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DECAF code cross-device investigation of disruption categorization and timing indicated by variations in the plasma current and vertical position

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Disruption detection and timing is essential to construct databases of disruptive plasma shots

- ❑ Plasma disruptions need to be avoided - or ultimately mitigated - in next-step tokamaks (ITER)

- ❑ Disruption forecasters evaluate their success rate w.r.t. timing of the disruption onset
  - ❑ Distinguishing between disruptive and non-disruptive shots is a first step in constructing database of disruptive plasma shots needed for

- ❑ Starting with all plasma shots, we need to know:
  - Did the plasma disrupt? Answer: yes/no
  - If yes, **when?**

- ❑ Cross-device, cross-research groups unified definitions of disruption timing can help in the search for best performance disruption forecasters
  - ❑ Here, disruption detection and timing is studied on multi-year, multi-device set of plasma shots

search for

Plasma current and vertical position abnormal waveforms can serve as disruption indicators

- ❑ Two usual paths to ‘*natural*’ loss of plasma confinement:

A

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**

B

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

- ❑ In both, ‘abnormal’ (= deviating from target) waveforms of I_p and *Z* can indicate an ongoing disruption

- ❑ Furthermore, I_p and *Z* are routinely monitored and feedback controlled in tokamaks
  - ❑ suitable candidates for widely applicable disruption detection and timing

- ❑ Plus, plasma can be *intentionally* terminated through DMS (firing MGI/SPI) or fast shut down

C → **Intentional plasma shut down** results in* → VDE/thermal quench/current quench

* It can be initiated while any of those already happened/ing!

- ❑ Current quench phase present (and easily detectable through I_p measurements in real-time) in all scenarios
  - ❑ suitable candidate for binary decision on whether plasma disrupted or not

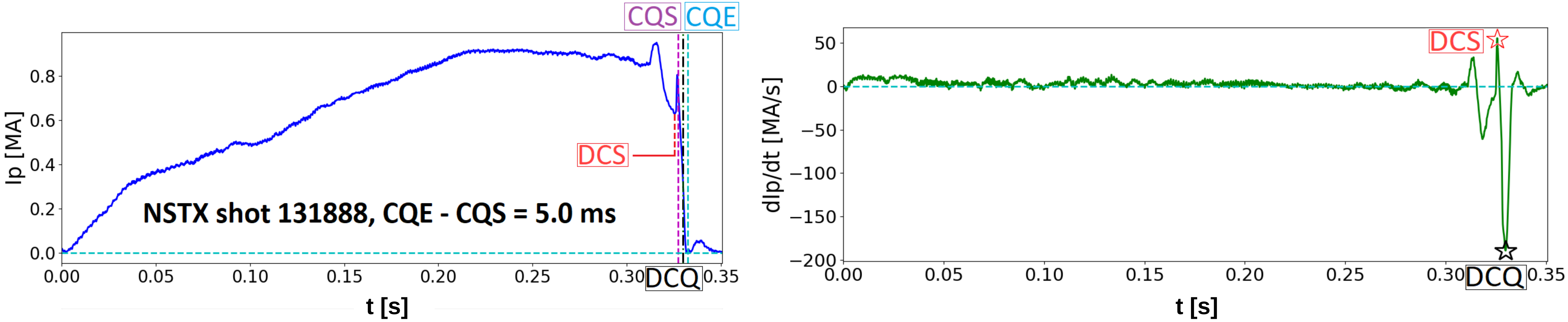
Z .. vertical position of magnetic axis; DMS .. disruption mitigation system
MGI .. massive gas injection; SPI .. shattered pellet injection

Abnormal I_p and Z waveforms captured in DECAF events/flags

- Abnormal waveforms captured in DECAF events/flags
  - Z: VDE – composed of
    - a) $abs(Z)$ displaced above threshold
    - b) dZ/dt exceeding threshold
    - c) $abs(Z) \cdot dZ/dt$ exceeding threshold
  - I_p: IPR – ratio of target to experimental I_p exceeding threshold
    - **DCQ** – dominant current quench, largest negative rate of change of I_p
    - **CQS**/**CQE** – current quench range, located around DCQ, delimited by start and end point flags
    - **DCS** – dominant current spike, largest positive rate of change of I_p

+ USD event - uncontrolled plasma shut down initiated by device protection system (KSTAR only)

→ example of events captured through variation of $\mathrm{d}I_p/dt$



Abnormal I_p and Z waveforms studied on multi-year and multi-device plasma shot database with DECAF – examples of DCEs

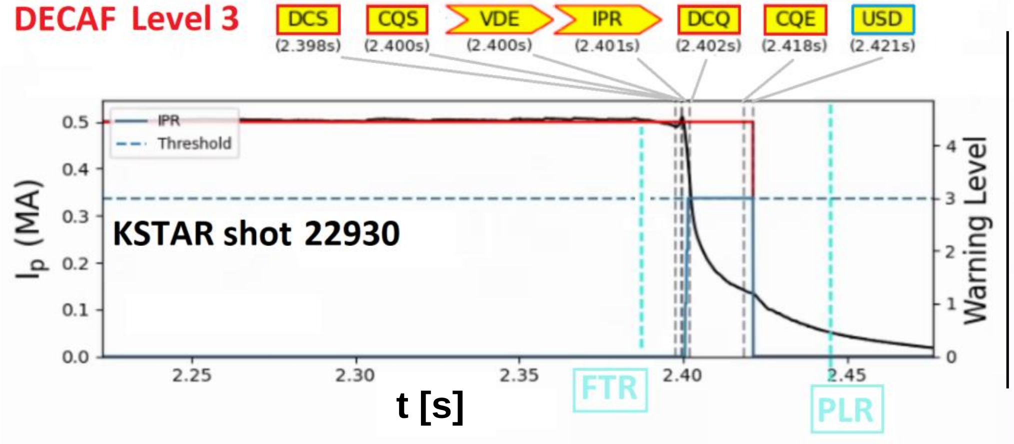
- DECAF run set up to detect abnormal I_p and Z in full year experimental campaigns:
  - 2021 MAST-U
  - 2009 NSTX
  - 2019-21 KSTAR (search for eventual year-to-year changes)

