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DECAF Cross-device model for halo currents generated during tokamak disruption interval – first steps

V. Zamkovska

S.A. Sabbagh, M. Tobin, J.D. Riquezes, G. Bustos-Ramirez
Department of Applied Physics, Columbia University, New York, USA
J. Butt
Mechanical and Aerospace Engineering, Princeton University, Princeton, USA
Y.S. Park
Korea Institute of Fusion Energy, KFE, Daejeon, Republic of Korea

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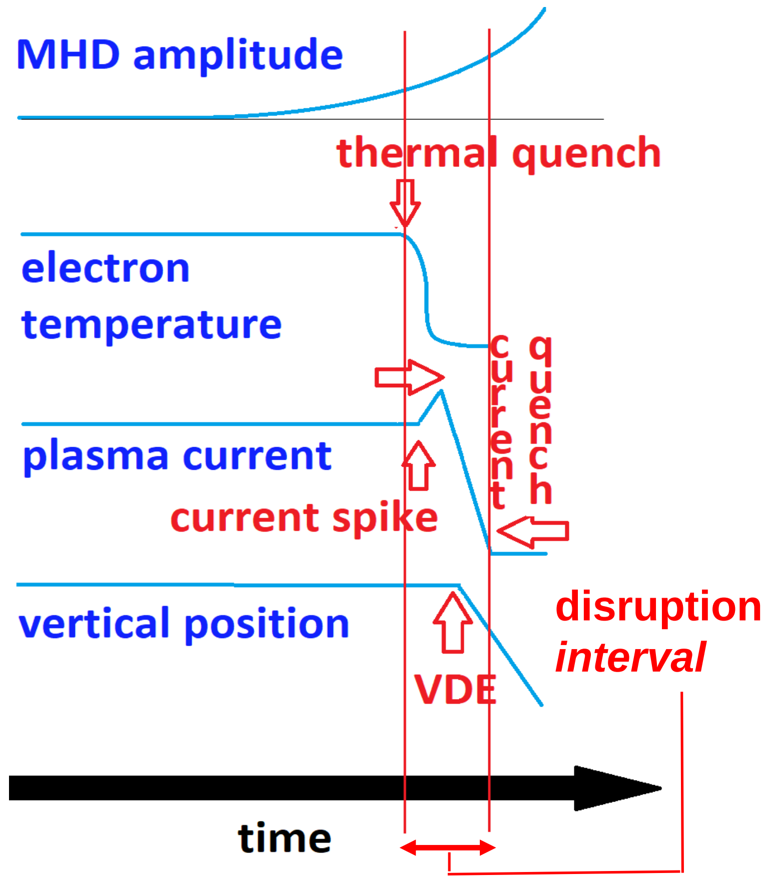
Sudden plasma collapses – disruptions – are common cross-device/shot in tokamaks

- Two usual paths to '*natural*' loss of plasma confinement:

MHD mode(s) of critical amplitude → magnetic field line stochastization → **thermal quench** → increased plasma resistivity → drop in loop voltage → transient increase in plasma current I_p ('current spike') → **current quench** → (possibly) **vertical displacement event (VDE)**

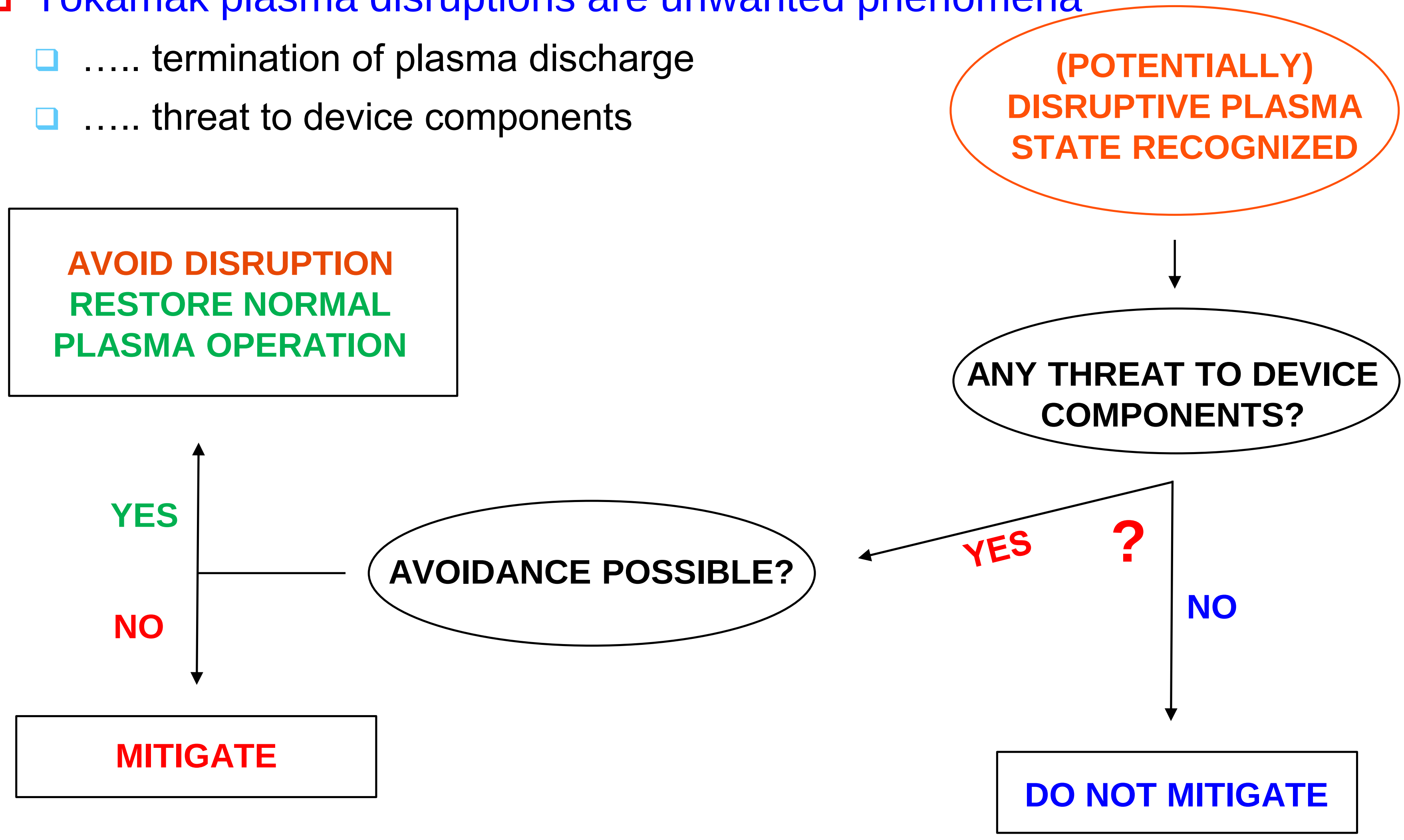
Elongated plasma → **vertical displacement event** → thermal & **current quench**



