EUROfusion

PSD-DCT Coordination meeting

Brief overview of EUROfusion Disruption and RE diagnostics and experiments in view of DEMO

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For RT-03 team, JET Contributors, AUG team, TCV team, COMPASS team

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Outline

- Disruption diagnostics
  - Overview of diagnostics groups
  - JET low temperature TS as an example
- RE diagnostics
  - Overview
  - HXR spectrometry
  - Photo-neutrons
  - Supra-thermal ECE and synchrotron radiation
- Most important results of experiments:
  - Unmitigated disruptions
    - Mostly statistical analyses, a couple dedicated experiments
  - Disruption mitigation
    - VDEs
    - SPI strategy optimization
  - Runaway beams
    - Benign termination and the limits

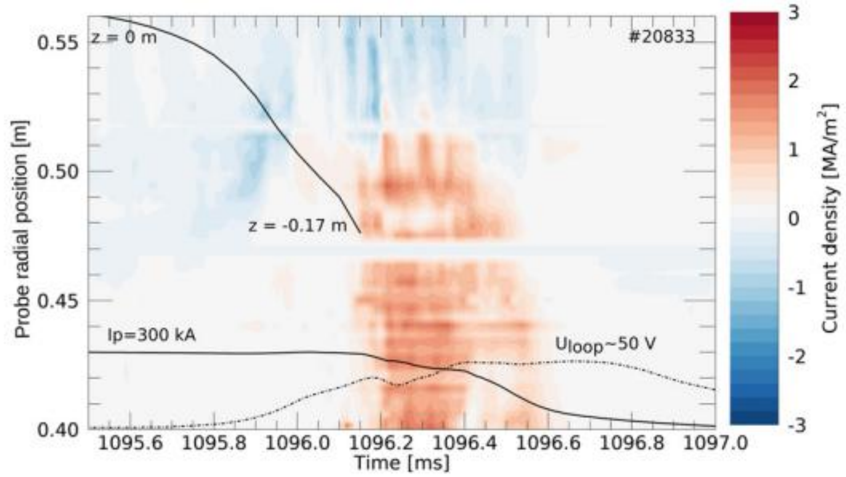
Disruption diagnostics

General issue – Toroidal and poloidal asymmetries

- Radiation:
  - Foil Bolometry (slow) and AXUV (degradation) – extended coverage needed for asymmetries
  - E.g. AUG very well equipped for dedicated SPI experiments
  - Synthetic diagnostics for interpretation: emis3D (Cherab based) Stein-Lubrano et al
- Temperature:
  - Challenging – fast, robust method needed
  - ECE – fast enough, radiation resistant?, but cut-off in mitigated disruptions
  - SXR – only for high temperature, just qualitative
  - Thomson Scattering – good spatial, poor time resolution, dedicated low temperature polychrom. of core channels needed, in mitigated disruptions affected by e.g. Ne lines, good results from JET – see further
- Density:
  - Challenging for standard equipment
  - Special interferometer HW or modifications – e.g. Dispersion interferometer for AUG
  - TS – as above and JET example
- Current and magnetic field, fluctuations
  - Usual inductive diagnostics, but special attention to the gains/integrator errors
  - Double DAQ systems proved useful – 1) good resolution for and smaller range + 2) poor res. large range
  - Radiation resistant Hall probes (Bismuth, Antimony) – useful for transients to some degree?
  - New radiation „resistant“ methods – fibre optics based current sensors

Disruption diagnostics II

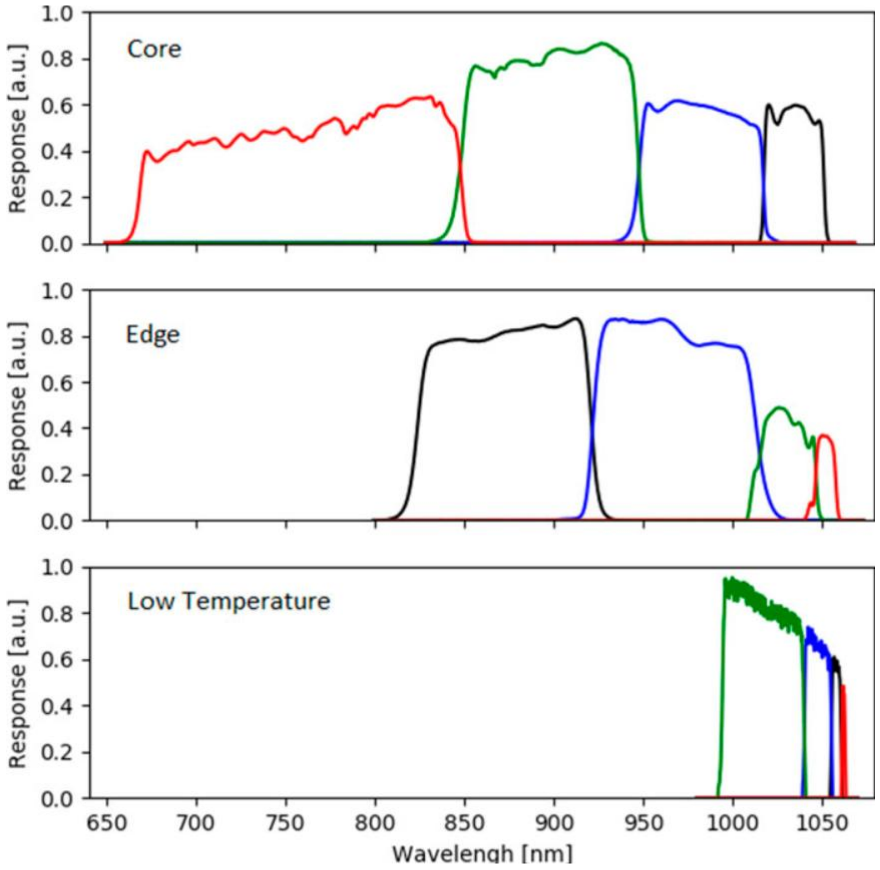
- Halo currents
  - Current shunts/dedicated tiles (AUG, COMPASS)
  - Langmuir and other probes (COMPASS)
  - Toroidal Mirnov coils
- Heat loads
  - Thermocouples
  - IR thermography
  - Dedicated calorimetry heads (more relevant for RE)
- Forces/strain/displacements
  - Accelerometers
  - Derived from magnetic measurmets
  - Strain sensors
  - Fast cameras with motion amplification processing



