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Cross-device DECAF investigation of abnormal evolution of plasma vertical position and current indicating disruptions and internal reconnection events

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DECAF modules as building blocks for studies of disruptive plasma state evolution

- DECAF[TM] is iteratively improving accuracy of its physics modules (goal > 98% TP rates) and understands them in context of technical modules
  - DECAF disruptive event chains analyzed and validated over large databases

- High accuracy of event modules allows DECAF's usage as a disruption characterization tool improving our understanding of disruptive plasma state evolution

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Abnormalities in I_p and/or Z waveforms

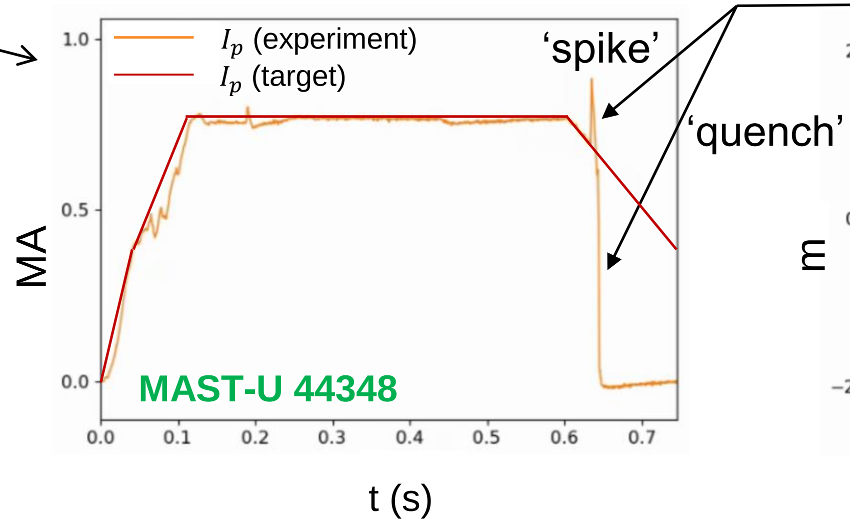
Careful!

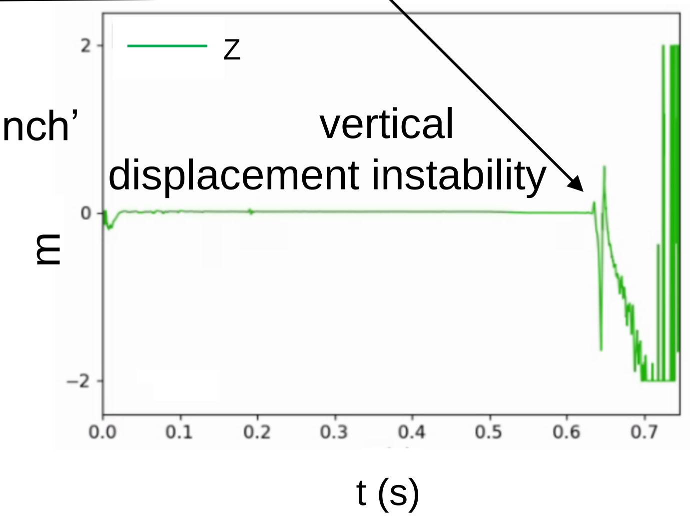
PROXIMITY TO DISRUPTION

- Building on accurate detection , here:
  - Binary disruption classifier based on current quench phase detection
  - Occurrence of disruptive chains of events capturing I_p and Z abnormalities and their location in the device operational space
  - Initial large-database survey of possible IRE triggering mechanisms

Abnormalities in I_p and Z are common disruption indicators

- Abnormal (deviating from planned target) evolution in I_p and Z waveform:





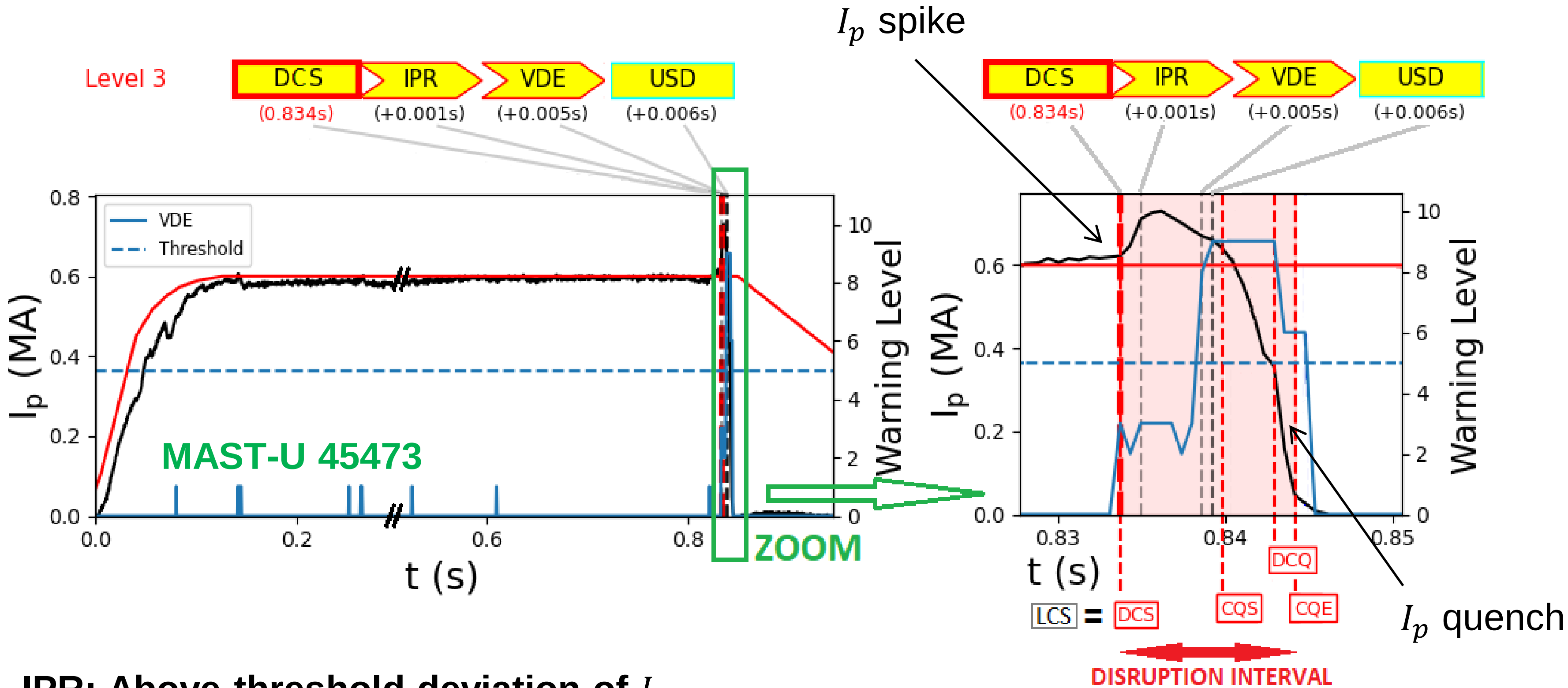
- Common cross-device/shot elements of disruptions