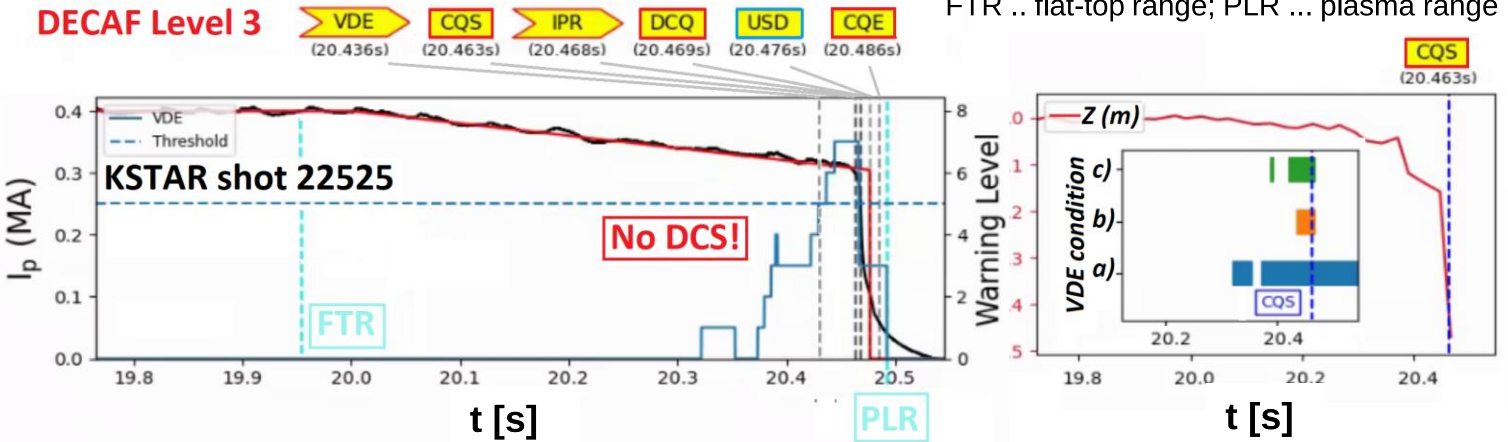
} cross-device survey

→ detected events constitute disruptive chain of events (DCE)

Examples of group A (thermal quench -> DCS first) and group B (VDE first) DECAF DCEs

FTR .. flat-top range; PLR ... plasma range



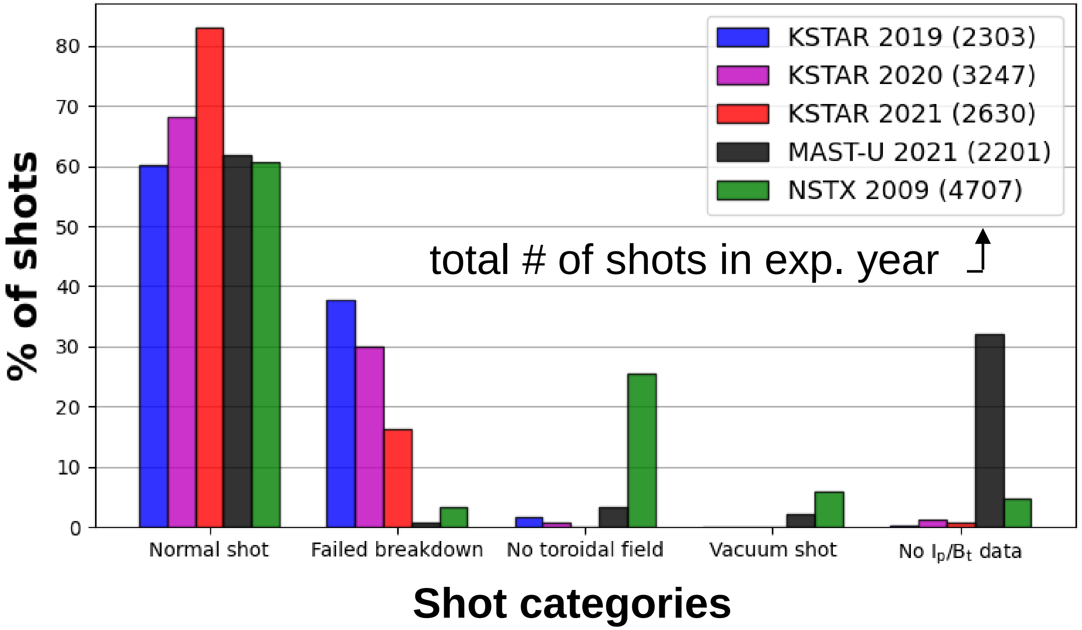


- In all group scenarios, CQS delimits the initiation of an irreversible phase of discharge that leads to plasma termination

  -> CQS considered as the binary disruption indicator (CQS detected -> plasma disrupted)

CQS as a binary indicator of (non)disruptive shots

- Plasma shot has to fall into ‘Normal shot’ category* to proceed to DCE analysis:



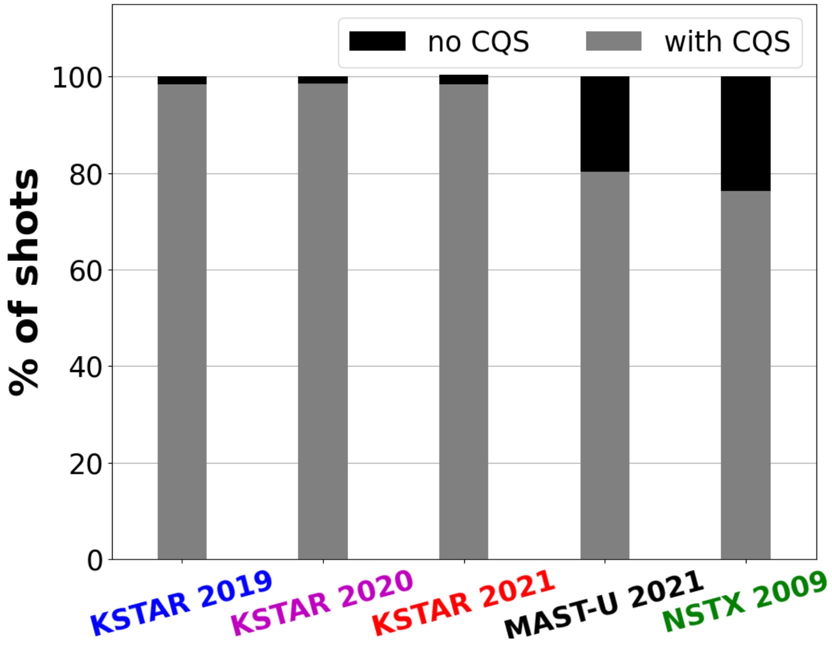
total # of shots in exp. year

- Out of all Normal shots some didn’t have all data for DCE analysis, final counting of shots with DCE:

KSTAR 2019:	1365	MAST-U 2021:	1040
KSTAR 2020:	2200	NSTX 2009:	2564
KSTAR 2021:	2175		

*See extra slides for more information about DECAF shot categorization

- Counting of shots with/without CQS:



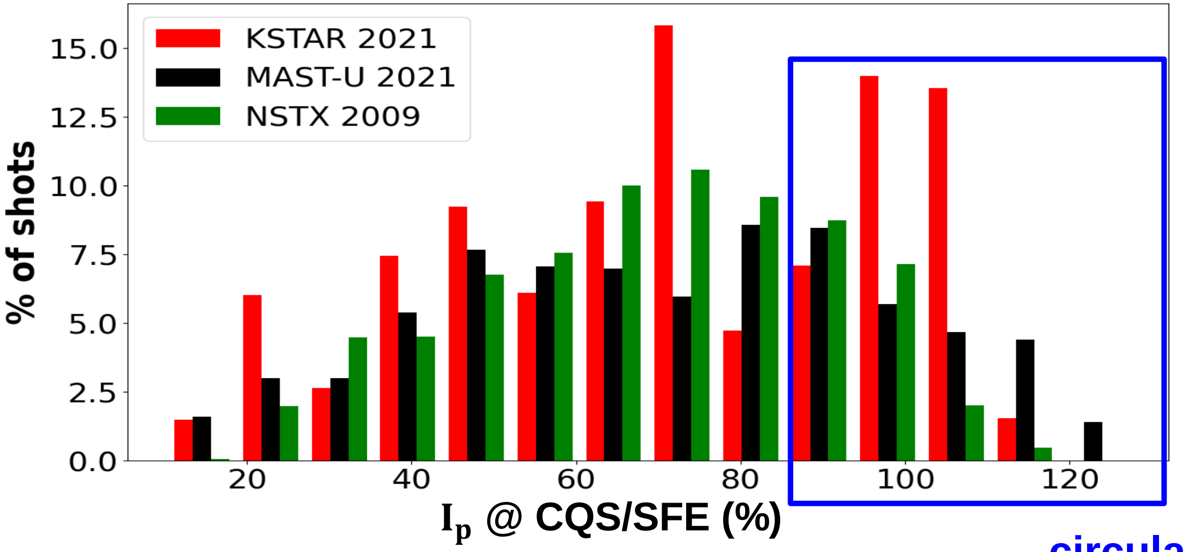
→ KSTAR has largest % of CQS shots, but USD is applied in > 99 % cases in all years

→ CQS precedes USD in ~ [87, 89, 69] % of cases in 2019-21

- In the following, focus is on cases with CQS and shots that reached stable flat-top phase:

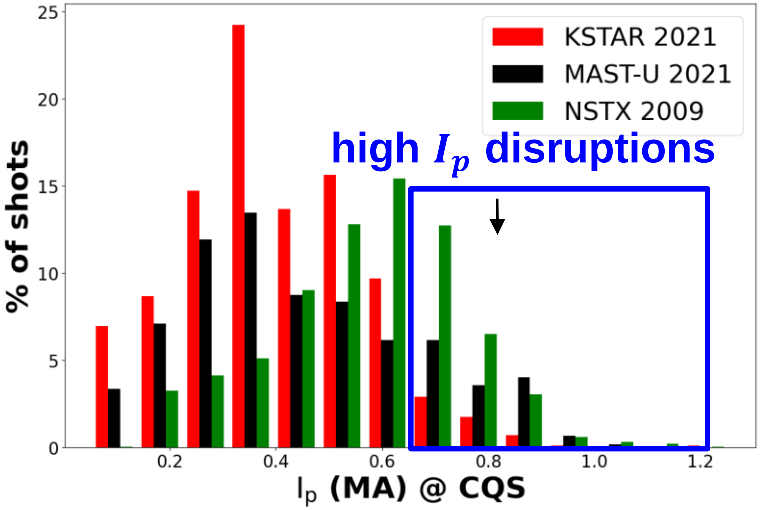
KSTAR 2019:	**1220**	MAST-U 2021:	**808**
KSTAR 2020:	**1950**	NSTX 2009:	**1881**
KSTAR 2021:	**2004**		

Databases of disruptive shots of interest can be constructed with knowledge of CQS timing

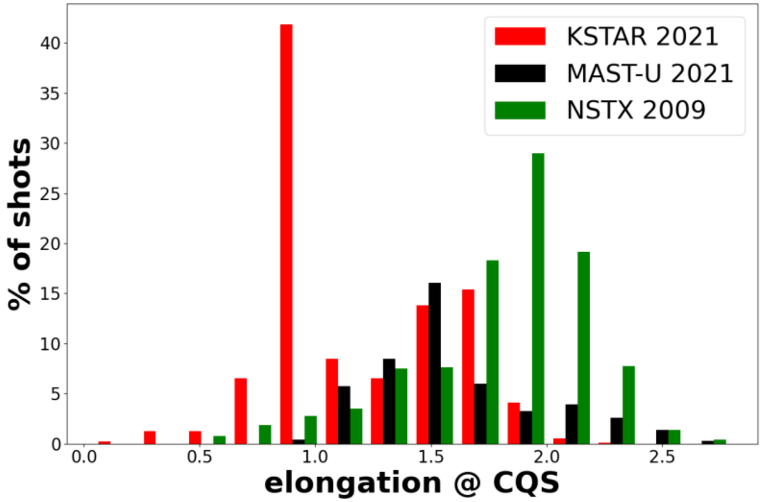


← **region of flat-top disruptions, % of CQS near flat-top:**

KSTAR 2019:	**33.8%**	MAST-U 2021:	**19.3%**
KSTAR 2020:	**36.0%**	NSTX 2009:	**13.5%**
KSTAR 2021:	**32.9%**		

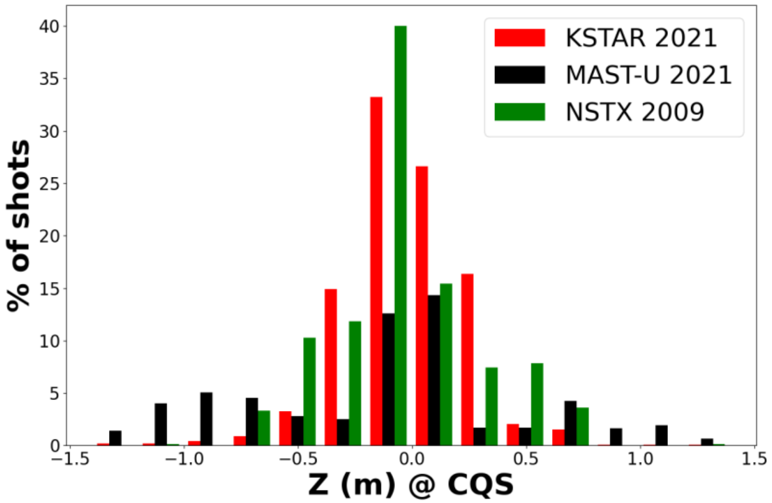


circular ← → **elongated plasmas at CQS**



large % of plasma vertically displaced at CQS

← →



Most frequent DCEs reveal usual disruption scenario

KSTAR 2019

	Shots with DCE #	Shots with DCE %
VDE → CQS → IPR → USD	79	21.2
VDE → DCS → CQS → IPR → USD	45	12.1
CQS → IPR → VDE → USD	37	9.9
DCS → CQS → IPR → VDE → USD	35	9.4
	Total:	**52.6**

