Seeding an avalanche: Which snowflake is most responsible?

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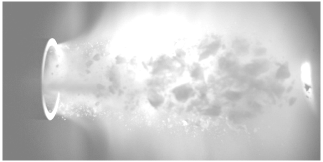
Outline

Background
Avalanche: the crime scene
Seeds: the usual suspects
Mitigation: can we prevent the crime?
Conclusion: assign the blame



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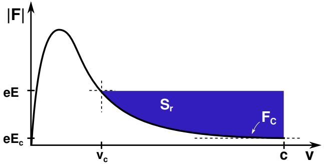
- Electrons from the high-energy “tail” of the distribution run away if $E > E_c$

  $E_c(\mathrm{V/m}) \simeq n_e(10^{21}\ \mathrm{m}^{-3})$



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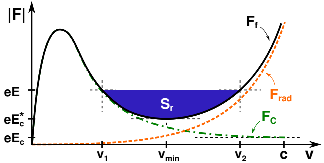
  $E_c(\mathrm{V/m}) \simeq n_e(10^{21}\ \mathrm{m}^{-3})$
- Radiation emission (synchrotron and Bremsstrahlung) is associated with a reaction force
- Presence of partially ionized atoms and instabilities can also affect the **critical electric field**
- Critical field for runaway is generally $E_c^* > E_c$

[Hesslow et al, PPCF 2018]



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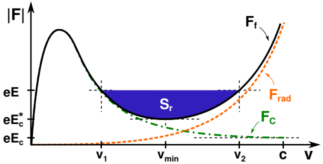
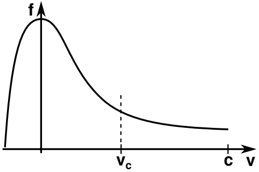


Avalanche:

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



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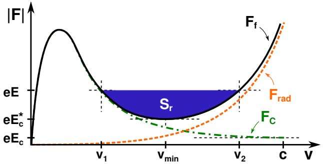

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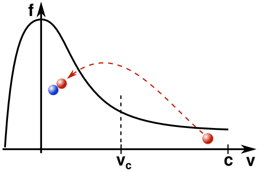

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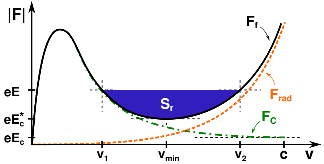

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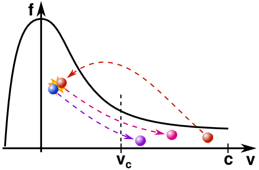

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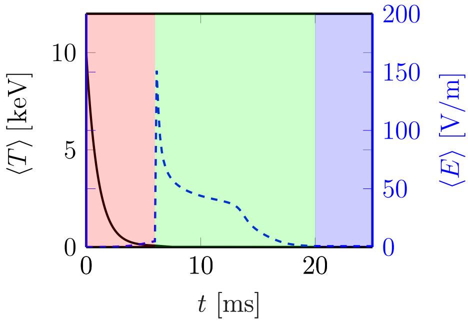
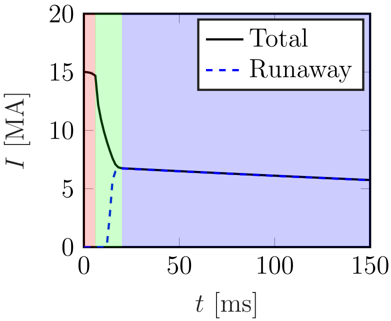
Tokamak disruption

- 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]

Avalanche growth rate

- 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&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 $\sim e^2$
- Potential avalanche multiplication in ITER $\sim e^{50}$

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- Potential avalanche multiplication in ITER $\sim e^{50}$
- **Stronger avalanching in the presence of partially ionized atoms**
- Reason: increased number of target electrons available for the avalanche process is only partially compensated by the increased friction force

[Hesslow et al, NF 2019]

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Dreicer seed

H Dreicer

- Momentum space diffusion feeds the runaway region with electrons
- *"The extension of the kinetic theory of ionized gases to include Coulomb interaction, elastic and inelastic collisions with molecule"* [Dreicer, PhD thesis 1955]