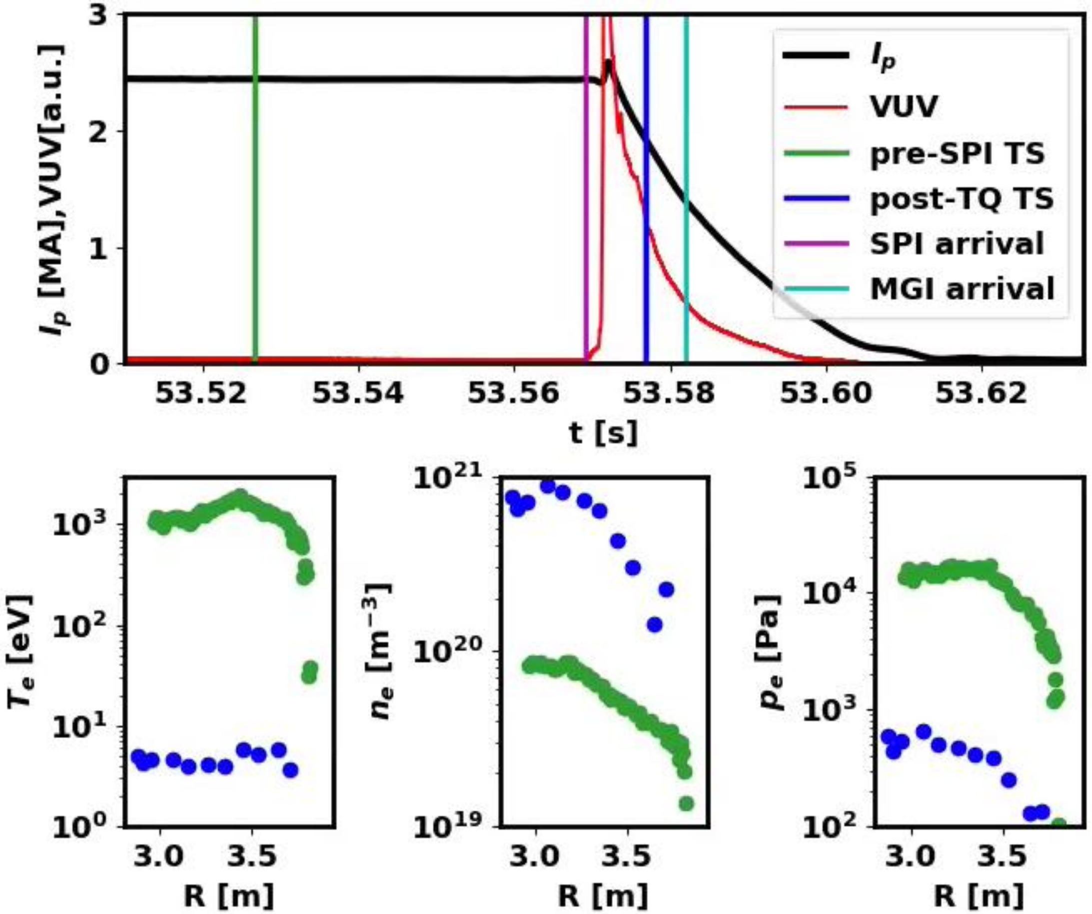
Langmuir probe measurement of halo current at COMPASS

Pre-TQ and Post-TQ TS measurements at JET

- 12 channels capable of measuring units of eV and high density
- Very valuable data for JET SPI campaigns in both pure D2 and Ne-doped pellets
- General TS limitation – low repetition freq.



Huang et al. Rev. Sci. Instrum. 95, 073530 (2024)



Classification of RE diagnostics

Companion plasma

Density
Interferometry
Reflectometry
…

Temperature
TS/low temperature TS

Composition
VIS, UV, VUV, etc. spectrometers

Radiation
Bolometers, etc.

