ELM Control by RMP* — Physics Basis, Concepts for ITER, and Advanced Techniques

*Resonant Magnetic Perturbation

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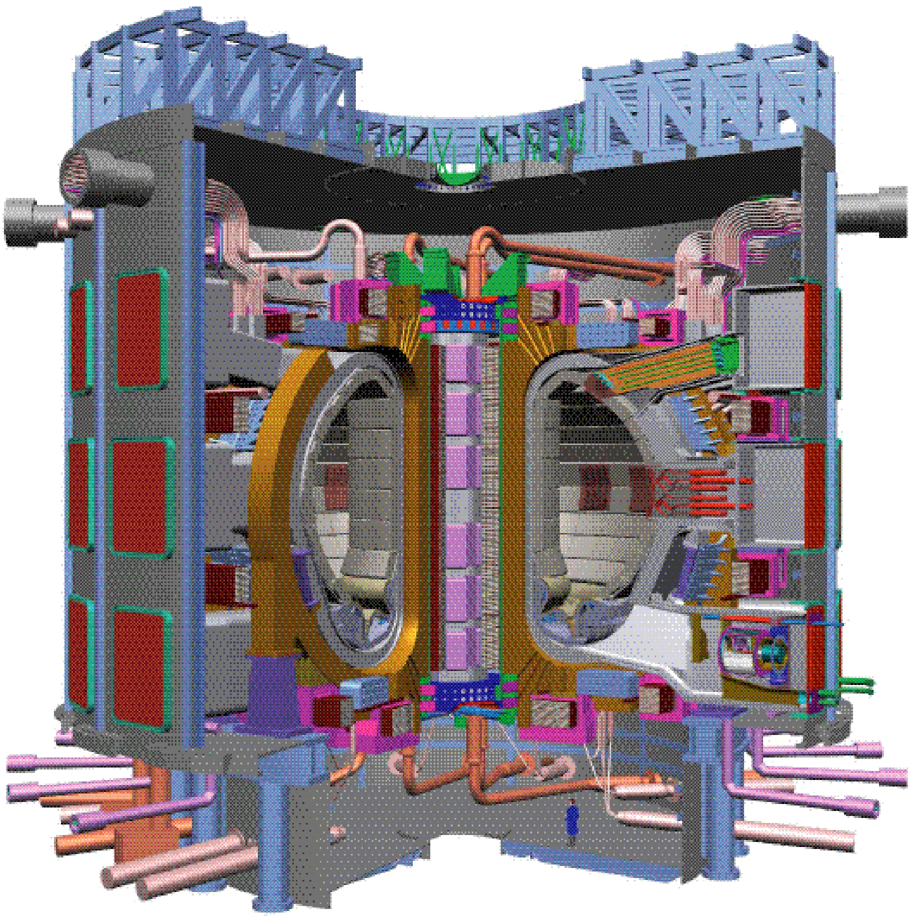

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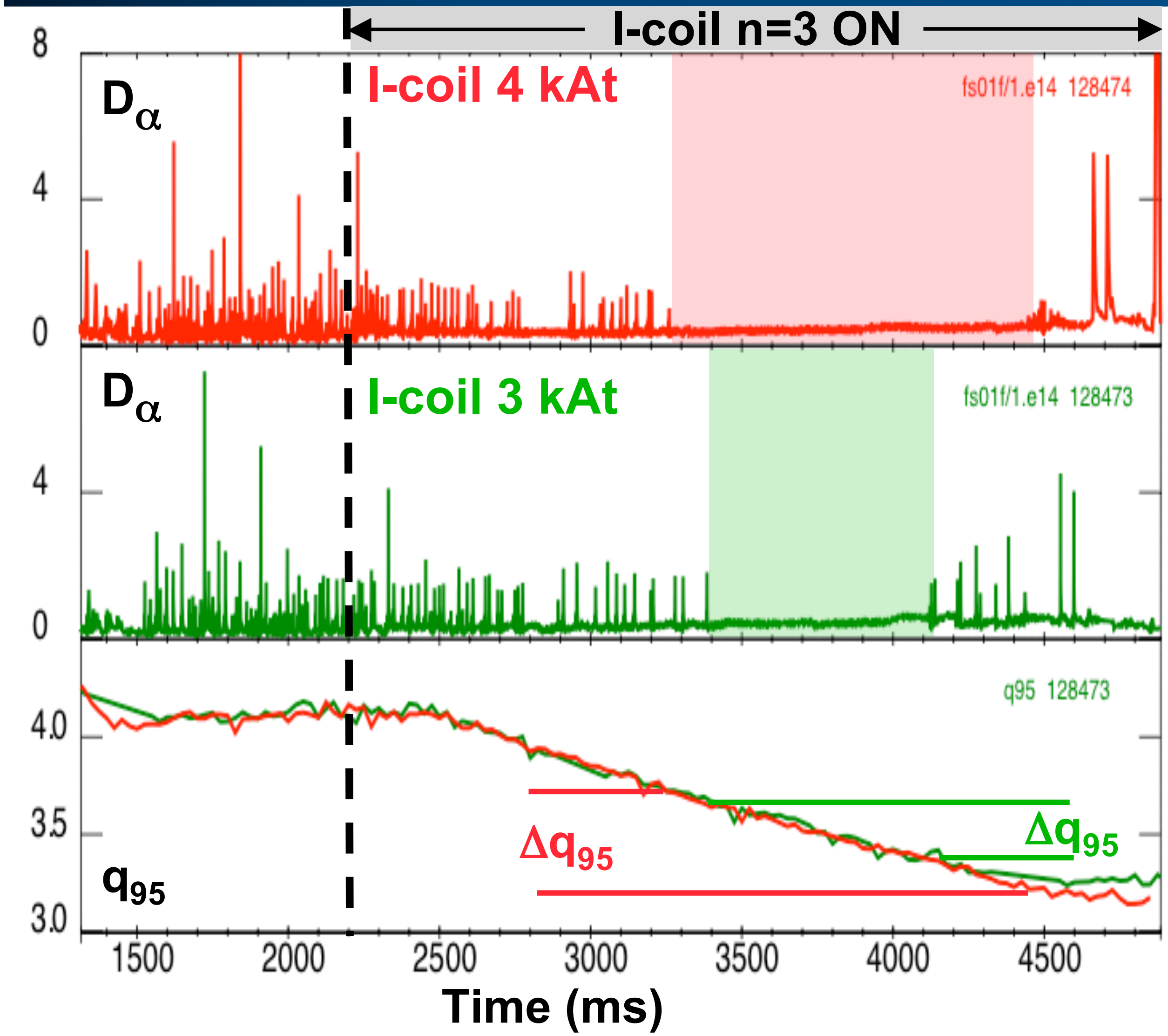
Contents

- Experimental basis for ELM control by RMP
  - DIII–D ELM control experience
  - Derived requirements for RMP ELM control in ITER
- RMP coils for ITER ELM control
  - Requirements
  - Coils on vacuum vessel internal wall, behind blanket
  - Coils around port plugs (equatorial and top)
- Rotation braking considerations
- Some thoughts on advanced RMP techniques

Experimental Basis of RMP ELM Control

Complete ELM Suppression by n=3 RMP is obtained in DIII–D by n=3 RMP, at ITER pedestal collisionality

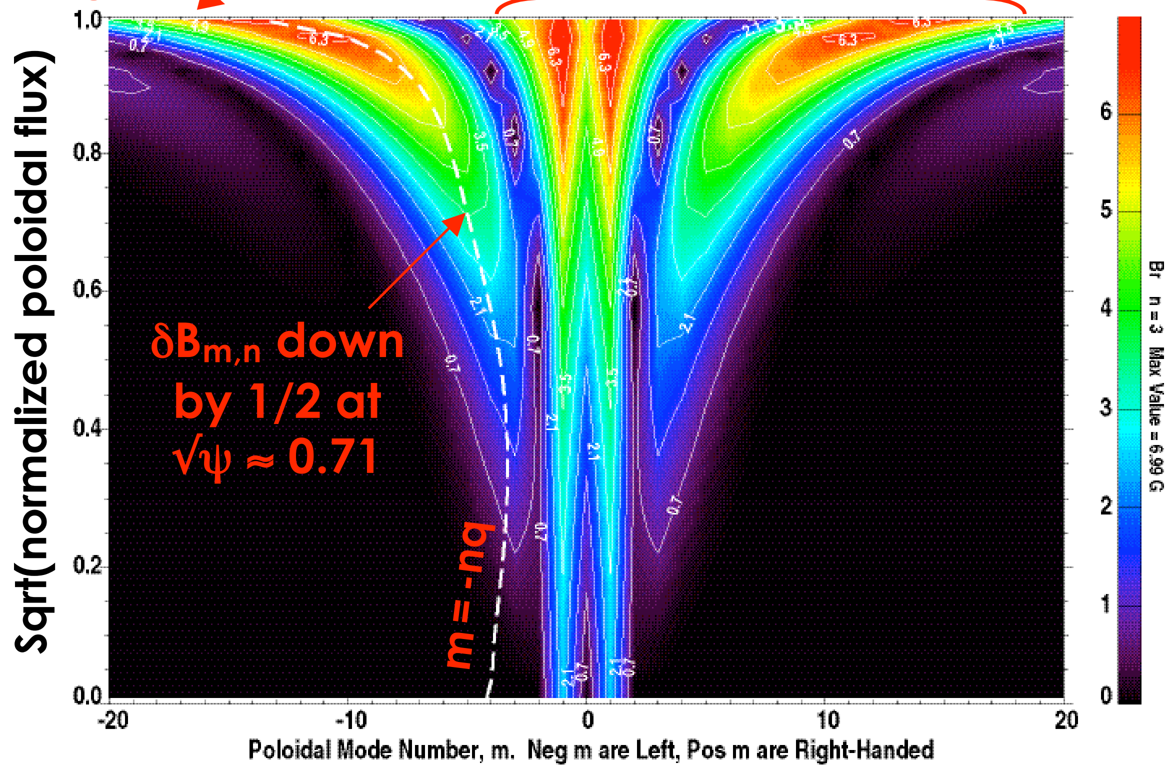


- Resonance window Δq_{95} for suppression increases with I-coil current
  - At 4 kA t, ELMs suppressed for $\Delta q_{95} \approx 0.50$
  - At 3 kAt, ELMs suppressed for $\Delta q_{95} \approx 0.30$
- q_{95} ramping slowly
- Also suppressed at $q_{95} \approx 7.2$ resonance with lower-pitched I-coil connection

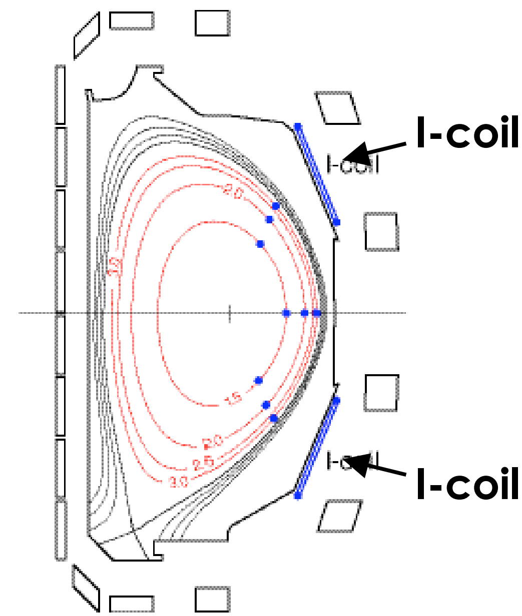
DIII–D I-coil Field is Example of Successful n=3 RMP Poloidal Harmonic Fourier Spectrum