- **!** Engineering events can influence the above schemes, even induce the disruption

Deployment of disruption mitigation system set by severity of disruption consequences

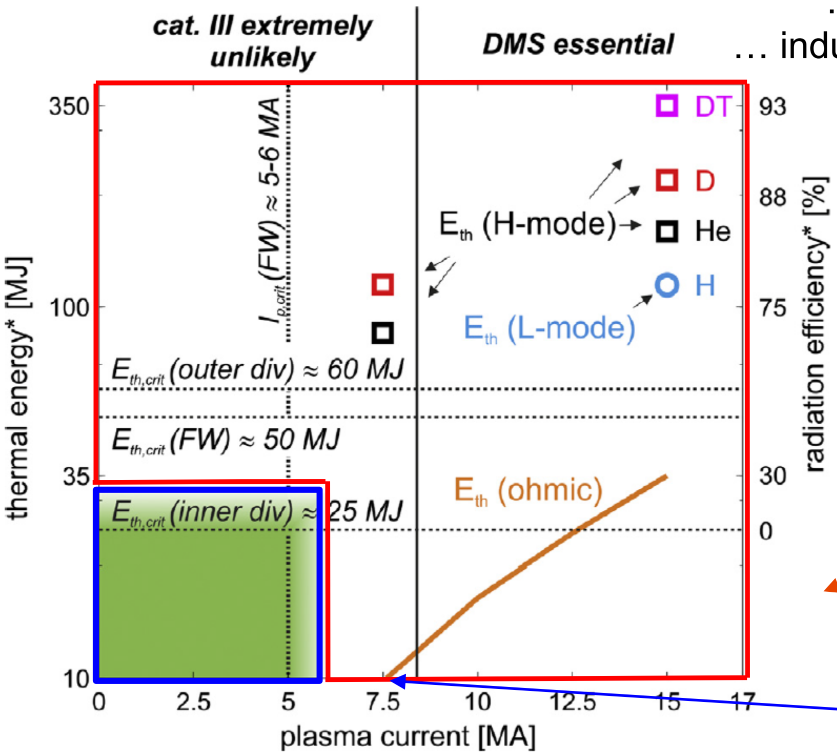
- Tokamak plasma disruptions are unwanted phenomena
  - ….. termination of plasma discharge
  - ….. threat to device components



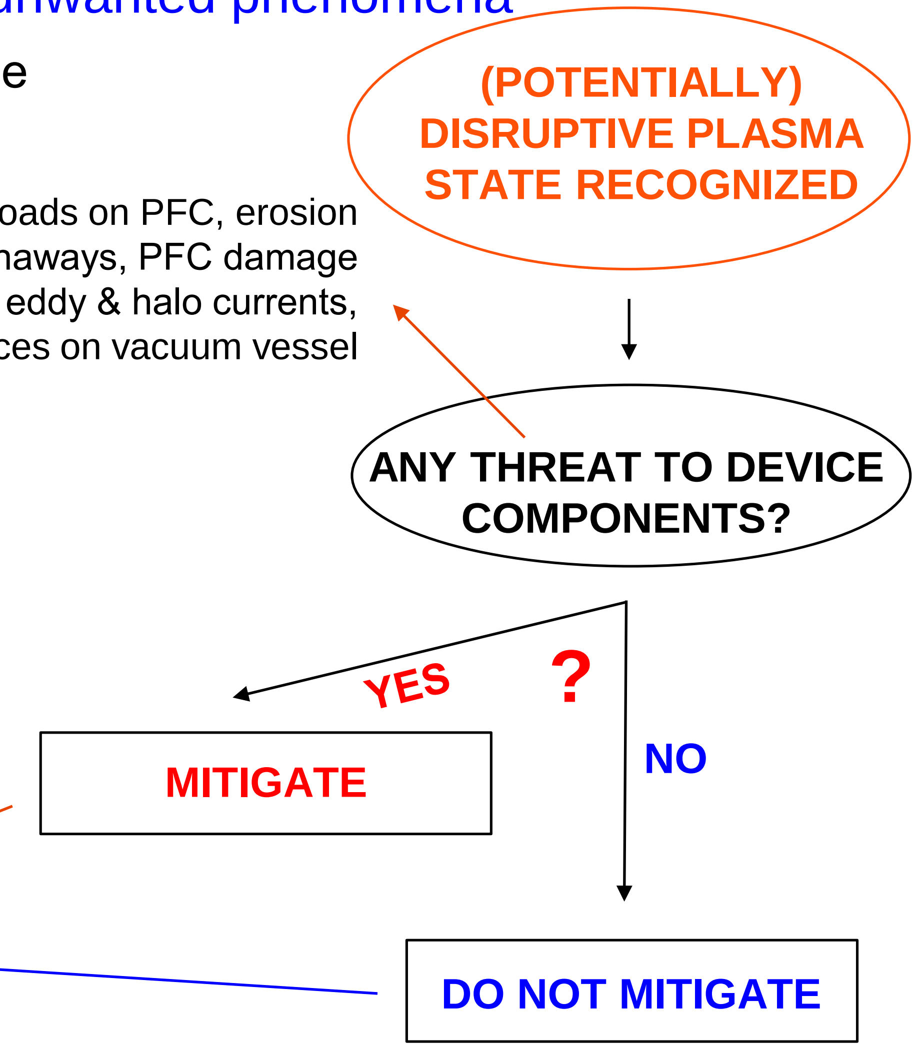
Disruptions severity set by pre-disruptive plasma state, shot phase, device configuration etc.

- Tokamak plasma disruptions are unwanted phenomena
  - ….. termination of plasma discharge
  - ….. threat to device components

… thermal loads on PFC, erosion
… runaways, PFC damage
… induced eddy & halo currents, forces on vacuum vessel



