Energy dependence of runaway electron transport in perturbed fields

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EUROfusion

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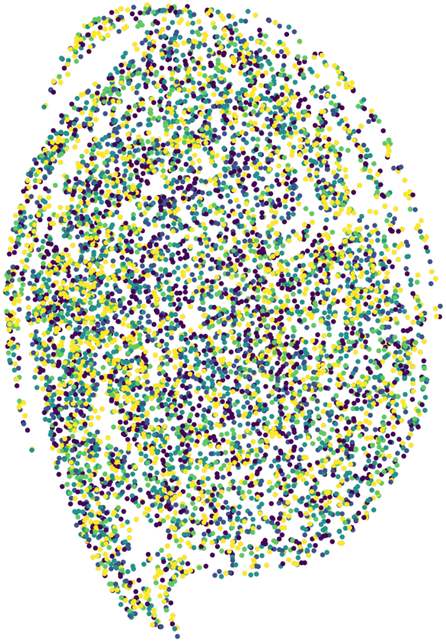
Stochastic field increases runaway electron losses

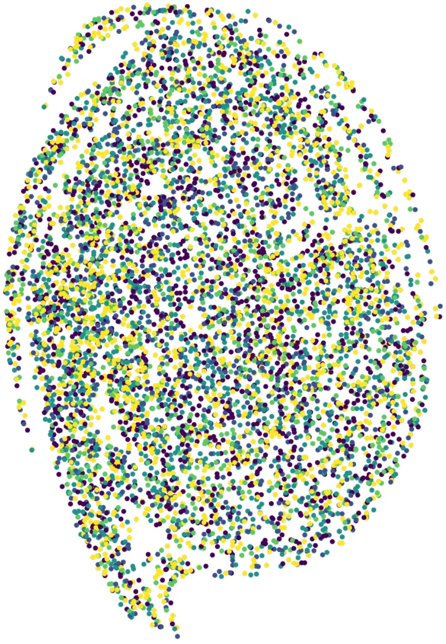
- Field fully stochastic after thermal quench.
- How the seed population is affected?



P. Helander et al, *Suppression of runaway electron avalanches by radial diffusion*, 2000

Stochastic field increases runaway electron losses

- Field fully stochastic after thermal quench.
- How the seed population is affected?
- Reduced kinetic model + coefficients capturing transport due to 3D field.



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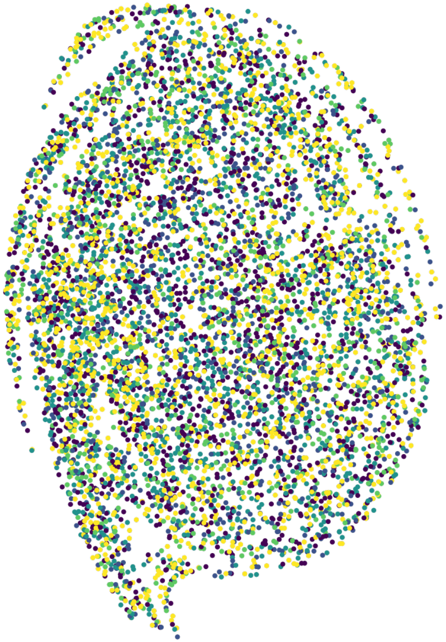

But!

- Transport lower in experiments than the Rechester-Rosenbluth diffusion.

I. Entrop et al, *Diffusion of runaway electrons in TEXTOR-94*, 1997

P. J. Catto et al, *Estimating the runaway diffusion coefficient in the TEXT tokamak from shift and* externally applied resonant magnetic-field experiments, 1991

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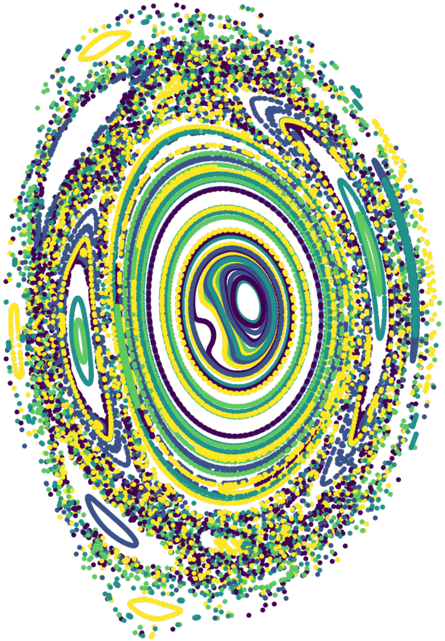

But!

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- Islands?

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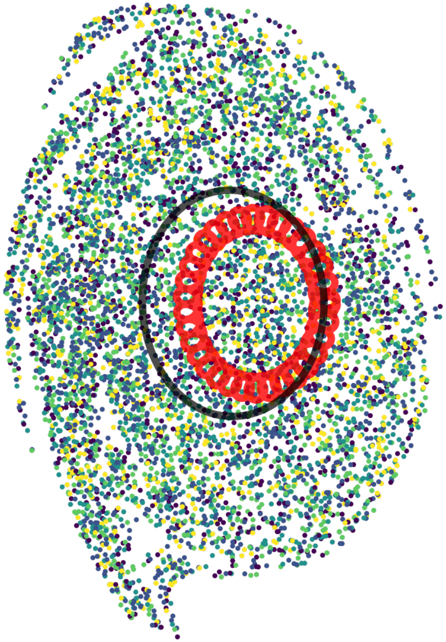

But!

- Transport lower in experiments than the Rechester-Rosenbluth diffusion.
- Islands? Or finite orbit-width effects?

Does finite orbit-width (FOW) effects lead to reduced RE transport?

We investigate this with orbit-following simulations.

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Results:

- Theoretical estimates for FOW effects valid in general.
- Non-uniform magnetic field structure could dominate.

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We investigate this with orbit-following simulations.

Results:

- Theoretical estimates for FOW effects valid in general.
- Non-uniform magnetic field structure could dominate.
- Islands probably have a larger effect on transport.
- Orbit-following tools needed to find the transport coefficients.

Introduction

- FOW effects in theory.

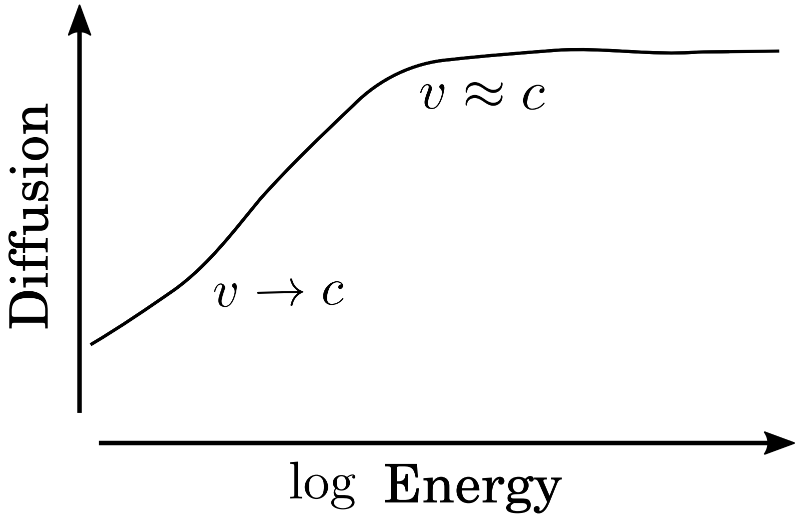
Validating theory with orbit-following simulations.

FOW effects in realistic magnetic fields.

Summary

Rechester-Rosenbluth diffusion

$$D \approx \frac{1}{\sqrt{2}} v_{\parallel} \lambda_{\parallel} \left(\frac{\delta B}{B} \right)^2$$



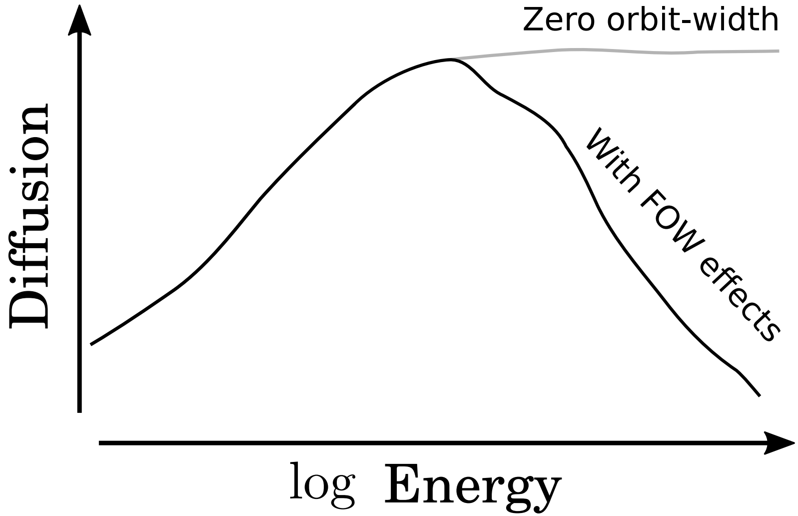
- Assumes zero orbit-width.
- Over-estimates transport of the more energetic electrons?