pitch-resonant ridge

3 large non-resonant side lobe ridges



ITER-similar shape in DIII–D

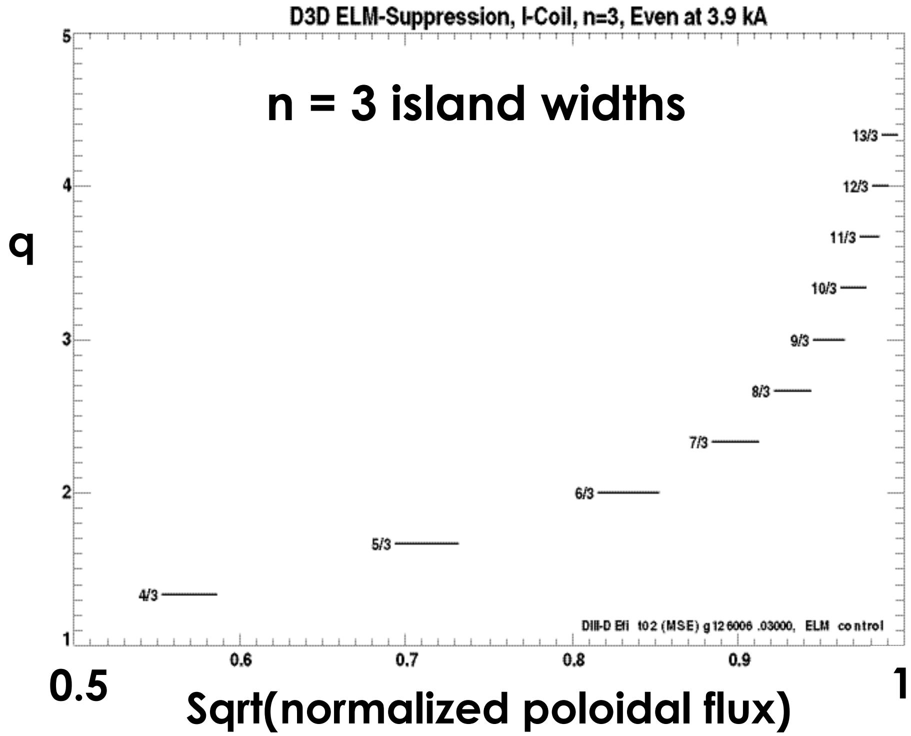


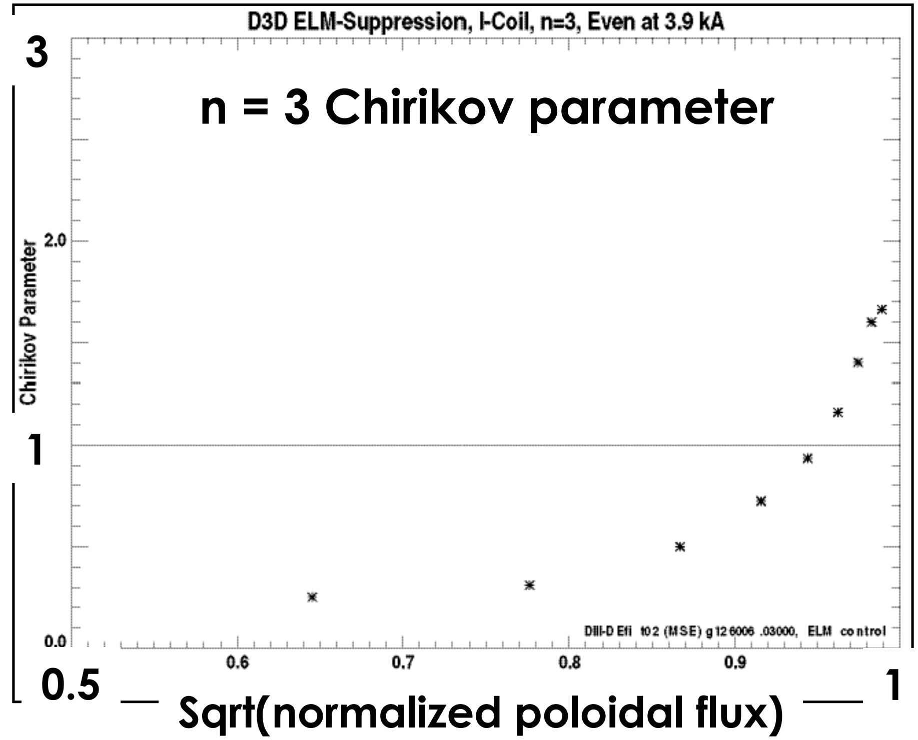
Magnetic lines in outer plasma rotate together; ∴ resonant ridge aligns with q(r)

- n=1 RMPs in DIII–D and JET reduce ELM sizes, but lock plasma before ELMs are suppressed

GENERAL ATOMICS

DIII–D Provides a Reference for n=3 ELM-Control: Island Overlap and Chirikov Parameter

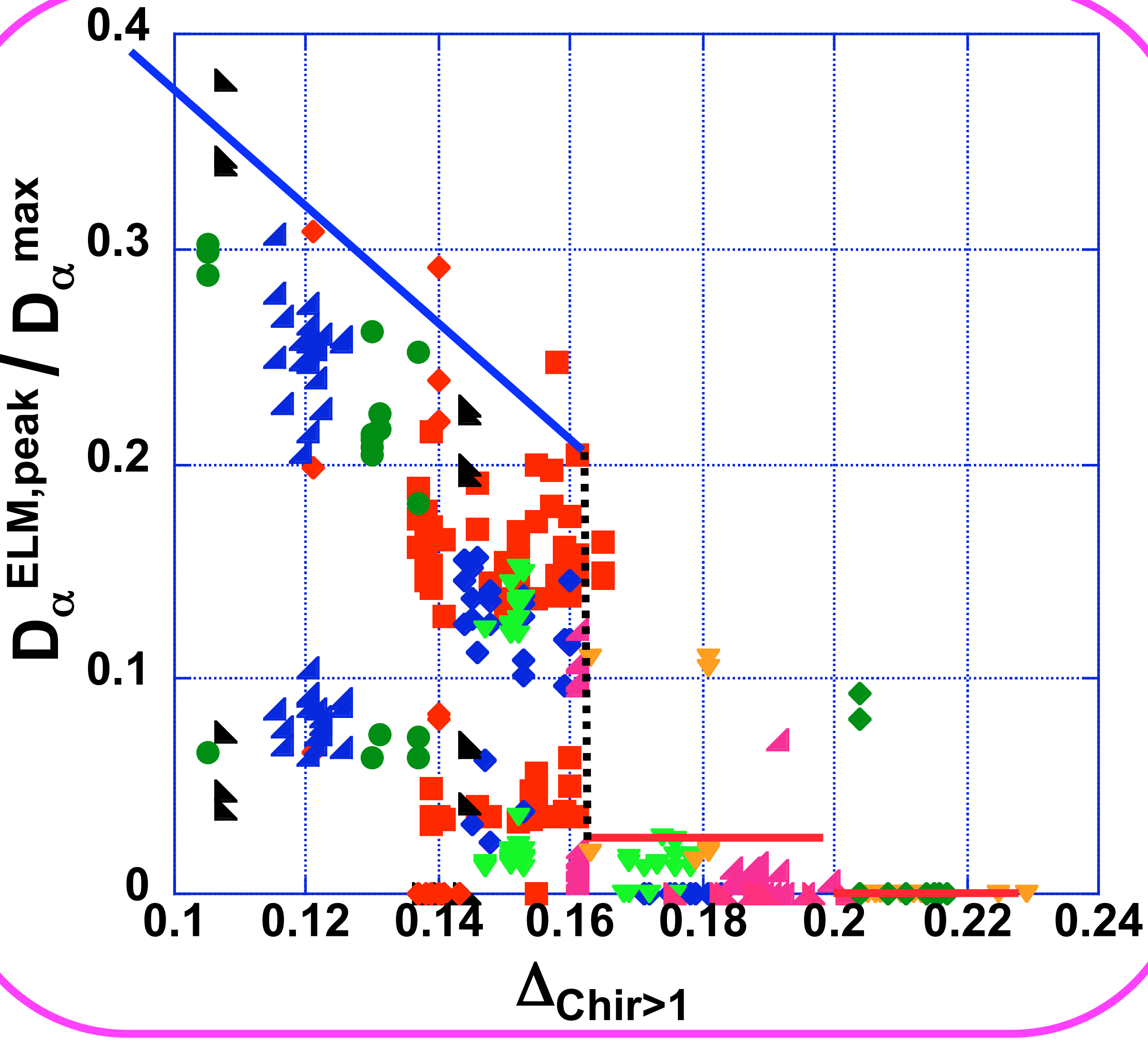




- Near edge, high shear makes islands narrower, but there are more m/3 rational surfaces and more island overlap near edge.

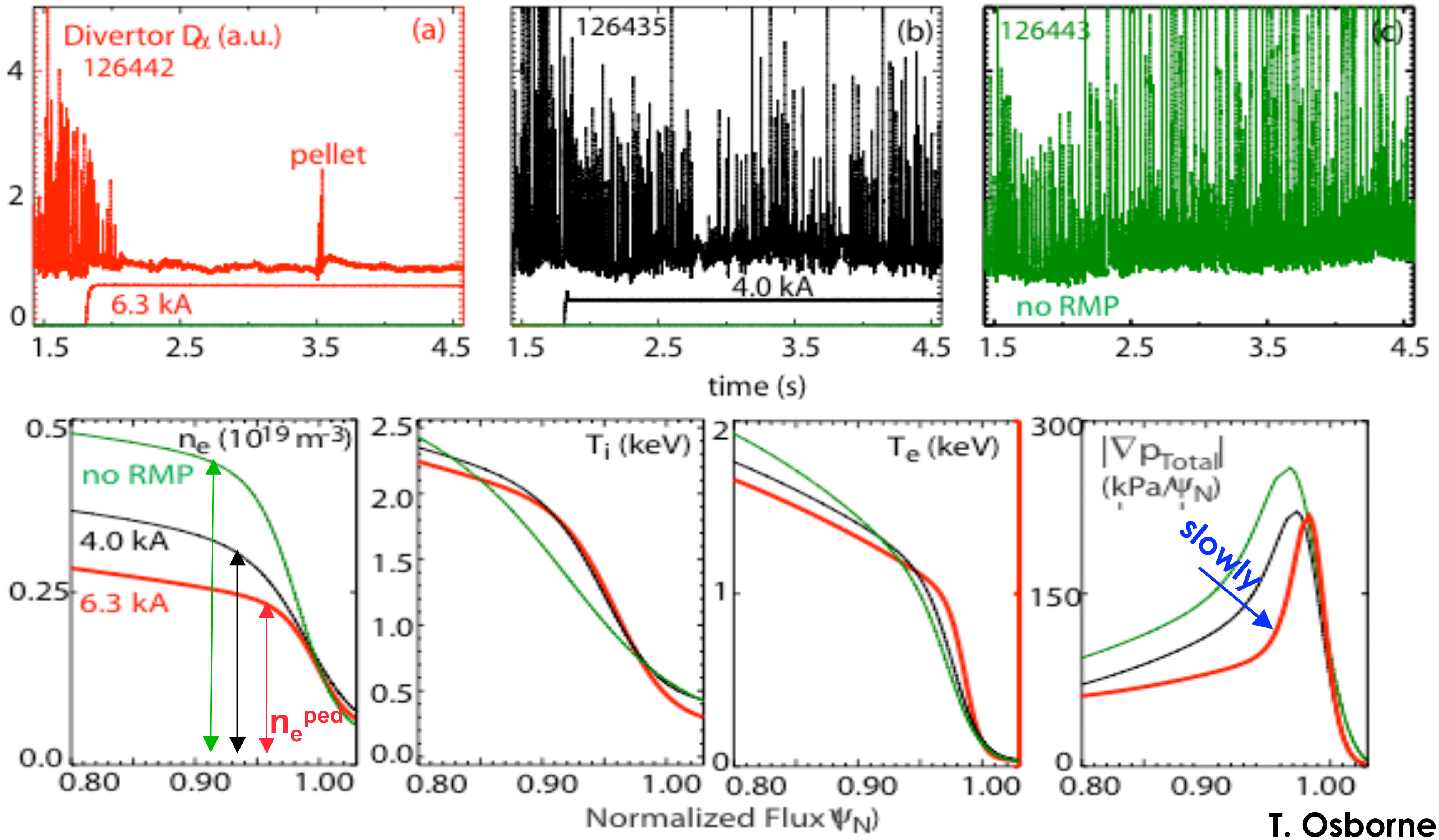
- Chirikov parameter > 1 outside of √flux > √0.90, more generally > √0.85

Maximum ELM Size Decreases as Island Overlap Region Width $\Delta_{Chir>1}$ Increases. Sharp Change to Very Small ELMs.



