

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. Fenstermacher¹⁾



M. Becoulet²⁾, P. Cahyna³⁾, J. Canik⁴⁾, C.S. Chang⁵⁾, T.E. Evans⁶⁾, P. Gohil⁶⁾, S. Kaye⁷⁾, A. Kirk⁸⁾, Y. Liang⁹⁾¹⁰⁾, A. Loarte¹¹⁾, R. Mainigi⁴⁾, O. Schmitz⁹⁾, W. Suttrop¹²⁾, (members), H. Wilson¹³⁾ (PEP ITPA Chair)

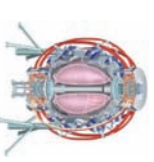
1) LLNL - Livermore, CA USA, 2) CEA/IRFM - Cadarache, France, 3) IPP - Prague Czech Repub, 4) ORNL - Oak Ridge, Tennessee USA, 5) Courant Institute NYU - NY, NY USA, 6) GA - San Diego, CA, USA, 7) PPPL - Princeton, NJ, USA, 8) EURATOM/CCFE Culham - Abingdon Oxon, UK, 9) Forschungszentrum Jülich, Jülich, Germany, 10) JET-EFDA - Abingdon, UK, 11) ITER - Saint Paul Lez Durance, France, 12) EURATOM-Max-Planck IPP - Garching, Germany, 13) Univ. York - Heslington, York, UK

Presented at the 23rd IAEA Fusion Energy Conference

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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), $\Delta_{\text{Chir}} > 1$ Greater Than ITER Guidance Value (0.165 in Ψ_N) Not Sufficient to Assure ELM Suppression
 - DIII-D databases at fixed q_5 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

Suppression Outside DIII-D

Goal	Task	Q1-09	Q2-09	Q3-09	Q4-09	Q1-10	Q2-10	Q3-10	Q4-10	Q1-11	Q2-11	Q3-11
1.1 (a) Suppress ELMs using RMPs on MAST		Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
1.1 (b) Suppress ELMs using RMPs on AUG		Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
1.1 (c) Explore potential to mitigate/suppress ELMs with mid-plane coils (NSTX, JET)		Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green

Model Development and Validation

1.2 (a) Model and compare vacuum RMP field for MAST and DIII-D with suppressed ELMs		Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
1.2 (b) Test model based on min stochastic width and alignment of perturbation with q against MAST and DIII-D data		Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
1.2 (c) If 1.2(b) is successful, predict scenarios for ELM suppression in advance of AUG expts 1.1(b)		Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
1.2 (d) Compare RMP data for on and off-mid-plane coils (JET, MAST, DIII-D, NSTX)		Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
1.2 (e) Interpret data from 1.2(d) using model developed in 1.2(d)		Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
1.2 (f) Predict ELM suppression criteria/regimes for ITER: optimise ITER coil design		Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
1.2 (g) Quantify the impact of torque and plasma rotation on ELM mitigation and suppression (DIII-D, JET, MAST, NSTX)		Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow

Pedestal Height and Width

1.3 (a) Compare pedestal height with and without RMP ELM suppression on DIII-D and MAST		Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue
1.3 (b) Compare measured pedestal height with RMP with EPEDI model predictions (JET,MAST,NSTX,AUG,DIII-D)		Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue
1.3 (c) Demonstrate the ability to maintain the required edge density during ELM suppression (DIII-D, MAST)		Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue
1.3 (d) Quantify impact of RMP on core transport and H-factor (JET,MAST,NSTX,DIII-D)		Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue

Divertor Power Loading

1.4 (a) Quantify impact of RMP-suppressed ELM regimes on divertor power loading (DIII-D, MAST)		Pink	Pink	Pink	Pink	Pink	Pink	Pink	Pink	Pink	Pink	Pink
1.4 (b) Make recommendations on need to rotate RMPs: input to AUG design (DIII-D, MAST)		Pink	Pink	Pink	Pink	Pink	Pink	Pink	Pink	Pink	Pink	Pink
1.4 (c) If necessary, explore impact of rotating RMPs on ELM suppression (JET, NSTX, AUG, MAST,DIII-D)		Pink	Pink	Pink	Pink	Pink	Pink	Pink	Pink	Pink	Pink	Pink

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)		Brown	Brown	Brown	Brown	Brown	Brown	Brown	Brown	Brown	Brown	Brown
1.5 (b) Quantify ability to suppress or mitigate ELMs close to LH transition threshold (NSTX, JET,AUG, MAST, DIII-D)		Brown	Brown	Brown	Brown	Brown	Brown	Brown	Brown	Brown	Brown	Brown

With Pellets

1.6 (a) Demonstrate RMP ELM suppression with ITER-like pellet fuelling (DIII-D, AUG, MAST)		Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue
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ITER Predictions

1.7 Demonstrate ability of modulated RMP fields to mitigate ELM size by at least a factor of 20		Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey
1.8 (a) Model the performance of the ITER RMP and optimise design		Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red

• 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 collisionality
- **Effect on P_{L-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, Rozhansky](#)
- 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

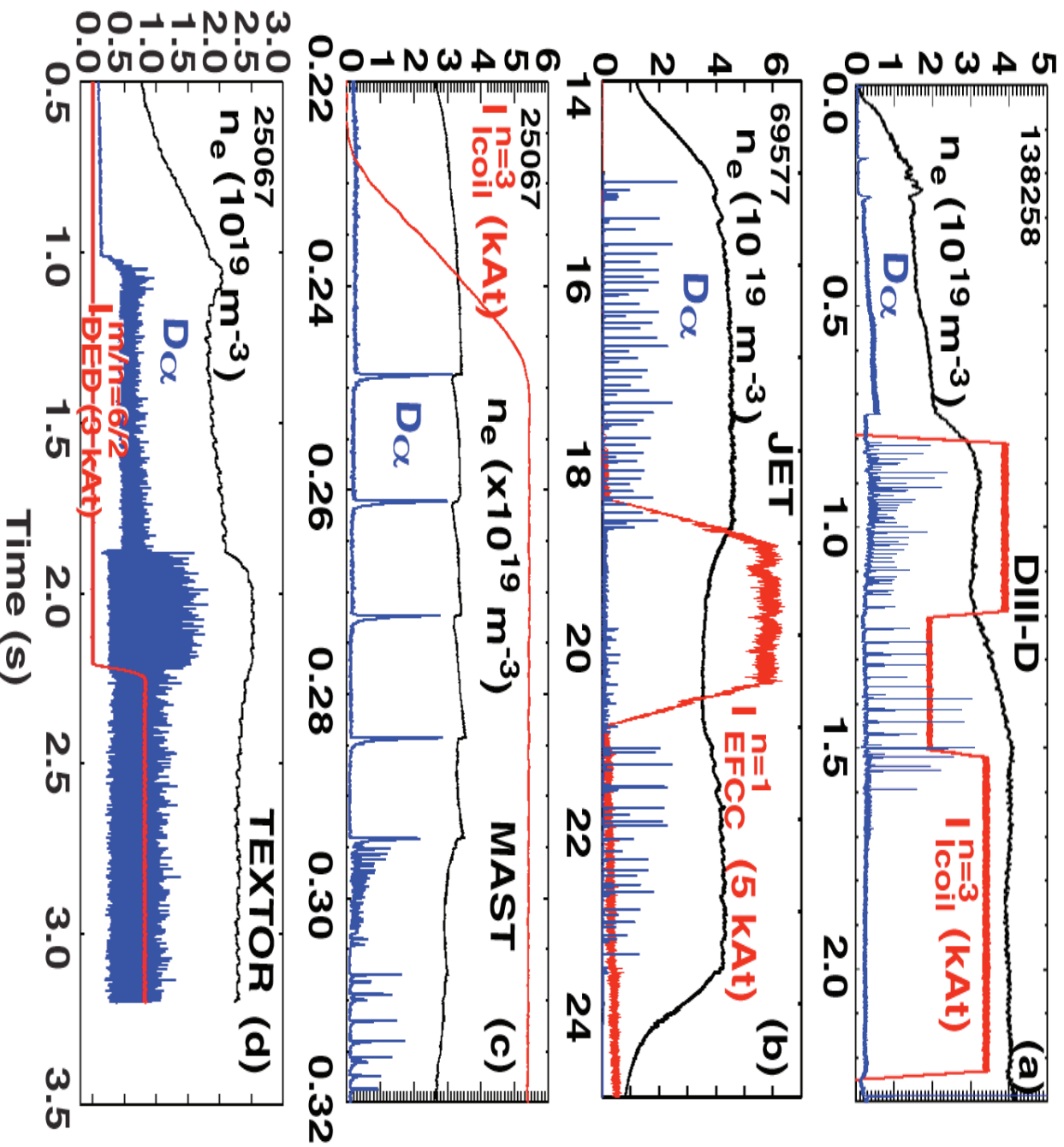
- Titus FTP/P6-32 Thurs pm

Theory / Modeling

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

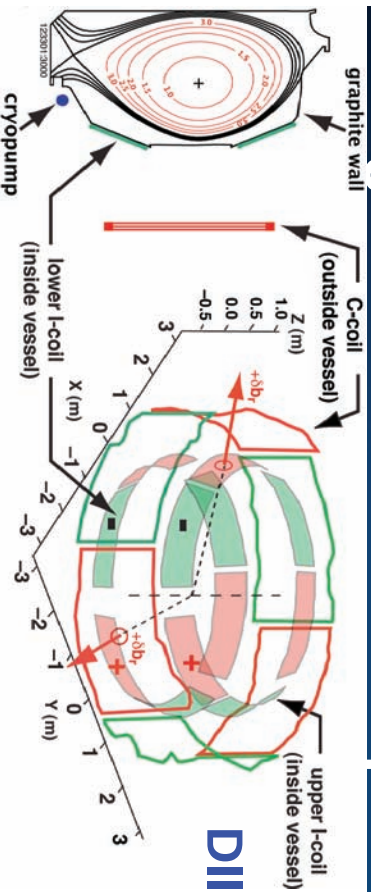
Selected International Results

ELMs Affected by Static RMP Fields in Multiple Devices

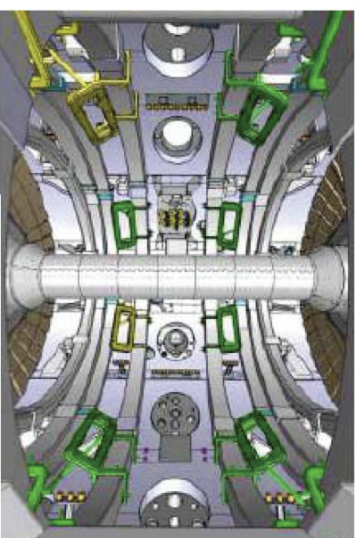
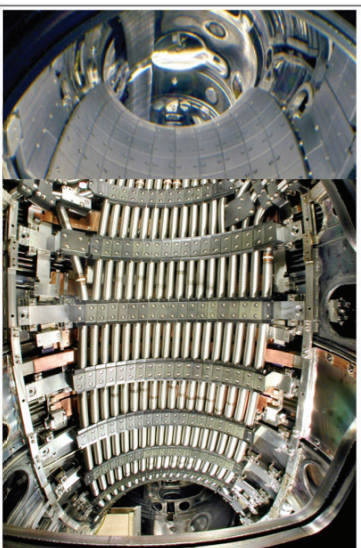


- ELM suppression obtained only in DIII-D so far
- ELM size mitigation in JET, MAST, TEXTOR (and DIII-D)
- Density reduction frequently seen when ELMs are mitigated
 - No additional density reduction at ELM suppression

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



TEXTOR $n=3$ I-coil and C-coil configuration (with even parity I-coil)



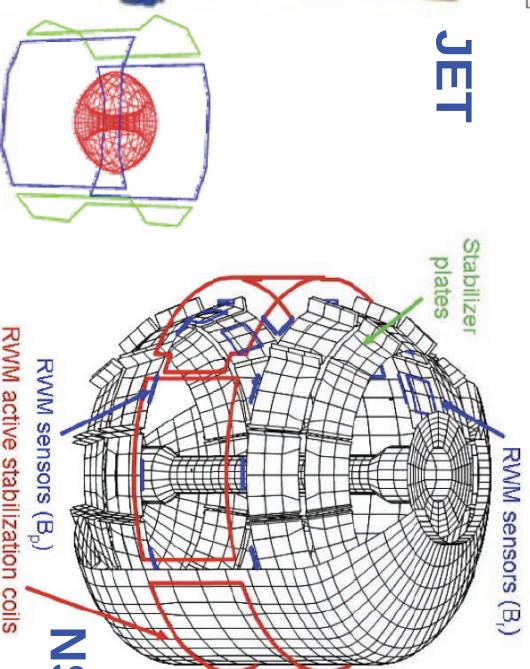
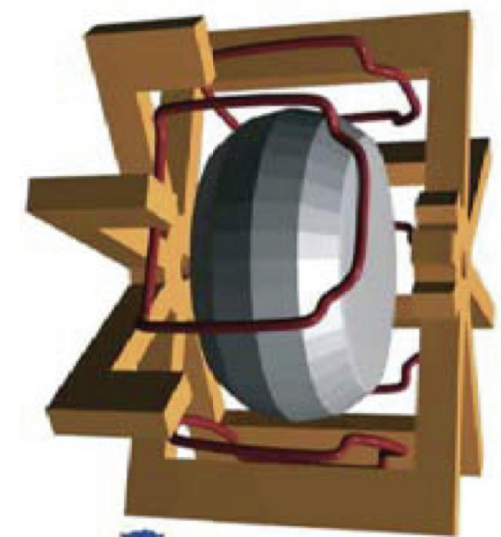
- Experiments focus on different RMP perturbations (PEP-19):

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

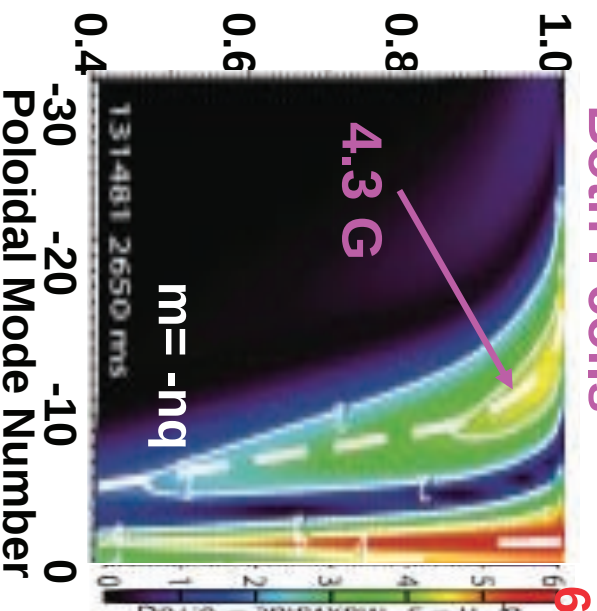
External Coils – PEP-25

- JET: $n=1$ and $n=2$ resonant and non-resonant
- NSTX: $n=3$ resonant, some non-resonant

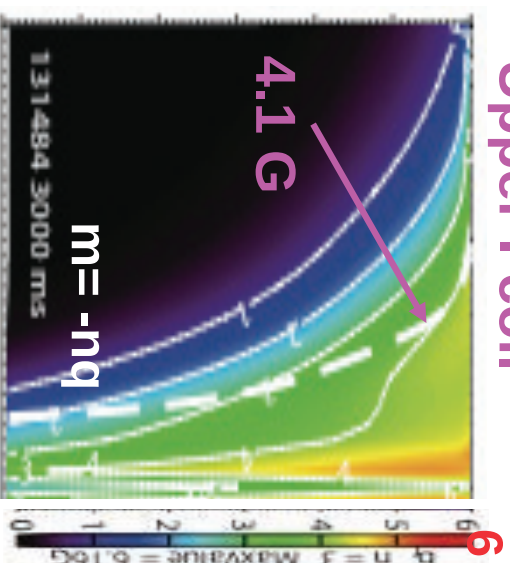


Coil Sets in DIII-D, JET, MAST, NSTX and TEXTOR Give Range of Static RMP Spectra

Both I-coils



Upper I-coil



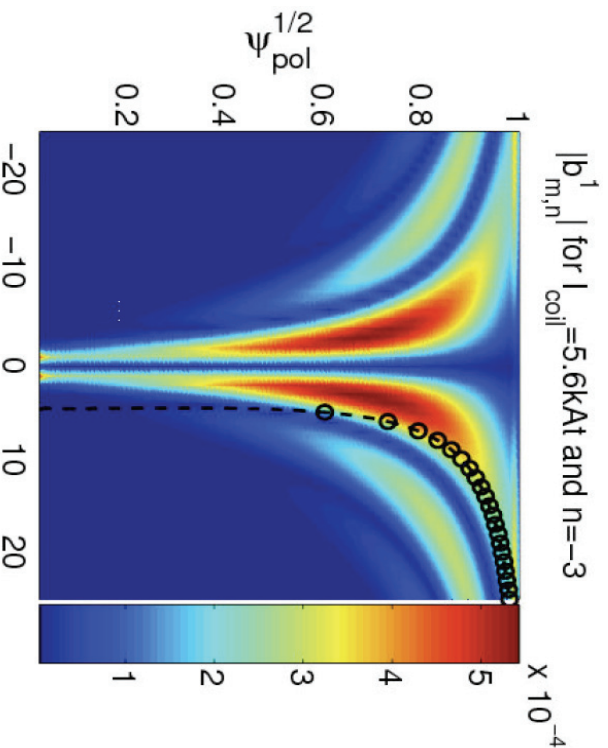
- Experiments focus on different

6 RMP perturbations (PEP-19):

- Internal Coils – PEP-23
 - DIII-D: $n=3$ resonant, some non-resonant, also $n=2$
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– External Coils – PEP-25