A. B. Rechester and M. N. Rosenbluth, *Electron Heat Transport in a Tokamak with Destroyed Magnetic Surfaces*, 1978

FOW effects reduce transport

$$D \approx \frac{1}{\sqrt{2}} v_{\parallel} \lambda_{\parallel} \left(\frac{\delta B}{B} \right)^2 \Upsilon$$

$$\Upsilon \leq 1$$

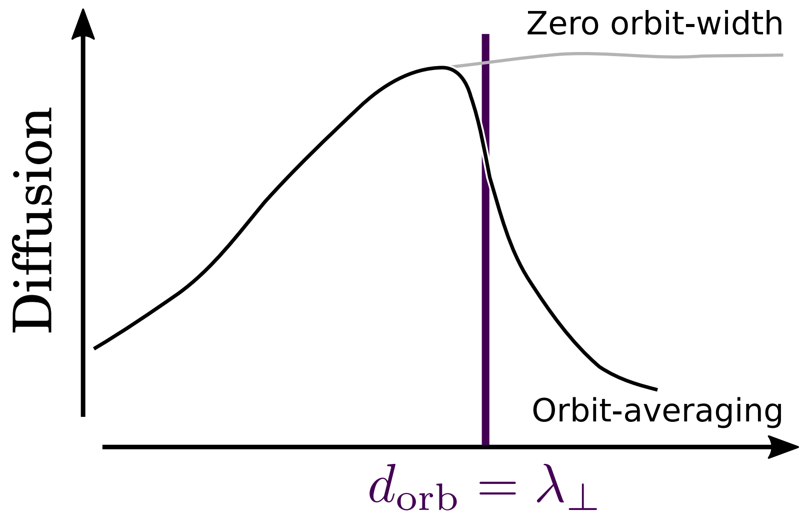


- Assumes zero orbit-width.
- Over-estimates transport of the more energetic electrons?

Orbit-averaging along poloidal orbit

- **When:**

$$\epsilon \equiv v_{\text{prec}} \frac{\tau_{\text{orb}}}{\lambda_\perp} < 1$$



- **Perturbation is averaged along particle's poloidal trajectory**

$$\Upsilon \propto \frac{1}{E} \quad \text{for} \quad d_{\text{orb}} > \lambda_\perp$$

J.R. Myra and P. J. Catto et al, *Quasilinear diffusion in stochastic magnetic fields: Reconciliation of drift-orbit modification calculations*, 1993

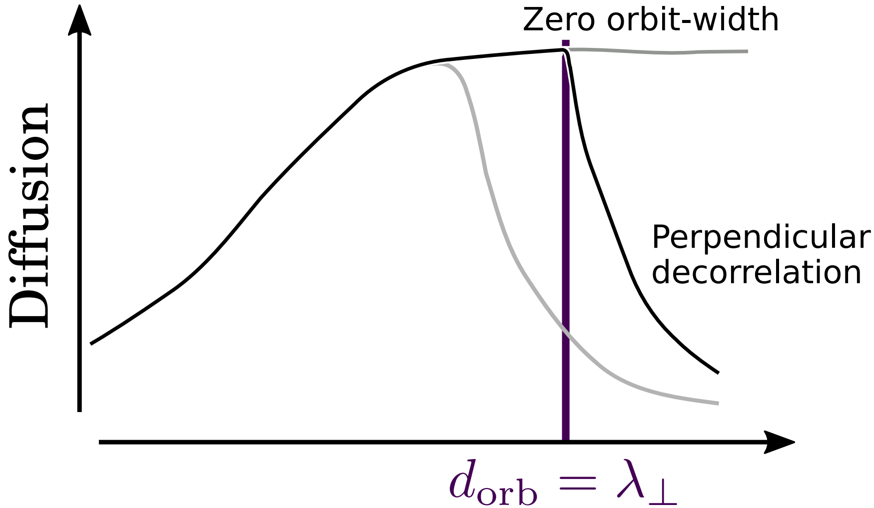
Perpendicular decorrelation

- When:

$$\epsilon > 1$$

$$d_{\text{orb}} > \lambda_\perp$$

$$\tau_\perp \equiv \frac{\tau_{\text{orb}} \lambda_\perp}{2\pi d_{\text{orb}}} < \tau_\parallel \equiv \frac{\lambda_\parallel}{v_\parallel}$$



- Poloidal drift leads to perpendicular decorrelation

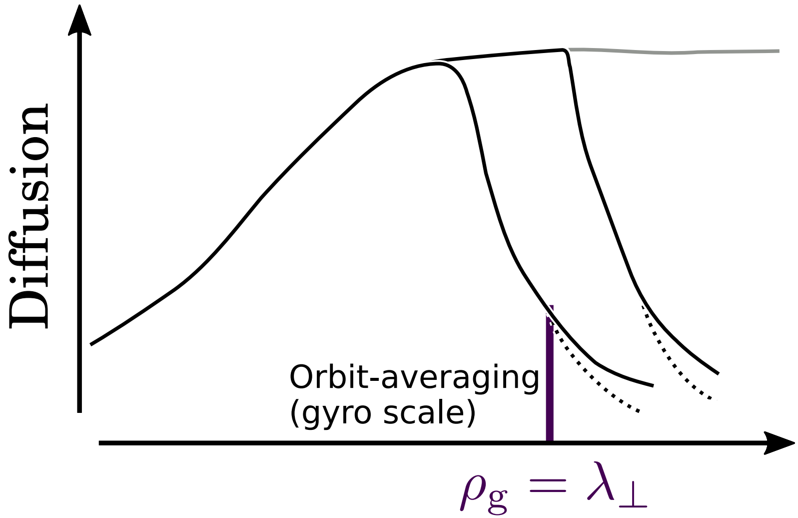
$\Upsilon \propto \frac{1}{E}$ for $d_{\text{orb}} > \lambda_\perp$

T. Hauff and F. Jenko, *Runaway electron transport via tokamak microturbulence*, 2009

Orbit-averaging along gyro-orbit

- When:

  $\rho_{\mathrm{g}} > 0.36\lambda_{\perp}$

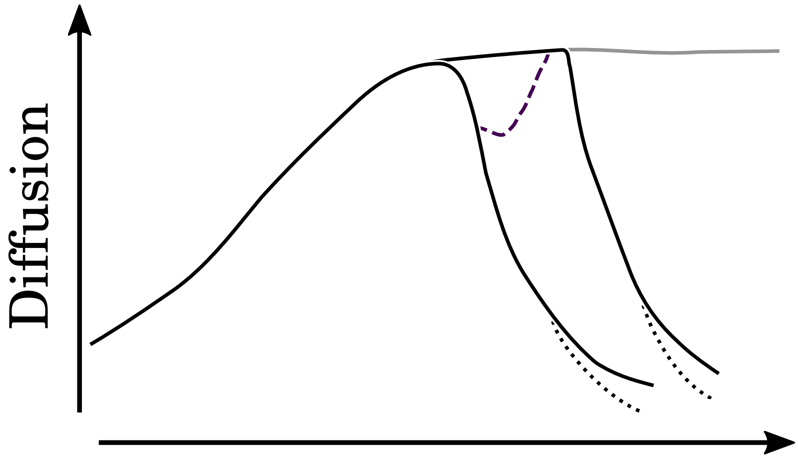


- Perturbation is averaged along particle's gyro-orbit

  $\Upsilon \propto \frac{1}{E^2}$ for $\rho_{\mathrm{g}} > \lambda_{\perp}$

T. Hauff and F. Jenko, *Runaway electron transport via tokamak microturbulence*, 2009

Transitional regime



- Bump: orbit-averaging becomes invalid before the perpendicular decorrelation kicks in.

Introduction

FOW effects in theory.

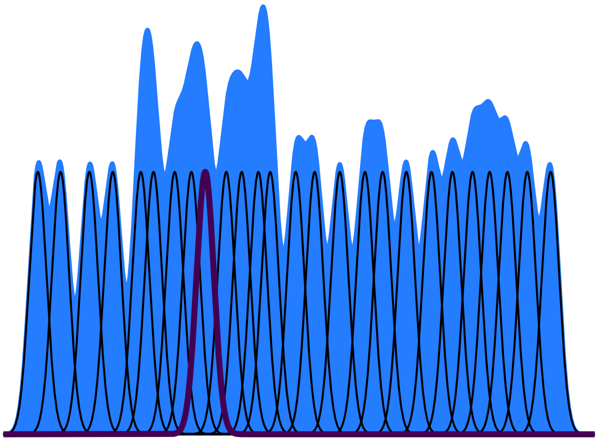
Two mechanisms: orbit-averaging and perpendicular decorrelation
Important when orbit width > perpendicular correlation length

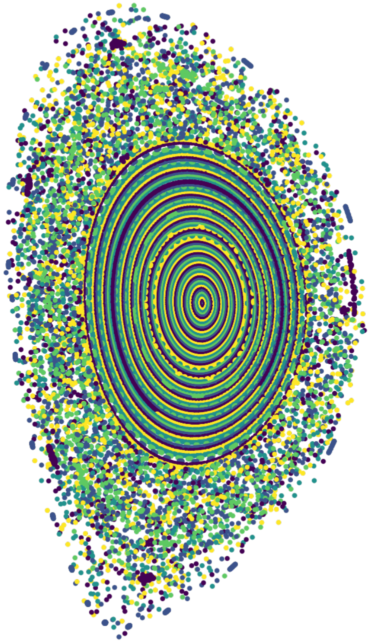
- Validating theory with orbit-following simulations.

