IAEA TM on Disruptions

Session on «Consequences»

MONDAY 20TH JULY 2020

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Introduction

13 contributions in this session

Presentation material (slides + audio/video) available on the web site

Discussion threads activated

Outline of this summary presentation

- Introduction of discussion threads
  - As reported on the web site
- «Clusterization» of papers according to discussion threads
  - A paper might contribute to several discussion threads, only «the most relevant» thread is reported
- Short summary of the contents of each paper
  - Full details available in the contribution material on the web site

Contributions

99	Simulation of MHD Instabilities with Runaway Electron Current using M3D-C1	Chen zhao
103	Runaway Electron Studies and Plasma Restart from a RE Beam on TCV	Umar Sheikh
107	Current flows towards the divertor during VDEs at COMPASS	Ekaterina Matveeva
114	Data on Runaway Electrons in JET II	Vladislav Plyusnin
120	Runaway seed formation during the thermal quench and the effects of radial transport of fast electrons	Ola Embreus
121	Current and thermal quench in JET and ITER disruptions	Henry Strauss
122	CarMa0NL Modelling of Plasma Disruptions on COMPASS-U for Scenarios with Positive and Negative Triangularity	Vadim Yanovskiy
124	Vessel Forces from a Vertical Displacement Event in ITER	Stephen Jardin
125	Analysis of the runaway electron distribution in an ASDEX Upgrade disruption using synchrotron radiation	Mathias Hoppe
126	Noll forces, stiffness model of vacuum vessel, and radial displacement data on JET	Leonid Zakharov
130	Strategy of an integrated limiter design for EU-DEMO first wall protection from plasma transient events	Francesco Maviglia
139	Validation of state-of-the-art runaway electron generation models in simulations of ASDEX Upgrade disruptions	Oliver Linder
153	Disruption consequence on metal wall tokamaks	Sergei Gerasimov

Discussion threads

Thread#1: Validation of disruption EM load models

Thread#2: Extrapolation of disruption EM loads to ITER

Thread#3: Plasma Facing Components damage and protection

Thread#4: Runaway seed formation

Thread#5: Runaway electron analysis, characterization and impact

Discussion thread#1

Validation of disruption EM load models

Contributions related this thread

- Contribution# 107: Matveeva
  - ATEC model and asymmetric halo currents model do not explain all experimental evidence in COMPASS
- Contribution# 126: Zakharov
  - Noll formula provides good fitting of JET data

Contribution#107

Ekaterina Matveeva et al. «Current flows towards the divertor during VDEs at COMPASS»

Possible points for discussion:

- Interpretation of eddy/halo current flows
- Is improvement needed in models or in experimental setup?

Key message:

Experiments have been carried out on COMPASS to better understand current pattern distribution within ITER vessel structure during VDE.

Motivation:

Validation of Asymmetric toroidal eddy currents (ATEC) model

R. Roccella et al, Nucl. Fusion 56 (2016) 106010

“Under certain conditions of plasma temperature (and thus resistivity) it is possible that neighboring dump plates are short-circuited in toroidal direction through the plasma. In this configuration, part of the toroidal current induced in the vacuum vessel (VV), which has the same sign as the plasma current, will flow in the dump plates of the sectors wetted by the plasma.’’

- Sideway force acting on divertor structure
- Misinterpretation of plasma current measurements (if magnetic coils are located behind the divertor)

Measurement:

Current flows from the plasma to floating divertor tiles during disruptions

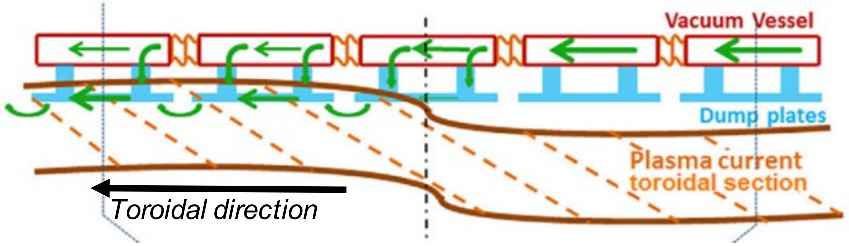
Purpose:

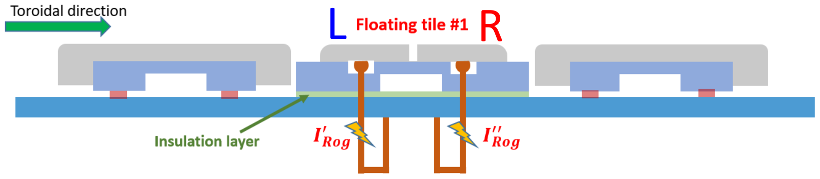
Find out whether part of the vessel eddy current is transferred to divertor tiles and flows in toroidal direction through the gaps between the tiles (resulting in a net sideway force)

Two special divertor tiles installed:

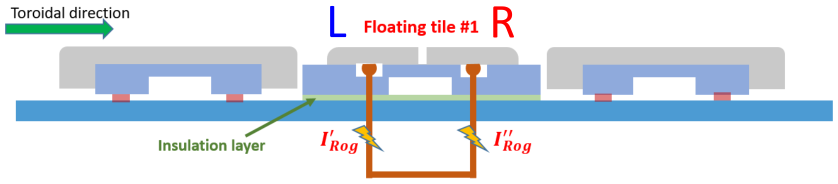
- Tile is insulated from the wall inside the VV
- Each segment is connected to the wall outside of the VV and current flow is measured by Rogowski coil.
- Two segments on the LFS are toroidally separated by a gap. We aim to find out whether part of eddy current is flowing through this gap during disruptions.

R. Roccella et al, Nucl. Fusion 56 (2016) 106010
VDE at JET



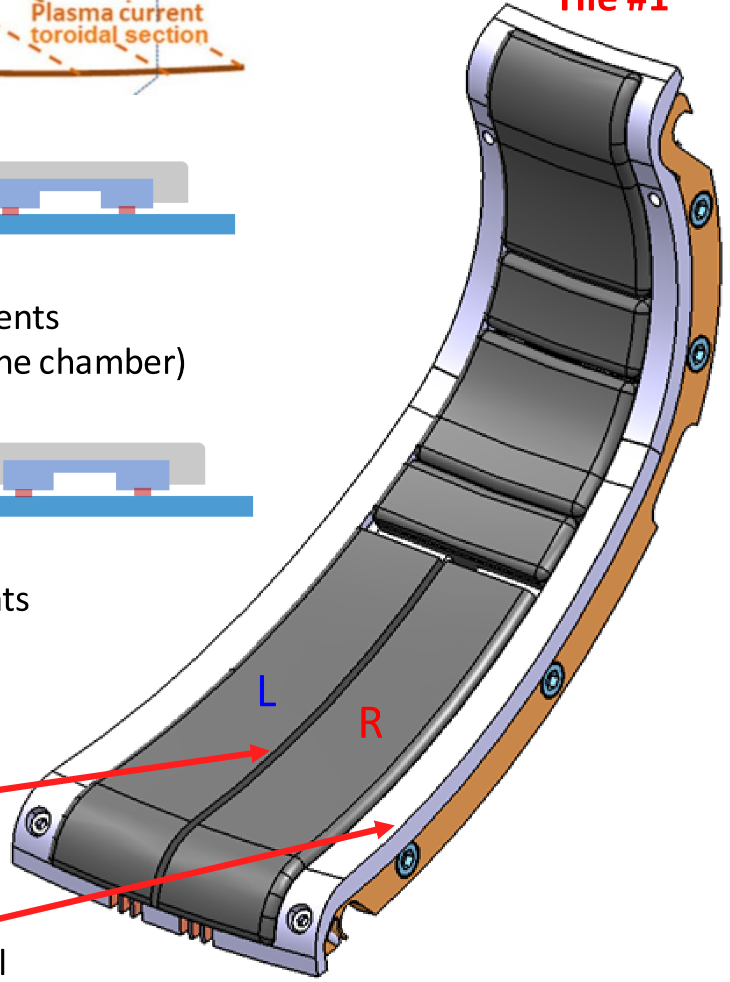


Grounded mode: Left and right segments are connected to the VV (outside of the chamber)



Floating mode: Left and right segments are connected to each other, no connection to the VV

Tile #1



Is there a short-circuit through the gap? (2.5 mm distance)

Boron nitride insulates graphite segments from the wall

Important observations:

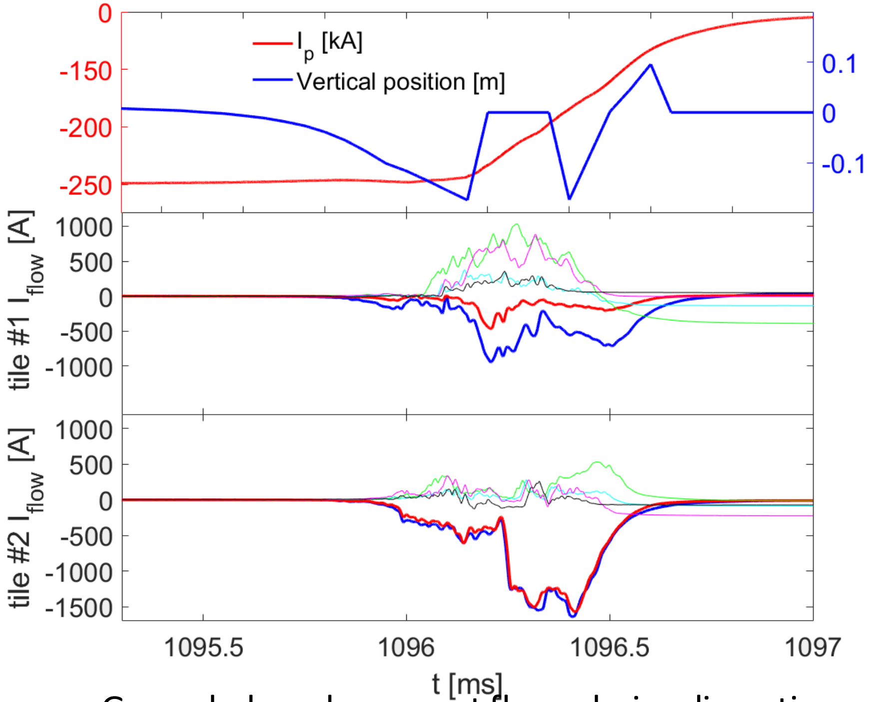
- Grounded mode: Left and Right segments of the tile #2 measure symmetric current flow, but the tile #1 **current flows are not symmetric**. This asymmetry's behavior depends on I_p and B_t direction.
- **Floating mode: there is current flow** up to 1 kA between Left and Right segments (connected to each other, **but no connection to the VV**)
- Langmuir probes measurements:
Plasma limiter point is moving in the area of Left and Right segments (complicated current flows data interpretation). Large positive floating potential is observed compared to Te (~10 eV), broad current density profile (1-2 MA/ m2). **It is suggested that Halo current might be limited by ion saturation current**. A separate dedicated experiment has been performed to confirm this.

Proposed hypotheses:

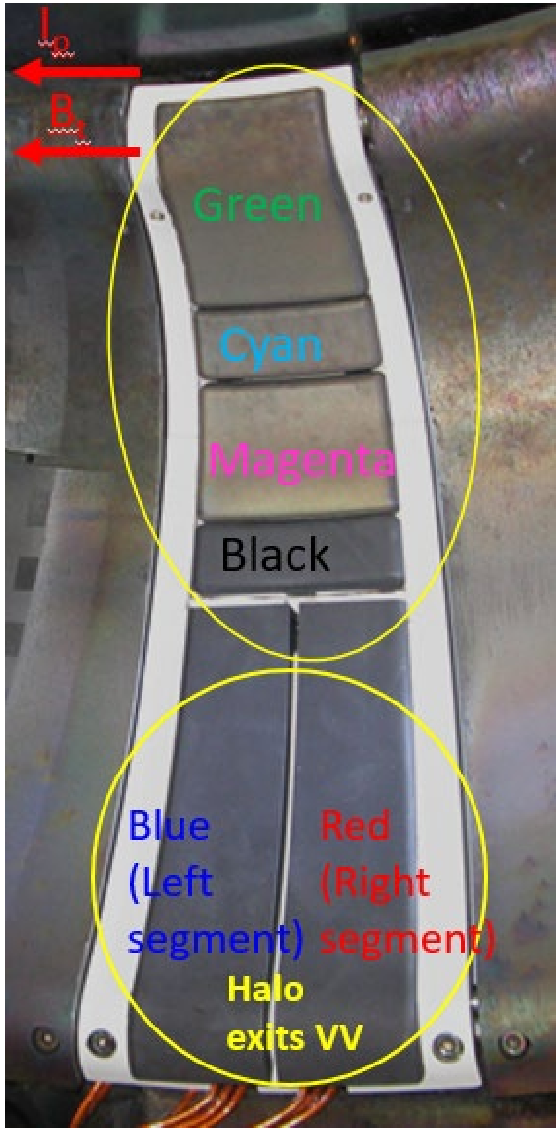
1) **Gaps between the segments are short-circuited** (according to ATEC model). Combination of Halo and eddy currents is measured.
2) **Non-symmetric Halo currents** are coming to the Left and Right segments. Reasons:
- Tiles might be shadowed
- Segments might be misaligned

Summary:

- None of the proposed hypotheses explains all the results obtained, only part of them
- New tiles with modified design will be installed in order to distinguish between the hypotheses



Grounded mode: current flows during disruption



Contribution#126

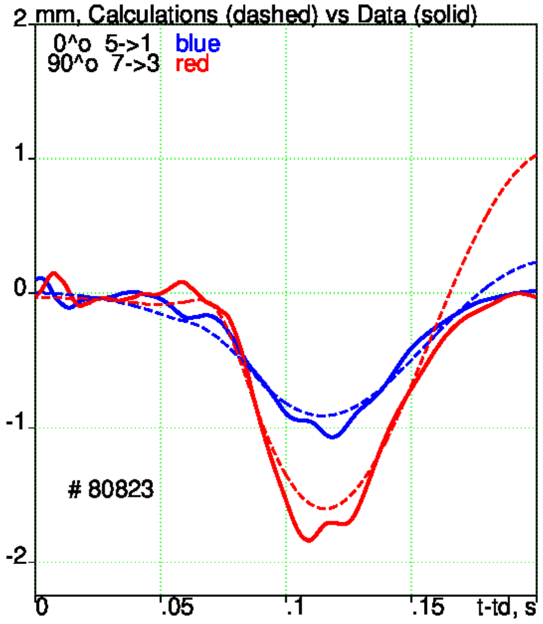
Leonid Zakharov et al. «Noll forces, stiffness of the vacuum vessel, and displacement data on JET»

Possible points for discussion:

- Mechanical model of the vessel (complexity, parameters)
- Comparison to ATEC model
- Use of Noll’s formula for extrapolation to ITER

Large 40 MN forces predicted by Noll's scaling $F_x = \frac{\pi}{2} B \, \Delta M_{IZ}$ of JET data to ITER in 2007 and theory behind it were challenged later on by the resistive mode theories, 3-D numerical simulations, and "halo" current models.

Presented here analysis of 23 AVDE disruption shots (out of total 1735 processed) demonstrates consistency of Noll's forces and stiffness model of the VV with displacement measurements on JET.



Solid curves in figure are waveforms of measured displacements.
Dashed curves are simulations using Noll's force.
Blue for octants 5->1
Red for octants 7->3

With one exception Noll forces reproduce the phase of displacements.
In 20 (out of 23) cases the accuracy in amplitude is better than expected 50 % of the stiffness model.

The results suggest that JET data, Noll's scaling, and strong physics behind it remain the most reliable source of force assessment in ITER AVDE.

Discussion thread#2

Extrapolation of disruption EM loads to ITER

Contributions related this thread

- Contribution# 121: Strauss
  - Short CQ time is beneficial for ITER, role of 1/1 mode, differences between JET and ITER
- Contribution#124: Jardin
  - Short CQ time is beneficial for ITER, role of 1/1 mode, cross-code benchmarking

Contribution#121

H. Strauss et al., «Current and thermal quench in JET and ITER disruptions»

Possible points for discussion:

- Is Noll force able to extrapolate correctly to ITER?
- Dependence of sideway forces on current quench time
- Thermal quench duration

Asymmetric wall force and thermal quench in JET disruptions

H. R. Strauss

- Asymmetric wall force ΔF calculated in M3DC1 and M3D simulations.
- simulations are consistent with JET data from AVDE shots
  - plasma scrapes off at the wall until edge $q = 1$, causing $(1, 1)$ mode.
  - ΔF decreases as current quench time decreases.
  - can mitigate wall force in ITER
- Thermal quench (TQ) time can depend of resistive wall time τ_{wall}
- TQ time can vary as $\tau_{wall}^{-4/9}$ due to resistive wall tearing nodes (RWTMs)
  - RWTM dominates parallel thermal conduction when edge $T \lesssim 200eV$.
  - In ITER, if RWTM is suppressed, might mitigate wall heat load and RE formation.