KSTAR 2020

	#	%
DCS → CQS → IPR → VDE → USD	140	18.6
VDE → CQS → IPR → USD	126	16.7
VDE → DCS → CQS → IPR → USD	113	15.0
CQS → IPR → VDE → USD	90	12.0
	Total:	**59.3**

KSTAR 2021

	#	%
DCS → CQS → IPR → VDE → USD	91	14.9
VDE → DCS → CQS → IPR → USD	72	11.8
VDE → CQS → IPR → USD	70	11.4
CQS → IPR → VDE → USD	53	8.7
DCS → VDE → CQS → IPR → USD	53	8.7
	Total:	**53.5**

→ Dominant VDE-initiated DCE in 2019 surpassed by dominant DCS-initiated DCE in next years

MASTU 2021

	Shots with DCE #	Shots with DCE %
DCS → CQS → IPR	62	19.3
DCS → VDE → CQS → IPR	56	17.4
VDE → DCS → CQS → IPR	40	12.4
VDE → IPR → CQS	30	9.3
	Total:	**58.4**

→ DCS-initiated DCEs most frequent

NSTX 2009

	#	%
VDE → IPR → CQS	320	17.8
IPR → VDE → CQS	205	11.4
VDE → CQS → IPR	195	10.8
VDE → DCS → IPR → CQS	128	7.1
DCS → IPR → CQS	119	6.6
	Total:	**53.7**

→ VDE-initiated DCEs most frequent

- Most frequent (≥ 50 % of cases) DCEs
- # of shots reduced w.r.t. slide 6 → only shots with Z and $I_{p,req}$ with data points at least 1 ms after CQS considered

Delay of events/flags within DCEs is event/flag-dependent

		Shots with DCE %
KSTAR 2019	**VDE $\xrightarrow{13}$ CQS $\xrightarrow{2}$ IPR $\xrightarrow{11}$ USD**	**21.2**
	VDE $\xrightarrow{19}$ DCS $\xrightarrow{3}$ CQS $\xrightarrow{2}$ IPR $\xrightarrow{18}$ USD	12.1
	CQS $\xrightarrow{3}$ IPR $\xrightarrow{2}$ VDE $\xrightarrow{8}$ USD	9.9
	DCS $\xrightarrow{3}$ CQS $\xrightarrow{5}$ IPR $\xrightarrow{3}$ VDE $\xrightarrow{16}$ USD	9.4
KSTAR 2020	**DCS $\xrightarrow{3}$ CQS $\xrightarrow{3}$ IPR $\xrightarrow{4}$ VDE $\xrightarrow{18}$ USD**	18.6
	VDE $\xrightarrow{13}$ CQS $\xrightarrow{2}$ IPR $\xrightarrow{11}$ USD	16.7
	VDE $\xrightarrow{12}$ DCS $\xrightarrow{3}$ CQS $\xrightarrow{2}$ IPR $\xrightarrow{18}$ USD	15.0
	CQS $\xrightarrow{2}$ IPR $\xrightarrow{3}$ VDE $\xrightarrow{10}$ USD	12.0
KSTAR 2021	**DCS $\xrightarrow{6}$ CQS $\xrightarrow{3}$ IPR $\xrightarrow{4}$ VDE $\xrightarrow{6}$ USD**	14.9
	VDE $\xrightarrow{8}$ DCS $\xrightarrow{3}$ CQS $\xrightarrow{5}$ IPR $\xrightarrow{11}$ USD	11.8
	VDE $\xrightarrow{9}$ CQS $\xrightarrow{2}$ IPR $\xrightarrow{8}$ USD	11.4
	CQS $\xrightarrow{2}$ IPR $\xrightarrow{3}$ VDE $\xrightarrow{4}$ USD	8.7
	DCS $\xrightarrow{10}$ VDE $\xrightarrow{3}$ CQS $\xrightarrow{2}$ IPR $\xrightarrow{10}$ USD	8.7

		Shots with DCE %
MASTU 2021	DCS $\xrightarrow{2}$ CQS $\xrightarrow{4}$ IPR	19.3
	DCS $\xrightarrow{4}$ VDE $\xrightarrow{6}$ CQS $\xrightarrow{1}$ IPR	17.4
	VDE $\xrightarrow{4}$ DCS $\xrightarrow{2}$ CQS $\xrightarrow{1}$ IPR	12.4
	VDE $\xrightarrow{12}$ IPR $\xrightarrow{2}$ CQS	9.3
NSTX 2009	VDE $\xrightarrow{10}$ IPR $\xrightarrow{5}$ CQS	17.8
	IPR $\xrightarrow{14}$ VDE $\xrightarrow{10}$ CQS	11.4
	VDE $\xrightarrow{10}$ CQS $\xrightarrow{1}$ IPR	10.8
	VDE $\xrightarrow{5}$ DCS $\xrightarrow{6}$ IPR $\xrightarrow{4}$ CQS	7.1
	DCS $\xrightarrow{5}$ IPR $\xrightarrow{4}$ CQS	6.6

- Timing in between events/flags within DCEs in form median (ms)

→ shortest delay in DCE follows DCS and CQS

→ delay prior USD shortened in 2021 KSTAR

Most frequent DCEs located in different parts of plasma parametric space

- Basic ‘natural’ disruption groups A (thermal quench → ‘DCS first’) and B (‘VDE first’) initiated through different physics cause

lower β_p ..

higher elongation ..

  - Associated DCEs *might be* located in different parts of device plasma parametric space

    → If confirmed, it might be possible to, for a given plasma state, forecast the upcoming DCE and adjust the disruption mitigation (avoidance) action accordingly