FOW effects in realistic magnetic fields.

Summary

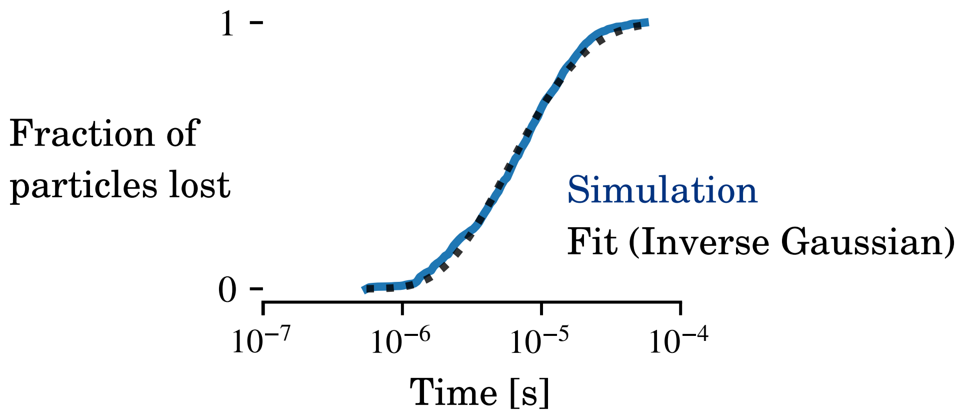
This is my playground

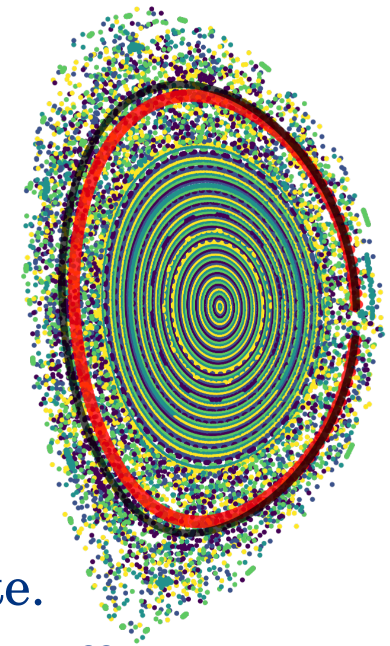




- Assume mode width $\approx \lambda_{\perp}$.
- 25 modes with $n < 10$ and $m < 20$.
- Each mode peaks at the resonant surface.
- Same amplitude and width.

These are my toys





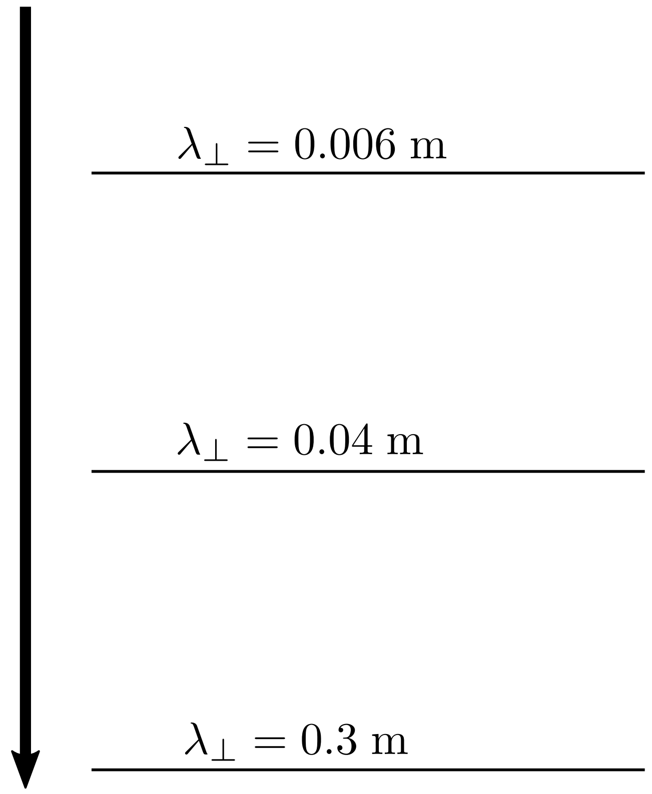
- Electrons initialized at the same radial position and simulated until losses saturate.
- Loss-time used to find advection-diffusion coefficients.
- Assumes radially uniform transport.

J. Varje et al, *High-performance orbit-following code ASCOT5 for Monte Carlo simulations in fusion plasmas*, 2019

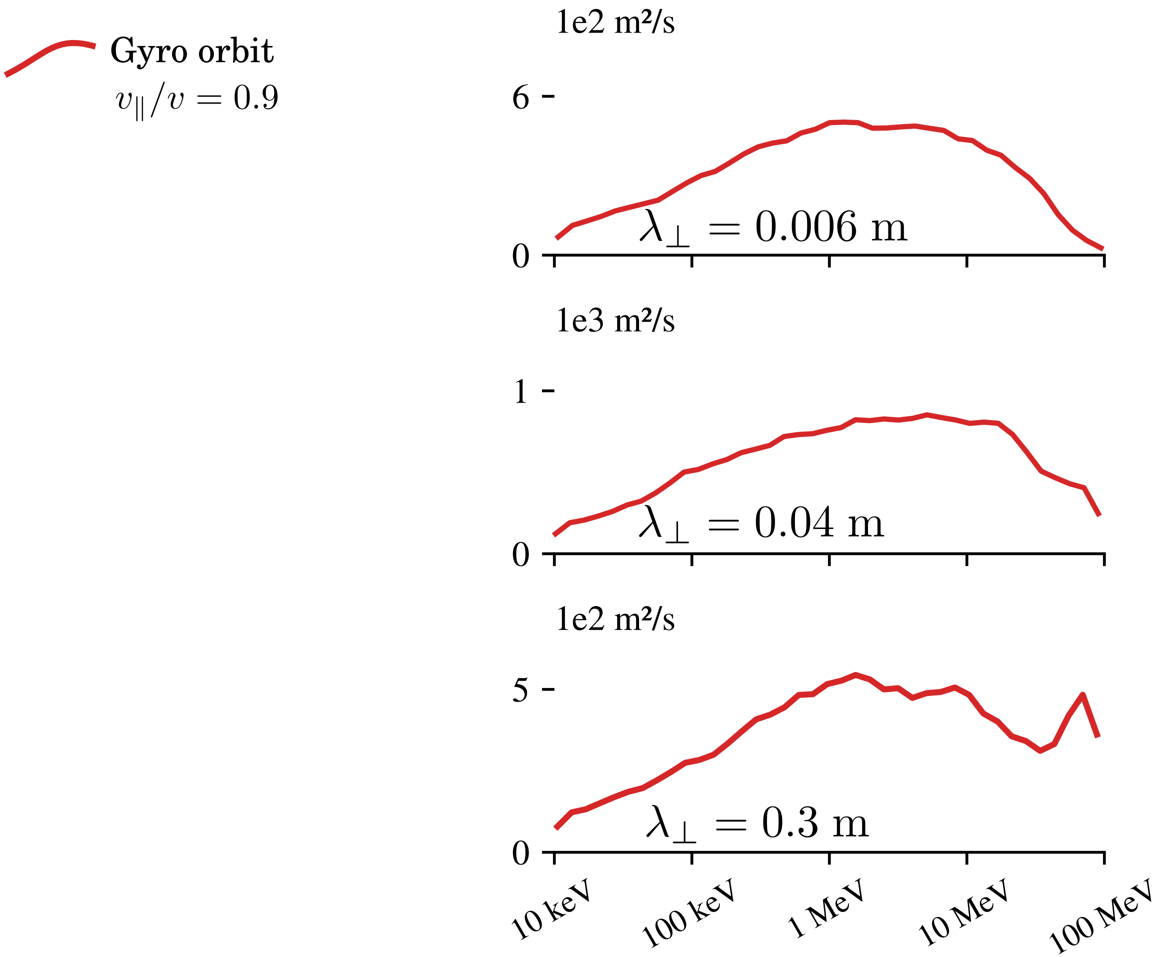
K. Särkimäki et al, *An advection-diffusion model for cross-field runaway electron transport in perturbed magnetic fields*, 2016

