3D Vacuum Magnetic Field Modeling of the ITER ELM Control Coil During Standard Operating Scenarios

by

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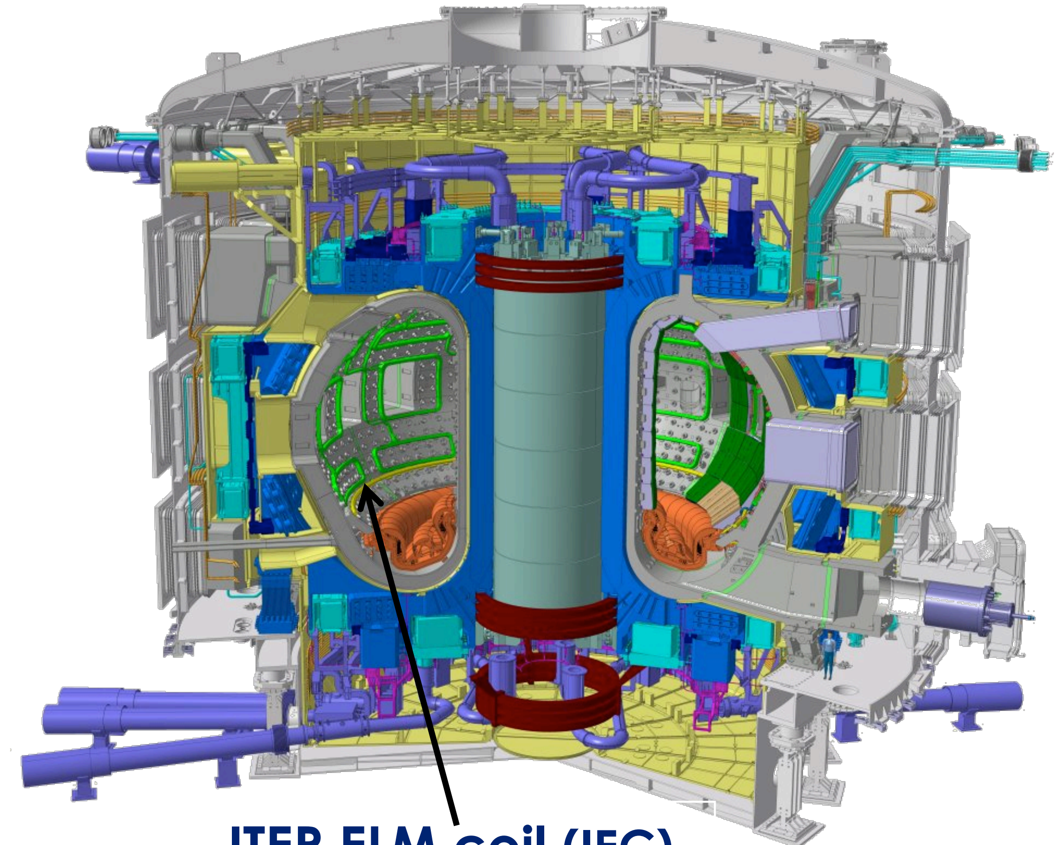

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Optimization of ITER ELM Coil Current & Phase is Based on a DIII-D Metric that is Correlated with ELM Suppression

- **Objective**
  - Determine minimum **ITER ELM Coil (IEC)** current needed to match the DIII-D Δ_{VIOW} metric for each ITER operating scenario

- **Approach**
  - Calculate:
    - **Vacuum Island Overlap Width (Δ_{VIOW})** and
    - **Fractional Phase Angle Operating Space (f_{PAOS})**

