EUROfusion

19th November 2024

RT-03 Strategies for disruption and run-away mitigation Discussion on proposals and allocated priorities

Discussion on proposals and allocated priorities

V. Igochine and A. Hakola

On behalf of WPTE TFLs
E. Tsitrone, N. Vianello, M. Baruzzo, D. Keeling, A. Hakola, V. Igochine, B. Labit

Research Topic Coordinators
O. Ficker, C. Reux, U. Sheikh

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Scientific objectives and machine time

Scientific Objectives
D1 Optimize disruption mitigations by single and multiple shattered pellet injection (SPI) at high plasma current and energy content in an all-metal environment to validate the ITER disruption mitigation strategy
D2 Quantify the required neon quantity for SPI into dilution cooled plasmas for sufficient thermal and current quench mitigation in ITER and the synchronisation requirements for dual deuterium/neon SPI in ITER
D3 Characterize/optimize the RE impact mitigation schemes and flushing effect with different deuterium injections techniques
D4 Determine the physics mechanisms generating run-away electrons in the current quench and in the plasma start-up phase
D5 Interpretative modelling of disruption mitigation dynamics (TSVV-8, TSVV-9) and prediction for ITER
D6 Quantify the radiation asymmetry during disruption mitigation with SPI
D7 Validate the modelling of image currents in conducting structures during disruption with halo current measurements

Allocation of discharges (tentative)

	AUG	TCV	MAST-U	WEST
2025	60	120	0	30

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Research Topic Coordinators:
O. Ficker, C. Reux, U. Sheikh, IO

Summary of the proposals

#	Title	Proponents
44	SPI injection velocity and fragment size effect on frad at AUG	Paul Heinrich
45	Characterisation of runaway electron transport in TCV	Joan Decker
46	Understanding fast electron generation during the TCV tokamak startup	Pedro Molina
47	Low-Z Benign Termination of RE beams on TCV, AUG and WEST	Umar Sheikh
48	Disruption study at ultra-low q95 < 2	Sergei Gerasimov
49	Exploring multiple injection schemes for disruption mitigation with SPI	Stefan Jachmich
50	Post-TQ mitigation with ITER-DMS-upper-port-like injection geometry	Stefan Jachmich
51	Effect of RMPs on material assimilation during SPI mitigated disruptions	Stefan Jachmich
52	Staggered SPI injection studies at AUG	Gergely Papp
53	SPI-triggered runaway electron scenario on AUG	Gergely Papp
54	Studying effect of neon content for the staggered SPI scheme	Ansh Patel
55	Identity experiments for benign termination of runaways on WEST AUG and TCV	Cédric Reux
56	Runaway electron position and shape control on WEST	Cédric Reux
57	Runaway impact studies on WEST	Cédric Reux
58	Use of ECRH to seed or mitigate runaway electrons on WEST	Cédric Reux
59	W influence on RE dynamics	Ondřej Ficker
60	Limiter-less RE beam compression at TCV	Ondřej Ficker
61	Application of 3D fields in synergy with SPI for runaway electron mitigation	Marco Gobbin
62	Runaway electrons at plasma start-up in WEST	Basilio Esposito
201	Measurements of runaways with FILD	J Poley

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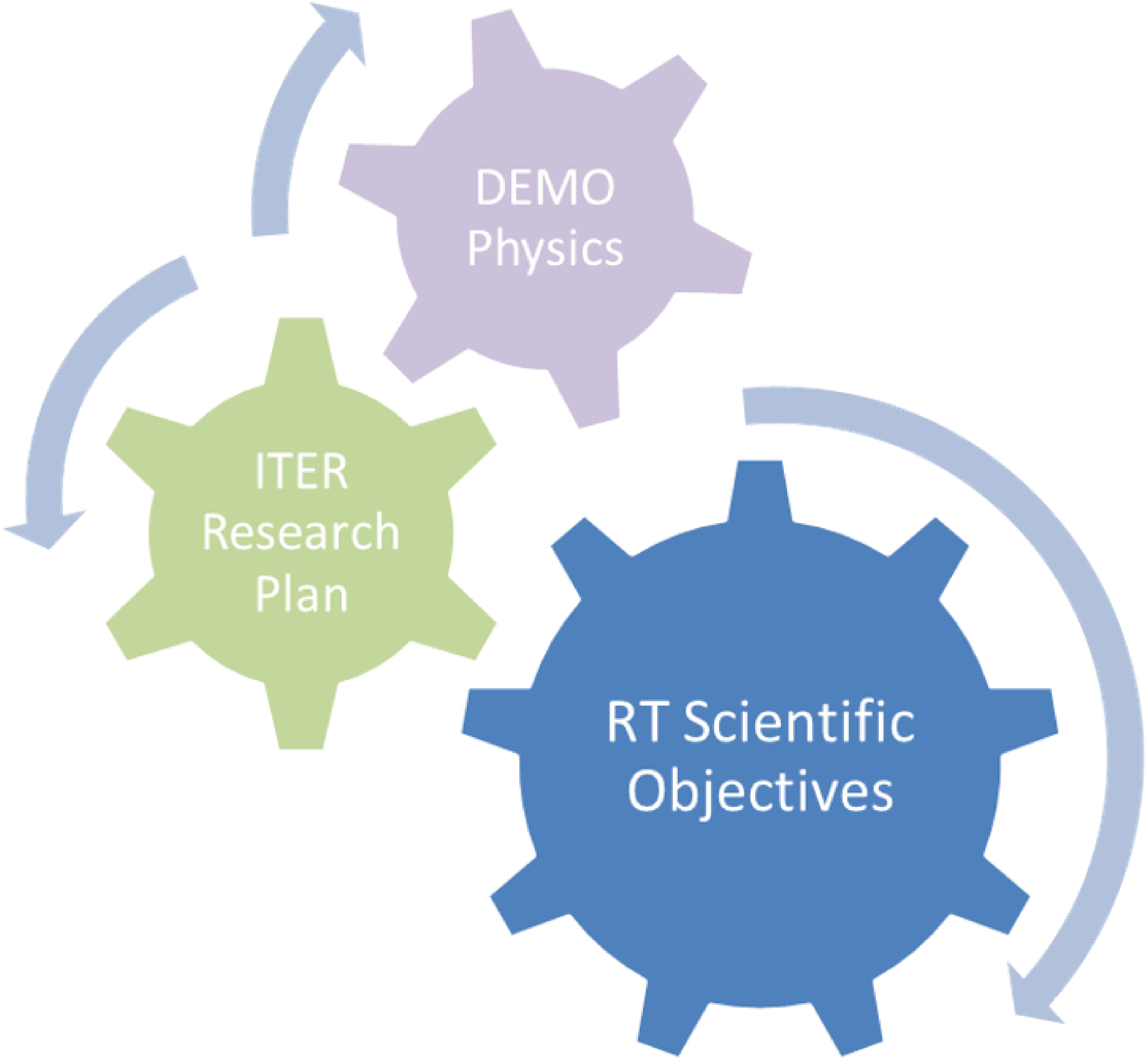
57	Run	Cédric Reux
58	Use	Cédric Reux
59	W ir	Ondřej Ficker
60	Limi	Ondřej Ficker
61	App	Marco Gobbin
62	Run	Basilio Esposito
201	Mea	J Poley

Tokamak	Request	Allocated (prelim.)	Overbooking factor
AUG	290	60	4.8
TCV	326	120	2.7
WEST	165	30	5.5

Prioritization scheme



All these aspects were considered by the TFLs when setting the priorities – according to the following scheme

P1: experimental priority

P2: will be done in 2025 if time allows after P1 experiments are completed

P3: back-up programme/not possible in 2025

PB: piggy-back experiment/pure analysis proposal

Proposal Evaluated according to the criteria:

Meeting the set Scientific Objectives

Size and feasibility

Team effort

Proposal's groups

All proposals were distributed in 4 groups:

- AUG SPI proposals
- Runaways during start-up
- Physics of runaway electrons
- Machine specific proposals

AUG SPI proposals

SPI injection velocity effect on f_{rad} at AUG

#44

- **Proponents and contact person:**
  Paul Heinrich, G. Papp et al. paul.heinrich@ipp.mpg.de
- **Sc. Background, Objectives & Strategy**
  - In the 2022 AUG shattered pellet injection (SPI) campaign a transition around 1.25-3% in trends are indicated but remains unexplained:
  •for **low** neon content (< 1.25%) large shards (low impact velocity component v_{perp}) are beneficial for radiating the energy (**blue** in (a) or in fig. (c))
  •for **high** neon content (> 3%) small shards seem beneficial (**orange** in (b) or in fig. (c))

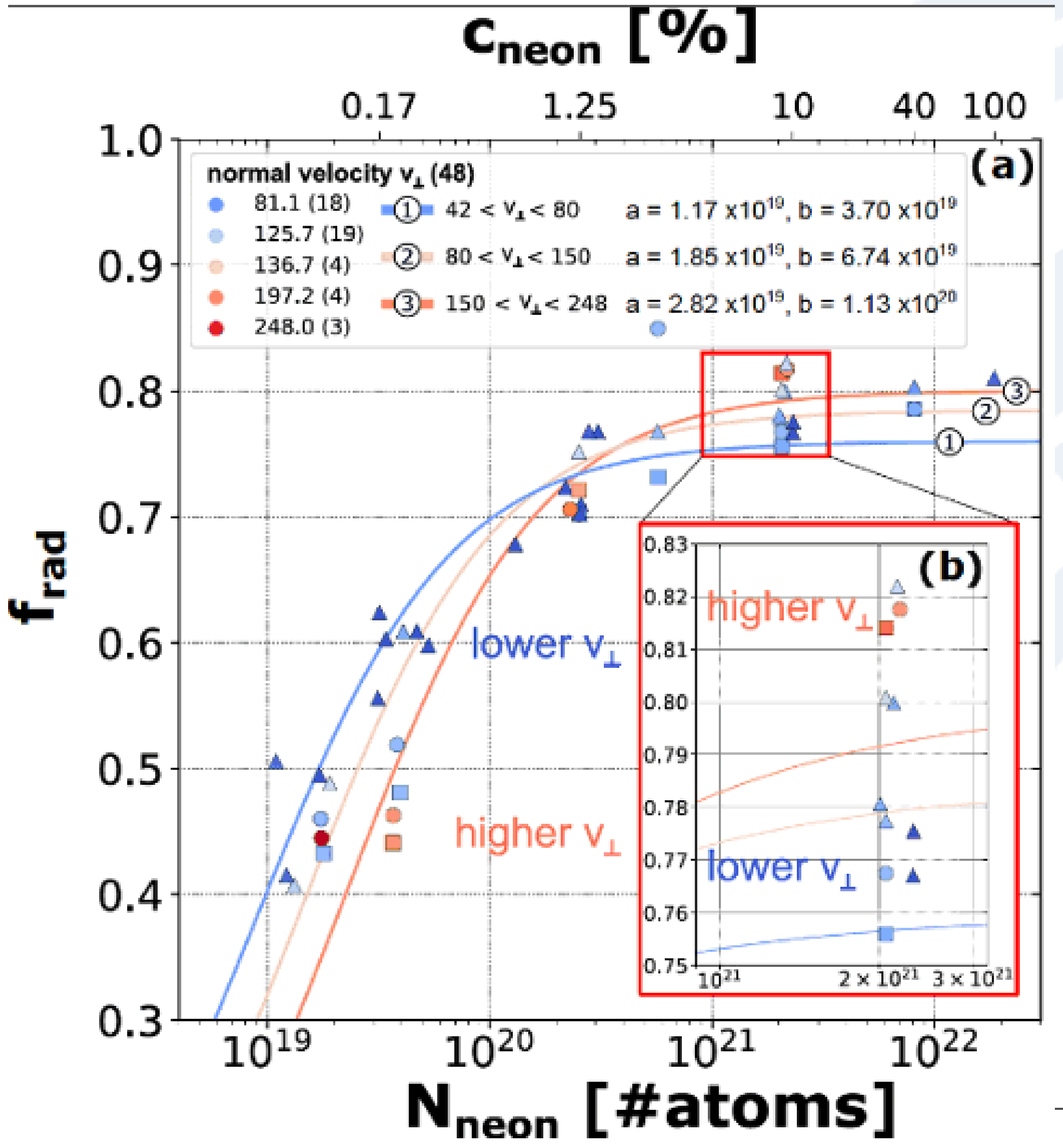
  ⇨ Investigation of the transition around 1.25-3% neon content @high v (target **A**)

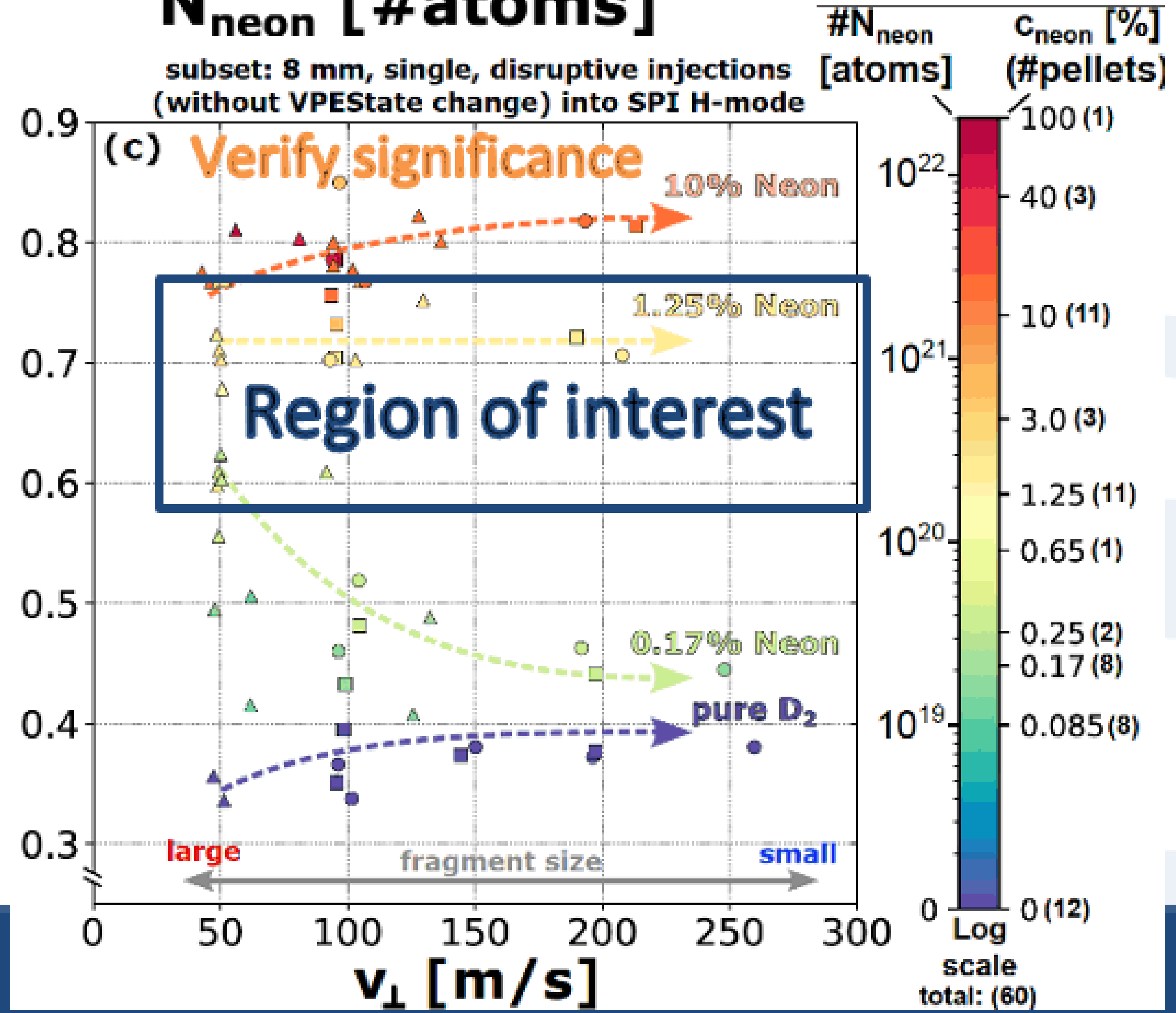
  ⇨ Verify trend for trace neon and especially high neon

- **Machine technical requirements**
  - 0.8MA @-1.8T, LSN with 10MW NBI + 3MW ECRH
  - Essential: SPI system, foil bolometers
  - Important: COO interferometry, fast visible cameras, Thomson scattering (burst mode), SXR

Proposed pulses

Device	# Pulses/Session	# Development
AUG	10 (min for scans) – 16 (desirable also for statistics – more than one pellet per critical parameter)	2-4 (in case of inconsistent target plasmas or stuck/broken/early pellets)





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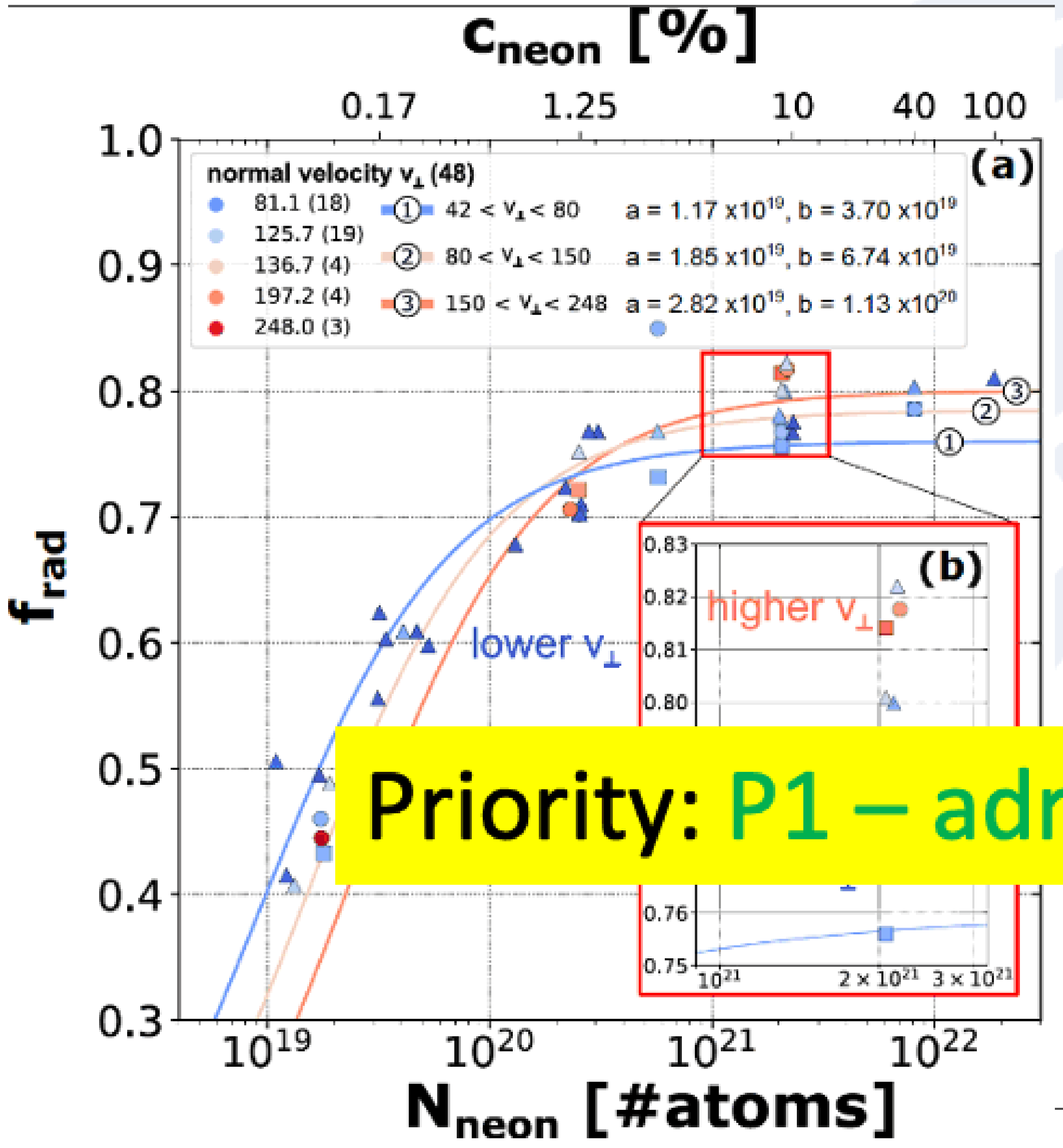
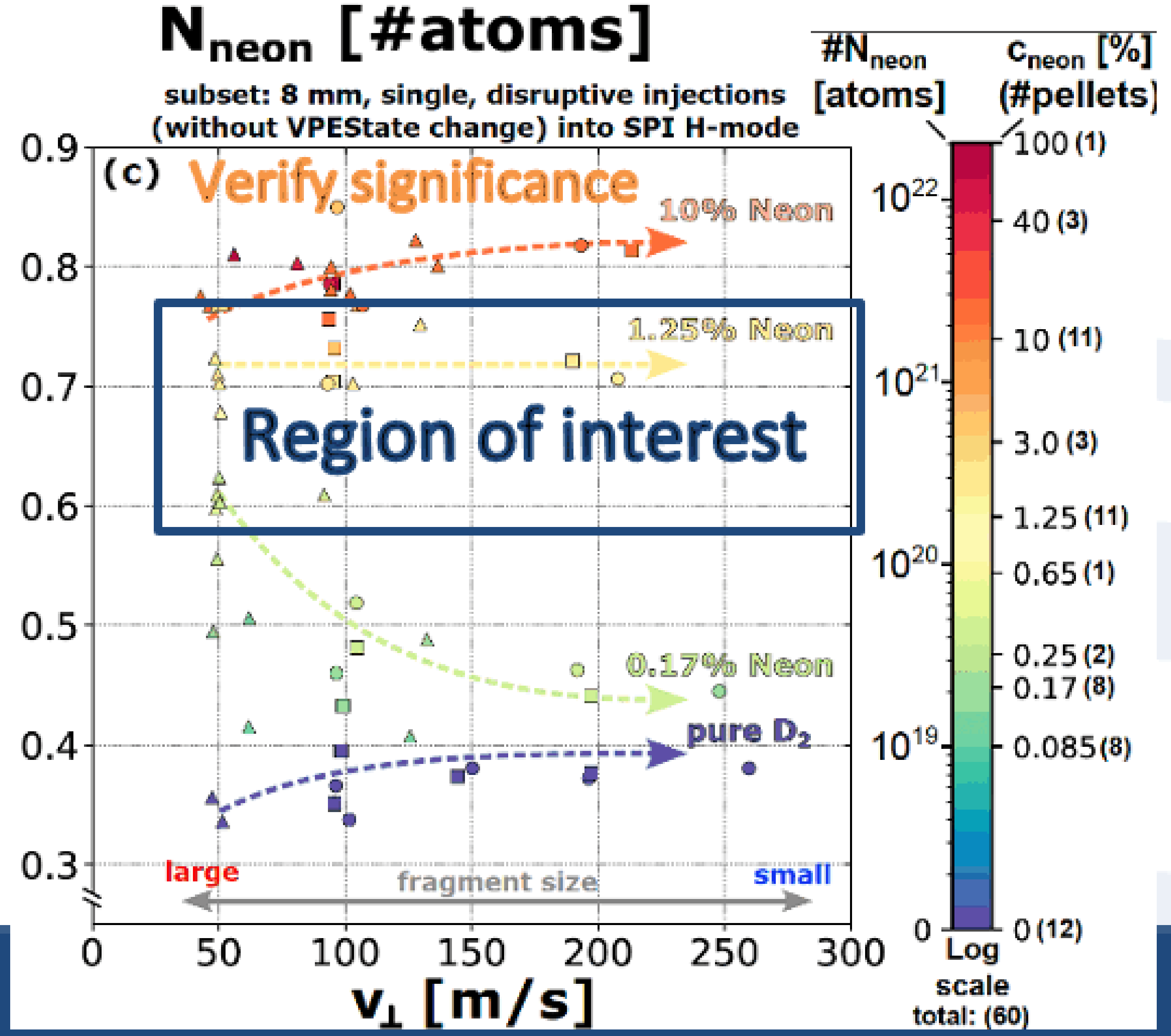


Priority: P1 – adresses D1 and D2



Exploring multiple injection schemes for disruption mitigation with SPI

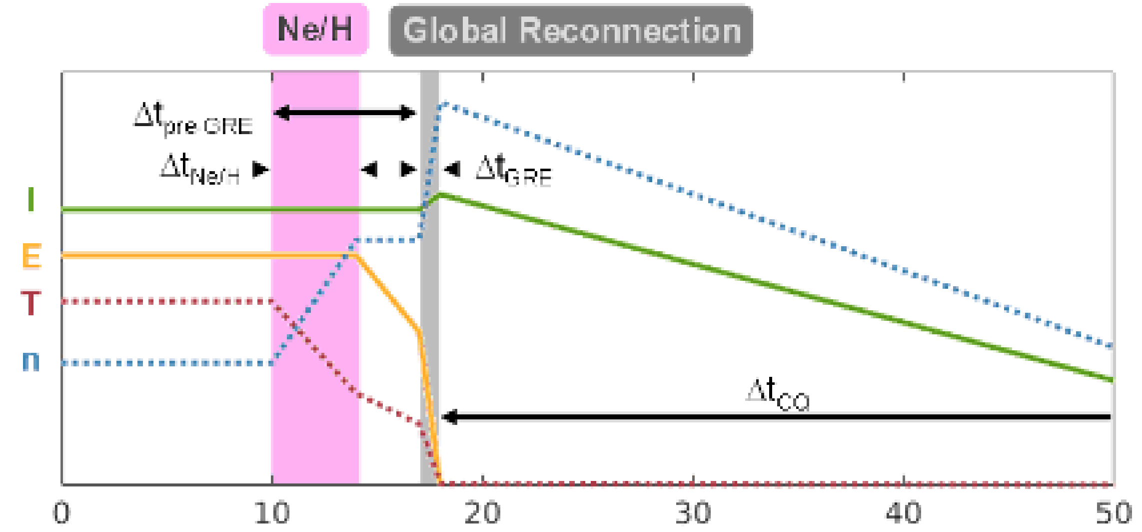
#49

- **Proponents and contact person:**
- Stefan Jachmich (stefan.Jachmich@iter.org), Javier Artola, Gergely Papp, Umar Sheikh, Ansh Patel, Paul Heinrich, Ondrej Ficker, Peter Halldestam, Sergei Gerasimov

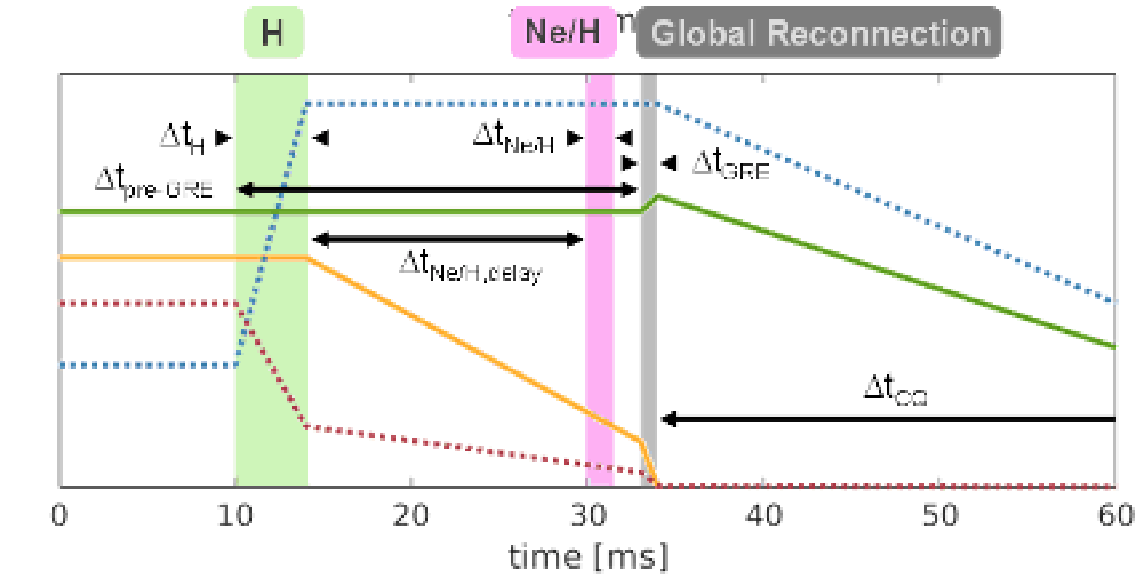
- **Scientific Background & Objectives**
  - ITER DMS foresees different injection schemes: staggered (H then Ne/H-pellet), multiple (2-3 Ne/H pellets) before the GRE and single post GRE
  - Pre-GRE phase is very sensitive to amount of Ne injected and plasma properties
    - → What is tolerable jitter to ensure that material of both pellets is assimilated?
    - → What is the maximum tolerable Ne-amount to reduce plamoid drift and maximise time for TQ-mitigation?
  - Post-GRE plasma have low Te and hence reduce assimilation efficiency
    - → How effective will be an additional Ne/D injection for CQ- control?