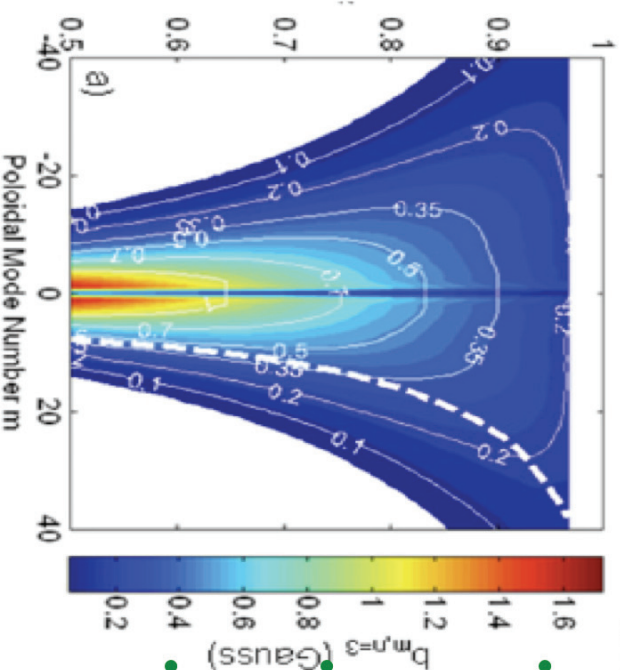
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Coil Sets in DIII-D, JET, MAST, NSTX and TEXTOR Give Range of Static RMP Spectra

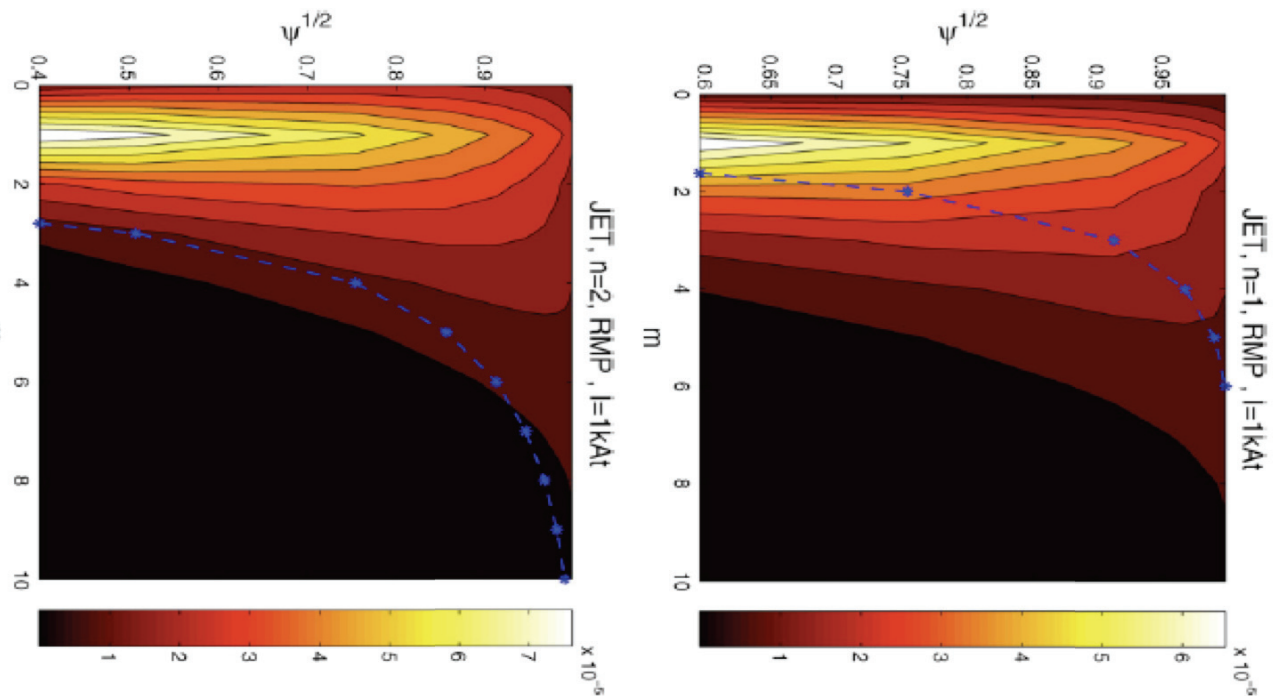
- Experiments focus on different RMP perturbations (PEP-19):

Internal Coils – PEP-23



- DIII-D: $n=3$ resonant, some non-resonant, also $n=2$
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External Coils – PEP-25



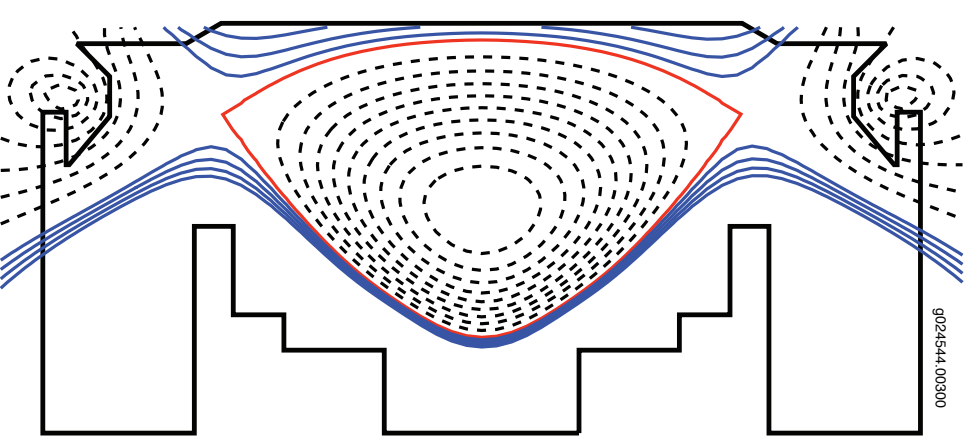
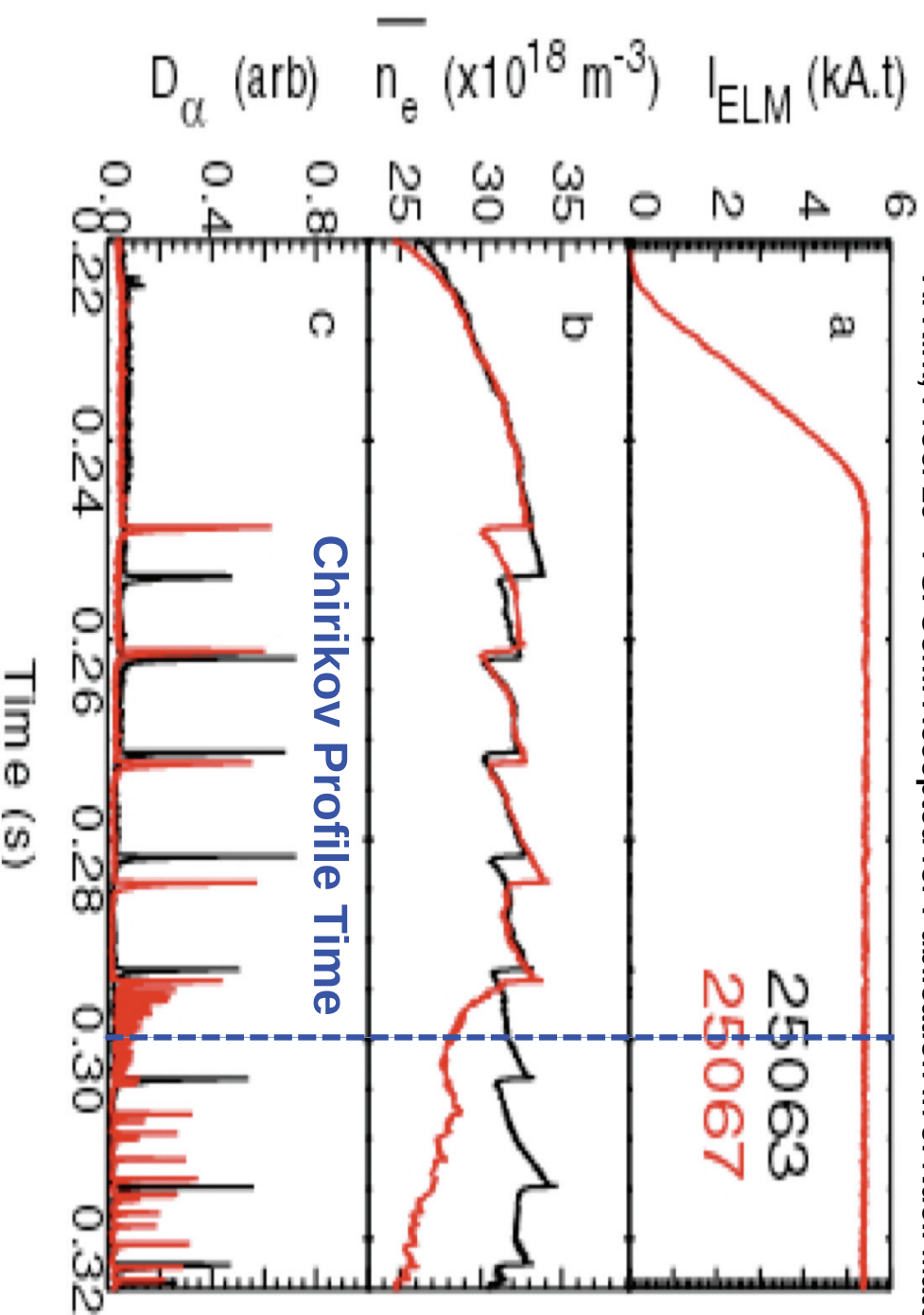
- JET: $n=1$ and $n=2$ resonant and non-resonant
- NSTX: $n=3$ resonant, some non-resonant

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

- **Show**
 - **RMP with n=3 and $\Delta_{\text{Chi}>1} = 0.265$ Produces Type-I $\rightarrow$ 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, $P_{\text{L-H}}$ increases 30-40%
 - PDF of j_{sat} inside LCFS broadens in L-mode, turbulence changes

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

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

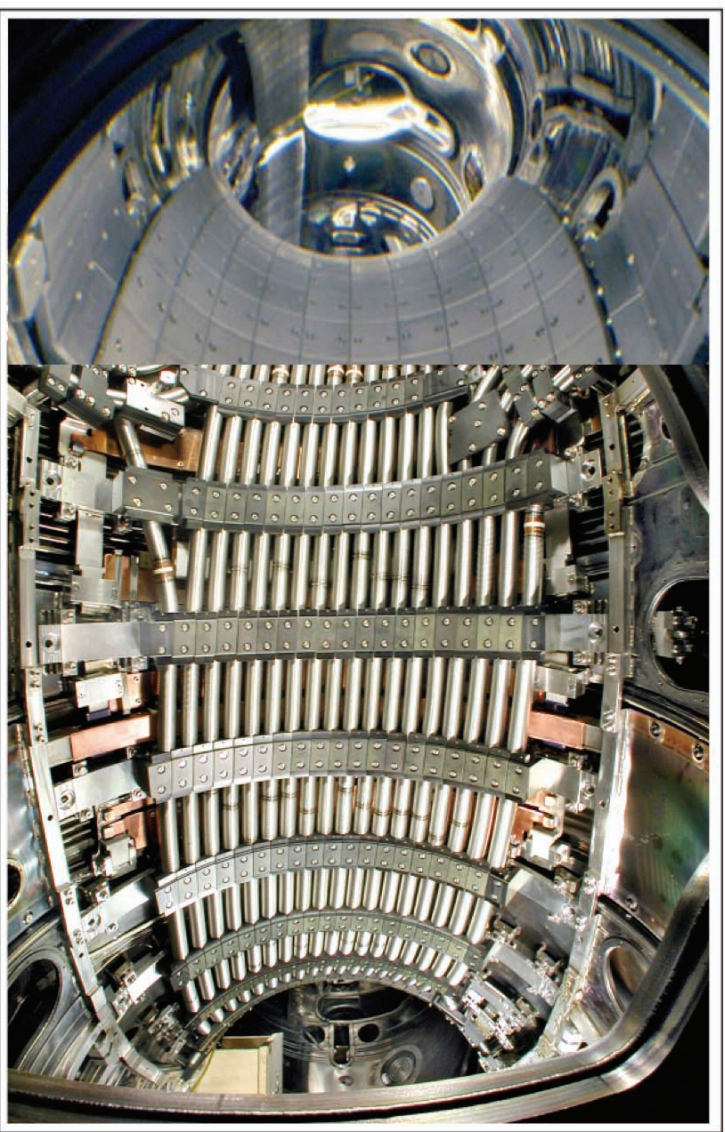


- Initial application of $n=3$ RMP does not change ELM character
- After four Type-I ELMs character changes to Type-IV and then to higher frequency Type-I

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

Show

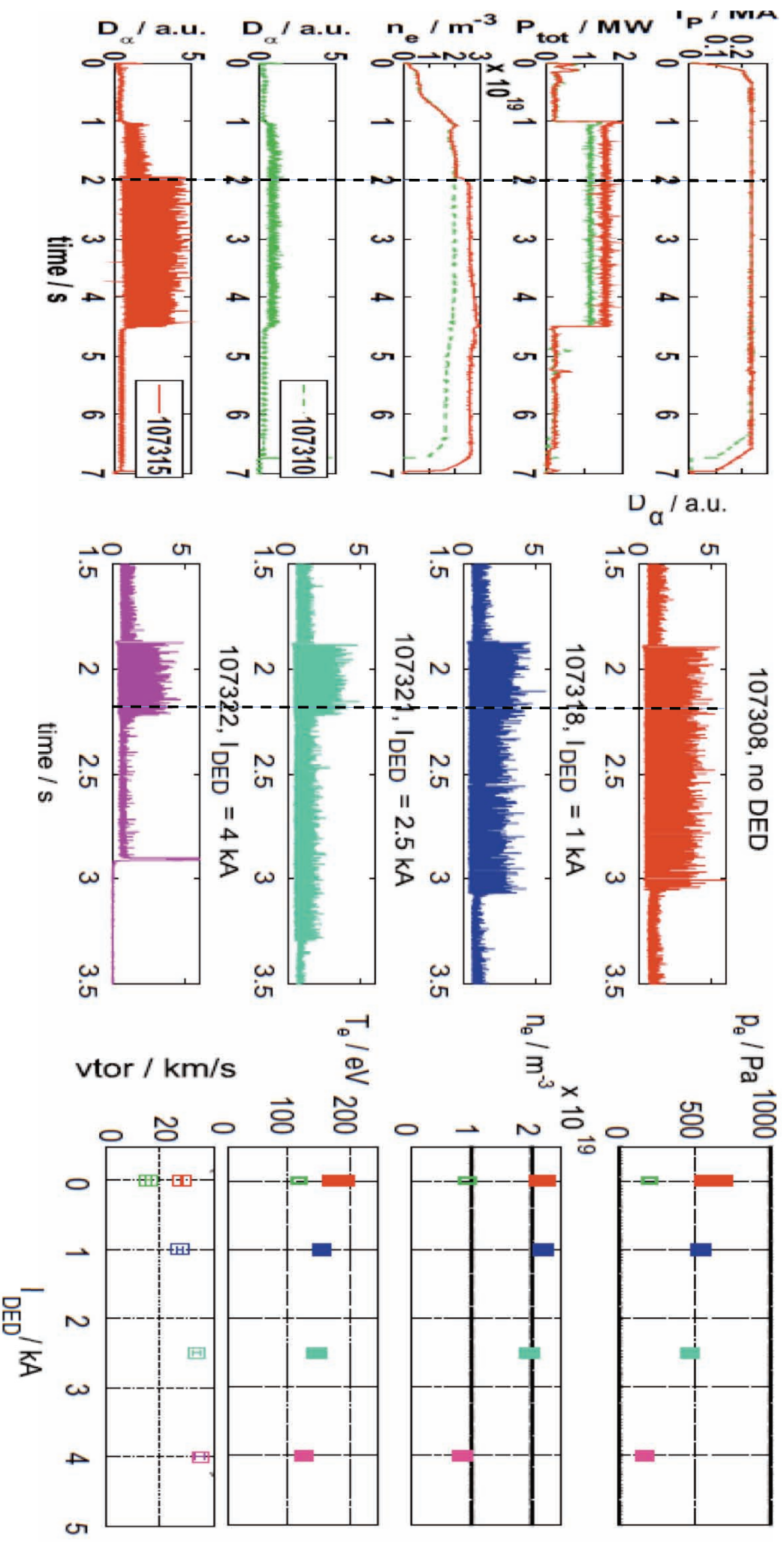
- Limiter H-mode achieved with NBI
- ELM mitigation seen with $m/n = 6/2$ perturbation from HFS internal DED
- ELM frequency increase, size and pedestal parameter reductions scale with DED current



