CHALMERS
UNIVERSITY OF TECHNOLOGY

Modelling runaway electrons

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EUROfusion

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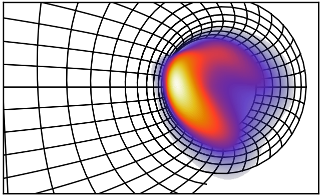
Outline

- Runaway generation
- Disruption mitigation
  - STEP
  - ITER
- Synthetic diagnostics and model validation
- Start-up runaways



Runaway generation

Disruption mitigation
- STEP
- ITER

Synthetic diagnostics and model validation

Start-up runaways

Dreicer seed

- Momentum space diffusion feeds the runaway region with electrons

$$\left(\frac{dn_r}{dt}\right)^{\mathrm{Dreicer}} = k n_e \hat{\nu}_{ee} \left(\frac{E_D}{E_\|}\right)^{3/8} \mathrm{e}^{-E_D/4E_\| - \sqrt{2E_D/E_\|}}$$

where $E_D/E_c = m_e c^2/T$.

[Connor and Hastie, 1975]

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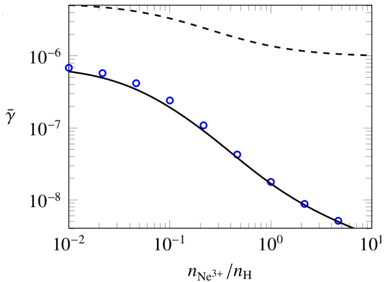
- In the presence of weakly ionized impurities: neural network (NN) trained on large database of kinetic simulations

[Hesslow JPP 2019]

Dreicer growth rate obtained by NN (solid), kinetic simulations (blue circles) and the Connor-Hastie formula (dashed)



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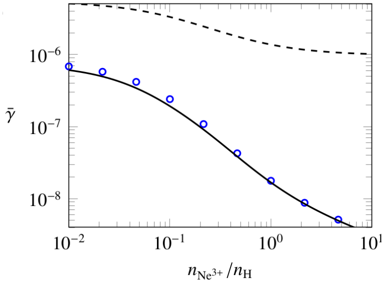
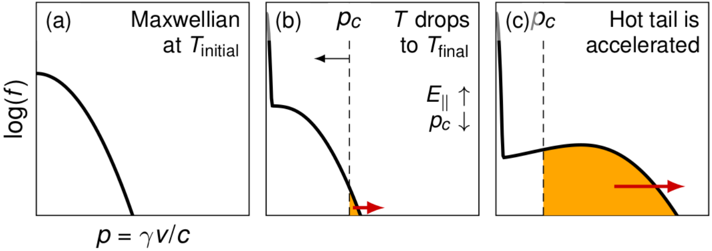
- Avoid using NNs outside their training range!



Hot-tail seed



- In case of sudden cooling an elevated tail of the distribution can run away

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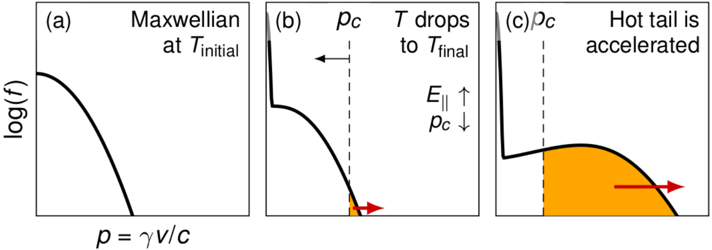

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- Slow electrons cooled down almost instantly (thin peak close to $p = 0$); electrons with higher velocity take longer to cool down

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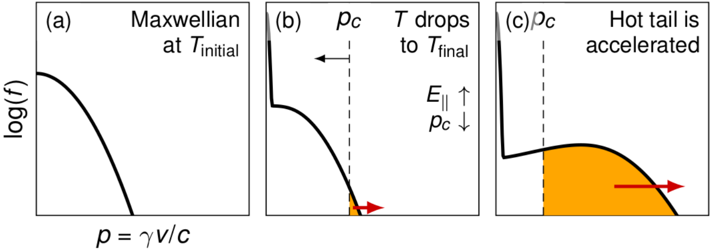

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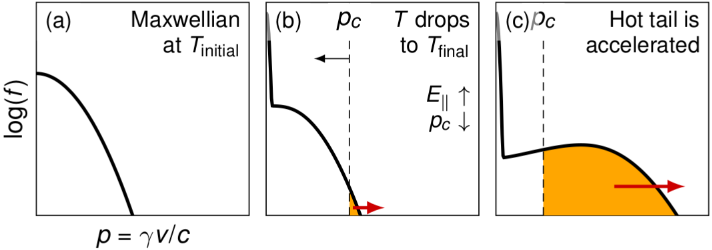

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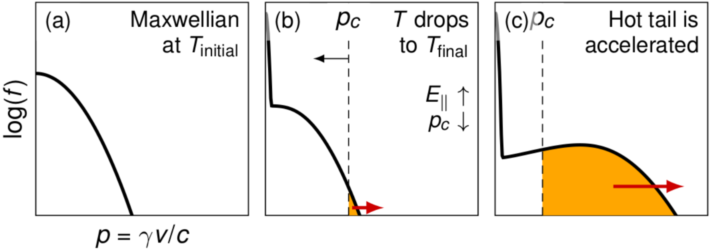

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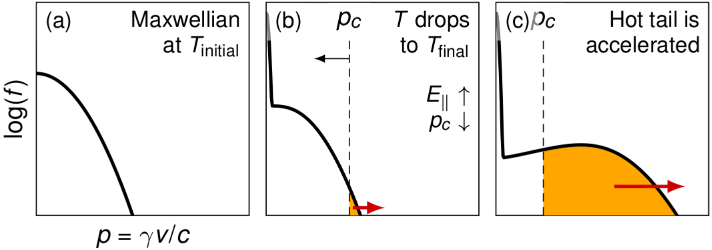

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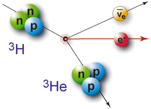
- Dominates over Dreicer generation if the cooling timescale is shorter than the collision time at the critical velocity

Tritium seed

- Tritium undergoes beta-decay generating fast electrons according to a continuous energy spectrum, part of which may be in the runaway region



$$\left(\frac{\partial n_{\mathrm{RE}}}{\partial t}\right)^{\mathrm{tritium}} = \ln\left(2\right)\frac{n_{\mathrm{T}}}{\tau_{\mathrm{T}}} f\left(W_{\mathrm{crit}}\right)$$