RE in plasma

Bremsstrahlung on plasma ions
HXR tomography systems
SXR cameras
HXR monitors
HXR spectrometers

Radiation in magnetic field: ECE and Synchrotron radiation
Vertical or standard ECE
MWIR, SWIR, VIS cameras
MSE collection systems
Tangential IR-VIS spectrometers

RE hitting solid structures

Bremsstrahlung
In-vessel scintillators exposed to RE

Photo-neutrons
Neutron monitors
Neutron tomography systems
Activation measurements

Impact IR thermography and calorimetry
MWIR wall protection systems
Thermocouples, Calorimetry heads

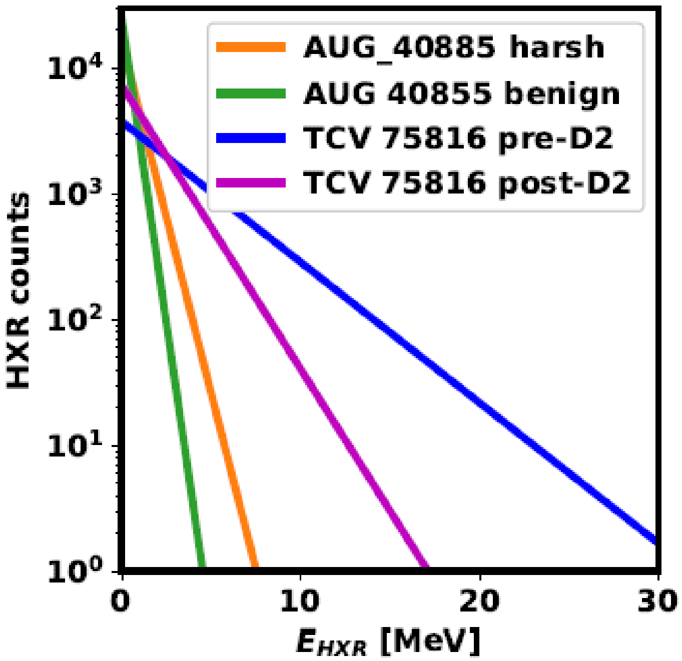
Cherenkov radiators, effects on el. probes, etc.

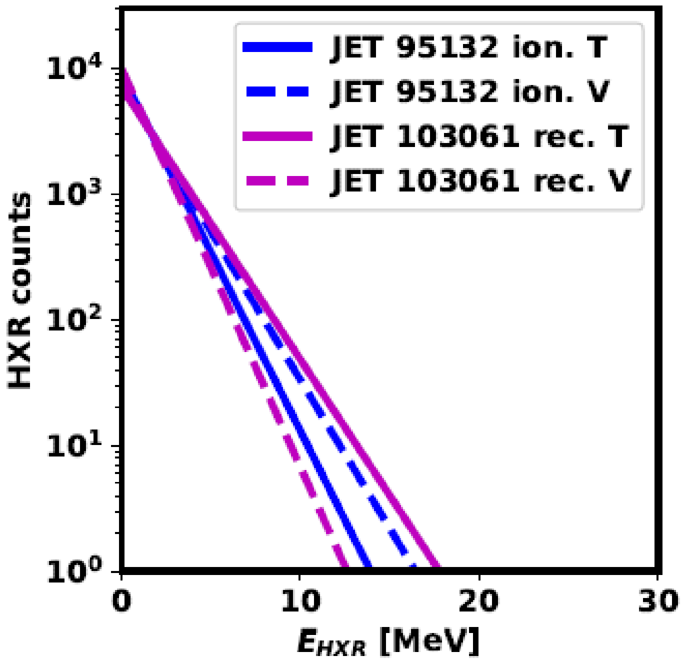
Magnetic equilibrium of the system beam-plasma – non-OH Ip, etc.

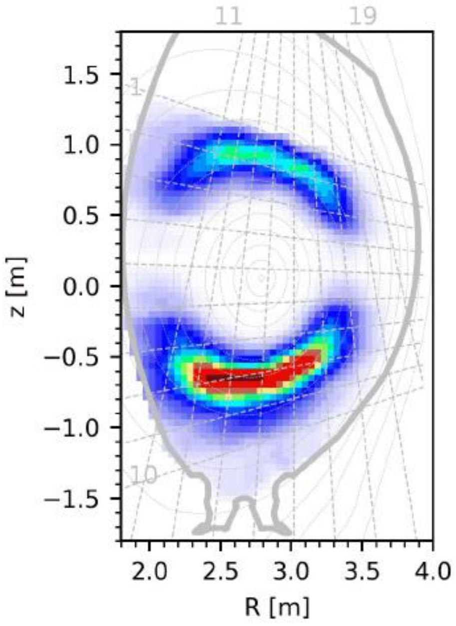
Magnetic instabilities/EM waves interacting with RE

