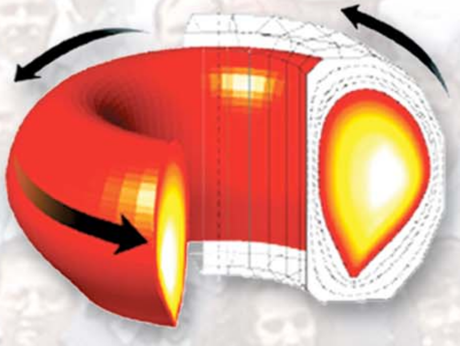
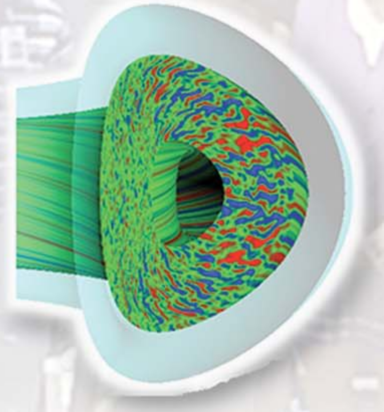
Thrust IT-1: ELM Control for ITER

Presented by
M.E. Fenstermacher



Presented to

DIII–D Program
Advisory Committee



January 31 - February 2, 2006

DIII–D
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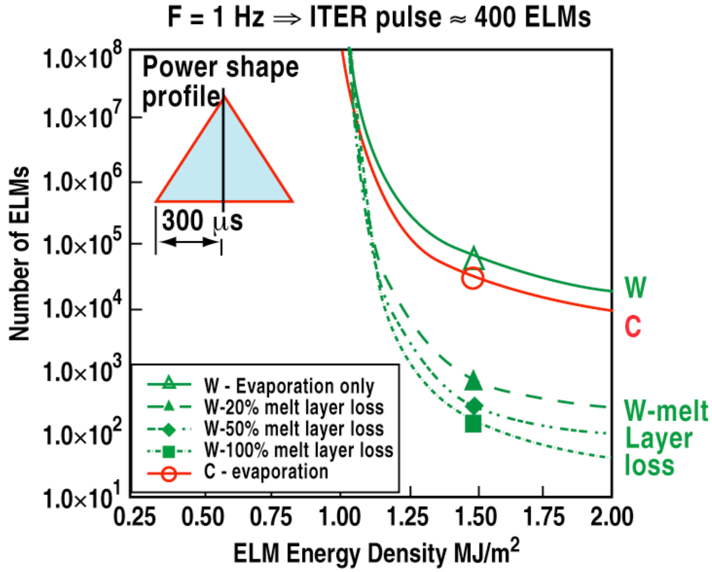
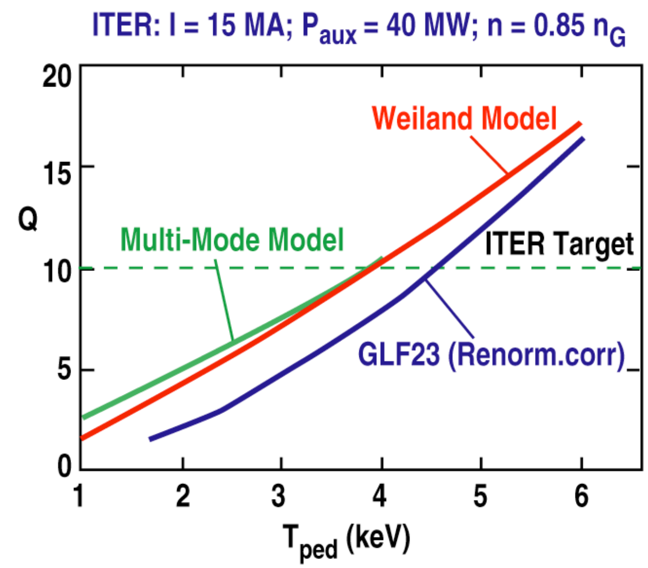
Understanding and Controlling ELMs is a Critical issue for ITER and all Future Tokamak Experiments

- **The goal of this research area is to:**
  - **Control ELM particle and energy losses without loss of core confinement**
- **Type-I ELMs in ITER could potentially limit the divertor and first wall lifetime**
- **ELM control must not degrade the pedestal**
  - **The pedestal is the boundary condition for the core --> for stiff profiles, pedestal height determines energy confinement and overall performance - Q**
- **Multi-disciplinary approach including transport, stability and boundary physics produces results**
  - **IAEA04 - Evans (oral), Fenstermacher, West**
  - **APS: 2004 Invited - Burrell, Moyer, Snyder, 2005 Invited - Burrell, Evans**
  - **EPS 2005 Invited : Burrell (Evans)**
  - **Numerous papers including 2 in PRL**





OUTLINE – Thrust IT-1 Aims to Qualify ELM Control Techniques for ITER

- **Motivation / goals and plan summary**
- **Near term plan to address ITER critical issues**
  - **Physics understanding and performance extension of ELM control regimes**
    - **ELM suppression by Resonant Magnetic Perturbations (RMP)**
    - **ELM-free QH-mode**
    - **Pellet Pacing of ELMs**
    - **Small-ELM Regimes**
- **Long term plan**
- **Summary**

Plan to Qualify ELM Control Techniques for ITER Combines Performance Extension and Physics Understanding

Goal: Control ELM particle and energy losses without confinement degradation with techniques that predictably extrapolate to ITER

- **Short term focus is empirical understanding and performance extensions - we want to be able to say:**
  - ELMs were completely suppressed in the ITER shape, at the ITER pedestal collisionality, and for zero toroidal rotation as in ITER, by application of n=3 RMP from the DIII-D I-coil
  - ELM-free QH-mode was obtained in plasmas with net co- momentum input to the core as in ITER
  - The ELM frequency was increased and ELM size reduced in DIII-D with the application of high frequency pellet injection that can be extrapolated to ITER

- **Long term focus is ability to predict ELM control in ITER from physics based understanding - we want to be able to say:**
  - ELM suppression by RMP is a viable process for ITER-like conditions and we understand the physics sufficiently to predict the constraints on a design for ITER RMP coils
  - QH-mode is a viable candidate ELM-free regime for ITER
  - From physics understanding of the reduction of ELM impact on PFCs using pellet pacing we can predict the constraints on the required design of a high frequency pellet injector for ITER

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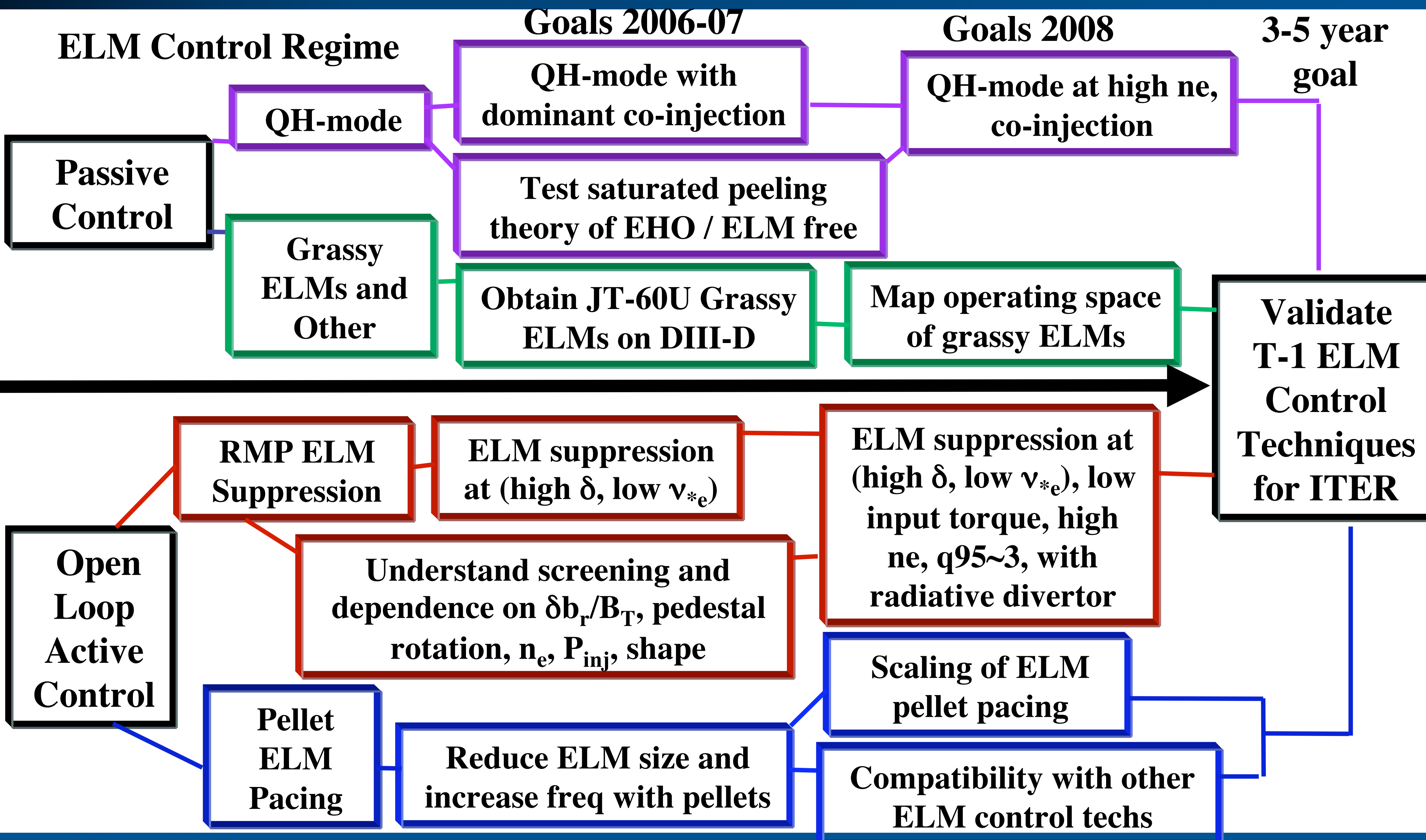
Thrust IT-1 ROF Proposal Statistics - 109 Proposals Covering 94 Unique Run Days

- **ELM Control for ITER received more proposals that any other area**
  - Total Unique Run Days Requested — 94
  - Total number of different participants — 43

Breakdown by sub-category:	Total 109	Working Area Leaders
RMP ELM Suppression with I-coil	57	Evans / Moyer
QH-mode studies	26	West / Burrell
Pellet ELM pacing and Combinations	11	Baylor / Jernigan
Small ELM regimes and Other ELM Control Techniques	15	Osborne / Maingi

- **Breakdown by location:**
  - US Fusion program — 91
  - Non-US fusion programs — 18
- **Proposals backlog after completion of 32 week campaign in 2006-7** — 78
- **ELM control proposals backlog at 20 run weeks per year ~ 8 years**

Roadmap Toward Thrust IT-1 Long Term Goal Reflects Multiple Possible Techniques



Thrust IT-1 ELM Control for ITER Addresses Urgent ITER Design Issues

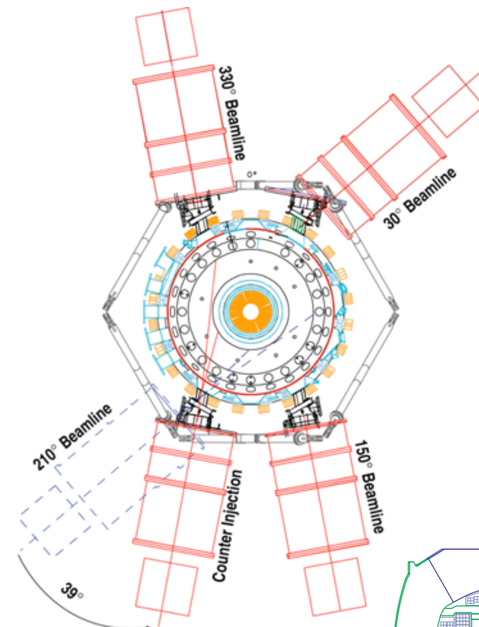
- **This thrust addresses 2005-06 ITPA High Priority Research Tasks for ELM control**
  - **Improve predictive capability of ELM characteristics through experimental studies and theory / modeling analysis, and develop small ELM and quiescent H-mode regimes, and ELM control techniques**
    - **Define physics requirements for pellet injection as ELM control scheme in ITER**
    - **Define physics requirements for ergodic field application as ELM control scheme in ITER**
    - **Integrate observations of ELM crash dynamics and initiate comparisons with developing models**
    - **Categorize small ELM regimes based on cross machine comparisons**

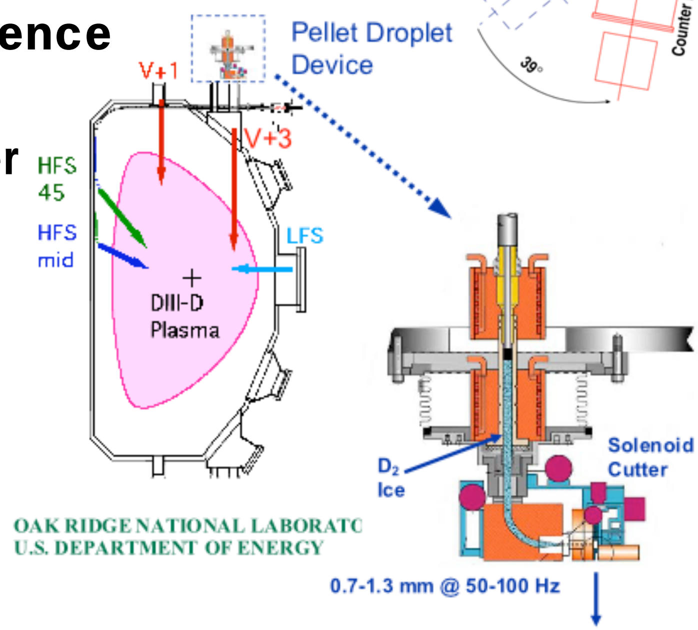
- **This thrust addresses ITER Design Issues that need urgent ITPA input**
    - **Design of coils to mitigate / control ELMs and RWMs**
    - **Pellet injector for ELM control**

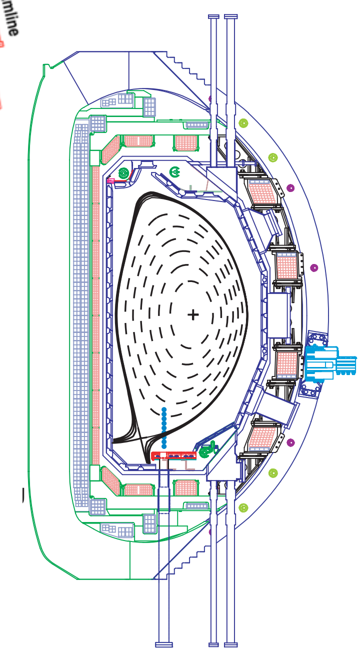
- **The proposed experiments fulfill several commitments to ITPA/IEA joint experiments**
  - **TP-5/PEP-14** QH/QDB Plasma Studies with JT-60U
  - **PEP-17** Small ELM regimes at low pedestal collisionality with JT-60U and JET

Thrust IT-1 ELM Control for ITER Uses New DIII–D Hardware to Address Urgent ITER Design Issues

- **Heavy use of new hardware will be applied to ITER urgent issues**
  - Beam balance variation for QH-mode, ELM suppression by RMP and “grassy” ELMs
    - QH-mode with co- core rotation
    - Physics of RMP screening and ITER PoP
  - Pumping of near ITER shape for RMP ELM suppression and for QH-mode
    - Physics of shape dependence and ITER PoP
  - High frequency pellet dropper hardware for ELM pacing
    - Physics of pellet paced ELMs triggering