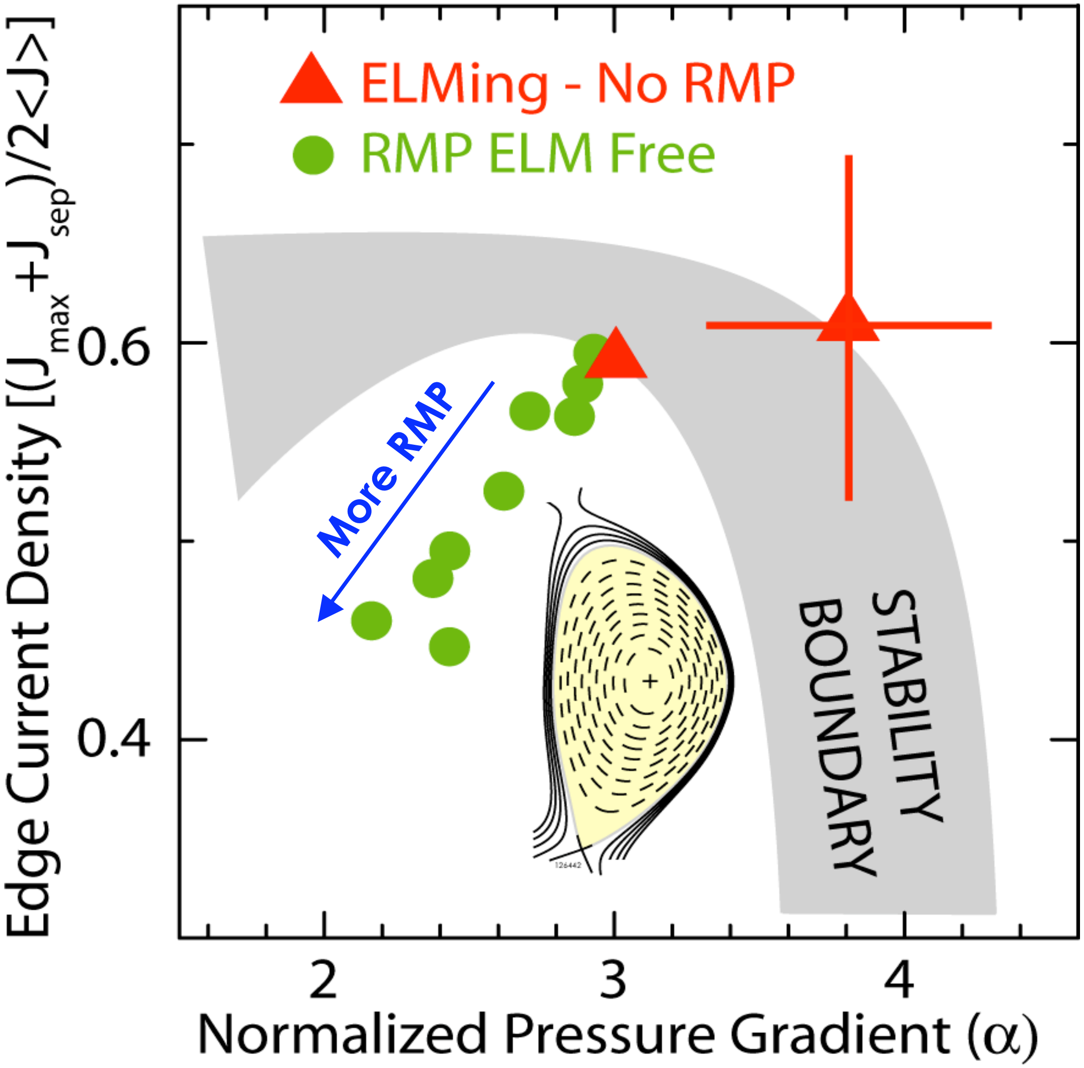
- Maximum ELM size decreases with overlap region width to $\Delta_{Chir>1} = 0.16$
- Factor of 10 decrease in maximum ELM size at q_{95}=3.6 for $\Delta_{Chir>1} > 0.165$
- No detectable ELMs for $\Delta_{Chir>1} > 0.2$

RMP Associates with Plasma Profile Changes in the Region $0.85 < \Psi_N < 0.95$



T. Osborne

Peeling-Ballooning ELM Stability Analysis Shows RMP Moves Operating Point Into Stable Region



- ELM suppression is consistent with linear P-B stability (ELITE)

  Figure is for low-δ, ITER Similar Shape (ISS) plasmas

- Operating point deeper into stable region at higher RMP strength

P. Snyder

Features of Experimental RMP ELM Control

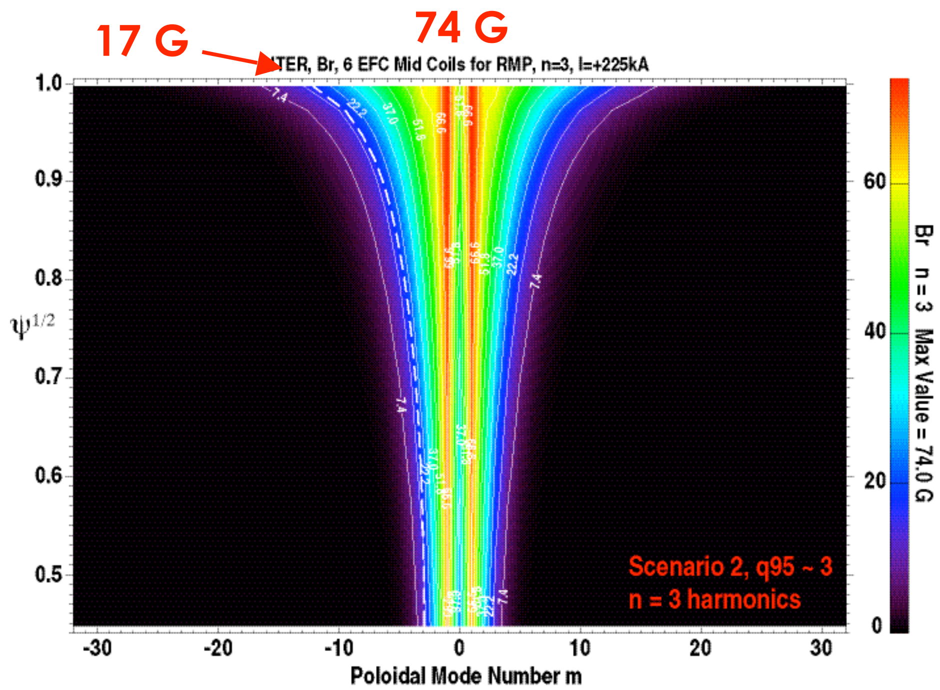
- RMP reduces plasma rotation, too much locks plasma (n = 1, 2)
- Complete ELM *Suppression* with n = 3, I-coil geometry, sufficient RMP, at ITER-like low pedestal collisionality ($\nu_e^* \sim 0.1$)
  - Reduced ELM amplitudes at $\nu_e^* \sim 1$
  - Complete suppression not seen so far with single-row array
- *Reduced* ELM amplitudes for n = 1, 2 (JET, DIII–D)
  - Plasma locks before suppression
- Critical *Resonant Magnitude*; somewhat like Chirikov parameter > 1 across outer 10% — 20% of Ψ_N
  - Error field and added n=1 fields contribute, too (DIII–D)
- ELMs stabilized (peeling-ballooning) by reduced pressure and bootstrap current in pedestal at low ν_e^*
- Data inconsistent with classic stochastic-B transport
  - Little Te decrease; get particle transport instead

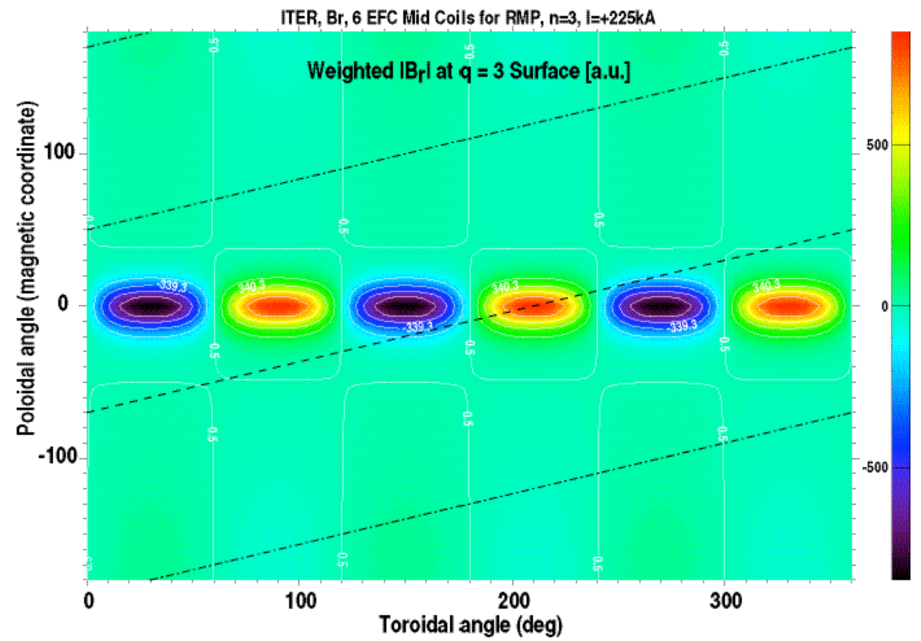
RMP Coils for ITER ELM Control

Considerations for ELM Control Coils for ITER

- We followed the existing paradigm and required:
  - Keep Chirikov parameter > 1 outside of √flux > √0.85
  - Work over a range of plasma q (i.e., ITER Scenarios 2, 3, 4)
  - Reduce resonant δB as rapidly as possible into core
    - I.e., 2-fold reduction of δB (4-fold in δB^2) by √flux = √0.64 = 0.8
  - Reduce δB elsewhere as much as possible in physical and spectral space
- A well-focused, movable, pitch-resonant spectral ridge in pedestal can meet these requirements
- New data coming from JET, DIII–D, MAST and others
- Numerical modeling also coming

ITER Error Correction Coils make ~4.5 x Larger NON-resonant lobes than resonant field: Unsatisfactory

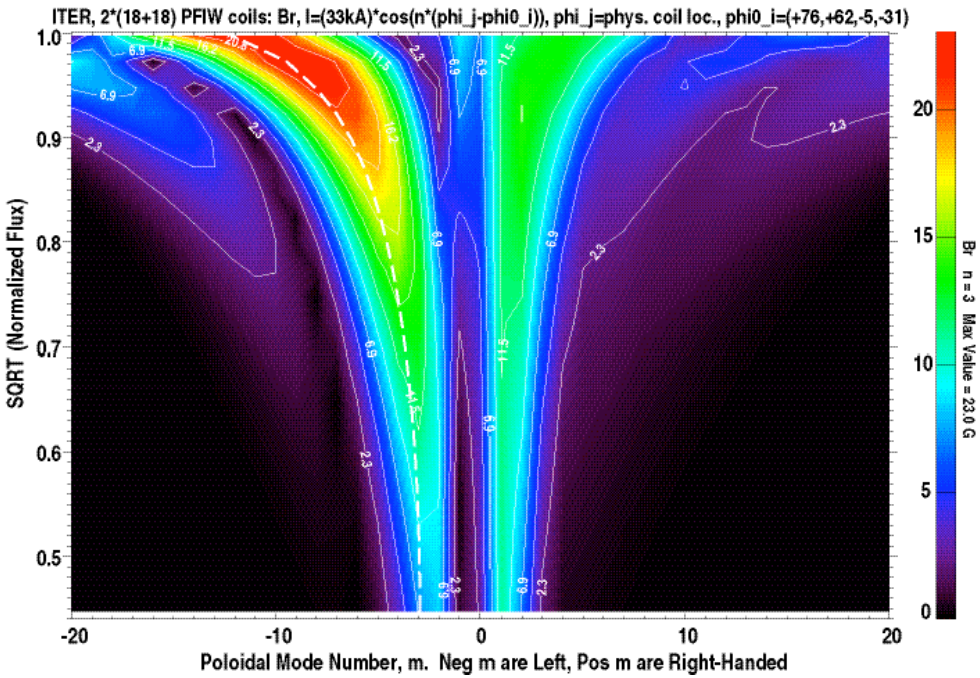


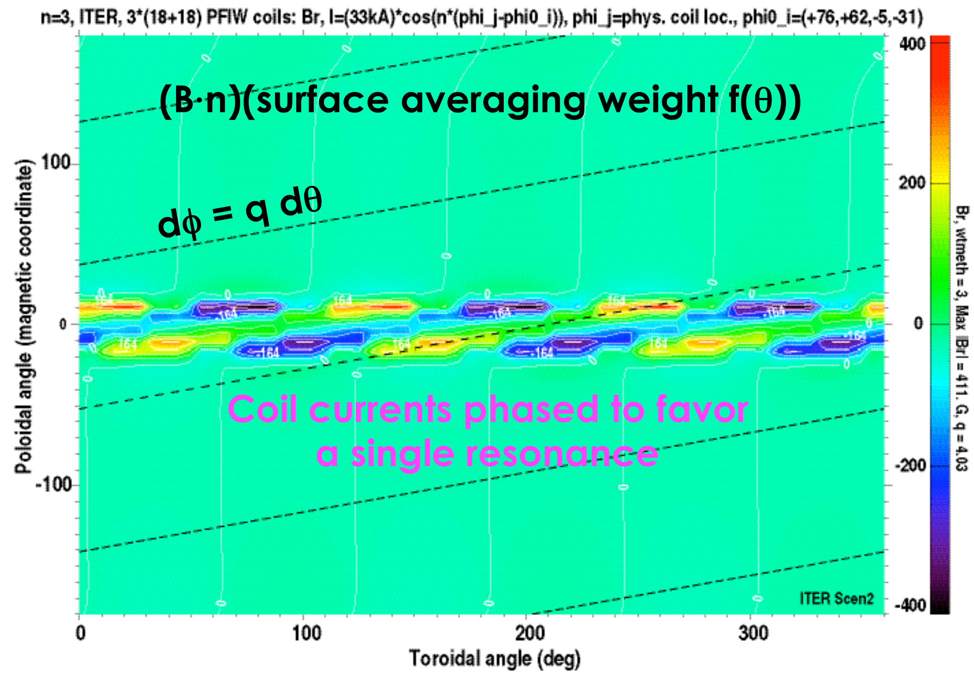


- ITER correction array: 6 Top + 6 Mid + 6 Bot coils attached to PF coils
- Case of 6 mid coils only (shown) is best
  - Top & Bot coils mainly just add to one or the other non-resonant lobe
- Worse non-resonant / resonant at higher q, due to rapidly vanishing higher-|m| harmonics