M. Lehnen et al./Journal of Nuclear Materials 463 (2015) 39–48

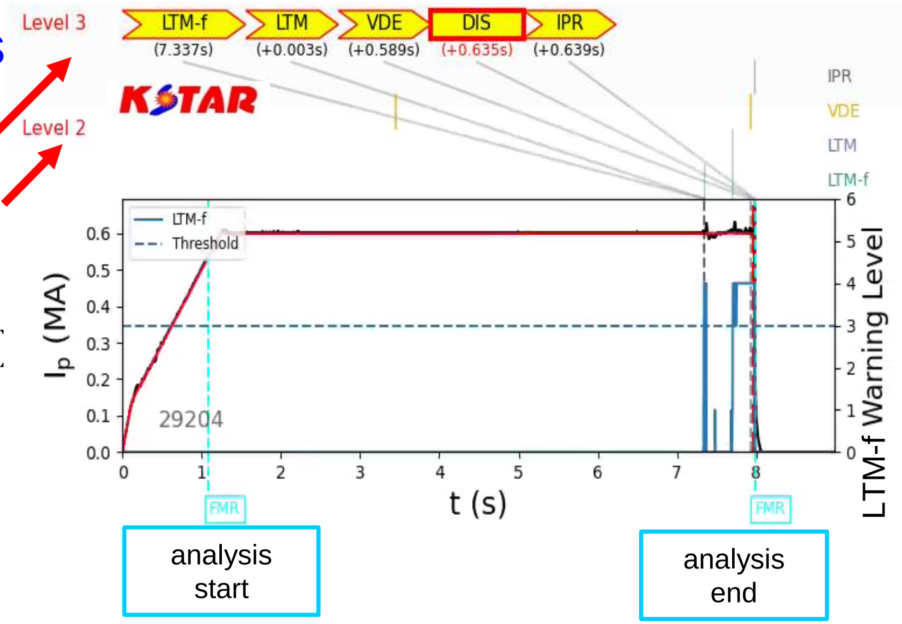


Implementation of ‘Do Not Mitigate’ flag in DECAF

- DECAF™ is expanding its capabilities:
  - Evaluating disruption severity
  - Informing on necessity of deployment of disruption mitigation system

Detour: DECAF code development builds from an extrapolable approach with strong initial success

- Disruption Event Characterization and Forecasting Research (DECAF*) expanded, including first real-time application with high accuracy forecasting
- Fully automated and abstracted physics-based disruption analysis of multiple tokamak device databases (KSTAR, MAST, MAST-U, NSTX, NSTX-U, AUG, DIII-D, ST-40, TCV, JET requested)
- Analyzing all plasma states (continuous and asynchronous events)
  - "Critical": (Level 3) disruption if no action taken
  - "Proximity": (Level 2) potential for "critical" events
  - "Ordered": (Level 1) events indicate steady operation (e.g. L-mode / H-mode, steady ELMing)



- "Forecaster events": give earliest warnings LTM-f
- DECAF expanded to real-time in KSTAR

First real-time DECAF experiments have produced 100% forecasting accuracy

- DECAF talks @ NSTX-U Science meetings: through January-February 2024

Implementation of ‘Do Not Mitigate’ flag in DECAF

- DECAF is expanding its capabilities:
  - Evaluating disruption severity
  - Informing on necessity of deployment of disruption mitigation system
- DNM (‘Do Not Mitigate’) flag indicating point after which mitigation not necessary

localized thermal & particle loads

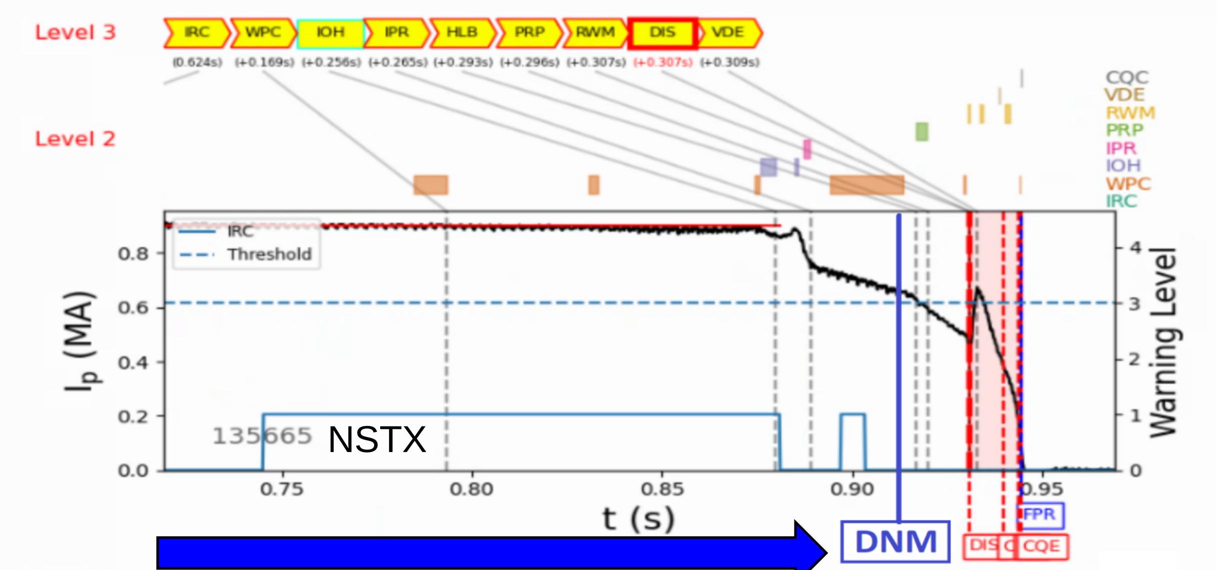
eddy in-VV currents

HALO CURRENTS

mechanical forces

material fatigue

VDE -> threats



Evaluating disruption severity throughout plasma shot

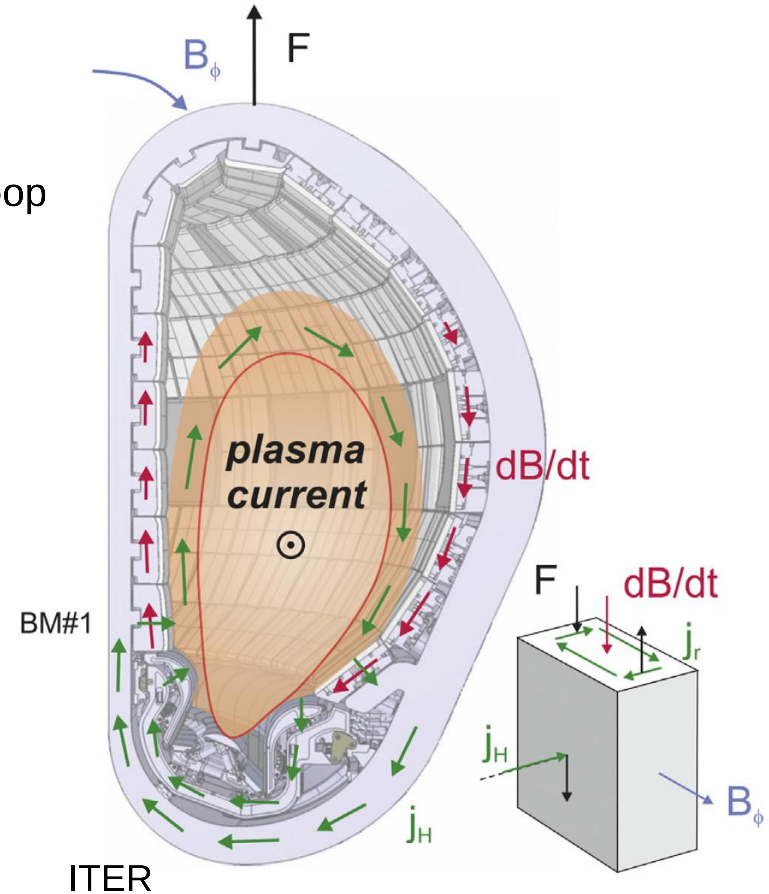
disruption interval

- Strictly speaking, in majority of *current* devices DNM would always apply
  - Need for projections/referencing to reactor-relevant plasmas and devices

