Massive-material-injection-triggered disruptions

What do we understand?
What is still unclear?

DE LA RECHERCHE À L'INDUSTRIE

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EUROfusion

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Foreword

- Presentation not focused on specific recent work

- Instead, will try to summarize current understanding, speculations and questions about Massive Material Injection (MMI) -triggered disruptions
  - MMI = Massive Gas Injection (MGI) or Shattered Pellet Injection (SPI)
  - Based mainly on JOREK and INDEX simulations
  - Focus on the pre-Thermal Quench (TQ) and TQ phases

Content

- What is the Thermal Quench (TQ)?
- TQ triggering mechanisms
  - The importance of a cold front
  - To have or not to have a cold front
  - Importance of non-axisymmetry
  - Characteristic // transport scales and T_e holes
  - The role of helical cooling
- TQ dynamics: difference between large and small I_p spike
- Field line stochasticity and implications for RE generation

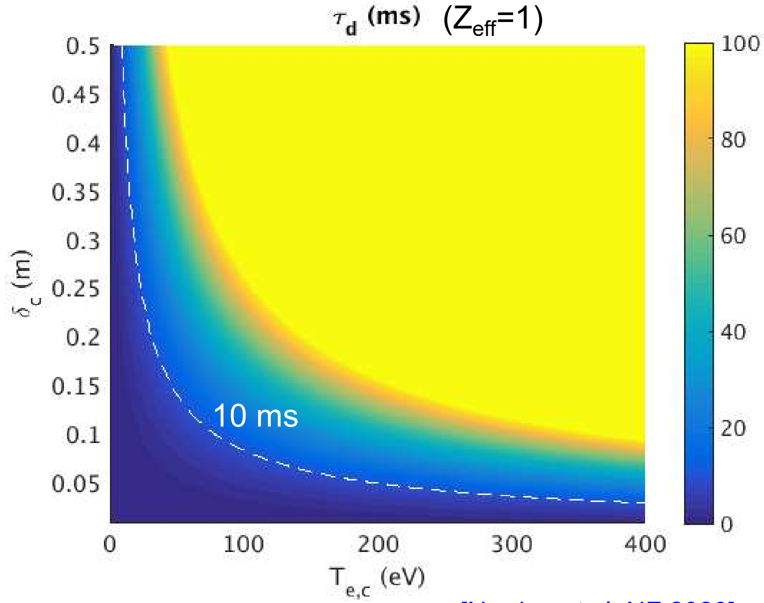
What is the Thermal Quench?

- As the name says, the TQ is a loss of thermal energy. OK, but…
- The TQ is typically associated to strong MHD activity and an I_p spike
- Nature of the MHD activity?
  - 2/1 tearing mode seems key in most cases [de Vries et al. NF 2016, Nardon et al. PPCF 2021, …]
  - 1/1 internal kink mode may participate, but probably does not suffice alone
    - Justification: 1/1 crash will not produce I_p spike unless edge plasma is very cold (think of sawteeth)… But if edge plasma is very cold, 2/1 TM should be present too
- A radiative collapse throughout the plasma is needed for a full TQ
  - Heat diffusion along stochastic FLs not efficient below ~100 eV [Ward & Wesson NF 1992]
  - Need impurity influx and mixing
  - Full TQ often not obtained in 3D non-linear MHD sims.!
    - Probably related to impurities, but difficult to investigate because of numerical issues

The importance of a cold front

- A cold front causes a current profile contraction and thereby drives MHD (in part. the 2/1 TM)
- What do we mean by 'cold'?
- Resistive current decay time in region of perp. size δ_c and resistivity η_c: $\tau_d = \mu_0 \delta_c^2 / \eta_c$
  - Spitzer resistivity: $\eta_c = 2.8 \times 10^{-8} \times Z_{eff} / T_{e,c}[keV]^{3/2}$
- τ_d can be compared to several things, e.g.:
  - For SPI, $\tau_{shards \rightarrow core}$
  - $\tau_{disruption\ warning}$
- We choose to compare τ_d to 10 ms to fix ideas

  → For τ_d to be < 10 ms, one needs $T_{e,c}$ < 30 eV when δ_c = 0.2 m
- Note that critical $T_{e,c}$ scales like $\delta_c^{-4/3}$!



