Implementation of a cross-device model for halo current in the DECAF code as a criterion for the determination of disruption mitigation action

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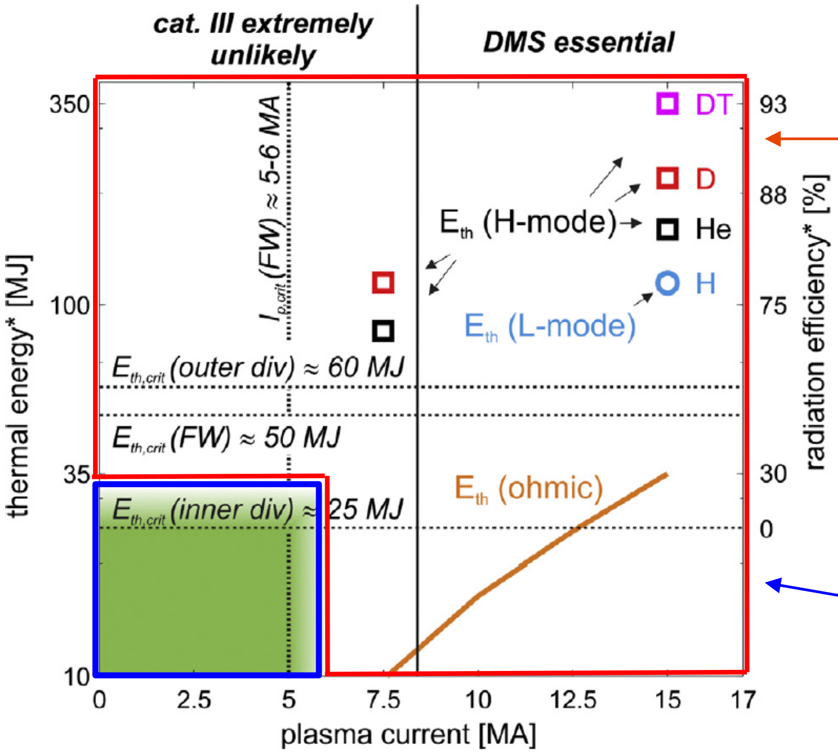
Disruptions severity set by pre-disruptive plasma state, shot phase, device configuration etc.

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



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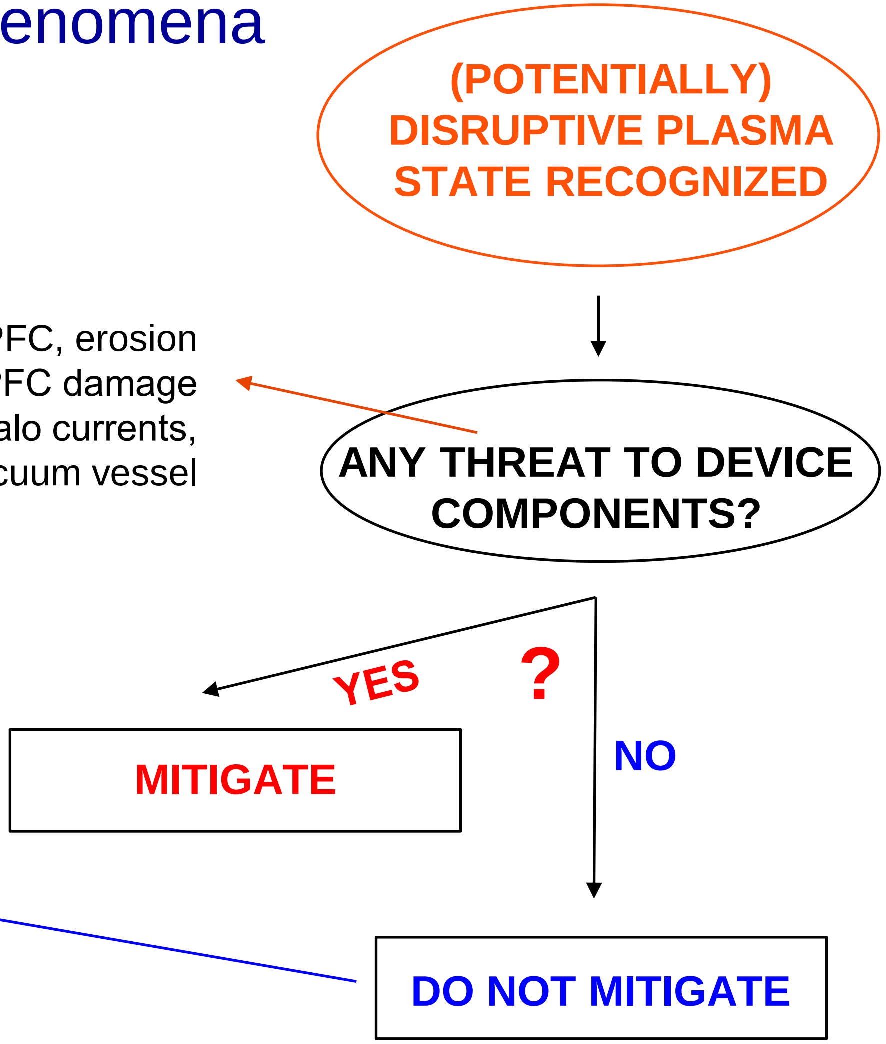
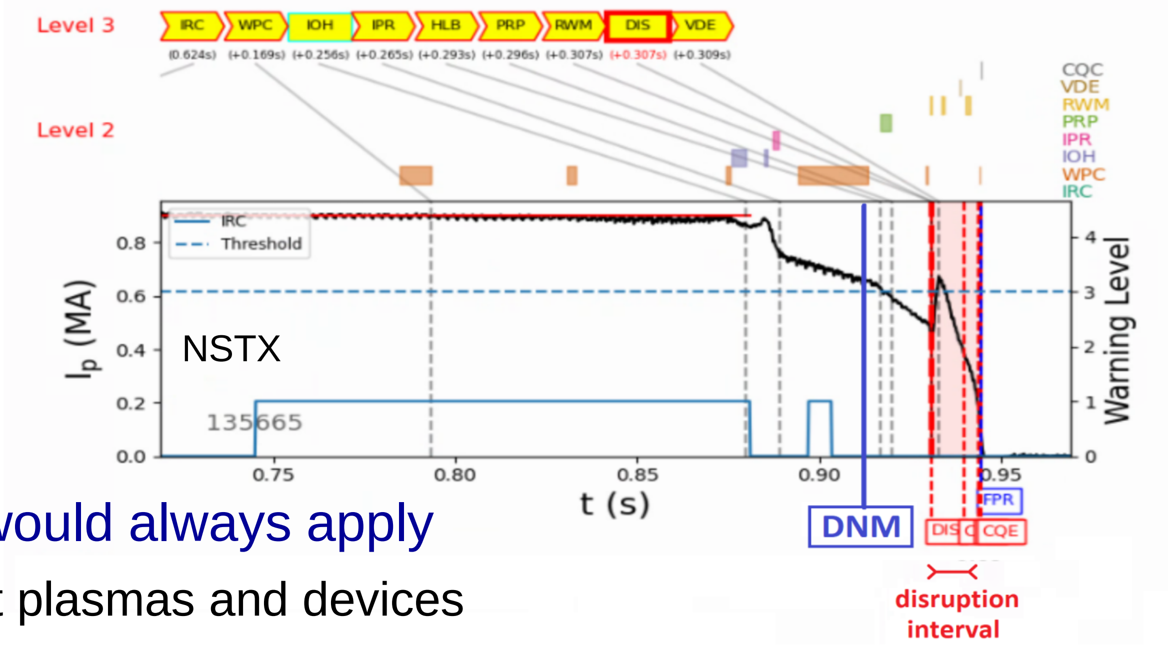
… thermal loads on PFC, erosion
… runaways, PFC damage
… induced eddy & halo currents, forces on vacuum vessel