Three cases with different mode width

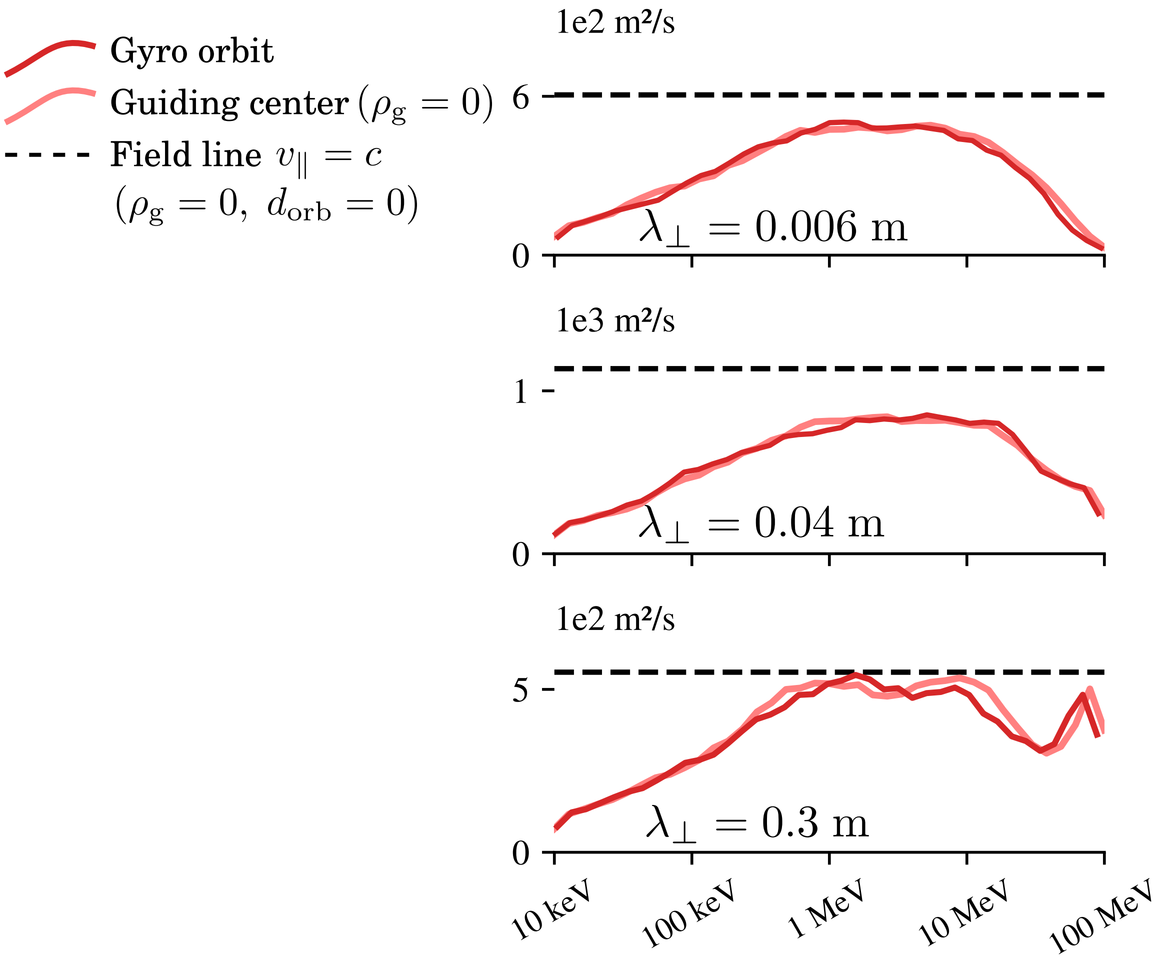
mode width and $\lambda_\perp$ increases



