Runaway electrons in disruptions: sliding and screening

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on behalf of the
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Runaway team




Ola Embréus	**Linnea Hesslow**	**Mathias Hoppe**	**George Wilkie**
PhD student	*PhD student*	*PhD student*	*Postdoc*

- Ola: Close collisions, Bremsstrahlung
- Linnea: Partial screening effects
- Mathias: Synthetic synchrotron diagnostics
- George: Self-consistent electric field

Tools available for runaway studies at Chalmers

- 0D2P relativistic Fokker-Planck solvers

  CODE – runaway electrons, linearized collision operator
  - synchrotron radiation
  - Bremsstrahlung
  - effect of partial screening NEW!
  - Rosenbluth-Putvinskii, Chiu-Harvey, Boltzmann avalanche operator

  NORSE – nonlinear collision operator NEW!

  CODION – runaway ions

- Radiation

  SOFT – synthetic synchrotron diagnostics NEW!

  SYRUP – synchrotron spectra

Outline

NORSE: NOn-linear Relativistic Solver for Electrons

Motivation

- The more runaways, the bigger the problem
- Existing tools break down when more than a few % runaways
- Such RE densities obtainable in experiments

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Features

- 2D in momentum space, no spatial dependence
- Full Braams & Karney collision operator
- Arbitrary electric field strengths
- Radiation reaction
- Time-dependent plasma parameters

Benchmark: relativistic weak-field conductivity

- Braams & Karney list conductivities
  - weak-field
  - large T range
  - same collision operator

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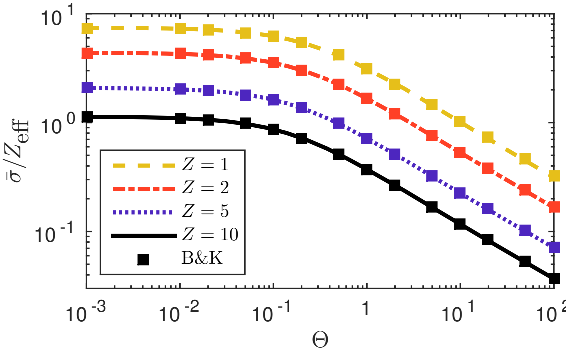
  - weak-field
  - large T range
  - same collision operator
- NORSE reproduces these perfectly



$\bar{\sigma}$: normalized conductivity

$\Theta = T/m_e c^2$

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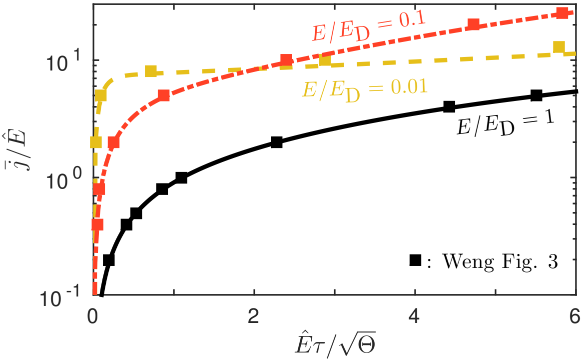
Benchmark: conductivity in strong fields

- Comparison to Weng et al. [PRL **100**, 185001 (2008)]
- They calculate modified Spitzer conductivity in strong E field
- Non-relativistic
- Nice agreement!

(Numerical heating in Weng's data for $E/E_{\mathrm{D}} = 0.01$)



$\bar{j}/\hat{E}$: normalized conductivity
$\hat{E}\tau/\sqrt{\Theta}$: normalized time

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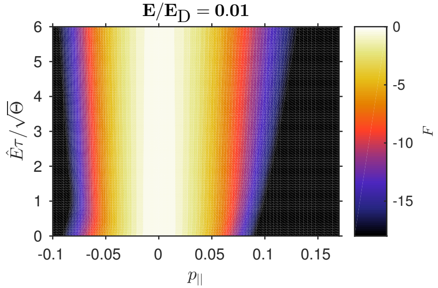
Distribution evolution



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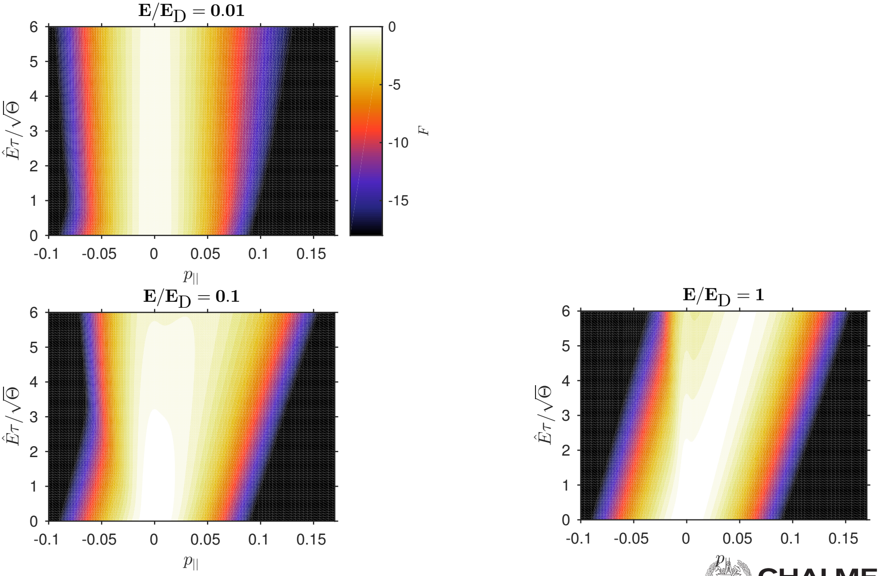

