Theory & Modelling activities in support of the ITER Disruption Mitigation System

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DE LA RECHERCHE À L'INDUSTRIE

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Disclaimer: ITER is the Nuclear Facility INB no. 174. This paper explores physics processes during the plasma operation of the tokamak when disruptions take place; nevertheless the nuclear operator is not constrained by the results presented here. The views and opinions expressed herein do not necessarily reflect those of the ITER organization.

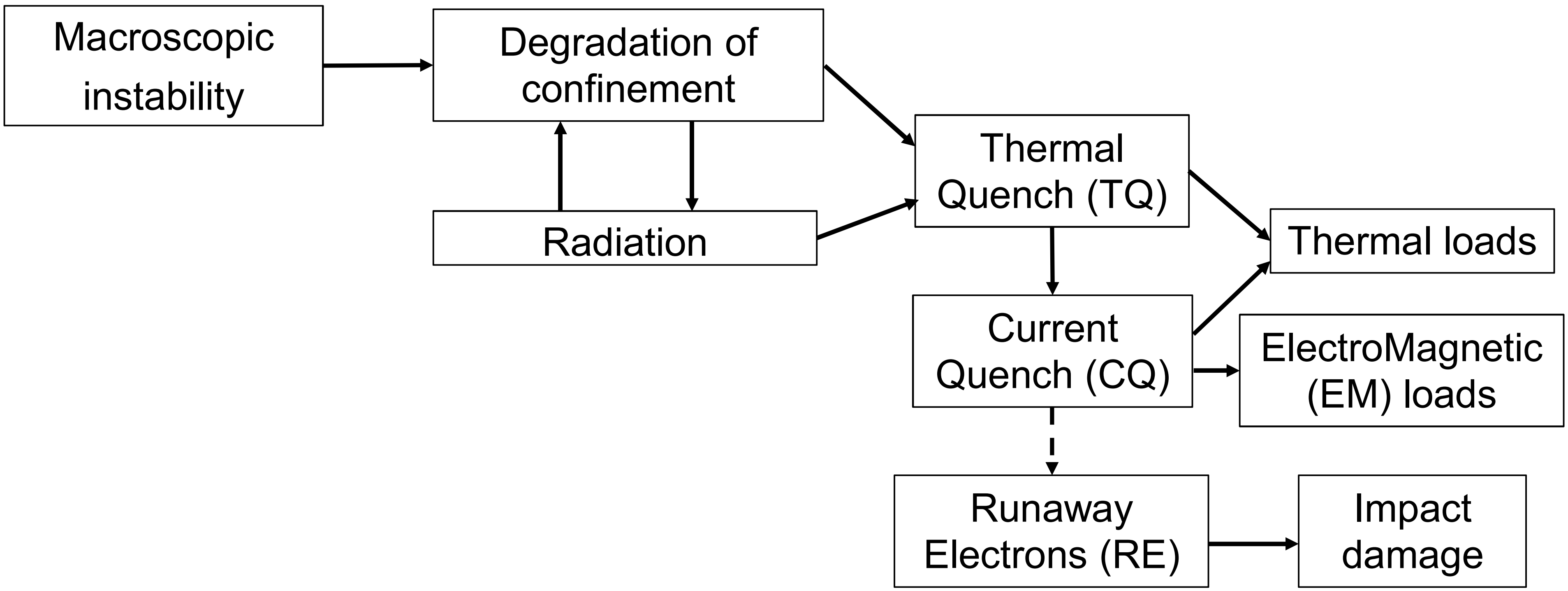
An international collaborative effort

- In 2018, a **Task Force** has been created to support the design and future operation of the **ITER Disruption Mitigation System (DMS)**
  - Covers technology, experiments, and **Theory & Modelling (T&M)**
- Organization of T&M activities:
  - 2 experts groups: 1) **Runaway Electrons (RE)**, 2) **3D MHD + pellets**
  - Common work plan discussed
  - Contributions voluntary or within collaboration agreements with ITER Organization + much support from domestic programmes (SciDAC, EUROfusion, …)

Outline

- Objectives and present design of the ITER DMS
- Runaway electrons:
  - Avoidance
  - Mitigation
- 3D MHD
- Pellet physics

Disruptions in 1 slide!