Contribution#124

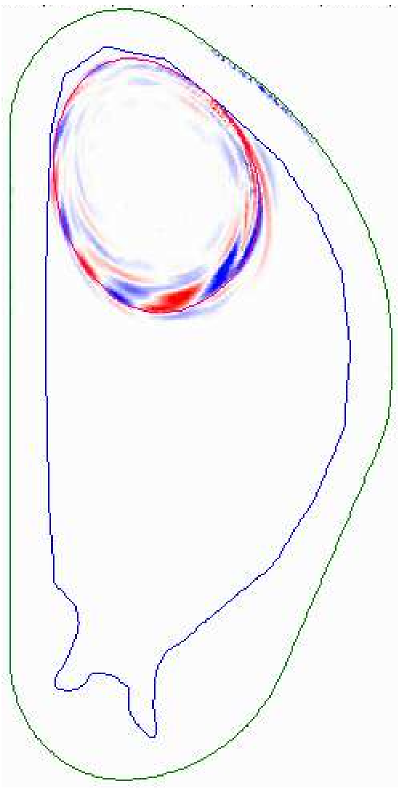
S. Jardin et al., «Vessel Forces from a Vertical Displacement Event in ITER»

Possible points for discussion:

- Is Noll force able to extrapolate correctly to ITER?
- Time behaviour of boundary q in ITER

Summary: Vessel Forces from a VDE in ITER

- Vertical force on ITER VV of 80-100 MN predicted by several codes, both 2D and 3D
  - Net vertical force almost independent of size of halo current
  - However, local stresses will depend on current paths and hence halo current
  - Slower current quenches lead to larger net forces
- Asymmetrical (sideways) forces arise from n=1 mode and associated halo currents
  - Mounting evidence that the m=1,n=1 mode is present in worst case disruptions
- Several 3D MHD codes are now modeling 3D VDEs
  - Requires MHD region, conducting structure, vacuum region
  - 3 Codes have performed verification benchmark exercise
- Code results and analysis shows max force at intermediate value of $\gamma\tau_W$
- JET modeling shows large forces only if q(a) → 1 during disruption
  - Larger sideways forces for slower current quenches
- Simulations of ITER with realistic structure have yet to show large sideways force
  - ITER unlikely to have q(a) < 1 (and large sideways force) during VDE unless Current Quench time is very long: > 200 ms



Discussion thread#3

Plasma Facing Components damage and protection

Contributions related this thread

- Contribution#153: Gerasimov
  - PFC melting in JET, disruption rate higher than ITER target
- Contribution#130: Maviglia
  - Sacrificial limiters to protect DEMO FW
- Contribution #122: Yanovskiy
  - Evaluation of forces, negative triangularity affects plasma trajectory during disruptions

Contribution#153

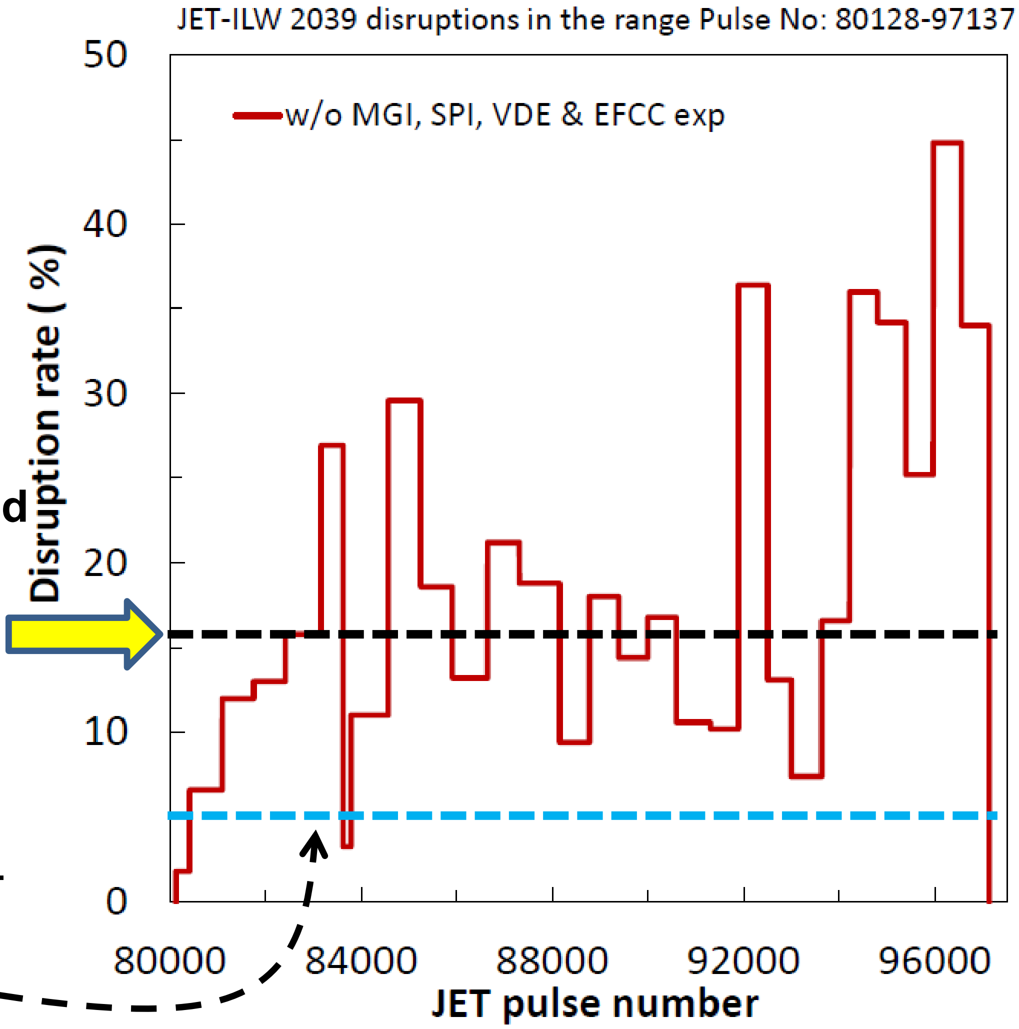
S. Gerasimov et al., «Disruption consequence on metal wall tokamaks»

Possible points for discussion:

- Disruption rate in view of ITER (and DEMO)
- Temperature measurements during AVDEs (and VDEs)

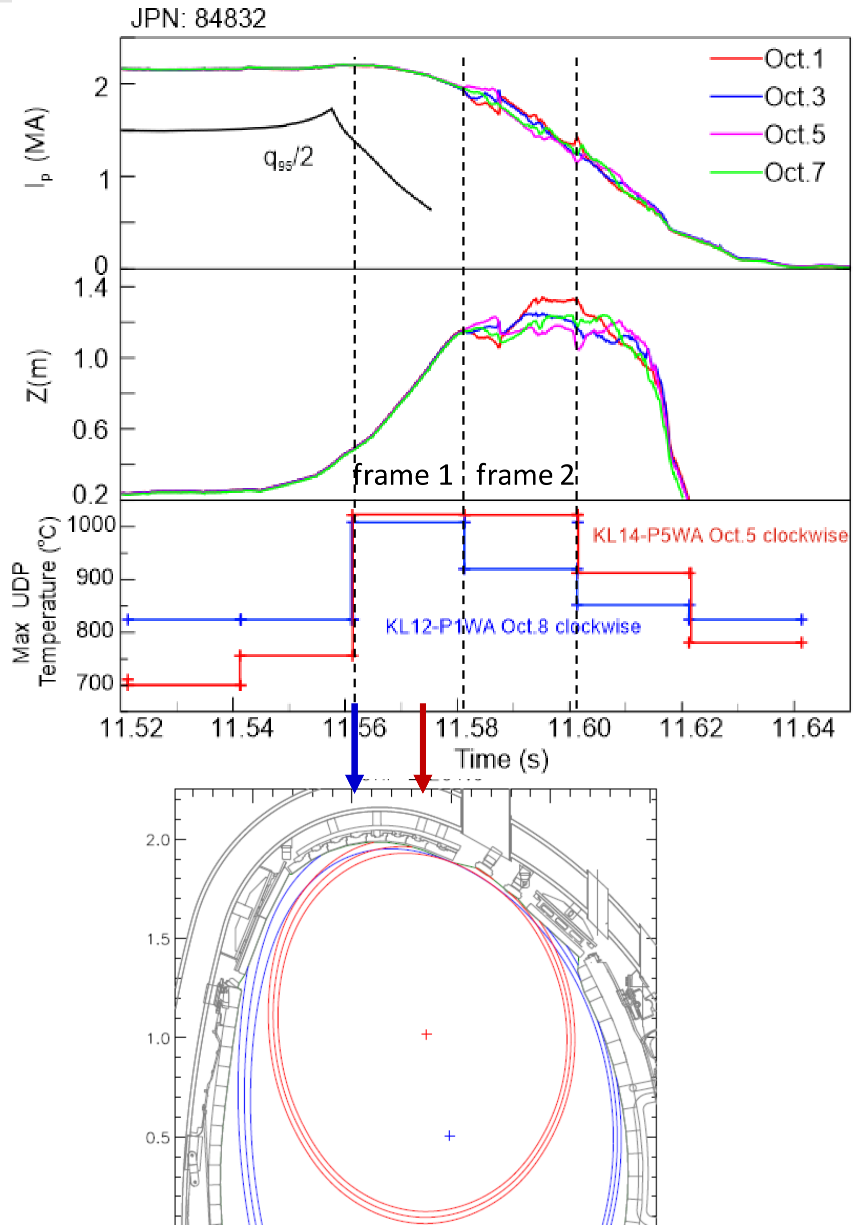
JET-ILW disruption rate: 24/08/2011 (first ILW plasma pulse) - 23/03/2020

