ELM Control by Resonant Magnetic Perturbations: Overview of Research by the PEP ITPA Group*

M.E. Fenstermacher (LLNL at DIII-D)

Presented at the Theory Coordinating Committee Tele-Conference
December 17, 2010

* The RMP ELM Control Working Group within the Pedestal and Edge Physics ITPA Topical Group:

- Members: one representative from each program exploring RMP physics worldwide.
- Goal: to coordinate both experimental and theory/modeling work toward elements of the RMP ELM Control Work Plan using joint interactions through the ITPA
- Process: Semi-annual conference calls and semi-annual ITPA meetings

ELM Control by Resonant Magnetic Perturbations: Overview of Research by the PEP ITPA Group

M.E. Fenstermacher[1)]

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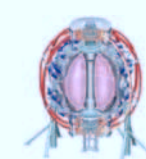
Presented at the 23rd IAEA Fusion Energy Conference
Daejeon, South Korea, October 11-16, 2010



Summary/Outline: Progress in RMP ELM Control Understanding From Multi-Machine Comparisons

- **Static RMP Fields Affect ELM Behavior in Several Tokamaks**
  - ELM mitigation in many devices
  - ELM suppression robust but unique to DIII-D

- **Island Overlap Region Width (Vacuum Fields), $\Delta_{Chir>1}$ Greater Than ITER Guidance Value (0.165 in Ψ_N) Not Sufficient to Assure ELM Suppression**
  - DIII-D databases at fixed q_{95} indicate condition may be necessary for suppression
  - Other conditions (perturbation pitch alignment, plasma beta and collisionality, etc.) may be important
  - Physics understanding must include plasma response

- **RMP Fields Above Threshold Strength Can Increase L-H Threshold Power**
  - Required RMP strength to increase P_{L-H} may be higher for predominantly non-resonant fields

- **Many Experimental Programs Installing or Considering Internal RMP Coils**

ITPA: Workplan Elements Support Execution of PEP ITPA Joint Experiments PEP – 19, 23, 25 for RMP Physics Understanding

	Goal	Task	Q1-09	Q2-09	Q3-09	Q4-09	Q1-10	Q2-10	Q3-10	Q4-10	Q1-11	Q2-11	Q3-11
Suppression Outside DIII-D	1.1	(a) Suppress ELMs using RMPs on MAST											
	1.1	(b) Suppress ELMs using RMPs on AUG											
	1.1	(c) Explore potential to mitigate/suppress ELMs with mid-plane coils (NSTX, JET)											
Model Development and Validation	1.2	(a) Model and compare vacuum RMP field for MAST and DIII-D with suppressed ELMs											
	1.2	(b) Test model based on min stochastic width and alignment of perturbation with q against MAST and DIII-D data											
	1.2	(c) If 1.2(b) is successful, predict scenarios for ELM suppression in advance of AUG expts 1.1(b)											
	1.2	(d) Compare RMP data for on and off-mid-plane coils (JET, MAST, DIII-D, NSTX)											
	1.2	(e) Interpret data from 1.2(d) using model developed in 1.2(b)											
	1.2	(f) Predict ELM suppression criteria/regimes for ITER; optimise ITER coil design											
	1.2	(g) Quantify the impact of torque and plasma rotation on ELM mitigation and suppression (DIII-D, JET, MAST, NSTX)											
Pedestal Height and Width	1.3	(a) Compare pedestal height with and without RMP ELM suppression on DIII-D and MAST											
	1.3	(b) Compare measured pedestal height with RMP with EPED1 model predictions (JET,MAST,NSTX,AUG,DIII-D)											
	1.3	(c) Demonstrate the ability to maintain the required edge density during ELM suppression (DIII-D, MAST)											
	1.3	(d) Quantify impact of RMP on core transport and H-factor (JET,MAST,NSTX,DIII-D)											
Divertor Power Loading	1.4	(a) Quantify impact of RMP-suppressed ELM regimes on divertor power loading (DIII-D, MAST)											
	1.4	(b) Make recommendations on need to rotate RMPs: input to AUG design (DIII-D, MAST)											
	1.4	(c) If necessary, explore impact of rotating RMPs on ELM suppression (JET, NSTX, AUG, MAST,DIII-D)											
Close to L-H Transition	1.5	(a) Quantify ability to suppress or mitigate ELMs with RMP in current ramp (NSTX,JET.AUG, MAST, DIII-D)											
	1.5	(b) Quantify ability to suppress or mitigate ELMs close to LH transition threshold (NSTX, JET,AUG, MAST, DIII-D)											
With Pellets	1.6	(a) Demonstrate RMP ELM suppression with ITER-like pellet fuelling (DIII-D, AUG, MAST)											
	1.7	Demonstrate ability of modulated RMP fields to mitigate ELM size by at least a factor of 20											
ITER Predictions	1.8	(a) Model the performance of the ITER RMP coil set, calculate divertor/wall power loads and optimise design											

- Work plan has been extended (hatched areas) from optimistic original proposed in 2008

ITPA: Workplan Elements Support Execution of PEP ITPA Joint Experiments PEP – 19, 23, 25 for RMP Physics Understanding

PEP-19 (O. Schmitz - TEXTOR) Basic Mechanisms of Edge Transport With Resonant Magnetic Perturbations in Toroidal Plasma Confinement Devices

- Devices: DIII-D, TEXTOR and substantial theory development

PEP-23 (T. Evans – DIII-D) Quantification of the Requirements for ELMs Suppression by Magnetic Perturbations from Internal Off Midplane Coils

- Devices: DIII-D, MAST
- Future Additions - ASDEX Upgrade, JET, NSTX

PEP-25 (Y. Liang – JET/TEXTOR) Inter-machine Comparison of ELM Control by Magnetic Field Perturbations from Midplane RMP Coils

- Devices: JET, DIII-D, MAST
- Future Additions - ASDEX Upgrade, NSTX

Any ELM Control Technique in ITER Must Satisfy General and Specific Requirements (Details in Loarte ITR/1-4)

GENERAL ELM CONTROL TOPICS

- Control of 1st ELM and during I_p ramps - Liang
- Compatibility with high core and separatrix densities – Petrie
- Low heat flux to FW – De la Luna, Schmitz
- Compatibility with high p^{ped} and low collisionaity
- Effect on $P_{L\text{-}H}$, toroidal rotation, core MHD and locked mode thresholds
- ELM character changes (P_{conv} vs. P_{cond}), changes to P_{avg} - Kirk
- ELM heat flux spatial distribution and time scale - De la Luna, Schmitz

RMP SPECIFIC TOPICS

- Is $\Delta_{chir>1} = 0.165$ sufficient?
- Has $\Delta f_{ELM} > 25x$ been achieved? Does ELM energy loss scale inversely with f_{ELM}
- Effect of toroidal rotation on RMP field shielding – Kirk, Sun, Chang, Liu, Rozhanshy
- Are heat flux asymmetries introduced, Does pattern need to be rotated? – De la Luna, Schmitz
- Does RMP ELM control change between ELM heat flux level /structure? - Petrie

RMP ELM Control Papers at 2010 IAEA Conference From ITER IO, Experiment, Theory/Modeling and Coil Design

ITER

- Loarte ITR/1-4 Mon pm

Experiment

- Canik EXC/8-1 Fri am
- Gohil EXC/2-4Ra Tues pm
- Kirk EXD/8-2 Fri am
- Liang EXS/P3-04 Weds am
- Maingi EXD/2-2 Tues pm
- Petrie EXC/P3-27 Weds am
- De la Luna EXC/8-4 Fri am
- Schmitz EXP/P3-30 Weds am
- Solana EXS/P3-05 Weds am
- Sun EXS/P3-06 Weds am

Coil Design

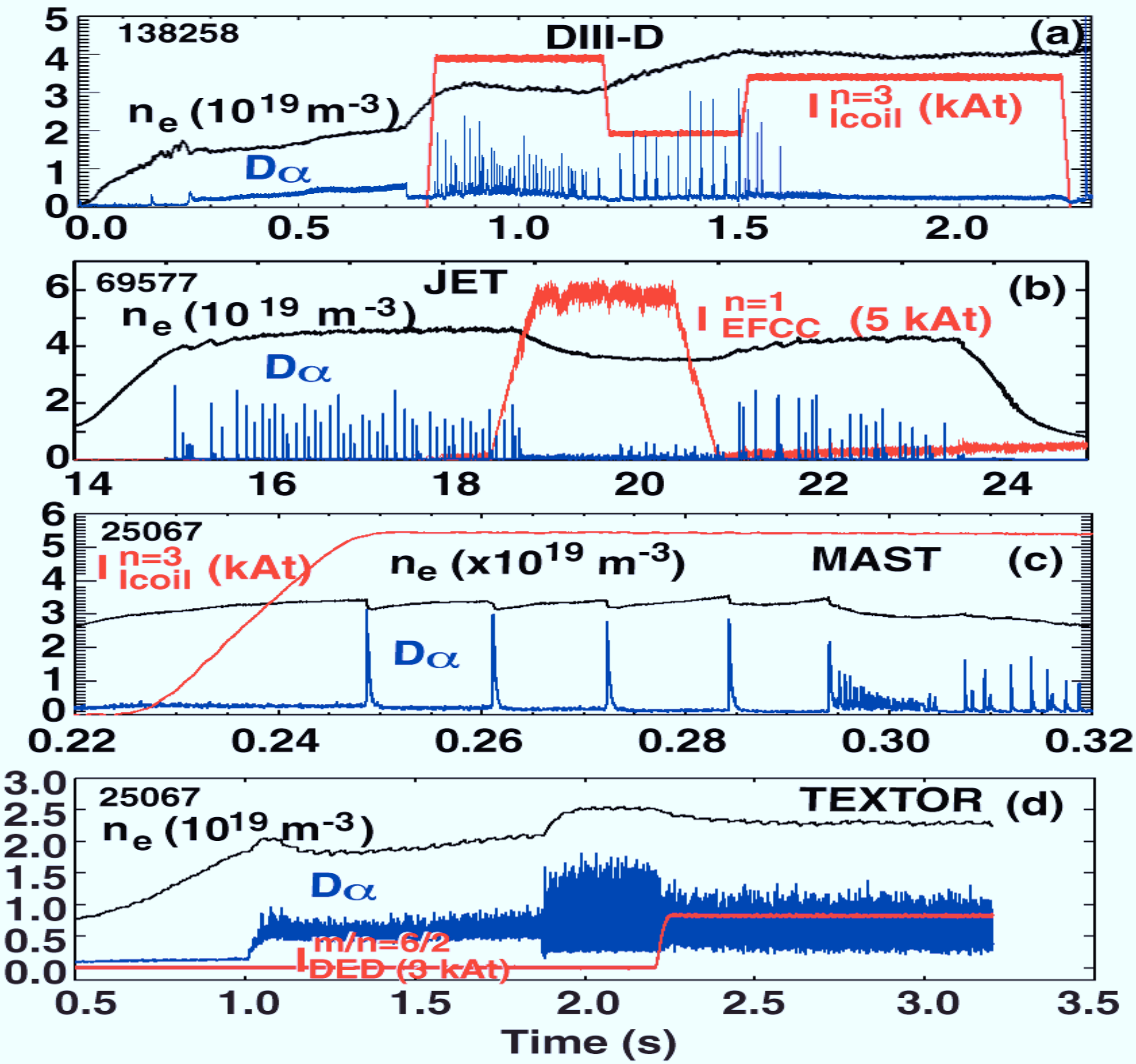
- Titus FTP/P6-32 Thurs pm

Theory / Modeling

Chang	THC/P4-04	Weds	pm
Liu	THS/P5-10	Thurs	am
Rozhansky	THC/P3-06	Weds	am

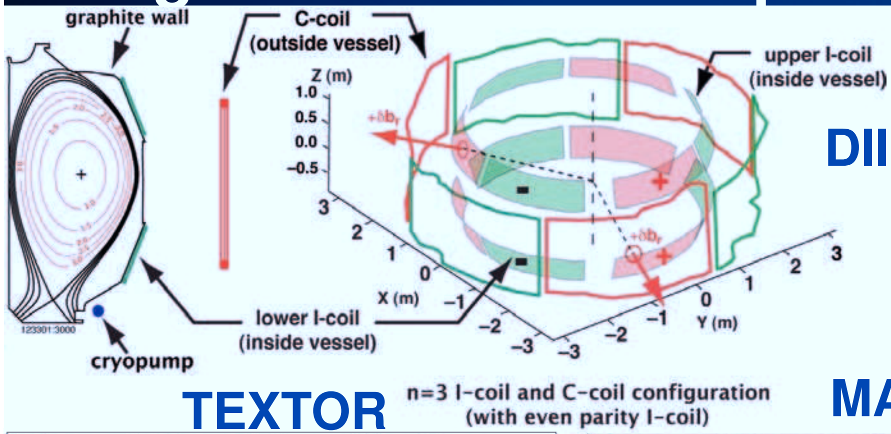
Selected International Results

ELMs Affected by Static RMP Fields in Multiple Devices



- ELM suppression obtained only in DIII-D so far
- ELM size mitigation in JET, MAST, TEXTOR (and DIII-D)
- Density reduction frequently seen when ELMs are mitigated
  - No additional density reduction at ELM suppression

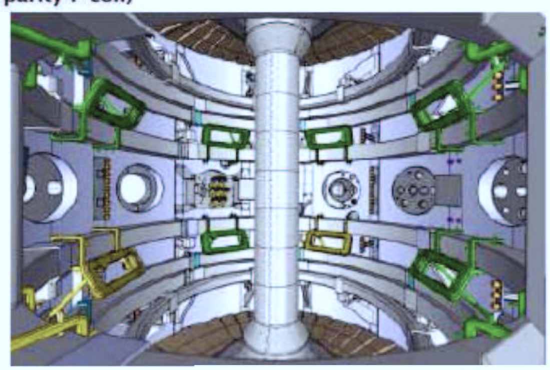
Coil Sets in DIII-D, JET, MAST, NSTX and TEXTOR Give Range of Static RMP Spectra



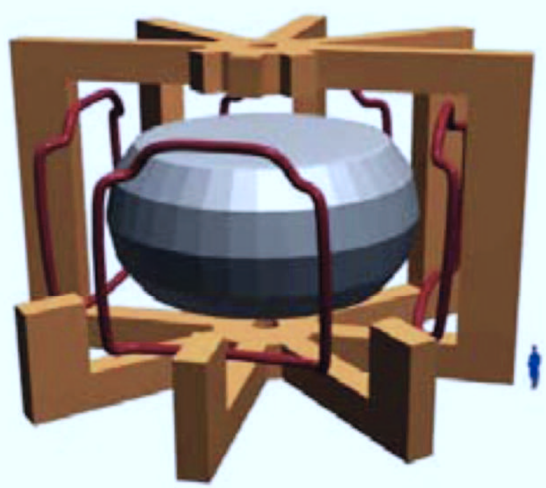
DIII-D

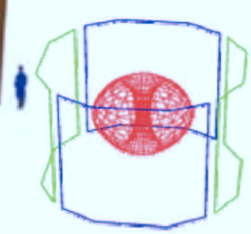
TEXTOR

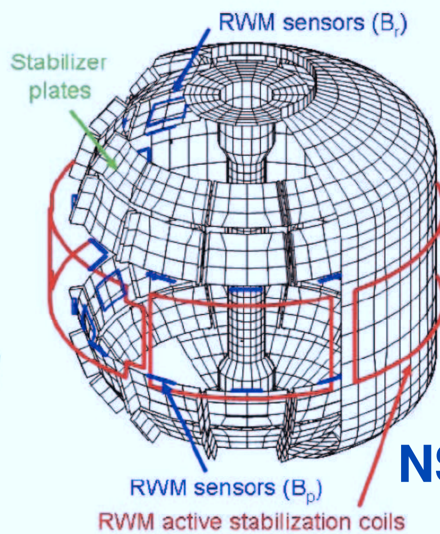
MAST



JET



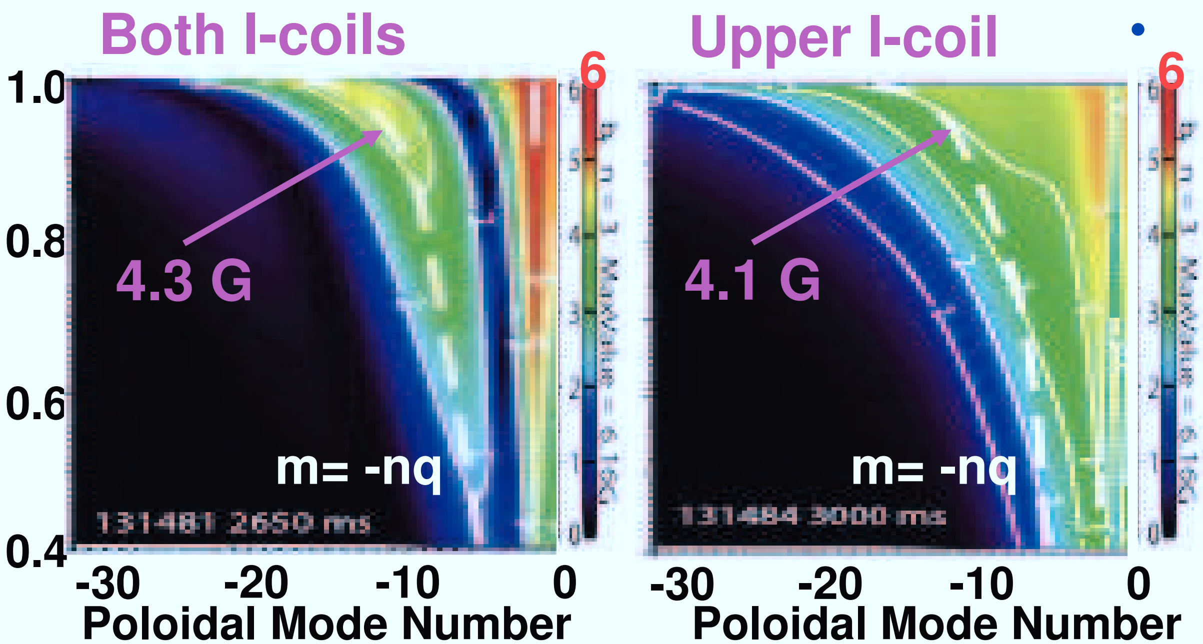


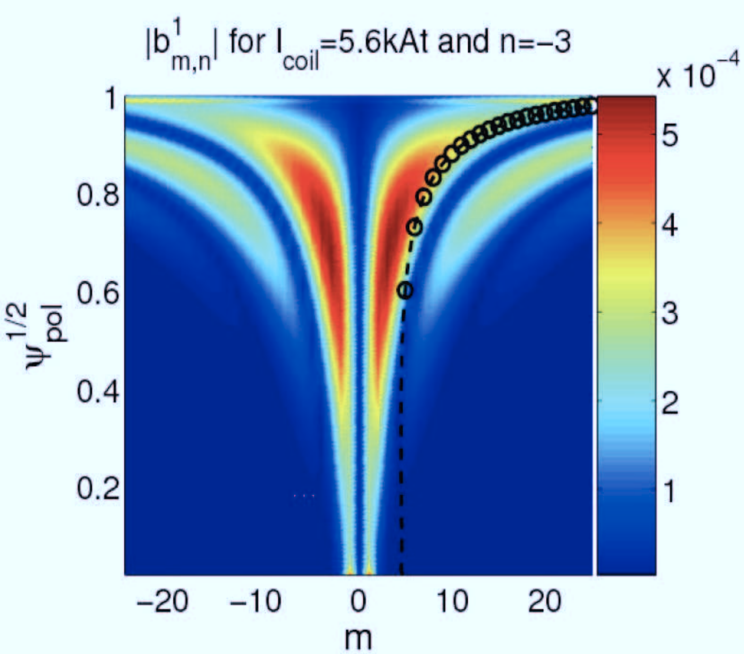


NSTX

- Experiments focus on different RMP perturbations (PEP-19):
  - Internal Coils – PEP-23
    - DIII-D: n=3 resonant, some non-resonant, also n=2
    - MAST: n=3 resonant and non-resonant
    - TEXTOR: m/n=6/2 helical, many other helical modes
  - External Coils – PEP-25
    - JET: n=1 and n=2 resonant and non-resonant
    - NSTX: n=3 resonant, some non-resonant

