Progress from the Chalmers group

Adam Stahl

REM Meeting
Pertuis, France
2015-06-17

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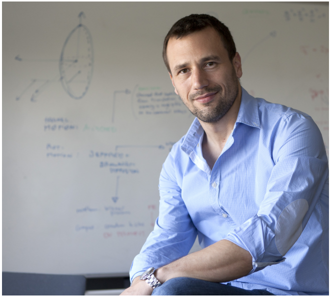
Ola Embréus **Eero Hirvijoki** **Tünde Fülöp** **Sarah Newton** **István Pusztai**



Joan Decker
Jubilee professor

Tools available for runaway studies at Chalmers

- Kinetics

  CODE – runaway electrons
  CODION – runaway ions

- Disruption modelling

  GO – 1D fluid code, consistent current and electric field evolution, atomic physics
  GO+CODE – see talk by Geri Papp (Thursday)

- Radiation

  SYRUP – synchrotron spectra
  DESERT – synchrotron detector images
  – Bremsstrahlung spectra

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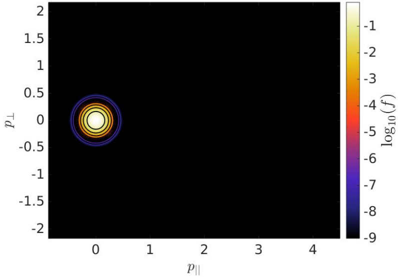
CODE (COllisional Distribution of Electrons)

Solves the kinetic equation for the electron distribution function

- 2D in momentum space, no spatial dependency
- Arbitrary electric field strength
- Fully relativistic
- Runaway generation
  - Dreicer
  - Avalanche
- Lightweight, continuum
- Very efficient steady-state solution



[Landreman, Stahl and Fülöp, CPC **185**, 847 (2014)]

Improvements to CODE

- Synchrotron radiation reaction
- Bremsstrahlung radiation reaction
- Improved avalanche operators
- GO+CODE-related
  - Time-dependent plasma parameters
  - Momentum conserving collision operator
  - More flexible input-handling
  - Automatic grid extensions
  - External runaways
- Full rewrite under way to improve usability

Synchrotron radiation reaction

- Electron emits synchrotron radiation – experiences reaction force. Acts as effective friction at high energies
- Derived from the Lorentz-Abraham-Dirac force under the assumption that magnetic force dominates dynamics ($F_m \gg F_E,\ F_{RR}$)
- Enters the kinetic equation as

$$\frac{\partial}{\partial \mathbf{p}} \cdot (\mathbf{F}_{\mathrm{rad}} f) = -\frac{1}{p^2}\frac{\partial}{\partial p}\left(\frac{\gamma p^3(1-\xi^2)}{\tau_r} f\right) + \frac{\partial}{\partial \xi}\left(\frac{\xi(1-\xi^2)}{\gamma \tau_r} f\right)$$

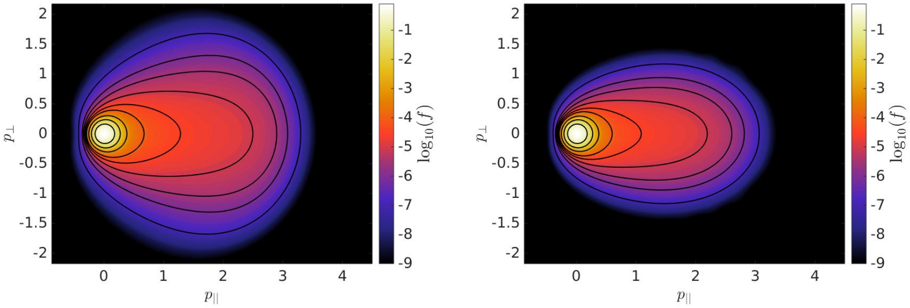
with

$$\tau_r = \frac{6\pi\varepsilon_0 (m_e c)^3}{e^4 B^2}, \quad p = \gamma v/c, \quad \xi = p_\parallel / p = \cos\theta$$

[Stahl, Hirvijoki, Decker, Embréus and Fülöp, PRL **114**, 115002 (2015)]