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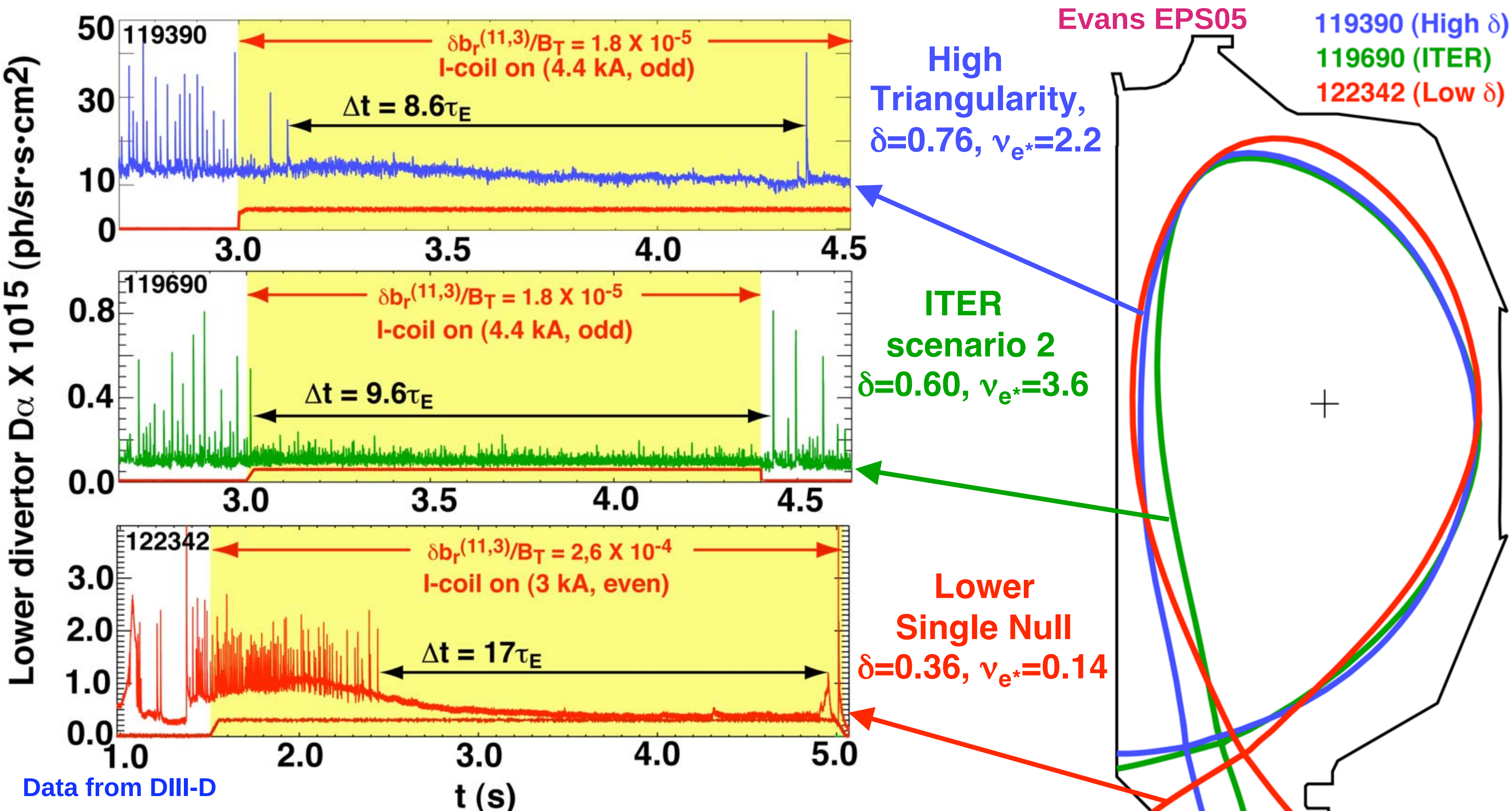
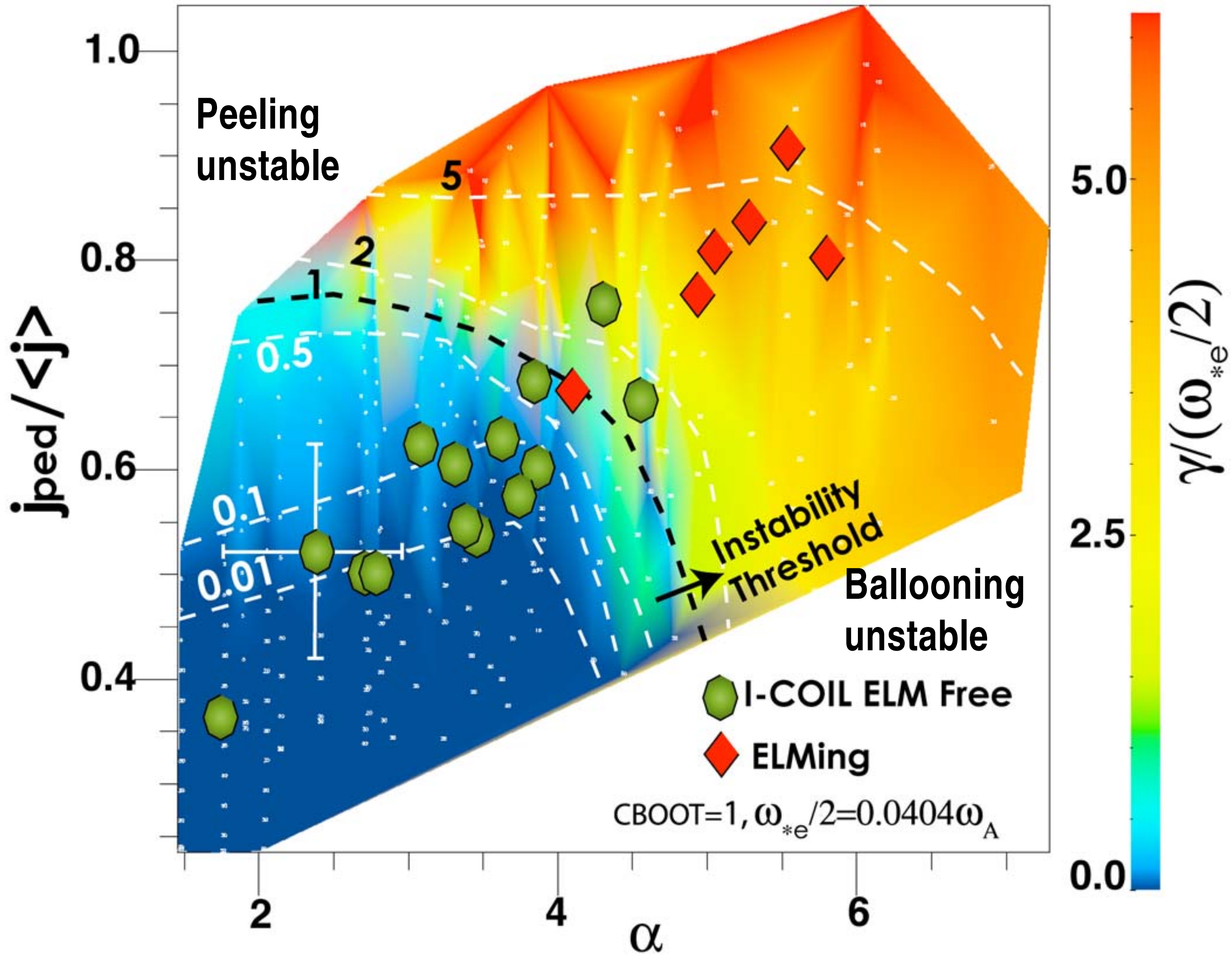
ELM Control Obtained Over Range of Shapes and Collisionalities



Data from DIII-D

P.R. Thomas, et al., EPS04
K.H. Burrell et al PPCF 2005
T.E. Evans, et al., PRL 2004
T.E. Evans et al. APS06 to be published in PoP
R. A. Moyer, et al., PoP 2005

RMP ELM-Free H-Modes can be Pushed Deep into Stable Region by Increasing the RMP Amplitude



T. H. Osborne, et al., 05 EPS

RMP ELM Control Achieved for a Range of Conditions

- **ELMs controlled at low ITER-collisionality pedestal for:**
  - **Power scan above a threshold - no upper power limit observed**
  - **RMP amplitude scan above a threshold - using n=3 RMP**
  - **Density scan below a threshold - using gas puffing**
  - **Well defined window in q95 - good ELM control for 3.5 < q95 < 3.9 with n=3 RMP**
- **Experiments in 2006-7 will use new DIII-D hardware capabilities to examine physics of dependence on plasma rotation, plasma shape, and pedestal collisionality**

International Collaborators Playing a Key Role in all Aspects of RMP Experiments

- **2003 on site participation:**

  Jeff Harris (ANU, Australia)
  Paul Thomas (CEA-Cadarache, France)
  Karl-Heinz Finken (TEXTOR,Germany)
  David Pretty (ANU, Australia)
  Nobuyoshi Ohyabu (NIFS, Japan)
  Sugura Masuzaki (NIFS, Japan)

- **2004 on site participation:**

  Jeff Harris (ANU, Australia)
  Paul Thomas (CEA-Cadarache, France)
  Marina Becoulet (CEA-Cadarache, France)
  Karl-Heinz Finken (TEXTOR,Germany)

- **2005 on site participation:**

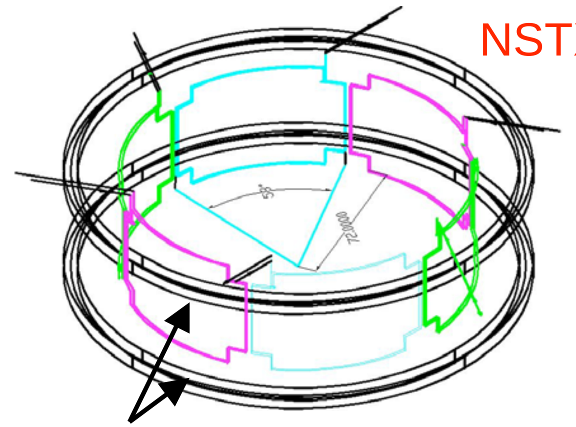
  Jeff Harris (ANU, Australia - remote)
  Pascale Monier-Garbet
  (CEA-Cadarache, France)
  Eric Nardon (CEA-Cadarache, France)
  Frederic Dubois (CEA-Cadarache, France)
  Michael Lehmen (TEXTOR,Germany)

Extensive Validation and Predictive Model Development Activity Underway

- DIII-D experiments in Thrust IT-1 will provide the bulk of the data on RMP ELM suppression - collaboration in experiments on TEXTOR and possibly on JET (if coils installed)
- Joint US/France/Germany plasma modeling evaluation:
  - TRIP3D (field line integration, US)
  - MISHKA (ELM stability, France)
  - TELM (stochastic transport, France)
  - E3D (3D Monte Carlo heat transport, Germany)
- Other modeling activities (on-going or beginning)
  - JETTO (JET-Culham) CAS3D (MPI-Greifswald)
    3D Turbulence (FSZ Juelich, MPI Garching)
    3D Fluid Transport EMC3-Eirene, (FSZ Juelich)
  - TRIP3D, TRIP3D-MAP, SURFMN, PROBE-GRID (GA, UCSD) PIES (PPPL) NIMROD (Tech-X, U. Wisc, SAIC) VMEC (PPPL, ORNL, UT Austin)
    GATO (GA) UEDGE (LLNL) ELITE (GA)
    Screening (Colombia U) BOUT(LLNL)

DIII-D Team Collaborating on and Evaluating Other Proposals for RMP ELM Suppression

- **Collaborating with NSTX on experiment to use RWM coil in n=3 mode to attempt ELM suppression**
  - **Expect $\delta B_r^{n=3}$ ~ 10^{-3}, modeling in progress**
- **Consulting with JET on design of dedicated RMP coils for ELM control**
  - **Focused on ITER prototype**
  - **Possible installation ~2008**
- **Evaluating use of ITER correction coils for ELM suppression by RMP**
  - **Using DIII-D physics understanding and analysis tools to evaluate scenarios**
  - **Working very closely with ITER staff - V. A. Chuyanov and Y. Gribov**



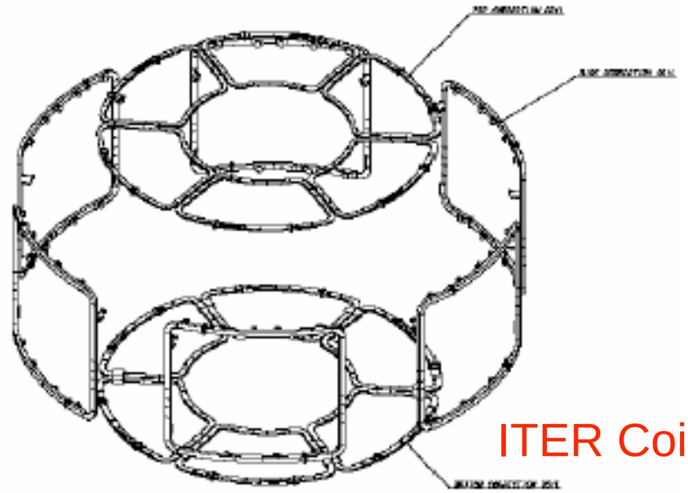
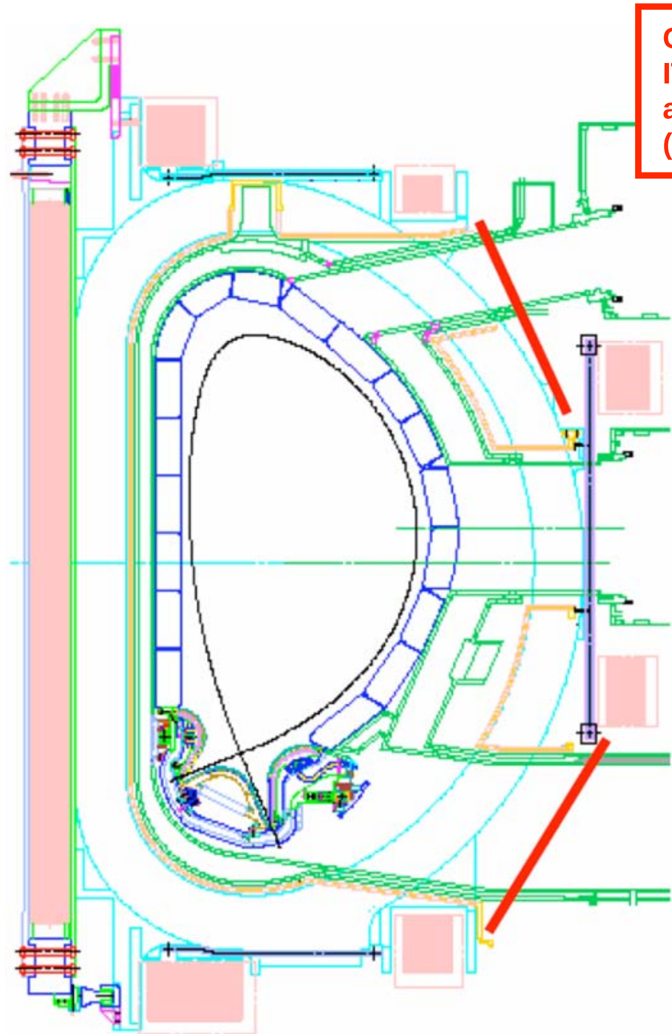
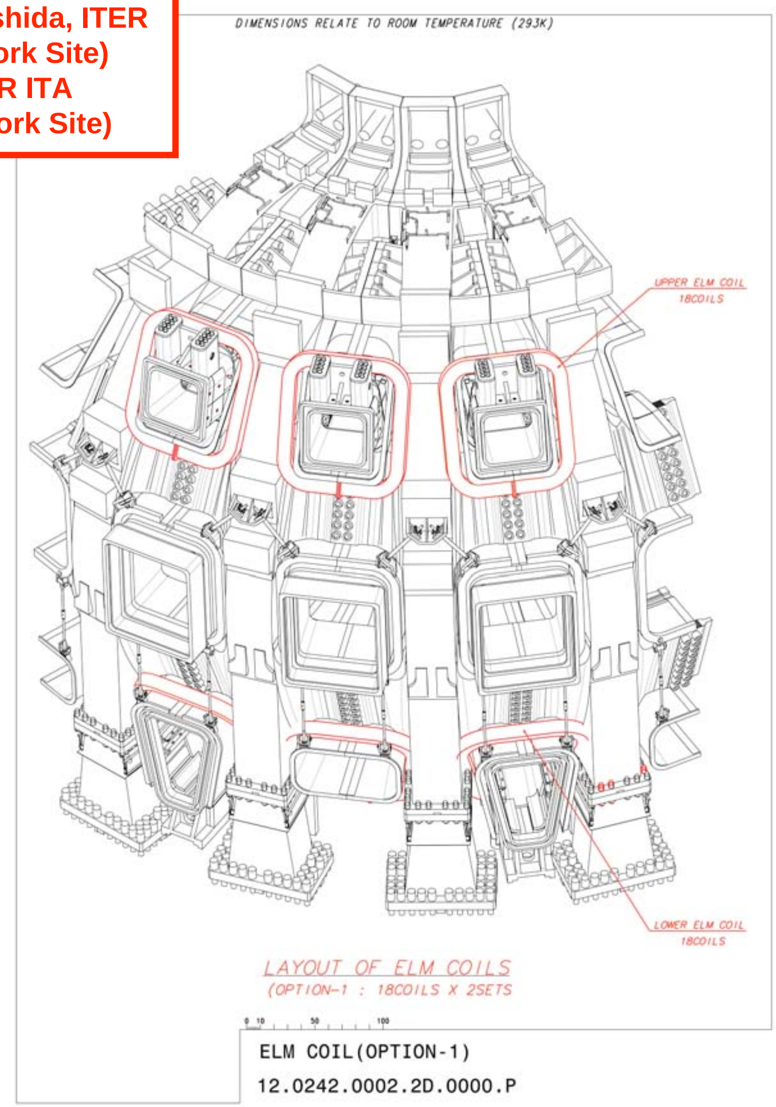


