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Modelling of Runaway Electron Dynamics in Tokamak Disruptions

IAEA FEC 2023, 20/10/23

E. Nardon, F.J. Artola, V. Bandaru, H. Bergström, J. Decker, I. Ekmark, T. Fülöp, P. Haldestam, 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 JOEUK team, JET contributors

Framework = EUROfusion TSVV 9 project + ITER DMS Task Force



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Energy Research



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

Outline

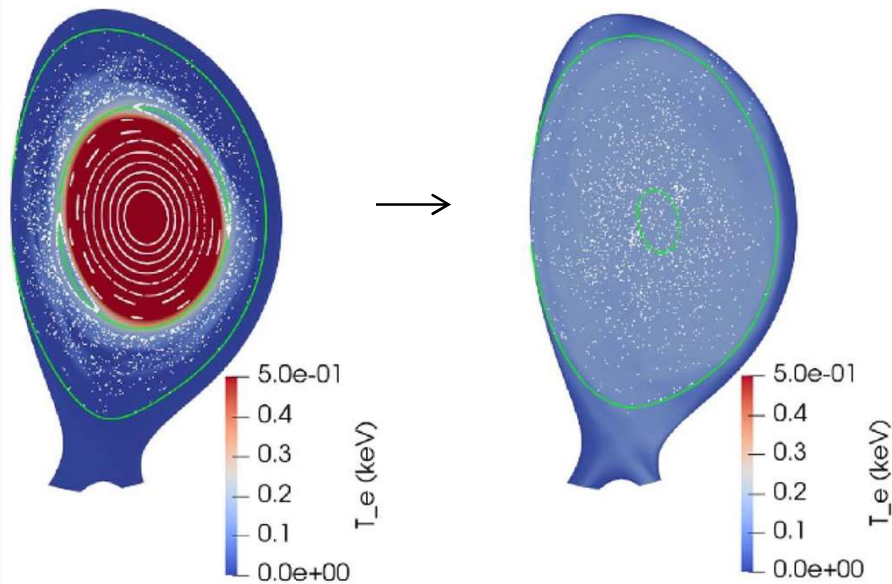


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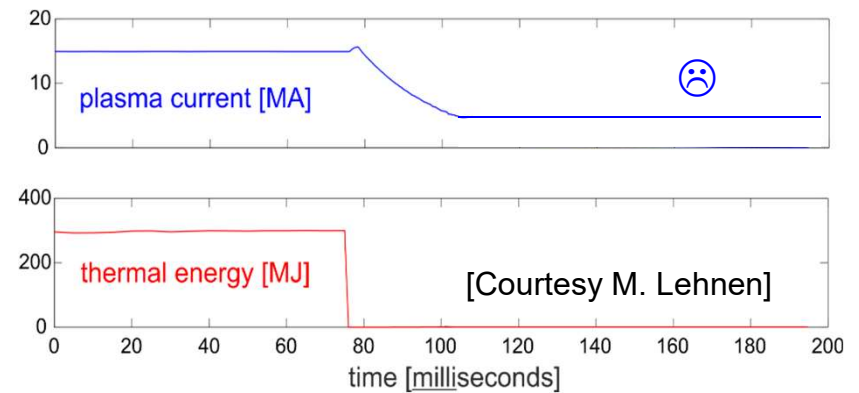
Disruptions



- 1) Thermal Quench (TQ):
 - MHD instability, \mathbf{B} stochastization
 - Radiative collapse
- 2) Current Quench (CQ):
 - Very high resistivity $\eta \rightarrow I_p$ decay
 - Large $\mathbf{E} = \eta \mathbf{j}$, typically $\gg E_c$
 - Sometimes, **RE beam**