Implementation of ‘Do Not Mitigate’ flag informing on disruption severity 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 plasma conditions not requiring collapse mitigation

localized thermal & particle loads
eddy in-VV currents
halo currents
mechanical forces
material fatigue



- Strictly speaking, in most *current* devices DNM would always apply
  - Need for projections/referencing to reactor-relevant plasmas and devices
  - Requested high accuracy of disruption forecasting and detection outside of DNM flag validity also in small to mid-size machines

*U.S. and international patents pending

DNM flag criteria address various damaging channels

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

- DNM (‘Do Not Mitigate’) flag indicating plasma conditions not requiring collapse mitigation

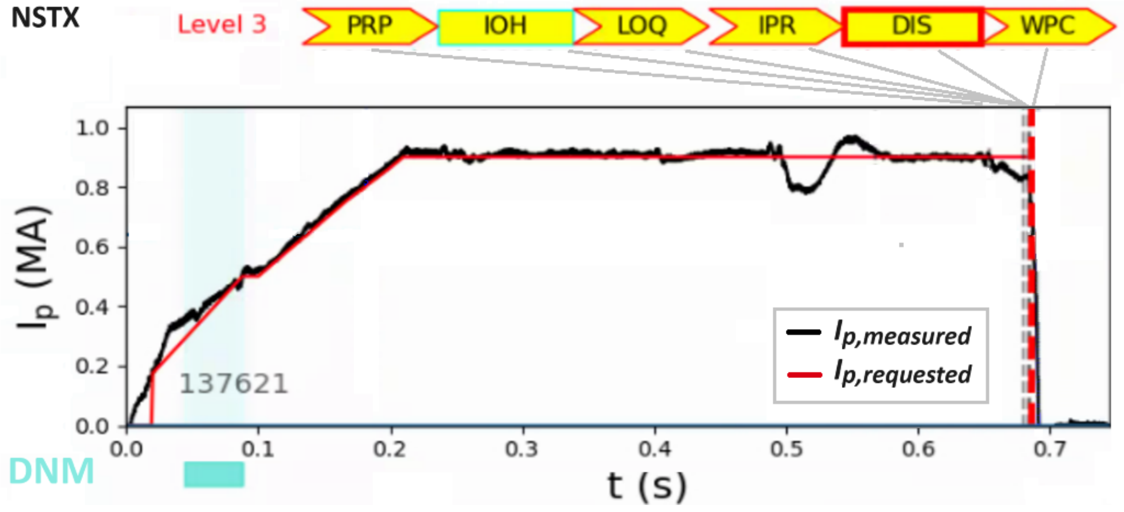
→ **Conditions:**

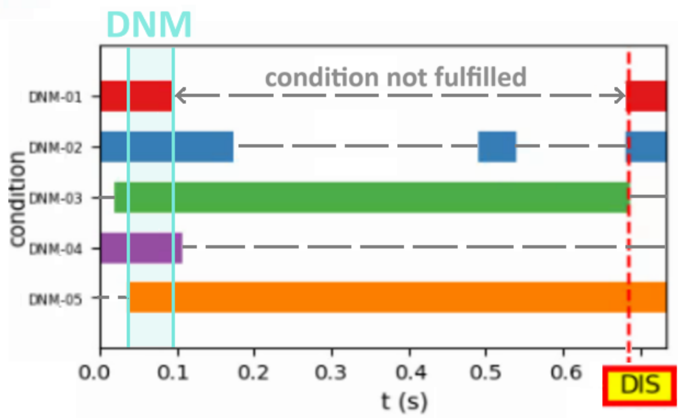
- $\boldsymbol{I_p} < \boldsymbol{I_{p,crit}}$ → lower risk of strong EM forces from in-VV currents and RE beam for low I_p
- $\boldsymbol{W_{mhd}} < \boldsymbol{W_{mhd,crit}}$ → lower risk of PFC damage for low plasma stored energy repository
- $\boldsymbol{I_{HC}/I_p}$ **x** ***TPF*** < $(\boldsymbol{I_{HC}/I_p\ x\ TPF})_{\boldsymbol{crit}}$ → halo current fraction x toroidal peaking factor below limit reduces EM loads and material fatigue
- $\boldsymbol{T_{e,core}} < \boldsymbol{T_{e,crit}}$ → analogy to condition on $\boldsymbol{W_{mhd,crit}}$
- $\boldsymbol{n_{e,core}} > \boldsymbol{n_{e,crit}}$ → lower risk of RE for plasmas of higher density