  - n_{T} is the tritium density
  - $\tau_{\mathrm{T}} \approx 4500$ days is the half-life of tritium
  - $f\left(W_{\mathrm{crit}}\right)$ is fraction of the electron spectrum above the critical runaway energy W_{crit}

$$f(W_{\mathrm{crit}}) = 1 - \frac{35}{8}\left(\frac{W_{\mathrm{crit}}}{Q}\right)^{3/2} + \frac{21}{4}\left(\frac{W_{\mathrm{crit}}}{Q}\right)^{5/2} - \frac{15}{8}\left(\frac{W_{\mathrm{crit}}}{Q}\right)^{7/2},$$

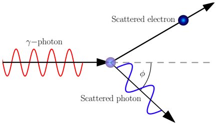
where $Q = 18.6\,\mathrm{keV}$ is the tritium decay energy

Compton seed

- In DT operation γ-photons emitted by the activated walls Compton scatter electrons to runaway region

$$\left(\frac{\partial n_{\mathsf{RE}}}{\partial t}\right)^{\gamma} = n_e \int \Gamma_\gamma(E_\gamma)\sigma(E_\gamma)dE_\gamma$$

- The energy of the γ-photons is much larger than the ionization potential for all species present in the plasma → both bound and free electrons can become runaways
- Compton seed **increases** with impurity content, due to the increased number of target electrons available for Compton scattering



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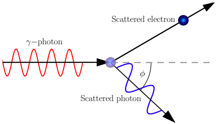

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  - Radiation transport calculations → gamma flux energy spectrum in ITER

    [Martin-Solis *et al*, NF 2017]

$$\Gamma_\gamma(E_\gamma) \propto \exp\left(-\exp\left(z\right) - z + 1\right) \;\; \text{with} \;\; z = \left[\ln\left(E_\gamma(\mathrm{MeV})\right) + 1.2\right]/0.8$$

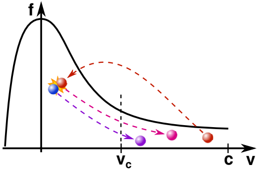
Details of the spectra will depend on the final configuration of the first wall and blanket

  - Photon flux from tungsten wall is much larger than from beryllium wall

    [Reali et al, PRX Energy 2023]

Secondary generation mechanism: avalanche

In close Coulomb collisions existing runaways can throw thermal electrons above the runaway threshold → exponential growth of runaways!



- Growth rate of runaway current due to avalanche proportional to toroidal electric field

$$\gamma_{RA} = \frac{1}{j_{RA}} \frac{dj_{RA}}{dt} \simeq \frac{eE}{2m_e c \ln \Lambda}$$

[Rosenbluth and Putvinski, 1997]

- During the disruption the electric field is produced by the decay of the plasma current
- Total number of e-folds during an avalanche can be estimated as

$$\gamma_{RA} t \simeq \frac{eEt}{2m_e c \ln \Lambda} \simeq \frac{I_p}{I_A \ln \Lambda}$$

where $I_A = 0.017\,\mathrm{MA}$.

- Present machines with plasma currents around 1 MA avalanche multiplication $\sim e^2$
- Avalanche multiplication in ITER $\sim e^{50}$

Effect of partial screening

- Avalanche growth rate sensitive to the effect of *partial screening*, i.e. the extent to which fast electrons can penetrate the bound electron cloud around the impurity ion

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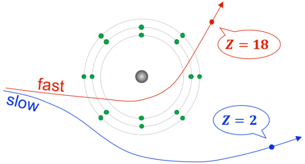

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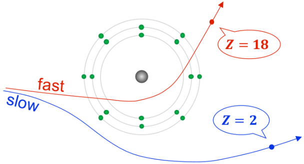

Stronger avalanching in the presence of weakly ionized atoms

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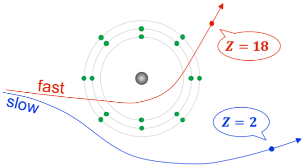

Stronger avalanching in the presence of weakly ionized atoms

- Increased number of target electrons available for avalanche is only partially compensated by the increased friction force [Hesslow et al, NF 2019]

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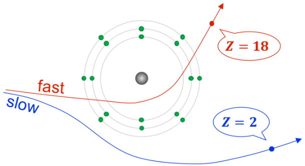

Stronger avalanching in the presence of weakly ionized atoms

- Increased number of target electrons available for avalanche is only partially compensated by the increased friction force [Hesslow et al, NF 2019]
- Growth rate $\propto E_{\|}^{3/2}$, a scaling predicted also for runaway breakdown in air [Gurevich & Zybin, Phys.-Usp. 2001]

Radiation reaction forces

Synchrotron:

- Emitted by runaways due to gyromotion, $P_{\text{tot}} \propto p_\perp^2$

Bremsstrahlung:

- Emitted in inelastic collision between runaways and bulk particles

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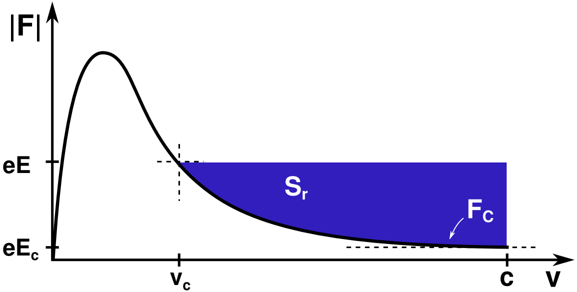

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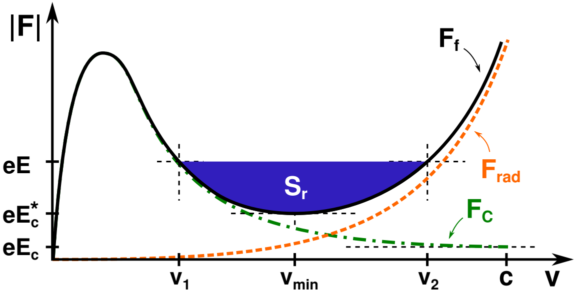


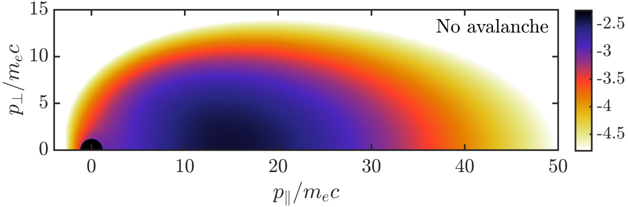
- Critical field for runaway is now E_c^* $(> E_c)$