- Radiation reaction force leads to a flow towards lower particle momenta and smaller pitch-angles
- Reduces runaway rate
- Can lead to bump formation in RE tail [see talk by Joan Decker (Friday)]

Without radiation reaction **With radiation reaction**



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Outline

Critical field in E/E_c ramp-up

- Experiments show $E/E_c > 3 - 5$ needed for RE generation when ramping up E/E_c
  [Granetz, et al., Phys. Plasmas **21**, 072506 (2014),
  Paz-Soldan et al., Phys. Plasmas **21**, 022514 (2014)]
- We study the RE dynamics using CODE
- Two effects contribute to explain the observation

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- We study the RE dynamics using CODE
- Two effects contribute to explain the observation
  - **Dreicer growth rate strongly T_e dependent** at fixed E/E_c
    - $E/E_D > 1\%$–2% is required for substantial growth
    - Applies when starting from a Maxwellian
  - **Synchrotron radiation reaction** leads to reduction in growth rate for small E/E_c
    - Synchrotron effects important for high T_e and low n_e
    - Runaway dynamics qualitatively different in disruption and flat-top scenarios

[Stahl, Hirvijoki, Decker, Embréus and Fülöp, PRL **114**, 115002 (2015)]

What about E/E_c ramp-down?

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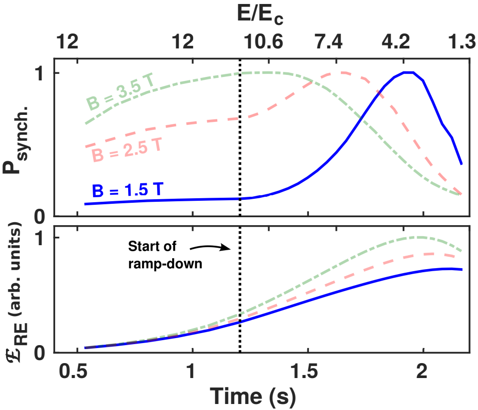
Runaway growth-to-decay transition

- Build up RE tail, then ramp down E/E_c
- In experiments, visual synchrotron and HXR signals transitions from growth to decay at $E/E_c = 3$–5
  [Paz-Soldan et al., Phys. Plasmas **21**, 022514 (2014)]
- Simulations (including avalanche generation) show transition in RE growth at only slightly above E_c (~ 1.1)

BUT

Runaway growth-to-decay transition

Synchrotron emission agrees with experiments!



[Stahl, Hirvijoki, Decker, Embréus and Fülöp, PRL **114**, 115002 (2015)]

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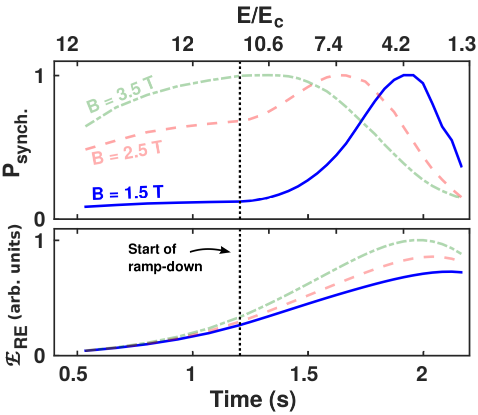
Runaway growth-to-decay transition

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



[Stahl, Hirvijoki, Decker, Embréus and Fülöp, PRL **114**, 115002 (2015)]

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Outline

Fast-electron Bremsstrahlung radiation reaction

- Runaways experience inelastic collisions with both ions and thermal electrons
- Bremsstrahlung is emitted – radiation reaction effectively an isotropic slowing-down force
- Accounted for by a model operator,
  $C_{\mathrm{B}}^{(m)} = -\frac{\partial}{\partial \mathbf{p}} \cdot \left(\mathbf{F}_{\mathrm{B}}(\mathbf{p}) f_e(\mathbf{p}) \right)$,
  chosen to get correct energy moment:
  $F_{\mathrm{B}}(p) = -\sum_b n_b \int \mathrm{d}\sigma_{e\text{-}b}\, \hbar\omega$

How does Bremsstrahlung emission affect runaway dynamics?