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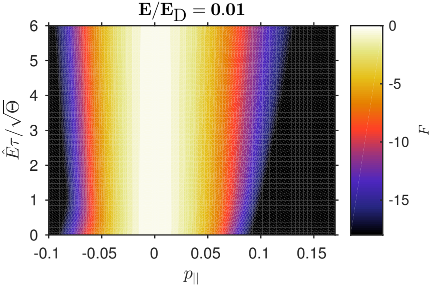

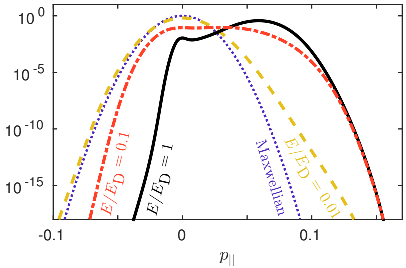

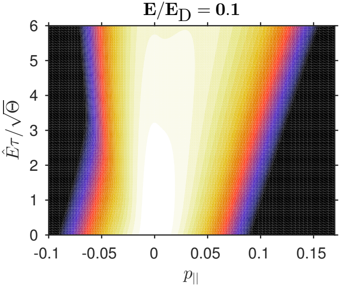

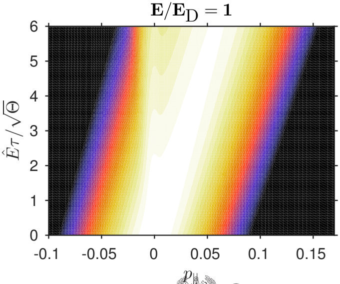

Bulk heating

- E field is a source of heat!
  - Must be removed in a linear treatment
  - Automatically accounted for in NORSE
- In practice bulk keeps temperature or even cools – a heat sink is useful

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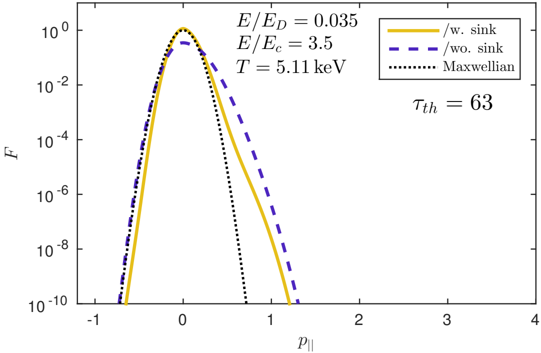

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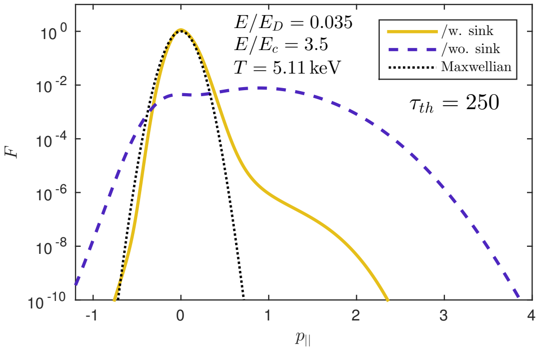

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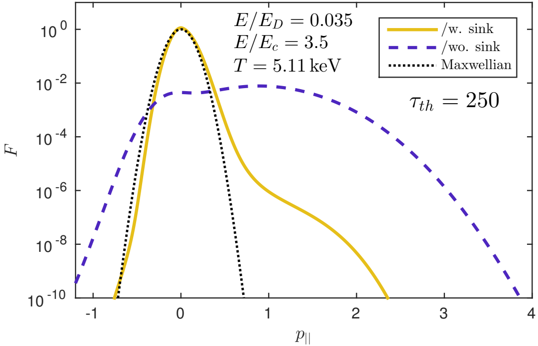

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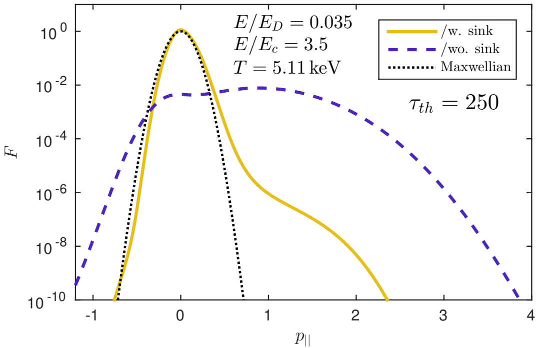

Current evolution and transition to slide-away is highly sensitive to the details of the sink!

