Generation of runaway electrons during the thermal quench

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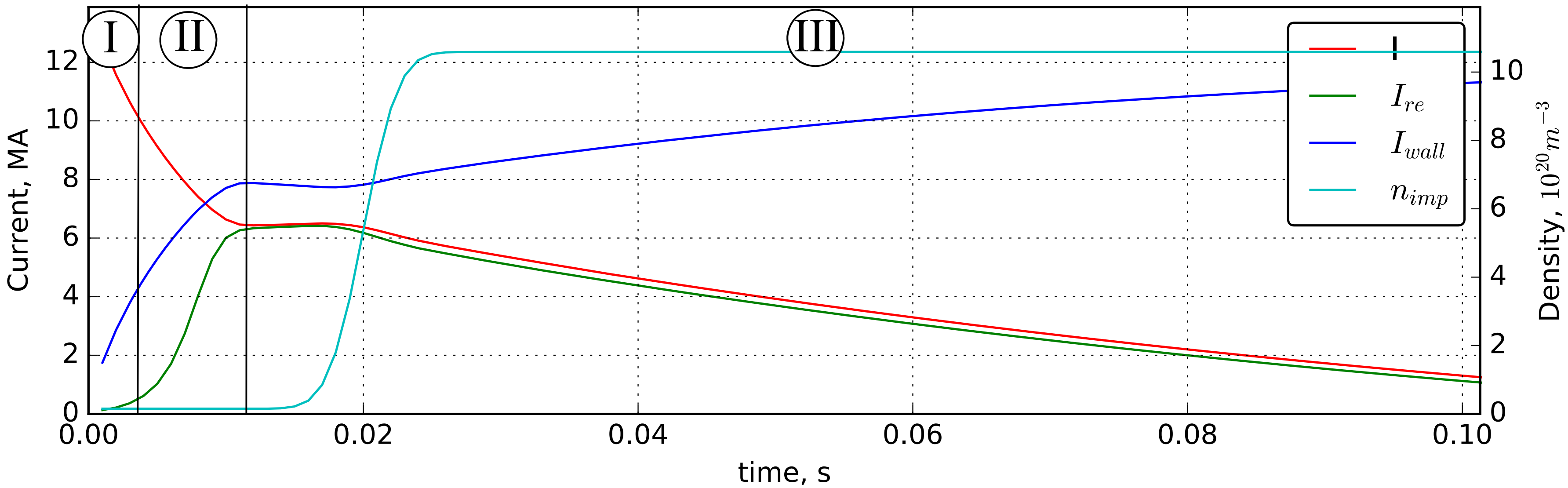
Sequence of "regimes" and models



(I) Dreicer mechanism [Gurevich 1960; Connor and Hastie 1975]

[Ismailov, Aleynikov, Konovalov, "Dreicer mechanism of runaway electron generation in presence of high-Z impurities", EPS 2016]

Hot-tail mechanism [Chiu 1998; Helander 2004; Smith 2008]

(II) A revised version of the "hot-tail" ideas brings interesting new results [**this presentation**]

(III)

Avalanche [Rosenbluth and Putvinski 1997]

"Near-threshold" regime [Aleynikov and Breizman PRL 2015]

Formation of the attractor due to synchrotron, electric field settles at $E_c(B,Z,n) > E_c$

Correct Z_{eff} and n_{eff} required to account for high-Z impurity.

The model

Consider, for example, the “killer-pellet” thermal quench (TQ)

1. Maxwellian pre-quench electrons (n_0, T_0) with Spitzer correction (j_0)
2. Pellet delivers cold ions and $n_{cold} > n_0$ after ionization
3. The timescales for collisions are:

$$\nu_{cold-cold} \gg \nu_{hot-cold} \gg \nu_{hot-hot}$$

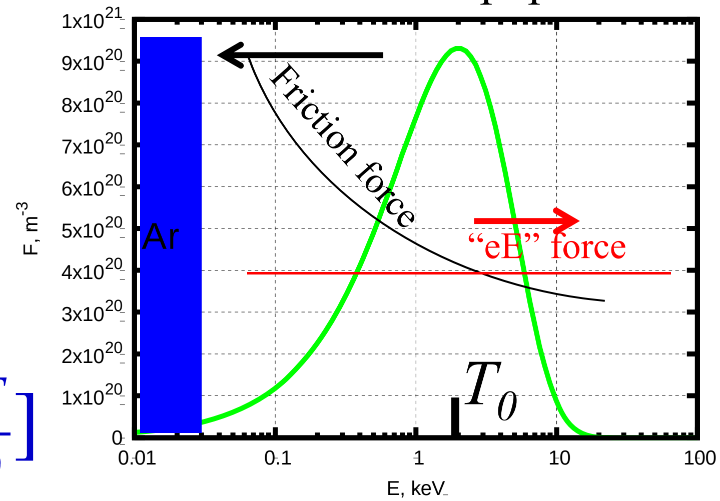
Neglected

4. Kinetic equation for the hot electrons

$$\frac{\partial F}{\partial t}+\frac{\partial}{\partial p}\left[E\cos\theta-1-\frac{1}{p^2}\right]F=$$

$$=\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\sin\theta\left[E\frac{\sin\theta}{p}F+\frac{(Z_{eff}+1)}{2}\frac{\sqrt{p^2+1}}{p^3}\frac{\partial F}{\partial\theta}\right]$$