  their detection

  simple, yet robust and widely applicable disruption indicators

DECAF captures I_p and Z abnormalities in its physics event modules

- DECAF captures those abnormalities in its physics events modules



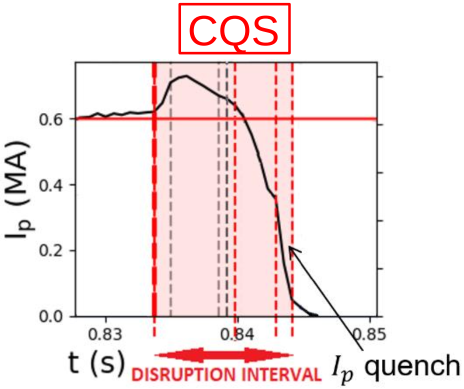
IPR: Above-threshold deviation of I_p experimental (black) from target (red)
VDE: Vertical Displacement Event

+ 'Technical' event
USD: Uncontrolled Shut Down

DCQ: Disruptive Current Quench
CQS/E: Current Quench Start/End
DCS: Disruptive Current Spike
LCS: Largest Current Spike

1 DECAF discriminates non-/disruptive shots through current quench phase detection

- Final I_p quench is irreversible
  - → suitable candidate for binary disruption indicator
    - → applied in DECAF through CQS event



- How many shots disrupted in the study set?

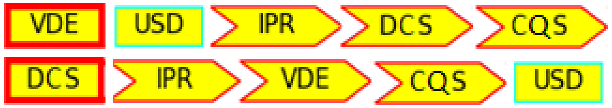
3 I_p spikes capture IREs, usually (?) non-disruptive, yet unwanted shot elements

- Internal Reconnection Events are predominantly a feature of spherical tokamaks
- Usually considered non-disruptive, but cause abrupt changes in plasma parameters profiles and shape
  - magnetic field line reconnection phenomenon, manifested through I_p spike
- What causes IREs? Can they disrupt plasma? Can they be avoided?
  → 'new' disruption precursor?

2

DCEs reflect physics program and engineering setup of a given device

- Events form Disruptive Chains of Events (DCEs)
  - of interest here: VDE, IPR, DCS, CQS (disruption indicator) + USD
  - their order and appearance within DCEs depend on:



- typical machine operation space and its limits

.. promotes various disruptive instabilities

- preprogrammed/emergency shot exit scenario

.. order and appearance is generally device-dependent!

- Disruption characterization through DCEs yields:
  - insight in physics and/or engineering elements driving disruptions
  - background for further study of disruption root causes
  - hints for future development of real-time plasma control and termination schemes, definition of disruption avoidance and mitigation strategies

Careful! Dominant DCEs can change year-to-year, campaign-to-campaign

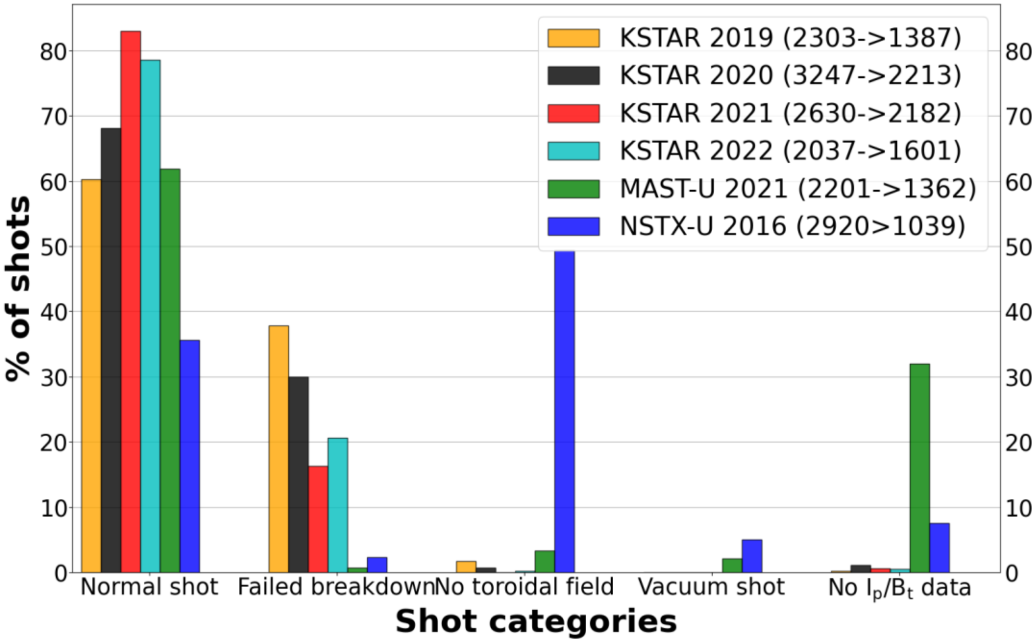
I_p and Z abnormalities explored with DECAF on multi-device/year shot database

- KSTAR 2019-2022, MAST-U 2021 and NSTX-U 2016

  -> use plasma current quench as a binary disruption indicator

  -> DCE statistics and occurrence in device operation space

  -> exploration of conditions for IREs onset

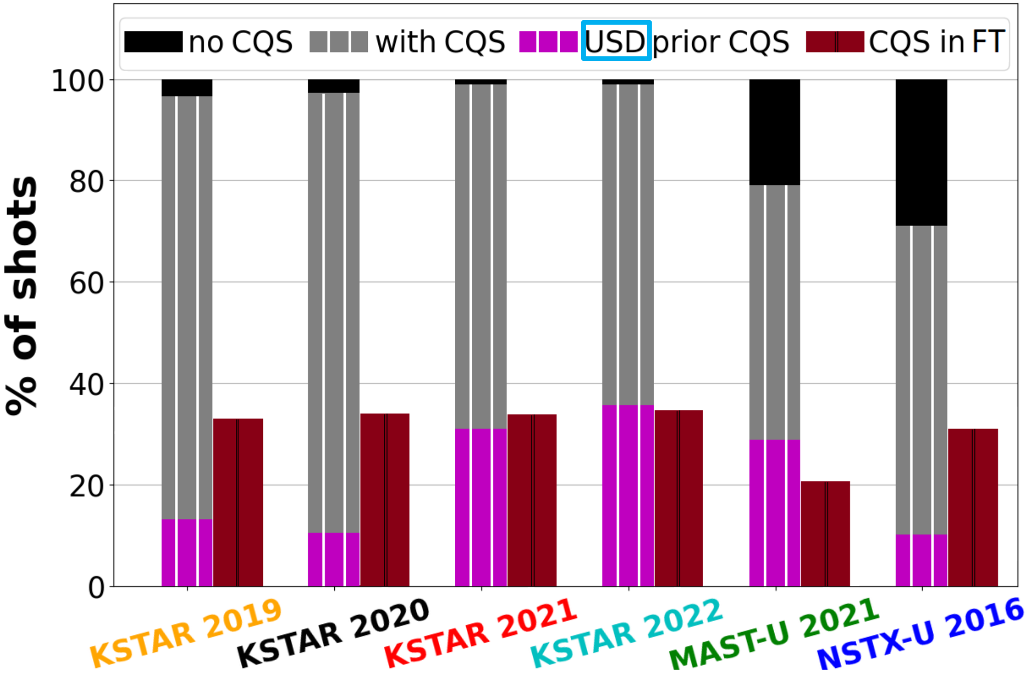


- Full device exp. years were analyzed with shot range:
  - first -> last attempt for a plasma
- DECAF basic shot categorization:
  - shots that passed the I_p breakdown fall into the 'Normal' category
  - DCEs were analyzed in those