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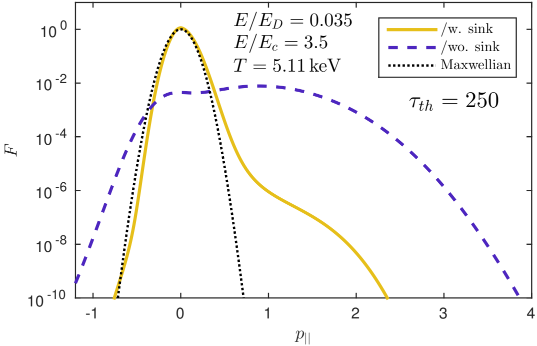

Current evolution and transition to slide-away is highly sensitive to the details of the sink!

Slide-away: Net parallel force experienced by electrons is positive in the entire momentum space.

Electric field

An ITER-like scenario calculated by GO [Smith et al (2006)]

- GO: generation of runaway electrons coupled to a diffusion equation for the electric field.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial E}{\partial r}\right) = \mu_0 \frac{\partial}{\partial t}\left(\sigma_{\|} E + n_r ec\right)$$

and

$$\frac{\partial n_r}{\partial t} = \left(\frac{\partial n_r}{\partial t}\right)^{Dreicer} + \left(\frac{\partial n_r}{\partial t}\right)^{avalanche}$$

- $T_e^{final} = 10\ \mathrm{eV}$, $B = 5.3\ \mathrm{T}$, $Z_{\mathrm{eff}} = 1$, $j_0 = 0.62\ \mathrm{MA/m^2}$, thermal quench time 1 ms.

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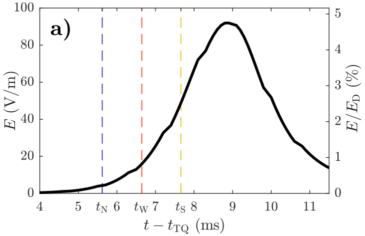

Electric field in V/m and normalized to the Dreicer field after the thermal quench.

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Transition to slide-away depends on the heat-sink

- **No heat sink**: all energy supplied by the electric field remains.
- **Weak heat sink**: the energy-removal rate of the heat sink is restricted to 0.5 MW/m^3
- **Strong heat sink**: keep the bulk temperature at 10 eV; any excess heat in the bulk region is removed

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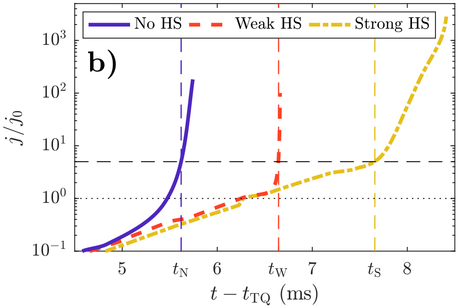

Normalized current density in the different heat-sink scenarios. Current density becomes half of the original at t_N (no HS), t_W (weak HS) and t_S (strong HS).

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Runaway electron population

- Maximum particle energies depend on the heat-sink scenario.
  - **No HS** and **weak HS**: particle do not reach relativistic energies
  - **Strong HS**: particle energies of 22 MeV are reached just before slide-away.

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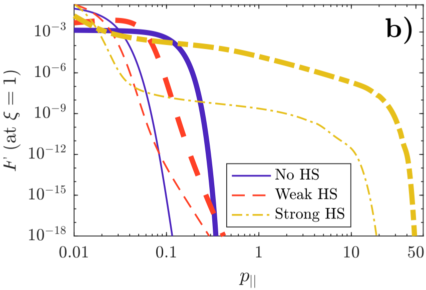

Tail of the parallel electron distribution. Thin lines f at t_N (no HS), t_W (weak HS) and t_S (strong HS), and thick lines f immediately before the transition to slide-away.

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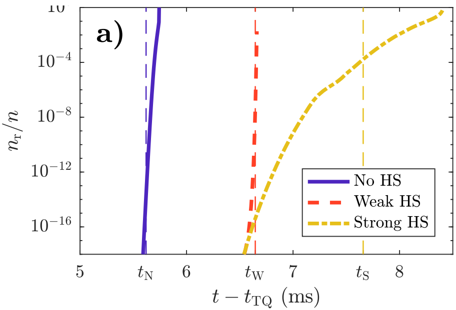
Runaway electron population

- Maximum particle energies depend on the heat-sink scenario.
  - **No HS** and **weak HS**: particle do not reach relativistic energies
  - **Strong HS**: particle energies of 22 MeV are reached just before slide-away.
- In the **strong HS** case the n_r/n grows more slowly and the runaways have time to reach high energies.



Runaway fraction

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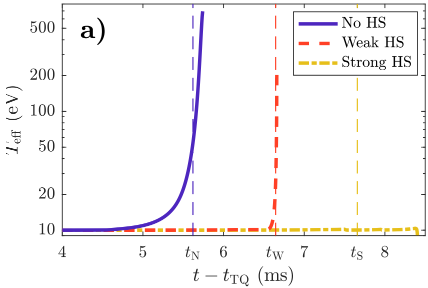
Feedback loop

- Collisional friction is lower in a hotter distribution
- Dreicer field is $\propto 1/T$.
- For a given field strength E/E_D increases as the bulk heats up.
- Decreasing n_{bulk} also leads to a positive feedback.
- Eventually the friction becomes low enough that the parallel balance of forces becomes positive everywhere: Slide-away!