Not Show

- L-mode-like pressure profile with small ELMs at highest $I_{DED} = 4 \text{ kA}$
- 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 ELMinig H-mode

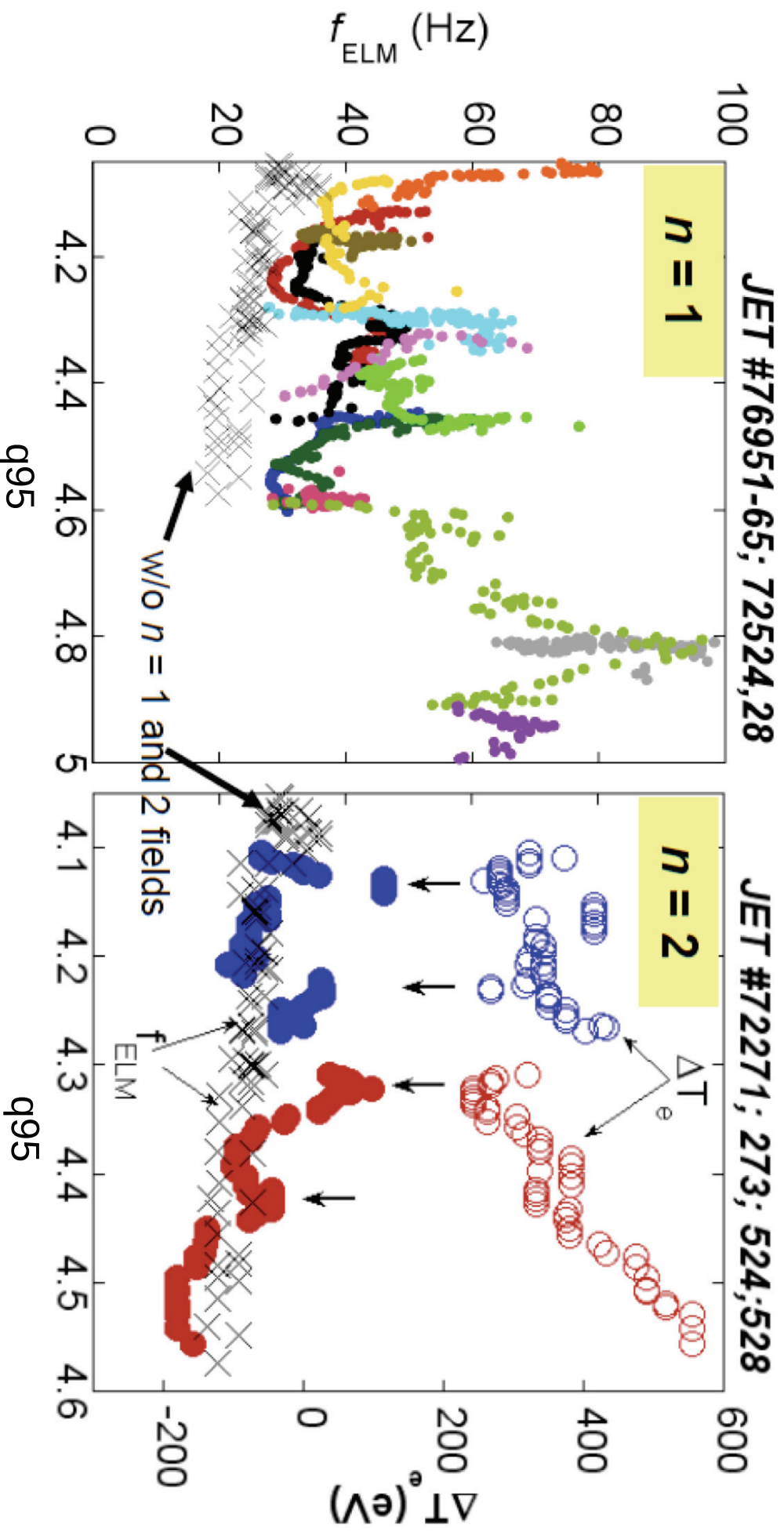


- $P_{NBI} = 1.6 \text{ MW}$, $q_{95} = 3.7$, DED in $m/n = 6/2$ configuration
 - Profiles with $I_{DED} = 4 \text{ kA}$ indicate L-mode
- B. Unterberg, JNM, 390–391 (2009) 351–354

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 1st 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

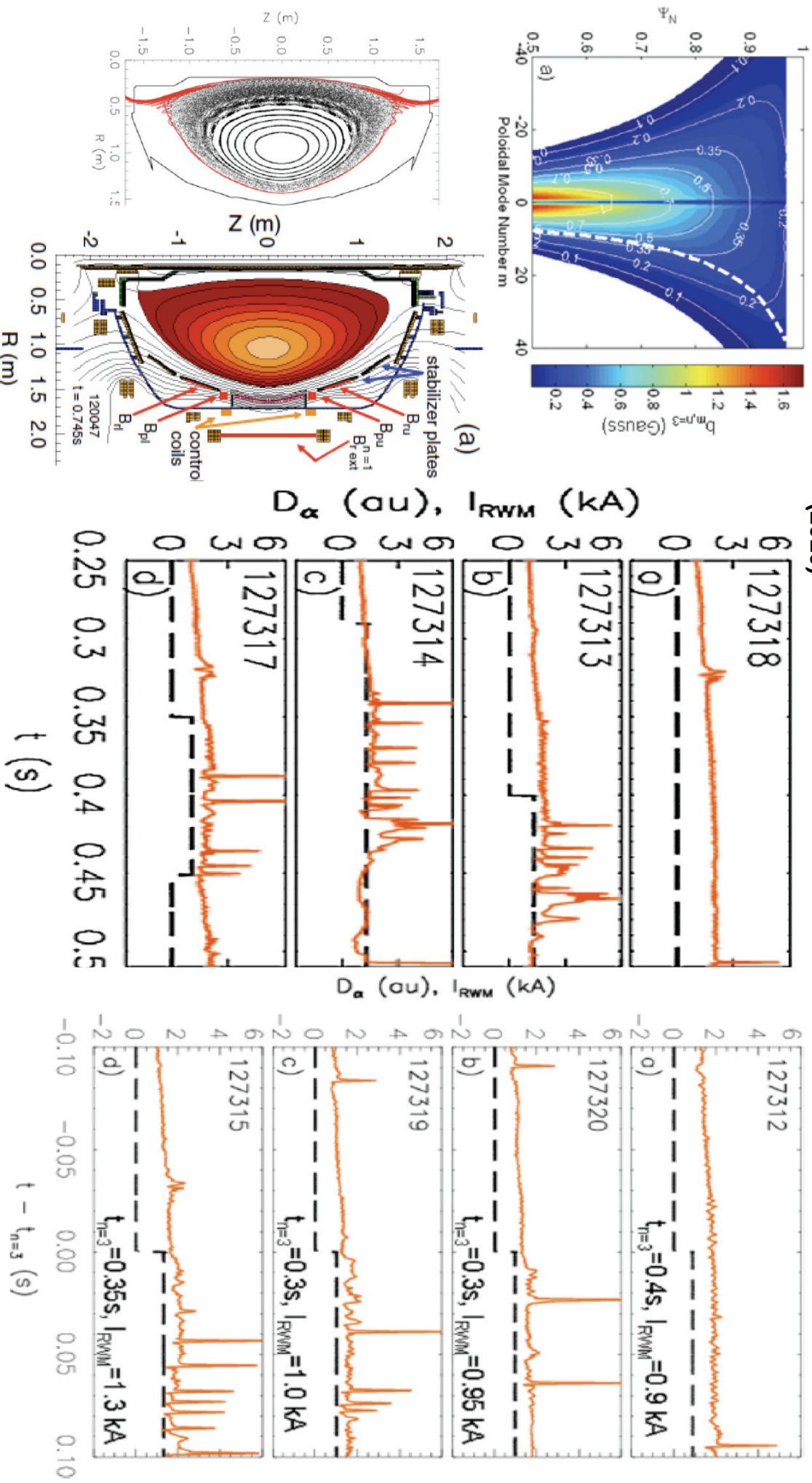
- Deep core perturbation using n=3 RMP from external coils
- RMP induces ELMs in an ELM-free H-mode
 - ELM start time follows RMP turn-on
 - ELM frequency increases with RMP amplitude

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

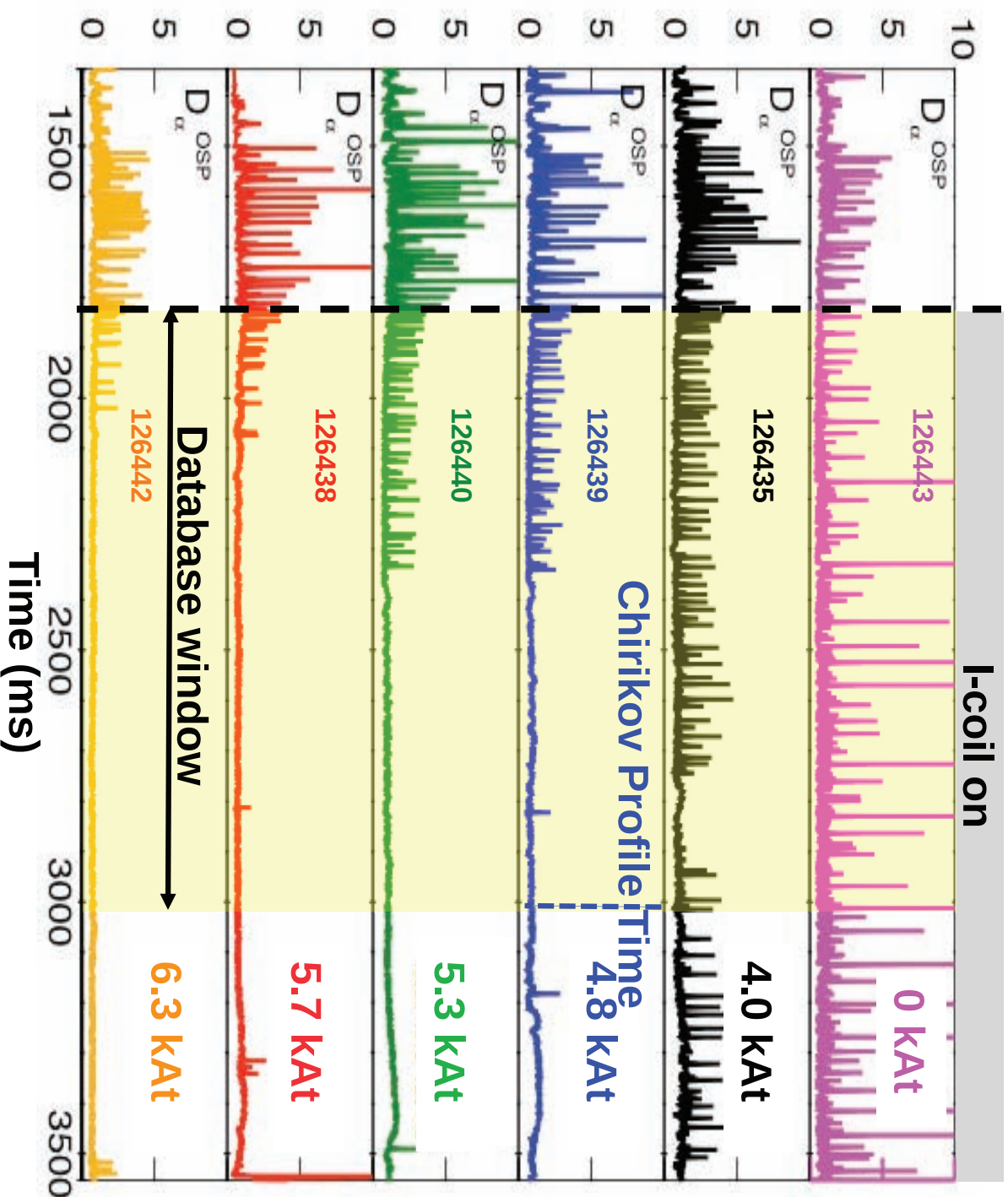


- **ELM response to RWM coil current tracks current on-time within 50 ms**

ISLAND OVERLAP WIDTH

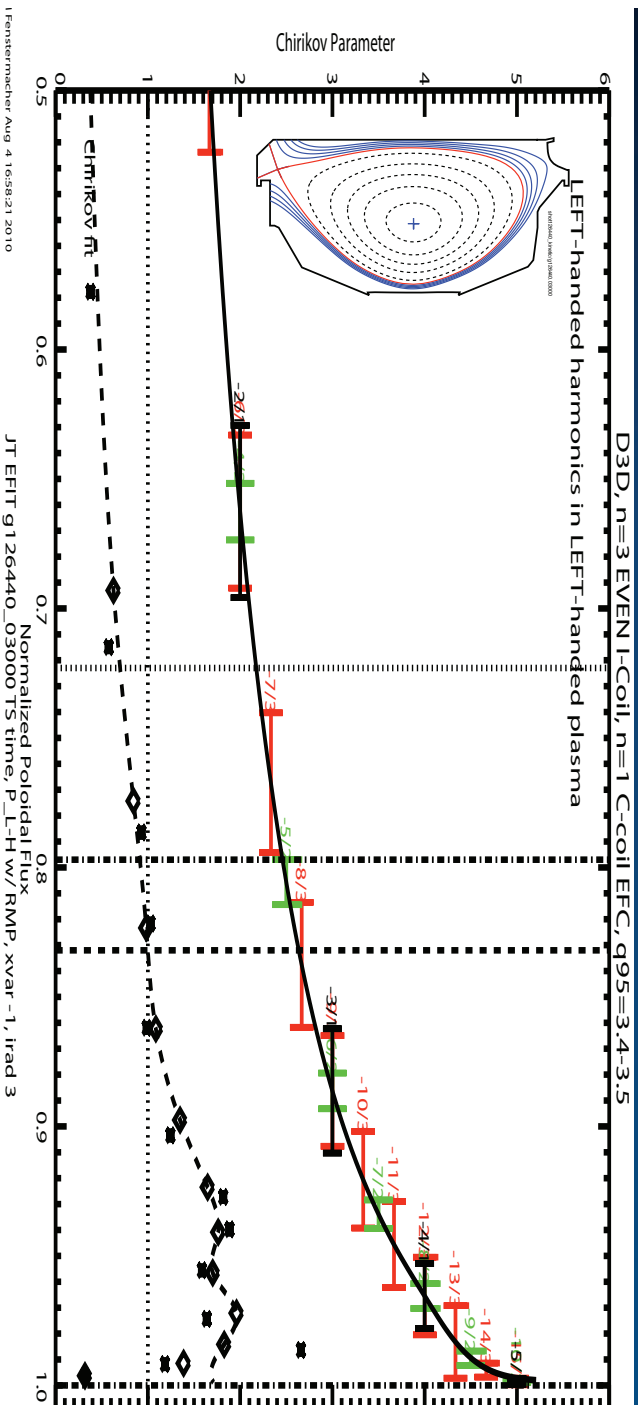
DIII-D: I-coil Current Scan at Fixed Shape and q_{95} Produces Systematic Change in ELM Behavior