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Objectives of the ITER DMS

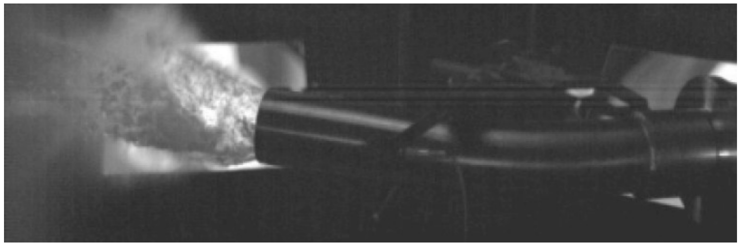
(Numbers below correspond to the baseline 15 MA H-mode scenario)

- **Radiate > 90% W_{th}** with as **little spatial peaking** as possible
- Set the CQ timescale in the right window for acceptable EM loads:
  50 ms < τ_{CQ} < 150 ms
- Avoid generating a RE beam (‘**RE avoidance**’)
- If a RE beam forms accidentally, avoid a damaging impact (‘**RE mitigation**’)

[M. Lehnen et al., J. Nucl. Mater. 463 (2015) 39]

Present design of the ITER DMS

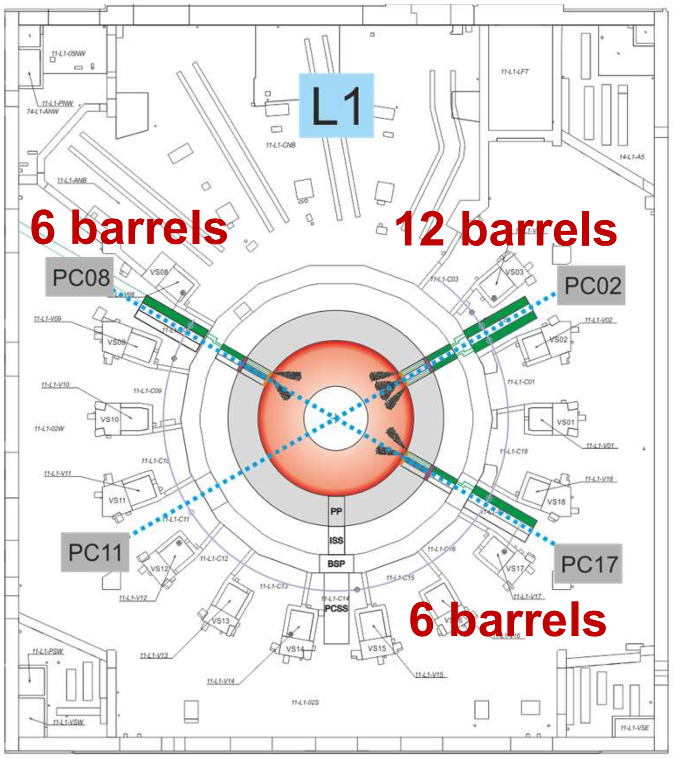
- **Shattered Pellet Injection** (SPI)
  - Pellet size > wine bottle cork
    - Cylinder of diameter 28.5 mm and length 57 mm
  - Material: $\mathbf{H_2}$**+Ne**
  - 1 pellet contains **~2 x $\mathbf{10^{24}}$ atoms**
  - Shattering by bend at end of flight tube
    - Number & size of shards depend on bend angle and pellet velocity
  - Velocity: **a few hundred m/s**



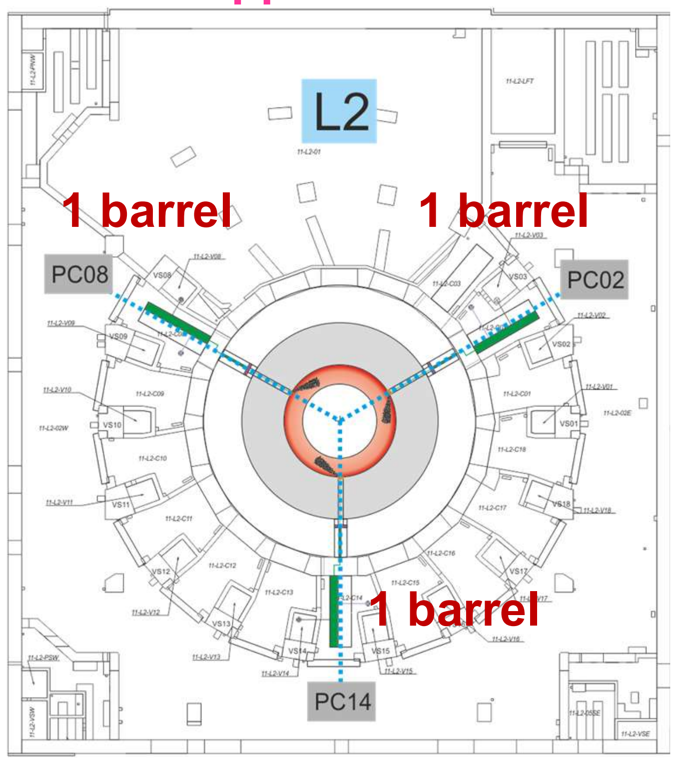
More details in [T. Luce et al., this conf.]