Initial hot and cold populations



1. The current density is constant during the TQ. The electric field evolves accordingly.

$$j_0=\int ev_{\|}F(t,E)\,dp\sin(\theta)\,d\theta+\sigma_{cold}E(t)$$

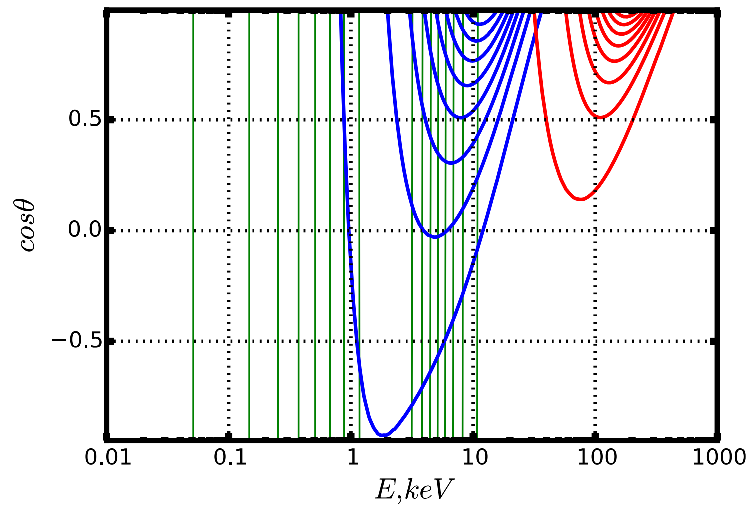
1. σ_{cold} is determined by hot population energy release and line-radiation

2D evolution of the hot electron distribution

Conservation of the total current prohibits slowing down of the **entire** hot population. The surviving hot electrons form a runaway beam.

Hot electron survival in the limit of σ_{cold}=0

In the limit of σ_{cold}=0 (i.e. T_{cold}=0) the total current is carried by the hot population.

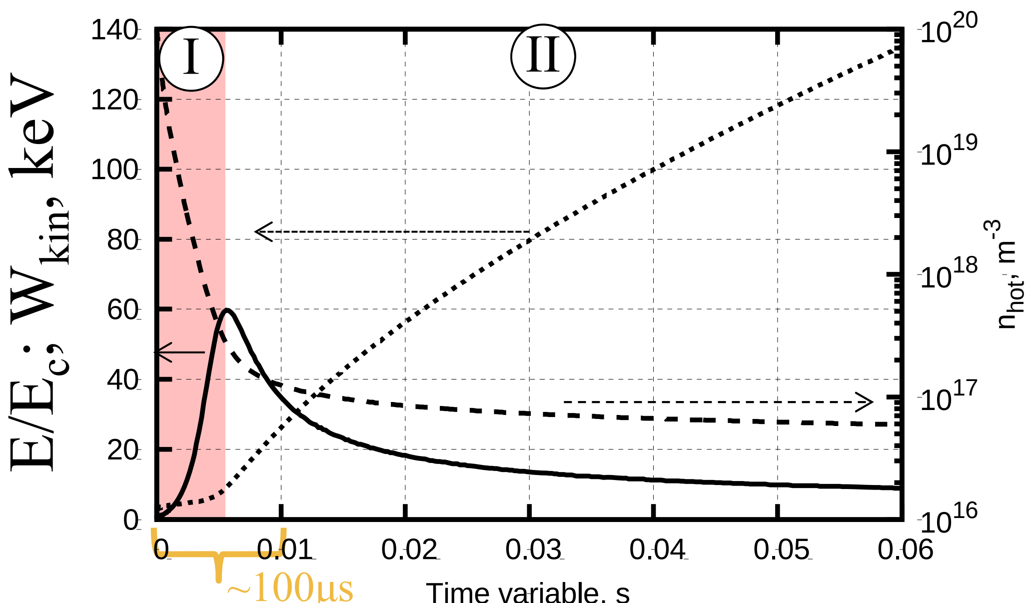


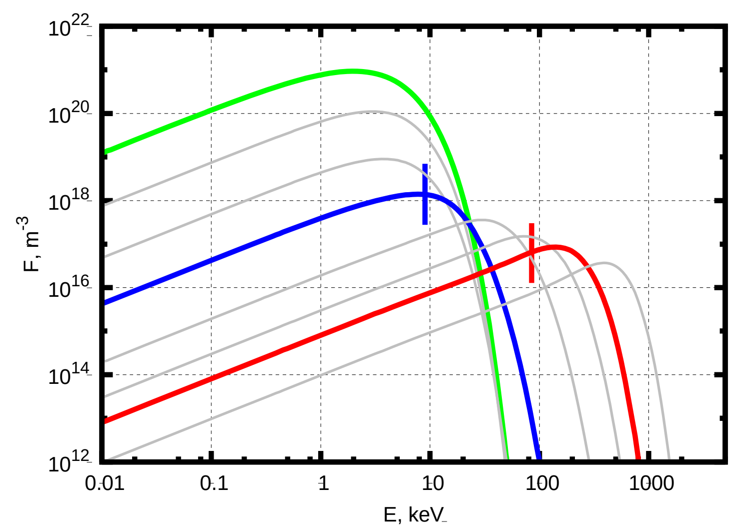
Phase I.

- Electric field rises in step with the loss of the hot population.
- The remaining hot electrons form a "beam" when

Phase II.