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  - Generation rate

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

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

[Connor&Hastie, 1975]

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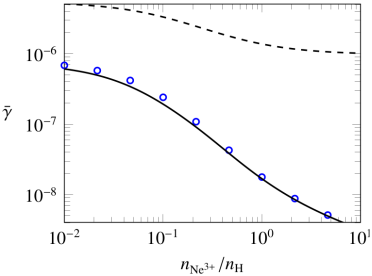
[Connor&Hastie, 1975]

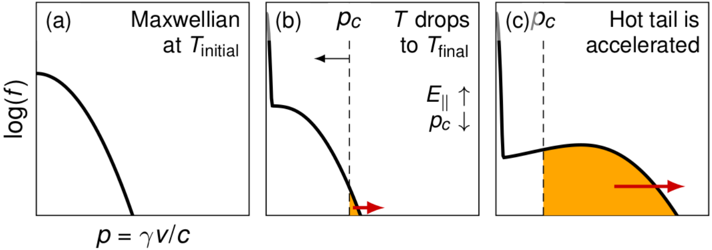
- In the presence of weakly ionized impurities Dreicer generation rate lower

  [Hesslow et al, JPP 2019]

- Figure shows the Dreicer generation rate in the presence of Ne^{3+}, obtained by neural network trained on kinetic simulations (solid), kinetic simulations (blue circles) and the Connor-Hastie formula (dashed)



Hot-tail seed



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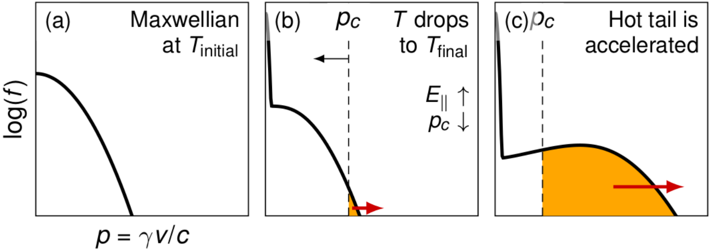

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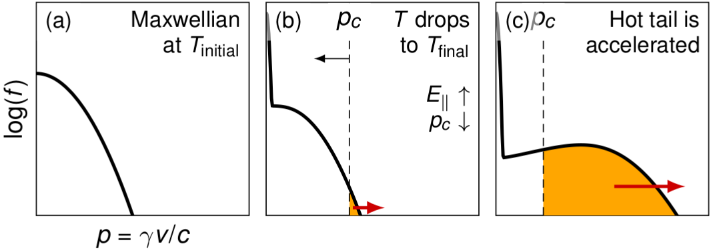

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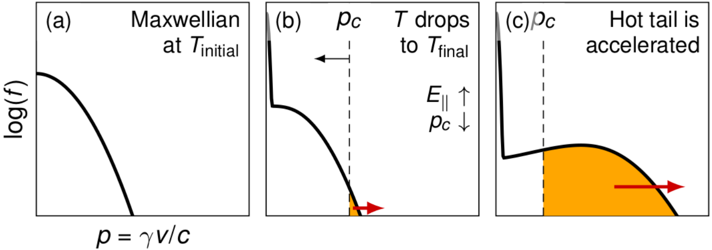

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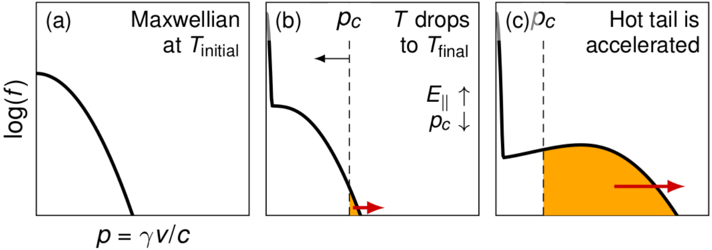