Coil Sets in DIII-D, JET, MAST, NSTX and TEXTOR Give Range of Static RMP Spectra





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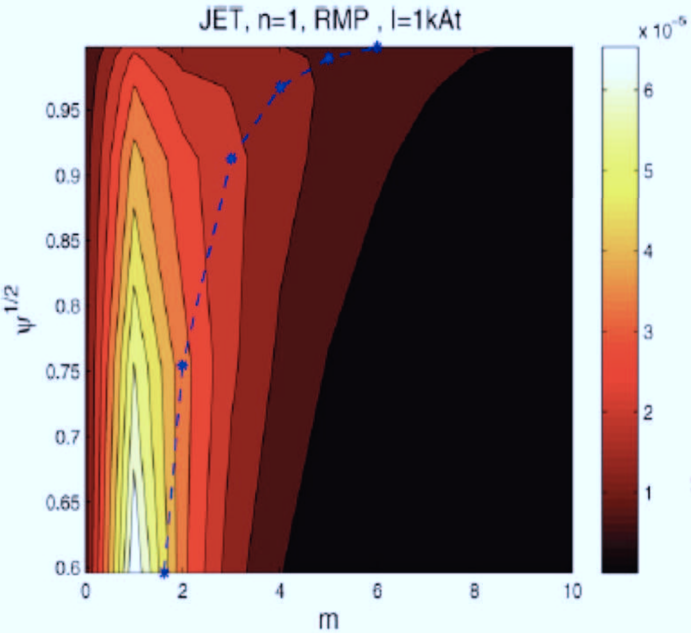

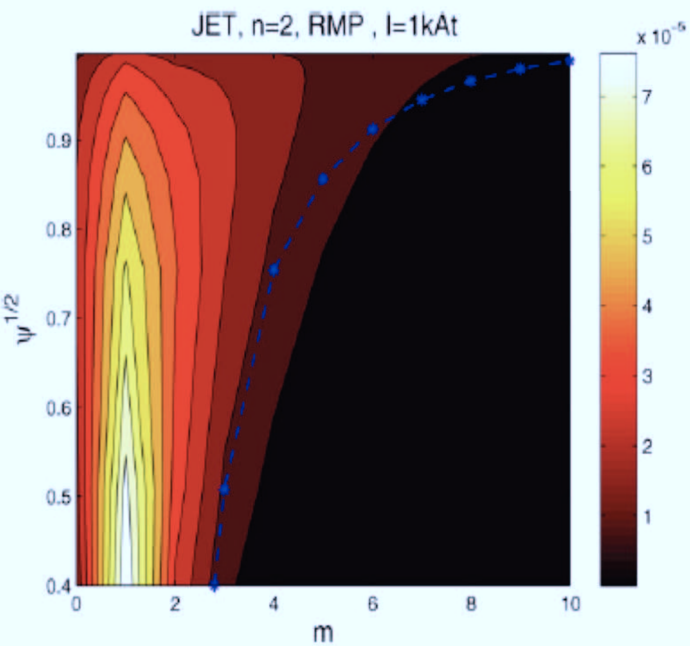

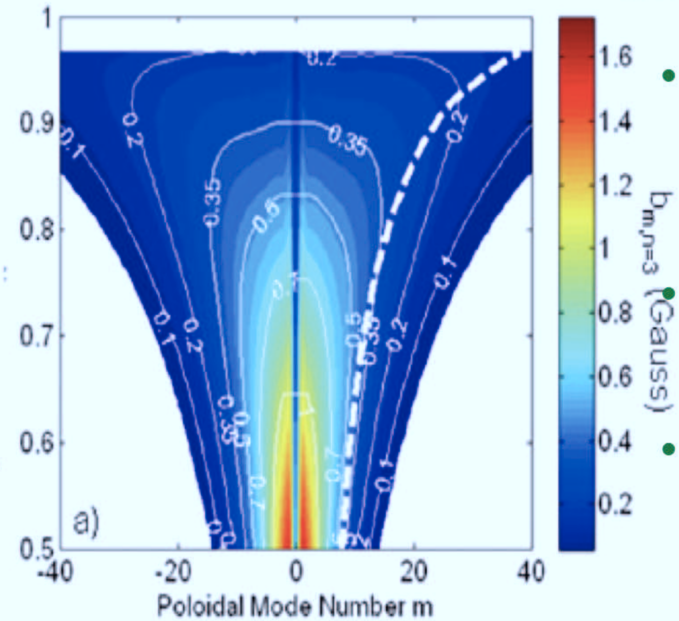

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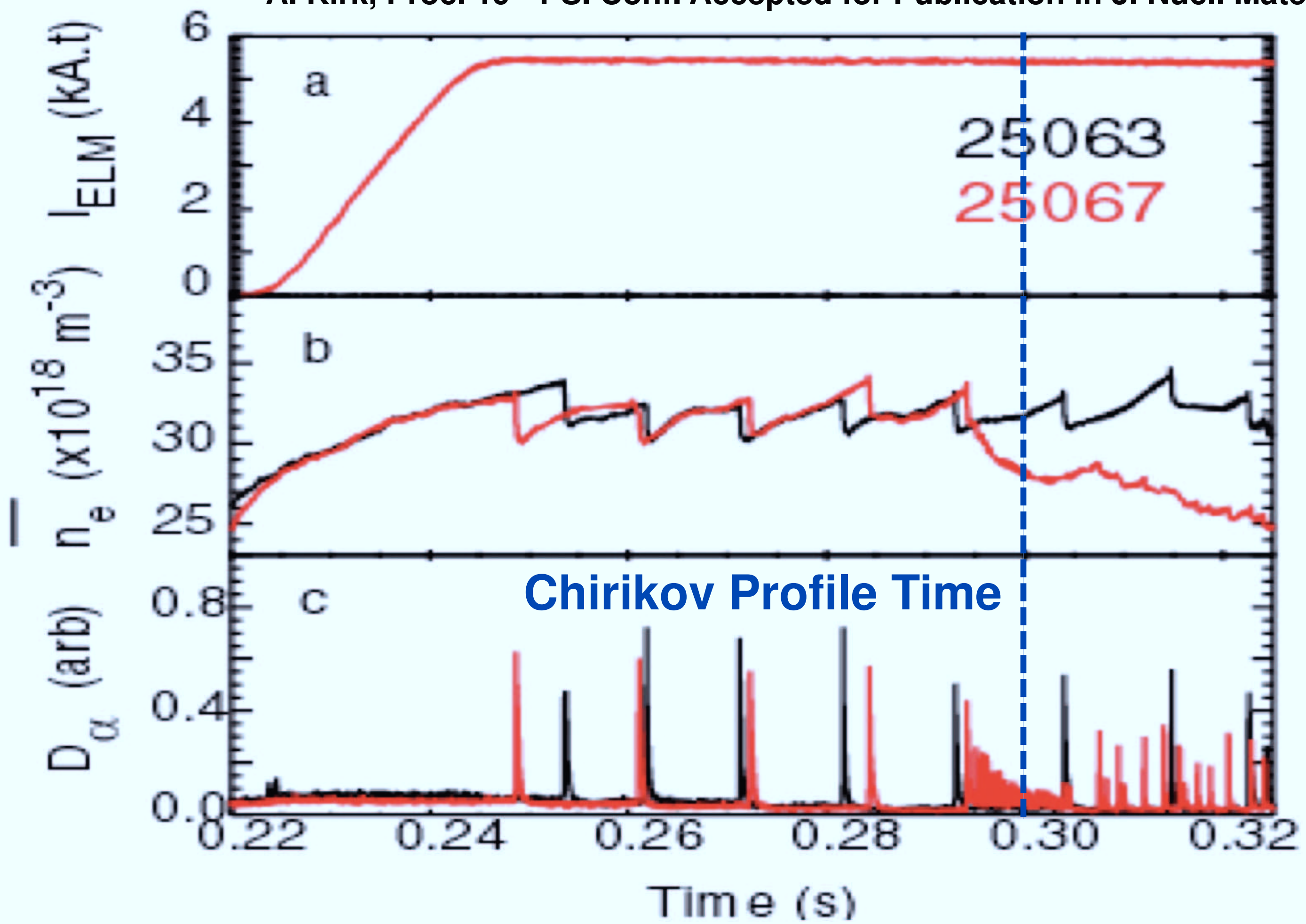
  - Internal Coils – PEP-23
    - DIII-D: n=3 resonant, some non-resonant, also n=2
    - MAST: n=3 resonant and non-resonant
    - TEXTOR: m/n=6/2 helical, many other helical modes
  - **External Coils – PEP-25**
    - **JET: n=1 and n=2 resonant and non-resonant**
    - **NSTX: n=3 resonant, some non-resonant**

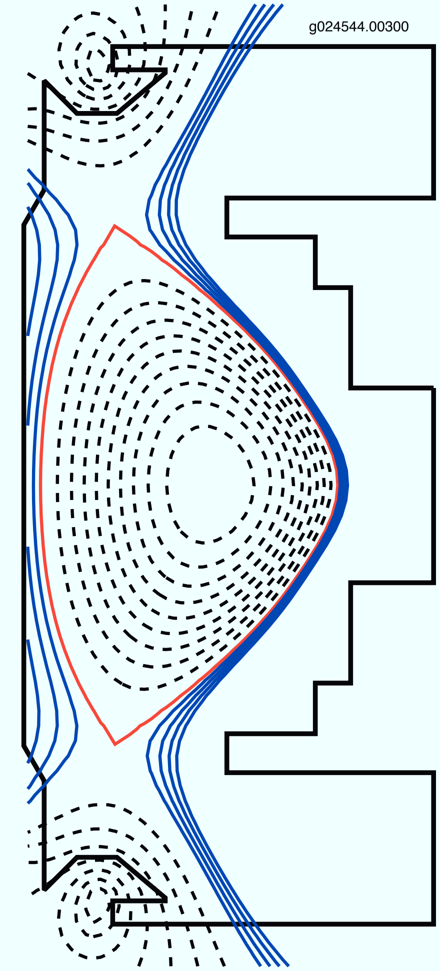
MAST: Evidence of ELM Modification With n=3 and n=2 RMPs But ELMs Not Suppressed

- Show
  - RMP with n=3 and $\Delta_{Chir>1}$ = 0.265 Produces Type-I –> Type-IV ELMs Transition and Density Pump-out
- Back-ups
  - Multiple scenarios tested: DN, high δ DN, low gapout DN, LSN, n=1, 2, 3
  - RMP changes ELM-free to ELMing, gives n_e control
  - Some evidence of ELM mitigation (f_{ELM} increase, ELM size decrease) in T-III regime
  - ELM frequency increase in ELMing H-mode but rotation drops
  - Density pump-out increases with perturbation strength in L-mode including in DIII-D-like ISS
- Not Show
  - Heat flux pattern consistent with vacuum model predictions
  - RMP delays L-H transition in Scenario 2, P_{L-H} increases 30-40%
  - PDF of j_{sat} inside LCFS broadens in L-mode, turbulence changes

MAST: RMP with n=3 and $\Delta_{Chir>1}$ = 0.265 Produces Type-I –> Type-IV ELMs Transition

A. Kirk, Proc. 19th PSI Conf. Accepted for Publication in J. Nucl. Mater.



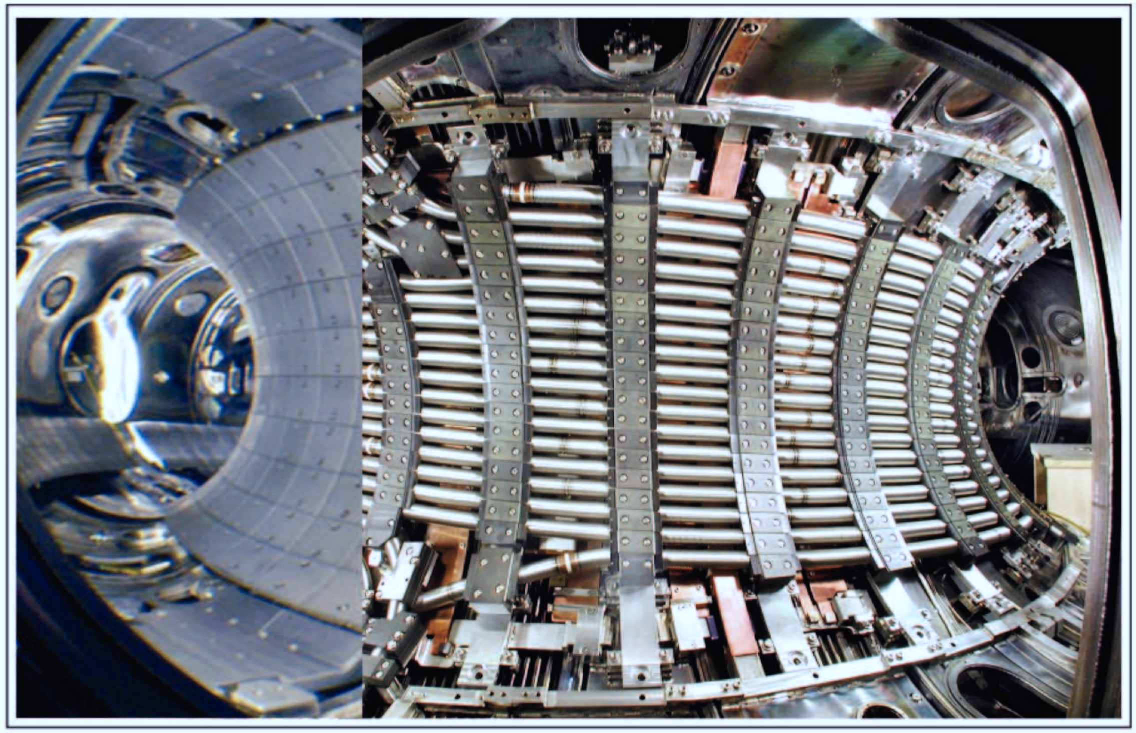


- Initial application of n=3 RMP does not change ELM character
- After four Type-I ELMs character changes to Type-IV and then to higher frequency Type-I

TEXTOR: ELMs Mitigated In Limiter H-mode With Pedestal Pressure Reduction

Show

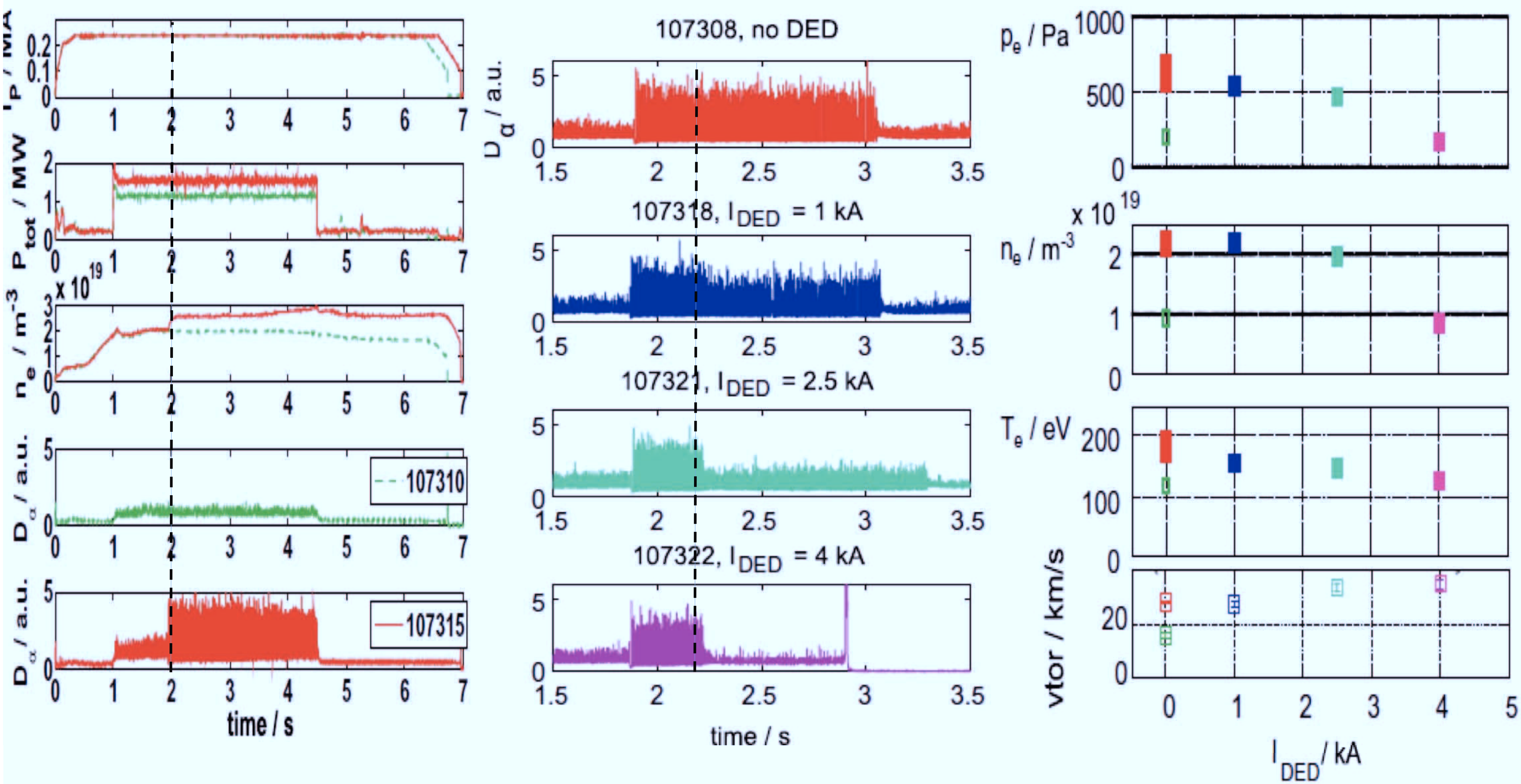
- Limiter H-mode achieved with NBI
- ELM mitigation seen with m/n = 6/2 perturbation from HFS internal DED
- ELM frequency increase, size and pedestal parameter reductions scale with DED current