Halo current as a serious thread to engineering integrity of reactor-relevant devices

- Halo currents (HC)
  - Currents outside LCFS arising during VDE due to flux conservation
    → intercept VV, form closed poloidal current loop
  - Studied extensively both theoretically and experimentally (cross-device)
  - Toroidal and poloidal components, crossing with B_T -> mechanical forces
    - Eventually exceeding device engineering limits (ITER, JET ..)
  - Critical features:
    - Onset time/conditions
    - (Maximum) amplitude
    - Duration
    - Toroidal asymmetry
    - Rotation

(some) diagnostic-dependency



M. Lehnen et al. / Journal of Nuclear Materials 463 (2015) 39–48

Implementing an abstracted cross-device model for HC in DECAF – step-wise approach

- **Goal: Bring a HC model into DECAF as one of DNM flag indicators**
  - Create a synthetic HC pulse that would approach the experiment as close as possible
- **Why *model*?**

→ Measurements not always available (e.g. [2] analyses HC for < 2200 NSTX 2008-2010 shots, while DECAF identified >> number of plasma shots)

→ Model implementation -> **early HC *forecaster***

- **Experimental HC pulse**
  - Onset time/conditions
  - (Maximum) amplitude
  - Duration
  - Toroidal asymmetry (TPF)
  - Rotation
  - *Details (fluctuations etc.)*
- **Modeled HC pulse**
  - Onset time/conditions
  - (Maximum) amplitude
  - Duration
  - Toroidal asymmetry (TPF)
  - Rotation

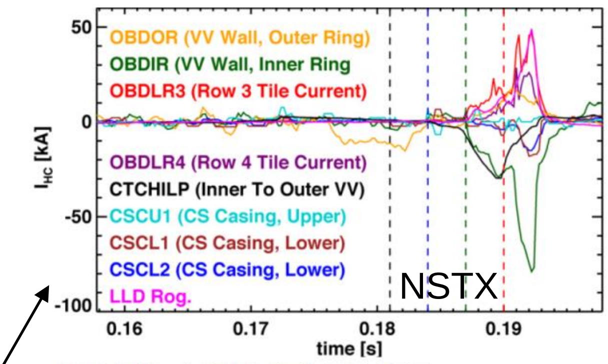
    Multi-machine scaling to ITER exists [11,13]
  - *Details (shape..)*
- **In DECAF, start with implementation of a simple, low fidelity model, iteratively improve**
  - Use past findings as a starting point

HC properties and origin studied extensively cross-device

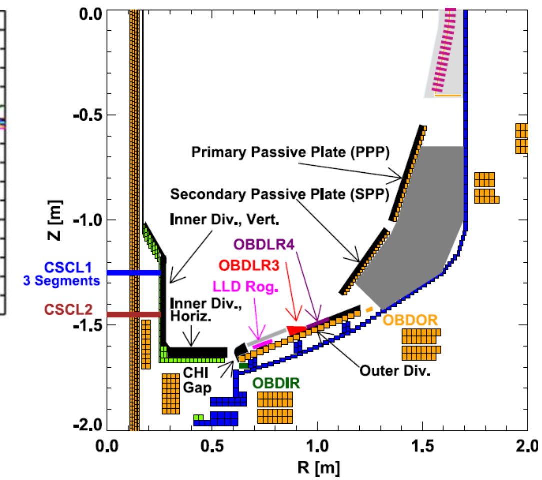
HC features:

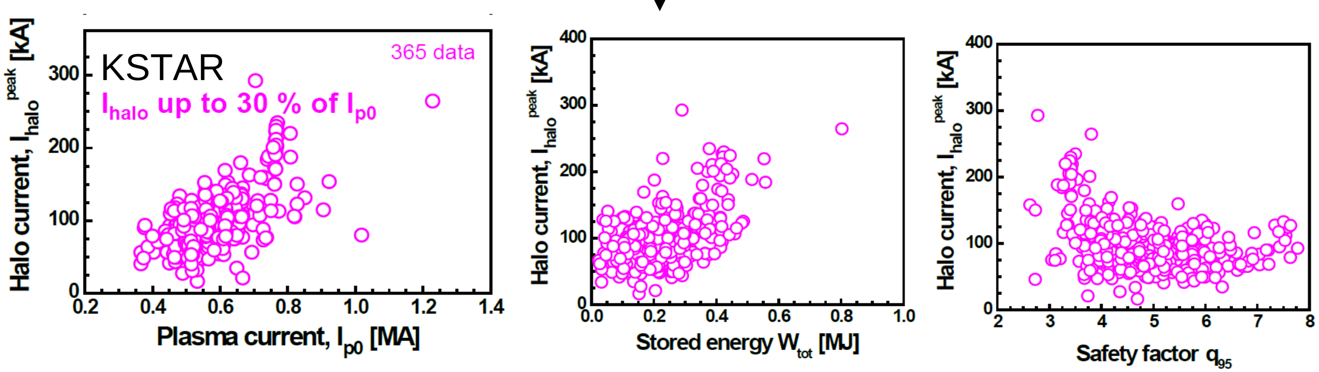
- Onset time/conditions
- (Maximum) amplitude
- Duration
- Toroidal asymmetry (TPF)
- Rotation

-> (some) diagnostic-dependency
-> cross-device trends captured



S.P. Gerhardt *et al* Nucl. Fusion **52** (2012) 063005





J.G. BAK/49th EPS conference /3-7 JUL. 2023

Theory/simulations

- [4,5,12]…

Features change when mitigation deployed

Peak amplitude decreased, PFC impact area increased (N. Schwarz et al., 2023 *Nucl. Fusion* **63** 126016)

Implementing an abstracted cross-device model for HC in DECAF - max amplitude

Modeled HC pulse

- Onset time/conditions
- **Maximum amplitude**
- Duration
- Toroidal asymmetry (TPF)
- Rotation
- Details (shape..)