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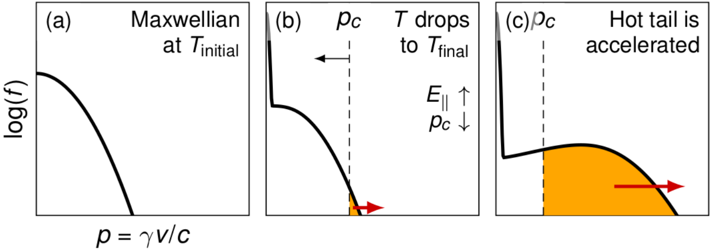

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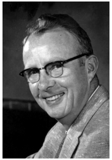
- Dominates over Dreicer generation if the cooling timescale is shorter than the collision time at the critical momentum

Tritium seed

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

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



LW Alvarez

- 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

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- 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
  - Radiation transport calculations (for a beryllium wall) → γ 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 wall
  - Total γ-flux is $\approx 10^{18}\ \mathrm{m}^{-2}\mathrm{s}^{-1}$ for an H-mode discharge at 15 MA and 500 MW fusion power

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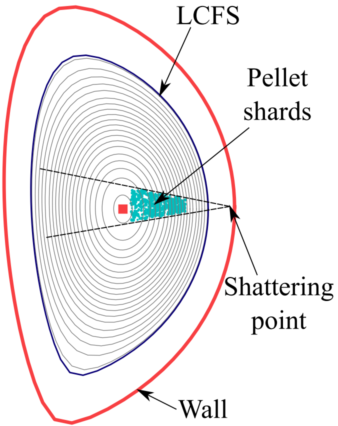
Massive material injection

- Reduce thermal loads and avoid harmful forces associated with eddy currents and halo currents
  - uniformly radiating thermal energy (noble gas)
  - control current quench duration
  - increase electron density and frictional drag (deuterium)
- Requirements for ITER [Lehnen et al, TSDW 2021]
  - 90% of thermal energy radiated
  - current quench time within reasonable limits ($50\,\mathrm{ms} < \tau_{\mathrm{CQ}} < 150\,\mathrm{ms}$)
  - low runaway currents ($I_{\mathrm{RE}}^{\mathrm{max}} < 150\,\mathrm{kA}$)



Shattered pellet injection

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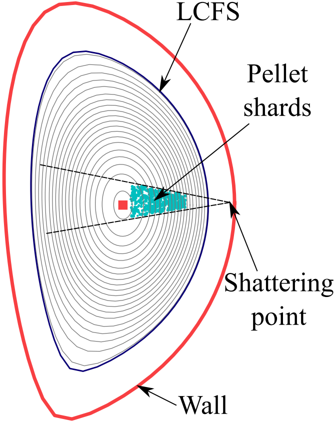


Shattered pellet injection

“How to safely extinguish a home-made star by throwing a snowball at it?”

[Vallhagen]

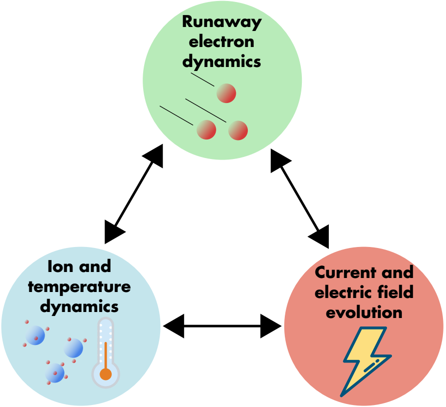
The DREAM simulation code

- Disruption Runaway Electron Analysis Model

  [Hoppe et al. CPC 2021]

  https://github.com/chalmersplasmatheory/DREAM
- 1D2P bounce-averaged fluid-kinetic framework
- Accounts for
  - runaway generation in a partially ionized plasma (both fluid and kinetic models)
  - electric field evolution
  - heat and particle transport for given magnetic field perturbation
  - ionization, recombination and line radiation processes
- Shattered pellet injection

  [Vallhagen et al, NF 2022]