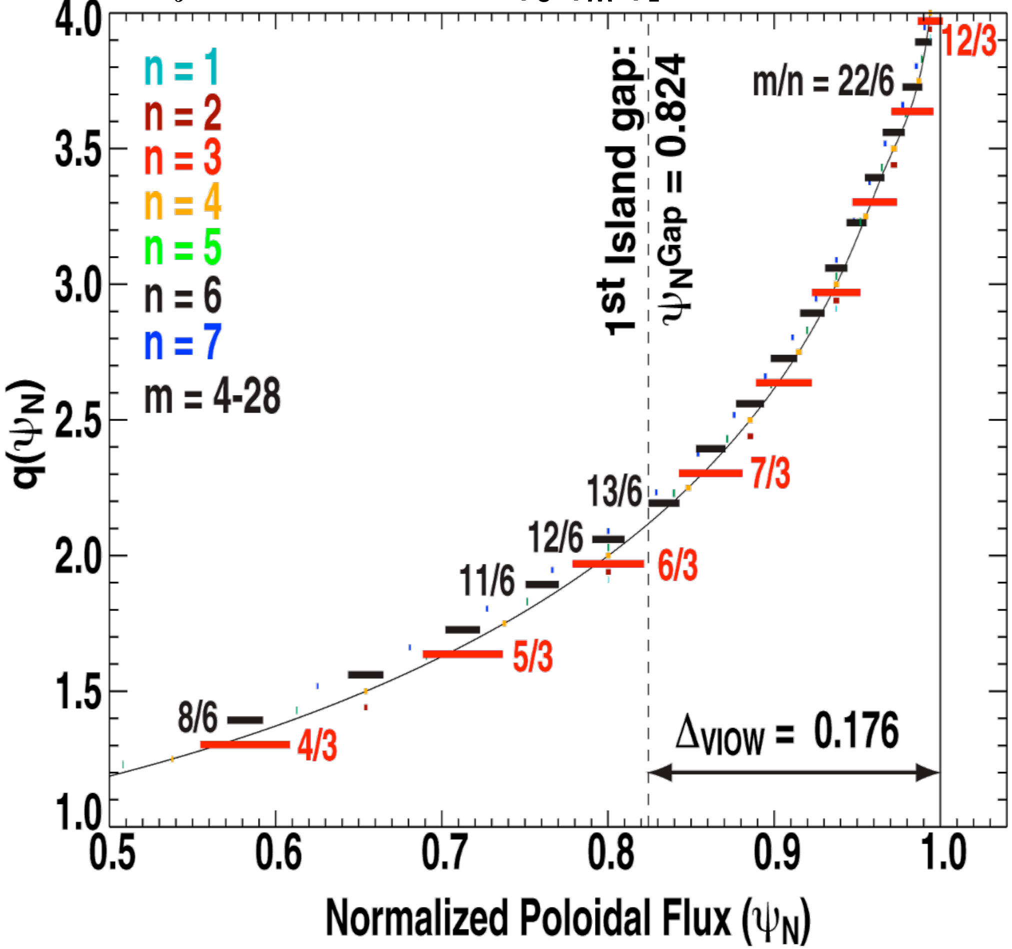
    versus IEC current and toroidal phase angle

- **Results and conclusions**

The Vacuum Island Overlap Width Parameter (Δ_{VIOW}) is a Metric for Comparing ELM Coil Performance Levels

- Δ_{VIOW} quantifies the edge region covered by overlapping magnetic islands
- ELM suppression in DIII-D is correlated with $\Delta_{VIOW} \geq 0.165$
- The IEC operating parameters are varied in order to change $\Delta_{VIOW} = 1 - \psi_N^{Gap}$ until
  - $\Delta_{VIOW} \geq 0.165$