Effective temperature of the bulk population

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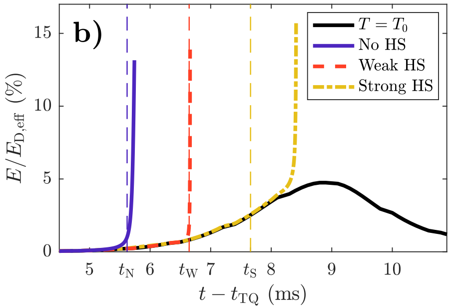

Effective normalized E-field strength

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Summary

NORSE [Stahl et al CPC (2017)]

- Relativistic, non-linear electron dynamics
- Radiative effects, time-dependent scenarios
- Efficient, freely available

Non-linear effects

- Conductivity different from Spitzer for strong fields
- Large heating of electron bulk by parallel E-field
- Slide-away at much weaker electric fields than previously expected.

Heat-sink

- Severity of disruptions can be affected by the properties of heat sink.

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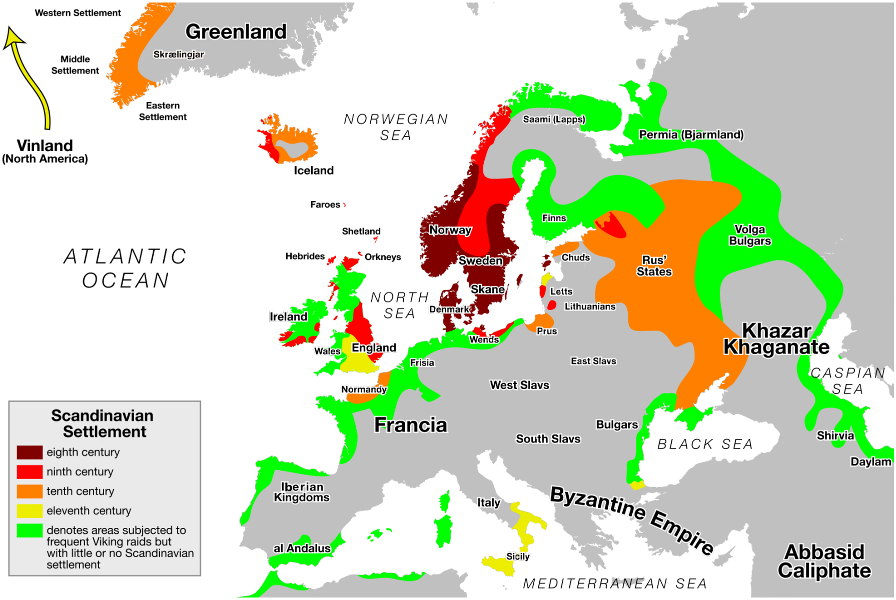
Western Settlement
Middle Settlement
Eastern Settlement
Greenland
Skrælingjar
Vinland
(North America)
NORWEGIAN SEA
Iceland
Faroes
Shetland
Orkneys
Hebrides
ATLANTIC OCEAN
Saami (Lapps)
Permia (Bjarmland)
Finns
Norway
Sweden
Chuds
Rus' States
Volga Bulgars
Skane
Letts
Lithuanians
NORTH SEA
Denmark
Ireland
Wales
England
Wends
Prus
Khazar Khaganate
Frisia
East Slavs
CASPIAN SEA
Normandy
West Slavs
Francia
Bulgars
South Slavs
BLACK SEA
Shirvia
Daylam
Iberian Kingdoms
Italy
Byzantine Empire
al Andalus
Sicily
MEDITERRANEAN SEA
Abbasid Caliphate
Scandinavian Settlement
eighth century
ninth century
tenth century
eleventh century
denotes areas subjected to frequent Viking raids but with little or no Scandinavian settlement

Outline

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Effect of partial screening

- Disruption mitigation via material injection: typically $n_Z > n_D$.
- In the cold post-disruption plasma, impurities are weakly ionized.
- Collision frequencies for fast electrons are expected to be enhanced.

Previous work

- **Elastic collisions**: Thomas–Fermi theory (limited to intermediate distances from the nucleus, and does not capture the shell structure of the ion): [Kirillov et al Fizika Plazmy (1975)] and [Zhogolev and Konovalov VANT (2014) **in Russian**]
- Kinetic simulations in [Aleynikov et al, IAEA proceedings 2014] refers to [Zhogolev& Konovalov] for details.
- **Inelastic collisions**: Rosenbluth–Putvinski rule of thumb: half of the bound electrons [Rosenbluth and Putvinski, NF (1997)]
- **Stopping-power formula for inelastic collisions** was used in a test-particle approach in [Martin-Solis et al PoP (2015)].

Modelling of the effect of partial screening

- Generalized collision operator including the effect of partial screening

$$C^{e}_{test} = \nu_D \mathcal{L}(f_e) + \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^3\left(\nu_S f_e + \frac{1}{2}\nu_{\|} p \frac{\partial f_e}{\partial p}\right)\right]$$

- Model elastic collisions quantum-mechanically using density functional theory.
- Using kinetic simulations demonstrate the effect of partial screening on the distribution function, current decay and critical electric field.
- Analytical expression of the enhanced critical electric field.