1 Prevalence of current quench phases detected within the study set

- Current quench (CQ) leading to complete plasma loss is irreversible
  - suitable binary disruption indicator applied in DECAF through CQS

- CQS may be caused by USD, this 'technical/intentional' disruption *must* be taken into account in *any* DCE analysis

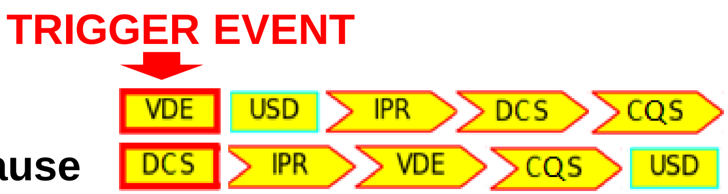


- Multi-device/year set:
  - -> very high % of disruptive shots in KSTAR in all years
  - -> USD preceded CQS in [13,11,31,36]% in KSTAR
    - change of USD deployment strategy in time
    - majority of CQs not caused by USD
  - -> in STs, CQS in about 70-80% of shots
  - -> majority of CQS out of I_p flat-top phase,
    - feedback control of critical plasma parameters may be off in I_p ramp-down to save device resources

- Overall high % of shots with CQs in study set

Different driving causes lead to distinct trigger events

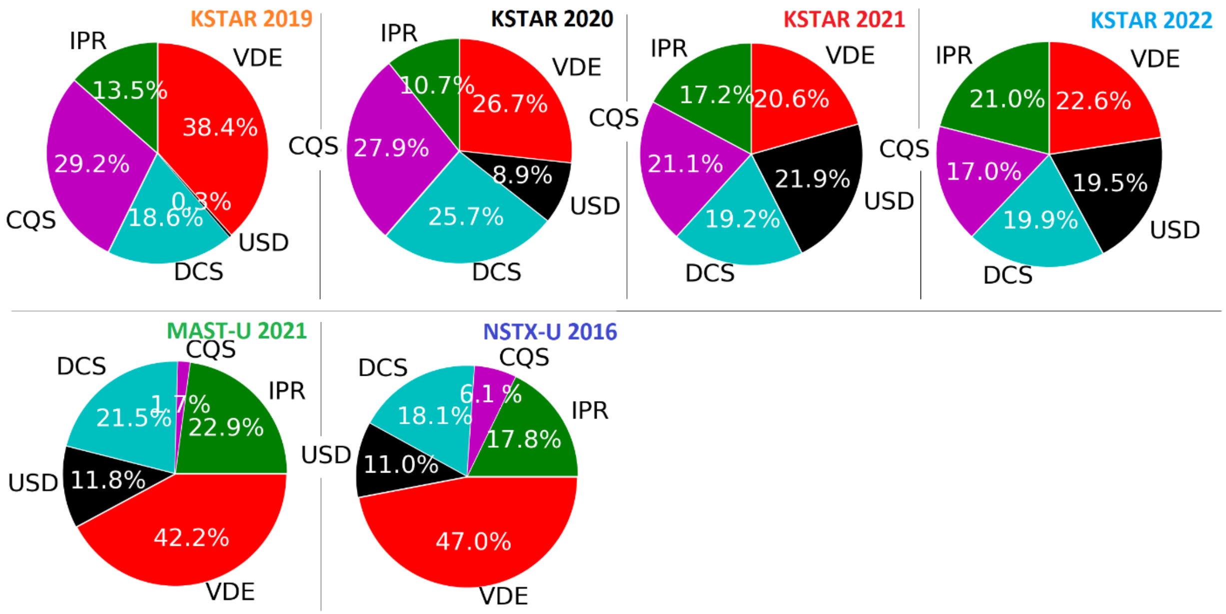
- DCE is initiated by a trigger event
  - Locations of shot within operational space and plasma predefined or emergency termination scenario(s) should be reflected in a structure of DCEs in a given device



Trigger event	**(Possible) driving cause**
VDE	Elongated plasmas prone to vertical displacement events
IPR	MHD instabilities modifying the current density distribution, temperature profiles etc., current drive not sufficient to meet the target
DCS	MHD modes (external kinks, rotating/locked tearing modes, ..), IREs (?) causing stochastization of the magnetic field lines
CQS	Driving cause outside of the study focus (other DECAF events)
USD	Fast plasma shut down following a recognition of off-normal plasma and/or machine state

Statistics of DCEs grouped per trigger event reveal major disruption scenario

- DCE is initiated by a trigger event
  - Location of shot within operational space and plasma predefined/emergency termination scenario(s) should be reflected in DCE's structure
  - Grouped per trigger event, dominant trigger events can be identified