Runaway electron dynamics

Ion and temperature dynamics

Current and electric field evolution

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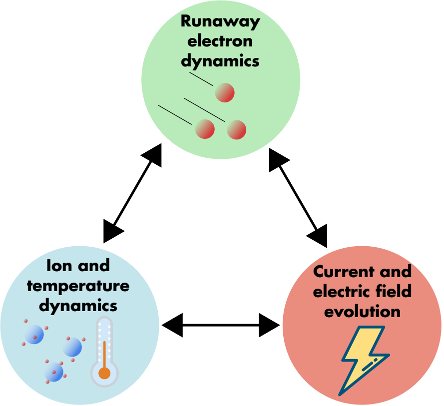


Runaway electron dynamics

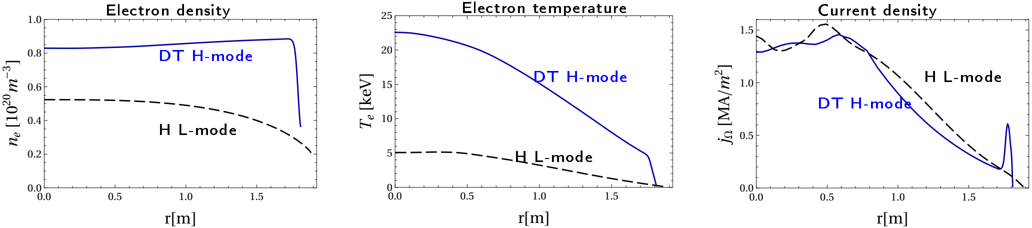
Ion and temperature dynamics

Current and electric field evolution

- Limitation: no vertical displacement event, no RE driven instabilities
- **Fast: allows exploration of large parameter regions**

ITER reference scenarios

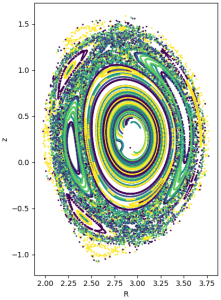
- DT H-mode and hydrogen L-mode scenarios with $I_p^{(0)} = 15\,\mathrm{MA}$

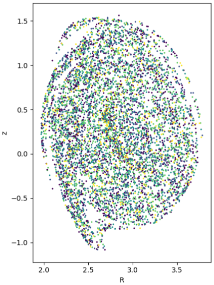


- Parameters
  - Pellet injection speed $v_p = 500\ \mathrm{m/s}$
  - Fragment velocity dispersion
    - uniform, with $v_p \pm \Delta v$, with $\Delta v / v_p = 0.4$
  - Injection spreading angle 10°
  - Numerical magnetic geometry, shaping held fixed
    - wall radius $2.8\,\mathrm{m}$ (match available magnetic energy content in JOREK)
    - resistive wall time $0.5\,\mathrm{s}$
  - Pellet composition varied
    - Standard: 1.8×10^{24} D atoms, 5×10^{22} Ne atoms
  - Shattered into $\sim$ 500 shards (# shards is varied)

Thermal quench (TQ) model

- Fingerprints (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
- 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



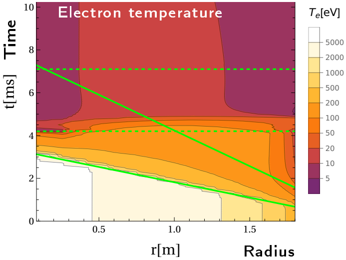


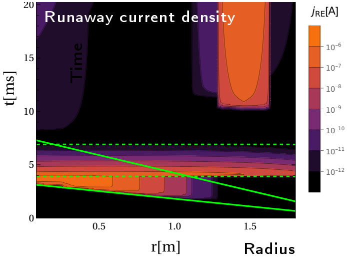
[Särkimäki et al, NF 2020]

Thermal quench (TQ) model

- Energy loss during TQ:
  - 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
- Rechester-Rosenbluth type **heat diffusion**, **prescribed** magnetic perturbation amplitudes $\delta B/B$
- Two alternatives to trigger the transport event
  - Ne-doped shards reach $q = 2$ (*"Early TQ"*)
  - T_e drops below $10\,\mathrm{eV}$ inside of $q = 2$ (*"Late TQ"*)
- Duration of transport event is assumed to be either $t_{\mathrm{TQ}} = 1\,\mathrm{ms}$ or $3\,\mathrm{ms}$
- $\delta B/B$ chosen so that T_e reaches $200\,\mathrm{eV}$ within t_{TQ} (either 1 ms or 3 ms) from transport alone
- RE transport calculated with same $\delta B/B$ as for heat diffusion [Svensson et al, JPP 2021]