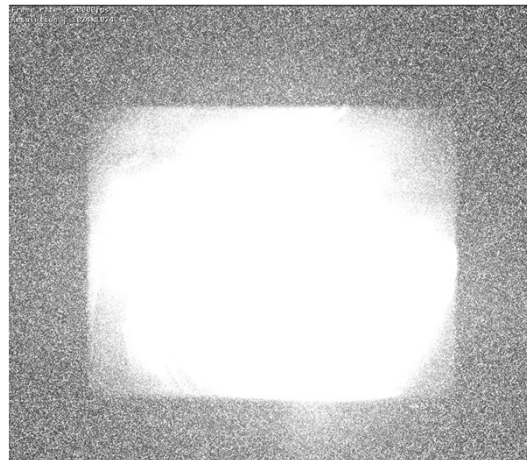
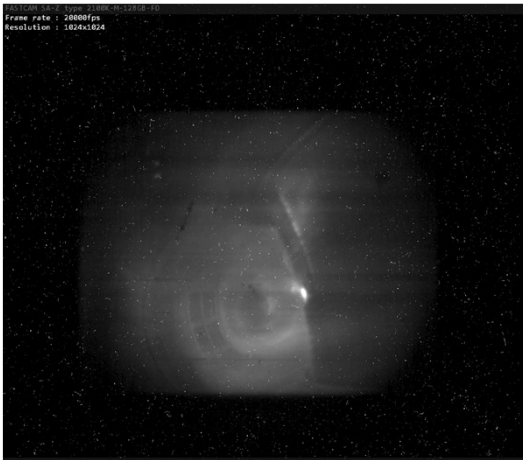
[Nardon PPCF 2021]



RE beam impact: fireworks...



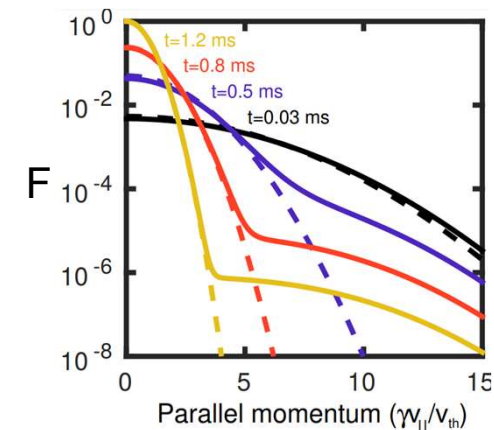
WEST #58003



Primary (seed) RE generation



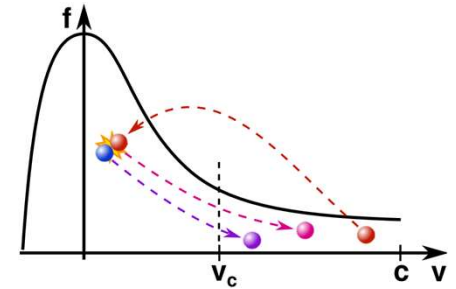
- **Dreicer:** collisional diffusion into RE domain [\[Connor NF 1975\]](#)
 - Typically negligible in ITER
- **Hot-tail:** related to fast cooling during the TQ [\[Smith PoP 2007\]](#)
 - Deviation from a Maxwellian distribution
 - Hard to predict because very sensitive to:
 - TQ timescale
 - e^- transport 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 $E \gg E_c$, avalanche gain G_{av} **scales exponentially with ΔI_p** !

E.g. $G_{av} = 1.9 \times 10^{16}$ 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](#)]

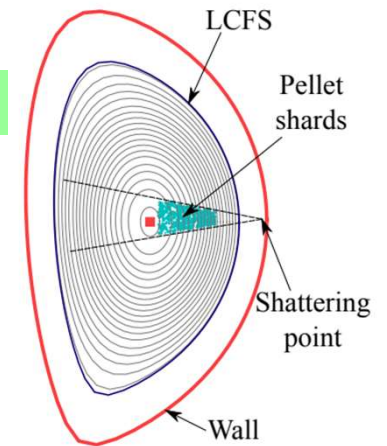
RE-handling strategies



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

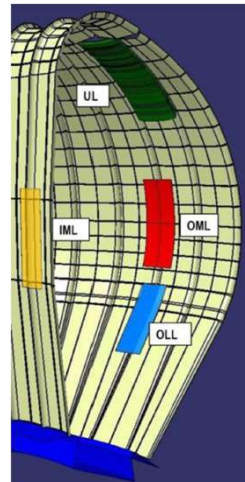
- One or several Ne+H pellets
- Aim: RE avoidance and/or mitigation

