# TSVV 9:
# Dynamics of Runaway Electrons in Tokamak Disruptions

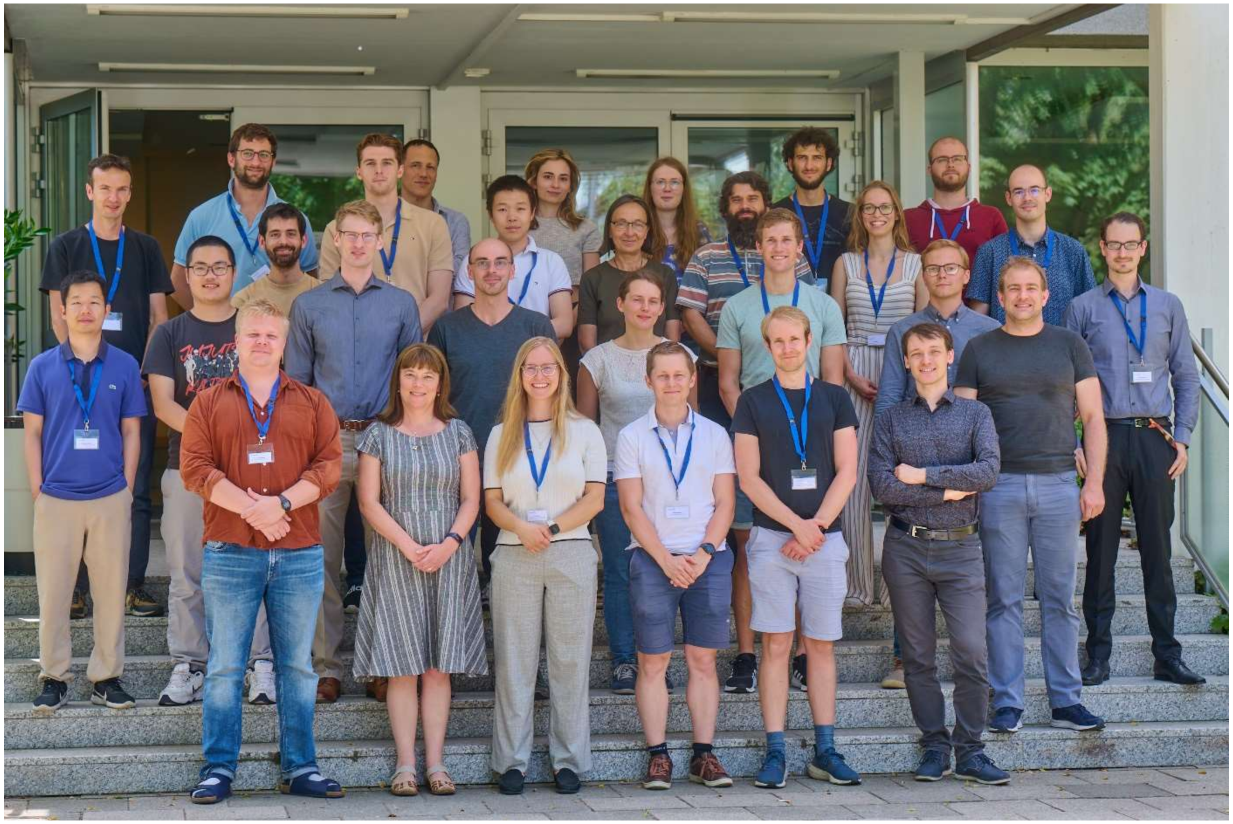
TSVV mid-term review, 11/09/23

E. Nardon, F.J. Artola, V. Bandaru, H. Bergström, J. Decker, L. Edes, I. Ekmark, T. Fülöp, P. Halldestam, M. Hoelzl, M. Hoppe, D. Hu, A. Järvinen, M. Lehnen, F. Lengyel, A. Matsuyama, S. Olasz, G. Papp, Y. Peysson, G.I. Pokol, I. Pusztai, C. Reux, K. Särkimäki, R. Saura, N. Schwarz, L. Singh, C. Sommariva, M. Tyschenko, O. Vallhagen, F. Vannini, J. Walkowiak, C. Wang, T. Wijkamp, F. Wouters, the JOREK team, JET contributors, …

Centre for Energy Research

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

# Team ☺



Group picture from the 10th Runaway Electron Modelling (REM) meeting, Garching, June 2023

# Outline

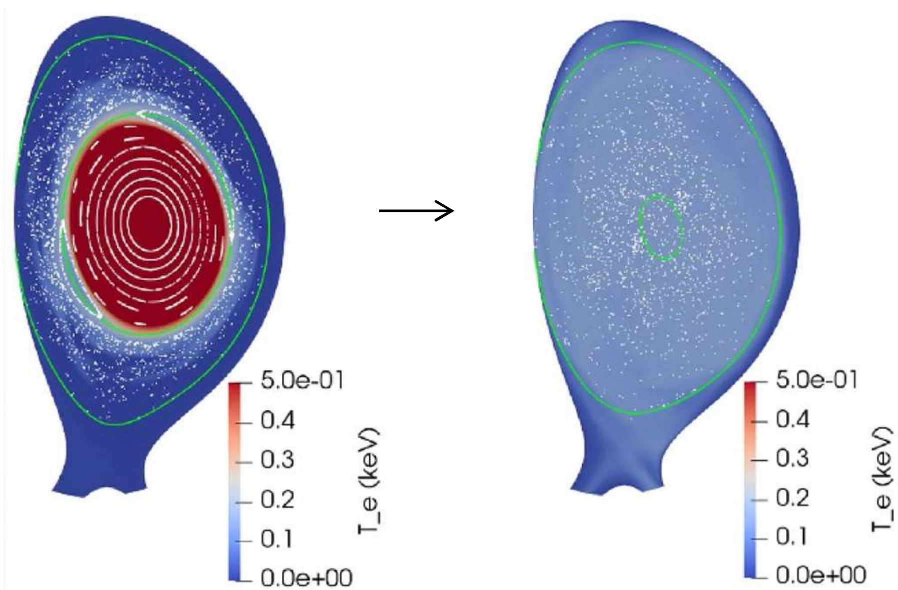
- Introduction: disruptions, Runaway Electrons (REs)
- Simulation tools
- Simulations for ITER
  - RE generation and avoidance
  - RE beam termination and mitigation
- Validation
- Other activities
- Conclusion

# Outline

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

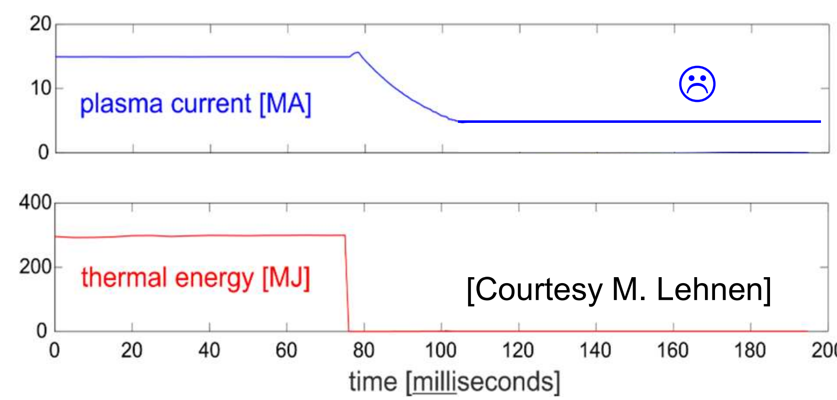
# Disruptions

- **Thermal Quench (TQ)**:
  - MHD instability, stochastization
  - Radiative collapse [Ward NF 1992]
  - Thermal flash on PFCs

