Modelling of Runaway Electron Dynamics in Tokamak Disruptions

Nardon E., Artola F.J., Bandaru V., Bergström H., Decker J., Ekmark I., Fülöp T., Halldestam P., Hoelzl M., Hoppe M., et al.

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IAEA FEC 2023, 20/10/23

E. Nardon, F.J. Artola, V. Bandaru, H. Bergström, J. Decker, I. Ekmark, T. Fülöp, P. Halldestam, M. Hoelzl, M. Hoppe, D. Hu, A. Järvinen, M. Lehnen, S. Olasz, G. Papp, Y. Peysson, G.I. Pokol, I. Pusztai, C. Reux, K. Särkimäki, R. Saura, C. Sommariva, O. Vallhagen, C. Wang, the JOREK team, JET contributors

Framework = EUROfusion TSVV 9 project + ITER DMS Task Force

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.
The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.
This work was partly funded by the ITER Organization.

Outline

- Introduction: disruptions, Runaway Electrons (REs)
- Simulation tools
- Validation
- Simulations for ITER
  - RE generation (avoidance)
  - RE beam termination (mitigation)
- Conclusion

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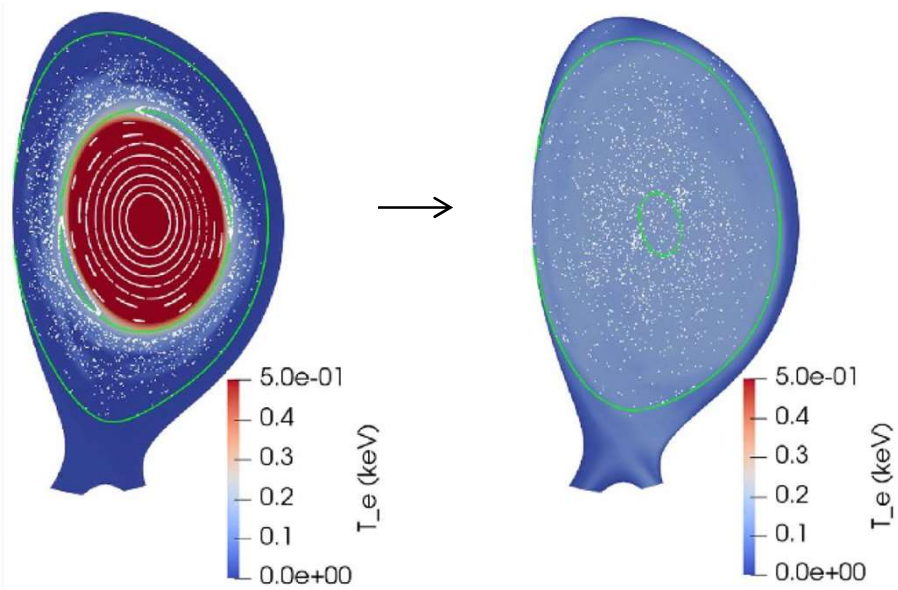
Disruptions

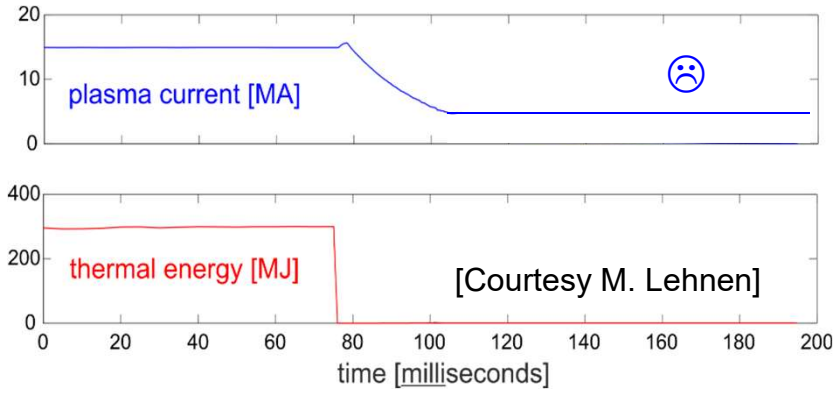
- **1) Thermal Quench (TQ)**:
  - MHD instability, **B** stochastization
  - Radiative collapse



[Nardon PPCF 2021]

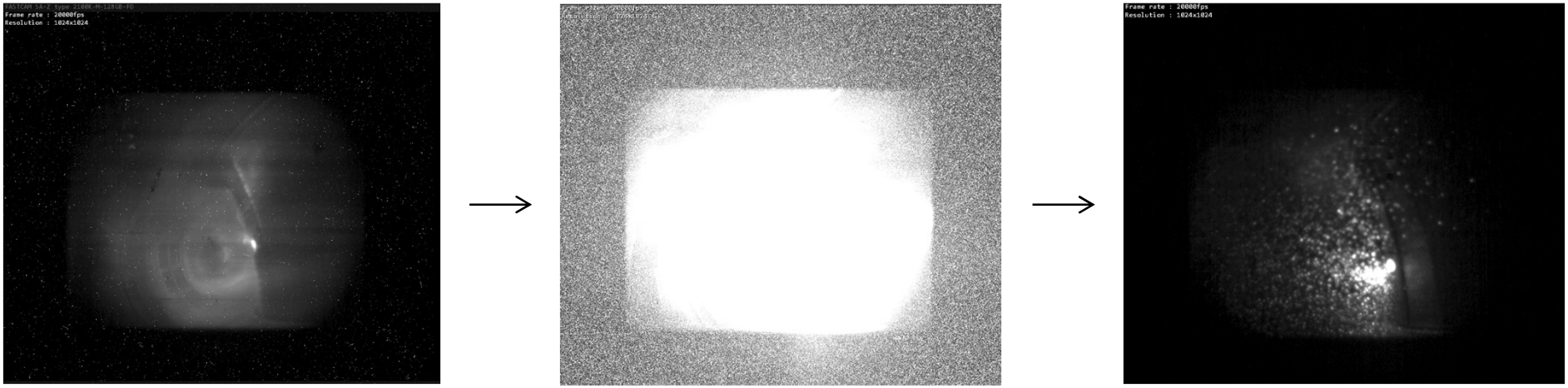
- **2) Current Quench (CQ)**:
  - Very high resistivity η → I_p decay
  - Large **E** = η j, typically **>> E_c**

