Exploration of mitigation systems for disruption generated Runaway Electrons in a STEP concept

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Introduction

- A significant threat is posed by the formation of relativistic Runaway Electrons (**RE**) during disruptions in the Spherical Tokamak for Energy Production (**STEP**)[1]
- Disruption induced RE beams have been observed to cause critical damage to the Plasma Facing Components structures (**PFC's**) on low megampere devices such as JET[2]
- Disruptions have been simulated using the advanced DREAM code[3] in a STEP preferred concept with a predicted operating current of > 20 MA
- Unmitigated scenarios see the generation of a no less than 10 MA RE beam. An impact of this beam would exceed the predicted first wall structural integrity limits and cause terminal damage to the PFC's which will need replacing[4]

DREAM

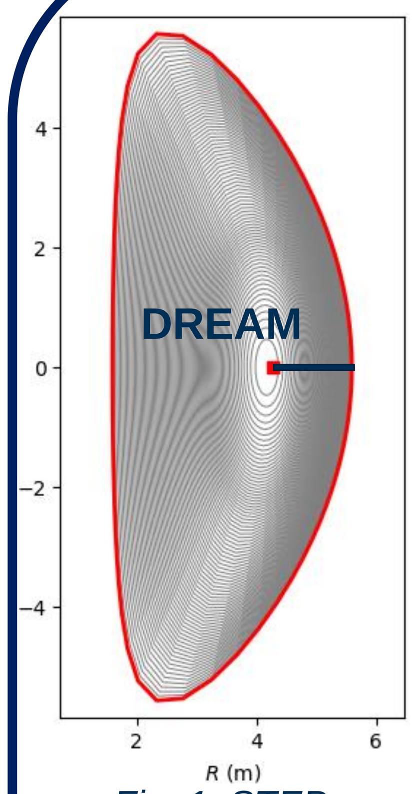


Fig. 1: STEP equilibrium modelled in DREAM, shaping effects included

- **D**isruption & **R**unaway **E**lectron **A**nalysis **M**odel
- State of the art flux-surface averaged 1-D code
- Advanced RE generation rates: Dreicer, Hot-tail, Tritium decay, Compton Scattering & Avalanche mechanisms

DREAM STEP inputs:

1. **FIESTA** Free-boundary equilibrium
2. **JETTO** Plasma profiles
3. **STEP** DMS specifications

STEP

STEP Key Parameters[1]

- I_p = 21 MA
- B_T = 3.2 T
- $T_{e,0}$ = 20 keV
- R_{geo} = 3.6 m
- A = 1.8 m
- $\kappa \sim 3$
- $P_{aux} \sim 150$ MW
- P_{fus} = 1.8 GW
- $n_{e,0} \sim 1.4\times10^{20}$ m^{-3}
- W_{th} = 520 MJ

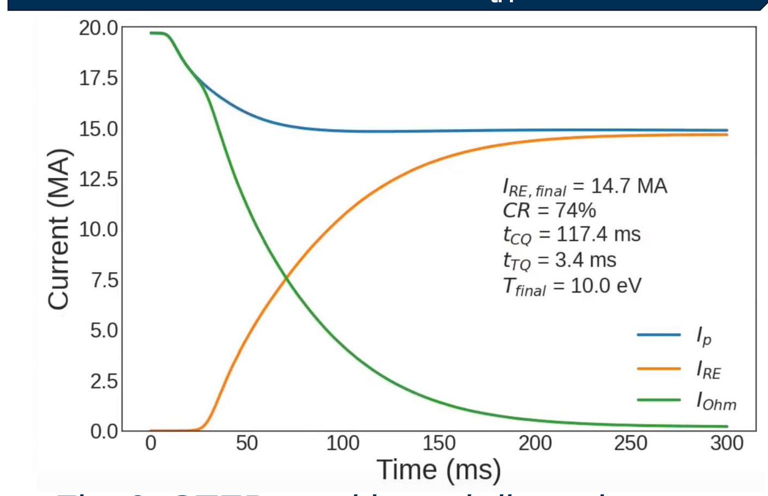


Fig. 2: STEP unmitigated disruption case

Idealized Impurity Injection

- Runaway Electron avoidance was tested using an Idealized (radially flat) Impurity Injection model with a Ne/Ar and D_2 mixture
- Radial electron transport due to field line disruption is imposed with $D \propto (\delta B/B)^2$
- Transport is activated during a prescribed Thermal Quench time with a self consistent Temperature & Electric field evolution
- Hot-Tail RE generation dominates the primary mechanisms with a very high Avalanche factor for the secondary generation mechanism