Late TQ, $t_{\mathrm{TQ}} = 3\,\mathrm{ms}$



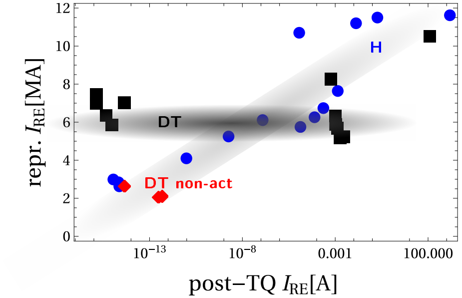


RE current vs post-TQ seed, in single pellet injection cases

- H plasma: Dreicer, hot-tail and avalanche generation
- DT plasma: all of the above plus tritium & Compton
  - initially nominal photon flux in ITER

    [Martín-Solís et al 2017 NF 57 066025]
  - reduced by $\times 10^{-3}$ after TQ when neutron bombardment of the wall is stopped
- RE current logarithmically sensitive to surviving non-activated seed

  [Vallhagen et al, JPP 2020]
- Reason for weak dependence: when runaway current becomes comparable to the Ohmic current, the electric field is reduced, which reduces the avalanche growth rate



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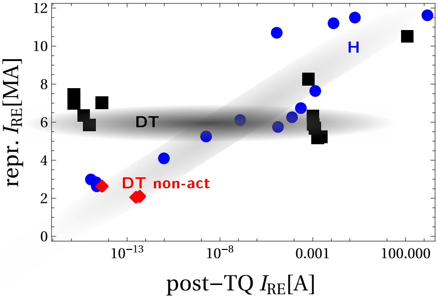
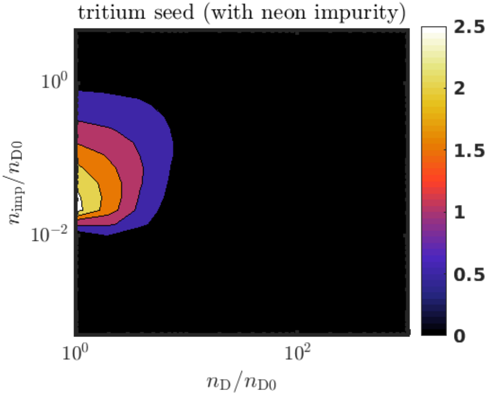
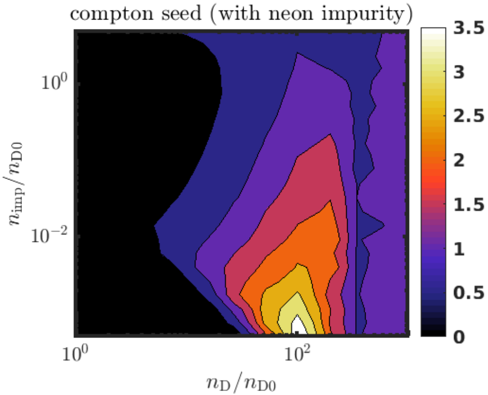


- DT plasma without activated seeds (tritium+Compton) follows the same trend
- **Activated** seed generation active after transport event as well ⇒ $5\text{-}6\,\mathrm{MA}$ floor in single stage injection cases

Seed runaways in DT fusion plasmas

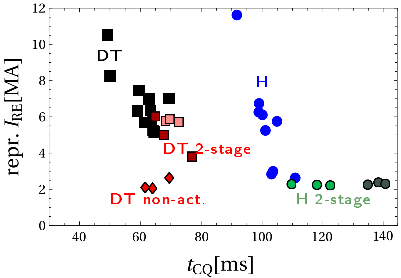
- Tritium seed **decreases** with increasing impurity content, due to the shorter CQ times and the increased critical energy
- Compton seed **increases** with increasing impurity content, due to the increased number of target electrons available for Compton scattering
- Figures show tritium and Compton seeds (in amperes) in an ITER-like disruption with uniformly distributed neon and deuterium
- Tritium + Compton → a few amperes of seed current is obtained almost independently of the injected amount of material


tritium seed (with neon impurity)


compton seed (with neon impurity)