  → Sometimes, **RE beam**



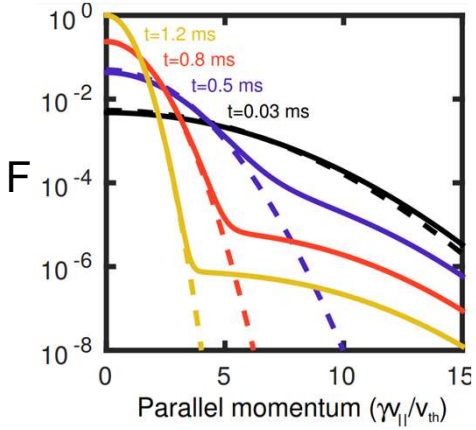
RE beam impact: fireworks…

WEST #58003



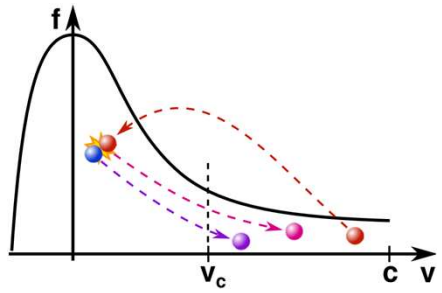
Primary (seed) RE generation

- **Dreicer**: collisional diffusion into RE domain [Connor NF 1975]
  - Typically negligible in ITER
- **Hot-tail**: related to fast cooling during the TQ [Smith PoP 2007]
  - Deviation from a Maxwellian distribution
  - Hard to predict because very sensitive to:
    - TQ timescale
    - e^- transport associated to stochastic **B**
  - Potentially by far largest seed in ITER disruptions



- **Nuclear** [Martín-Solís NF 2017]
  - Small but active during CQ → Expect no strong stochastic losses
  - **Tritium β decay**
  - **Compton scattering** by wall-emitted γ rays

Secondary RE generation: the avalanche



- Close ('knock-on') collisions can generate 2 REs from 1

→ **Exponential growth** in RE population

- Initial theory by Rosenbluth and Putvinsky [Rosenbluth NF 1997]

→ When E >> E_c, avalanche gain **G_{av} scales exponentially with ΔI_p!**

E.g. **G_{av} = 1.9 × 10^{16} in ITER** (15 MA) vs. 1.8 × 10^3 in JET (3 MA) [Hender NF 2007]

- Theory extended to account for **bound electrons** around partly ionized impurities

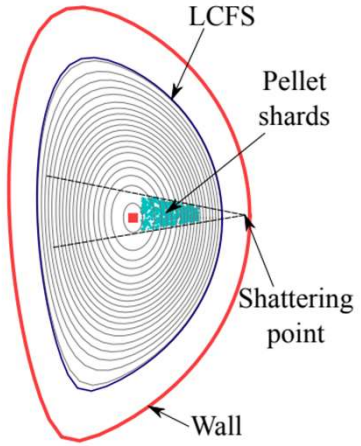
→ Too many impurities can strongly **boost G_{av}** [Hesslow NF 2019]

RE-handling strategies

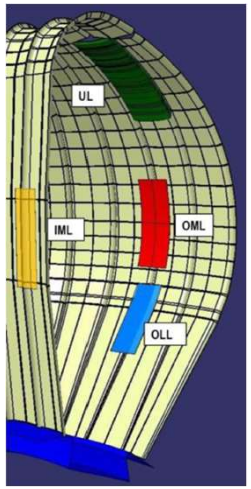
ITER: Shattered Pellet Injection (SPI) [Lehnen JNM 2015]

- One or several Ne+H pellets
- Aim: RE avoidance and/or mitigation

[Lehnen, this conf., Oral, Tue.]



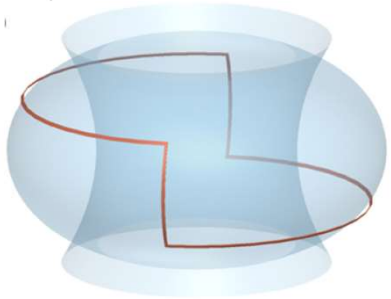
EU-DEMO: sacrificial limiters
[Maviglia FED 2022]



SPARC: RE mitigation coil

- Passive system
- Induced current from $dI_p/dt \rightarrow$ **B** stochasticity $\rightarrow$ RE avoidance

[Izzo, this conf., Oral, Fri. am]



[Tinguely PPCF 2023]

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Simulation tools: 2 main workhorses

- **DREAM kinetic** code
  - Solves 1D flux-surface-averaged transport equations
  - Self-consistently evolves e^- distribution function

[Hoppe CPC 2021]

- **JOREK 3D MHD** code with different models for REs
  - RE fluid [Bandaru PRE 2019]
  - Test e^- [Sommariva NF 2018] [Särkimäki NF 2022]
  - PiC model (kinetic e^- + MHD) in development [Bergström TSDW 2023]

[Hoelzl NF 2021]

[Hoelzl, this conf., Ov. P., Mon.]