HXR measurements – essential work horse

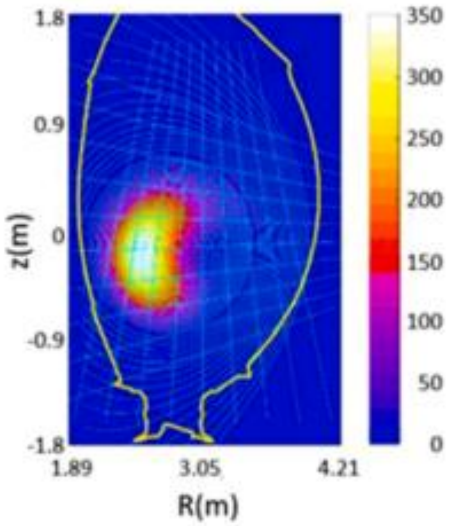
- Bremsstrahlung from RE – plasma impurity interaction or RE-PFC interaction
- Monitoring mostly losses – fluxes can be modulated by various MHD instabilities, huge range of fluxes depending on RE population and loss duration
- HXR affect non-HXR diagnostics – can be used for flux estimates in some cases (dots in camera pixels, …)
- Spectrum: large scintillators needed – gamma spectrometers dedicated to fusion reaction can be used
- Cameras – JET – may provide additional insight (location, pitch angle) but interpretation difficult
- ITER HXR spectrometer – solution with optical path and remote PMT – very poor resolution, challenging







E. Pantonin, PhD thesis, 2022



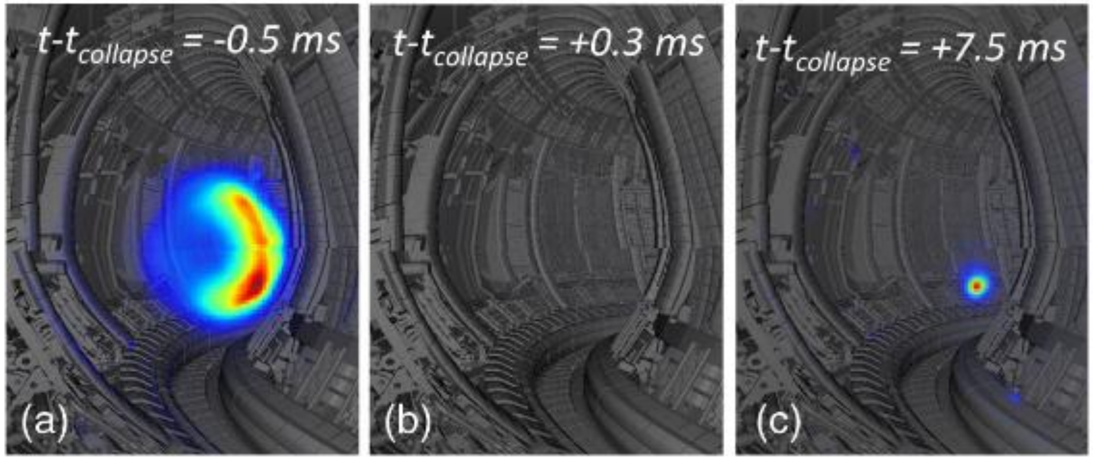
M. Gelfusa et al. FED 2021

Photo-neutrons

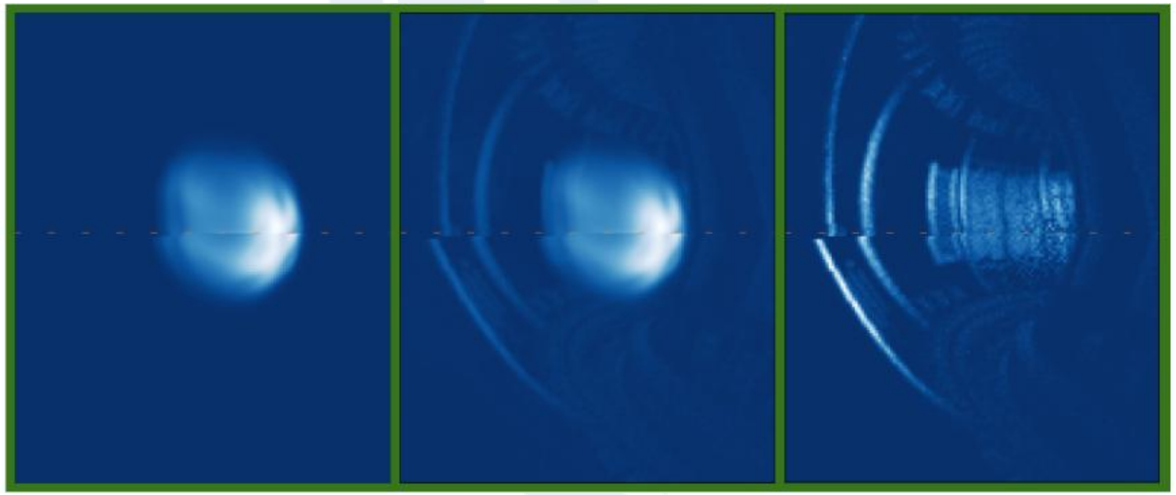
- <u>Motivation: good neutron diagnostics in DEMO</u>
- Deviation of neutron spectra and profile from expected fusion neutron signal – diagnostics design be ready for this
- A many-step process:
  RE -> HXR photon -> photo-neutron -> ions in the detector -> photons in the scintillator –> electrons (again) in PMT
- Stable slightly neutron-rich isotopes are the best (e.g. C-13, Be-9, multiple W and Mo isotopes, etc.) – thresholds 1.7 MeV (Be-9) and more
- Direct (e,n) reactions possible but very, very rare
- HXR not bound by magnetic field -> **reaction in solid materials orders of magnitude more probable** than in plasma/gas
- Very limited number of reactions mapped properly (-> cross-section data in MCNP, GEANT4, FLUKA limited; openMC - no PN physics at all…)
- Neutron energy spectra -> in **principle = HXR-spectra(E – Eth)*cross-section**
- Directionality -> suppressed by neutron collisions (detectors used typically sensitive to thermal neutrons) – **very good for shot-to-shot comparison with varying beam termination locations effect suppressed**
- At termination: **photo-neutron number <=> heat loads from high energy RE**

