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Physics of the creation and mitigation of runaway electron beams in presence of their background plasma

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Disruptions and runaways

- **Disruptions: threat to a reliable operation of future devices including ITER**
- 3 kinds of effects : heat loads, electromagnetic forces, runaway electrons
- Most difficult consequence to mitigate: runaway electrons (MAs at 5-20 MeV)
  - RE generation gain through avalanche: 10^4 at JET, 10^{16} on ITER.
  - But **large uncertainties** on the generation conditions and loss mechanisms.
  - ➔ We might be too pessimistic about ITER runaways (remember JET-C vs. JET-ILW)

- 2 options to mitigate runaways:
  - Prevent their initial generation.
  - **Suppress the runaway beam once it has appeared**
- ITER possible strategy:
  - One injection to mitigate heat/EM loads
  - Second injection to suppress runaways

Main question to be addressed: under which conditions runaway beam suppression is feasible ?

Outline

- JET Runaway experiments – runaway electrons and their background plasma
  - Experimental setup and background
  - Mitigation efficiency: geometry effect and current effect
  - Background plasma characterization
  - Mitigation efficiency: background plasma effects
  - Vertical stability and link to mitigation efficiency

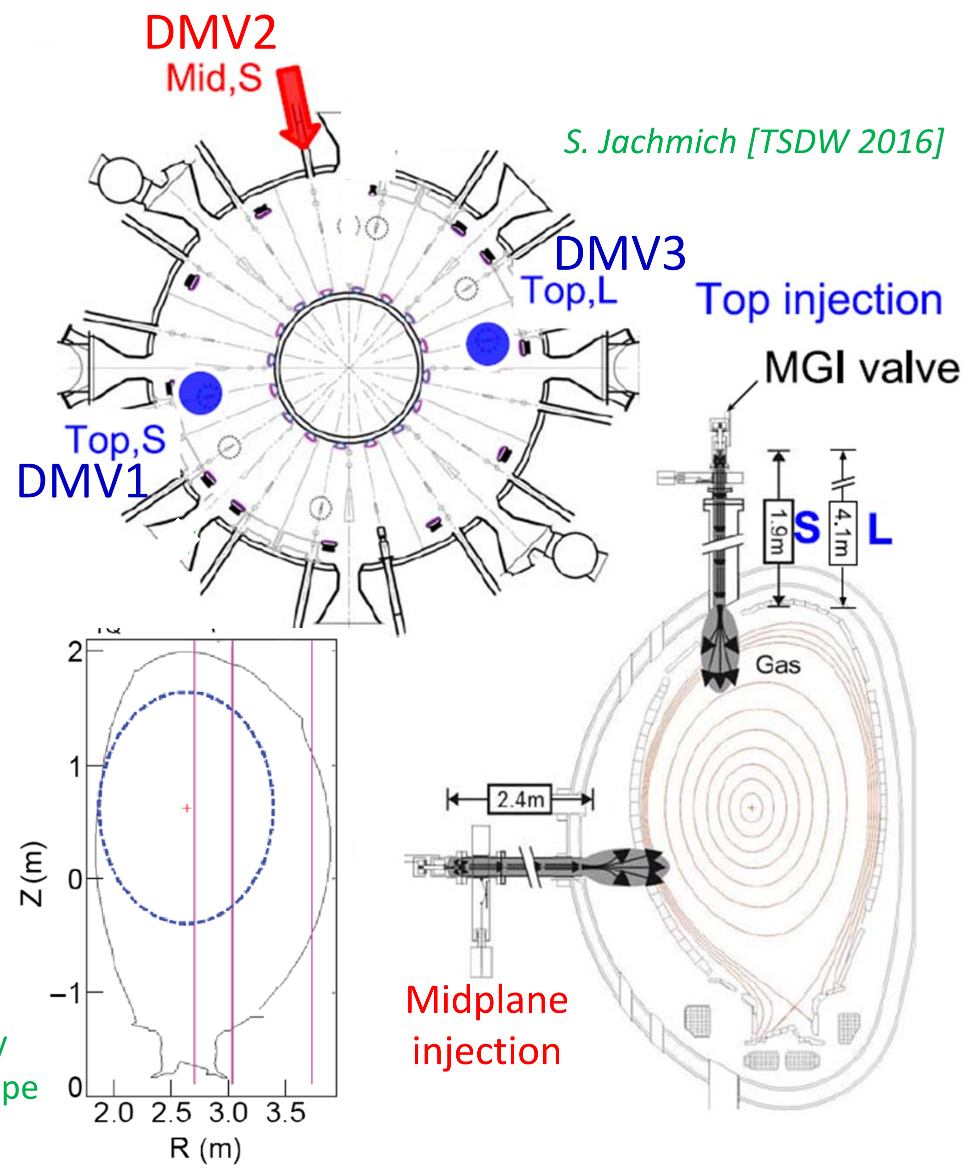
- Bonus: JET runaway kinetic + MHD simulations – C. Sommariva's work
  - Magnetic topology during a disruption
  - Runaway survival following thermal quench
  - Effect of the effective electric field

JET

JET experimental setup

- JET equipped with 3 Disruption Mitigation Valves (DMVs)
  - 2 on top (DMV1 & DMV3)
  - 1 on midplane (DMV2)

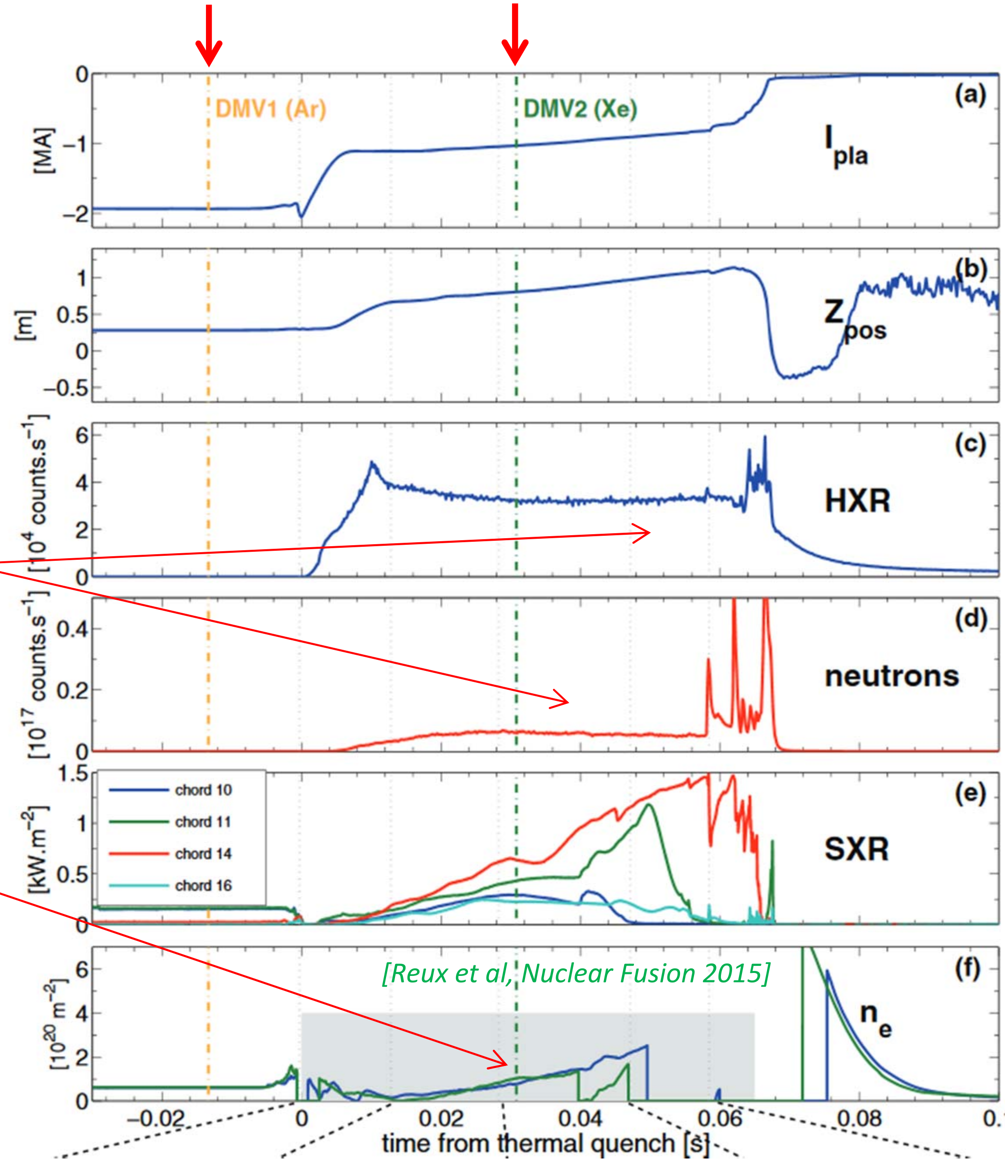
	DMV1	DMV2	DMV3
Volume [l]	0.65	0.975	0.35
P_{inj} [bar]	36	50	50
Gas [Pa.m^3]	1000	4500	1700
Tube [m]	4.1	2.4	1.9
Orifice [mm]	10	30	30
ToF (D_2+Ar)[ms]	2.0	1.2	1.0