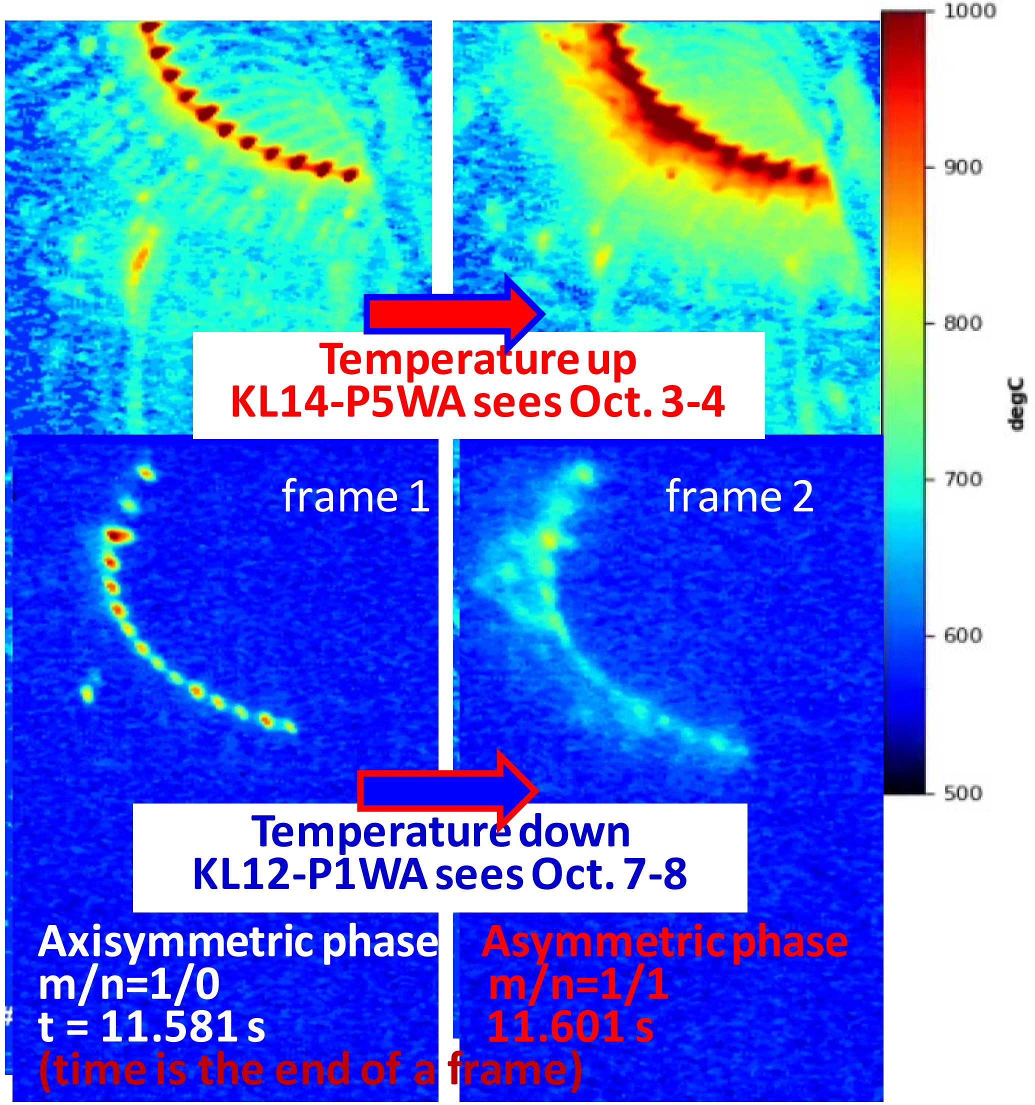
- **Total number of <u>Plasma</u> shots: 13467**
- **2039 "unintended" disruptions with $|I_p^{dis}| > 0.8$ MA**
- **High disruption rate (up to ~ 50%)** attributed to exploration of operational space for high performance plasmas
- **Average disruption rate of unintended disruption is ~ 16%**
- **16% disruption rate** is considerably above the ITER target (~ 5%) at 15 MA.



***2554** disruption shots = **2039 "unintended"** + 515(480 disruption experiments (MGI, SPI, VDE and EFCC) + 35 human errors, hardware/software tests/faults)*