Not Show

- L-mode-like pressure profile with small ELMs at highest I_{DED} = 4 kA
- Target heat flux patterns in L-mode agree with vacuum modeling
- Similar multi-resonance effects on T_e profiles in DIII-D and TEXTOR vs q_{95} (O. Schmitz, PRL 2009)

TEXTOR: ELM Size Mitigated With Increasing DED Current In Limiter ELMing H-mode



- P_{NBI} = 1.6 MW, q_{95} = 3.7, DED in m/n = 6/2 configuration
- Profiles with I_{DED} = 4 kA indicate L-mode

B. Unterberg, JNM, 390–391 (2009) 351–354

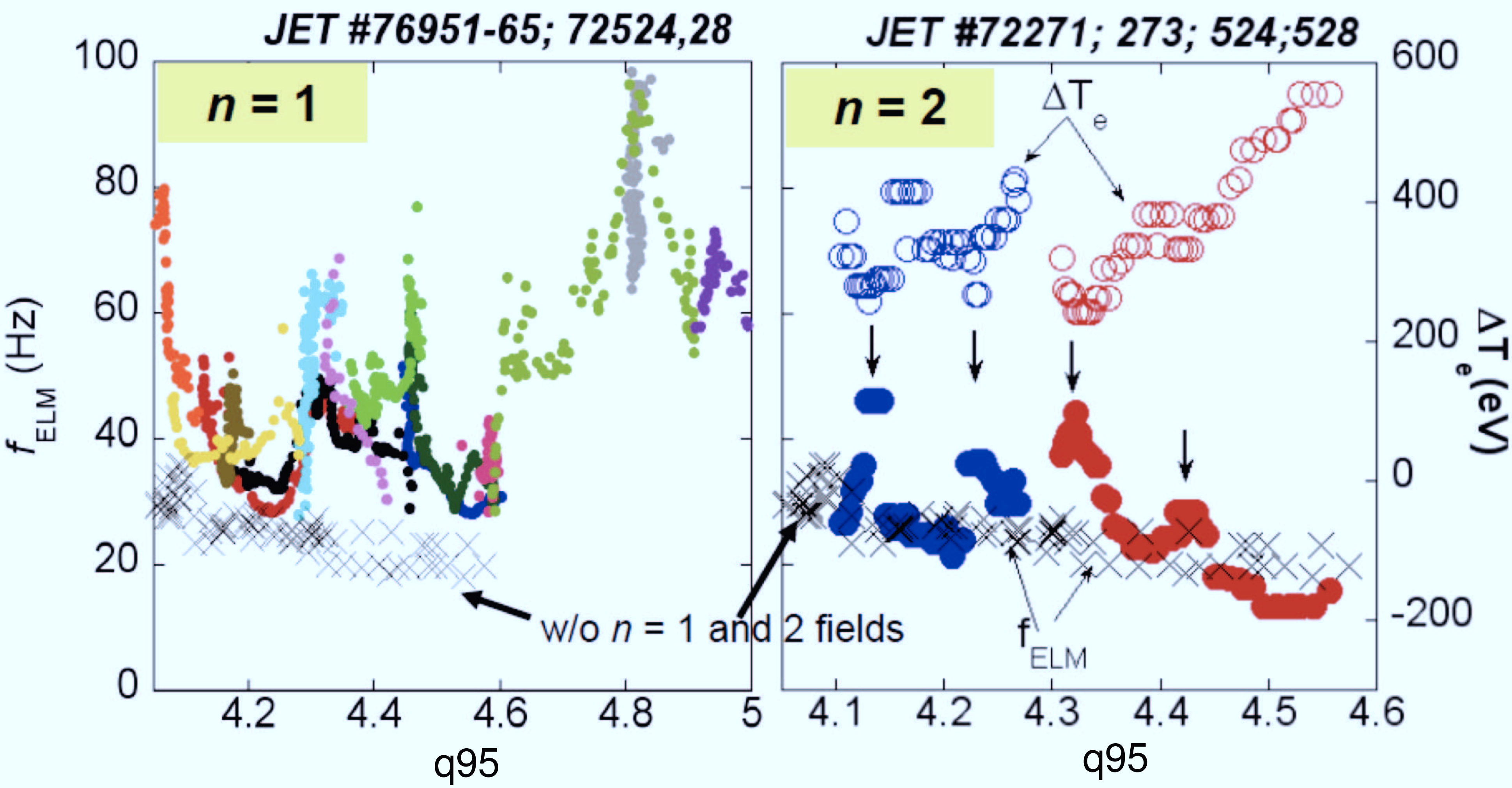
JET: ELMs Mitigated But Not Suppressed With Both n=1 And n=2 Perturbations From External Coils

- Show
  - Evidence for multiple q_{95} resonances of mitigated ELM frequency, n=1 and n=2

- Back-ups
  - Mitigation with n=1 and n=2 perturbations but not suppression
  - EFCC current window for mitigation decreases with q_{95} decrease
  - Compensation of n_e pump-out with optimized gas puff rate or pellets but energy confinement is not recovered
  - Strong rotation braking (50%) with n=1 fields

- Not Show
  - PDF of j_{sat} narrows to small ELMs with n=1 RMP
  - Evidence of RMP perturbation from SP splitting (n=1 and n=2)
  - Application of RMP fields before vs after 1^{st} ELM
  - Effect of RMP fields on P_{L-H}
  - Comparison of EFCC ELM control and toroidal ripple or vertical kicks
  - ELM control in He plasma – Mitigation not as pronounced as in D2

JET: Evidence Of Multiple Resonances In ELM Frequency vs. q_{95} Seen For Both n=1 and n=2 Fields



- **Possible explanation in terms of ideal peeling mode model by Gimblett et al [*C G Gimblett et al., PRL, 96, 035006-1-4(2006)] currently being investigated***

Y. Liang, Published in PRL (2010)

NSTX: ELMs Triggered In ELM-free H-mode With Li-Conditioning Using n=3 Perturbations

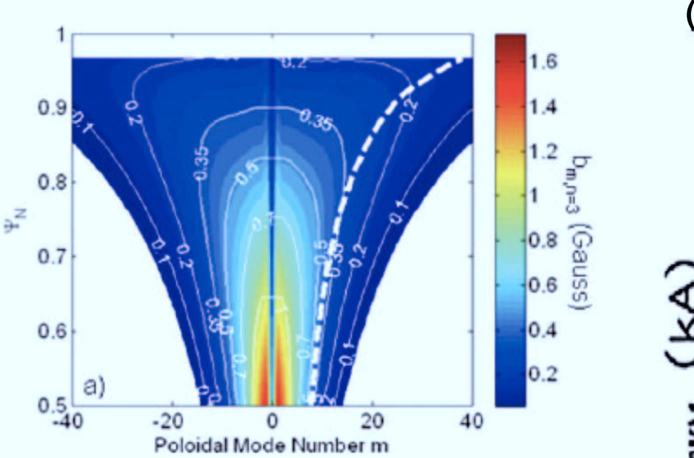
Show

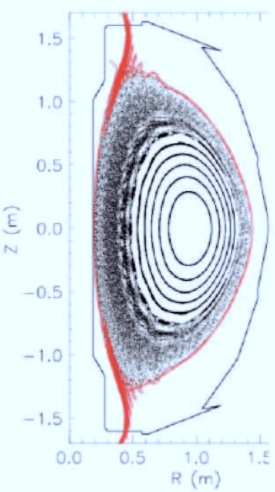
- Deep core perturbation using n=3 RMP from external coils
- RMP induces ELMs in an ELM-free H-mode
  - ELM start time follows RMP turn-on
  - ELM frequency increases with RMP amplitude

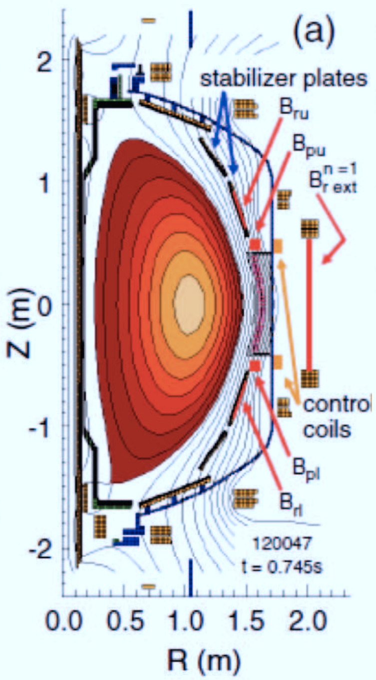
Not Show

- T_e profile changes with RMP but not n_e profile

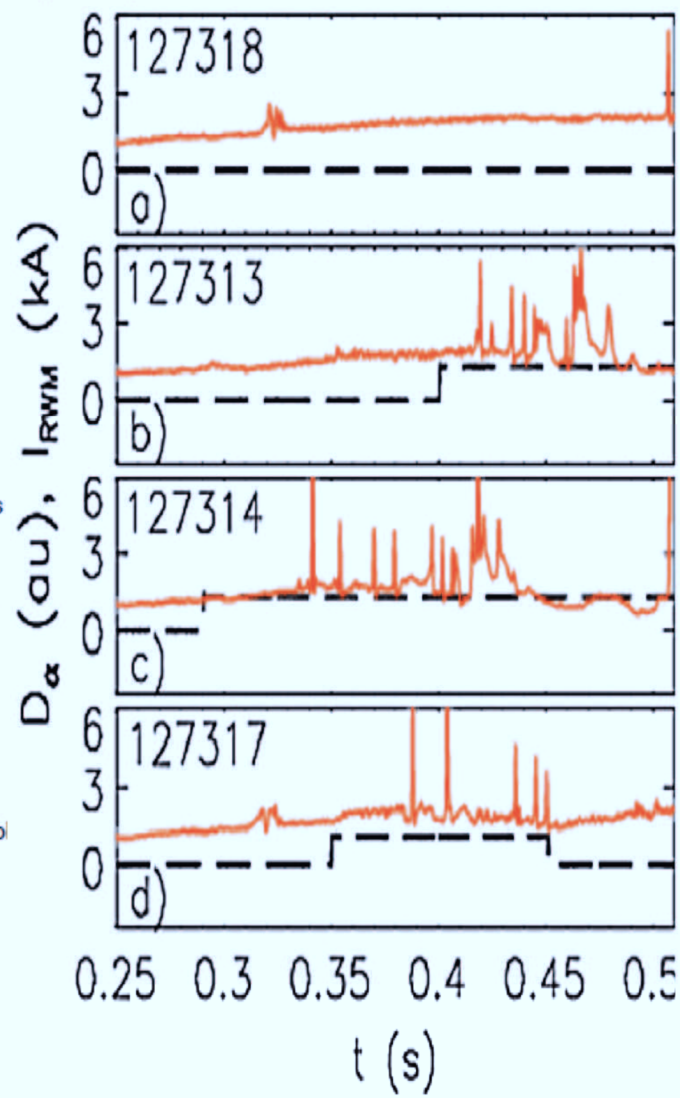
NSTX: n=3 Fields Produce ELMs From ELM-free Plasma, ELM Frequency Increases with RWM Coil Current



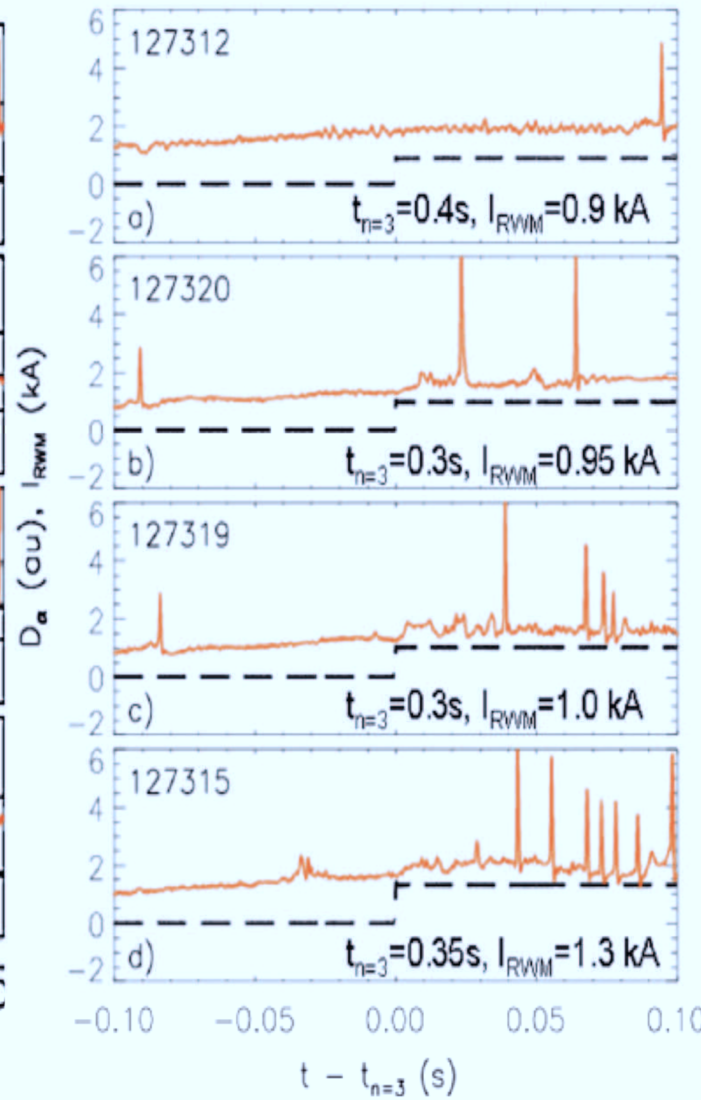




J.M. Canik *et al.*, PRL 104, 045001 (2010)



J.M. Canik *et al.*, Nucl. Fusion 50 (2010) 034012

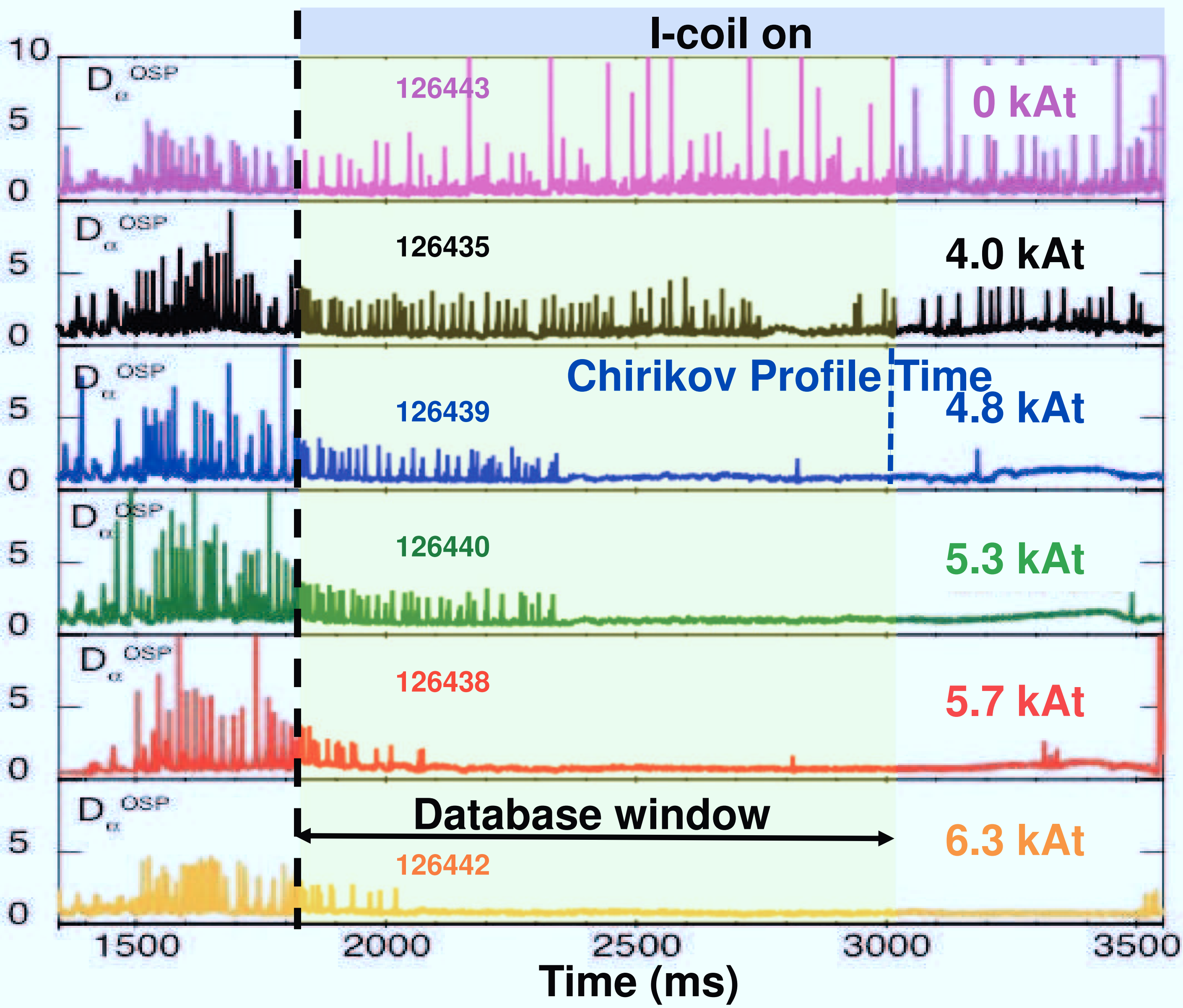


- ELM response to RWM coil current tracks current on-time within 50 ms

ISLAND OVERLAP WIDTH

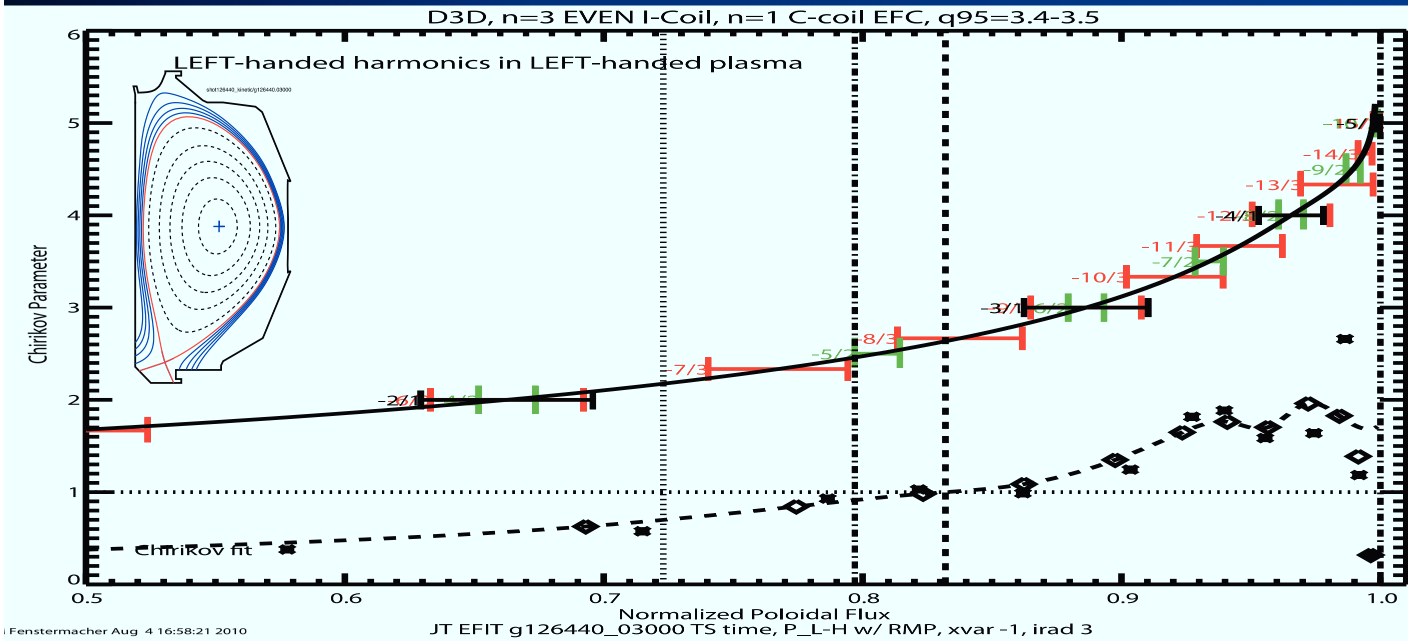
DIII-D: I-coil Current Scan at Fixed Shape and q_{95} Produces Systematic Change in ELM Behavior