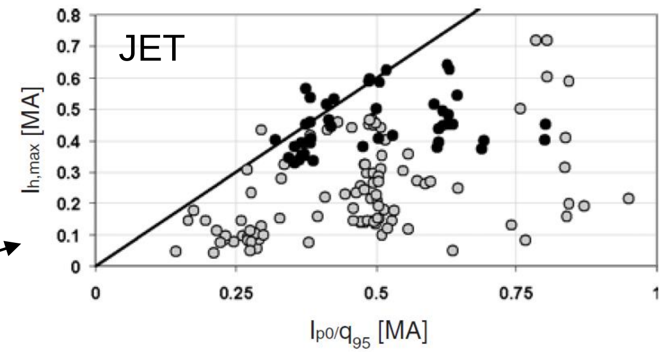
-> large scatter in max(I_{HC}) vs. plasma parameters

-> common cross-device *upper limit*

$$\mathbf{max}(\boldsymbol{I_{HC}}) \propto \boldsymbol{A} \cdot \boldsymbol{I_p/q_{95}} \quad (1)$$

I_p, q_{95} .. pre-disruptive
A .. geometrical factor & resistive plasma and halo times

-> with A guess, (1) easily calculated during shot



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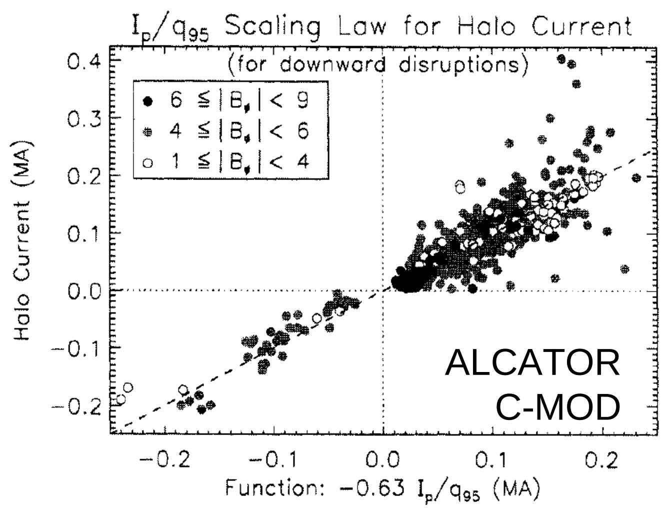
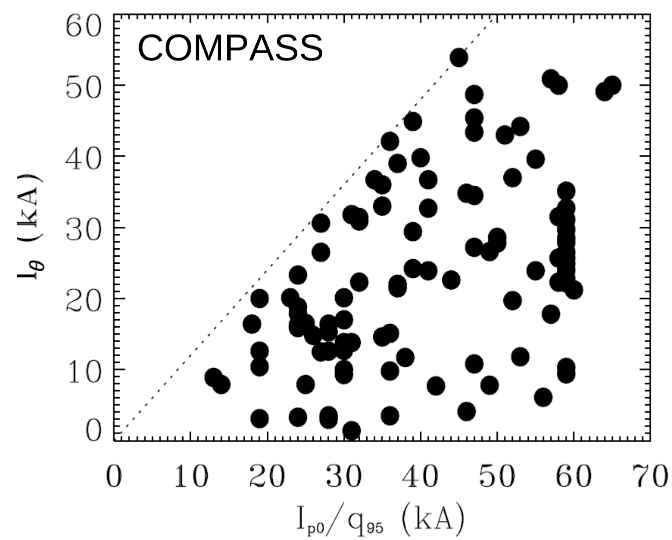


GRANETZ et al. NUCLEAR FUSION, Vol. 36, No. 5 (1996)



P.J. Knight et al. Nuclear Fusion, Vol. 40, No. 3 (2000)

Implementing an abstracted cross-device model for HC in DECAF – shape and onset time

❑ Modeled HC pulse

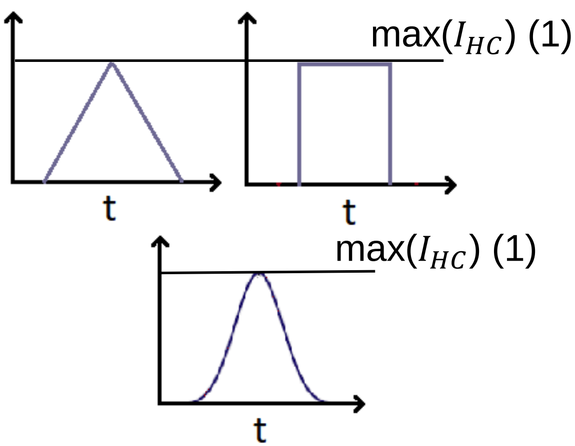
- **Onset time/conditions**
- Maximum amplitude
- Duration
- Toroidal asymmetry (TPF)
- Rotation
- **Details (shape..)**

3D VDEs simulated with nonlinear 3D MHD codes

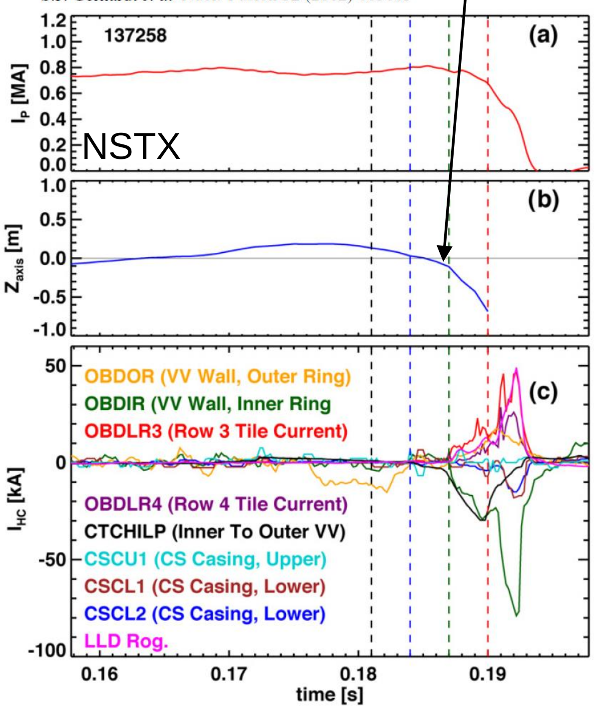
[4] Effective halo stability -> dI_{HC}/dt

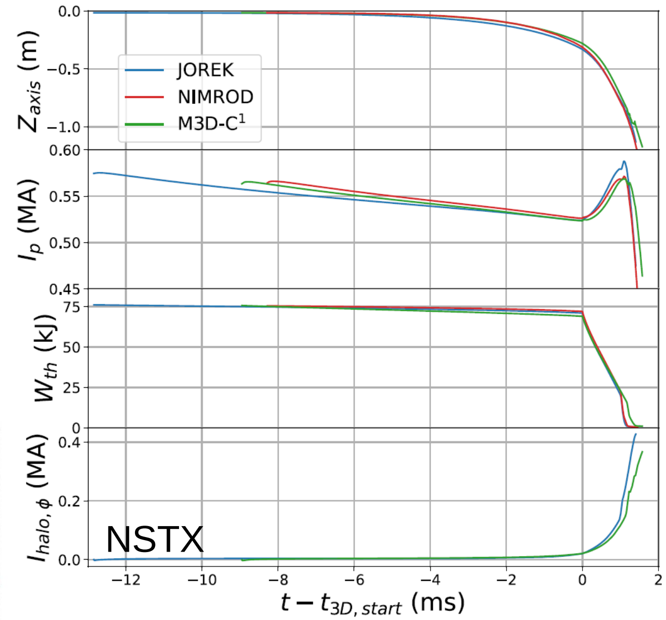
Empirical exp. threshold on Z_{axis}, gaps etc.