JET-ILW runaway experiments - background

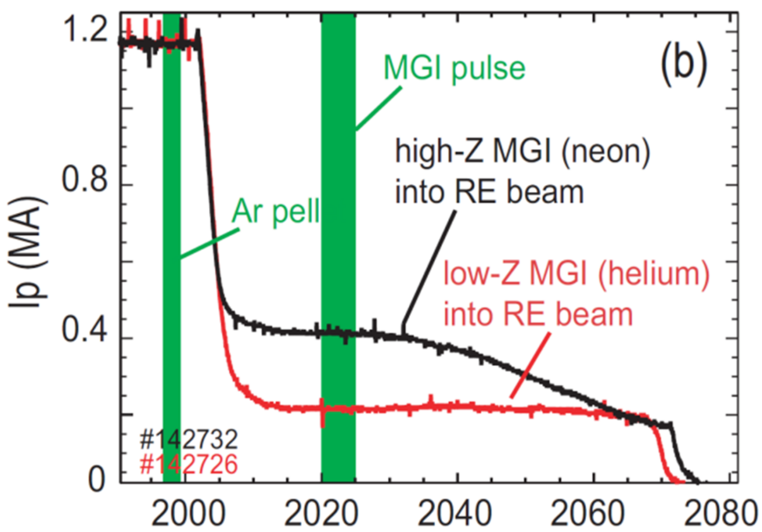
- JET runaway experiments in 2014: first mitigation attempts using massive gas injection
  - Runaway beam created using **massive argon injection** (Disruption Mitigation Valve n°1)
  - RE beam mitigation using Ar, Kr, Xe injection in the beam phase (DMV2 → 4400 Pa.m^3)
- Result: **no apparent effect** of the second injection on the RE beam
- Only effect seen in visible radiation range
- Presence of a cold dense background plasma

No penetration of the second injection neutrals into the runaway beam region

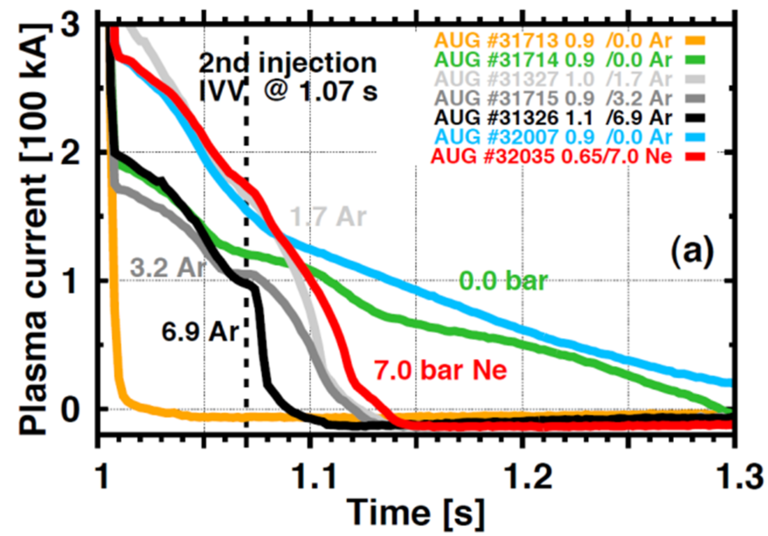


JET runaway experiments – context

- Other smaller devices: better efficiency of second « killer » injection
  - DIII-D: RE beam triggered with Ar pellet, killed with MGI (12 Pa.m^3 atoms)
  - Asdex-U: RE beam triggered with Ar MGI, killed with MGI (70 Pa.m^3 atoms)



[Hollmann et al., Nuclear Fusion 2013]

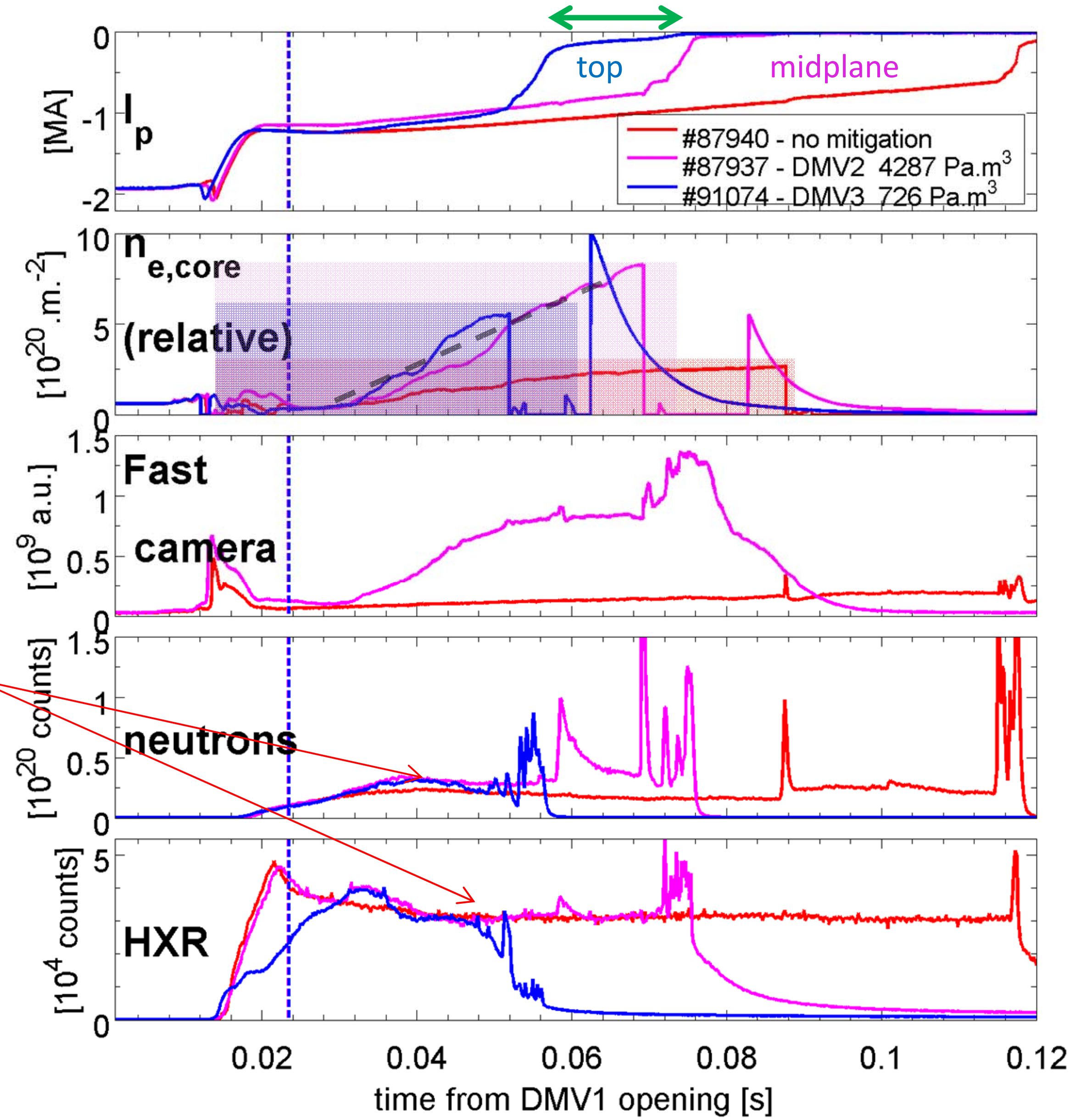


[Papp et al., IAEA FEC 2016]

- Why is JET different? ➔ Bad penetration of the second injection. Why?
  - Geometry effect : the gas plume misses the beam?
  - Current screening effect?
  - Shielding by the background plasma?

Geometry effect: upper port vs. midplane injection

- Mitigation attempts on the same target runaway beam:
  - DMV2 (midplane port)
  - DMV3 (upper port)
- Runaway beam duration 15 ms shorter with DMV3, but within the uncertainties of the runaway beam duration
- Similar density rise following the injections
- No effect on HXR and neutrons, no soft landing of the runaway beam