Fig 8 Layout of the Correction Coils, for Error Field Correction and RWM Control

Answers Needed Very Soon – Preliminary ELM Control Coil Designs for ITER in Progress

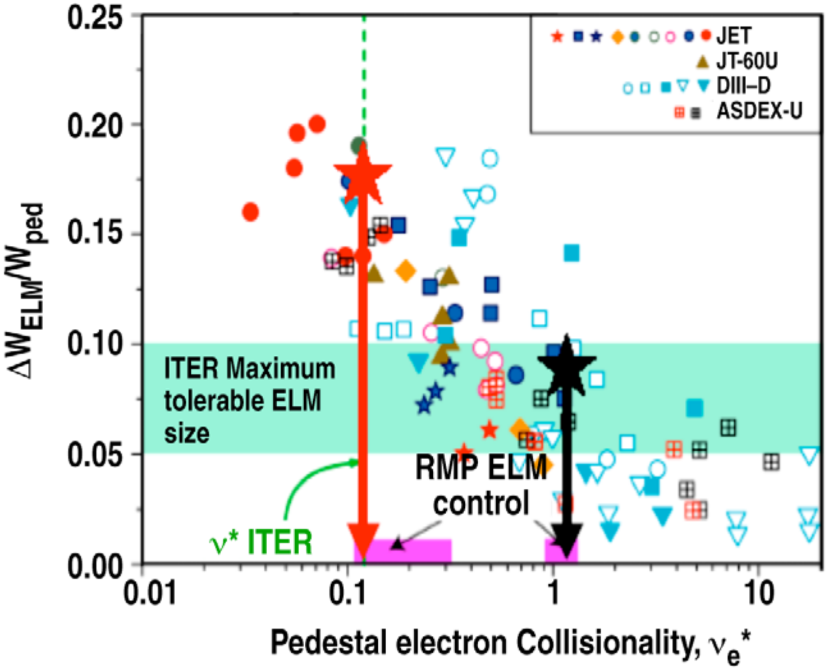


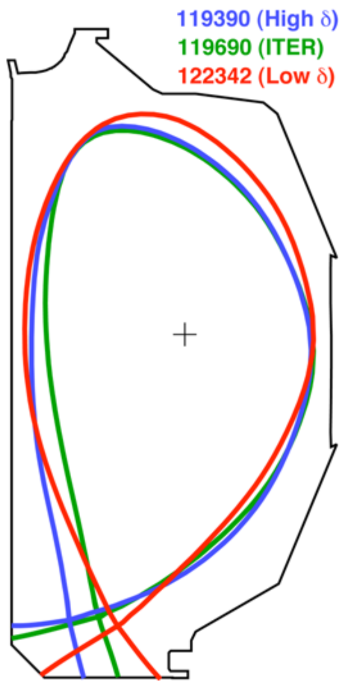
Courtesy of K. Yoshida, ITER ITA (Naka Joint Work Site) and Y. Gribov, ITER ITA (Garching Joint Work Site)

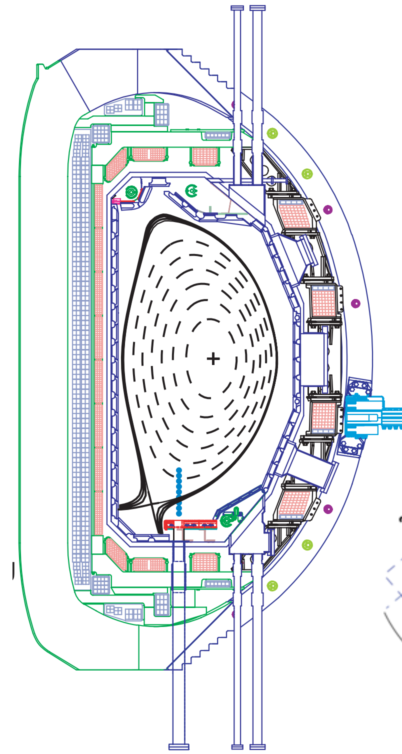


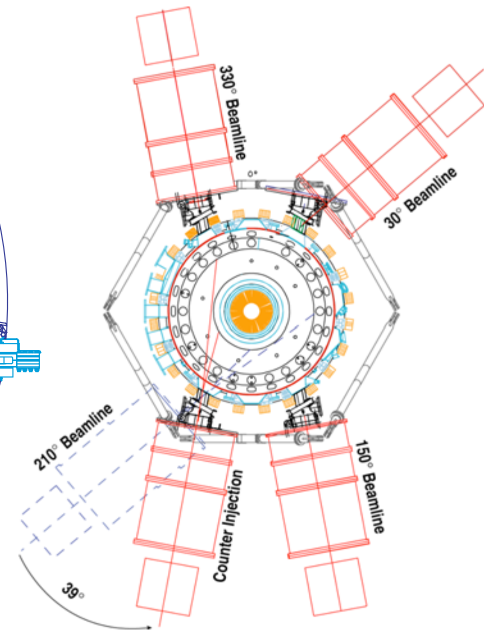
- **Option 1 ITER ELM control design can be configured for n = 1, 3, 6 or 9**

Balanced Beam and High δ Pumping Capability will Allow Attempts of RMP ELM Suppression at ITER Shape and Rotation









- **Low collisionality RMP ELM suppression at low δ will be extended to high δ with the new pumping capability and to low core rotation with the new balanced beam capability**

RMP ELM Suppression Proposals for 2006–7 Address Both Physics Questions and Performance Extension Goals

- **Understand the critical physics elements for scaling RMP ELM suppression to burning plasmas - ITER and beyond**
  - Is ELM suppression physics at (low ν_e*, high δ) the same as at (low ν_e*, low δ) ?
    - Do the pedestal profiles (–> transport) respond the same at high δ ?
    - How is the pedestal stability affected at high δ (Type I versus II/III)?
  - What is the dependence of ELM suppression on pedestal rotation?
  - Is plasma screening (via β and/or rotation) a key part of the physics?

2006 plan limit

  - Separate the dependence of suppression on density, ν_e*, and δ
  - Document ELM suppression in up/down symmetric discharges ("stellarator symmetry") for modeling with stellarator boundary codes
- **Apply this understanding to extend ELM suppression performance to ITER-relevant conditions**
  - Achieve ELM control in a strongly shaped plasma with low net torque input, low ν_e*, and high pedestal density

Goal I – Validate ELM Suppression by RMP as a viable technique for ITER Priority A 7.0 d, B 4.0 d, PB - 4 Exp

- **Shape / discharge development**
  - Re-establish good ELM suppression in high δ LSN — A1 1.0 d
  - Re-establish good ELM suppression in low δ LSN — B4 1.0 d
- **Performance extension**
  - Extend low ν* high δ to ITER low rotation — A2 1.0 d — Milestone 161
- **Increase physics understanding**
  - Effect of plasma screening on RMP fields in pedestal — A3 1.0 d — Milestone 161

2006 plan limit

- **Performance extension**
  - Assess power and n_e limits to ELM control — A4 1.0 d
- **Increase physics understanding**
  - Assess δBr/BT scaling of suppression — A5 1.0 d
- **Compatibility of RMP ELM Control with other systems**
  - RMP ELM control with radiative divertor — A6 1.0 d
- **Increase physics understanding**
  - Role of shape: δ and squareness — A7 1.0 d

Goal I – Validate ELM Suppression by RMP as a Viable Technique for ITER Priority A 7.0 d, B 4.0 d, PB - 5 Exp

- **Compatibility of RMP ELM Control with other systems**
  - NTM avoidance, Hybrid, ITBs, Fastwave ICH, HFS pellet fueling — B2 1.0 d — PB 2 Exp
- **Increase physics understanding**
  - Dependence on SOL/divertor conditions — B1 1.0 d
  - n_e vs collisionality dependence of small ELM-like events during suppression — B3 1.0 d
  - Dependence of ELM control on mode spectrum — PB 1 Exp
- **ELM control with RMP tool development**
  - Real time q95 control — PB 1 Exp

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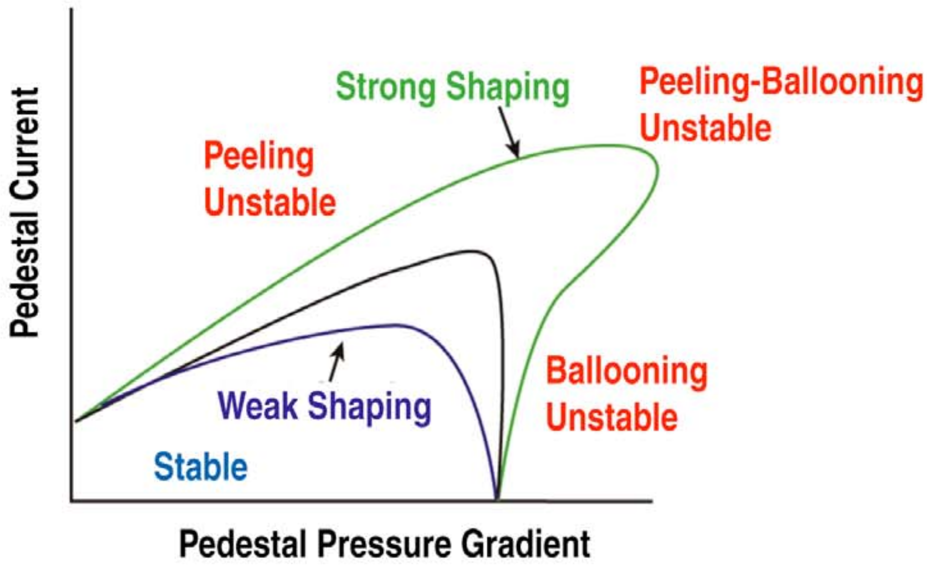
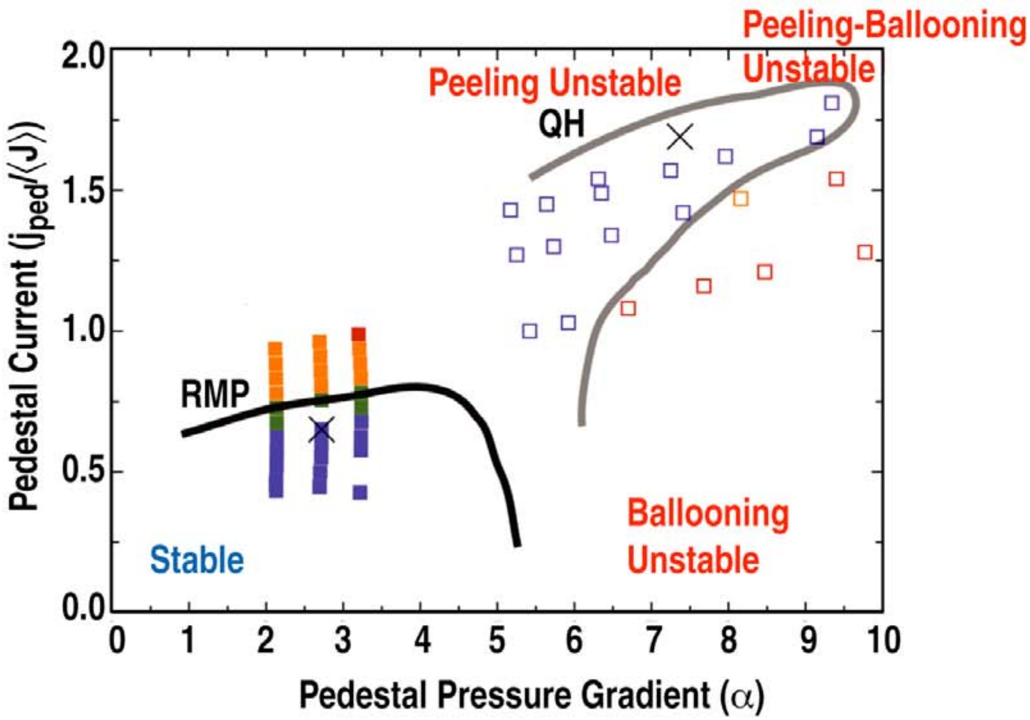
RMP ELM-Free H-Modes and QH Modes Both Stable and Near Peeling Boundary

Schematic P-B Stability Diagram

[P.B. Snyder, H.R. Wilson PoP2002]