DNM flag issued if all criteria for benign disruption are satisfied

- DNM ('Do Not Mitigate') flag indicating plasma conditions not requiring collapse mitigation
  - I_p < $I_{p,crit}$ **(*DNM-01*)**
  - W_{mhd} < $W_{mhd,crit}$ **(*DNM-02*)**
  - I_{HC}/I_p x ***TPF*** < $(I_{HC}/I_p\ x\ TPF)_{crit}$ **(*DNM-03*)**
  - $T_{e,core}$ < $T_{e,crit}$ **(*DNM-04*)**
  - $n_{e,core}$ < $n_{e,crit}$ **(*DNM-05*)**

- If and only if all conditions are satisfied, DNM is issued

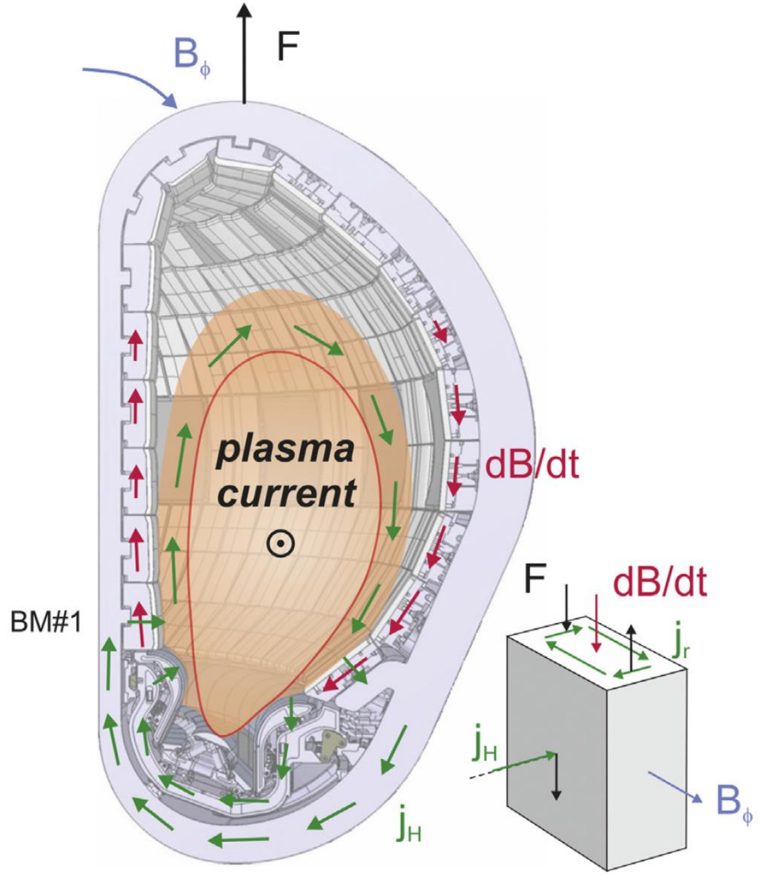




Halo current is a serious threat to engineering integrity of reactor-relevant devices

- Halo currents (HC) ← **part of one of DNM flag criteria**
  - 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 cumulatively exceeding device engineering limits
    through material fatigue (ITER, JET ..)
  - Critical features:
    - Onset time/conditions
    - (Maximum) amplitude
    - Duration
    - Toroidal asymmetry
    - Rotation

(some) diagnostic-dependency



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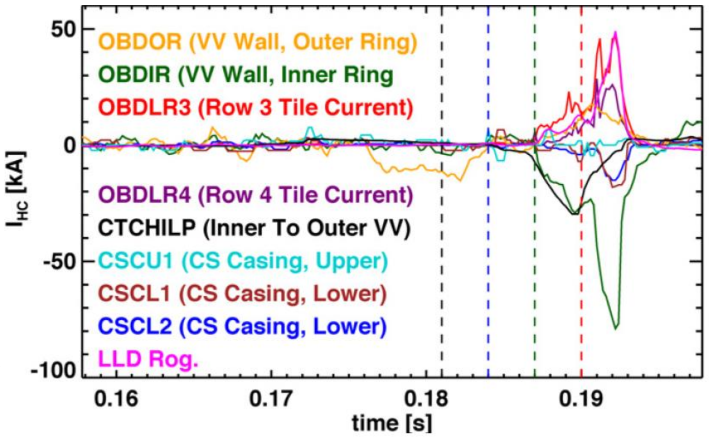
HC properties and origin studied extensively cross-device

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

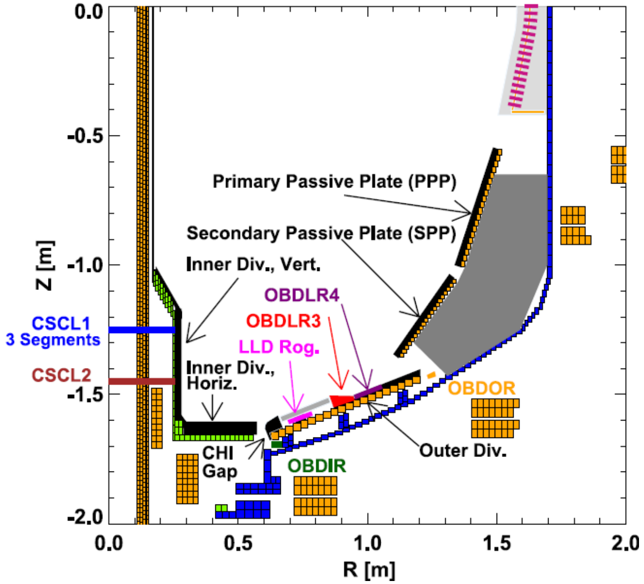
-> (some) diagnostic-dependency
-> cross-device trends captured

- Features changed when mitigation deployed
  - Peak amplitude decreases, PFC impact area increased [14]