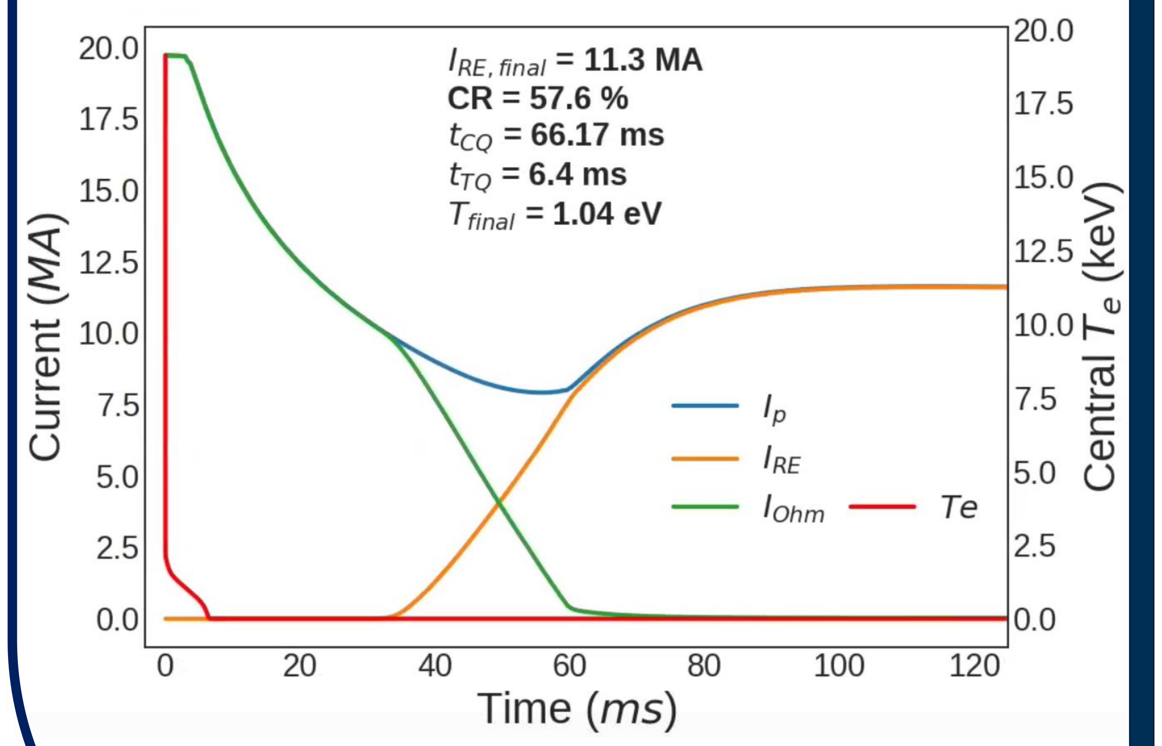


Fig. 3: Typical STEP idealized impurity injection DMS simulation: $n_{Ar} = 1\times10^{19}$ m^{-3}, $n_{D2} = 1\times10^{21}$ m^{-3}, and a magnetic perturbation of $\delta B/B = 2\times10^{-3}$