Gas plume geometry is not responsible for the lack of efficiency

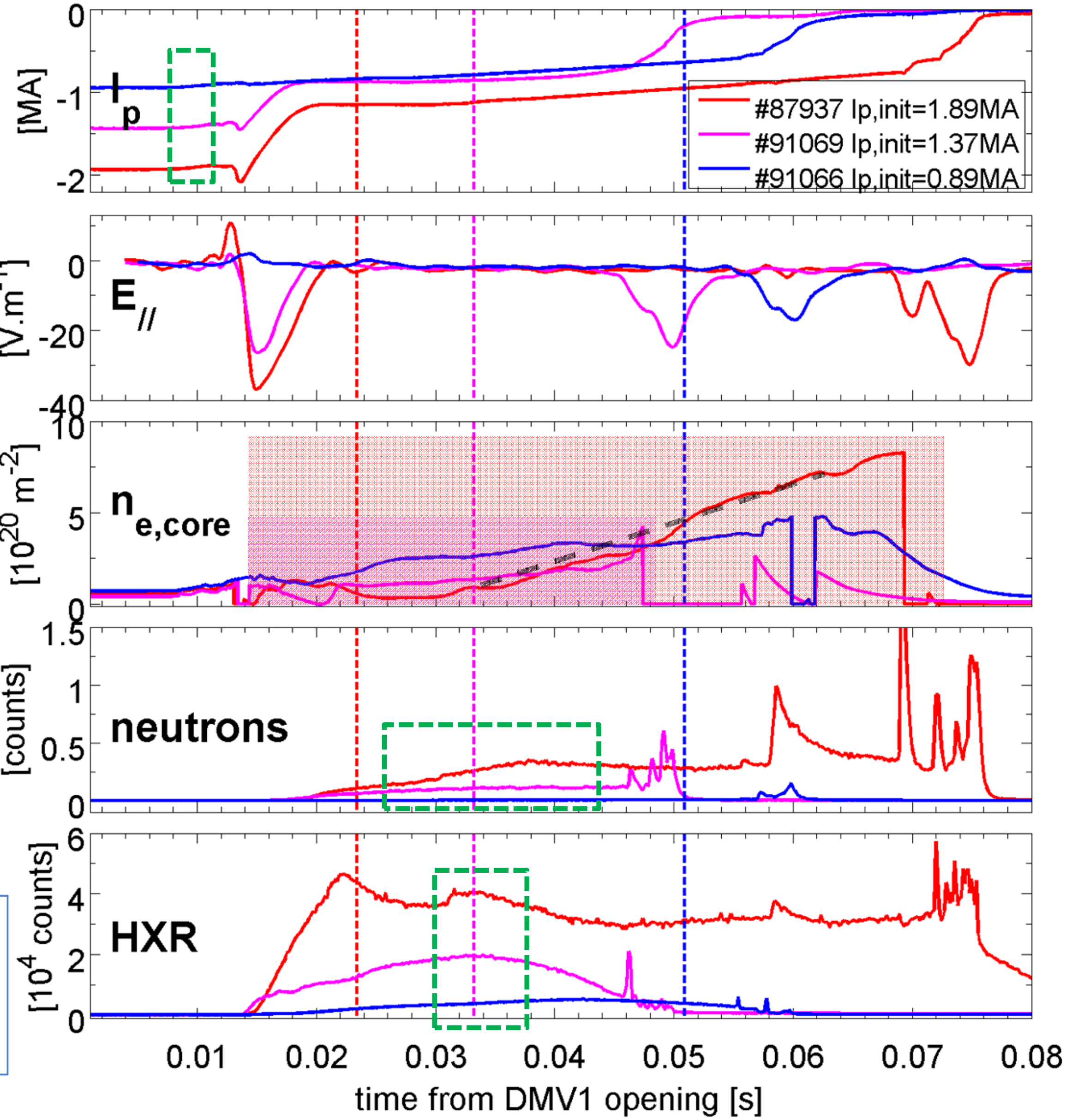
JET

Current screening effect

- JET RE currents are higher than in any other device
- Reduction of the RE current by reducing the pre-disruption plasma current
- Major change on the runaway population: **much lower energies**
  - HXR counts twice lower for 2.0MA/1.5MA
  - Almost no neutrons for 1.0 MA

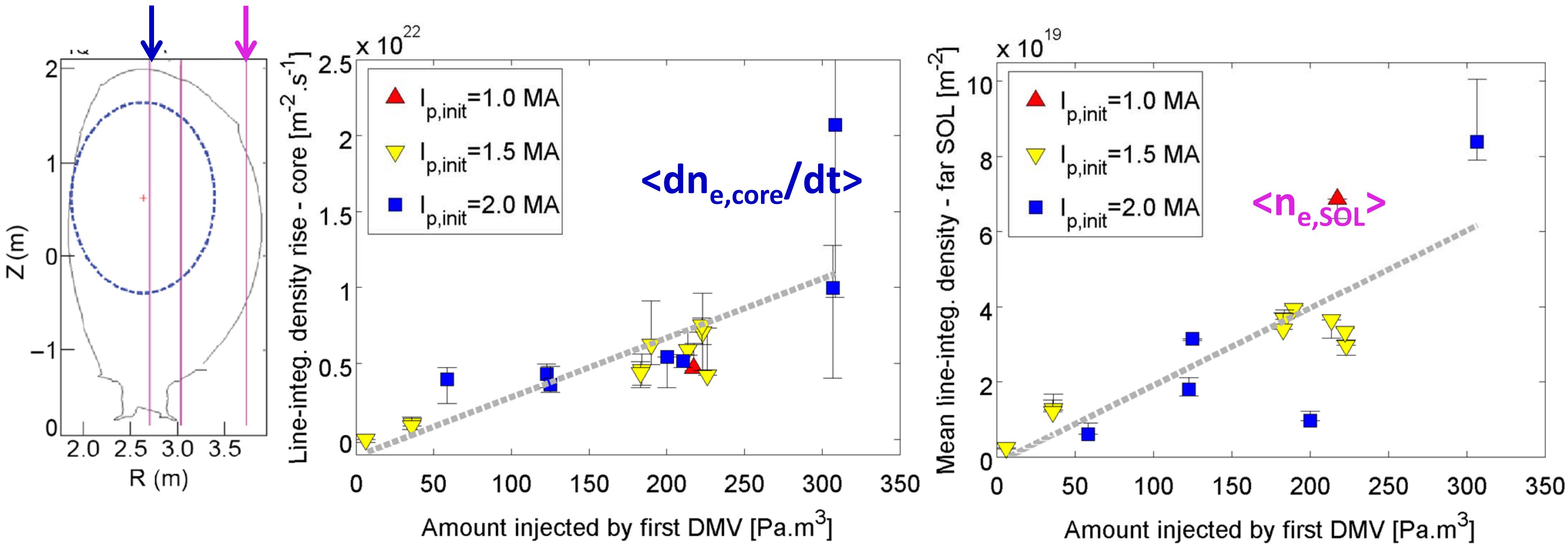
➔ Runaway population at lower energy, but no easier penetration of the killer gas

Ability of MGI to suppress RE not directly related to their current/energy



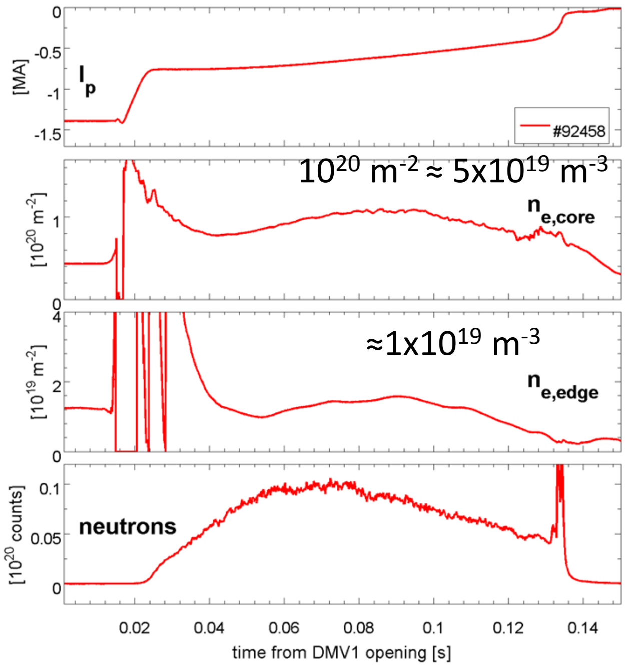
Background plasma density

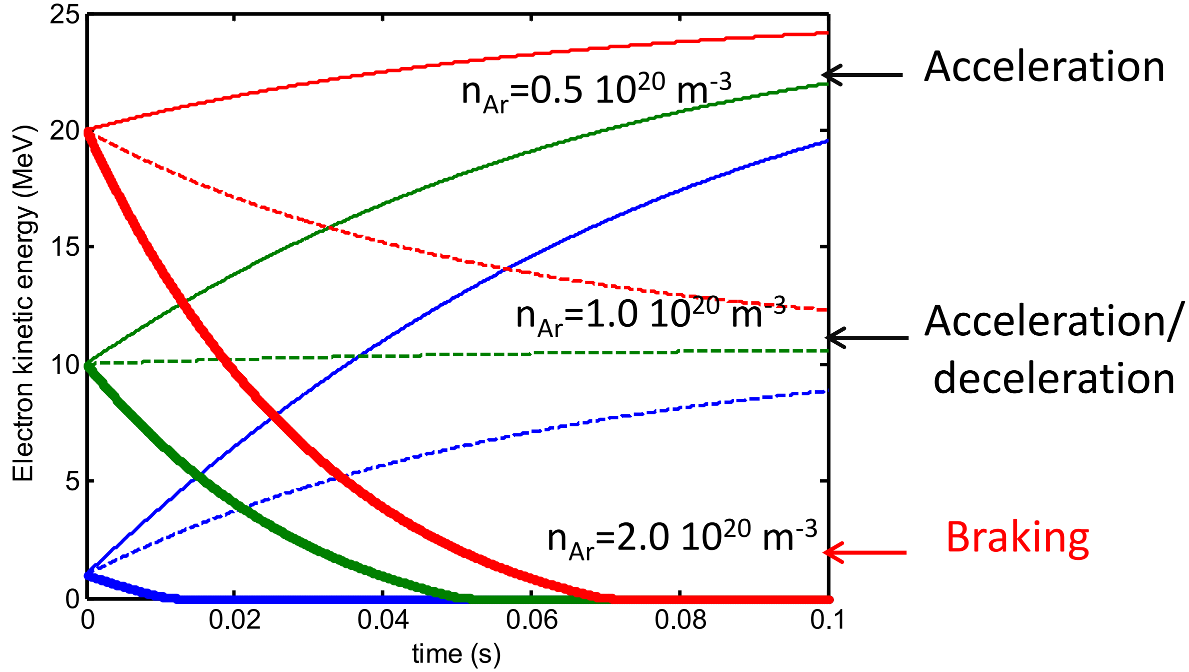
- Background plasma evolution during the RE beam phase (without any second « killer » injection)
  - Density increase in the core
  - Constant density in the far-SOL
- **Density increases with increased triggering-injection content**