GENERAL ATOMICS

A Better ITER RMP "Reference Case": n = 3 from 4 rows of 18 coils toroidally, between blanket & wall





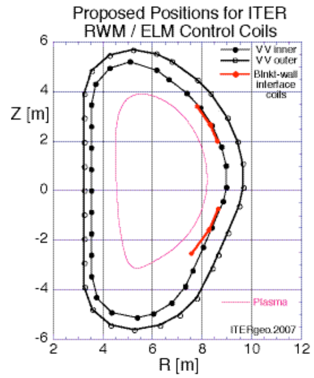
n = 3

Half max. at $\sqrt{\psi} \approx 0.62$

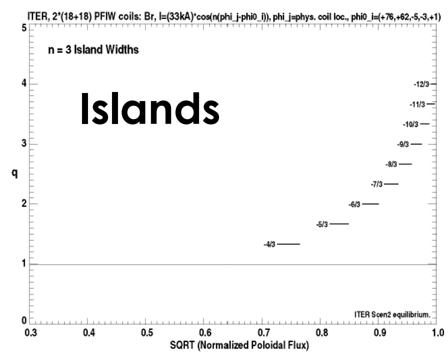
One 60% side lobe

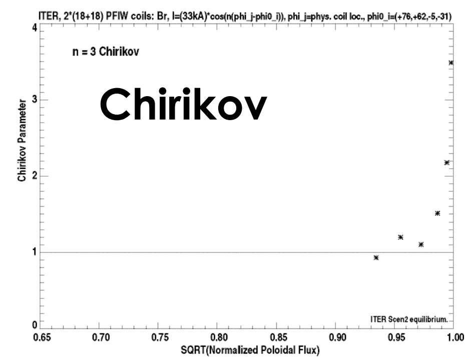
33 kA peak

Using ITER Scenario 2, low-q, hi-β equilibrium

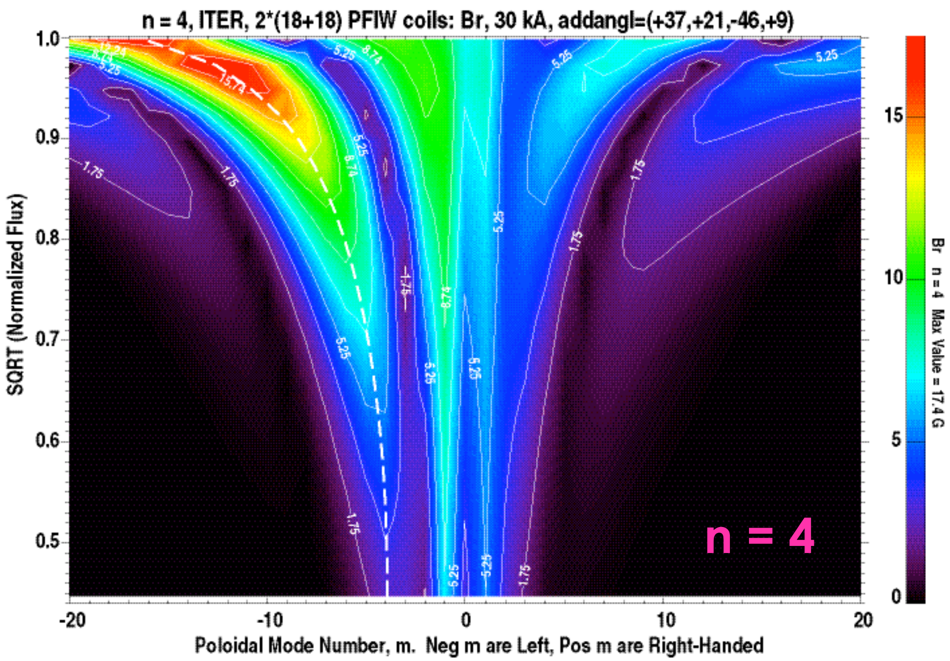


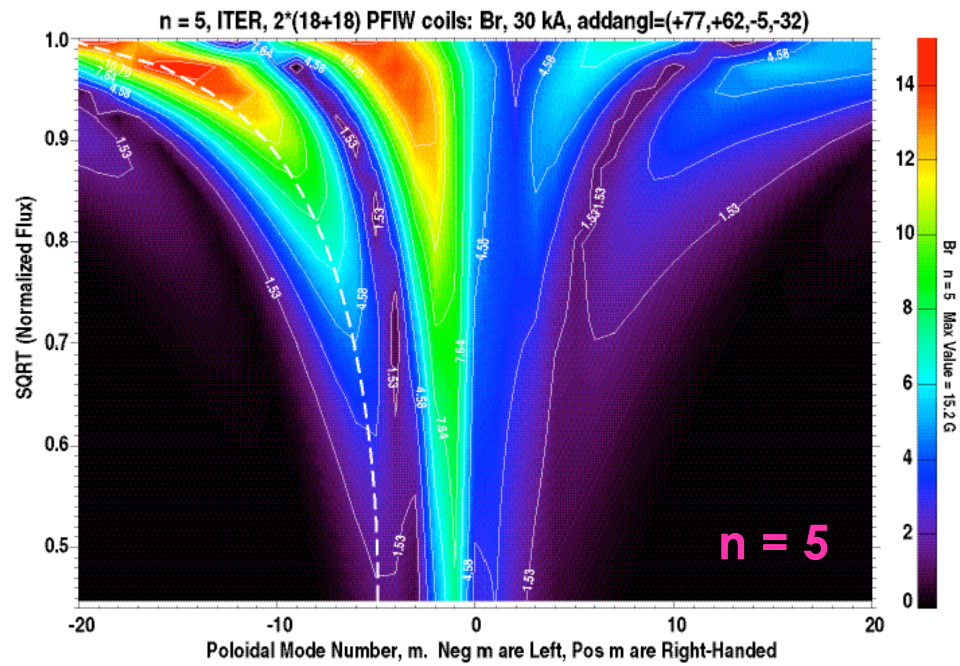
Using 4x18 coils





Higher-n fields penetrate less deeply, but side lobe magnitudes increase for n > 4



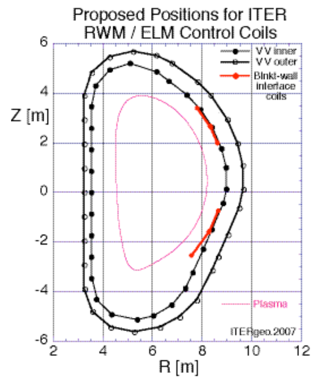


n = 4

Half max. at √ψ ≈ 0.78

One 65% side lobe

30 kA peak



Using 4x18 coils

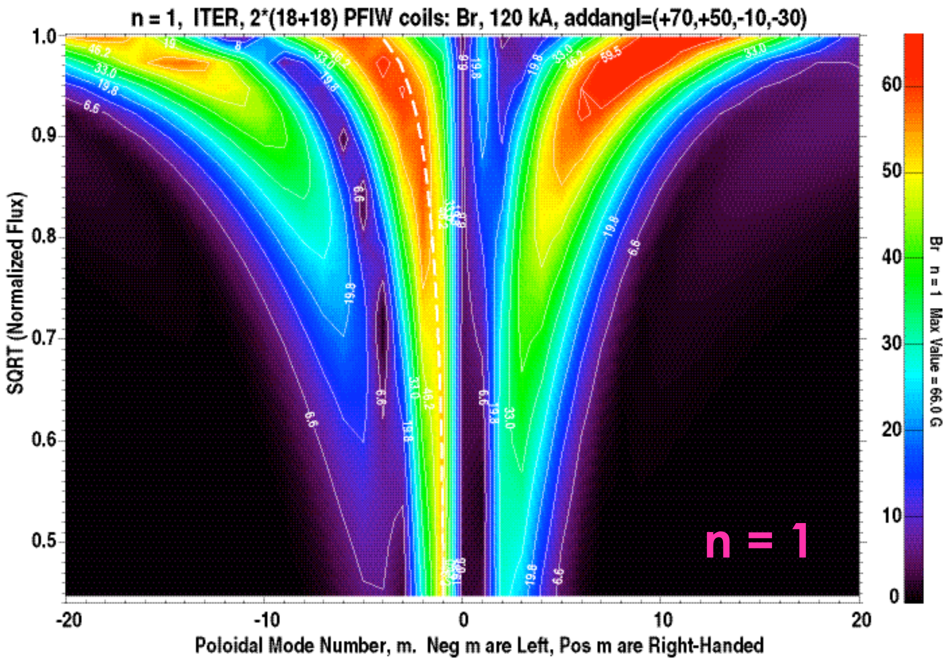
n = 5

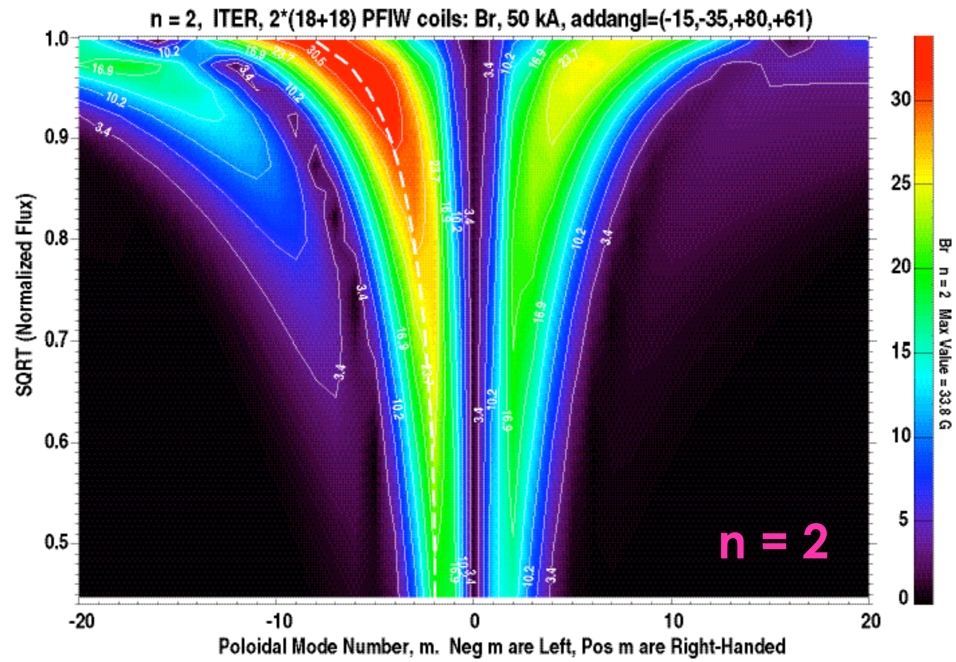
Half max. at √ψ ≈ 0.82

~ 100% side lobe

Current still 30 kA, but it increases at n ≥ 6

Lower-n fields penetrate more deeply and require more current to meet pedestal Chirkov goal