[\[Lehnen, this conf., Oral, Tue.\]](#)



EU-DEMO: sacrificial limiters

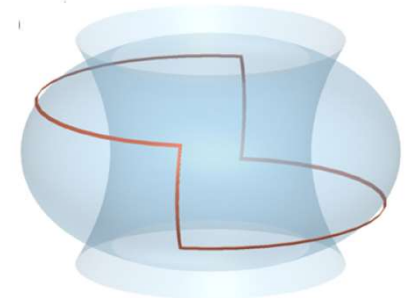
[\[Maviglia FED 2022\]](#)



SPARC: RE mitigation coil

- Passive system
- Induced current from $di_p/dt \rightarrow \mathbf{B}$ 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



- **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, this conf., Ov. P., Mon.]



Outline

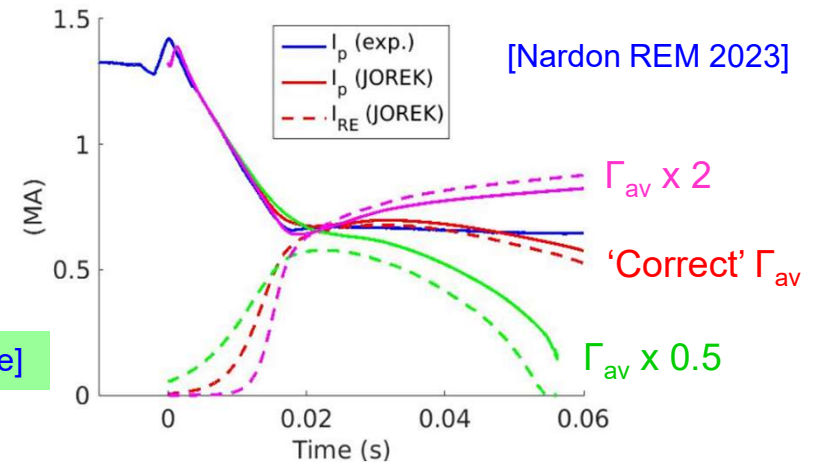


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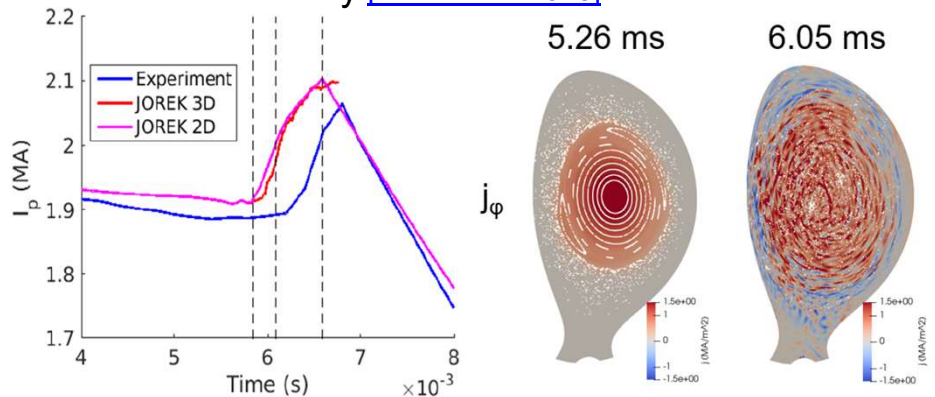
Work is ongoing to validate each aspect of our models



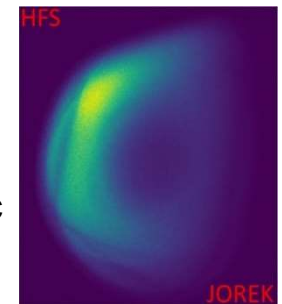
- **Avalanche:** RE generation by Ar MGI in JET #95135 simulated with DREAM and JOREK (2D)
 - Input parameters ↔ Knobs for fitting data
 - **Validation or fancy fit?** → Test by **falsifying** the avalanche gain Γ_{av} → Correct Γ_{av} gives best match
 - Looks like (preliminary) **validation** ☺
 -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