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

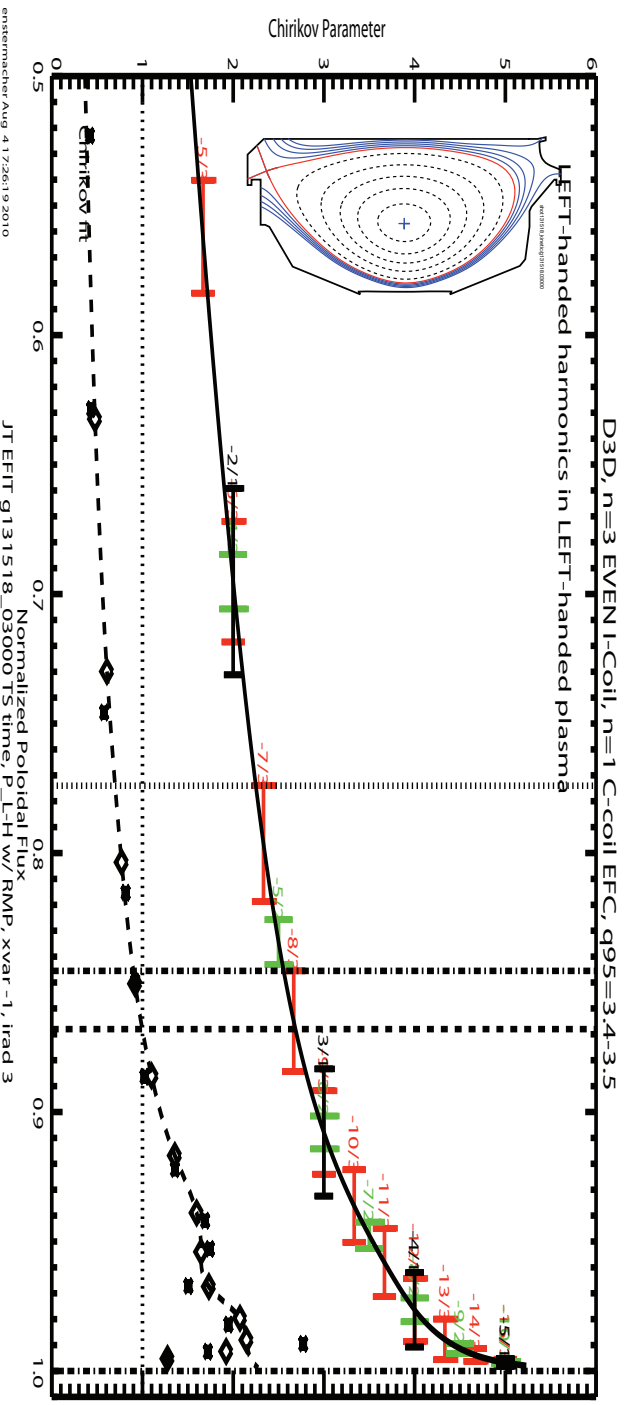


- Provides multi-ELM sampling
 - 24 kinetic EFIT timeslice windows per shot
 - Multiple ELMs for many of the EFIT windows
- Similar sampling of other scans
- Complete suppression earlier at higher I-coil current

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



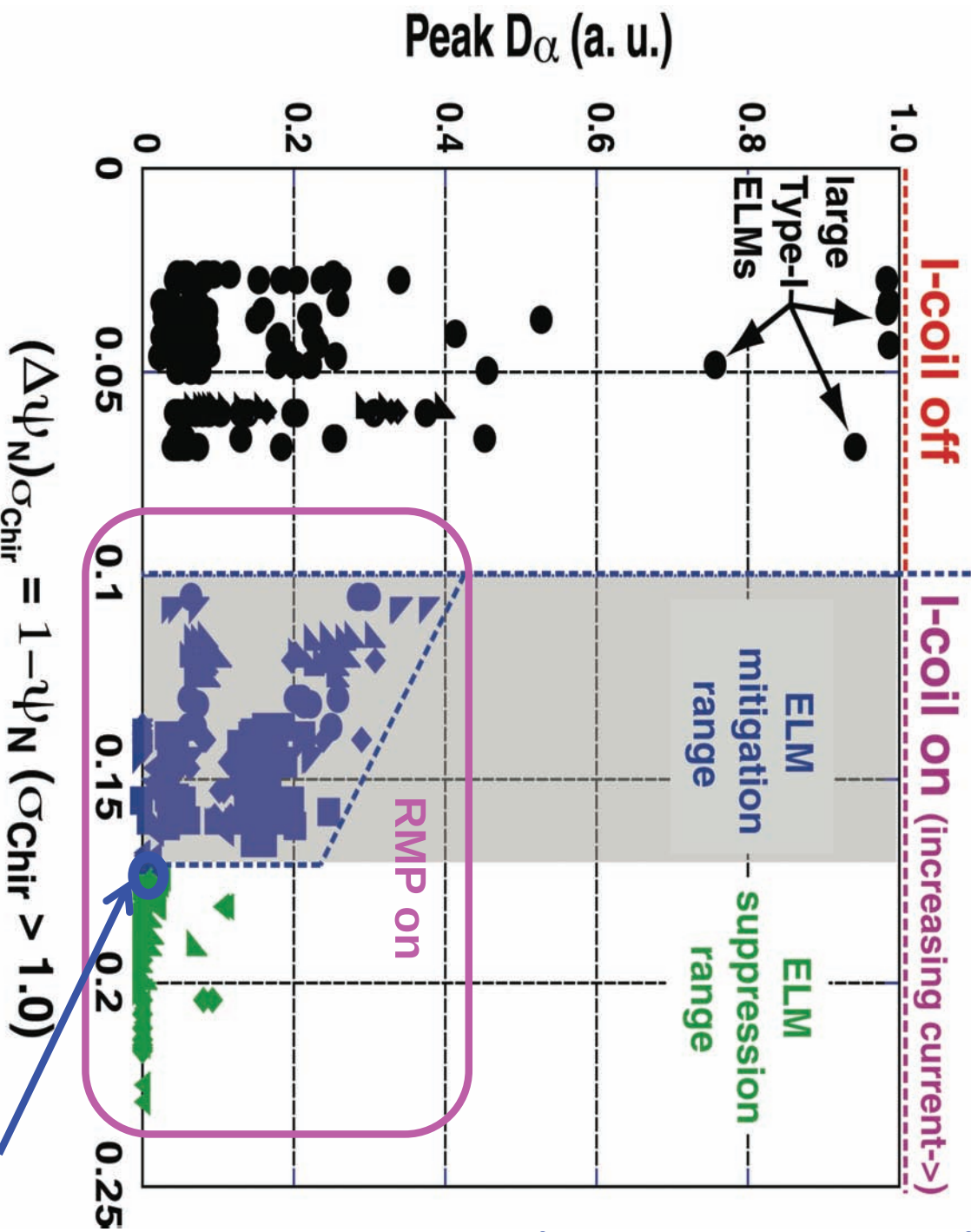
- Applied n=3 RMP fields from internal coils + n=1 fields from EFC coils + intrinsic error fields contribute



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

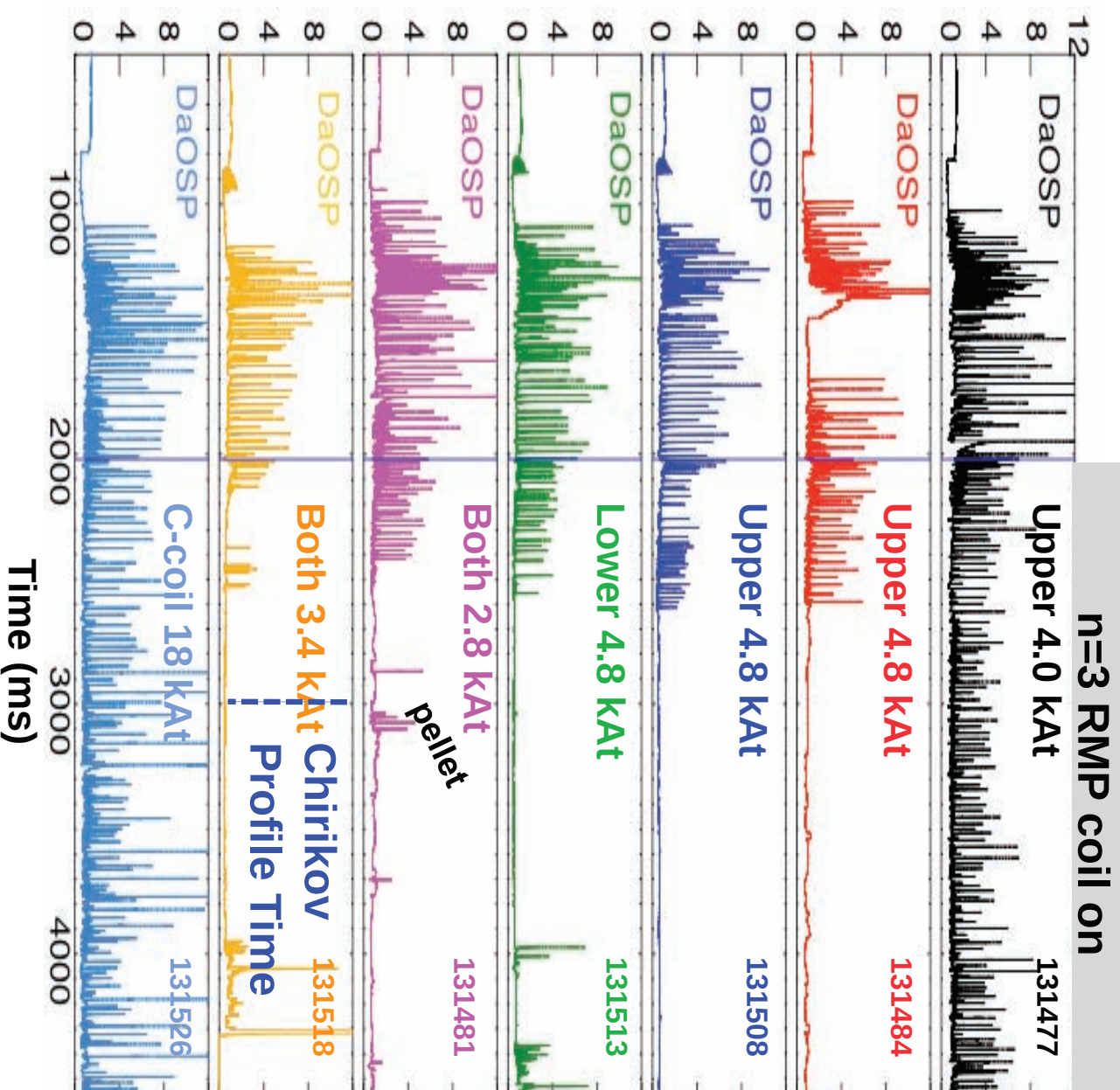
- Full spectrum of ELM sizes both without and with RMP

- Consistent with non-linearity of ELM instability

Chirikov

Profile Time

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

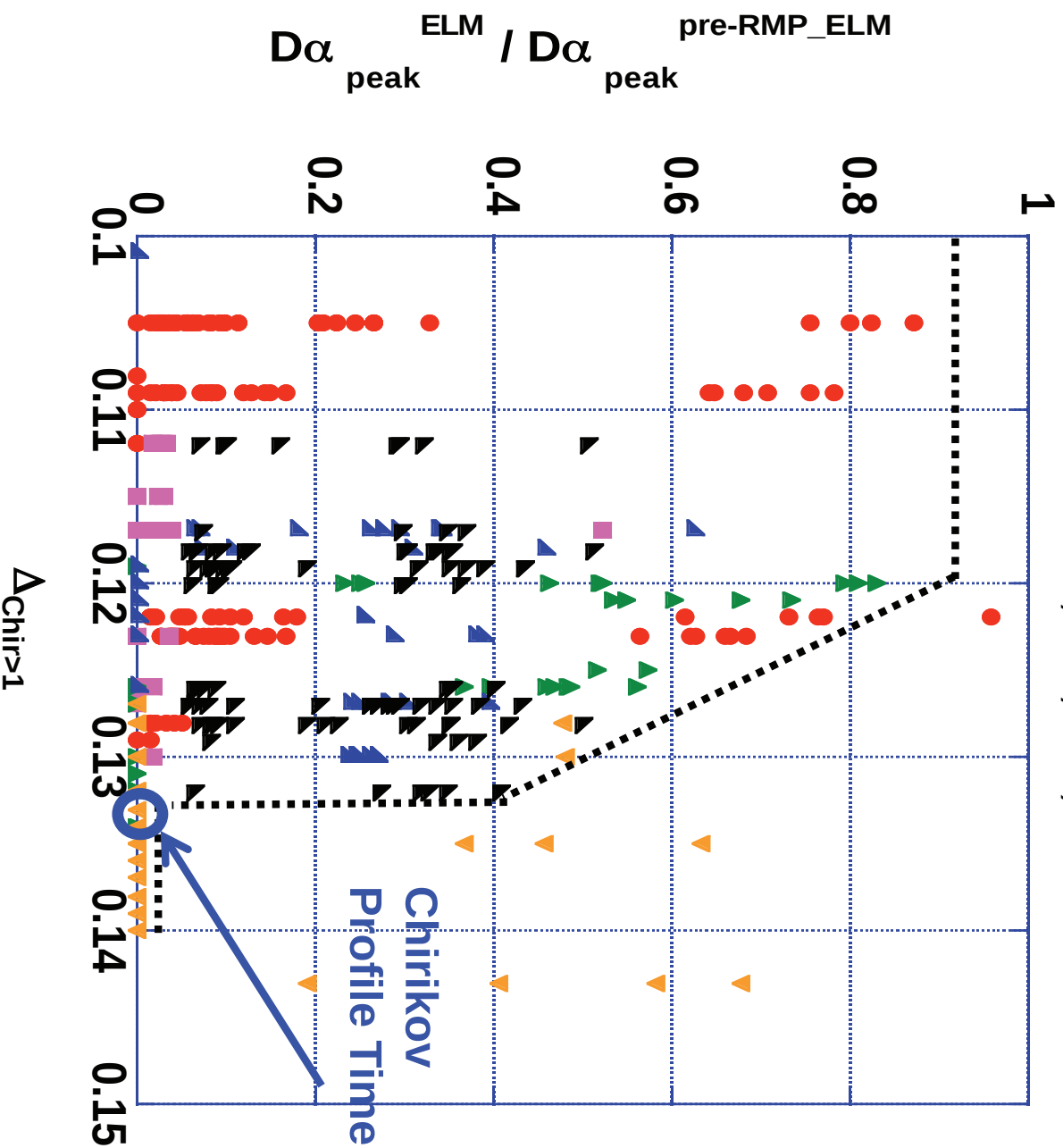


- Upper I-coil row alone at two coil currents
- Lower I-coil row alone
- Both I-coil rows at two coil currents
- C-coil n=3 RMP did not show much ELM change