Non-thermal ECE and Synchrotron radiation

- Early RE detection in plasmas Microwaves – IR – VISible
- Funcion of energy, pitch angle, local magnetic field
- DEMO relevant (ECE, IR with W mirrors can survive significant DPA)
- Vertical ECE configuration used for exclusively suprathermal signal
- Tangential IR or VIS cameras optimal, but other configuration can also see stray/reflected SR
- Very evolved synthetic diagnostics – SOFT, JOREK-fastcam, SERECH (Cherab based) – the diagnostics layout of DEMO can be simulated to see what it can see



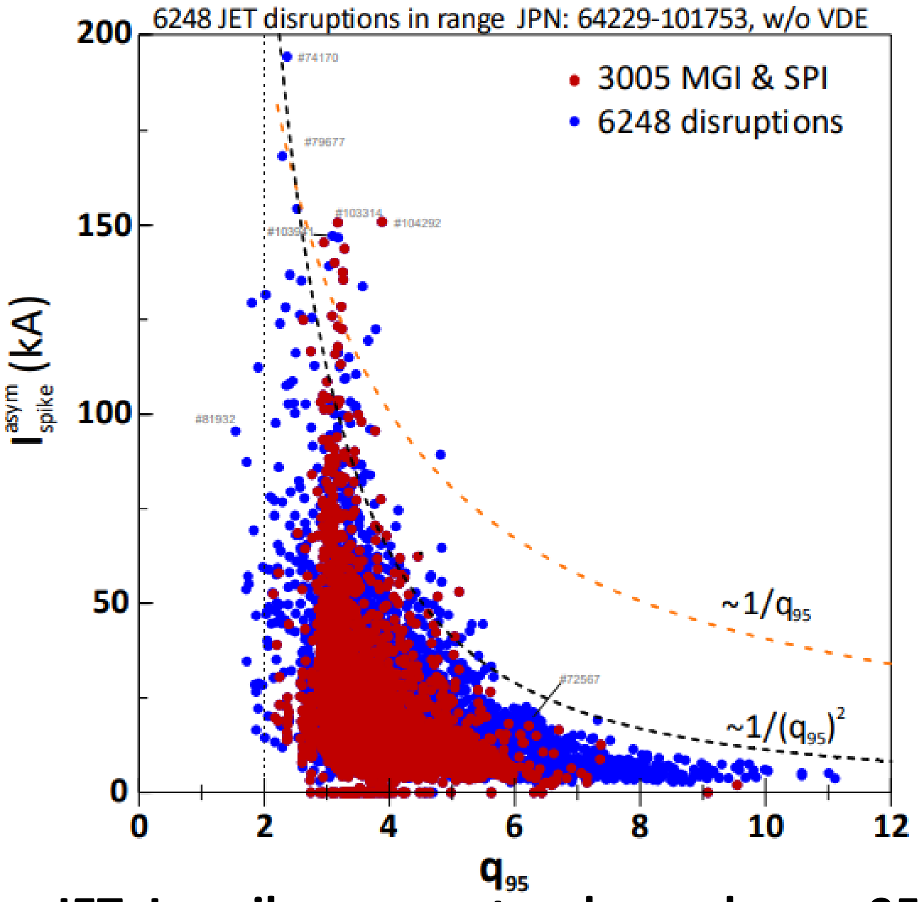
JET SR observation – RE regeneration – REUX et al. PRL 2021