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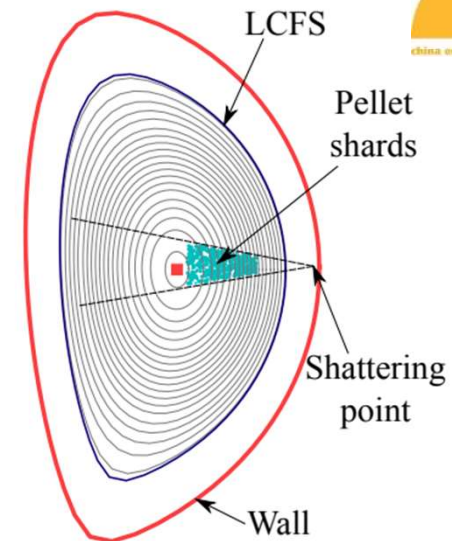
Predicting RE generation (avoidance) in ITER with DREAM (1/2)



[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 $50 \text{ ms} < \tau_{\text{CQ}} < 150 \text{ ms}$
- 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

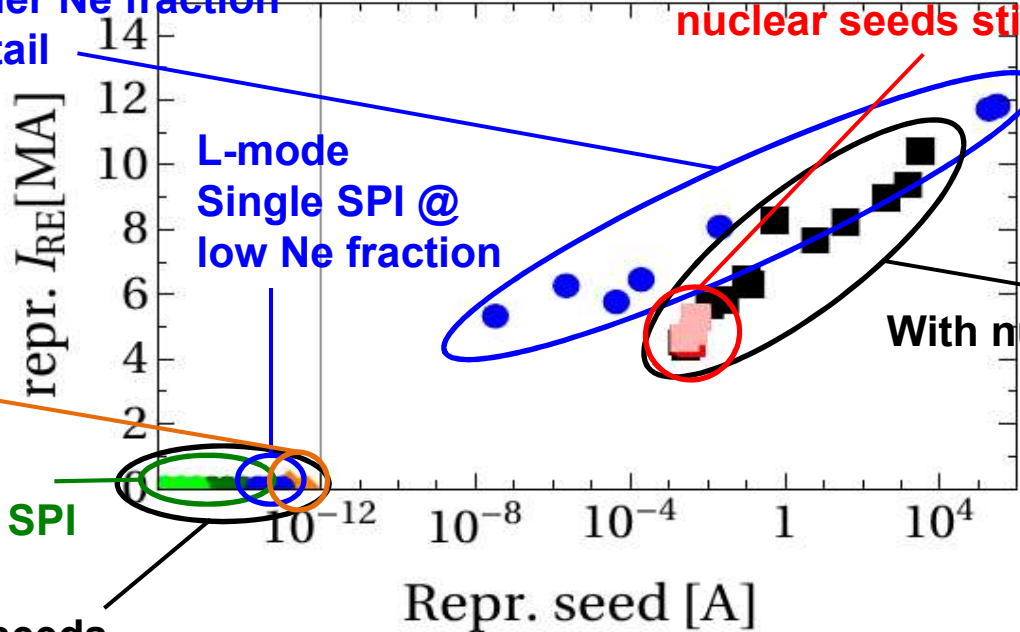
→ Too much hot-tail

H-mode w/o nuclear seeds is manageable

L-mode Staggered SPI

W/o nuclear seeds
With good hot-tail suppression

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



With nuclear seeds (H-mode)