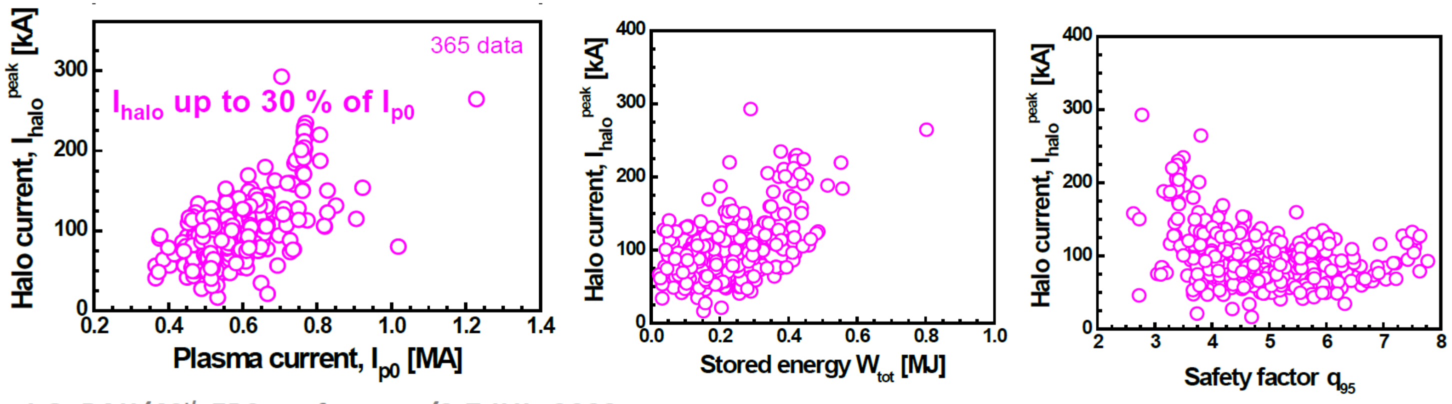
NSTX



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



KSTAR



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

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

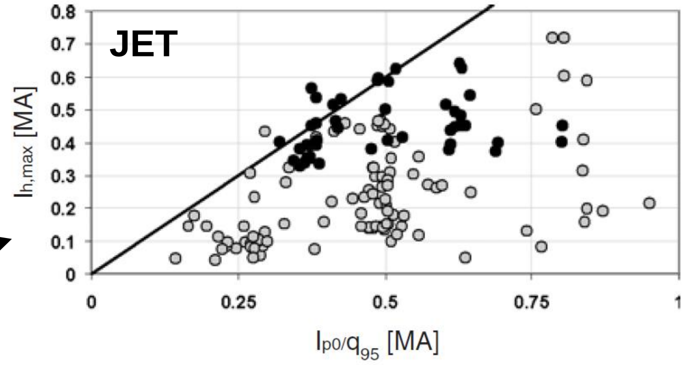
- Modeled HC pulse
  - Onset time/conditions
  - **Maximum amplitude**
  - Duration
  - Toroidal asymmetry (TPF)
  - Rotation
  - Details (shape..)

-> large scatter in max(I_{HC}) vs. plasma parameters
-> common cross-device *upper limit*

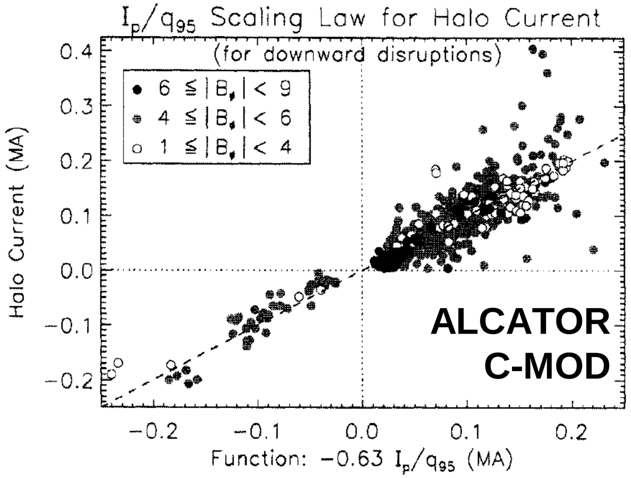
max(I_{HC}) ∝ $A \cdot I_p/q_{95}$ (1)

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

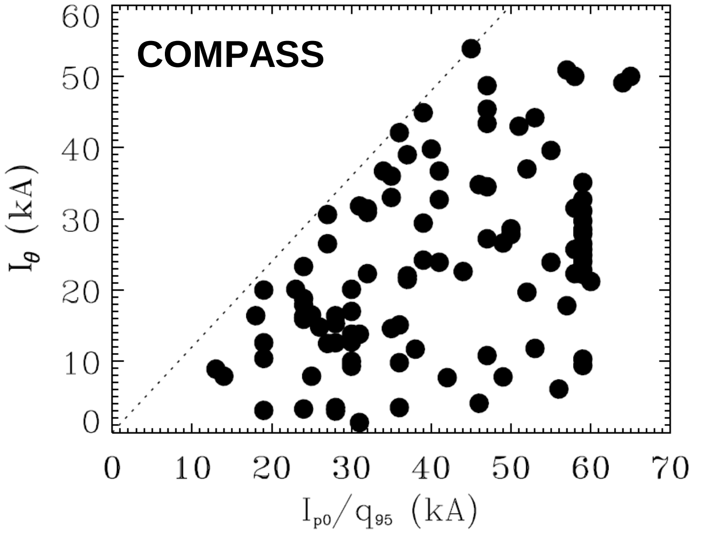
-> with A guess, (1) easily calculated during shot



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



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



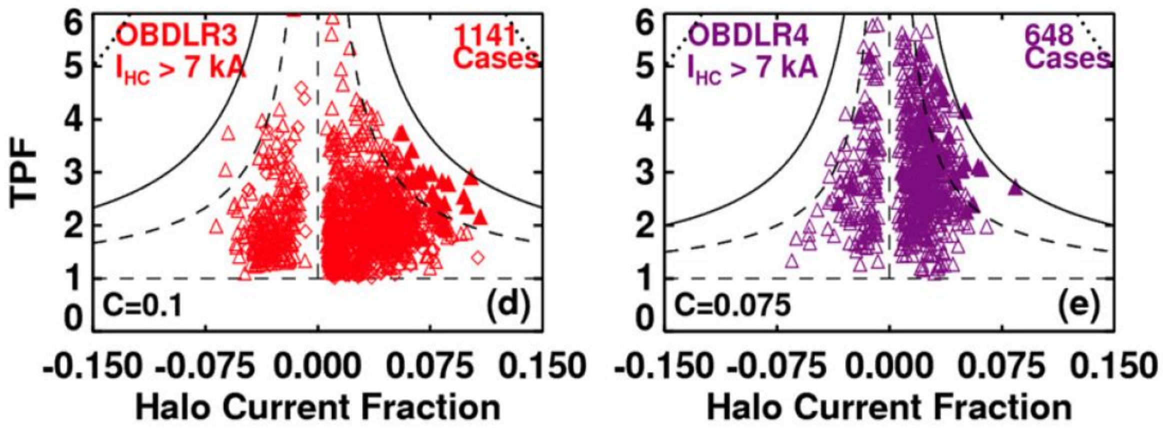
P.J. Knight et al. Nuclear Fusion, Vol. 40, No. 3 (2000)