- **Experimental Strategy/Machine Constraints and essential diagnostic**
  - Essential: SPI, fast camera, bolometers, standard diagnostic for density measurements.
  - Dual injection into "SPI" H-mode: timing scan
  - Repeat with low Wth-plasma (i.e. ohmic)
  - Pure-D injection into seeded plasma: 1) single to examine pre-TQ dynamic, 2) timing scan for dual inj.
  - For selected case attempt CQ-control after staggered injection scheme.

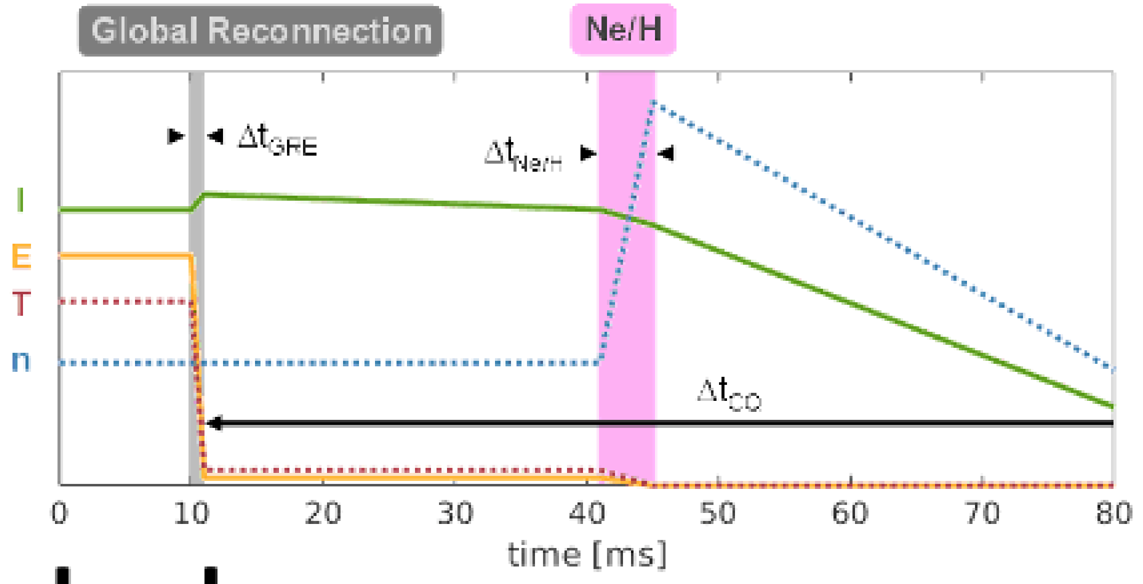
Multiple Ne/H



Staggered



Post-GRE



Proposed pulses

Device	# Pulses/Session	# Development
AUG	36	4
MAST-U	0	0
TCV	0	0
WEST	0	0

Exploring multiple injection schemes for disruption mitigation with SPI

#49

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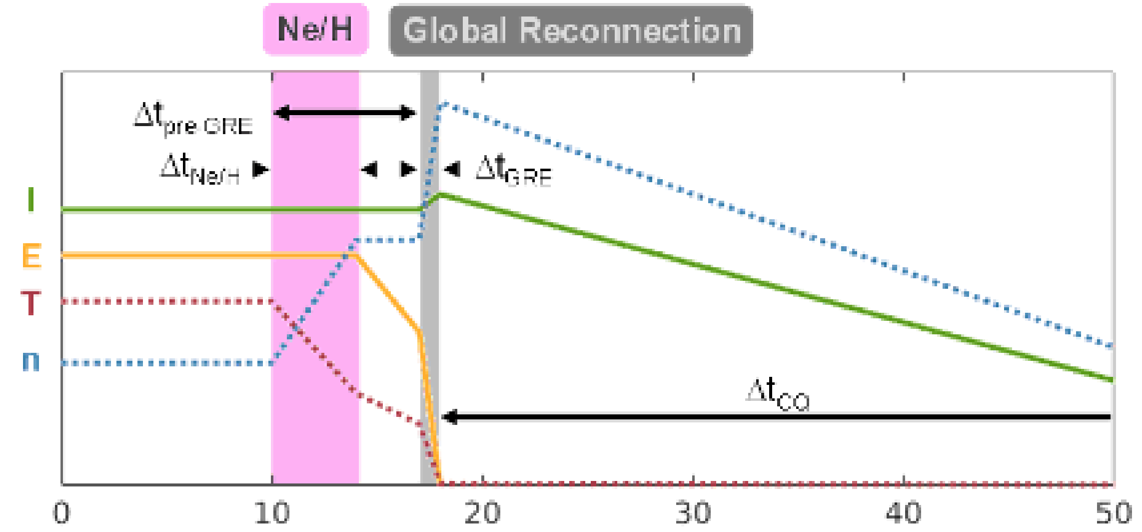
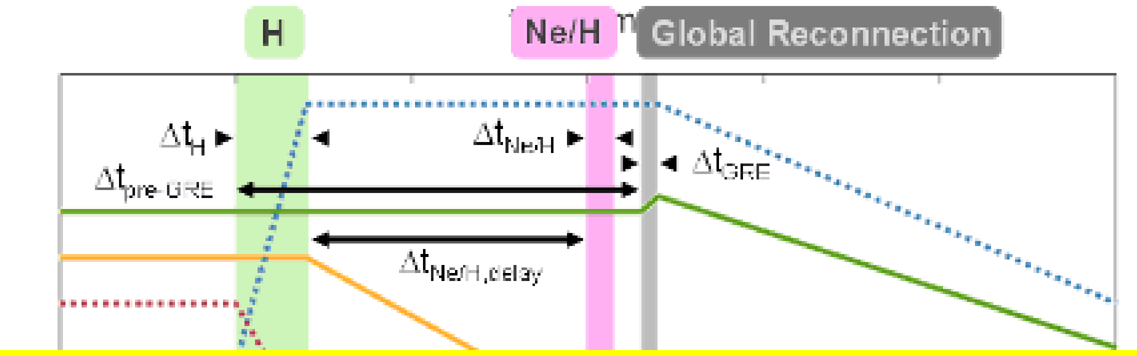


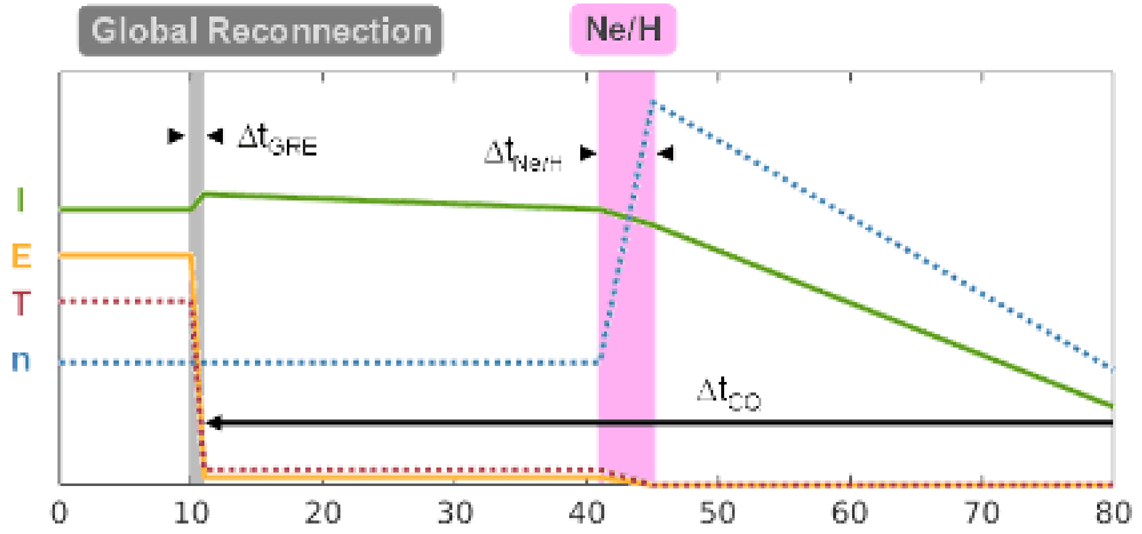
Staggered



Priority: P1 – adresses D1 and D2

time [ms]

Post-GRE



Proposed pulses

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AUG	36	4
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WEST	0	0

Post-TQ mitigation with ITER-DMS-upper-port-like injection geometry

#50

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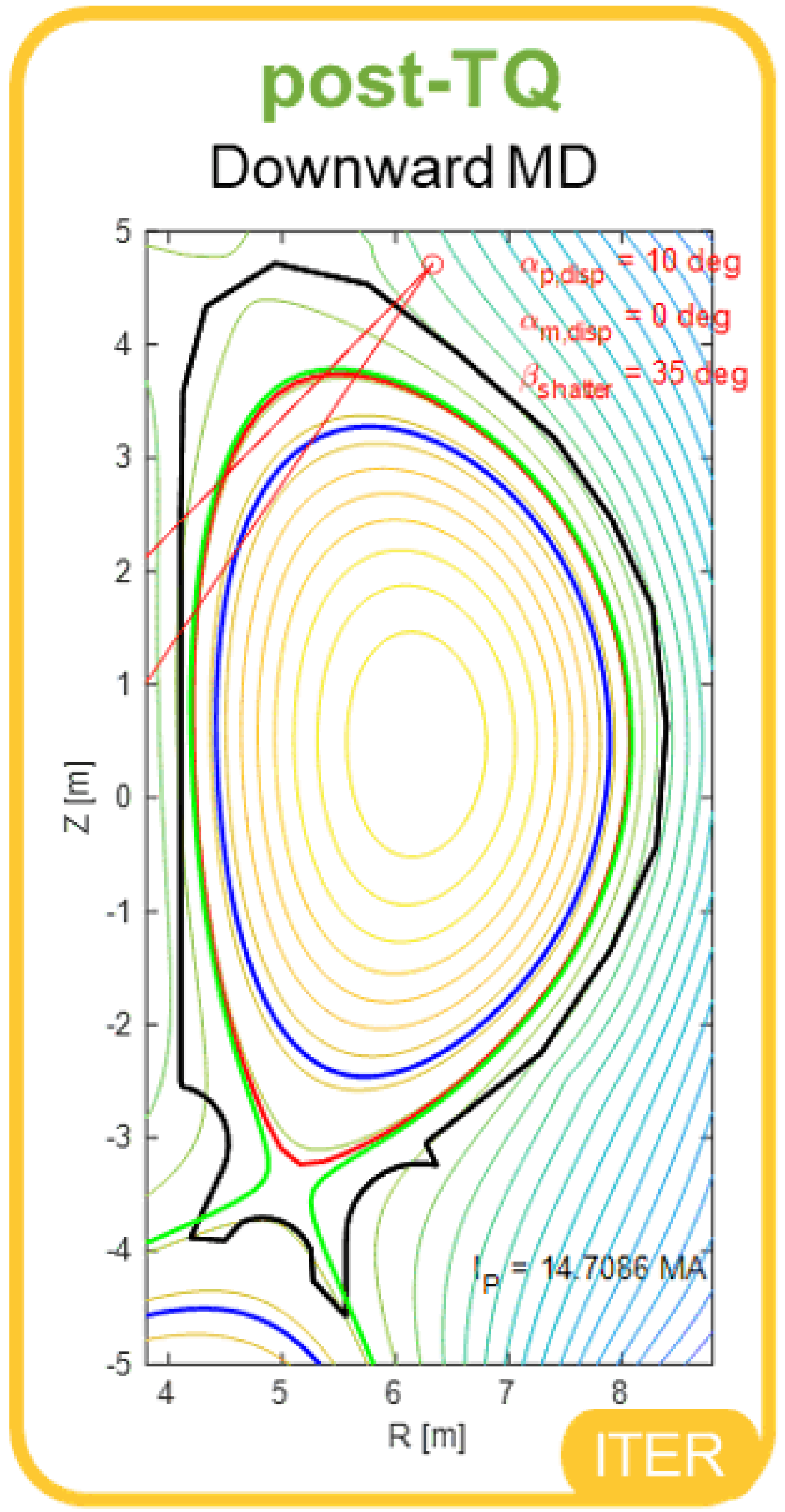
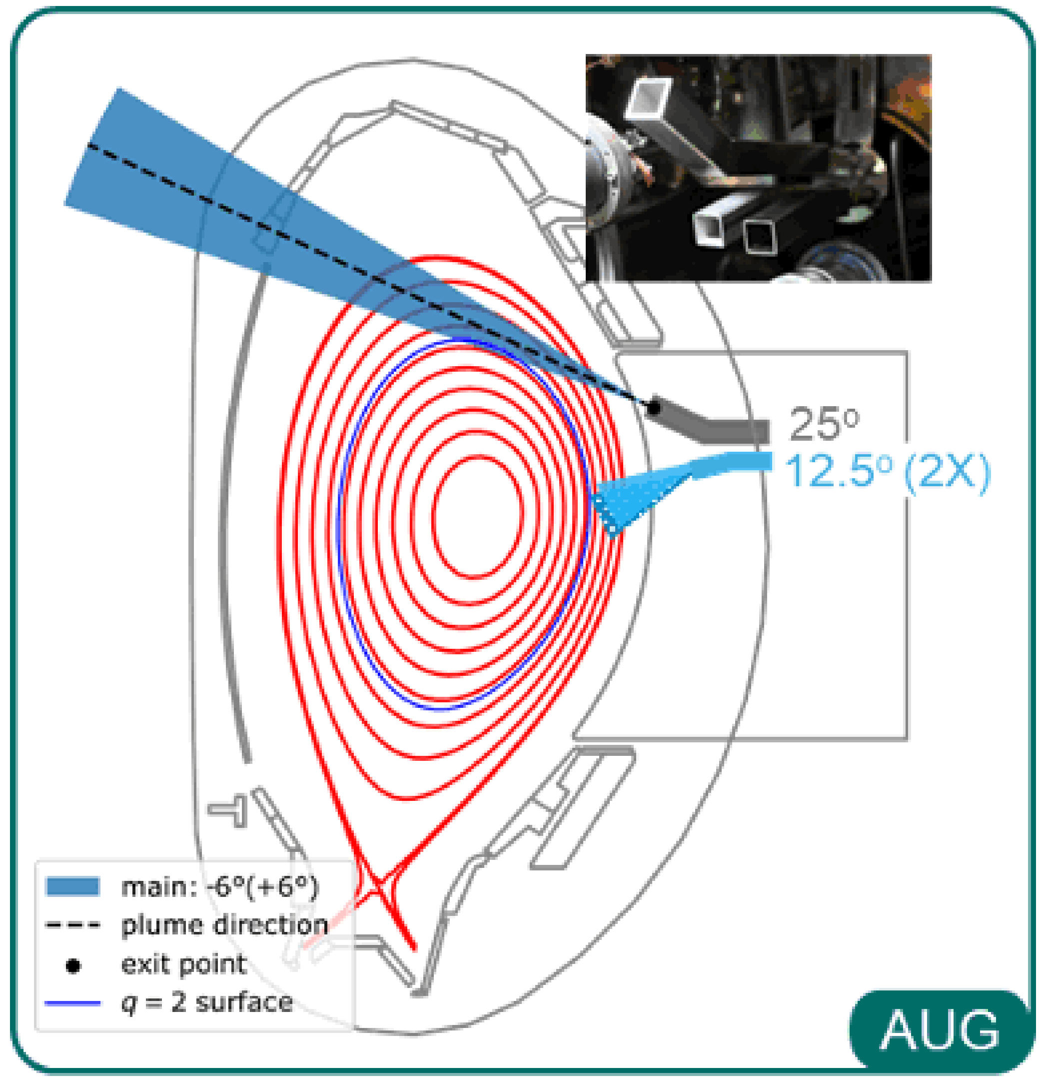
- **Scientific Background & Objectives**
  - ITER DMS must be capable to accelerate CQ and radiate the magnetic energy in case pre-TQ injection has been missed.
  - Plasmas typically have very low Te and assimilation might be very poor.
  - ITER DMS utilises specific geometry and "gaseous" fragments.
    → Effectiveness of UP-like injection after TQ has been triggered?

- **Experimental Strategy/Machine Constraints and essential diagnostic**
  - Essential: SPI, fast camera, bolometers, standard diagnostic for density measurements.
  - Plasma disruption to be provoked through e.g. MGI, impurity gas injection …
  - SPI to be triggered on CQ-detection or pre-timed





Proposed pulses

Device	# Pulses/Session	# Development
AUG	8	4
MAST-U	0	0
TCV	0	0
WEST	0	0

Post-TQ mitigation with ITER-DMS-upper-port-like injection geometry

#50

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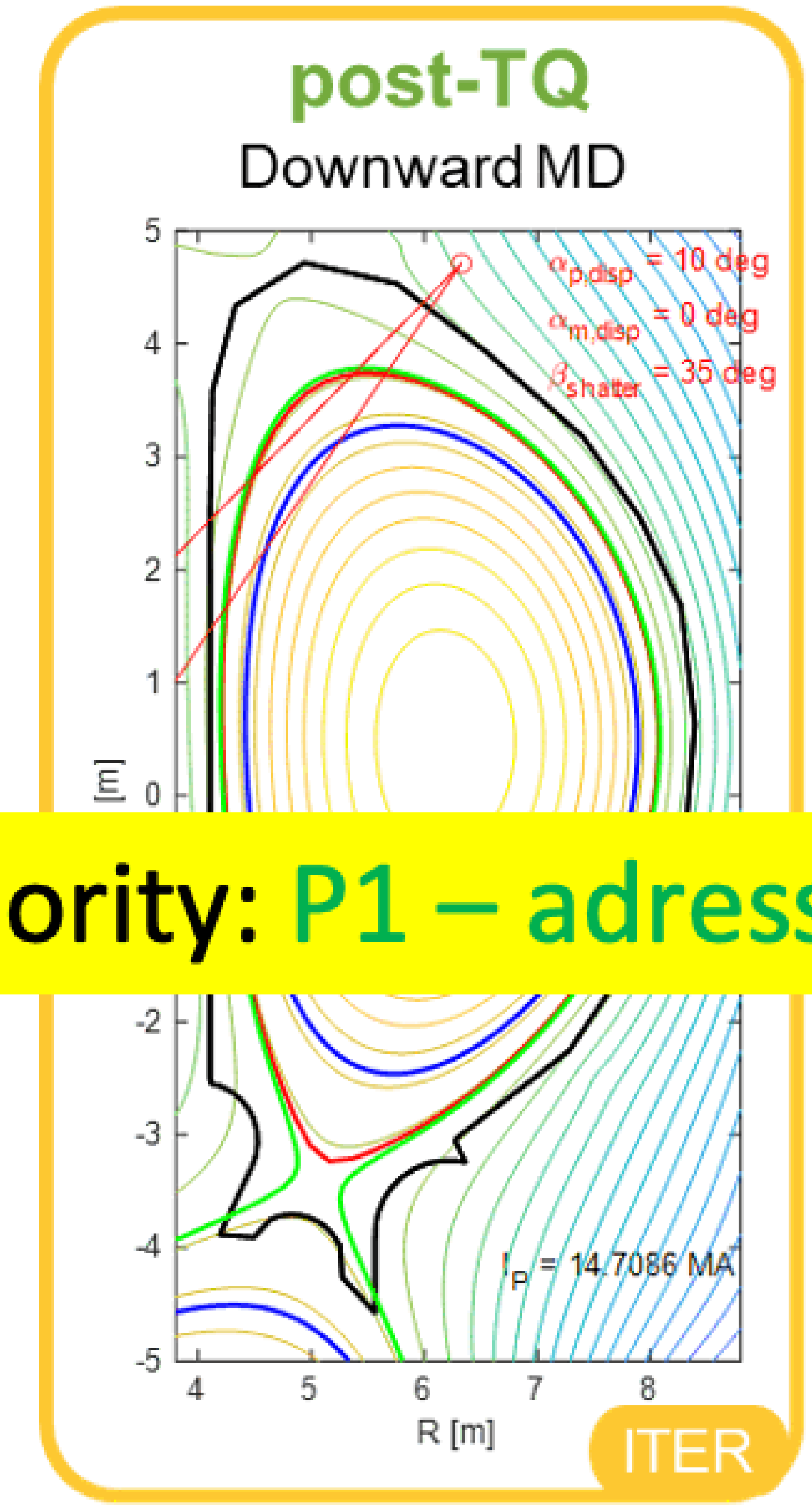

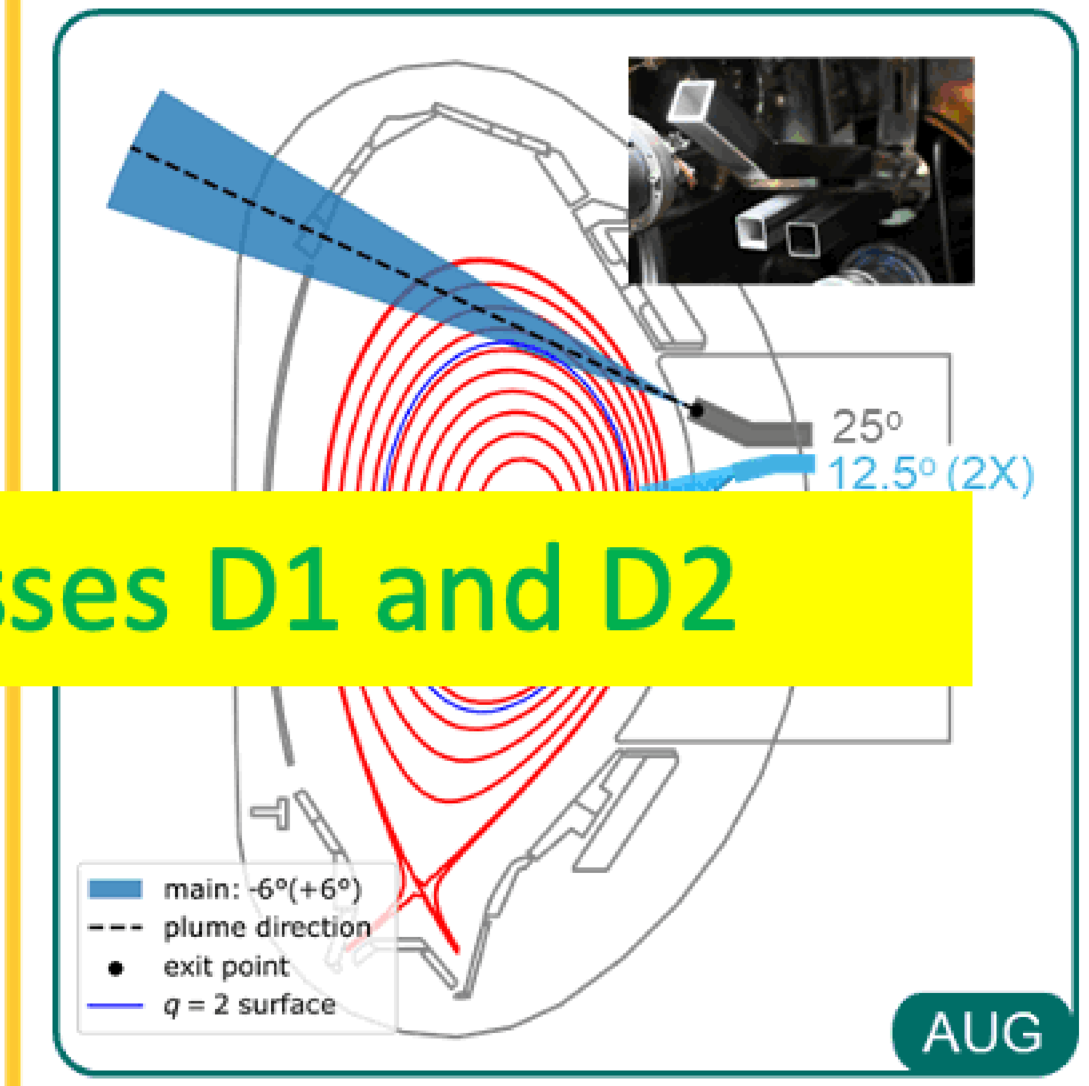

Priority: P1 – adresses D1 and D2

Proposed pulses

Device	# Pulses/Session	# Development
AUG	8	4
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TCV	0	0
WEST	0	0

Effect of RMPs on material assimilation during SPI mitigated disruptions

#51

Proponents and contact person:

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- **Scientific Background & Objectives**
  - Mitigation of ELMs during H-mode phases to reduce the heat onto the divertor by using edge magnetic field stochastisation is common method for many tokamaks including ITER.
  - Key function of SPI is to fuell the plasma prior the CQ to reduce the likelihood of RE generation.
  - Additional transport due to fieldline stochasticity leads to losses in the plasma edge, where most of the injected material is deposited.

  → Assess and quantify the effect of RMPs on material assimilation of deuterium SPI.

- **Experimental Strategy/Machine Constraints and essential diagnostic**
  - Essential: SPI, fast camera, bolometers, standard diagnostic for density measurements.
  - Use existing H-mode scenario with RMPs for ELM mitigaytion and inject D-SPI (two velocities)
  - Comparison with H-mode plasma with similar ne/Te-pedestal needed: repeat above injections.