Summary: ITER discharges with 15 MA initial plasma current

- Two-stage injection
    - First an injection of hydrogen to **cool the plasma through dilution**
    - Then a Ne-doped injection, which **radiatively dissipates** the thermal enegy
    - Leaves time for temperature equilibration to **minimize hot-tail**
- Best performing case:
    - Late TQ, $t_{\mathrm{TQ}} = 3\,\mathrm{ms}$
    - Two-stage injection with 3 full pure H pellets followed by 1 Ne doped pellet after $5\,\mathrm{ms}$.
    - Relatively low Ne content (few $\%$)
- Two-stage injection can reduce the RE current
    - $\sim 4\,\mathrm{MA}$ in DT H-mode
    - $\sim 2\,\mathrm{MA}$ in H L-mode
- t_{CQ} can be kept within required range



Circles: H L-mode, squares: DT H-mode
Black and blue: single injection
Red and green: 2-stage
Red diamonds: DT non-activated
Dark red/green: shifted deposition
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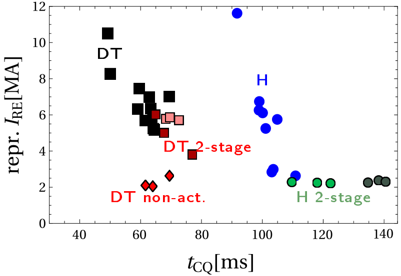

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Compton seed dominates

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

“In W the proportion of kinetic energy of neutrons converted into electromagnetic γ radiation approaches 99%, which is higher than the light generation efficiency of LED devices, whereas in Be this fraction is less than 1%.”

[Reali, Gilbert, Boleininger & Dudarev, PRX Energy 2023]

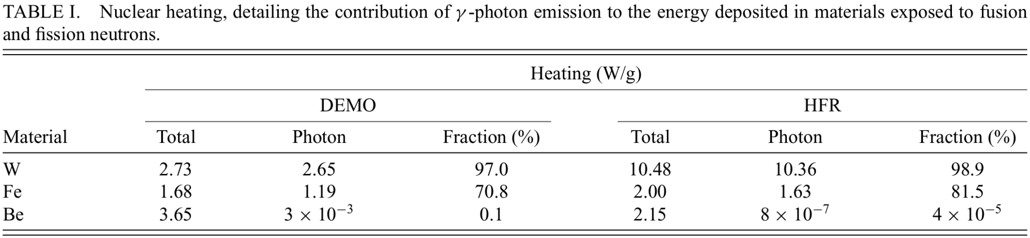

TABLE I. Nuclear heating, detailing the contribution of γ-photon emission to the energy deposited in materials exposed to fusion and fission neutrons.

	Heating (W/g)					
	DEMO			HFR		
Material	Total	Photon	Fraction (%)	Total	Photon	Fraction (%)
W	2.73	2.65	97.0	10.48	10.36	98.9
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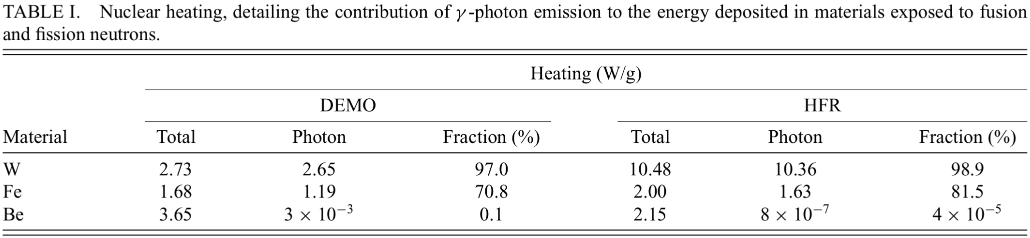

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DREAM simulations with 10 times larger γ flux give 0.7 MA larger RE current

Background

Avalanche: the crime scene

Seeds: the usual suspects

Mitigation: can we prevent the crime?