[Nardon et al. NF 2020]

To have or not to have a cold front (1/3)

- JOREK SPI simulations sometimes produce a cold front, sometimes not…
- Reasons are under investigation
- $\tau_{sim.} \sim \tau_{shards \rightarrow core}$ probably plays a key role

All for pure Ne or mixed Ne+D_2 SPI

Machine / Scenario	Author of sims.	Cold front?	R(m) / a(m)	Pellet velocity (m/s)	$\tau_{shards \rightarrow core}$ ($\sim\tau_{sim}$) (ms)	$\langle n_{Ne} \rangle$ when shards reach the core ($10^{19} m^{-3}$)
ITER Hyd. L-mode	Di Hu	Marginal	6.2 / 2	500	4.0	1.0
JET H-mode	Daniele Bonfiglio	Yes	2.96 / 1.25	200	~10*	2.1
KSTAR H-mode	Sang-Jun Lee	No	1.8 / 0.5	400	1.2	2.0

*Shards path does not quite pass through plasma center

To have or not to have a cold front (2/3)

- Simple considerations help interpret results from previous slide…
- Idealized picture: SPI = 2 step process
  - 1) Ablation and dilution cooling
  - 2) Radiative Collapse (RC)
- 2 steps because ablation rate ~ $T_e^{5/3}$ → Drops strongly as T_e drops
- Self-reg. via abl. rate → T_e 'always' ~ a few 100 eV after 1st phase

→ Generating a cold front with SPI requires RC

(origin of the idea of pure D_2 SPI [Nardon et al. NF 2020])

- Time it takes for RC to occur (very simple model – isolated system):

$$\tau_{RC} \sim eT_e n_e / P_{rad} \sim eT_e / (L_{rad} n_{imp})$$

Assuming $L_{rad} \sim 10^{-33}$ W.m^3 and $T_{e,\text{post-1st phase}} \sim 400$ eV, one gets:

$$\tau_{RC} \sim 6 \times 10^{16} / n_{imp}$$

→ E.g. for $n_{imp} = 2 \times 10^{19}$ m^{-3}, $\tau_{RC} \sim 3$ ms

Radiative cooling rate (L_{rad})
at coronal equilibrium

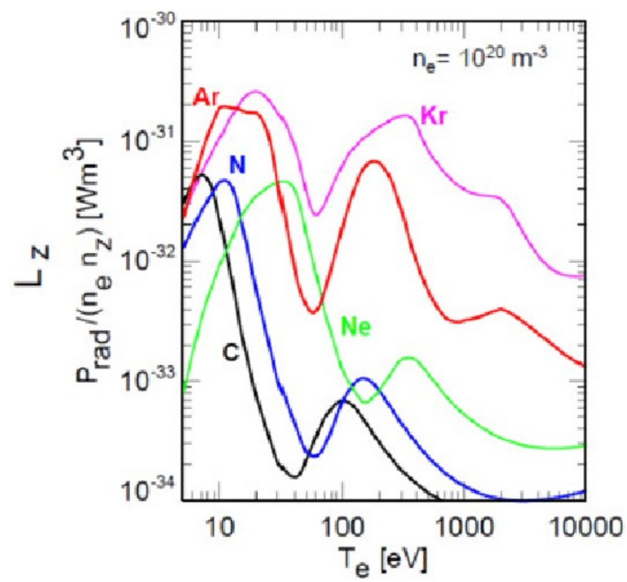


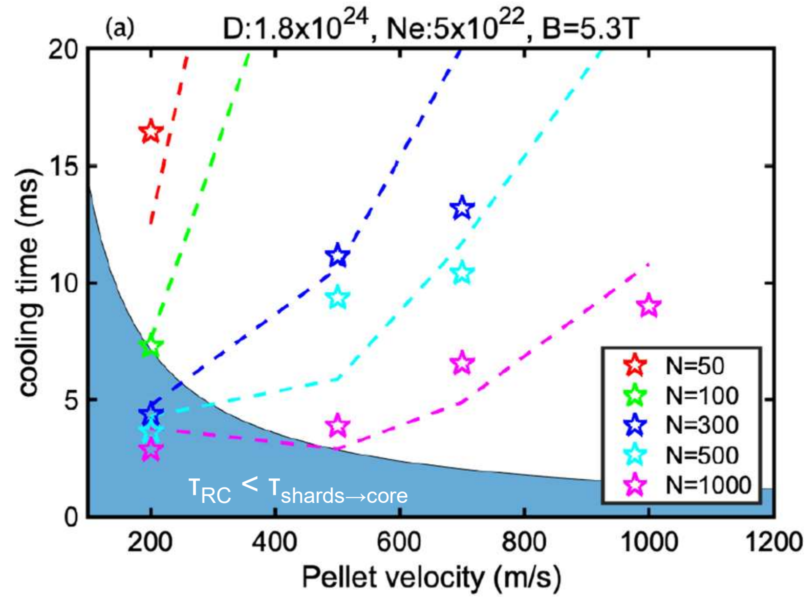
Fig. from https://www.researchgate.net/figure/Cooling-rate-Lz-as-sum-of-bremmstrahlung-recombination-and-line-radiation-from-ADAS-for_fig1_315457459

To have or not to have a cold front (3/3)

- INDEX 1.5D transport modelling and simple 0D model show that τ_{RC} can be < or > $\tau_{shards \rightarrow core}$ depending on pellet velocity, shard size, etc.

- Suggests possibility of diluting the plasma before triggering the TQ

- But these are axisymmetric results…



Stars = INDEX sims.; Dashed lines = 0D model

[Matsuyama et al., to be submitted]

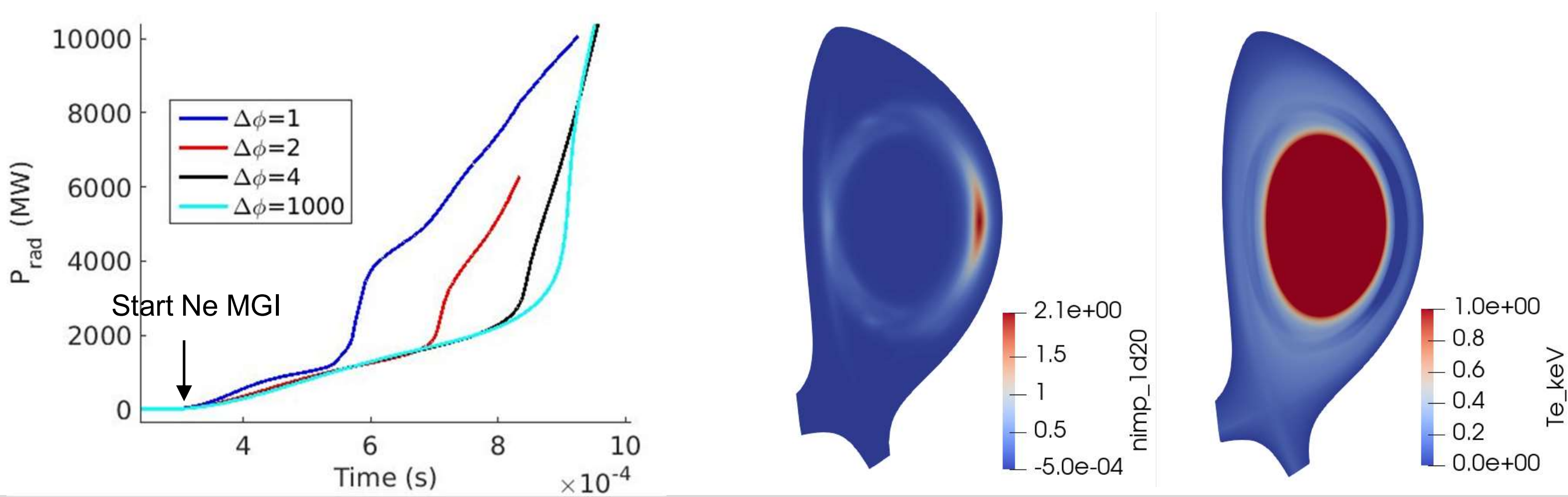
Importance of non-axisymmetry: effect of ablation plasmoid spatial extent