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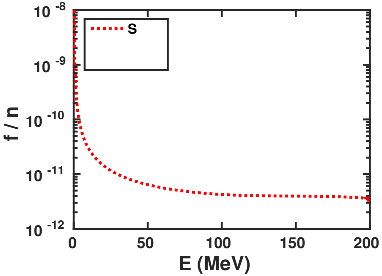
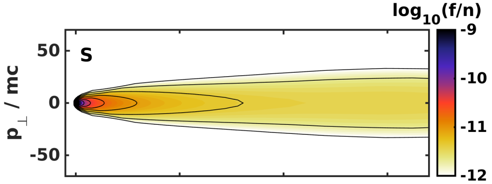
How does Bremsstrahlung emission affect runaway dynamics?

- Bremsstrahlung stopping power $< eE_c$ for energies below 100–200 MeV (for typical parameters)
- **Bremsstrahlung usually negligible** as often $E \gg E_c$ in disruptions

Effects of Bremsstrahlung radiation reaction





Parameters:

$n_e = 1 \cdot 10^{20}$ m^{-3}, $T_e = 10$ keV,
$B = 0.5$ T, $E/E_c = 2$, $Z_{\rm eff} = 3$

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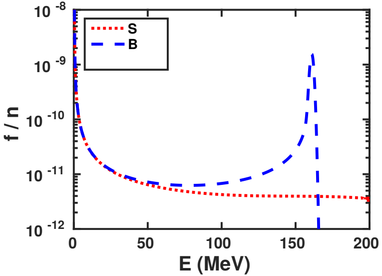

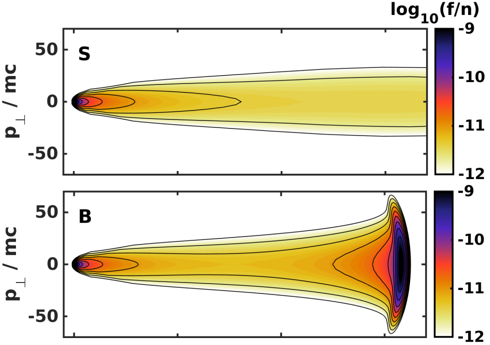

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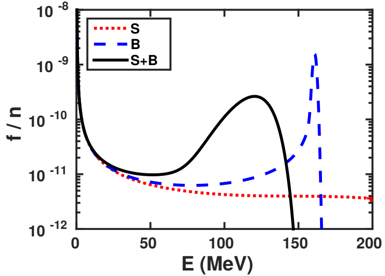

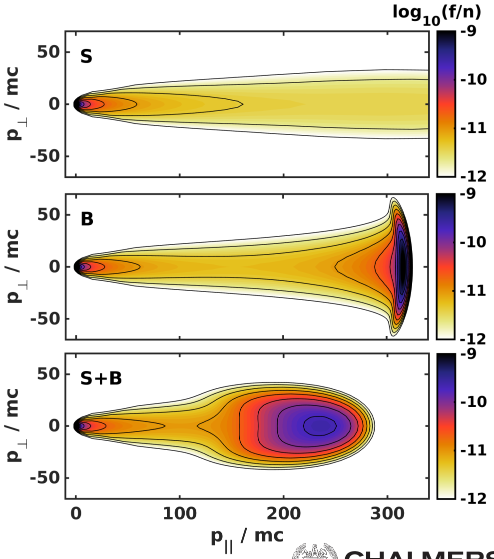

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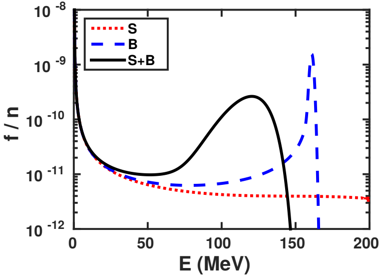