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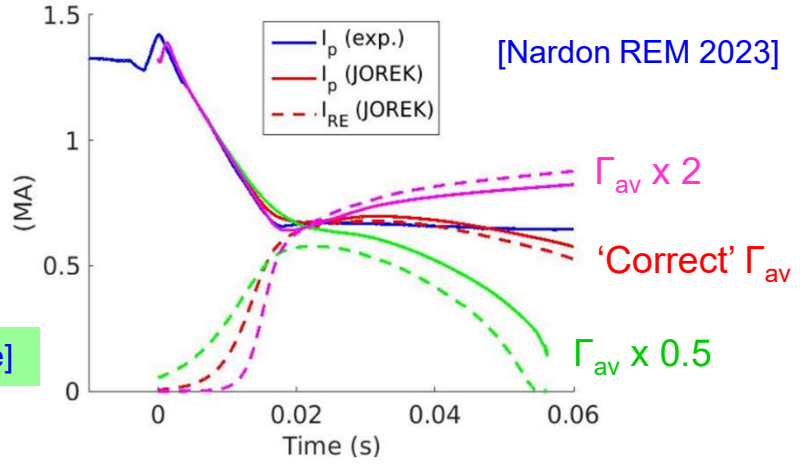
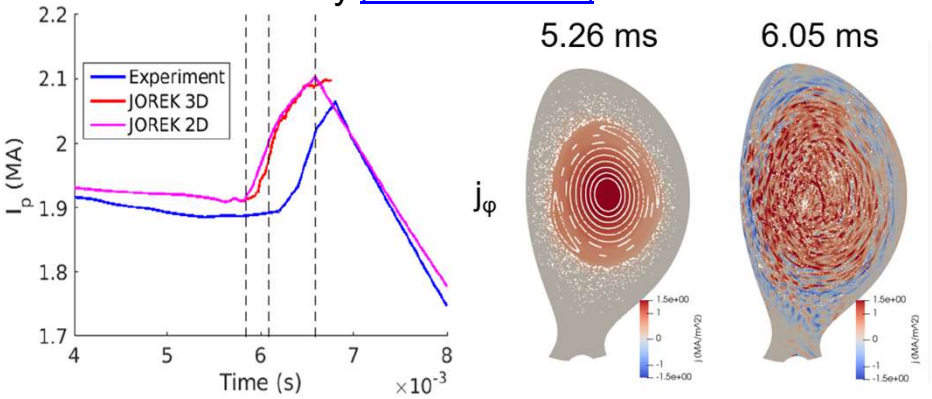
Work is ongoing to validate each aspect of our models

- **Avalanche:** RE generation by Ar MGI in JET #95135 simulated with DREAM and JOREK (2D)
  - Input parameters ↔ Knobs for fitting data → **Validation or fancy fit?** → Test by **falsifying** the avalanche gain Γ_{av} → Correct Γ_{av} gives best match → Looks like (preliminary) **validation** ☺
  - **Bayesian optimization framework** can be used for objectivity [Järvinen JPP 2022] [Järvinen, this conf., P/2, Tue]

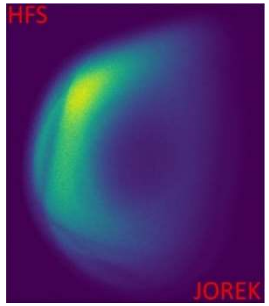


[Nardon REM 2023]

- **TQ and stochastic losses:** JOREK 3D simulation of JET Ar MGI reproduces **I_p spike** and supports its link with stochasticity [Nardon NF 2023]



- **RE beam termination:** JOREK 3D RE fluid simulation of benign termination in JET #95135, building on [Bandaru PPCF 2021]
  - Now involving **synthetic synchrotron diagnostic** [Sommariva EPS 2023]



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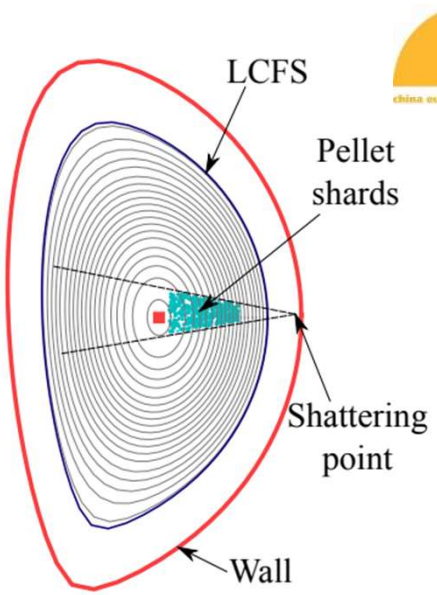
Predicting RE generation (avoidance) in ITER with DREAM (1/2)

[Vallhagen, this conf., P/3, Wed.]