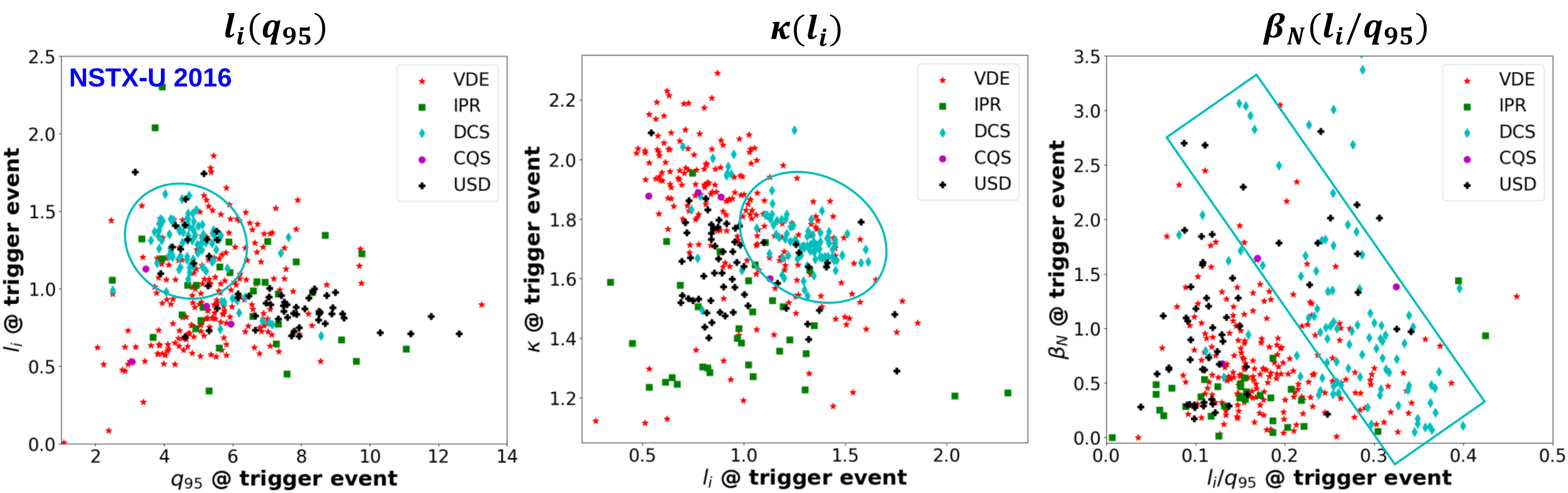
<- plasmas reaching FT and I_p and Z measurements surpassing the CQS considered here (to ensure DCE completeness):
KSTAR 2019-2022: [1079,1953,2009,1499]
MAST-U 2021: 849
NSTX-U: 557

- MAST-U and NSTX-U incline mainly to VDEs
- VDE % reduces in time in KSTAR
  - change of strategy in prevention of this type of instability

2 Trigger events located in different parts of device operational space (NSTX-U example)

- DCEs grouped per trigger driven by different destabilizing mechanism
  .. thus located in different parts (limits) of the machine operation space

- Example of NSTX-U 2016, plasma parameters calculated at trigger event time:



<u>Example of DCS trigger event:</u>
One dominant cluster of DCS points in $l_i(q_{95})$ space
DCS tightly clustered in $\kappa(l_i)$ space, roughly coincides with VDE, VDE @ upper *$\kappa(l_i)$ boundary*
DCS cluster at the stability limit within the $\beta_N(l_i/q_{95})$ space & at highest values of l_i/q_{95}

2 Trigger events located in different parts of device operational space (MAST-U example)

- DCEs grouped per trigger driven by different destabilizing mechanism

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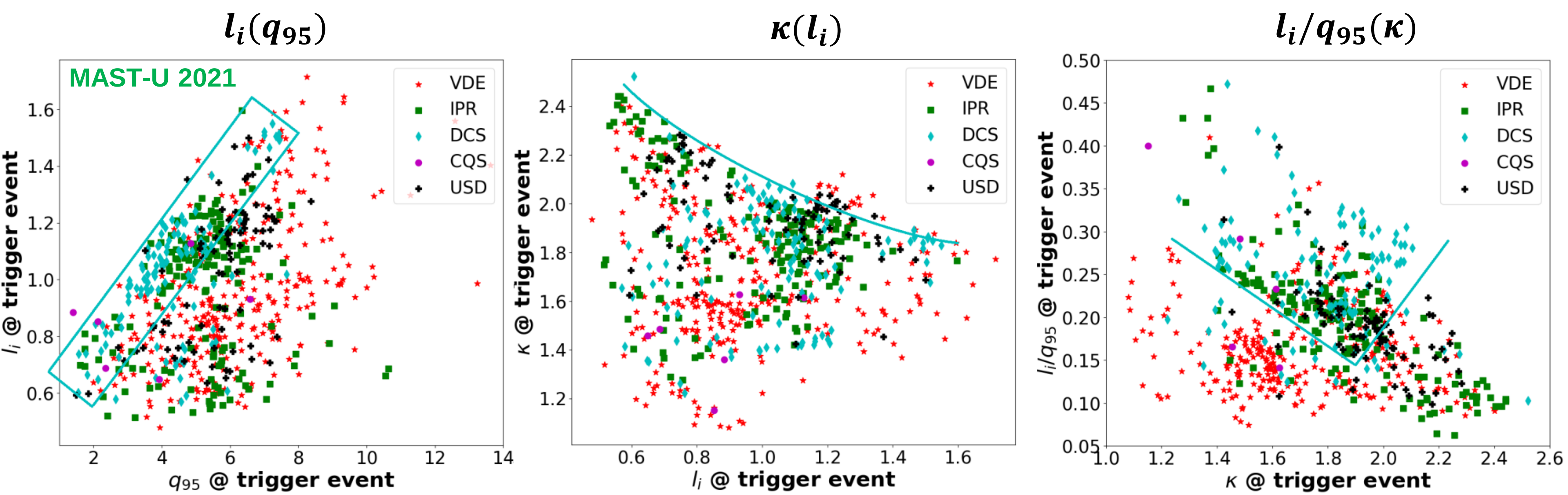

<u>Example of DCS trigger event</u>

-> DCS frequent along $\kappa(l_i)$ stability limit & at highest values of l_i/q_{95} ratio

-> DCS points concentrated in $l_i(q_{95})$ space along the stability limit (1)

2 Trigger events located in different parts of device operational space (MAST-U example)

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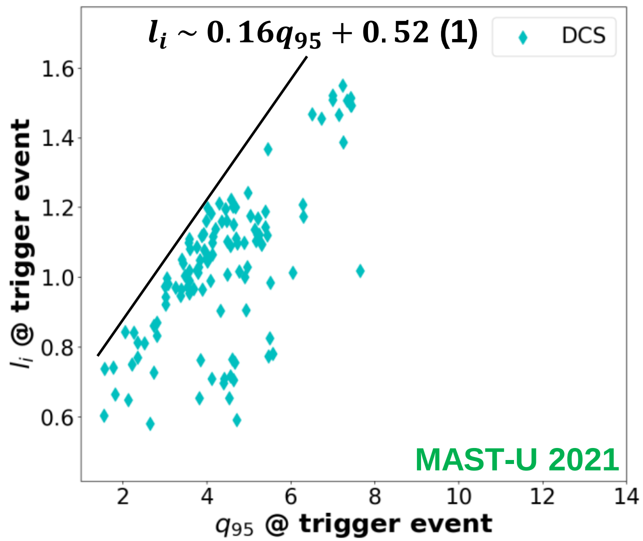
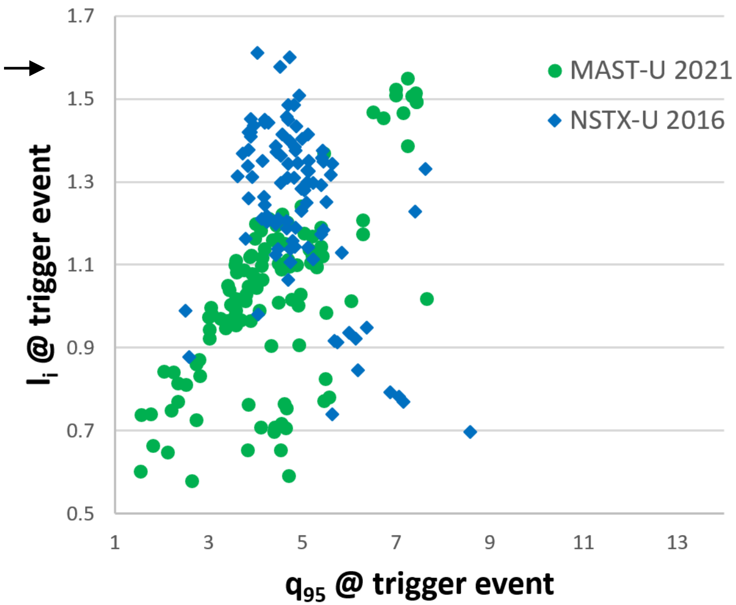
$l_i(q_{95})$