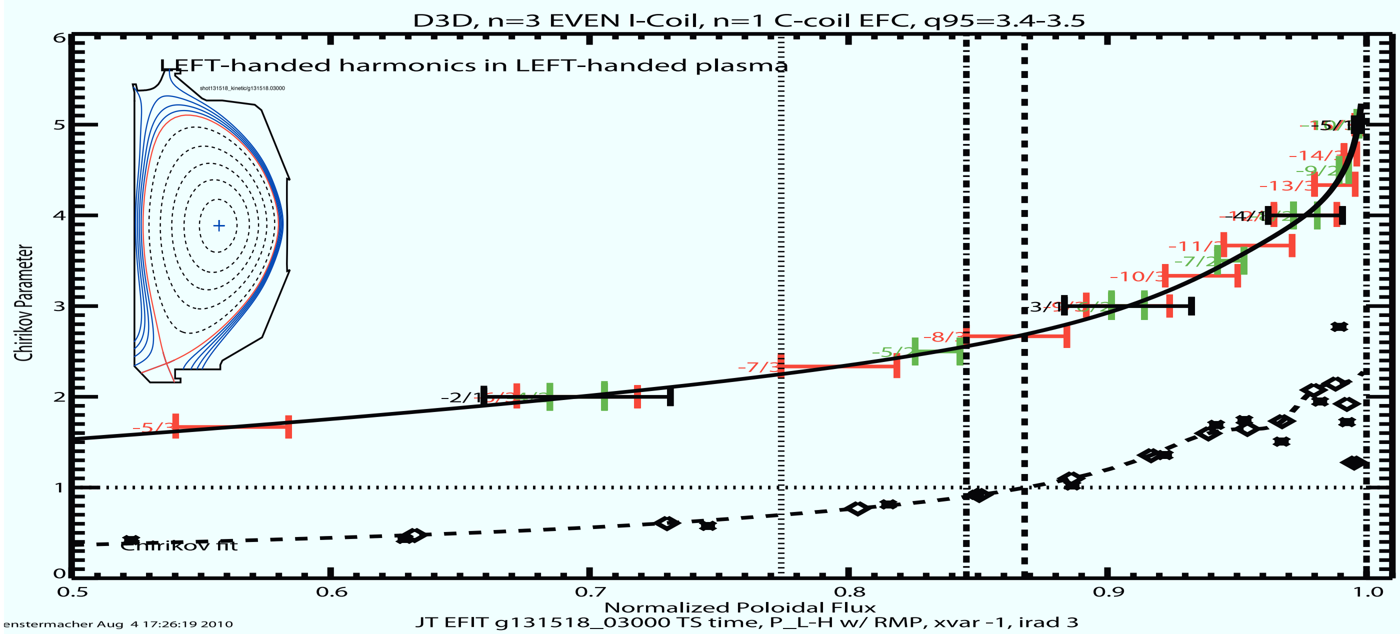
Fenstermacher, M.E., Evans, T.E. *et al.*, PHYSICS OF PLASMAS 15, 056122 2008



- Provides multi-ELM sampling
  - 24 kinetic EFIT timeslice windows per shot
  - Multiple ELMs for many of the EFIT windows
- Similar sampling of other scans
- Complete suppression earlier at higher I-coil current

Chirikov Profiles From DIII-D n=3 Internal, Off-Midplane I-coil Cases

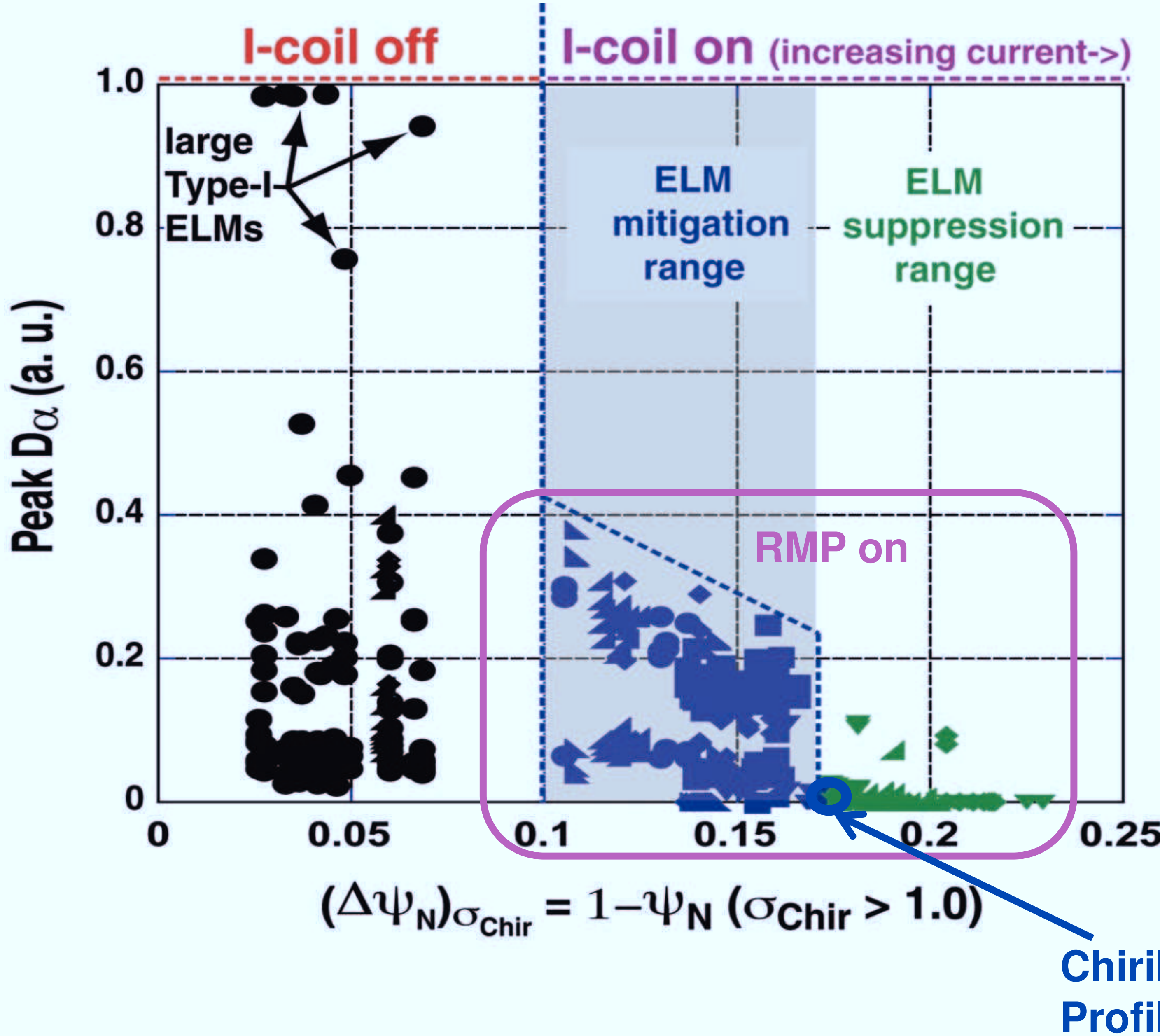




- Applied n=3 RMP fields from internal coils + n=1 fields from EFC coils + intrinsic error fields contribute

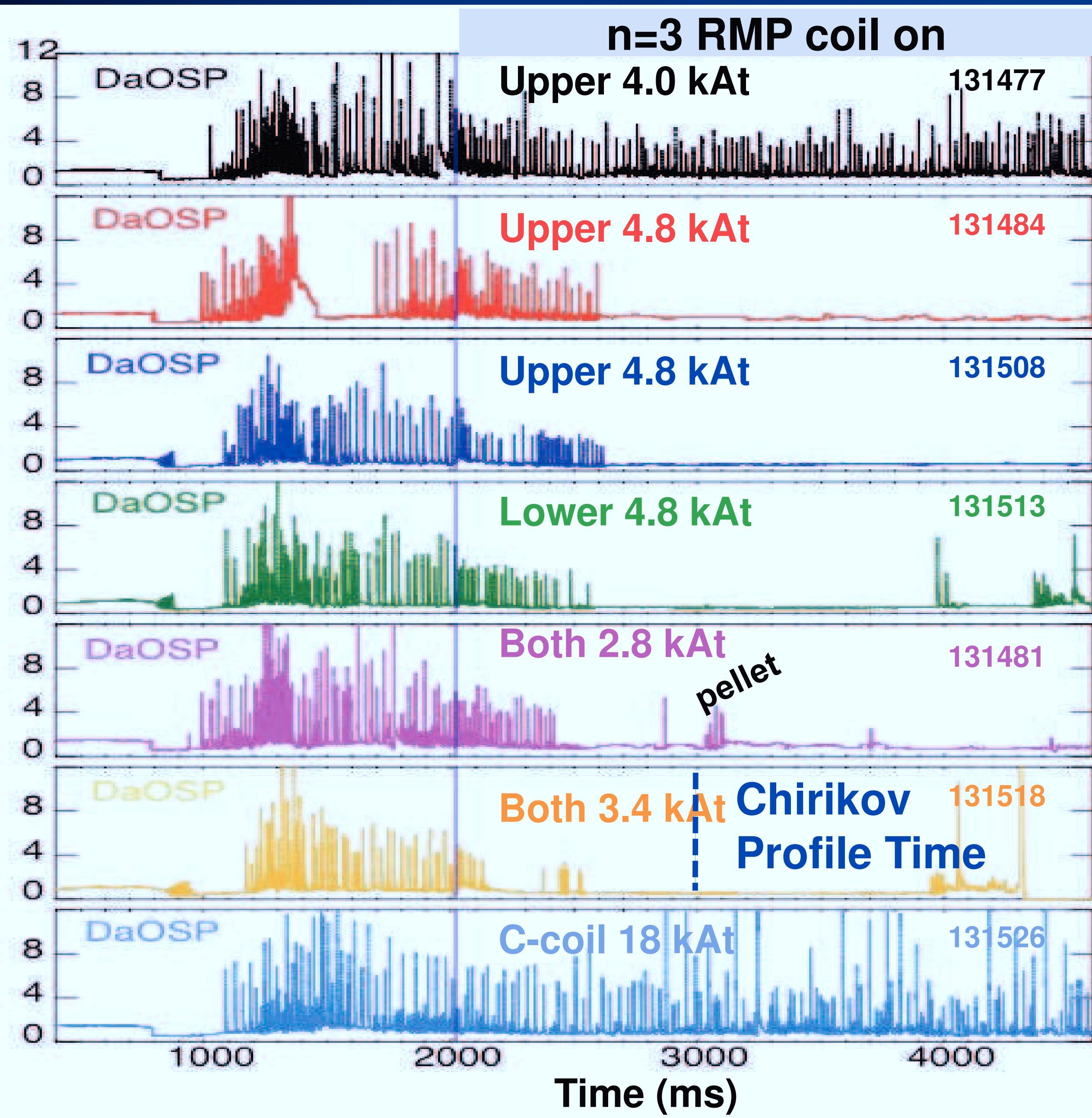
DIII-D: Maximum ELM Size Correlated with Edge Region Width Satisfying Chirikov Parameter > 1.0

Fenstermacher, M.E., Evans, T.E. *et al.*, PHYSICS OF PLASMAS 15, 056122 2008



- ELM size from fast D_α at outer divertor strikepoint
  - Normalized to largest ELMs without RMP in database
- Full spectrum of ELM sizes both without and with RMP
  - Consistent with non-linearity of ELM instability

DIII-D: ELMs Suppressed With Both Or Either Single I-coil Row

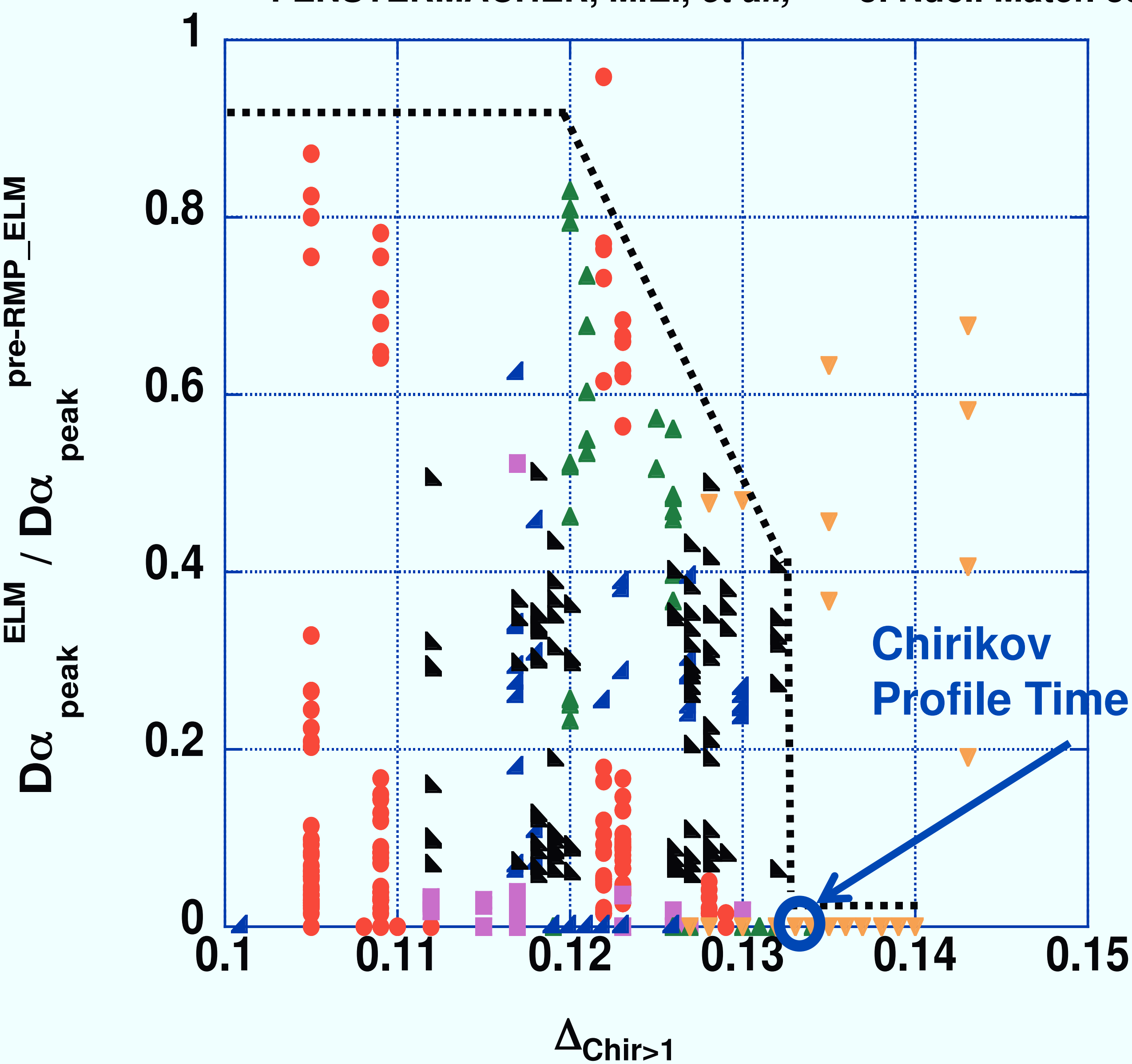


- Upper I-coil row alone at two coil currents
- Lower I-coil row alone
- Both I-coil rows at two coil currents
- C-coil n=3 RMP did not show much ELM change

Fenstermacher, M.E., *et al.*, Nucl. Fusion 48 (2008) 122001

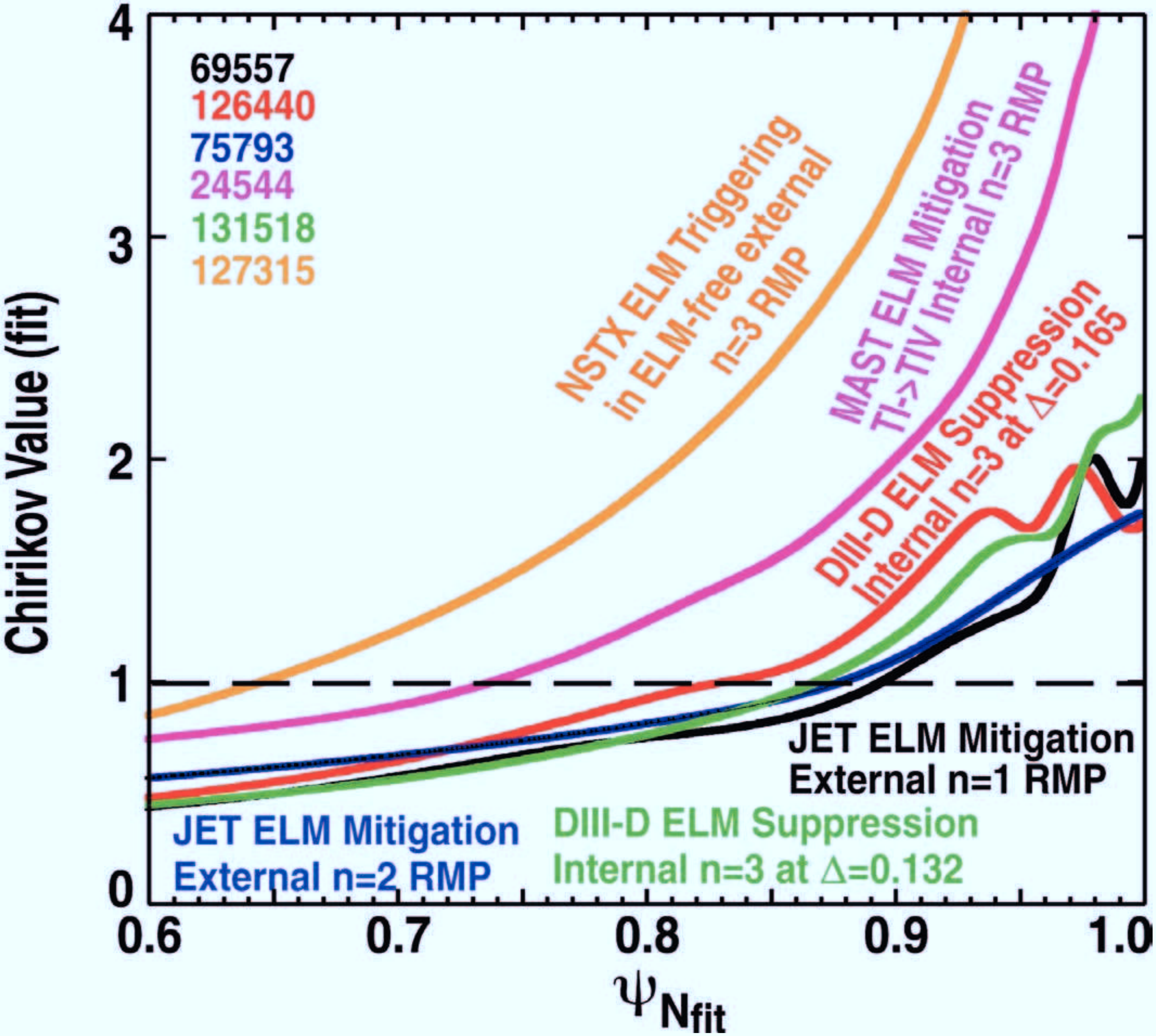
Ordering With Width of Island Overlap Region From One vs Two Rows Database Cautions Against Over Interpretation