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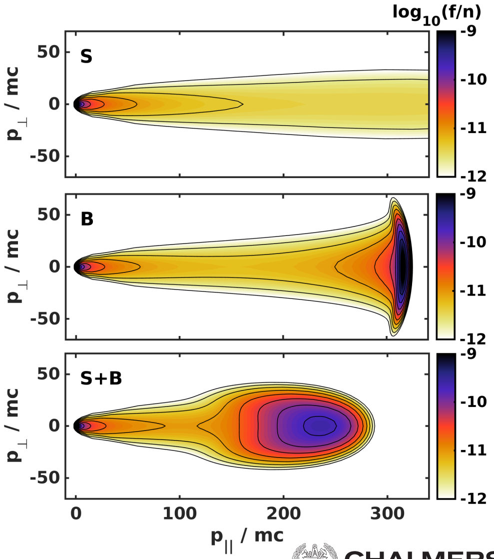
Bremsstrahlung increases pitch-angle scattering – can significantly affect the distribution function!



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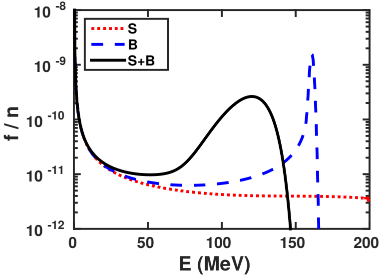

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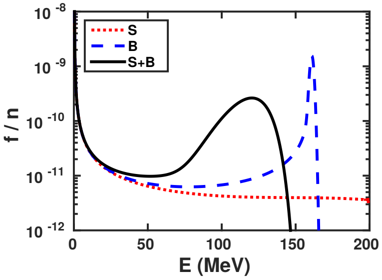
Parameters:

$n_e = 1 \cdot 10^{20}$ m^{-3}, $T_e = 5$ keV,
$B = 2$ T, $E/E_c = 3$, $Z_{\text{eff}} = 3$

Effects of Bremsstrahlung radiation reaction



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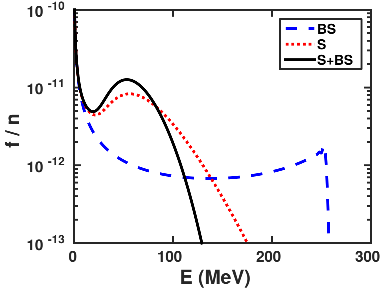

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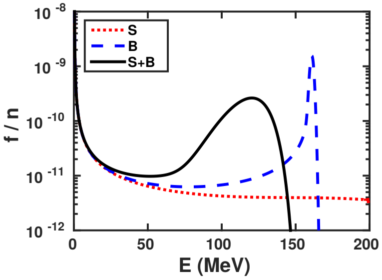

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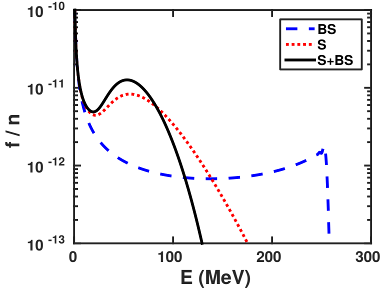

Parameters:

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Conclusion: Bremsstrahlung significant when $E \sim E_c$ and B small.

Work in progress: Study characteristics of emitted radiation

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Outline

Rosenbluth-Putvinski operator

- Knock-on collision = large-angle collision
- A runaway can transfer a large amount of momentum to another particle in one collision – can lead to avalanche
- If we let $p \to \infty$ for incoming particle, the source is

$$S_{\mathrm{RP}}(p, \xi) = \frac{n_r \nu_{\mathrm{rel}}}{4\pi \ln \Lambda} \delta(\xi - \xi_2) \frac{1}{p^2} \frac{\partial}{\partial p} \left(\frac{1}{1 - \sqrt{1 + p^2}} \right)$$

[Rosenbluth and Putvinski, Nucl. Fusion **37**, 1355 (1997)]

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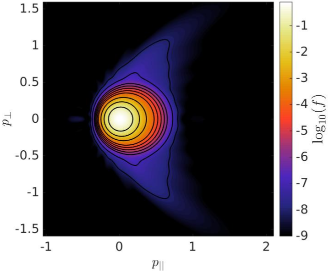
[Rosenbluth and Putvinski, Nucl. Fusion **37**, 1355 (1997)]