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

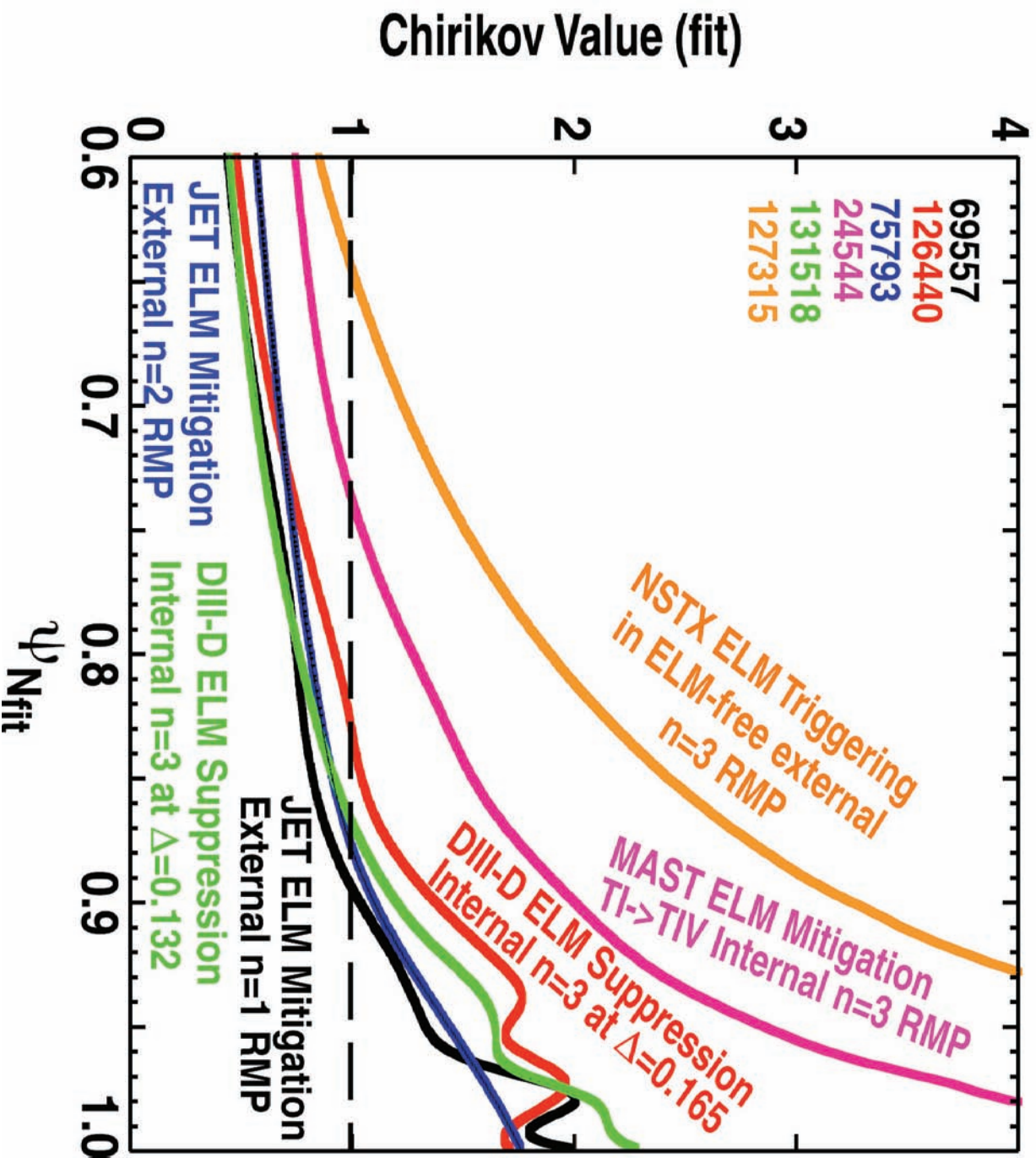
Ordering With Width of Island Overlap Region From One vs Two Rows Database Cautions Against Over Interpretation

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



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

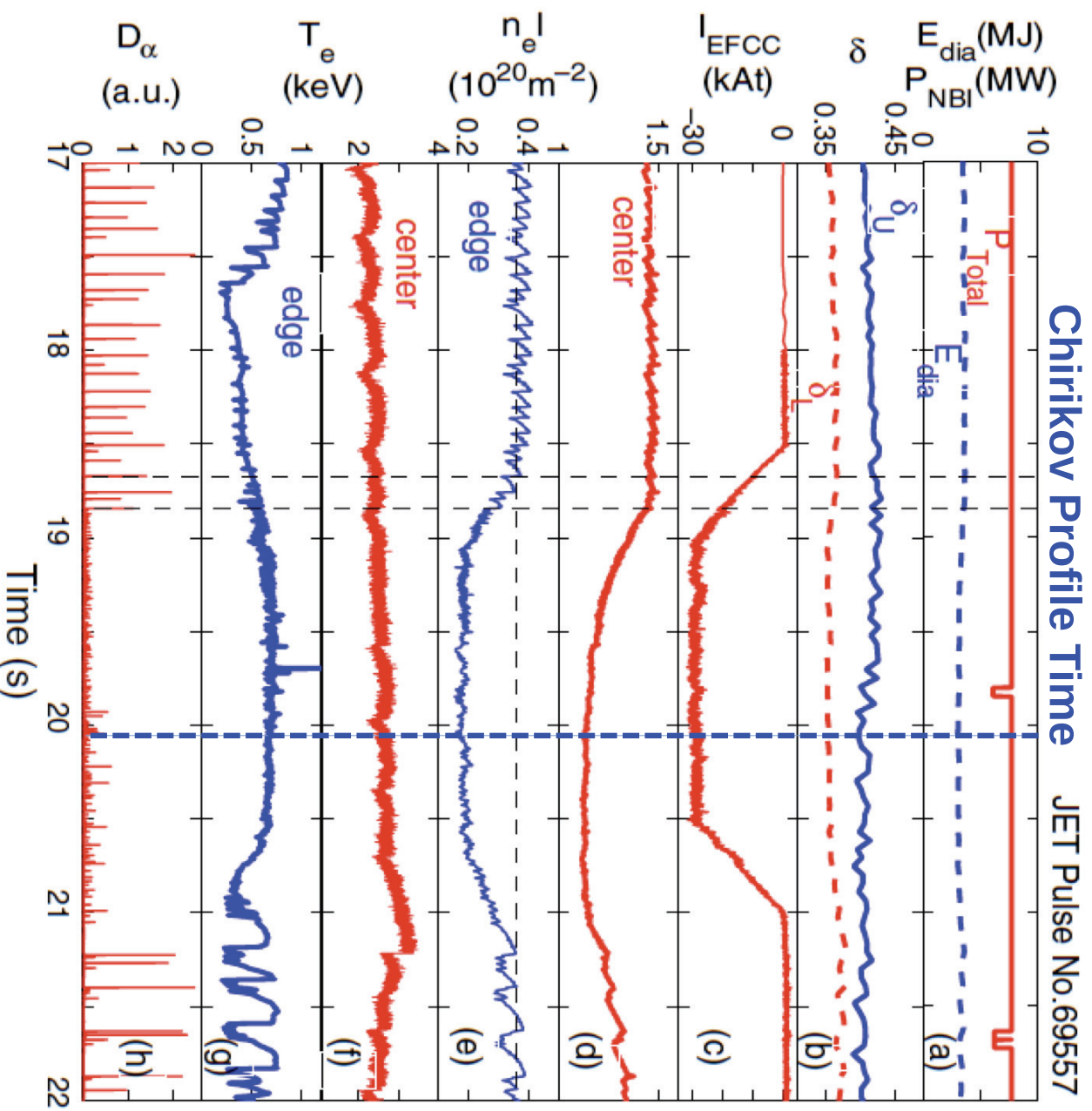
Vacuum Island Overlap Width Is Not Sufficient to Assure ELM Suppression



- 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

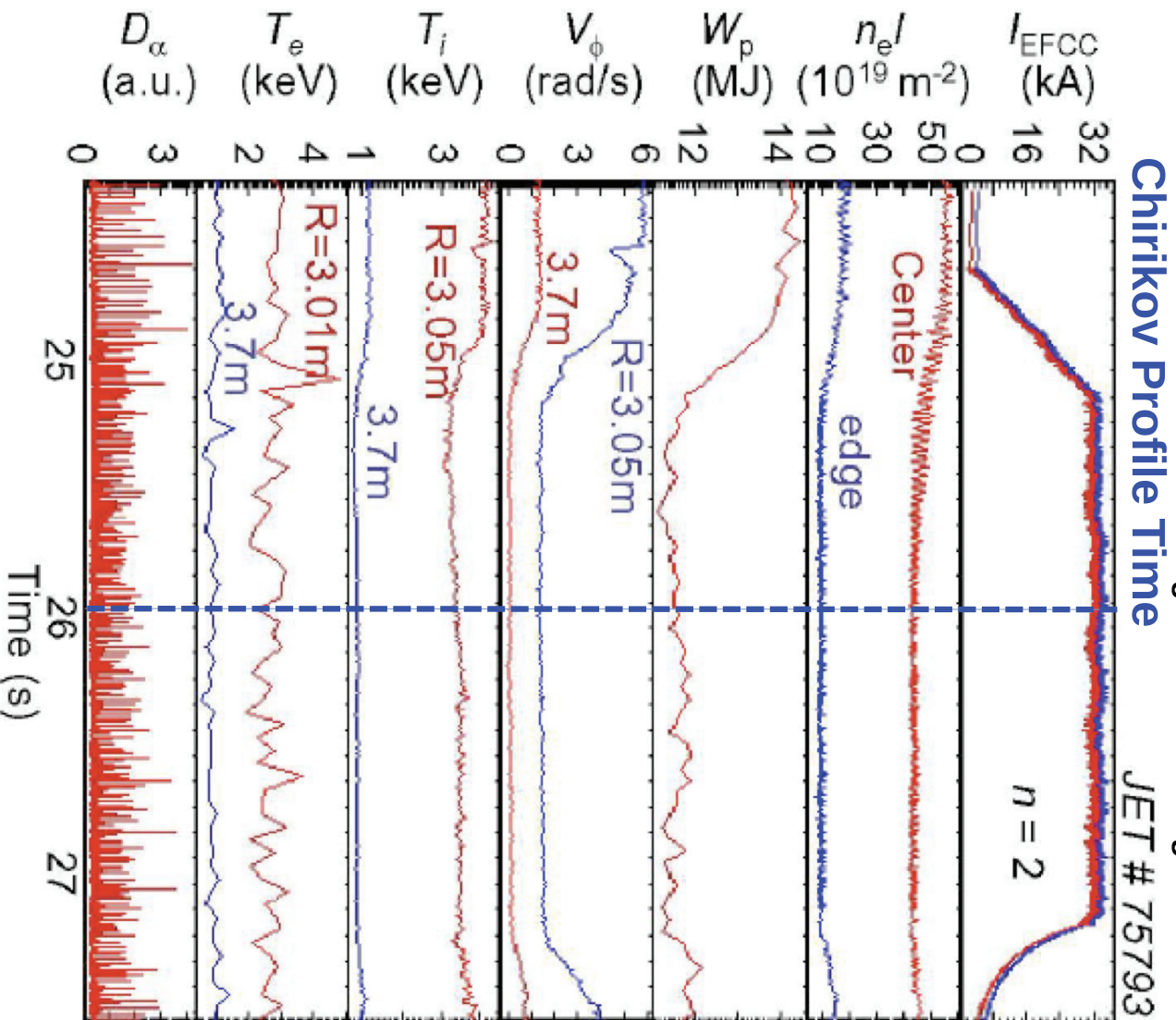
Y. Liang et al., Nucl. Fusion 50 (2010) 025013



- 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*

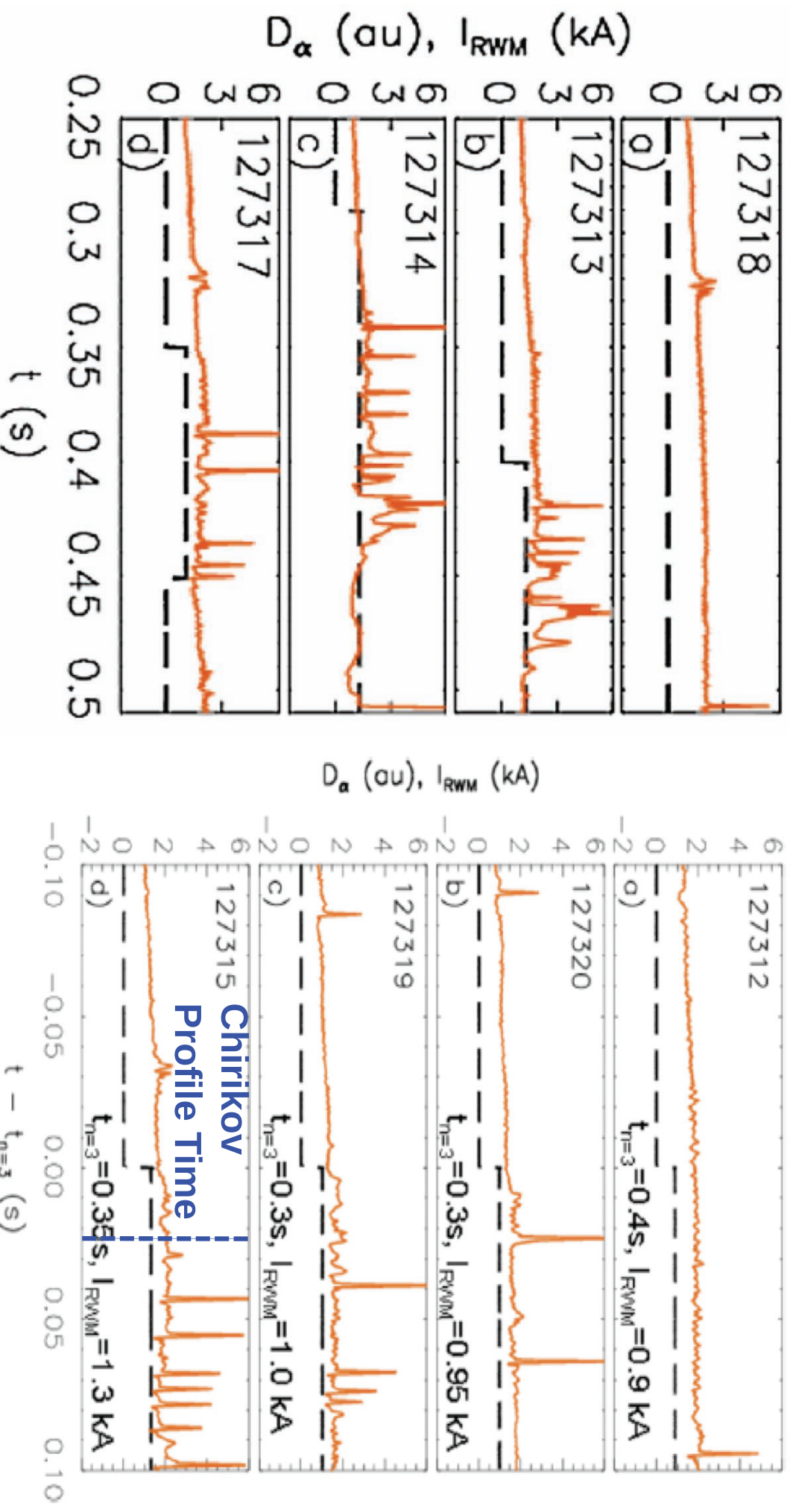


- During the RMP from the EFCC, the equilibrium (EFIT) reconstructed by averaging full coils set from different toroidal cross sections – Octants #1, 3, 5 and 7
 - This process can compensate for the direct pick up from the EFCC perturbation
- Intrinsic error fields small, neglected in SURFMN analysis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

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)