FENSTERMACHER, M.E., *et al.*, J. Nucl. Mater. 390–391 (2009) 793



- Threshold for this experimental day was $\Delta_{Chir>1}$ = 0.132
  - Threshold for run day in April 2007 was $\Delta_{Chir>1}$ = 0.165
- Outliers with ELMs for $\Delta_{Chir>1}$ above threshold
- Timeslices without ELMs for $\Delta_{Chir>1}$ less than threshold
- SATISFYING THRESHOLD IN $\Delta_{Chir>1}$ IS ONLY A GUIDE TO REQUIREMENTS FOR RMP COIL DESIGN

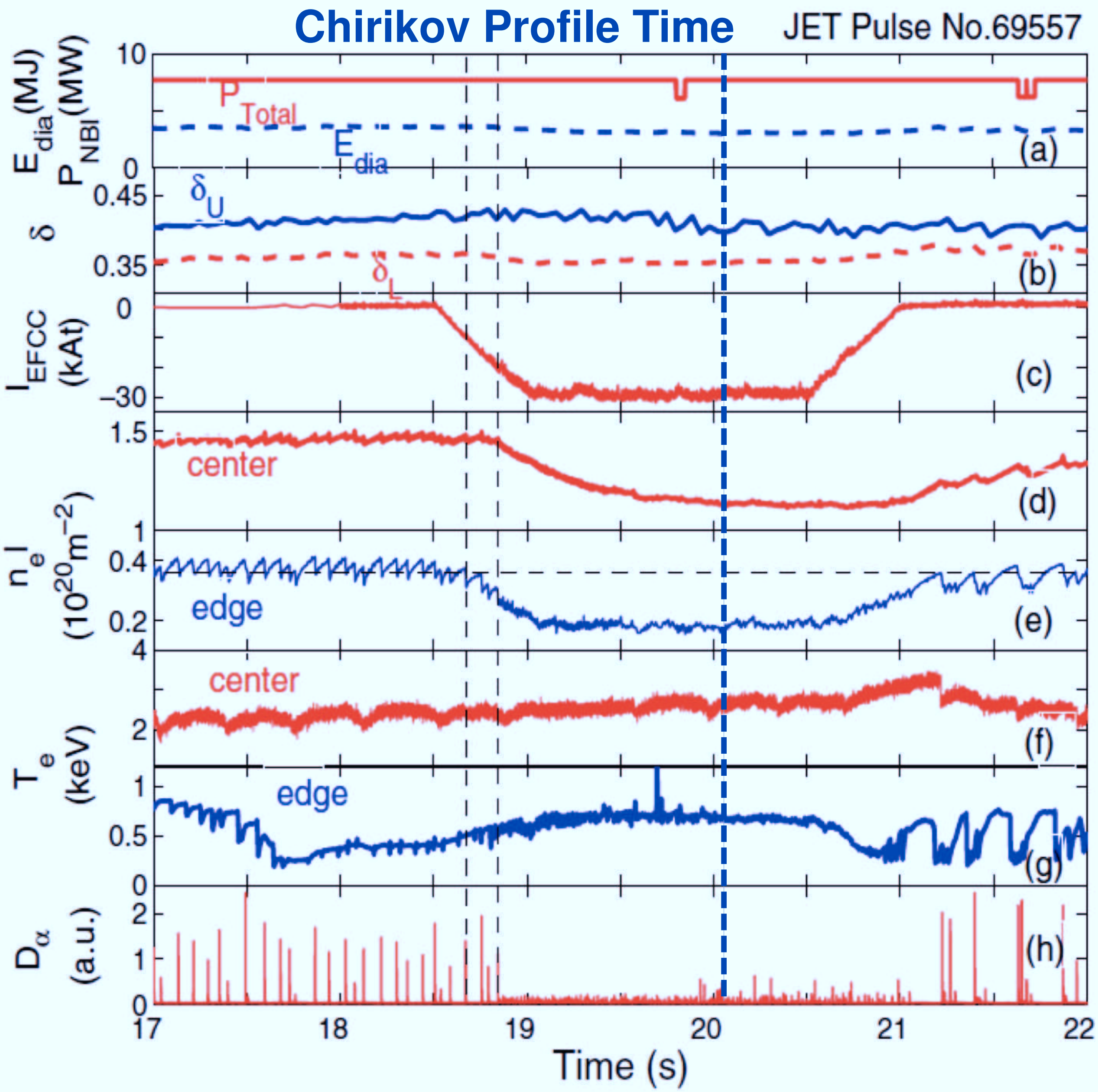
Vacuum Island Overlap Width Is Not Sufficient to Assure ELM Suppression



- Overlap widths comparable to ITER guidance criterion from DIII-D achieved in other devices without ELM suppression
  - Frequently obtain ELM mitigation
- Overlap width is ordering parameter for RMP strength between devices but not physics driver of suppression

JET: Chirikov Profiles Calculated For Conditions During ELM Mitigation With n=1 RMP Fields

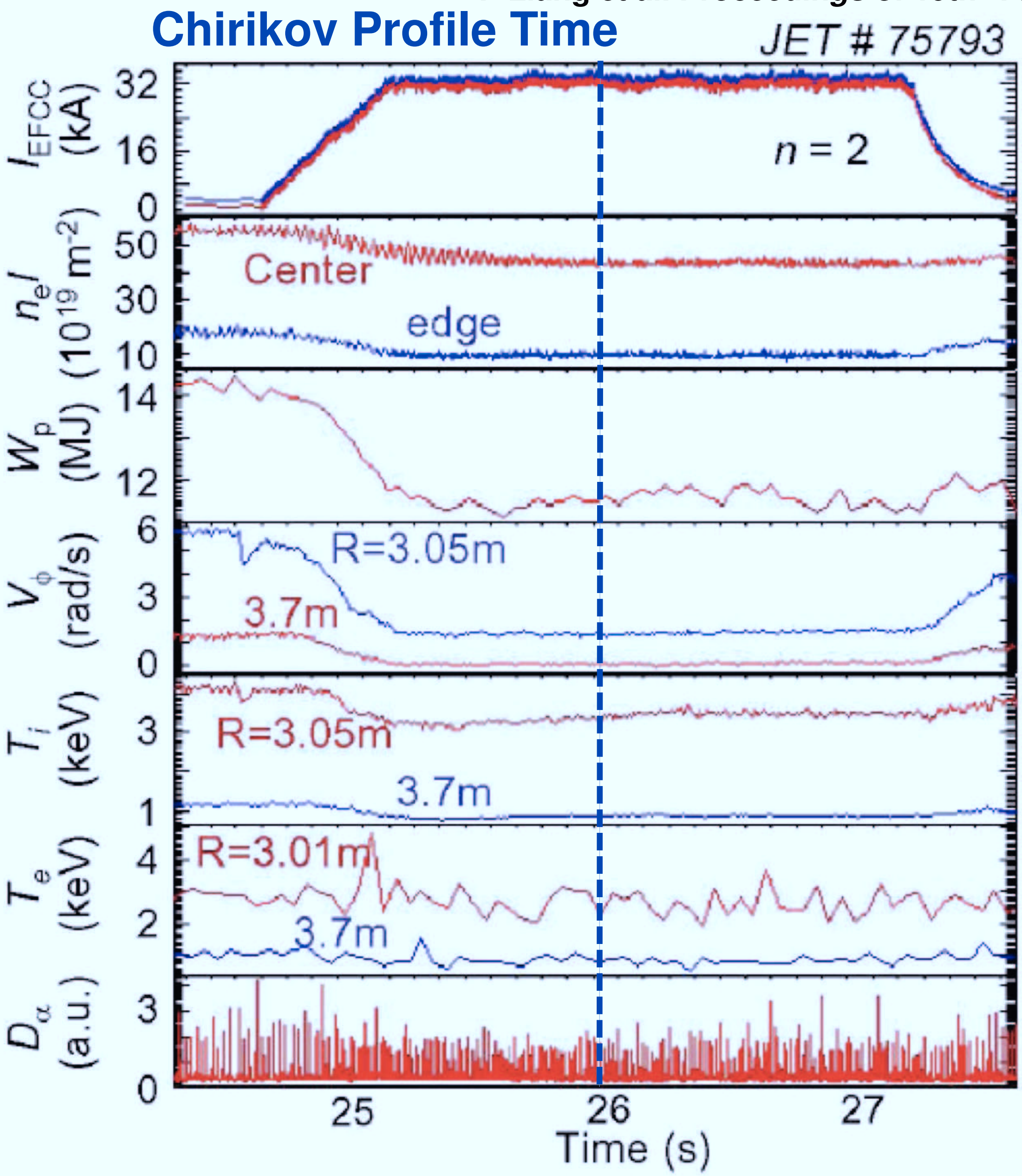
Y. Liang *et al.*, Nucl. Fusion 50 (2010) 025013



- During the RMP from the EFCC , the equilibrium (EFIT) reconstructed by averaging full coil sets from different toroidal cross sections – Octants #1, 3, 5 and 7
  - This process can compensate for the direct pick up from the EFCC perturbation
- Intrinsic error fields small, neglected in SURFMN analysis
- Standard EFITs (ie. no calculation of $j_{bs}(\Psi)$ from profiles)

JET Chirikov Profiles Calculated During ELM Mitigation With n=2 RMP Fields

Y. Liang *et al. Proceedings of* 19th ITC conference on Plasma and Fusion Research*, 2010*



- During the RMP from the EFCC , the equilibrium (EFIT) reconstructed by averaging full coils set from different toroidal cross sections – Octants #1, 3, 5 and 7
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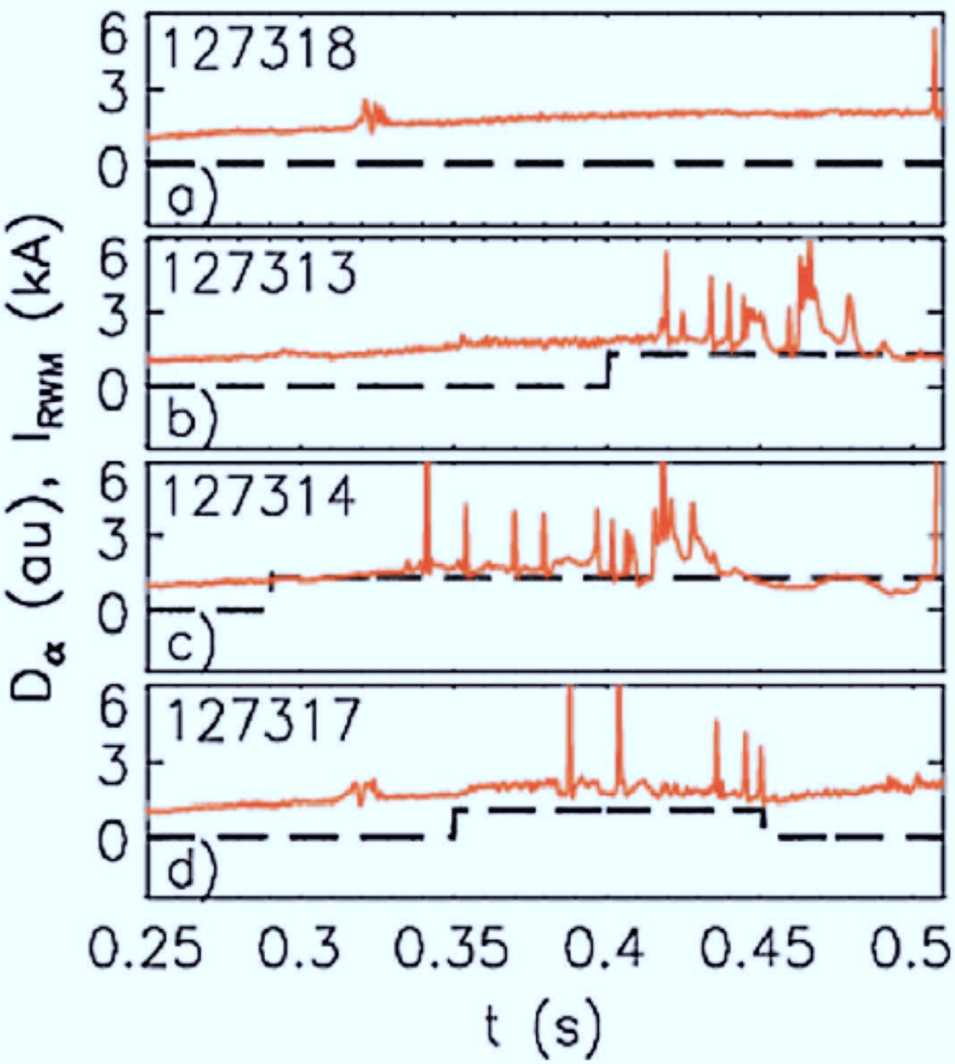
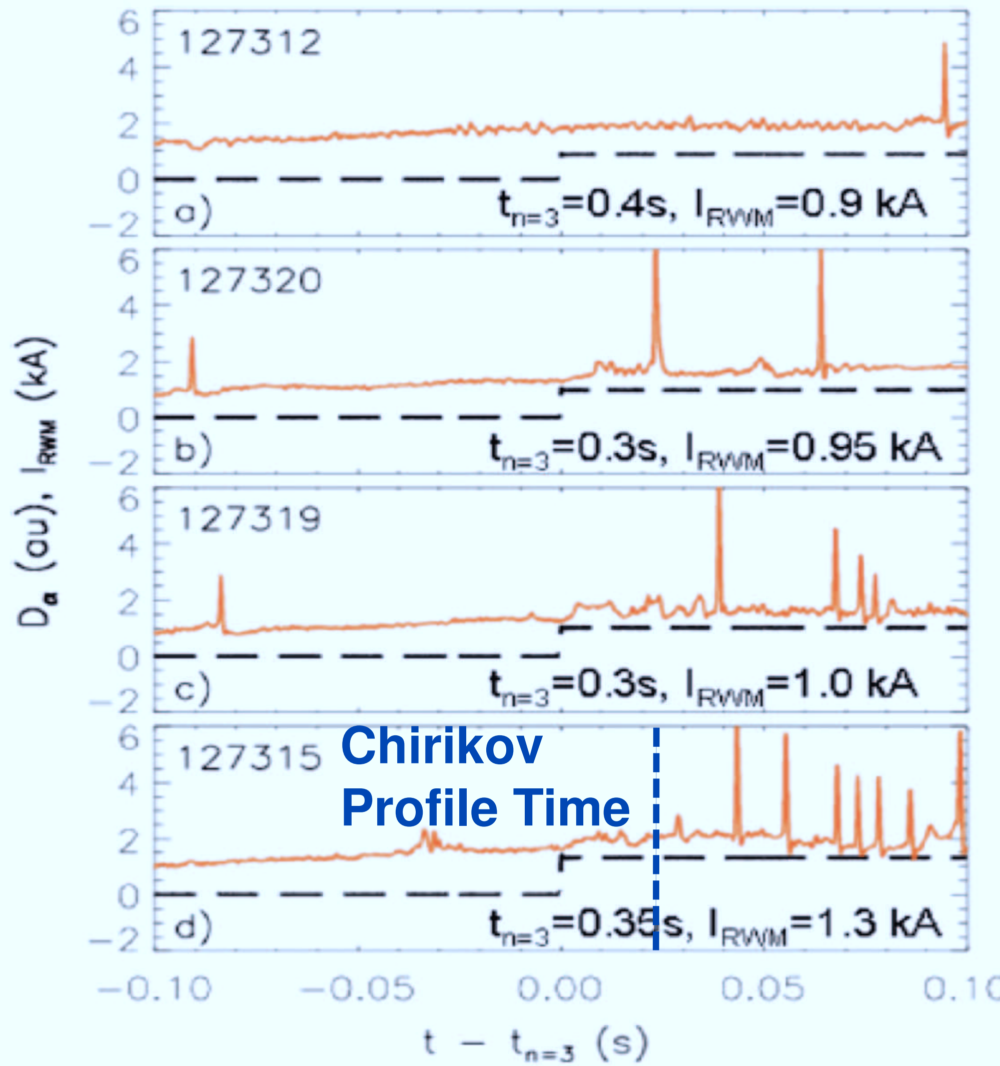
NSTX: n=3 Fields Trigger ELMs From ELM-free Plasma, f_{ELM} Increases with RMP Coil Current

J.M. Canik *et al.*, PRL 104, 045001 (2010)