$l_i(q_{95}) \rightarrow$

MAST-U 2021 vs. NSTX-2016



<u>Example of DCS trigger event (NSTX-U)</u>
-> DCS frequent along $\kappa(l_i)$ stability limit & at highest values of l_i/q_{95} ratio
-> DCS points concentrated in $l_i(q_{95})$ space along the stability limit (1)

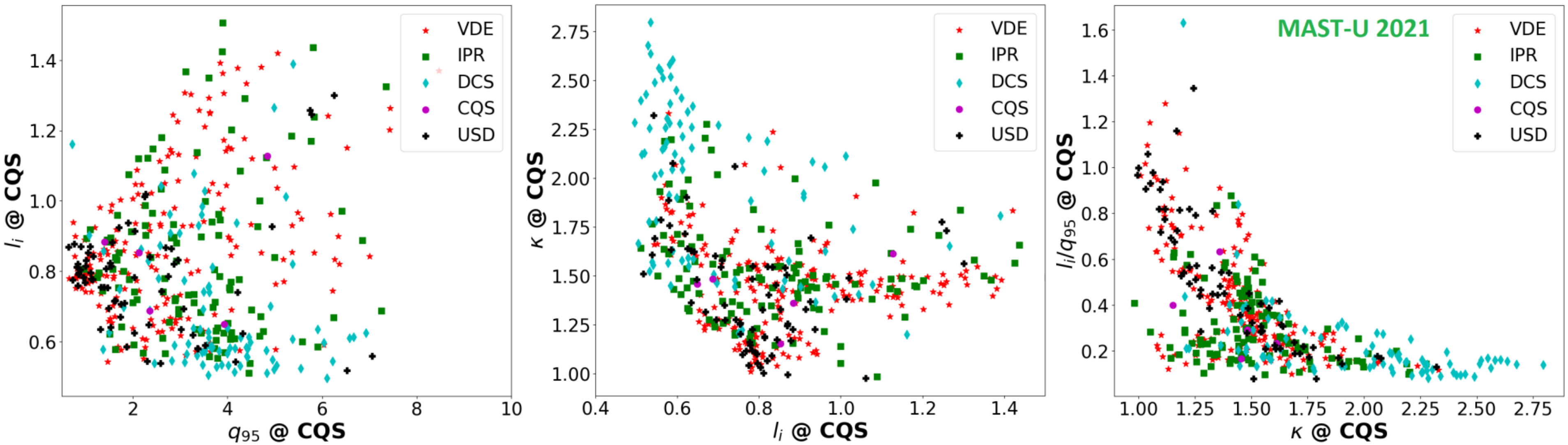
Disruption dynamics bound with trigger event (MAST-U example)

2

- Example of MAST-U 2021, selected plasma parameters calculated at the trigger event time (previous slide) vs. at the onset of the current quench phase (CQS)

Event sequence	Δt (median ± mad) (ms)
VDE -> CQS	6.1 ± 4.3
IPR -> CQS	63.8 ± 57.7
DCS -> CQS	1.3 ± 0.7
USD -> CQS	6.7 ± 5.5

time separation between trigger event <-> CQS



-> Large drop in l_i in the $l_i(q_{95})$ space within short Δt, indicating fast flattening of the current density profile (DCS)
-> Large change of κ within Δt in VDEs
-> Generally large drop in l_i/q_{95} (prior drop in l_i), ? increases in VDE ($q_{95} \sim 2$ stability limit frequently met in VDE)
└→ important for assessment of severity of disruption consequences

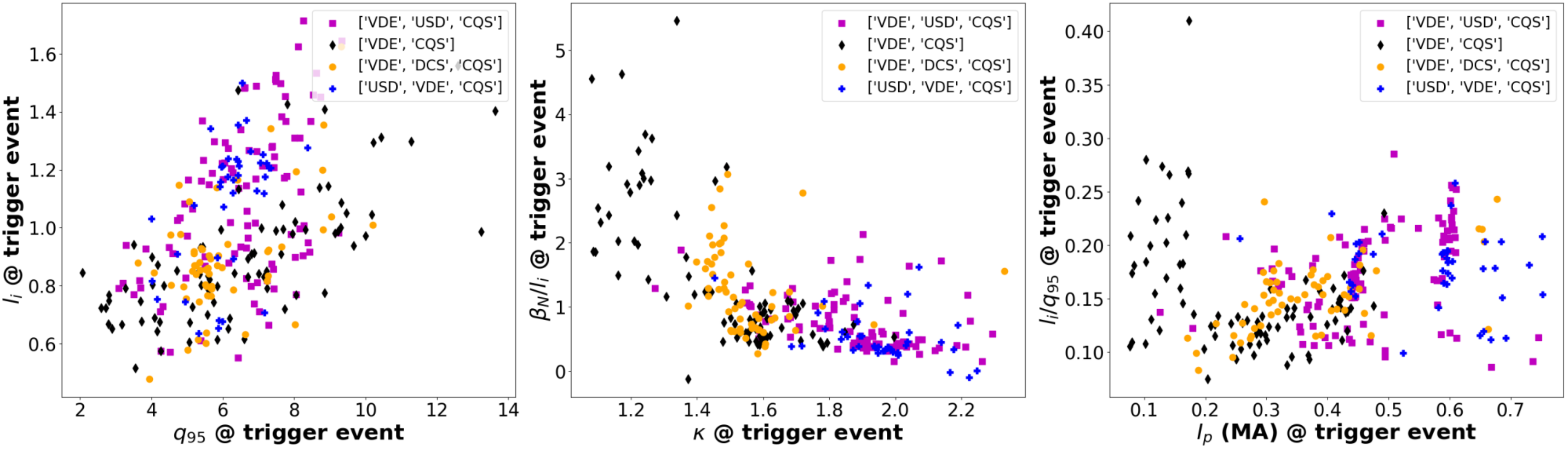
Individual chain of events located in different parts of device operational space

2

- Individual DCEs driven by different disruption cause, events within chain depend on particular plasma/machine details