Proposed pulses

Device	# Pulses/Session	# Development
AUG	6	6
MAST-U	0	0
TCV	0	0
WEST	0	0

Effect of RMPs on material assimilation during SPI mitigated disruptions

#51

Proponents and contact person:

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Priority: P2 – definitely interesting, but more priority is given to the other SPI proposals which allows to finalize scans and adresses D1 and D2

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Proposed pulses

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MAST-U	0	0
TCV	0	0
WEST	0	0

SPI-triggered runaway electron scenario on ASDEX Upgrade

#53

- **Proponents and contact person:**

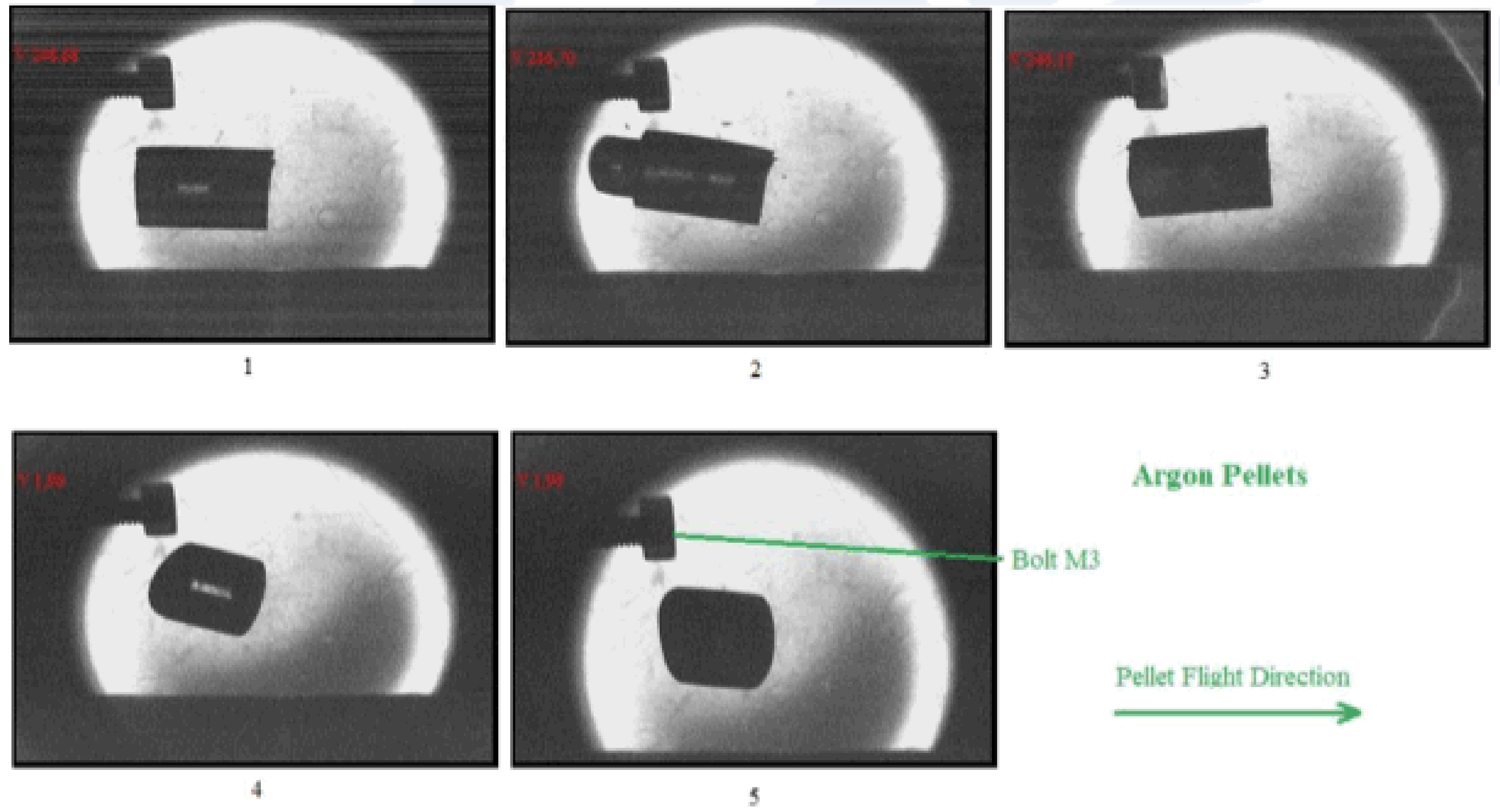
Gergely Papp, P. Halldestam, P. Heinrich, V. Bandaru (IPP), U. Sheikh, J. Decker (SPC), M. Hoppe (KTH), O. Vallhagen (Chalmers), S. Gerasimov (UKAEA)
gergely.papp@ipp.mpg.de

- **Scientific Background & Objectives**

  The goal is to develop an SPI-induced runaway electron scenario on ASDEX Upgrade, and to perform param. scans.
  - Modeling input for combined SPI+RE model validation (little data available so far)
  - Potential alternative AUG RE scenario in case of in-vessel MGI valve issues mid-campaign
  - Scenario development aided by DREAM simulations

- **Experimental Strategy/Machine Constraints and essential diagnostic**
  - Needs development of Ar SPI recipes on non-shot days!
  - Injection of Ar pellets into typical MGI RE scenario plasmas, such as e.g. #41337 (limiter, L-mode, ne =3e19)
  - Needs Ar SPI, COO interferometry, bolometry, HXR, ECE, fast cameras (vis+IR)

Shadowgraphy of argon pellets during commissioning (PELIN)



Proposed pulses

Device	# Pulses/Session	# Development
AUG	5	3
MAST-U	-	-
TCV	-	-
WEST	-	-

#53

SPI-triggered runaway electron scenario on ASDEX Upgrade

Priority: P1 – adresses D1 and D2

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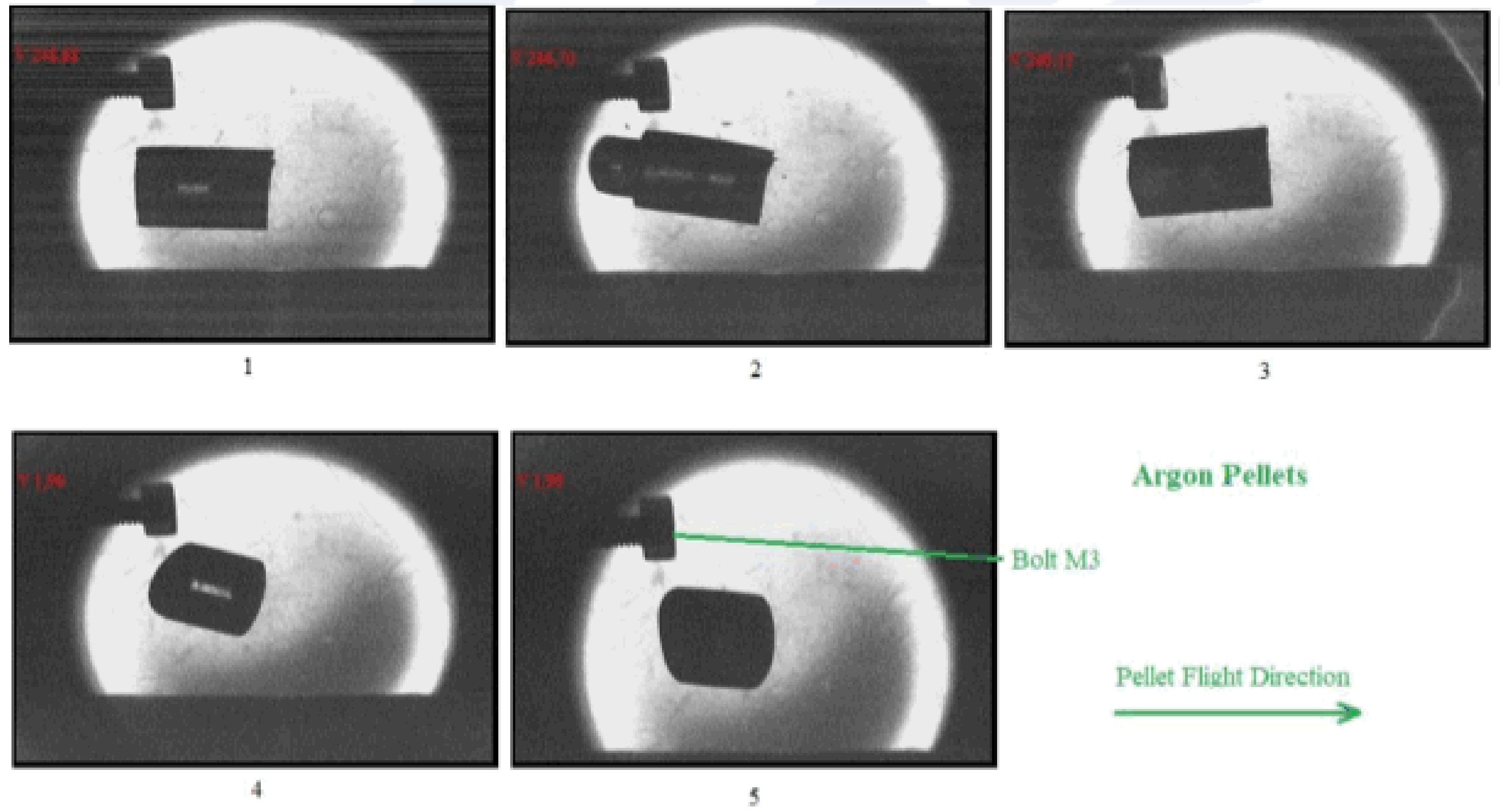


Proposed pulses

Device	# Pulses/Session	# Development
AUG	5	3
MAST-U	-	-
TCV	-	-
WEST	-	-

Studying the effect of neon content for the staggered SPI scheme

#54

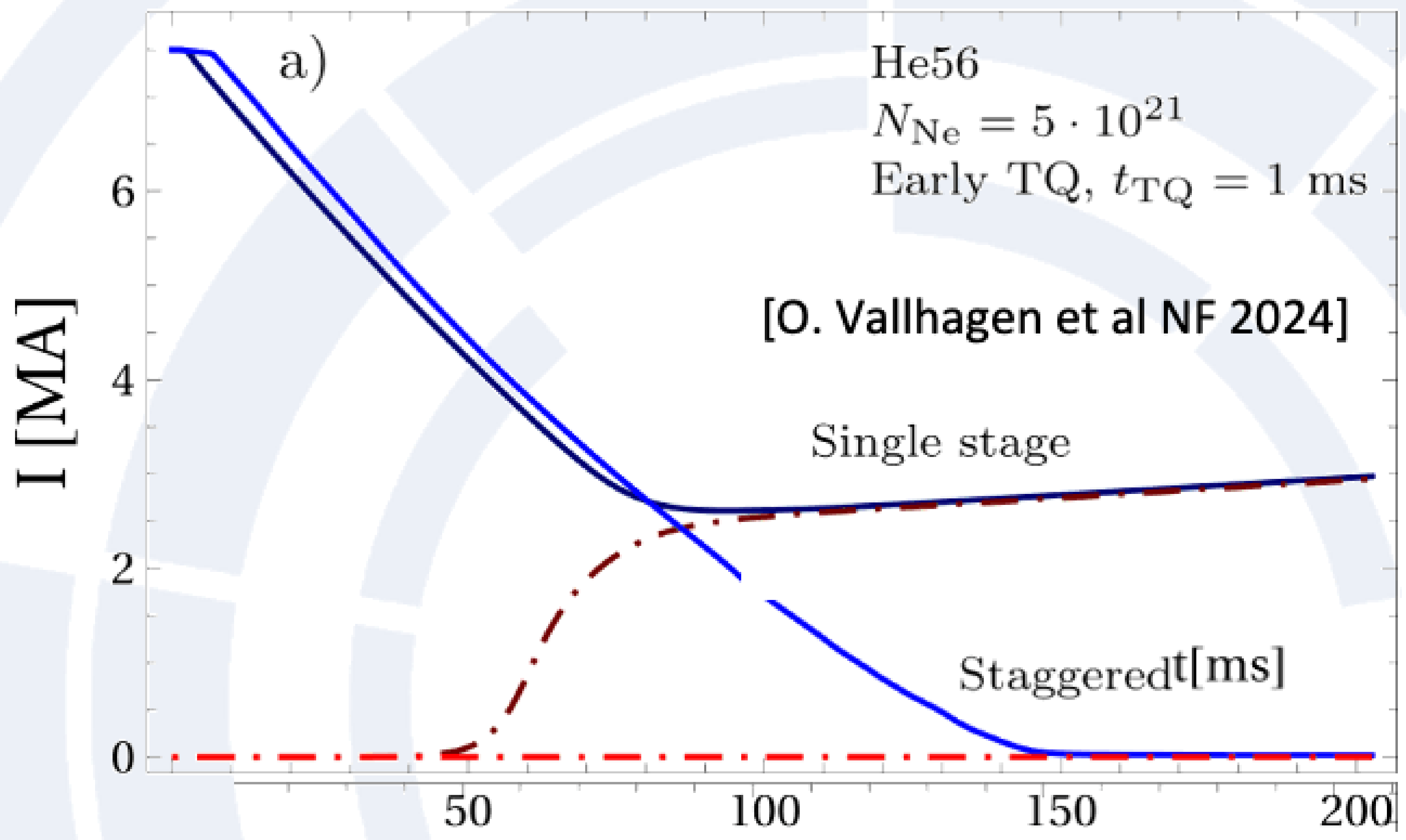
- **Proponents and contact person:**

Anshkumar Patel, G. Papp, P. Heinrich, P. Halldestam
Anshkumarhimanshu.patel@ipp.mpg.de

- **Scientific Background & Objectives**
  - Optimize the neon content in the staggered injection scheme proposed for ITER
  - Determine proposed neon doping amount required in first pellet to suppress the plasmoid drift for sufficient density rise for runaway electron avoidance
  - Assess viability and effectiveness of second injection in a cold plasma (after first injection) and short pre-TQ duration

- **Experimental Strategy/Machine Constraints and essential diagnostic**
  - Determine optimal neon doping amount in first pellet for supression of plasmoid drift and sufficiently long pre-TQ for second injection (3 discharges)
  - Test 2-3 different composition for the second pellet to study dependence of mitigation on neon content in second pellet (3 discharges)
  - If not already available, carry out a single injection with a mixed D_2/Ne pellet with similar content as the total content in the staggered injections as a comparable scenario (1 injection)

Simulated plasma current for single vs staggered injection



Proposed pulses

Device	# Pulses/Session	# Development
AUG	7/1	-
MAST-U	-	-
TCV	-	-
WEST	-	-

Studying the effect of neon content for the staggered SPI scheme

Priority: P1 – adresses D1 and D2

#54

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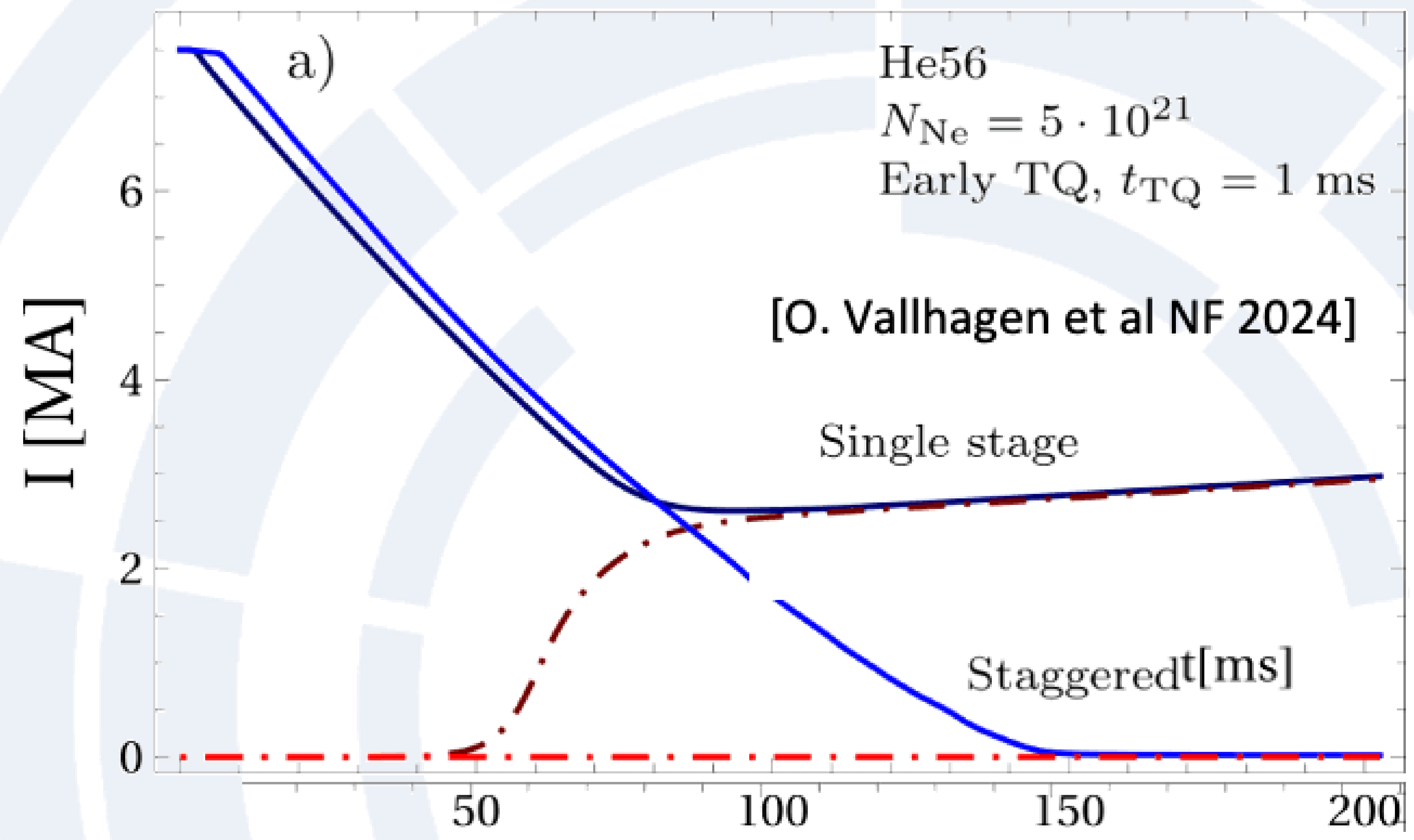
  - If not already available, carry out a single injection with a mixed D_2/Ne pellet with similar content as the total content in the staggered injections as a comparable scenario (1 injection)

Simulated plasma current for single vs staggered injection



Proposed pulses

Device	# Pulses/Session	# Development
AUG	7/1	-
MAST-U	-	-
TCV	-	-
WEST	-	-

Application of 3D fields in synergy with SPI for RE mitigation

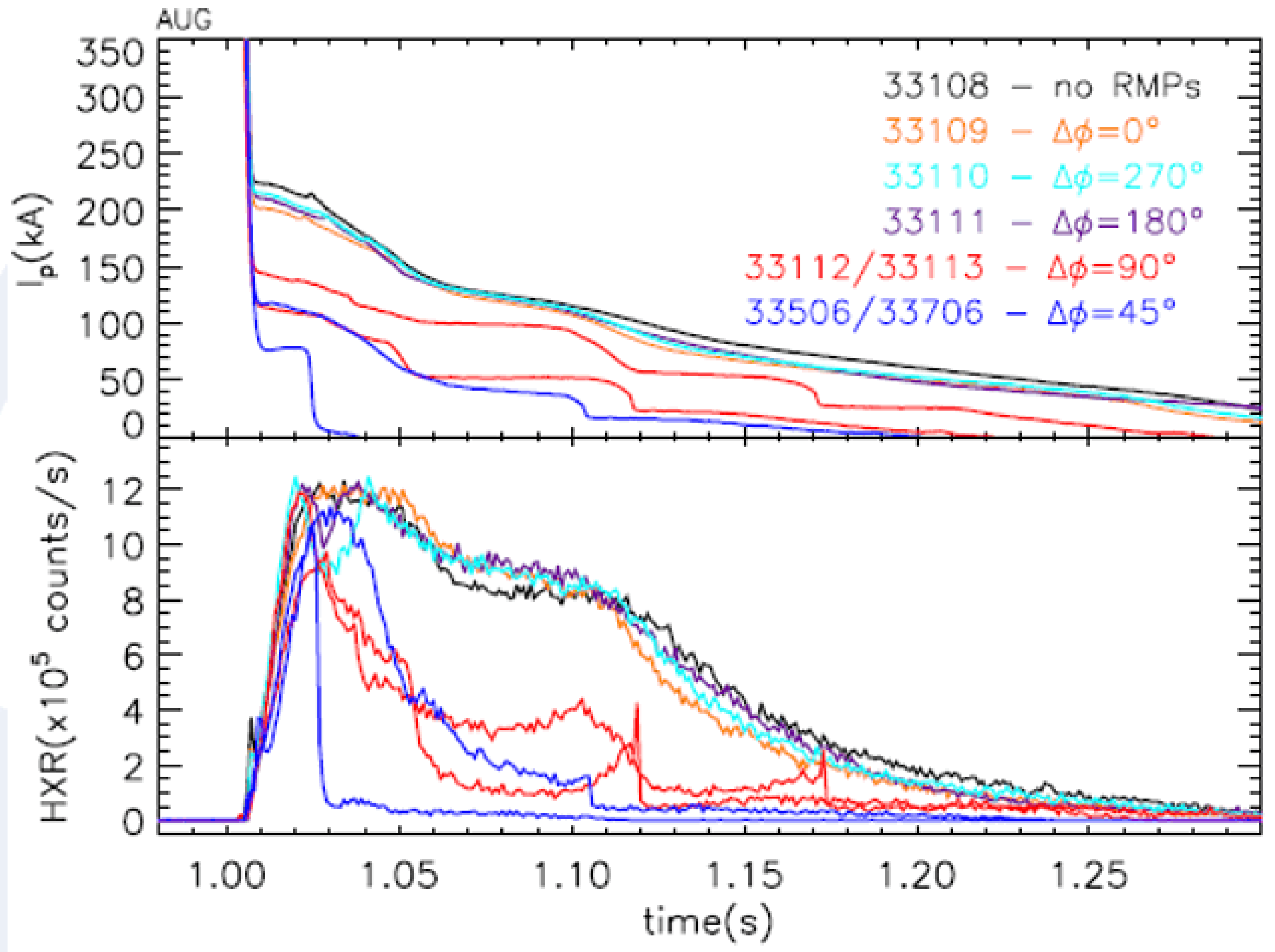
#61

- **Proponents and contact person:**

- M.Gobbin, O.Ficker, L.Marrelli, L.Pigatto, G.Papp, D.Terranova, E.Tomesova
  marco.gobbin@igi.cnr.it

- **Scientific Background & Objectives**
  - Magnetic perturbations (MP) are still considered as complementary RE dissipation methods in more devices (DIII-D, JT-60SA,DTT,SPARC) and recently have been applied successfully in AUG and COMPASS [1-2].
  - MP could be used to minimize the RE beam formation if applied prior to the current quench. The reduced RE beam current in this way could be more easily dissipated by SPI.
  - In AUG during a RE beam scenario, we propose to:
  - explore the possibility of reducing the final RE current acting with MP applied from the pre-disruption phase before the SPI injection;
  - determine the B-coil configuration more efficient to guarantee the maximum RE reduction when MP are applied in combination with SPI injection;
  - investigate the effect of MP on the SPI injection (also piggy-backed to other proposals).

- **Experimental Strategy/Machine Constraints and essential diagnostic**
  - The same scheme suggested in the proposal *"SPI-triggered runaway electron scenario on AUG"* could apply also to these experiments: 0-8-1MA/2.5T, IWL circular, ECRH 2-4 gyrotrons, D gas.
  - Execution of one reference shot: generation of a RE beam followed by SPI during the RE beam phase without MP (1shot).
  - Apply n=1 MP from a time preceding the disruption (500ms) and the SPI, performing a scan in the B-coil differential phasing (5 shots);
  - Diagnostics: COO interferometer, bolometry, magnetics, fast visible cameras, fast IR camera (desired), HXR, ECE, Ar MGI or Ar SPI to generate the RE beam.
  - For modelling/data interpretation: MARS-F, VMEC, ORBIT.



Past experiments with RE mitigation by MP in AUG: a reduction of the post-disruption RE current is obtained (down to -50%) for the differential phasing between upper/lower coils which maximizes the plasma response to the applied MP.

Proposed pulses

Device	# Pulses/Session	# Development
AUG	6	

[1] Gobbin M at al, Front. Phys. 12:1295082. (2024)
[2] Mlynar J et al, Plasma Phys. Control. Fusion 61 014010 (2019)

Application of 3D fields in synergy with SPI for RE mitigation

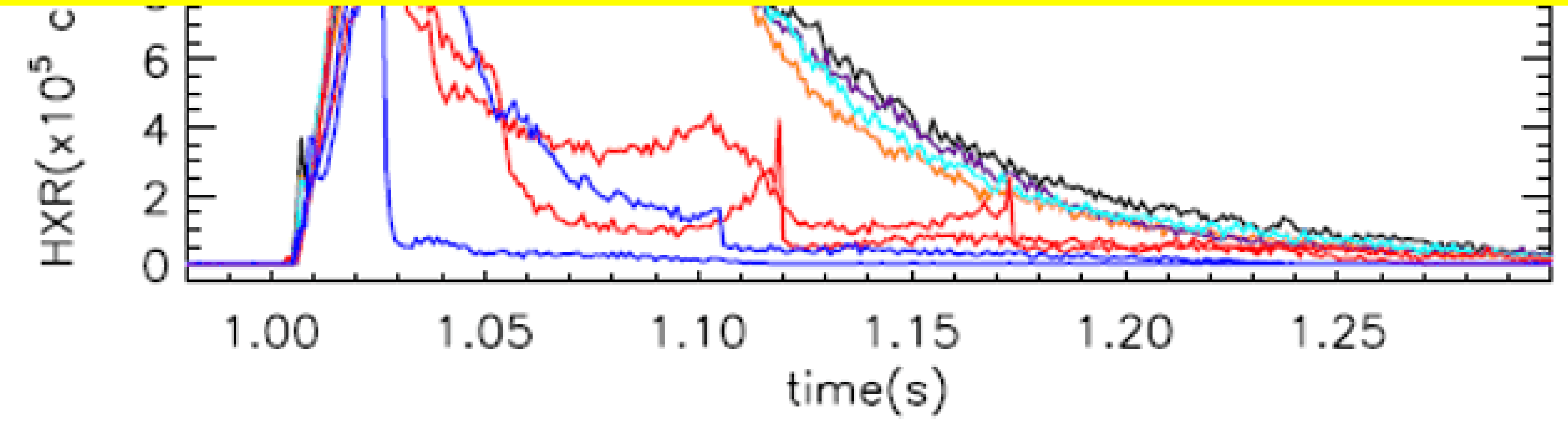
#61

Priority: P2 – definitely interesting, but more priority is given to the other SPI proposals which allows to finalize scans and adresses D1 and D2

- **Proponents and contact person:**
- M.Gobbin, O.Ficker, L.Marrelli, L.Pigatto, G.Papp, D.Terranova, E.Tomesova
  marco.gobbin@igi.cnr.it

- **Scientific Background & Objectives**
  - Magnetic perturbations (MP) are still considered as complementary RE dissipation methods in more devices (DIII-D, JT-60SA,DTT,SPARC) and recently have been applied successfully in AUG and COMPASS [1-2].
  - MP could be used to minimize the RE beam formation if applied prior to the current quench. The reduced RE beam current in this way could be more easily dissipated by SPI.
  - In AUG during a RE beam scenario, we propose to:
  - explore the possibility of reducing the final RE current acting with MP applied from the pre-disruption phase before the SPI injection;
  - determine the B-coil configuration more efficient to guarantee the maximum RE reduction when MP are applied in combination with SPI injection;
  - investigate the effect of MP on the SPI injection (also piggy-backed to other proposals).

- **Experimental Strategy/Machine Constraints and essential diagnostic**
  - The same scheme suggested in the proposal "*SPI-triggered runaway electron scenario on AUG*" could apply also to these experiments: 0-8-1MA/2.5T, IWL circular, ECRH 2-4 gyrotrons, D gas.
  - Execution of one reference shot: generation of a RE beam followed by SPI during the RE beam phase without MP (1shot).
  - Apply n=1 MP from a time preceding the disruption (500ms) and the SPI, performing a scan in the B-coil differential phasing (5 shots);
  - Diagnostics: COO interferometer, bolometry, magnetics, fast visible cameras, fast IR camera (desired), HXR, ECE, Ar MGI or Ar SPI to generate the RE beam.
  - For modelling/data interpretation: MARS-F, VMEC, ORBIT.