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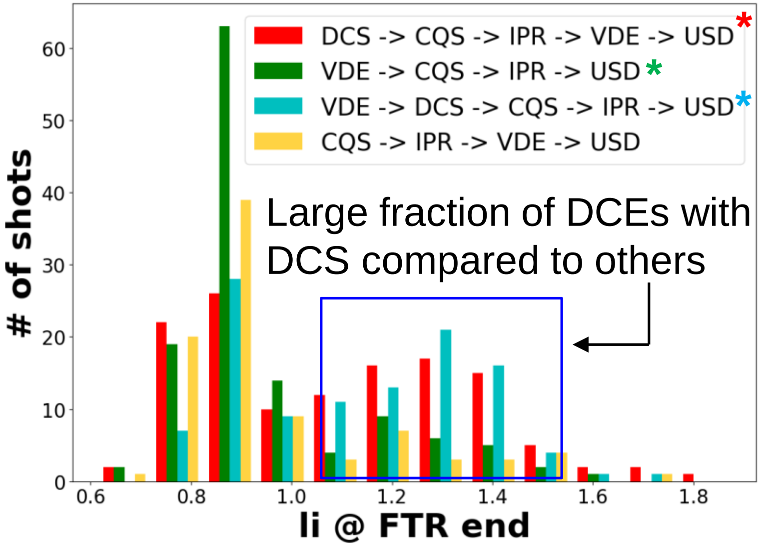
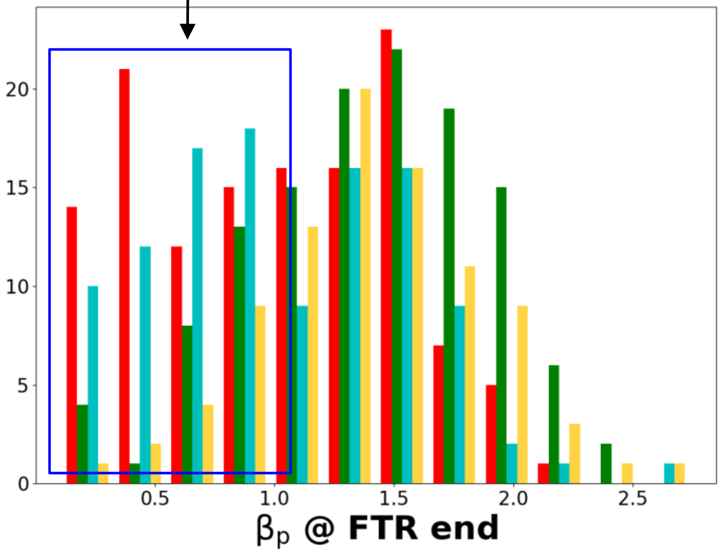
KSTAR 2020

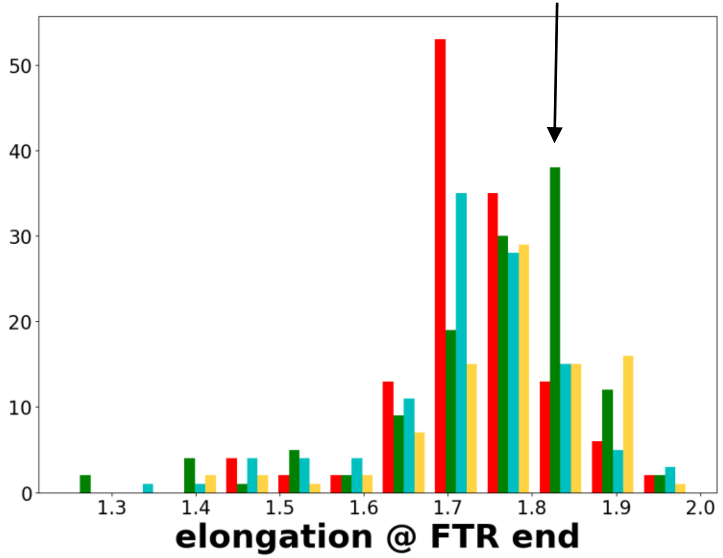


Large fraction of DCEs with DCS compared to others

Populated predominantly by DCE containing DCS



Pure ‘VDE first’ DCE peaks at ~ 1.85, others at lower values

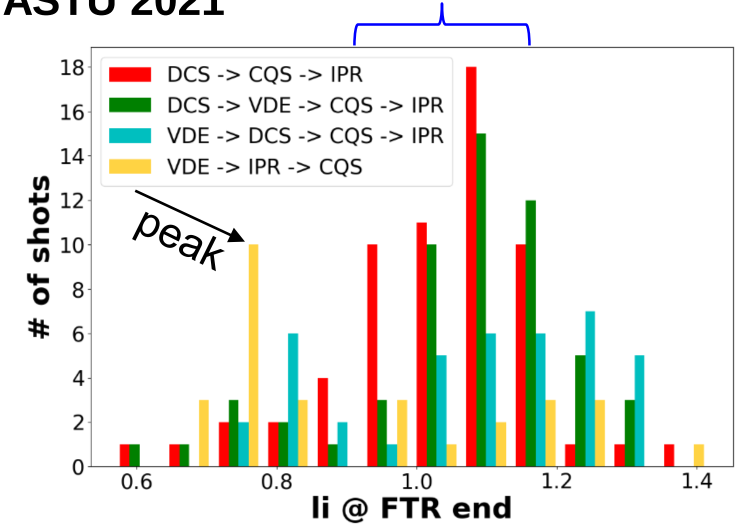


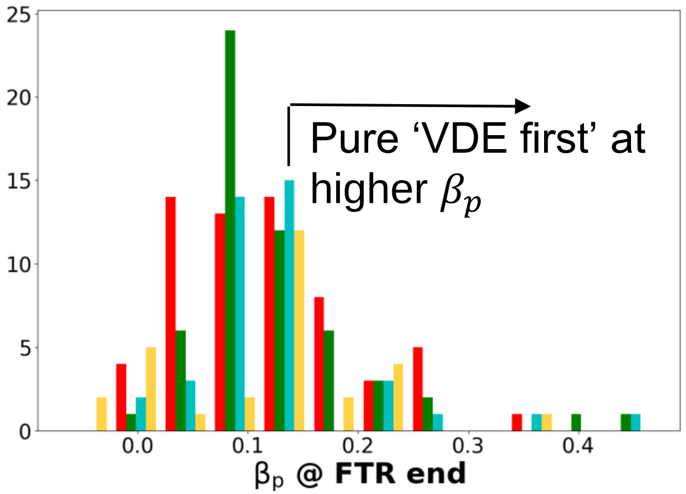
* Pure ‘VDE first’ scheme ** DCS included in DCE (*‘DCS first’)