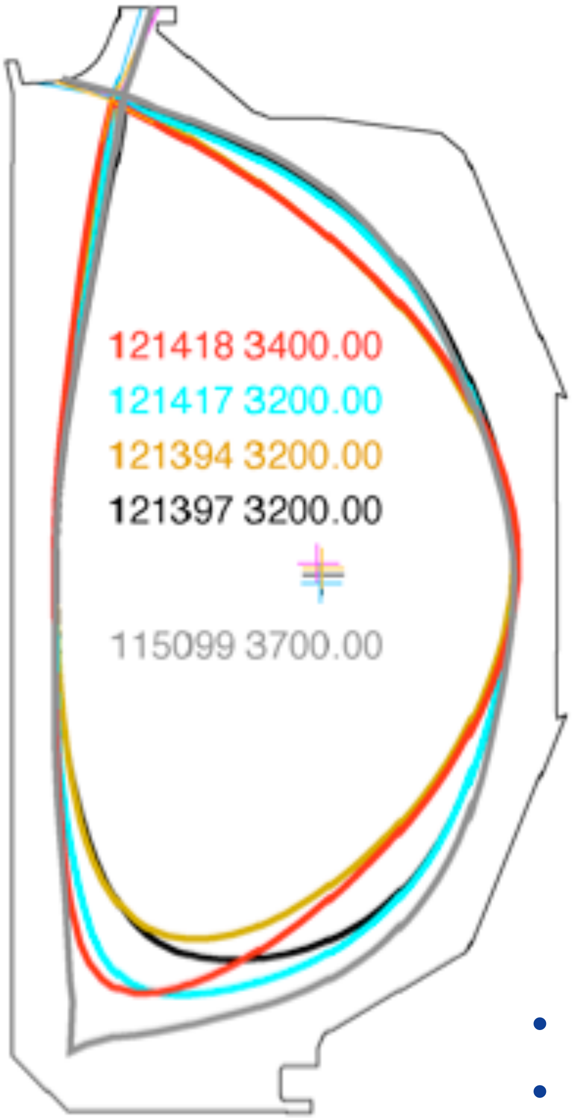


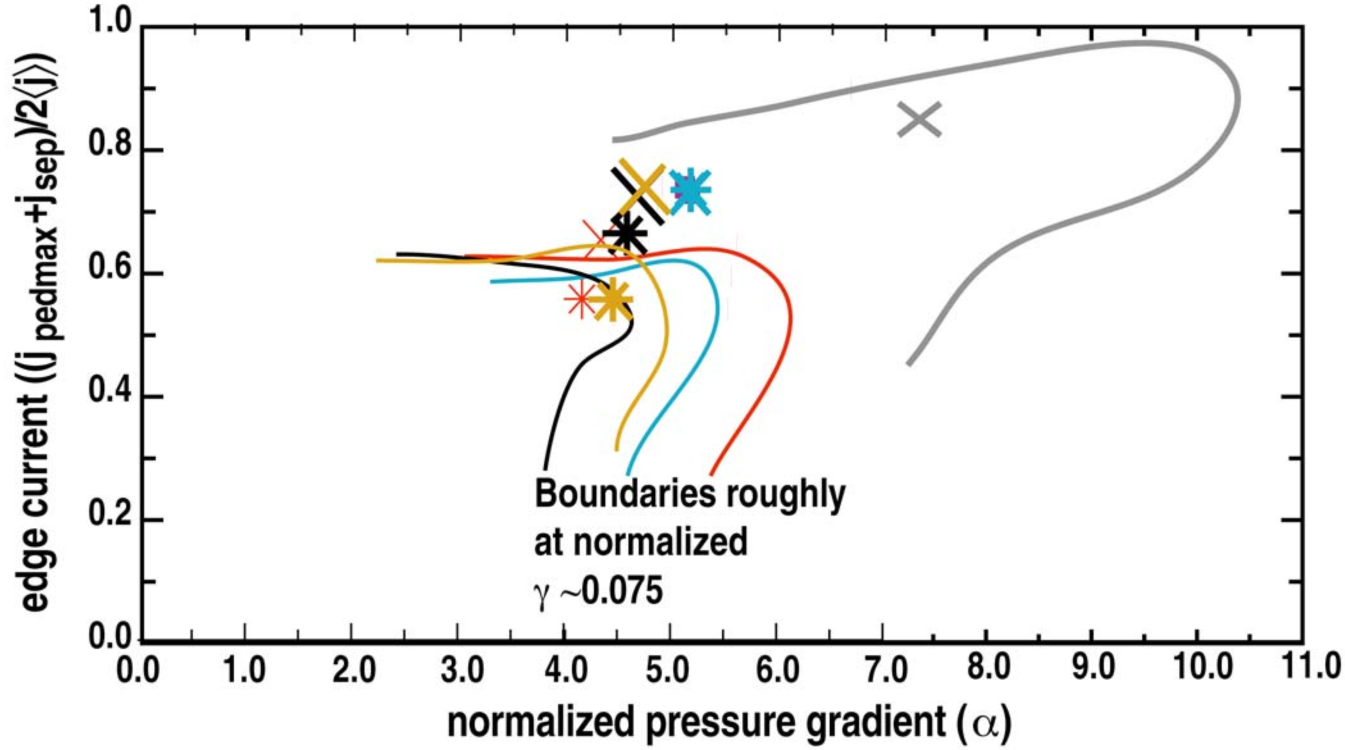
Shaping: RMP weak, QH strong



- Strong shaping allows access to higher ∇P such as in QH-modes
- P-B stability boundaries are a strong function of plasma shape
  - At present RMP ELM-free discharges can not access low ν_{e*} in strongly shaped plasmas (because of pump location)
- In 2006, low ν_{e*} RMP ELM-free operations in strongly shaped plasmas will be investigated

QH-Mode Stable Operating Space Increases with Increased Triangularity and Reduced Squareness

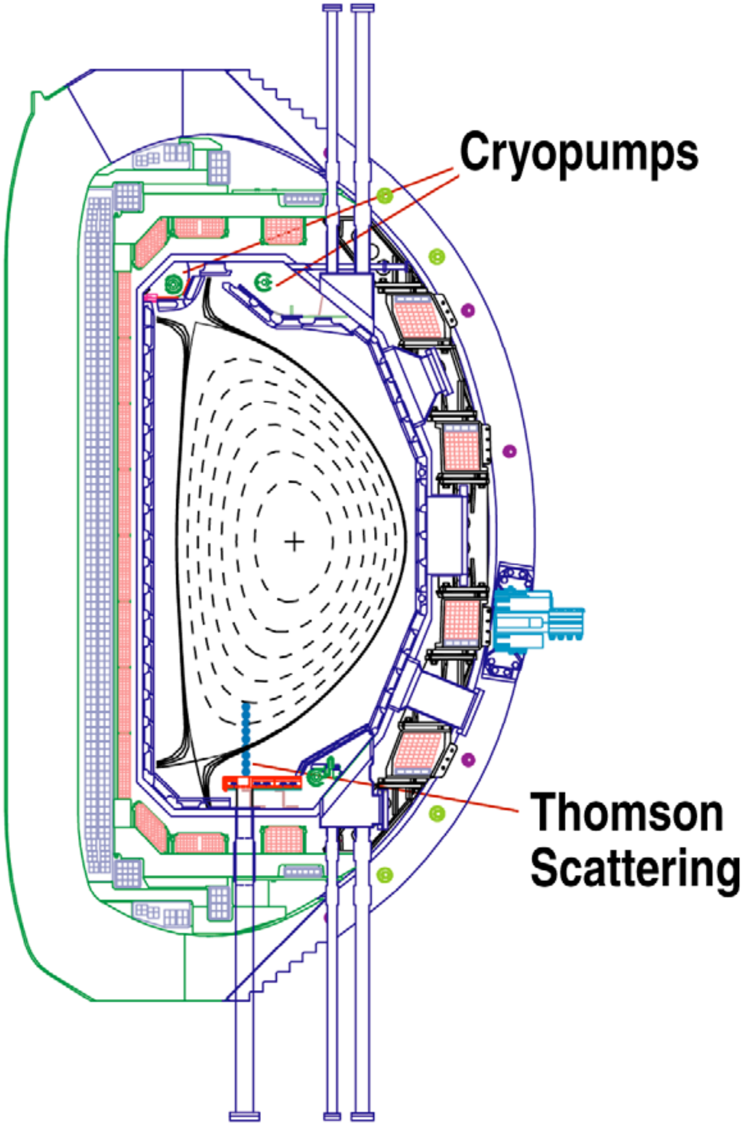




- **Triangularity advantages very clear (yellow-->red-->gray)**
- **Advantage to reduced squareness more subtle (cyan-->red)**

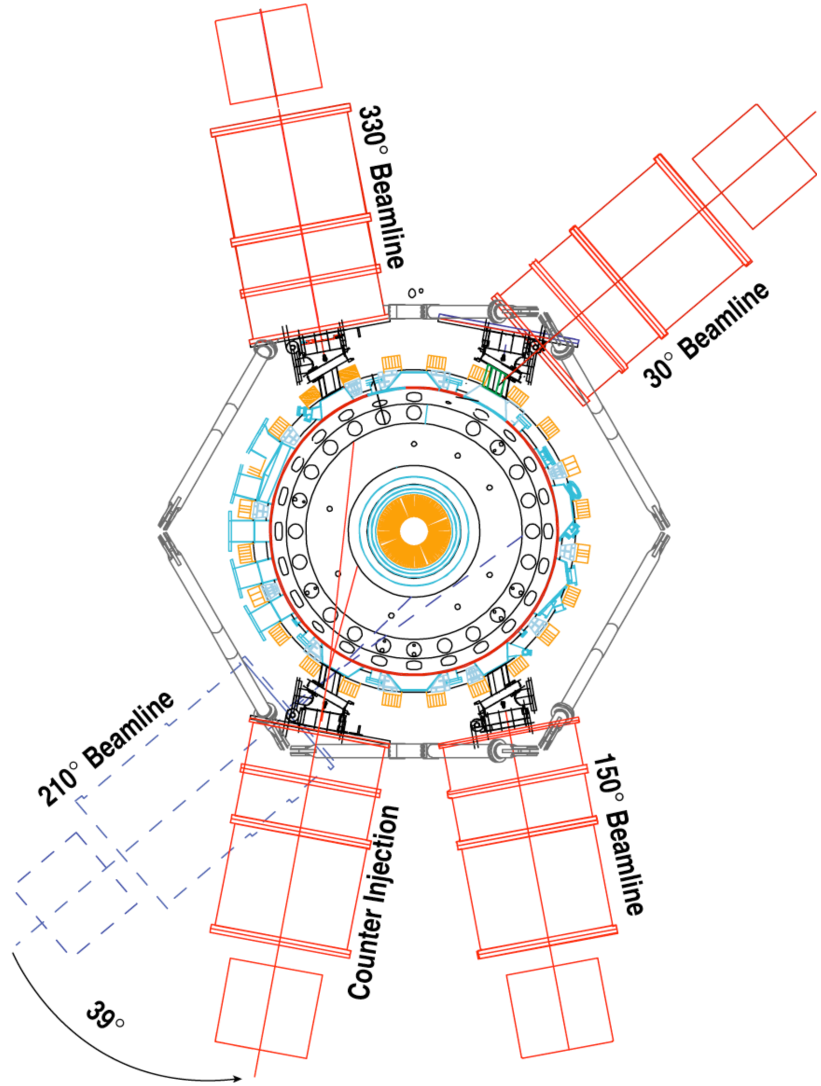
New High δ Lower Pumping Capability Will be Very Important to Understanding Density Dependence of QH-mode

- **DIII-D QH-mode found in low to moderate density plasmas, $0.07 < n_e^{ped}/n_{GW} < 0.48$**
  - High shaping allows higher pedestal density, edge current and pressure
- **New lower divertor will provide density control for high δ, DN QH-mode plasmas**



Ability to do CTR + CO NBI in DIII-D is Essential to Understand QH-mode Pedestal Physics

- **Counter edge rotation may be a key physics attribute**
  - **Obtained with counter beam injection (reversed Ip) in DIII-D**
    - **Pursuing indications of CO-NBI QH-mode 2005**
  - **Obtained with several beam injection combinations in JT60-U ITPA joint experiments**
    - **All combinations showed counter rotation in pedestal**
- **Experiments in 2006 will exploit multiple combinations of CTR + CO NBI for QH-mode studies**
  - **Ion loss vs momentum balance**
  - **QH-mode possible with single CTR beam**



QH-mode Goals and Key Physics Questions for 2006-7 Campaign

- Determine role of plasma rotation and counter neutral beam injection in creating and sustaining the QH-mode.
  - Can we produce QH-mode with dominant co-injection and edge co-rotation?
  - Alternatively can we maintain QH and counter edge rotation with dominant co-injection

- EHO investigations
  - Test Phil Snyder's new hypothesis about EHO being saturated peeling mode

2006 plan limit

- Explore higher triangularity and higher density QH-mode plasmas
  - Test peeling-ballooning mode theory under a broader range of conditions
  - Explore high performance QH/QDB at high pedestal pressures achieved in highly shaped DN configuration

- Explore synergistic effects between QH-mode and RMPs

Goal II – Validate QH-mode as a Viable ELM Free Regime for ITER Priority A 6.0 d, B 2.0 d, PB - 1 Expt

Milestone 161

- Role of edge rotation in ELM stabilization and QH maintenance
  - QH-mode in normal I_p w/ Counter NBI — A1 1.0 d
  - Co- vs Counter- beam balance - ITPA — A2 1.0 d
- EHO Physics vs Rotation (Milestone 161)
  - Expts to check new theories by Snyder — A3 1.0 d

2006 plan limit

  - Rotation studies in high n_e DN — A4 1.0 d
  - EHO Physics investigations — A6 1.0 d
- Double null QH pedestal performance — A5 1.0 d
  - Increase QH-mode edge pressure at higher δ using density control in DN
  - Explore stable, high performance QDB studies at high β_N
- I-coil perturbations of QH-mode edge
  - QH pedestal control using AC I-coil — B1 1.0 d
  - Improved access to QH / EHO with steady n=3 I-coil — B2 1.0 d
- Compatibility of QH-mode with other systems
  - QH-mode with deep pellet fueling — PB - 1 exp

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Pellet Pacing Results in AUG Suggest that Smaller, Lower Velocity Pellets May be Advantageous

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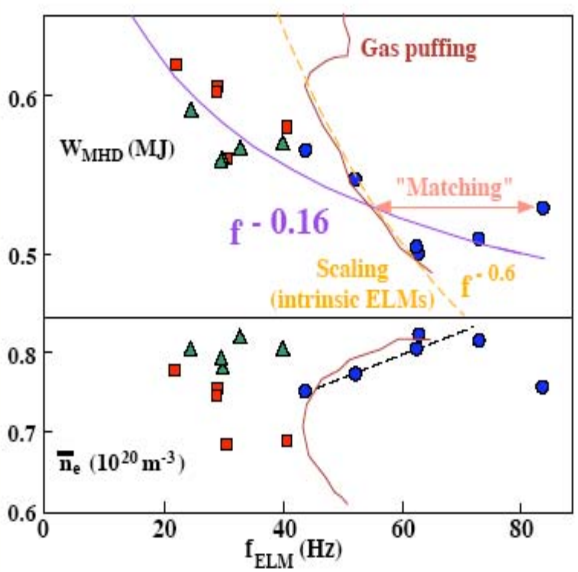
ELM pacing by pellets: I: Operational features

Prop. No. 676
P.T. Lang, L.R. Baylor

IPP



AUG results: ELM pacing can result in mitigation, but causes mild reduction of confinement.

Due to convective losses imposed by pellet fuelling still present?

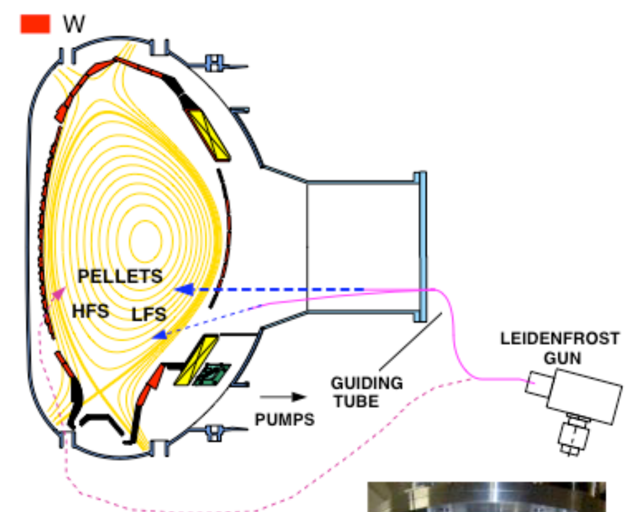
If yes, these losses should depend on the injection geometry.