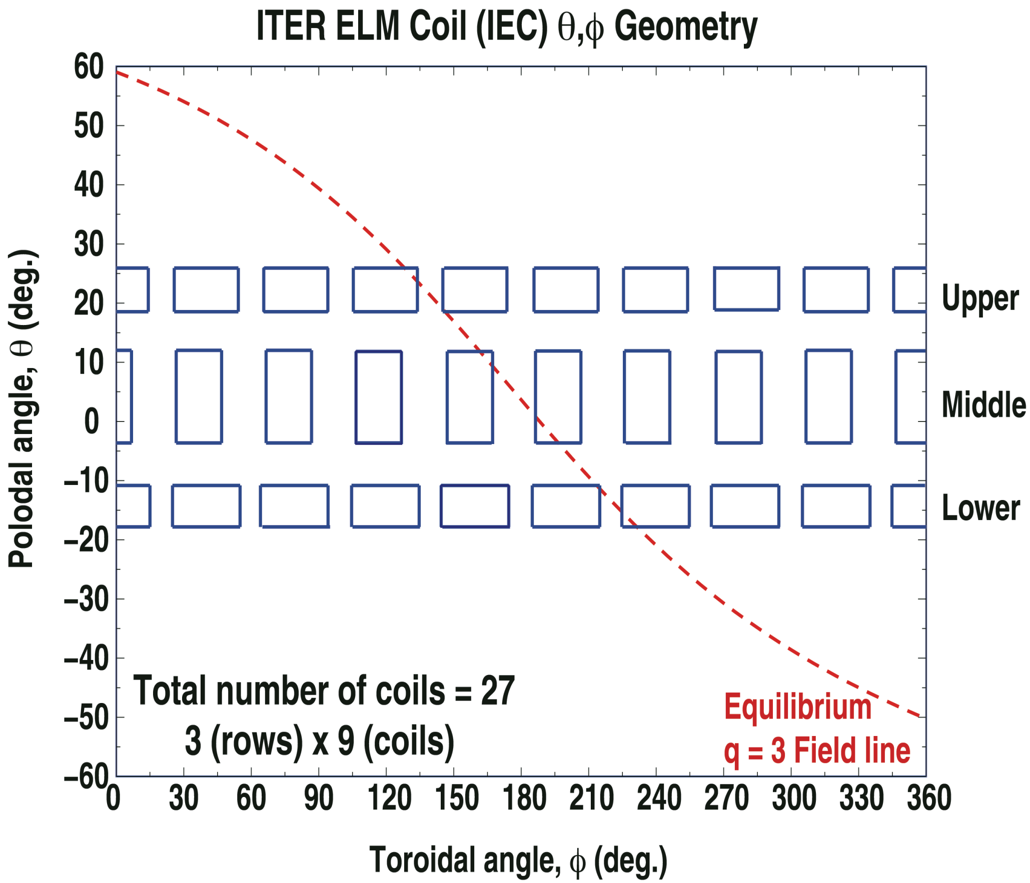
Magnetic Island Widths Versus ψ_N in an ITER 15 MA Q_{DT} = 10 H-mode Plasma
I_0 = 45 kAt, n = 3, $\phi_U:\phi_M:\phi_L$ = 86°:0°:36°



Δ_{VIOW} Depends on the Peak IEC Current (I_0) and the Toroidal Phase Angle (ϕ_r) of the Current in Each Row of Coils

- **27 individually powered IEC window-frame coils allow for**
  - Smooth toroidal rotation of the perturbation fields
  - Differential toroidal phase variations between rows

- **Δ_{VIOW} and f_{PAOS} studies done using a cosine waveform**
  - $I_j = I_o \cos\left[n\left(\phi_j - \phi_r\right)\right]$