[Hesslow et al, PRL (2017)]

Effect of partial screening

- Definitions
  - **Complete screening:** the electron interacts only with the net ion charge
  - **No screening:** the electron experiences the full nuclear charge
- **Elastic collisions**
  - Interaction strength proportional to the charge squared.
  - No screening enhances the interaction strength by a factor $X^2 = (Z/Z_0)^2$, where Z_0 is the ionization state and Z is the charge number of the nucleus.
- **Inelastic collisions** (leading to excitation of the ion)
  - Increase the effective electron density of the plasma, as experienced by the fast electron.
  - The rate of e-e collisions will be an order X larger.

Elastic collisions ν_D^{ei}

Cross section in Born approximation, valid for $v/c \gg Z\alpha$

$$\frac{d\sigma_{ej}}{d\Omega} = \left(\frac{r_0^2}{4p^4}\right)\left(\frac{\cos^2(\theta/2)p^2+1}{\sin^4(\theta/2)}\right)|Z_j - \boldsymbol{F_j(q)}|^2$$

$$\text{Form factor: } \boldsymbol{F_j(q)} = \int \rho_{e,j}(r)e^{-i\mathbf{q}\cdot\mathbf{r}/a_0}\,d\mathbf{r}$$

$q = \frac{2p}{\alpha}\sin(\theta/2)$, $p = \gamma\frac{v}{c}$, Z: atomic number, Z_0: net charge

Limits:

Low energy $|Z - F| \to Z_0$: **complete screening** (usual case)

High energy $|Z - F| \to Z$: **no screening** (interaction with nucleus)

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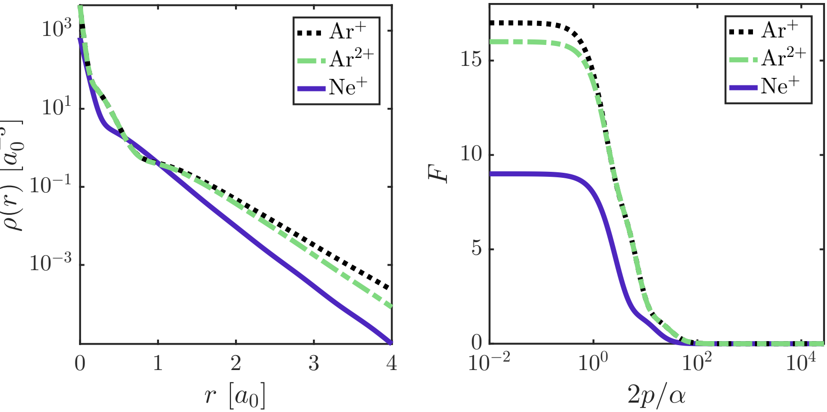
Elastic collisions: density and form factor

From density functional theory (DFT)



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Elastic collisions ν_D^{ei}

$$\nu_D^{ei} = \nu_{D,\mathrm{cs}}^{ei}\left(1 + \frac{1}{\sum_j n_j Z_{0,j}^2}\sum_j n_j Z_{0,j}^2 \frac{g_j(p)}{\ln\Lambda}\right)$$

completely screened
collision frequency

DFT simulations

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completely screened collision frequency

Full formula

$$g_j(p) = \int_0^1 \left(\frac{[Z_j - F_j(q)]^2}{Z_{0,j}^2} - 1\right)\frac{dx}{x}$$

DFT simulations

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TF-DFT model

$$g_j(p) = \frac{2}{3}(X_j^2 - 1)\ln(y_j^{3/2}+1) - \frac{2}{3}\frac{(X_j-1)^2 y_j^{3/2}}{y_j^{3/2}+1}$$

$X_j = Z_j/Z_{0,j}$

effective length a_j

$y_j = 2a_j p/\alpha$

DFT simulations

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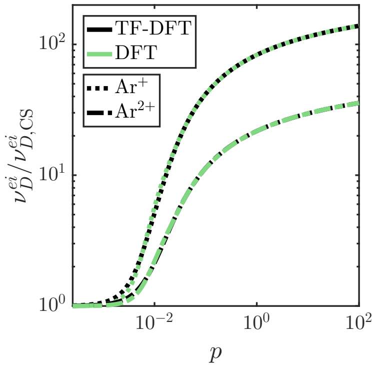
Enhancement of deflection frequency ν_D^{ei}

- Compare to completely screened
- Excellent agreement between analytical model (TF-DFT) and full DFT
- Significant effect already at $p \sim p_c \sim 0.1$
- $p \gg 1$: $\nu_D^{ei}/\nu_{D,\mathrm{CS}}^{ei} \sim (Z/Z_0)^2 \sim 10^2$
- Parameters: $T = 10\ \mathrm{eV}$, $n_{\mathrm{Ar}^+} = 10^{20}\ \mathrm{m}^{-3}$



