Electron Energization in Non-Relativistic Magnetic Reconnection

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Connecting Micro and Macro Scales: Acceleration, Reconnection and Dissipation in Astrophysical Plasmas
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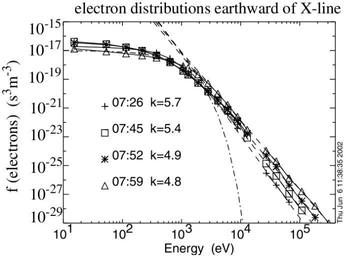
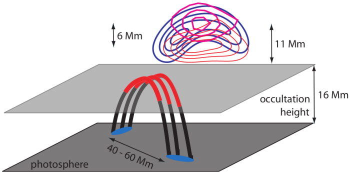
Motivation

- Reconnection energizes electrons
    - Solar flares
    - Magnetospheres
    - Pulsar flares, . . .

- **What processes drive electron energization?**
- **How efficient are these processes?**





When is reconnection an efficient accelerator?

- **Peak (non-relativistic) electron acceleration requires Fermi acceleration & strong 3D transport ($b_g \sim 1$)**

- Guide field (b_g) controls the acceleration mechanism
  - Use 2D PIC simulations to isolate mechanism efficiency
  - Strong guide field, $b_g \gtrsim 1$, throttles Fermi acceleration

- b_g controls 3D transport
  - Compare 2D & 3D simulations to isolate role of 3D transport
  - Stochastic 3D field enhance electron acceleration
  - Strong 3D transport requires a guide field $b_g > 0$

Energization Mechanisms I: Fermi Acceleration

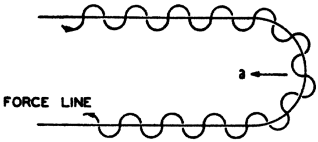
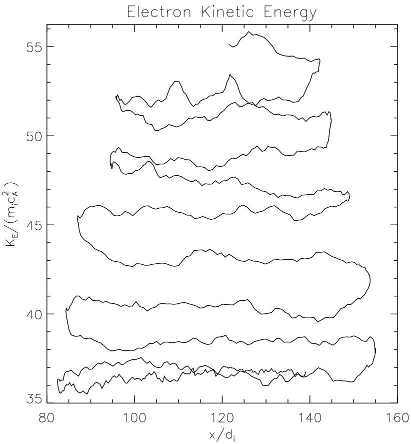
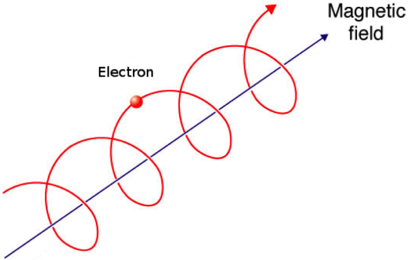


FIG. 1. Type *B* reflection of a cosmic-ray particle.



- Moving field lines slingshot charged particles
- Particle with initial parallel velocity $v_{||}$ reflecting from field line moving at v_A gains energy: $v_{||} \rightarrow v_{||} + 2v_A$

Energization Mechanisms II: $E_{||}$ and Betatron



- $E_{||}$:
  - Changes $v_{||}$
  - Difficult to sustain on large scales; electrons quickly move to cancel
- Betatron (conservation of $\mu \propto v_{\perp}^2/B$)
  - Changing **B** induces an *emf* that changes $v_{\perp}$.
  - In reconnection, the magnetic field decreases and the *emf* opposes gyration (i.e., reduces $v_{\perp}$).

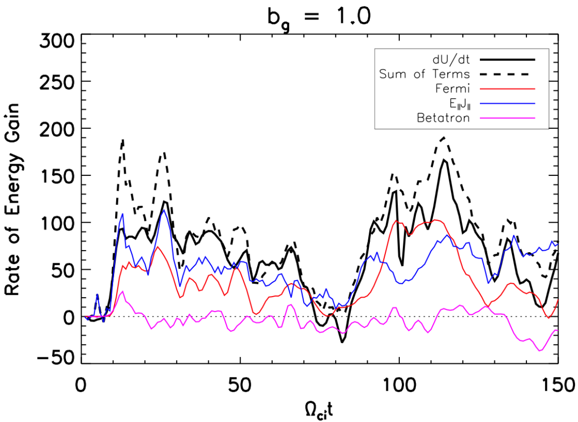
How Particles Gain Energy

Bulk expression, guiding-center limit

$$
\begin{aligned}
d\epsilon/dt = \quad & \gamma m v_{\|}^2 (\mathbf{u}_E \cdot \boldsymbol{\kappa}) && \text{Fermi Reflection} \\
+ \quad & q E_{\|} v_{\|} && \text{Parallel Electric Fields} \\
+ \quad & \frac{m v_{\perp}^2}{2B} \left(\frac{\partial B}{\partial t} + \mathbf{u}_E \cdot \boldsymbol{\nabla} B \right) && \text{Betatron Acceleration}
\end{aligned}
$$

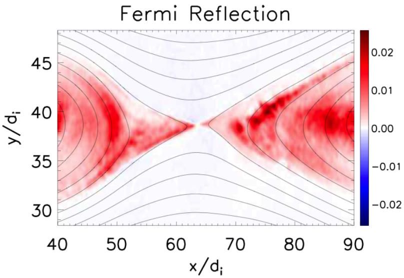
- Particle energy: ϵ
  Magnetic field curvature: $\boldsymbol{\kappa} = \mathbf{b} \cdot \boldsymbol{\nabla}\, \mathbf{b}$
  Perpendicular plasma flow: $\mathbf{u}_E = c\,(\mathbf{E} \times \mathbf{B})/B^2$
- Fermi and $E_{\|}$ affect $v_{\|}$.
  Betatron affects $v_{\perp}$, is usually unimportant.