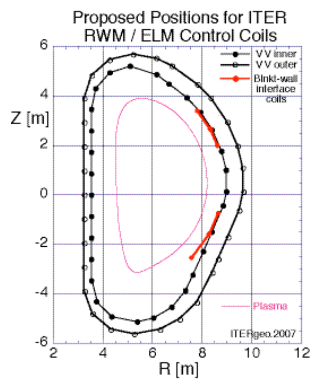


n = 1

Half max. nonexistent

Two large side lobes

120 kA peak



Using 4x18 coils

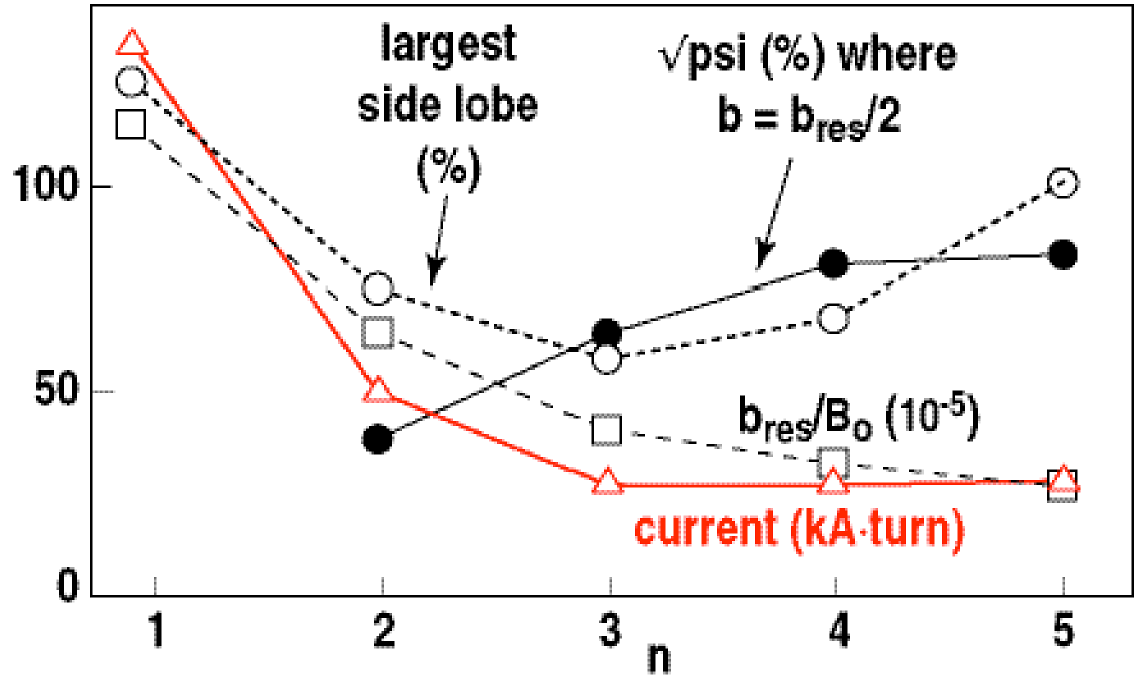
n = 2

Half max. very deep

~ 75% side lobe

50 kA peak

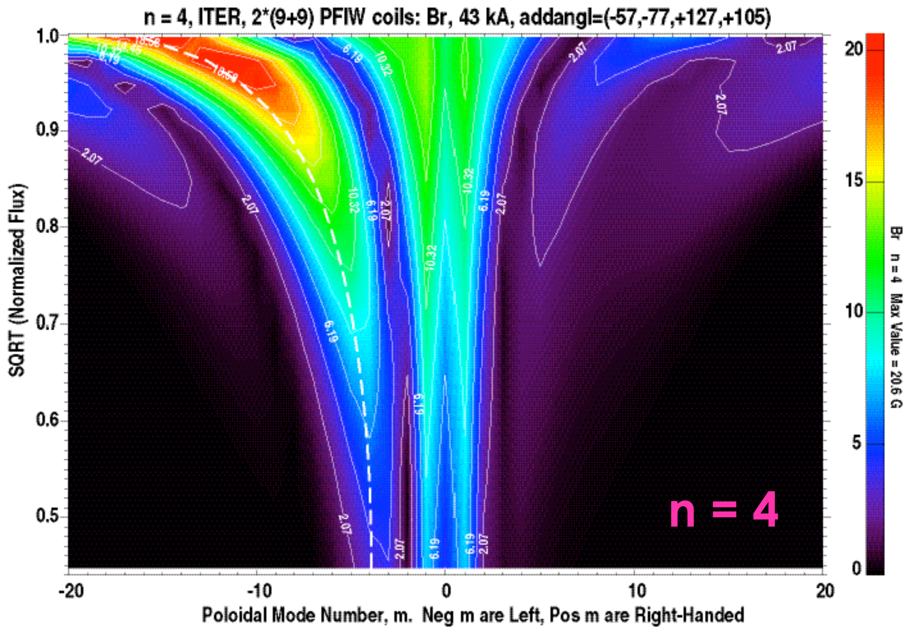
Summary of toroidal mode (n) scan in 4 x 18 coils on vessel inner wall

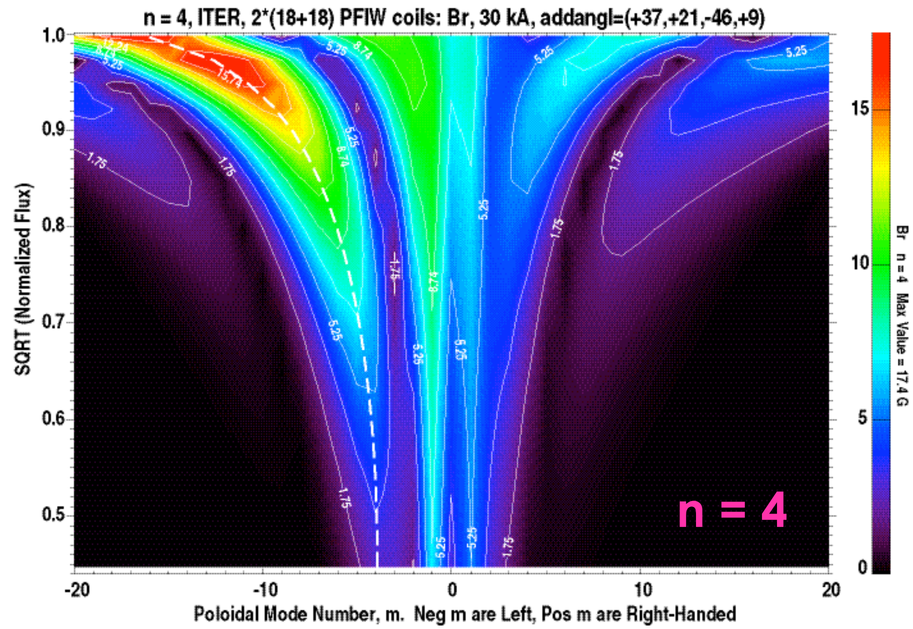


- Low-n fields make few islands, must apply large b, make too much unwanted field components
- High-n fields easily make Chirikov > 1, but eventually make unwanted side lobes in finite coil arrays
- n = 4 seems like best compromise and was used in most of the study

4 x 9 coils toroidally yield field spectra up to n=4 not much different from 4 x 18 coils. Prefer 9!

4 x 9 coil set, n=4 — Compare with ⇒ previous 4 x 18 coil set, n=4



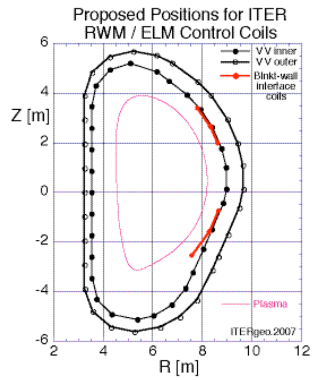


n = 4, only 9 coils/row

Very similar resonant lobe

Two 70% side lobes

43 kA peak



Using 4x9 coils

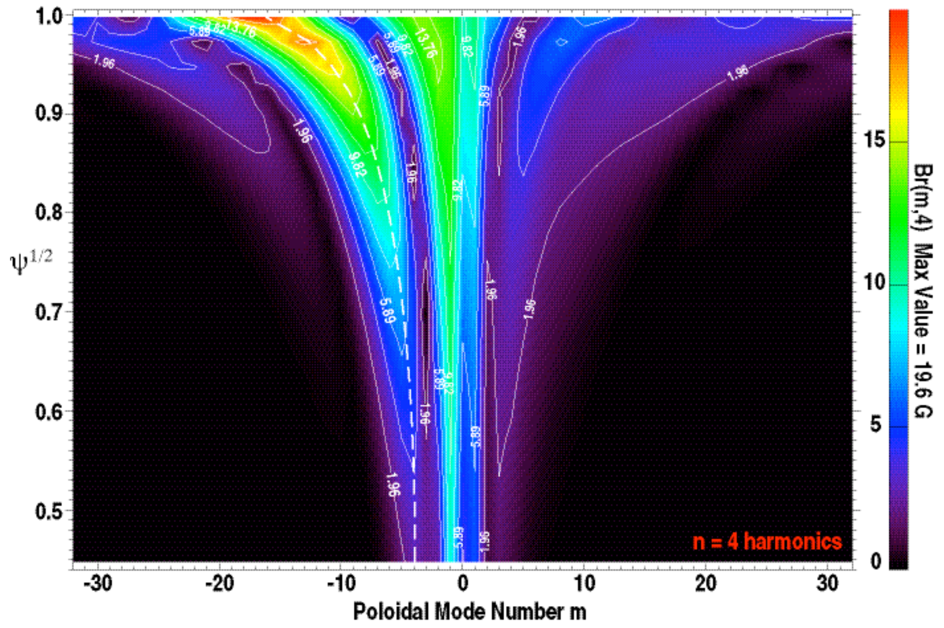
previous 4 x 18 coils, n = 4

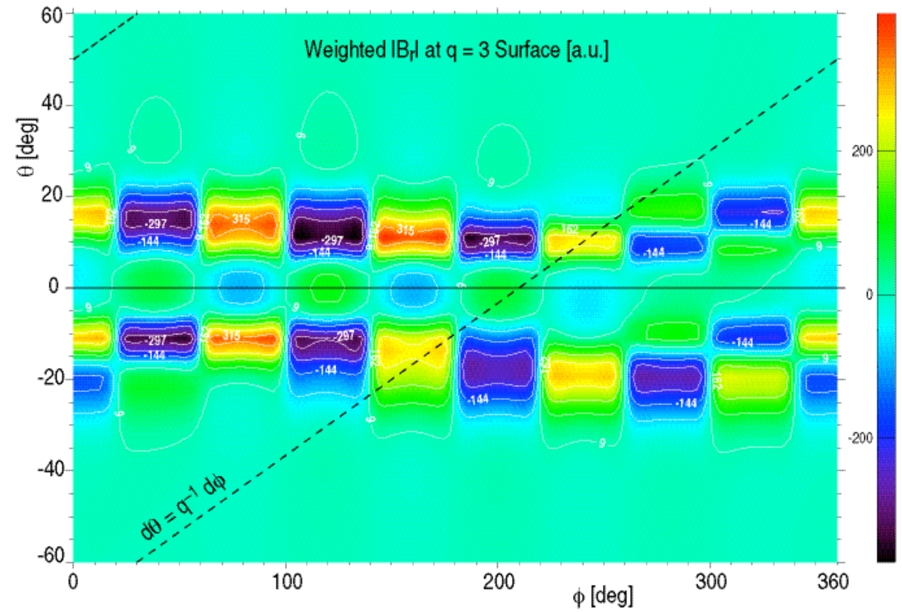
Repeat previous n=4 plot

One 65% side lobe

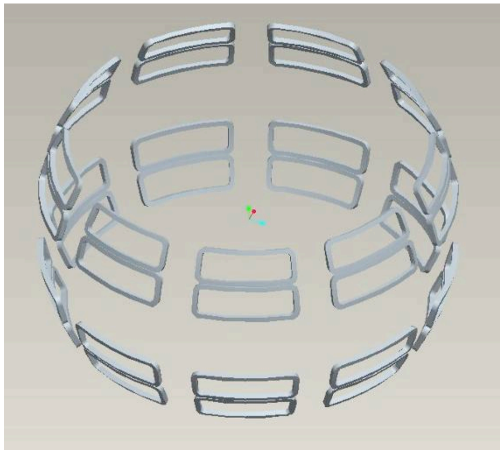
30 kA peak

Refined Current Distribution on 4 x 9 Coils Makes Mainly n=4 Harmonics Efficiently