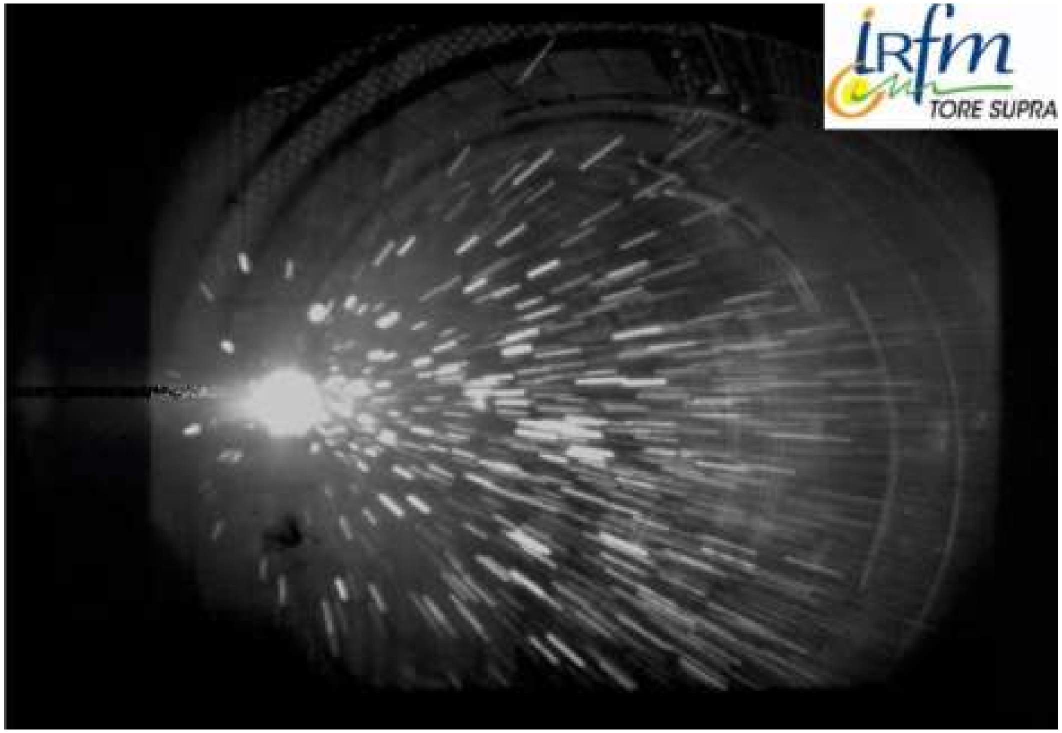



[Nardon PPCF 2021]

- **Current Quench (CQ)**:
  - Very resistive post-TQ plasma
  - $I_p$ decay
  - Electromagnetic loads from:
    - Eddy currents (fast CQ)
    - Halo current (slow CQ)
  - Thermal flash on PFCs
  - Large E, typically >> $E_c$

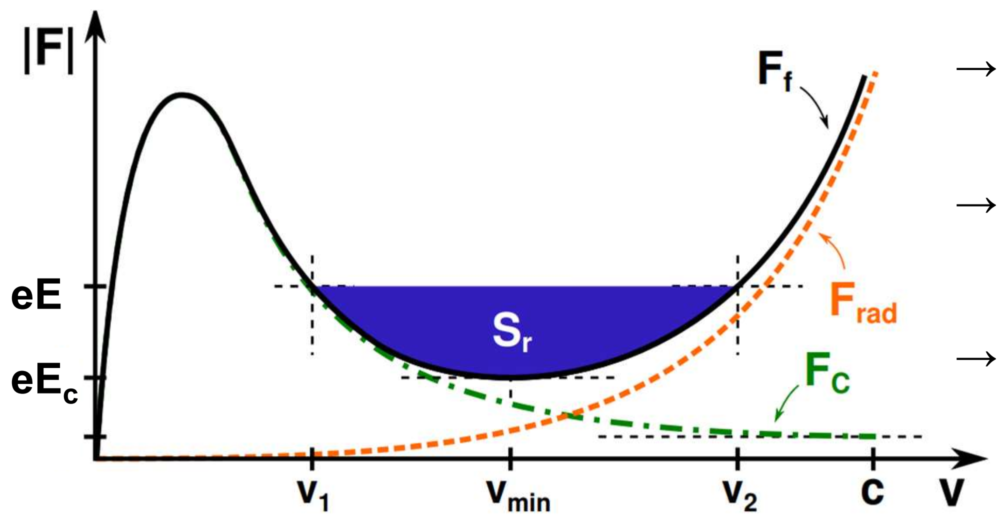


# RE beam impact: fireworks…



# Runaway electrons

**Force on an electron from collisional friction and synchrotron radiation**




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

→ When $E > E_c$, electrons faster than the **'critical velocity'** $v_1$ are likely to run away

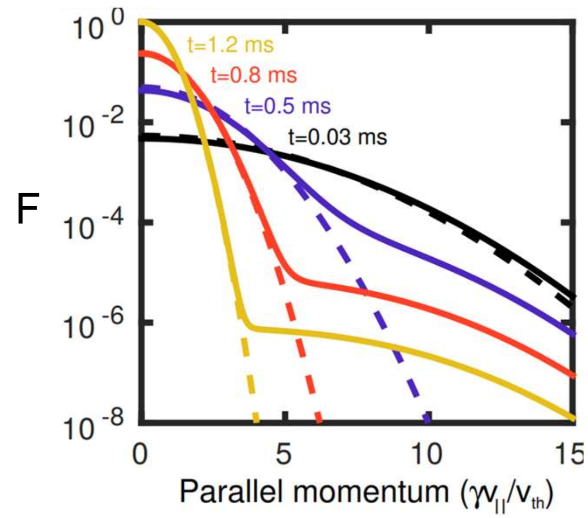
→ RE energy is limited (typically to **~10-20 MeV**) by radiation reaction forces

Review papers: [Breizman NF 2019] [Boozer PoP 2015]

# Primary ('seed') RE generation mechanisms (1/2)

- **Dreicer**: collisional diffusion into RE domain [Connor NF 1975]
  - Typically negligible in ITER

- **Hot-tail**:
  - In case of fast cooling (e.g. TQ), $e^-$ distribution function F deviates from a Maxwellian
  - Strong RE production if E rises (due to bulk cooling) faster than collision time at critical velocity [Smith PoP 2007]
  - Hard to predict but potentially by far largest seed in ITER

