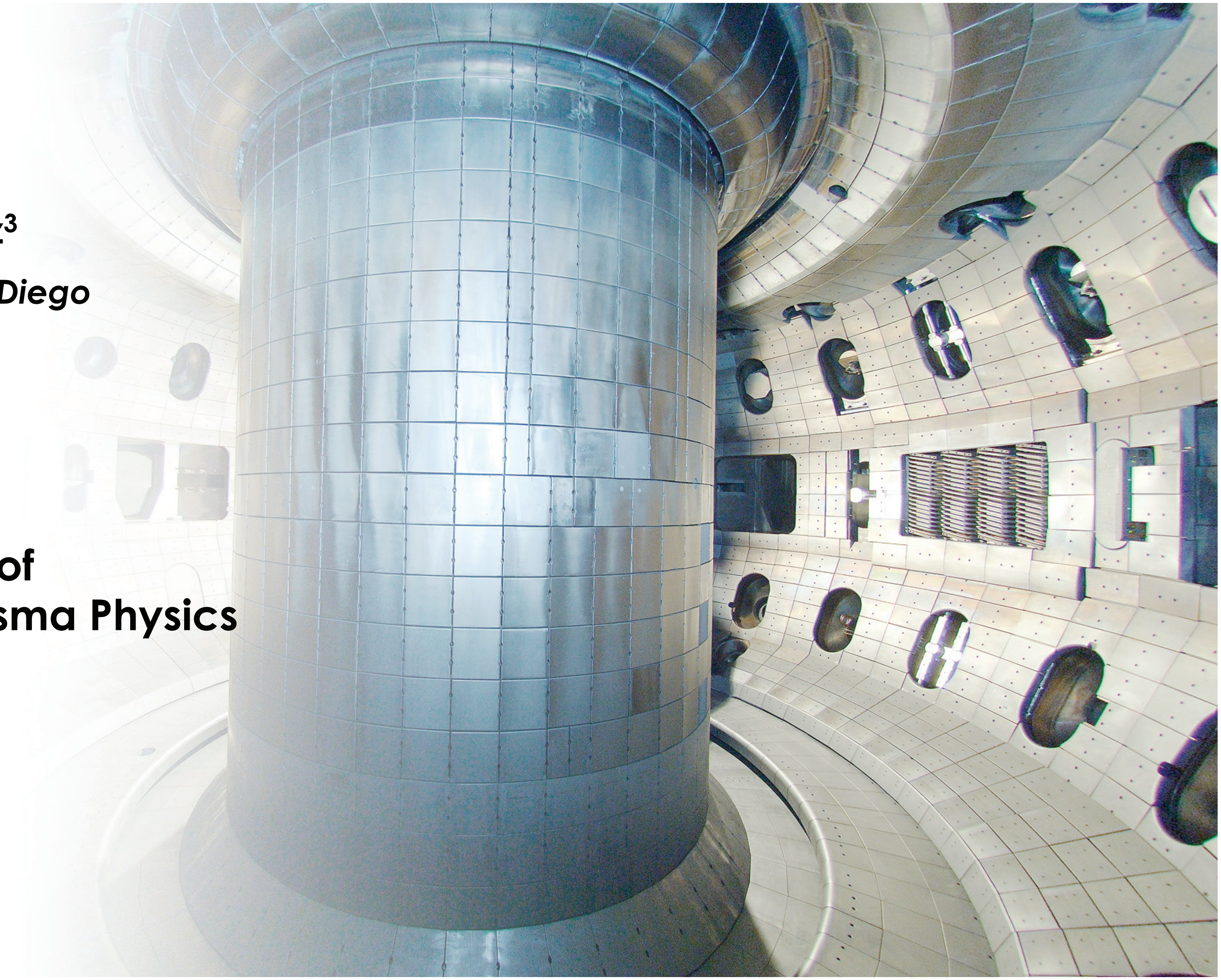
Numerical Analysis of Resonant Magnetic Perturbations for ELM Control in ITER



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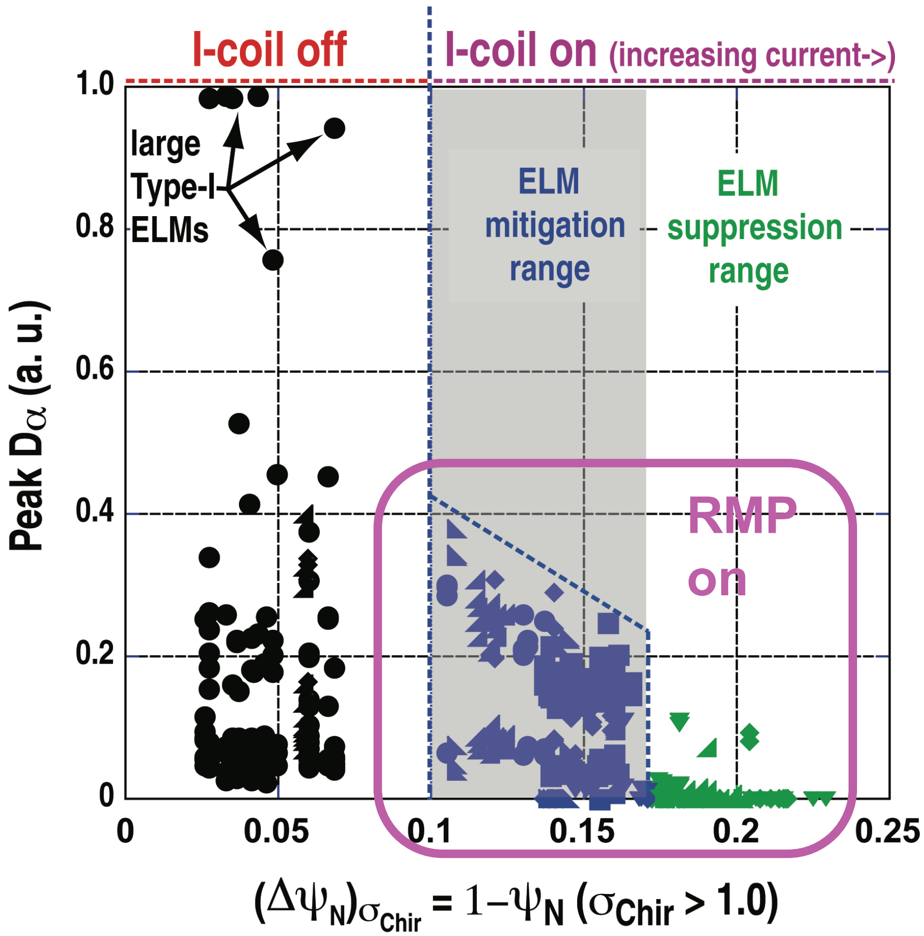
Perturbed Vacuum Magnetic Field Modeling is Correlated with ELM Suppression in DIII-D