Problems:

- $\propto n_r$ – all runaways considered to have infinite momentum
- Secondary runaways can be generated with higher energy than any of the existing runaways!
- No change to incoming particle in collision – does not conserve particle number, energy or momentum
- δ-function in ξ gives oscillations (numerical)



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Chiu-Harvey operator

An improved operator is available!

$$S_{\rm CH}(p,\xi) \propto \frac{p_{\rm in}^4 f_{\xi=1}(p_{\rm in}) \sum(\gamma,\gamma_{\rm in})}{\gamma p \xi},$$

Σ is the Møller scattering cross-section
$f_{\xi=1}$ is pitch-angle averaged distribution

[S.C. Chiu, et al., Nucl. Fusion **38**, 1711 (1998), R.W. Harvey et al., Phys. Plasmas. **7**, 4590 (2000)]

Improvements:

- Finite p_{in}
- Secondary particle momenta restricted by kinematics
- No δ-function in ξ

Unresolved:

- All incoming runaways have $\xi = 1$ ($\theta = 0$)
- No change to incoming particle – not conservative
- Arbitrary lower cutoff in p to avoid double-counting FP collisions

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Fully conservative operator

- Start from the Boltzmann equation to make operator
  - fully consistent with FP collisions
  - conservative
- Apply buckets of algebra and angle transformations
- Source term reduces to S_{CH}, with $f_{\xi=1} \to f$
- Sink terms are added, integration boundaries are changed

Improvements:

- Uses full distribution for incoming particles (not pitch-averaged)
- Conserves particles, energy and momentum
- No double-counting of FP collisions

Unresolved:

- Some numerical issues remain

Work in progress!

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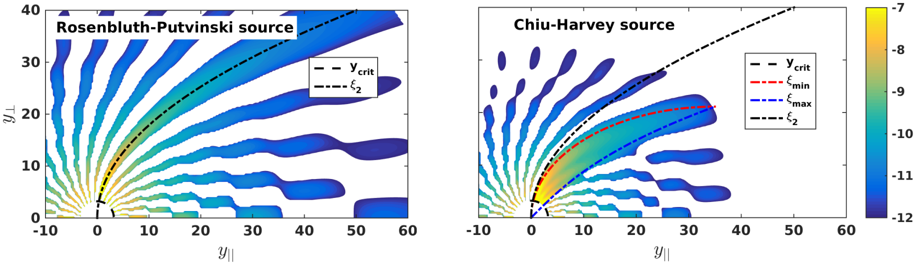
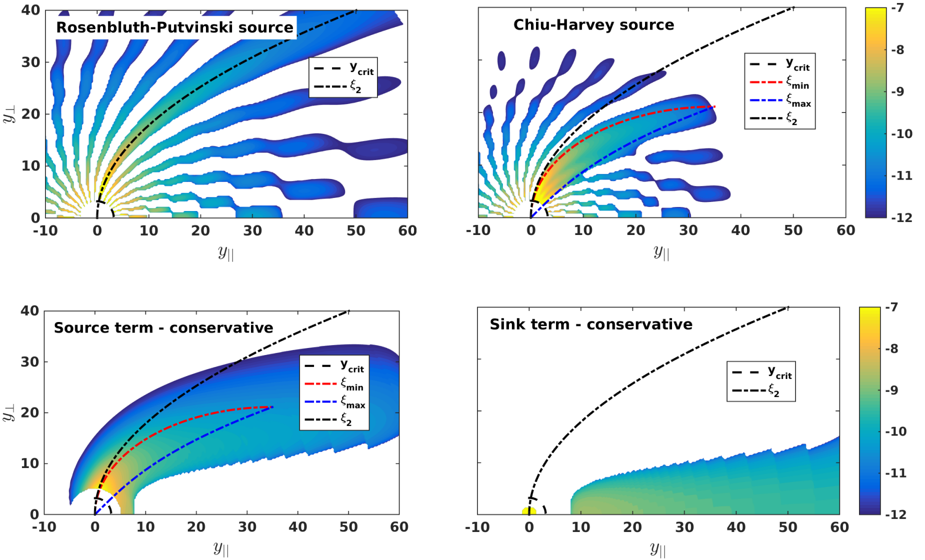