[Hesslow et al, PPCF (2018)]

Modelling of runaway momentum dynamics

Solve the kinetic equation for the electron distribution function:

$$\frac{\partial f}{\partial t} + \underbrace{E_\parallel \frac{\partial f}{\partial p_\parallel}}_{\text{acceleration}} + \underbrace{\frac{\partial}{\partial \boldsymbol{p}} \cdot (\boldsymbol{F}_{\mathsf{RR}} f)}_{\text{radiation-reaction}} = \underbrace{C_e[f]}_{\text{collisions}} + \underbrace{C_{\mathsf{knock\text{-}on}}[f]}_{\text{avalanche}} + \underbrace{C_{\mathsf{brems}}[f]}_{\text{Bremsstrahlung}}$$



Normalized momentum distribution $\log_{10} f$ for $n_e = 10^{20}\ \mathrm{m}^3$, $T_e = 1\ \mathrm{keV}$, $Z_{\mathrm{eff}} = 5$, $B = 1.8\ \mathrm{T}$

Runaway generation

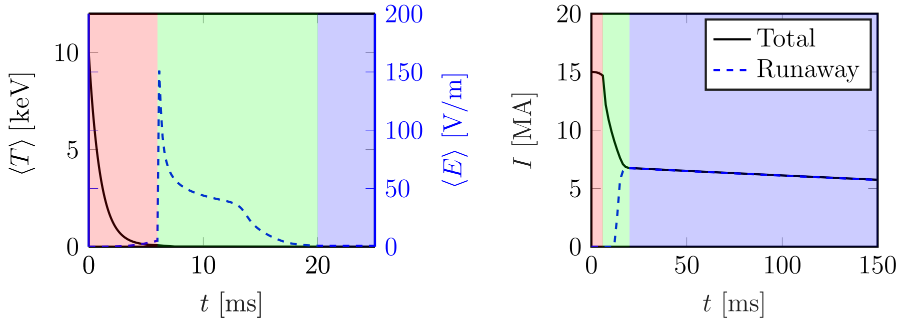
Disruption mitigation

- STEP
- ITER

Synthetic diagnostics and model validation

Start-up runaways

- Partial loss of magnetic confinement and release of stored thermal energy
- Plasma cools quickly (thermal quench, TQ)
- Resistivity rises catastrophically → difficult to drive the current
- High electric field is induced (current quench, CQ)
- Plasma current is partly replaced by a current of runaway electrons
- Electrons are accelerated to tens of MeV, can cause substantial damage



[Data adapted from Vallhagen JPP 2020]

Disruption mitigation

- Reduce thermal loads and avoid forces associated with eddy currents and halo currents
  - 90% of thermal energy radiated
  - current quench time within reasonable limits ($50\,\mathrm{ms} < \tau_{\mathrm{CQ}} < 150\,\mathrm{ms}$)
  - low runaway currents ($I_{\mathrm{RE}}^{\max} < 150\,\mathrm{kA}$) [Lehnen et al, IAEA-TSDW 2021]

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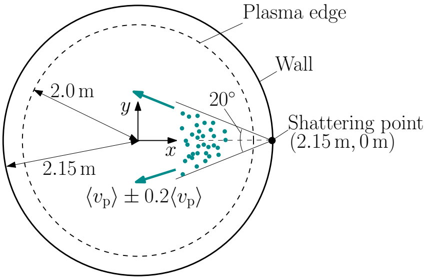
- Material injection
  - e.g. shattered pellet injection (SPI)



[Vallhagen et al, NF 2022]

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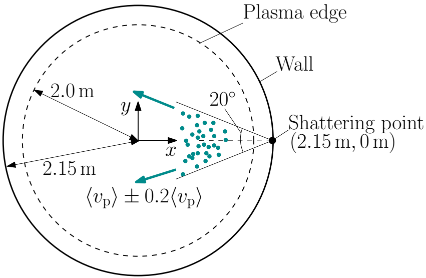
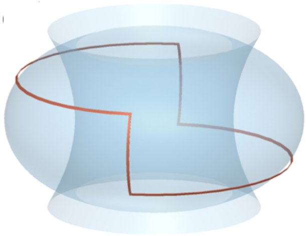


[Vallhagen et al, NF 2022]

- Magnetic perturbations
  - e.g. generated by passive conducting structures driven by the voltage induced during the disruptions

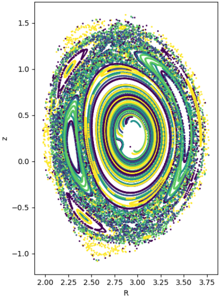


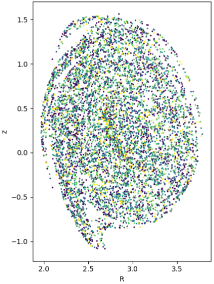
[Sweeney et al, JPP 2020]

[Tinguely et al, NF 2021, PPCF 2023, Izzo et al, NF 2022]

Topology of magnetic field is modified during the TQ

- Figures: Poincare maps of the perturbed magnetic field in a JET disruption induced by argon injection
  - Timeslices correspond to 1.9 ms (upper figure) and 2.5 ms (lower figure) after the argon injection
  - Simulations performed by E Nardon, CEA, with the JOREK code
  - Flux-surfaces re-heal after the TQ
- Energy loss:
  - radial transport due to MHD instabilities
  - line radiation due to impurity influx
- MHD-induced energy loss likely to dominate in the initial part of TQ
- Hot-tail generation is efficient in the early phase of the disruption
- Part of the hot-tail is lost due to the breakup of the magnetic surfaces during the TQ

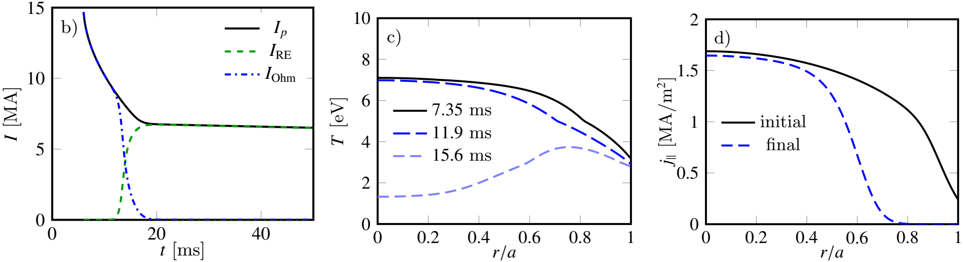




[Särkimäki et al, NF 2020]