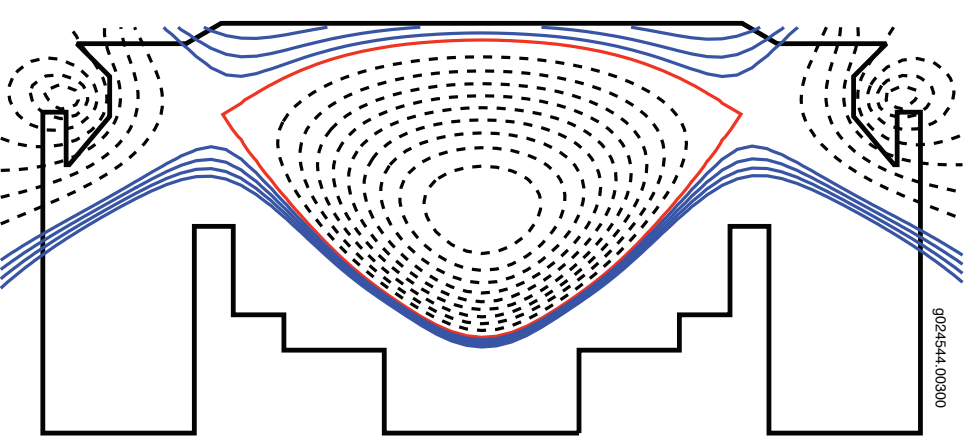
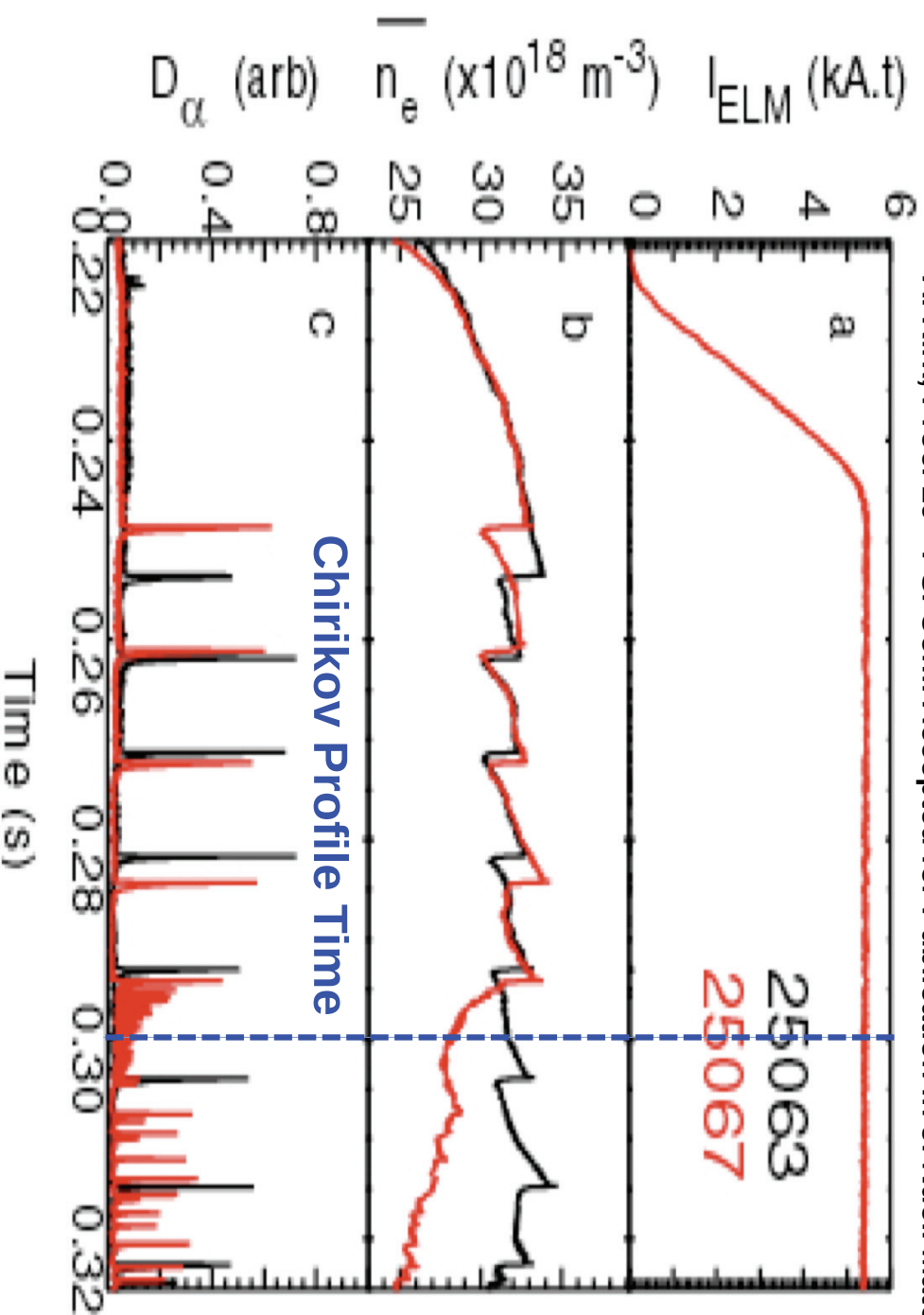
J.M. Canik et al., Nucl. Fusion 50 (2010) 034012



- 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 $\Delta_{\text{chir}} > 1 = 0.265$ Produces Type-I $\rightarrow$ Type-IV ELMs Transition

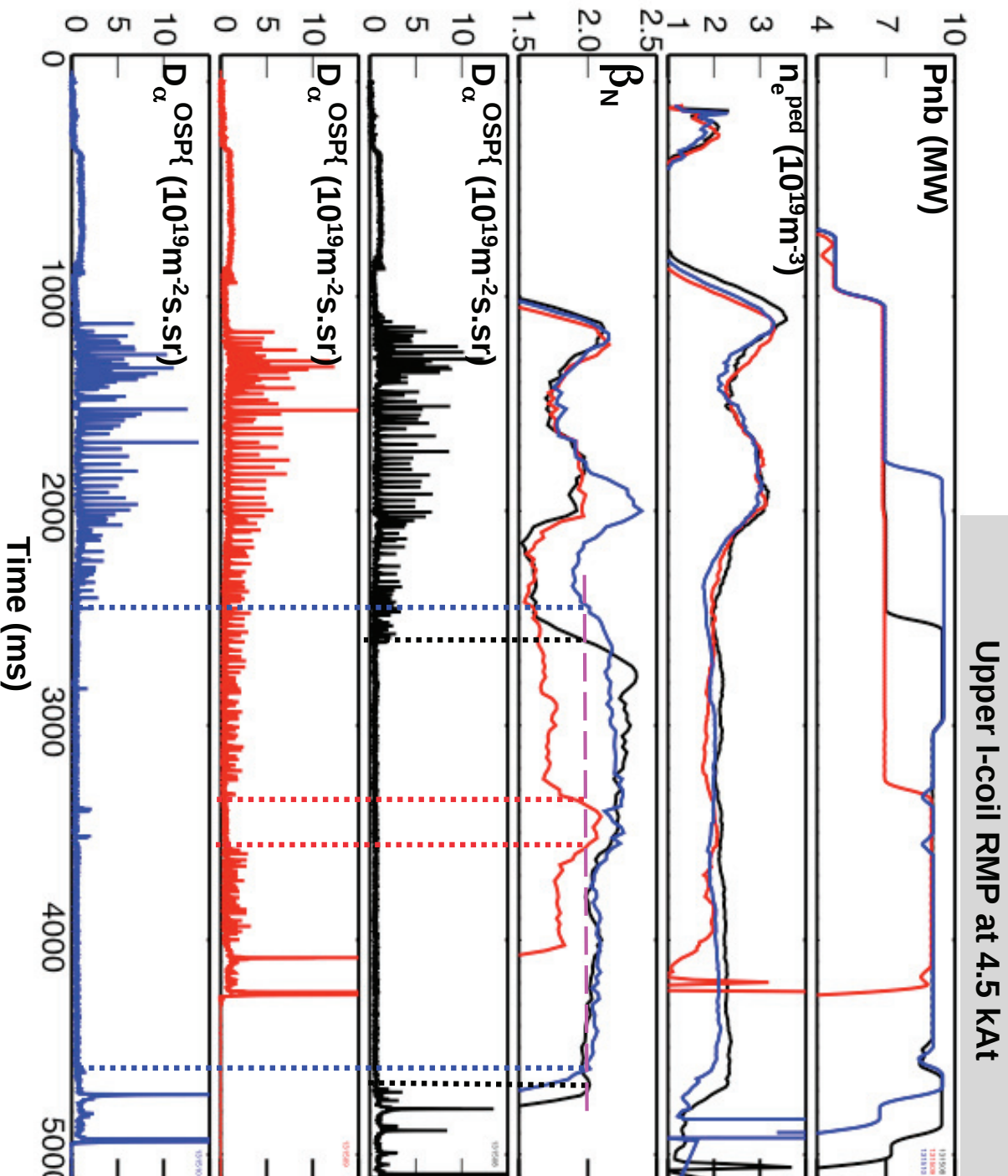
A. Kirk, Proc. 19th PSI Conf. Accepted for Publication in J. Nucl. Mater.



- 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

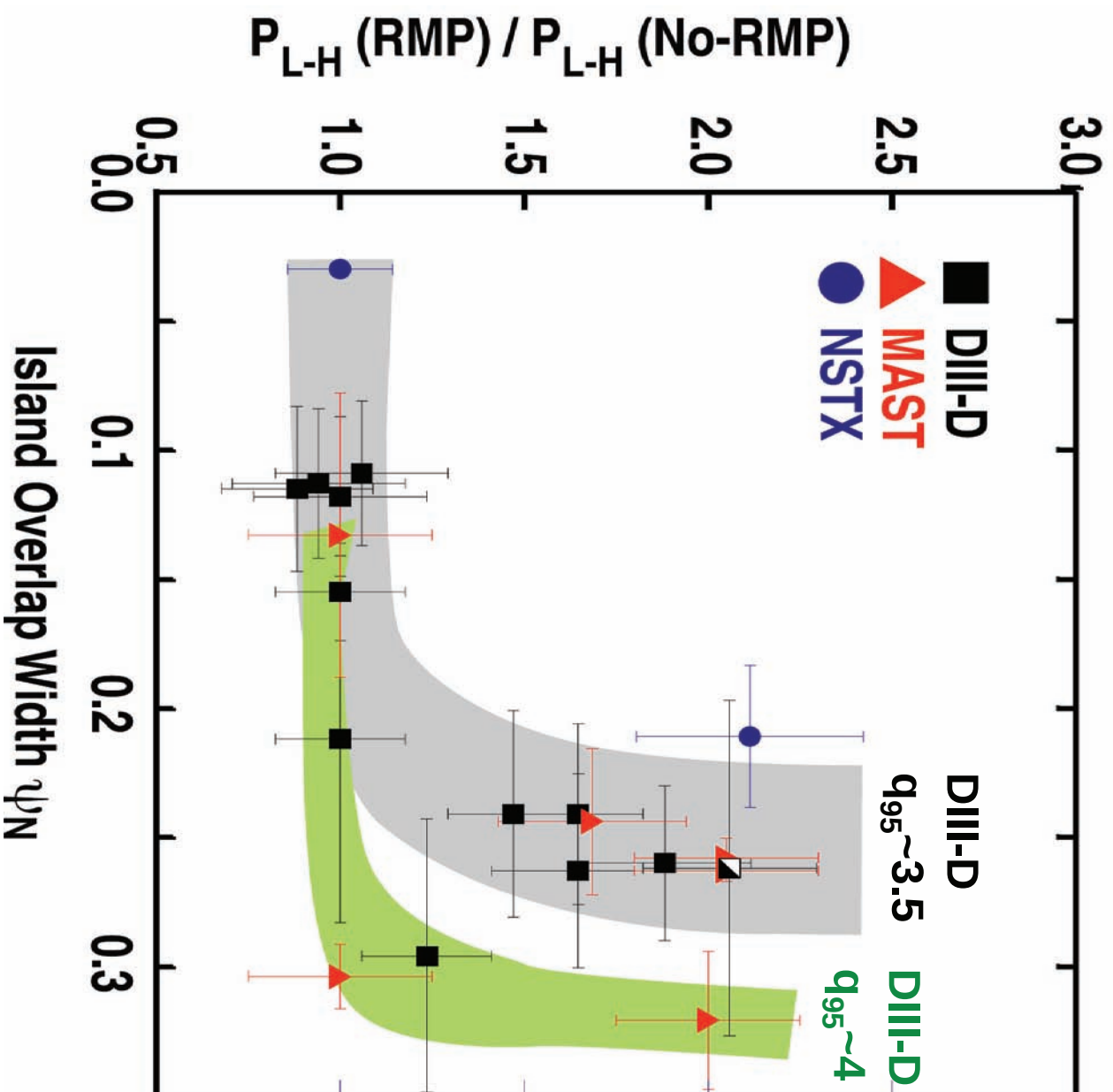
Plasma β or β_N May Be Important For Achieving ELM Suppression



- Identical I-coil current
- Power step delay changes timing of ELM suppression
 - $n_{e \text{ ped}}$ and $\Delta\text{chir}_{>1}$ 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

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

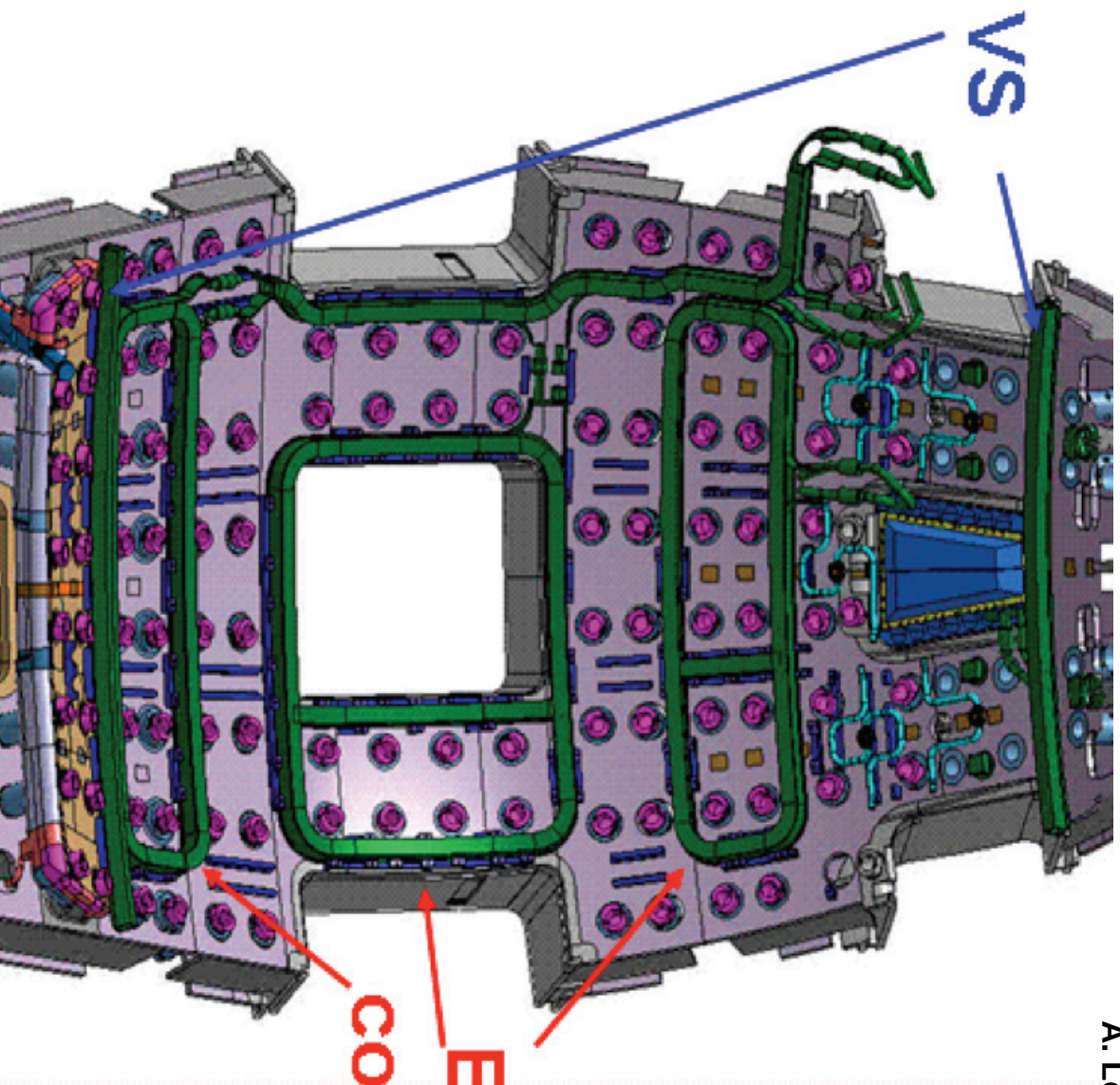
Multiple Devices Plan Coil Upgrades To Increase Physics Understanding Of RMP ELM Control