Present design of the ITER DMS

Equatorial level



Upper level



Equatorial ports

28.5 mm pellets for

- TQ heat load mitigation
- CQ heat load mitigation
- CQ EM load mitigation
- RE avoidance
- RE mitigation

Upper ports

For post-TQ injection

- CQ heat load mitigation
- CQ EM load mitigation

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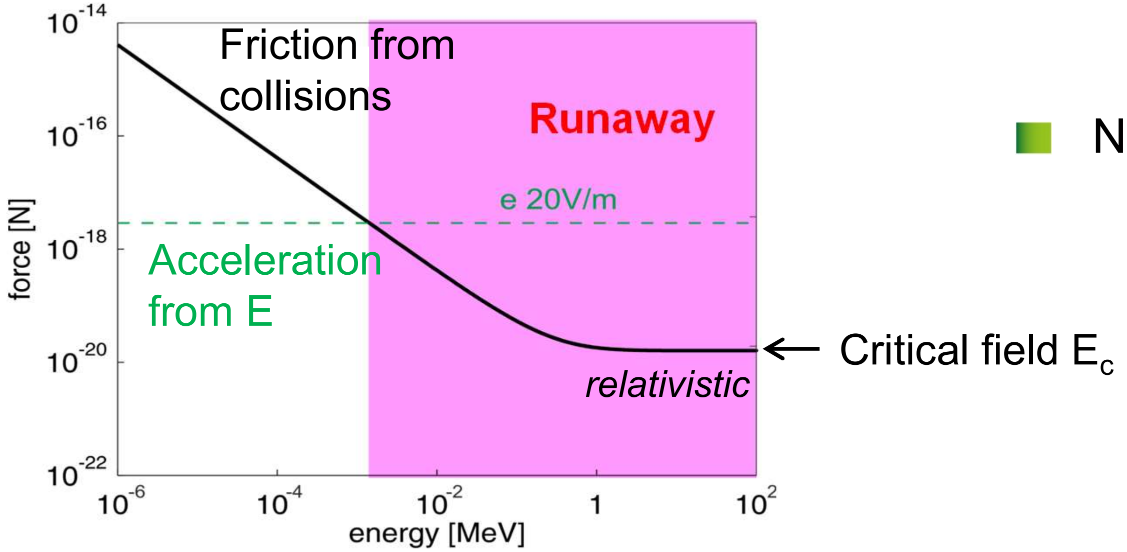
Runaway electron generation mechanisms

Forces on a test electron



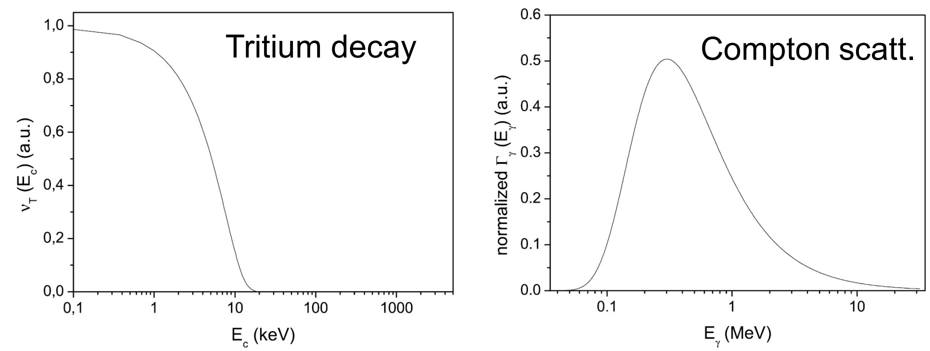
- Note: friction ~ n_e
  - Impacts runaway region and critical electric field E_c

- 2 types of mechanisms may populate the RE region: **primary ('seeds')** and **secondary** generation

[B. Breizman et al., Nucl. Fusion 59, 083001 (2019)]
[A. Boozer, Phys. Plasmas 22, 032504 (2015)]

Runaway electron generation mechanisms

- 'Classical' seeds:
  - Dreicer (diffusion from Maxwellian into RE region): expected to be negligible in ITER
  - **Hot tail** (consequence of non-Maxwellian distribution resulting from TQ)
    - Hard to predict: depends on TQ timescale, stochastic losses, …
    - Potentially very large for hot ITER plasmas
- 'Nuclear' seeds (only in **active phase** of ITER operation):
  - **Tritium β decay**
  - **Compton scattering** of γ's from activated wall
  - Small but 'guaranteed'



[J.R. Martín-Solís et al., Nucl. Fusion 57, 066025 (2017)]

- Secondary: **avalanche.** Gain in RE pop. scales exponentially with I_p → G_{ITER} >> $G_{present\ tokamaks}$