Pure neon injection: $n_{\mathrm{Ne}} = 10^{20}\,\mathrm{m}^{-3}$

- ITER-like current quench with material injection
- DT plasma with initial plasma current $I_0 = 15\,\mathrm{MA}$, $j(r) = j_0\left[1-(r/a)^2\right]^{0.41}$
- $n_e = 10^{20}\,\mathrm{m}^{-3}$, flat
- $T_0 = 20\,\mathrm{keV}\left[1-(r/a)^2\right]$, T_f flat
- Injected material uniformly distributed at the beginning of the simulation



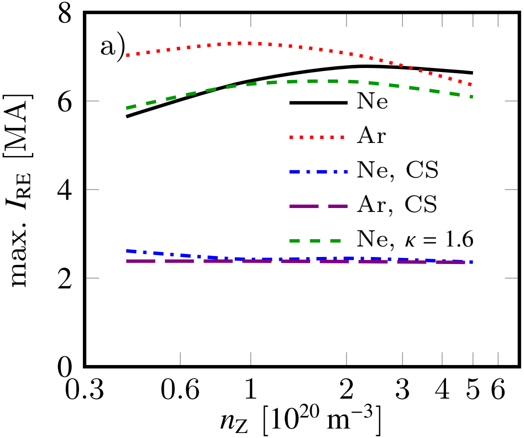
[Vallhagen *et al*, JPP (2020)]

Maximum runaway current as function of injected noble gas density

- Two models for avalanche generation:
    - with partial screening

      [Hesslow *et al*, NF (2019)]
    - with complete screening (CS): assuming that the electron interacts only with the net ion charge

      [Rosenbluth and Putvinski, NF (1997)]
- Effect of partial screening increases the final runaway current for both argon and neon injections



[Vallhagen *et al*, JPP (2020)]

Effect of magnetic perturbations

- Radial losses reduce the number of runaway electrons participating in the avalanche → can reduce the growth rate of the exponentiation
- Take advantage of the separation of the time-scales [Helander et al, PP 2000]
- Generalized calculation, includes radiation and momentum-space-dependent diffusion [Svensson et al, JPP 2021]
  - Assume rapid pitch-angle dynamics → solve for the pitch angle distribution
  - Integrate the kinetic equation over pitch-angle → reduced kinetic equation
  - Find lowest-order solution, neglecting transport and radiation effects. Use this to evaluate the transport term to next order
  - Integrate over momentum to find the runaway density
  - Couple with the evolution of the electric field

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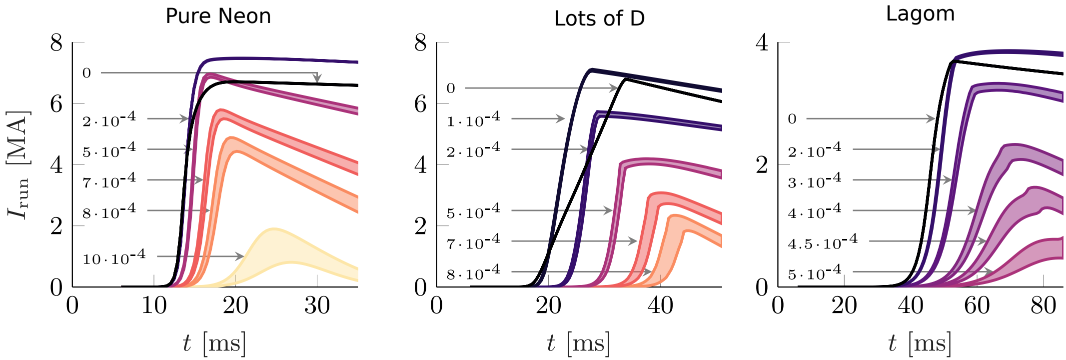
Use a momentum-space dependent diffusion coefficient

$$D(p) \propto (\delta B/B)^2 \, \frac{p}{1+p^2}$$

and calculate the runaway current for ITER-like current quench with material injection

Runaway current with material injection and magnetic perturbations



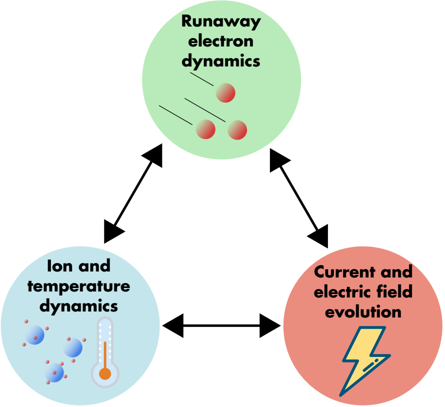
- Pure Ne: $n_{\mathrm{Ne}} = 10^{20}\,\mathrm{m}^{-3}$;
- Lots of D: $n_{\mathrm{Ne}} = 8 \times 10^{18}\,\mathrm{m}^{-3}$, $n_{\mathrm{D}} = 4 \times 10^{21}\,\mathrm{m}^{-3}$;
- Lagom: $n_{\mathrm{Ne}} = 8 \times 10^{18}\,\mathrm{m}^{-3}$, $n_{\mathrm{D}} = 7 \times 10^{20}\,\mathrm{m}^{-3}$

- For small $\delta B/B$ the maximum runaway current increases, but for larger perturbation levels it is reduced.

[Svensson et al, JPP 2021]

DREAM (Disruption Runaway Electron Analysis Model)

- 1D2P bounce-averaged fluid-kinetic framework for electron acceleration and energy dissipation processes following a disruption
- Accounts for
  - heat and particle transport for given magnetic field perturbation
  - ionization/recombination and line radiation processes
  - electric field induction/diffusion
  - runaway generation in a partially ionized plasma (both fluid and kinetic models)
  - shattered pellet injection
  - opacity to Lyman radiation
  - ion transport



https://github.com/chalmersplasmatheory/DREAM

[Hoppe et al, CPC 2021]

Electron kinetics

- DREAM allows the electron distribution to be evolved using the full kinetic equation (most computationally expensive)
- It also supports solution of simplified equations at a reduced computational cost

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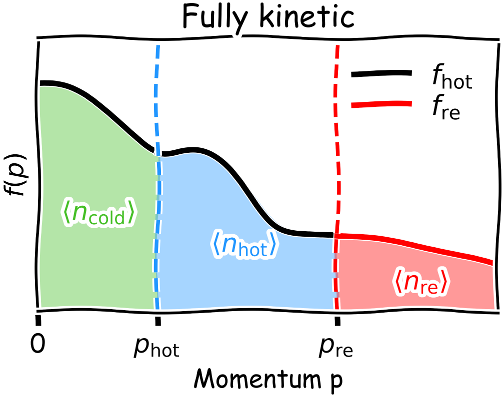
Electron dynamics is qualitatively different on three typically well separated momentum scales:

- **Cold:** $p \sim p_{\rm thermal}$

  ohmic current, joule heating and many atomic processes
- **Hot:** $p \sim p_{\rm c}$

  runaway generation
- **Runaway:** $p > p_{\rm c}$

  dynamics in this region determines the synchrotron and bremsstrahlung radiation emitted by REs



Electron kinetics

- DREAM allows the electron distribution to be evolved using the full kinetic equation (most computationally expensive)
- It also supports solution of simplified equations at a reduced computational cost

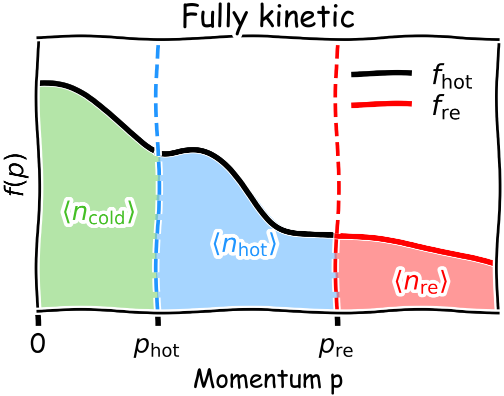
Electron dynamics is qualitatively different on three typically well separated momentum scales:

- **Cold:** $p \sim p_{\mathrm{thermal}}$

  ohmic current, joule heating and many atomic processes
- **Hot:** $p \sim p_{\mathrm{c}}$

  runaway generation
- **Runaway:** $p > p_{\mathrm{c}}$

  dynamics in this region determines the synchrotron and bremsstrahlung radiation emitted by REs



Electrons in each of these regions can be modelled either by solving the **kinetic equation** or be treated as a **fluid**

Runaway generation

Disruption mitigation
- STEP
- ITER

Synthetic diagnostics and model validation

Start-up runaways

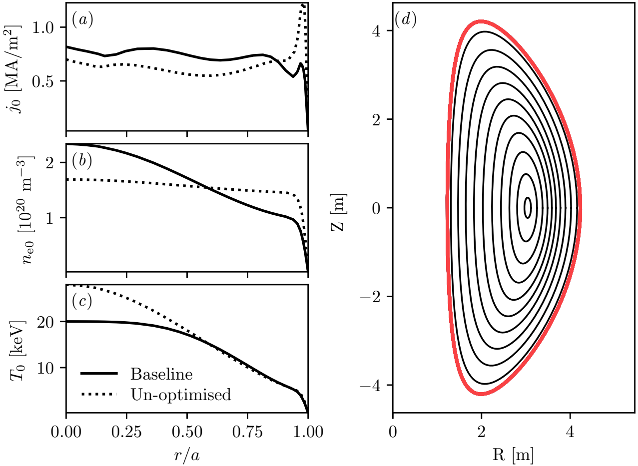
Burning Spherical Tokamak (BurST)

STEP (Spherical Tokamak for Energy Production) programme in the UK is designing a prototype fusion energy plant

BurST is a preliminary high power spherical tokamak design

[Patel, PhD thesis]

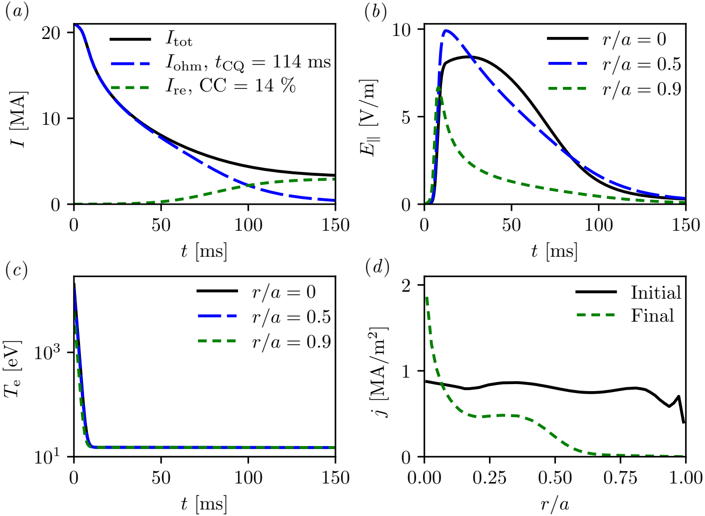
- Major radius 3 m
- Minor radius 1.5 m
- Plasma current 21 MA
- Magnetic field 1.8 T
- Elongation of outermost flux surface 2.8



[Berger et al, JPP 2022]

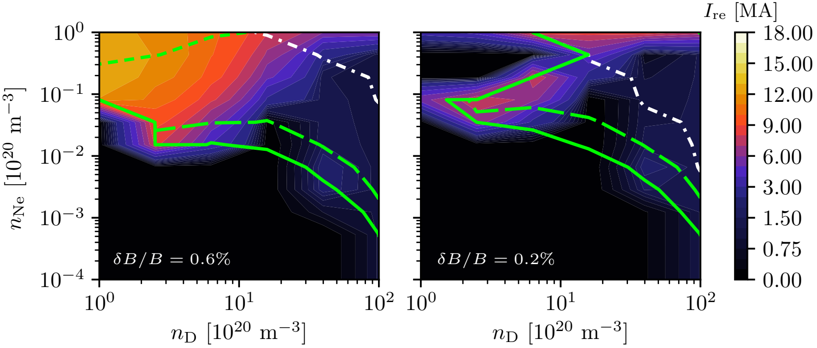
Current and electric field evolution in a BurST disruption

- Temperature decay time scale $t_0 = 1\,\mathrm{ms}$
- Final temperature 15 eV
- Deuterium-tritium plasma
- Perfectly conducting wall
- No material injection
- Compton source is not included
- Fraction of initial current converted to runaways 14%



Mitigation with material injection

- Injection of deuterium and neon, uniformly distributed
- Two cases:
  - fast thermal quench ($\delta B/B = 0.6\%$)
  - slow thermal quench ($\delta B/B = 0.2\%$)
- Transport active until temperature decays to 100 eV



Above the white dash-dotted line: transported fraction is $< 10\%$
Green lines: solid $t_{\mathrm{CQ}} = 150$ ms, long dashed $t_{\mathrm{CQ}} = 100$ ms, short dashed $t_{\mathrm{CQ}} = 20$ ms