Impurity Injection Scan

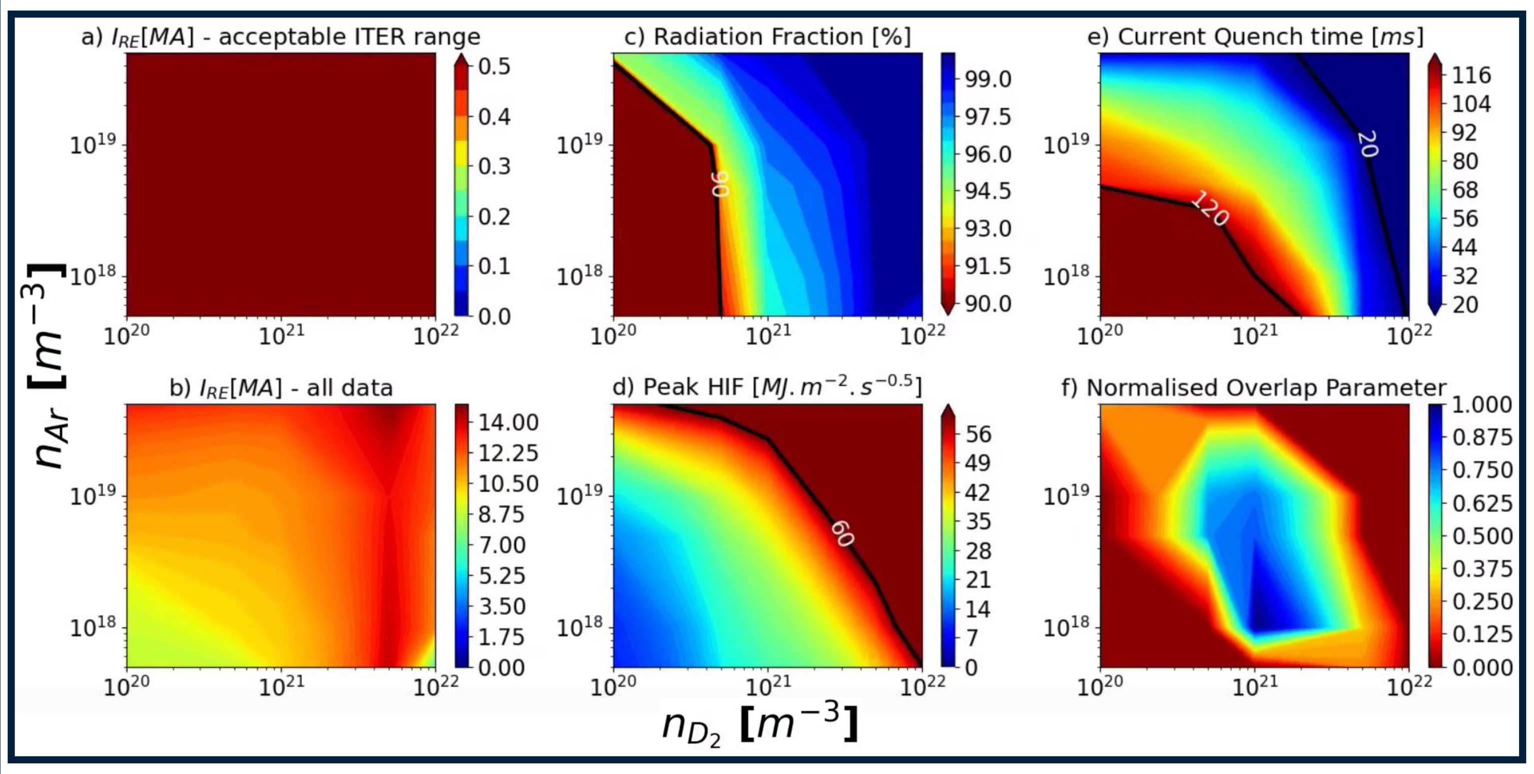


*Fig.4: Idealized impurity injection of Ar+D_2 with a magnetic perturbation $\delta B/B = 2\times10^{-3}$ scan. Key DMS constraints are graphed against the varying injected impurity densities. Plot **f)** combines the constraints displaying a possible operating window for the DMS (excluding RE current)*

Scans over multiple parameters:

1. Impurities: Ne + D_2 or Ar + D_2
2. Transport coefficients: $\delta B/B$ = 2&6 x10^{-3}
3. Impurity Densities: $10^{17} \leq n_{imp} \leq 10^{22}$ m^{-3}

DMS constraints

- $I_{RE} < 0.5$ MA
- $f_{rad} > 90\%$
- $20 \leq t_{CQ} \leq 120$ ms
- $HIF_{peak} < 60$ MJ.m^{-2}.s$^{-0.5}$