Past experiments with RE mitigation by MP in AUG: a reduction of the post-disruption RE current is obtained (down to -50%) for the differential phasing between upper/lower coils which maximizes the plasma response to the applied MP.

Proposed pulses

Device	# Pulses/Session	# Development
AUG	6	

[1] Gobbin M at al, Front. Phys. 12:1295082. (2024)
[2] Mlynar J et al, Plasma Phys. Control. Fusion 61 014010 (2019)

#52

Staggered SPI injection studies at AUG

- **Proponents and contact person:**

Gergely Papp, P. Heinrich, A. Patel., P. Halldestam, M. Hoelzl, W. Tang (IPP), S. Jachmich, J. Artola (ITER), U. Sheikh (SPC), J. Svoboda (IPP-CAS), S. Gerasimov (UKAEA), O. Ficker (IPP-CAS)
gergely.papp@ipp.mpg.de

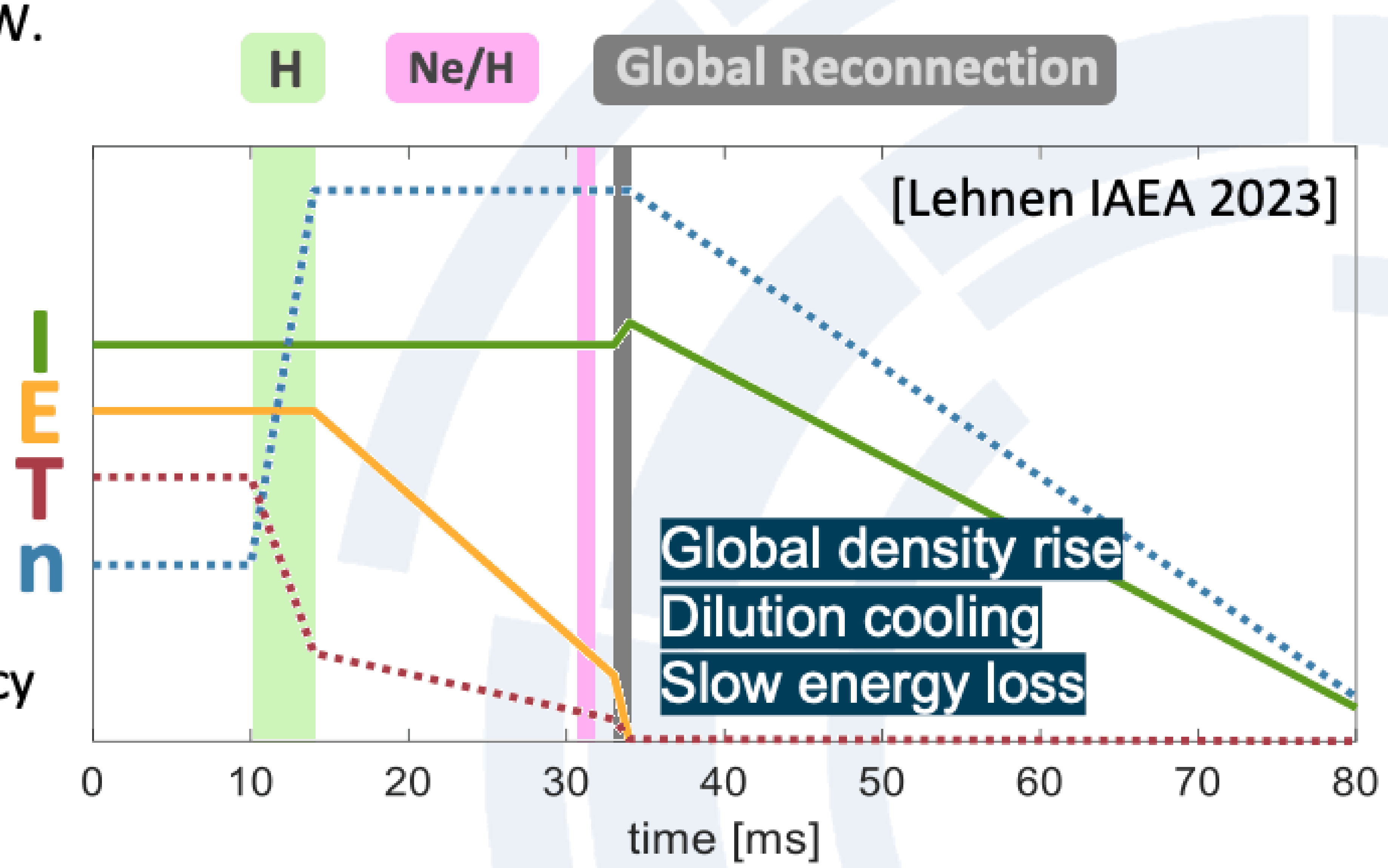
- **Scientific Background & Objectives**

AUG is the only European tokamak with ILW & SPI
The only tokamak with diverse SPI heads

- Staggered injection is foreseen for the ITER DMS
- Large number of variables influence the DMS efficiency
- A robust dataset is necessary for extrapolation and model validation for the ITER DMS

- **Experimental Strategy/Machine Constraints and essential diagnostic**
    - Scan SPI composition (D+D, 3x D+Ne/D, 3x Ne/D fractions), relative timings, velocities, target plasmas (2-3 points each)
    - A large number of short discharges is needed for scans
      Can be efficiently executed on dedicated SPI days
    - Exact program will be determined using the results of ongoing analysis and modeling work

ITER Staggered injection scheme



Proposed pulses

Device	# Pulses/Session	# Development
AUG	90	3
MAST-U	-	-
TCV	-	-
WEST	-	-

#52

Staggered SPI injection studies at AUG

- **Proponents and contact person:**

Gergely Papp, P. Heinrich, A. Patel., P. Halldestam, M. Hoelzl, W. Tang (IPP), S. Jachmich, J. Artola (ITER), U. Sheikh (SPC), J. Svoboda (IPP-CAS), S. Gerasimov (UKAEA), O. Ficker (IPP-CAS)
gergely.papp@ipp.mpg.de

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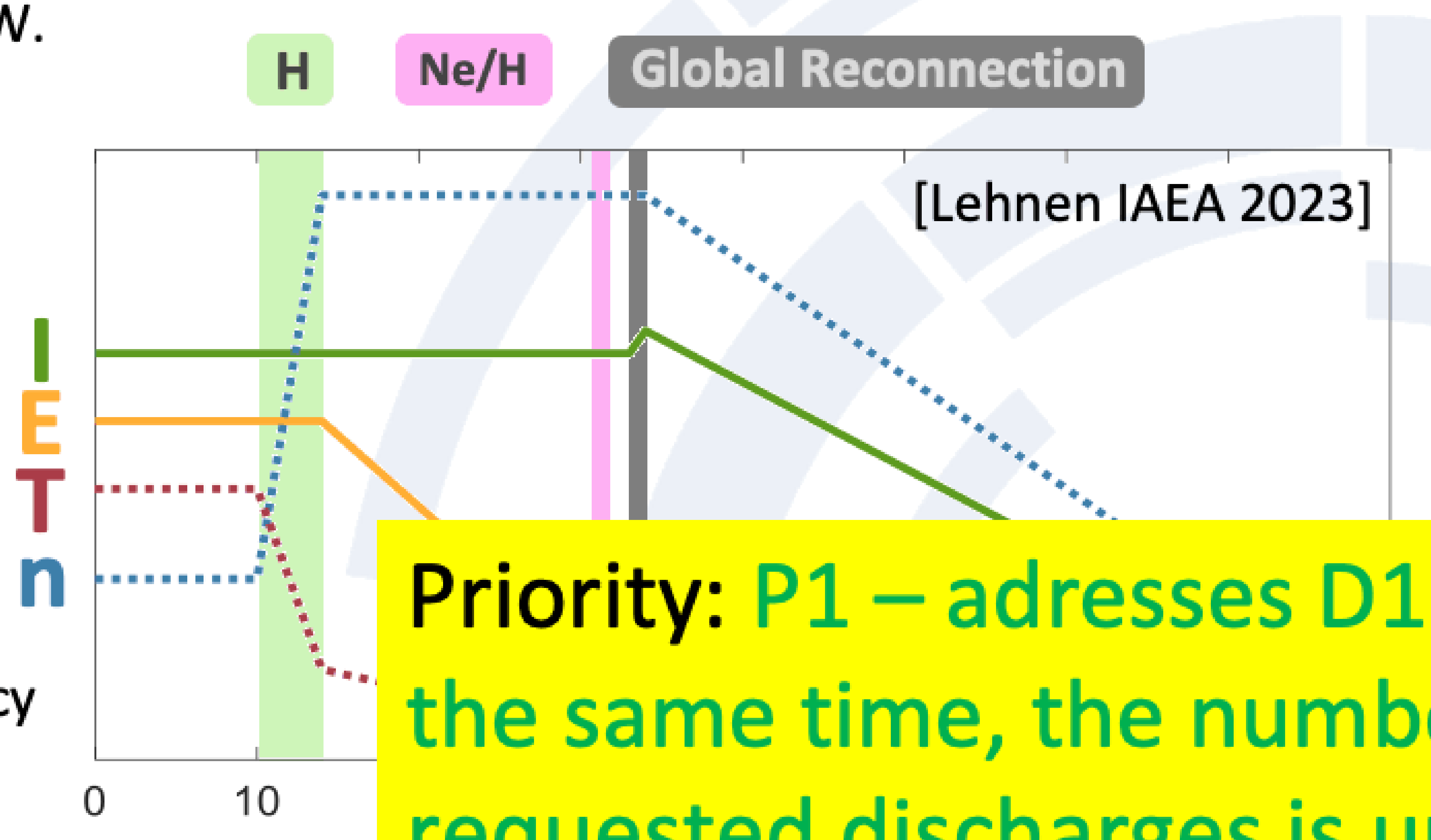


Priority: P1 – adresses D1 and D2. At the same time, the number of the requested discharges is unrealistic and has to be reduced.

Proposed pulses

Device	# Pulses/Session	# Development
AUG	90	3
MAST-U	-	-
TCV	-	-
WEST	-	-

Runaways during the start-up

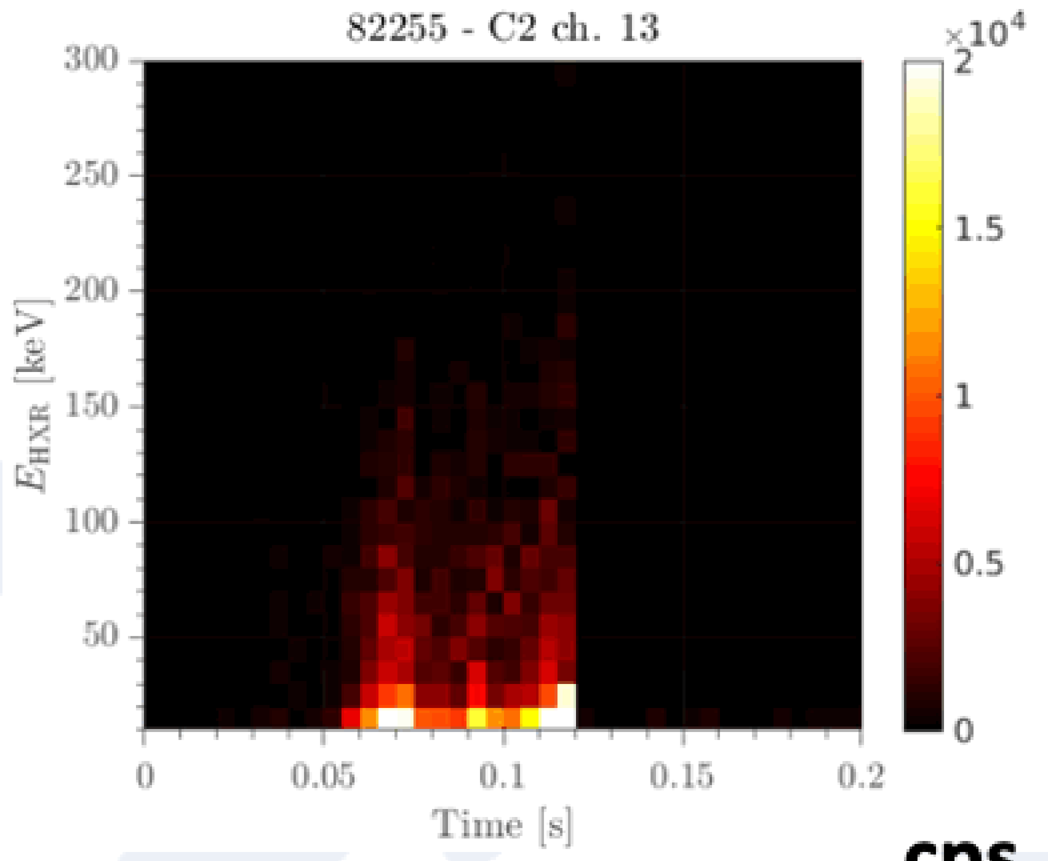
Understanding fast electron generation during the TCV tokamak startup: compare and contrast inductive and ECH startup scenarios

#46

- **Proponents and contact person:**
  - Pedro Molina-Cabrera (pedro.molina@epfl.ch), Mathias Hoppe, Joan Decker, Stefano Coda, et. al.

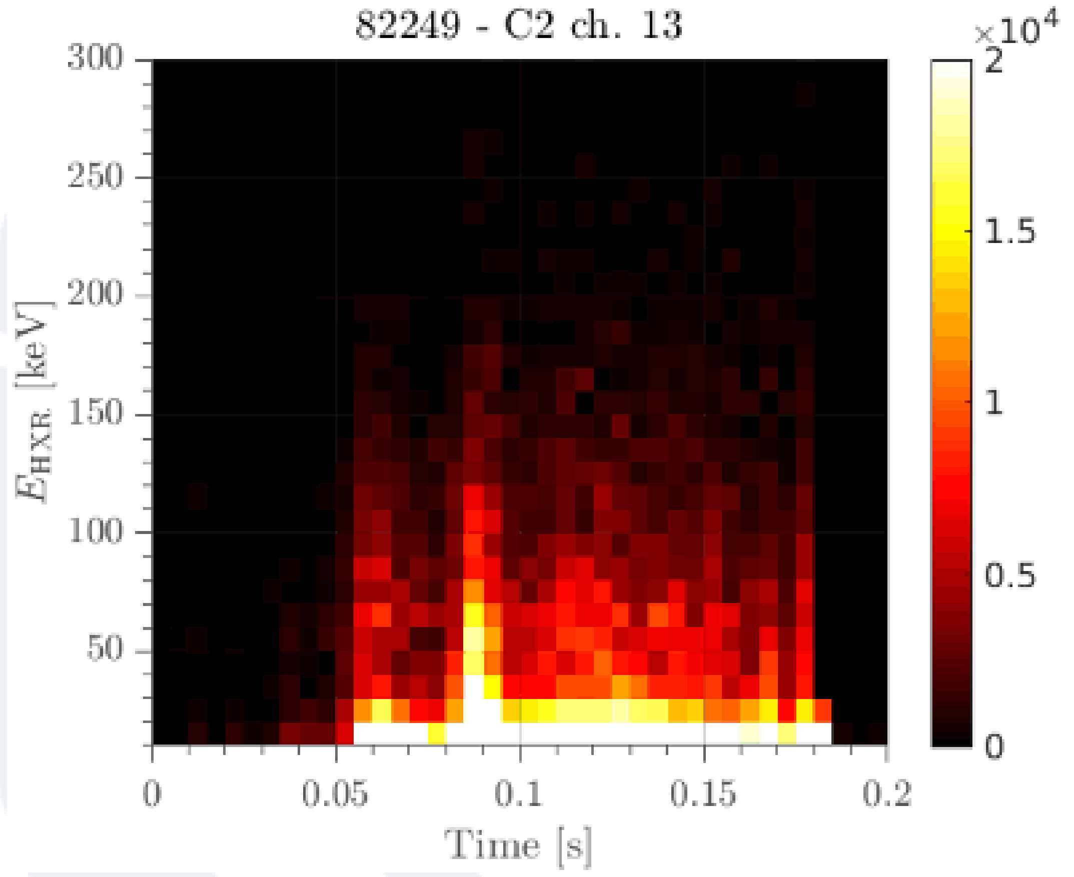
- **Scientific Background & Objectives**
  - Continue exploration of experimental space for the generation of fast electrons during the startup via inductive methods
  - Develop an ECH pre-ionization startup scenario and explore experimental settings leading to the production of fast-electrons
  - Develop an ECH-assisted burn-through scenario and explore experimental settings leading to the production of fast-electrons
  - Support experiments with STREAM simulations

- **Experimental Strategy/Machine Constraints and essential diagnostic**
  - Essential diagnostics: fast-electron diagnostics: HXRS, VECE, PMTX, MANTIS, FastCam, APGs
  - SCD control system required to carefully control V-loop
  - A recently boronized machine would be appreciated to easily achieve low densities
  - X2 ECH system. Variable power from 100kW-1MW. Flexible TCV launchers



30mPa prefill

cps

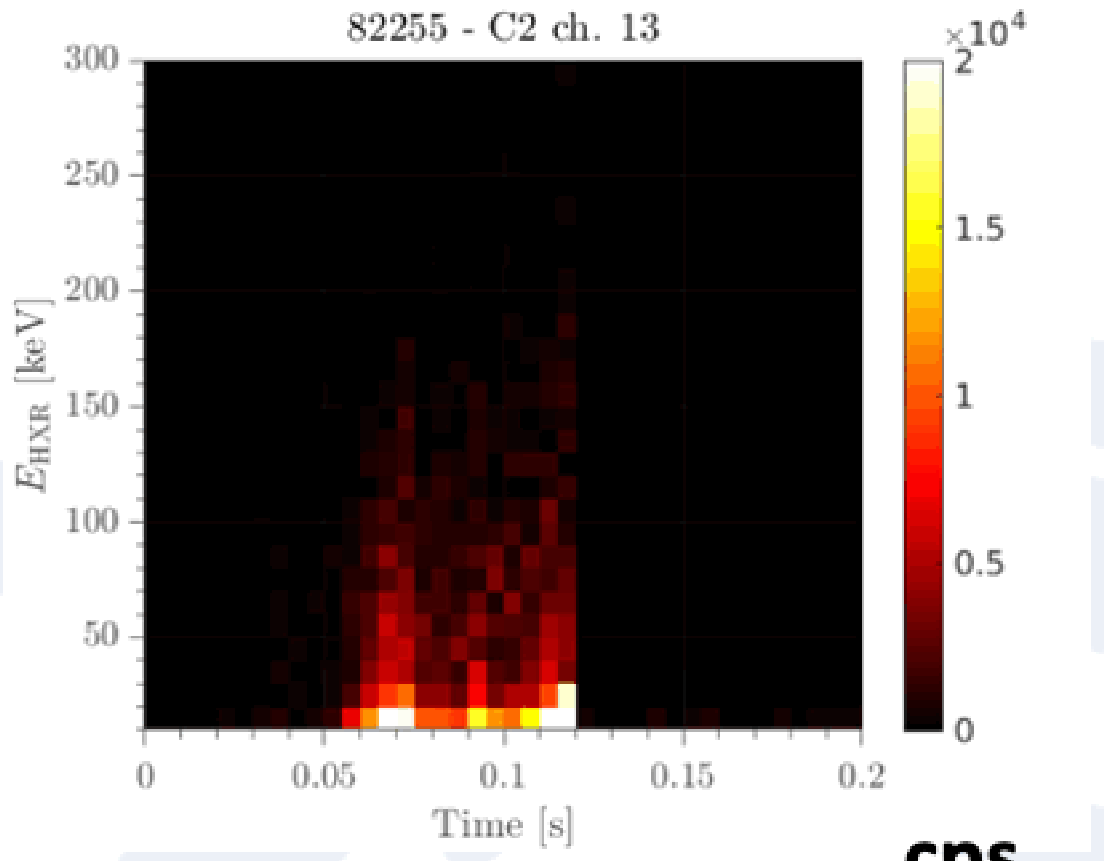


4mPa prefill

Device	# Pulses/Session	# Development
AUG		
MAST-U		
TCV	30	30
WEST		

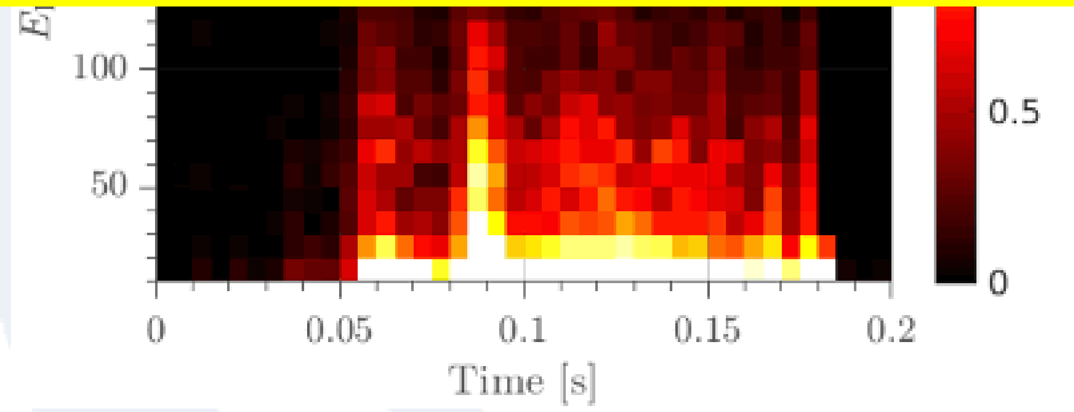
Understanding fast electron generation during the TCV tokamak startup: compare and contrast inductive and ECH startup scenarios

#46



30mPa prefill

Priority: P1 – definitely for starting of the operations in new large tokamaks and adresses D4



- **Proponents and contact person:**
  - Pedro Molina-Cabrera (pedro.molina@epfl.ch), Mathias Hoppe, Joan Decker, Stefano Coda, et. al.

- **Scientific Background & Objectives**
  - Continue exploration of experimental space for the generation of fast electrons during the startup via inductive methods
  - Develop an ECH pre-ionization startup scenario and explore experimental settings leading to the production of fast-electrons
  - Develop an ECH-assisted burn-through scenario and explore experimental settings leading to the production of fast-electrons
  - Support experiments with STREAM simulations

- **Experimental Strategy/Machine Constraints and essential diagnostic**
  - Essential diagnostics: fast-electron diagnostics: HXRS, VECE, PMTX, MANTIS, FastCam, APGs
  - SCD control system required to carefully control V-loop
  - A recently boronized machine would be appreciated to easily achieve low densities
  - X2 ECH system. Variable power from 100kW-1MW. Flexible TCV launchers

Device	# Pulses/Session	# Development
AUG		
MAST-U		
TCV	30	30
WEST		

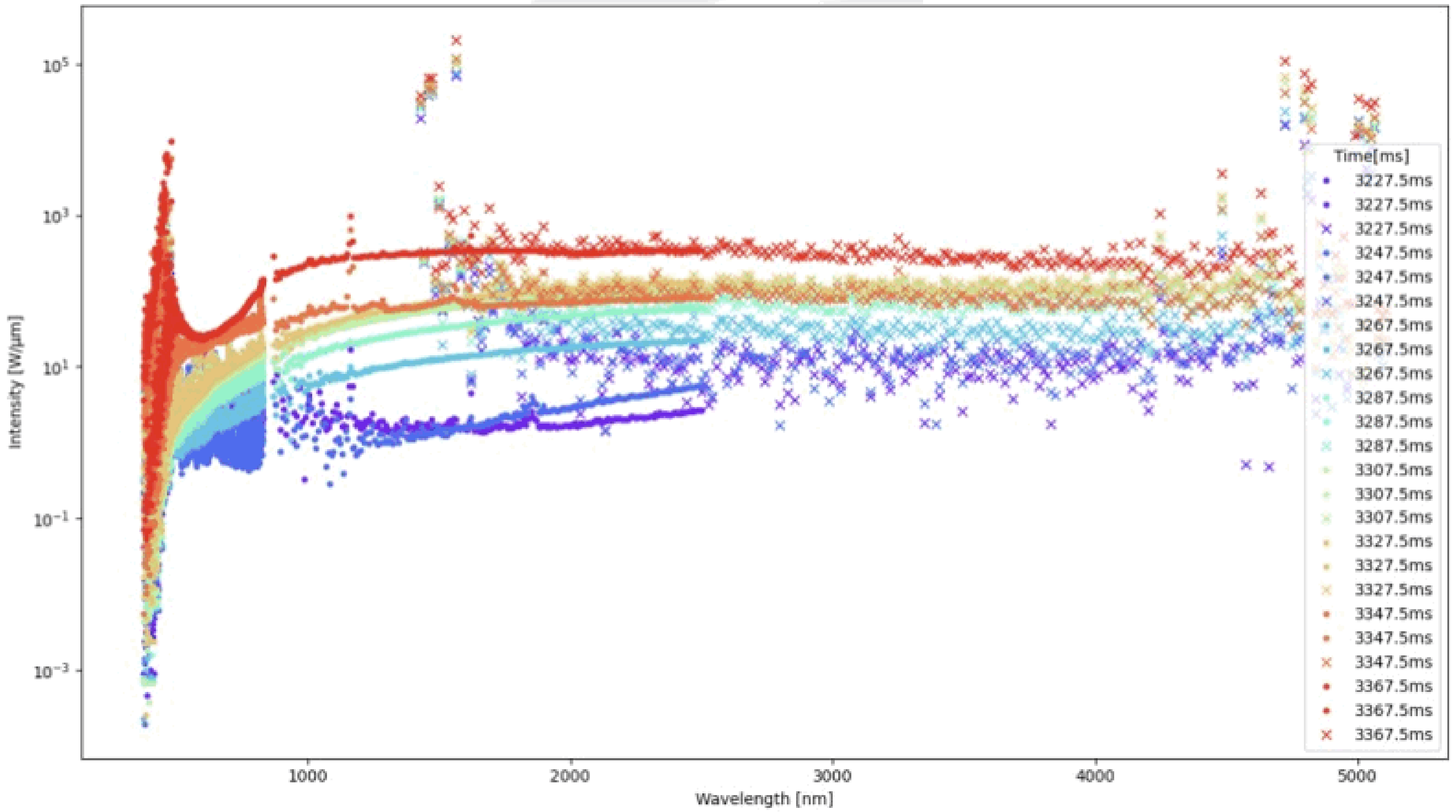
Runaway electrons at plasma start-up in WEST

#62

- **Proponents and contact person:**
  basilio.esposito@enea.it et al.

- **Scientific Background & Objectives**
  Explore runaway dynamics at start-up: study how the number and energy of runaways depend on plasma start-up conditions and how they vary in time, thus providing input data for extrapolation on ITER.

- **Experimental Strategy/Machine Constraints and essential diagnostic**
  - Perform a detailed comparison in a single device (WEST) of runaway formation at start-up by a systematic scan of some parameters (such as current ramp-up rate and ne)
  - Combination of synchrotron radiation images and spectra measurements compared with SOFT code simulated images and spectra will be used to infer information on the runaway distribution function and its evolution in time.
  - Necessary Diagnostics:
    - Runaway Electron and Imaging Spectroscopy (REIS) system
    - Visible and fast infrared cameras



Runaway synchrotron radiation spectrum measured in RE experiments in WEST in 2024 campaign (wavelength range 500-5000 nm)

Proposed pulses

Device	# Pulses/Session	# Development
WEST	20	20

Runaway electrons at plasma start-up in WEST

#62

Priority: P1 – important for starting of the operations in new large tokamaks and adresses D4

- **Proponents and contact person:**
  basilio.esposito@enea.it et al.