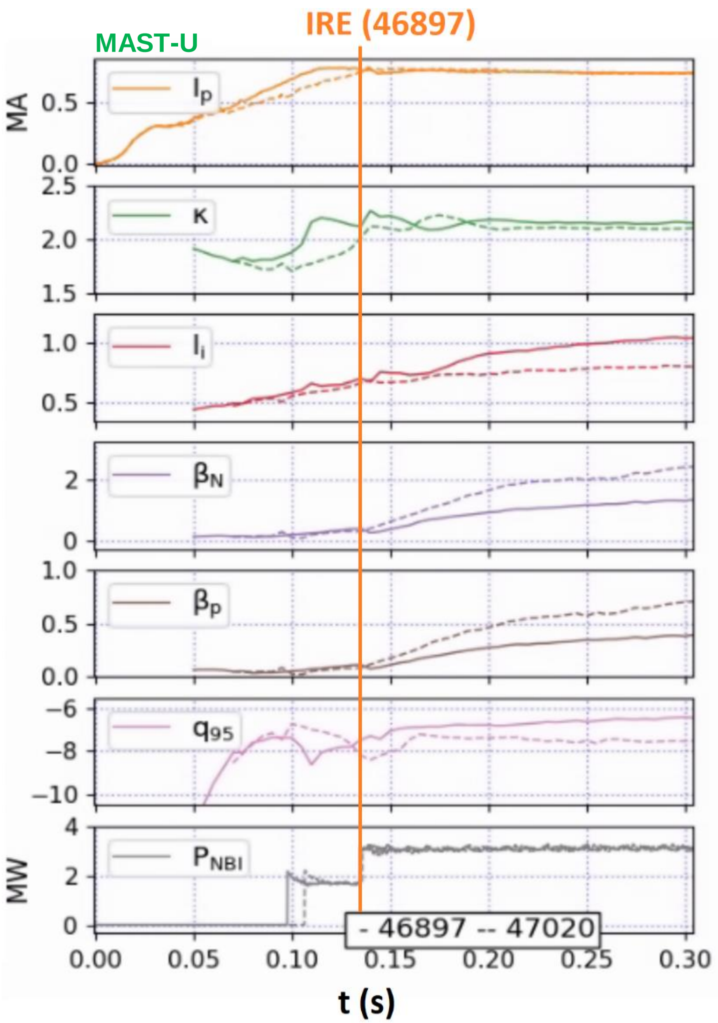
.. DCEs may be located in different parts (limits) of the machine operation space as well

- Example of MAST-U 2021, selected plasma parameters calculated at the trigger event time of the particular DCE (4 most frequent DCEs):

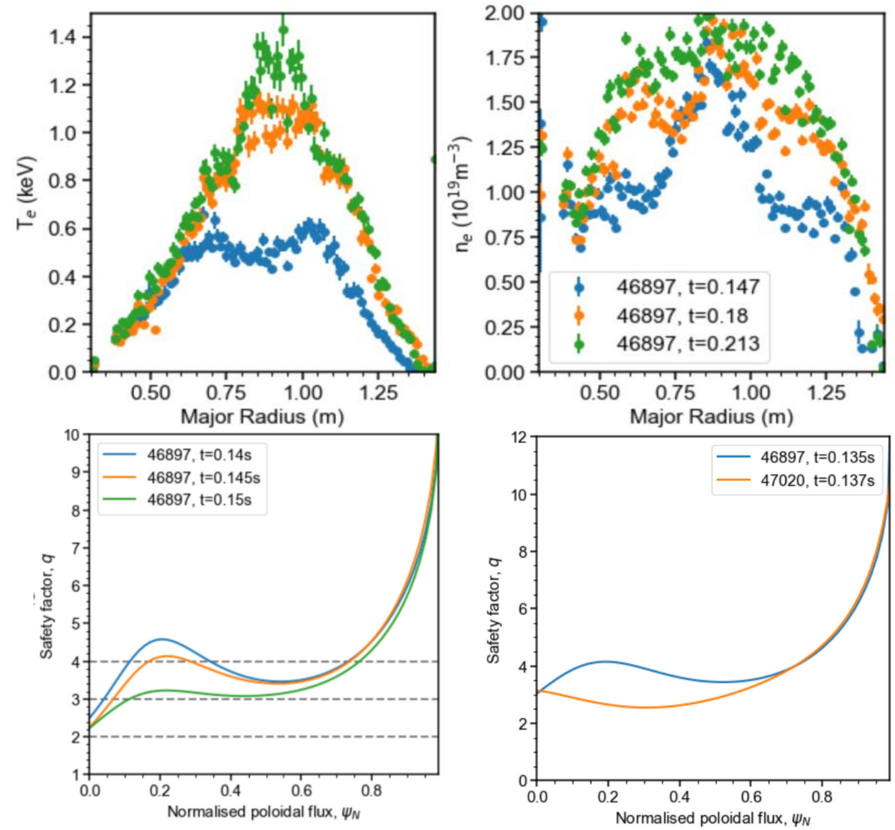


3 IREs in early I_p flat-top lead to less performant plasmas

- IREs have sudden and strong impact on plasma shape and profiles



unwanted shot elements



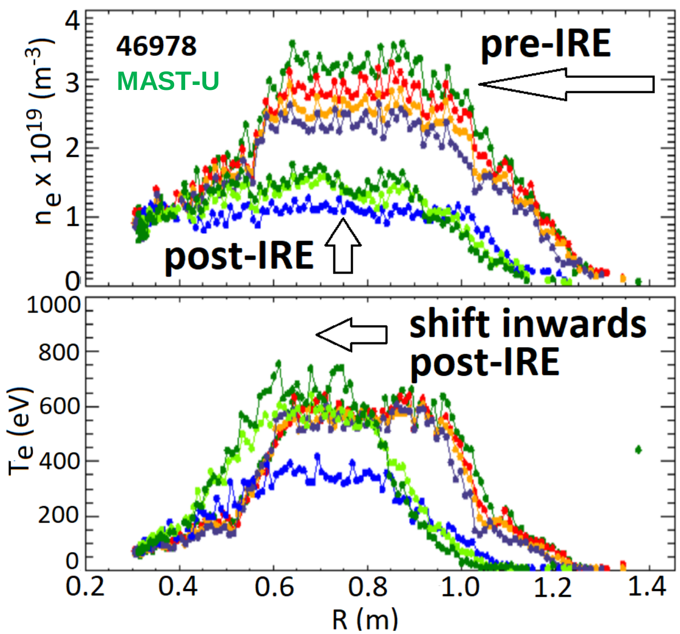
(S. Gibson, CCFE, EPS 2023 poster)

