TSVV 9: Modelling of Runaway Electron Dynamics in Tokamak Disruptions

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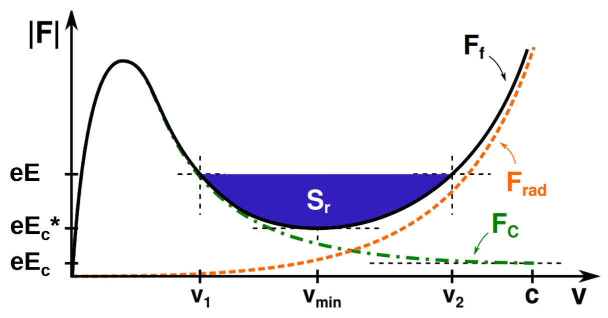
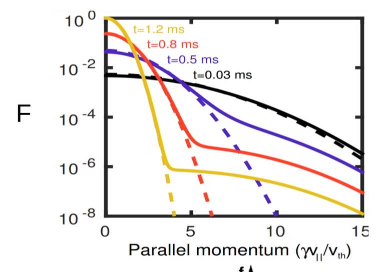
**See the author list of Maggi et al., Nucl. Fusion 64 (2024) 112012

Introduction to disruptions and Runaway Electrons (REs)

Disruption = 1) Thermal Quench (TQ): MHD instability, **B** stochastization, radiative collapse; 2) Current Quench (CQ): high resistivity η, large E = η j, possibly RE beam

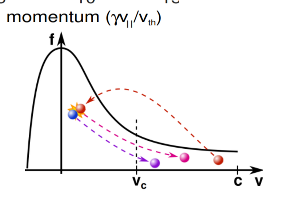


Primary (seed) RE generation
- **Dreicer**: collisional diffusion into RE domain [Connor NF 1975]; typically negligible in ITER
- **Hot-tail**: related to fast cooling during TQ [Smith PoP 2007]
  - Hard to predict because very sensitive to TQ timescale and e⁻ transp. in stochastic **B**
  - Potentially by far largest seed in ITER disruptions



- **Nuclear** [Martín-Solís NF 2017]: Small but active during CQ
  - **Tritium β decay**
  - **Compton scattering** by wall-emitted γ rays

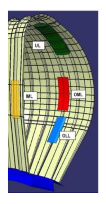
Secondary RE generation: the avalanche
- Close collisions can generate 2 REs from 1 → Exponential growth
- Initial theory by Rosenbluth and Putvinsky [Rosenbluth NF 1997]



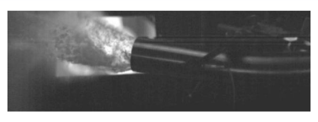
→ When E >> E_c, avalanche gain G_{av} **scales exponentially with ΔI_p!**
E.g. **G_{av} = 1.9 × 10¹⁶ in ITER** (15 MA) vs. 1.8 × 10³ in JET (3 MA) [Hender NF 2007]
- Bound e⁻ around partly ionized impurities can strongly boost G_{av} [Hesslow NF 2019]

RE handling strategies

EU-DEMO: sacrificial limiters [Maviglia FED 2022]



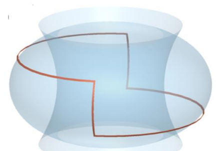
ITER: Shattered Pellet Injection (SPI)



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

[Lehnen JNM 2015] [Lehnen IAEA FEC 2023]

SPARC: passive RE Mitigation Coil [Tinguely PPCF 2023]



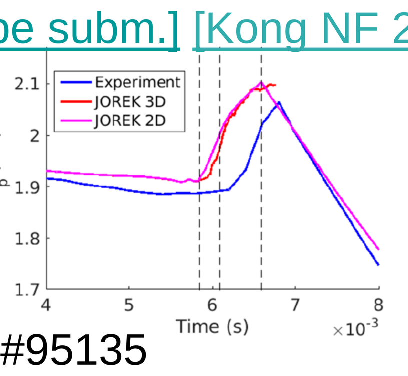
- Induced current from dI_p/dt → **B** stochasticity → RE avoidance