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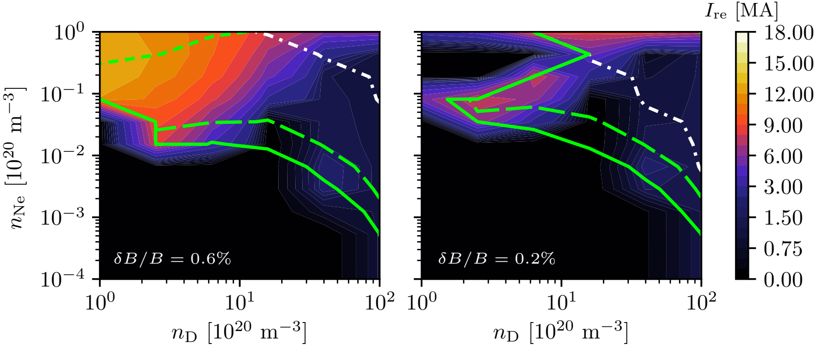

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Compton source not included!

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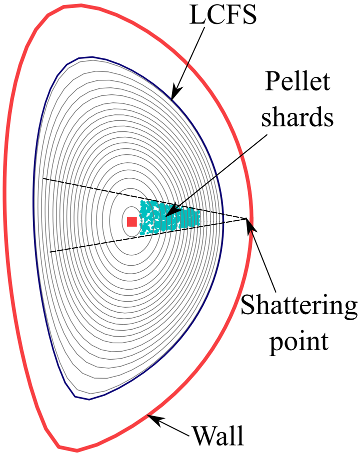
Shattered pellet injection modelling

- SPI fragment sizes follow the Parks distribution

  [Parks et al, 2017 TSDW]
- A **Neutral Gas Shielding** (NGS) model for ablation
  - Allows for H-Ne mixture and non-monoenergetic heat flux
- **Instantaneous deposition** in the form of neutrals
  - Radially shifted deposition possible to emulate drift effects
- Systematically **benchmarked** to INDEX and JOREK simulations



[Vallhagen et al, NF 2022]

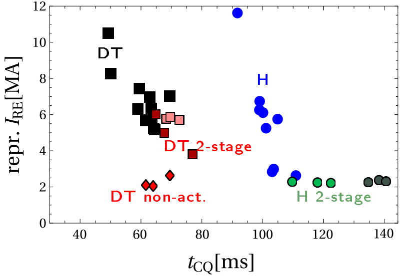
Parameters

- Baseline
  - Pellet injection speed $v_p = 500\ \mathrm{m/s}$
  - Fragment velocity dispersion
    - uniform
    - with $v_p \pm \Delta v$, with $\Delta v / v_p = 0.4$
  - Injection spreading angle 10°
  - Numerical magnetic geometry
    - wall radius $2.8\,\mathrm{m}$ (match magnetic energy content in JOREK)
    - resistive wall time $0.5\,\mathrm{s}$
  - Single pellet injection
    - 1.8×10^{24} D atoms
    - 5×10^{22} Ne atoms
  - Shattered into 487 shards
- Variations
  - Neon quantity adjusted to give a CQ time of 50 or 100 ms in baseline cases (D quantity adjusted to keep the total number of atoms in the pellet constant)
  - Injection of several pellets, simultaneously or in two stages, starting with pure D injection followed by a mixed injection
  - Pellet shattered into more (5185) or fewer (68) shards

ITER discharges with 15 MA initial plasma current

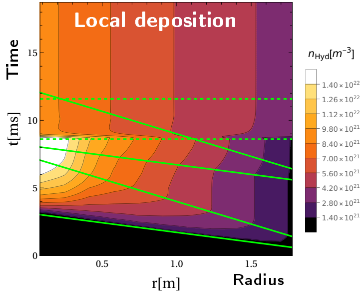
- DREAM in fluid mode with Dreicer, hot-tail, tritium, Compton and avalanche generation
- Strong avalanche leads to **MA-scale runaway currents**
- Best performing cases:
  - Two-stage injection with 3 full pure H pellets followed by 1 Ne doped pellet after $5\,\mathrm{ms}$.
- **Two-stage injections help** hydrogen assimilation and reduce hot-tail
- Runaway current is likely to be overestimated as the vertical displacement, kinetic effects and RE transport during the CQ are not included

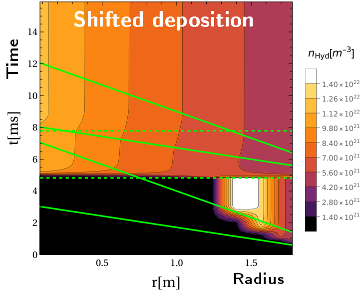
Final RE current
as function of CQ time



Effect of displaced material deposition

- Pure hydrogen pellet clouds are expected to drift towards the low-field side
- To mimic this effect, the material deposition of the first pellet with no neon content (in staggered injection) is shifted outward by $\approx 0.2\,\mathrm{m}$
- Shards unaffected by their own dilution cooling, ablate very rapidly
- **Deposition profile can be very strongly shifted**
- Large dilution cooling $(\times 1/200)$ at deposition peak
- May trigger TQ before neon-doped shards enter
- Density profiles become eventually similar due to ion transport
  $\rightarrow$ RE currents are comparable with and without shift





Runaway generation

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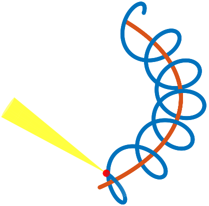
Start-up runaways

Synchrotron radiation

- Runaway electrons emit synchrotron radiation and bremsstrahlung which can be used to obtain information about their distribution
- Strongly biased in the direction of the motion of the electrons → helps to differentiate it from background line radiation
- Radiation depends on momentum and real-space distribution of runaways
  - can provide insight into their pitch-angle, energy and spatial distribution
    [Paz-Soldan, PP 2018, Tinguely, NF 2018, PPCF 2018]



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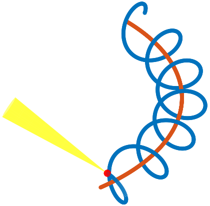
- Synchrotron radiation measurements have been performed on tokamaks since the early 90s [Finken et al, NF 1990, Jaspers et al, JNM 1995]
- Advanced synthetic diagnostic tools are now available e.g. KORC [Carbajal et al, PPCF 2017] and SOFT [Hoppe *et al*, NF 2018]



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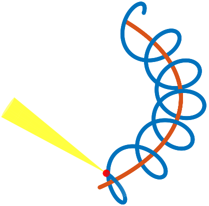