$p = \gamma \frac{v}{c}$, $E = 10\ \mathrm{MeV} \leftrightarrow p = 20.$

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Inelastic collisions ν_S^{ee}

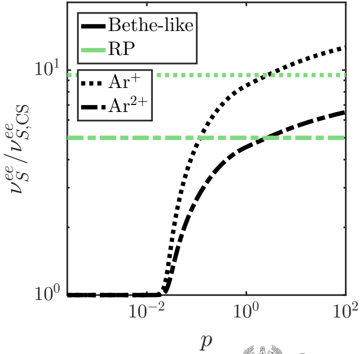
Bethe stopping power formula (matched with low energy asymptote)

$$\nu_S^{ee} = \nu_{S,\mathrm{cs}}^{ee}\left\{1 + \sum_j \frac{n_j N_{e,j}}{n_e \ln\Lambda}\left[\frac{1}{k}\ln\left(1+h_j^k\right) - \beta^2\right]\right\},$$

$h_j = p\sqrt{\gamma-1}/I_j$, $k=5$, $\beta = v/c$

I_j mean excitation energy [Sauer et al, Advances in Quantum Chemistry 2015]

- Rosenbluth–Putvinski rule of thumb: $\nu_{S,\mathrm{rp}}^{ee} \approx \nu_{S,\mathrm{cs}}^{ee}\left(1 + \frac{1}{2}\sum_j \frac{n_j}{n_e} N_{e,j}\right)$, where N_e is the number of bound electrons.
- RP rule of thumb leads to greater enhancement than the full formula up to $p \simeq 1$.



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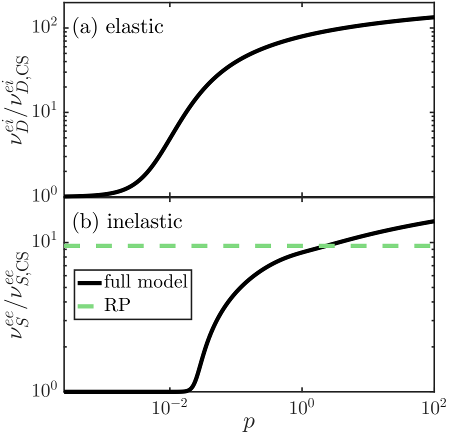
- Enhancement due to elastic collisions kicks in for lower momenta and is larger for high momenta than the corresponding one for inelastic collisions.



Parameters: $T = 10$ eV, $n_{\mathrm{Ar}^+} = 10^{20}$ m^{-3}

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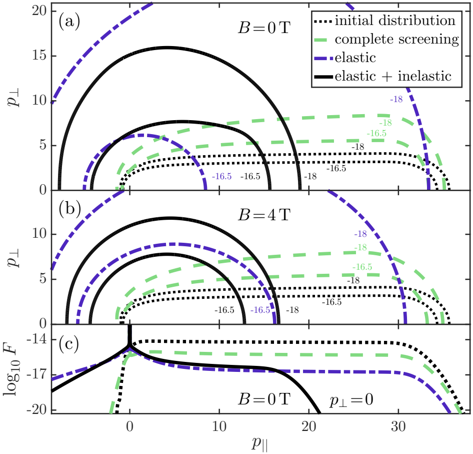
Effect on distribution function

- Implemented in CODE.
- Collisional deceleration of initial beam-like distribution.
- Contours of $\log_{10}(F)$, $F = (2\pi m_e T)^{3/2} f_e / n_e$
- Parameters: 25 ms collisional deceleration $T = 10$ eV, Ar^+, $n_{\mathrm{Ar}} = n_{\mathrm{D}} = 10^{20}$ m^{-3}



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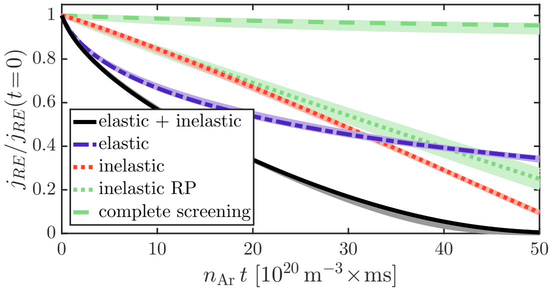
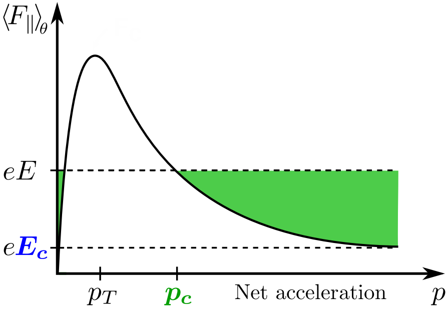
Current decay



- Same initial distribution as previous figure.
- Decay time is proportional to $1/n_{Ar}$ for $n_{Ar} \gtrsim n_D$.
- Bands represent $n_{\mathrm{Ar}} \in [0.5\, n_{\mathrm{D}}, 100\, n_{\mathrm{D}}]$.
- RP model underestimates the decay rate and shows a different current evolution.