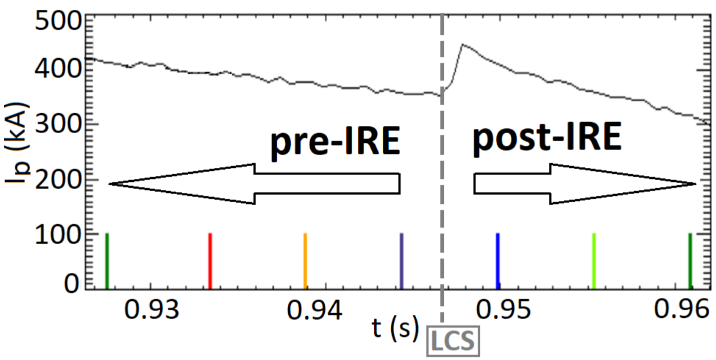
<- empirically, IREs eliminated in early FT by reducing I_p ramp-up rate

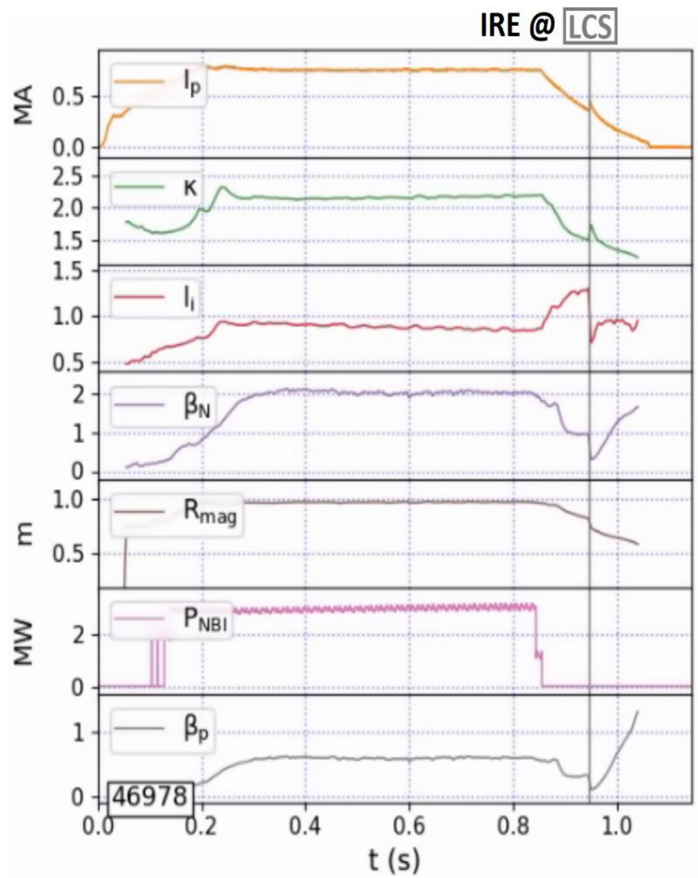
3 IREs in I_p ramp-down induce sudden variations in plasma shape and profiles (disruptions?)

- IREs have sudden and strong impact on plasma shape and profiles

<-> unwanted shot elements







<- empirically, IREs frequently located at LCS (I_p spike of largest amplitude)

<- some plasma parameters can recover pre-IRE state

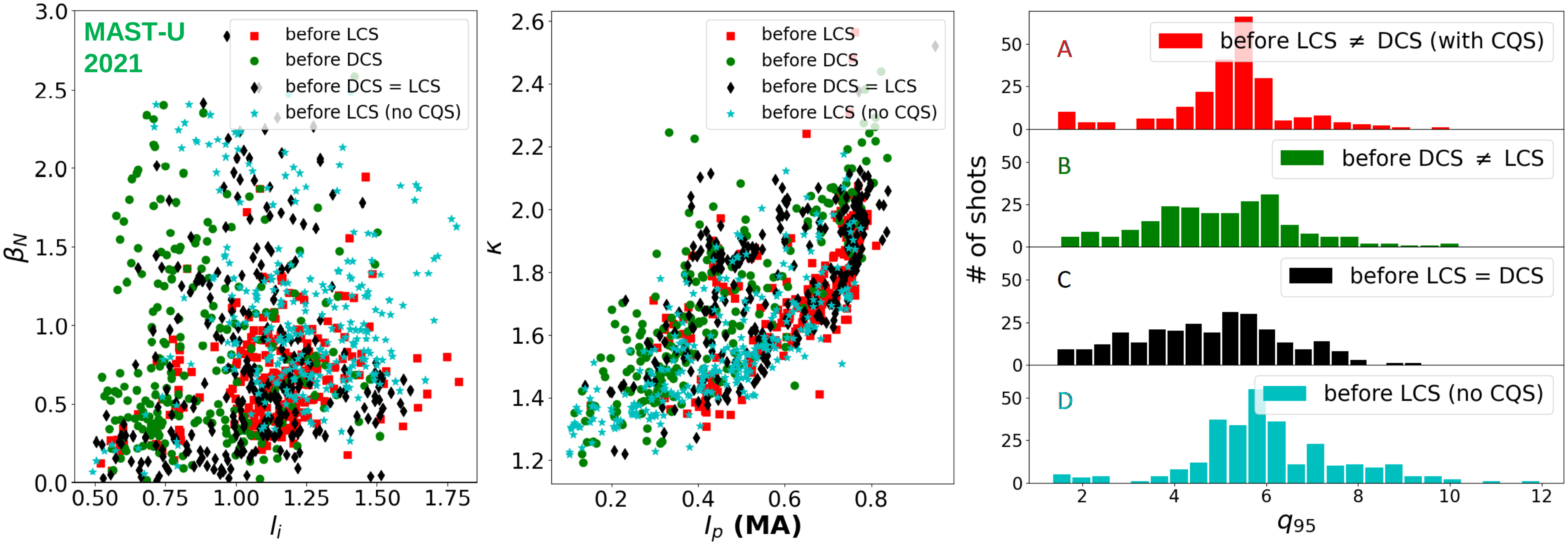
-> IREs generally considered non-disruptive

… but, can they induce a disruption?
… how to avoid them entirely?

Initial exploration of conditions for IREs onset (MAST-U)

❑ Several ‘spike’ scenarios:

A: LCS (likely an IRE) not imminently followed by a disruption
B: Current spike imminently followed by a disruption, spike of not the largest amplitude
C: LCS coinciding with DCS (can be IRE the disruption trigger?)
D: LCS in non-disruptive plasma