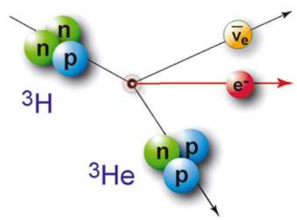


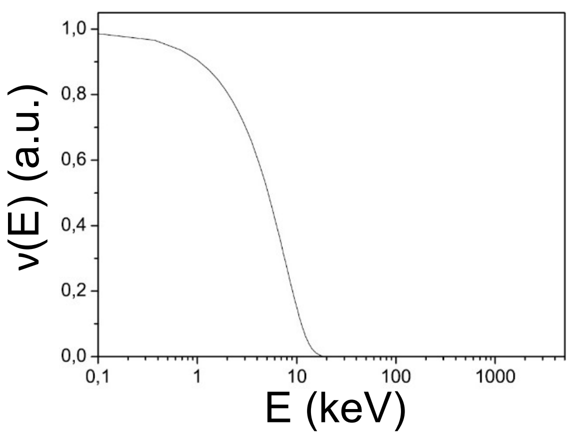
# Primary (‘seed’) RE generation mechanisms (2/2)

**<u>‘Nuclear’ seeds:</u>**

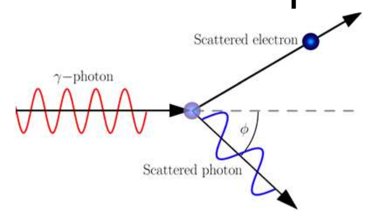
Small but active throughout CQ

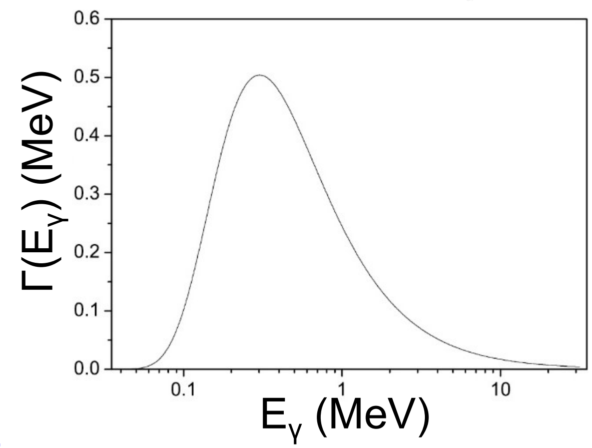
- **Tritium β decay**




- **Compton scattering** by wall-emitted γ’s



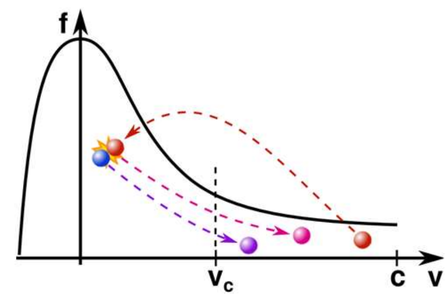




[Martín-Solís NF 2017]

# Secondary RE generation mechanism: 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]

$$\frac{dn_r}{dt} = \sqrt{\frac{\pi}{2}}\frac{n_r(E_{||} - E_c)}{3E_c\tau\ln\Lambda}$$

(note: $E_{||} \approx \partial_t\psi/R$)

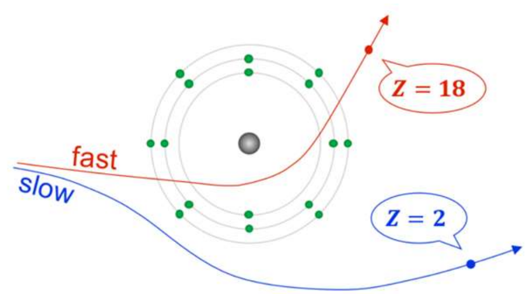
→ When $E_{||} >> E_c$, $\log(G_{av}) \sim \Delta\psi \sim \Delta I_p$

→ Avalanche gain **$G_{av}$ scales exponentially with $I_p$!**

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

- Theory extended to account for **bound electrons**
  - Targets for knock-on collisions, not fully compensated by additional friction (charge screening!)

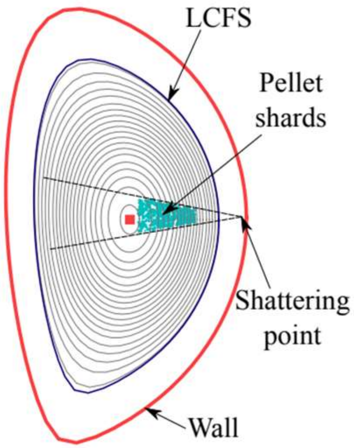
  → Can strongly **boost $G_{av}$** [Hesslow NF 2019]



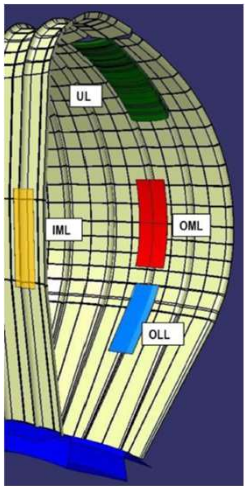
# RE-handling strategies

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

- One or several Ne+H pellets (flexible mixture ratio)
- RE avoidance and/or mitigation
- Also in charge of thermal and electromagnetic loads mitigation

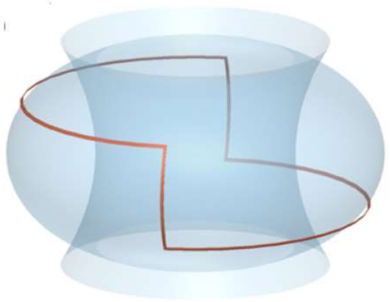



**EU-DEMO: sacrificial limiters**
[Maviglia FED 2022]




## SPARC: RE Mitigation Coil

- Passive system
- Induced current from $dI_p/dt$ → B stochasticity → RE avoidance



[Tinguely PPCF 2023]

# Outline

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

# Simulation tools

**2 main 'workhorses':**

- **DREAM kinetic** code [Hoppe CPC 2021]
  - Solves 1D flux-surface-averaged transport equations
  - Self-consistently evolves $e^-$ distribution function using bounce-averaged kinetic equation
    - Different levels of description, from full kinetic to fluid-like

- **JOREK 3D MHD** code with different models for REs [Hoelzl NF 2021]
  - RE fluid [Bandaru PRE 2019]
  - Test (relativistic) electrons [Sommariva NF 2018] [Särkimäki NF 2022]
  - PiC model for self-consistent kinetic electrons + MHD (next slides)
  - Strong interaction with TSVV 8!