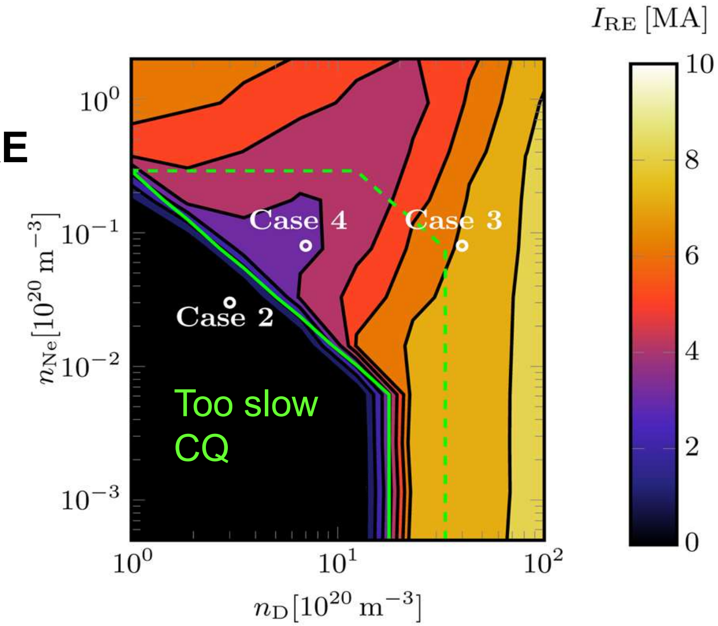
Runaway electron avoidance with Ne+H_2 SPI

- Raise in n_e from H_2 injection reduces all seeds… except for **Compton** (~independent of n_e)
  → Would need to reach **n_e ~ 2-4 x 10^{21} /m^3** to avoid large beam from Compton-initiated avalanche [J.R. Martín-Solís et al., Nucl. Fusion 57, 066025 (2017)]

- …However, recent simulations with GO find a **multi-MA RE beam** forms, **whatever the assimilated Ne+H_2 mixture**
  - Key issue: **recombination** for large H_2 injection

- GO is cylindrical → Effect of MHD instabilities during CQ?
  - Will be studied with JOREK

- **Hot tail** generation also remains a risk for mixed Ne+H_2 SPI

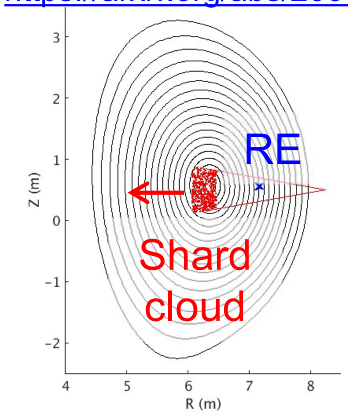


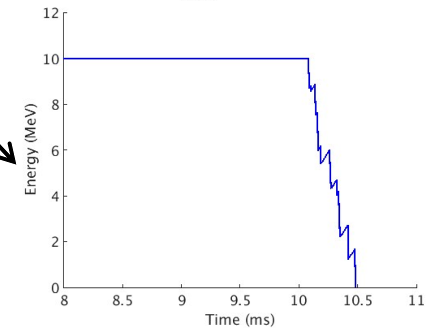
[O. Vallhagen et al., J. Plasma Phys. 86, 475860401 (2020)]

Runaway electron avoidance: alternative ideas

[E. Nardon et al., https://arxiv.org/abs/2007.01567]

- **Hot tail generation** could be suppressed by a **2 step scheme**: 1) H_2 SPI, 2) Ne SPI
  - H_2 SPI → dilution cooling without immediate TQ → Promising for non-active phase
- Active phase: **post-TQ injection** of solid fragments to **stop nuclear seeds** before they avalanche
- **Waves / kinetic instabilities**
  - Role seen and understood for RE generation in quiescent plasmas [Spong PRL 2018, Liu PRL 2018]
  - Role in disruptions suggested by observations [Lvovskiy PPCF 2018 & NF 2019]





Runaway electron mitigation with high Z injection

- In ITER, high vessel conductivity implies $\mathbf{Z_p = f(I_p)}$ for fast CQ

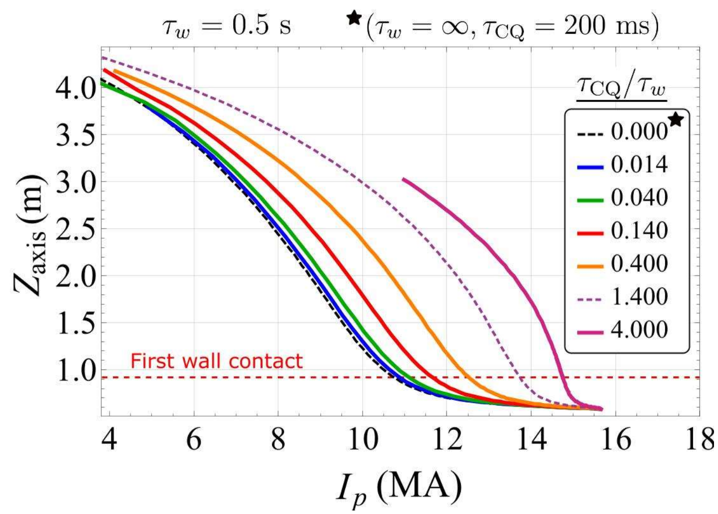
  → Strongly limits possibility to reduce I_p before impact

- **Pessimistic outlook** for strategies based on **high Z material injection** according to DINA modelling

  [S. Konovalov et al., IAEA FEC 2016]