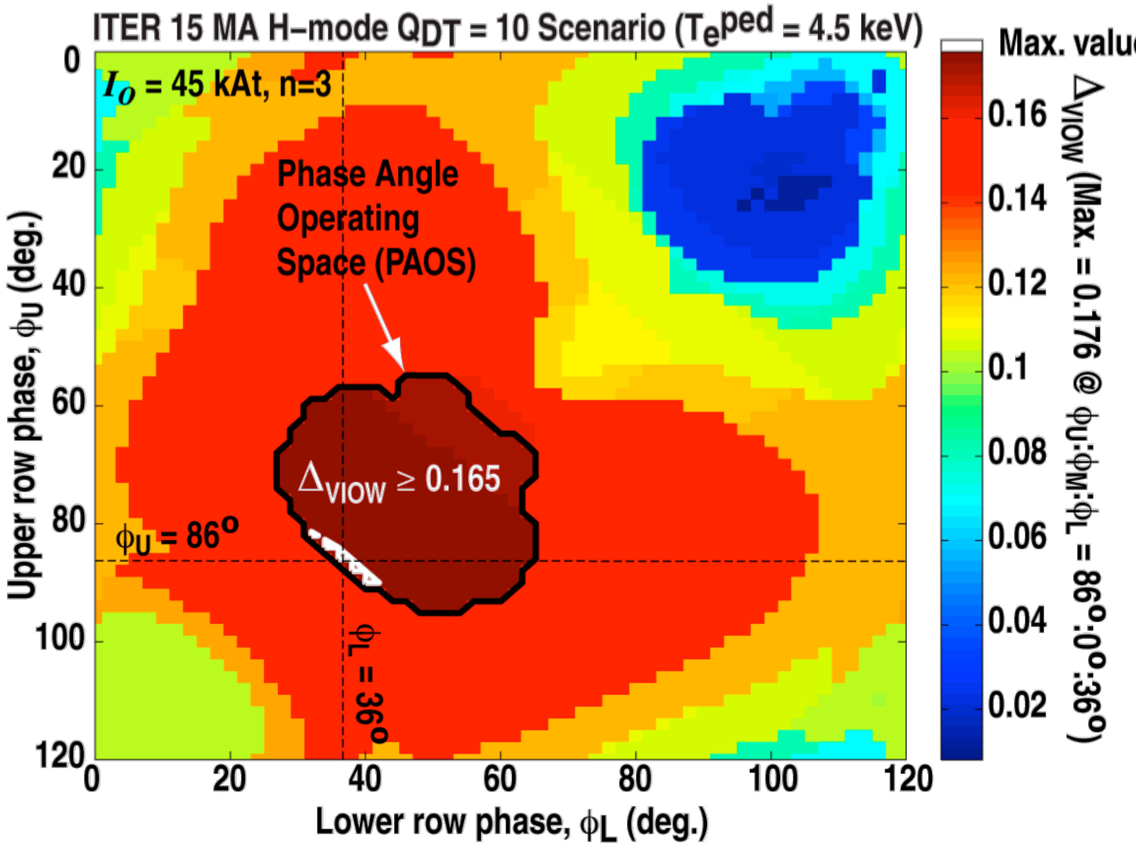


IEC Phase is Varied at Each Current Between 5 and 90 kAt to Identify $\Delta_{VIOW} \geq 0.165$ Threshold Current and f_{PAOS}

- Vary upper and lower IEC phase in 2^0 steps
- Vary IEC current in 5 kAt steps
- Changes in Δ_{VIOW} with ϕ_U and ϕ_L at each IEC current define the
  - Phase Angle Operating Space (PAOS) boundary

    and

  - Fractional Phase Angle Operating Space: f_{PAOS} = (# f_{PAOS} pixels)/(total # pixels)



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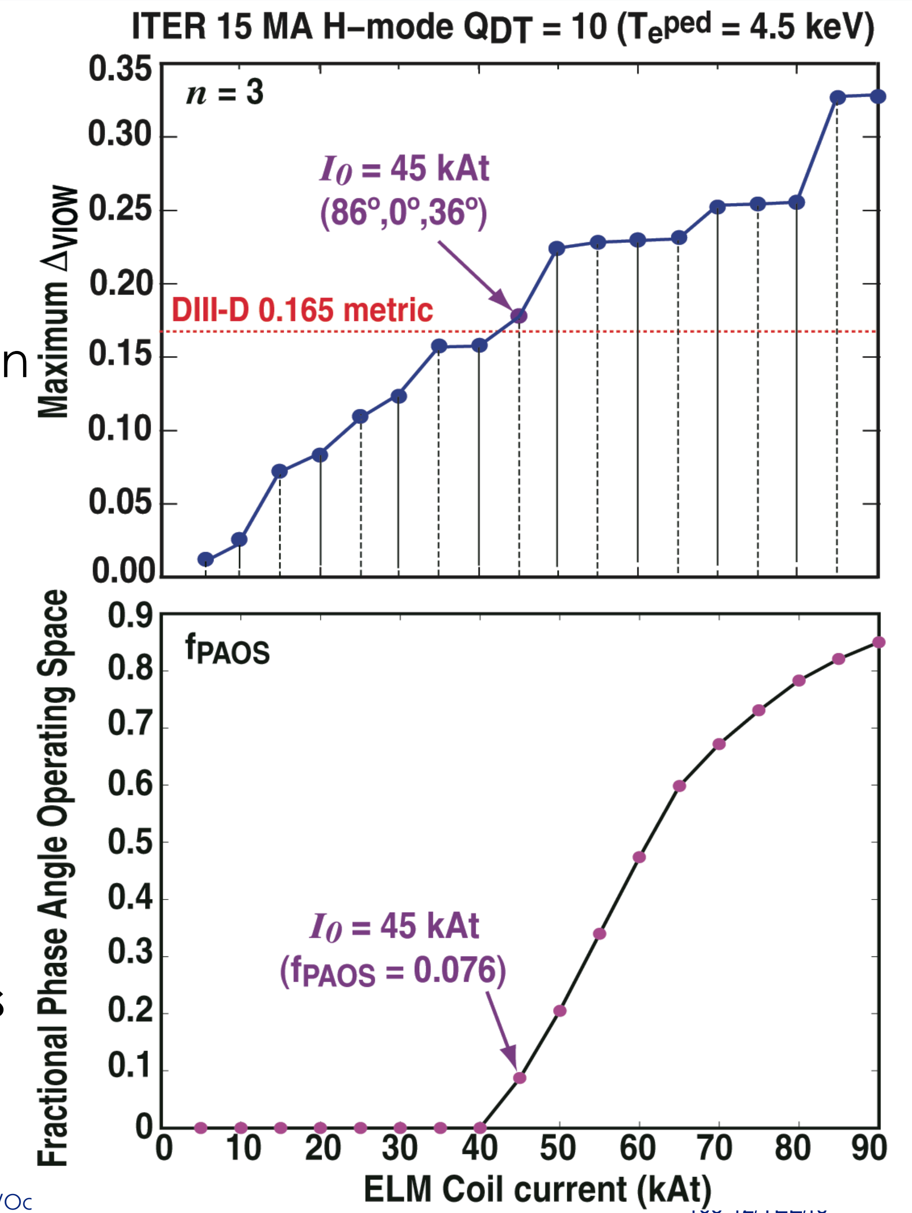
Increasing the IEC Current Above the Δ_{VIOW} = 0.165 Threshold Expands the Fractional Phase Angle Operating Space (f_{PAOS})