Both codes are well-documented, version-controlled, (partly) IMAS-integrated, ...
We are happy to train **new users** on an individual basis. → Contact us: eric.nardon@cea.fr

Other tools: LUKE, ETS, SOFT, …

# Self-consistent PiC model for REs in JOREK in development (1/2)

- JOREK **electron pusher** evolves a population of **kinetic electrons**
- **Moments** of kinetic electron population used in the fluid equations
  - 2 possible **coupling schemes**: via **current** or via **pressure** → Implemented both

Current coupling scheme

[Bergström TSDW 2023]

$$\frac{\partial \rho_b}{\partial t} + \nabla \cdot (\rho_b \boldsymbol{u}_b) = S_{\rho_b}$$

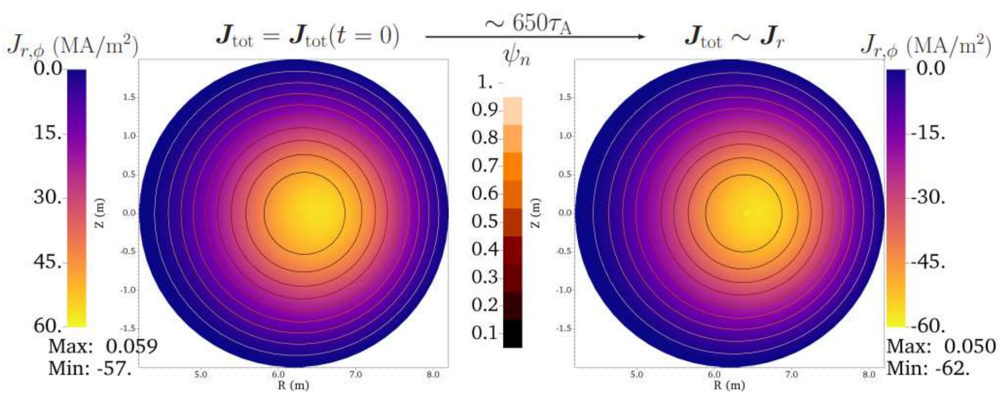
$$\rho_b \left( \frac{\partial \boldsymbol{u}_b}{\partial t} + \boldsymbol{u}_b \cdot \nabla \boldsymbol{u}_b \right) = (\boldsymbol{J} - \boldsymbol{J}_r) \times \boldsymbol{B} - \nabla p_b + \boldsymbol{S}_{\boldsymbol{u}_b}$$

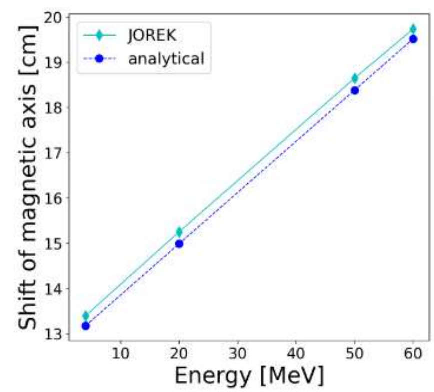
$$\frac{\partial p_b}{\partial t} + \boldsymbol{u}_b \cdot \nabla p_b + \Gamma p_b \nabla \cdot \boldsymbol{u}_b = (\Gamma - 1) \left( Q_b - \nabla \cdot \boldsymbol{h}_b + S_{p_b} \right)$$

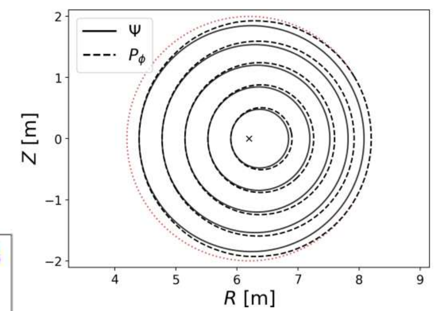
$$\boldsymbol{E} = -\boldsymbol{u}_b \times \boldsymbol{B} + \eta (\boldsymbol{J} - \boldsymbol{J}_r) - \frac{1}{\sigma_e} (\nabla p_e + \boldsymbol{S}_{\boldsymbol{u}_e})$$

# Self-consistent PiC model for REs in JOREK in development (2/2)

- First verification step: compare **shift of flux surfaces** due to curvature drift of REs with analytical estimate [Bandaru PoP 2023 (accepted)]




[Bergström TSDW 2023]

→ **Good match!**

→ Moving on to **3D tearing mode** simulations

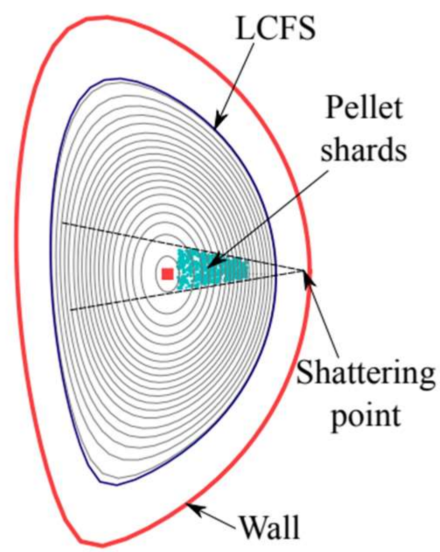
# Outline

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

# Predicting RE generation/avoidance in ITER with DREAM (1/5)

**Setup:**

[Vallhagen IAEA 2023]

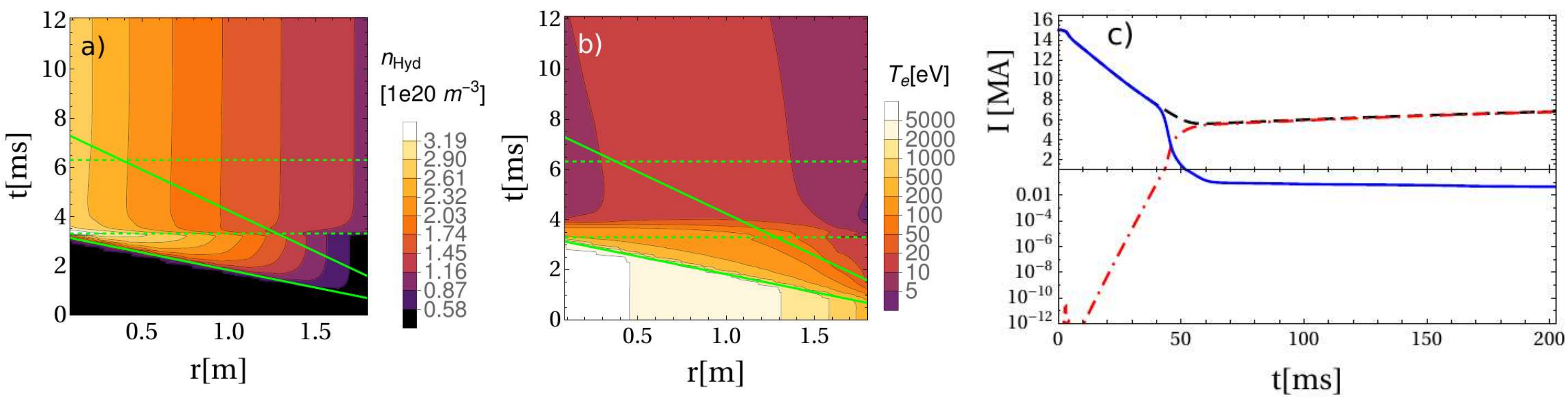



- **Wide range of scenarios**: H-mode / L-mode at 15 / 7.5 / 5 MA
  - With or w/o **nuclear seeds**
- **Single** Ne+H SPI or 2-stage (**'staggered'**) SPI (pure H then Ne+H)
  - Ne quantity adjusted so that 50 ms < $\tau_{CQ}$ < 150 ms
- Pellet ablation based on **Neutral Gas Shielding** model [Zhang NF 2022]
- Ad hoc **TQ model**
  - Tested 2 TQ onset criteria:
    - Ne shards @ q=2 ('early TQ')
    - $T_e$ < 10 eV anywhere inside q=2 ('late TQ') – Based on MHD argument (cold front)
  - **Rechester-Rosenbluth** heat transport; δB set so as to obtain a desired $\tau_{TQ}$ (1 or 3 ms)
  - Same δB used for RE transport
  - Strong particle mixing via large advection and diffusion coefficients