Electric field decays slowly as the surviving electrons accelerate





Seed reduction by the bulk conductivity

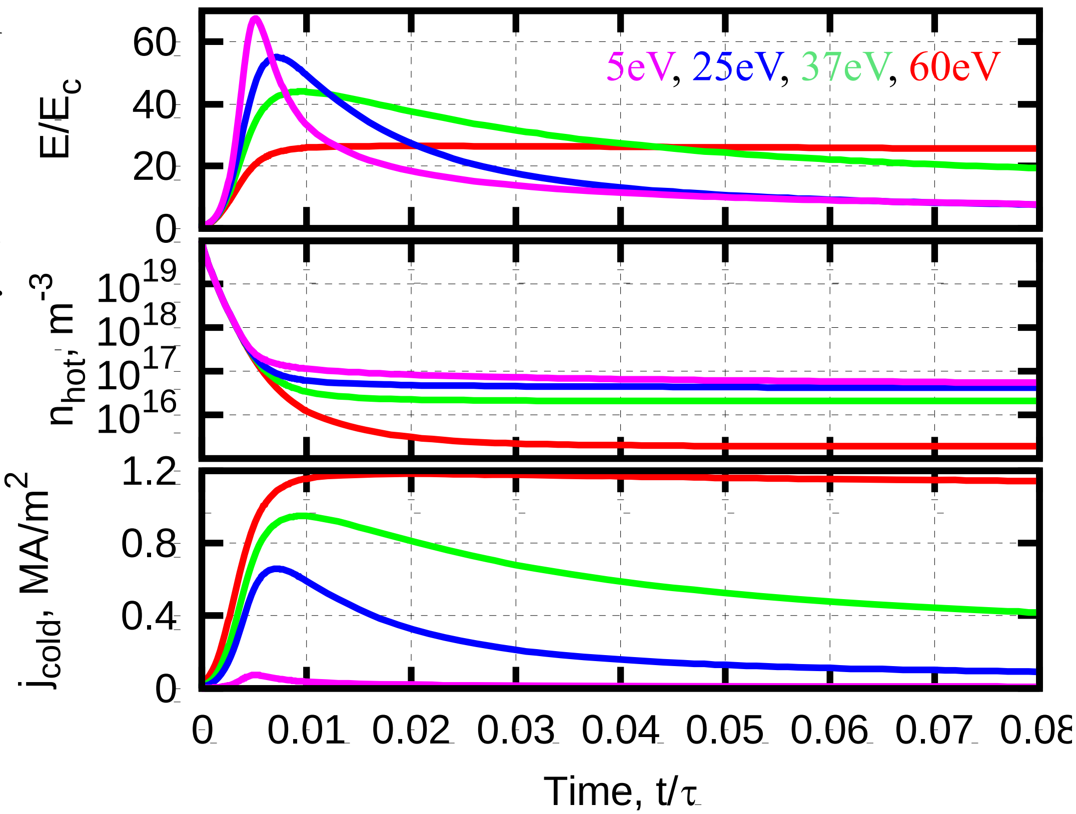
- If σ_{cold}=0, all the post-TQ current is carried by the hot electron beam (no need for the avalanche).

- Finite σ_{cold} reduces the electric field and makes it more difficult for the hot electrons to survive.

Lower temperature

⬇

More "surviving electrons"



Cooling down on impurities

- If instantaneous deposition of neutrals is assumed (valid for pellet injection)
- The ordering of collisions and ionization:
  - Initially, only hot electrons ionize impurity neutrals

$$\frac{dn_{cold}}{dt} = n_{hot} n_{imp} \left\langle v\sigma_i \right\rangle_{Maxwell}$$

  - Thompson ionization cross-section

$$\sigma_i = \frac{\pi e^4}{(4\pi\varepsilon_0)^2} \frac{1}{E} \left(\frac{1}{I} - \frac{1}{E} \right)$$

- **If n_{imp} is large** than ionization rate is faster than thermalisation of cold electrons with hot population (Spitzer slowing-down time).
- In particular, in few keV plasma, ionisation rate for first few Argon electrons

$$\frac{1}{n_{hot}} \frac{dn_{cold}}{dt} \approx n_{imp} 10^{-15} m^3 s^{-1}$$

- For $n_{Ar} > 10^{19} m^{-3}$ a separate "cold" Maxwellian population will be formed quicker than in a fraction of a millisecond

$$\nu_{cold-cold} \gg \nu_{hot-cold} \gg \nu_{hot-hot}$$

Self-consistent TQ

- Self-consistent temperature evolution:

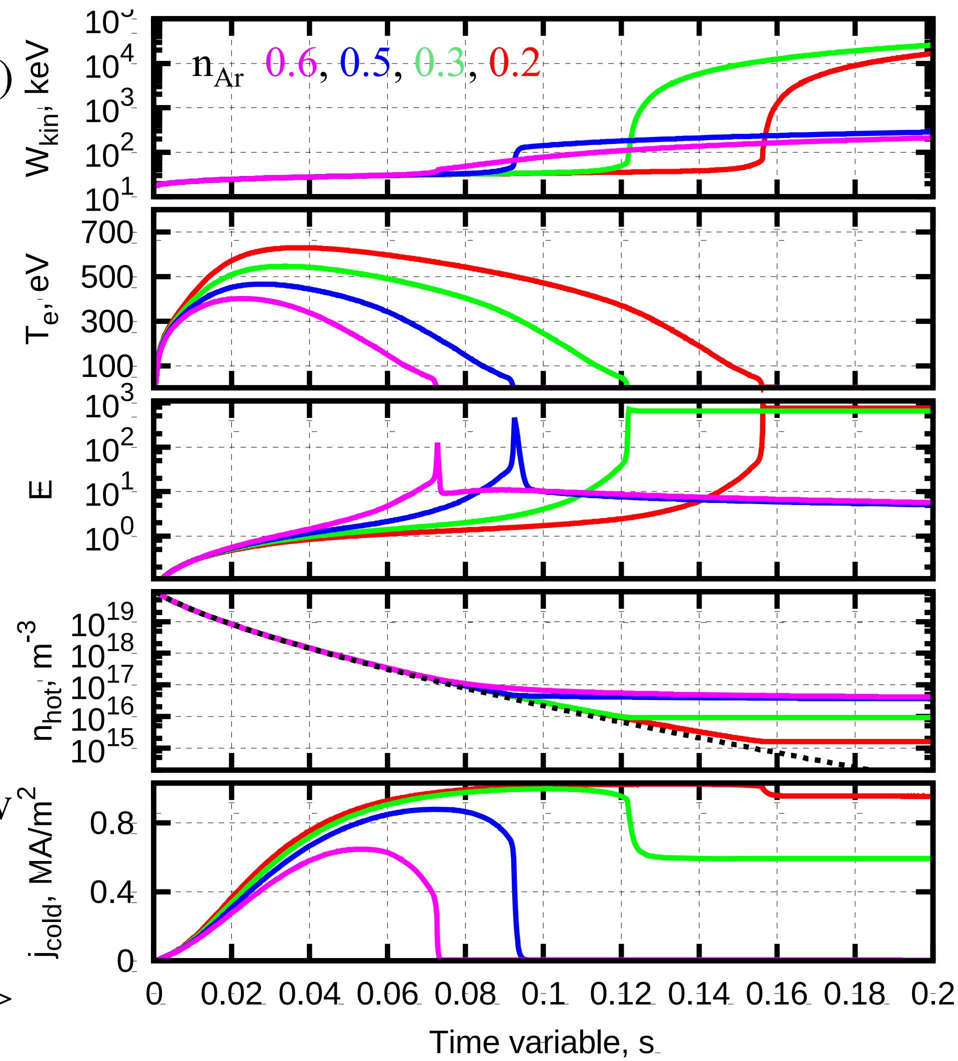
$$\frac{\partial (W_{th}+W_{ionization})}{\partial t} = P_{stopping}(F) + \frac{j_{cold}^2}{\sigma_{cold}} - n_{imp} n_{cold} L(T)$$