Rosenbluth-Putvinski source
Chiu-Harvey source
y_crit
ξ_2
ξ_min
ξ_max
y_⊥
y_||
-7
-8
-9
-10
-11
-12

$$y = \gamma v / v_{Th}$$



$$y = \gamma v / v_{Th}$$

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Outline

Dynamics of runaway ions – CODION

Motivation: Are runaway ions responsible for observed low mode number TAEs? [Fülöp & Newton, PoP **21**, 080702 (2014)]

- Largely analogous to electron runaway
- Use CODION to study ion distribution – adaptation of CODE
- Significant improvement over analytical models!

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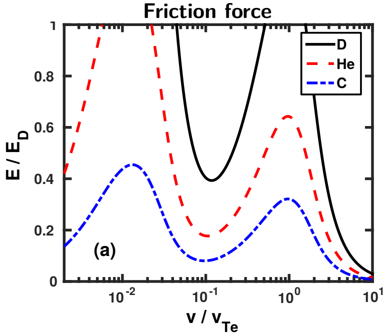


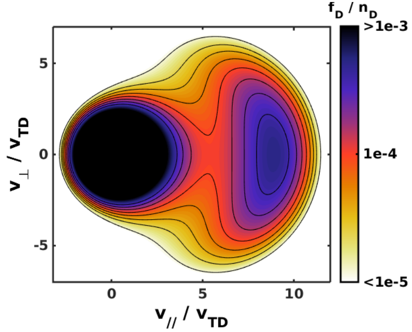
- Key difference to electron runaway: multiple peaks in friction force
- Direction of acceleration depends on Z/Z_{eff}

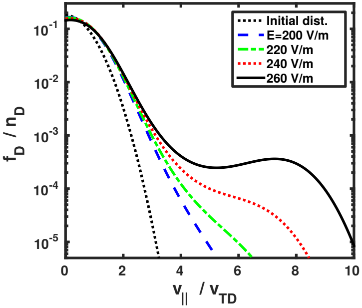
Parameters:

$n_C/n_D = 0.4\%$, $n_{He}/n_D = 5\%$, $Z_{\text{eff}} = 1.2$

[Embréus, Newton, Stahl, Hirvijoki and Fülöp, Phys. Plasmas **22**, 052122 (2015)]

Dynamics of runaway ions – Results

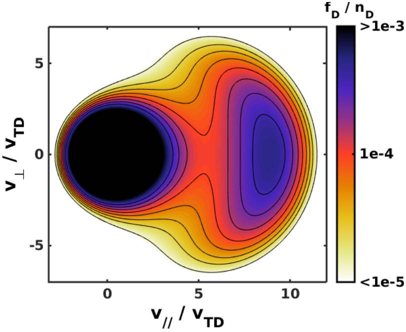


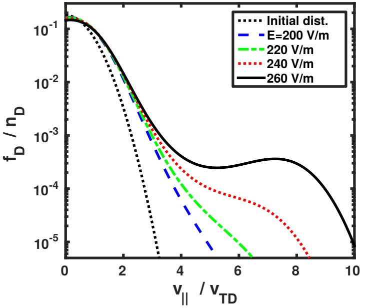


- Typical runaway ion distribution exhibiting a large high-energy bump.
- D distribution after 2 ms of acceleration in disruption

[Embréus, Newton, Stahl, Hirvijoki and Fülöp, Phys. Plasmas **22**, 052122 (2015)]

Dynamics of runaway ions – Results





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

- D distribution after 2 ms of acceleration in disruption
- Here, $v_A/3 \sim$ 30-50 v_{TD}

Runaway ion energy too low to drive Alfvénic instabilities!