- **Scientific Background & Objectives**
  Explore runaway dynamics at start-up: study how the number and energy of runaways depend on plasma start-up conditions and how they vary in time, thus providing input data for extrapolation on ITER.

- **Experimental Strategy/Machine Constraints and essential diagnostic**
  - Perform a detailed comparison in a single device (WEST) of runaway formation at start-up by a systematic scan of some parameters (such as current ramp-up rate and ne)
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Runaway synchrotron radiation spectrum measured in RE experiments in WEST in 2024 campaign (wavelength range 500-5000 nm)

Proposed pulses

Device	# Pulses/Session	# Development
WEST	20	20

Physics of runaway electrons

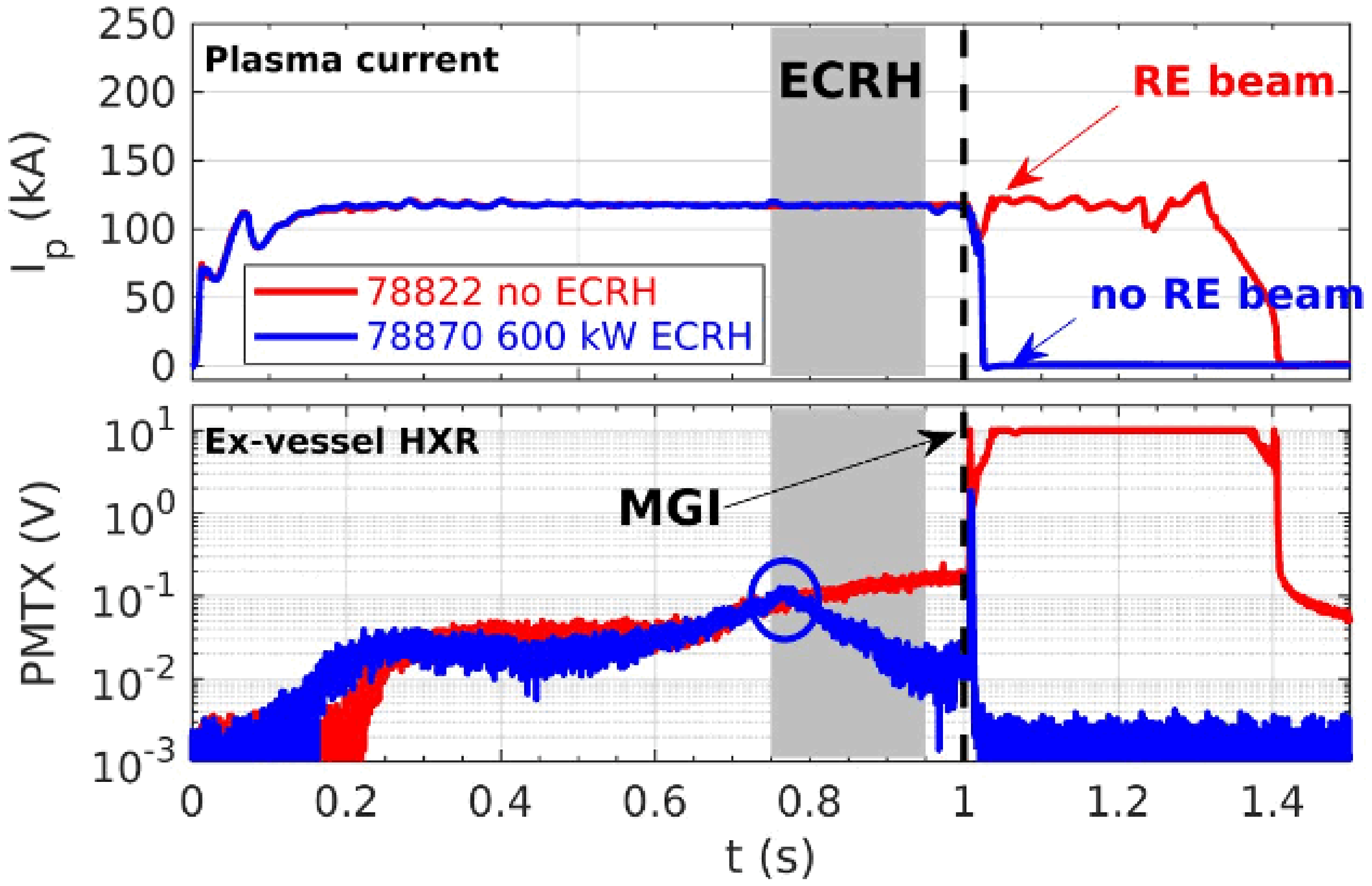
Characterisation of runaway electron transport in TCV and AUG

#45

- **Proponents and contact person:**
  joan.decker@epfl.ch , et al

- **Scientific Background & Objectives**
  - Runaway electrons (REs) are a serious concern for fusion reactors
  - Application of RE modelling codes to fusion reactors requires better predictive models for RE transport and confinement
  - Recent experiments show that external heating and MHD impact RE transport
  - **Objectives** : characterise RE transport before, during and after disruptions
    - Identify mechanisms behind enhanced seed RE transport during ECRH/NBH
    - Study impact of ECRH/NBH on RE beam formation during disruptions
    - Explore the effect of plasma waves & instabilities on RE confinement

- **Experimental Strategy/Machine Constraints and essential diagnostic**
  - Using new and upgraded diagnostics for RE transport and plasma instabilities
    - Apply ECRH/NBH in the presence of RE seed, vary heating & plasma parameters
    - Apply ECRH/NBH during or after the disruption, vary heating & MGI parameters
    - Study interplay between RE current/transport and MHD equilibrium/stability
  - **Essential non-standard diagnostics**
    - TCV : HXRS, LaBrDoRE, BGO, ECE, FILD, SPR, TPCI, MANTIS, IR, RADCAM, ICE, LHPD, PDI
    - AUG : COO interferometer, bolometry, fast visible cameras, fast IR camera, HXR, ECE



J. Decker et al, Nucl. Fusion 64 106027 (2024)

Proposed pulses

Device	# Pulses/Session	# Development
AUG	4	0
MAST-U		
TCV	60	20
WEST		

Characterisation of runaway electron transport in TCV and AUG

#45

- **Proponents and contact person:**
  joan.decker@epfl.ch , et al

- **Scientific Background & Objectives**
  - Runaway electrons (REs) are a serious concern for fusion reactors
  - Application of RE modelling codes to fusion reactors requires better predictive models for RE transport and confinement
  - Recent experiments show that external heating and MHD impact RE transport
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    - Identify mechanisms behind enhanced seed RE transport during ECRH/NBH
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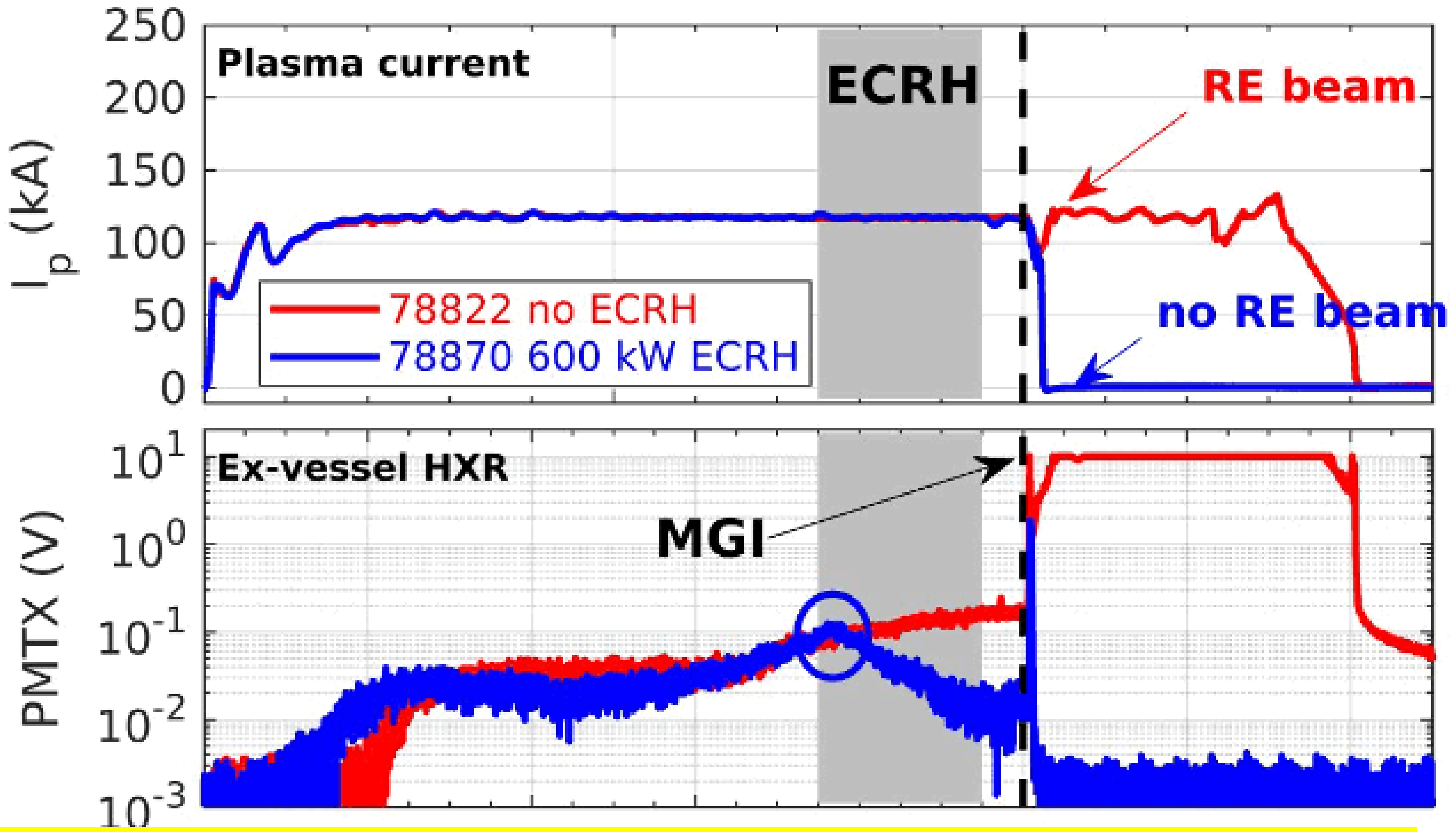


Priority: P1 – adresses D3 and D4

J. Decker et al, Nucl. Fusion 64 106027 (2024)

- **Experimental Strategy/Machine Constraints and essential diagnostic**
  - Using new and upgraded diagnostics for RE transport and plasma instabilities
    - Apply ECRH/NBH in the presence of RE seed, vary heating & plasma parameters
    - Apply ECRH/NBH during or after the disruption, vary heating & MGI parameters
    - Study interplay between RE current/transport and MHD equilibrium/stability
  - **Essential non-standard diagnostics**
    - TCV : HXRS, LaBrDoRE, BGO, ECE, FILD, SPR, TPCI, MANTIS, IR, RADCAM, ICE, LHPD, PDI
    - AUG : COO interferometer, bolometry, fast visible cameras, fast IR camera, HXR, ECE

Proposed pulses

Device	# Pulses/Session	# Development
AUG	4	0
MAST-U		
TCV	60	20
WEST		

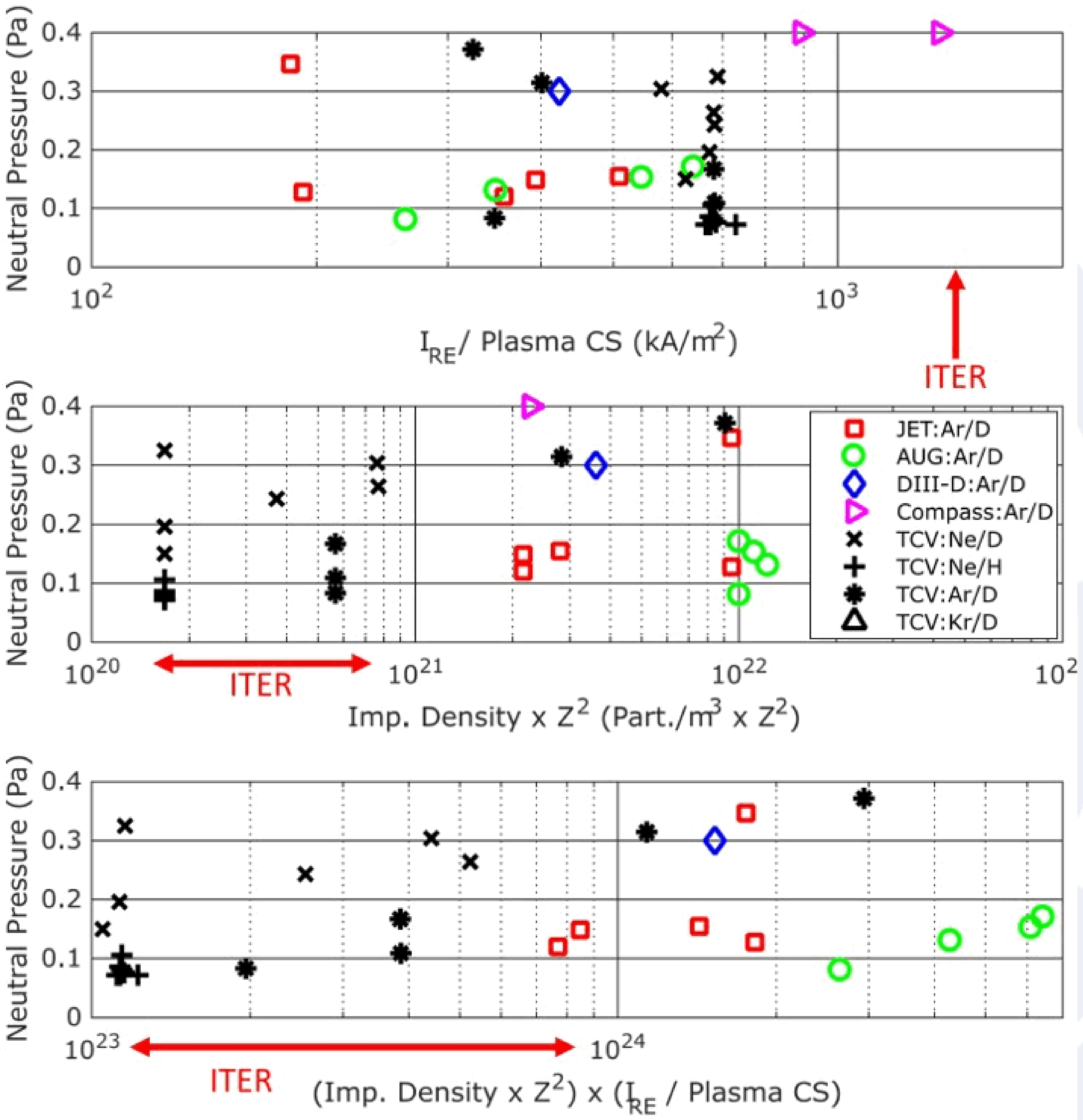
#47

Benign Termination of RE Beams on TCV, AUG and WEST

- **Proponents and contact person:**
  Umar Sheikh (umar.sheikh@epfl.ch) et al.

- **Scientific Background & Objectives**
- RE mitigation is critical for ITER
- Low-Z benign termination may be the solution, explored on AUG, COMPASS, DIII-D, JET and TCV
- Neutral pressure range (upper and lower limit) for technique needs to be determined
- Understanding of the final collapse required
- Modelling is progressing to understand the power balance for scaling between machines (figure) and for extrapolation to ITER and

- **Experimental Strategy/Machine**
- Develop benign termination scenario on WEST
- Explore timescales of recombination for lower limit on TCV and AUG (MGI vs SPI)
- Define upper limit in neutral pressure and RE current scaling (TCV+AUG+WEST)
- Quantify RE current quench rate at extreme pressures for extrapolation to ITER (TCV)
- Study of path to low q-edge, including VDEs (TCV)
- Scaling of Bt for final collapse (TCV)
- Exploit the new IR camera views to get 3D information on the final collapse of the RE beam (TCV)



Device	# Pulses/Session	# Development
AUG	21	8
MAST-U	0	0
TCV	85	20
WEST	Scenario required	20

Benign Termination of RE Beams on TCV, AUG and WEST

#47

Priority: P1 – adresses D4 and inportant for ITER/DEMO but requires a lot of pulses for scans in AUG. Can be partially done without AUG.

- **Proponents and contact person:**
  Umar Sheikh (umar.sheikh@epfl.ch) et al.

- **Scientific Background & Objectives**
  - RE mitigation is critical for ITER
  - Low-Z benign termination may be the solution, explored on AUG, COMPASS, DIII-D, JET and TCV
  - Neutral pressure range (upper and lower limit) for technique needs to be determined
  - Understanding of the final collapse required
  - Modelling is progressing to understand the power balance for scaling between machines (figure) and for extrapolation to ITER and

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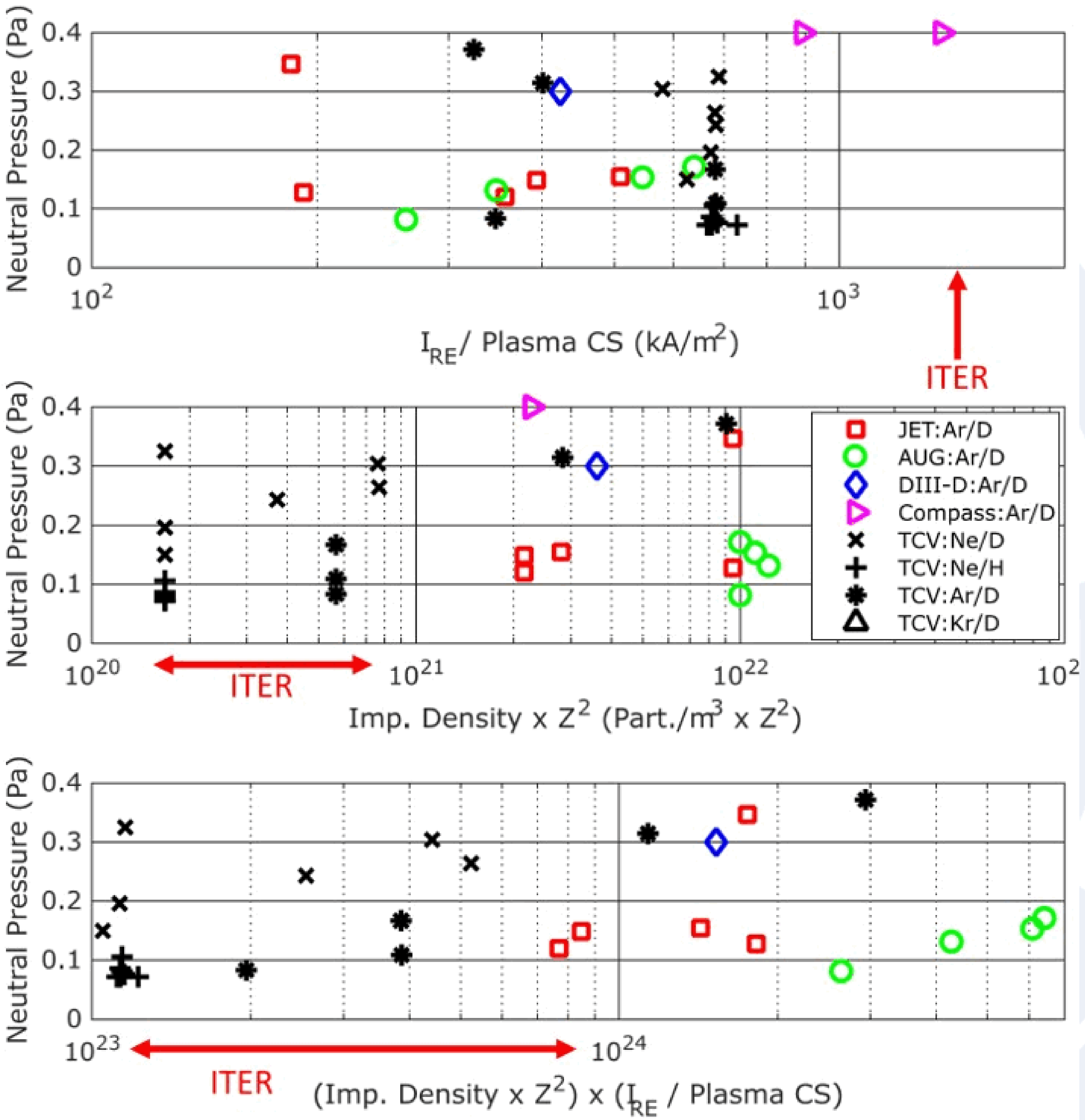
  - Develop benign termination scenario on WEST
  - Explore timescales of recombination for lower limit on TCV and AUG (MGI vs SPI)
  - Define upper limit in neutral pressure and RE current scaling (TCV+AUG+WEST)
  - Quantify RE current quench rate at extreme pressures for extrapolation to ITER (TCV)
  - Study of path to low q-edge, including VDEs (TCV)
  - Scaling of Bt for final collapse (TCV)
  - Exploit the new IR camera views to get 3D information on the final collapse of the RE beam (TCV)

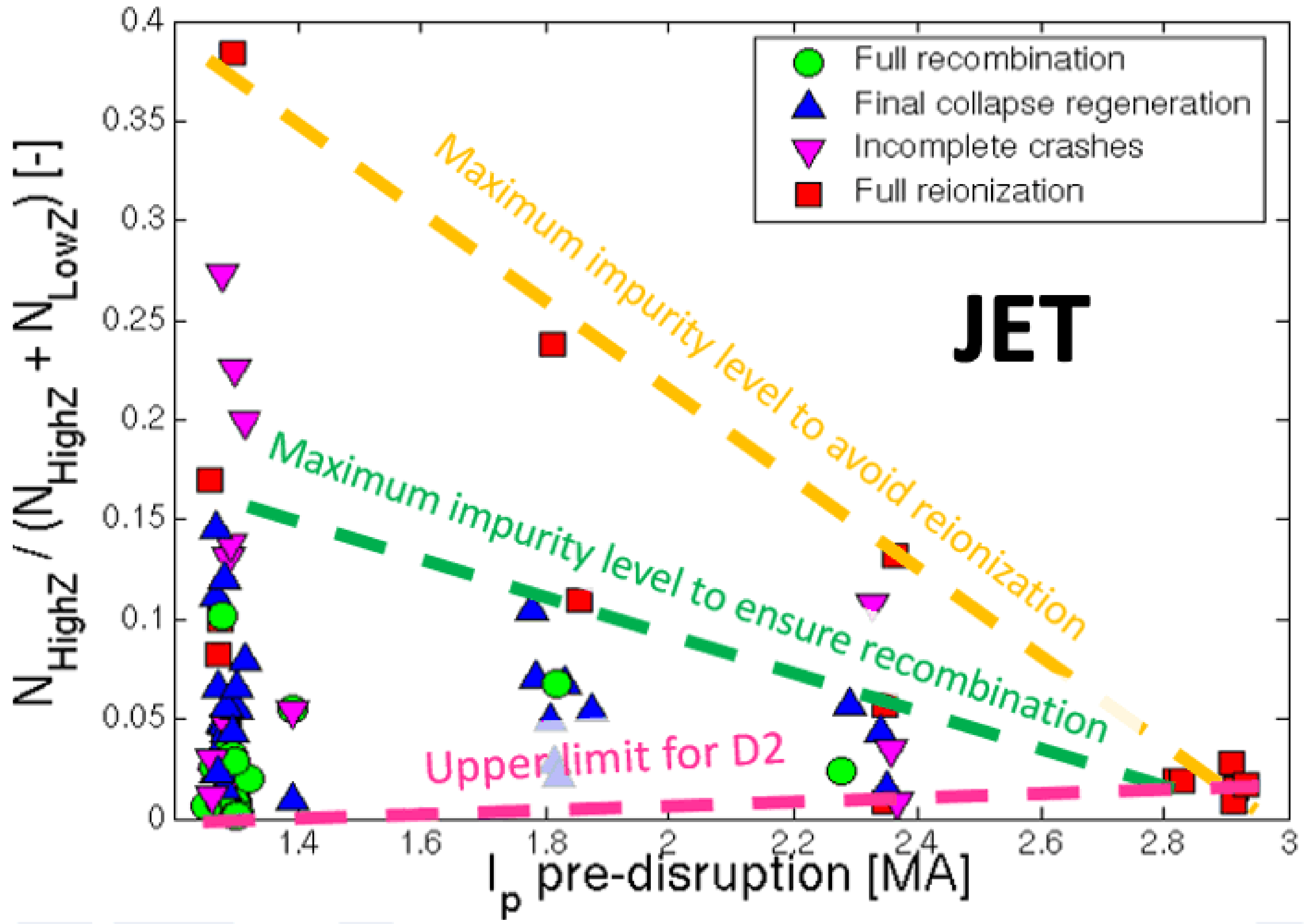


Device	# Pulses/Session	# Development
AUG	21	8
MAST-U	0	0
TCV	85	20
WEST	Scenario required	20

Identity experiments for benign termination of runaways on WEST, AUG and TCV

#55

- **Proponents and contact person:** cedric.reux@cea.fr
- **Scientific Background & Objectives**
  - Recent experiments on JET/TCV/AUG have established scalings (I_{RE}, N_{D2}, N_{Ar}, …) for the efficiency of benign termination scenario
  - But other scalings are unclear: initial plasma current, runaway current density, injection timing, final collapse conditions, maximum low-Z pressure allowed, H_2 vs. D_2…
  - Need to design the experiments so that results can be compared straight away between machines.
- **Experimental Strategy/Machine Constraints and essential diagnostic**
  - Impurity quantities : impact on the recombination and on the collapse *(normalized to vessel volume)*
  - Scan in initial plasma current
  - Scan in Toroidal field to change the runaway current density
  - Scan in injection timing *(normalized to vessel radius – pellet/gas transit time)*
  - Scan in compression speed *(normalized to vessel radius)*
  - Comparison between single vs. multiple injections
  - Benign termination with VDEs
  - Upper limit of H_2 vs D_2 *(normalized to VV volume)*
  - Multiple reionization/recombination cycles



Proposed pulses

Device	# Pulses/Session	# Development
AUG	42	
MAST-U		
TCV	42	
WEST	42	10

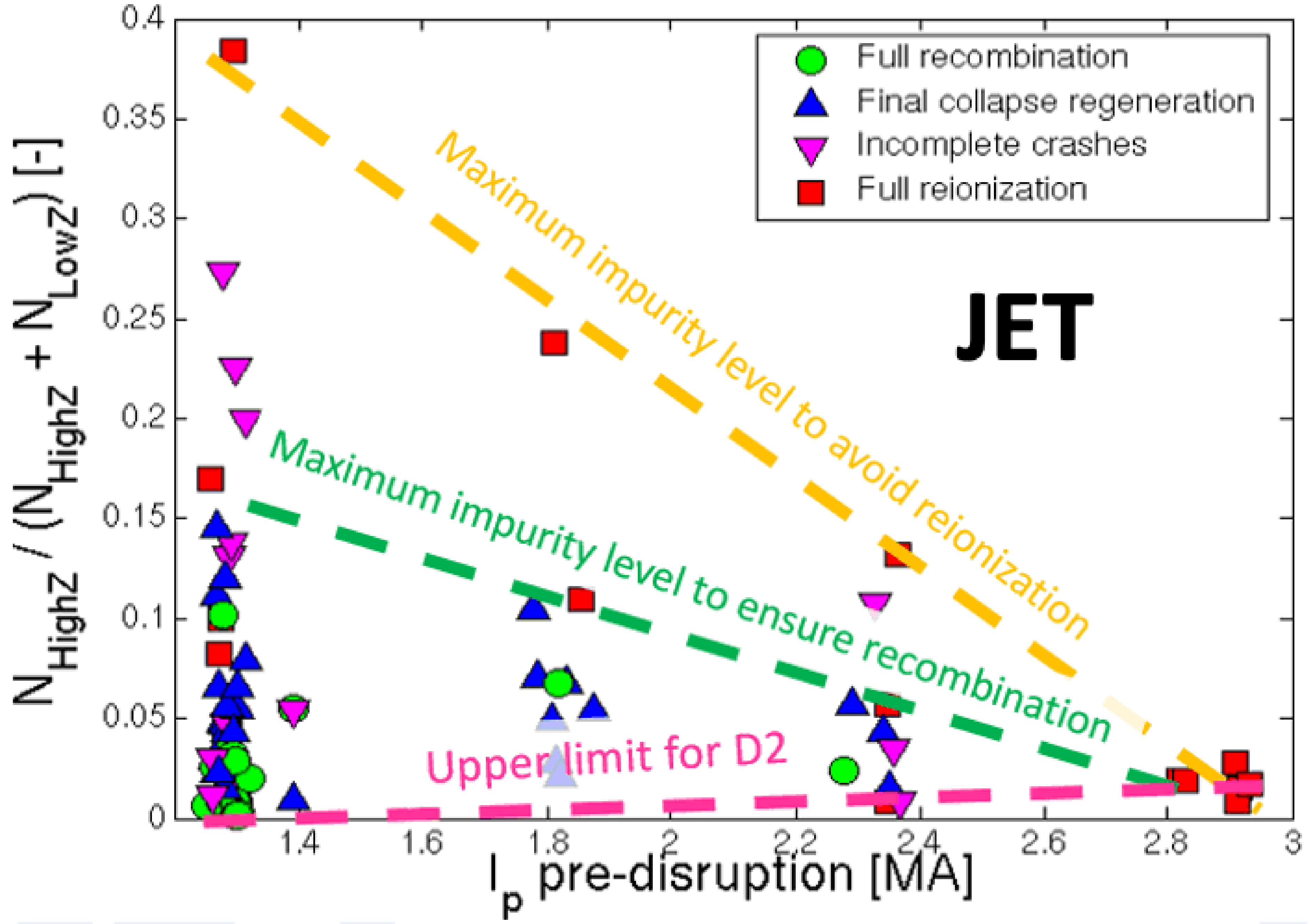
Identity experiments for benign termination of runaways on WEST, AUG and TCV

#55

- **Proponents and contact person:** cedric.reux@cea.fr
- **Scientific Background & Objectives**
  - Recent experiments on JET/TCV/AUG have established scalings (I_{RE}, N_{D2}, N_{Ar}, …) for the efficiency of benign termination scenario
  - But other scalings are unclear: initial plasma current, runaway … injection timing, final collapse conditions, … pressure allowed, H_2 vs. D_2…
  - … the experiments so that results can be compared … between machines.