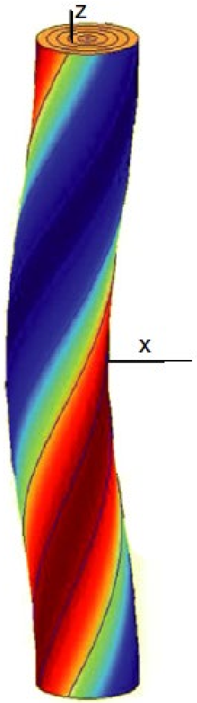
AVDE melted Upper Dump Plates



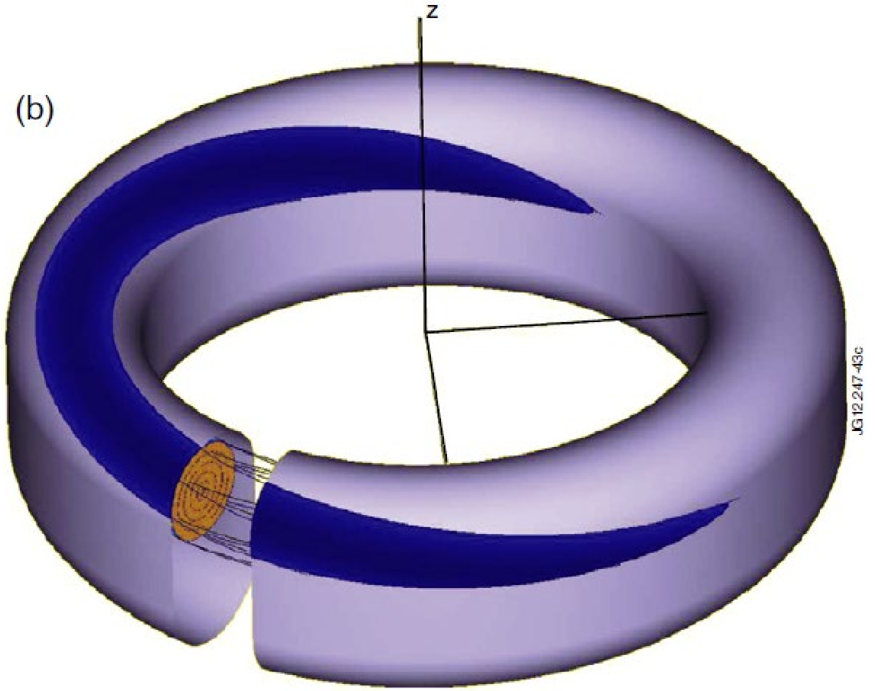


S. Gerasimov. Disruption consequence on metal wall tokamaks

AVDE melted Upper Dump Plates



Asymmetric phase of VDE, m/n=1/1



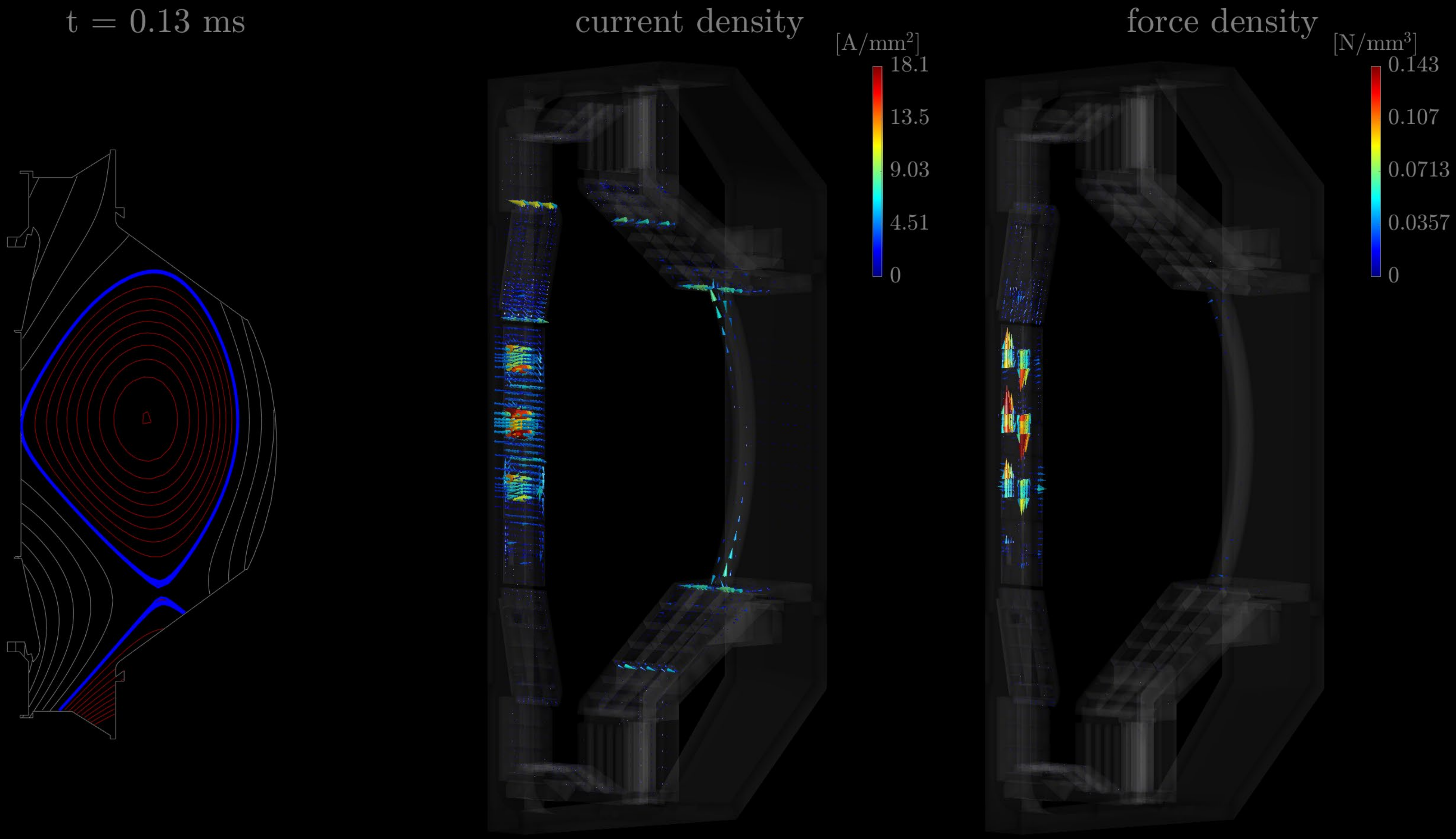
AVDE plasmas share current with wall, this current causes sideways vessel displacement but also melts the wall

Contribution#122

Vadim Yanovskiy et al., «CarMa0NL Modelling of Plasma Disruptions on COMPASS-U for Scenarios with Positive and Negative Triangularity»

Possible points for discussion:

- Effect of negative triangularity: trajectory of plasma during disruption
- Can we experimentally validate modelling?



CarMa0NL modeling of the fastest COMPASS-U transient: 0.1 ms TQ followed by 0.3 ms CQ

Summary

- The fastest COMPASS-U transients with positive and negative triangularities have been analyzed with CarMa0NL.
- It has been shown that the force distribution in the wall strongly depends on the pre-disruption plasma equilibrium.
- The results are being currently used to optimize the mechanical design of the COMPASS-U wall.
- At the moment halo currents are considered only for evolutionary equilibrium modeling. But future work will include also calculation of the forces related to the halo current.

* CarMa0NL modeling for positive triangularity has been already validated on COMPASS, EAST, JET and TCV. To increase the credibility of modeling for negative triangularity, it might be of interest to perform benchmarking with experimental data.

Contribution#130

Francesco Maviglia et al., «Strategy of an integrated limiter design for EU-DEMO first wall protection from plasma transient events»

Possible points for discussion:

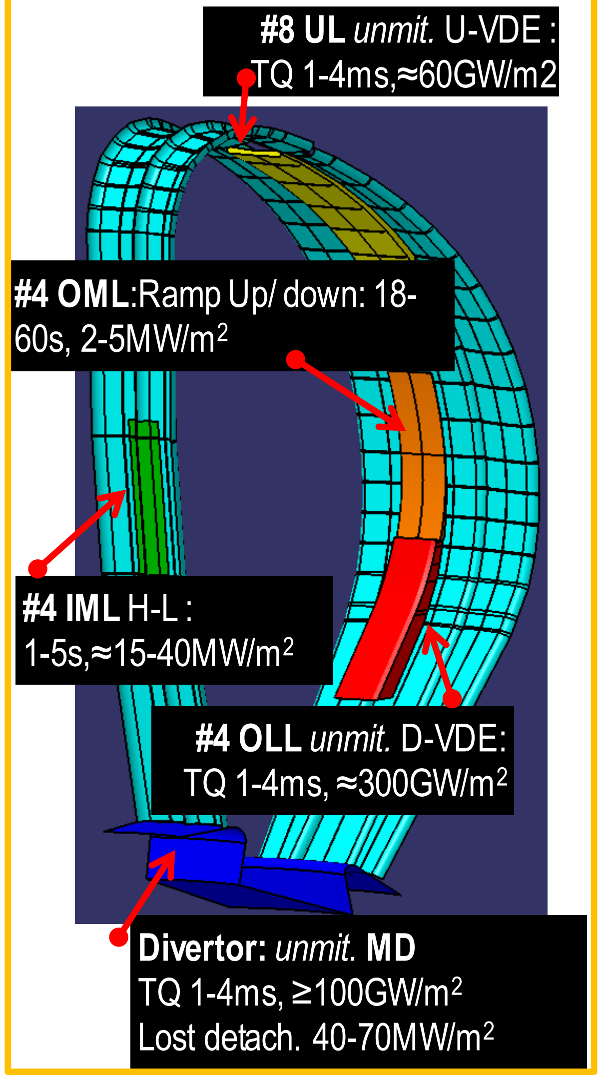
- Is it possible to foresee all plasma-wall contact locations?
- How reliable are the present estimations of damages on PFC to guarantee viability of the concept of “sacrificial limiter”?

Summary slide: EU-DEMO FW protection strategy

- Discrete limiters proposed to protect DEMO FW (FW optimized for tritium breeding, with max HF≈1-2MW/m^2), from transients.
- Would this community agree that a “complete” list of perturbations should allow to foresee all plasma-wall contact locations?
  - Present machine operators already involved in the discussion.
  - DEMO shall have less flexible scenarios than ITER, far from disruptivity.
- How reliable are the present damage estimations on damages on PFC (e.g. including assumptions on vapor shielding, REs, excluding EM loads that can be designed for):
  - Can be reasonably excluded that damages to sacrificial limiter cooling pipes could occur (with dedicated design). Where to test?
  - Would the molten W (tens of kg?) irreparably damage other PFC or the limiters itself? What it is ITER prediction?
  - Could a “mildly damaged” sacrificial limiter sustain few “transient events”?
  - Could a sacrificial limiter be used to shield the divertor?

Not all questions can be answered now: next steps?