DNM-03: $(I_{HC}/I_p\ x\ TPF)_{crit}$ uses for HC amplitude Eq.(1)
→ The most 'pessimistic' (i.e. maximum) I_{HC} amplitude

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

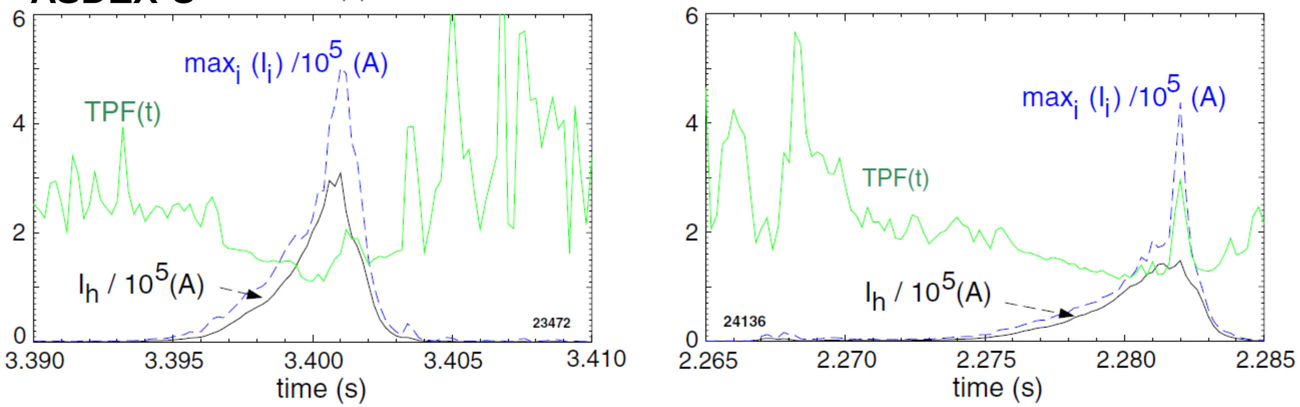
- Modeled HC pulse
  - Onset time/conditions
  - Maximum amplitude
  - Duration
  - **Toroidal asymmetry (TPF)** ⟶ $\text{TPF} = \frac{max(J_{HC})}{mean(J_{HC})}$ (2)
  - Rotation
  - Details (shape..)

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)

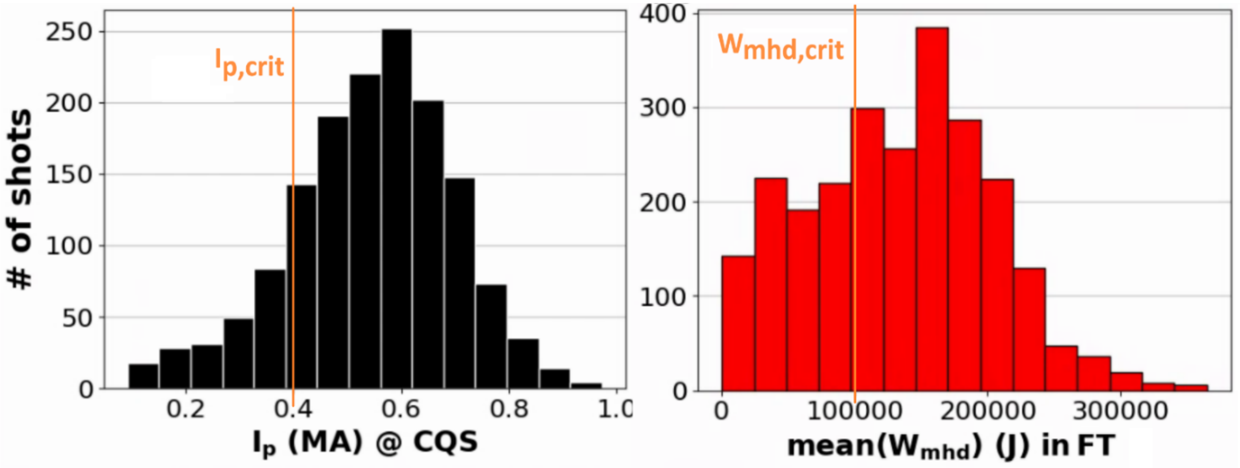
→ if no experimental data, use empirical values

First application of DNM flag on an extensive plasma shot database (NSTX 2009 year) - setup

- NSTX equipped with extensive HC (and other) diagnostics
- DNM critical parameter setup:

* ITER engineering limit (Lehnen 2015)

Parameter	$I_{p,crit}$ (MA)	$W_{mhd,crit}$ (kJ)	$(I_{HC}/I_p \, x \, TPF)_{crit}$	$T_{e,crit}$ (keV)	$n_{e,crit}$ (m^{-3})
Threshold	0.4	100	0.58*	1.0	2e19



NSTX 2009
Total # of shots: 2815
----
① DNM -> DIS : 8.3 %
② DIS -> DNM : 10.4 %
③ DIS no DNM : 31.9 %
④ DNM no DIS : 30.5 %
⑤ no DNM, no DIS : 18.9 %

- DNM and DIS** DECAF events requested in the analysis

** DIS = disruption time indicator [6,18]

Various DNM and DIS scenarios reveal details on plasma termination and impact on collapse consequences