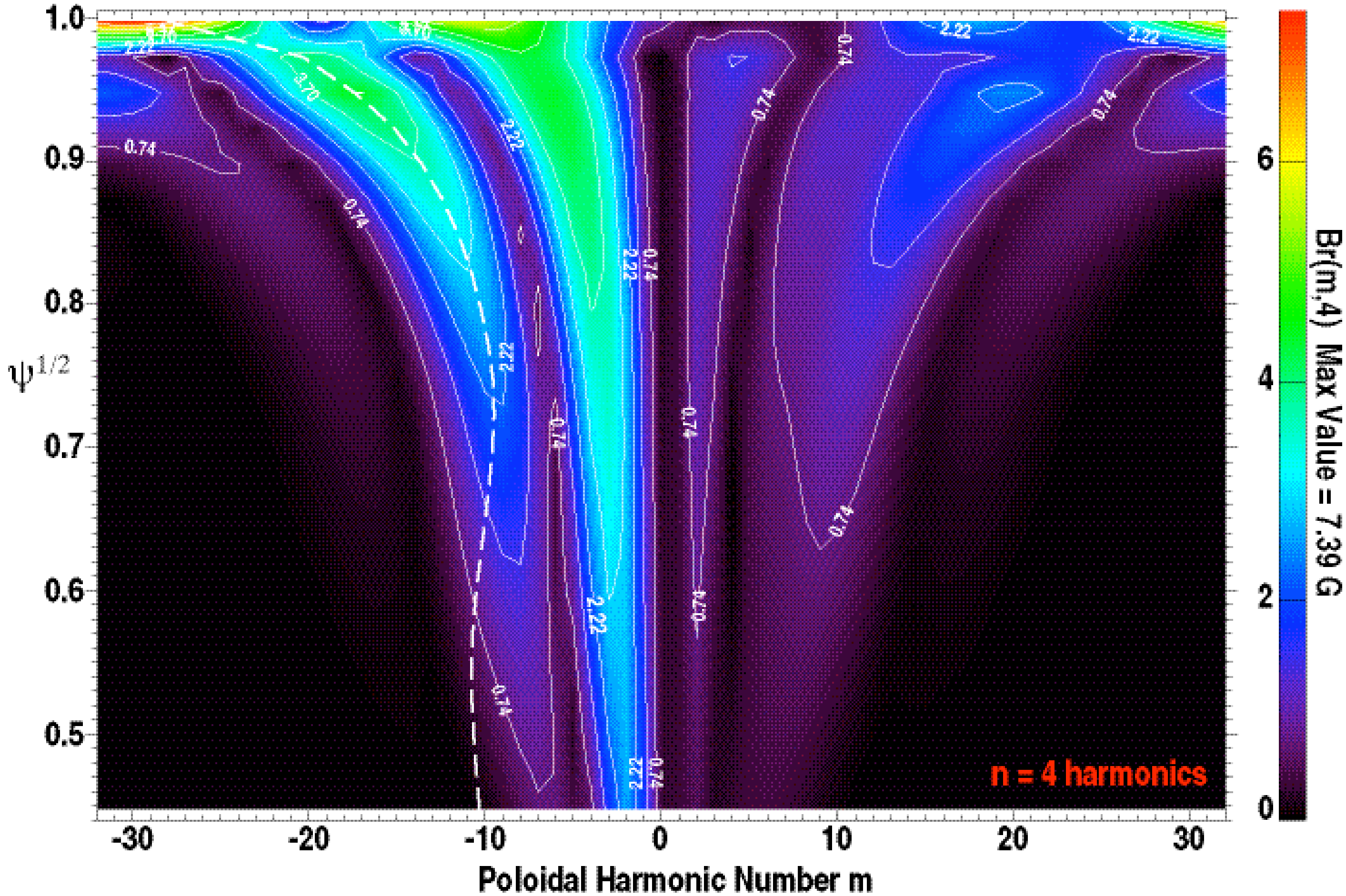


- This more recent calculation aligns the resonant lobe more effectively



- Although approximation of n=4 on just N=9 coils is rough, the relative phases of currents in the 4 rows are chosen to make all 4 periods nearly equal from B-line point of view

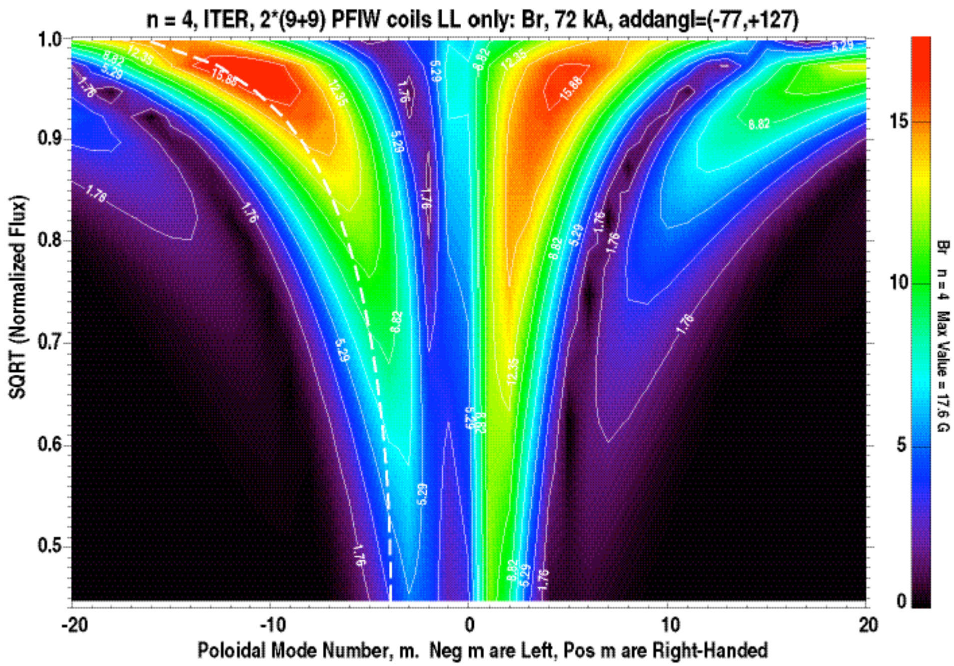
4 x 9 coils on vessel wall also work for ITER Scenario 4 AT plasma (q_{95} ~ 5)

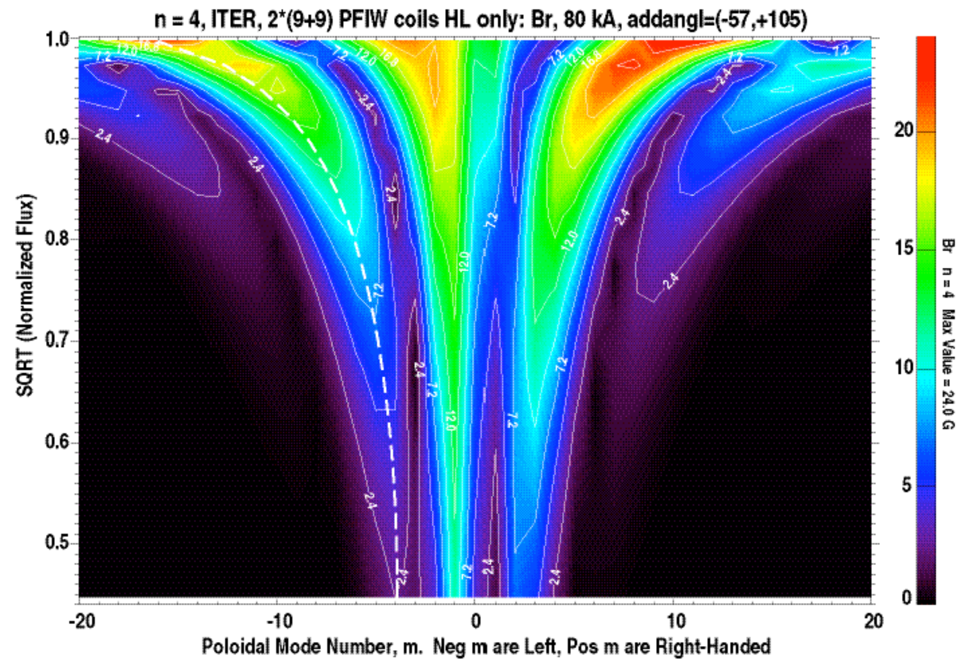


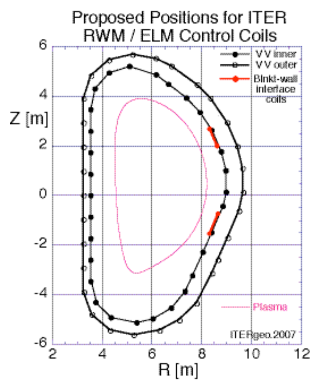
- Only 11 kA; it's easy to make many small islands in high-q edge
- One side lobe at ~100% of pedestal lobe

GENERAL ATOMICS

Two-Row coil sets give large spectral side lobes







2x9 coils

n = 4

Half max. at $\sqrt{\psi} \approx 0.68$

One large side lobe

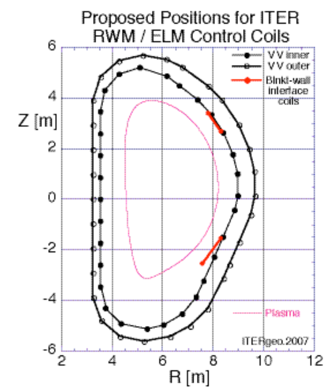
72 kA peak

n = 4

Half max. at $\sqrt{\psi} \sim 0.8$

Two large side lobes

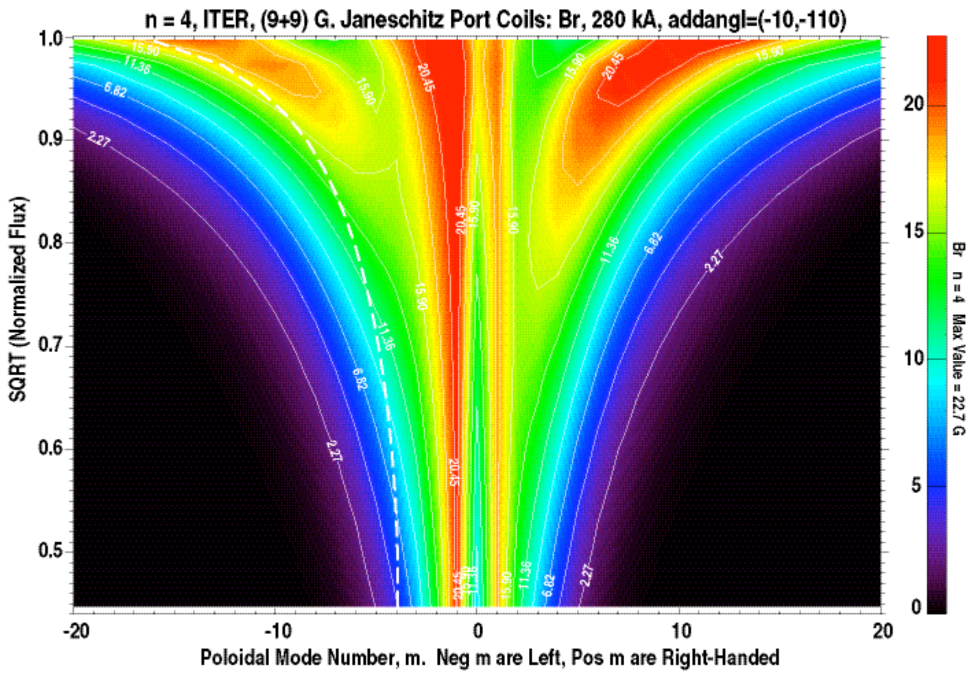
80 kA peak

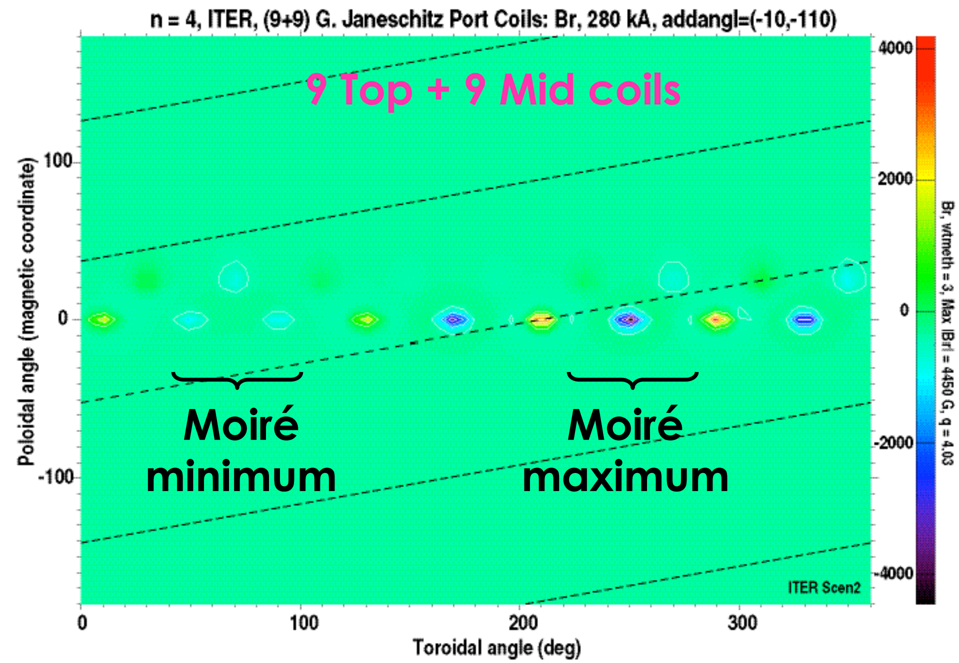


2x9 coils

GENERAL ATOMICS

Coils wound on Top and Mid Port Plugs have little control of spectrum, because Top's field is weak