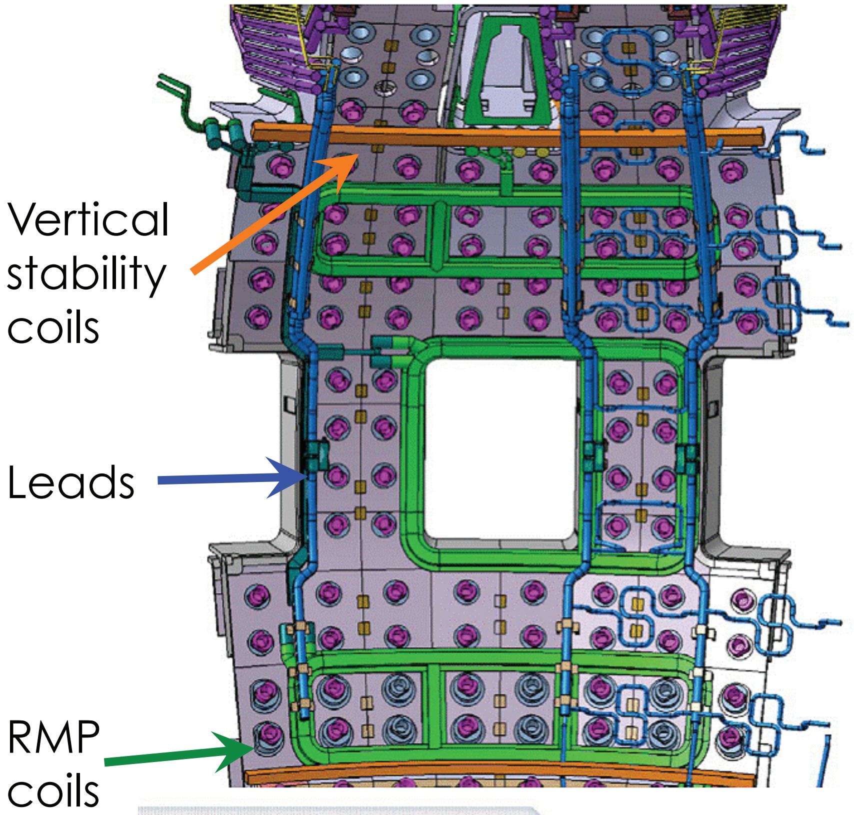


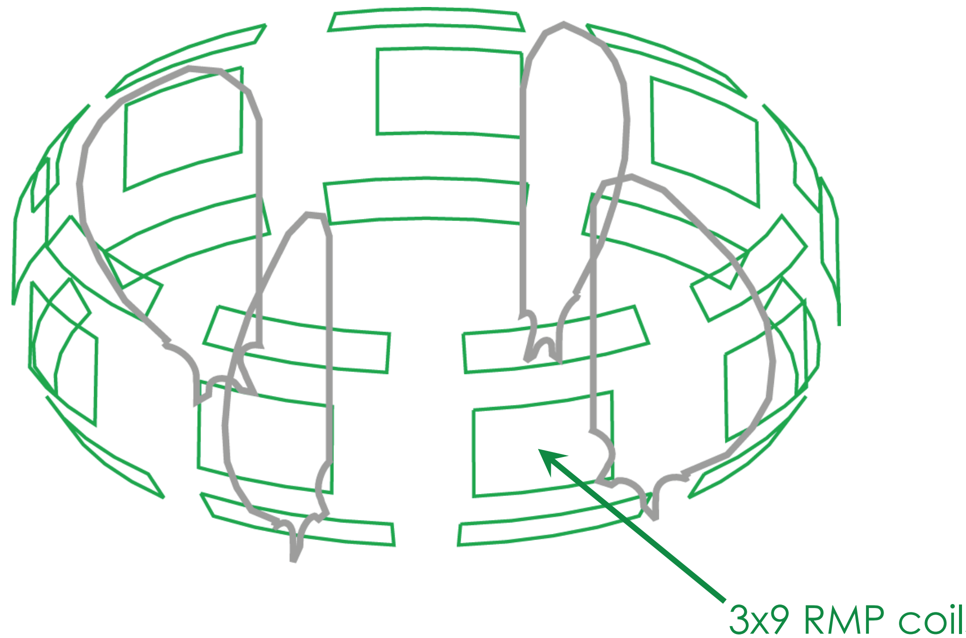
Fenstermacher, M.E., Evans, T.E. *et al.*, PoP **15**, 056122 2008

- **Perturbed vacuum magnetic field model**
  - D_{CHIR}
  - Field Line Loss ratio
- **Criteria for ELM suppression D_{CHIR} = 0.165**
- **Underlying physics of RMP ELM suppression are not well understood**
- **Plasma response is important (i.e. MARS-F, M.J. Lanctot BI3.00002) and should be included in the future study**

The 3x9 RMP ITER Coil Geometry was Implemented in TRIP3D

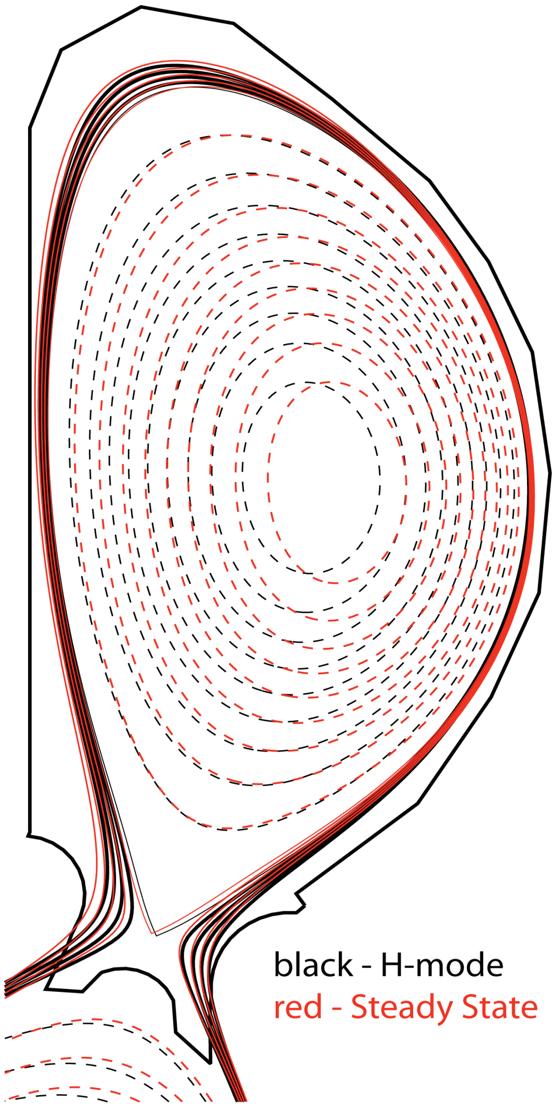
Internal RMP coils
(view from inside)

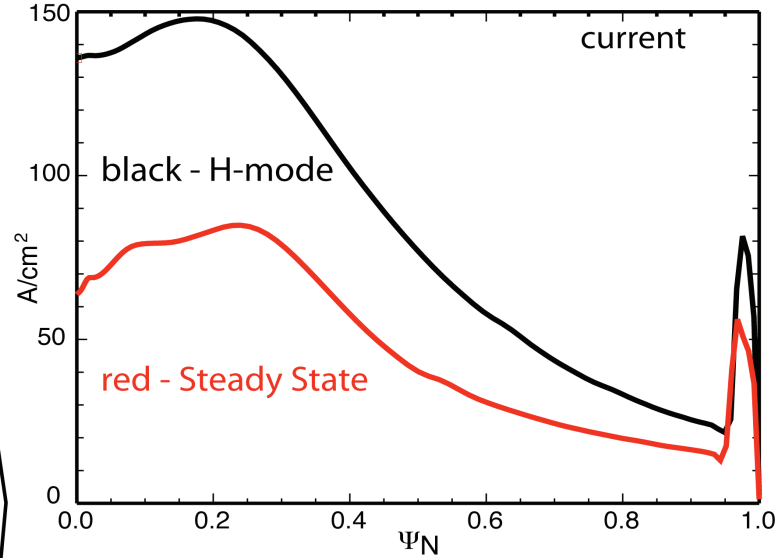


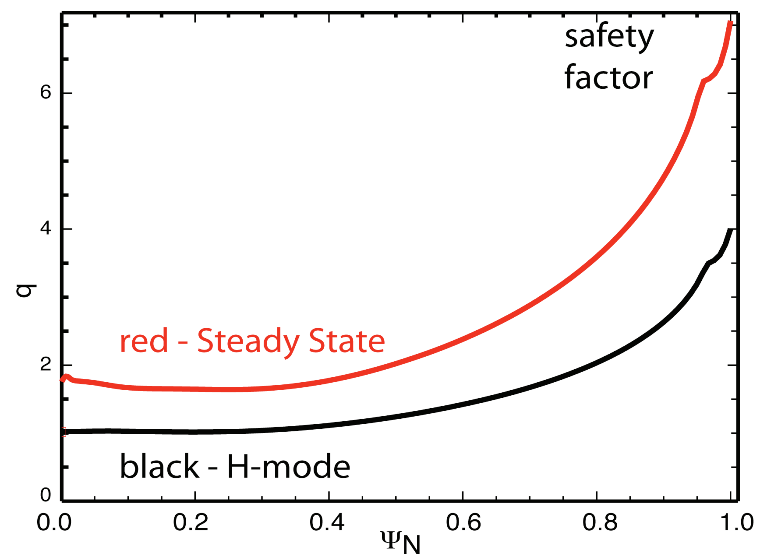


- **ITER's design includes**
  - Internal RMP coils (3 rows by 9 coils)
  - Error Field Correction coils (3 rows by 6 coils, not shown)
- **EFC coils have little effect on RMP ELM suppression**
- **Implemented ITER wall geometry**

Vacuum Field Modeling Being Done with ITER H-mode and Steady State Equilibria Generated by Corsica







ITER Scenarios:

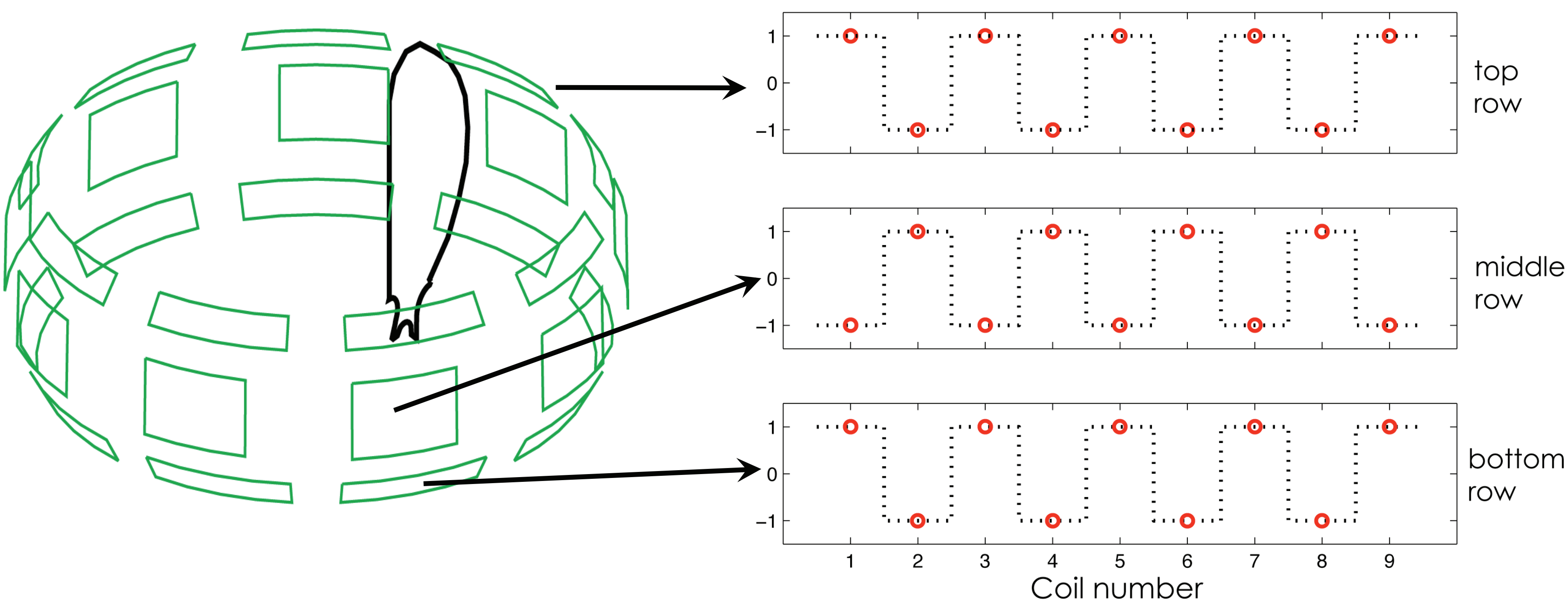
- **H-mode**
  I_p = -15 MA
  B_T = -5.3 T
  $q_{95} \approx 3.2$
- **Steady State**
  I_p = -9 MA
  B_T = -5.3 T
  $q_{95} \approx 5.9$

from T.A. Casper

Modeling of ITER 3x9 RMP Fields has been Done Using Square, Cosine and Sine Wave Coil Currents

RMP coils n=4 90 kAt square waveform

	1	2	3	4	5	6	7	8	9
top row	-1	1	-1	1	-1	1	-1	1	-1
middle row	1	-1	1	-1	1	-1	1	-1	1
bottom row	-1	1	-1	1	-1	1	-1	1	-1



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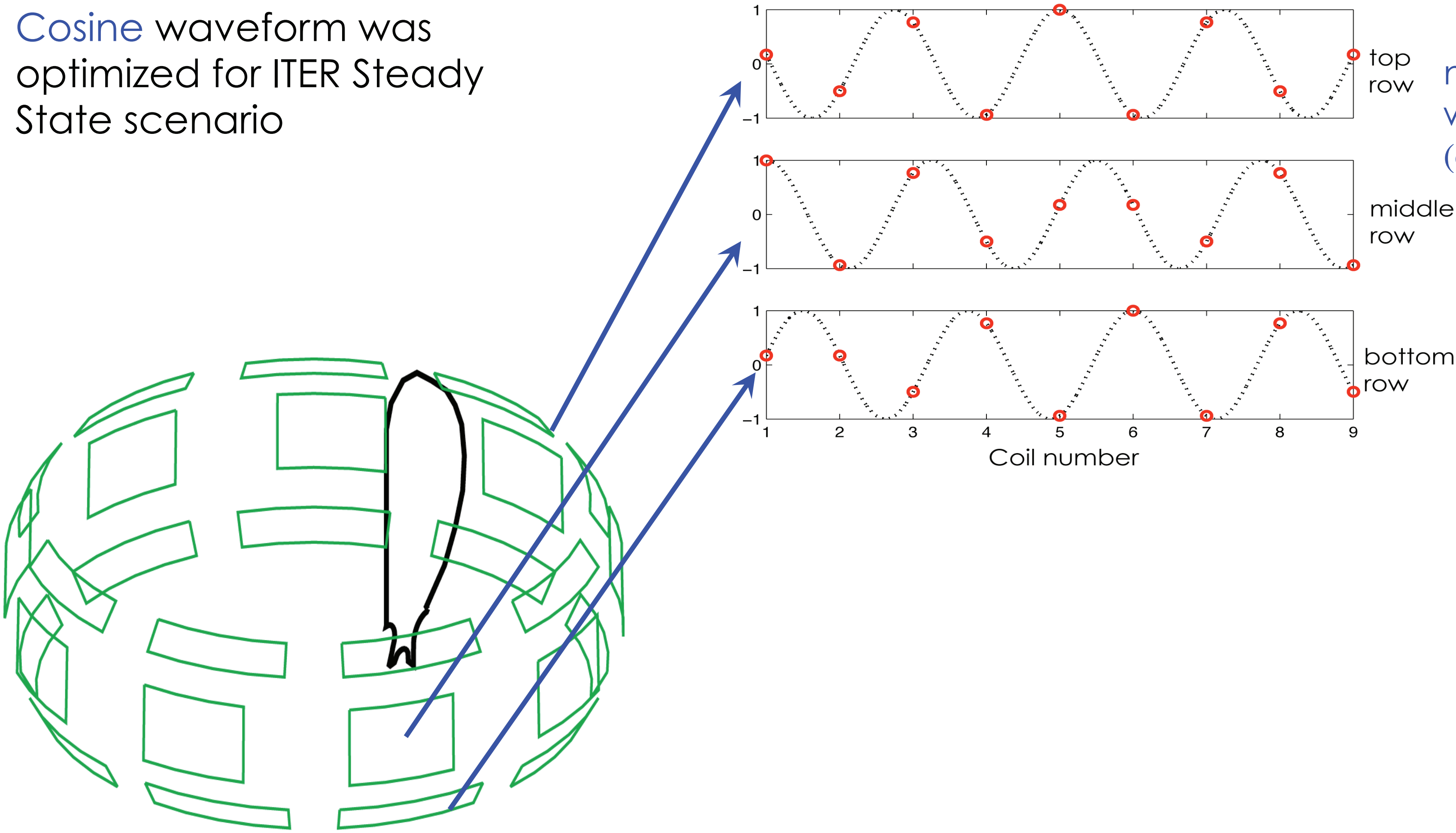
Cosine waveform was optimized for ITER Steady State scenario



n=4 cosine waveform
(ϕ-70°, ϕ, ϕ+70°)

Modeling of ITER 3x9 RMP Fields has been Done Using Square, Cosine and Sine Wave Coil Currents