- Wide range of scenarios, **with or w/o nuclear seeds**
- 2 types of **SPI schemes**:
  - **Single** Ne+H
  - **Staggered**: pure H then Ne+H
    - 2 step cooling: 1) dilution, 2) radiative collapse
    - Benefit: hot-tail suppression
- Ne quantity adjusted so that 50 ms < τ_{CQ} < 150 ms
- Basic model for pellet ablation plasmoid drifts in some simulations
- Ad hoc TQ model informed by 3D MHD simulations → [Hu, this conf., P/9, Sat.]
  - Particle mixing
  - Rechester-Rosenbluth e^- transport

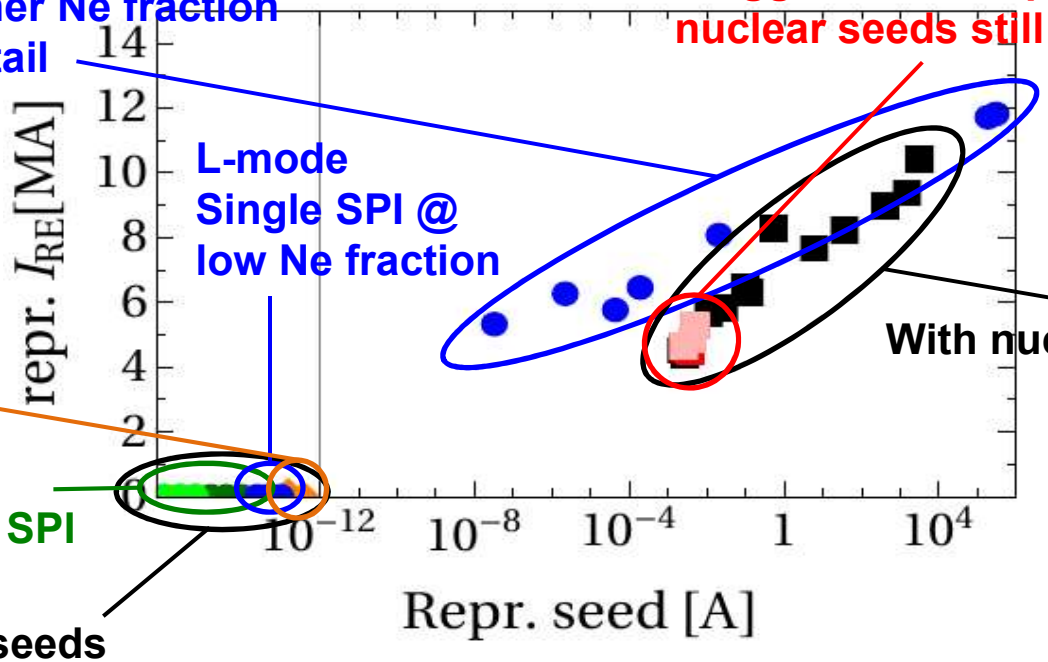
Predicting RE generation (avoidance) in ITER with DREAM (2/2)

Results for 15 MA L-mode w/o nuclear seeds and H-mode with nuclear seeds

→ Avalanche produces a **multi-MA beam unless seed is extremely small**

L-mode
Single SPI @ higher Ne fraction
→ Too much hot-tail

Staggered SPI suppresses hot-tail but nuclear seeds still give a large beam



H-mode w/o nuclear seeds is manageable

L-mode
Single SPI @ low Ne fraction

With nuclear seeds (H-mode)

L-mode
Staggered SPI

W/o nuclear seeds
With good hot-tail suppression

Effect of vertical movement assessed with JOREK

- DREAM simulations use a fixed plasma geometry

- Effect of vertical movement on **avalanche gain G_{av}**?

→ Use JOREK 2D simulations

- On each toroidal flux (Φ) surface, **$\log(G_{av}) \sim \Delta\psi$**, where ψ ≡ poloidal flux [Boozer PoP 2015]
  - Δ between t=0 and when surface becomes LCFS

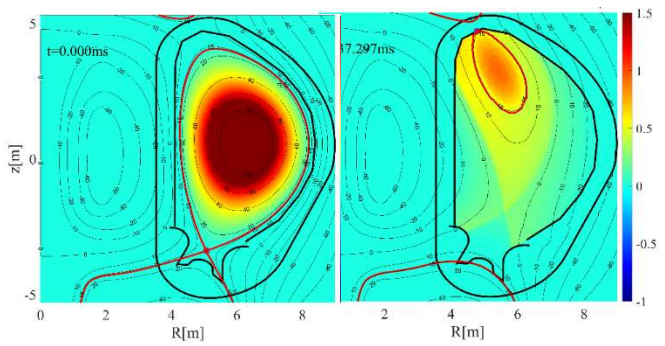
- JOREK finds that **$\psi_{LCFS} \approx$ constant** in time
  - Related to ~ ideal behaviour of the wall
- In contrast, in DREAM, **$\psi_{LCFS} \downarrow$ in time** → Larger Δψ