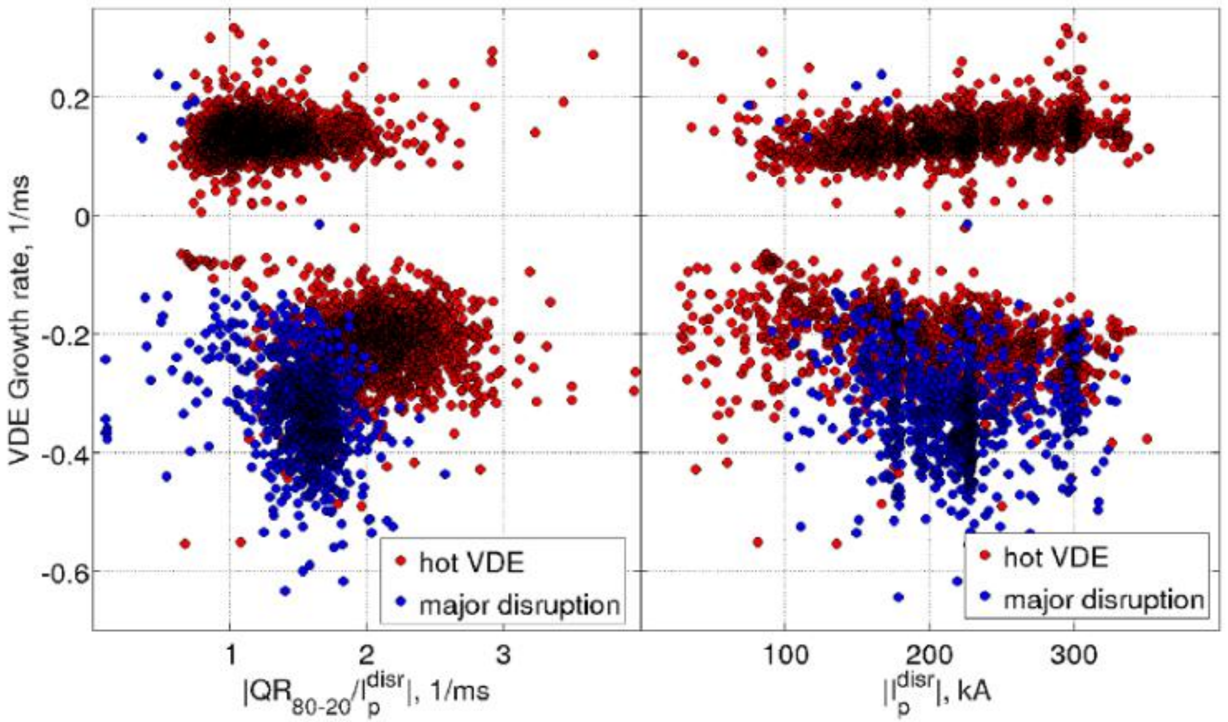
SERECH simulation including reflections – Tomes et al. ECPD 2025

Statistical analysis of disruptions – multi-device, JET, COMPASS

- Extensive studies based mostly on magnetic diagnostics
- But: machine specific - PFC material Be/W vs C and other parameters of the experiment affect the result
- Scaling of halo currents, asymmetries, growth rates



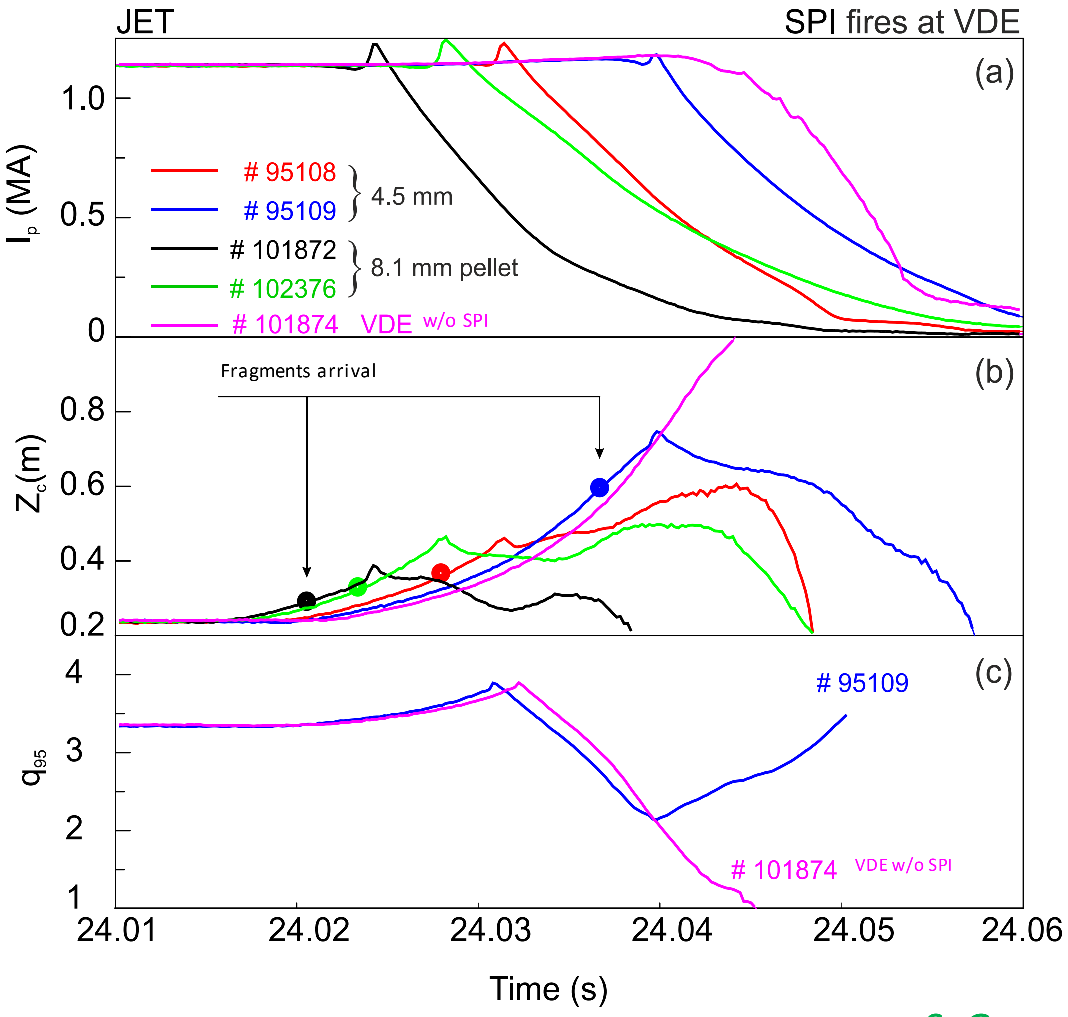
JET: Ip spike assymetry depends on q95
Gerasimov et al. REM 2025