EU-DEMO: prelim. HF estimations



Discussion thread#4

Runaway seed formation

Contributions related this thread

- Contribution#120: Embreus
  - Effects of radial transport of fast electrons. Can radial losses suppress hot-tail formation while > 90% energy radiated? Suppression of avalanche by radial transport during current quench. Impact of TQ dynamics on hot-tail seed.
- Contribution#139: Linder
  - Impact of partially ionized impurities not negligible for RE Evolution
- Contribution #103: Sheikh
  - Correlation of t_{CQ} with injection amount and Z. Neon Flushed With Second D2 Injection. Background Plasma Heating.

Contribution#120

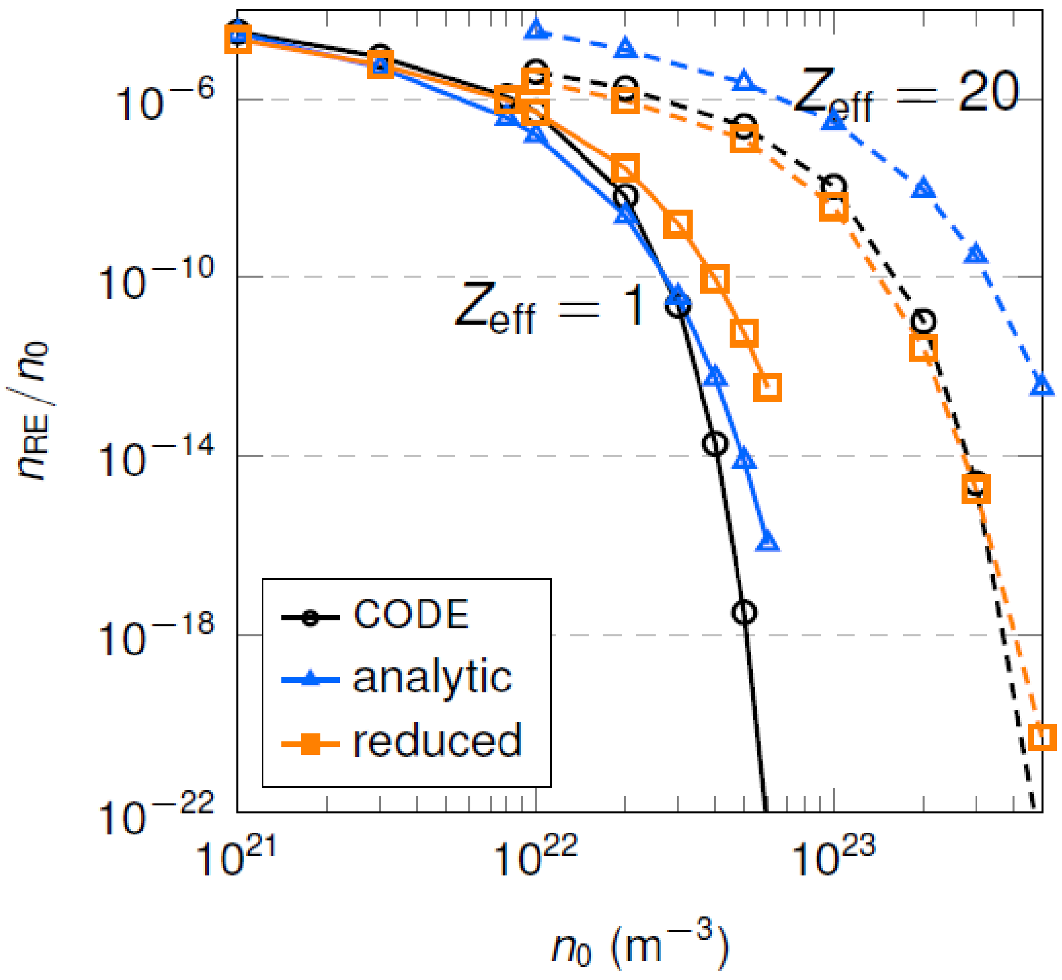
Ola Embreus et al., «Runaway seed formation during the thermal quench and the effects of radial transport of fast electrons»

Possible points for discussion:

- Role of radial transport
- Can we suppress hot tail and radiate >90% total energy?

Runaway seed formation during the thermal quench and the effects of radial transport of fast electrons. O Embreus *et al*, Chalmers Univ. Tech.

- Ongoing work to accurately model seed formation and radial losses using simplified models
- In upcoming research, aim to address:
  - (How) can radial losses suppress hot-tail formation while $> 90\%$ energy radiated?
  - What level of transport is needed to suppress excessive avalanche multiplication?
  - How does hot-tail seed depend on TQ dynamics?



Contribution#139

Oliver Linder et al., «Validation of state-of-the-art runaway electron generation models in simulations of ASDEX Upgrade disruptions»

Possible points for discussion:

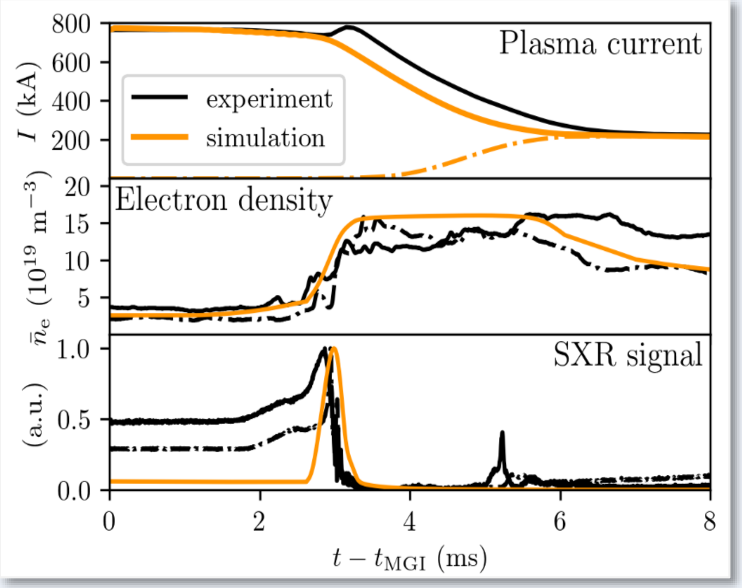
- Impact of impurity on RE generation

Linder *et al.* Validation of RE generation models in simulations of AUG

Main plasma: experiment

With 1D transport code ASTRA-STRAHL applied to Ar MGI in AUG #33108

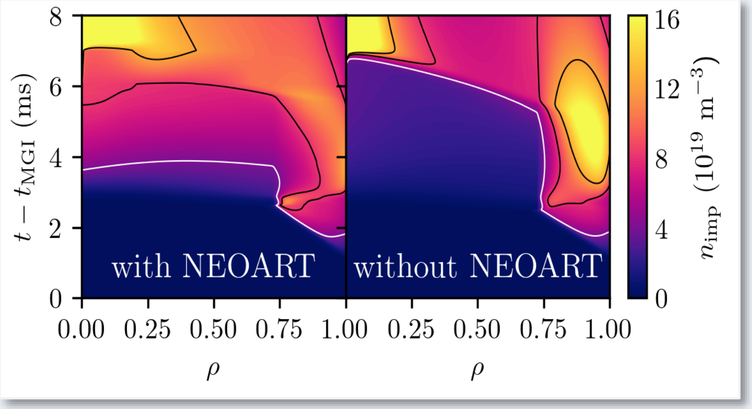
- **Key observations reproduced:** $I(t)$, $n_e(t)$, TQ occurrence
- **Entire disruption covered:** pre-TQ, TQ, CQ



→ **1D ansatz suitable to model MGI**

MMI: material transport

- Neutral propagation with v_{th}
- **Additional transport** (D_{add}, v_{add}) to **mimic MHD** effect inside $\rho_{q=2}$: $D_{add} = D_{add}^{max} \exp(-t'/\tau_{add})$ Otherwise gas penetration too slow (neoclassical fluxes cancel)
- **Neoclassical effects important** with additional transport

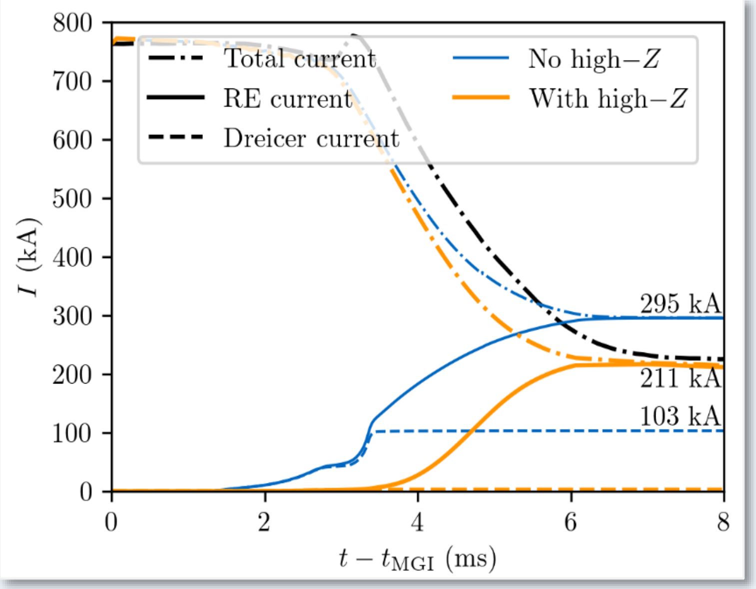


→ **Governed by MHD & neoclassical**

RE generation: model validation

Impact of high-Z on RE generation:

Dreicer	Avalanche
✔ Hesslow '19	✔ Hesslow '19
✖ Connor '75	✖ Rosenbluth '97



No experimental agreement without
→ **High-Z effects NOT negligible**

Contribution#103

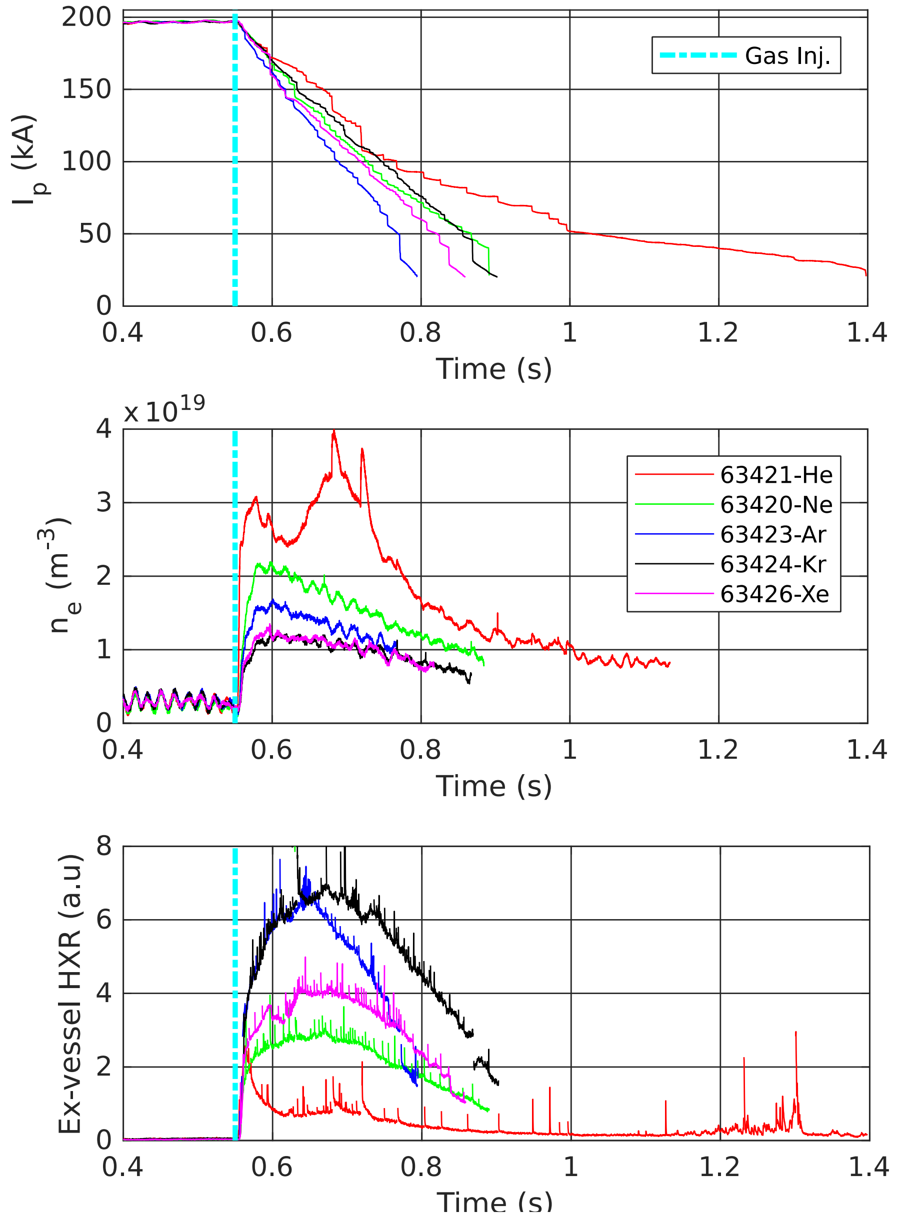
Umar Sheikh et al., «Runaway Electron Studies and Plasma Restart from a RE Beam on TCV»

Possible points for discussion:

- Impact of impurities and amount of injection on current quench time
- Effect of plasma background parameters

Summary Slide 1/2

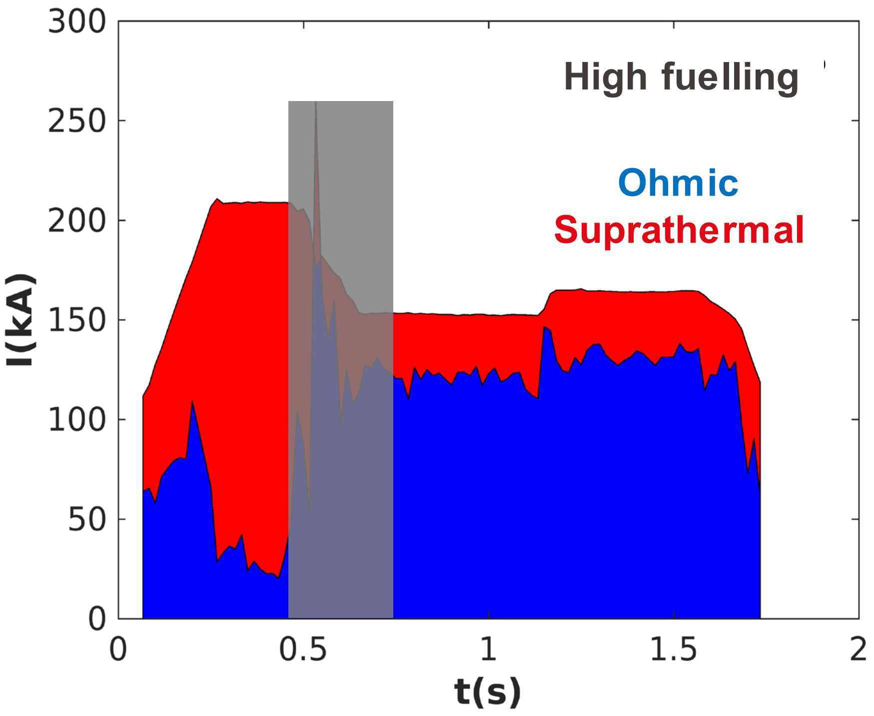
- Confined RE beams reliably created on TCV via MGI
- Natural decay rates with He, Ne, Ar, Kr, Xe covered
- Flushing and background plasma heating demonstrated
- D_2 primary injection led to RE beam followed by background plasma re-established at 1keV
- Only a small subset of full TCV RE database
  - Data available for model validation and collaboration