1) Hot electrons heat the "cold" bulk via Coulomb collisions

2) The bulk overtakes a fraction of the current

3a) Bulk conductivity drops due to radiative losses

3b) The hot population decreases in the meantime



There are two possible outcomes:

1. Prompt conversion regime: purple & blue

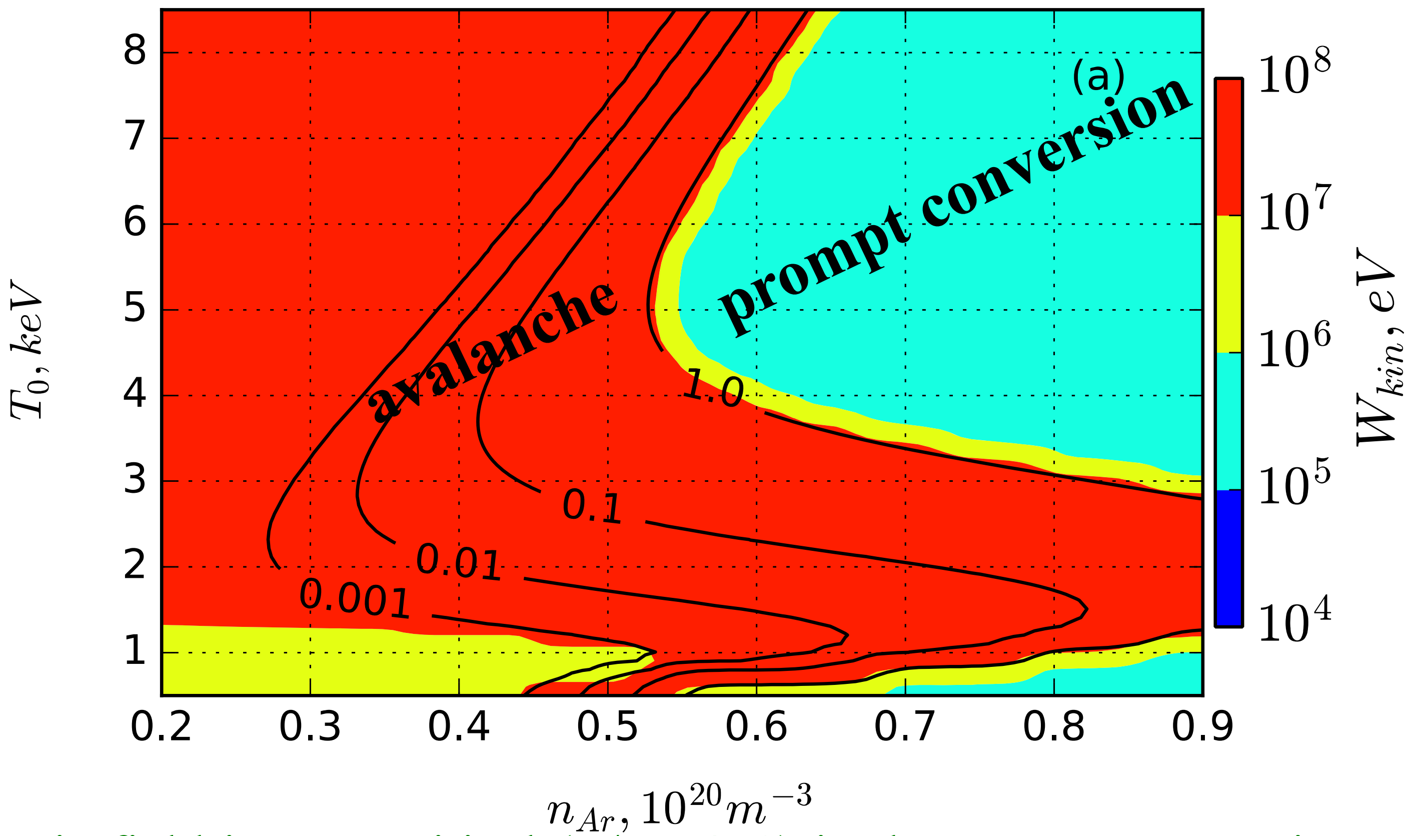
Low energy REs carry the total current at low electric field.

2. Seed for avalanche regime: green & red

Ohmic current requires high electric field -> high energy REs + avalanche.