- $(P_{rad})_{plasmoid} \sim \int n_e n_{imp} dV \sim \int n_{imp}^2 dV \sim N_{imp}^2/V_{plasmoid}$
  - Assumptions: electrons mainly come from impurities; L_{rad} independent of T_e

→ Radiative Collapse (RC) easier for smaller $V_{plasmoid}$

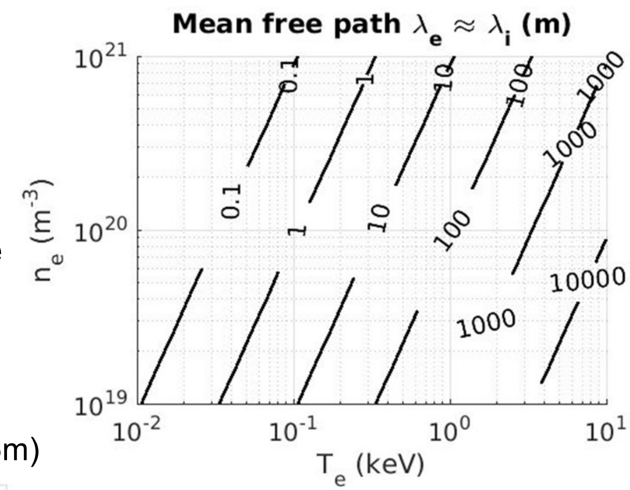
- In JOREK & INDEX simulations, $V_{plasmoid}$ is usually largely exaggerated → RC much harder than in reality!

JOREK sims. of Ne MGI in ITER: scan in toroidal extent of Ne source ΔΦ

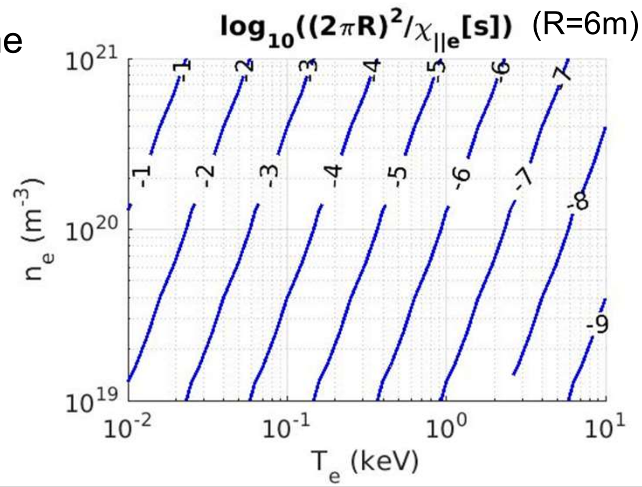


Characteristic // transport scales and T_e holes

- Typically, length of plasmoid's flux tube $L_{//} \sim 4\pi^2 aR/r_{plasmoid} >> 2\pi R$
- Below a certain T_e, $\lambda_e << L_{//} \rightarrow$ // heat transport is diffusive
  - $\lambda_e \equiv$ electron mean free path
  - Transition to diffusive regime happens <u>before</u> radiative collapse
- Below a certain T_e, $\tau_{\chi//} > \tau_{RC} \rightarrow$ Expect T_e hole
  - $\tau_{\chi//} \equiv$ // thermal diffusion time
  - $\tau_{RC} \equiv$ radiative collapse time