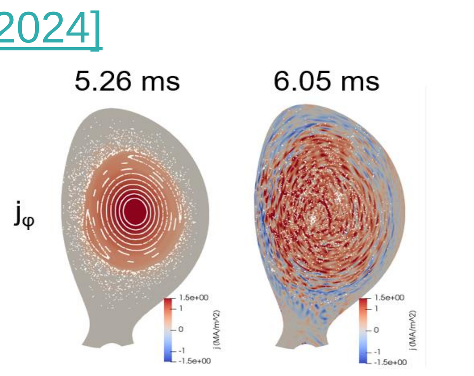
Simulation tools

- **DREAM kinetic code** [Hoppe CPC 2021] [Hoppe EPS 2024]
  - Solves 1D flux-surface-averaged transport equations
  - Self-consistently evolves e⁻ distribution function
  - Interfaced with synthetic synchrotron rad. code SOFT [Hoppe NF 2018]
- **JOREK 3D MHD code with different models for REs** – Close **collab. with TSVV 8** [Hoelzl NF 2021] [Hoelzl NF 2024]
  - RE fluid [Bandaru PRE 2019]
  - Test e⁻ [Sommariva NF 2018] [Särkimäki NF 2022]
    - Being further developed for hot tail modelling [Puel REM 2024]
  - PiC model (kinetic e⁻ + MHD) now **operational** [Bergström EPS inv. & PPCF 2024 sub.]
    - Being further developed for avalanche modelling [Wouters REM 2024]

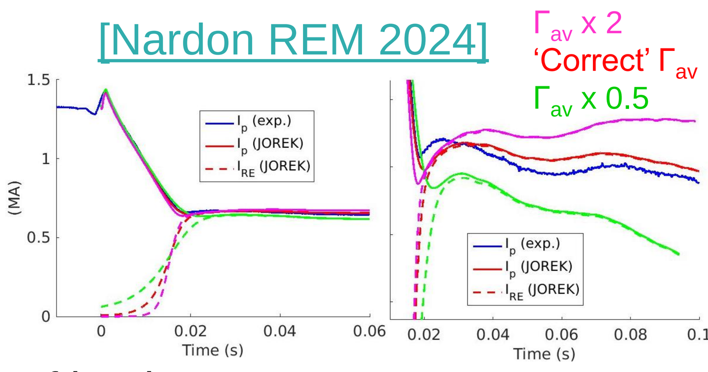
Code validation, in collaboration with WPTE-RT03 and TSVV 8

- **Shattered Pellet Injection:** DREAM and JOREK sims. for ASDEX Upgrade, JET, etc. [Halldestam EPS 2024] [Tang NF 2024 to be subm.] [Kong NF 2024]
- **TQ and stochastic losses:** JOREK sim. of JET Ar MGI reproduces **I_p spike** and supports its link with **B** stochasticity [Nardon NF 2023]

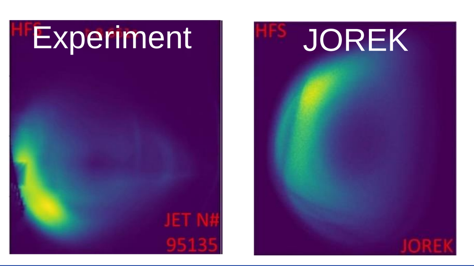




- **Avalanche:** RE generation by Ar MGI in JET #95135 simulated with DREAM and JOREK (2D) [Nardon REM 2024]
  - Input parameters ↔ Knobs for fitting data → **Validation or fancy fit?** → Test by **falsifying** the avalanche gain Γ_{av}
  - **Bayesian optimization framework** developed and used for objectivity [Järvinen JPP 2022]



- **RE beam termination:** JOREK 3D RE fluid simulation of benign termination in JET #95135, building on [Bandaru PPCF 2021]
  - Aiming for more realistic sims., e.g. crossing stab. boundary [Singh REM 2024], and using synch. rad. for validation [Sommariva EPS 2023]