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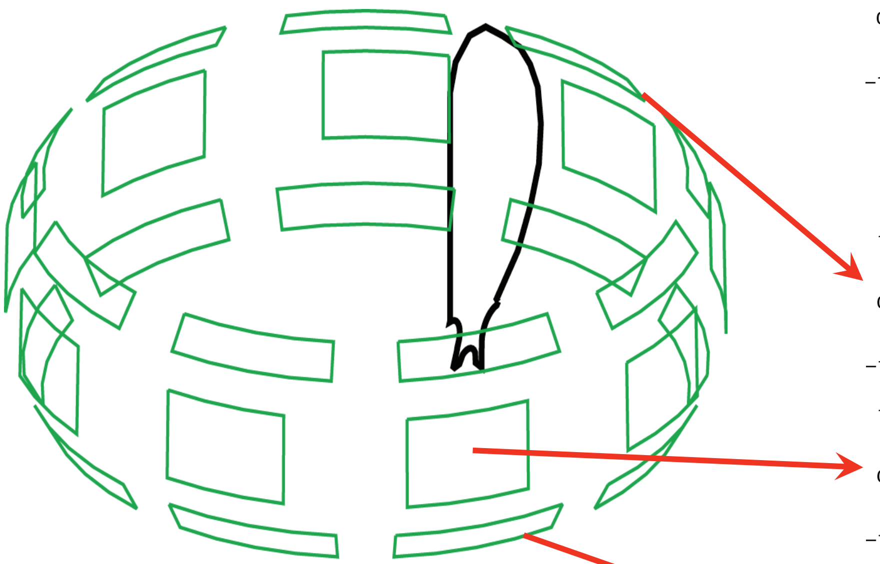
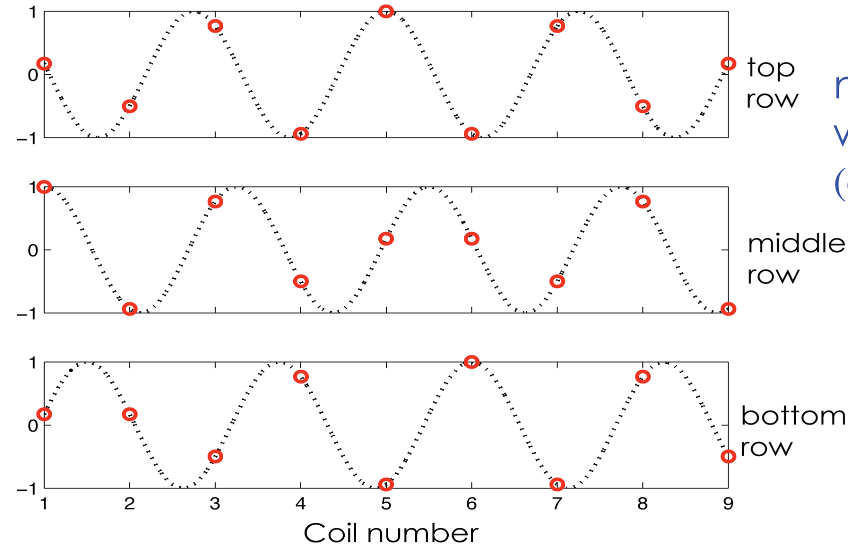
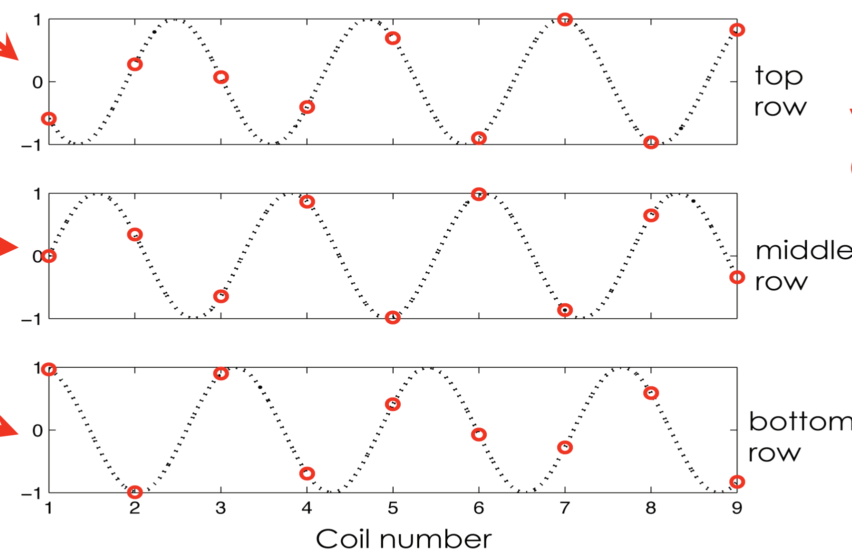
Sine waveform was optimized for ITER H-mode scenario





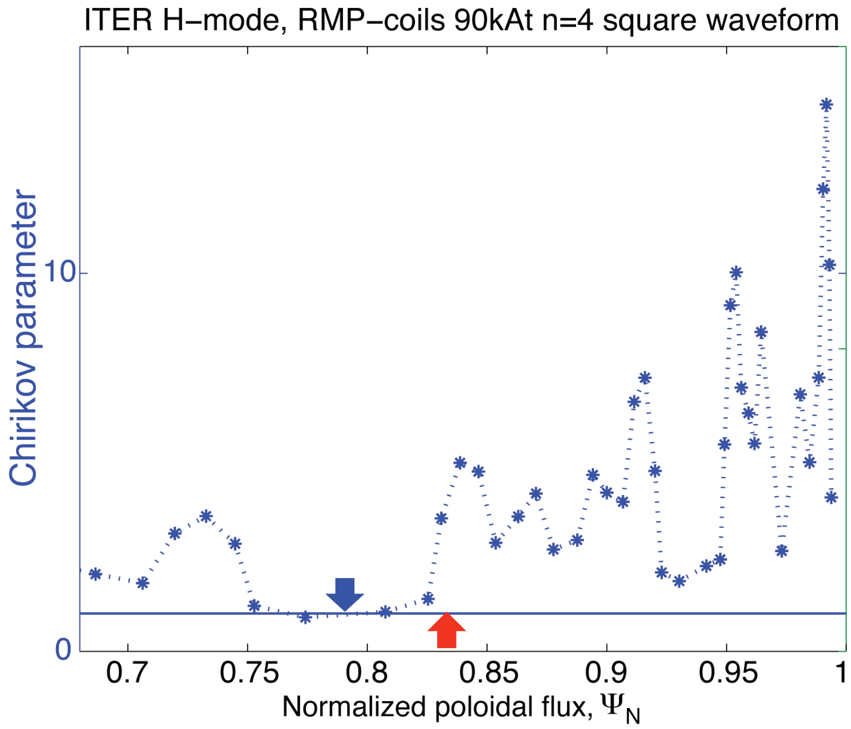
n=4 cosine waveform (ϕ-70°, ϕ, ϕ+70°)



n=4 sine waveform (ϕ+54°, ϕ, ϕ-64°)

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Vacuum Island Overlap width and Field Line Loss in ITER H-modes Exceeds the DIII-D ELM Suppression Criteria



Chirikov parameter – vacuum magnetic island overlap parameter

- width of island overlap region $\Delta_{CHIR} = 0.18 - 0.23$ exceeds the criteria for ELM suppression in DIII-D $\Delta_{CHIR} = 0.165$

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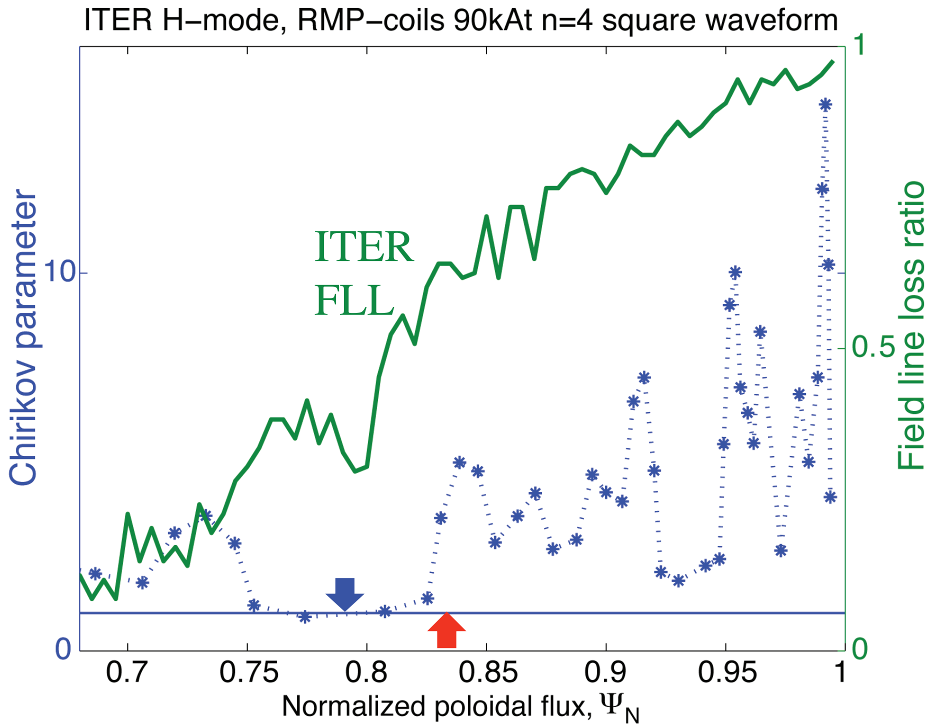

Chirikov parameter – vacuum magnetic island overlap parameter

Field Line Loss ratio - ratio of field lines that hit the divertor to the total number of field lines started on a particular flux surface

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- TRIP3D vacuum field line tracing code
- Field Line Loss Fraction has broad radial profile