Background plasma density determined by the initial injection

Background plasma neutral content



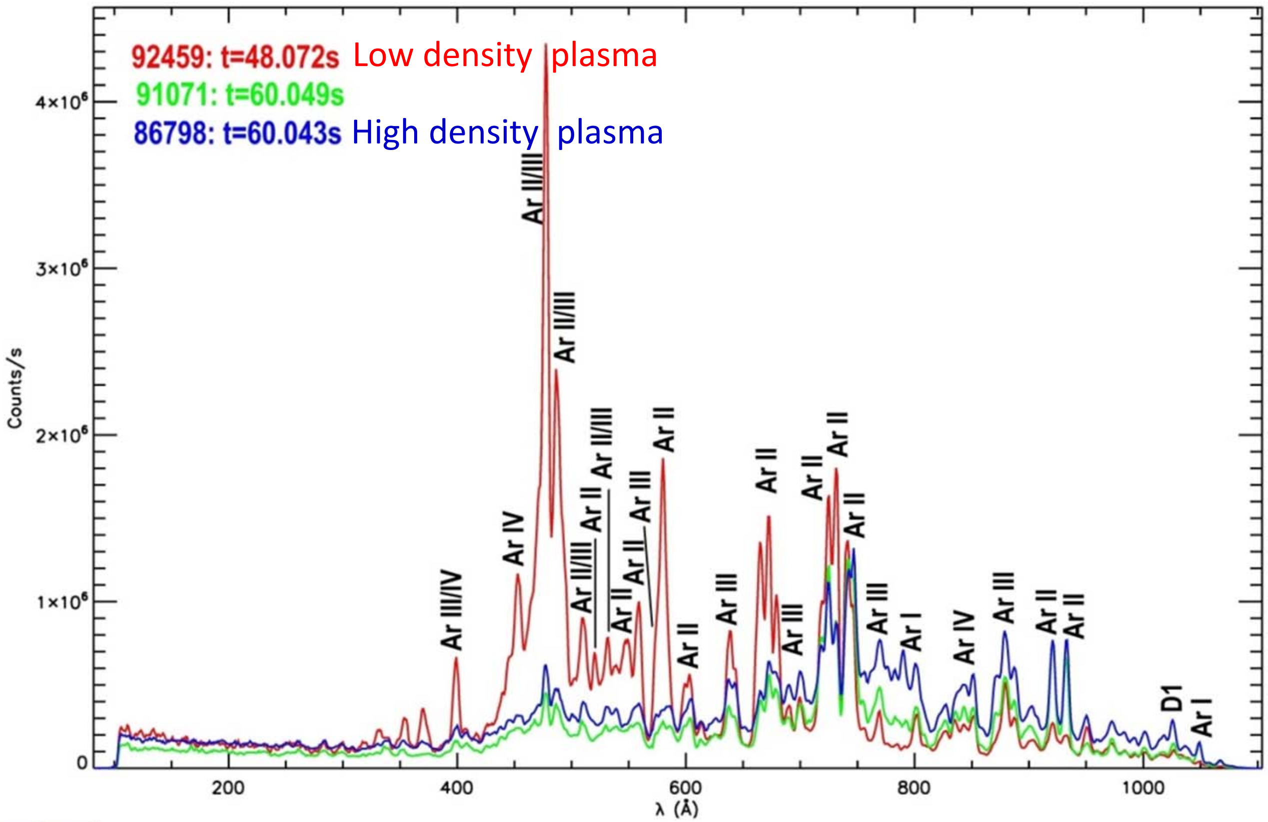


- Stopping power from ESTAR calculations + synchrotron losses
- neutral density not higher than 1.0 10^{20} m^{-3}: (otherwise RE are braked)
- Background plasma: most likely mainly ions
- Power transfer from runaway collisions large enough to sustain the background plasma (5-20 MW)

Low neutral content in the background plasma

Background plasma temperature

- VUV spectra during the RE beam phase: indicates Ar II, III, IV lines, no Ar I.
- Assuming collisional radiative equilibrium: **T_e ~ 5-15 eV.**
  ➔ **hotter than DIII-D background plasma** (1-2eV) *[Hollmann et al, Nuclear Fusion 2013]*
- Temperature constant during the beam phase



Background plasma temperature: 5-15 eV

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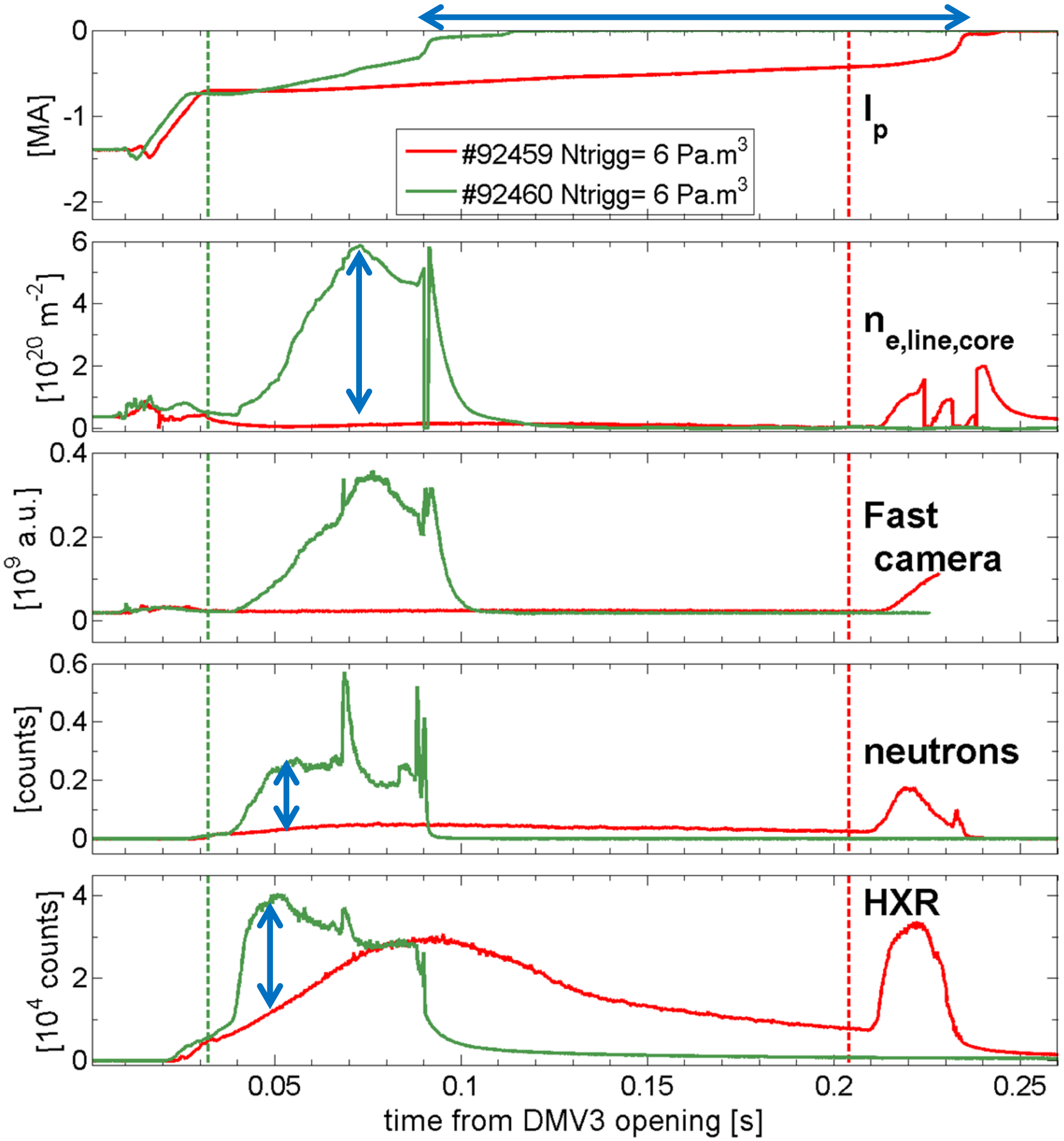
Injection in a lower density background plasma

- **RE beam responds to the injection:**
  - Current decays more quickly
  - Shortening of the runaway beam
  - Density rise ($\Delta n_{e,l} > 5\times10^{20}$ m^{-2} in 40 ms)
  - Increase of HXR and neutrons indicating RE losses.