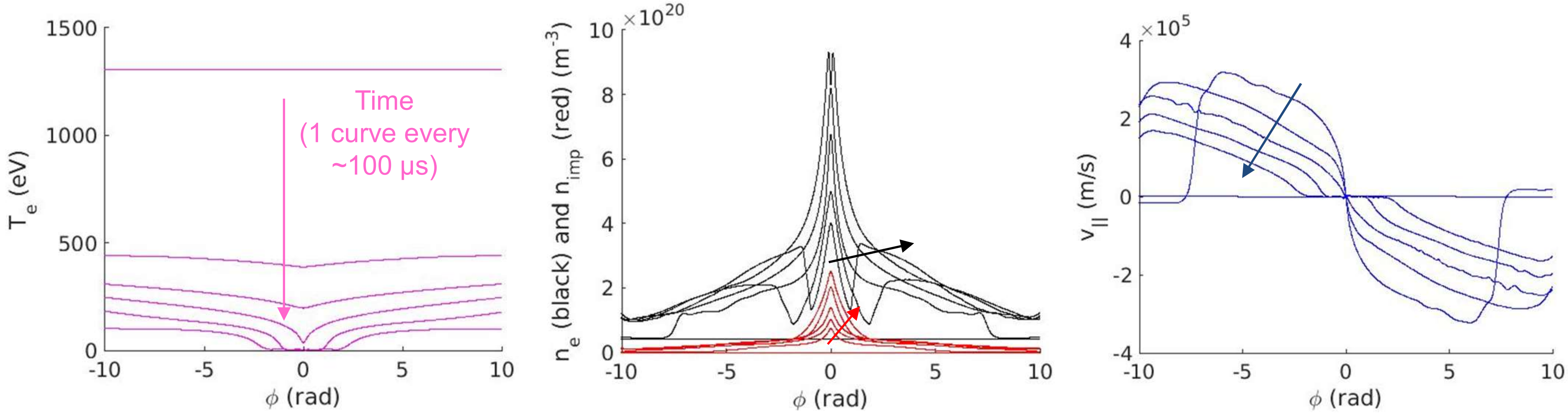
Estimate of $\tau_{\chi//}$



Characteristic // transport scales and T_e holes

- As expected, T_e holes appear in JOREK simulations

<u>JOREK sim. of Ne MGI in ITER</u>



→ Should probably think of SPI as creating many T_e holes (which merge?)

→ Consequences on P_{rad} and its asymmetry, on MHD?

→ Consequences of JOREK lacking resolution to get realistic plasmoids & T_e holes?

The role of helical cooling (1/2)

- Magnetic island = quasi-isolated helical flux tube
- A thermal instability (collapse) can develop there [Rebut and Hugon, IAEA 1984]: 'radiative tearing mode'

  Resistivity ↑↑ → Current decays inside the island → Island grows further (like for NTMs)
- Potential effect can be roughly estimated, assuming all current initially inside island is removed
  - Method:

    1) Estimate δI from j_0 and island width w: $\delta I \approx j_0 \pi a w/m$

    2) Estimate δB_r from δI (Biot and Savart): $\delta B_r \approx \mu_0 m \delta I/(2\pi^2 a) \approx \mu_0 j_0 w/(2\pi)$

    3) Use w from island theory ($\sim \delta B_r^{1/2}$)

    4) Solve for w

$$w = 4\left(\frac{rq\hat{B}_r}{mq'B_\theta}\right)_s^{1/2}$$

[Wesson, Tokamaks]

  - Crude estimate:

    $q/q' \approx a$; $r \approx a$; $B_\theta \approx B/10$

    $\rightarrow w \approx 10a(\delta B_r/(mB))^{1/2} \rightarrow w \approx 2.10^{-5} a^2 j_0/B \approx 5 I_p[MA]/B$ → Huge!

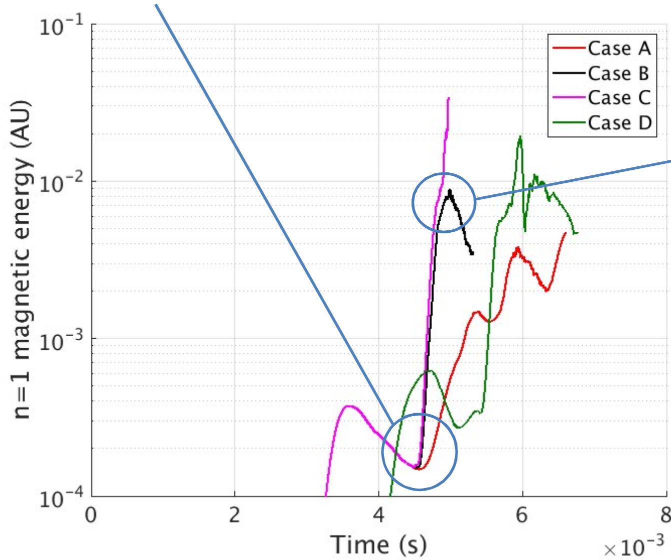
→ This is a potentially very strong mechanism!