Effect of vertical movement assessed with JOREK

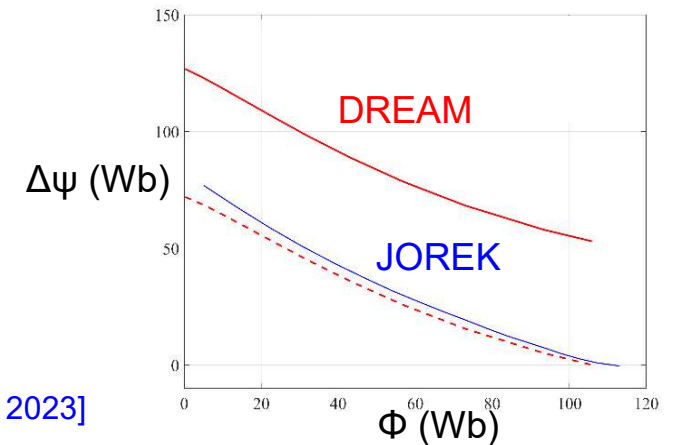
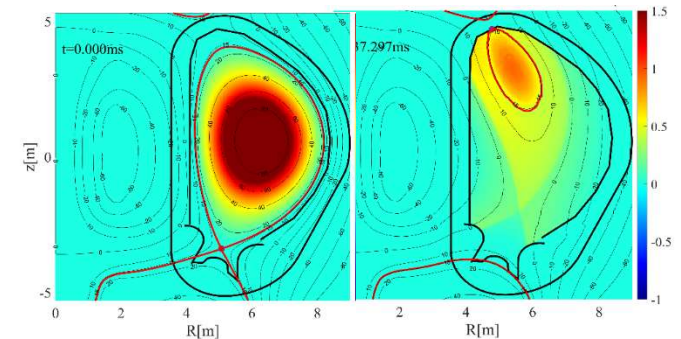


- DREAM simulations use a fixed plasma geometry
- Effect of vertical movement on **avalanche gain G_{av}** ?
→ Use JOREK 2D simulations
- On each toroidal flux (Φ) surface, **$\log(G_{av}) \sim \Delta\psi$** , where $\psi \equiv$ poloidal flux [\[Boozer PoP 2015\]](#)
 - Δ between $t=0$ and when surface becomes LCFS
- JOREK finds that **$\psi_{LCFS} \approx \text{constant}$** in time
 - Related to \sim ideal behaviour of the wall
- In contrast, in DREAM, **$\psi_{LCFS} \downarrow$ in time** → Larger $\Delta\psi$
- **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

JOREK 2D simulation for 15 MA ITER case

(Simple model for Ne+H injection and TQ)

0 ms 37 ms j (MA/m²)



[\[Wang REM 2023\]](#)

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



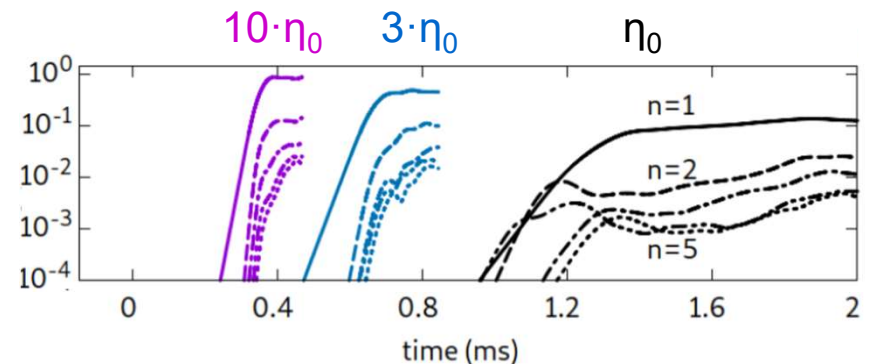
- In present machines, a **benign RE beam termination** can be obtained via H or D injection into the beam [\[Paz-Soldan NF 2021\]](#)
 - Associated to **fast and large MHD instability**
- Could this work in ITER?



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 [\[Nardon PoP 2023\]](#)