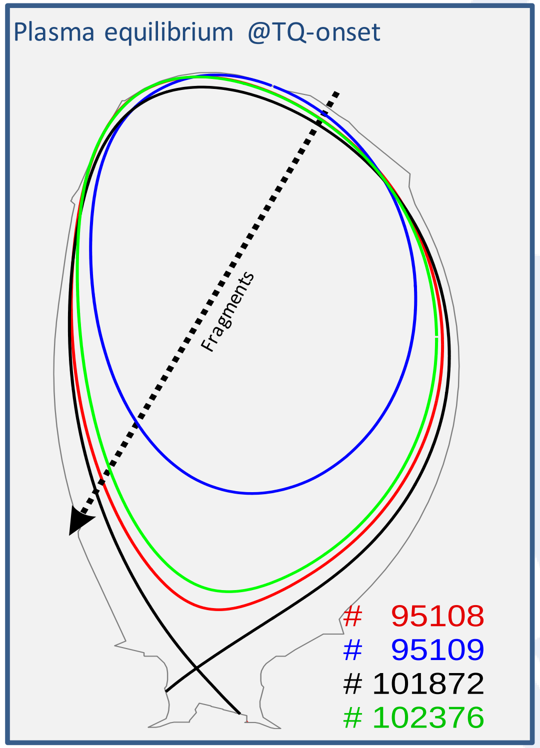


VDE: growth rate vs CQ rate and plasma current – Matveeva et al. PPCF 2022

Mitigated VDEs

- VDE and SPI are pre-timed
- SPI initiates TQ, followed by CQ.





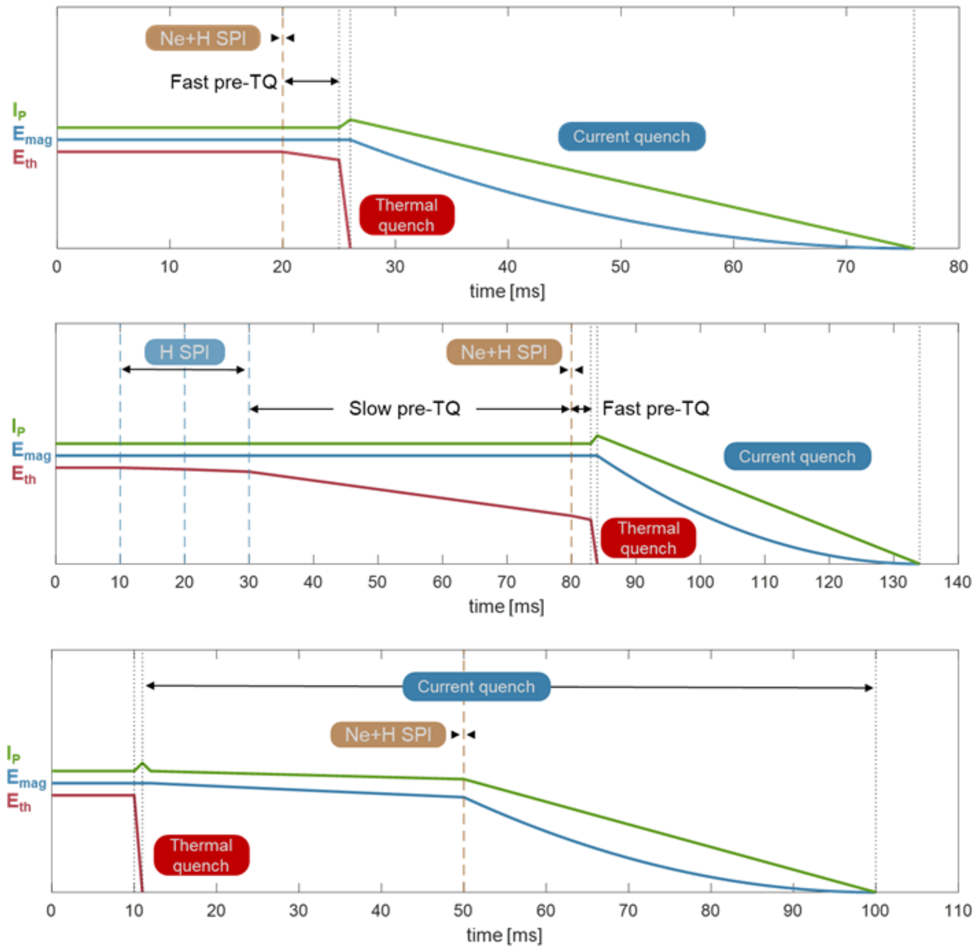
S. Gerasimov, EPS 2023

- Exponential **current centroid Zc-motion is interrupted (not plasma)** and enters quasi-stationary phase
- Fall rate of Ip drop increases, which prevents the fall of the safety factor q95.
- This excludes the excitation of the m/n = 1/1 kink mode responsible for AVDE
- Pure D pellet prolongs CQ significantly
- In line with AUG experiments N. Schwarz, J. Artola et al. and related JOREK modelling