- NSTX equipped with extensive HC (and other) diagnostics

NSTX 2009
Total # of shots: 2815
----
① **DNM -> DIS : 8.3 %**
② **DIS -> DNM : 10.4 %**
③ **DIS no DNM : 31.9 %**
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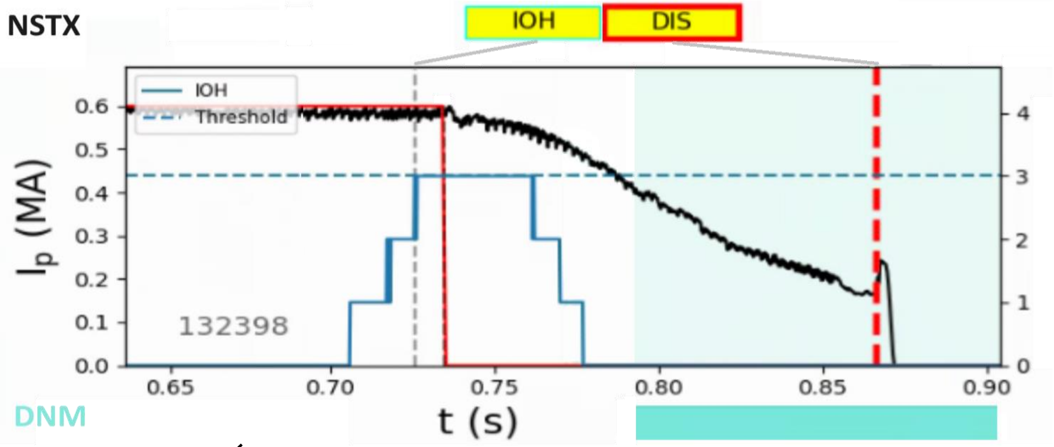
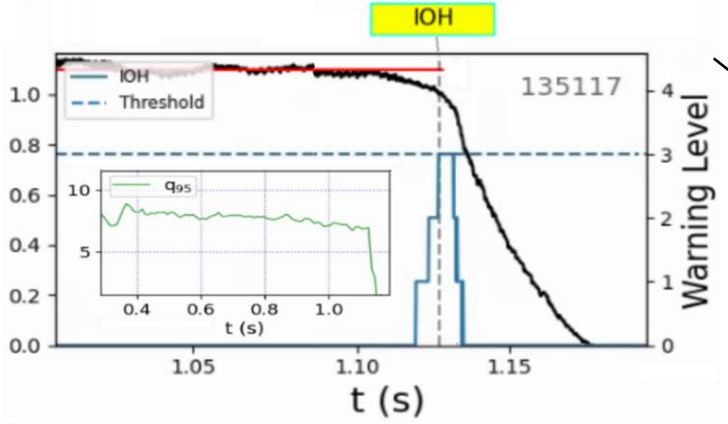
⑤ **no DNM, no DIS : 18.9 %**

① DNM preceding DIS (8.3%): DNM issued prior DIS



⑤ no DIS, no DNM flag (18.9%): neither DIS nor DNM detected



→ In both cases, **IOH** technical DECAF event detected
IOH : Ohmic coil current limit met -> start I_{OH} ramp-down

① 132398: I_p decay rate ~ 3.6 MA/s, DNM issued
⑤ 135117: I_p decay rate ~ 20 MA/s, q_{95} drops, no DNM

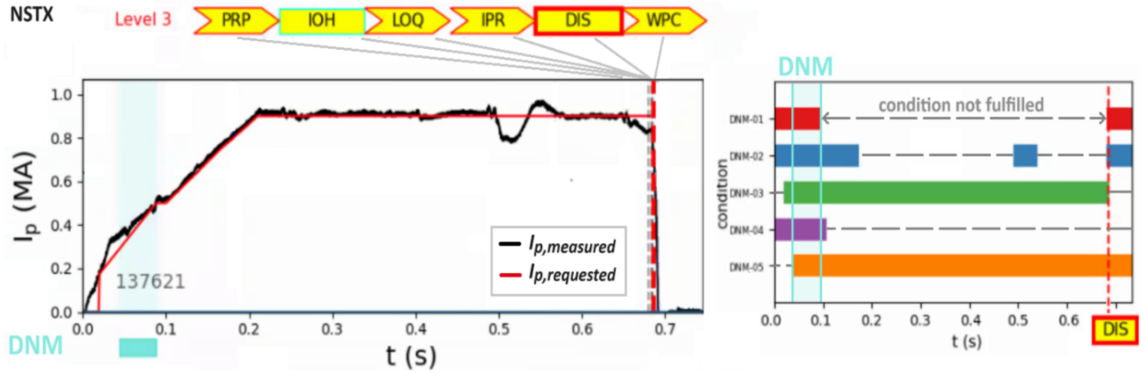
Various DNM and DIS scenarios reveal details on plasma termination and impact on collapse consequences

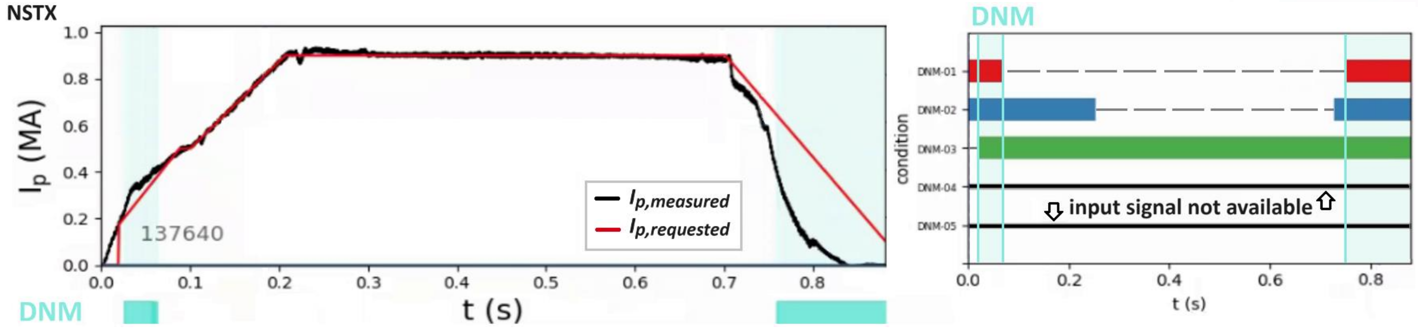
- NSTX equipped with extensive HC (and other) diagnostics

NSTX 2009
Total # of shots: 2815
----
① **DNM -> DIS : 8.3 %**
② **DIS -> DNM : 10.4 %**
③ **DIS no DNM : 31.9 %**
④ **DNM no DIS : 30.5 %**
⑤ **no DNM, no DIS : 18.9 %**

② DIS followed by DNM (10.4%): typically a DIS later in I_p ramp-down, followed by a slow I_p quench phase