- **Better penetration of the Krypton mitigation injection**

First time at JET that a RE beam can be acted upon with MGI



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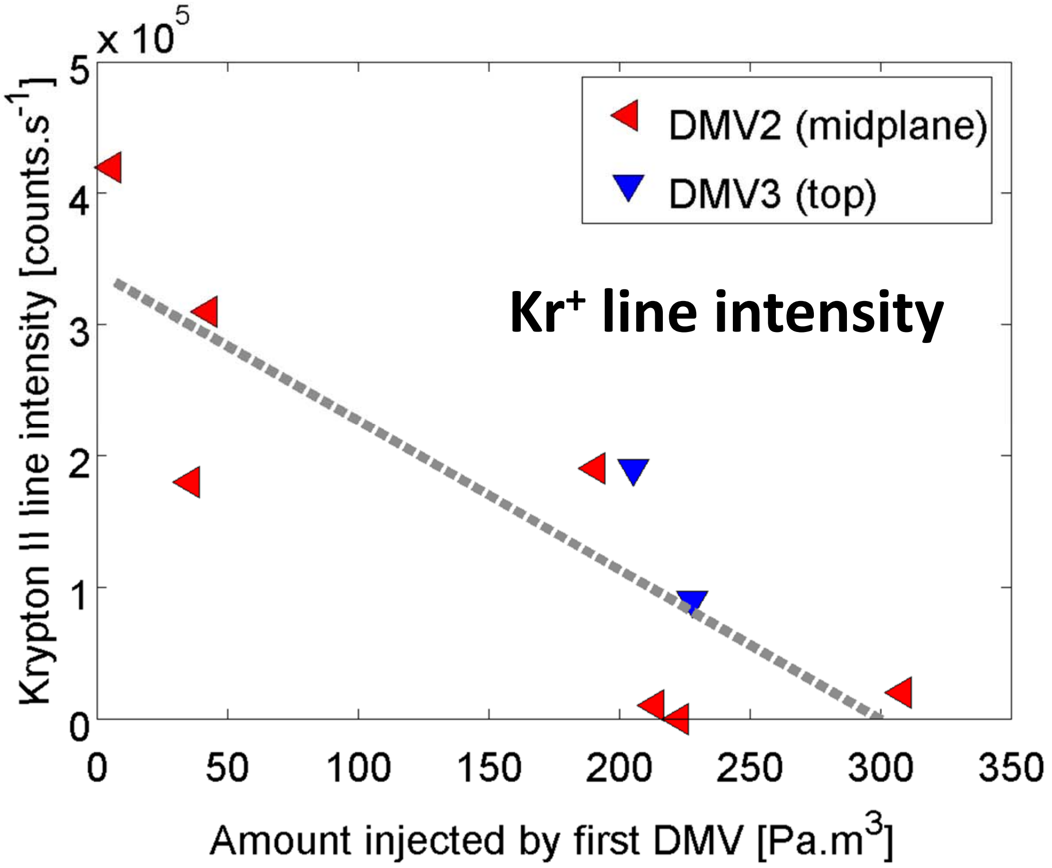
Second injection mixing efficiency

- Krypton line visible following the second (killer) injection.
- **Kr^+ line** (no neutrals) ➔ consistent with the plasma temperature
- The lower the background plasma density is, the more intense is the Kr line

Penetration of the second injection more efficient in low-density background plasmas

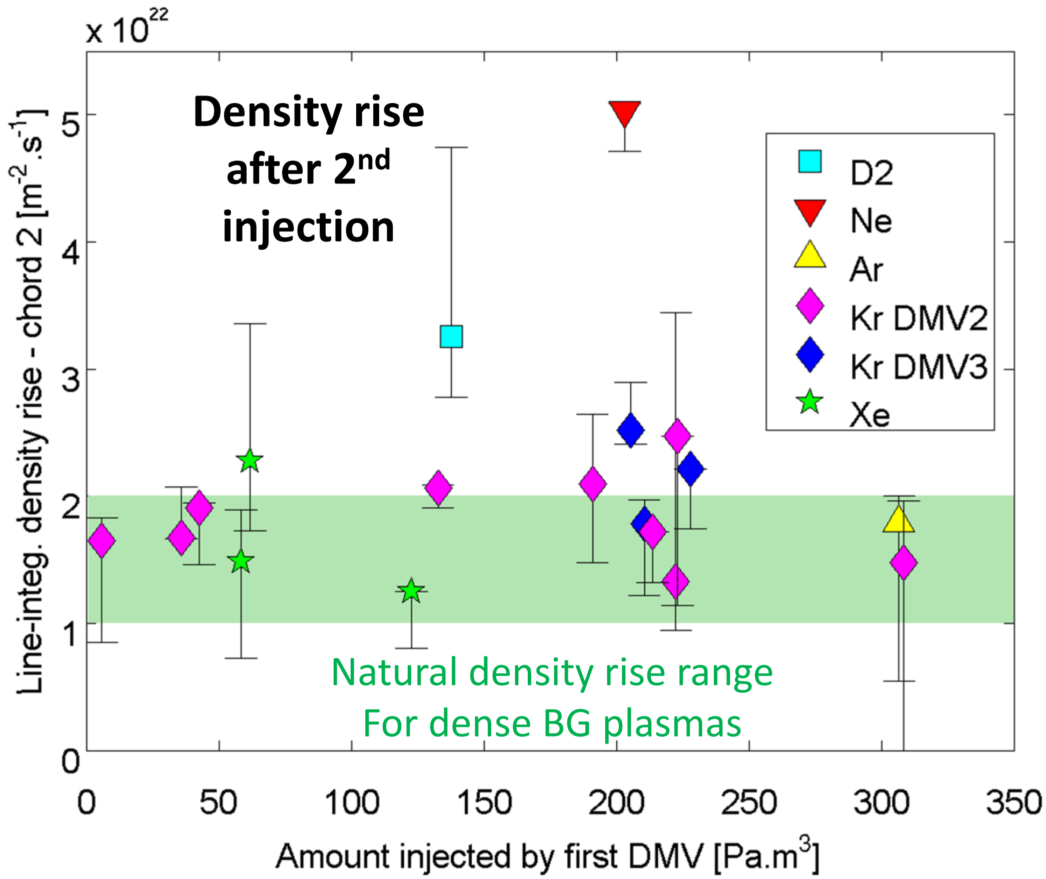


Second injection mixing efficiency

- Density rise following the second injection: only moderately faster than the « natural » density rise of a dense background plasma

- Mitigation gas mixed only if the background plasma is low enough in density
- **Self-limiting penetration as the density builds up.**

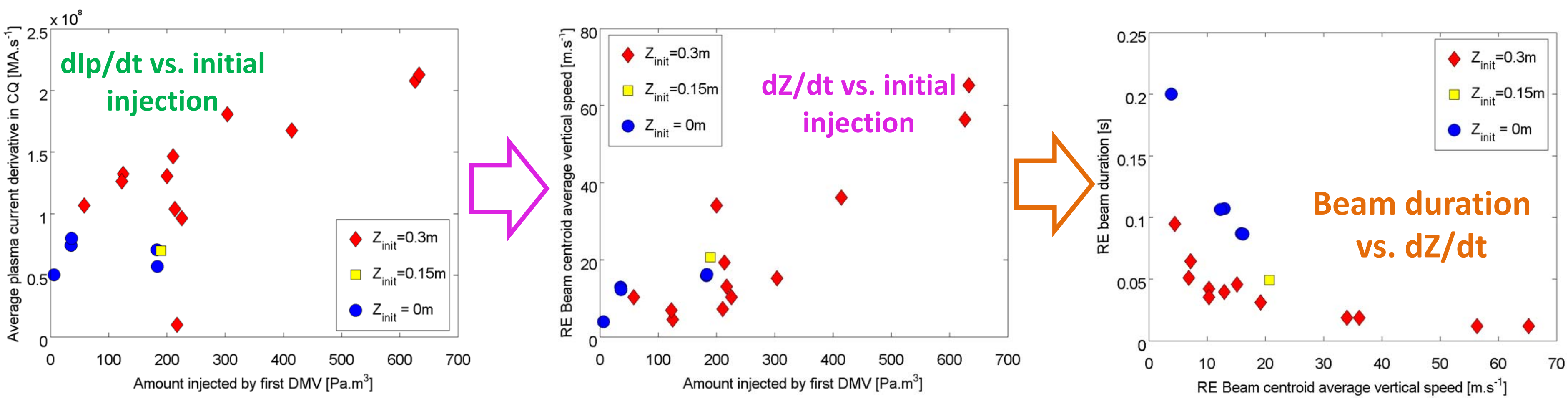
- Better with Ne and D2?



For a given gas: saturation of the maximum rate at which the density increases

Vertical stability and background plasma

- JET runaway beams: vertically unstable
- The more gas is used to trigger the disruption, the more unstable.
  - Larger disruption-triggering injection ➔ more impurities at thermal quench ➔ faster current quench
  - ➔ more difficult for the control system to catch up
  - ➔ shorter beam
- Also holds for second injection: vertically destabilizing

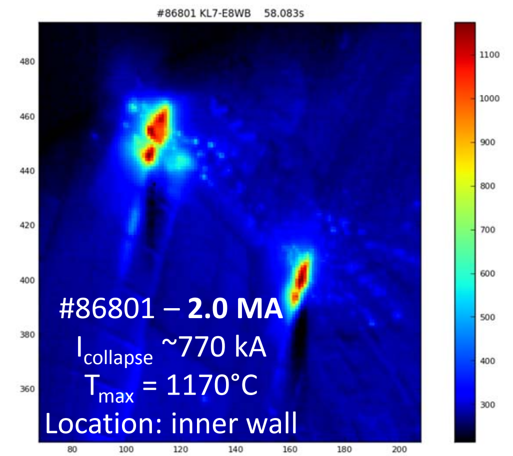


Vertical stability, RE beam lifetime and background plasma are linked

Beam mitigation: when is the best time to act?