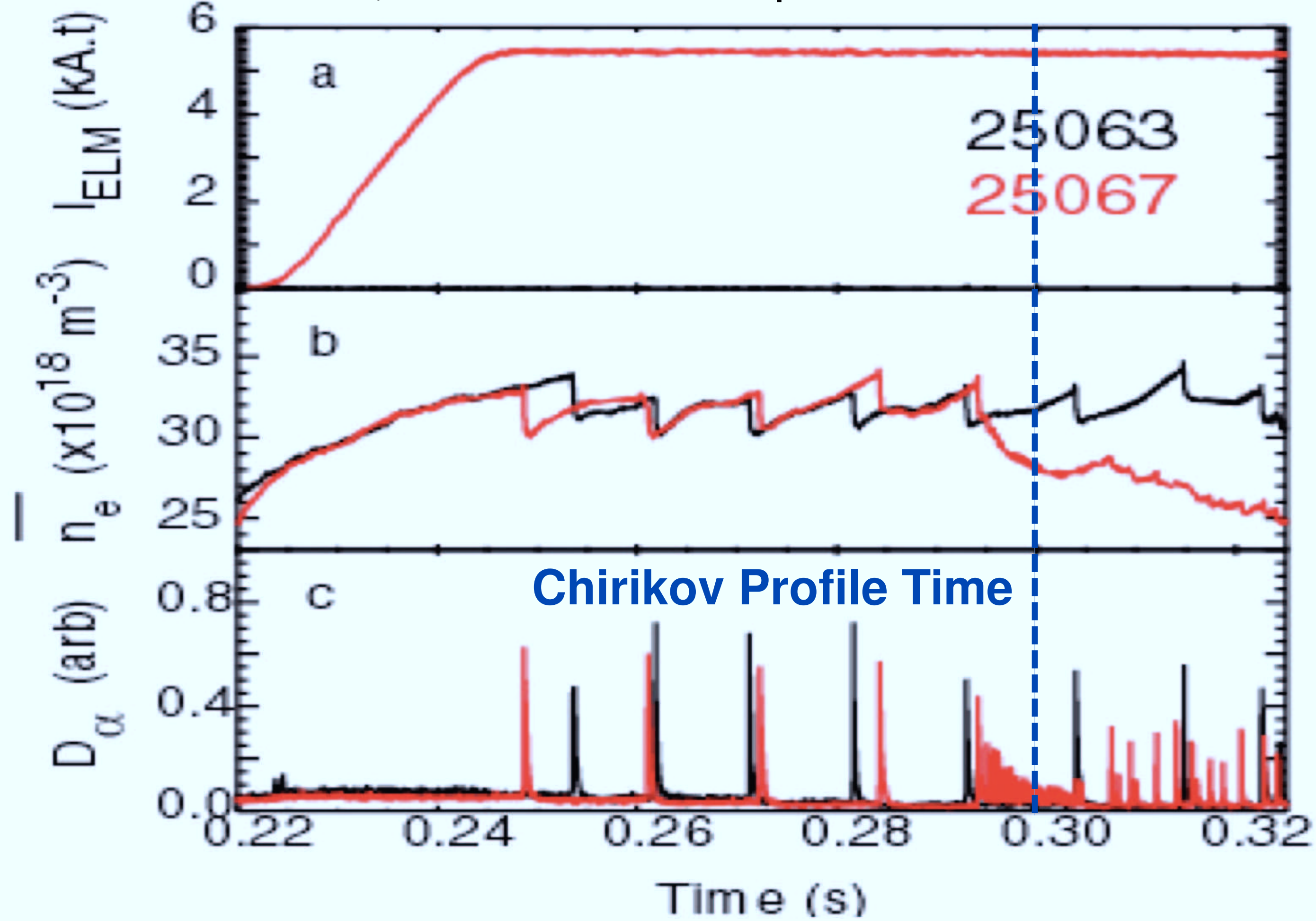
J.M. Canik *et al.*, Nucl. Fusion 50 (2010) 034012

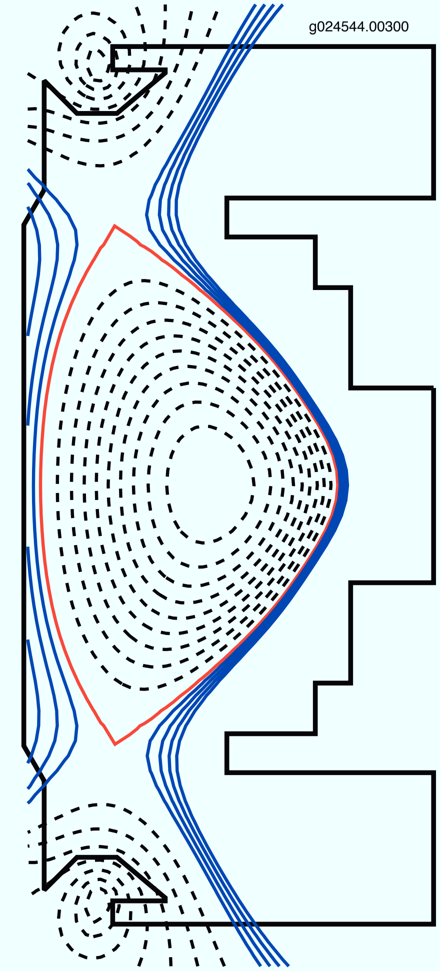


- ELM response to RMP coil current follows current on-time within 50 ms
- Higher frequency ELMs triggered at higher RMP current

MAST: RMP with n=3 and $\Delta_{Chir>1}$ = 0.265 Produces Type-I –> Type-IV ELMs Transition

A. Kirk, Proc. 19th PSI Conf. Accepted for Publication in J. Nucl. Mater.



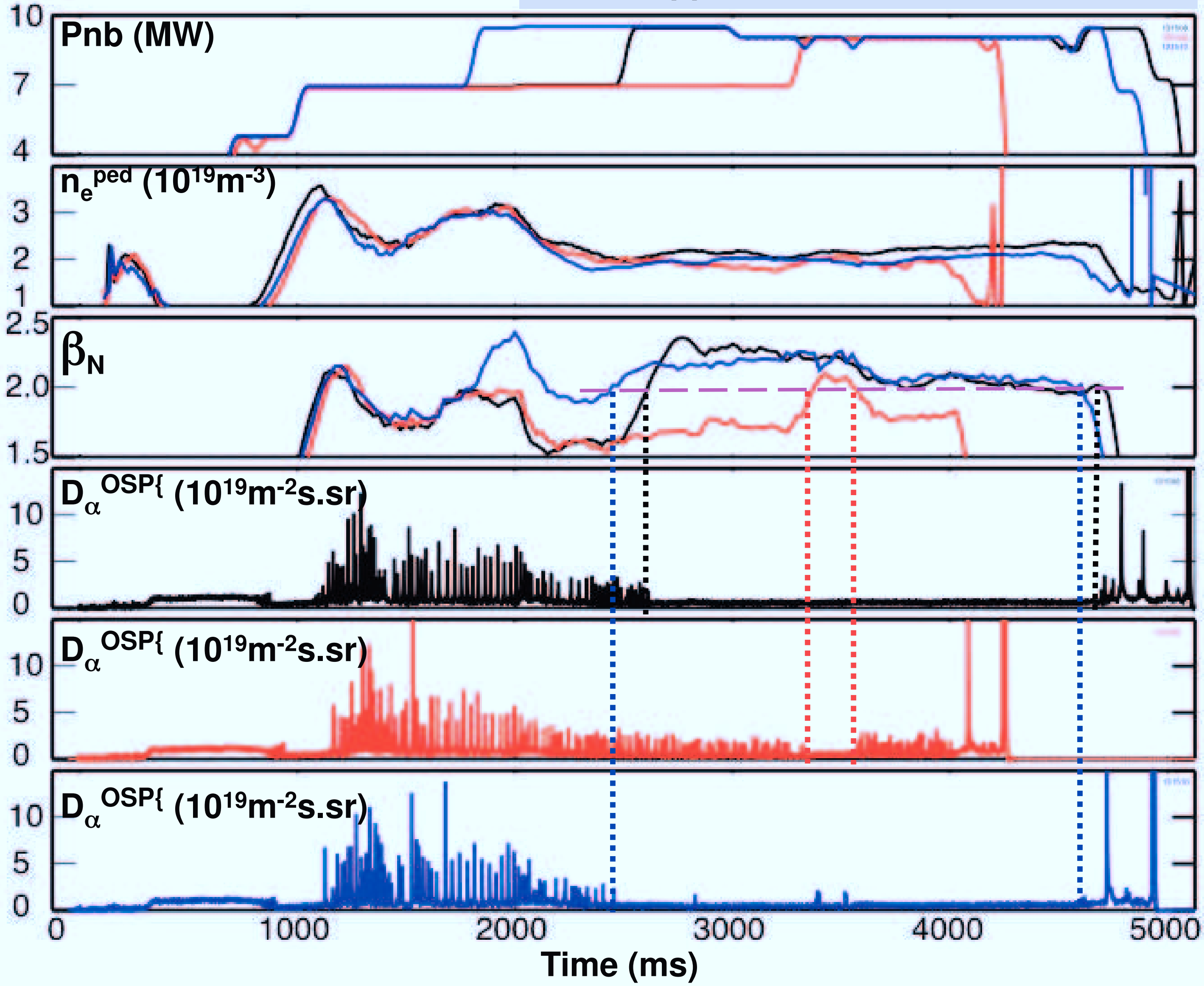


- Initial application of n=3 RMP does not change ELM character
- After 4 Type-I ELMs character changes to Type-IV and then to higher frequency Type-I

OTHER IMPORTANT CRITERIA

Plasma β or β_N May Be Important For Achieving ELM Suppression

Upper I-coil RMP at 4.5 kAt



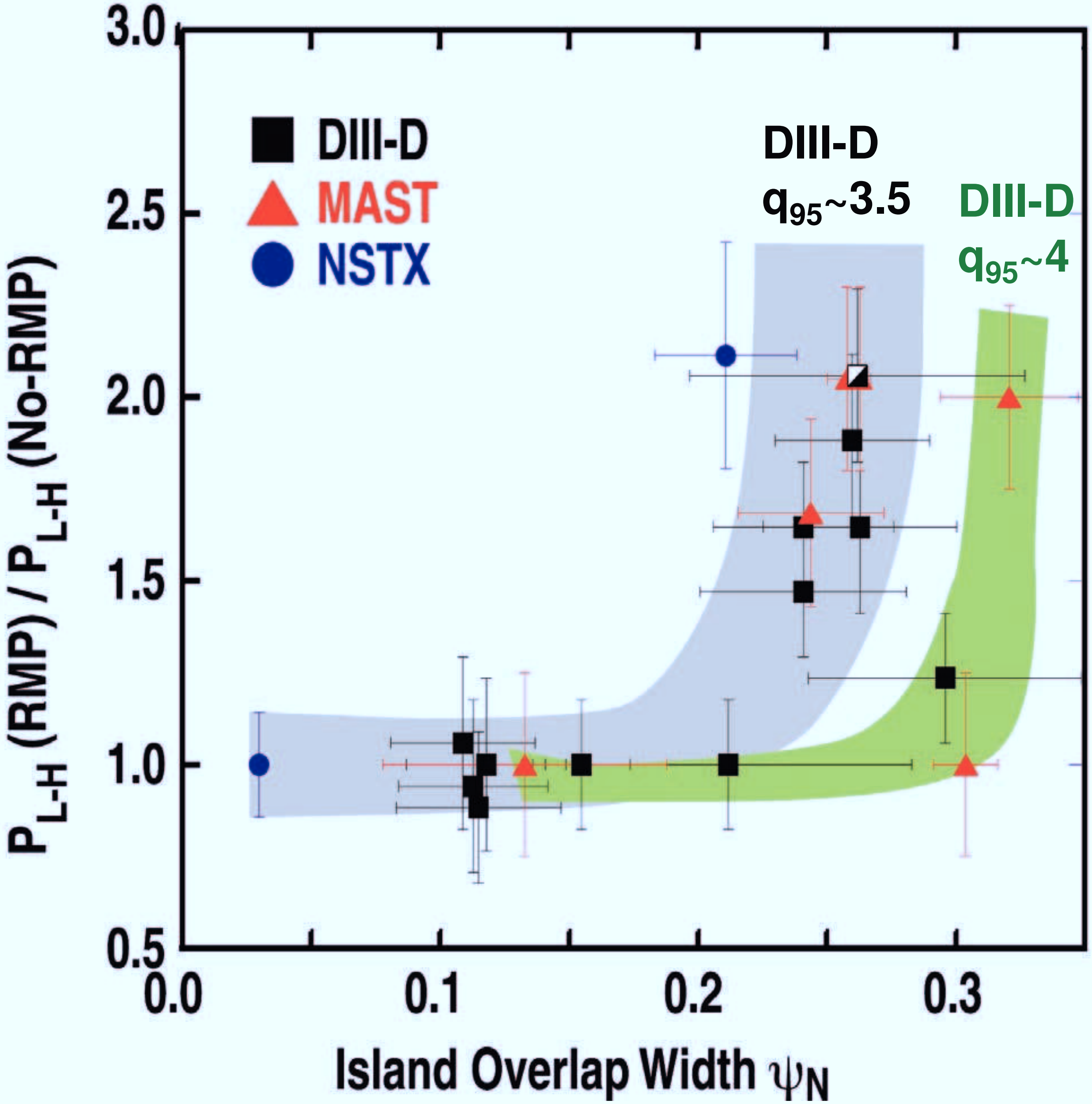
- Identical I-coil current
- Power step delay changes timing of ELM suppression
  - n_e^{ped} and $\Delta_{Chir>1}$ nearly constant
- Suppression and ELMs return correlated with β threshold
  - P_{inj} and T_{inj} do not correlate with ELM behavior
- Plasma response to RMP fields sensitive to β

Orlov, D. *et al.*, Nucl. Fusion 50 (2010) 034010

M.E. Fenstermacher et al. JNM 390–391 (2009) 793–796

RMP EFFECT on P_{L-H}

L-H Transition Power Increases for RMP Beyond Threshold Strength



- Required RMP strength to increase P_L-H depends on RMP spectrum
  - Strongly resonant spectrum P_L-H increases for overlap width > 0.2
  - Weakly resonant spectrum P_L-H increases for overlap width > 0.3
- DIII-D Experiments Use Steps in NBI Power to Determine L-H Threshold With RMP
- MAST: L-H Threshold Power Determined From Scan of n=3 I_{ELM} at Fixed P_{NBI}

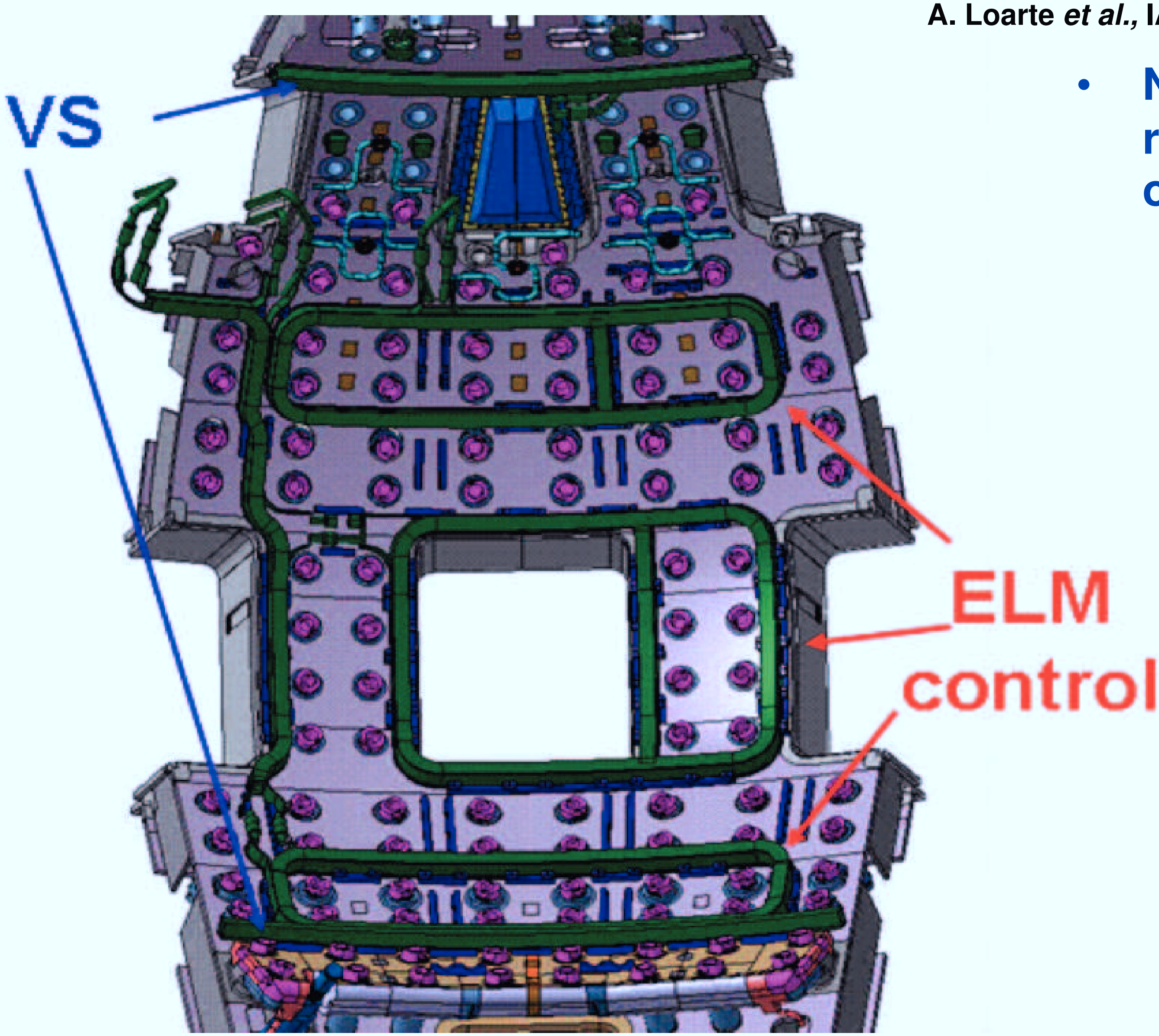
FUTURE COIL UPGRADES

Multiple Devices Plan Coil Upgrades To Increase Physics Understanding Of RMP ELM Control

All Planned Upgrades Are Internal Coils

- MAST installing additional 6 below outer midplane coils
  - Upper row of 6 + Lower row of 12 coils – H-mode expts start June 2011
- AUG installing LFS coils
  - Initial set (2010) 2 x 4 above and below outer midplane – Start Jan 2011
  - Upgraded set (2011) 2 x 8 above and below outer midplane – Start Oct 2011
  - Ultimate set (2012) 3 x 8 above, below and on outer midplane (ITER-like)
- DIII-D evaluating plans to ultimately install coils on HFS center post
  - Initial set 3 x 6 above, below and on inner midplane, n=1, 2, 3
  - Ultimate set 3 x 12 for rotatable n=3 or 4, and up to n=6
- JET considering design of 8 upper + 24 mezzanine internal coil set
- NSTX considering design of 2 x 12 above and below outer midplane coils
- COMPASS will start with 4 coils, studying upgrade to 8
- KSTAR coils capable of RMP fields – H-mode achieved Nov 2010
- JT60-SA set of 3 x 6 coils with limited toroidal coverage
- TCV considering 3 x 6 coils above, below and on outer midplane