  - Due to $Z_p = f(I_p)$ and $\mathbf{E_{mag} \rightarrow E_{kin}}$ **conversion** (RE generation & acceleration during beam termination)

2D JOREK simulations

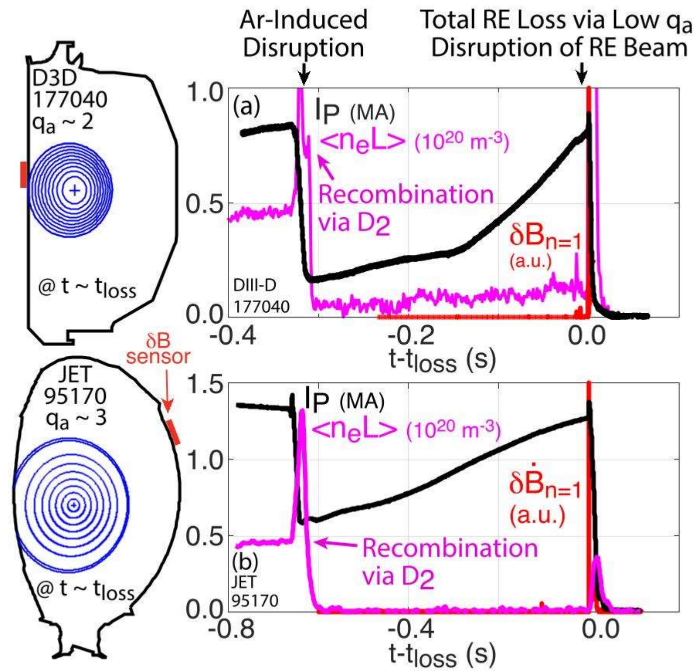


Courtesy J. Artola

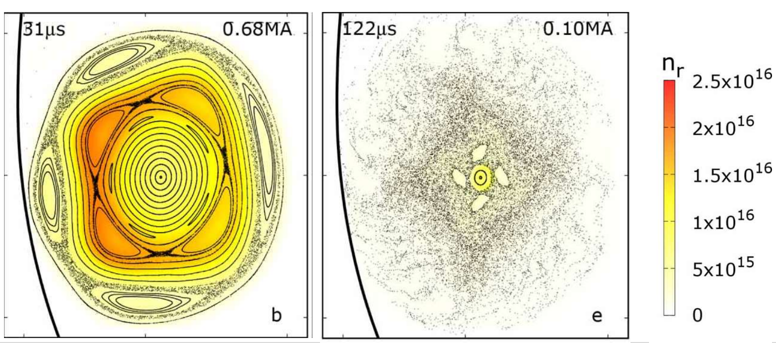
More on this topic:
[D. del-Castillo-Negrete et al., this conf.]
[M. Beidler et al., this conf.]

Runaway electron mitigation with low Z injection

- **D_2 SPI** (or MGI) **into RE beam** leads to **benign termination** at DIII-D and JET: promising!
  - RE loss due to violent MHD instability
    - Large wetted area
  - No generation of new REs thanks to clean background plasma after D_2 injection
  - → Little E_{mag} → E_{kin} conversion



JOREK sim. of RE beam termination at JET



[C. Paz-Soldan, this conf.]
[V. Bandaru et al., Plasma Phys. Control. Fusion 63, 035024 (2021)]
[Y. Liu et al., Nucl. Fusion 59, 126021 (2019) & Phys. Plasmas 27, 102507 (2020)]
[C. Liu, Phys. Plasmas, in prep.]
[C. Reux et al., Phys. Rev. Lett., in press]