Synchrotron-detecting Orbit Following Toolkit (SOFT)

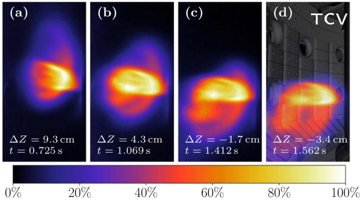
- simulates synchrotron radiation detection (camera, spectrometer etc)
- used at Alcator C-Mod, ASDEX-U, DIII-D, EAST, FTU, JET and TCV

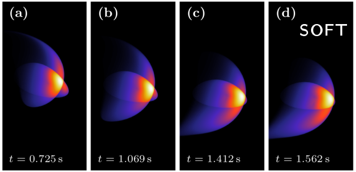
https://github.com/hoppe93/SOFT2

Synchrotron radiation in a vertically translated plasma in TCV

In TCV, a high current conversion, fully developed runaway beam can be displaced vertically over a distance comparable to the minor radius

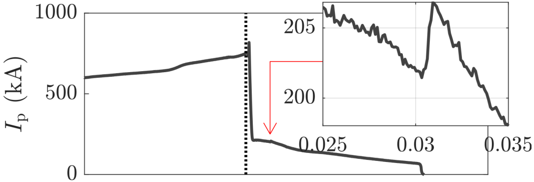
- Experimental synchrotron images of a vertically moving runaway beam sweeping past the detector in TCV
  [Hoppe et al, NF 2020]
- Runaway synchrotron spot shape dependence on the vertical distance between the runaway beam and camera matches simulations well
- Validates the geometrical aspect of the theory underlying the synthetic diagnostic





Synchrotron radiation diagnostics in ASDEX Upgrade

AUG #35628: deliberately triggered disruption with injection of argon



[Hoppe et al, JPP 2021]

- runaway plateau forms with a starting current of 200 kA, duration 200 ms
- zoom-in shows secondary current spike around 5 kA

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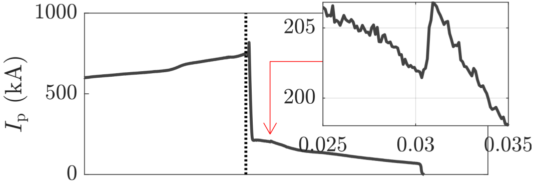

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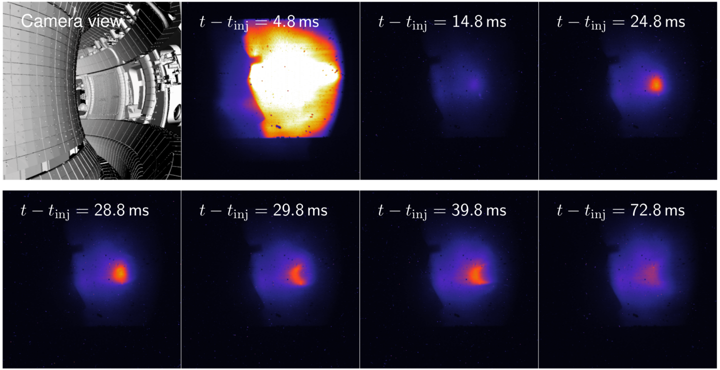
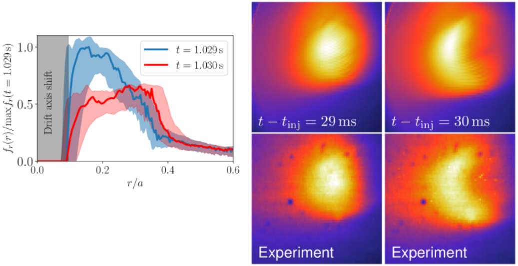
Fast visible camera showing synchrotron radiation images



Synthetic synchrotron radiation diagnostic

Coupled fluid-kinetic modelling → distribution function input to SOFT

- Hot-tail seed population multiplied by close collisions: high-energy remnant seed + current carrying avalanche component
- Remnant seed accelerated to high energies dominates synchrotron emission
- Analytic model for the evolution of the runaway seed component allows to reconstruct the radial density profile of the runaway beam
- Explanation for the sudden pattern transition is a spatial redistribution of the runaway current
- Correlated with MHD activity



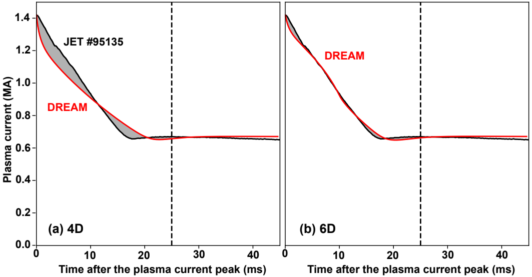
Left: Inverted radial density profiles for the video frames at the magnetic reconnection event
Right: Corresponding inverted synthetic synchrotron radiation images obtained using SOFT

[Hoppe et al, JPP 2021]

Validation of runaway electron simulations

- Numerical tools require input parameters that are not constrained by the available experimental information
- A typical validation exercise is a multi-parameter (manual) optimization to calibrate the uncertain input parameters
- Bayesian inference algorithms include uncertainty quantification and are less subjective
- Example of uncertain parameters:
    - post thermal quench temperature
    - runaway seed profile
    - fraction of assimilated argon
    - wall resistivity

Current quench simulations for JET (#95135)



Red: predicted plasma current with the recommended optimal input parameters;
Black: experimental plasma current

[Järvinen et al, JPP 2022]

https://github.com/aejarvin/BO_FOR_RE_SIMULATIONS

Runaway generation

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Synthetic diagnostics and model validation

Start-up runaways

Modelling of startup runaways

- Tokamak start-up characterized by low electron densities and strong electric fields → ideal for formation of superthermal electrons

  [Knoepfel & Spong, NF 1979]
- Start-up scenarios in ITER risk runaway production due to the low prefill gas pressure required for plasma burn-through

  [de Vries et al, NF 2019, NF 2023]
- Presence of superthermal electrons affects the plasma resistance, ionization rate coefficients → alter the dynamics

- STartup Runaway Electron Analysis Model (STREAM) builds on the fluid version of DREAM [Hoppe et al, JPP 2022]

  `https://github.com/chalmersplasmatheory/STREAM`
- Includes RE generation self-consistently with plasma density, temperature, ion-charge state and electric field evolution
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- Coupling to the conducting structures in the wall
- Burn-through model benchmarked to DYON and experimental results on JET

Idealized ITER-case with low prefill gas ($p_{\mathrm{prefill}} = 0.08\,\mathrm{mPa}$)

Start with low density to achieve burn-through, then raise density to prevent runaway generation.

