Enabling Research Project

Tünde Fülöp

and

Ola Embréus, Eero Hirvijoki and Adam Stahl

Chalmers University of Technology

March 6, 2015

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Ion runaway:
Motivation

Low-mode number TAEs observed?

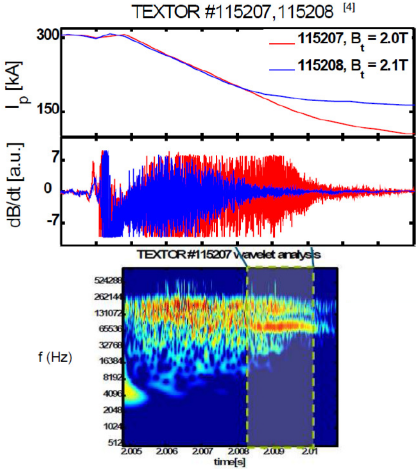
$$f \approx 60\text{-}260\,\mathrm{kHz}$$

Resonant velocity:

$$v_A/3 < v_{Te}$$

Runaway of ions responsible?

[Fülöp & Newton, PoP 21, 080702 (2014)]

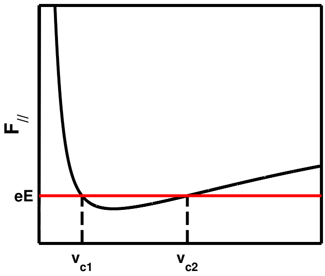


Largely analogous to electron runaway, but:

1. Non-monotonic friction
2. Non-monotonic distribution!

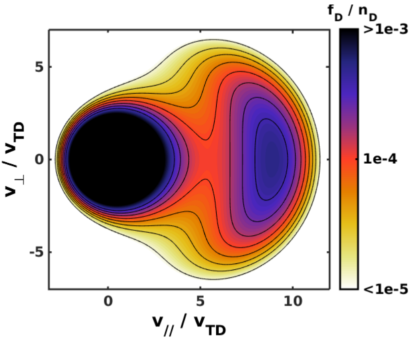
CODION:

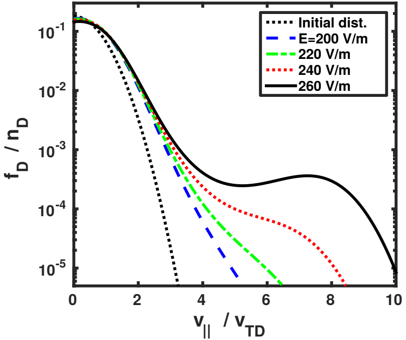
an extension of CODE to ions



Ion runaway:

Results





Typical runaway ion distribution exhibiting a large high-energy bump.

Bump energy too low to drive Alfvénic instabilities:

$$v_\mathrm{A}/3 \sim 30 - 50\, v_\mathrm{D}$$

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Force on a particle: The Lorentz-Abraham-Dirac force

$$\mathbf{K} = \frac{e^2\gamma^2}{6\pi\varepsilon_0 c^3}\left[\ddot{\mathbf{v}} + \frac{3\gamma^2}{c^2}\left(\mathbf{v}\cdot\dot{\mathbf{v}}\right)\dot{\mathbf{v}} + \frac{\gamma^2}{c^2}\left(\mathbf{v}\cdot\ddot{\mathbf{v}} + \frac{3\gamma^2}{c^2}\left(\mathbf{v}\cdot\dot{\mathbf{v}}\right)^2\right)\mathbf{v}\right],$$

Landau Approximation: insert the Lorentz force into $\mathbf{K}$, (no $\mathbf{E} - field$)

$$\mathbf{K} = -\nu_r\left(\mathbf{p}_\perp + \frac{p_\perp^2}{(mc)^2}\mathbf{p}\right) - \epsilon_B\,\nu_r\Omega^{-1}B^{-1}\dot{\mathbf{B}}\times\mathbf{p},\ \text{with}\ \nu_r = \frac{e^4B^2}{6\pi\varepsilon_0\gamma(mc)^3}$$

Guiding-center transformation: $Z^\alpha = (\mathbf{X}, p_\|, \mu)$, $\langle\,\cdot\,\rangle$ is the gyroaverage

$$\mathcal{K}^\alpha_{gc} = \left\langle\left\{\mathcal{T}_{gc}^{-1}x^i, Z^\alpha\right\}_{gc}\left(\mathcal{T}_{gc}^{-1}K_i\right)\right\rangle,$$

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Guiding-center radiation-reaction force

Gyro-averages

"Force" on spatial position: $\dot{\mathbf{X}}$ is the guiding-center velocity

$$\mathcal{K}^{\mathbf{X}} = -\epsilon_B \frac{\nu_r}{\Omega_\parallel^\star} \frac{2\mu B}{mc^2} \left(\hat{\mathbf{b}} \times \dot{\mathbf{X}} + 3 v_\parallel \, \varrho_\parallel \, \boldsymbol{\kappa} \right),$$