# Predicting RE generation/avoidance in ITER with DREAM (2/5)

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

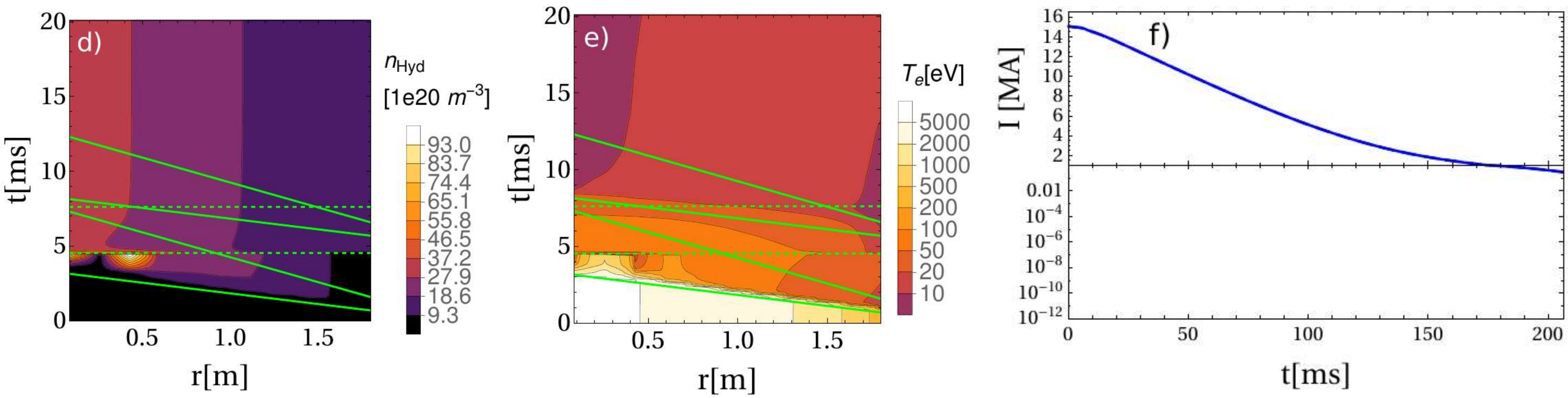
$\tau_{TQ}$ = 3 ms; $\tau_{CQ}$ = 100 ms; TQ onset criterion: late




- **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/avoidance in ITER with DREAM (3/5)

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

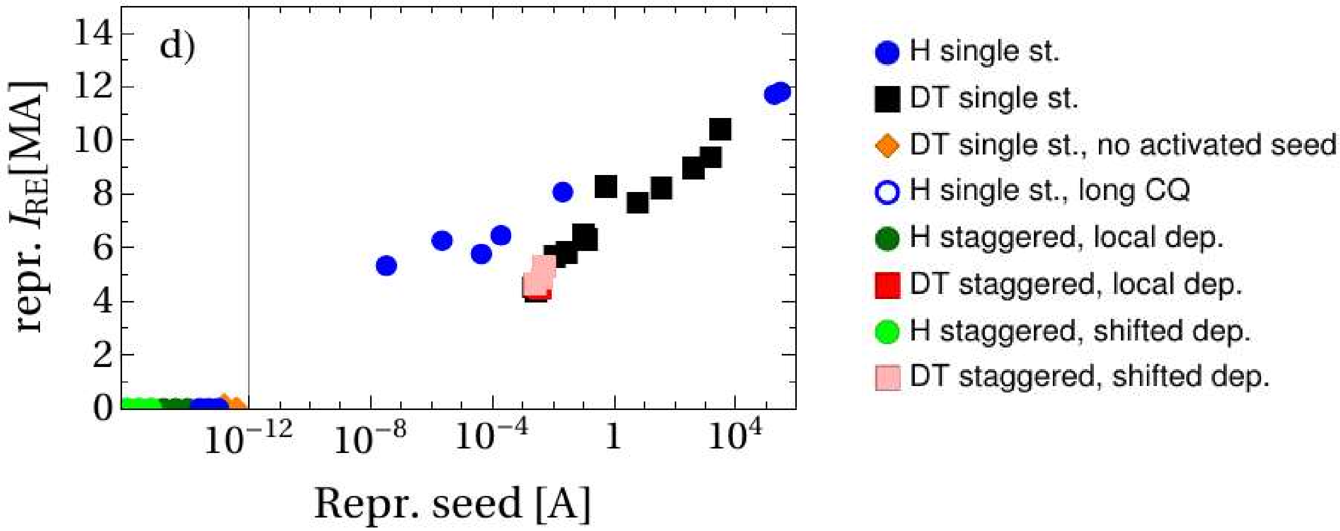



- More gradual cooling + larger rise in $n_e$ → **Negligible hot-tail** generation → **No RE beam**

# Predicting RE generation/avoidance in ITER with DREAM (4/5)

**Compilation of results for 15 MA L-mode ('H') and H-mode ('DT') scenarios**

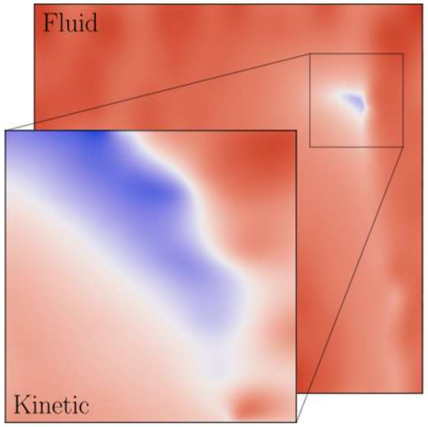
**Nuclear seeds**: off for 'H', on for 'DT'



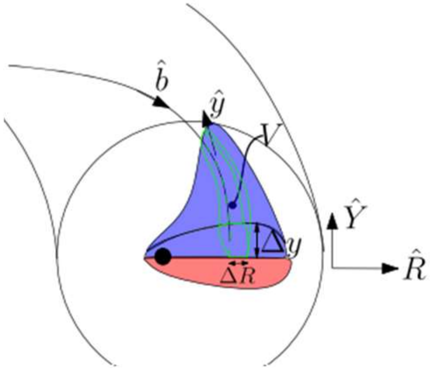

- **'H'** → **RE avoidance successful** for all staggered SPI cases and some single SPI cases
- **'DT'** → Because of **nuclear seeds**, **multi-MA beam** predicted for all cases
  - Indicative value of tolerable RE current: 150 kA [Lehnen TSDW 2021]

# Predicting RE generation/avoidance in ITER with DREAM (5/5)

- **Bayesian optimisation** with **different levels of precision** in DREAM [Ekmark REM 2023]
  - Fast scoping with RE fluid model, refinement with full kinetic model




- A possible issue with the staggered SPI scheme: strong **drift** towards LFS for **pure H ablation plasmoids**
  - May strongly reduce fueling efficiency
  - Model developed [Vallhagen JPP 2023], to be used in DREAM