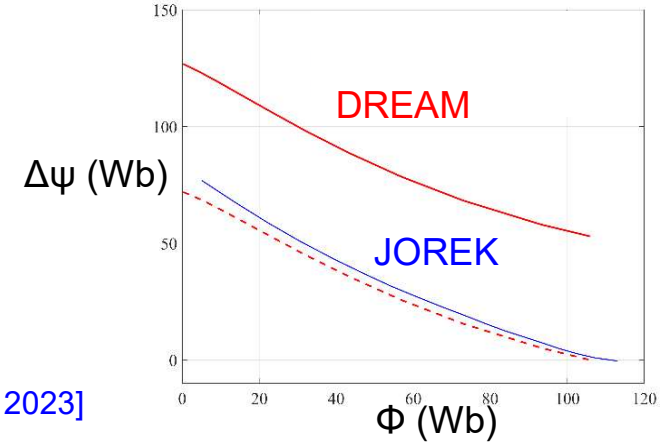
→ **G_{av} in DREAM too large** by several orders of magnitude

- **Impact unclear (G_{av} remains very large)**, under investigation with both DREAM and JOREK [Wang REM 2023]

JOREK 2D simulation for 15 MA ITER case

(Simple model for Ne+H injection and TQ)





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RE beam termination (mitigation) studied with JOREK (1/2)

- In present machines, a **benign RE beam termination** can be obtained via H or D injection into the beam [Paz-Soldan NF 2021]
  - Associated to **fast and large MHD instability**

- Could this work in ITER?

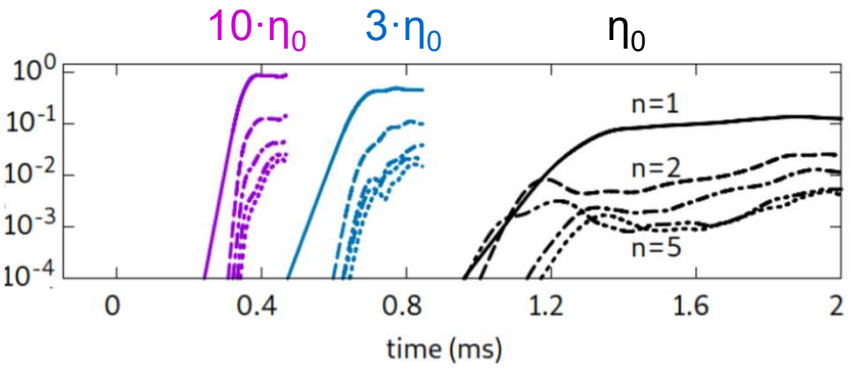
JOREK ITER simulations [Bandaru in prep.]

- Intentional generation of a large (9 MA) beam

- No model for H injection but studied **effect of background plasma resistivity η**
  - H injection is expected to increase η

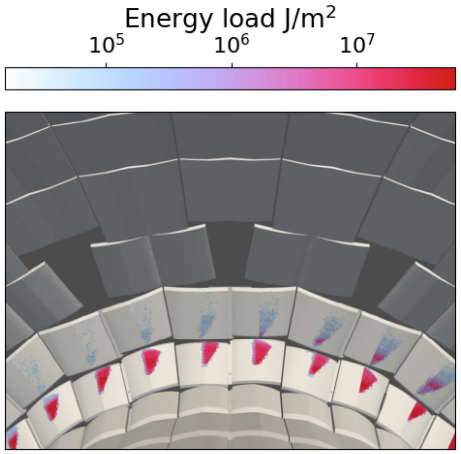
→ **MHD grows faster and larger at higher η**
  - Qualitatively consistent with observations
  - May be due to slower relative growth of secondary modes at larger η [Nardon PoP 2023]

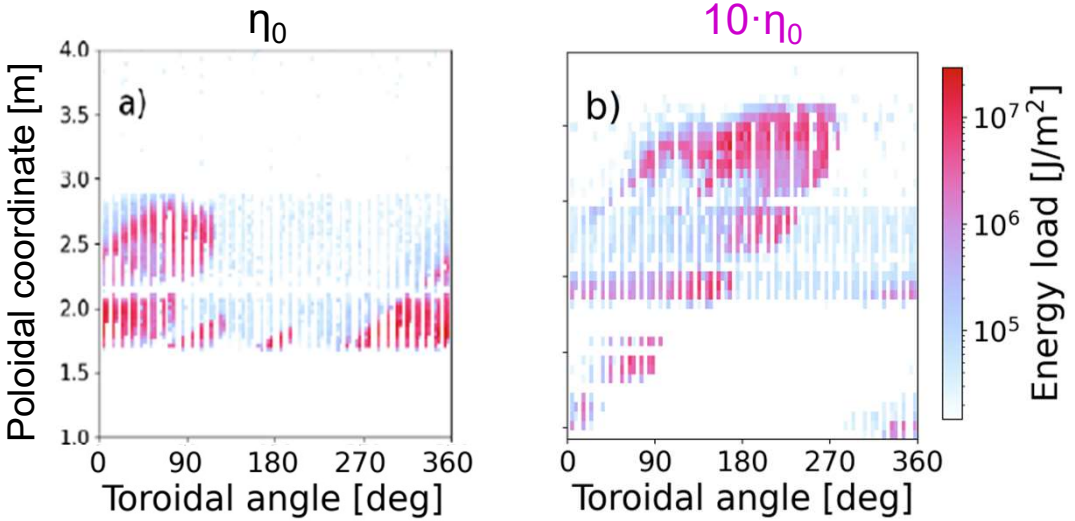
Magnetic energy in n≠0 toroidal harmonics



RE beam termination (mitigation) studied with JOREK (2/2)

- **Heat loads** calculated with test particles and realistic 3D wall model
  [Bergström TSDW 2023]