Diffusion as a function of energy

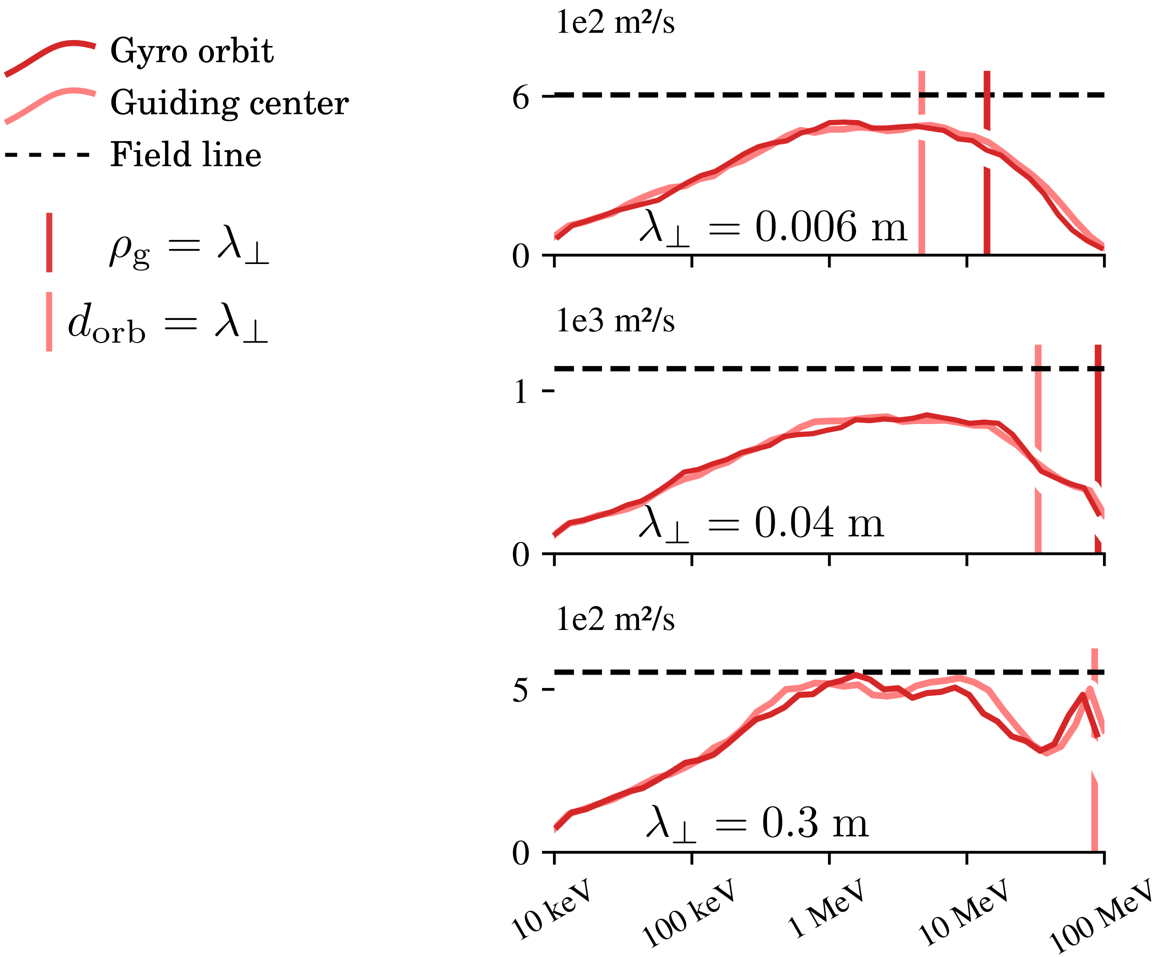


Separate gyro and orbit-width effects

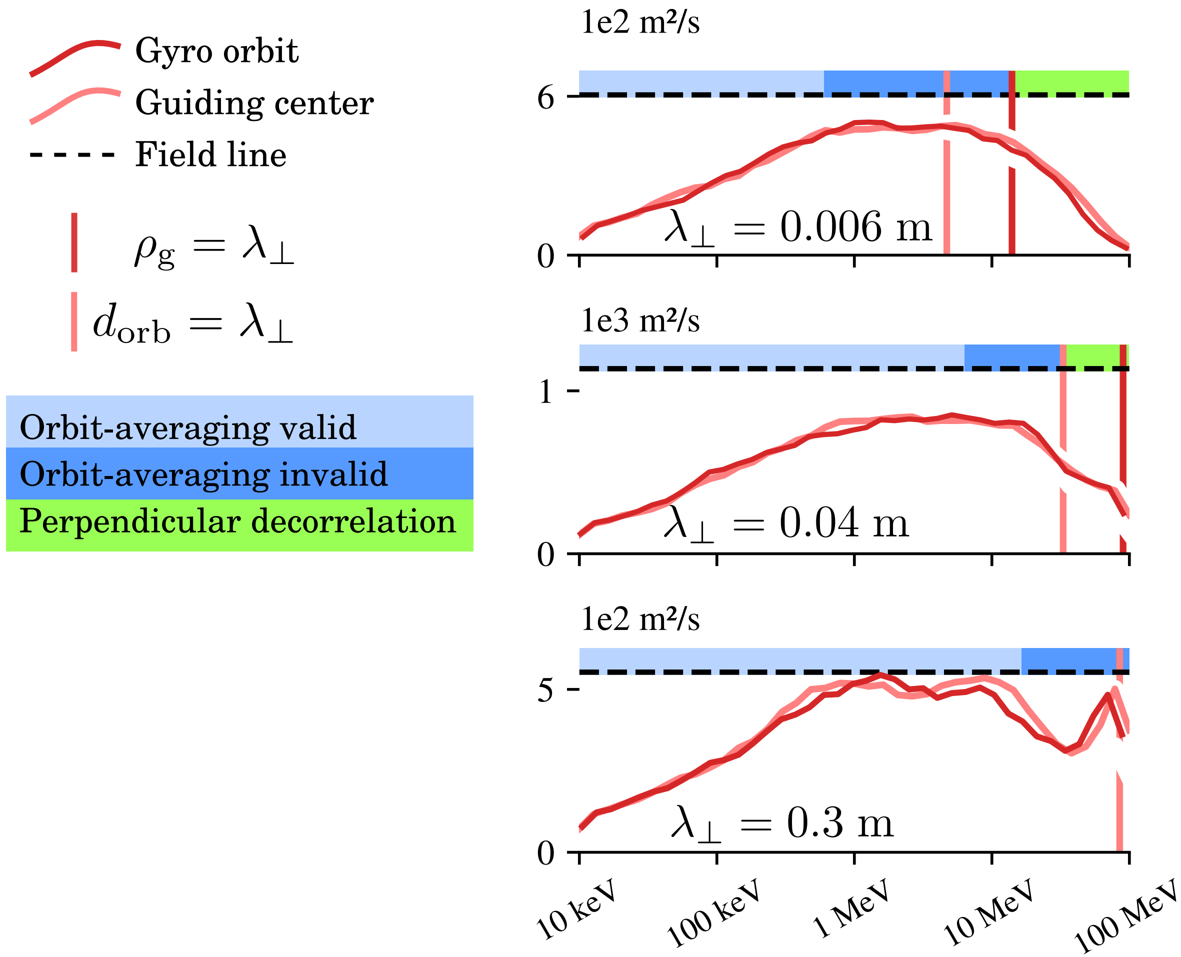


$\Upsilon \leq 1$

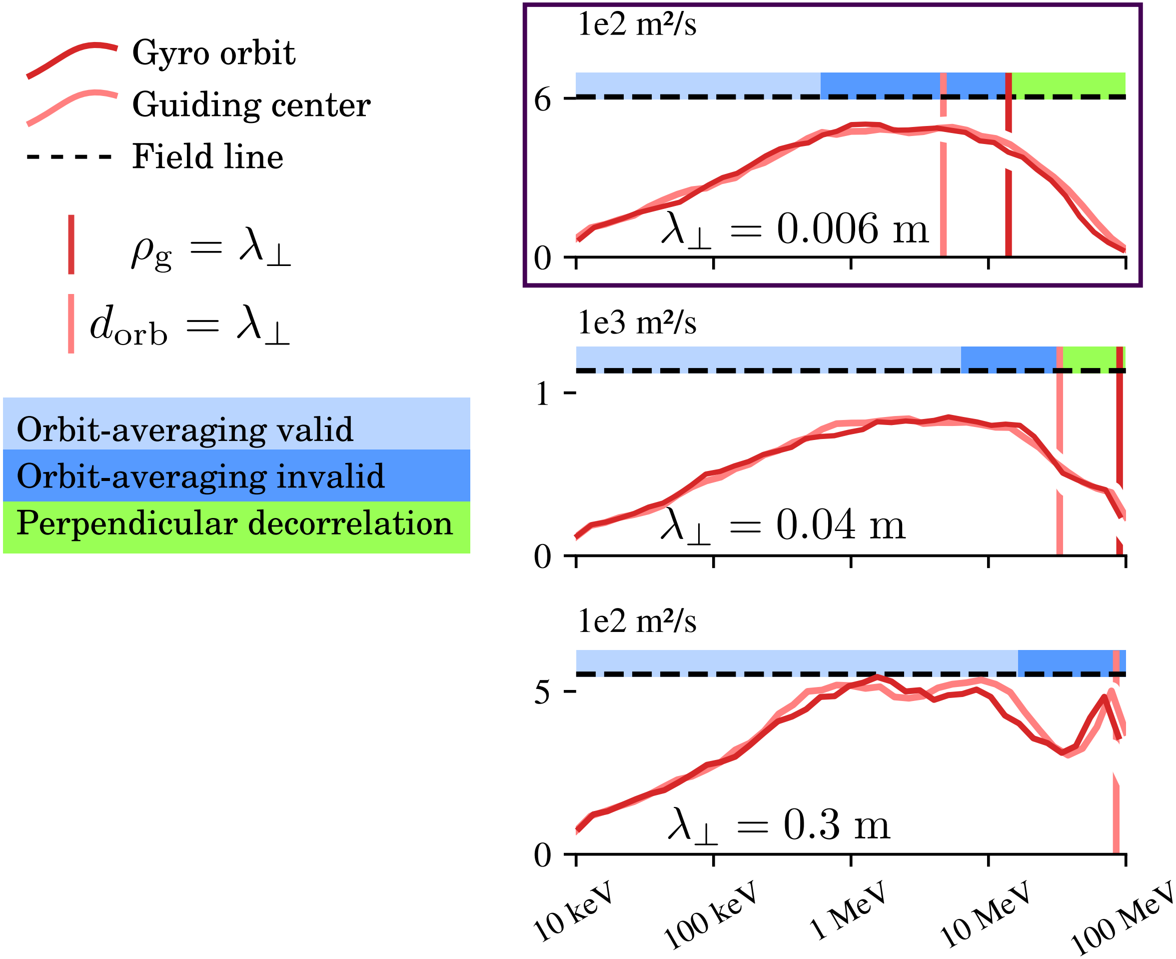
Thresholds for significant FOW effects

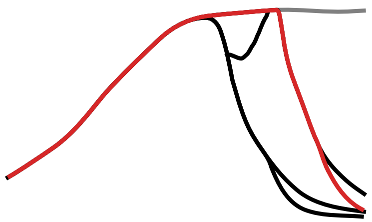


Plot criteria for the different mechanisms

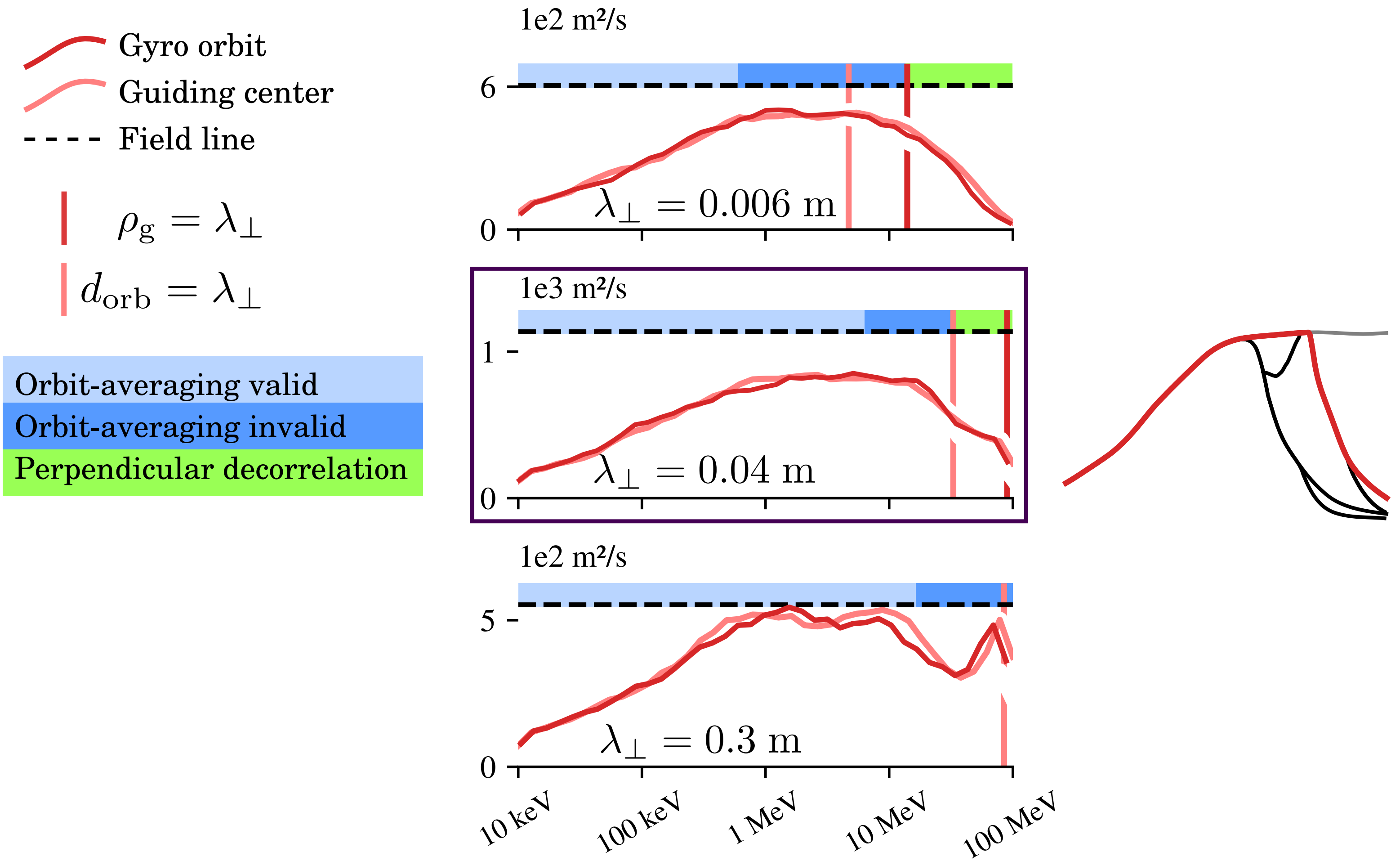


Correlation length < gyroradius





Correlation length < orbit width



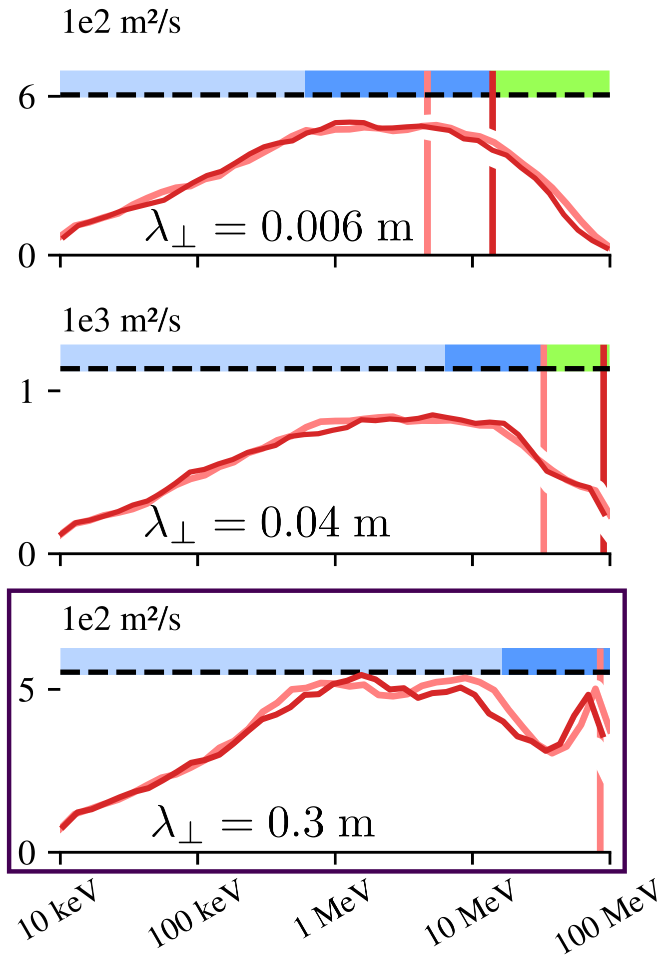
Correlation length > orbit width

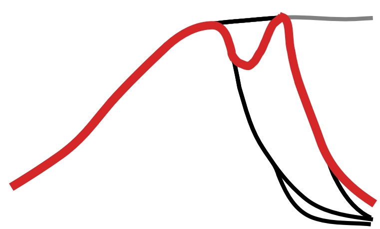
Gyro orbit
Guiding center
Field line

$\rho_g = \lambda_\perp$

$d_{orb} = \lambda_\perp$

Orbit-averaging valid
Orbit-averaging invalid
Perpendicular decorrelation





Introduction

FOW effects in theory.

Validating theory with orbit-following simulations.

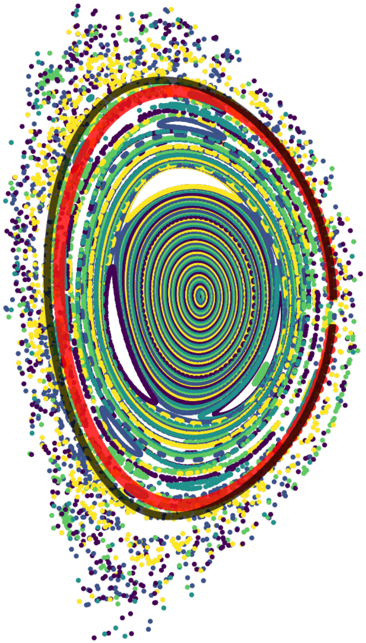
Theory and simulations agree in general.