The role of helical cooling (2/2)

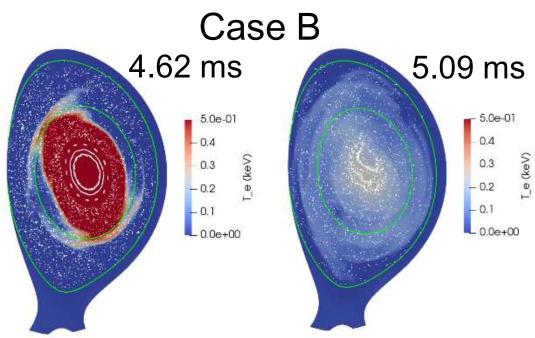
- Numerical experiments based on an Ar MGI case in JET

  Cases B and C diverge from A as we move the Ar source into the 2/1 island to promote thermal drive

[Nardon et al. PPCF 2021]



Cases B and C diverge from each other later on because of larger Ar source in C → Stronger thermal drive

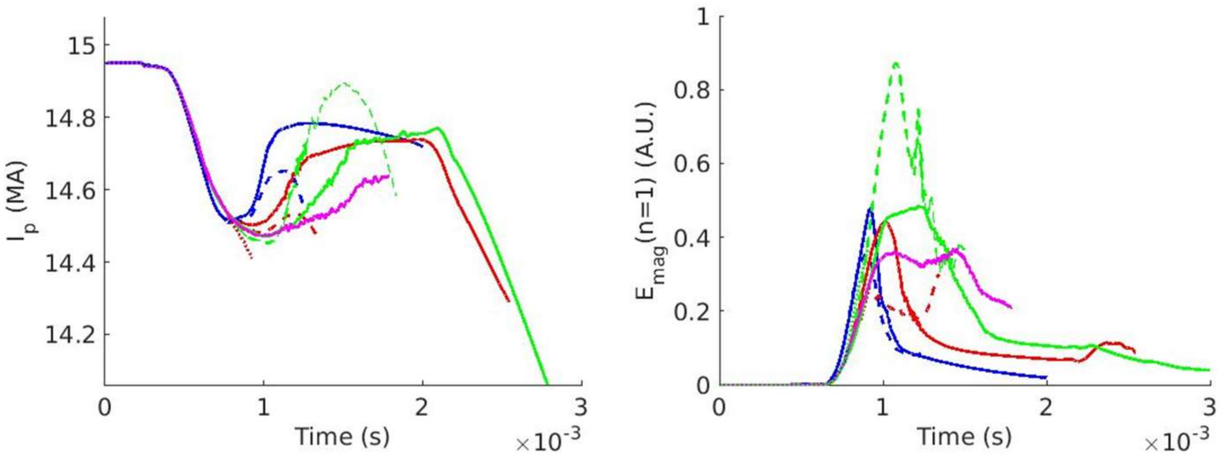


- Note: at some point, magnetic stochasticity appears

  → Heat arrives and 'fights' thermal drive

- It is relatively 'easy' to get a small I_p spike with JOREK
  - Correlated with n=1 (probably 2/1) mode amplitude

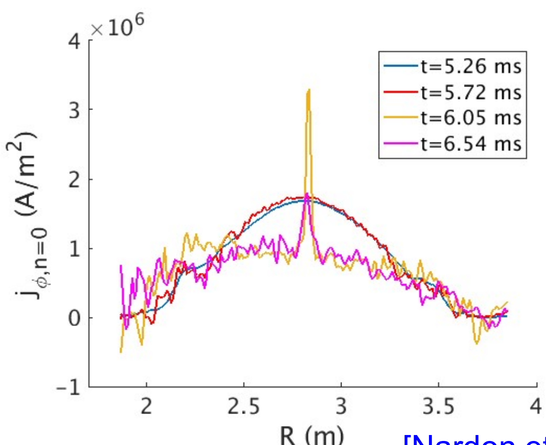
JOREK sims. of MGI in ITER (done for 'academic' purposes)