Most frequent DCEs located in different parts of plasma parametric space

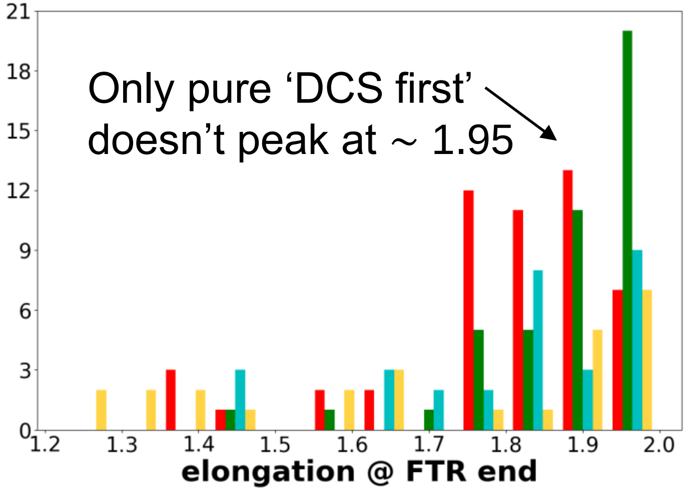
MASTU 2021

Pure ‘DCS first’ dominant location



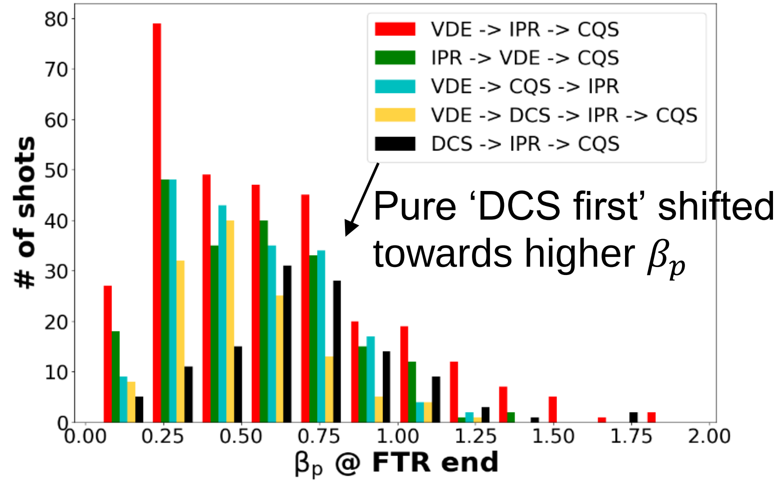


Pure ‘VDE first’ at higher β_p



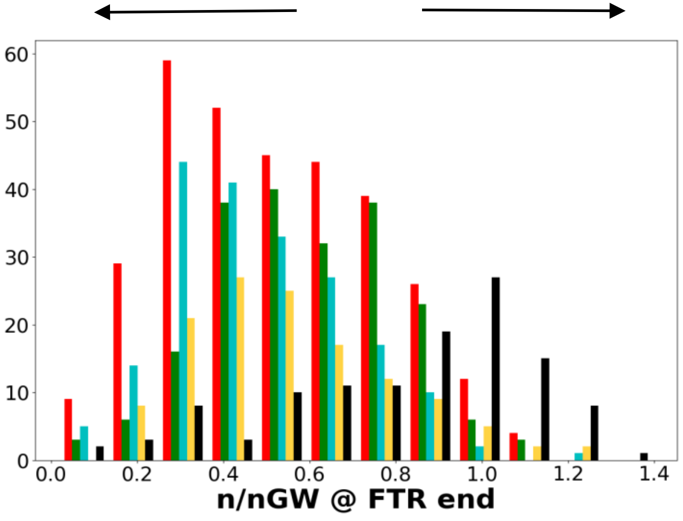
Only pure ‘DCS first’ doesn’t peak at ~ 1.95

NSTX 2009

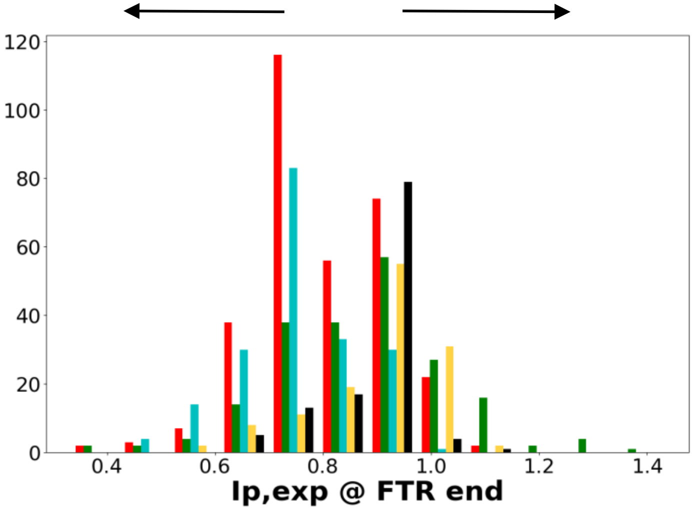


Pure ‘DCS first’ shifted towards higher β_p

VDE first vs. DCS first

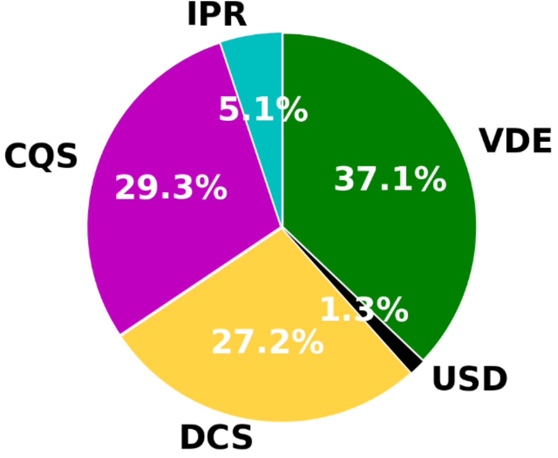


VDE first vs. DCS first

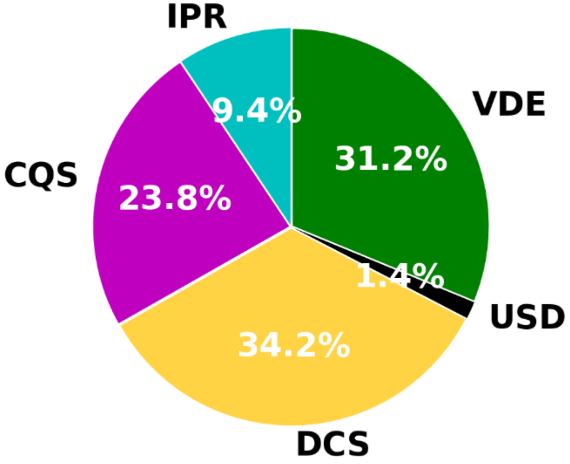


Percentage of first DCE events/flags reveal device’s dominant disruption scenario