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- **3D MHD**
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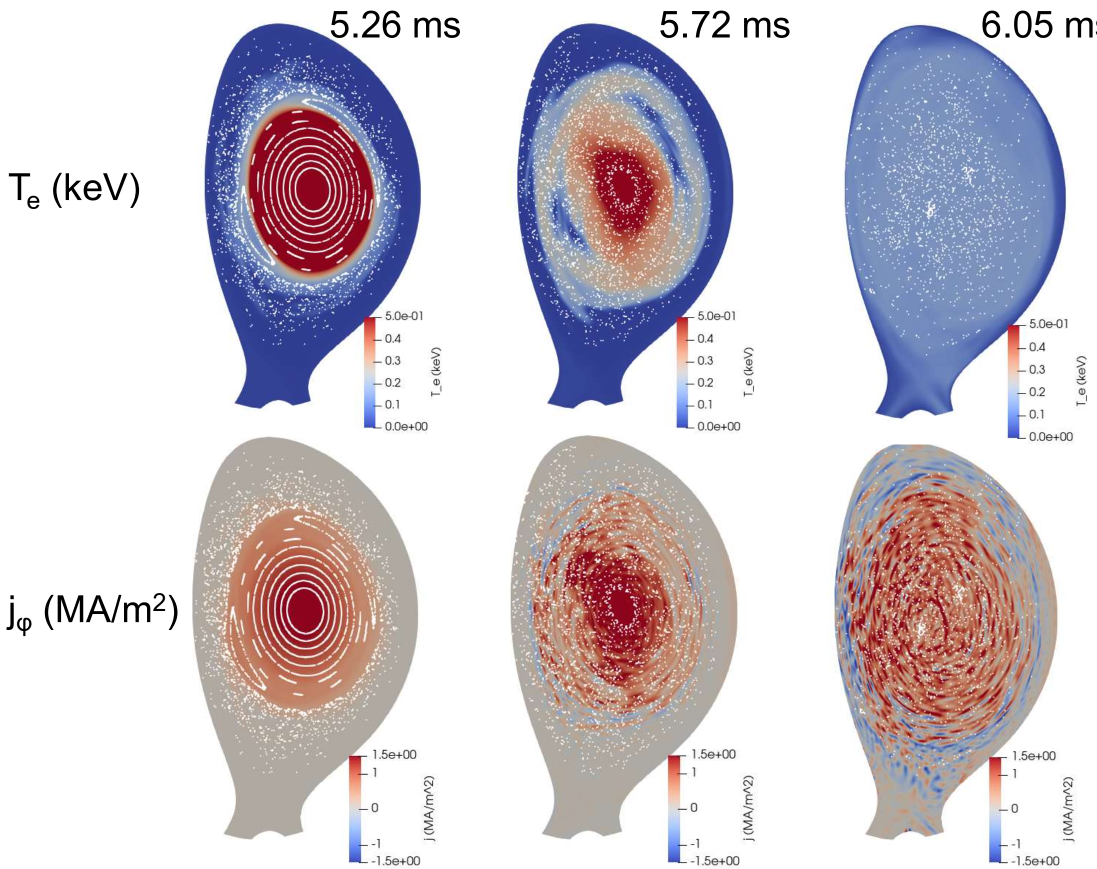
3D MHD: insights on pre-TQ & TQ dynamics

JOREK sim. of disruption triggered by Argon Massive Gas Injection (MGI) at JET



- Material injection
  → cold front penetration
  + helical cooling
  → tearing modes
  → stochastization
- m/n=2/1 mode dominant
- 1/1 mode also important if q=1 surface large

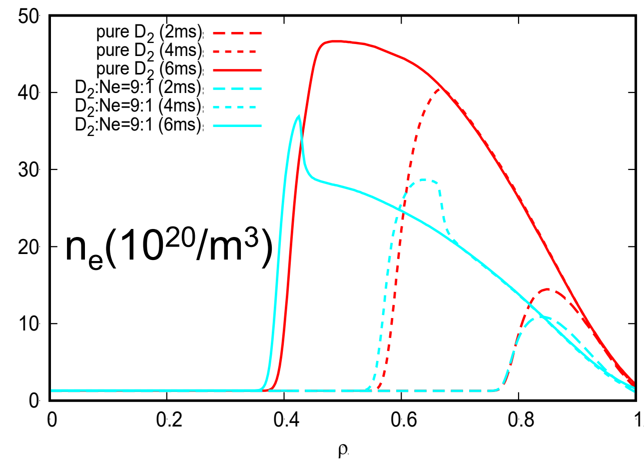
[E. Nardon et al., in prep.]

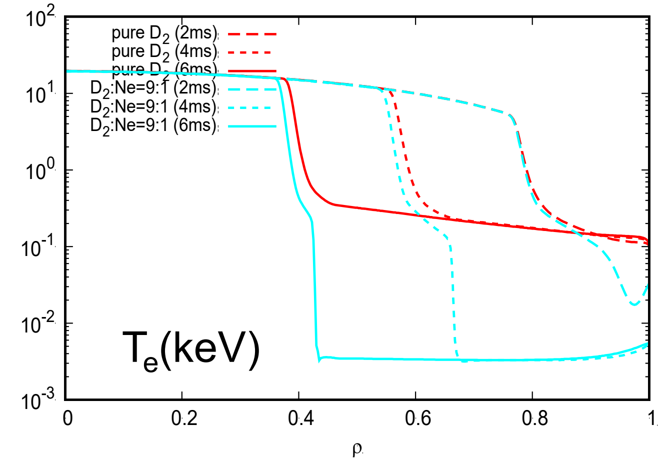
The logic behind the 2 step SPI scheme

$Ne+D_2$ (10+90%) vs. Pure D_2 SPI

INDEX 1.5D simulations

ITER baseline 15 MA H-mode, 28 mm pellet, V_p=200 m/s, N_{shards} = 300





$Ne+D_2$ SPI:

Radiative collapse in cold front

→ T_e goes down to a few eV

→ Resistive j_φ decay time < a/V_p

→ Modification of j_φ profile

→ Likely to trigger an early TQ

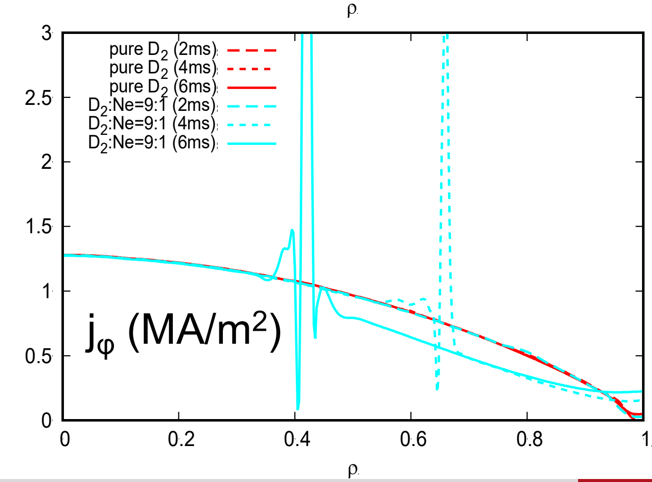
Pure D_2 SPI:

Only dilution cooling

→ T_e remains > 100 eV

→ Resistive j_φ decay time > a/V_p

→ No immediate TQ (confirmed with JOREK)



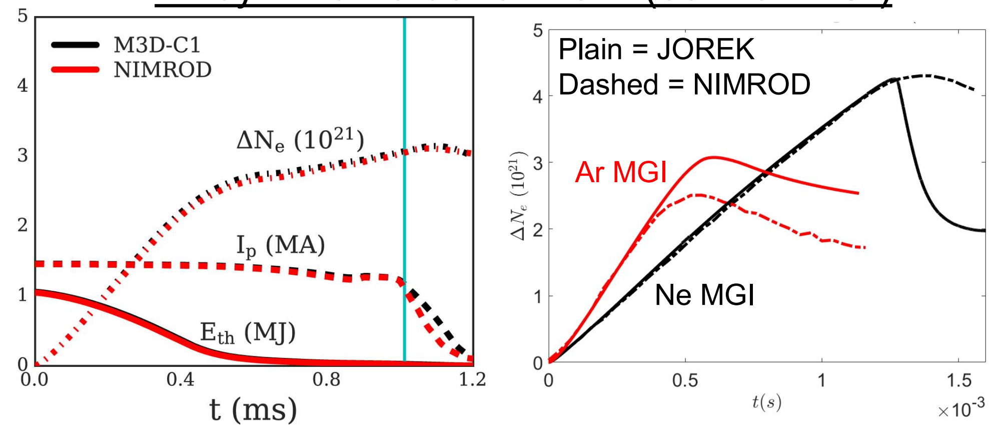
[E. Nardon et al., Nucl. Fusion 60, 126040 (2020)]

3D MHD: verification & validation

- M3D-C1/NIMROD/JOREK **benchmarks** of impurity models (and more)

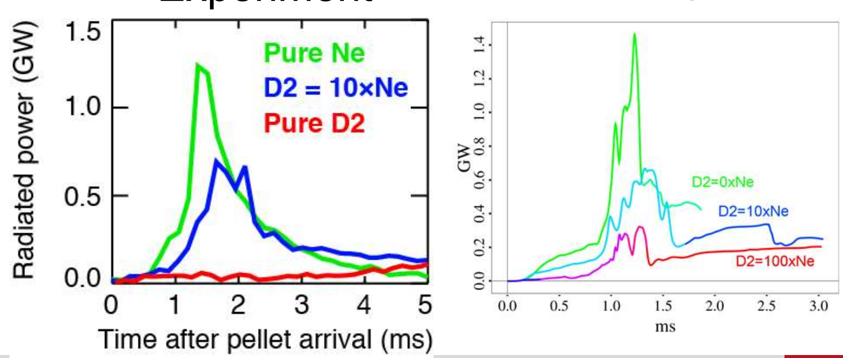
[B. Lyons et al., Plasma Phys. Control. Fusion 61, 064001 (2019)]
[D. Hu, DTF progress meeting, 10/03/21]

Axisymmetric benchmark (central MGI)