Critical electric field

- Important for generation and decay
- Constant $\ln\Lambda$ and no screening or radiation effects: $E_c = \frac{n_e e^3 \ln\Lambda_0}{4\pi\epsilon_0^2 m_e c^2}$



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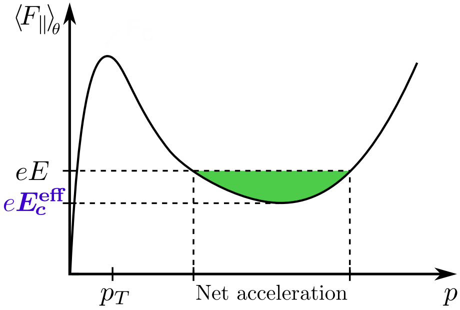
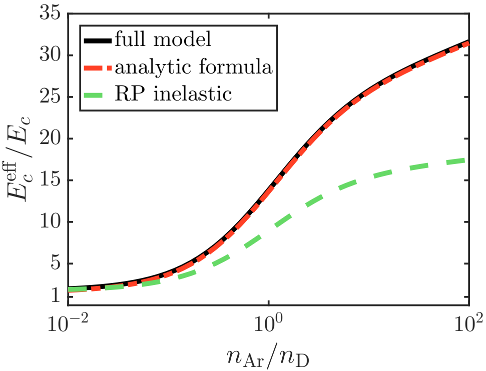
- E_c enhanced by
  - Partially ionized atoms
  - Synchrotron radiation
  - Bremsstrahlung
  - Energy-dependent Coulomb logarithm $\ln\Lambda$



Enhanced critical electric field E_c^{eff}

- Large enhancement of E_c^{eff} due to partial screening
- Significant effect from elastic collisions
- RP model underestimates E_c^{eff}



$$\frac{E_c^{\text{eff}}}{E_c} \approx 1 + \frac{1}{\ln \Lambda_0}\left(7 - \ln\sqrt{T_{\text{eV}}} + 240\frac{n_{\text{Ar,tot}}}{n_e}\right)$$

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Derivation of E_c^{eff}

- Assume fast pitch-angle dynamics in Fokker–Planck equation:[1]

$$\frac{\partial \bar{f}}{\partial t} = \frac{\partial}{\partial p}\left[(p\nu_S - eE\xi)\bar{f}\right] + \frac{\partial}{\partial \xi}\left[(1-\xi^2)\underbrace{\left(\frac{eE}{pmc}\bar{f} + \frac{1}{2}\nu_D\frac{\partial \bar{f}}{\partial \xi}\right)}_{=0}\right]$$

where $\bar{f} = p^2 f$.

- Averaged force balance: $\langle eE_c^{\mathrm{eff}}\rangle = \min_p p\nu_S$
- Up to triply ionized argon[2] $n_{\mathrm{Ar}} \gtrsim 0.1 n_{\mathrm{D}}$ (synchrotron neglected)

$$\frac{E_c^{\mathrm{eff}}}{E_c} \approx 1 + \frac{1}{\ln\Lambda_0}\left(7 - \ln\sqrt{T_{\mathrm{eV}}} + 240\frac{n_{\mathrm{Ar,tot}}}{n_e}\right)$$

[1] Lehtinen et al, JGR (1999), Aleynikov and Breizman, PRL (2015)
[2] Hesslow et al, PRL (2017); Details in Hesslow et al, EPS (2017)

Simulate dissipation of runaway beam [1/2]

- Linear current decay predicted[1] : $-\dfrac{\partial j}{\partial t} \propto E \approx E_c^{\mathrm{eff}}$
- Implemented in Fokker–Planck solver CODE with 0-D inductive electric field[2]

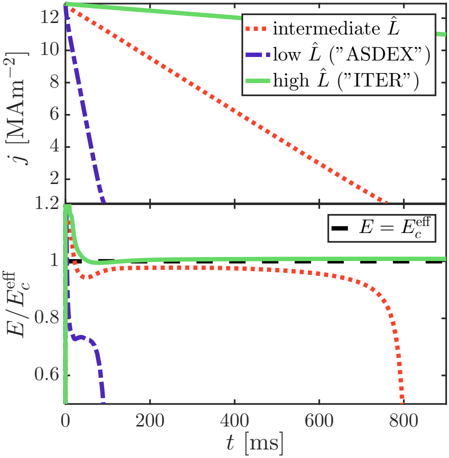
$$E = -\hat{L}\frac{\partial j}{\partial t}, \quad \hat{L} = \frac{AL}{2\pi R} \sim \frac{\mu_0 A}{2\pi}$$

- Forward-beamed initial distribution obtained by simulation with large E-field, average runaway energy: 17.2 MeV

[1]Breizman NF (2014)
[2]Wilkie et al in preparation; Stahl et al EPS P2.150

Simulate dissipation of runaway beam [2/2]

- Test $-\hat{L}\dfrac{\partial j}{\partial t} = E \overset{?}{\approx} E_c^{\text{eff}}$
- Good agreement at high inductance:
  $\rightarrow$ current decay rate is $\propto E_c^{\text{eff}}/\hat{L}$
- Enhanced $E_c^{\text{eff}} \Rightarrow$ faster dissipation
- Parameters: $T = 10$ eV, Ar^+ with $n_{\text{Ar}} = 4 n_{\text{D}}$, $n_{\text{D}} = 10^{20}$ m^{-3}, initial average runaway energy 17.2 MeV



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Summary: partial screening

Enhanced collision frequencies

- Analytical expressions for the deflection and slowing-down frequencies.
- Significant enhancement compared to complete screening, already at sub-relativistic electron energies.