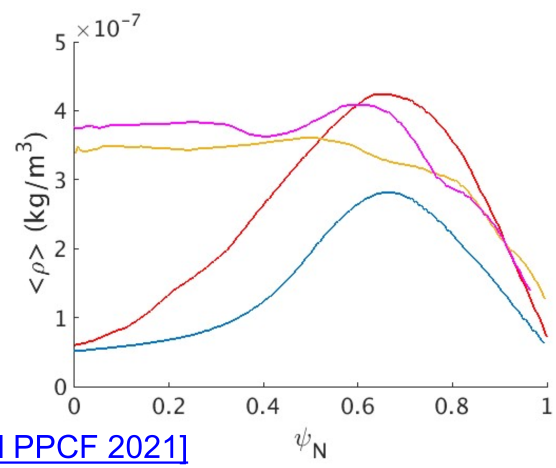
TQ dynamics: difference between large and small I_p spike (2/2)

- It is much harder to get a large (realistic*) I_p spike due to numerical issues
  - *Not all experimental disruptions have a large I_p spike
- JOREK sims. with large I_p spike have a distinct strong macroscopic flow in the core (even w/o 1/1 mode)
  - Mixes poloidal flux → flattens $j_{||}/B$ and gives the large I_p spike
  - Mixes particles & impurities
- Needs investigations!

JOREK sim. of Ar MGI in JET with large realistic I_p spike

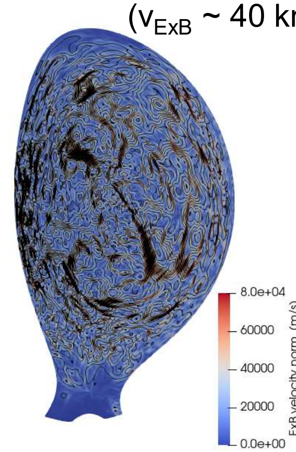


[Nardon et al PPCF 2021]

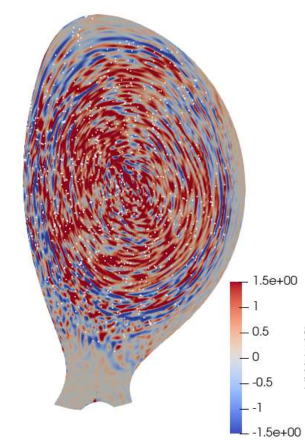


ExB streamlines

(v_{ExB} ~ 40 km/s)



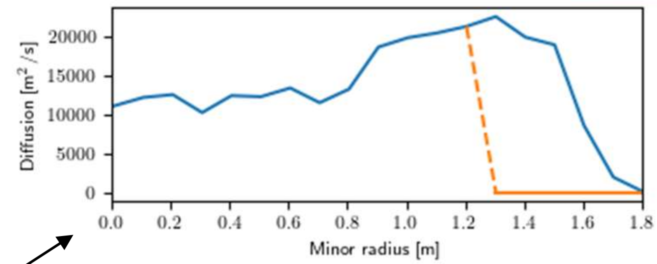
j_Φ

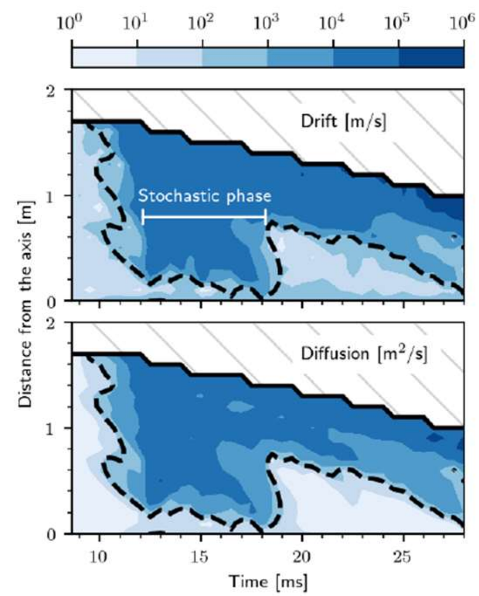


Field line stochasticity and implications for REs

- Stochastic transport is not just 'on' or 'off'
- Konsta Särikimäki calculates advection and diffusion coefficients by post-processing JOREK sims. with test electrons – see his talk on Wednesday!
- Edge Transport Barrier (ETB) found in ITER SPI sim. by Di Hu with marginal cold front (no large 2/1 mode)
- No ETB in a cold VDE simulation which starts with a large MHD crash including large 2/1 tearing mode [Artola NF 2022]