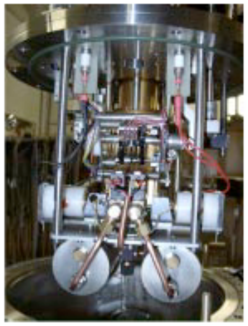
LFS/HFS deposion profiles differ due to fast cloud drift
LFS deposition closer to edge, less particle sustainment time,
less <T> of lost particles, less losses than from HFS)

Compare pacing using different injection locations

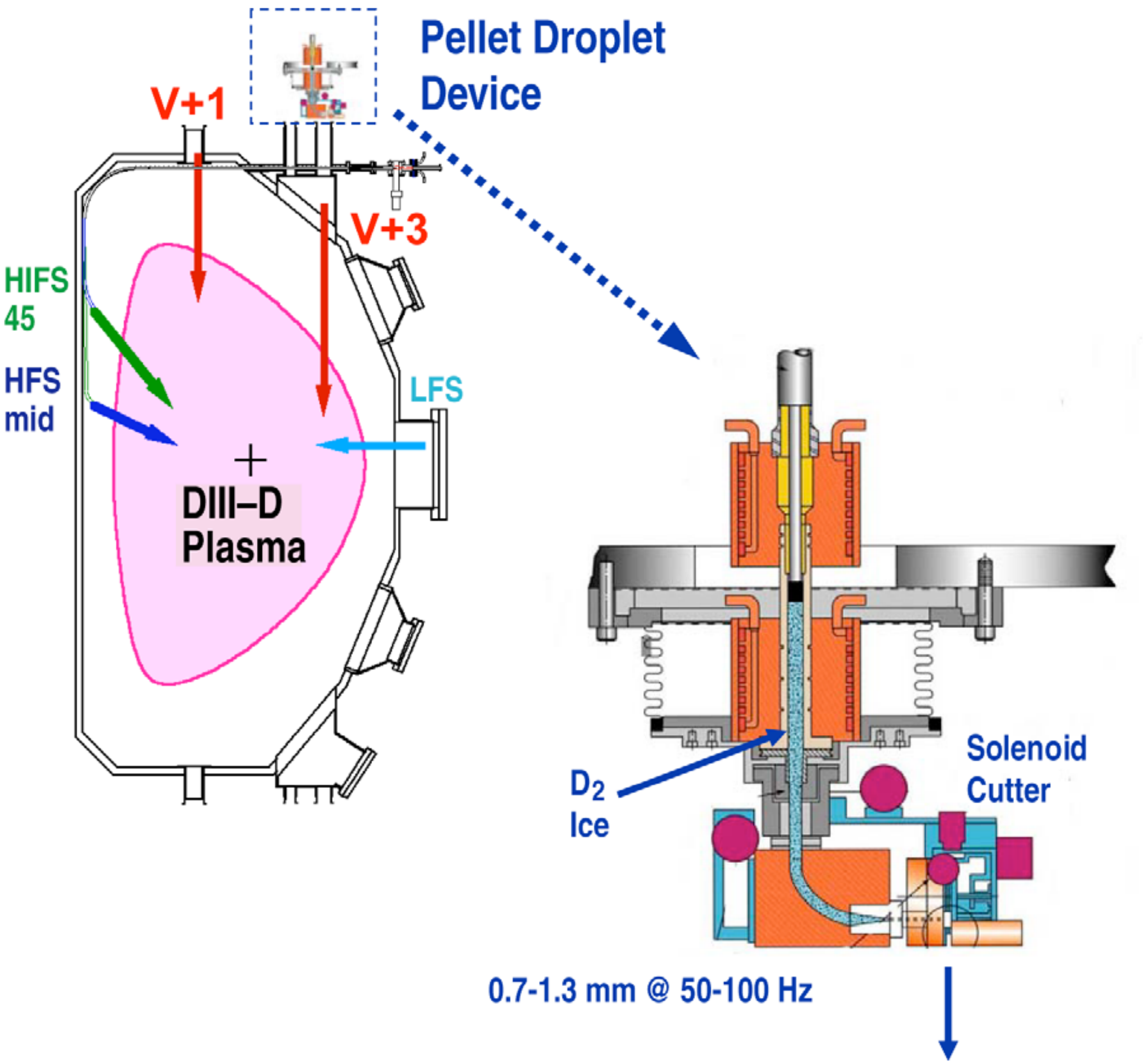
DIII-D 2006 Research Opportunities Forum, November 15.-17. 2005 P.T. Lang 1

- **DIII-D pellet dropper plans complement AUG plans for LFS injection**





New Pellet Dropper Should Provide Desirable Pellets for Pellet ELM Pacing



- **Hardware anticipated to be ready for piggy back testing summer 2006**
  - **Frequency 50-100 Hz**
  - **Pellet size 0.7 - 1.3 mm**
  - **Pellet composition = D_2**
  - **Pellet velocity at SOL edge ~10 m/s**
  - **Anticipated penetration depth, T_e ~ 2cm, 400 eV**
  - **Pedestal penetration about half way up steep gradient**
- **Dedicated experimental time planned early in FY07**

Pellet Pacing and Combination Proposals Address both Physics Questions and Performance Extension Goals

- **Good experimental ideas exist toward answering physics questions, eg.:**
  - Are induced ELMs different than natural ELMs of the same size?
    - Are there differences between ELMs from fueling pellets and ELMs from pedestal pacing pellets?

2006 plan limit

  - Can induced ELMs reduce loads to plasma facing components?
  - What are the trigger conditions (plasma operating point parameters and pellet imposed perturbation) for paced ELMs?
  - What are the onset dynamics of induced ELMs & how do they compare with intrinsic ELMs?
  - How is the transition from intrinsic ELMs to mitigated, paced ELMs achieved?
  - What is the effect of paced ELMs on energy and particle confinement?
- **Good experimental ideas exist toward performance extension goals, eg.:**
  - Can higher frequency, smaller Type-I ELMs be achieved without confinement degradation using high frequency pellets in the edge?

Pellet Pacing and Combinations of Pellets with Other ELM Control Techniques Priority A 1.5 d, B 1.5 d, PB - 4 expt

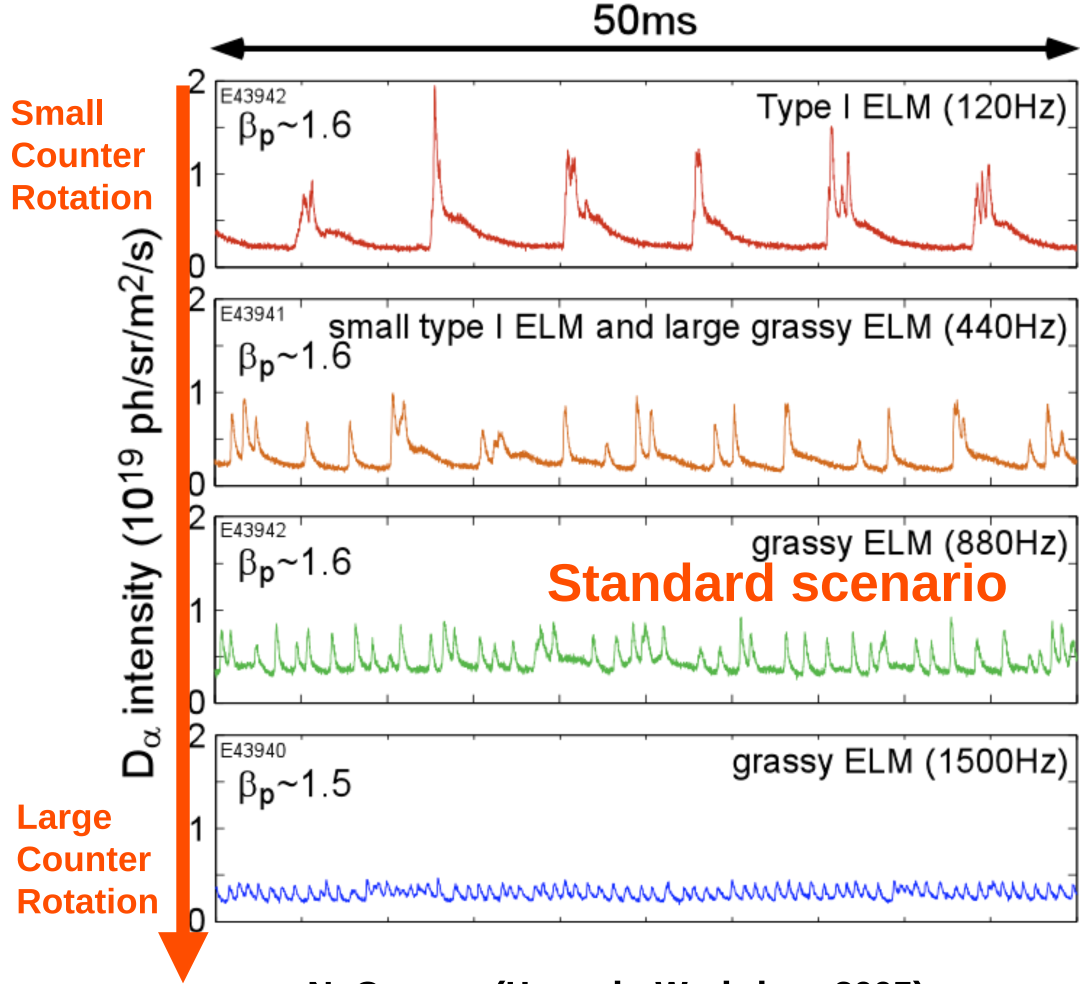
• Hardware commissioning			PB 2.0 expt
• Capability Exploration			PB 1.0 expt
2006 plan limit			
• ELM Pacing Physics	A1 0.5 d		
• ELM Pacing Physics	A1 0.5 d		PB 1.0 expt
• Compatibility of pellet fueling with ELM control techniques	A2 0.5 d	B1 0.5 d	
• Use pellet dropper to fill in physics gaps in other RMP control techniques		B2 1.0 d	

OUTLINE - Thrust IT-1 Aims to Qualify ELM Control Techniques for ITER

- Motivation / goals and plan summary
- Near term plan to address ITER critical issues
  - Physics understanding and performance extension of ELM control regimes
    - ELM suppression by Resonant Magnetic Perturbations (RMP)
    - ELM-free QH-mode
    - Pellet Pacing of ELMs
    - Small-ELM Regimes
- Long term plan
- Summary

New Flexibility of Momentum Injection Balance Should Allow Studies of "Grassy" ELM Regime on DIII-D

Grassy ELM Regime in JT-60U



N. Oyama (H-mode Workshop 2005)

- **Grassy ELMs observed on JT-60U and JET**
  - **Accessed by high poloidal beta and possibly counter rotation**
- **Not seen previously on DIII-D without capability for varying injected momentum balance**
- **ITPA/IEA joint experiments "strongly encouraged" DIII-D to participate in PEP-17 on Grassy ELMs**

Small ELM Regimes and Other ELM Control Tech. Proposals Address Both Physics Questions and Performance Goals

- **Physics Questions - Small ELMs:**

2006 plan limit

  - What is dependence of grassy ELM regime on β_p, near DN shape, P_{inj} ?
  - What is dependence of ELM size and fast dynamics on toroidal rotation?
- **Physics Questions - Other ELM Control Tech:**
  - What is the physics of ELM filament formation and propagation?
  - What is the role of SOL currents in ELM dynamics?
- **Performance extension goals, eg.:**
  - Can we achieve the JT60-U grassy ELM regime on DIII-D?
  - Can we achieve small ELMs by separation of the n_e and T_e profiles (steep gradient regions)?
  - Can we achieve C-MOD style "large ELMs" on DIII-D in dimensionless pedestal parameter similarity experiments?

Small ELMs and Other ELM Control Techniques
Priority A1.5 d, B 4.0 d, C 2.0 d, PB- 1 expt

- **Small ELM regimes**

2006 plan limit

  - Obtain small ELMs at high β_p > 1.6, higher q, and ν_{e*}~0.1 - ITPA "Grassy ELMs" A1 0.5 d
  - Obtain small ELMs through control of rotation or rotational shear A1 0.5 d
  - Obtain small ELMs by controlling n vs T profiles B1 1.0 d
  - Small oscillations (Type-II) with RMP at ν_{e*}~1 B2 1.0 d
- **Other ELM Control Techniques:**
  - Improved understanding of T-I, II, and III ELM energy loss mechanism
    - SOL current role in ELM dynamics A2 0.5 d
    - Pedestal perturbation dynamics and ELM filament formation B3 1.0 d
    - C-Mod/DIII-D Type-I ELM comparison B4 1.0 d
  - ELM elimination with n=1 traveling field PB- 1 expt
  - Quasi-coherent mode C1 1.0 d
  - VH-mode with better pumping C2 1.0 d

Thrust IT-1 Run Plan Proposal for 2006-7 Addresses All High Priority ELM Control Tasks for ITER

2006-7 Priority	A	B	C	PB
• Validate ELM Suppression by application of RMP as ELM control technique for ITER	7.0 d	4.0 d		4 exp
❖ Decision after A1 exp on ELM suppression at high δ_{low}				
• Validate QH-mode as ELM-free regime for ITER	6.0 d	2.0 d		1 exp
❖ Decision after A1 exp on QH-mode with normal I_p				
• Validate pellet ELM pacing as an ELM control technique for ITER	1.5 d	1.5 d		4 exp
• Explore small ELM regimes applicable to ITER	1.5 d	4.0 d		2.0 d, 1 exp
• Total Dedicated Run Time	16.0 d	11.5 d		2.0 d, 10 exp

- ***Run time in 2006 will allow 6 days shared by RMP and QH-mode studies. Pellet ELM pacing work will be done in piggyback***

Summary - Thrust IT-1 Seeks to Qualify ELM Control Techniques for ITER

- **The near term experimental plan for 2006-7 makes heavy use of new hardware**
  - New counter NBI for beam balance studies
    - RMP ITER rotation performance extension and RMP fields screening physics
    - QH-mode performance extension and EHO physics
  - New high δ lower pumping capability
    - RMP at low collisionality in ITER high d shape
    - QH-mode high d performance extension to high density
  - High frequency pellet dropper
    - ELM pellet pacing - ITPA critical issue for ITER
    - Edge pedestal control in RMP ELM suppression and QH-mode
- **The near term experimental plan for 2006-7 addresses highest priority ITER issues**
  - Does the ITER design need RMP coils for ELM control?
  - Does ITER need a high frequency pellet injector for ELM control?
  - Is QH-mode a viable ELM suppressed regime for ITER?