Scan over initial plasma parameters

Contour plot of the survived hot electron population density (normalized to j_0/ec)
>1.0 is the **prompt conversion** regime (100% is sub-MeV RE current)

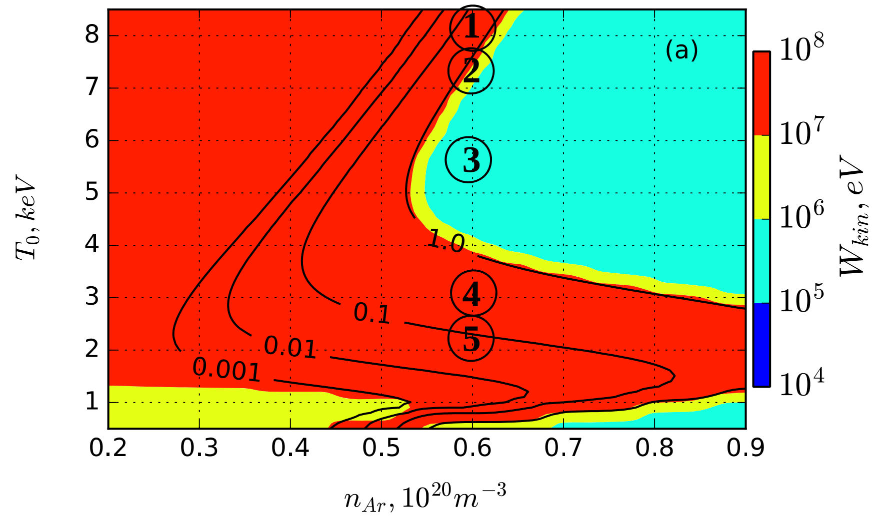


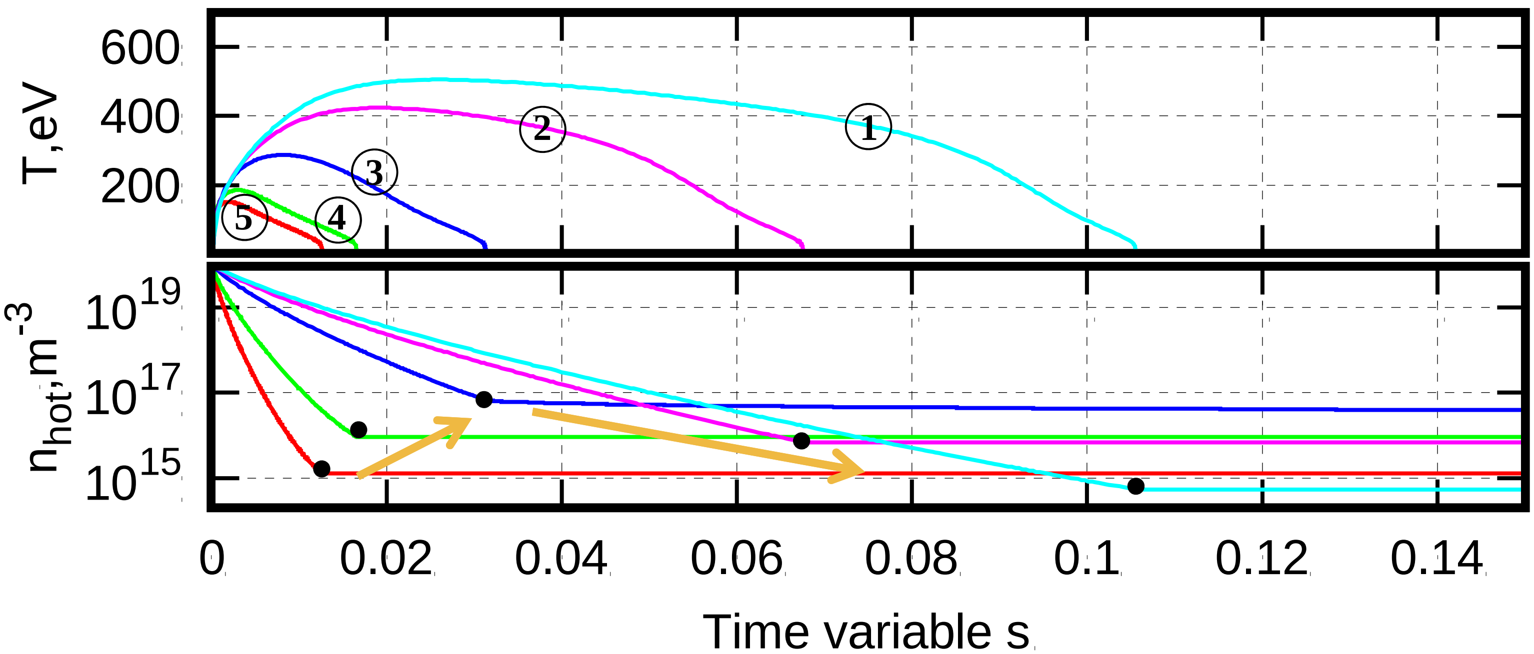
- The electric field is supercritical (E/E_c~4÷8) in the prompt conversion regim (due to relatively slow transformation of the 100keV RE into 1MeV RE current)
- The seed density has a non-monotonic dependence on pre-quench temperature with a maximum at T_0~4keV

Non monotonic behavior of $n_{re}(T_0)$

- Bulk cooling down time is a monotonic function of T_0
- Hot population decay rate is a monotonic function of T_0