- **NO** scenario found with a $I_{RE} < 7$ MA
- Possible operating windows which satisfy other DMS constraints
- Neon marginally outperforms Argon in final RE current reduction
- Assumed transport coefficients are generous and uniform spatially + temporally for ideal case modelling (unrealistic)
- Overall, Idealized Impurity Injection is insufficient for runaway electron avoidance in STEP

Runaway Electron Mitigation Coil

- Effects of a Runaway Electron Mitigation Coil (**REMC**) were explored with DREAM
- REMC's, like that planned for SPARC[5], disrupt the fluxes surfaces within the plasma via external magnetic perturbations, increasing RE transport
- Within DREAM, this is modelled by imposing extra radial electron transport during the decay of the ohmic current
- Significant RE generation suppression was seen in the REMC simulations
- However, amplitude of δB/B is unknown and will vary radially (lower in the core). As such, this is an optimistic scenario

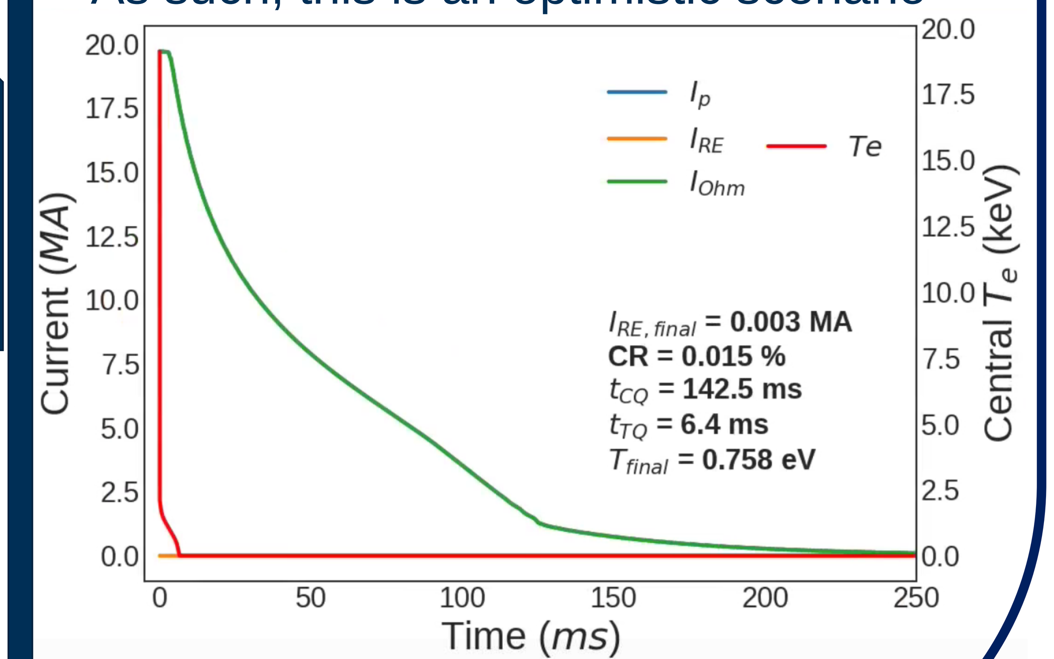


Fig. 5: Fig 3 simulation, altered with extra $\delta B/B = 1\times10^{-3}$ at 20ms, throughout the current quench

Shattered Pellet Injection

Multi-stage, synchronised, SPIs for loads mitigation:

1. **RE Avoidance Inj.** – Pure D_2 from HFS, 12 Injectors
2. **TQ/CQ inj.** – Argon + D_2, LFS at 4 toroidal locations (15 inj.)
3. **RE Mitigation inj.** – Pure D_2 in RE beam, 30 Injectors