Ne+D_2 SPI in DIII-D

Experiment NIMROD



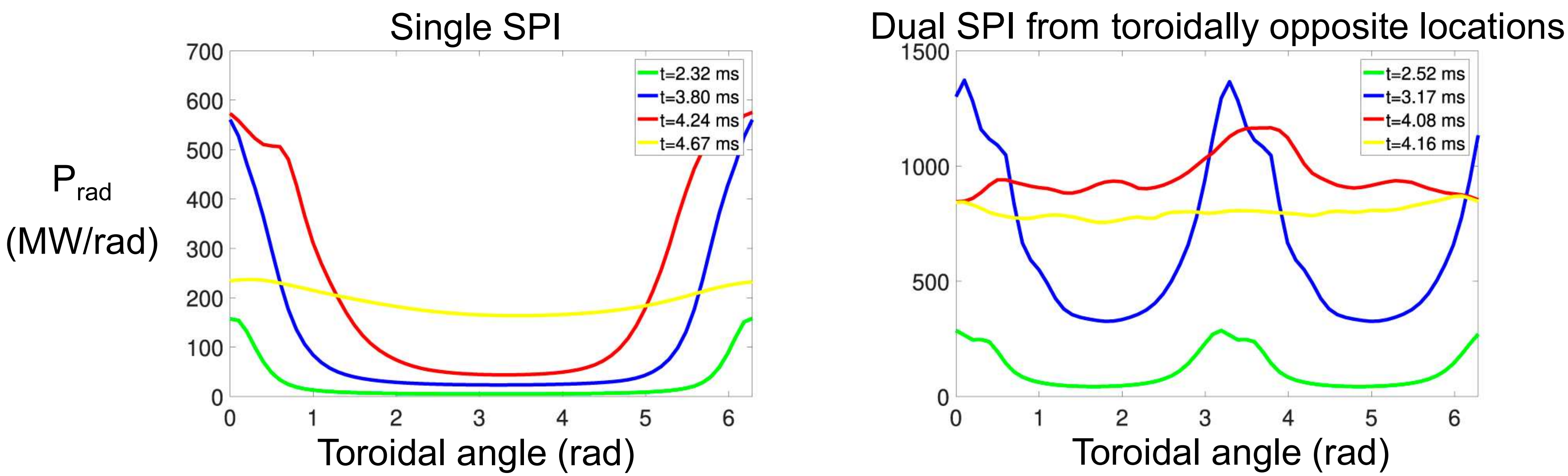
- **Validation** is progressing on DIII-D, JET, KSTAR, soon ASDEX Upgrade, …
  - Getting more quantitative and detailed (synthetic diagnostics)

[C. Kim et al., Phys. Plasmas 26, 042510 (2019)]

3D MHD: ITER predictions

- No quantitative recommendations yet
- Simulations suggest **dual SPI** may **reduce radiation asymmetries**

JOREK sims. of mixed Ne+D_2 SPI in ITER (same total quantity in the 2 cases)



[D. Hu et al., Nucl. Fusion 61, 026015 (2021)]

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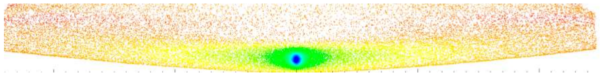
Pellet physics

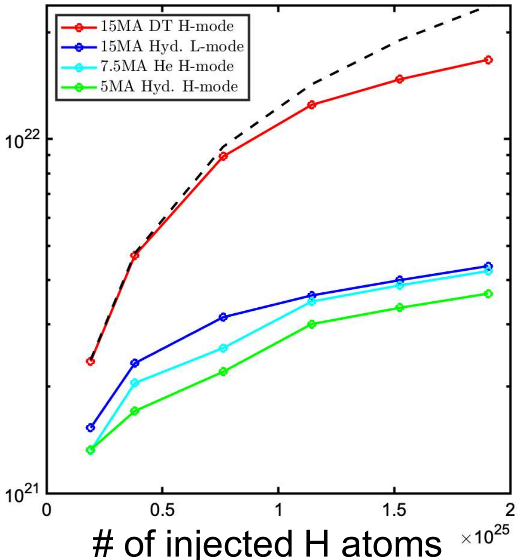
- SPI involves a **collective effect**: first shards 'sacrifice themselves' to allow next shards to penetrate further [P. Parks, Princeton TSDW 2017]
- **Ablation model** for integrated simulations?
  - Neutral Gas Shielding (NGS)-like models seem relevant
  - NGS confirmed and refined by dedicated codes

    [R. Samulyak et al., Nucl. Fusion 61, 046007 (2021)][N. Bosviel et al., Phys. Plasmas 28, 012506 (2021)]



  - But should be applied in the right way: SPI is very perturbative in contrast to fuelling pellets
- Strong dependence of ablation on **target plasma**
  - May require adjusting SPI params. to target

$\langle n_e \rangle$ (m^{-3}) after pure H_2 SPI



More on this topic: [D. Shiraki et al., this conf.][A. Matsuyama et al., this conf.]

Summary and Outlook

- Wealth of T&M activities within the ITER DMS Task Force, **addressing all important issues**
- During the **non-active phase**, **RE avoidance** might be obtained with **2 step SPI scheme**
  - To be confirmed by further studies
- Present situation **critical** concerning **RE avoidance** during the **active phase** of ITER operation
  - Calls for further modelling and exploration of alternative schemes
- **RE mitigation** also **uncertain** but strategy based on a **D_2 (or H_2) SPI into the beam** to obtain a benign termination might lead to a solution
- **Heat loads** mitigation generally **less critical** but difficult to quantify in experiments
  - **3D MHD simulations** will be essential to **optimize SPI parameters**
- Also ongoing efforts on **EM loads** modelling, incl. 3D MHD, e.g. [S. Jardin et al., this conf.]
  - Will be taken into account to define an **integrated disruption mitigation strategy**