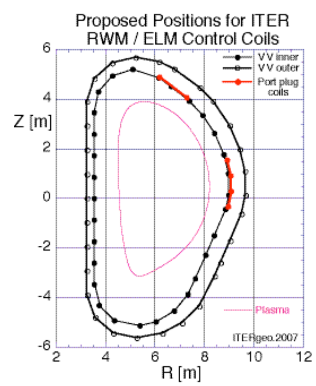


n = 4

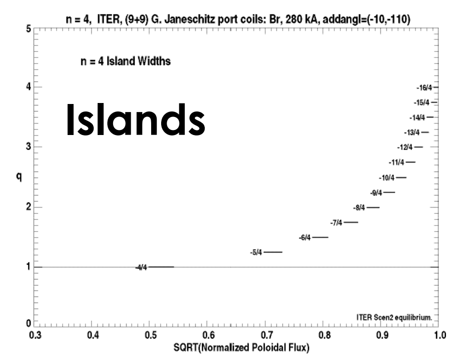
Half max. at $\sqrt{\psi} \approx 0.66$

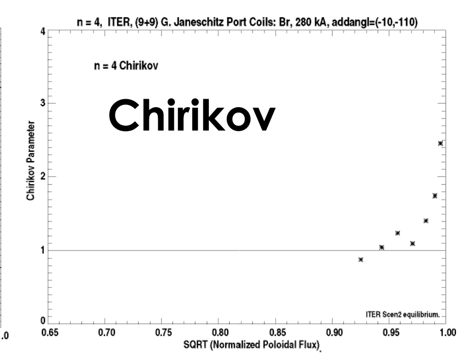
Side lobes > main lobe

280 kA peak

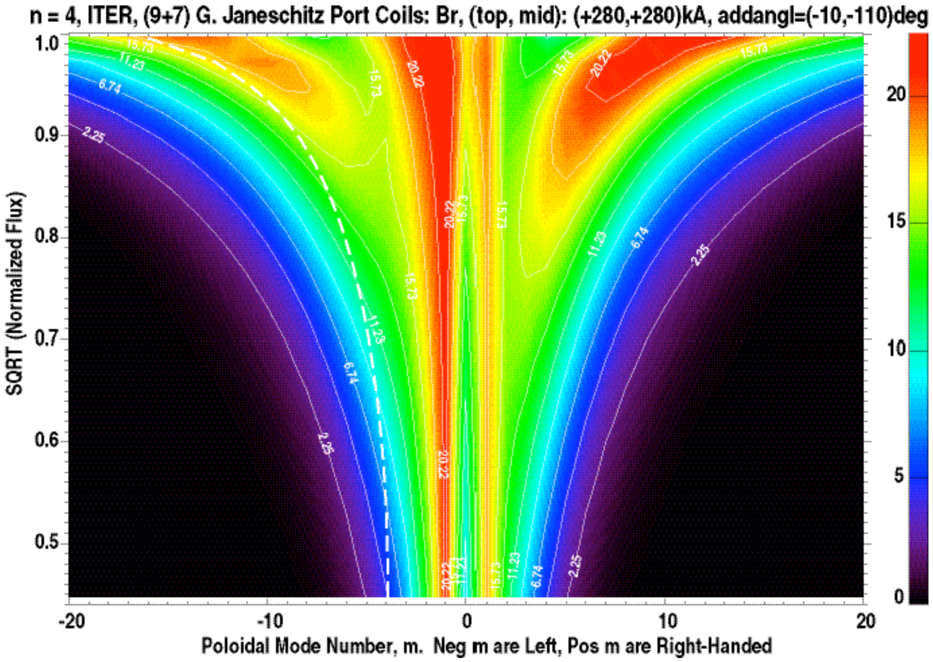


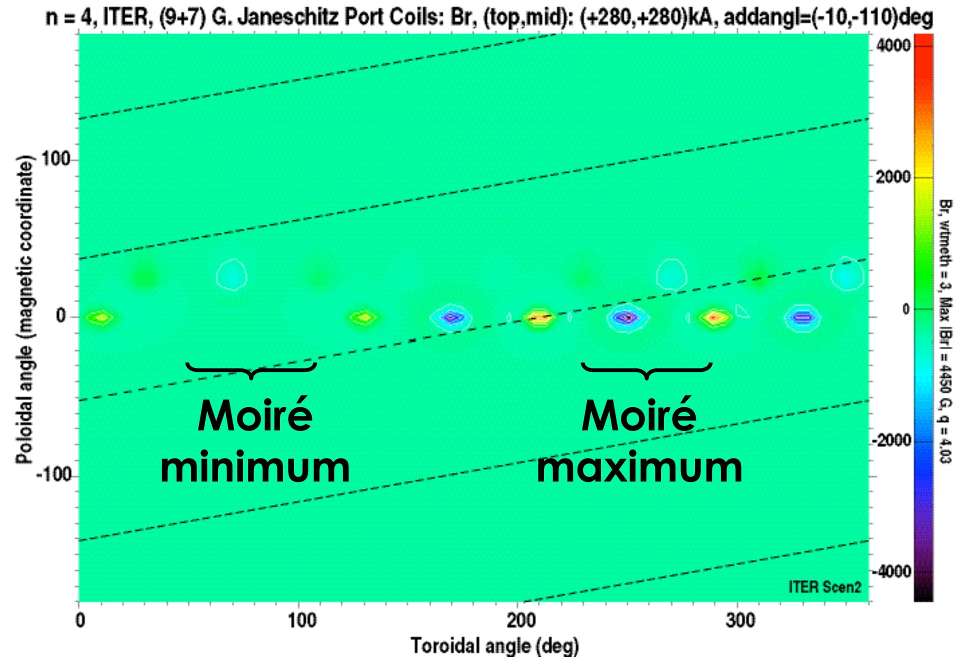
9 top + 9 mid coils





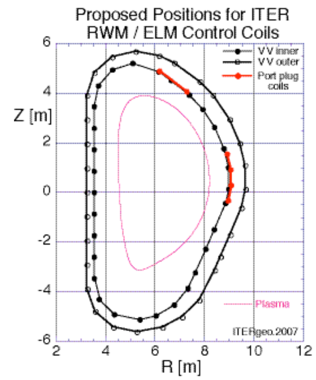
Neutral Beams take 4 of 18 contiguous ports, leave only 7 mid-plane port plugs for coils





n = 4

Nearly same as 9 top + 9 mid port plug coils



9 top + 7 mid coils

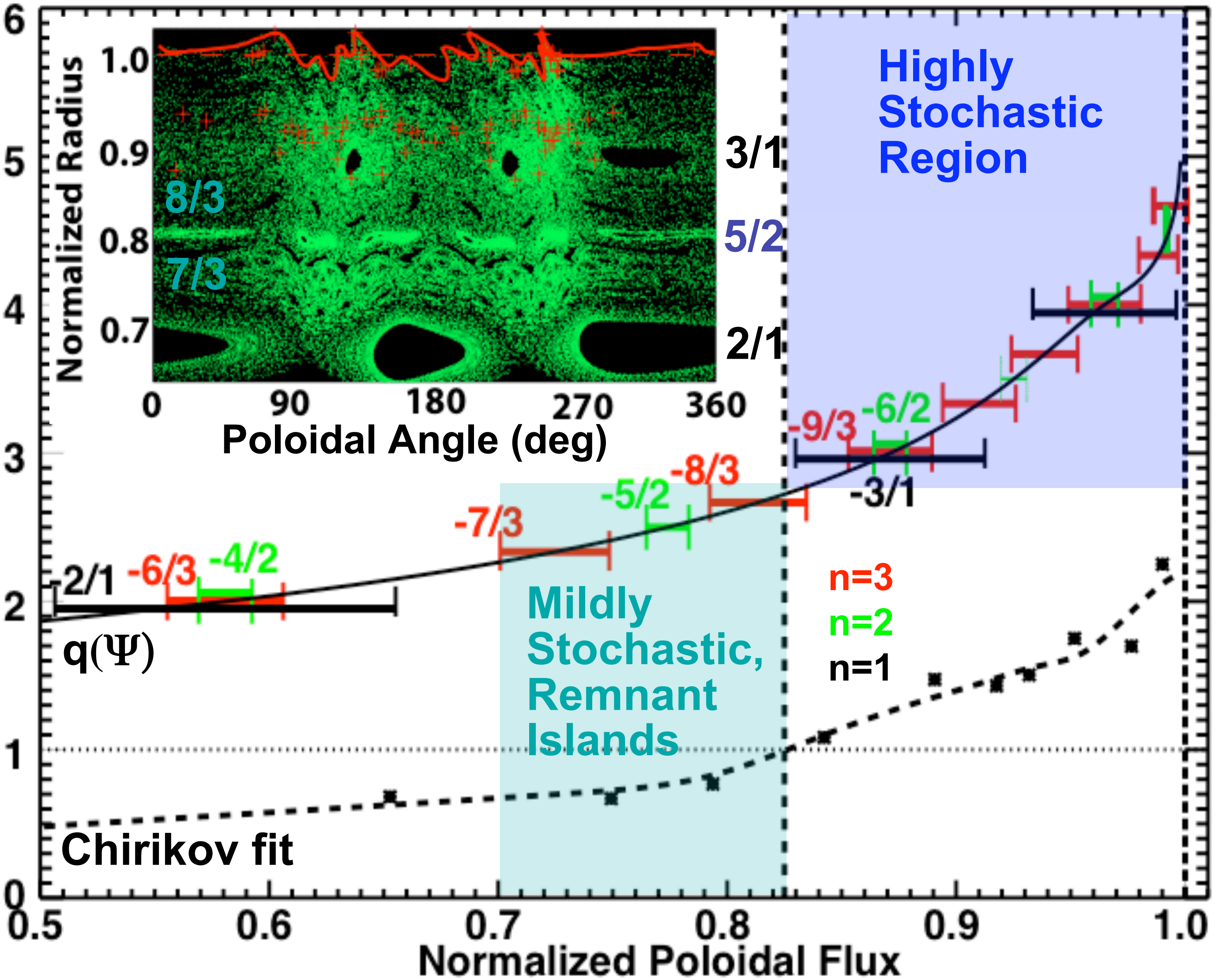
n = 4

Current distribution Moiré minimum was aligned with the Mid port gap to minimize effect missing ports