- **The minimum IEC current required to satisfy $\Delta_{VIOW} \geq$ 0.165 varies with**
  - q(r) from one operating scenario to another and
  - The toroidal phase angle of the curren in each row of the IEC
- **Increasing the IEC current causes gaps between neighboring islands deeper in the plasma to close**
  - Closing gaps between large islands results in Δ_{VIOW} steps
- **Increasing the IEC current after crossing Δ_{VIOW} = 0.165 expands f_{PAOS} allowing improved 3D field control**



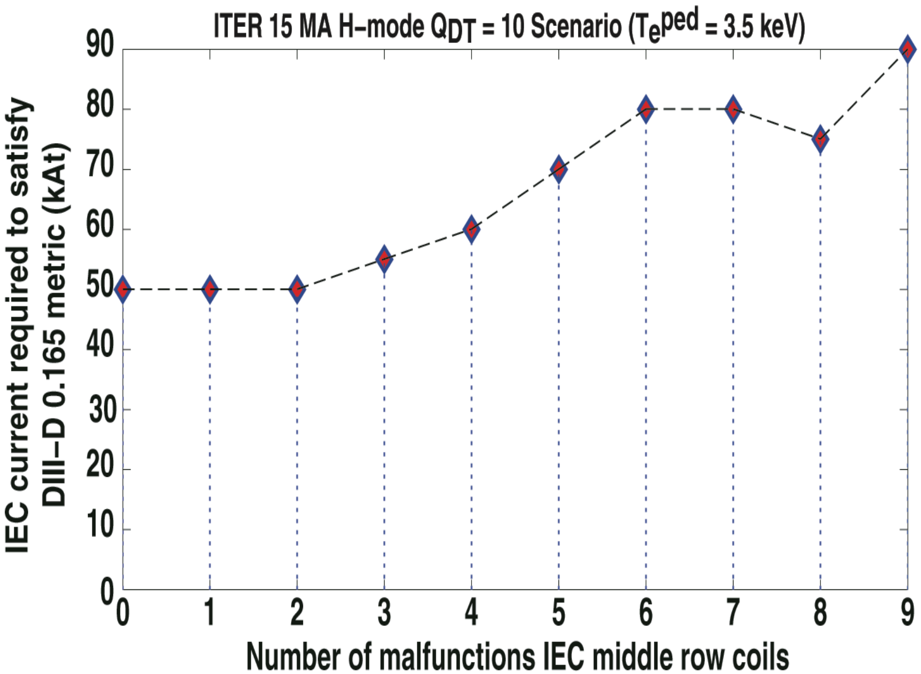
IEC Currents Needed to Satisfy Δ_{VIOW} = 0.165 with an n = 3 Waveform are Well Below the 90 kAt IEC Design Limit