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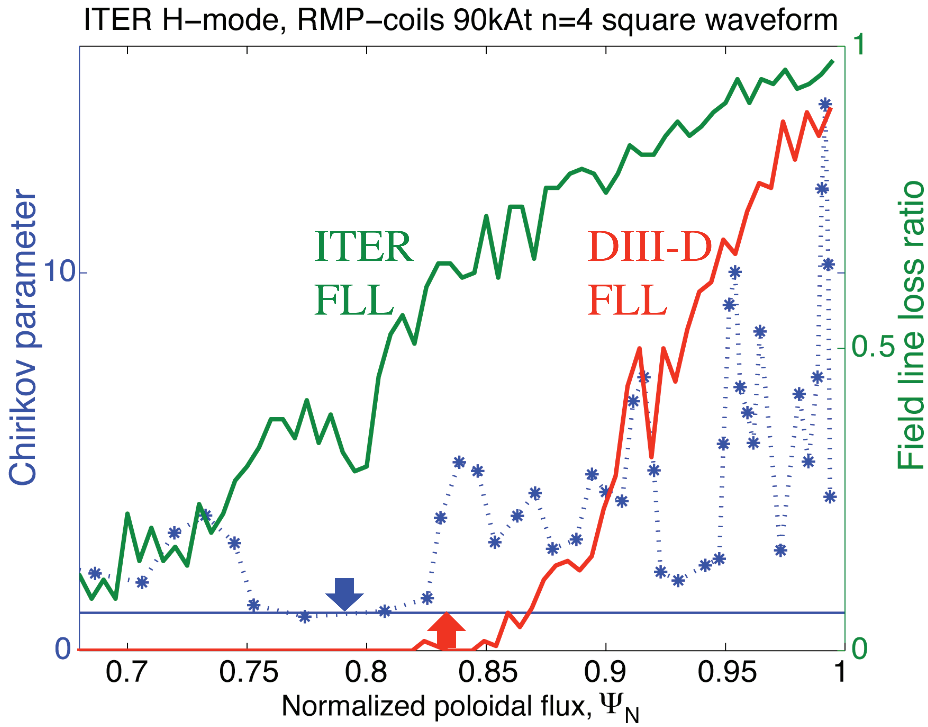

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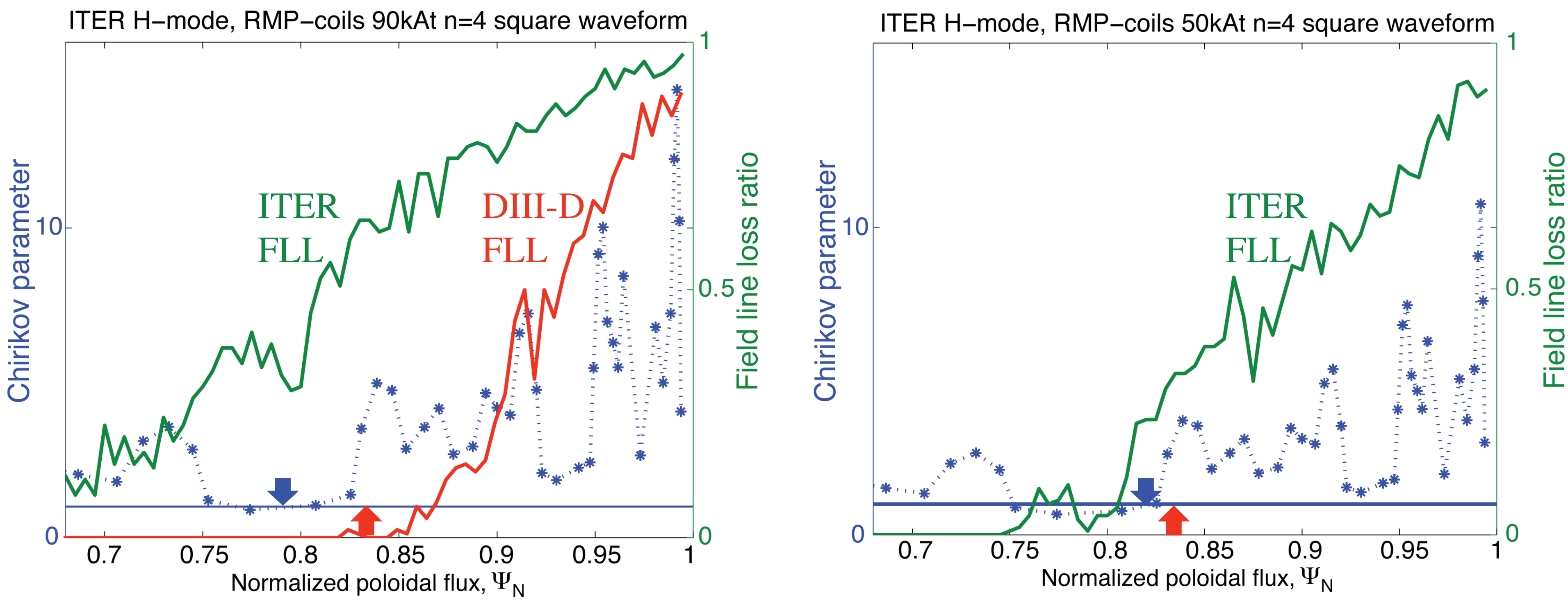

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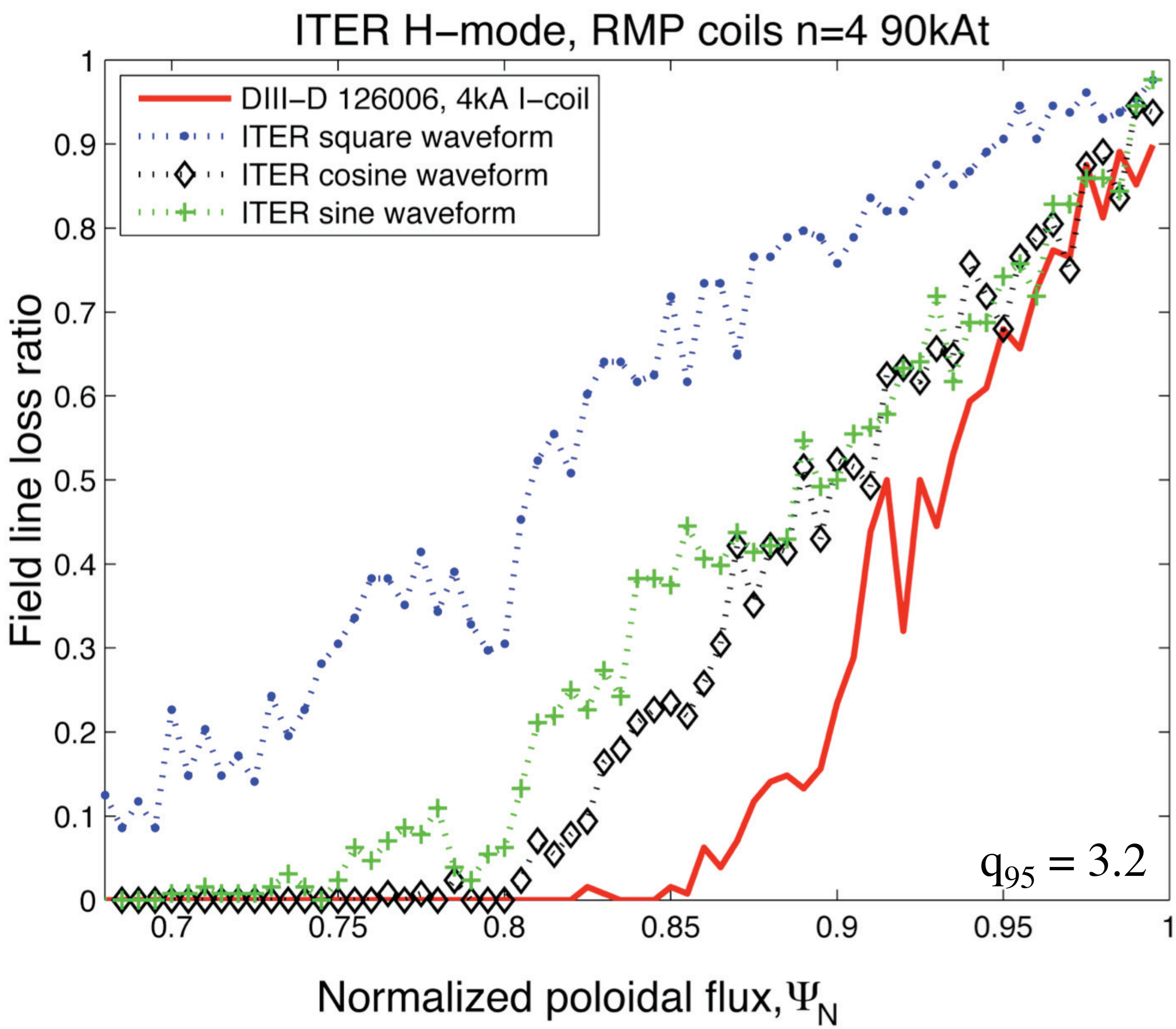
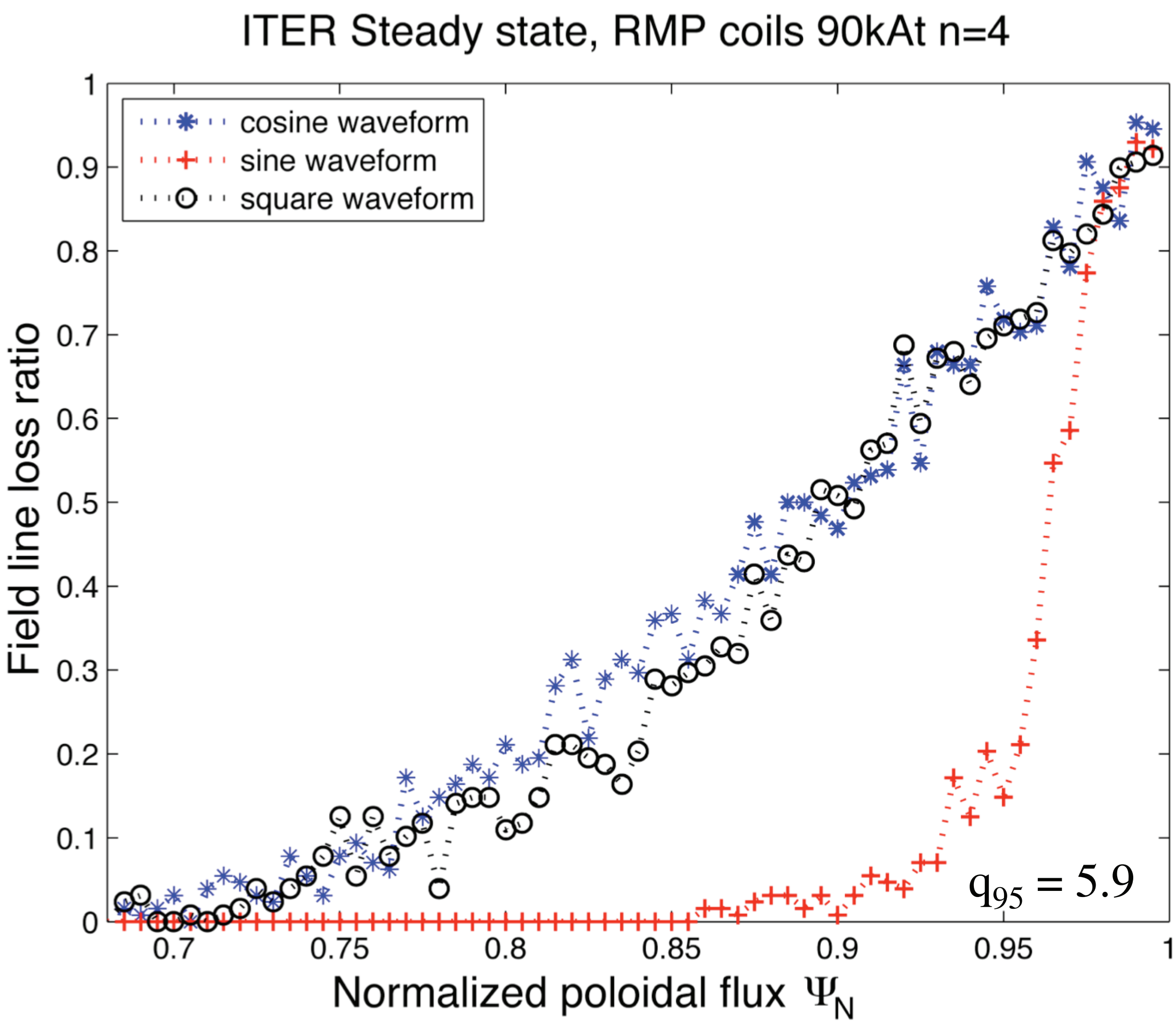
Field Line Loss is more sensitive to RMP current amplitude than island overlap width