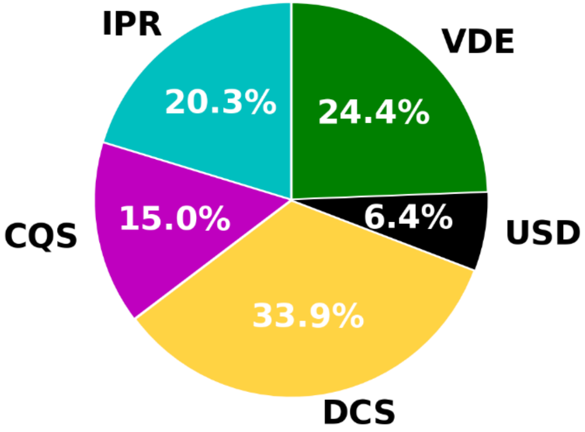
KSTAR 2019



KSTAR 2020



KSTAR 2021



→ USD initiates only minority of DCEs and it’s % increased significantly in 2021

→ VDE initiates ↘

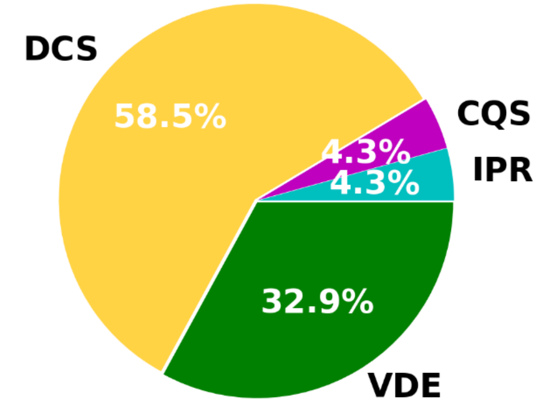
CQS ↘ DCEs over years

IPR ↗

→ IPR initiated DCEs might be caused by locked mode affecting I_p prior DCS

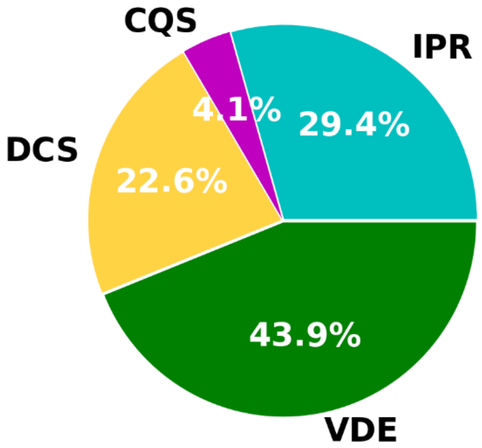
→ DCS initiated DCEs might be caused by kink-like MHD instability