- Vertically unstable beams at JET always end up with a final collapse
  - Still unclear what triggers the collapse (and why some experiments manage to lead the runaway current down to zero without it)
  - Most of the impact damage associated with the final loss

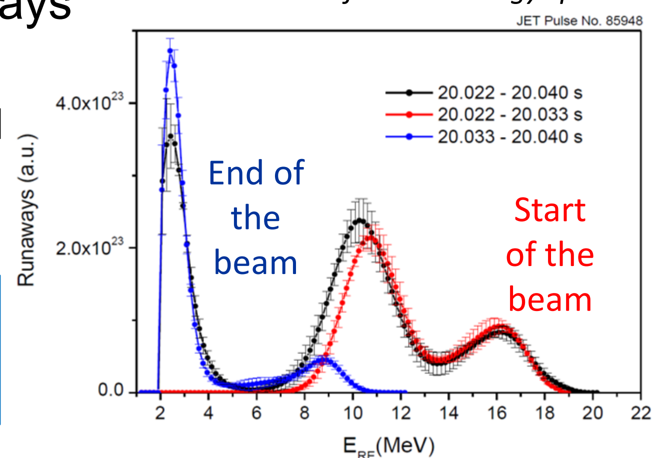
- 2nd injection: not clear how it affects the beam final collapse and runaway damage
  - Seems to be more dependent on the initial runaway current, runaway energy and background plasma
  - Mitigation injection makes the collapse happen quicker
  - Unclear trends on runaway damage because of various locations, currents and energies



- Some growing evidence that the runaway energy decays along the beam phase
  - Should MGI/SPI wait until runaway energy has decayed enough?
  - But fire before the « natural » collapse?

Mitigation strategy to be assessed not only with shortening RE beam or Ip @ final collapse

Reconstruction of the RE energy spectrum



Conclusions

- **Background plasma characteristics (density, temperature) determined by the initial injection triggering the disruption:**
  - Less gas used for the disruption ➔ lower density background plasma
  - Temperature and density for JET BG higher than on other machines
- **Penetration of the second (mitigation injection) highly dependent on the background plasma**
  - Better penetration in low-density background plasma
  - Saturation of the density rise (self-limiting)
- **Vertical stability and background plasma are related**
  - The denser the background plasma, the more vertically unstable
  - Figure of merit to decide when firing MMI to be defined

Ad: More at APS 2017 (C. Reux, invited talk)

- **Shattered Pellet Injection may enhance penetration but effect on vertical stability to be assessed. ➔ 2018 JET campaigns**

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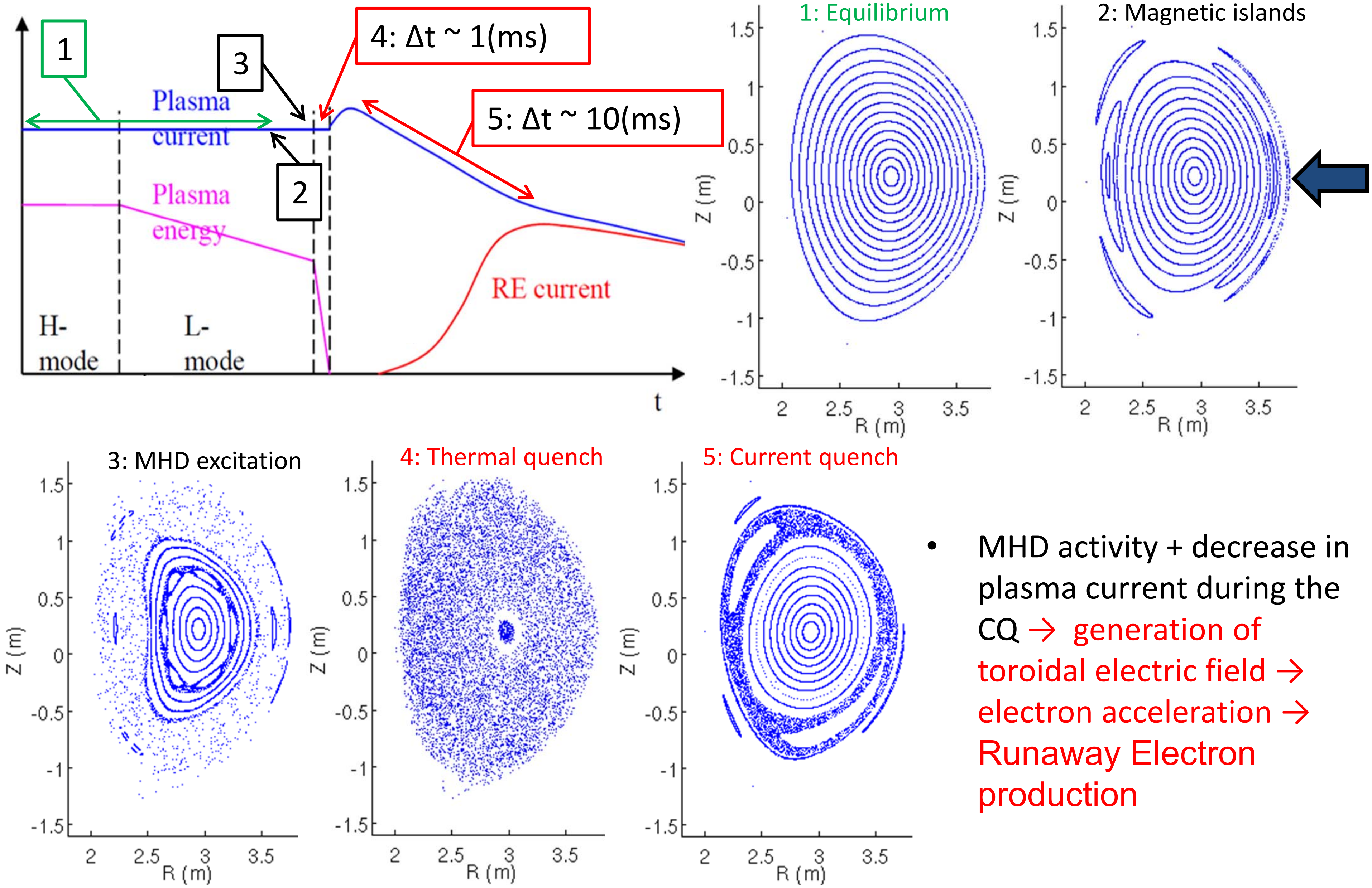
JET

Disruption phenomenology (Simulation of JET #86887)



- MHD activity + decrease in plasma current during the CQ → generation of toroidal electric field → electron acceleration → Runaway Electron production

Context and contribution of the present work

Interactions between MHD in disruption thermal quench (TQ) and primary RE generation (runaway seed for avalanche) are still poorly understood

$\Rightarrow$ These interactions are critical especially for :

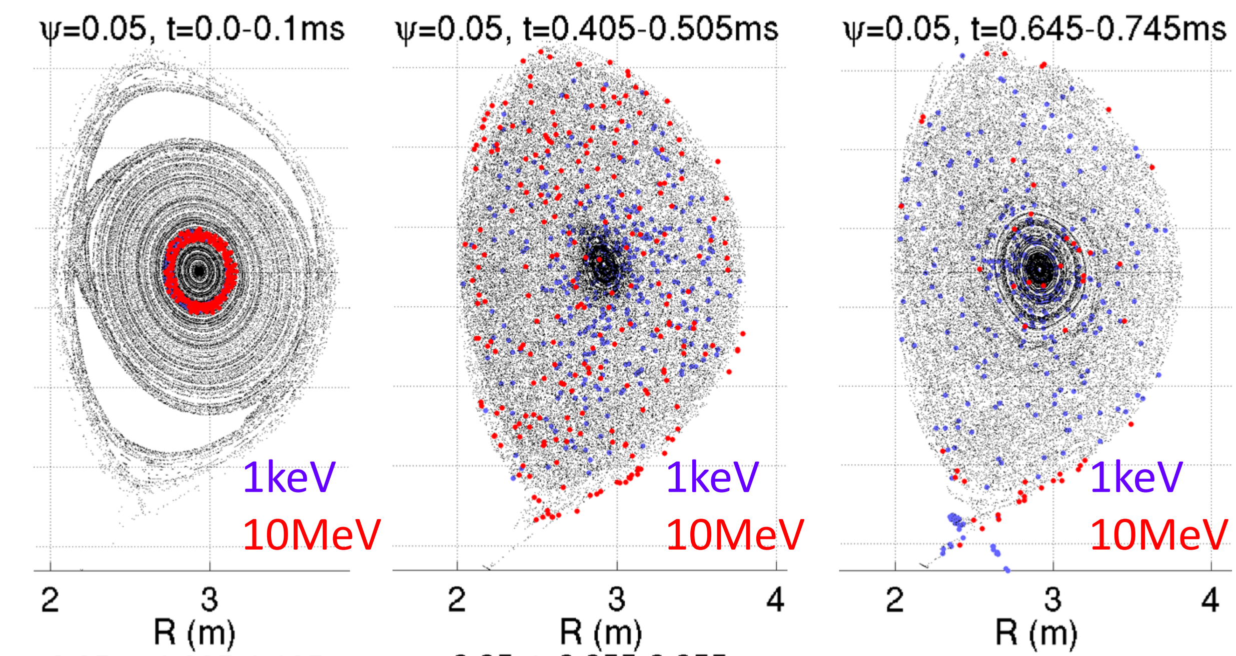
1. Hot Tail mechanism → How many pre-TQ hot electrons remain confined through the TQ phase?
2. Dreicer mechanism → Can electrons be accelerated due to MHD-related electric fields during the TQ phase?