Vacuum Field Line Loss in ITER is Broader than in DIII-D RMP ELM Suppressed Discharges



- **90 kAt n=4 square wave: field lines are lost from the plasma starting below Ψ_N=0.7**
  95% FLL in the pedestal
- **90 kAt n=4 cosine waveform:**
  broad field line loss profile starting from Ψ_N=0.8
  FLL ratio of 80% in the pedestal region
- **90 kAt n=4 sine waveform: broad field line loss profile starting from Ψ_N=0.75**
  FLL ratio of 80% in the pedestal region
- **Sine waveform was optimized for ITER H-mode scenario and has a broader FLL profile than cosine waveform**

Sufficiently Large Vacuum FLLs are Found in ITER Steady State Scenario



- **In the ITER Steady State scenario, square and cosine n=4 90 kAt waveforms show good results producing sufficient vacuum Field Line Loss**
- **The sine wave is not optimized for the Steady State scenario in ITER and has a moderate vacuum Field Line Loss profile**
- **ITER RMP coils can be optimized for various scenarios and for different q_{95}**

H-mode Coil Failure Analysis Indicates that the Vacuum Island Overlap Criteria is Maintained with 1–3 Dead Coils

RMP coils n=4 90kAt square waveform

	1	2	3	4	5	6	7	8	9
top	-1	1	-1	1	-1	1	-1	1	-1
middle	1	-1	1	-1	1	-1	1	-1	1
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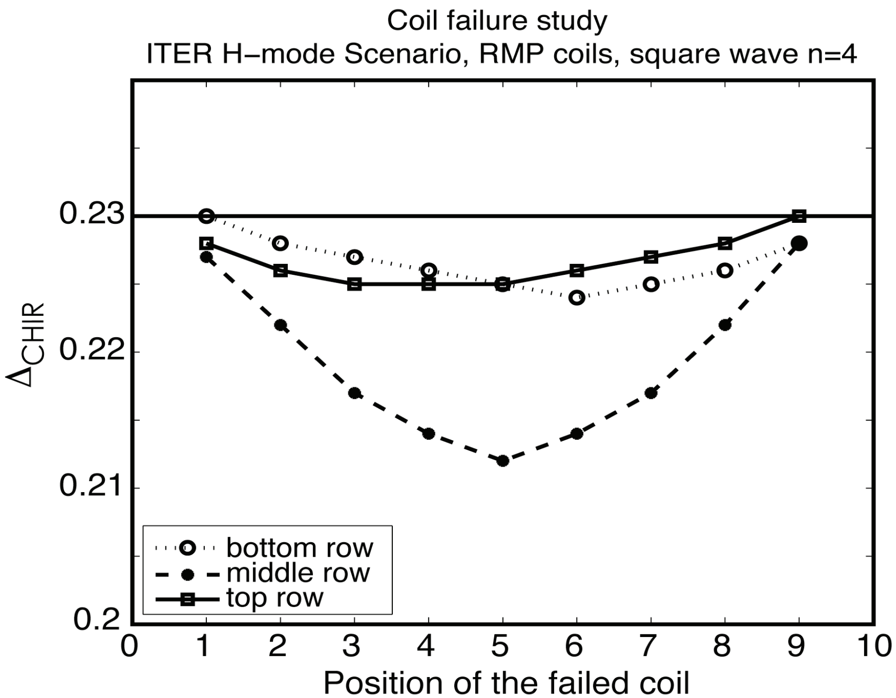

Single coil failure

- **15 MA (H-mode) scenario, RMP coils only**
- **The target value for ELM suppression is Δ_{CHIR} = 0.165**
- **Solid black line at Δ_{CHIR} = 0.23 corresponds to all 27 coils working normally**