MASTU 2021



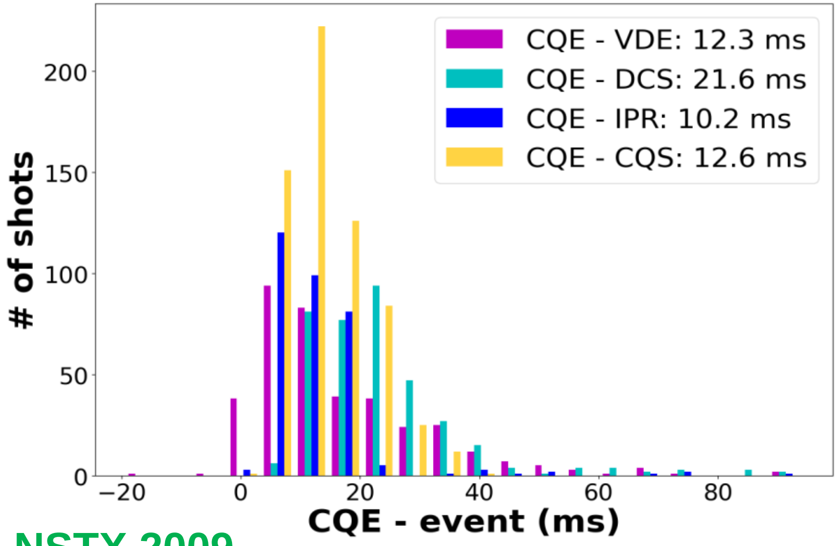
→ ‘DCS first’ dominant DCE

NSTX 2009

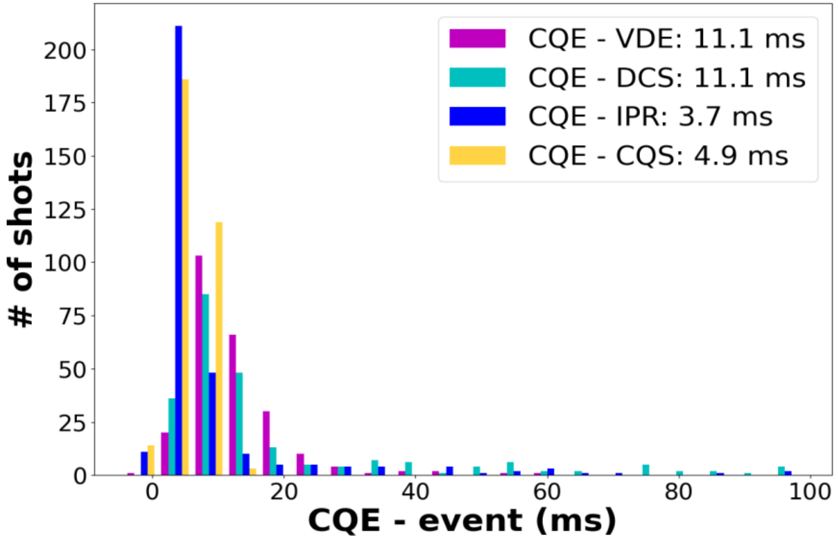


→ ‘VDE first’ in largest % of DCEs

Selection of the most suitable disruption timing indicator

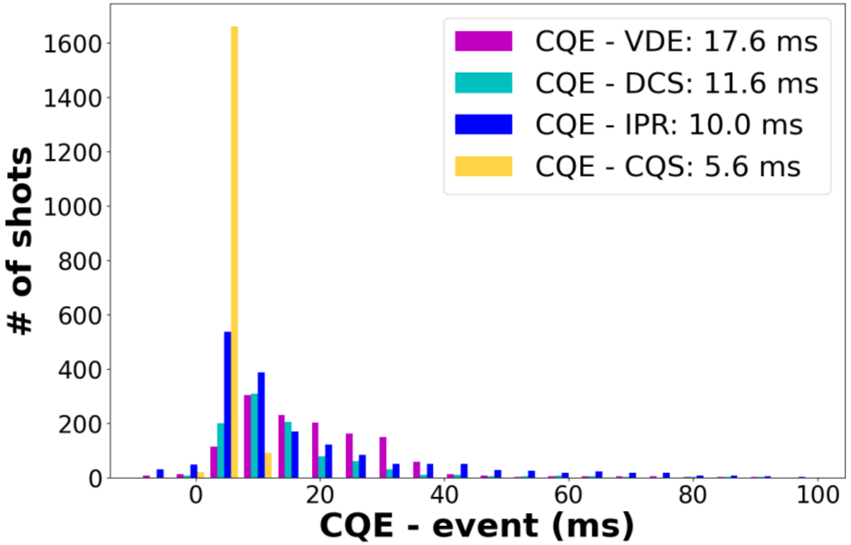


MASTU 2021

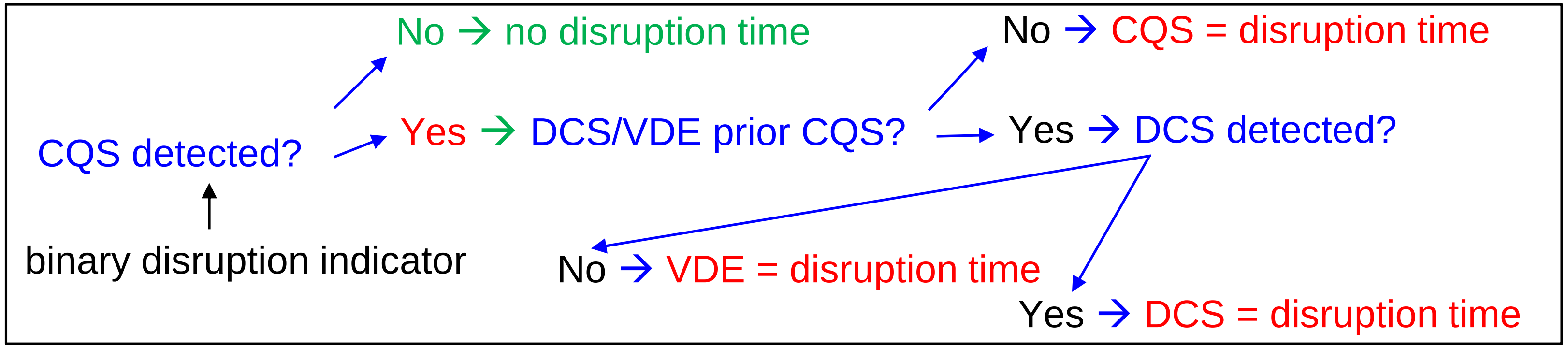


- ❑ Delay between CQE and here studied events/flags given in plot legend in form median(time) (ms)

NSTX 2009



- ❑ IPR often detected after CQS → unsuitable candidate for disruption timing
- ❑ Possible disruption timing scheme:



No → no disruption time

No → CQS = disruption time

CQS detected?

Yes → DCS/VDE prior CQS?

Yes → DCS detected?

binary disruption indicator

No → VDE = disruption time

Yes → DCS = disruption time

SUMMARY

- Reliable disruption indicator and timing are pre-requisite for construction of disruption databases of interest
  - Here, disruption indicator and timing surveyed through examination of abnormal I_p and Z waveforms
  - Analysis conducted on multi-device and multi-year shot databases (KSTAR 2019-22, MAST-U 2021, NSTX 2009)
- Start of the current quench phase is a suitable candidate for disruption binary indicator
  - Current quench phase is present in all disruptive chains of events
- Disruption onset time is proposed to follow a decision logic implementing a detection of a dominant current spike (indicator of a prior thermal quench) and vertical displacement event
- Disruptive chains of events are device-specific and locate themselves (to some extent) in certain regions of the plasma parametric spaces
- ! Special attention should be paid to intentionally induced disruptions, e.g. through firing DMS
  - Those cases should be treated with care when constructing disruptive databases as the disruption might not necessarily reflect the underlying disruption physics root cause
  - Information on intentional disruptions is missing in the here studied NSTX and MAST-U databases (next-step priority)

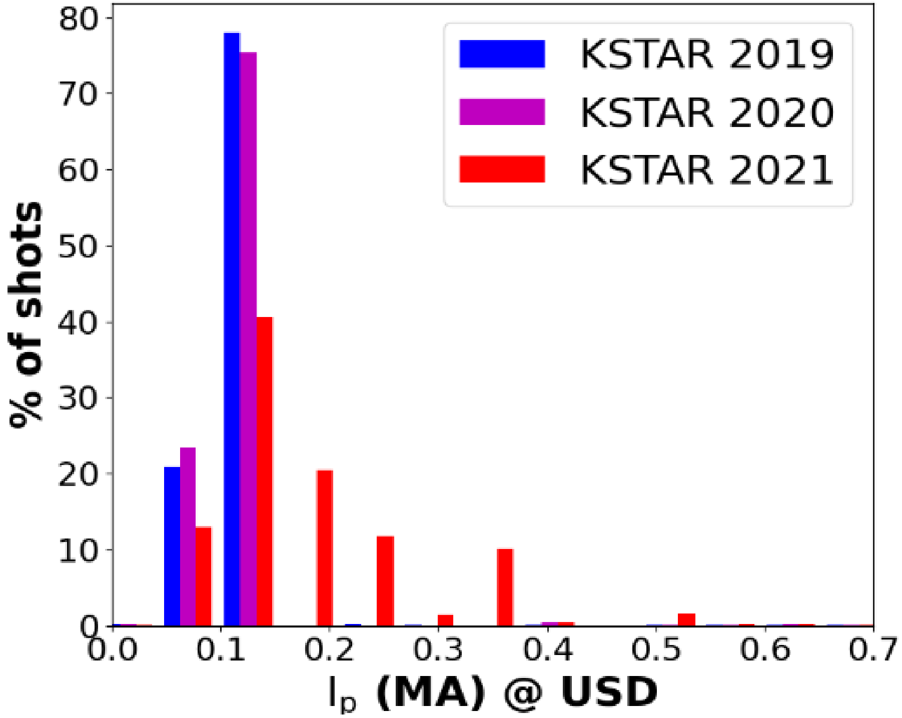
References

[1] S.A. Sabbagh et al. Proc.27th IAEA Fusion Energy Conference, Ahmedabad, India (2018)
[2] P.C. de Vries et al., Nuclear Fusion **56** (2015) 026007
[3] V. Klevarova et al., Fusion Engineering and Design **160** (2020) 111945
[4] A. Pau et al., Fusion Engineering and Design **125** (2017) 139-153
[5] S-H. Hahn et al., Fusion Engineering and Design **156** (2020) 111622
[6] M.H. Woo et al., Fusion Engineering and Design **128** (2018) 168-174
[7] P.C. de Vries et al., Nuclear Fusion **58** (2018) 056023

Extra slides

Statistics on uncontrolled shut down deployment in KSTAR 2019-20

- KSTAR has largest % of CQS shots, but USD is applied in > 99 % cases in all years
  - CQS precedes USD in ~ [87, 89, 69] % of cases in 2019-21



→ In 2019-20 USD mainly deployed at $I_p \leq 0.1$ MA

→ From 2021 also at higher I_p

Basic DECAF shot categorization

- DECAF accepts *any* shot, but interest is in shots that entered later stage of I_p ramp-up – only those are suitable for DECAF *event* analysis
  - Those shots are found through ‘categorization’ algorithm
    - Every shot sent to DECAF is assigned a basic discharge category
    - Basic engineering signals are needed for categorization

Order of evaluation

Category	**Toroidal field B_t**	**Plasma current I_p**
No I_p/B_t data	B_t OR I_p missing	
No toroidal field	$mean(\|B_t\|) < B_{t,vac}$	-
Vacuum shot	$mean(\|B_t\|) \geq B_{t,vac}$	$\|mean(I_p)\| < I_{p,vac}$
Failed breakdown	$mean(\|B_t\|) \geq B_{t,vac}$	$I_{p,vac} \leq \|mean(I_p)\| < I_{p,fizzle}$
Normal shot	Otherwise	

- Shot has to fall into ‘Normal shot’ category to be further processed by DECAF