[Embréus, Newton, Stahl, Hirvijoki and Fülöp, Phys. Plasmas **22**, 052122 (2015)]

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Outline

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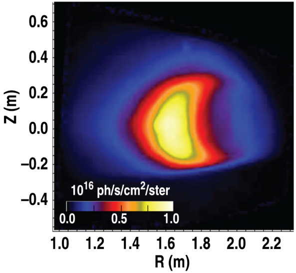
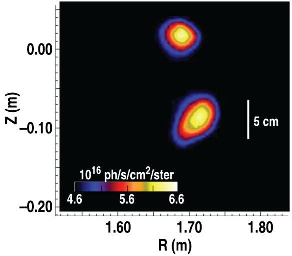
Synchrotron detector images

- Interesting synchrotron spot shapes observed in DIII-D, EAST
  [Yu, et al., Phys. Plasmas **20**, 042113 (2013), Zhou, et al., PPCF **55**, 055006 (2013)]
- What can these shapes tell us about the RE beam?
- **Spot shape not trivially related to spatial distribution of REs!** Depends also on
  - *q*-value
  - beam density profile
  - momentum space distribution
    - pitch
    - emitted synchrotron power
- Investigated by BSc students





[Yu, et al., Phys. Plasmas **20**, 042113 (2013)]

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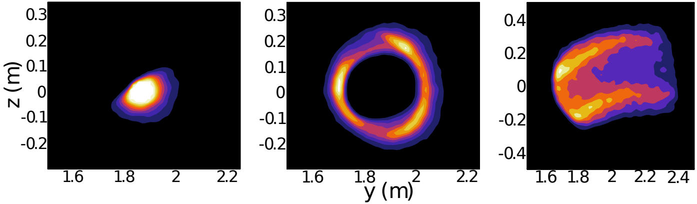
DESERT – DEtected Synchrotron Emission from Runaways in a Torus

- Method based on earlier work
  [Pankratov, Plasma Phys. Rep. **22**, 535 (1996), Zhou et al., Phys, Plasmas **21**, 063302 (2014)]
- Extended to include
  - more general validity
  - runaway distributions
  - intensity-dependence in detector image

Work in progress!

Teaser:



Parameters:

From EAST shot,
RE beam radius 30 cm,
Experimental q profile,
Distribution of particle energies and pitches

[M. Nordin, M, Johansson and O. Jaldehag, *Simulering av synkrotronstrålning från runaway-elektroner i fusionsplasma*, BSc thesis, Chalmers University of Technology/Gothenburg University (2015)]

Outline

Conclusions – recent work at Chalmers

Elevated critical electric field can largely be explained by

- Temperature dependence of RE growth rate
- Synchrotron radiation damping of RE growth rate
- Redistribution of electrons in momentum space (for E/E_c drop)

Bremsstrahlung has small effect on runaway distribution

except when E/E_c close to unity and B is small

- Can lead to sharp non-monotonic features
- Can have unexpected synergies together with synchrotron RR

Conservative knock-on collision operator – Work in progress!

- Derivation based on Boltzmann operator performed
- Several issues with current operators are resolved

Conclusions – recent work at Chalmers

Runaway ion dynamics

- Successfully treated numerically
- Not likely to drive TAEs in tokamaks

Other/works in progress

- Looking into synchrotron detector images
- GO+CODE [talk by G. Papp]
- Bump-on-tail in RE distributions [talk by J. Decker]

Recent papers

CODE: [Landreman, Stahl and Fülöp, CPC **185**, 847 (2014)]
Critical field: [Stahl, Hirvijoki, Decker, Embréus and Fülöp, PRL **114**, 115002 (2015)]
Runaway ions: [Embréus, Newton, Stahl, Hirvijoki and Fülöp, Phys. Plasmas **22**, 052122 (2015)]
Bump-on-tail: [Hirvijoki, Pusztai, Decker, Embréus, Stahl and Fülöp, to appear in J. Plasma Phys.,
Decker, Hirvijoki, Embréus, Peysson, Stahl, Pusztai and Fülöp, arxiv.org/abs/1503.03881]
EXEL-wave: [Pokol, Kómár, Budai, Stahl and Fülöp, Phys. Plasmas **21**, 102503 (2014)]