-> simulated pulse shape and ramp-up, growth rate



S.P. Gerhardt *et al* Nucl. Fusion **52** (2012) 063005





F. J. Artola, et al. Phys. Plasmas **28**, 052511 (2021)

-> experimental fluctuations in I_{HC} difficult to reproduce via modelling

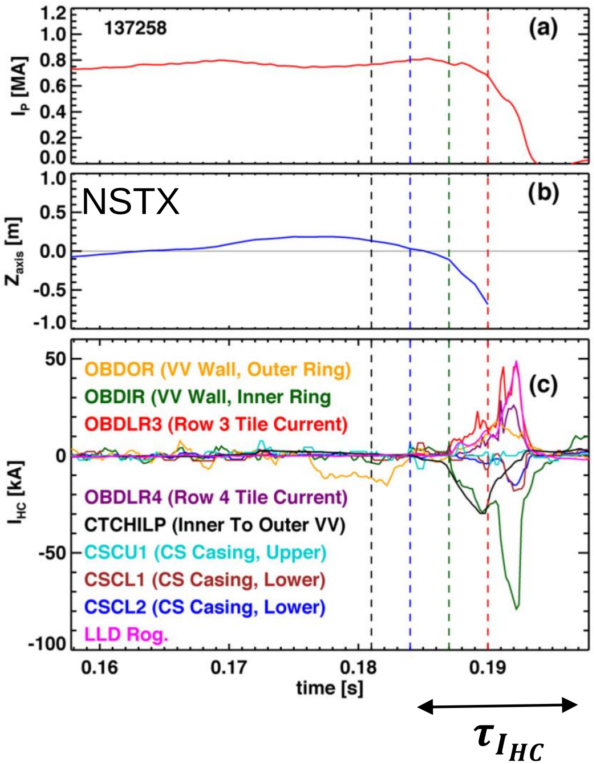
Implementing an abstracted cross-device model for HC in DECAF – shape and onset time

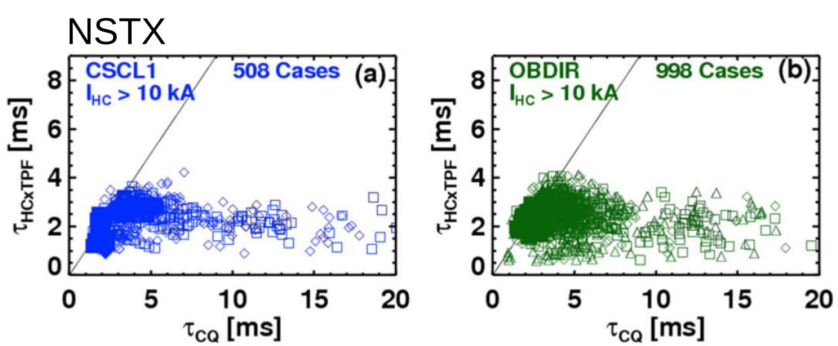
❑ Modeled HC pulse

- Onset time/conditions
- Maximum amplitude
- **Duration**
- Toroidal asymmetry (TPF)
- Rotation
- Details (shape..)

-> sets duration of force exerted on device
-> must be comparable to disruption characteristic timescales (τ_{CQ} …)

S.P. Gerhardt *et al* Nucl. Fusion **52** (2012) 063005





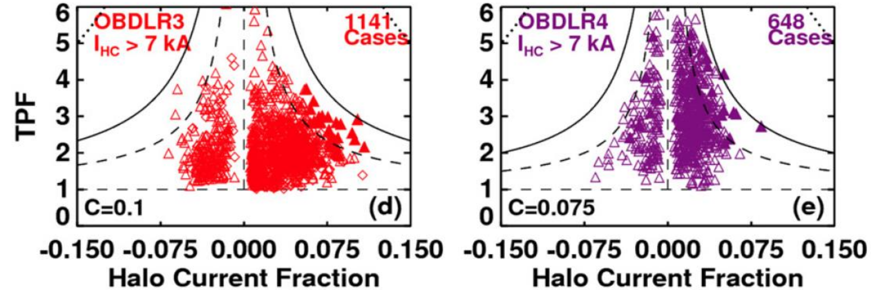
Implementing an abstracted cross-device model for HC in DECAF – TPF

❑ Modeled HC pulse

- Onset time/conditions
- Maximum amplitude
- Duration
- **Toroidal asymmetry (TPF)**
- **Rotation** ⟶ .. to be addressed
- Details (shape..)

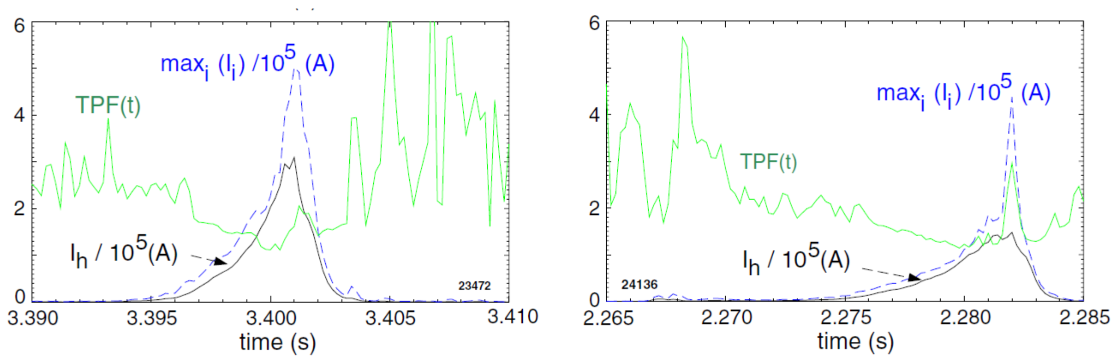
$$\text{TPF} = \frac{max(J_{HC})}{mean(J_{HC})} \qquad (2)$$

NSTX



S.P. Gerhardt *et al* Nucl. Fusion **52** (2012) 063005

ASDEX-U



G. Pautasso *et al* Nucl. Fusion **51** (2011) 043010

-> no clear parametric dependence for TPF

-> use experimental values (that is not ideal, a model is desired)