Work in this Area Over the Longer Term Could Significantly Impact ITER Decisions on ELM Control

- **DIII-D has unique capabilities in ELM control research**
  - Only internal RMP coils in the world for ELM control by n=3 perturbation
  - Very flexible momentum injection capability for RMP ELM Control and QH-mode studies
  - Small, slow, high frequency pellets with LFS injection for ELM pacing
  - Toroidal rotation control for investigating physics of small ELMs regimes

- **On the 5-10 year time scale, strengthening the DIII-D ELM Control research area could certainly have a significant positive impact on ITER and future tokamak reactors**

Backup Slides

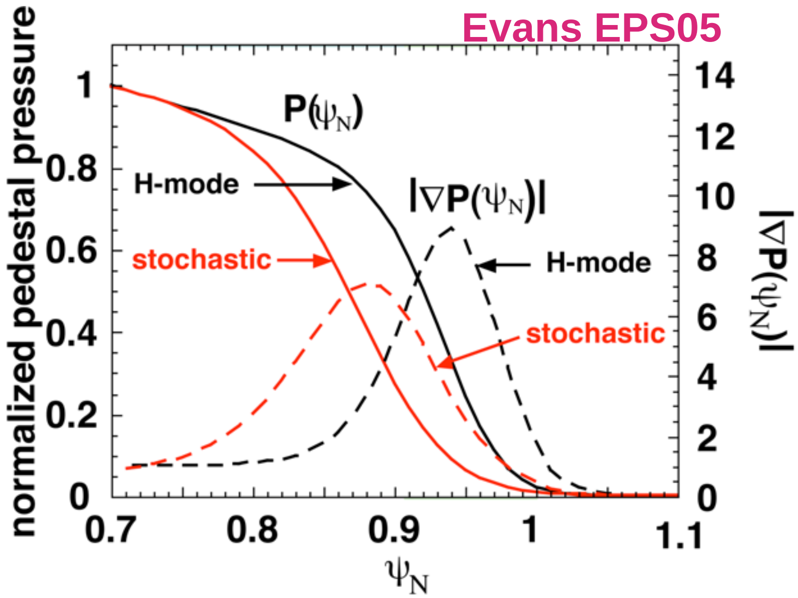
Thrust IT-1 Run Plan Proposal for 8 weeks in 2006

	Priority A	B	C	PB
• Validate ELM Suppression by application of RMP as ELM control technique for ITER	3.0-4.0 d	7.0 d		4 exp
❖ Decision after A1 exp on ELM suppression at high δ_{low}				
• Validate QH-mode as ELM-free regime for ITER	3.0-4.0 d	5.0 d		1 exp
❖ Decision after A1 exp on QH-mode with normal I_p				
• Validate pellet ELM pacing as an ELM control technique for ITER	0.5 d	2.5 d		4 exp
• Explore small ELM regimes applicable to ITER	0.5 d	5.0 d	2.0 d, 1 exp	
• Total Dedicated Run Time	8.0 d	19.5 d	2.0 d, 10 exp	

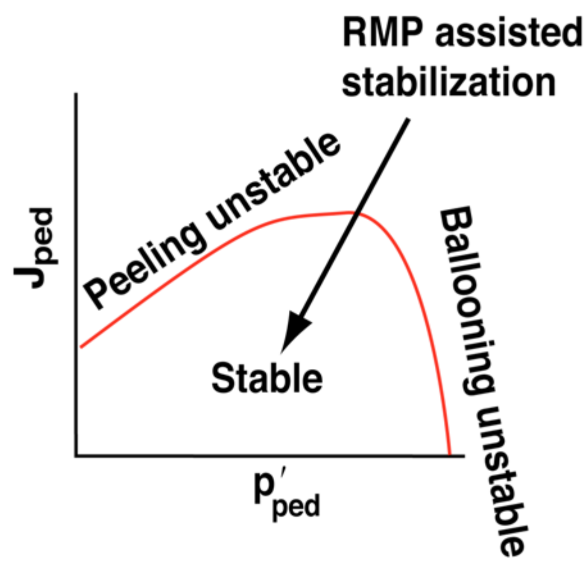
- Commissioning or other special preparation
  - RMP and QH-mode experiments require 210 beams and lower outer pump
  - Pellet dropper tests must be done during startup days
  - Reversed Ip campaign may be required for QH-mode & Small ELM regimes

Original Concept: Edge Resonant Magnetic Perturbation (RMP) → Stochastic ELM Stabilization

- **Edge RMP → stochastic magnetic field in pedestal → increased edge energy transport:**
  - **Increased edge energy transport → reduced pedestal pressure gradient**



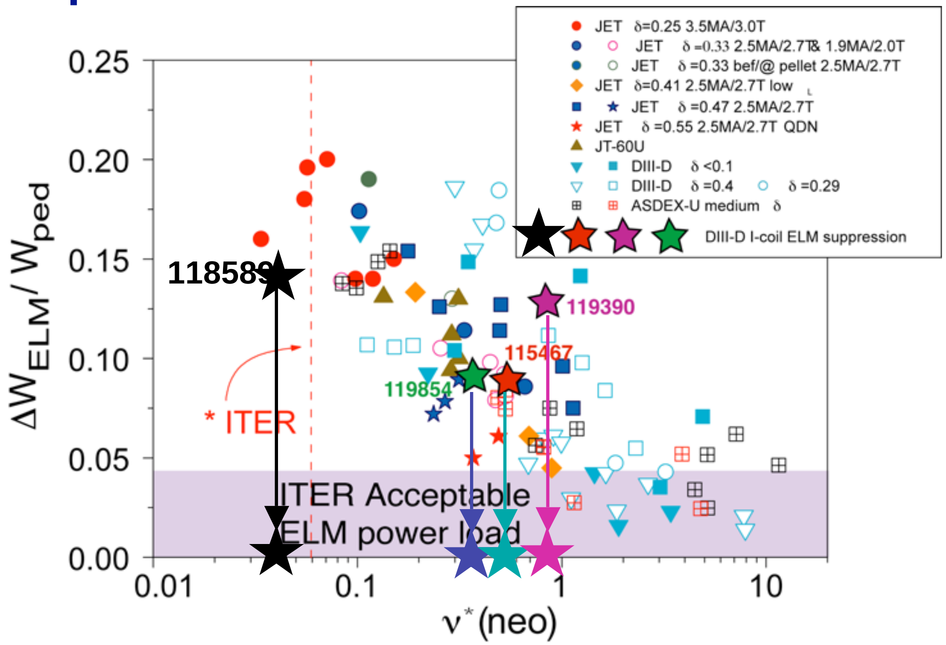
- **Reduced pedestal pressure gradient → stable P-B operating point**
  - **Operating point controlled with RMP amplitude**
  - **Maintain good H-mode confinement (high pedestal T_e)**



- **ELM impulses eliminated**

ELM Suppression at Lower n* (More ITER Relevant) Expected in Planned Experiments with Larger Magnetic Perturbation

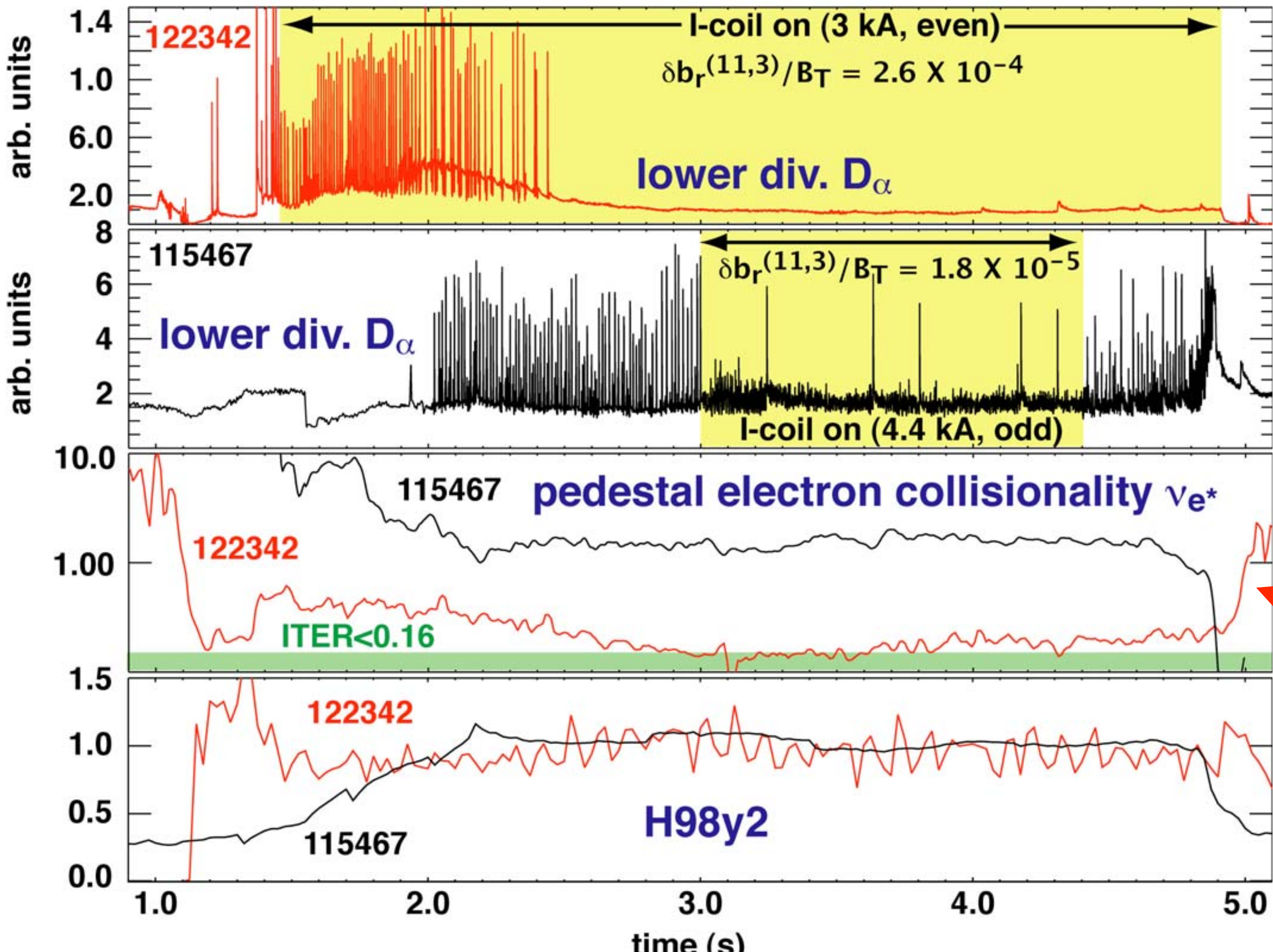
- ν* < 0.1 --> more ITER relevant ELM suppression regime
- To decrease ν*, need to lower n_e^{ped} or increase B_T --> larger $\delta B_r^{n=3}$
- Plan in 2005 is experiments with $\delta B_r^{n=3} = 10^{-3}$ (2003-04 used $\delta B_r^{n=3} = 10^{-4}$)
  - Tested I-coil at 6.3 kA
- Plan in 2006 is high $\delta B_r^{n=3}$ with enhanced pumping of ITER shape using new high δ lower divertor
- Proposal beyond 2006 - coils designed specifically for ELM suppression mode spectrum



$$\nu^* \propto n_e / T_e^2$$

$$\nu^* \propto 1 / \beta_{ped}^2 \left(n_{ped}^3 / B^4 \right)$$

Strong RMP Configuration Results in Long Quiescent ELM-Free H-Modes



Evans EPS05

New: strong edge RMP (even parity) results –
→ ELMs completely eliminated

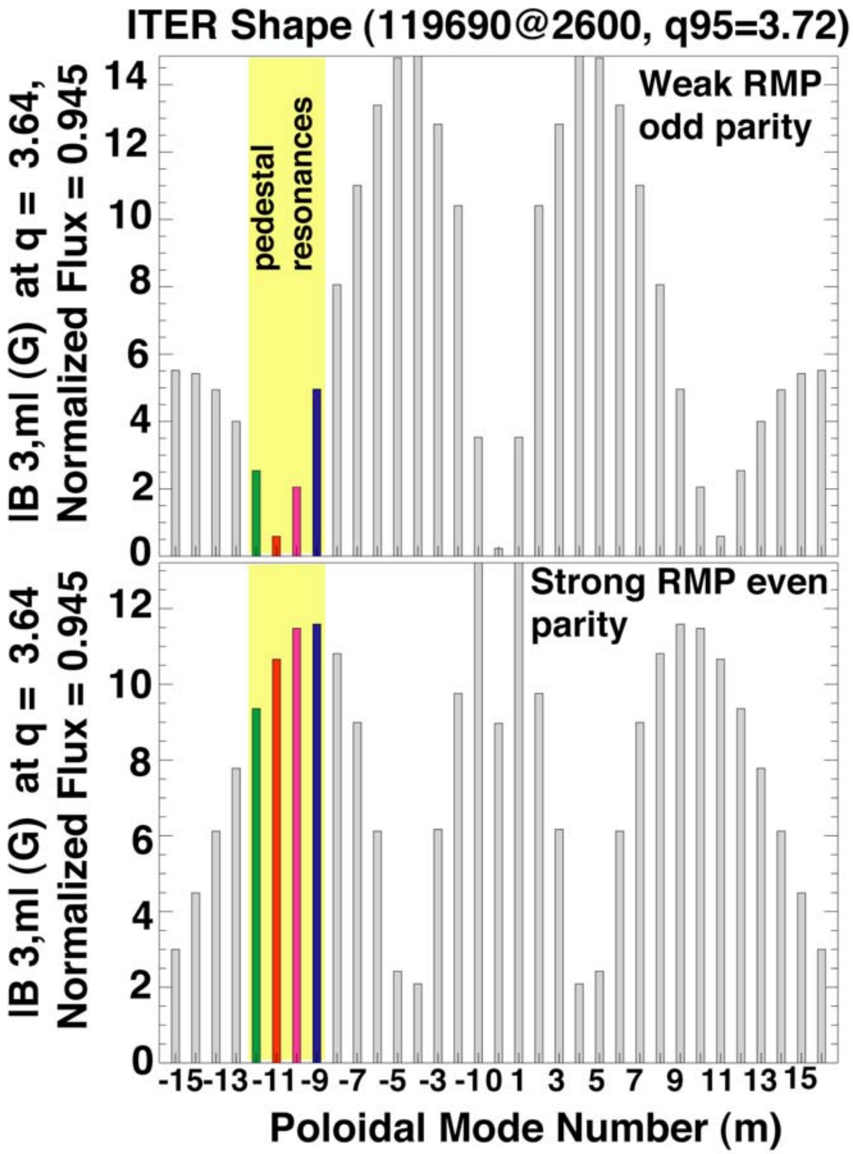
Previous: weak edge RMP (odd parity) results –
→ Some intermittent ELMs remain

ν_{e*} at ITER target in strong edge RMP case

With ν_{e*} < 0.2 ELMs are eliminated for 2.6 s (~17τ_E) - limited only by hardware constraints

P.R. Thomas, et al., EPS04   T.E. Evans, et al., PRL 2004   R. A. Moyer, et al., PoP 2005
K.H. Burrell et al PPCF 2005   T.E. Evans et al. APS06 to be published in PoP

I-Coil Parity Controls Pedestal RMP Amplitude



Evans EPS05

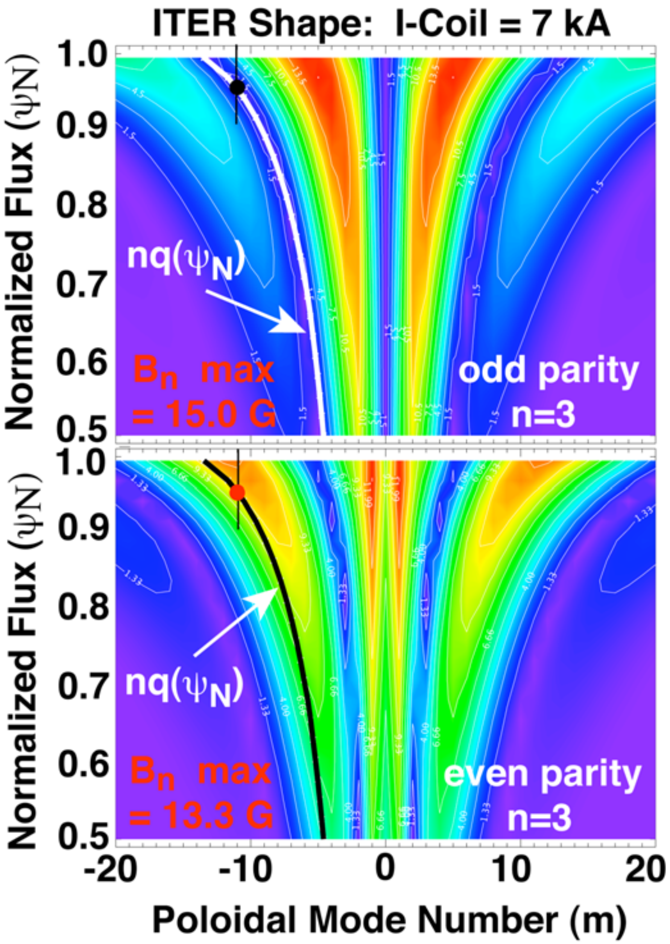
<u>Previous Results: odd parity → weak edge RMP</u>