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

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

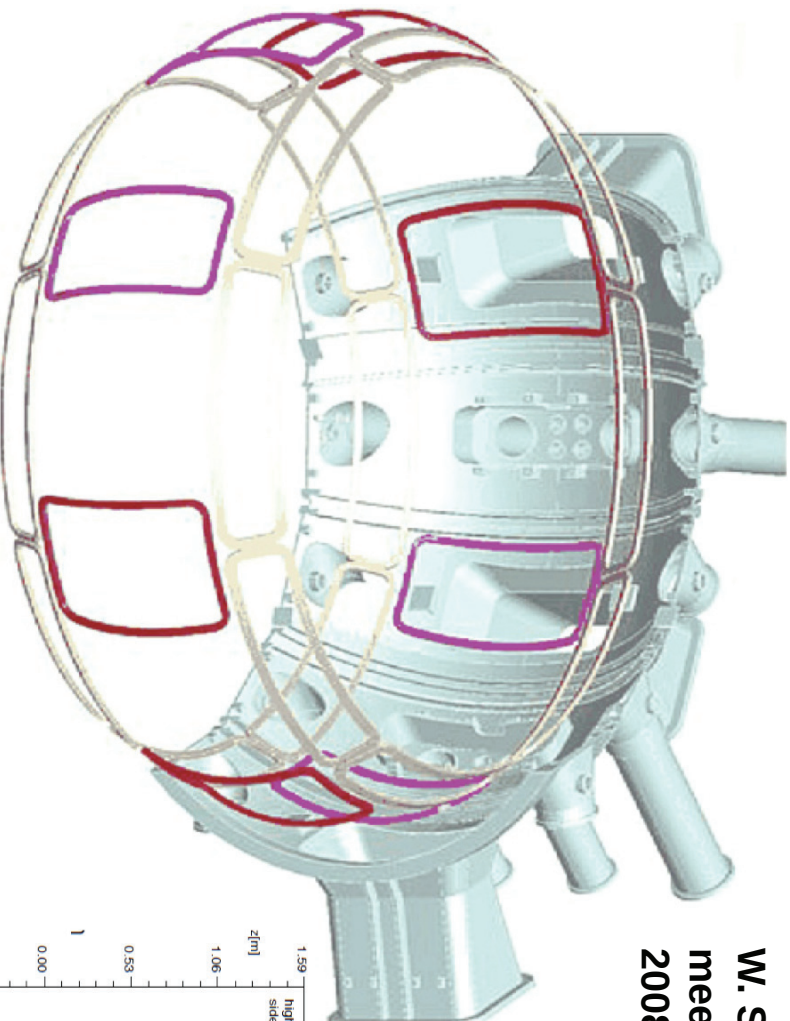


- Nine internal RMP coils per row above, below and on outer midplane
 - Current requirement guided by island overlap region width correlated with ELM suppression in DIII-D
 - 90 kAt for $\Delta_{\text{Chir}>1} = 0.165$ with 20% margin
- All coils independently powered
 - Allows $n=4$ or toroidally rotatable $n=3$ RMP fields
 - Allows optimization for range of q_{95}

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

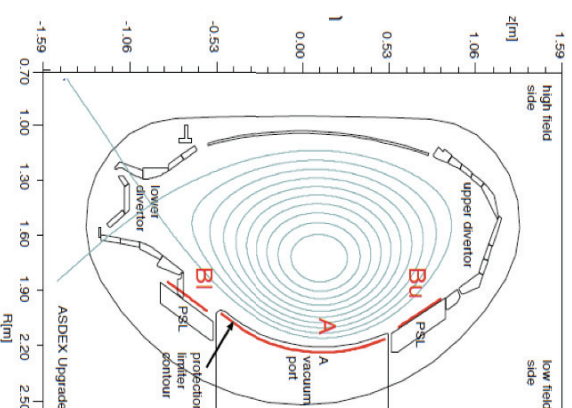
UNDER CONSTRUCTION

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



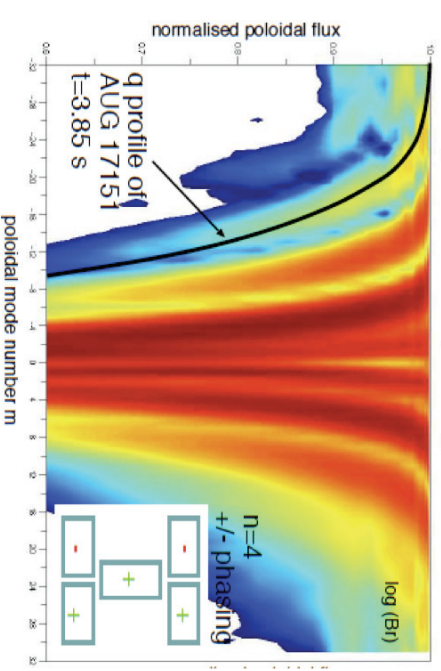
W. Suttrop et al. / Fusion Engineering and Design 84 (2009) 290–294

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



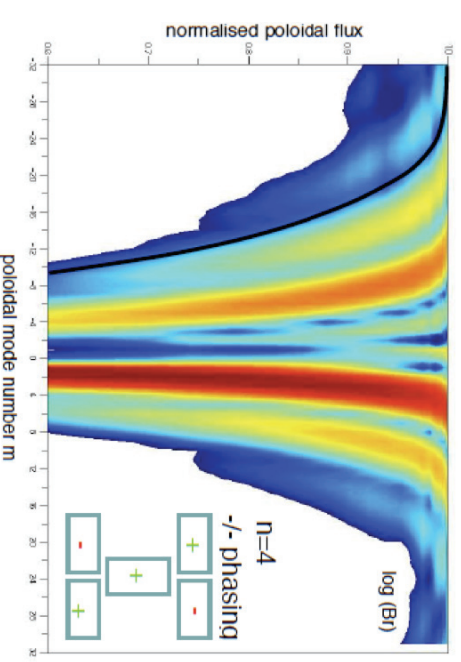
Resonant

$n = 4$ plus-minus phasing



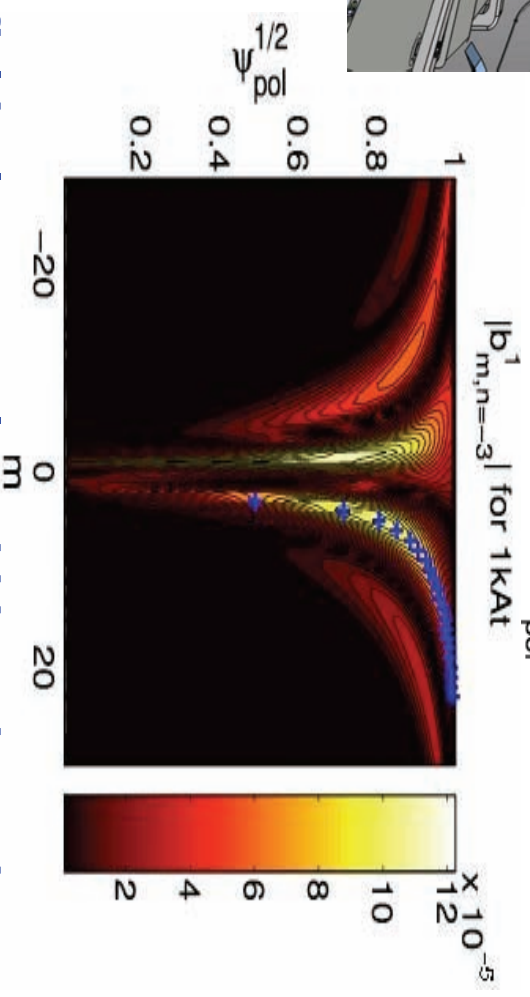
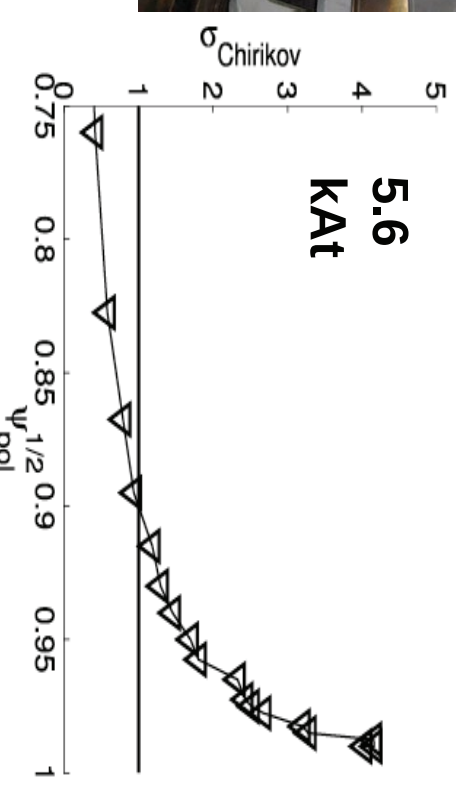
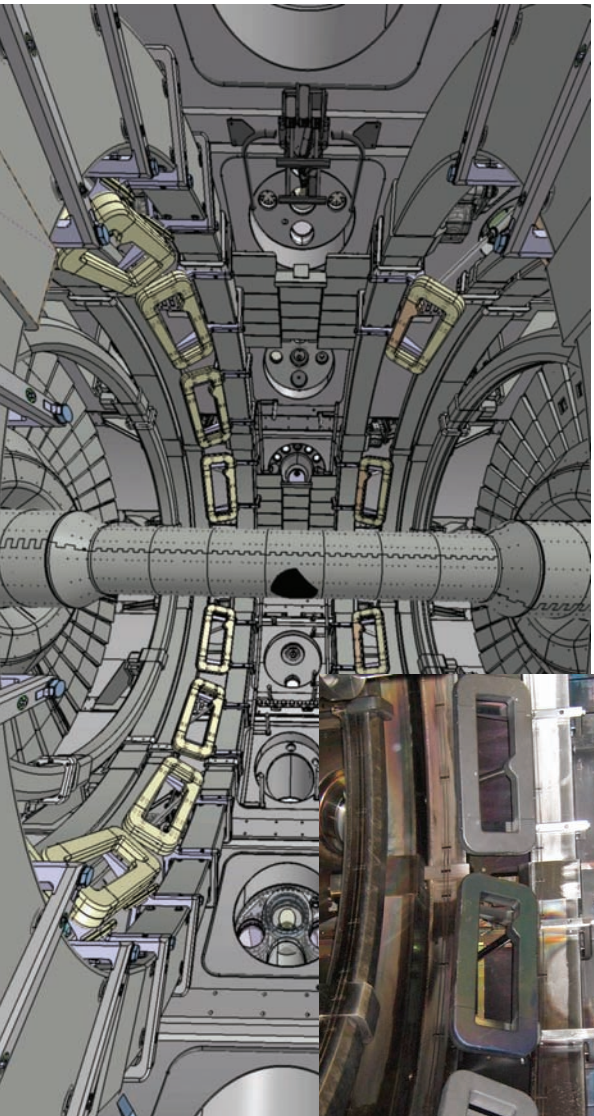
Not resonant

$n = 4$, 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



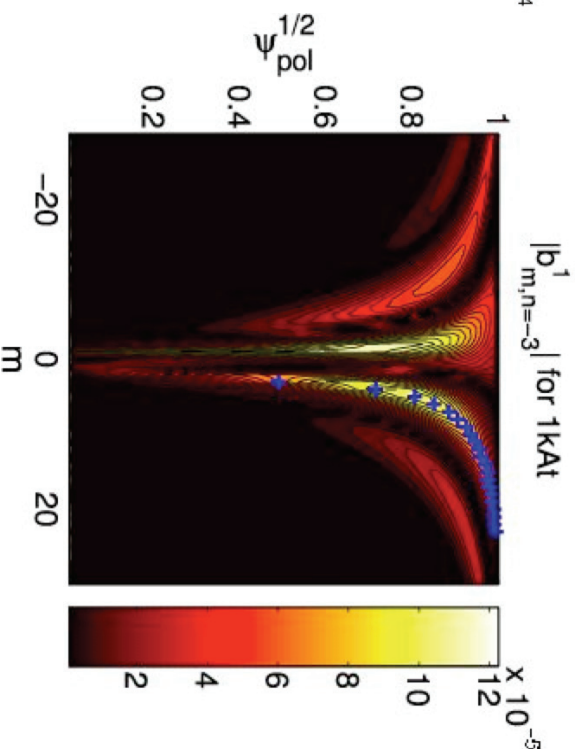
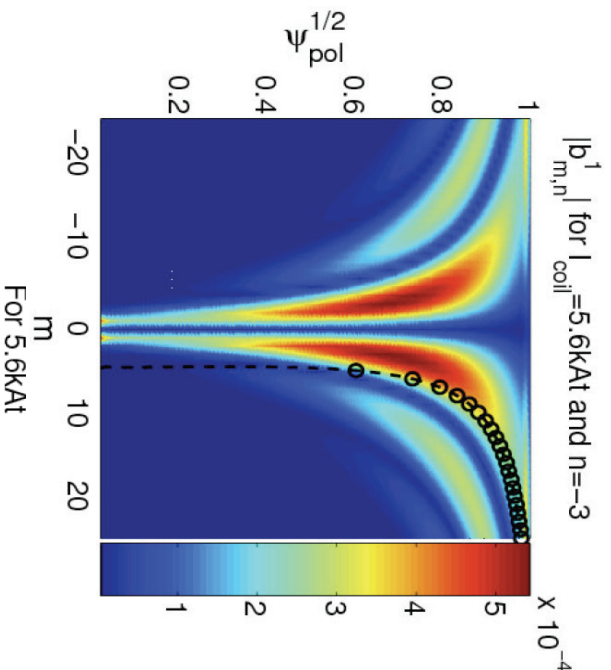
A. Kirk, *private communication* (2010)

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

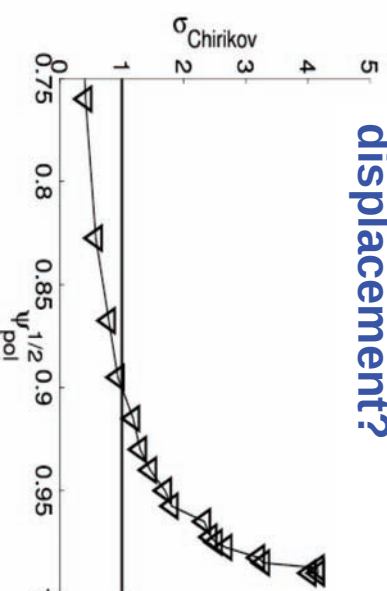
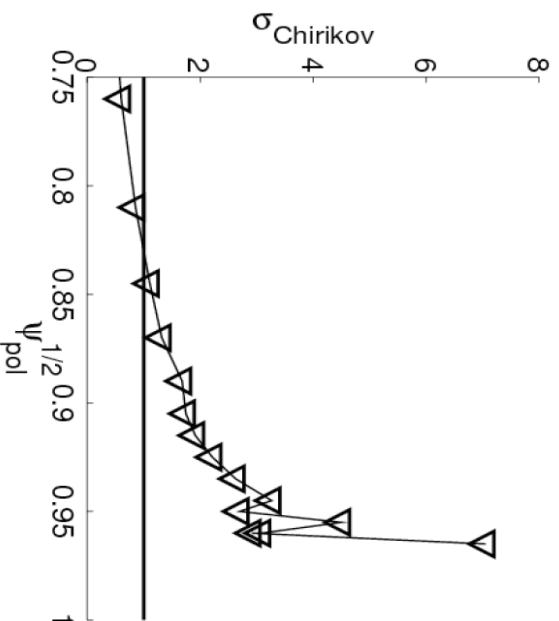
1.1 Reproduce RMP ELM suppression on at least one tokamak other than DIII-D - MAST Internal Off-Midplane Coils