→ Missing the cold front probably has important consequences on predicted stochastic losses (among other things)





[Särkimäki, submitted, https://arxiv.org/abs/2203.09344]

Summary & Outlook

- Generation of cold front and helical cooling probably key to TQ trigger and dynamics
- These depend on energetics of plasmoids and their environment (question of the radiative collapse)…
- …Which depends on the spatial extent of the plasmoids

→ Should be investigated and consequences for JOREK modelling with over-sized plasmoids drawn

- Practical question for ITER DMS: is it possible to dilute the whole plasma before triggering a TQ?
  - Pure H_2 SPI would seem ideal but suffers from plasmoid drifts → Poor fueling efficiency
  - What about $\varepsilon Ne+(1-\varepsilon)H_2$?
  - Or maybe still pure H_2, but lots of it?

- Physics of the TQ has to be clarified
  - Numerical issues still a bottleneck to study cases with a large I_p spike

Backup slides

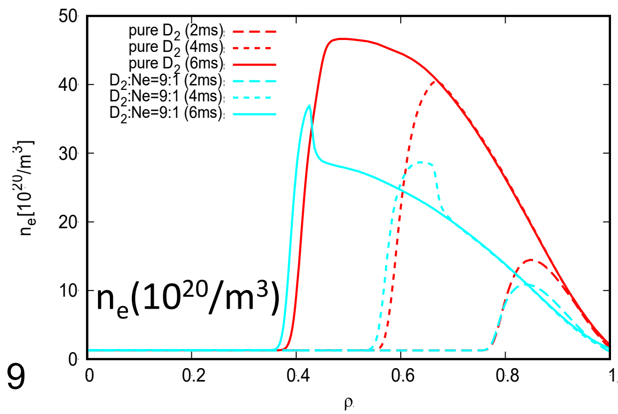
Pure D_2 SPI may be needed to fuel enough before triggering a TQ

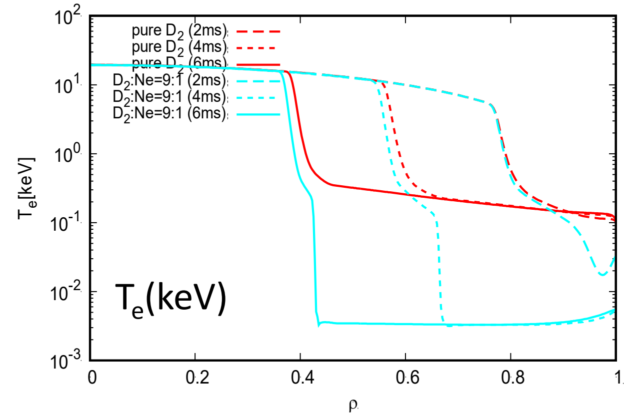
ITER baseline 15MA H-mode plasma

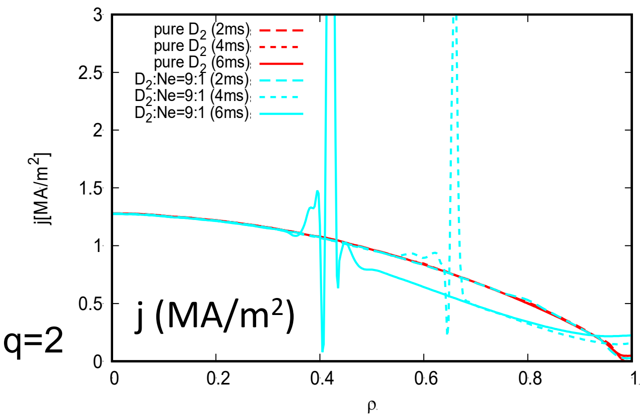
Single 28.5mm (L/D=2) pellet, V_p =200m/s, N_{shards}=300: pure D_2 vs. D_2:Ne=9:1

INDEX sims.

A. Mastuyama, 2019







<u>With Ne+D_2 SPI:</u>

Radiative collapse in cold front

⇒ T_e goes down to a few eV

⇒ Resistive j decay time < a/V_p

⇒ Modification of j profile

⇒ TQ triggering when cold front reaches q=2