GENERAL ATOMICS

Multiple-n Fields

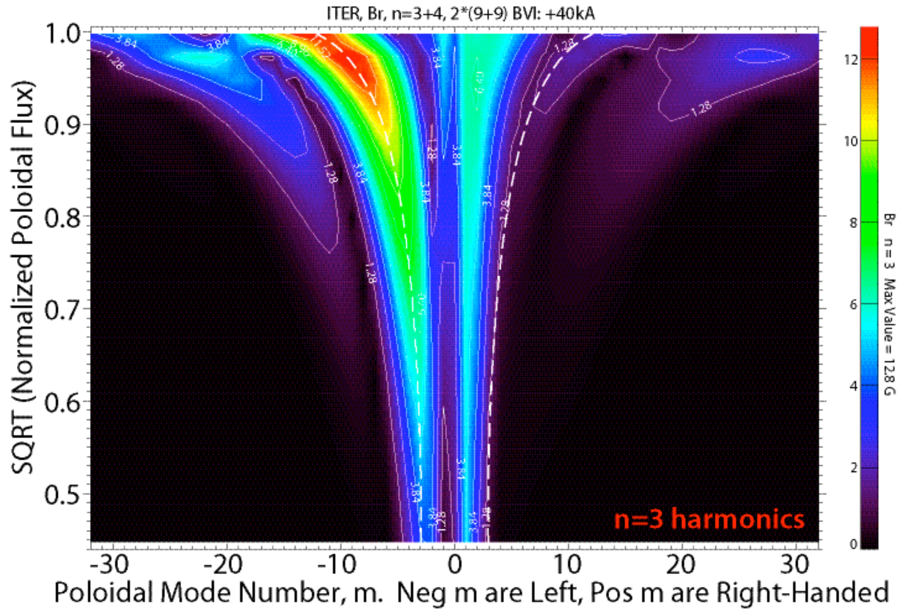
Error Fields and Added n=1 can fill in some gaps between n=3 islands and Increase Stochasticity

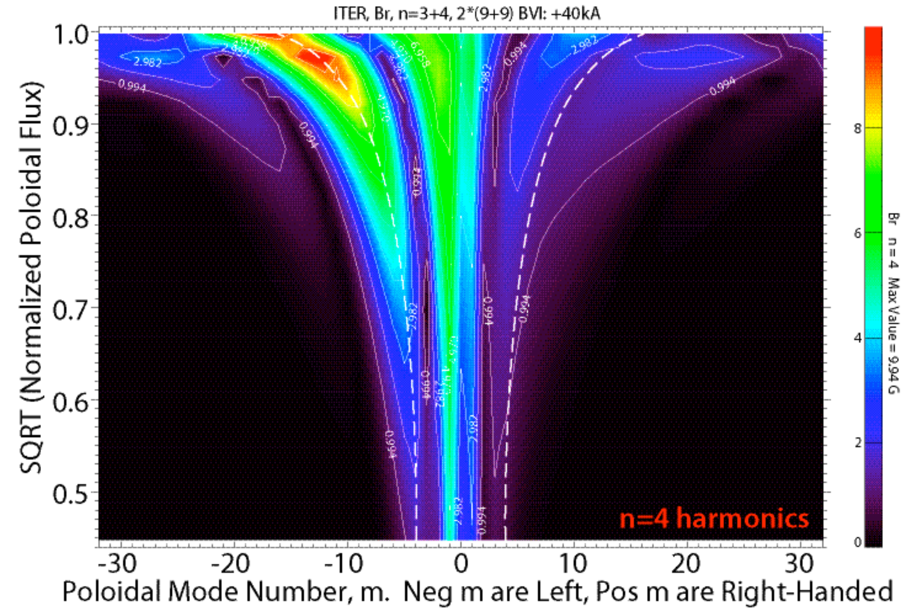


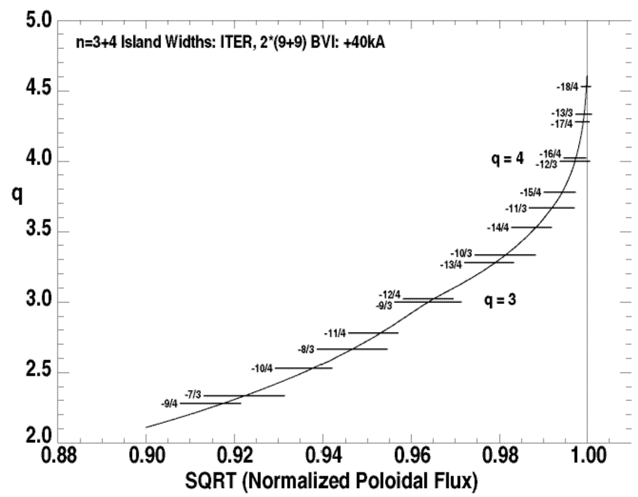
- Stochastic region from q~3 surface outward
- Additional tests with reduced n=3 showed that added n=1 from C-coil can bring back ELM suppression

M.E. Fenstermacher

n=3 + n=4 Current Distribution in ITER 4 x 9 Array on Vessel Gives More Island Overlap at Same 40 kA

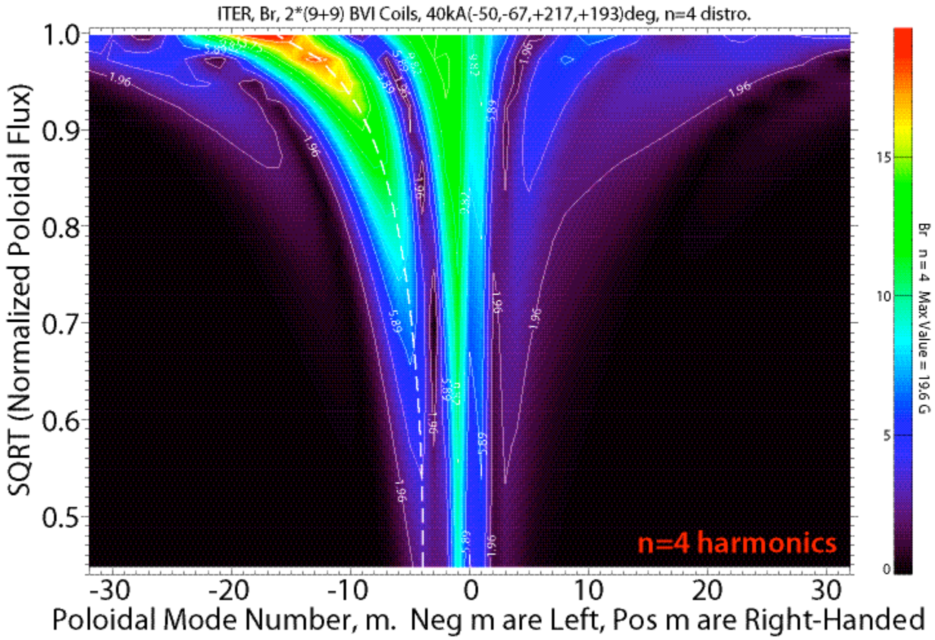


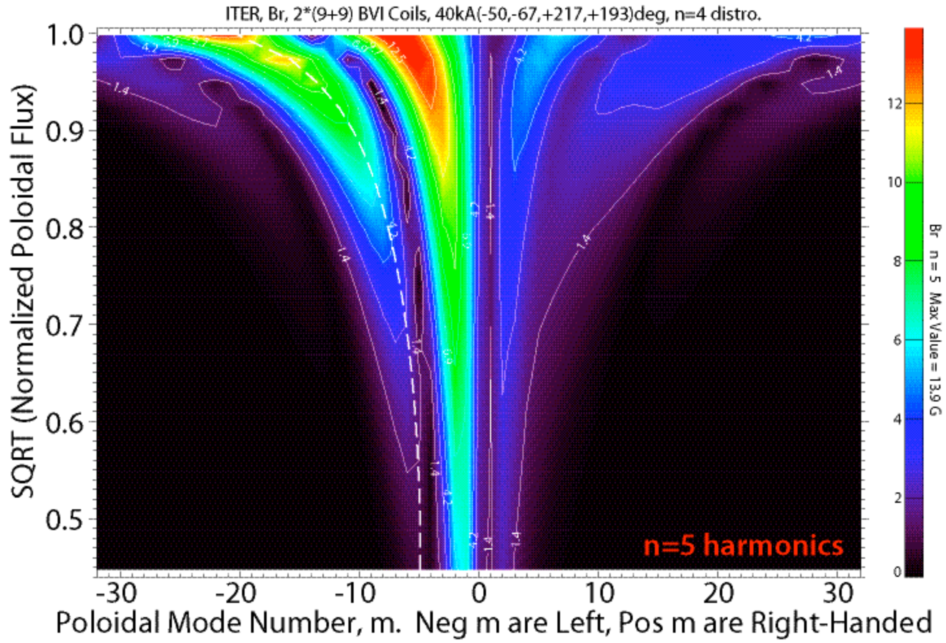


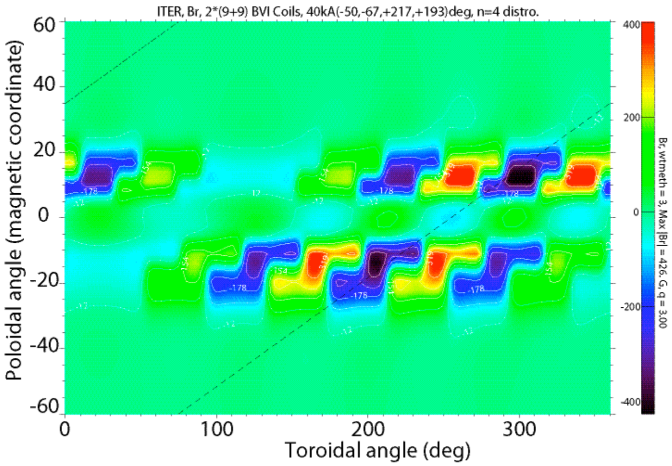


- **Denser set of islands and good overlap for same peak coil current as from a single harmonic current distribution gives finer-scale stochasticity.**
  - **Will plasma really prefer this?**

An n=4 Distribution in 4 x 9 Array with All Moiré Aligned along a B-line Adds n=5 Resonant Field







- **Same 40 kA peak current makes combined n=4 + n=5 B-field, finer stochasticity, than "balanced" distribution shown earlier**
- **Favorable tradeoff?**

Most Proposed RMP Coils Have Large Relative Non-Resonant Braking Factor (NRBF)

$$\mathrm{NRBF} = \sum_{n\neq 0} n^2 \left(\left| \mathbf{B} / B_{0,0} \right|_{m,n} \right)^2$$

evaluated away from edge and magnetic axis

Some Indicators of Side Effects of Candidate Proposed ITER ELM Control Coils					
Indicator Name	**ITER Error Correction Mid coils, n=3 225 kA·t peak**	**Vessel Wall 4 rows of 9 coils n=4 55 kA·t peak**	**Vessel Wall 18 Mid, Picture Frame, n=4 100 kA·t peak**	**0.5 m coils on 14 Mid Port Plugs, n=4 310 kA·t peak**	**14 Mid & 18 Top Port Plugs n=4 300 kA·t pk**
B_{res}/B_0 [10^{-4}]	3.3	4.9	4.9	4.7	5.0
Radius for half B_{res} [$\sqrt{\psi}$]	Never drops to half	0.77	0.61	0.60	0.64
q at half B_{res}	Never drops to half	1.45	1.05	1.05	1.1
B_{res} at q = 2 [10^{-4} T]	17	20	21	21	20
Non-Resonant Braking Factor [10^{-8}]	3200	595	2900	3100	3200

Need to learn if this is important or not

Summary and Conclusions (1)

- Physics of ELM control by δB is not yet well understood
  - Experiments demonstrate feasibility, provide some guidance
  - Cannot prescribe necessary & sufficient conditions
  - Should choose a coil set that can meet a range of possibilities
- ITER Error Field Correction Coils appear unsatisfactory
  - Resonant components stay large into magnetic axis (vacuum field)
  - Very large non-resonant harmonics
- ELM Control Coils on Vessel Wall, behind blanket:
  - Close enough and extended enough to tailor B-field
    - Analogous to phased array antenna
    - Can adjust to plasma q
  - n=4 seems to be a good tradeoff

Summary and Conclusions (2)

- A wall mounted array of 4 rows of 9 coils each has the flexibility to apply ELM control fields with desired spectral content over a range of q, as demonstrated here by examples of predominantly resonant spectra.
  - 4-row array limits side lobes rather well up to n = 4, even with only 9 coils toroidally, and needs only 40~50 kA peak
- ELM Control Port Plug (Top & Mid) Coils:
  - Large non-resonant harmonics at low |m|
  - Top & bottom port plug coils make little contribution; abandoned
  - Reduction of mid-plane band by NB ports has limited effect
- Non-resonant braking may be an important issue
  - Not yet well understood and verified. Needs physics attention.