Priority: P1 – adresses D4 and inportant for ITER/DEMO. Clear candidate as complimentary proposal for #47

- **…rategy/Machine Constraints and …ostic**
  - …pact on the recombination and on the collapse *(normalized to vessel volume)*
  - …rrent
  - … change the runaway current density
  - … *(normalized to vessel radius – pellet/gas transit time)*
  - … …eed *(normalized to vessel radius)*
  - Comparison between single vs. multiple injections
  - Benign termination with VDEs
  - Upper limit of H_2 vs D_2 *(normalized to VV volume)*
  - Multiple reionization/recombination cycles



Proposed pulses

Device	# Pulses/Session	# Development
AUG	42	
MAST-U		
TCV	42	
WEST	42	10

Disruption study at ultra-low q95 < 2

#48

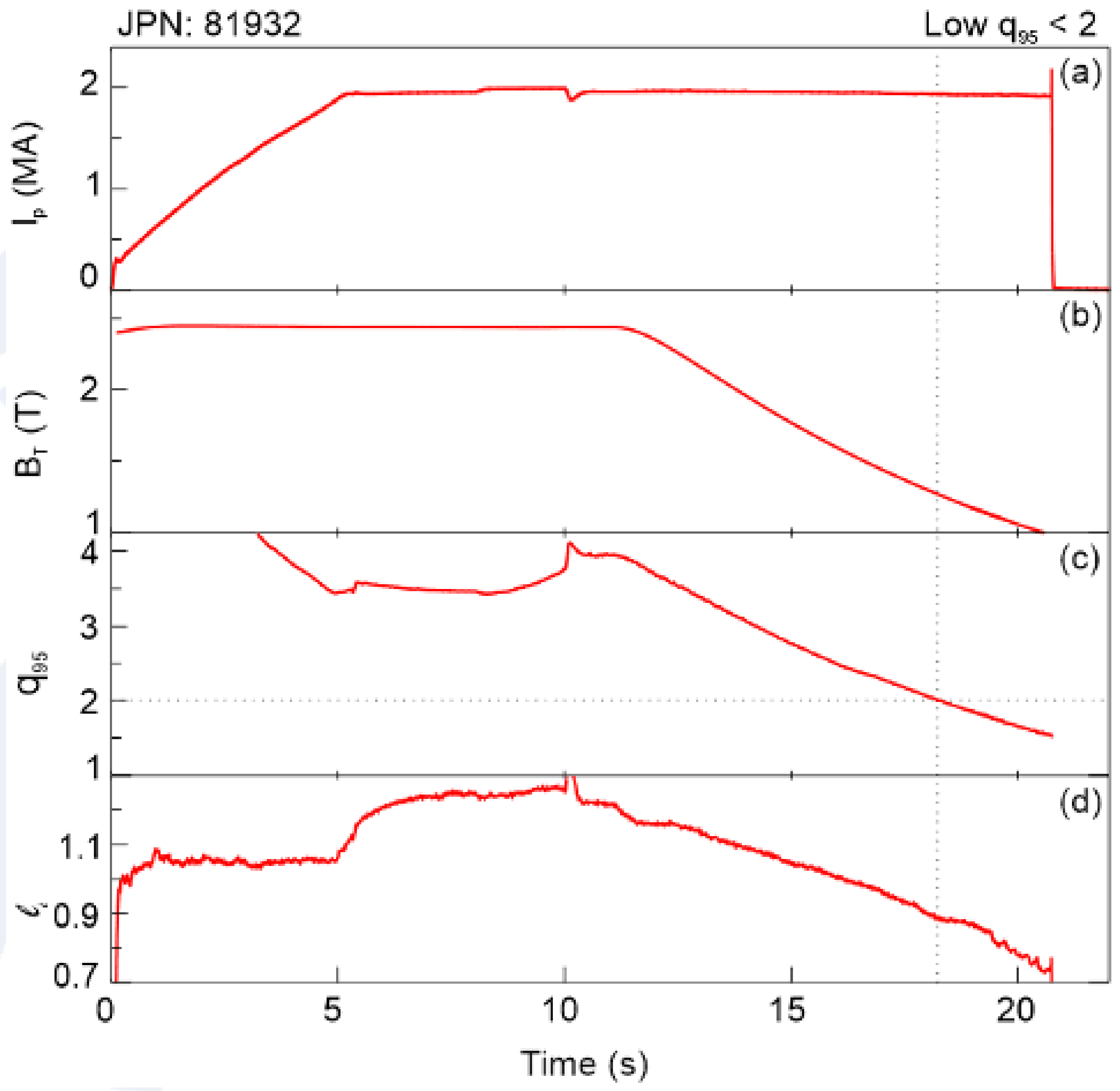
- **Proponents and contact person:**
  sergei.gerasimov@ukaea.uk et a.

- **Scientific Background & Objectives**
  - It is now widely believed that the tearing mode at q=2 is responsible for the disruptions (natural, VDE, SPI/MGI initiated). Accordingly, models are being developed that require the presence of q = 2 inside plasma. However, on JET it was shown that in VDE q95 drops to unity and non-disruptive plasma survived at low q95 down to ~1.5, see Figure.
  - Studying the nature of disruption under extreme conditions (low q95 ~ 1.5) will help to better understand the physics of disruptions and improve models
  - Investigate the q95 limits in natural disruptions (AUG, MAST-U, TCV)

  \- Thermal Quench characterization (AUG, MAST-U, TCV)
  - Study effect of pellet(AUG) and MGI(AUG&TCV) on plasma with q95 < 2

  \- Characterization of interaction of pellet/MGI with low q < 2 plasma (AUG&TCV)

- **Experimental Strategy/Machine Constraints and essential diagnostic**
  - Develop a low q95 < 2 plasma scenario, mainly using JET method (AUG, MAST-U, TCV)
    - ECE, TS, MHD, SXR, Fast cameras as essential diagnostic
  - Inject pellet/MGI to plasma with q95 < 2 (AUG&TCV)



JET low q X-point plasma scenario

Proposed pulses

Device	# Pulses/Session	# Development
AUG	9 pulses	3
MAST-U	15 pulses	5
TCV	25 pulses	5
WEST	N/A	N/A

Disruption study at ultra-low q95 < 2

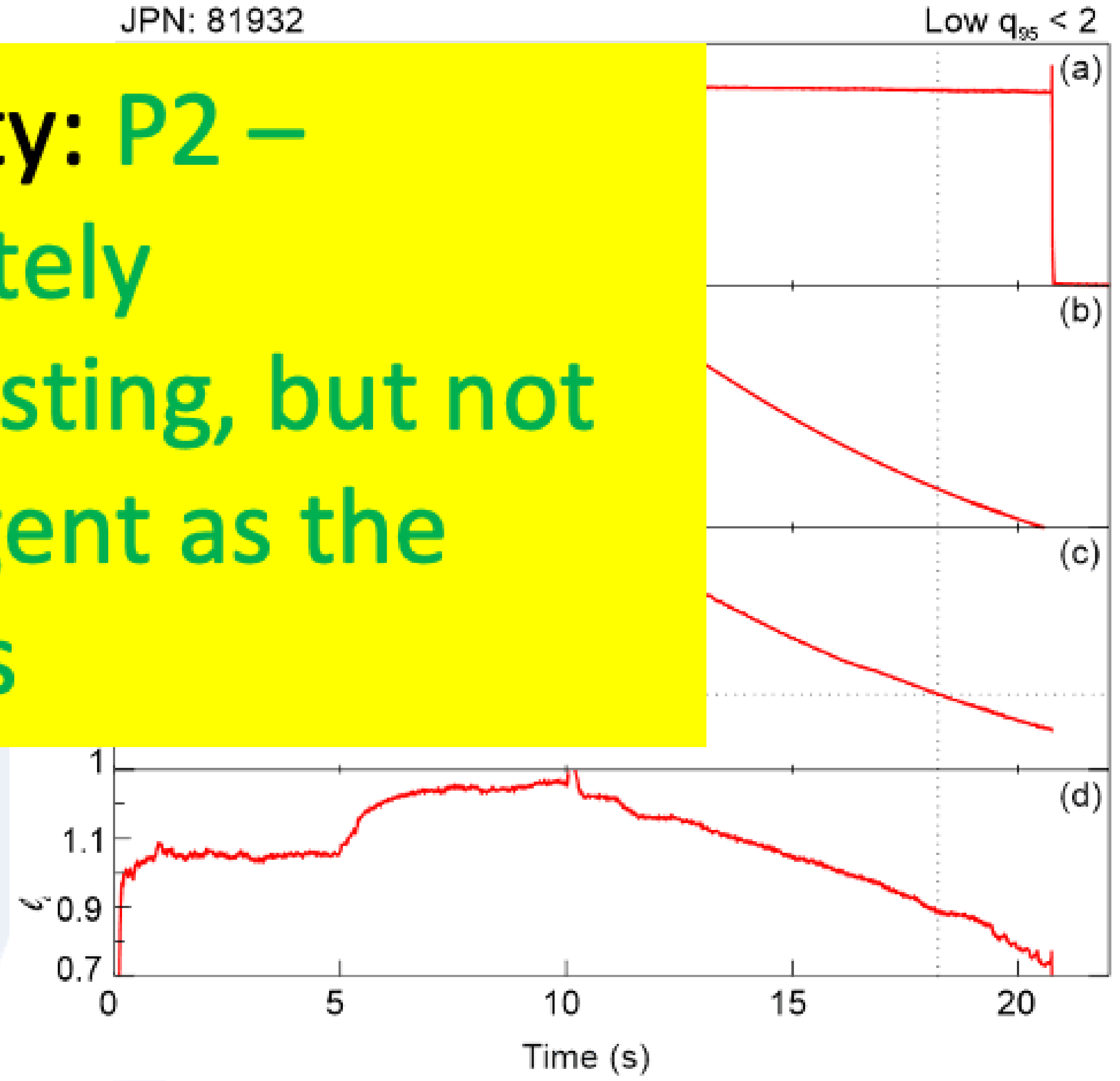
#48

Priority: P2 – definitely interesting, but not so urgent as the others

- **Proponents and contact person:**
  sergei.gerasimov@ukaea.uk et a.

- **Scientific Background & Objectives**
  - It is now widely believed that the tearing mode at q=2 is responsible for the disruptions (natural, VDE, SPI/MGI initiated). Accordingly, models are being developed that require the presence of q = 2 inside plasma. However, on JET it was shown that in VDE q95 drops to unity and non-disruptive plasma survived at low q95 down to ~1.5, see Figure.
  - Studying the nature of disruption under extreme conditions (low q95 ~ 1.5) will help to better understand the physics of disruptions and improve models
  - Investigate the q95 limits in natural disruptions (AUG, MAST-U, TCV)
  - Thermal Quench characterization (AUG, MAST-U, TCV)
  - Study effect of pellet(AUG) and MGI(AUG&TCV) on plasma with q95 < 2
  - Characterization of interaction of pellet/MGI with low q < 2 plasma (AUG&TCV)

- **Experimental Strategy/Machine Constraints and essential diagnostic**
  - Develop a low q95 < 2 plasma scenario, mainly using JET method (AUG, MAST-U, TCV)
    - ECE, TS, MHD, SXR, Fast cameras as essential diagnostic
  - Inject pellet/MGI to plasma with q95 < 2 (AUG&TCV)



JET low q X-point plasma scenario

Proposed pulses

Device	# Pulses/Session	# Development
AUG	9 pulses	3
MAST-U	15 pulses	5
TCV	25 pulses	5
WEST	N/A	N/A

Tungsten influence on RE dynamics

#59

- **Proponents and contact person:**

Ondřej Ficker ficker@ipp.cas.cz
Umar Sheikh, Cédric Reux, Jedrzej Walkowiak, Vladislav Plyusnin, Sergei Gerasimov

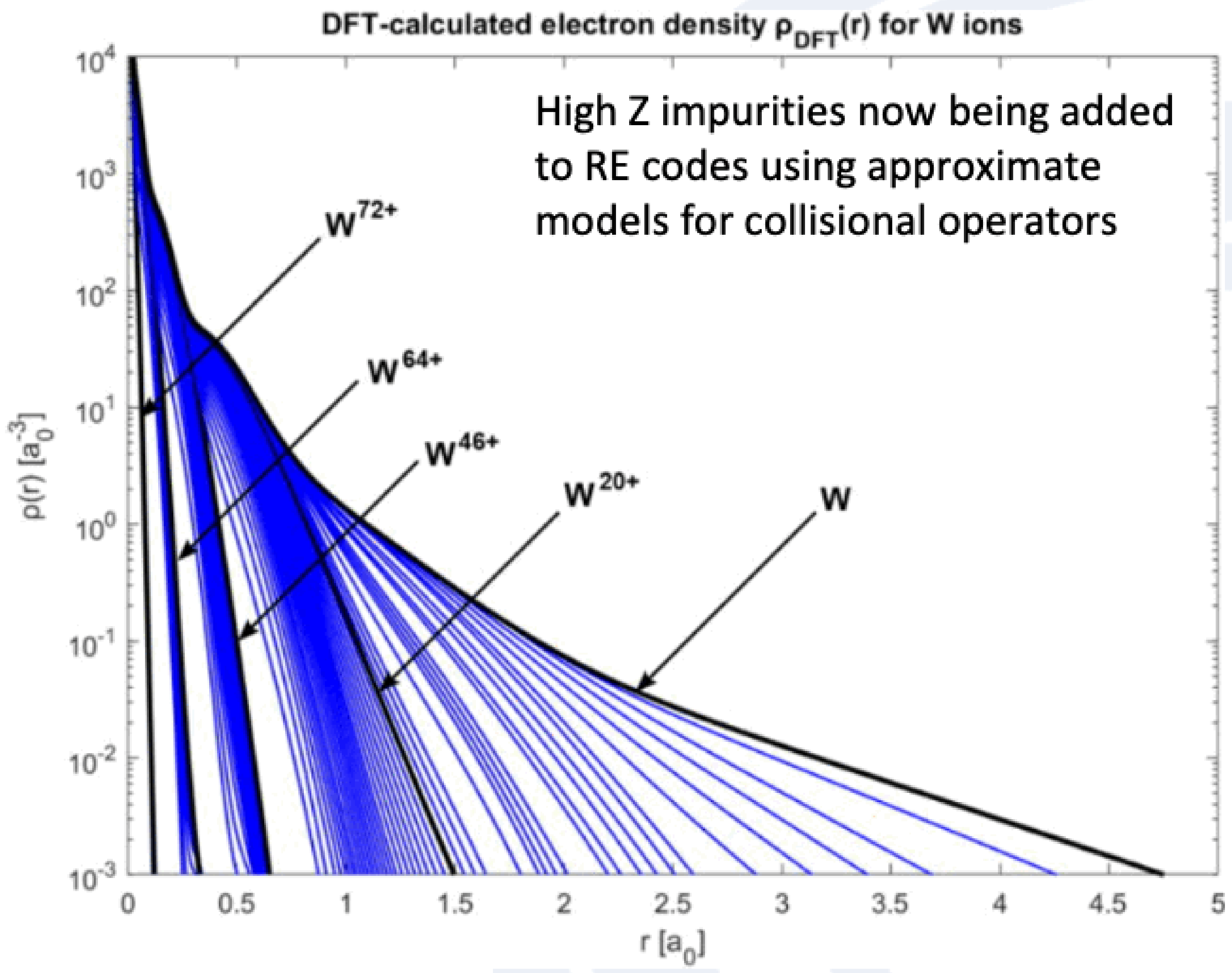
- **Scientific Background & Objectives**
  - New ITER baseline – W important during disruption and RE beam
  - Modelling efforts ongoing – W effects being added to DREAM

  Objectives:
  - Design scenario with enhanced W concentration during disruption with RE generation
  - Quantify the effect of tungsten if possible

- **Experimental Strategy/Machine Constraints and essential diagnostic**

  Standard RE beam generation scenario for AUG and WEST + tungsten laser blow-off
  - Optimise timing of W LBO during MGI/SPI disruption with RE beam generation
  - Run scan in the pre-disruption current/and or W concentration (if controlled variation is possible)

  RE diagnostics, bolometers/SXR, W spectroscopy



[Walkowiak et al. *Phys. Plasmas* 29, 022501 (2022)]

Proposed pulses

Device	# Pulses/Session	# Development
AUG	4	1
MAST-U	-	-
TCV	-	-
WEST	3	1

Tungsten influence on RE dynamics

#59

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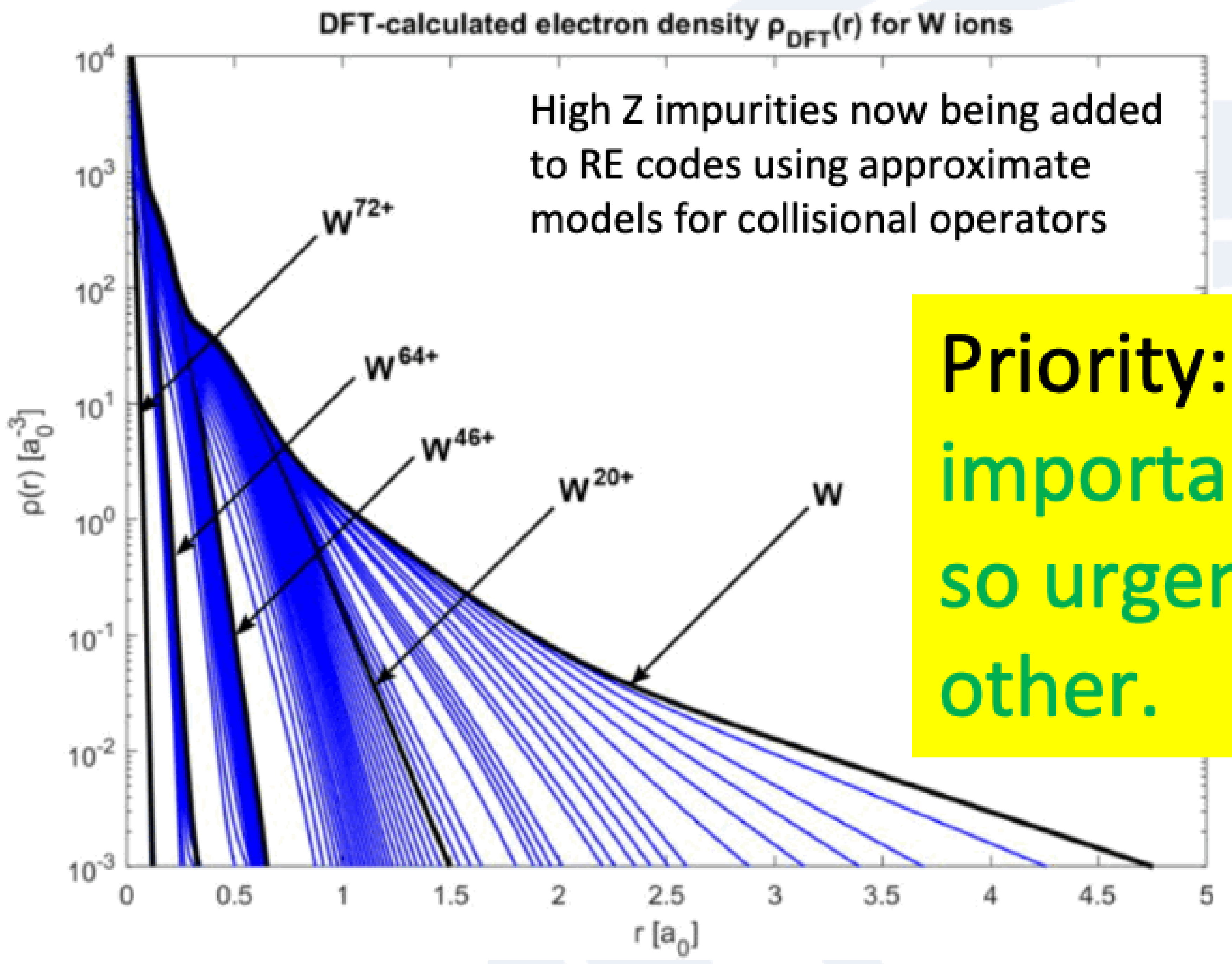


[Walkowiak et al. *Phys. Plasmas* 29, 022501 (2022)]

Priority: P2 – important, but not so urgent as the other.

Proposed pulses

Device	# Pulses/Session	# Development
AUG	4	1
MAST-U	-	-
TCV	-	-
WEST	3	1

#60

Limiter-less RE beam compression at TCV

- **Proponents and contact person:**
  Ondřej Ficker ficker@ipp.cas.cz
  Umar Sheikh, Sergei Gerasimov

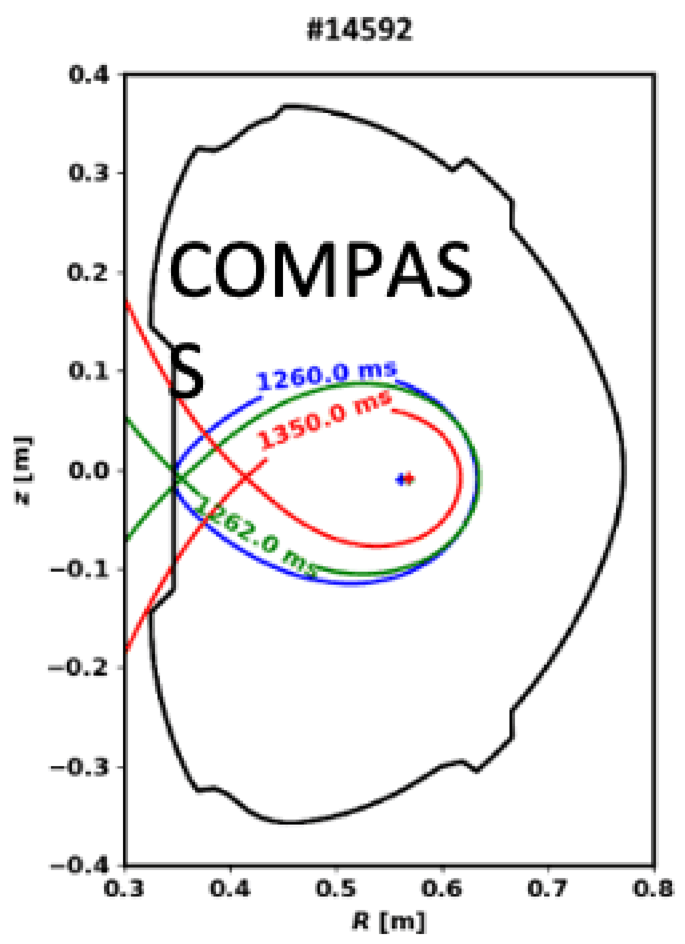
- **Scientific Background & Objectives**
  - LOW q, safe RE beam terminaiton without confined volume-limiter contact observed on COMPASS
  - HFS X-point observed on TCV as well

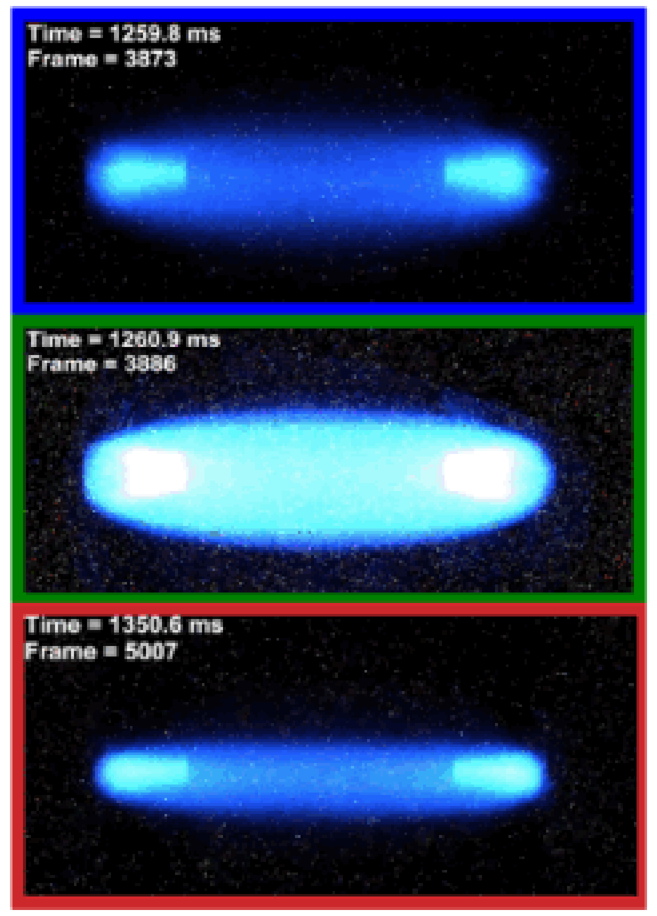
  Objectives:
  - Characterise this termination configuration
  - Find out wheter similar method is accessible at the larger machines
  - Can this regime help understaning “standard” benign termination?

