloys and model liquid metals
A13	Design coil systems for stellarator-like edge / MHD stability

What are the Requirements for a Confinement Device to Support, *e.g.*, an Initiative to Tame the PMI ?

R1	Input power / plasma surface area <~ 1 MW/m2
R2	Input power / major radius >~ 50 MW/m
R3	Heating power / H-mode threshold power > 6, at n = nG
R4	Stored energy / major radius ~ 5 MJ/m
R5	Flexible poloidal field system capable of wide variation in flux expansion and ability to divert field lines to large R
R6	Non-axisymmetric coils to produce stellarator-like edge and improve MHD stability
R7	High temperature ~ 1000K first wall operational capability
R8	Replaceable first wall and divertor
R9	Pulse length ~ 200 – 1000 sec; total on-time ~ 10^6 sec / year
R10	Extensive access for surface and plasma diagnostics, PFC services
R11	Deuterium and trace tritium operational capability
R12	Synergy with a Fusion Materials Irradiation Facility

Conclusions

NCSX project is being closed out carefully

NSTX collaboration is producing exciting results

- ETG mode identification
- Lithium
- Non-axisymmetric physics

ITER is central to the U.S. and PPPL fusion program

The MRI instability is nearly in our grasp

We need to think carefully about ReNeW

- Questions → Program Elements → Requirements