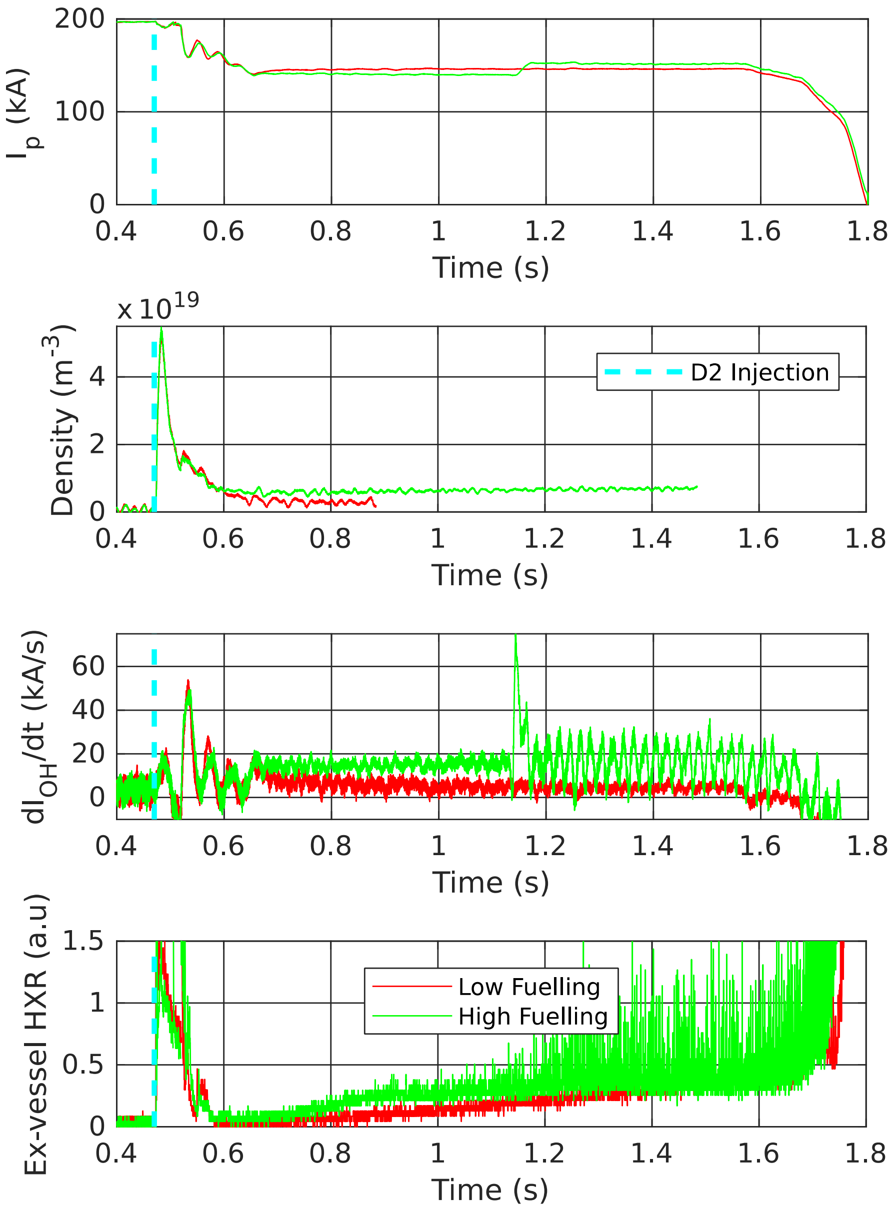


Summary Slide 2/2

U. Sheikh

- Heating of background plasma measured following a D_2 MGI disruption
- LUKE modelling predicts high post-disruption Ohmic contribution to I_p





Discussion thread#5

Runaway electron analysis, characterization and impact

Contributions related this thread

- Contribution#125: Hoppe
  - Analysis of the runaway electron distribution in disruption using synchrotron radiation. Circular synchrotron pattern. Synchrotron intensity increase. Synchrotron pattern shape transition.
- Contribution#99: Zhao
  - Simulation of MHD Instabilities with Runaway Electron Current using M3D-C1
- Contribution #114: Plyusnin
  - RE generation events have been grouped on parameters of disrupting discharges and RE parameters (magnetic fields, plasma currents, CQ rates, inferred runaway current fractions, etc.). Elaborated database is ready for use as initial data setup for the modeling and for further benchmarking of the results of numerical simulations

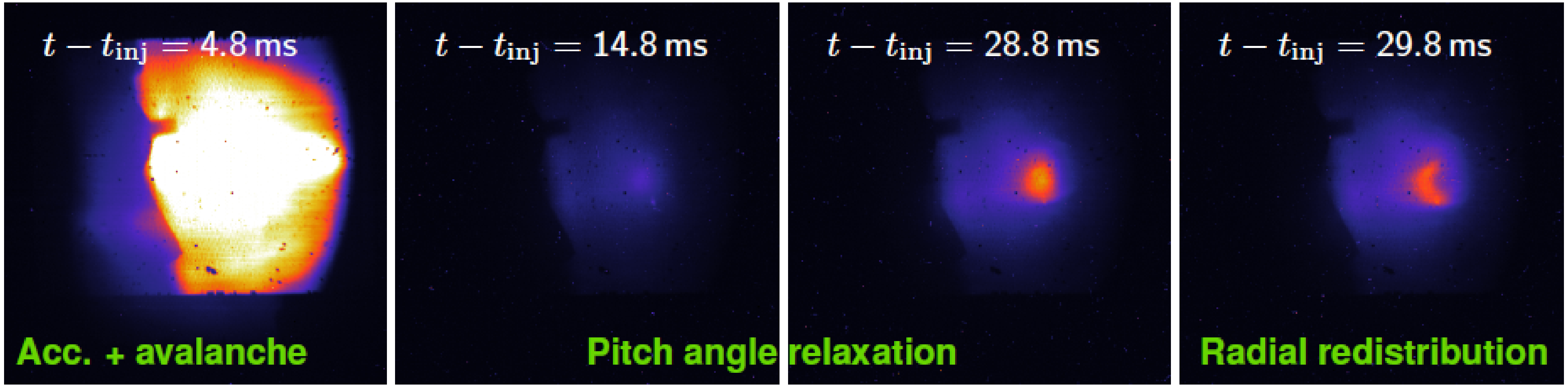
Contribution#125

Mathias Hoppe et al., «Analysis of the runaway electron distribution in an ASDEX Upgrade disruption using synchrotron radiation»

Possible points for discussion:

- Synchrotron emission dominated by remnant seed?
- Synchrotron pattern shape transition: what is the physics behind?

M. Hoppe *et al* – *"Analysis of the runaway electron distribution in an ASDEX Upgrade disruption using synchrotron radiation"*



- **RE evolution during ASDEX-U disruption analysed**
- **Distribution function has two components:**
  - Avalanche component (dominates current)
  - Remnant seed (dominates synchrotron emission)
- **Forward + backward modelling give detailed insight into experiment**
  - Circular synchrotron pattern reproduced with fluid-kinetic and synchrotron simulations
  - Synchrotron intensity increase explained by pitch angle scattering
  - Synchrotron pattern shape transition due to radial density redistribution

Contribution#99

Chen Zhao et al., «Simulation of MHD Instabilities with Runaway Electron Current using M3D-C1»

Possible points for discussion:

- Can the modelling tool (M3D-C1 + RE source term) be applied to other devices eg. JET

- Presentation summary

1. The runaway current perturbation of 1/1 and 2/1 mode is peaked around the rational surface. The RE current causes a finite real frequency to 1/1 and 2/1 mode. If the runaway speed is large enough, it does not affect the growth rate and real frequency when it increases. The scale length of the runaway current becomes smaller with higher runaway speed. (Chen et. al. 2020, Chang et. al. already submit)
2. We developed an eigensolver using MATLAB to solve 1/1 and 2/1 mode with RE. The results are consistent with M3D-C^1 results. And the runaway electrons have restrained the resistivity correction effect in high resistivity cases.
3. The runaway electrons have convection and diffusion in nonlinear phase and the runaways restrained the sawtooth.
4. We have already developed the source term for runaways in M3D-C1 to study the runaway generation in experiment, and the result using the DIII-D parameter shows that the plasma current has been fully carried by runaway electrons, which is similar with experiment.

Contribution#114

Vladislav Plyusnin et al., «Data on Runaway Electrons in JET II»

Possible points for discussion:

- Shape effects on RE generation: what is the physics behind?
- Use of database to support simulations

Summary slide on Data on RE in JET II (V. Plyusnin et al.) (1)

- The data on disruption generated RE in JET is retrieved for entire history of JET operations.
- RE generation events have been grouped on parameters of disrupting discharges and RE parameters (magnetic fields, plasma currents, CQ rates, inferred runaway current fractions, etc).
- New data on maximal conversion of plasma currents into RE ones is found in JET (≈ 80%)
- Elaborated database is ready for use as initial data setup for the modeling and for further benchmarking of the results of numerical simulations;

JET

Summary slide on Data on RE in JET II (V. Plyusnin et al.) (2)

- A detailed comparison of RE generation parameters in circular and X-point plasmas revealed strong differences in their CQ parameters and efficiency of RE generation.
- Analysis of RE generation dynamics allowed establishing the set and ranges of plasma parameters (safety factor q_{95}, plasma internal inductance, etc., as well as electron temperature and density) affecting the RE generation or increasing efficiency of this process.
- An analysis of the collected RE data will be continued in parallel with continuation of JET experiments on generation and suppression of RE

What next?

Now we take questions

- on the present summary presentation
- "technical" questions on specific contributions
  - Authors are encouraged to answer directly

Scientific discussion on the presentations should be carried out during the upcoming "Discussion" slots

Thank you for your contributions and let's have a interesting discussion!