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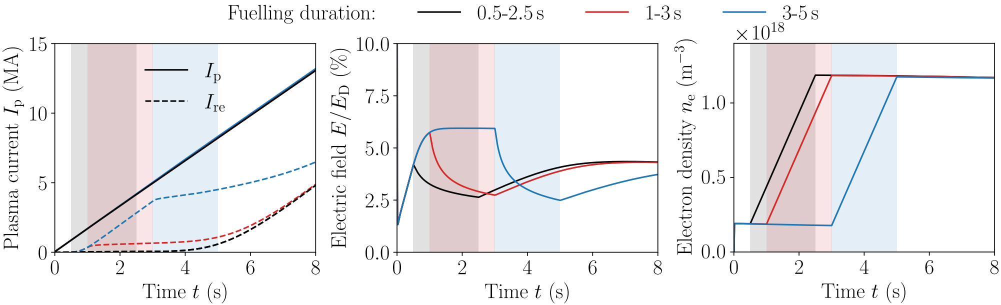
Start with low density to achieve burn-through, then raise density to prevent runaway generation.

- Most crucial parameter for generation of runaways is $E/E_D \propto n_e^{-1}$
- Inject neutral D for 2 seconds, constant rate (see shaded regions)
- Plasma current almost exactly the same, but fraction of runaway current differs



Conclusions

Fantastic development of runaway diagnostics and modelling during the past decade

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Open questions

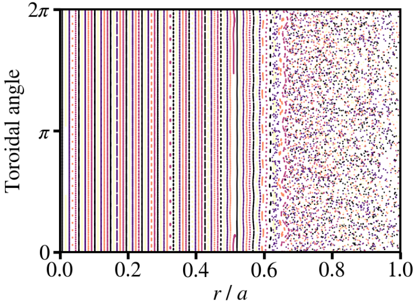
- Can we defeat avalanche?
- Essential role of magnetic perturbations
- Impact of MHD & kinetic instabilities and equilibrium evolution
- Validation of theoretical models with experiments

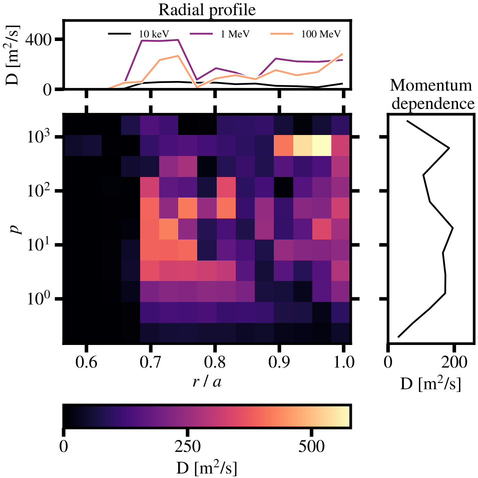
The effect of externally applied perturbations

- Artificial resonant magnetic perturbations at the plasma edge to create a stochastic layer

$$\delta\mathbf{B} = \nabla \times \sum_{n,m} \alpha_{nm}(\rho)\cos(n\zeta - m\theta - \phi_{nm})\mathbf{B}$$

[Särkimäki *et al*, Nuclear Fusion 2020]



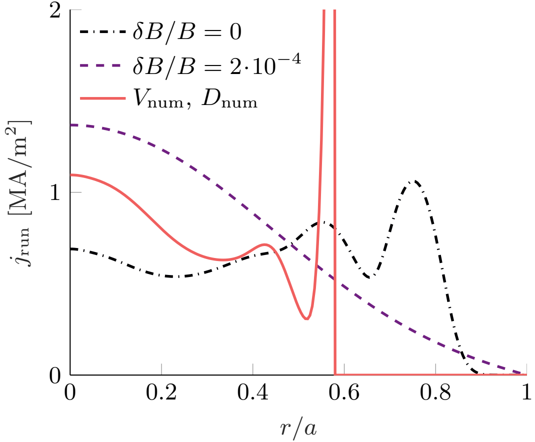


- Transport coefficients evaluated numerically with ASCOT.

Radial and momentum dependence for a fixed pitch $p_{\|}/p = 0.99$.

Runaway current density for Case 3

- Maximum runaway current is reduced to 5.6 MA with a constant $\delta B/B$ and 4.6 MA with the ASCOT advection and diffusion coefficients.
- With constant $\delta B/B$, the final runaway current profile is on-axis.
- Large transport at the edge leads to strong current filaments at the interface to the stochastic region.
- Such a current profile is likely to be very unstable → could lead to magnetic perturbations penetrating deeper into the plasma.



Alfvénic instabilities

- Alfvénic instabilities observed during the current quench
  - DIII-D (correlated with runaway loss)
    [Lvovskiy et al, PPCF 2018]
  - ASDEX Upgrade (no clear effect on runaways)
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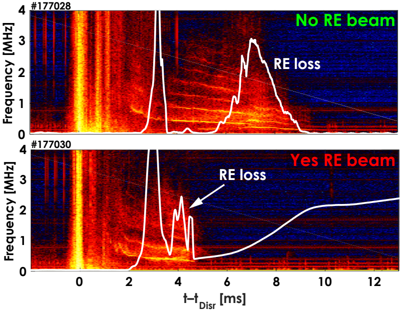
- Compressional Alfvén Eigenmodes at higher frequency and Global Alfvén Eigenmodes at lower frequency were proposed



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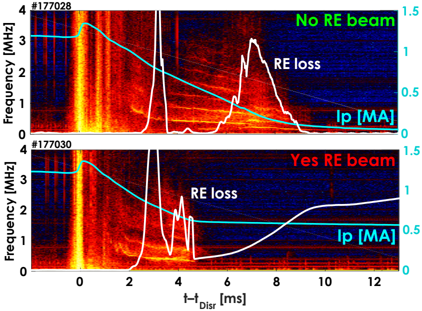

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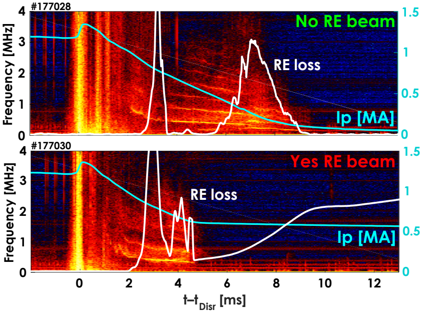

Exploring external launch of similar waves worth considering