③ DIS, no DNM flag (31.9%): conditions not met for DNM prior DIS, typically a disruption with fast I_p quench phase





④ DNM flag issued, no DIS (30.5%): non-disruptive plasma termination

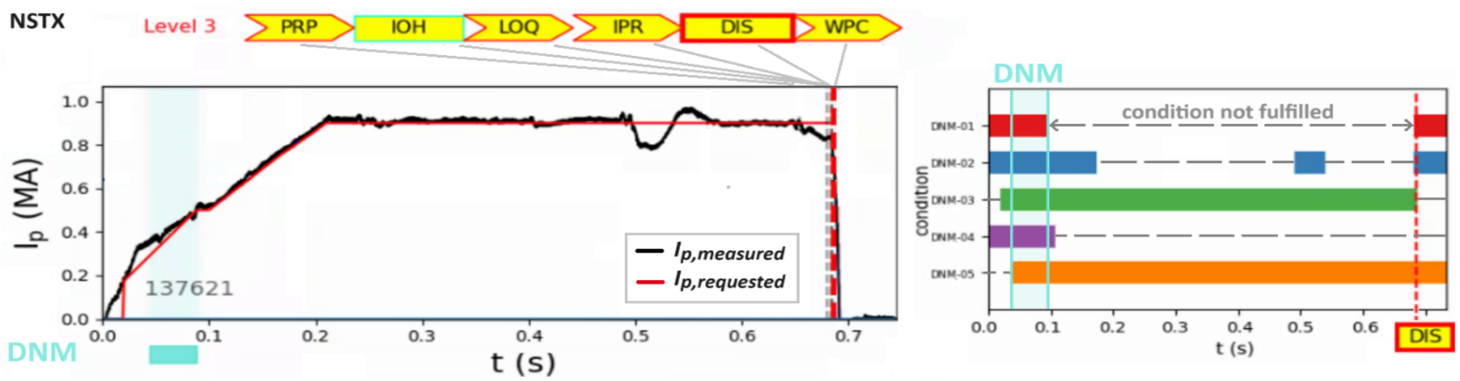
Various DNM and DIS scenarios reveal details on plasma termination and impact on collapse consequences

- NSTX equipped with extensive HC (and other) diagnostics

NSTX 2009
Total # of shots: 2815
----
① DNM -> DIS : 8.3 %
② DIS -> DNM : 10.4 %
③ DIS no DNM : 31.9 %
④ DNM no DIS : 30.5 %
⑤ no DNM, no DIS : 18.9 %

② DIS followed by DNM (10.4%): typically a DIS later in I_p ramp-down, followed by a slow I_p quench phase

③ DIS, no DNM flag (31.9%): conditions not met for DNM prior DIS, typically a disruption with fast I_p quench phase



→ These groups (~ 42 % cases in total) pose particularly high accuracy requirements on disruption forecasting and detection

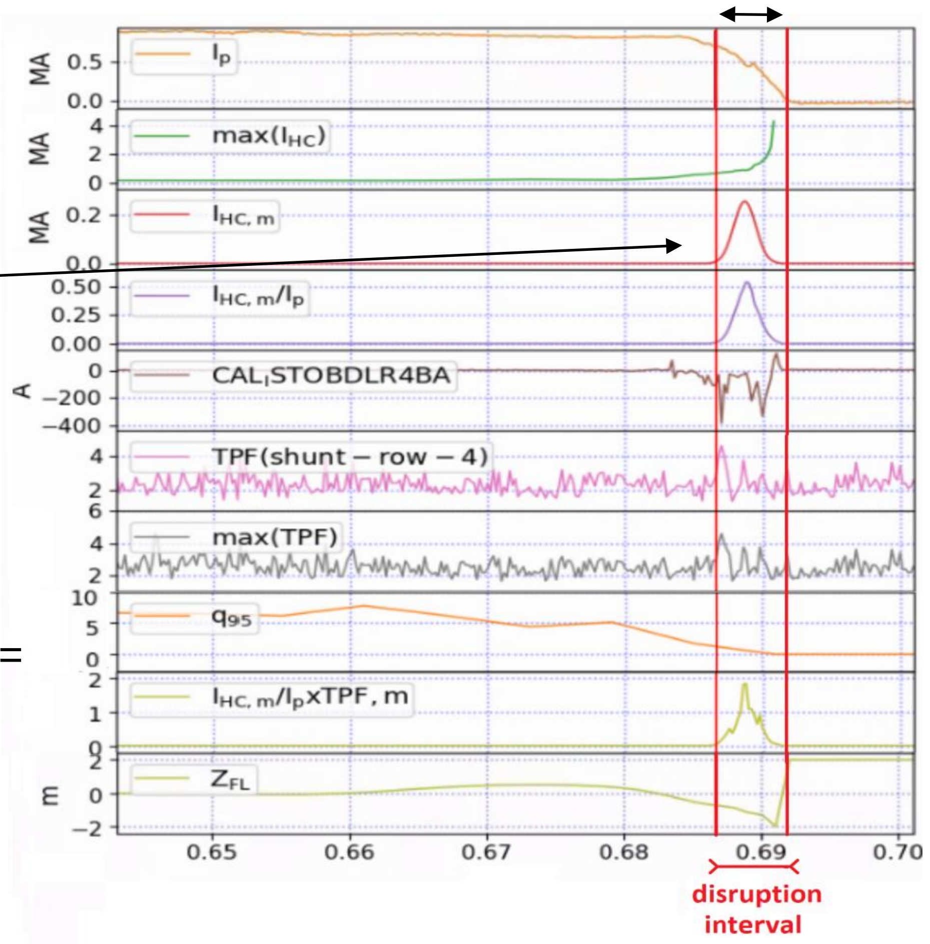
Implementing an abstracted cross-device model for HC in DECAF

- Apart from application in DNM, full shape HC pulse modelled in DECAF, potential for its coupling to VDE forecaster [19]

- 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



Coupling of modeled I_{HC}/I_p x TPF with VDE prediction allows forecasting of disruption severity

- Important engineering factor:
  - I_{HC}/I_p x TPF
  - Most device data points < 0.75
  - Engineering limits for ITER calculated in the past = 0.58 (DNM-03)