Conclusion: assign the blame

Who is most responsible for our shattered DREAMs?

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  - exponentially sensitive to E/E_D

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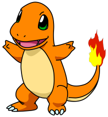

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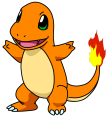

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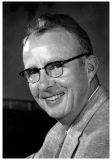

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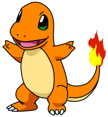

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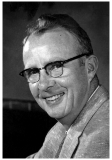

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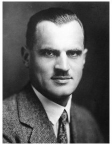
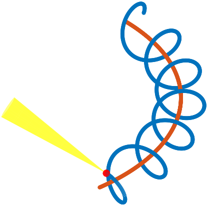


- Compton seed
  - dominates in activated scenarios
  - increases in the presence of massive material injection
  - particularly worrisome in case of a tungsten wall

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 et al, PP 2018, Tinguely et al, NF 2018, PPCF 2018]



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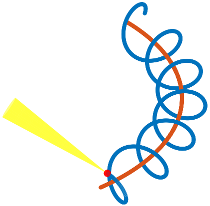

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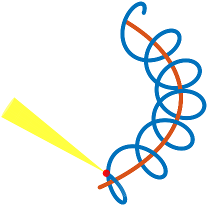


Synchrotron-detecting Orbit Following Toolkit (SOFT)

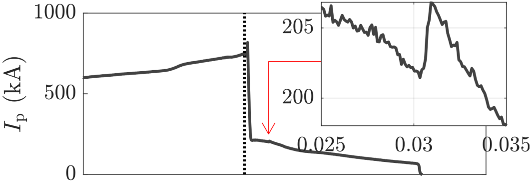
- simulates synchrotron radiation detection (camera, spectrometer etc)
- used at Alcator C-Mod, ASDEX-U, DIII-D, EAST, FTU, JET and TCV

https://github.com/hoppe93/SOFT2

Synchrotron radiation diagnostics in ASDEX Upgrade

AUG #35628: deliberately triggered disruption with injection of argon

[Hoppe et al, JPP 2021]



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- zoom-in shows secondary current spike around 5 kA

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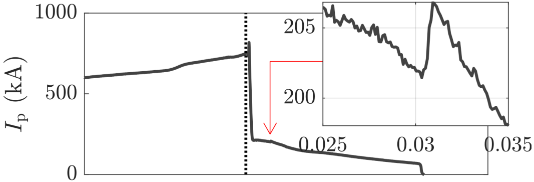

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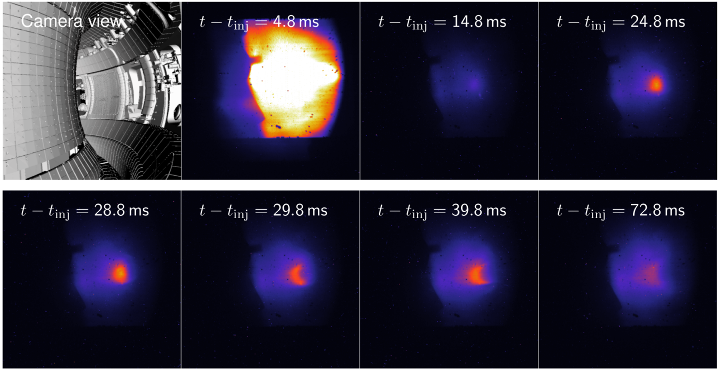
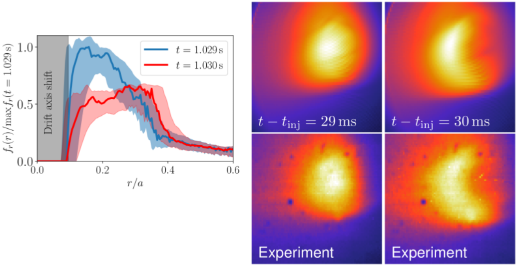
Fast visible camera showing synchrotron radiation images



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 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]