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

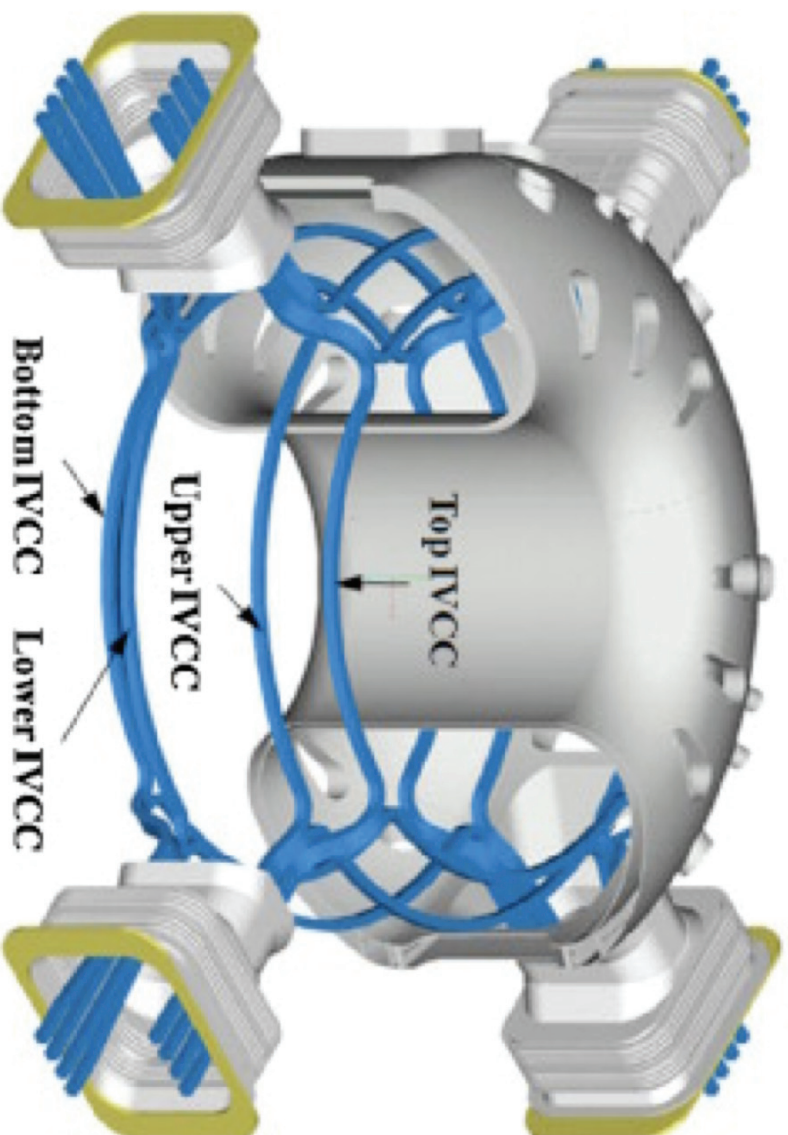
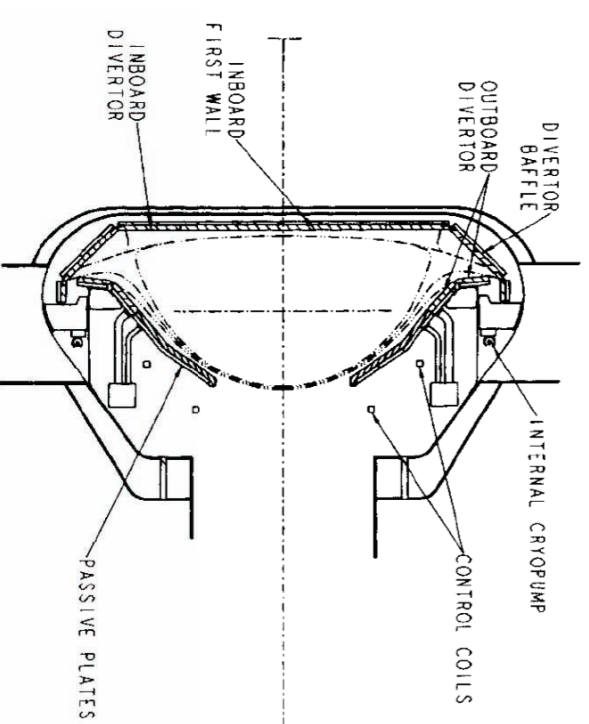


Fig. 1. Configuration of the KSTAR vacuum vessel and IVCC coils.

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

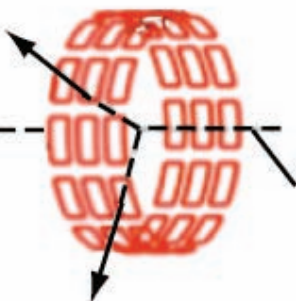


PROPOSED - CONSIDERED

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

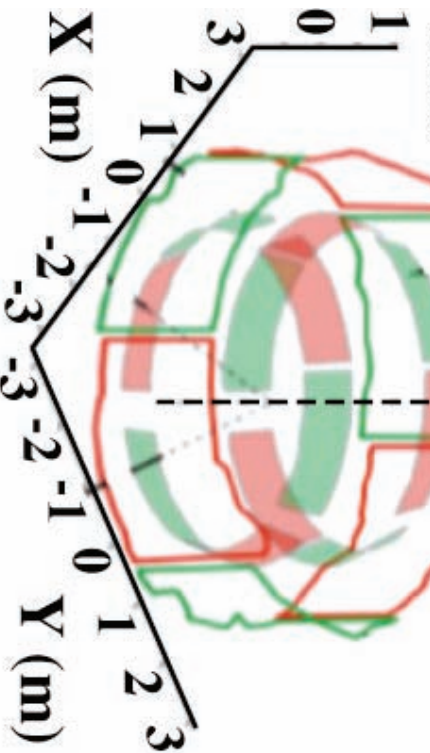
3x12 center

post coils



12 internal

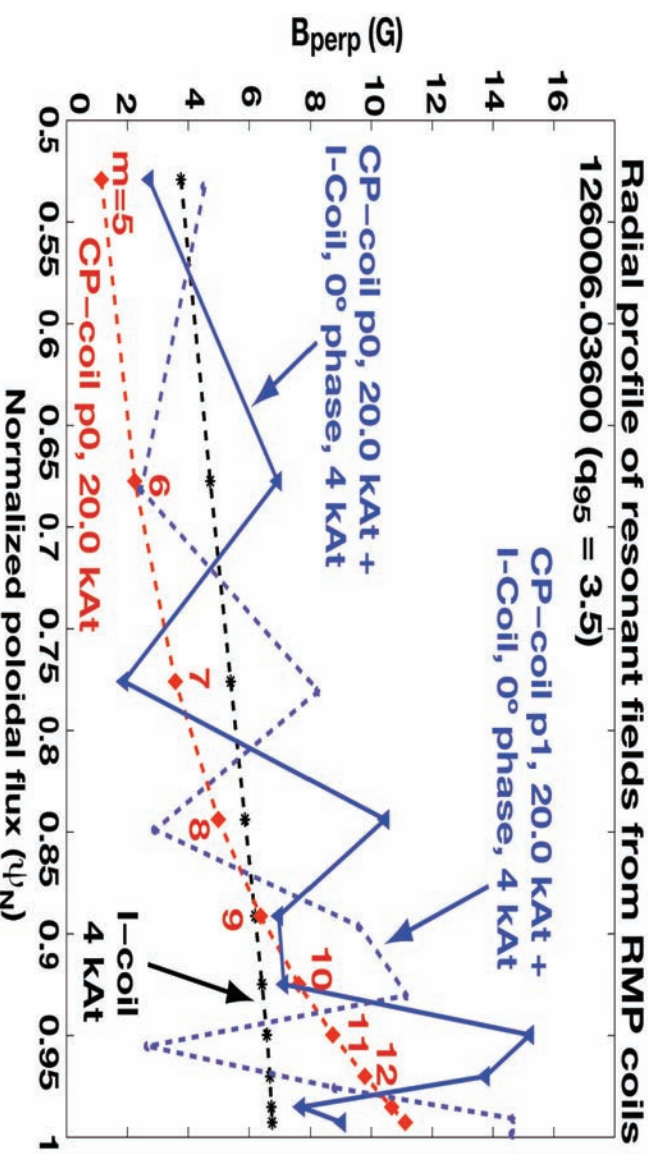
coils



6 external coils

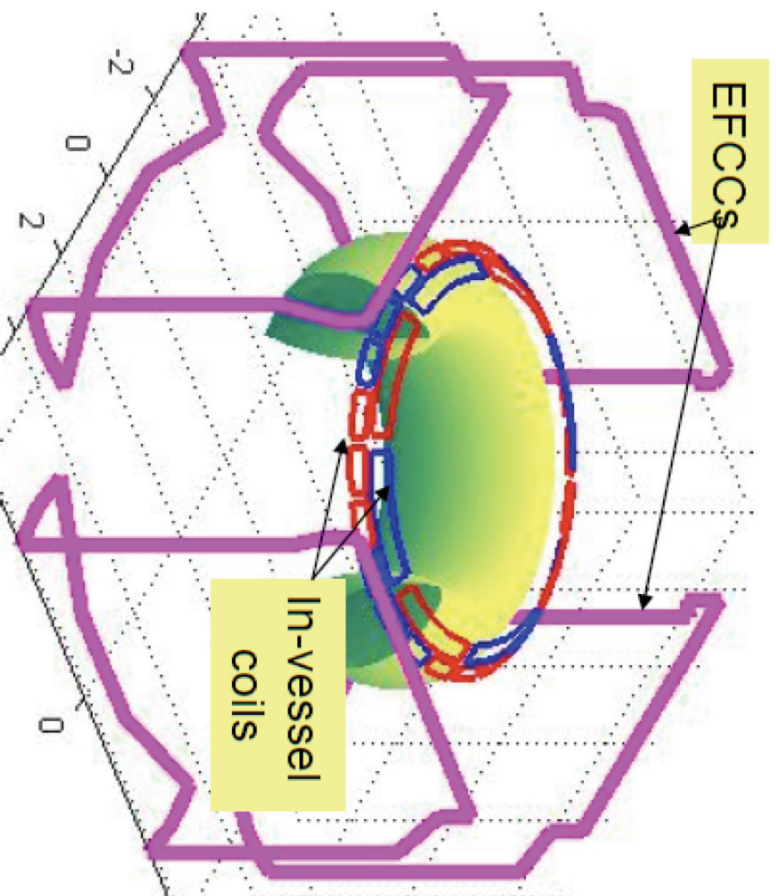
• Would provide control of:

- 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

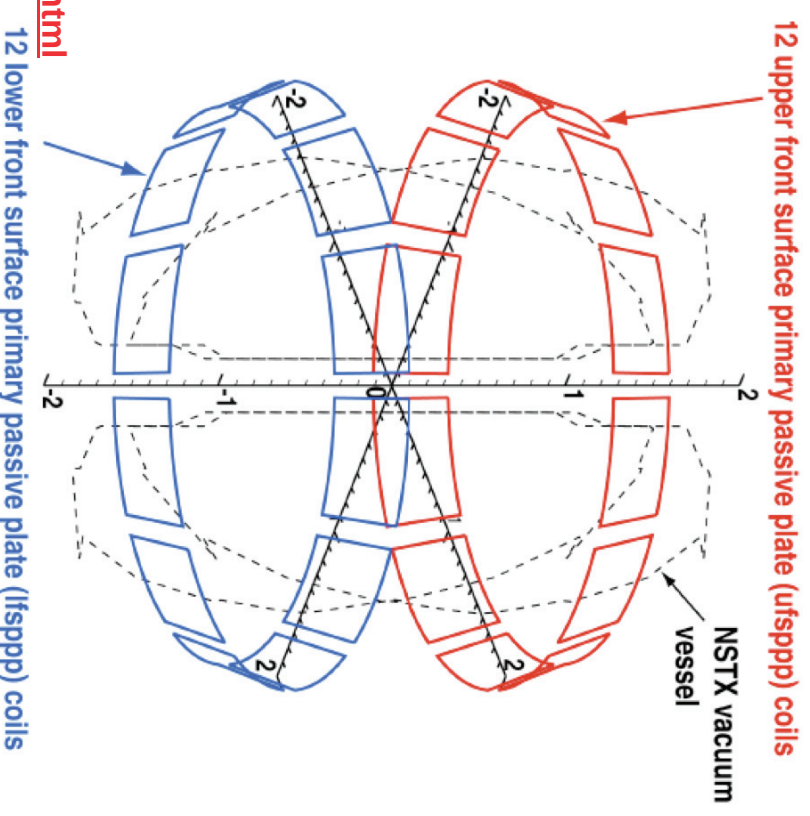


- NSTX: Considering 12 coils above and 12 below outer midplane
- Would be capable of static $n=6$ and rotatable $n=4$ RMP fields

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

- JET: Considering coils above outer midplane
 - 8 upper coils
 - 24 mezzanine coils

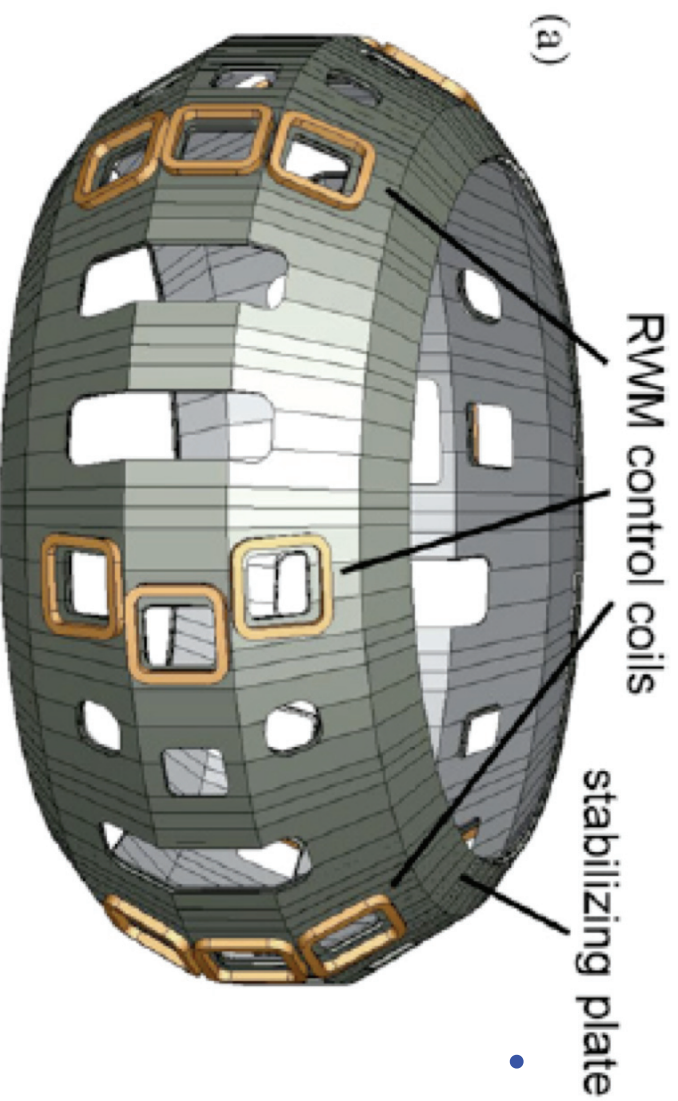
- Would be capable of rotatable $n=4$ with single row



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

T. Fujita *et al.*, 2007 Nucl. Fusion 47 1512

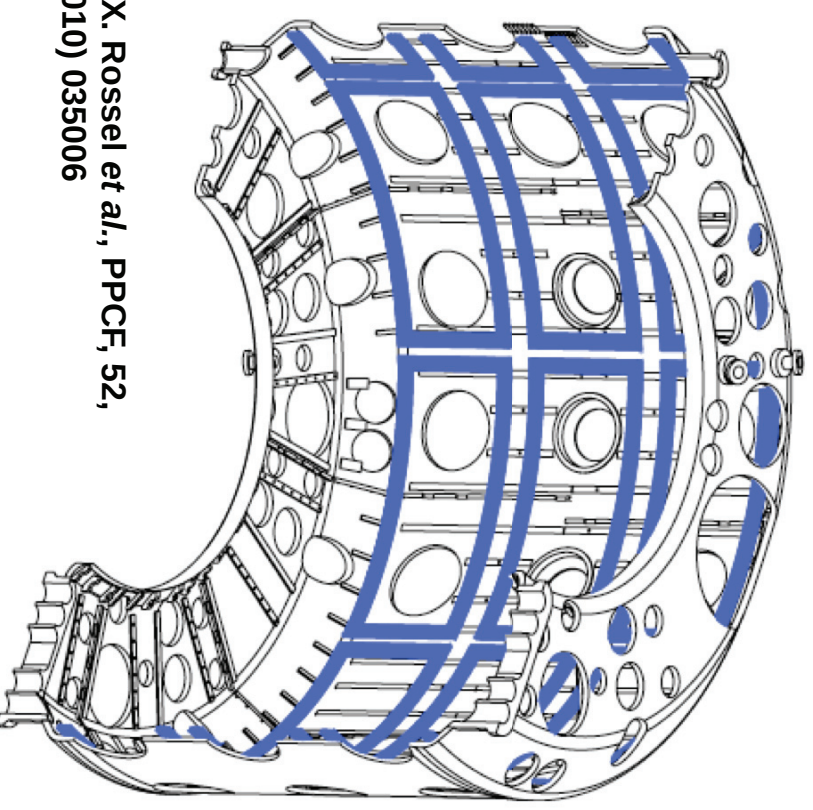
M. Kikuchi *et al.*, IAEA, 2006



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

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



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 ($V_{\text{vacuum fields}}$), $\Delta_{\text{chir}} > 1$ 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