→ Losses follow a **helical pattern** which is **more extended at larger η**
→ More distributed heat loads at larger η… but peak value similar

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Conclusion

- **Validation** of DREAM and JOREK underway using Bayesian optimisation and synthetic diagnostics

- Regarding **predictions**, ITER is our main focus, but we also work on EU-DEMO, SPARC, STEP, …
  - REs are an **important concern** for **high I_p nuclear machines**
  - **RE mitigation coil** seems promising based on modelling with DREAM+

ITER outlook:

- DREAM predictions for **RE generation at 15 MA:**
  - **With nuclear seeds, multi-MA beam** whatever the SPI settings
  - **W/o nuclear seeds, negligible beam** with appropriate SPI settings (e.g. staggered SPI)
  - Future work:
    - Take vertical motion and 3D MHD into account (→ smaller G_{av})
    - Refine hot-tail predictions (JOREK 3D simulations), ablation plasmoid drifts and nuclear seed estimates

- JOREK simulations of **RE beam termination** at I_{RE} = 9 MA show benefit of increasing η
  - Future work:
    - Include explicit model of H SPI into the beam
    - Model cases with smaller I_{RE}

- Overall, full RE avoidance unlikely but **combined minimization of I_{RE} + mitigation with H SPI** might work…
  → **To be assessed!**

Backup slides

Other activities

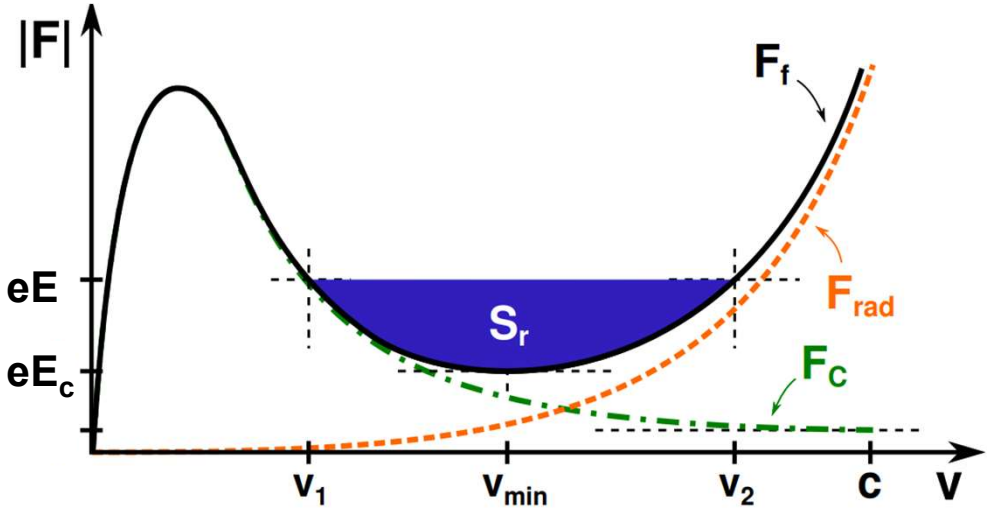
- Related to **other EUROfusion Work Packages (validation + interpretation)**
  - WP-TE:
    - Interaction with **experimental teams on JET, ASDEX Upgrade, TCV, WEST**
    - DREAM modelling of **RE generation in TCV** [Hoppe EPS 2023]
    - DREAM modelling of **effect of ripple on REs in TCV** [Wijkamp REM 2023]
    - DREAM modelling of **benign termination in TCV** [Hoppe in prep.]
    - DREAM modelling of **SPI/MGI in ASDEX Upgrade** [Halldestam REM 2023] [Edes REM 2023]
  - WP-SA: DREAM+SOFT study on **EDICAM camera** for SR measurement in **JT60-SA** [Olasz FED 2023]

- Related to **ITER**
  - DREAM+ study of **effect of alpha-particle-driven modes** on RE generation in ITER [Lier NF 2023]
  - JOREK modelling of **SPI - hot tail interaction** in ITER [Hu NF 2022]
  - Study on **start-up REs** with STREAM [Hoppe JPP 2022]

- Related to **other future machines**
  - DREAM and JOREK modelling of RE gen. and term. in **EU-DEMO** [Lengyel REM 2023] [Vannini REM 2023]
  - DREAM modelling of **spherical tokamak reactor** [Berger JPP 2022]
  - DREAM modelling of the **RE Mitigation Coil in SPARC** [Tinguely PPCF 2023]
  - JOREK modelling of **SPI and RE generation in DTT**
  - SOFT modelling of **REIS diagnostic for DTT** [Hoppe ENEA report 2023]

Runaway electrons [Breizman NF 2019] [Boozer PoP 2015]