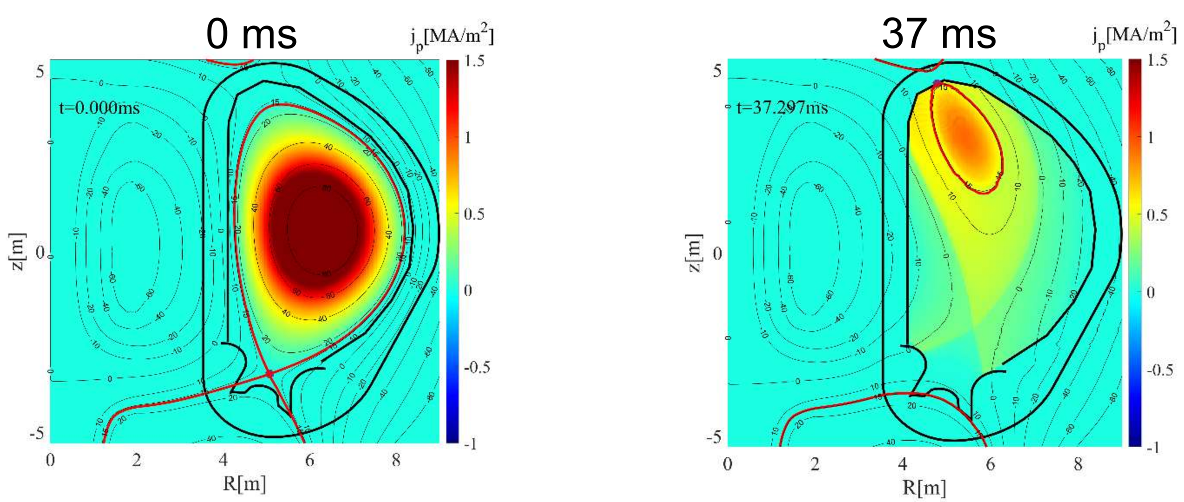
# Effect of vertical movement assessed with JOREK (1/2)

- DREAM simulations use a fixed plasma geometry
- In reality, the plasma is moving **as a result of the $I_p$ decay**
- Part of $I_p$ becomes **halo current**

**<u>JOREK 2D simulation for 15 MA ITER case</u>**

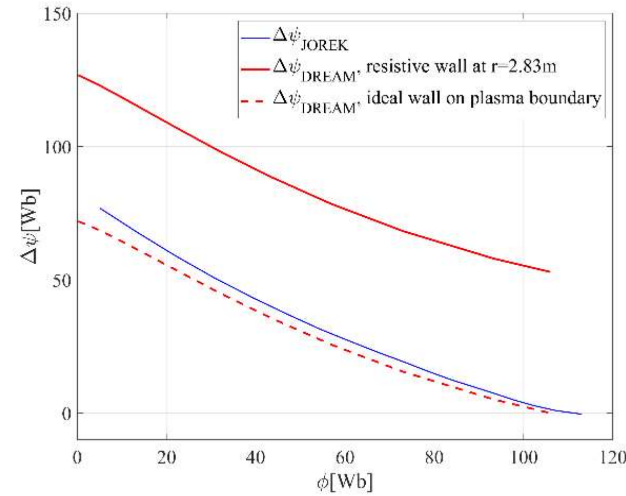
(Simple model for Ne+H injection and TQ)

[Wang REM 2023]



# Effect of vertical movement assessed with JOREK (2/2)

- REEs are ~ tied to **toroidal flux (Φ)** surfaces [Boozer PoP 2015]
- On each Φ surface, $\log(G_{av}) \sim \Delta\psi$ → **$\Delta\psi(\Phi)$ profile** is key
  - $\Delta\psi$ to be taken between t=0 and moment when surface becomes LCFS
- JOREK simulations find that **$\psi_{LCFS}$ remains ≈ constant**
  - Related to ~ ideal behaviour of the wall on this timescale




- In contrast, in DREAM simulations, **$\psi_{LCFS}$ decreases in time → larger $\Delta\psi$**

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

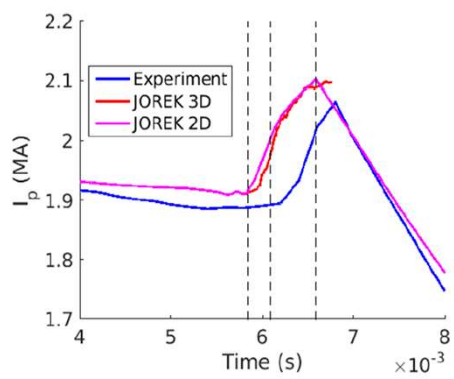
- Impact unclear ($G_{av}$ remains very large) → **Under investigation** both with DREAM and JOREK

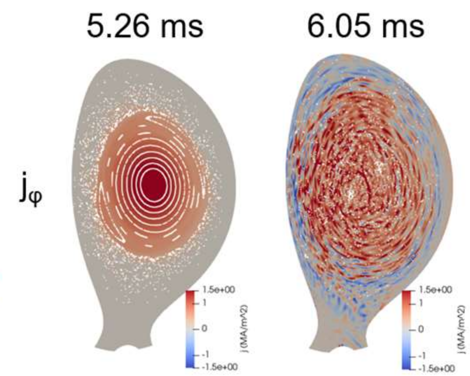
# Electron losses due to 3D MHD studied with JOREK

- Hot-tail seed losses during or shortly after TQ? RE losses during CQ?

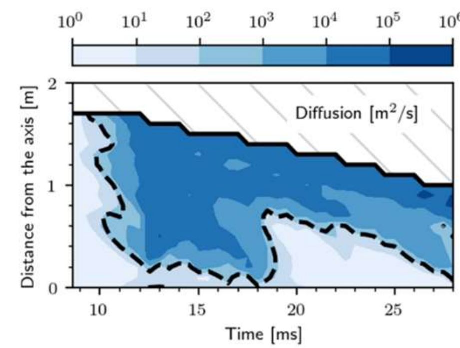
→ **Validate** 3D JOREK disruption simulations, **understand dynamics of stochasticity**

- JOREK simulation of JET Ar MGI reproduces **$I_p$ spike** and supports its link with stochasticity [Nardon NF 2023]




- 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

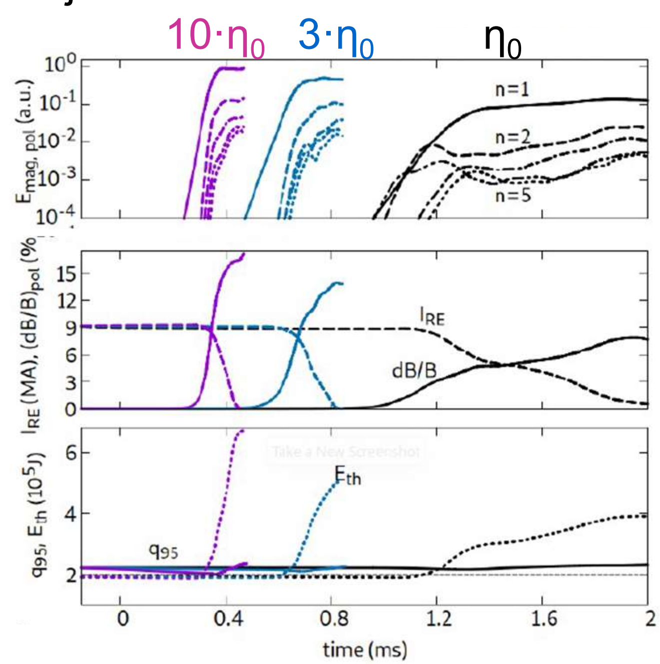
# Outline

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

# RE beam termination studied with JOREK (1/3)

- 2 possible processes involved in RE beam termination (depending on $q_{95}$ evolution):
  - 1) **Axisymmetric scrape-off** as beam moves into the wall
  - 2) 'Sudden' losses due to **3D MHD instability** ← **Our focus**