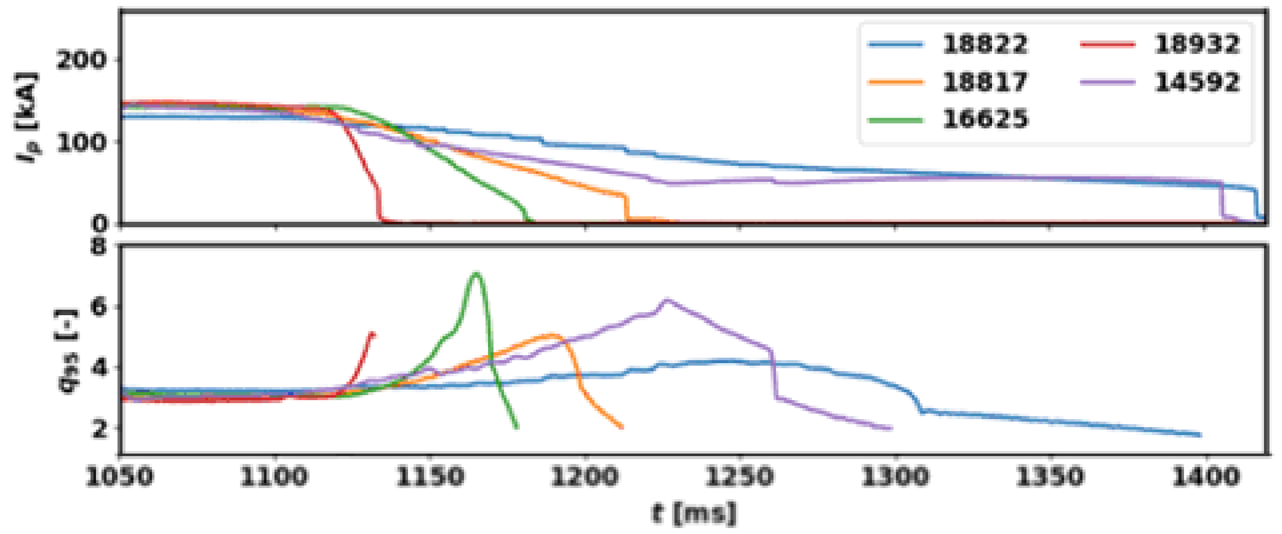
- **Experimental Strategy/Machine Constraints and essential diagnostic**

  Standard TCV RE beam scenario (low n_e, 200 kA/1.44T + Ne or Ar MGI) + modification of position/shape control
  - Understand options to vary $B_v(R)$ with TCV PF coils
  - Prepare optimal compression strategy
  - Scan in suitable parameter (e.g. RE beam current)

  Best available setup for **heat load, HXR** and **synchrotron radiation diagnostic**







Proposed pulses

Device	# Pulses/Session	# Development
AUG	-	-
MAST-U	-	-
TCV	6	3
WEST	-	-

Limiter-less RE beam compression at TCV

#60

Priority: P1 – inportant for runaways beam control.

- **Proponents and contact person:**
  Ondřej Ficker ficker@ipp.cas.cz
  Umar Sheikh, Sergei Gerasimov

Scientific Background & Objectives

- LOW q, safe RE beam terminaiton without confined volume-limiter contact observed on COMPASS
- HFS X-point observed on TCV as well

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- Characterise this termination configuration
- Find out wheter similar method is accessible at the larger machines
- Can this regime help understaning “standard” benign termination?

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  Standard TCV RE beam scenario (low n_e, 200 kA/1.44T + Ne or Ar MGI) + modification of position/shape control
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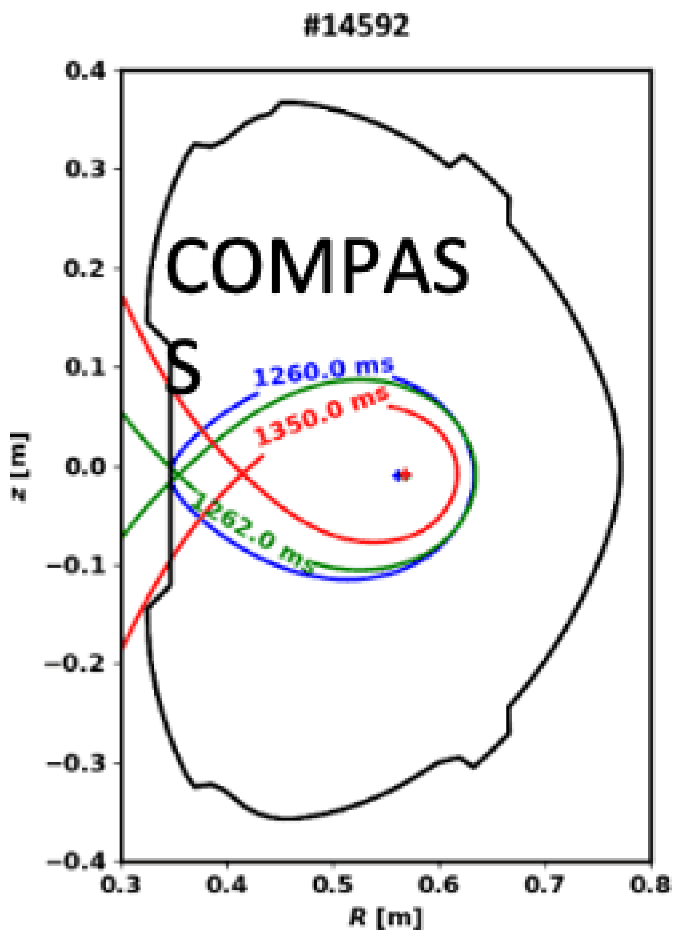

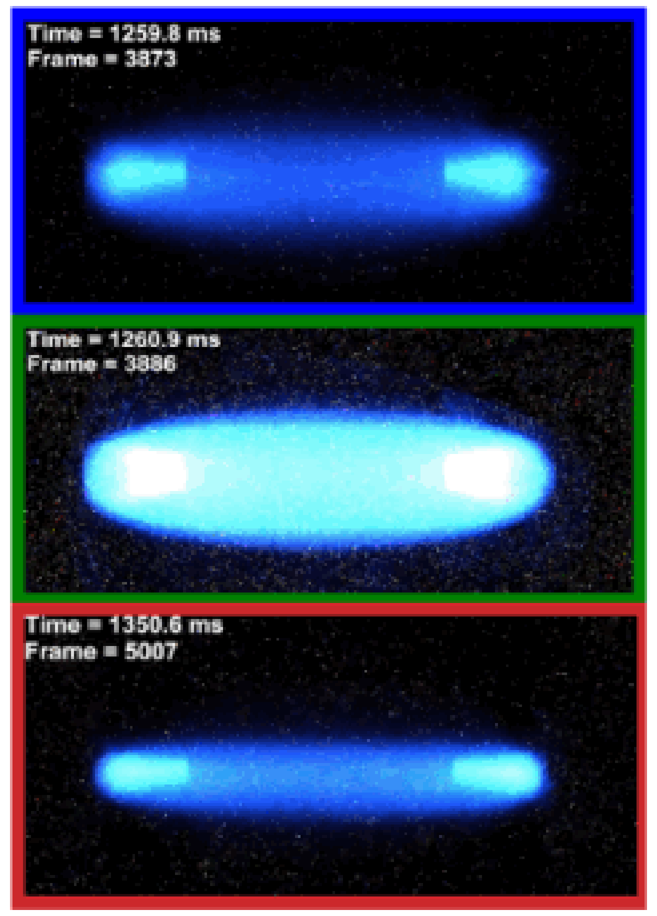

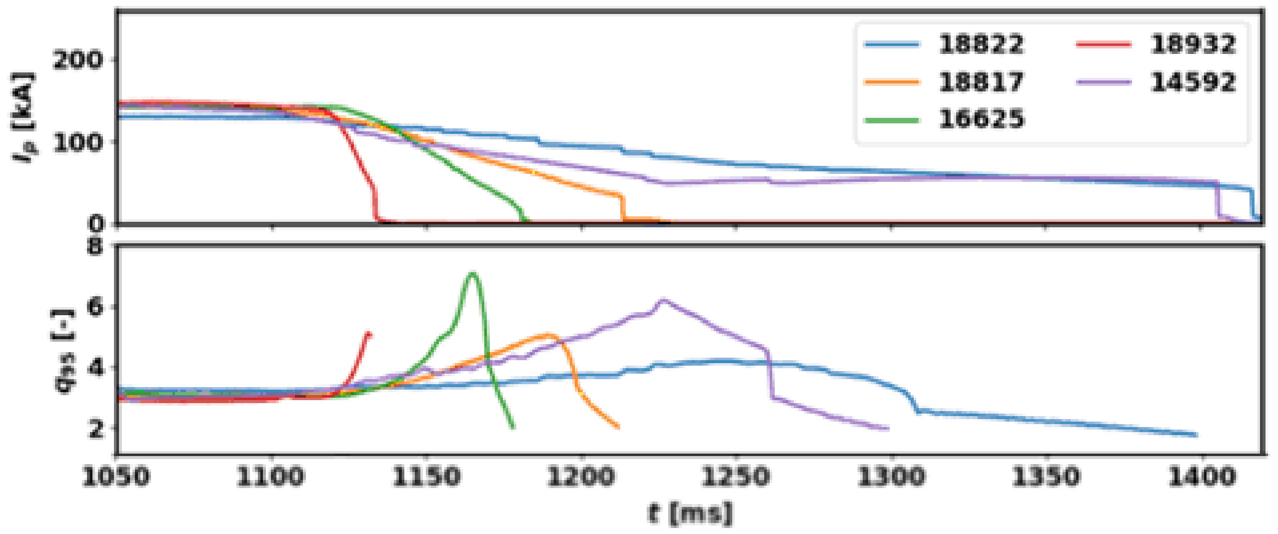

Proposed pulses

Device	# Pulses/Session	# Development
AUG	-	-
MAST-U	-	-
TCV	6	3
WEST	-	-

Machine specific proposals

Control of the runaway electron beam position and shape on WEST

#56

- **Proponents and contact person:** cedric.reux@cea.fr
- **Scientific Background & Objectives**
  - Position control of runaway beams is known to be difficult
  - Only partial control is available for ITER.
  - Benefit to be able to send the runaway beam to less sensitive components
  - Shaping is known to reduce runaway generation (X-point tokamaks need to use limiter shapes to generate them)

- **Experimental Strategy/Machine Constraints and essential diagnostic**

- Position control improvements:
  - Force a voltage request on vertical field coils to pull the plasma away from the inner wall at the disruption. Adjust voltage depending to optimize the beam duration. 4 pulses
  - Repeat on radial field coils if vertical stability becomes an issue. 2 pulses.
- In flight elongation
  - Once a long enough beam is obtained, scan the divertor coil current to elongate the beam. 4 pulses
- If beams are too short despite the position control attempts: comparison of pre-disruption shapes
  - Run a low-elongation X-point shape (minimize the elongation while keeping an Xpoint). 2 pulses for adjustments.
  - Run a high elongation limiter shape (maximize the elongation while keeping a limited shape). 2 pulses for adjustments.

Proposed pulses

Device	# Pulses/Session	# Development
AUG	0	
MAST-U	0	
TCV	0	
WEST	10	10

Control of the runaway electron beam position and shape on WEST

#56

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- **Scientific Background & Objectives**
  - Position control of runaway beams is known to be difficult
  - Only partial control is available for ITER.
  - Benefit to be able to send the runaway beam to less sensitive components
  - Shaping is known to reduce runaway generation (X-point tokamaks need to use limiter shapes to generate them)

Priority: P1 – important for future experiments on effect of runaways on the wall. RT03 develops the scenario and ways to control landing of the RE beam, RT06 then checks what will happen to the wall components

- **Experimental Strategy/Machine Constraints and essential diagnostic**

- Position control improvements:
  - Force a voltage request on vertical field coils to pull the plasma away from the inner wall at the disruption. Adjust voltage depending to optimize the beam duration. 4 pulses
  - Repeat on radial field coils if vertical stability becomes an issue. 2 pulses.
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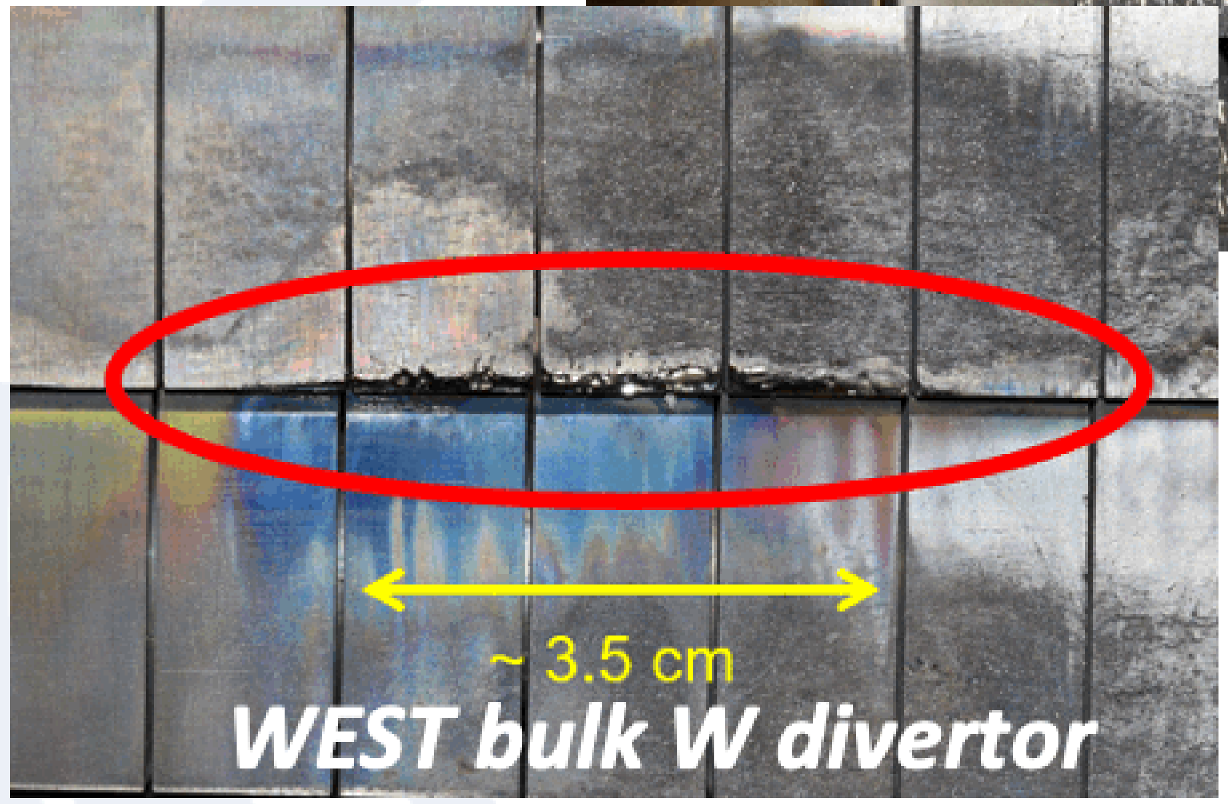
Proposed pulses

Device	# Pulses/Session	# Development
AUG	0	
MAST-U	0	
TCV	0	
WEST	10	10

Post-disruption runaway electron impact studies on WEST

#57

- **Proponents and contact person:** cedric.reux@cea.fr
- **Scientific Background & Objectives**
  - Runaway impact physics is poorly understood
  - Only a few controlled experiments in the past 20 years.
  - Impacts need to be understood to assess the risks for ITER.
  - Goal: reduce uncertainties on :
    - Toroidal asymmetries
    - Impact angles and wetted area
    - Amount of energy deposited : conversion from magnetic to kinetic energy, runaways vs. ohmic power
    - Runaway energy at impact
    - Deposition duration



- **Experimental Strategy/Machine Constraints and essential diagnostic**
  - Repeat an impact scenario to assess the variability of the impact pattern
  - Scan the edge safety factor to change the MHD behaviour at impact
  - Repeat the same runaway beam scenario but move the impact location poloidally
    - Get isolated impacts to facilitate post-mortem analysis
  - Measure the impact characteristics with dedicated diagnostics: thermocouple tile, fast visible and IR cameras, HXR spectrometer (SIGARS), REIS

Proposed pulses

Device	# Pulses/Session	# Development
AUG	0	
MAST-U	0	
TCV	0	
WEST	14	5

Post-disruption runaway electron impact studies on WEST

#57

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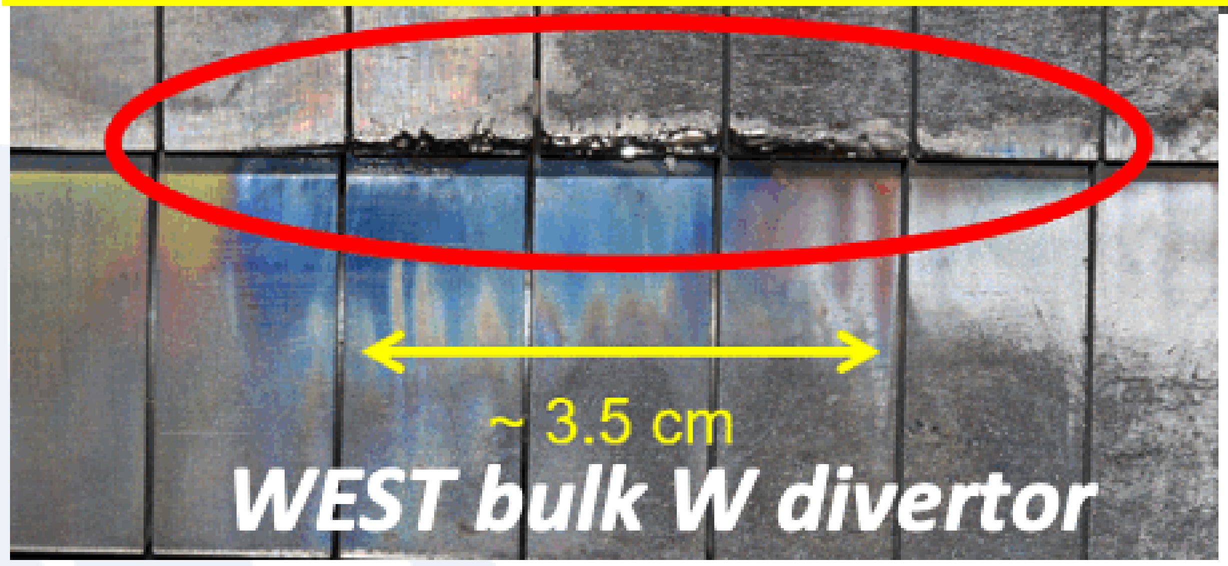
Priority: P1 – important for future ITER/DEMO. Works here in collaboration with RT06.



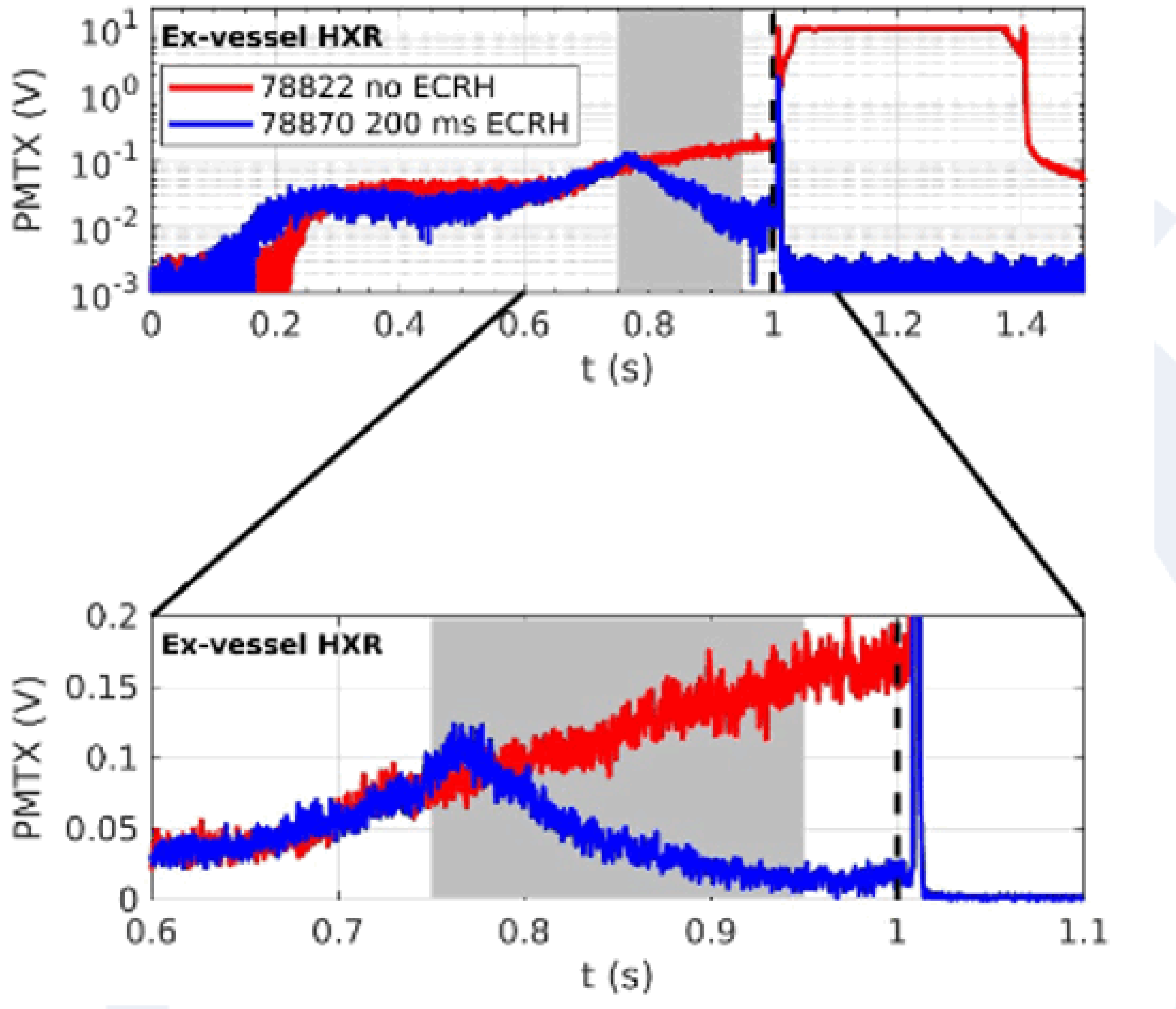
Proposed pulses

Device	# Pulses/Session	# Development
AUG	0	
MAST-U	0	
TCV	0	
WEST	14	5

Influence of ECRH on the runaway formation on WEST

#58

- **Proponents and contact person:** cedric.reux@cea.fr
- **Scientific Background & Objectives**
  - ECRH can be used either to seed runaway electrons (AUG, HL-2A) or to suppress them (TCV, FTU).
  - ECRH is the main plasma heating method for the early operational phases of ITER
  - It will be active starting at breakdown, which is a runaway-prone phase.
  - Studying the effect of ECRH on runaway formation at high field and low density is useful for ITER.



Expulsion of REs by ECRH on TCV [Decker NF 2024]

- **Experimental Strategy/Machine Constraints and essential diagnostic**
  - Scan ECRH power on a low density ohmic limited plasma just above the critical density to form flat-top runaway electrons. Reference pulse 60083 but with density 2.5e19 m^{-2} .Add ECRH in 5 steps of up to 500 kW (or more if available). 5 pulses.
  - Scan ECRH power in a very low density plasma (with runaways) to assess the effect on the runaway population. Reference pulse #60083. Add ECRH in 5 steps up to 500 kW (or more if available).
    - Measure effect of ECRH using dedicated diagnostics: fast visible and IR cameras (+SOFT reconstruction), HXR spectrometer (SIGARS), REIS

Proposed pulses

Device	# Pulses/Session	# Development
AUG	0	
MAST-U	0	
TCV	0	
WEST	10	0

Influence of ECRH on the runaway formation on WEST

#58

Priority: P2 – interesting, but not so urgent as previous two.