Force on an electron from collisional friction and radiation reaction forces



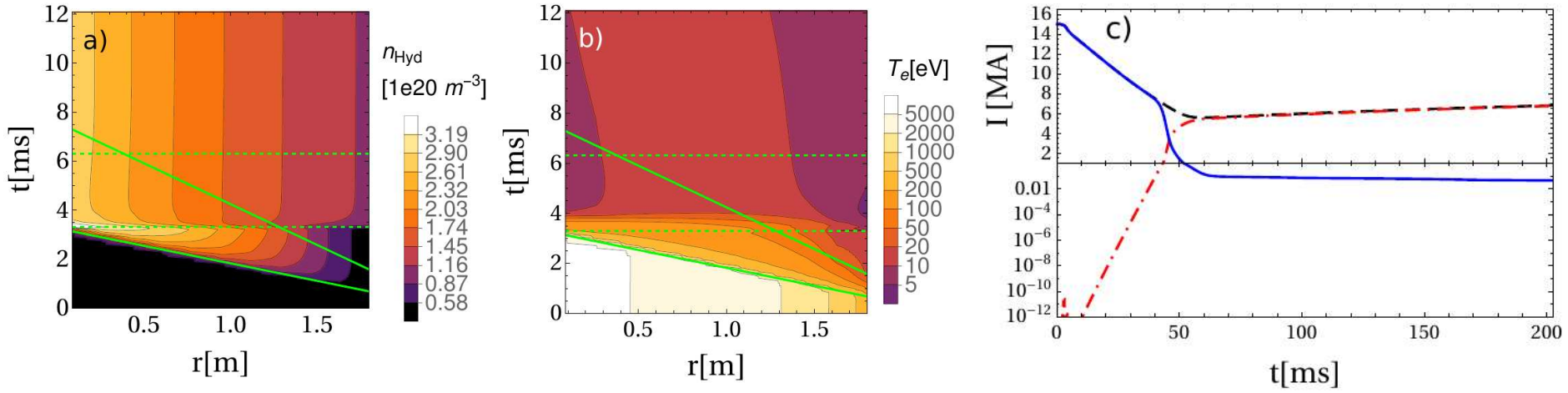
→ Electrons may run away whenever $E > E_c$ (**'critical electric field'**)

→ RE energy is limited (typically to **~10-20 MeV**) by radiation reaction forces

Predicting RE generation in ITER with DREAM

Example of single Ne+H SPI in 15 MA L-mode w/o nuclear seeds

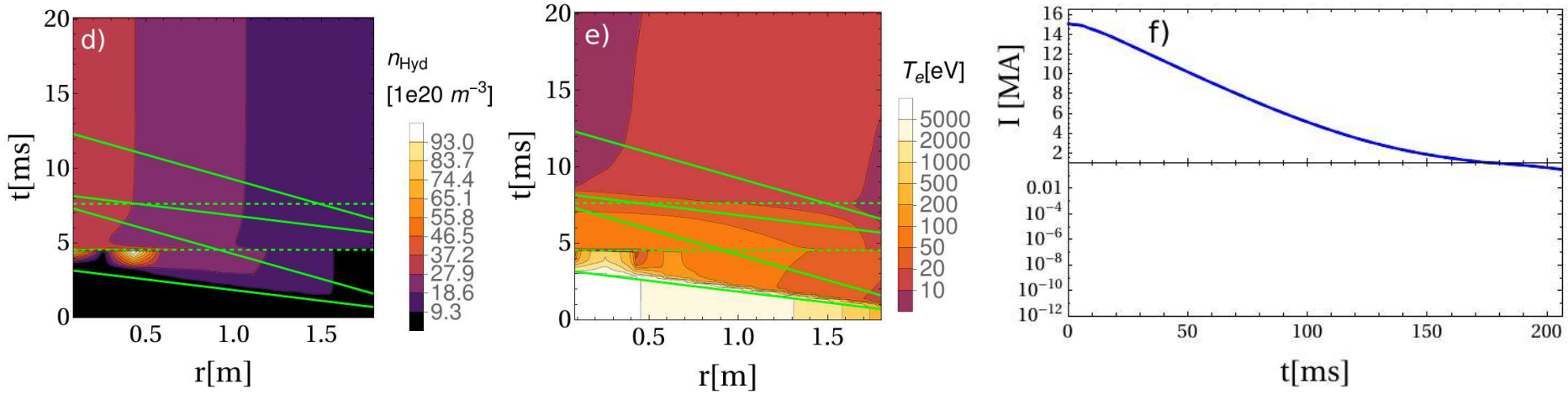
τ_{TQ} = 3 ms; τ_{CQ} = 100 ms; TQ onset criterion: T_e < 10 eV anywhere inside q=2



- **Fast radiative collapse** in the core → **Hot-tail** generation
- Small remaining hot-tail seed after transport event (~10^{-10} A) but very large G_{av} → **~6 MA beam**

Predicting RE generation in ITER with DREAM

Now with staggered (pure H then Ne+H) SPI (otherwise same parameters)



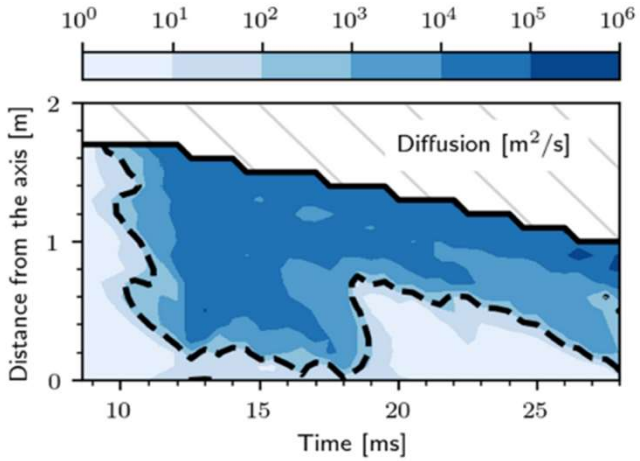
- Larger rise in n_e + more gradual cooling → **Negligible hot-tail** generation → **No RE beam**