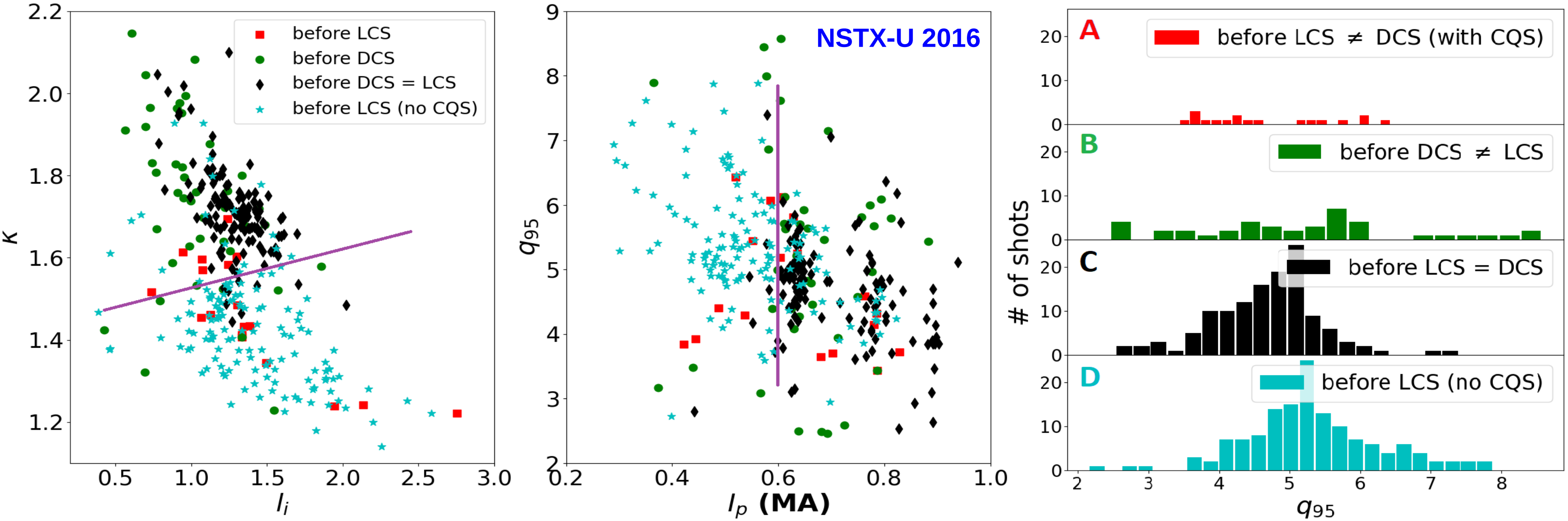
- A and D sensitive to $q_{95} \sim 5.5$
- Clear clustering of A-D groups within $\beta_N(l_i)$ and $\kappa(I_p)$ spaces ⟶ distinct plasma conditions likely promote different scenarios

3

Initial exploration of conditions for IREs onset (NSTX-U)

Several ‘spike’ scenarios:

- A: LCS (likely an IRE) not imminently followed by a disruption
- B: Current spike imminently followed by a disruption, spike of not the largest amplitude
- C: LCS coinciding with DCS (can be IRE the disruption trigger?)
- D: LCS in non-disruptive plasma



- C and D sensitive to $q_{95} \sim 5.3$
- Clear separation of (A,B)-(C,D) groups within $\kappa(l_i)$ and $q_{95}(I_p)$ spaces

$\longleftrightarrow$ distinct plasma conditions likely promote different scenarios

Summary

- DECAF code used to characterize several aspects of disruptions on a multi-device/year database of plasma shots
  - Binary disruption classifier based on current quench phase detection
  - Occurrence of disruptive chains of events capturing I_p and Z abnormalities and their location in the device operational space
  - Initial large-database survey of possible IRE triggering mechanisms
- Current quenches detected in majority of plasma shots, but device emergency and preprogrammed shot scenario may drive significant portion of disruptions
- Dominant DCEs can vary over time (following a device operation and/or configuration modification), disruption avoidance strategies must be adjusted
- DCE trigger events located in different parts of operational space
- Details of the equilibrium profiles and role of external heating and momentum input will be further studied in the context of IREs
  - Ultimate goal: understanding of IREs onset, their elimination in plasma shots

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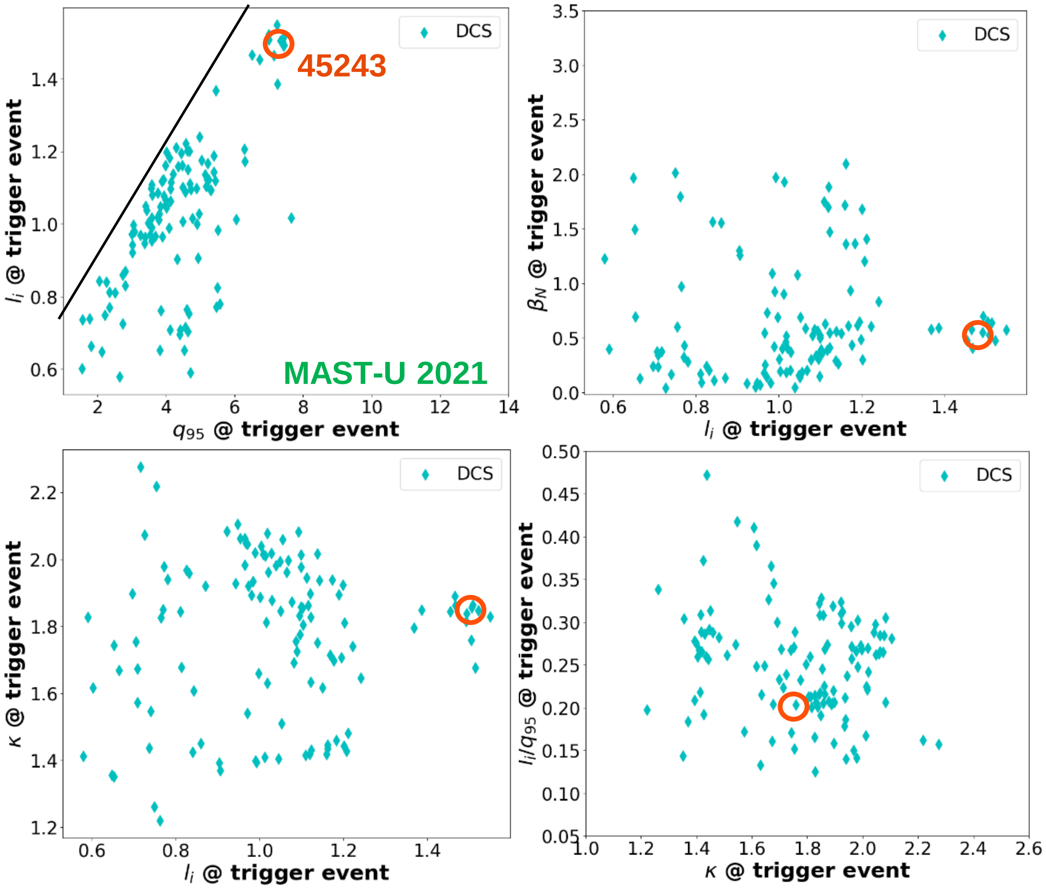
Trigger events located in different parts of device operational space (MAST-U example)

- DCEs grouped per trigger driven by different destabilizing mechanism

$l_i \sim 0.16 q_{95} + 0.52$ **(1)**



<u>Example of DCS trigger event:</u>

-> DCS frequent along $\kappa(l_i)$ stability limit & at highest values of l_i/q_{95} ratio

-> DCS points in concentrated in $l_i(q_{95})$ space along the stability limit (1)