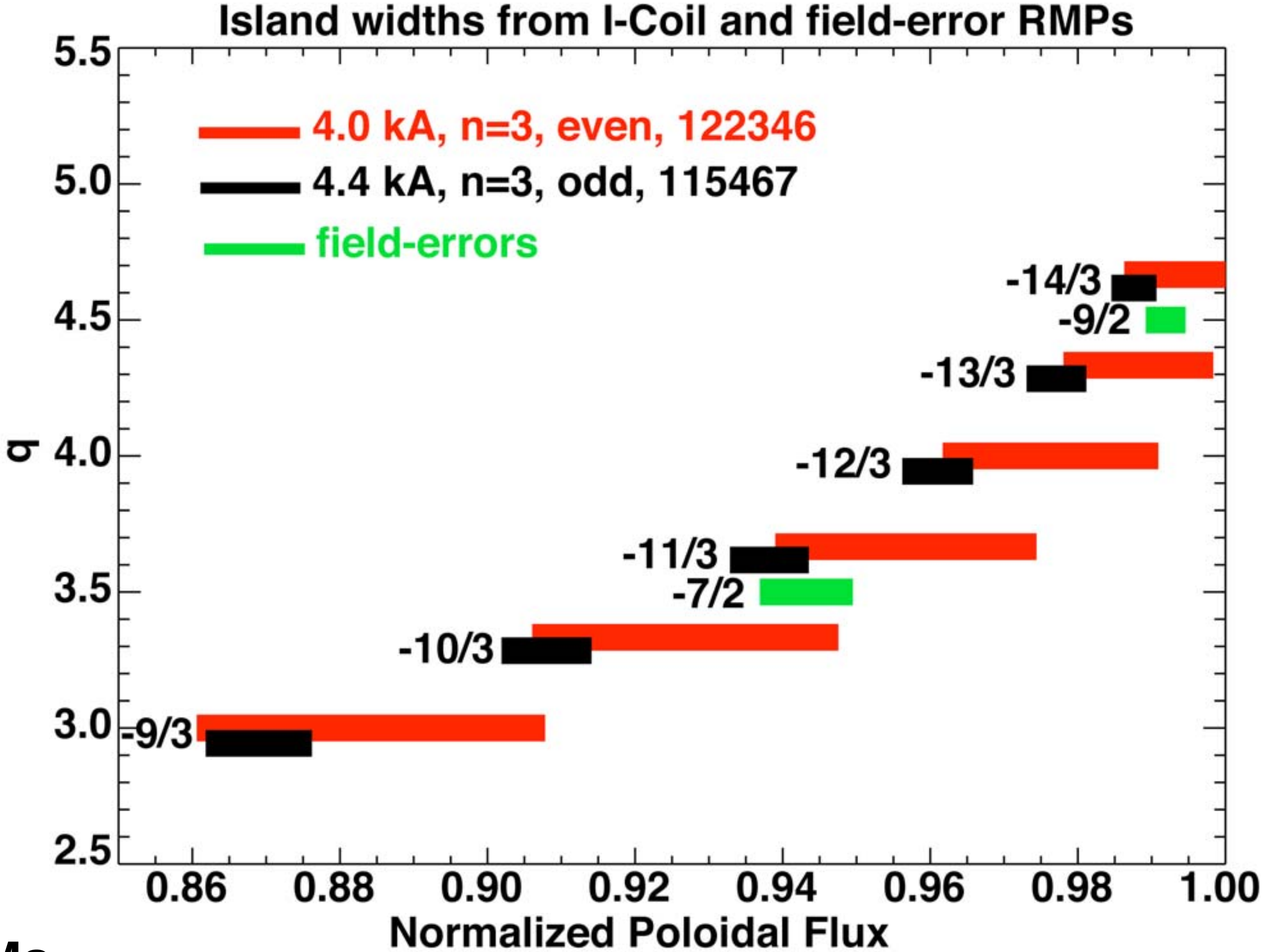
→ ELMs suppressed with little or no profile changes – high collisionality

<u>New Results: even parity → strong edge RMP</u>

→ ELMs suppressed by controlling ∇P – low collisionality

I-Coil Parity Controls Pedestal Island Overlap



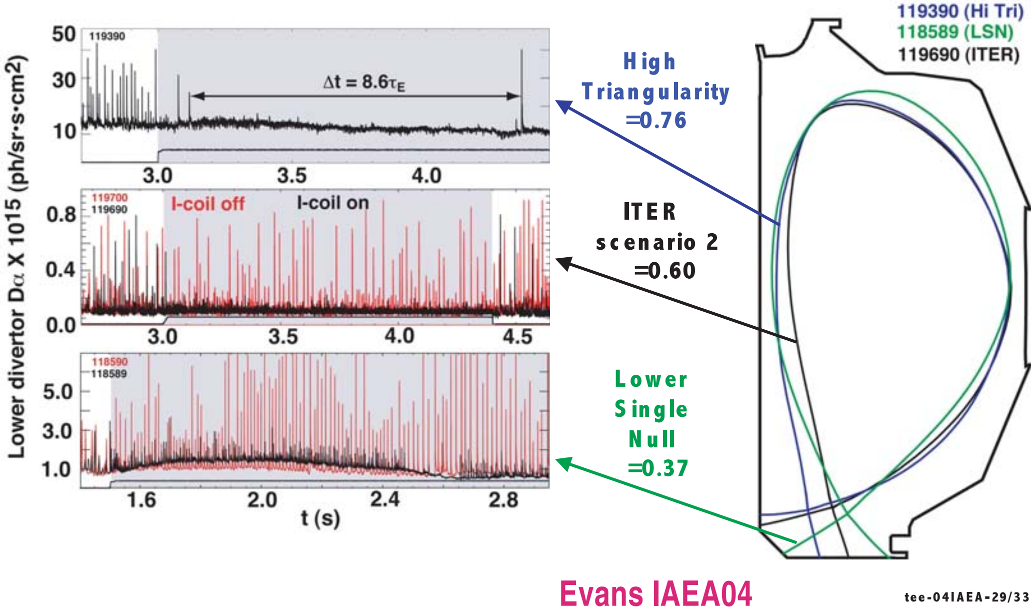


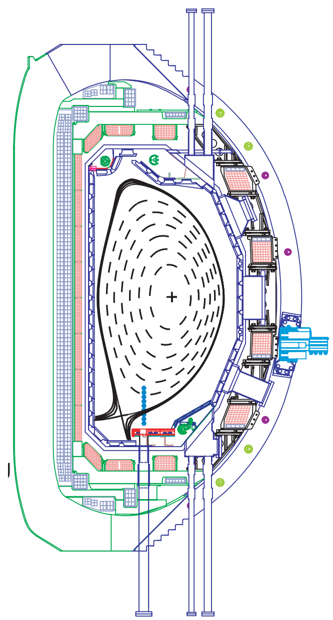
Both parities suppress ELMs

- **Odd (weak RMP) → small islands → little or no change in pedestal**
- **Even (strong RMP) → stochastic → transport / pedestal control**

ELMs Completely Suppressed in ITER Scenario 2 Shape with n=3 I-coil Perturbations – Existence Proof

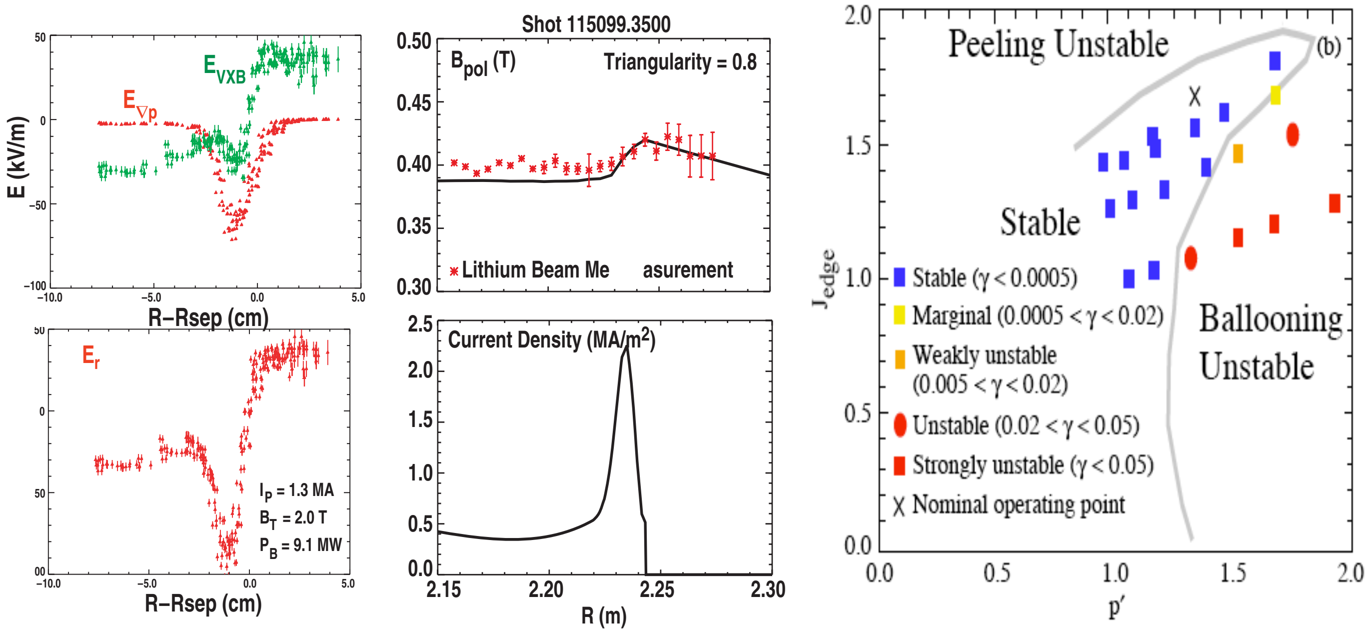
- **ELM suppression in a range of shapes (triangularities) shows applicability of technique to ITER - progress on a long term ELM control goal**
- **Details of plasma response show some dependence on shape and collisionality - may lead to better physics understanding of suppression physics**
- **Increased I-coil current and high δ pumping expected to further expand operating window - eg. ITER-like ν^***





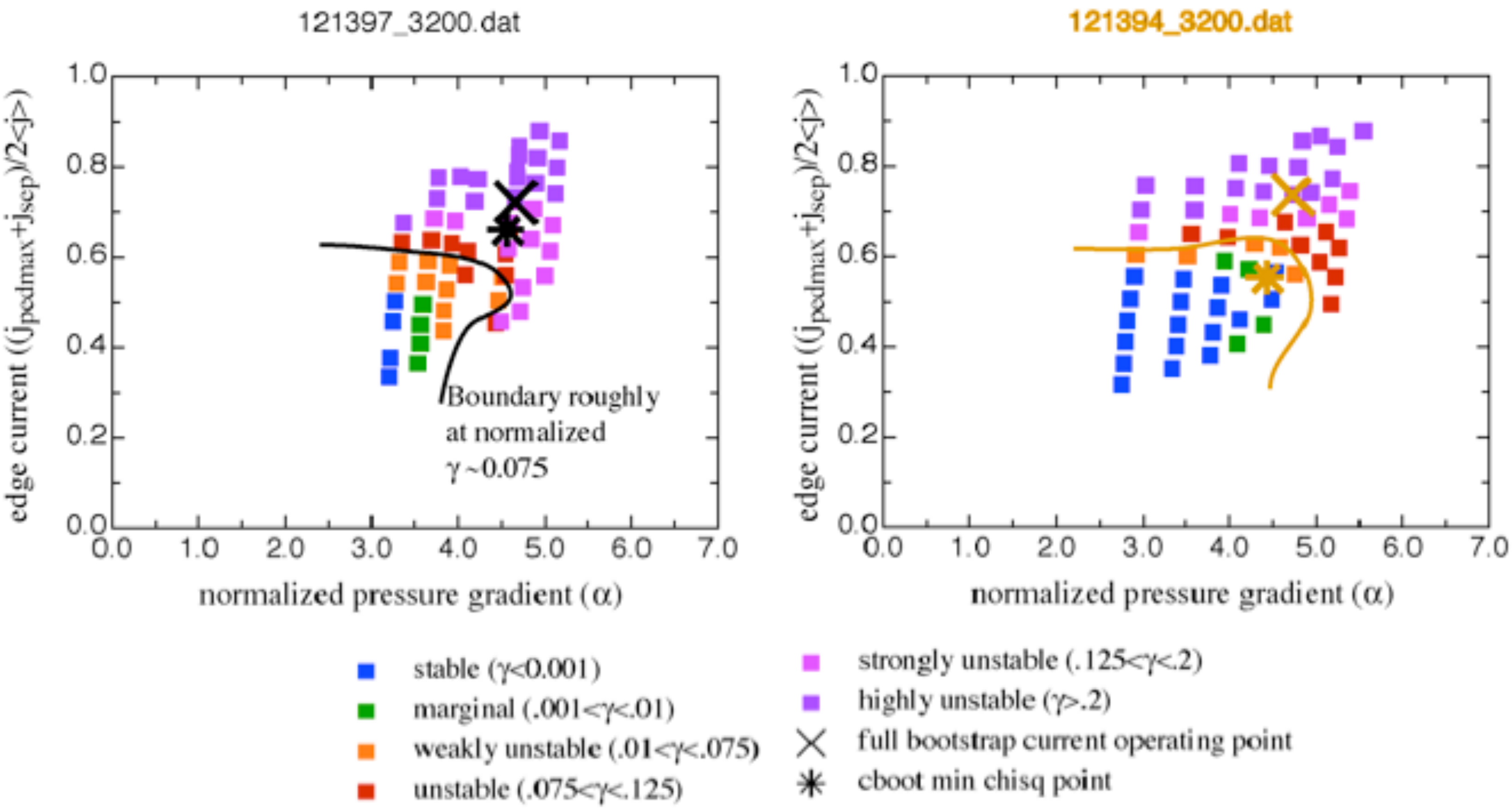
Physics Understanding of QH Edge Stability will Continue to Advance Using Profile Data, Kinetic Equilibrium and ELITE

- **QH stability analysis tools now developed - need to analyze cases over a wide range of conditions**
  - **Current density (NCLASS - validated by j_{edge} measurement) and measured pressure profiles constrain CORSICA equilibrium used by ELITE**
- **QH pedestal transport needs to be analyzed by GYRO, GLF23-U**
- **Example: Stability analysis of the high-δ QH-pedestal**
  - **Marginally stable - Analysis of surrounding perturbed equilibria shows instability boundary**
  - **Consistent with return of ELMs In upward Ip ramp experiments**



West IAEA04, Burrell APS04

Linear Stability Boundaries Determined by Running ELITE with Variations in Edge Current Density and Pressure Gradient



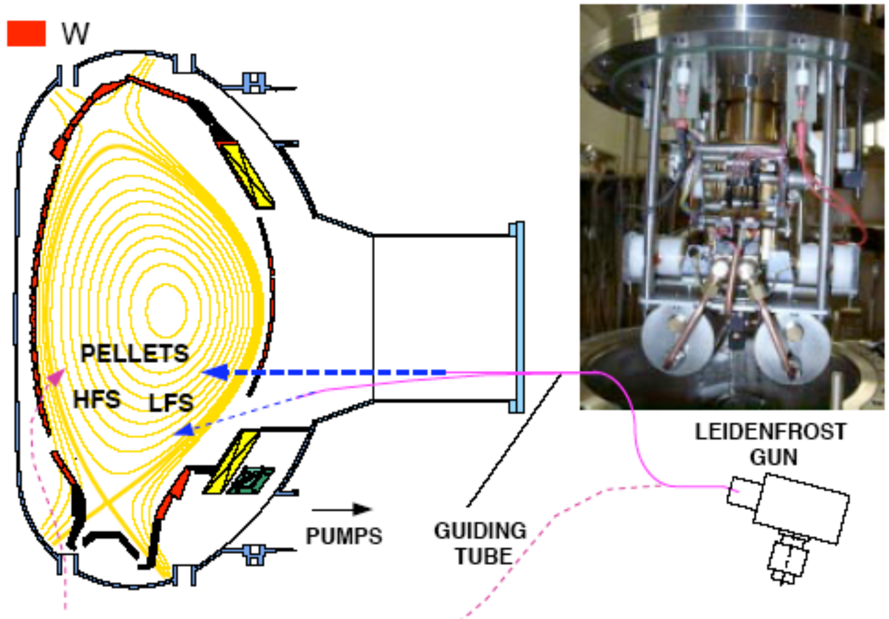
- **For ELM-free QH-mode, operating points with full edge bootstrap current from theory somewhat further into unstable regime than bootstrap model with coefficient chose to minimize χ^2 with magnetics.**