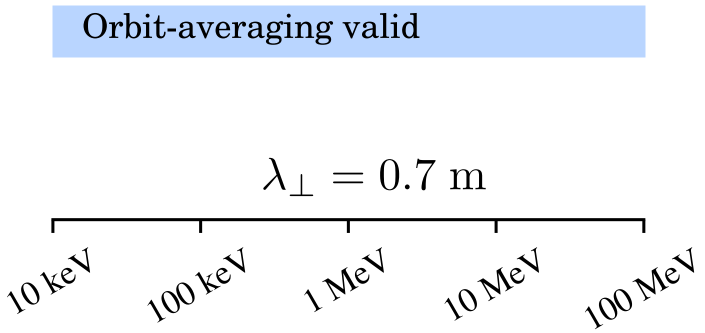
Some discrepancy in regards to orbit-averaging and gyro-orbit effects.

- FOW effects in realistic magnetic fields.

Summary

ITER: flat-top with ELM control coils

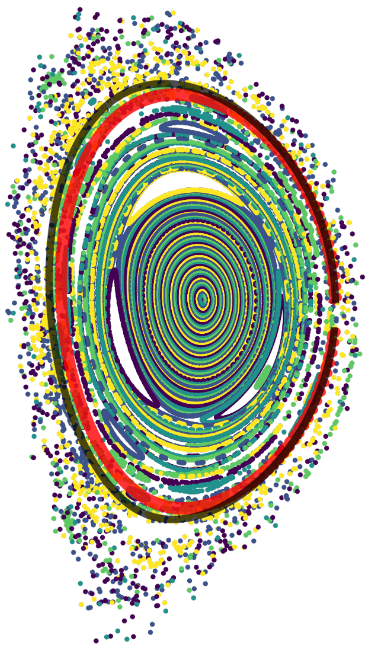


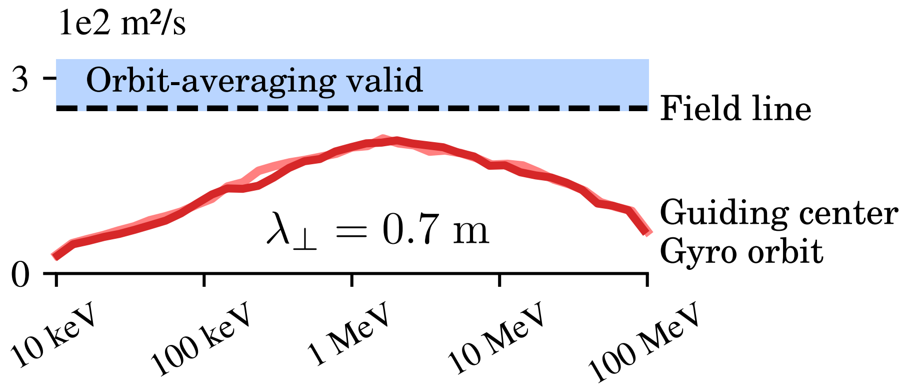


- **Orbit-averaging valid up to 100 MeV.**
- $d_{\rm orb} > \lambda_\perp$ **at 600 MeV;** $\tau_\perp < \tau_\parallel$ **at 2 GeV.**

K. Särkimäki et al, *An advection-diffusion model for cross-field runaway electron transport in perturbed magnetic fields*, 2016

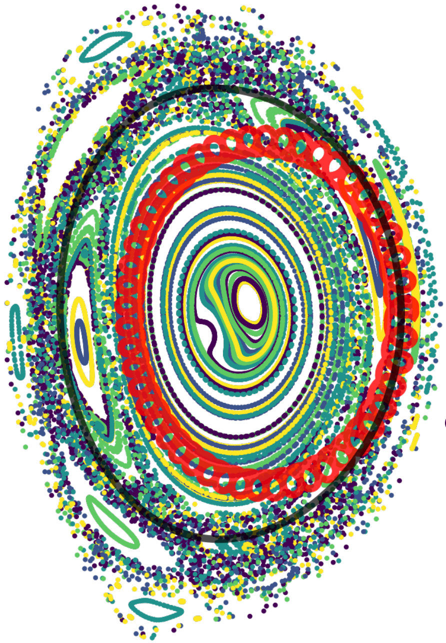
ITER: flat-top with ELM control coils

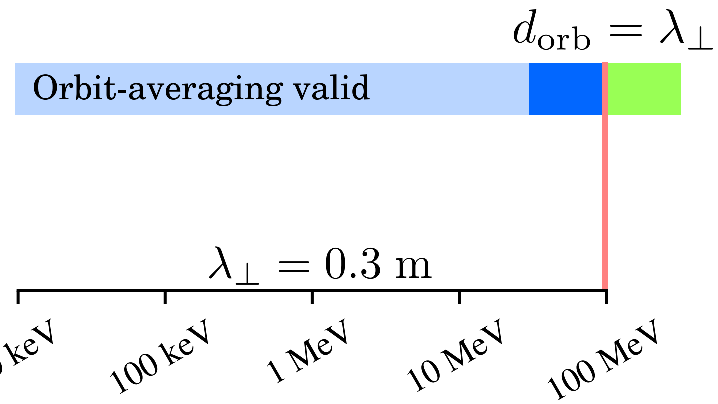




- Orbit-averaging valid up to 100 MeV.
- $d_{\mathrm{orb}} > \lambda_\perp$ at 600 MeV; $\tau_\perp < \tau_\parallel$ at 2 GeV.
- More sizeable and earlier reduction than what theory predicts.
- Caused by the localised perturbation?