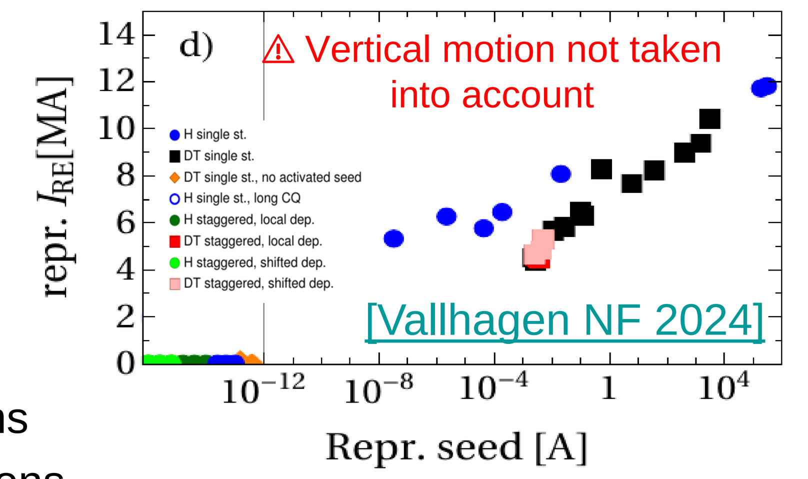
Application to future machines other than ITER

- **SPARC**: DREAM sims. of RE avoidance with REMC [Tinguely PPCF 2023]
- **EU-DEMO**: DREAM → gen. [Pokol REM 2024], JOREK → impact [Vannini PST 2024]
- **DTT**: JOREK sims. of RE gen. & impact [Emanuelli SOFT 2024]
- **JT60-SA**: DREAM & SOFT sims. of RE gen. & synchrotron meas. [Olasz REM 2024]
- **STEP**: DREAM sims. of RE gen. [Fil NF 2024]

ITER RE generation (avoidance) simulations with DREAM and JOREK

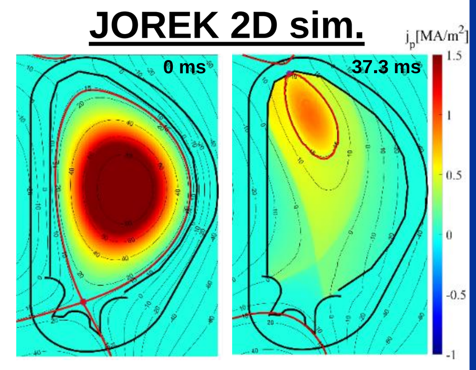
DREAM setup:
- Wide range of scenarios, **with or w/o nuclear seeds**
- 2 types of SPI schemes
  - **Single** Ne+H
  - **Staggered**: pure H then Ne+H
    2 step cooling: 1) dilution, 2) rad. collapse
    Benefit: hot-tail suppression
- Ne quantity adjusted so that 50 ms < τ_{CQ} < 150 ms
- **Ad hoc TQ model** informed by 3D MHD simulations
  - Particle mixing + RR e⁻ transport [Hu NF 2023 & 2024]

DREAM results for 15 MA L-mode ('H') w/o nucl. seeds and H-mode ('DT') with nucl. seeds



⚠ JOREK suggests possible important impact of vertical motion
- On each tor. flux surf., **log(G_{av}) ~ Δψ** [Boozer PoP 2015]
  - Δ is between t=0 and when surface becomes LCFS
- JOREK finds that ψ_{LCFS} ≈ constant, related to nearly ideal wall
- Can **reduce G_{av} by orders of magnitude**

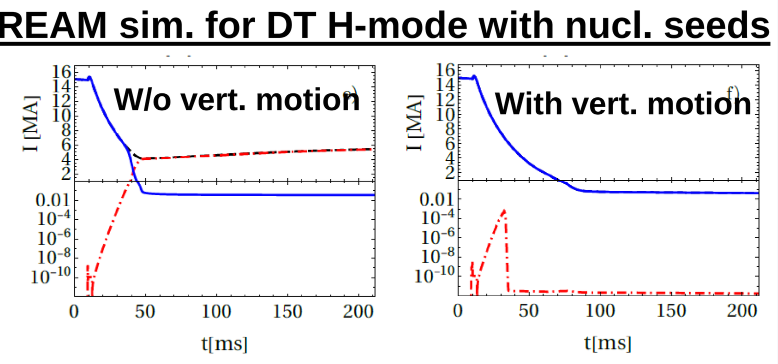
JOREK 2D sim.