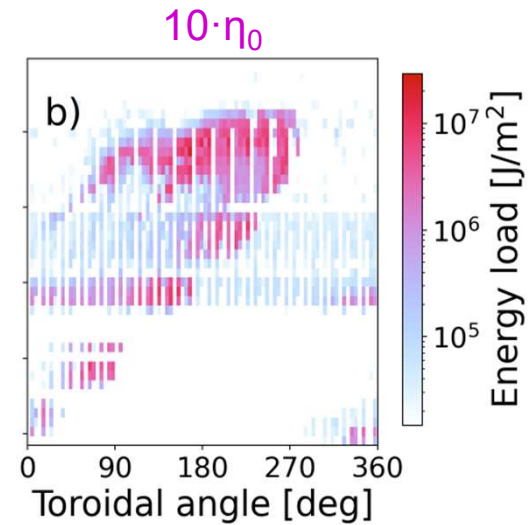
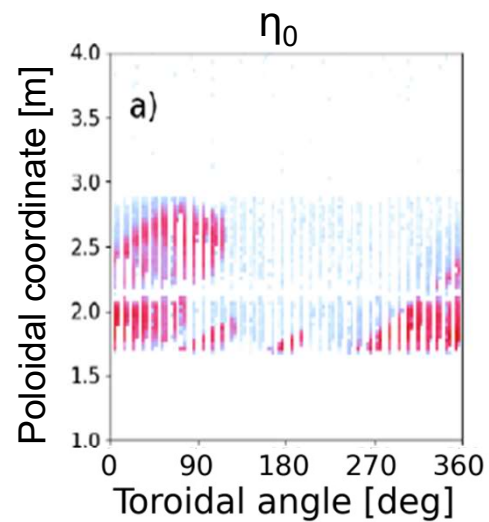
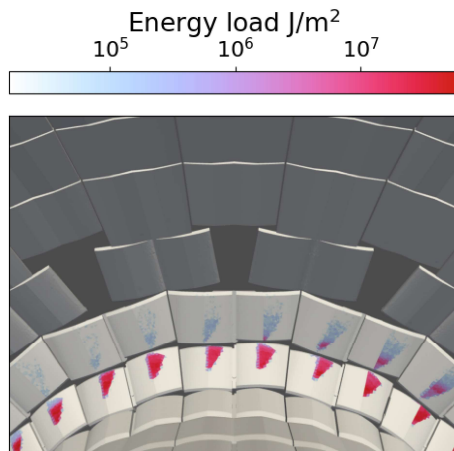
Magnetic energy in $n \neq 0$ toroidal harmonics



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 JOEREK 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 (\rightarrow smaller G_{av})
 - Refine hot-tail predictions (JOEREK 3D simulations), ablation plasmoid drifts and nuclear seed estimates
- JOEREK 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...
 \rightarrow **To be assessed!**



Backup slides

Other activities

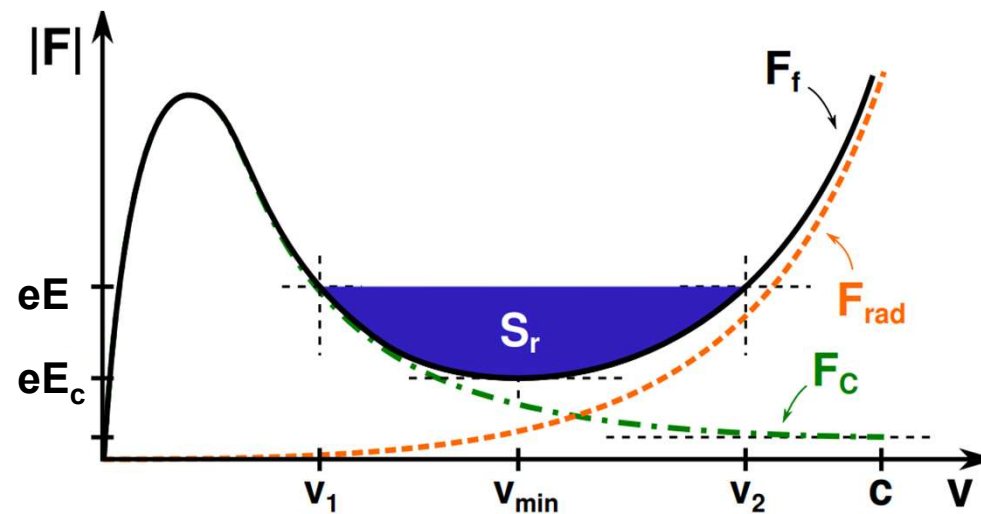


- Related to **other EUROfusion Work Packages (validation + interpretation)**
 - WP-TE:
 - Interaction with **experimental teams on JET, ASDEX Upgrade, TCV, WEST**
 - DREAM modelling of **RE generation in TCV** [[Hoppe EPS 2023](#)]
 - DREAM modelling of **effect of ripple on REs in TCV** [[Wijkamp REM 2023](#)]
 - DREAM modelling of **benign termination in TCV** [[Hoppe in prep.](#)]
 - DREAM modelling of **SPI/MGI in ASDEX Upgrade** [[Haldestam 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')