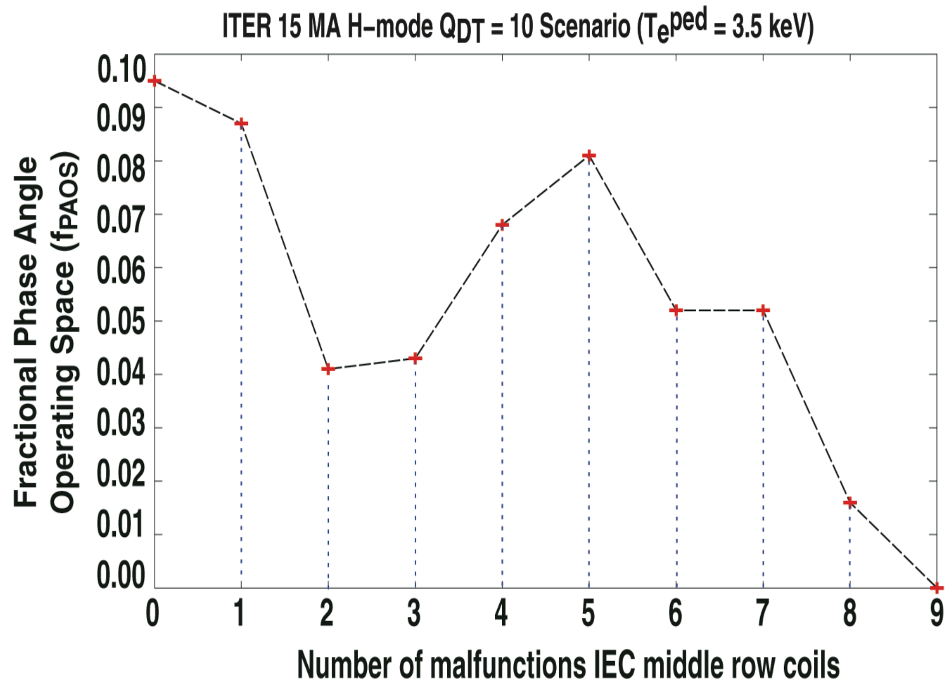
Minimum n=3 IEC needed to obtain Δ_{VIOW} = 0.165

Scenario Name	I_0 (kAt)	Max. Δ_{VIOW}
15 MA H-mode Q_{DT} = 10, (3.5 keV)	50	0.2097
15 MA H-mode Q_{DT} = 10, (4.5 keV)	45	0.1757
15 MA H-mode Q_{DT} = 10, (5.5 keV)	35	0.1702
15 MA H-mode Q_{DT} = 10, (6.5 keV)	40	0.1801
15 MA H-mode Quasi-DN	45	0.1869
9 MA H-mode Q_{DT} = 5 (SS)	20	0.2069
9 MA H-mode Q_{DT} = 5 (β_p =1.25)	25	0.1674
7.5 MA H-mode q_{95}=3.0	25	0.1837
10 MA H-mode rampup	35	0.1831
10 MA H-mode rampdown	35	0.1730

- **Additional IEC current capability provides flexibility for:**
  - Dealing with random coil malfunctions
  - Compensating for uncertainties due to the plasma response and in the physics of ELM suppression
  - Combining enhanced field-error correction capability with ELM control

The $\Delta_{VIOW} \geq 0.165$ Criterion Can be Satisfied with 8 Malfunctioning Coils in the Most Demanding ITER Scenario





- **Initially, coil failures reduce the available operating space without having to increase the peak n=3 coil current**
- **As additional coils malfunction the peak current must be increased**
  - The peak current can be increased to accommodate up to 8 malfunctions

Primary Conclusions

- **The IEC current needed to satisfy the DIII-D Δ_{VIOW} metric varies from 20 to 50 kAt depending on the ITER operating scenario used**
  - These current are expected to increase when the plasma response is include in the modeling
- **The fractional Phase Angle Operating Space (f_{PAOS}) is typically small at the threshold current but expands rapidly with the IEC current**
- **As many as 8 of the 27 coils can malfunction in the most demanding ITER operating scenario while still meeting the DIII-D Δ_{VIOW} metric**
  - The maximum number of coil malfunctions allowed is expected to be reduced when the plasma responses is included in the modeling
- **Similar IEC threshold currents are needed to satisfy the DIII-D Δ_{VIOW} metric with either n=3 and n=4 waveforms**