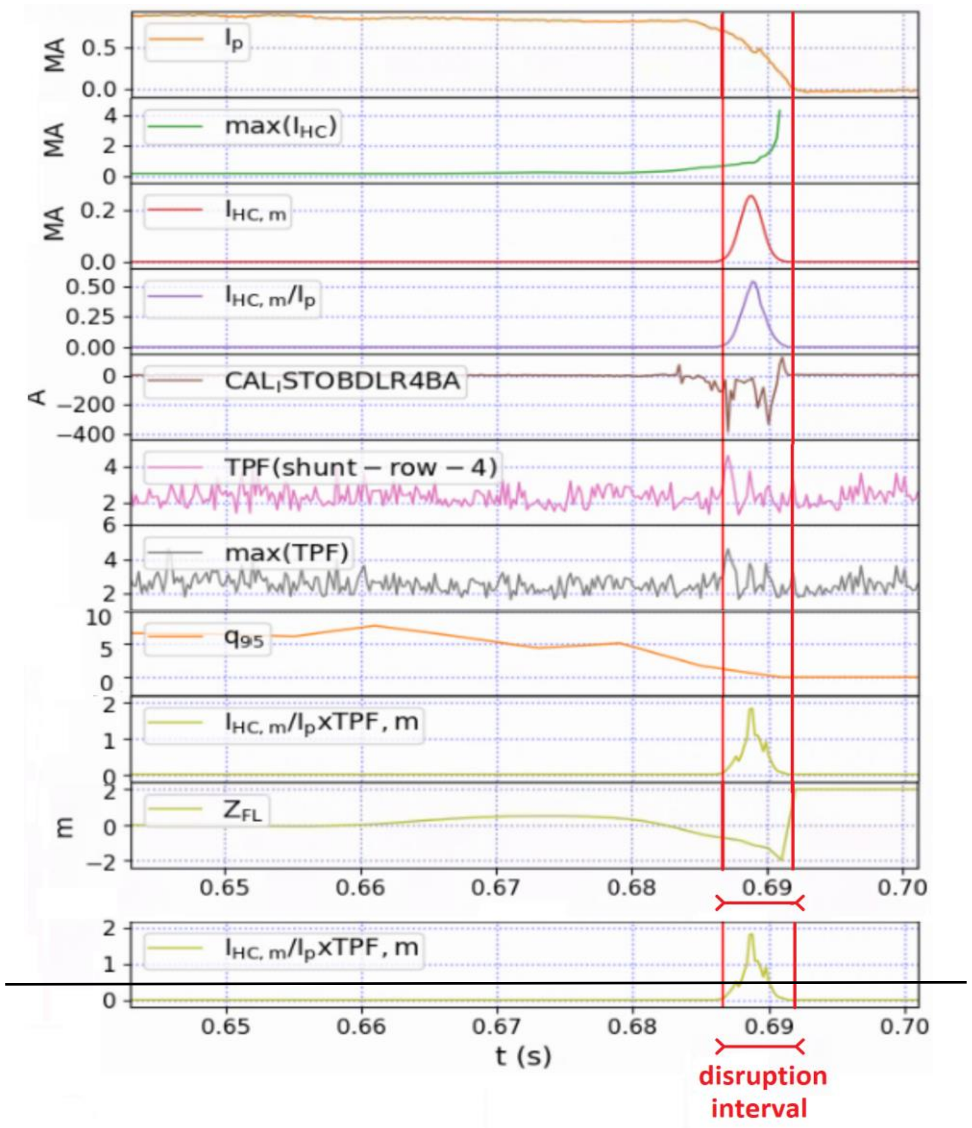
- Coupling:

  → **VDE forecasted**

  → **I_{HC}/I_p x TPF < 0.58**

  → **OK for HC EM loads**

NSTX 137258



TPF· I_{HC}/I_p = 0.58

DECAF code extended for multi-conditional evaluation of disruption consequences including model for halo current

- Plasma disruptions can threaten future reactor-relevant tokamaks on many fronts
- DECAF expanded to recognize disruptions that no longer pose threat to machine and do not require mitigation
  - Multi-conditional approach addressing various disruption-caused device damaging channels
- First application of Do Not Mitigate flag on a large shot database revealed details of plasma termination and their impact on collapse consequences
- High accuracy disruption forecasting and detection of outmost importance in collapses happening outside of DNM validity
- Future:
  - Refine/expand DNM criteria

REFERENCES

- [1] S.P. Gerhardt *et al.*, 2012 *Nucl. Fusion* **52** 063005
- [2] S.P. Gerhardt *et al.*, 2011 *Rev. Sci. Instr.* ***82*** *103502*
- [3] G. Pautasso *et al.*, 2011 *Nucl. Fusion* **51** 043010
- [4] A.H. Boozer, 2015 *Phys. Plasmas* **22** 102511
- [5] F.J. Artola *et al.*, 2021 *Phys. Plasm.* **28** 052511
- [6] S.A. Sabbagh *et al.*, 2023 *Phys. Plasm.* **30** 111945
- [7] P.J. Knight *et al.*, 2000 *Nucl. Fusion* **40** 325-337
- [8] R.S. Granetz *et al.*, 1996 *Nucl. Fusion* ***36*** 545
- [9] V. Riccardo *et al.*, 2004 *Plasma Phys. Control. Fusion* ***46*** 925
- [10] Y. Neyatani *et al.*, 1999 *Nucl. Fusion* ***39*** 559
- [11] C.E. Myers *et al.*, 2018 *Nucl. Fusion* **58** 016050
- [12] A.H. Boozer, 2013 *Phys. Plasm.* **20** 082510
- [13] A.R. Saperstein *et al.*, 2023 *Phys. Plasm.* **30** 042506
- [14] N. Schwarz et al., 2023 *Nucl. Fusion* **63** 126016
- [15] M. Lehnen et al., 2015 *Jour. Nucl. Materials* **463** 39-48
- [16] D.A. Humphreys and A.G. Kellman 1999 *Phys. Plasmas* **6** 2742-56
- [17] S. Sadakov et al., 2015 *Fusion Eng. Des.* **98** 1601-4
- [18] V. Zamkovska et al. 2024 *Nucl. Fusion* **64** 066030
- [19] M. Tobin et al., 2024 Vertical Instability Forecasting and Controllability Assessment of Multi-device Tokamak Plasmas in DECAF with Data-driven Optimization, accepted for publication in PPCF