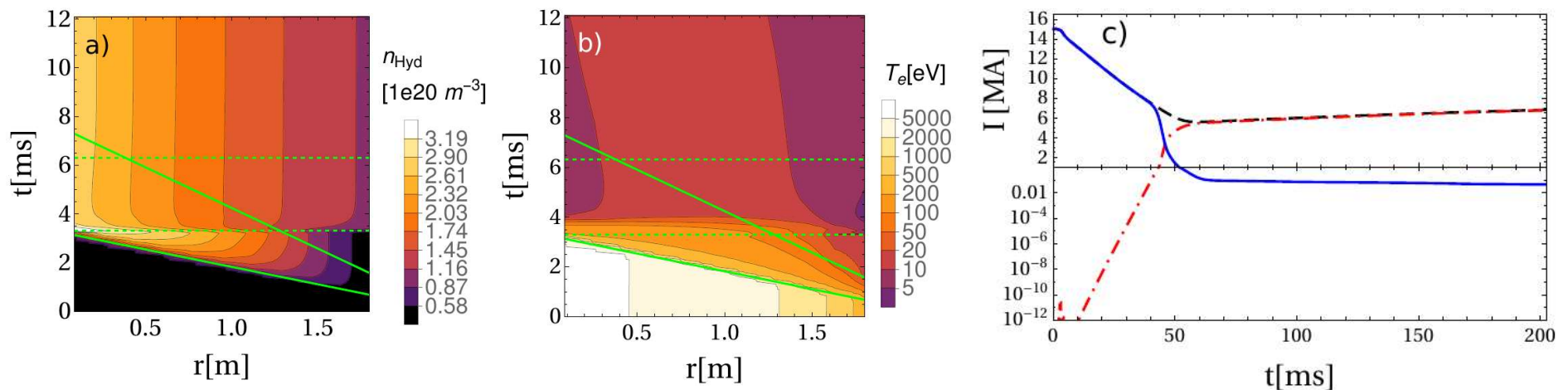
→ RE energy is limited (typically to **~10-20 MeV**) by radiation reaction forces

Predicting RE generation in ITER with DREAM



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

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

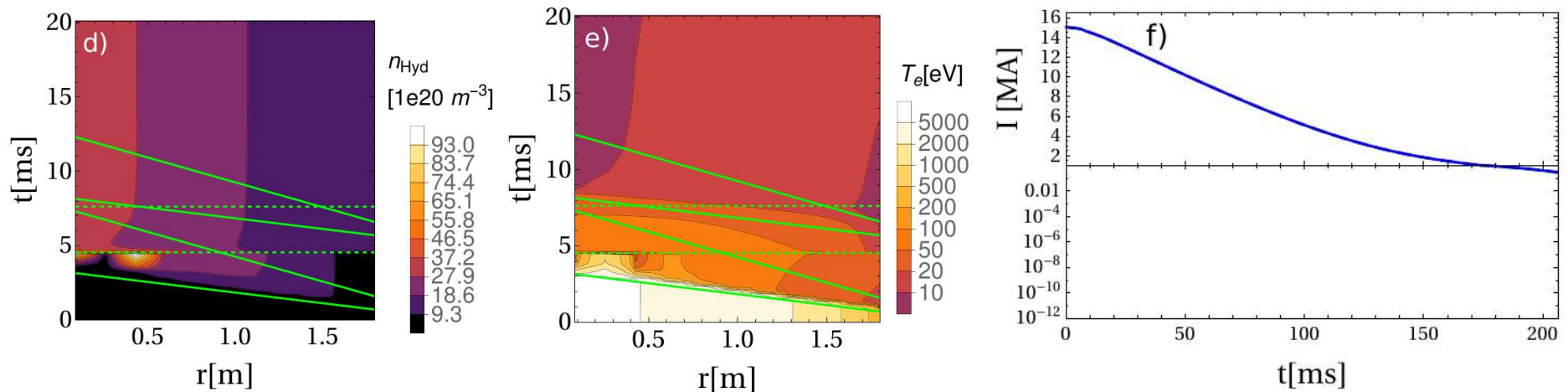


- **Fast radiative collapse** in the core → **Hot-tail** generation
- Small remaining hot-tail seed after transport event ($\sim 10^{-10}$ A) but very large G_{av} → **~ 6 MA beam**