[Wang NF 2024]

DREAM sim. for DT H-mode with nucl. seeds

→ **DREAM simulations being revisited accounting for vertical motion** [Vallhagen JPP 2024 subm.]
→ RE beam not produced anymore in certain cases

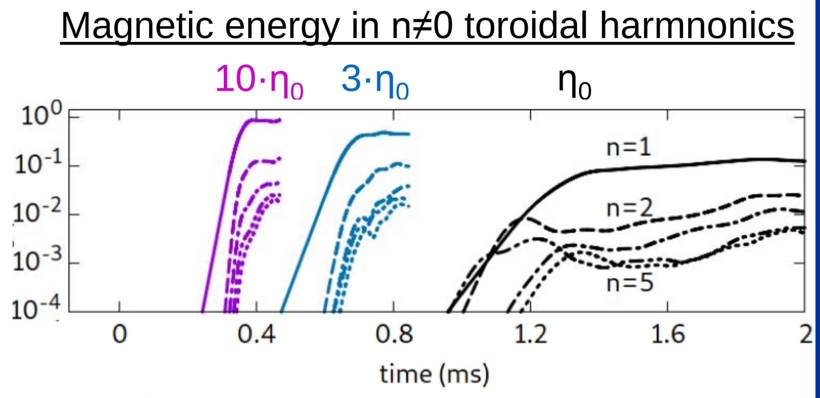


Also DREAM work on **kinetic vs. fluid predictions** and **Bayesian optimisation of RE avoidance in ITER** [Ekmark JPP 2024]

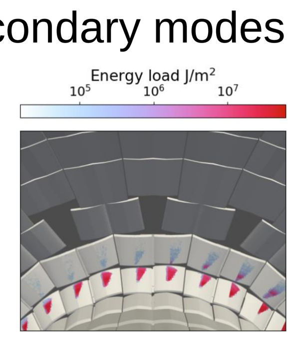
JOREK simulations of RE beam termination [Bandaru NF 2024]

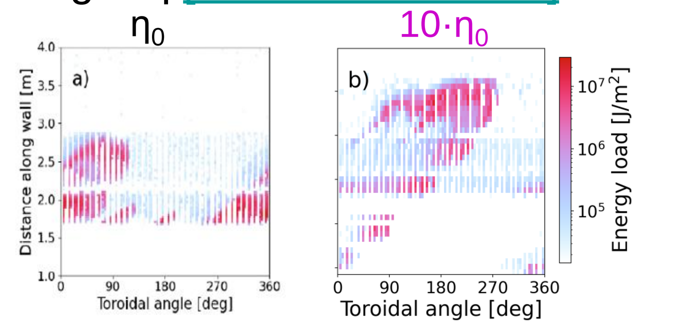
- Objective: **benign term.** after H inj. into beam, like in present exp. [Paz-Soldan NF 2021]
  - Associated to **fast and large MHD instability**
- Simulate a large (I_{RE} = 9 MA) beam
- No model for H injection but studied effect of resistivity η as a rough proxy

Magnetic energy in n≠0 toroidal harmonics



→ **MHD grows faster and larger at higher η**
  - Qualitatively consistent with observations
  - May be due to smaller growth of secondary modes at larger η [Nardon PoP 2023]
- **Heat loads** calculated with test particles and realistic 3D wall model [Bergström PPCF 2024]
→ Helical pattern, broader at larger η
→ Smaller averaged heat load at larger η (but peak value similar)





TSVV 9: self-assessment

- A generally **successful project but still a lot to do!**
- **DREAM-JOREK synergy** is extremely useful
- **Very good interaction** within the team and with the community (progress meetings, REM meetings, RT03 meetings, …) but **travel budget has been a limiting factor**

Plans for 2025 and beyond

- RE generation models: **improve SPI models** (TQ onset & dynamics, plasmoid drift, rocket effect, …), address MHD stability of post-TQ plasma, address impact of W sputtering, reach detailed validation
- RE mitigation models: **improve/develop models for {RE beam + companion plasma} & SPI into this system**, validate; collaborate with S. Ratynskaia et al. on **RE impact modelling**
- Apply models to future machines
  - **Help ITER choose strategy and pellet size (dilemma avoidance vs. mitigation?)**
  - Other machines: SPARC, EU-DEMO, JT60-SA, DTT, STEP, …
- We propose to **pursue TSVV 9 beyond 2025**

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