- The resulting seed density is not monotonic, with a maximum at T_0~4keV





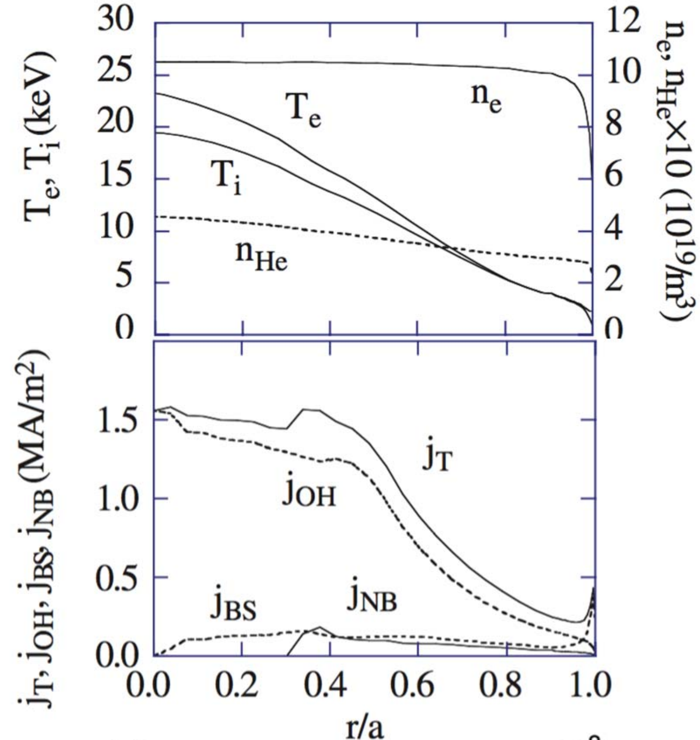
Argon and Neon in ITER

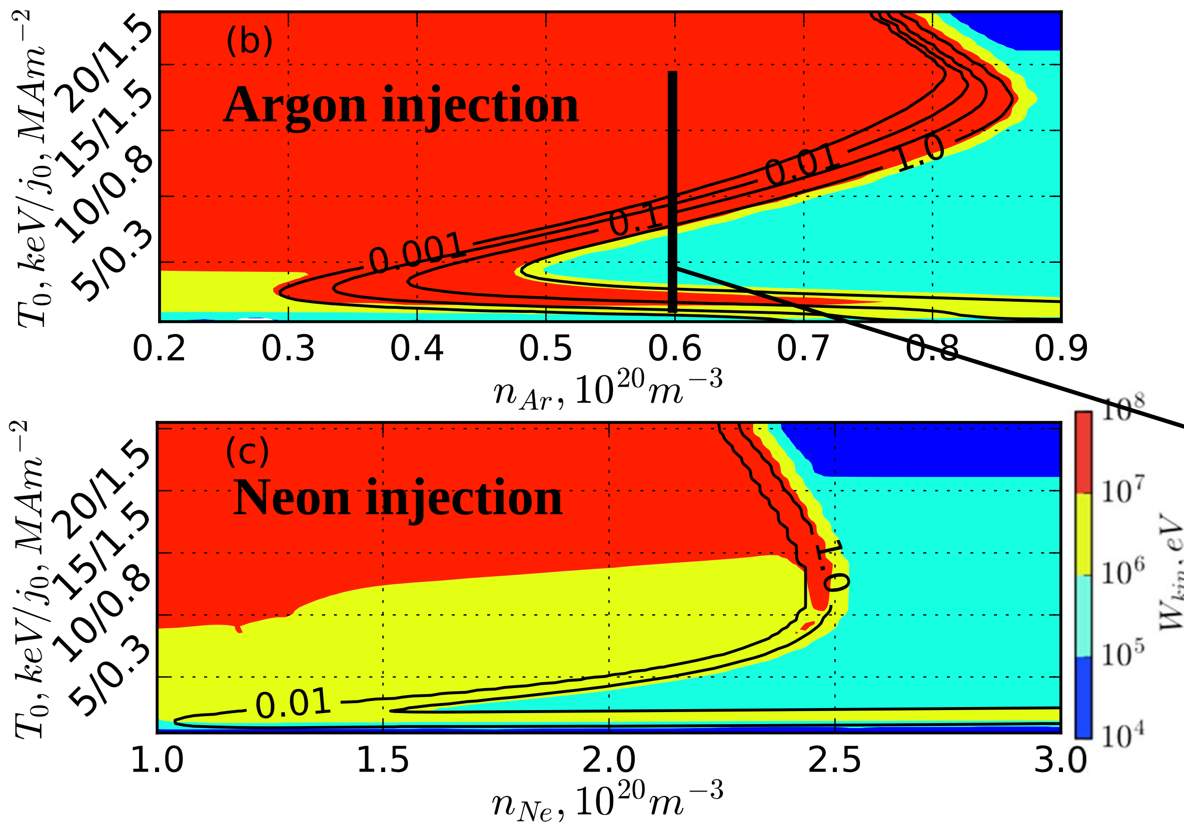
Both T_0 and j_0 determine n_{re} (with n_0 and n_{imp})

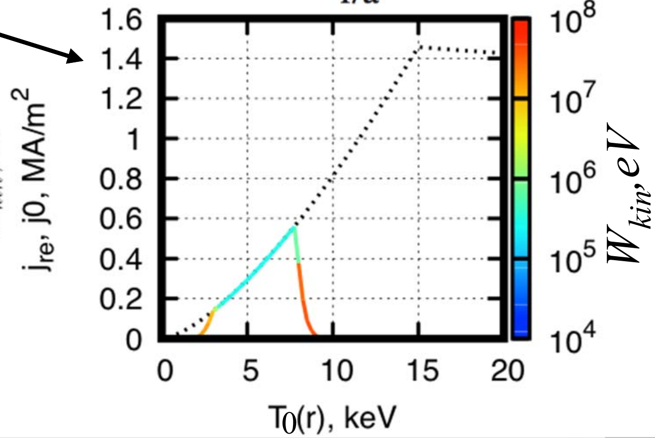
For ITER-relevant profiles (Ar injection):

1. Prompt conversion of full current for $n_{Ar}>10^{20}m^{-3}$
2. RE-free disruption for $n_{Ar}<3\times10^{19}m^{-3}$
3. Non-monotonic radial RE profile

[B.Green, PPCF **45** (2003) 687]