Force on the parallel momentum:

$$\mathcal{K}^{p_\parallel} = -\nu_r \, p_\parallel \frac{\mu B}{mc^2} \left(2 + \epsilon_B \varrho_\parallel \tau_B \right) - \epsilon_B \, \nu_r \frac{p_\perp \gamma^2}{2} \varrho_\perp \tau_B,$$

Force on the magnetic moment:

$$\mathcal{K}^{\mu} = -\nu_r \, \mu \left(1 + \frac{2\mu B}{mc^2} \right) \left(2 + \epsilon_B \varrho_\parallel \tau_B \right),$$

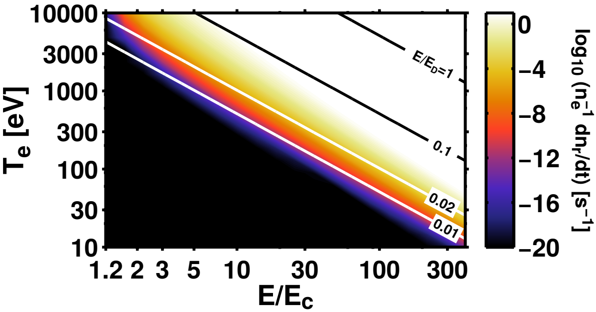
Definitions:

$$\varrho_\parallel = \frac{p_\parallel}{eB}, \; \varrho_\perp = \frac{p_\perp}{eB}, \; \Omega_\parallel^\star = \Omega \left(1 + \epsilon_B \varrho_\parallel \tau_B \right), \; \tau_B = \hat{\mathbf{b}} \cdot \nabla \times \hat{\mathbf{b}}, \; \boldsymbol{\kappa} = \hat{\mathbf{b}} \cdot \nabla \hat{\mathbf{b}}$$

Critical electric field for runaway electron generation:

- Experiments seem to show $E/E_c > 3-5$ needed for RE generation
- We study the RE dynamics using CODE
- RE growth rate strongly temperature dependent at fixed E/E_c
- Raises the *effective* critical field

At $T_e =$ 2–4 keV, a field of at least $E/E_c =$ 3–5 is needed for significant growth



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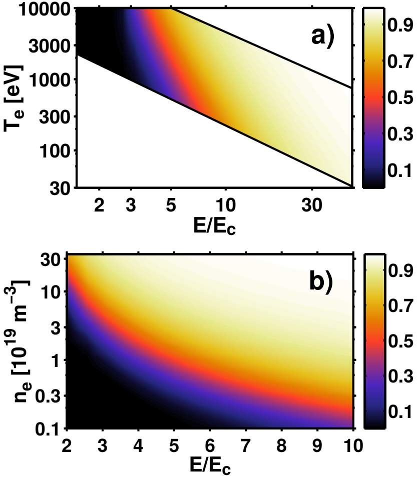
A. Stahl, E. Hirvijoki, J. Decker, O. Embréus and T. Fülöp,
Accepted for publication in PRL, http://arxiv.org/abs/1412.4608

Critical electric field for runaway electron generation:
Synchrotron back-reaction

- Classical critical field derivation only considers Coulomb collisions
- Synchrotron radiation back-reaction effectively introduces additional drag
- Leads to reduction in growth rate which can be very strong for weak electric fields
- Raises the effective critical field
- Strength of synchrotron effects $\propto B^2 T_e^{3/2} / n_e$
- Important at high temperature and low density

Plots show change in growth rate
$(\Gamma_{\text{w. synch}} / \Gamma_{\text{no synch}})$



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Critical electric field for runaway electron generation:

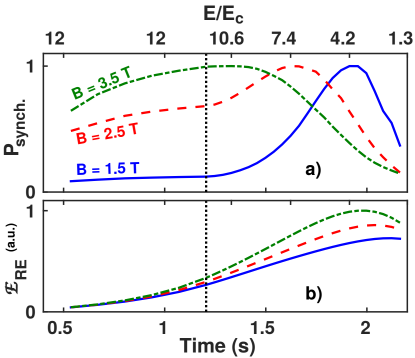
Growth-to-decay transition

- Experiments also considered transition from RE growth to decay
- Build up RE tail, then ramp down E/E_c (ramp up density)
- Visual synchrotron and HXR signals shows transition at $E/E_c = 3$–5

- Simulations show transition at only slightly above E_c (1.1)

BUT

- Synchrotron emission agrees with experiments!
- Emitted synchrotron power sensitive to particle energies and pitches
- Observed reduction is **not RE decay** but redistribution of REs in momentum space
- Runaways are still gaining energy when the emission declines



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Experiments showing increased threshold electric field for runaway growth can be explained by:

1. Temperature dependence of RE growth rate at fixed E/E_c
2. Dampening effect of synchrotron emission (to some extent)

Apparent elevated RE growth-to-decay threshold is likely an artifact due to:

- Redistribution of runaways in momentum space as the field strength decreases $\implies$
- Change in emitted synchrotron and bremsstrahlung power