- Key experimental finding: **benign RE termination** after H injection into beam associated to **fast and large MHD instability** [Paz-Soldan NF 2021]



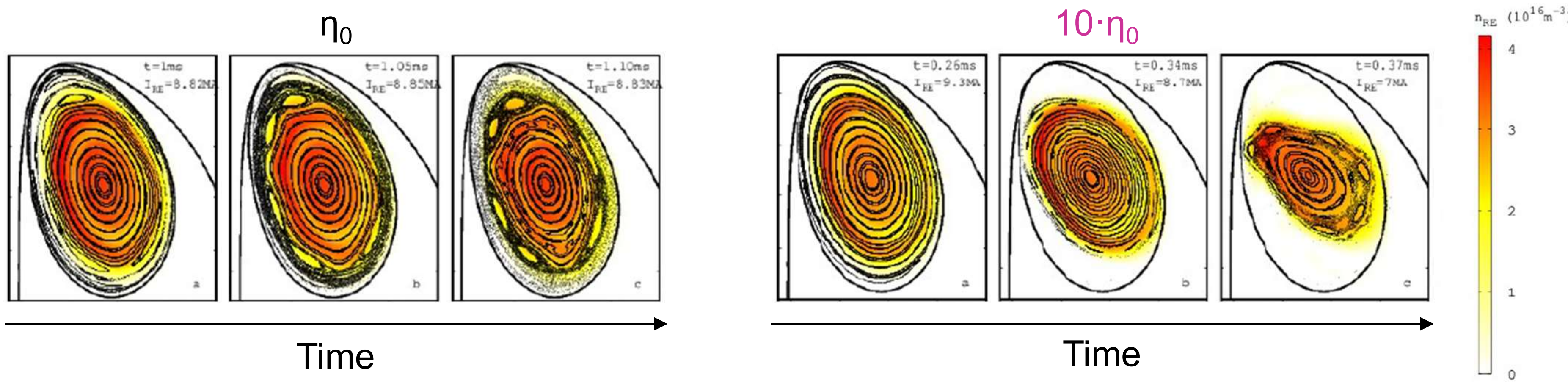

**<u>JOREK 2D → 3D ITER simulations</u>** [Bandaru in prep.]

- Intentional generation of a large (9 MA) beam

- No explicit model for H injection yet but studied effect of background plasma resistivity (η)
  - H injection is thought to increase η

→ **MHD grows faster and larger at higher η**
  - Qualitatively consistent with observations

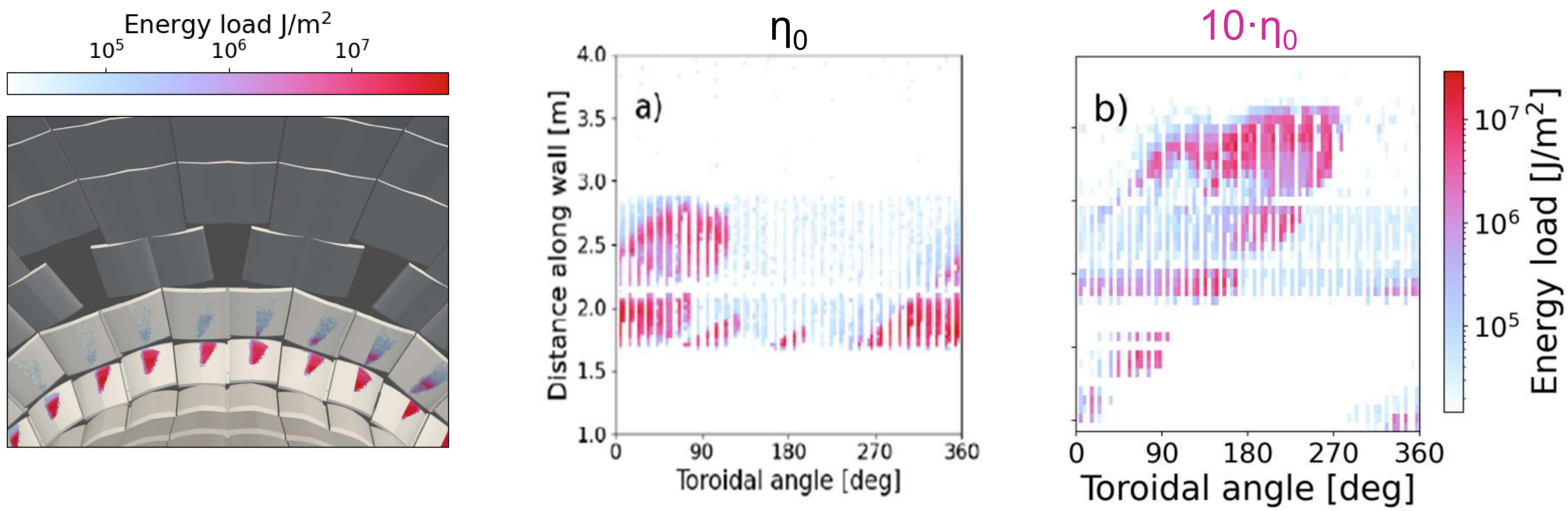
# RE beam termination studied with JOREK (2/3)




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

# RE beam termination studied with JOREK (3/3)

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



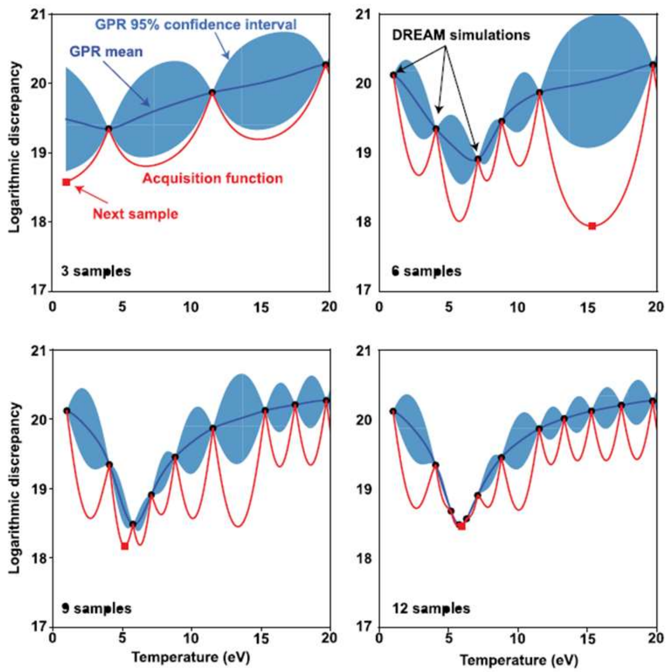

→ Losses follow a helical pattern which is more spread at larger η
→ Smaller averaged heat load at larger η (but peak value similar)