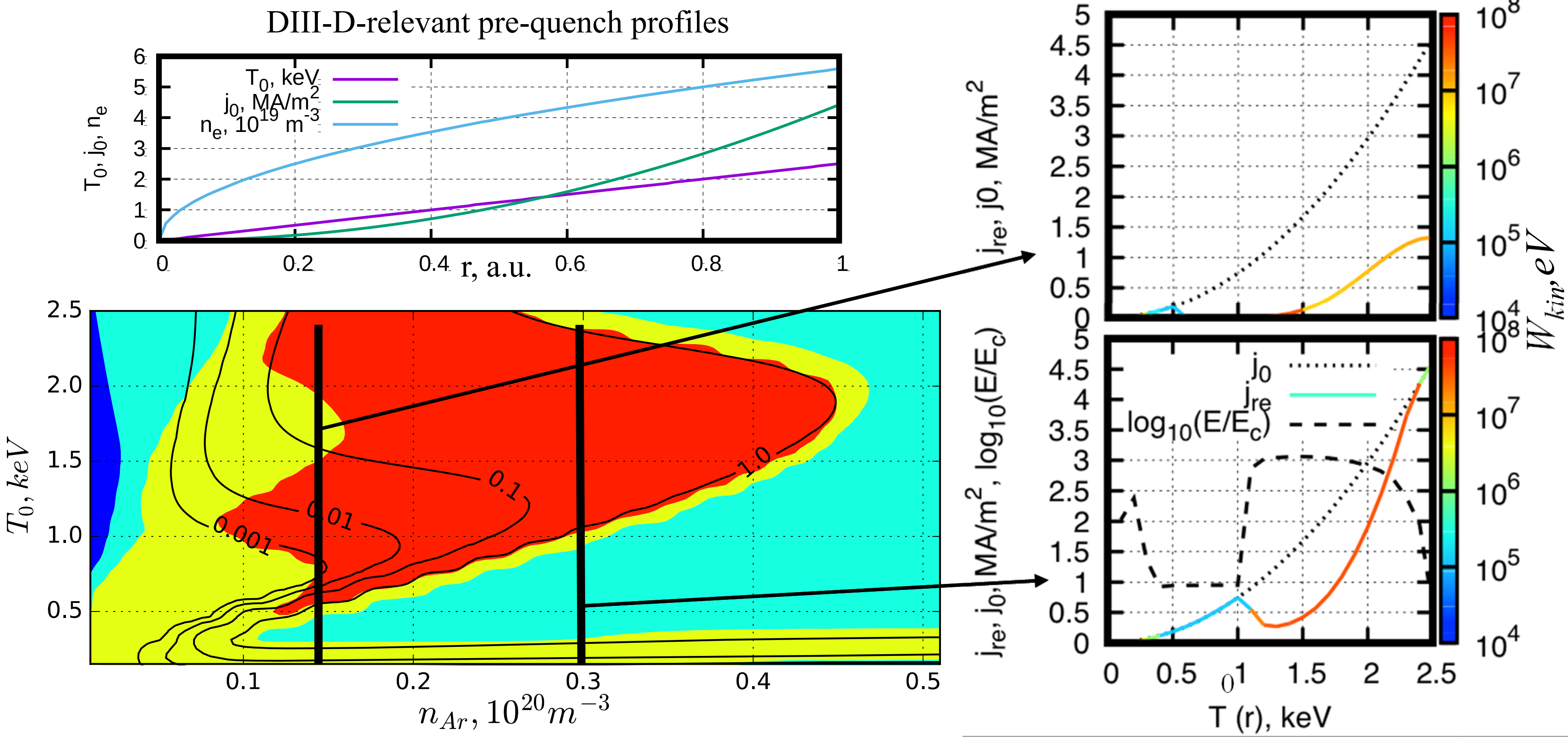




Argon injection in smaller machines

DIII-D is different from ITER:

1. $T_0 < 5$ keV exhibit peaking of the RE seed toward the core
2. High current density (~3 MA/m^2) facilitates hot electron survival and favors the Dreicer generation
3. Decrease of n_0 (and n_0/n_{Ar}) at the periphery leads to prompt conversion in this area



Summary of RE generation model

- Prompt conversion of the pre-quench current into the sub-MeV RE current is feasible for abundant impurity injection.

  Note: Prompt conversion looks tolerable for the plasma position control. The subsequent slow decay of the RE current should follow the near-threshold regime governed by the impurity amount.

- RE formation is less efficient at high pre-quench temperatures (>4keV), which should produce significant radial variation of the runaway seed (in contrast with the present-day < 4keV experiments, where REs are peaked at the core).

- Non-uniformity of the plasma allows the post-quench current to be carried by two distinct runaway populations (a sub-MeV and an ultra-relativistic).

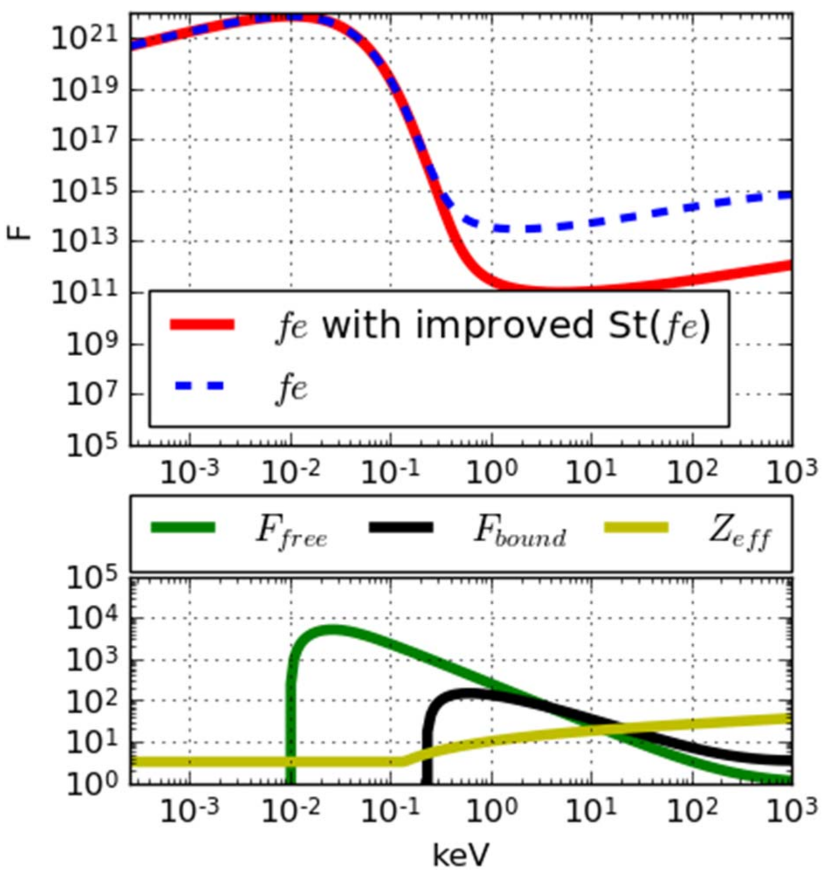
- [P.Aleynikov, B.N.Breizman, Generation of runaway electrons during the thermal quench in tokamaks, Manuscript submitted for publication]