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**

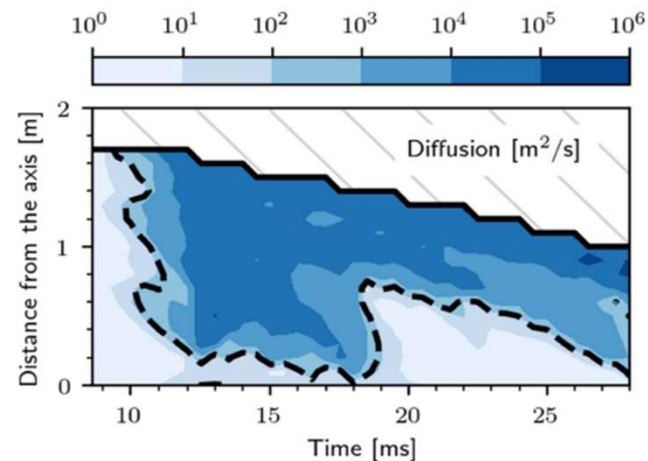
→ Staggered scheme promising (w/o nuclear seeds!) but note **possible issue**: pure H ablation plasmoids may experience a strong **drift** towards LFS

- Model developed [\[Vallhagen JPP 2023\]](#), to be used in DREAM

Electron losses due to 3D MHD studied with JOREK

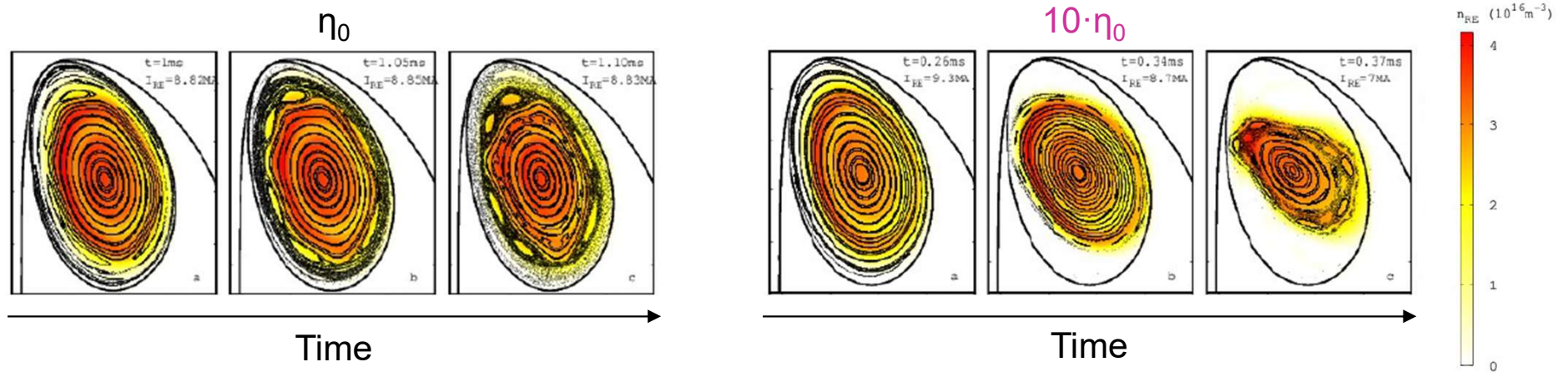


- Hot-tail seed losses during or shortly after TQ? RE losses during CQ?
- JOREK test electron pusher applied to assess **transport in ITER 3D CQ simulation** [\[Särkimäki NF 2022\]](#)
 - (Long stochastic phase but unclear if this is realistic)



- 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