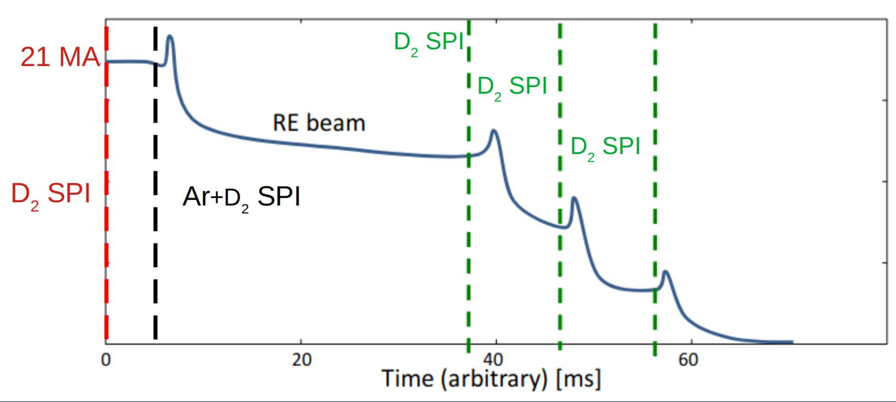
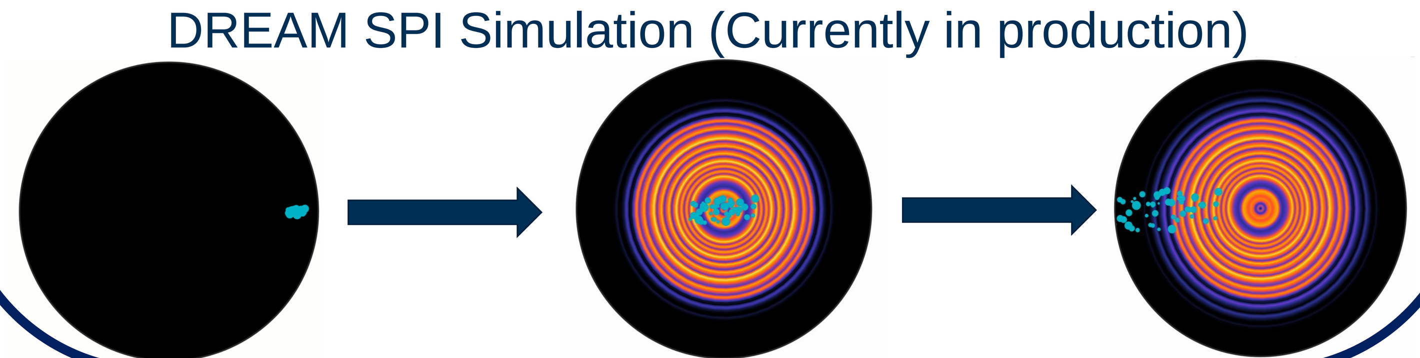


Fig. 6: Multiple staged SPI, using Ar and D_2 is STEP current disruption mitigation strategy

DREAM SPI Simulation (Currently in production)



Conclusions

- Utilizing the sophisticated DREAM code, detailed simulations can be explored for future devices such as STEP and ITER.
- Current research, conducted for STEP's latest concept, shows total runaway electron avoidance can't be achieved in a high current, reactor-grade fusion plasma.
- Novel REMC simulations provide a potential complementary DMS for STEP, offering more promising RE mitigation. With this alternate DMS, many technical, scientific and engineering challenges would have to be overcome before the system could be deemed a viable solution.
- At present, STEP is planned to have ~ 30 D_2 SPI systems for RE beam mitigation. While the capabilities of SPI systems have been verified on other fusion devices e.g. JET[6], it is paramount research is conducted on DREAM and more comprehensive codes e.g. JOREK, to validate the proficiency of an SPI system for RE mitigation in a fusion device such as STEP.

[1] MEYER, H. et al., "The Physics of the Preferred Plasma Scenario for STEP", EPS Conference on Plasma Physics, (2022)
[2] REUX, C. et al., "Runaway electron beam generation and mitigation during disruptions at JET-ILW",Nuclear Fusion 55 093013 (2015)
[3] HOPPE, M. et al., "DREAM: A fluid-kinetic framework for tokamak disruption runaway electron simulations",Comp. Phys. Comm. 268 108098 (2021)
[4] CHEN, L. et al. "Modelling runaway electron induced damage to ITER plasma-facing components", Asia-Pacific Plasma Physics Conference (2021)
[5] IZZO, V. A. et al., "Runaway electron deconfinement in SPARC and DIII-D by a passive 3D coil", Nucl. Fusion 62 096029 (2022)
[6] REUX, C. et al., "Physics of runaway electrons with shattered pellet injection at JET", Plasma Phys. Control. Fusion 64 034002 (2022)

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