SPI strategy experiments - JET and AUG (ongoing)

Interesting results:

- Plasmoid drift that is preventing assimilation is suppressed by Ne content below 0.1%
- In seeded scenarios, present impurity can replace mitigation impurity doping in effect (Sheikh et al. NF 2025)
- SPI successfully triggered from various real-time signals, e.g. hollow temperature profile from ECE



Mixed Ne/H SPI (multiple)

Fast pre-Thermal Quench (TQ) of a few milliseconds

BUT: Arrival time critical for multiple SPI

Staggered SPI

Slow pre-TQ (several 10 ms) after H SPI

Significant pre-TQ energy loss

Dilution cooling aids RE avoidance (T_e < 1 keV)

BUT: plasmoid drift limits H-assimilation

Post-TQ SPI

DMS trigger upon TQ or Δz detection
→ SPI not triggered pre-TQ

Thermal & EM load mitigation during CQ for I_P>~10MA

BUT: injection geometry and low Te limits assimilation

Figure and description - S. Jachmich

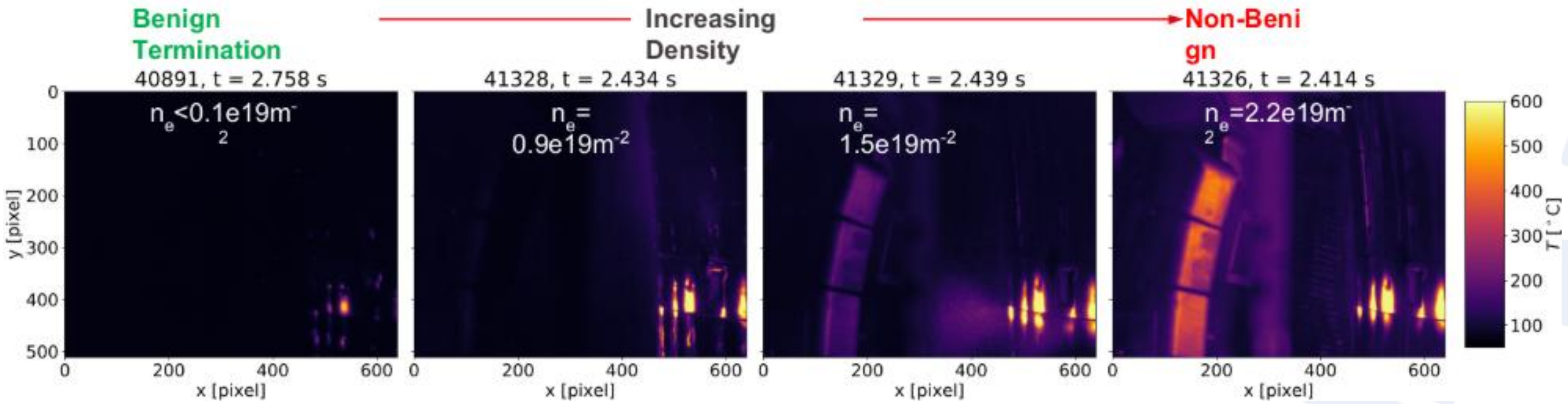
RE beams - Benign termination

- Currently the most promising strategy for mitigation of post-disruption RE beam: JET, AUG, TCV, WEST (COMPASS, DIII-D)
- Timing constraints for ITER (~150 ms VDE)
- Two ingredients:

1) Recombination of companion plasma
   - Contains impurities from primary disruption mitigation
   - Achieved by hydrogen or deuterium injections – fueling valves/MGI/SPI
   - Lower (low Z fraction) and upper (significant collisional ionization by RE) limits exist

2) MHD instability assuring rapid loss of RE
   - Spreads heat loads from RE on the PFC
   - Fast loss prevents regeneration (magnetic->kinetic energy conversion) via avalanche

Other strategies include various methods to increase RE losses – e.g. passive disruption mitigation coils, etc.



AUG HFS IR thermography of RE termination U. Sheikh REM 2025

Conclusions

- Disruption diagnostics – improved for recent dedicated experiments (Low temperature Thomson scattering, dispersion interferometer), what is applicable in DEMO needs to be analyzed
- RE diagnostics – wide variety of principles, some of them applicable to diagnostics foreseen for DEMO, dedicated studies can be performed with synthetic diagnostics and modelling input
  - HXR, Photo-neutrons, ECE and Synchrotron radiation, Effects on equilibrium
- Statistical evolutions of disruptions from many devices – many results namely from magnetic diagnostics
- Ongoing research in physics understanding of disruption mitigation by SPI and optimization of the scheme for ITER – many interesting results that are gradually reported
- RE beam physics – benign termination currently the most promising approach (recombined companion plasma + fast MHD instability), but characterized by upper and lower limit – that are further studied on multiple devices (AUG exps tomorrow?)
- Other RE mitigation methods include supporting losses via various methods – passive helical coils, injection of waves, etc.
- RE beam position control essential in present experiments, but probably cannot be achieved in ITER (and DEMO?)