ITER: Design of Internal RMP Coils Subject To Many Constraints



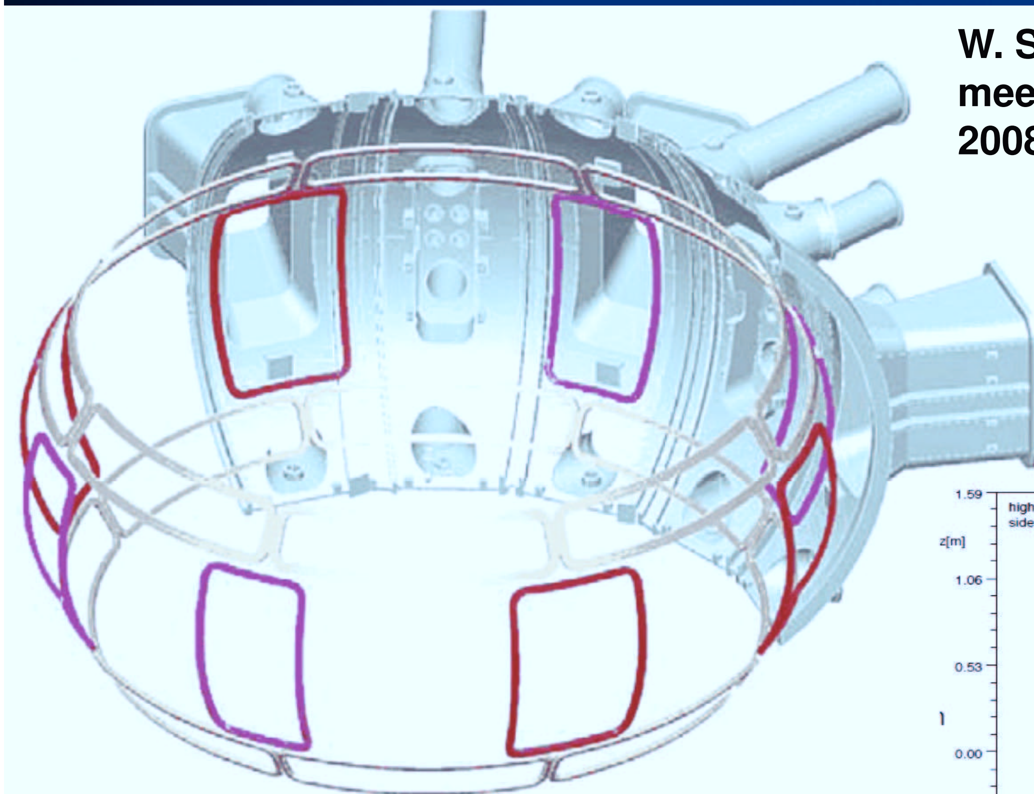
M.J Schaffer *et al.*, Nucl. Fusion 48 (2008) 024004

A. Loarte *et al.*, IAEA 2010 Daejeon, ITR/1-4

- **Nine internal RMP coils per row above, below and on outer midplane**
  - **Current requirement guided by island overlap region width correlated with ELM suppression in DIII-D**
    - **90 kAt for $\Delta_{Chir>1}$ = 0.165 with 20% margin**
  - **All coils independently powered**
    - **Allows n=4 or toroidally rotatable n=3 RMP fields**
    - **Allows optimization for range of q95**

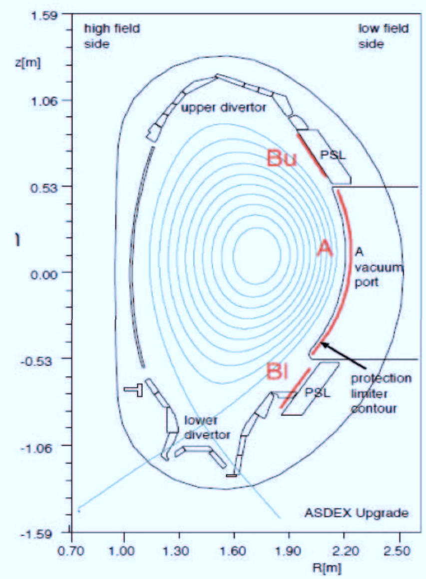
UNDER CONSTRUCTION

ASDEX-Upgrade: ITER-like Design of New Internal Coils Under Construction



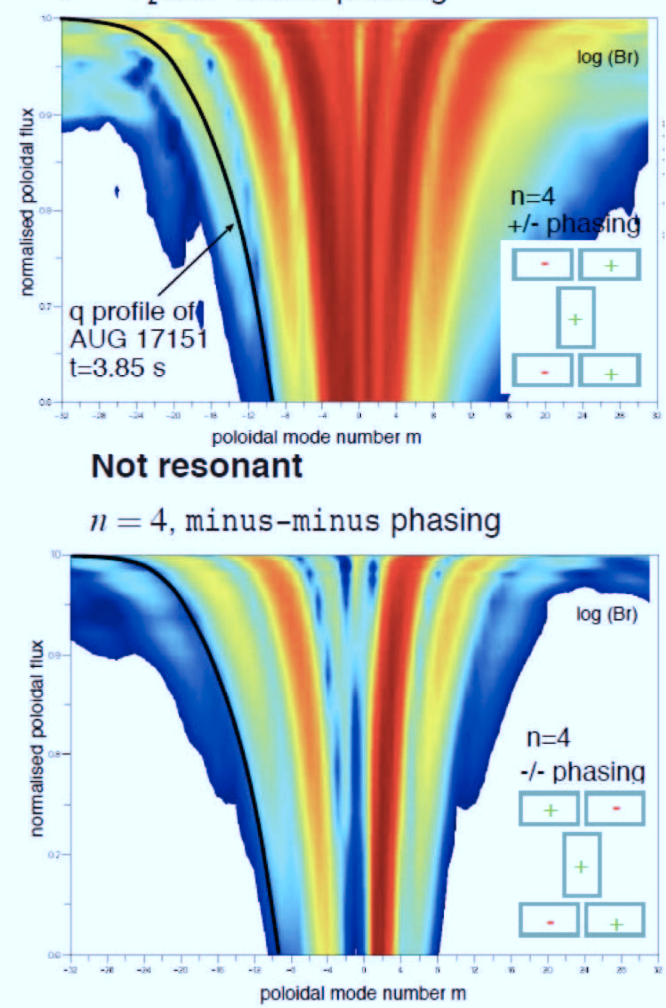
W. Suttrop et al. / Fusion Engineering and Design 84 (2009) 290–294

W. Suttrop, PEP ITPA meeting, GA, May 2008



Resonant

$n = 4$ plus-minus phasing

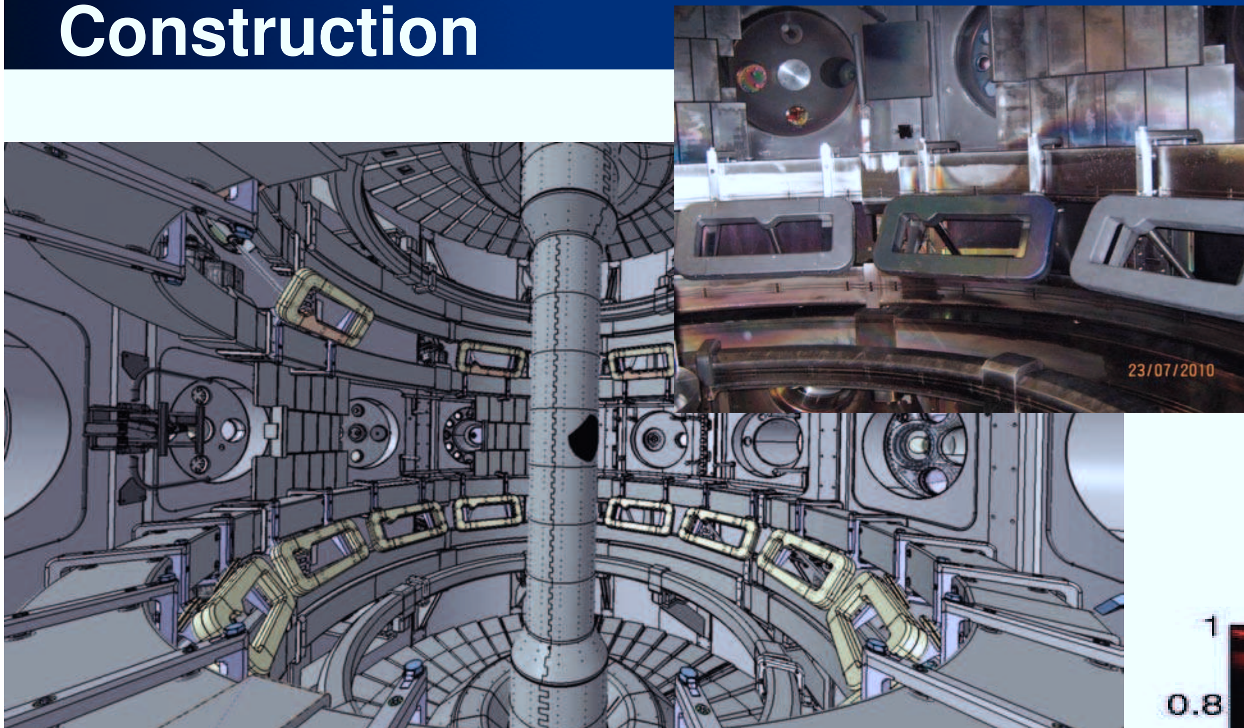


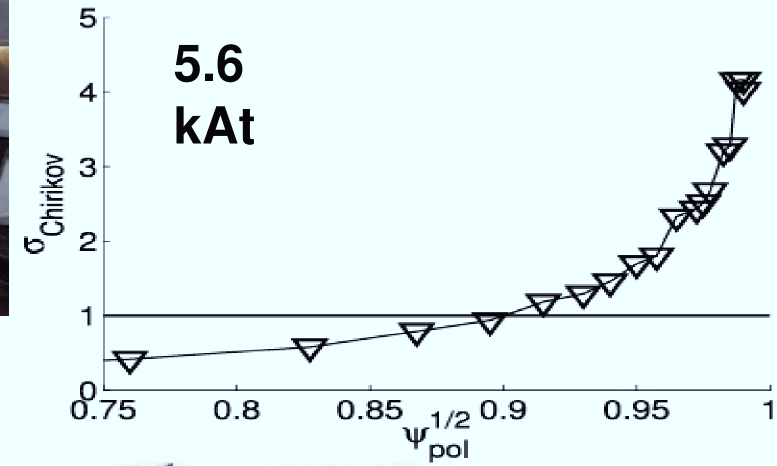
Not resonant

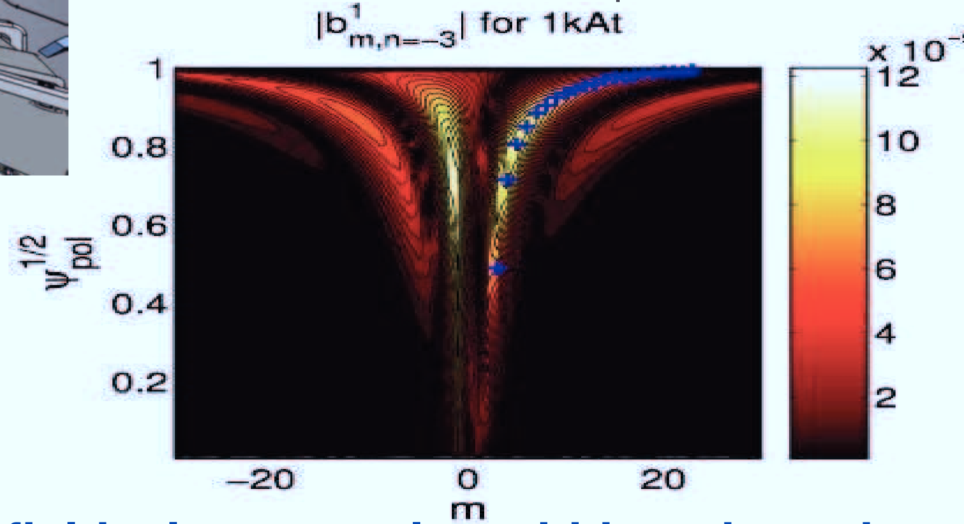
$n = 4$, minus-minus phasing

- **Allows up to n=4 static RMP fields, n=3 toroidally rotatable RMP fields**
- **Combination of on and off midplane coils will allow large variation of resonant vs. non-resonant components**

MAST: 6 Additional Below Midplane Coils Under Construction







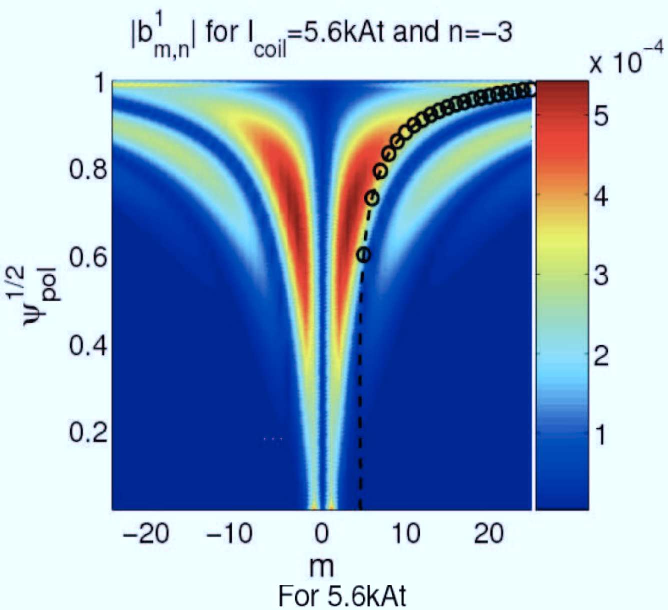
A. Kirk, private communication (2010)

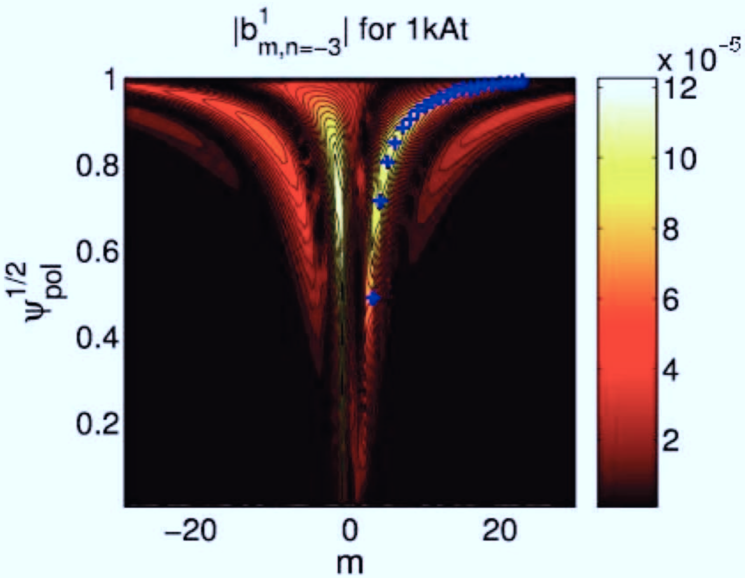
A. Kirk et al.*, Nuc. Fus. 50, 034008 (2010)*

- **Up to n=6 static and n=4 rotatable RMP fields, large overlap width and good pitch alignment for n=3**
- **Radial localization and mode purity for n>3 limited due to single row of 12 coils**
- **12 coil lower row optimum for LSN ITER shape plasmas**

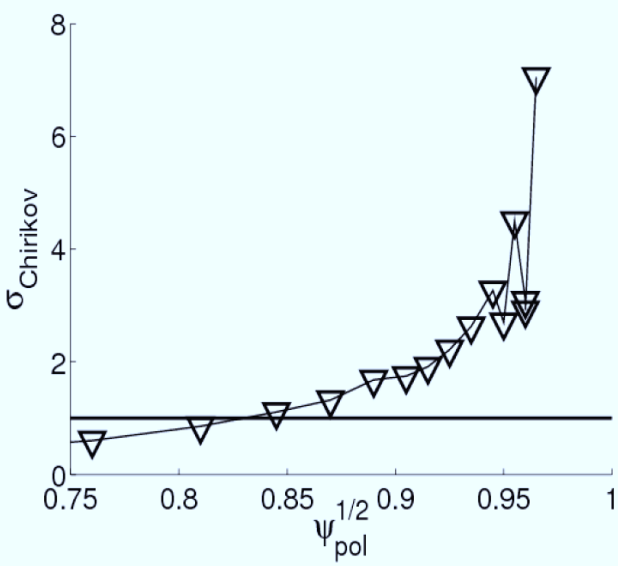
1.1 Reproduce RMP ELM suppression on at least one tokamak other than DIII-D - MAST Internal Off-Midplane Coils

Kirk

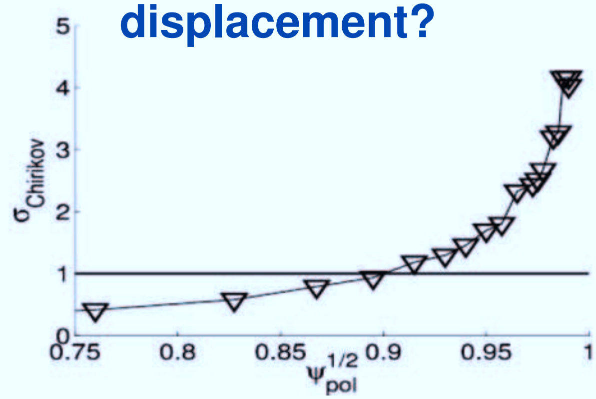




New 12-coil lower row plus full size LSN shape improves key issues - geometric coupling to coils (LSN shape), pitch alignment of RMP, collisionality and ρ^*



Smaller $\Delta_{chir>1}$ but better alignment and larger Xpt displacement?



KSTAR: In Principle Internal Coils Can Be Used to Generate RMPs

H.K. Kim *et al.*, Fusion Eng and Design Volume 84, Issues 2-6, June 2009, Pages 1029-1032

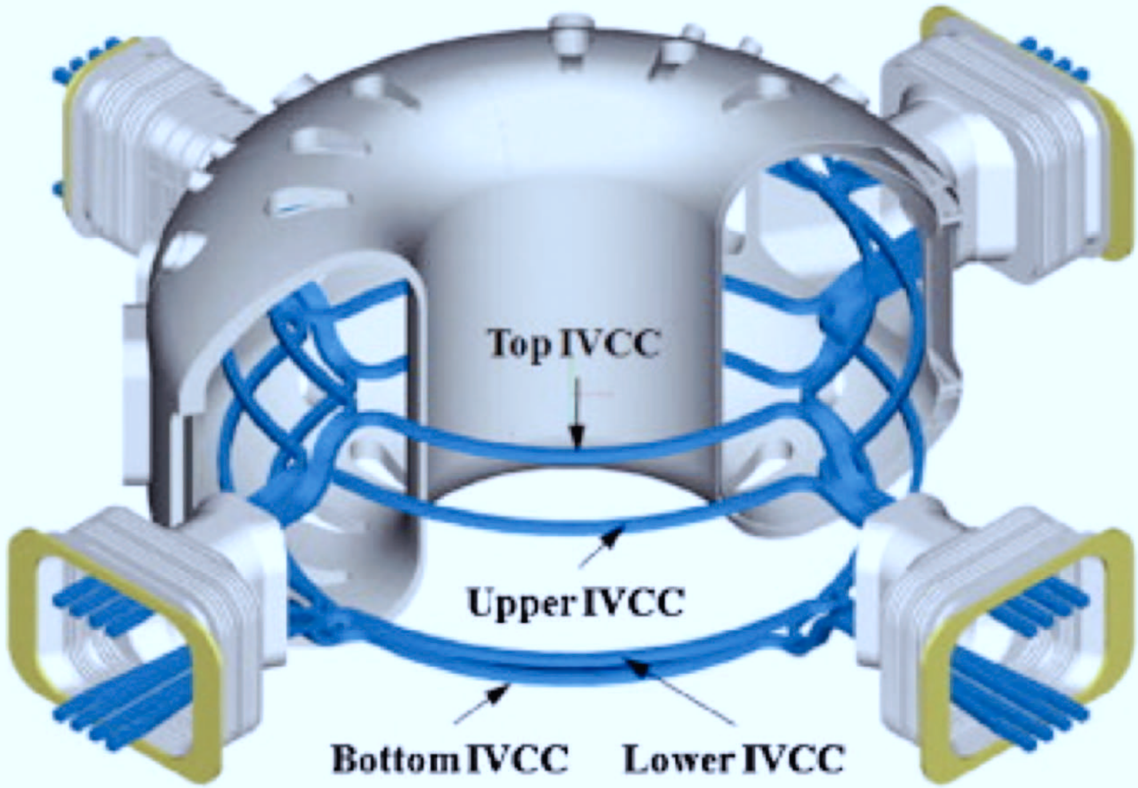


Fig. 1. Configuration of the KSTAR vacuum vessel and IVCC coils.