-> if no experimental data, use empirical values

Implementing an abstracted cross-device model for HC in DECAF – full shape

❑ Modeled HC pulse

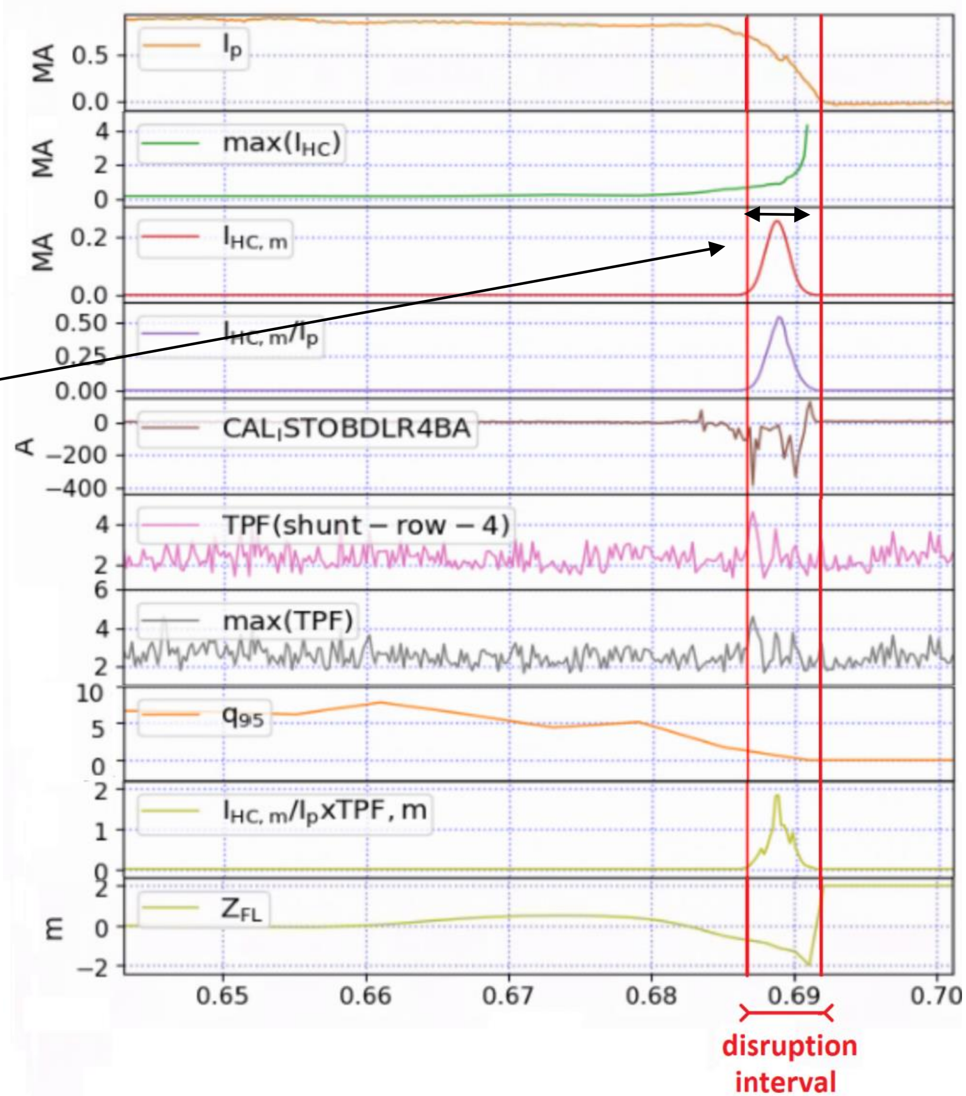
- Onset time/conditions
- Maximum amplitude
- Duration
- Toroidal asymmetry (TPF)
- Details (shape..)

❑ Example NSTX 137258:

- Threshold on Z_{axis}
- Maximum amplitude (1)
- Empirical duration τ_{HC}
- TPF preferred experimental
- Gaussian shape signal

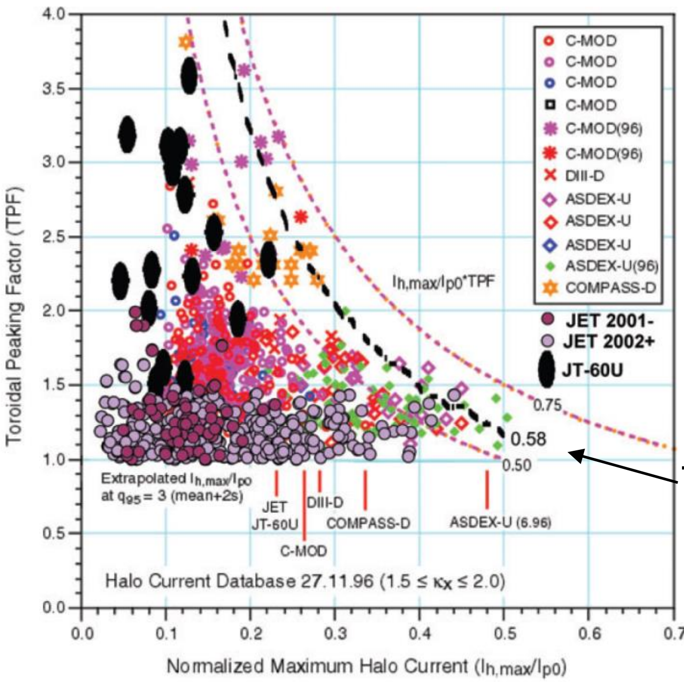
→ Maximum possible amplitude = unmitigated case

NSTX 137258



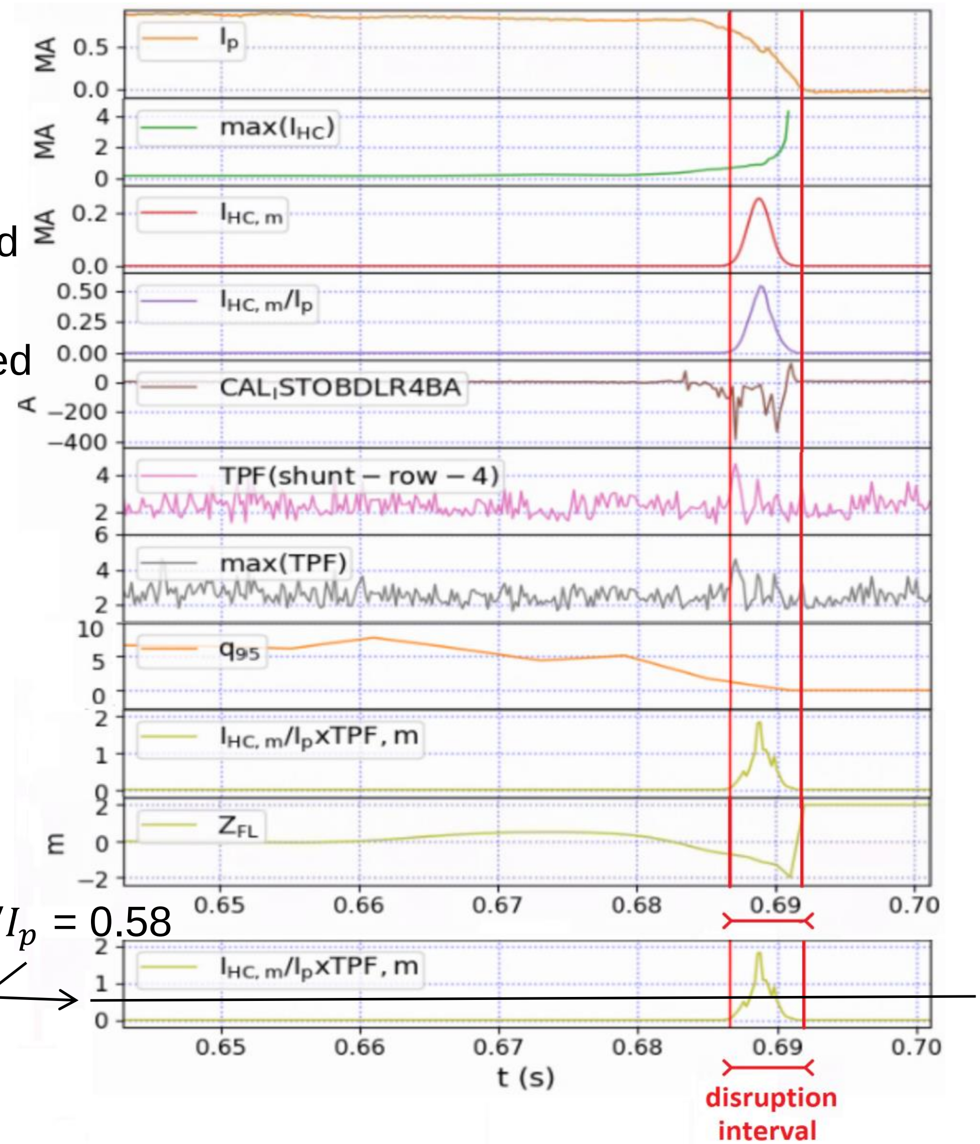
Application of product TPF· I_{HC}/I_p in HC-related DECAF event