- **Proponents and contact person:** cedric.reux@cea.fr
- **Scientific Background & Objectives**
  - ECRH can be used either to seed runaway electrons (AUG, HL-2A) or to suppress them (TCV, FTU).
  - ECRH is the main plasma heating method for the early operational phases of ITER
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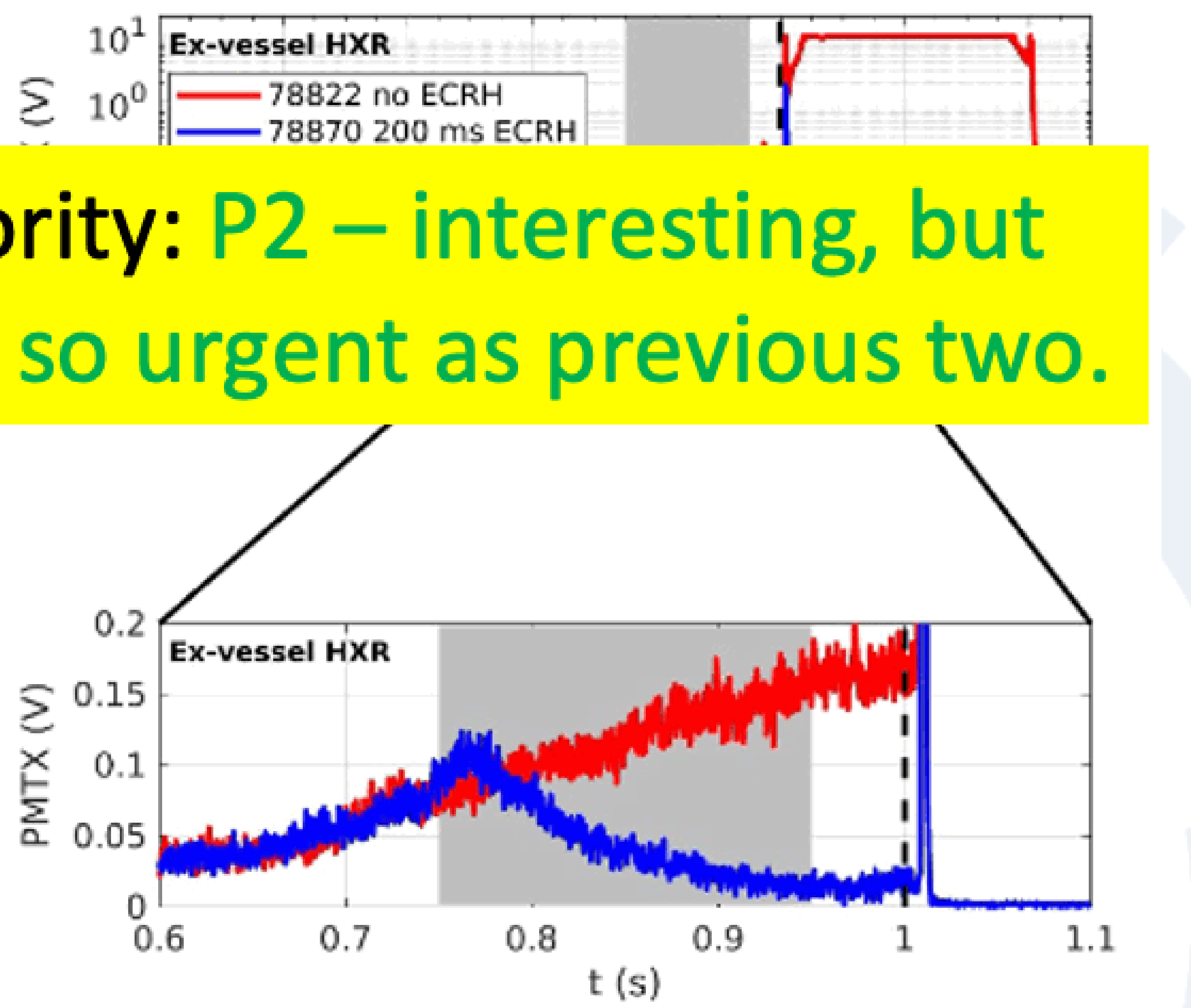

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  - Measure effect of ECRH using dedicated diagnostics: fast visible and IR cameras (+SOFT reconstruction), HXR spectrometer (SIGARS), REIS

Proposed pulses

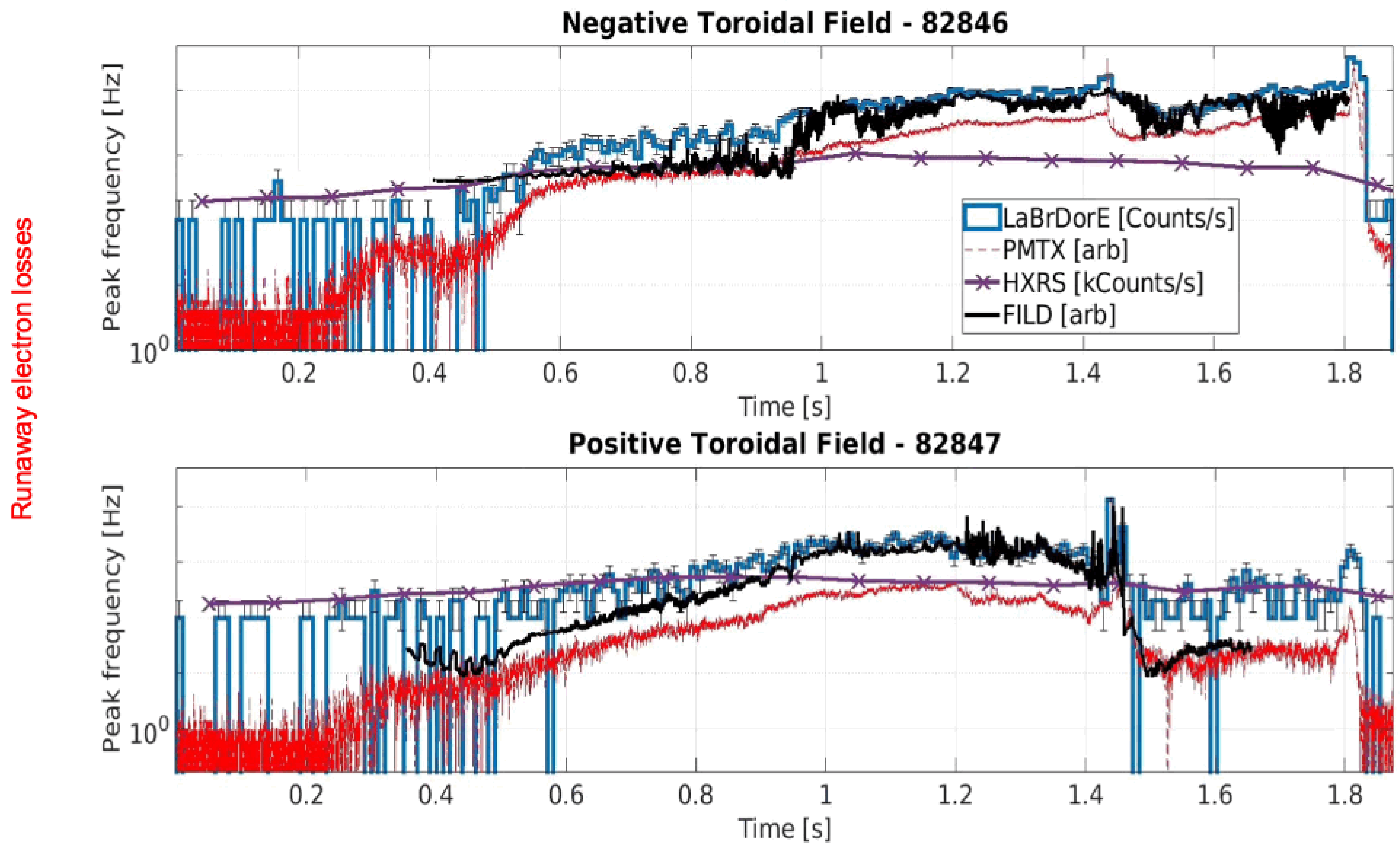
Device	# Pulses/Session	# Development
AUG	0	
MAST-U	0	
TCV	0	
WEST	10	0

Measurement of RE losses (with FILD)

J. Poley-Sanjuán

#201

- Both TCV's FILD cameras observe a signal correlated with multiple Runaway electrons (RE) diagnostics.
- These new measurements can potentially allow us to retrieve the apparent velocity-space of the RE losses.
- Dedicated studies in multiple scenarios on TCV are foreseen to study these RE losses.



Measurement of RE losses (with FILD)

J. Poley-Sanjuán

Priority: P2/PB – it is rather diagnostic development and unclear physical mechanisms

#201

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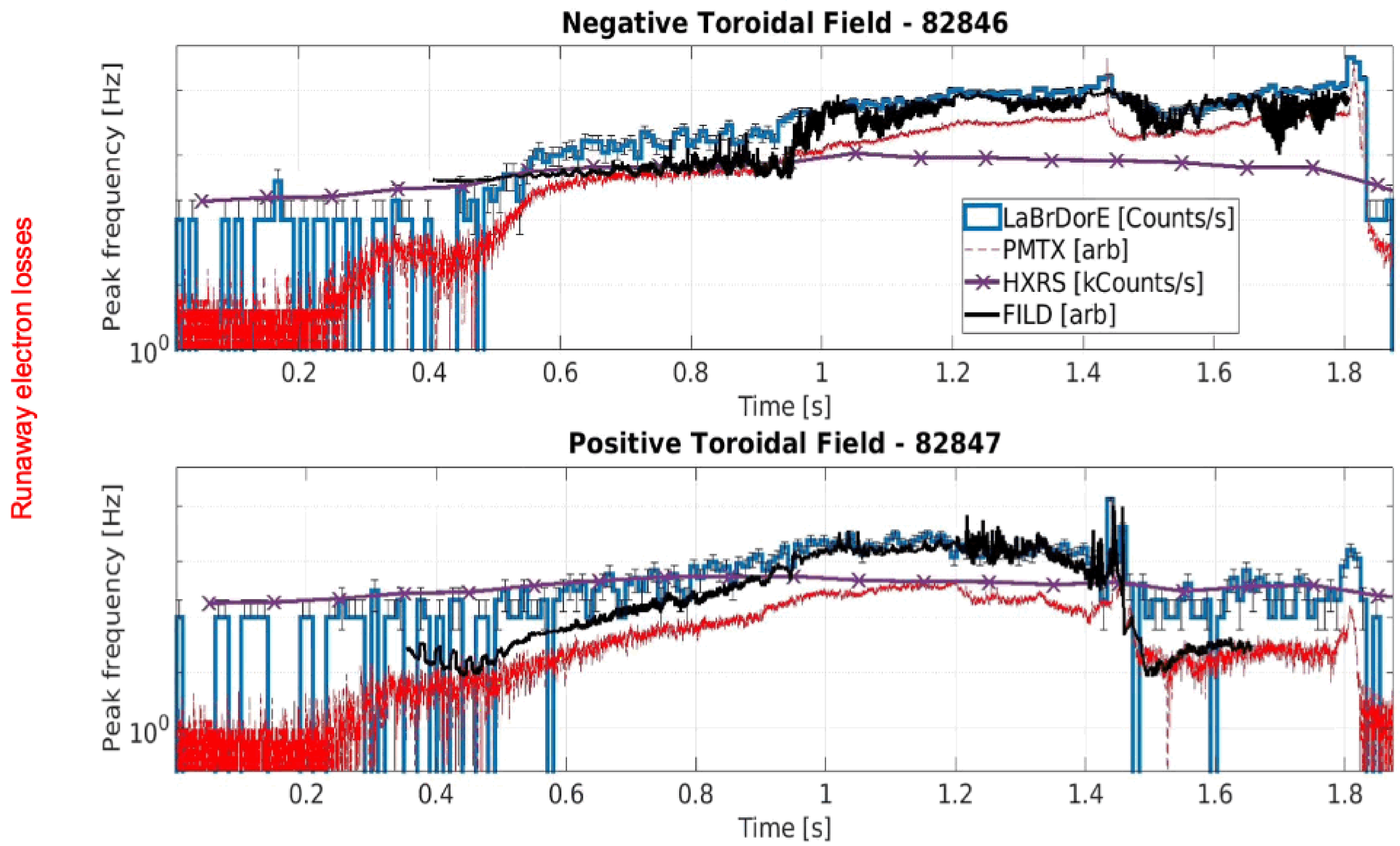


Effect of CQ dynamics and Zeff on RE generation in WEST/TCV/AUG disruptions.

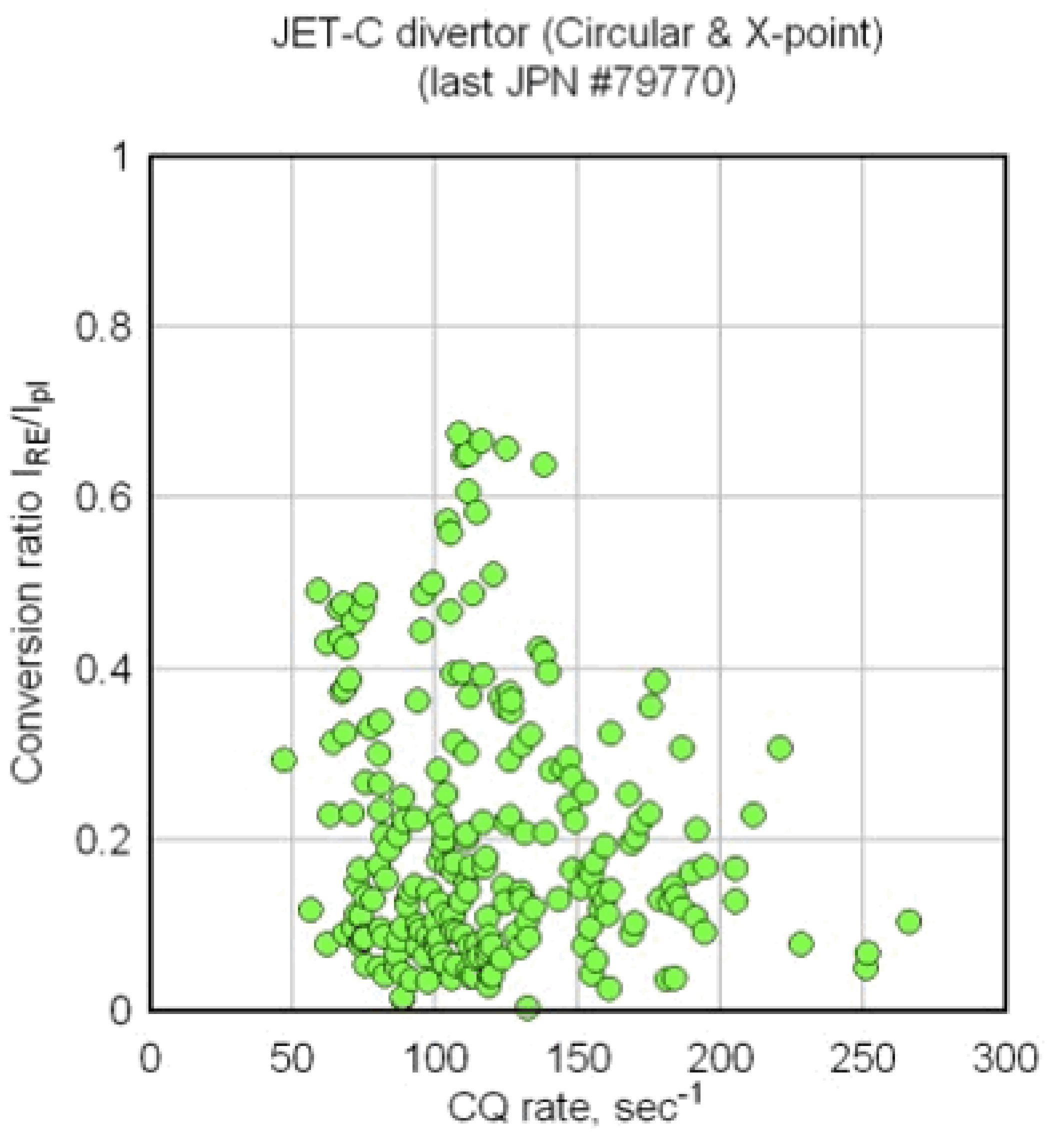
- **Proponents and contact person:**
  vladislav.plyusnin@euro-fusion.org
- **Scientific Background & Objectives**

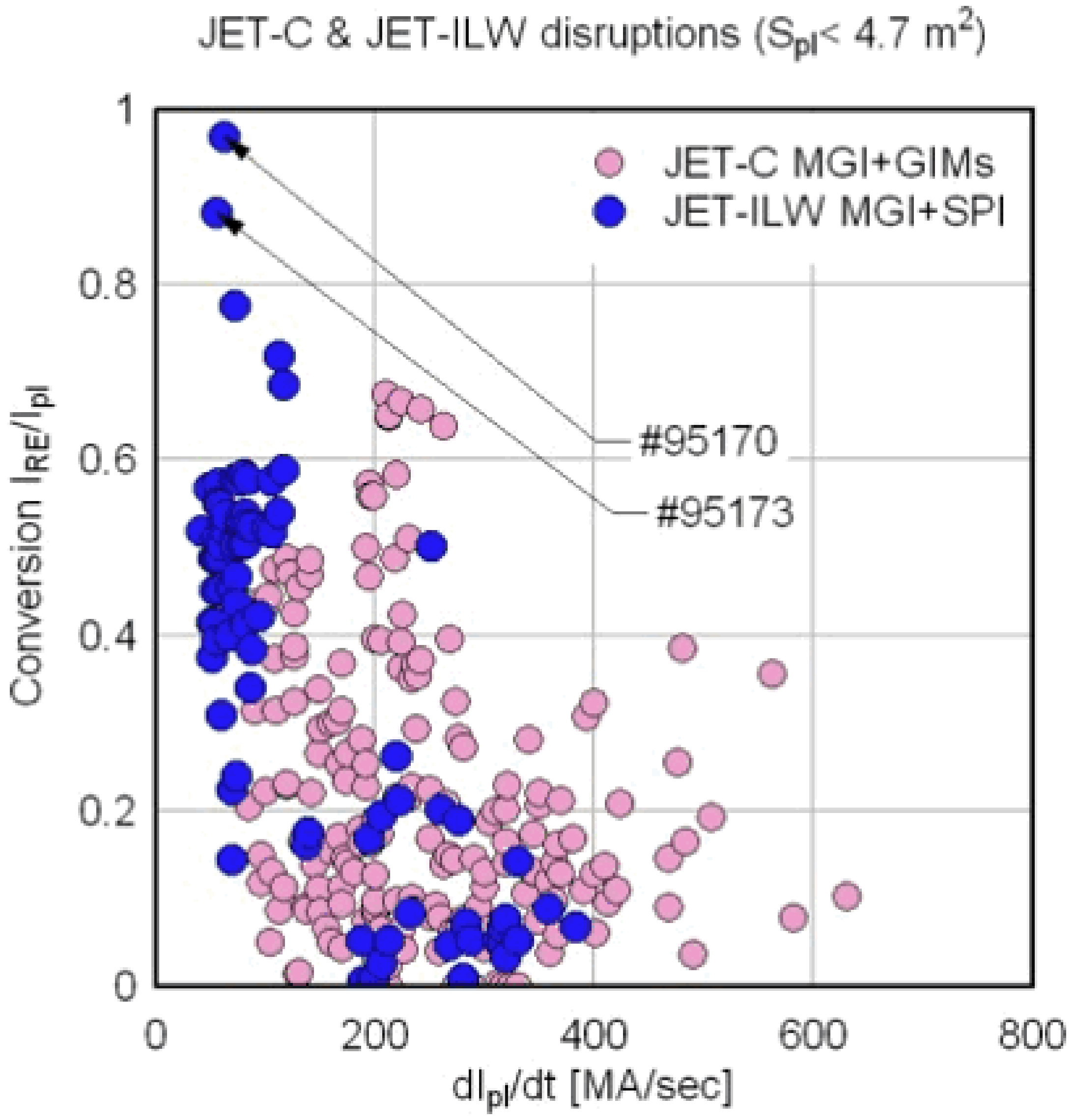
Experiments on RE termination in JET/ TCV/ AUG allowed mapping of benign termination scenario at certain sets of experimental configurations and parameters. However, significant part of data on generation and termination of RE requires addition. clarification and establishing links between TCV/AUG/WEST and JET parameters.

Study of CQ and RE formation stage will help to incorporate the data from different tokamaks and make it predictable RE parameters and those of surrounding plasmas, etc. in wide range of plasma currents and temperature and density.

- **Experimental Strategy/Machine Constraints and essential diagnostic**

•Scan CQ variation in at wide variation of plasma parameters (Ipl, Zeff, Ne and Te), High Ip is necessary
•Explore effect of plasma current redistribution process (dynamics of li) on RE evolutions.
•Special attention will be given to scaling on disrupting plasma current values and dynamics of plasma geometry evolution during TQ and CQ stages.
•It is proposed to perform exploration study of characteristics of RE process in NT in TCV.
•HXR,SXR, magnetics, photoneutrons





Proposed pulses - #tbd, default use data from proposal "Identity exp-s…" (C.Reux)

Device	# Pulses/Session	# Development
AUG	data from "Identity exp. (C.Reux)	
MAST-U		
TCV	data from "Identity exp. (C.Reux)	
WEST	data from "Identity exp. (C.Reux)	

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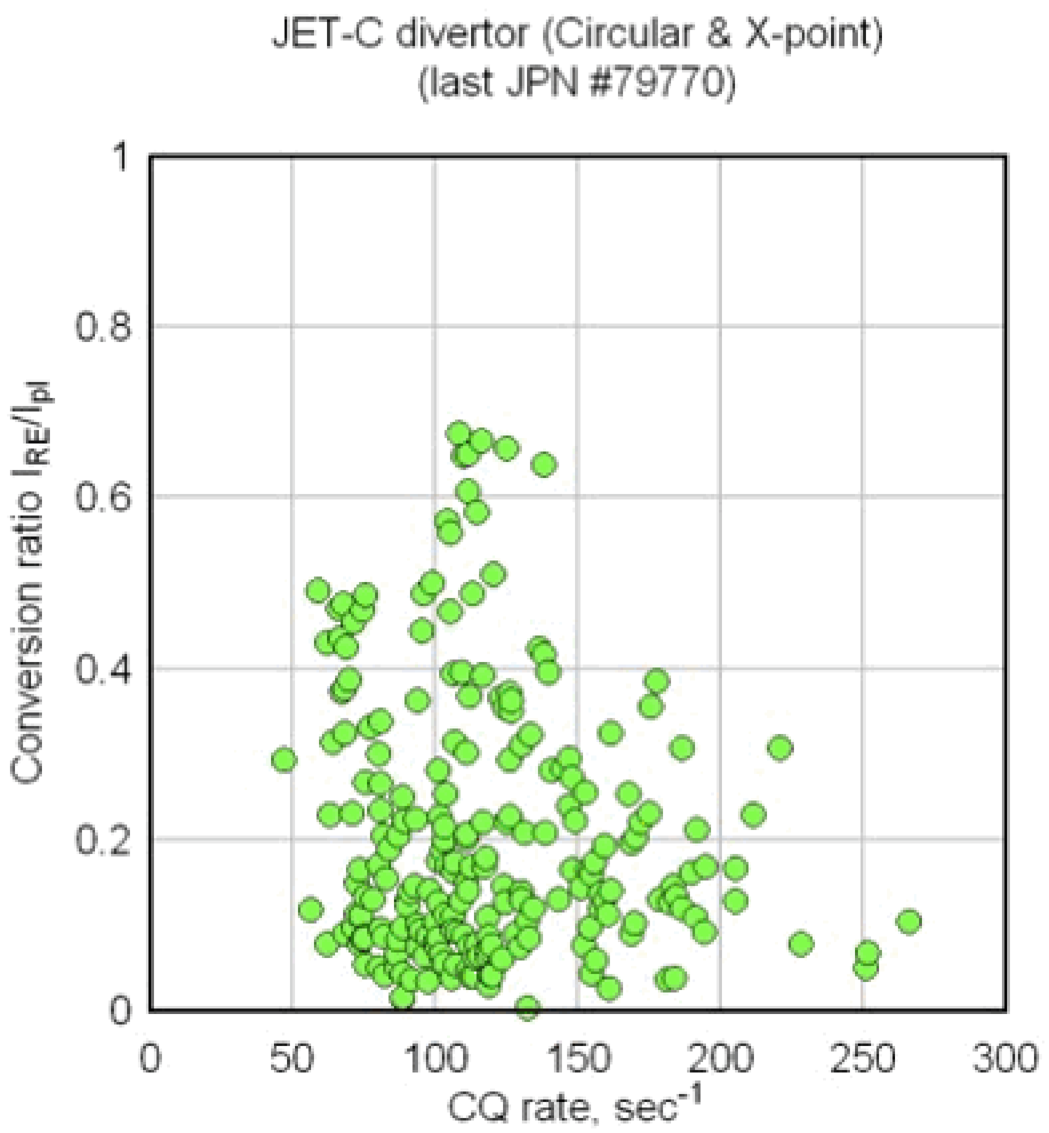

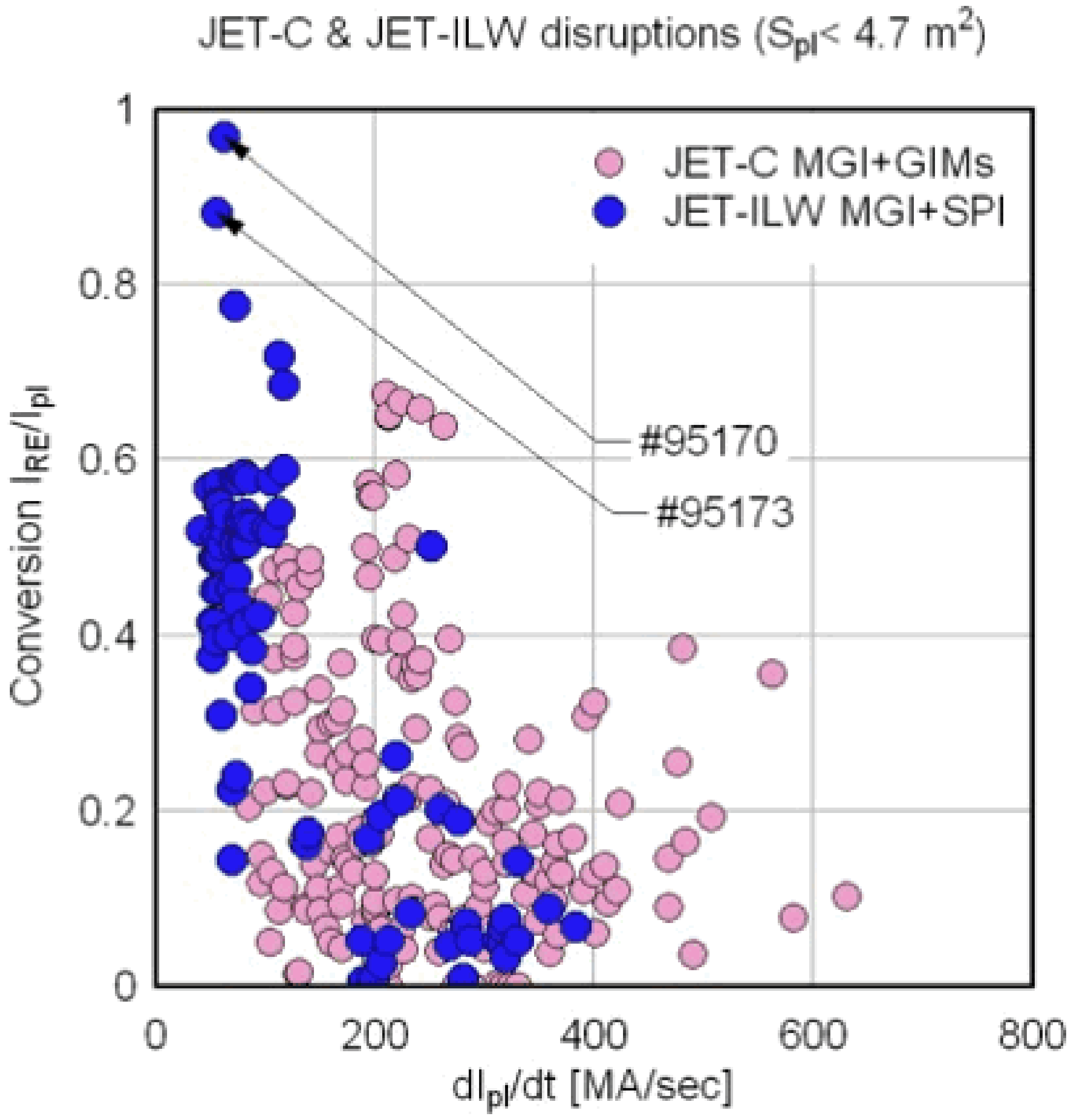

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Device	# Pulses/Session	# Development
AUG	data from "Identity exp. (C.Reux)	
MAST-U		
TCV	data from "Identity exp. (C.Reux)	
WEST	data from "Identity exp. (C.Reux)	

Priority:
P1/PB – It is always important to compare different devices. This proposal does not require dedicated discharged.

Conclusions

- Proposals **address relatively well the main objectives of RT-03**, especially D1-D5
  - ✓ No proposals submitted for D7 – this tasks requires more dedicated diagnostics
- **Largest contributor to the scientific programme** is TCV and AUG in 2025 with some dedicated experiments on WEST and MAST-U
  - ✓ Aim to take the multimachine aspects into account even in the absence of JET.
- **AUG SPI programme to be carried out almost exclusively in 2025** and the details of the programme to be decided at a later stage, but the proposed main ideas are:
  - ✓ The total number of discharges provisionnaly allocated for AUG for SPI is 40 (from total 60 for AUG).
  - ✓ RTCs could think how to redistribute this in the most optimal way.
  - ✓ The rest 20 is for non-SPI proposals.
- Experiments on WEST would **benefit from a safe and reliable RE scenario**
  - ✓ To be discussed which part of this should be done under WPTE, keeping the limited number of discharges in mind.

Allocation of discharges for RT03

	AUG	TCV	MAST-U	WEST
2025	60	120	0	30