JET: before the thermal quench

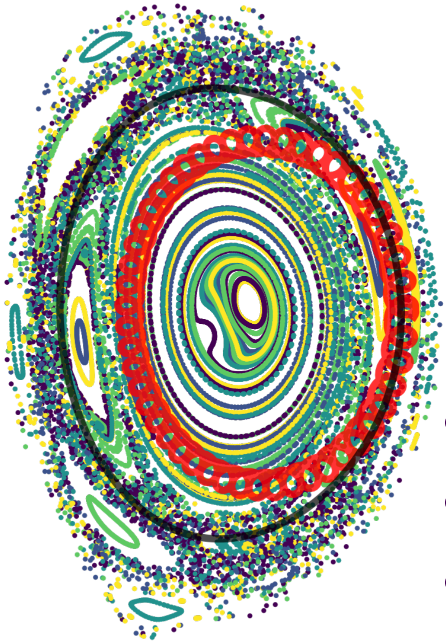


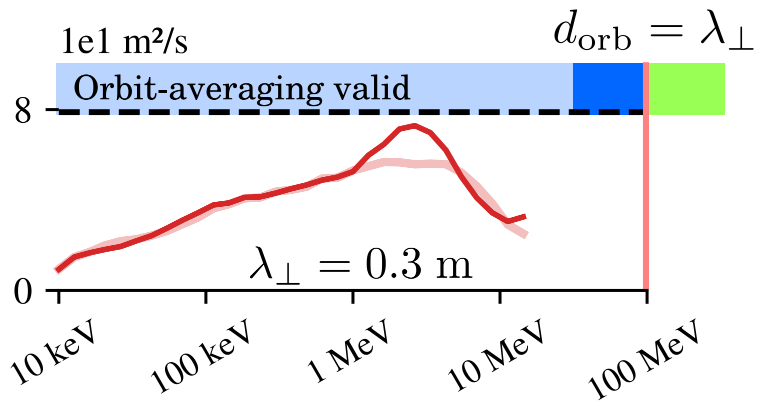


- Orbit-averaging valid up to 50 MeV.

E. Nardon et al, *Progress in understanding disruptions triggered by massive gas injection via 3D non-linear MHD modelling with JOREK*, 2016

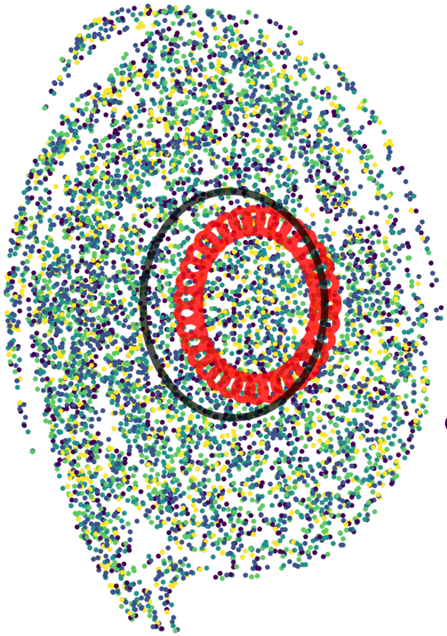
JET: before the thermal quench

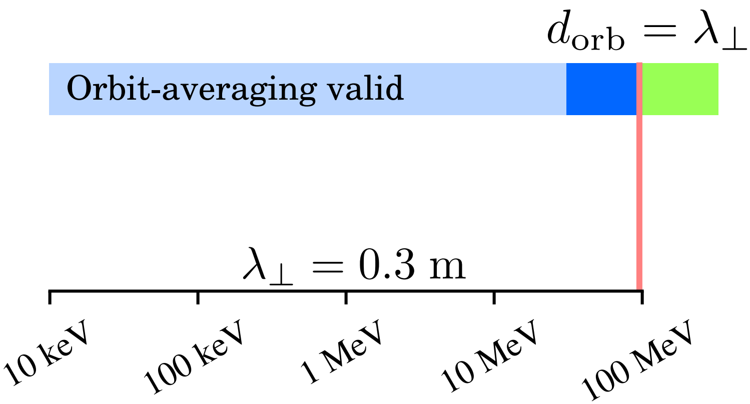




- Orbit-averaging valid up to 50 MeV.
- Particles confined after 20 MeV.
- More energetic particles spend more time inside the well-confined region.
- Note the low diffusion.

JET: during the thermal quench





- Orbit-averaging valid up to 50 MeV.

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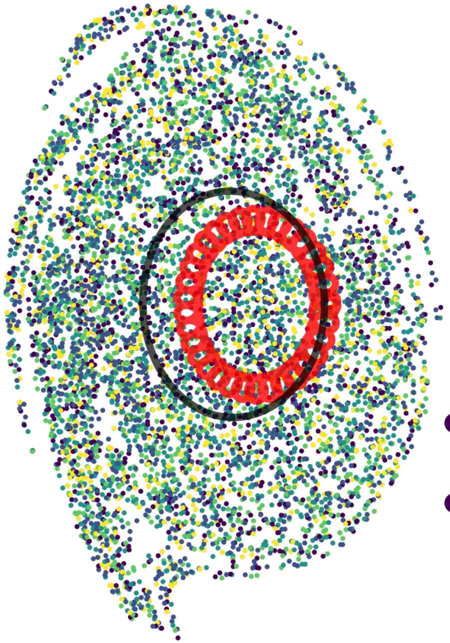
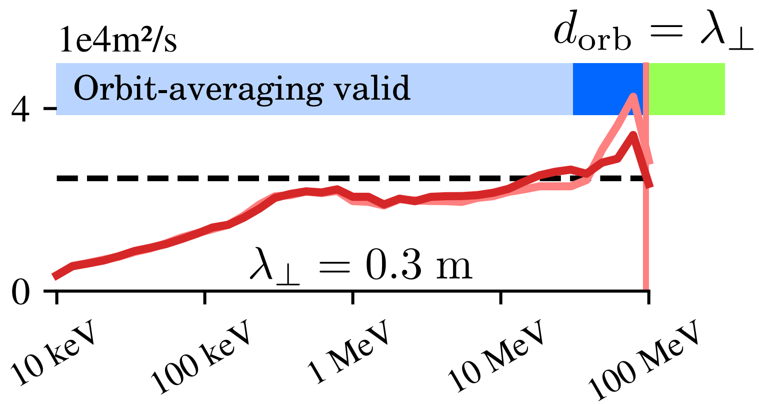
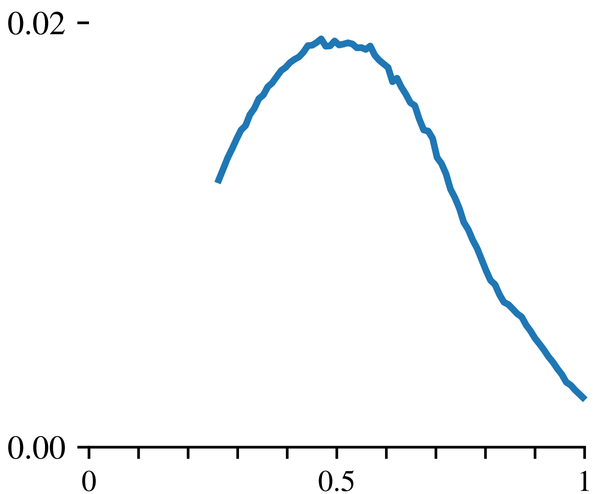


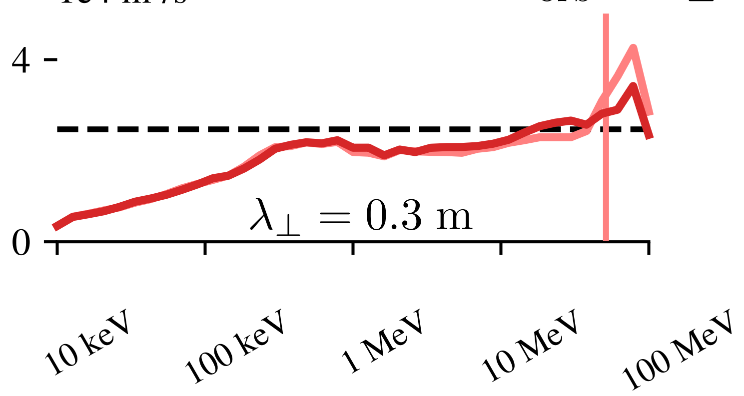


- Orbit-averaging valid up to 50 MeV.
- $\Upsilon > 1$ (!)