- Important engineering factor:
  - TPF· I_{HC}/I_p
  - Most device data points < 0.75
  - Engineering limits for ITER calculated in the past
  - Possible implementation in HC-related DECAF event



V Riccardo *et al* Plasma Phys. Control. Fusion **46** (2004) 925–934

NSTX 137258



TPF· I_{HC}/I_p = 0.58

Application of product TPF· I_{HC}/I_p in HC-related DECAF event

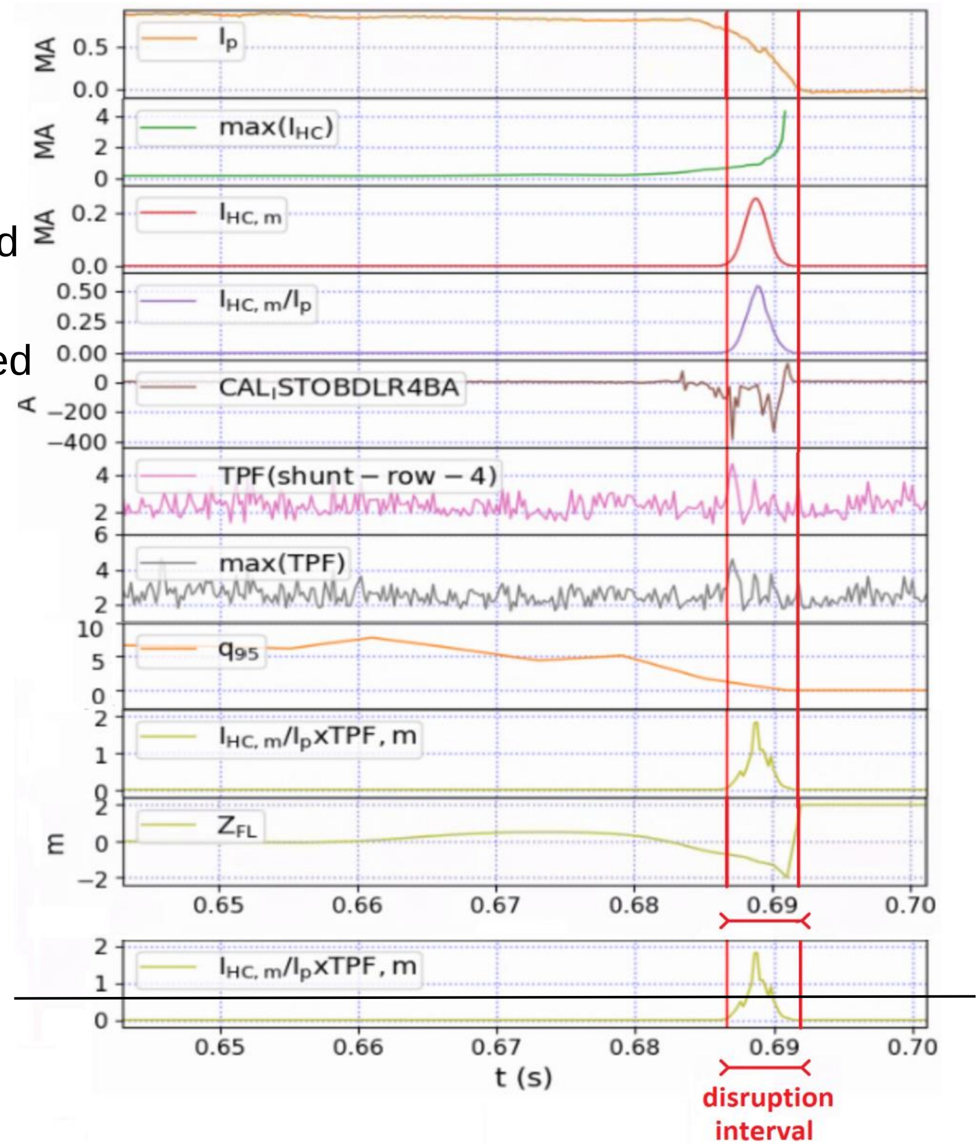
- Important engineering factor:
  - TPF· I_{HC}/I_p
  - Most device data points < 0.75
  - Engineering limits for ITER calculated in the past
  - Possible implementation in HC-related DECAF event

VDE upcoming

→ TPF· I_{HC}/I_p < 0.58

→ DNM

NSTX 137258



TPF· I_{HC}/I_p = 0.58

First steps in implementing a cross-device halo current model in DECAF taken, to be continued ..

- Plasma disruptions can threaten future reactor-relevant tokamaks on many fronts

- DECAF moves forward in recognizing disruptions that no longer pose threat to machine and do not require mitigation

- Induced in-vessel eddy and halo currents pose a major threat through forces applied on VV
  - Onset conditions, properties etc. studied extensively both theoretically and experimentally

- First steps taken on the path on implementing an abstracted cross-device model for halo current in DECAF
  - One of the possible criteria determining the necessity for disruption mitigation
  - More steps to be taken!
    - Model improvements, compare with experiment
    - Connection to VDE forecaster (NSTX-U Science meeting 01/29/2024, Matthew Tobin)

Any thoughts/suggestions?

- Any suggestions/comments?
  - All comments welcome (vklevar2@pppl.gov)

THANK YOU!

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