AUG Plans to Use Smaller, Slower Pellets Including from LFS in Future Experiments, Similar to DIII-D

ASDEX Upgrade

Outlook: tool optimisation at ASDEX Upgrade

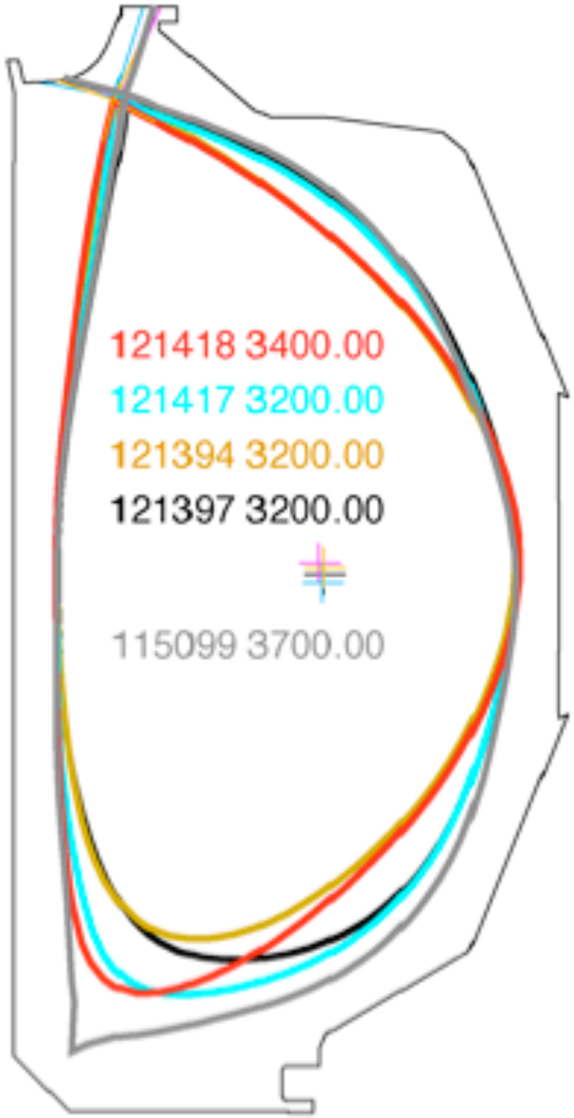
We are still (until July 2005) using our refuelling system for ELM control investigations, but soon (C2005/06) we will...



- inject slower pellets
- inject smaller pellets
- inject at higher rate (143 Hz in testbed)
- inject from different locations

This should allow for advanced operational features and improved physics related investigations

Theory of QH-mode pedestal stability studied by varying plasma squareness and triangularity



Lower δ Higher Squareness 121397 3200.00

$\delta = 0.47$ $\kappa = 1.87$ $Sq_{up}=0.45$ $q_{95} = 4.30$

Lower δ Lower Squareness 121394 3200.00

$\delta = 0.54$ $\kappa = 1.83$ $Sq_{up}=0.35$ $q_{95} = 4.24$

Higher δ Higher Squareness 121417 3200.00

$\delta = 0.61$ $\kappa = 1.95$ $Sq_{up}=0.45$ $q_{95} = 4.88$

Higher δ Lower Squareness 121418 3400.00

$\delta = 0.67$ $\kappa = 1.92$ $Sq_{up}=0.35$ $q_{95} = 4.95$

Highest δ Higher Squareness

$\delta = 0.81$ $\kappa = 2.1$ $Sq_{up}=0.45$ $q_{95} = 5.4$

Very Preliminary ITER Coil Designs Considering Several Options - US Leadership Needed to Guide This Design Process

- **Two options being evaluated:**
  - **Option-1 -> 18 coils x 2 sets (upper and lower)**
  - **Option-2 -> 6 coils x 2 sets (upper and lower)**
- **Coil current: 480 kA-turns (48 turns)**
- **Coil cross section:**
  - **284.3 mm x 230.6 mm (normal area)**
  - **420.3 mm x 366.6 mm (insulation flange)**
- **Poloidal locations: upper and lower VV ports near TF case**
- **Possible modifications needed:**
  - **Option-1, thermal shield (upper coils), TF gravity support (300 mm x 200 mm - lower coils)**
  - **Option-2, thermal shield (upper coils), flange and support plate at TF gravity support (lower coils)**

Goal I - Validate ELM Suppression by RMP as a viable technique for ITER - Performance Extension - 20 Proposals

- **ROF Performance Extension proposals toward this goal (submission order):**
  - 543 Fenstermacher ITER PoP ELM Suppression by RMP
  - 544 Fenstermacher Re-establish Low nu* ELM Suppression in High Triangularity LSN
  - 545 Fenstermacher ITER Shape Low nu* ELM Suppression in High Triangularity Near DN
  - 548 Fenstermacher Higher Density Low nu* ELM Suppression in High Triangularity LSN
  - 549 Fenstermacher Low Rotation Low nu* ELM Suppression in LSN Shape
  - 589 Petrie Can Injected Impurities Be Screened Effectively During ELM Suppression?
  - 590 Petrie Is the Radiating Divertor Scenario Compatible With ELM Suppression?
  - 634 JayakumarELM modification in Hybrid Discharges
  - 666 Perkins Operation of Fast Wave antennas with stochastic edge supression of ELMs.
  - 669 *M. Becoulet* Double Barrier plasmas with edge controlled by I-coils
  - 670 *M. Becoulet* Double Barrier plasmas with edge controlled by I-coils (duplicate of 669)
  - 672 Kaye DIII-D/NSTX ELM Mitigation Similarity Experiment
  - 679 *Parail* Power dependence of ELM frequency in RMP experiment
  - 685 Gohil Real time control of q in RMP experiments
  - 690 *Parail* Dependence on the level of gas puffing of the ELM frequency in RMP experiment
  - 708 *Parail* Detailed study of ELM suppression efficiency vs Icoil current amplitude
  - 755 Wade ELM Suppression at q95 ~ 3
  - 969 Evans Low triangularity, low nu*, RMP ELM control shape development
  - 978 Evans High triangularity, low nu*, RMP ELM control shape development
  - 1013 Evans q95=3 low nu* RMP ELM control

Goal I - Validate ELM Suppression by RMP as a viable technique for ITER - Physics Understanding - 37 Proposals

- **ROF Physics Understanding proposals toward this goal (submission order):**
  - 725 Wade Fast CER data during EQ Transition in Low Collisionality RMP Discharges
  - 738 Unterberg Influence of mag topology on stochastic loss layer transport during ELM suppression
  - 799 Evans High resolution pedestal profiles during RMP ELM control
  - 818 Makowski Observation of stochastic edge with fast MSE diagnostic
  - 838 Evans Is RMP screening a significant factor in RMP ELM control discharges?
  - 942 Evans Are small bursts in high ν^* RMP ELM suppressed state related to stellarator ELMs?
  - 979 Evans Ultra low BT RMP ELM control
  - 991 Moyer Dependence of “small events” on mode spectrum, density, shape, and collisionality
  - 993 Moyer Investigation of Plasma Shielding of RMP with internal magnetic measurements
  - 997 Moyer Role of inward particle pinches in the H-mode and ELM suppressed Discharges
  - 1002 Osborne Physics of Type I ELM Suppression with Odd I-Coil Parity at Medium Collisionality
  - 1004 Osborne NTM Stability in Even Parity, Low Collisionality I-Coil ELM Suppressed Discharges
  - 1010 Evans Exploration of mode spectrum effects in low nu* RMP ELM control discharges
  - 1019 Evans Can the low nu* RMP ELM control power limit be exceeded in DIII-D?
  - 1024 Evans Can low nu* RMP ELM control be obtained in reverse BT?
  - 1031 Lao Rotational Plasma Response to Resonant Magnetic Perturbations
  - 1041 Rhodes Slow modulation of I-coil for perturbation studies
  - 1047 Watkins Determine RMP character through target plate profiles
  - 1050 Zeng Investigation of density and magnetic fluctuations during ELM suppression phase
  - 1051 Watkins Observe magnetic perturbations through edge and x-point gas puffing
  - 1056 Watkins How does the SOL vary with magnetic balance and magnetic perturbations?

Goal I - Validate ELM Suppression by RMP as a viable technique for ITER - Physics Understanding - 37 Proposals

- **ROF Physics Understanding proposals toward this goal (submission order):**
  - 1058 Saibene ELM suppression (even vs odd parity) at low nu* in standard ELMy H-modes
  - 1059 Sartori Dependence of max ne for ELM suppression on I-coils current (perturbation intensity)
  - 1060 Saibene Effect of nu* on I-coil ELM suppression in ELMy H-modes
  - 1061 Sartori Effect of plasma shape (triangularity) on ELM suppression at low nu*
  - 1062 Loarte Effect of I-coil polarity on ELMs at high n/nu*
  - 1063 Loarte Effect of input power on ELM suppression/reduction at high n/nu*
  - 1064 Buttery ELM control with n=1 fields
  - 1067 P. Thomas Density and collisionality effects in plasmas with the edge controlled by the I-coils
  - 1076 Joseph RMP effects in DN plasmas
  - 1077 Joseph Rotating RMP physics
  - 1088 Zeng Characteristics of the small ELM during non-RMP in low collisionality plasma
  - 1094 Snyder Importance of Pumping Efficiency in RMP Low Density Discharges
  - 1095 Zeng Effect of RMP location on ne and Te profiles in low collisionality plasma
  - 1131 Schaffer ELM Control by Flexible-Spectrum I-Coil Fields
  - 1134 Solomon Hysteresis of I-coil current requirement for ELM suppression
  - 1135 West Enhance the negative electric field well in RMP ELM suppressed and VH modes

Goal II - Validate QH-mode as a viable ELM-free regime for ITER - Performance Extension - 14 Proposals

- **ROF Performance Extension proposals toward this goal (submission order):**

Normal IP		
560	Fenstermacher	QH-mode with co- core rotation
562	Fenstermacher	Pellet Pacing of ELMs in QH-mode Discharges
563	DeGrassie	What Fraction of NBI Must be Counter to Obtain QH-mode?
721	West	Inducement of EHO using high frequency I-coil
830	Solomon	Rotation requirements for QH-mode
877	Burrell	QH-mode with balanced beams
Reversed IP		
564	Fenstermacher	High Performance QH-mode with Counter Ip
613	DeGrassie	Are Standard QH-mode and RMP ELM-suppression Symbiotic or Incompatible?
703	Lasnier	The role of stochasticity and fast ion orbit loss in QH mode boundaries
720	West	QH mode stability and Er studies in balanced double null discharges
756	Gohil	Maximize ne in QH-mode plasmas with different plasma rotation and strong shaping
881	<u>*Nave*</u> (Jackson)	Extending the ELM-free Period in co-injection plasmas
882	Burrell, Stambaugh	RF sustained QH-mode
1008	Jayakumar	Achieving betan>3 in QH mode with RWM control

Goal II - Validate QH-mode as a viable ELM-free regime for ITER - Physics Understanding - 11 Proposals

- **ROF Physics Understanding proposals toward this goal (submission order):**
  - Normal IP
  - 1092 Doyle Low density co-/balanced-NBI QH-mode
  - Reversed IP
  - 620 Jayakumar Hybrid scenario in QH mode
  - 652 Gohil (JT60-U co-authors) Effect of plasma rotation on QH-mode plasmas
  - 775 Leonard ECH Modification of the Edge Bootstrap Current in QH-mode
  - 878 Burrell Investigate high triangularity QH-mode
  - 880 Burrell Effect of error field minimization on QH-mode plasmas
  - 898 Burrell RMP effects on QH-mode and EHO
  - 934 Casper Co- vs counter-NBI QH/QDB
  - 938 Casper ECH/ECCD in pedestal region to explore peeling-ballooning mode stability
  - 1089 Snyder QH Shape and Density Access Comparisons to Theory
  - 1090 Snyder Detailed study of the EHO and comparisons to theory

Goal III- Validate Pellet Pacing/combinations with other methods as viable ELM Control techniques for ITER - 11 Proposals

- **ROF Performance Extension proposals toward this goal (submission order):**
  - 558 Fenstermacher ELM Modification by Pellet Pacing
  - 658 Gohil Double Barrier plasmas using ELM pacing pellets
- **ROF Physics Understanding proposals toward this goal (submission order):**
  - 698 Baylor Test of Pellet dropper for ELM triggering
  - 762 Leonard Pellet triggered ELM Energy loss
  - 865 Takahashi Measurement of Sheath Conditions at Divertor Plates during ELM Pacing by Pellet Injection Experiment
- **ROF Combination proposals toward this goal (submission order):**
  - 559 Fenstermacher Pellet Pacing of ELMs in RMP ELM suppression Discharges Combo: performance Pellet ELM Pacing and RMP ELM Suppression
  - 671 *M. Becoulet* Compatibility of ELM control by I-coils with fuelling by pellets Combo: performance Pellet ELM Pacing and RMP ELM Suppression and QH-mode
  - 676 *Lang* ELM triggering by pellets for intensity control and physics investigation Combo: physics Pellet ELM Pacing and RMP ELM Suppression and QH-mode
  - 699 Baylor Test of ELM suppression with a stochastic boundary and pellet injection Combo: performance Pellet Fuelling and RMP ELM Suppression
  - 941 Evans Is particle pump out in low nu* RMP ELM control shots due to enhanced transport or reduced sources? Combo: physics RMP ELM Suppression, Pellet ELM Pacing
  - 1018 Casper High collisionality operation for BOUT modeling studies Combo: performance RMP ELM Suppression, QH-mode

Goal IV - Explore small ELM regimes (7 Proposals) and other ELM control techniques for ITER (9 Proposals)

- **ROF Performance Extension proposals - Small ELMs (submission order):**
  - 706 Leonard Grassy ELM comparison with JT-60U
  - 976 Osborne Grassy ELMs in DIII-D
  - 1052 Watkins ELM control through x-point gas puffing
- **ROF Physics Understanding proposals - Small ELMs (submission order):**
  - 659 Maingi Dependence of ELM size and structure on toroidal rotation
  - 667 Gohil Affecting changes in ELM characteristics through plasma rotation
  - 1053 Zeng Dynamics of pedestal perturbations of ELMs of type II, II and I
  - 1054 Zeng Dynamics of pedestal perturbations of ELMs of type II, II and I
- **ROF Performance Extension proposals-Other ELM Control (submission order):**
  - 700 Terry C-Mod/DIII-D ELM Comparison
  - 863 Takahashi Controlling ELMs and SOLC in High betaN Shots Using Externally Applied n=1 Field
  - 871 Jackson Induced Rotation using n=1 Rotating Fields
  - 879 Jackson VH-mode with double OSP pumping
- **ROF Physics Understanding proposals-Other ELM Control (submission order):**
  - 717 Zeng Formation and radial propagation of ELM filament structure in DIII-D
  - 858 Takahashi Role of SOL Current (SOLC) in ELM Dynamics
  - 970 Rudakov Role of coherent modes on edge pedestal and ELM behavior
  - 977 Osborne Small ELMs with Large Peped by Controlling the Relationship of Te and ne Profiles
  - 1071 *Liang* Influence of the plasma rotation on the Type-I ELMy H-mode