$\Rightarrow$ These questions are addressed introducing test particles in JOREK:

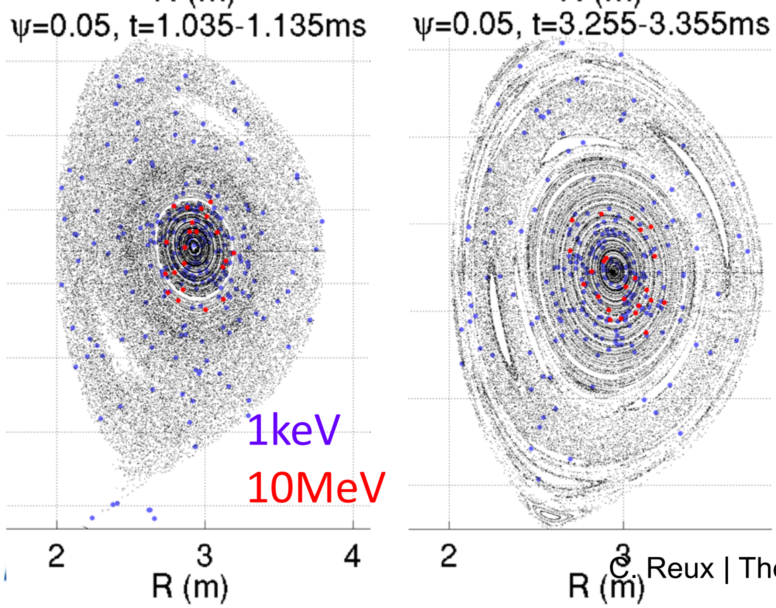
- Both guiding center [3] (GC) and full orbit (FO) [4] models have been implemented and tested
- A simple model of drag force is implemented [5] (for GC only)
- 3D-time varying MHD fields are used
- No feedback on the MHD solutions is considered

[3] J.R. Cary, A.J. Brizard, Rev. Mod. Phys., p.693, 2009
[4] R.Zhang et al., Phys. Plasmas, vol.22, p.044501, 2015
[5] J. R. M.-Solis et al., Phys. Plasmas, vol.22, p.092512, 2015

Overview of electron dynamics in the JET #86887 simulation

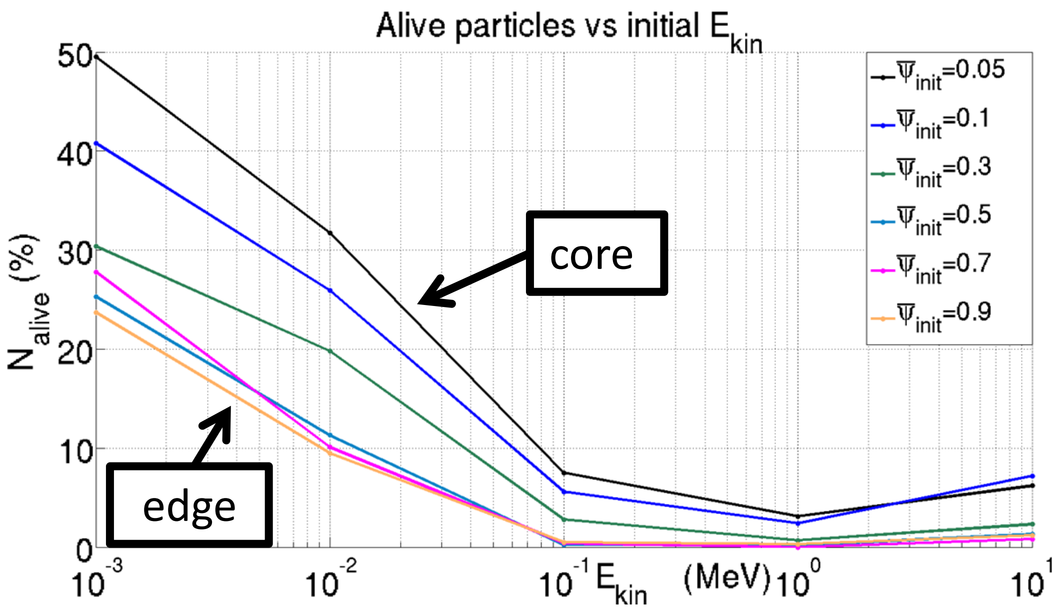


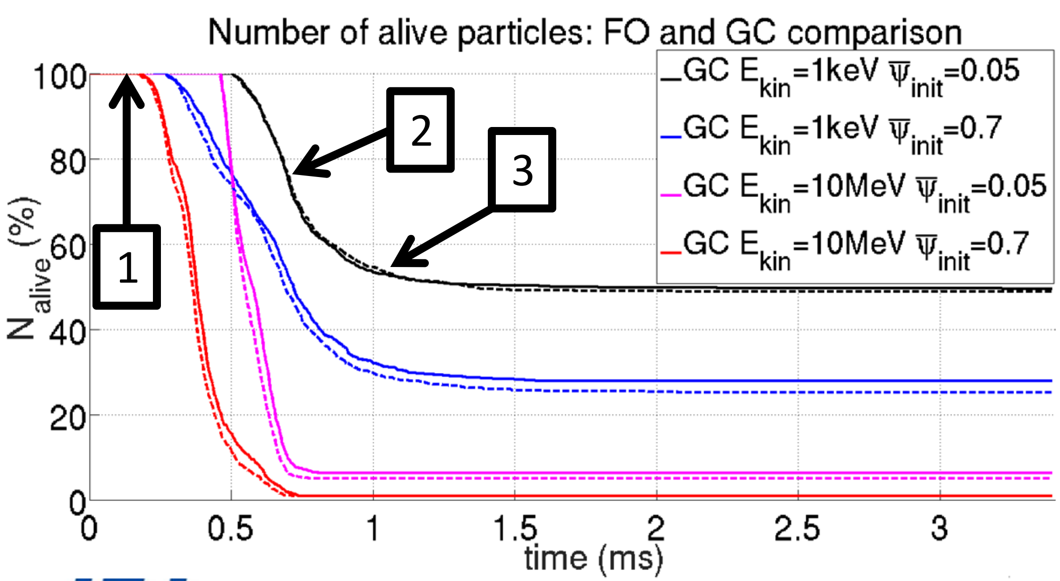
- Electric field from dψ/dt are turned off → no GC acceleration before TQ
- Mono-energetic, mono-pitch angle, deeply passing electrons initialized on a magnetic surface



- Electrons are reconfined due to reformation of closed magnetic flux surfaces during the CQ phase
- Reformation of magnetic surfaces in two steps: (1^{st}) fast generation in the core, (2^{nd}) later formation at the edge

Fraction of surviving electrons vs initial energy and position





Trend	Losses
E_{kin} ↗ (<1MeV)	↗
E_{kin} ↗ (>1MeV)	↘
$\overline{\psi}_{init}$ → core	↘
$\overline{\psi}_{init}$ → edge	↗

- Electrons are never totally lost (high surviving fraction for $E_{kin} \leq 10$keV)
- Transport is mostly parallel to the field lines
- Orbit averaging for $E_{kin} > 1$MeV

Electron loss process:

1) Electrons diffuse and start to be lost
2) Electron loss (deconfinement)
3) Magnetic surfaces reform → losses stop → electrons are reconfined

⇒ Loss profiles of FO and GC are in good agreement

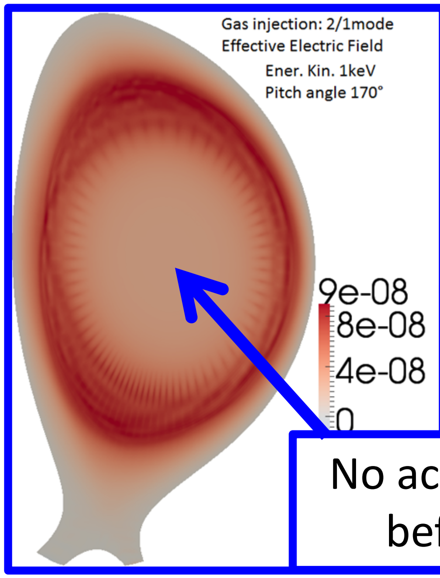
A possible mechanism for RE generation in TQ:
Accelerating *effective* electric field

Effective electric field ($E_{eff} = (qE_{/\!/} + F_{coll/\!/})/|q|$) at different disruption time:

$\Rightarrow$ Blue = accelerating $\mathrm{E_{eff}}$ field

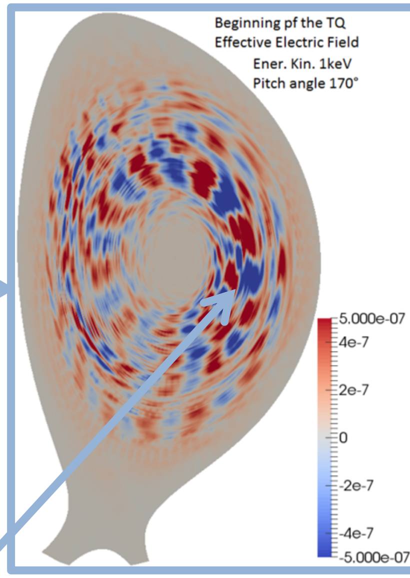
$\Rightarrow$ Red = decelerating $\mathrm{E_{eff}}$ field

If particles are accelerated during the TQ, they can become RE during the CQ

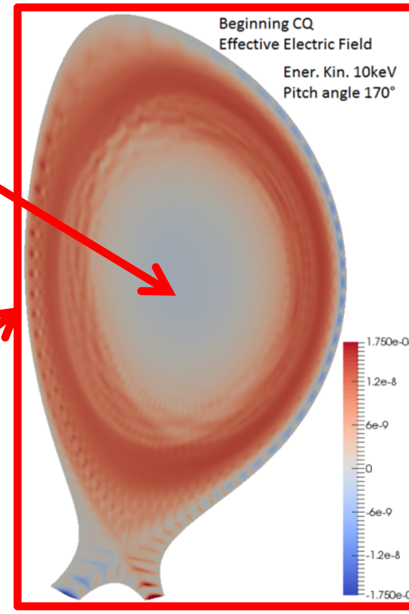


No acceleration before TQ

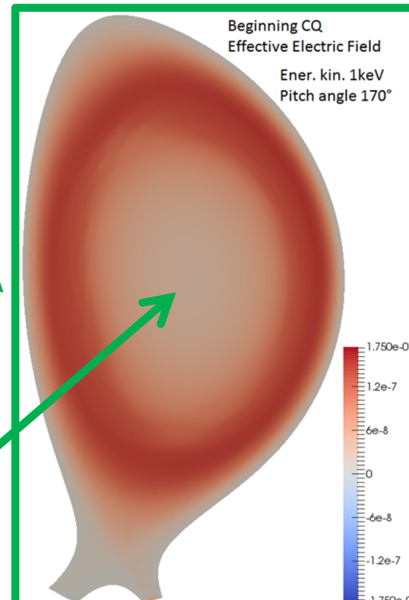
TQ



CQ:@ 10keV



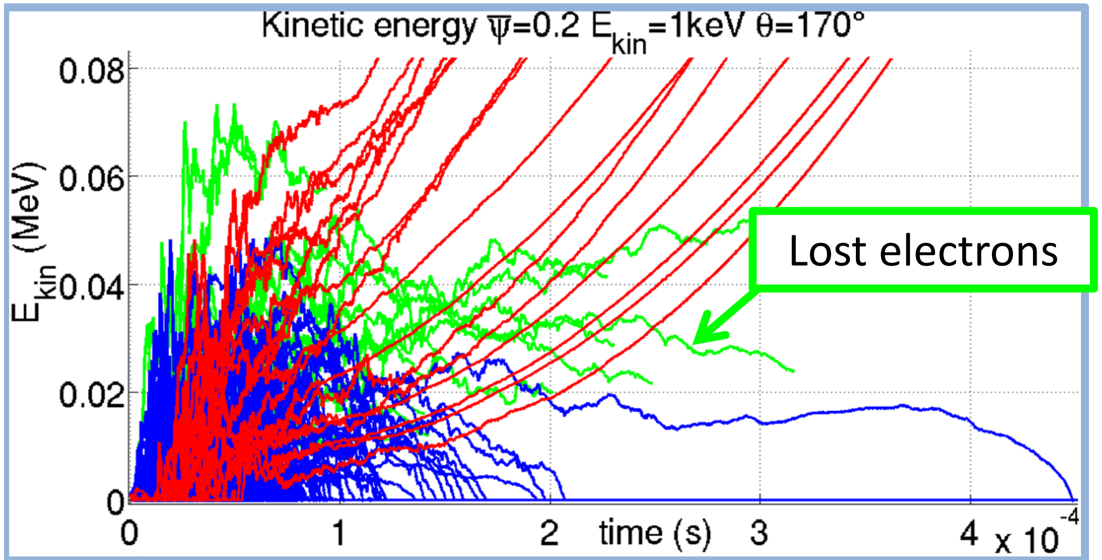
CQ:@ 1keV



Regions of accelerating and decelerating $\mathrm{E_{eff}}$ are found during the TQ: particles can be accelerated

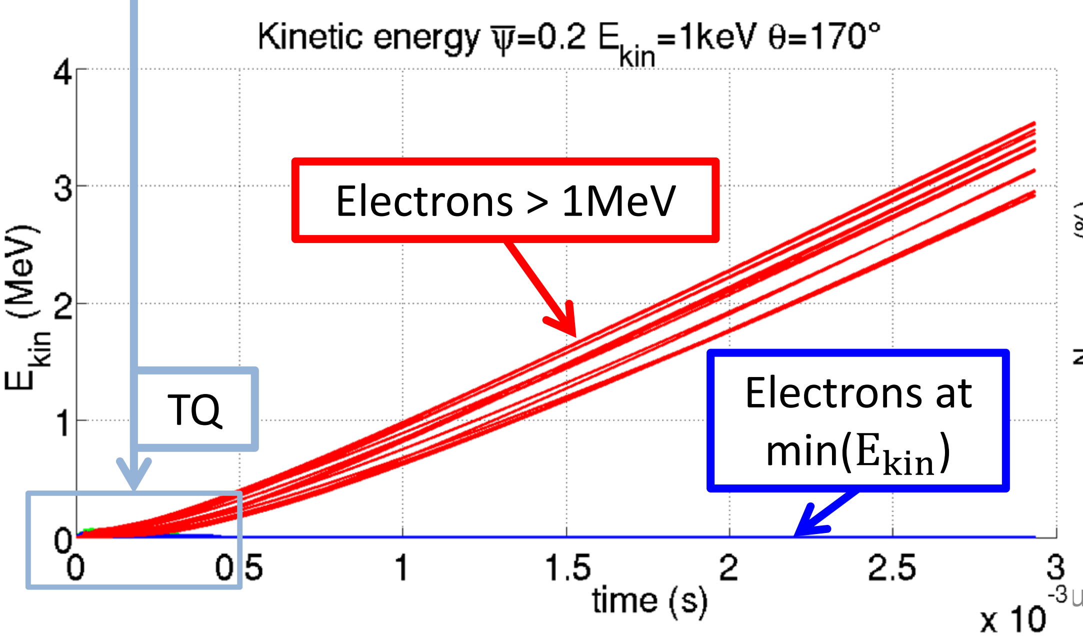
If particles are not accelerated during the TQ, the collisional drag does not allow RE generation

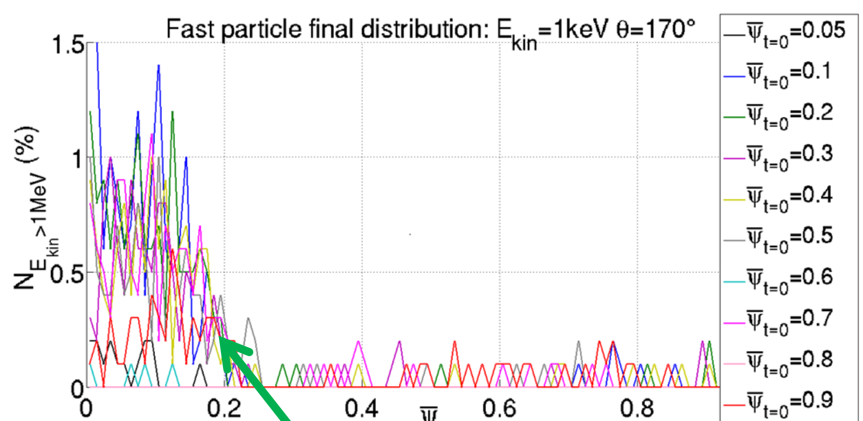
JET



1keV electrons initialized just before the TQ: full E field and drag force

1. Electrons can interact with cells of accelerating E_{eff} → increase of electron energy during the TQ
2. If not deconfined during the TQ → electrons become REs during the CQ
3. Reformation of closed magnetic flux surfaces centers the RE seed at plasma core





Accelerated electrons are focused at the plasma core region

Summary – runaway simulations

- Simulations suggest that Hot Tail mechanism is possible

  $\Rightarrow$ Closed magnetic surfaces reform before the complete loss of fast electrons to the wall/divertor regions

- Direct electron acceleration (Dreicer mechanism) is observed during the disruption TQ phase:
  1. Electrons can interact with accelerating electric filed during the TQ phase
  2. After acceleration they can remain confined due to reformation of closed magnetic surfaces
  3. Surviving accelerated electrons become RE during the CQ phase

- Electrons can have three possible ‘fates’ during the TQ:
  1. Being deconfined (lost to the wall)
  2. Being confined and thermalized
  3. Being confined and accelerated → Primary RE generation

- In JET experiments REs are not always seen while in these simulations they frequently appear:
  - Deconfinement mechanisms can be underestimated
  - Acceleration mechanism can be overestimated

JET