G.S. Lee *et al.*, Nuclear Fusion, Vol. 40, No. 3Y (2000)

- Static n=1 or n=2 RMPs from 2 rows of internal, off-midplane coils
- Narrow poloidal coil should give good radial localization
- Time response limited by passive plates skin time

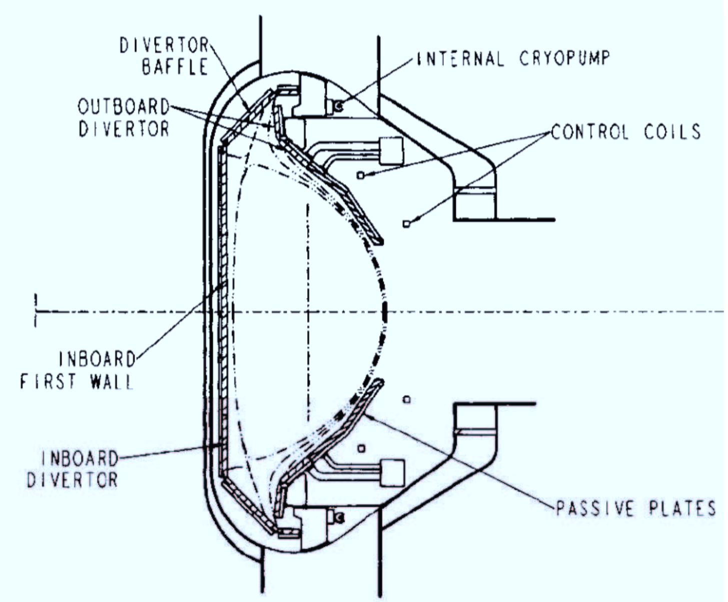
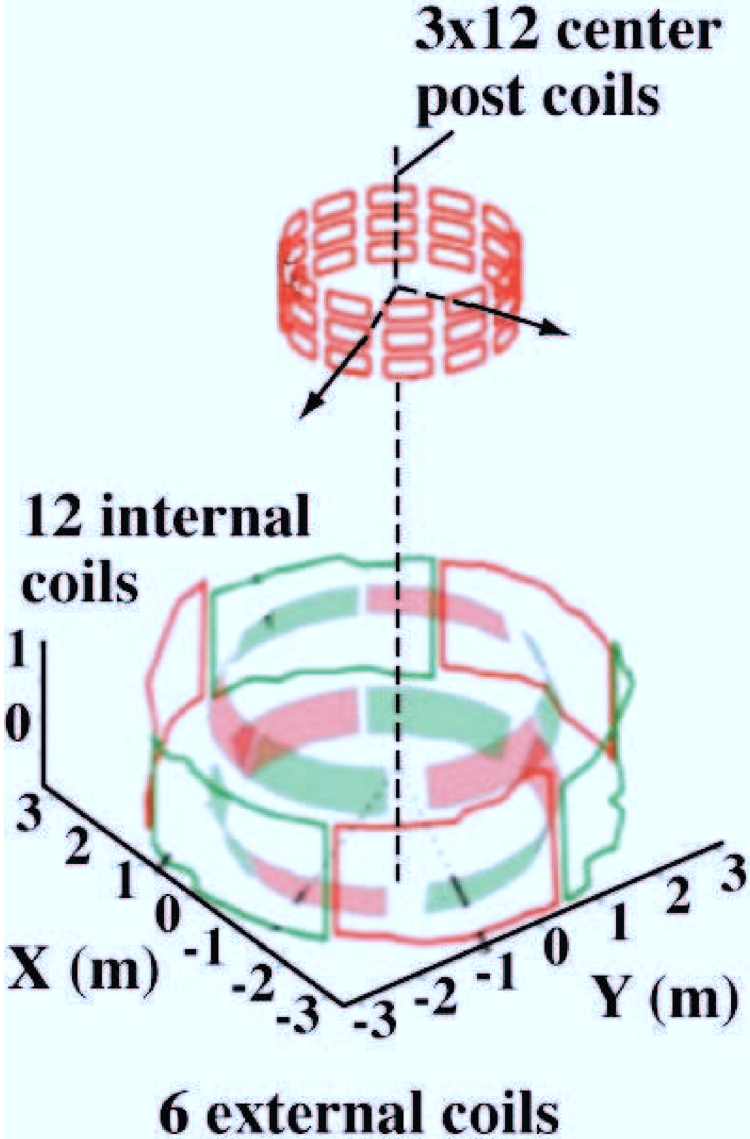


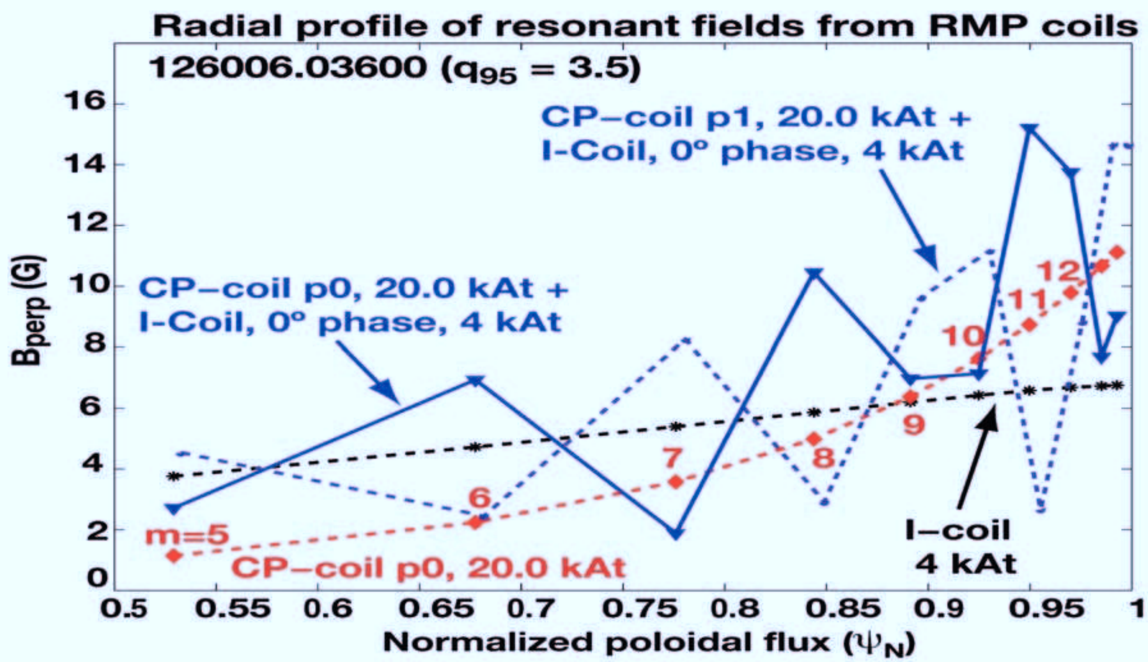
Figure 4. Cross-sectional view of KSTAR.

PROPOSED - CONSIDERED

DIII-D: CP-Coil (Plus the C- and I-coils) Would Significantly Increase RMP Physics Flexibility

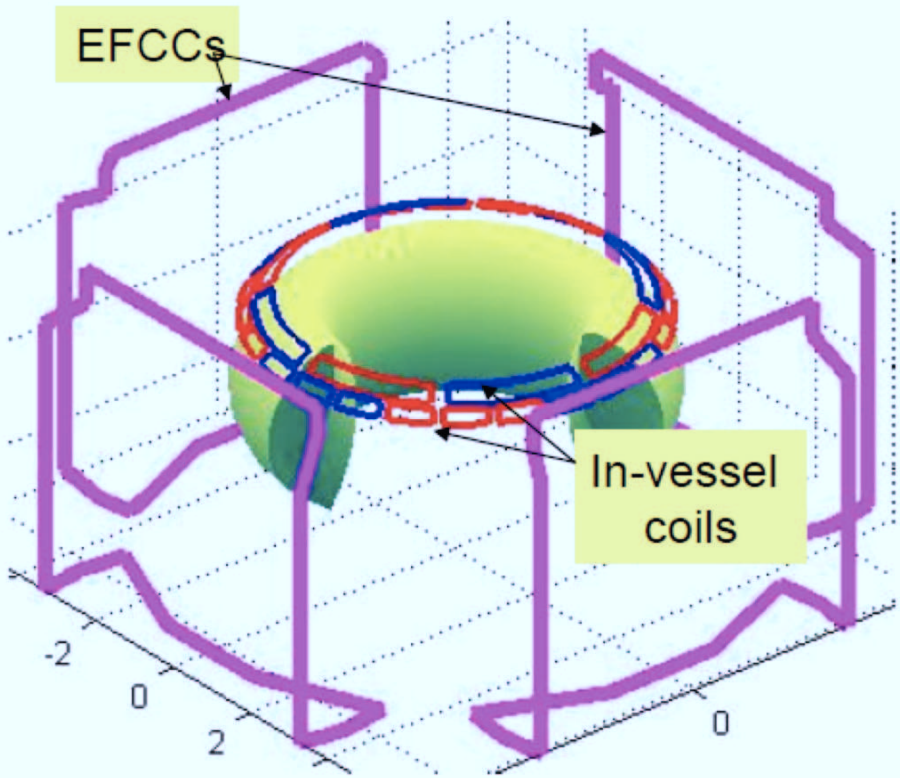


- **Would provide control of:**
  - Radial profile, localization
  - Poloidal profile
  - Toroidal rotation of RMP
    - Physics diagnostics
    - Heat flux spreading tests



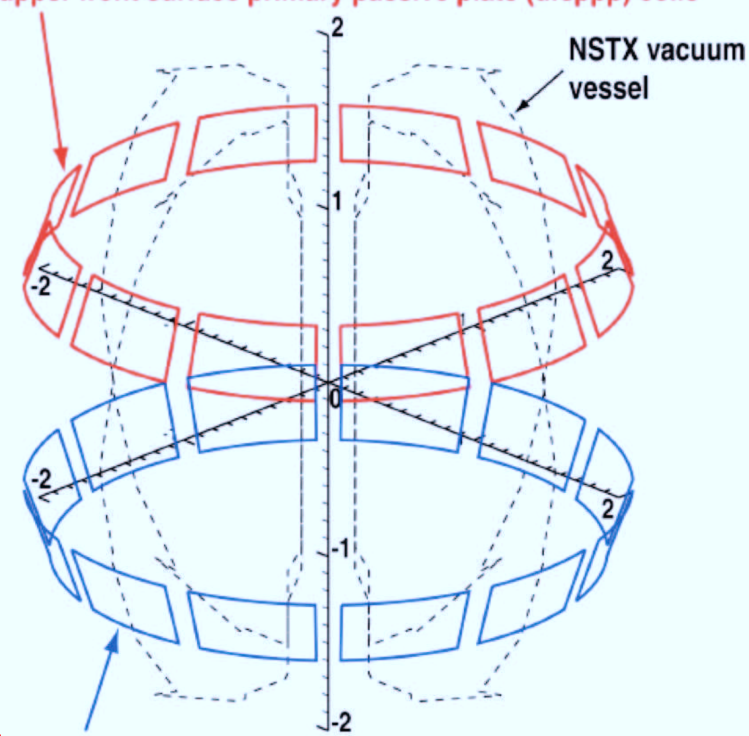
JET and NSTX: Considering Design Options for Internal Off-Midplane Coils

C. Lowry *et al.*, Bull Am. Phys. Soc., Vol. 54, (2009) 329



- JET: Considering coils above outer midplane
  - 8 upper coils
  - 24 mezzanine coils
- Would be capable of rotatable n=4 with single row

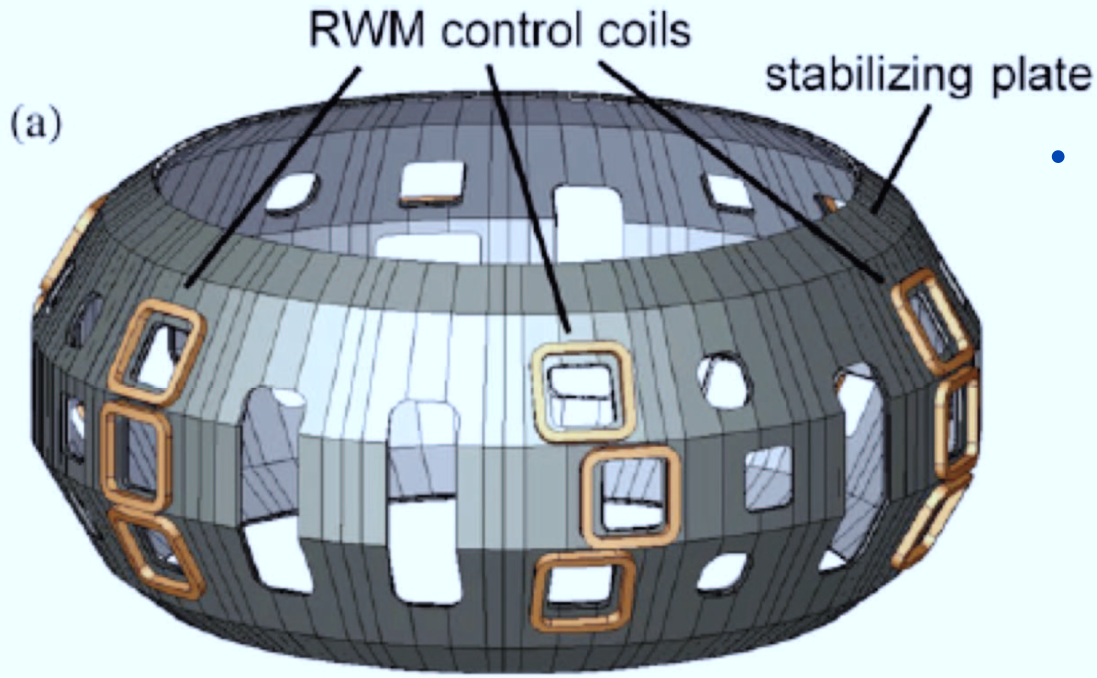
- NSTX: Considering 12 coils above and 12 below outer midplane
- Would be capable of static n=6 and rotatable n=4 RMP fields



NSTX Research 5-Year Plan for 2009-13, http://nstx.pppl.gov/fiveyearplan.html

JT60-SA and TCV: Internal Coils Under Study Primarily for RWM Control Could Produce RMPs

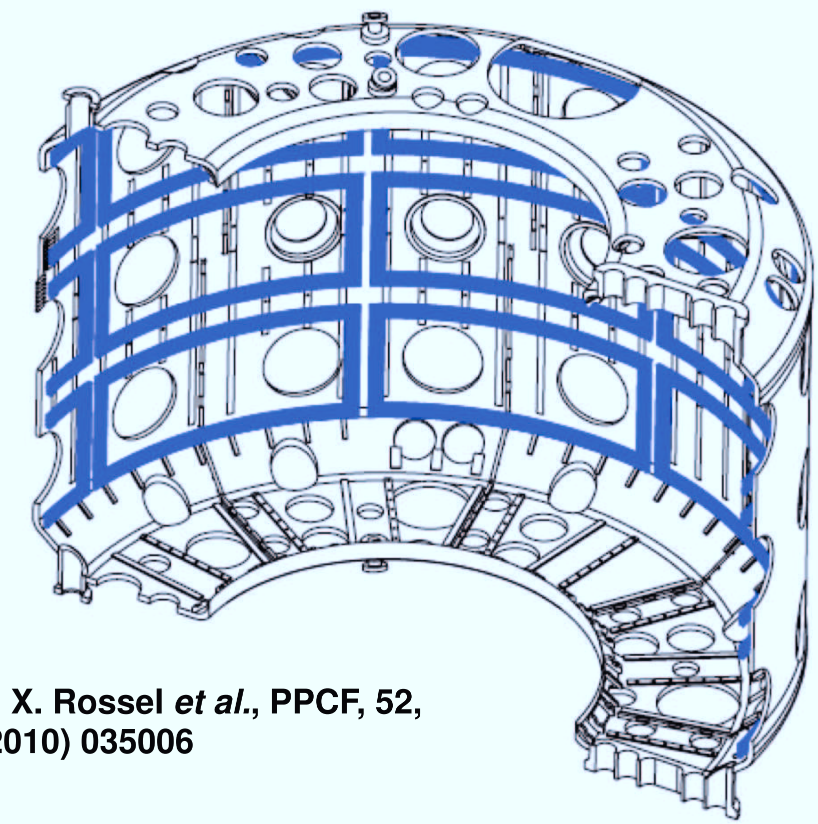
T. Fujita *et al.*, 2007 Nucl. Fusion 47 1512   M. Kikuchi et al., IAEA, 2006



M. Matsukawa *et al.*, IAEA 2006, FT/P7-5

- JT60-SA: Considering 6 coils above, below and on outer midplane
- Narrow toroidal extent would produce mixed spectrum

- TCV: Considering 6 coils above, below and on outer midplane
- Large toroidal extent would allow focused static n=3 fields



J. X. Rossel *et al.*, PPCF, 52, (2010) 035006

Summary/Outline: Progress in RMP ELM Control Understanding From Multi-Machine Comparisons

- **Static RMP Fields Affect ELM Behavior in Several Tokamaks**
  - ELM mitigation in many devices
  - ELM suppression robust but unique to DIII-D
- **Island Overlap Region Width (Vacuum Fields), $\Delta_{Chir>1}$ Greater Than ITER Guidance Value (0.165 in Ψ_N) Not Sufficient to Assure ELM Suppression**
  - DIII-D databases at fixed q_{95} indicate condition may be necessary for suppression
  - Other conditions (perturbation pitch alignment, plasma beta and collisionality, etc.) may be important
  - Physics understanding must include plasma response
- **RMP Fields Above Threshold Strength Can Increase L-H Threshold Power**
  - Required RMP strength to increase P_{L-H} may be higher for predominantly non-resonant fields
- **Many Experimental Programs Installing or Considering Internal RMP Coils**