→ Staggered scheme promising (w/o nuclear seeds!) but note **possible issue**: pure H ablation plasmoids may experience a strong **drift** towards LFS

  - Model developed [Vallhagen JPP 2023], to be used in DREAM

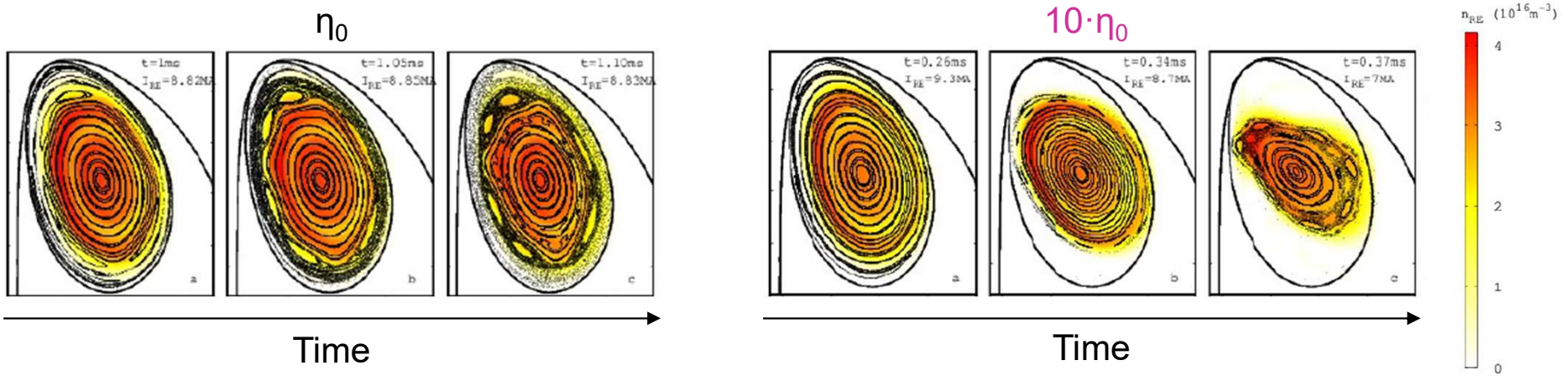
Electron losses due to 3D MHD studied with JOREK

- Hot-tail seed losses during or shortly after TQ? RE losses during CQ?
- JOREK test electron pusher applied to assess **transport in ITER 3D CQ simulation** [Särkimäki NF 2022]
  - (Long stochastic phase but unclear if this is realistic)

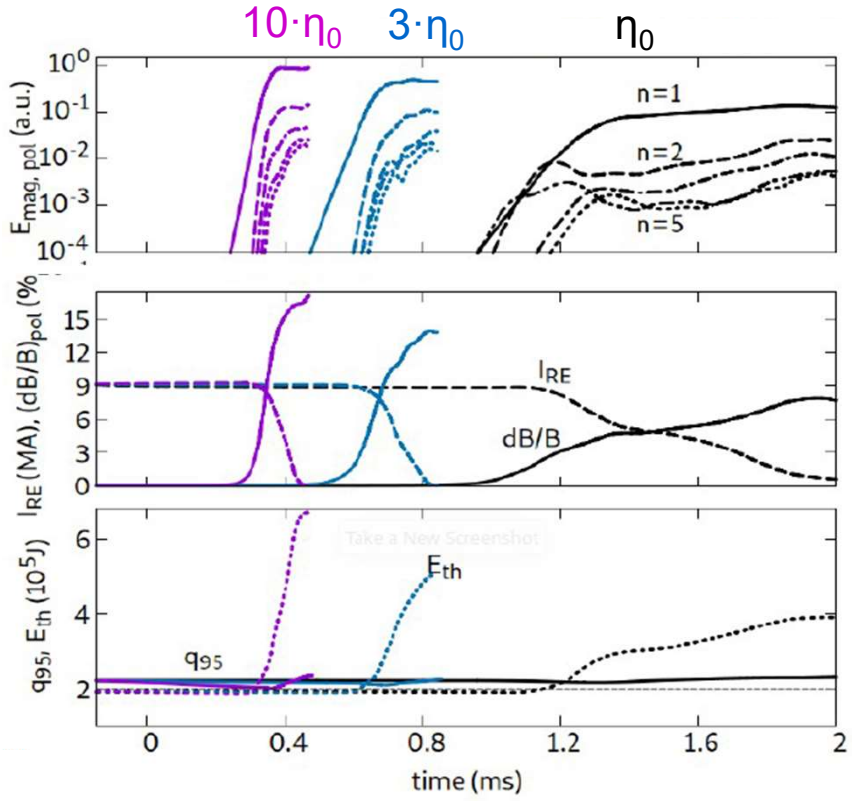


- ITER **SPI sims.** underway [Hu NF 2023] and **hot-tail predictions** planned

RE beam termination studied with JOREK (2/3)



- Clear effect of η on Poincaré cross-sections
  - Smaller role of secondary modes at larger η [Nardon PoP 2023]
  - May explain larger MHD growth


10·η0
3·η0
η0
n=1
n=2
n=5
Emag, pol (a.u.)
IRE
dB/B
(dB/B)pol (%
IRE (MA),
Eth
q95
q95, Eth (10^5 J)
time (ms)