Current decay time is reduced

- Low inductance case: current decay time is approximately half compared to the RP rule of thumb.
- High inductance case: current decay rate is $\propto E_c^{\mathrm{eff}}/\hat{L}$

Critical electric field

$$\frac{E_c^{\mathrm{eff}}}{E_c} \approx 1 + \frac{1}{\ln \Lambda_0}\left(7 - \ln\sqrt{T_{\mathrm{eV}}} + 240\frac{n_{\mathrm{Ar,tot}}}{n_e}\right)$$

Highlights

- Recent papers
  - NORSE: A solver for the relativistic **non-linear** Fokker-Planck equation for electrons in a homogeneous plasma
    [Stahl, Landreman, Embréus and Fülöp, CPC **212**, 269 (2017)]
  - Runaway-electron formation and electron **slide-away** in an ITER post-disruption scenario
    [Stahl, Embréus, Landreman, Papp and Fülöp, JPCS **775** 012011 (2016)]
  - Effect of **partially ionized impurities** on fast electron dynamics
    [Hesslow, Embréus, Stahl, DuBois, Papp, Newton and Fülöp, PRL **118**, 255001 (2017)]
- In preparation
  - SOFT: a synthetic **synchrotron diagnostic** for runaway electrons
    [M Hoppe et al]
  - On the relativistic **large-angle** electron collision operator for runaway avalanches in plasmas [O Embréus et al]

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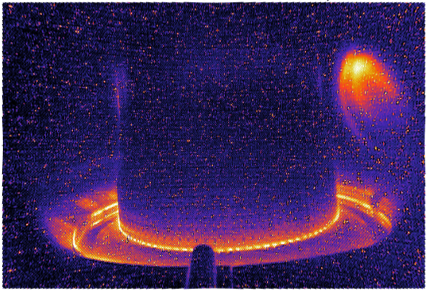
Outline

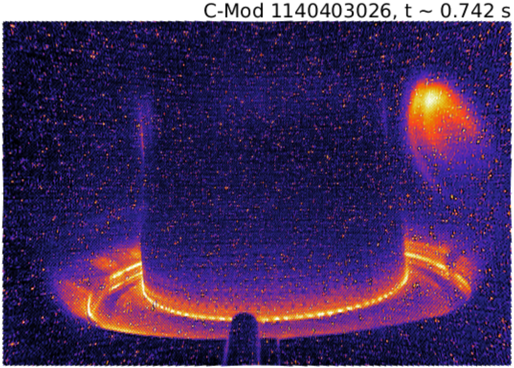
SOFT: Synthetic synchrotron diagnostics

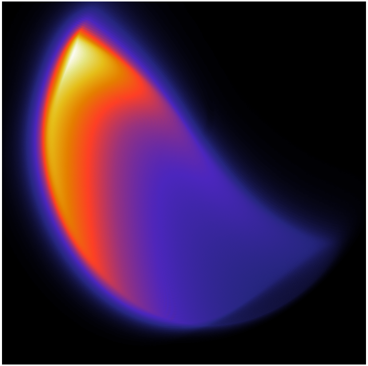
- SOFT – Synchrotron-detecting Orbit Following Toolkit
- Takes spectrum, camera location/size/viewing direction into account
- Uses experimentally obtained magnetic equilibria
- Solves the guiding-center equations of motion to distribute particles poloidally (accounts for geometric effects)
- Momentum-space distribution of runaways (e.g. obtained by CODE) given as input



Experimental image provided by A Tinguely and R Granetz

Strange synchrotron image? A case for SOFT!





M. Hoppe, et. al., *EPS 2017 conference*, (2017).

Spare slides

Heat-sink

- The total energy change can be written as

$$\frac{\mathrm{d}W}{\mathrm{d}t} = m_e c^2 \int_{\mathbf{\Omega}} \mathrm{d}^3 p \,(\gamma - 1)\left(-\frac{e\mathbf{E}}{m_e c} \cdot \frac{\partial f}{\partial \mathbf{p}} + \frac{\partial}{\partial \mathbf{p}} \cdot (\mathbf{F}_{\mathrm{s}} f) + k_{\mathrm{h}} \frac{\partial}{\partial \mathbf{p}} \cdot (\mathbf{S}_{\mathrm{h}} f) \right)$$

  from which k_{h} can be determined in each time step by demanding that $\mathrm{d}W/\mathrm{d}t = 0$.
- $\mathbf{S}_{\mathrm{h}}(p)$ is an isotropic function of momentum (a natural choice is a Maxwellian).
- The momentum space need not necessarily encompass the entire population domain.
- Im the figures $\mathbf{\Omega}$ is the bulk of the distribution, which was defined as all particles with $v < 4v_{Th0}$ where v_{Th0} is the thermal speed at the initial temperature.

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