- 1D seed + avalanche calculations are ongoing

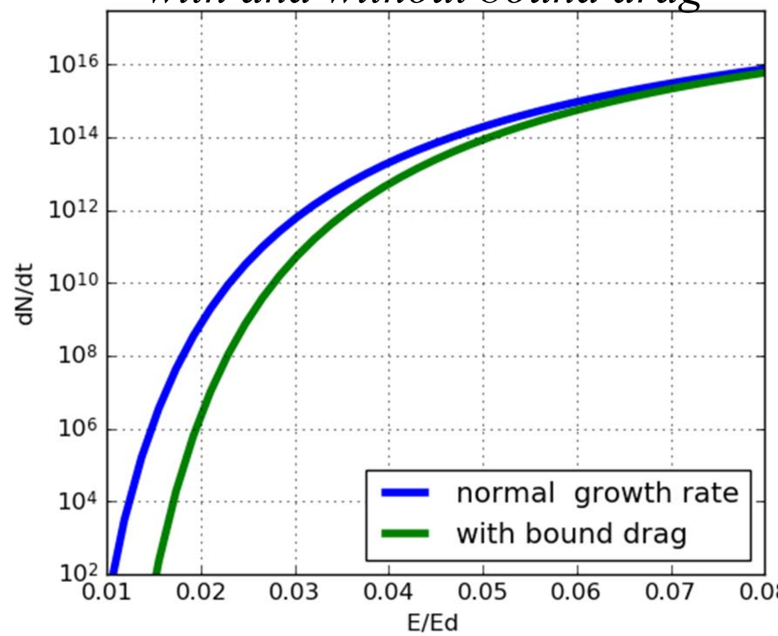
Extra

Dreicer mechanism in presence of high-Z impurities

- As electrons accelerate they start to interact with bound electrons and scatter on shielded high-Z impurities, unlike thermal electrons.
- **"Extra" friction reduces the Dreicer flow**
- The effect is less pronounced at high electric field



Dreicer rate dependence on electric field with and without bound drag



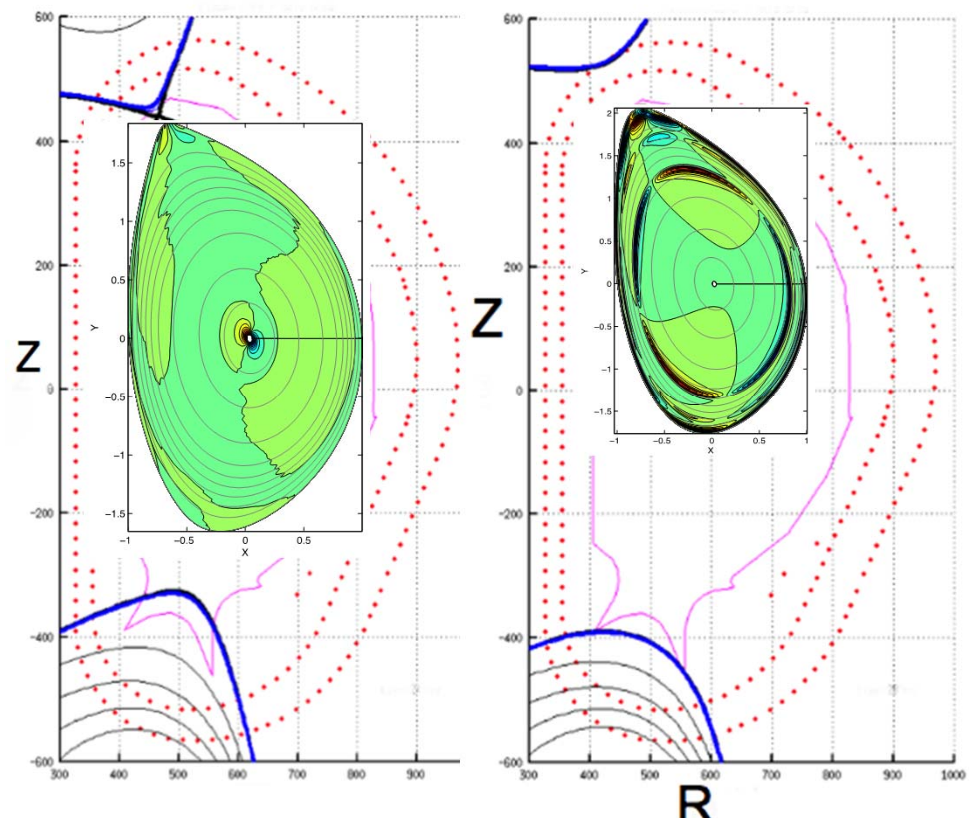
[Ismailov, Aleynikov, Konovalov, "Dreicer mechanism of runaway electron generatio in presence of high-Z impurities", EPS 2016]

MHD stability of post-disruption plasmas in ITER

- 2D plasma evolution with DINA
- Linear MHD stability analysis of unperturbed equilibrium with CASTOR and MISHKA

- A variety of different modes can appear in post-disruption plasma with RE

- Results are sensitive to the RE seed profile



[K. Aleynikova, G.T.A. Huijsmans, P. Aleynikov, *Linear MHD stability analysis of post-disruption plasmas in ITER*, Plasma Physics Reports **42** (2016)]

DIII-D QRE modeling

- Experimental data is used to calculated the evolution of the distribution function
- The time-dependent kinetic equation is solved numerically

Without the avalanche a clear bump is formed around p_{max} after the puff

DIII-D QRE modeling

- Experimental data is used to calculated the evolution of the distribution function
- The time-dependent kinetic equation is solved numerically

With avalanche the bump almost disappears