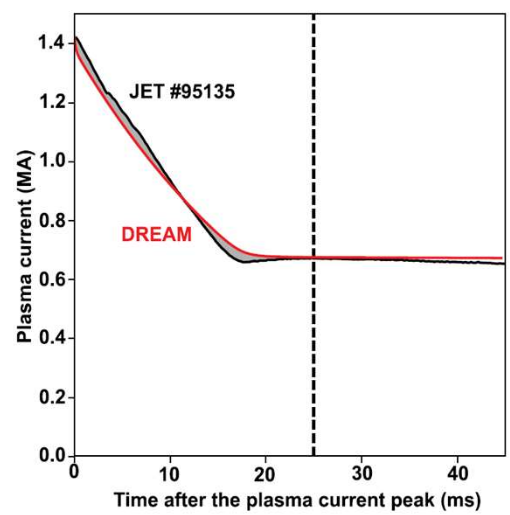
# Outline

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

# Validation of avalanche model with DREAM and JOREK (1/2)

- **Bayesian optimisation framework** applied to DREAM simulations of RE generation by Ar massive gas injection in JET #95135 [Järvinen JPP 2022]
  - Adjusts input parameters to get best possible match to experimental data

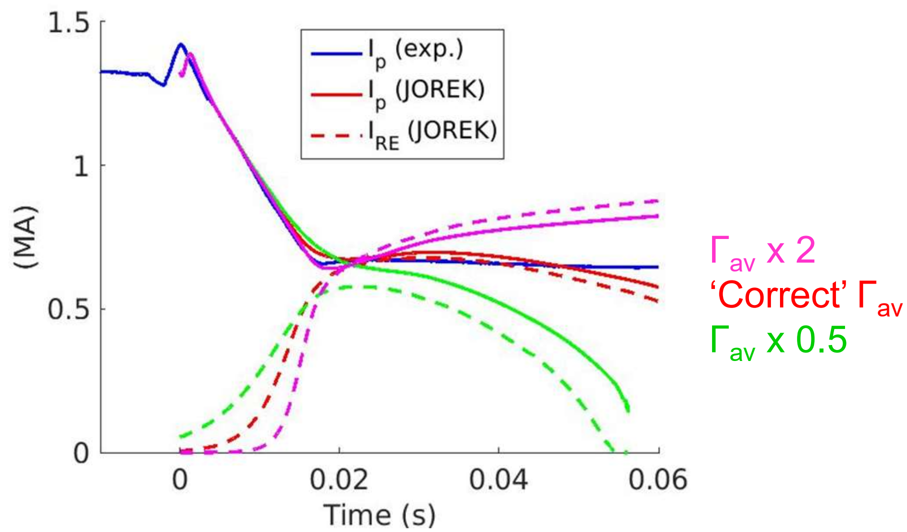



  - Now including 2D synchrotron radiation images using SOFT [Järvinen IAEA 2023]

# Validation of avalanche model with DREAM and JOREK (2/2)

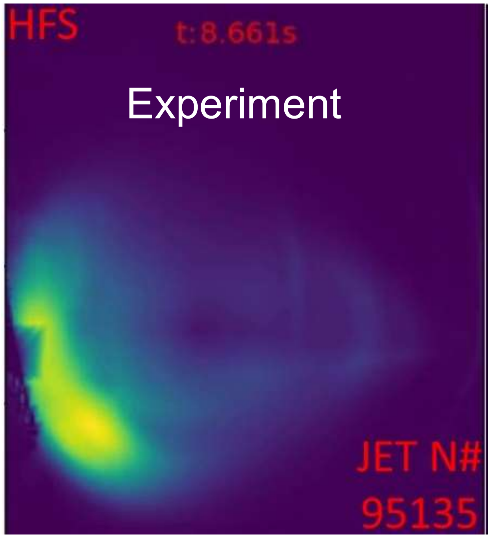
- Same case studied with JOREK RE fluid model [Nardon REM 2023]
- Input parameters adjusted by hand
  - $n_{Ar} \leftrightarrow dI_p/dt$ in early CQ
  - RE seed $\leftrightarrow I_{RE}$@plateau
- **Validation or fancy fit?** → Test by **falsifying** the avalanche gain $\Gamma_{av}$
  - Parameters adjusted for each case to get best possible match

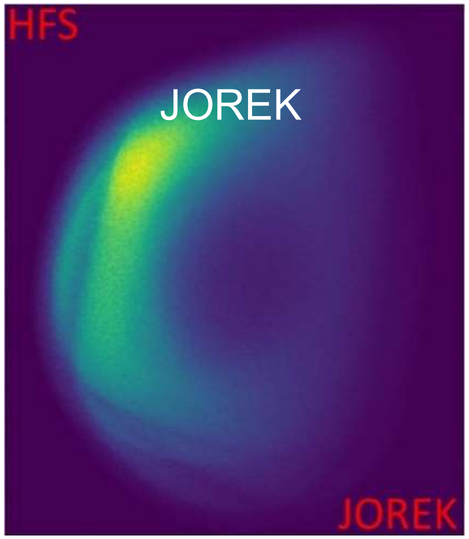



→ Correct $\Gamma_{av}$ gives best agreement → Looks like **validation** ☺
  - Plan to use Bayesian optimization framework for an objective assessment

## Validation of RE beam (benign) termination modelling with JOREK

- Validation underway on JET #95135 (benign termination after D SPI) with the RE fluid model
  - Building on [Bandaru PPCF 2021] [Nardon PoP 2023]
  - Synthetic synchrotron radiation diagnostic developed and applied [Sommariva EPS 2023]
    - Shows magnetic islands



# Outline

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

# Many other activities…

- Related to **other WPs (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]

# Outline

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

# Conclusion

- TSVV 9 and collaborators are busy on several fronts: **development, validation, predictions**, …
- Main current development: **PiC model in JOREK**
- DREAM and JOREK **validation** underway on **JET, ASDEX Upgrade and TCV** for both generation and termination of RE beams, using **synthetic diagnostics** and **Bayesian optimisation** framework
- Predictions: main focus is currently on **ITER**
  - DREAM predicts **negligible beam with appropriate SPI settings** at 15 MA **w/o nuclear seeds**
  - DREAM predicts **multi-MA beam** whatever the SPI settings at 15 MA **with nuclear seeds**
  - **$G_{av}$ overestimated** in DREAM due to ignoring vertical motion, but **impact unclear**
  - **Hot-tail seed** uncertain → Will be investigated with JOREK
  - **γ flux** from activated wall uncertain (especially from W wall)
  - RE beam **termination** is being studied with JOREK (up to now at $I_{RE}$ = 9 MA)
    - Need to model cases with **smaller $I_{RE}$**
    - Need to push modelling of **mitigation by H SPI** into the beam (recombination, Ne 'purge', …)
  - Also supporting other future machines (**EU-DEMO, SPARC, STEP, DTT**, …)
- Contact: eric.nardon@cea.fr