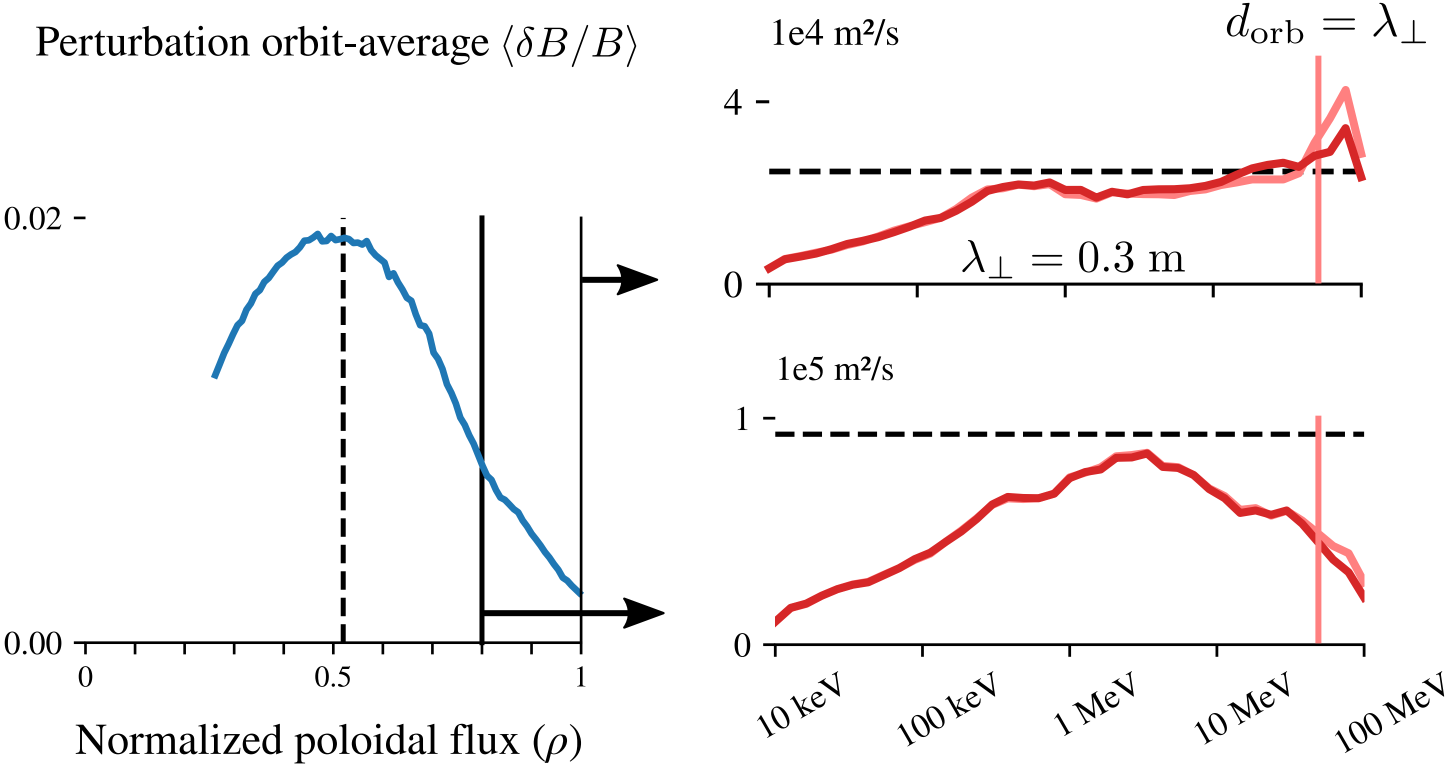
Transport barrier at the edge

Perturbation orbit-average $\langle \delta B/B \rangle$



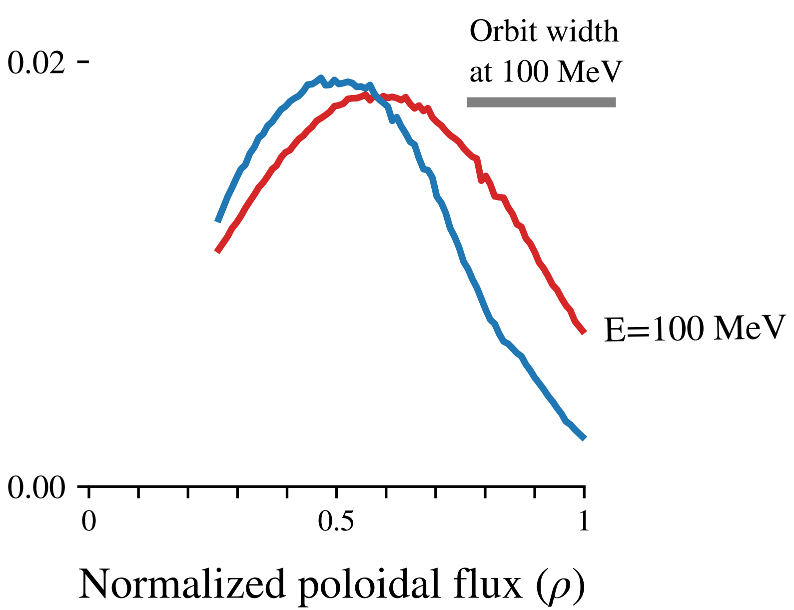


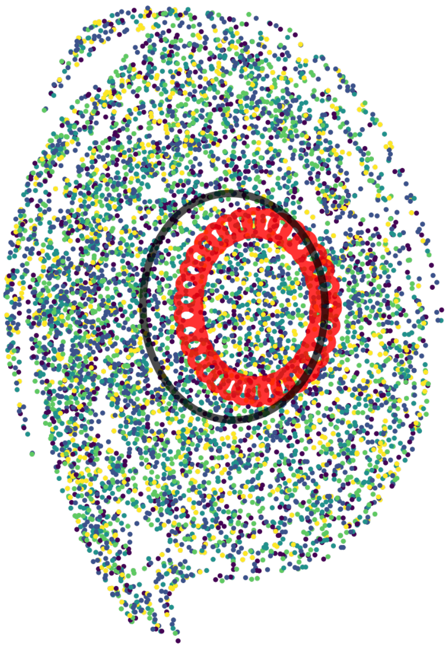
What if we remove the barrier?



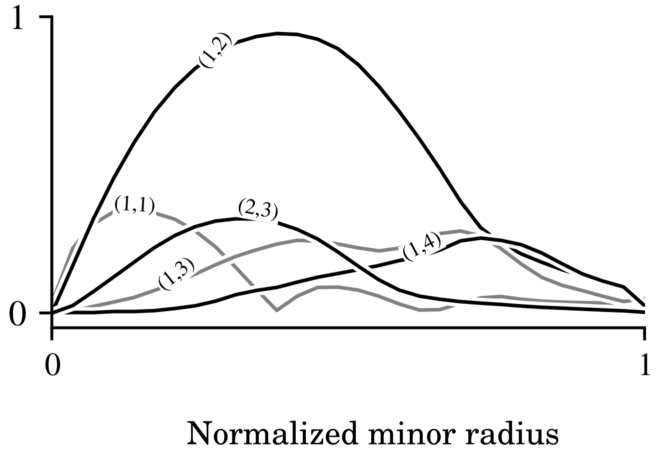
Barrier lower for energetic electrons

Perturbation orbit-average $\langle \delta B/B \rangle$





Are these results generalizable?



- FOW effects not relevant if $d_{\text{orb}} \ll \lambda_\perp$.
- $\lambda_\perp \approx$ mode width.
- Mode width ~ minor radius.

Introduction

FOW effects in theory.

Validating theory with orbit-following simulations.

FOW effects in realistic magnetic fields.

Other effects dominate.

Again discrepancy in orbit-averaging; is it due to localised perturbation?

- Summary

Transport reduction at zero orbit width

- Assuming small Kubo number $\mathcal{K} = (\lambda_{\|}/\lambda_{\perp})(\delta B/B) < 1$.
- Rechester-Rosenbluth diffusion should correspond to the numerical zero orbit width result (field line).

Transport reduction at zero orbit width

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	$\mathcal{K}$	$D_{\mathrm{RR}}/D_{\mathrm{NUM}}$
The tests	0.007	1
	0.1	0.9
	0.3	0.8
ITER coil	0.003	2
JET edge stoc.	0.03	80
JET full stoc.	0.2	5

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$D_{\mathrm{RR}} \gg D_{\mathrm{NUM}}$ (JET edge stoc. and JET full stoc.)

Transport reduction at zero orbit width

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JET edge stoc.	0.03	80	Islands?
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Summary

- Theoretical estimates for FOW effects valid in general.
- Non-uniform magnetic field structure could dominate.
- Islands probably have a larger effect on transport.
- Orbit-following tools needed to find the transport coefficients.
- Future work involves finding what effect perturbations have on the seed population and the avalanche growth rate.

(What was left out)

- Advection coefficient, pitch dependence, evaluation of autocorrelation lengths.

K. Särkimäki et al, Assessing energy dependence of the transport of relativistic electrons in perturbed fields with orbit-following simulations, Preprint: https://arxiv.org/abs/2006.03726