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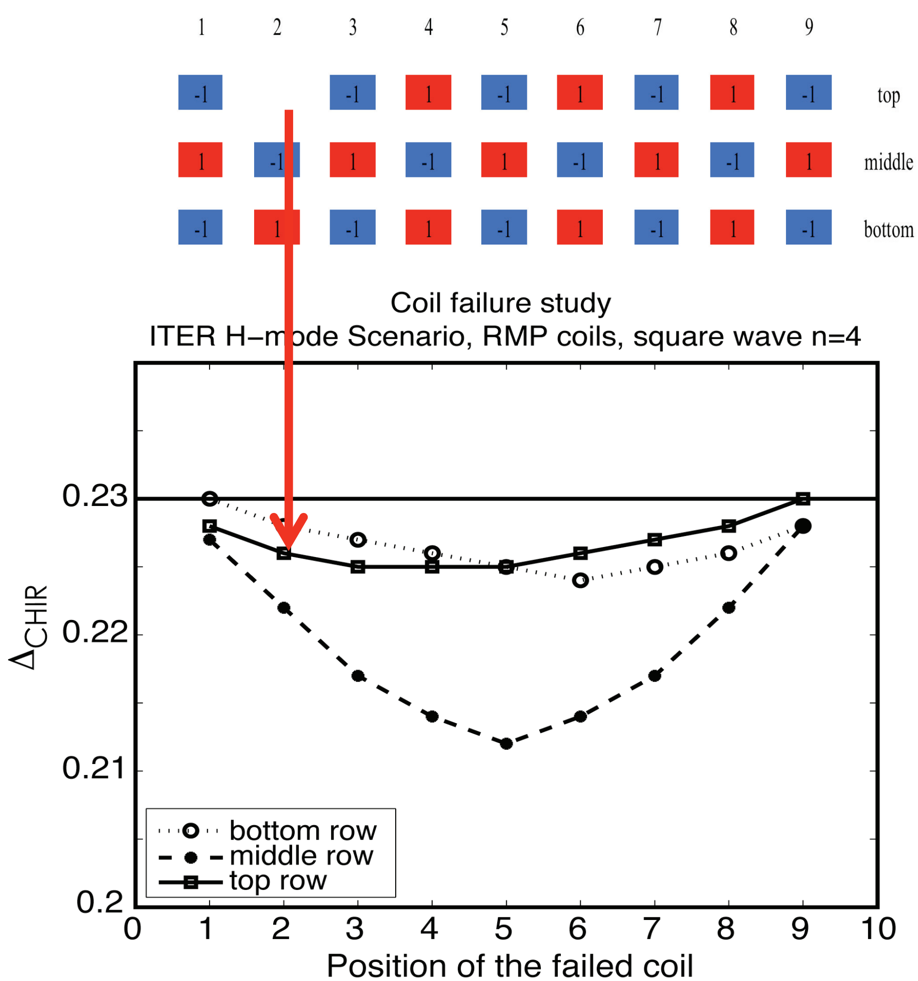

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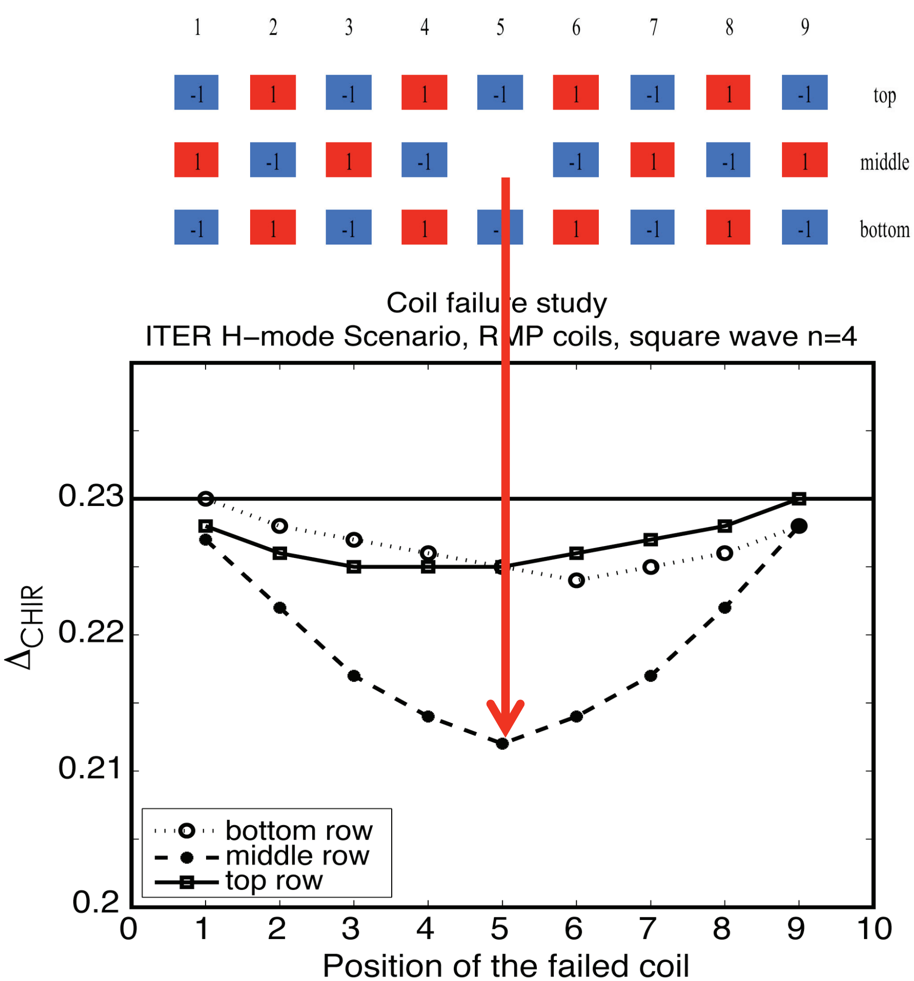

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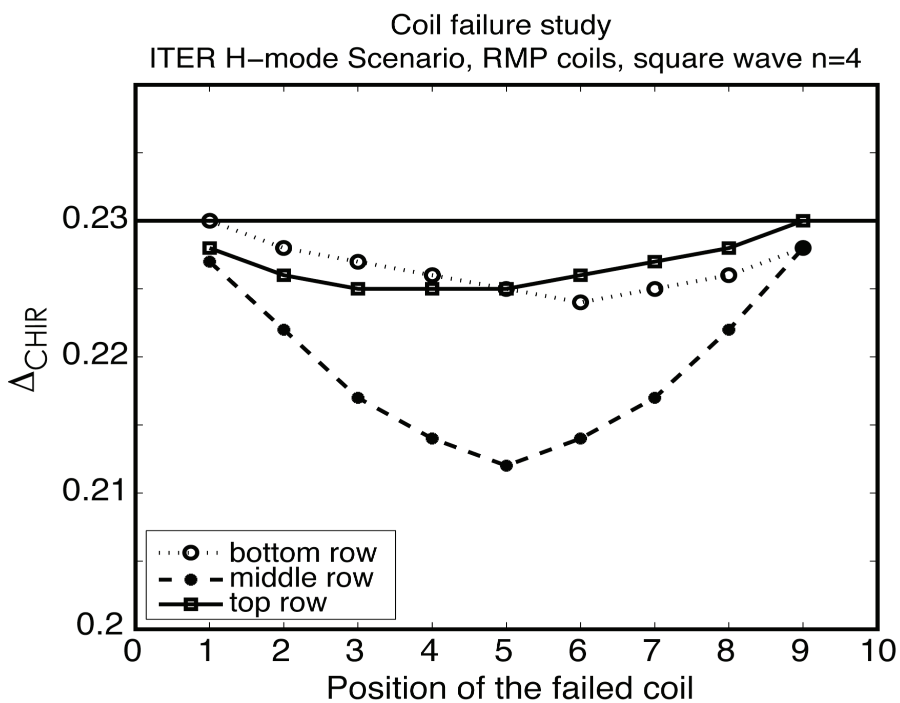

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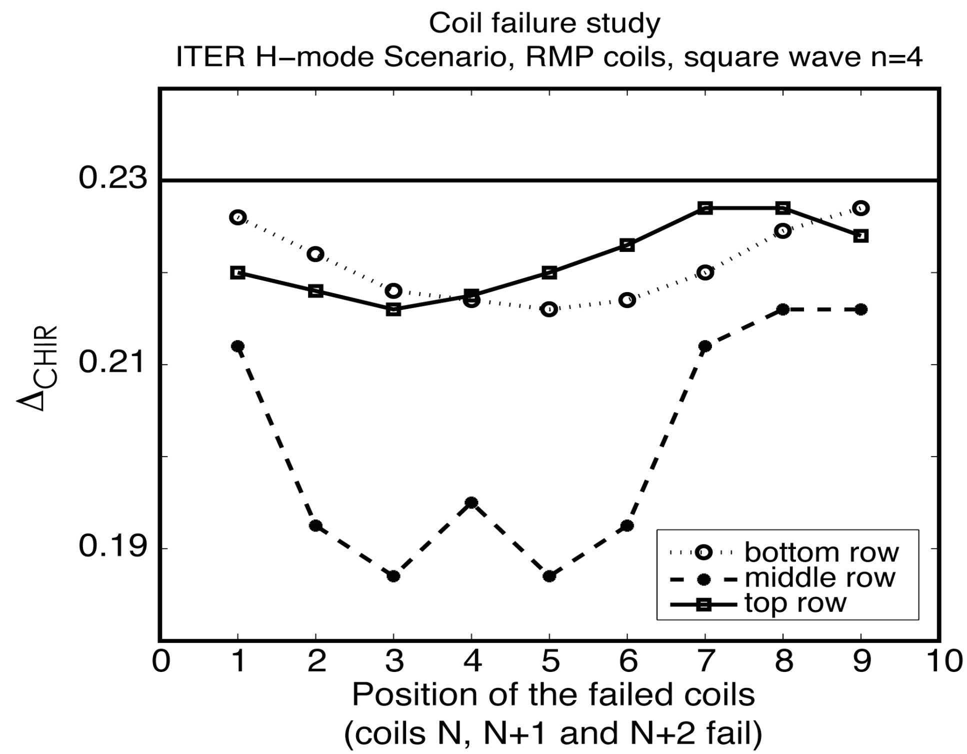

Triple coil failure

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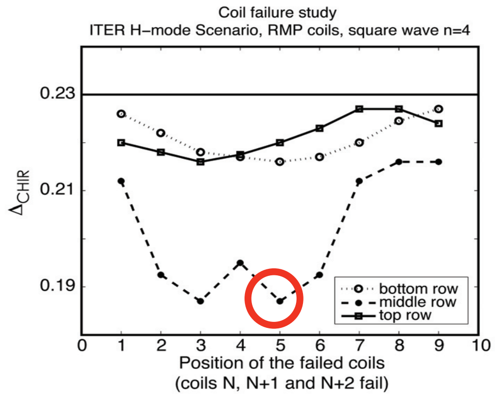
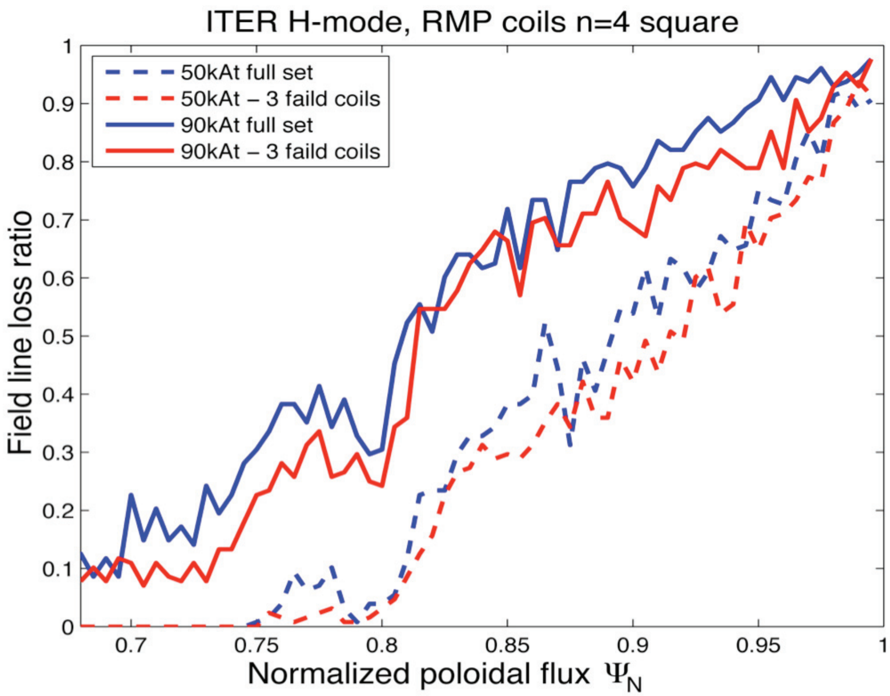
H-mode Coil Failure Analysis Indicates that the Vacuum FLL Criteria is Maintained with 3 Dead Coils in a Single Row





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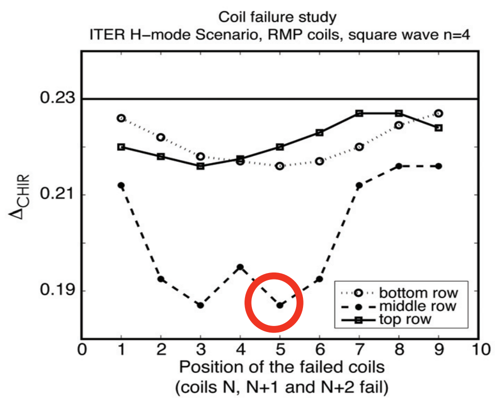

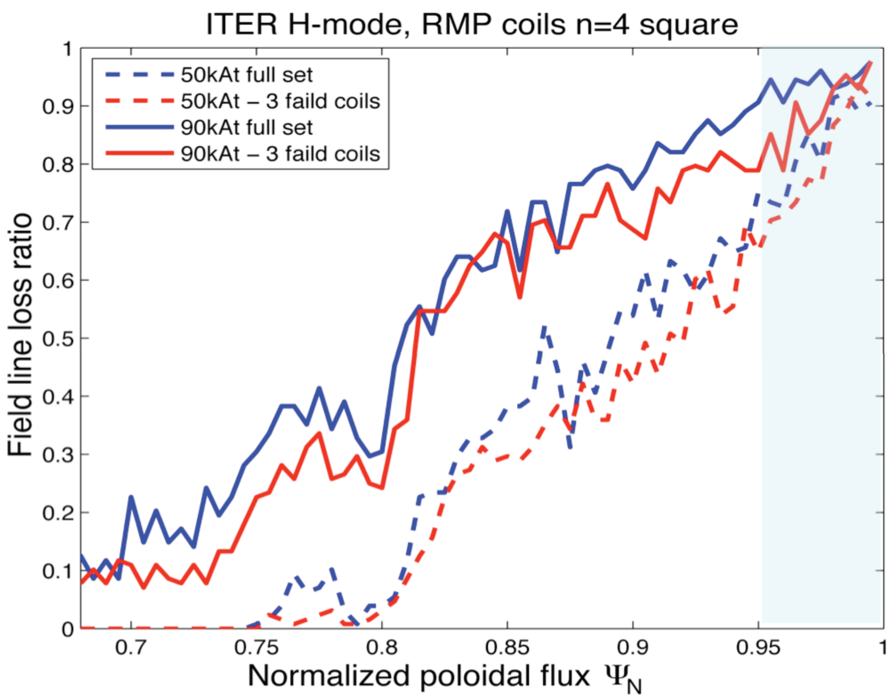

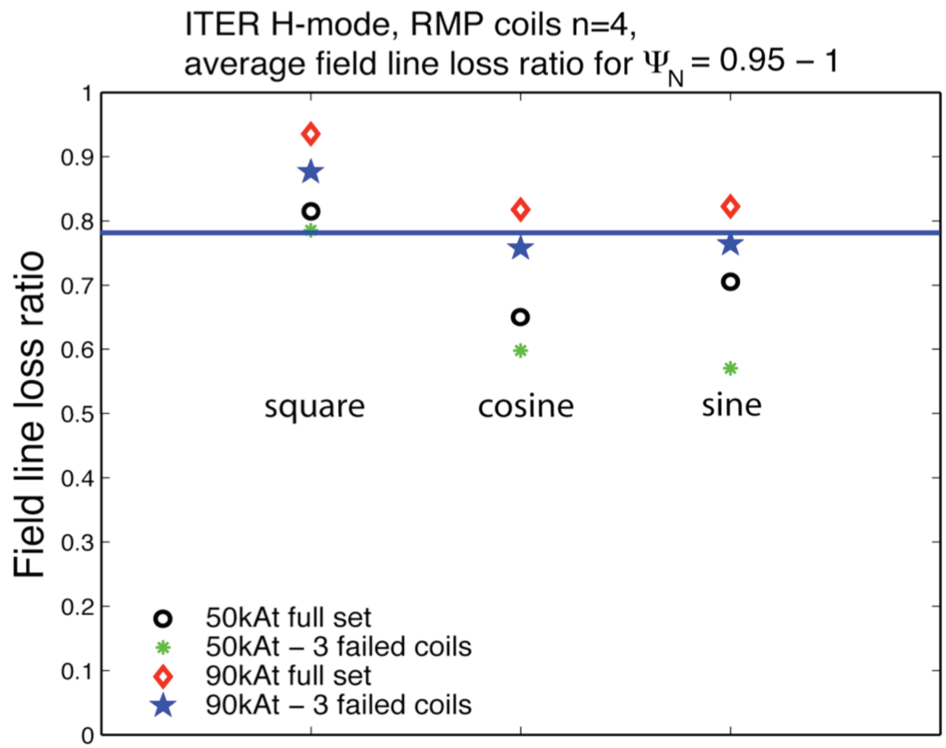

The vacuum FLLF value for successful ELM suppression in DIII-D ITER similar shape shot with 4 kA n=3 even parity I-coils is

FLLF = 0.7763

Summary

- Current design of ITER RMP coil set exceeds the DIII-D criteria correlated with ELM suppression using either a square, cosine or sine wave
- The studied n=4 square, cosine and sine waveforms show very good vacuum island overlap region width values and vacuum field line loss radial profiles for both H-mode and Steady state operation in ITER
- These configurations and current distributions are robust and show good characteristics over a range of RMP coil current amplitudes and phases
- ITER RMP coils have flexibility for different q_{95}
- They also provide a significant operational margin in the event of up to three isolated coil loop failures