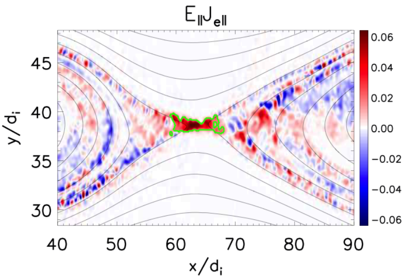
Does this work?



- Guiding-center limit matches electron energization in the simulation.
- Fermi reflection and $E_{||}$ are both important.
- Betatron acceleration is small.

2D Simulations: Isolate Mechanisms

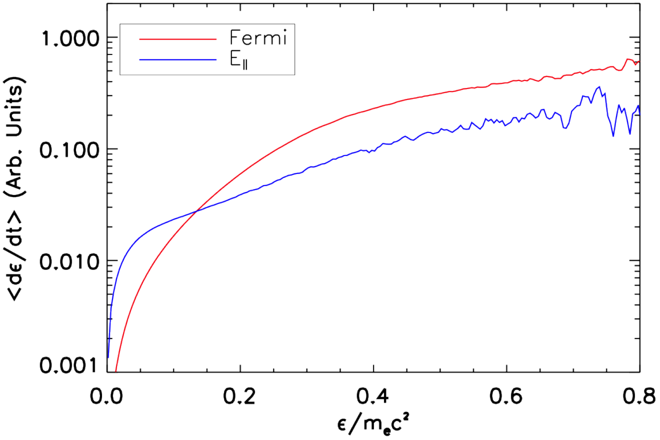




- **Fermi acceleration**
- Reflection from reconnection outflows: volume-filling acceleration
- Strong energy scaling: $d\epsilon/dt \propto \epsilon$

- **Parallel electric fields**
- Primarily 'linear accelerator' at X-line localized to diffusion region ($>$ 50% of $E_{\|}$ energy conversion).
- Weak energy scaling: $d\epsilon/dt \propto \epsilon^{1/2}$

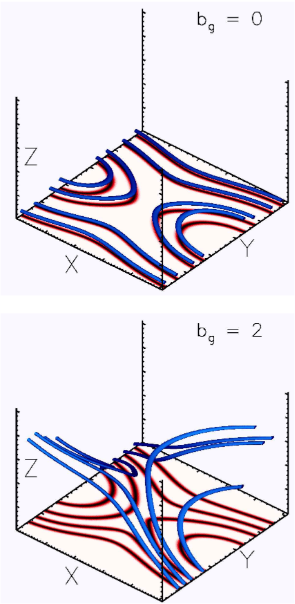
Efficient energization requires Fermi acceleration



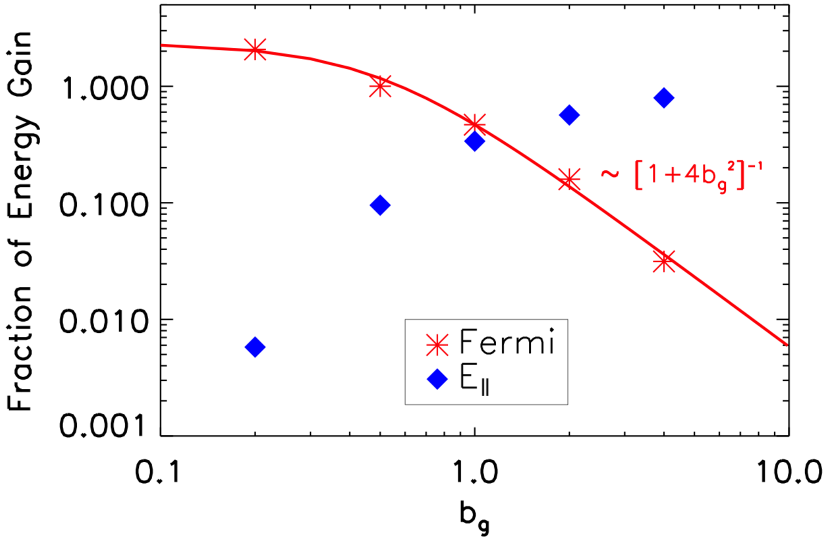
- $E_{\parallel}$ scales weakly with energy compared to Fermi.
  - Primarily drives bulk heating (not energetic electrons)
- **Efficient energization occurs in the Fermi-dominated regime**

The guide field determines the dominant mechanism

- **A strong guide field throttles Fermi acceleration**
  - $b_g \sim 0$: head-on reflection (strong kick)
  - $b_g \gg 1$: glancing reflection (weak kick)
- $E_{\|}$: Guide field directs particles along reconnection E_z (only in diffusion region).

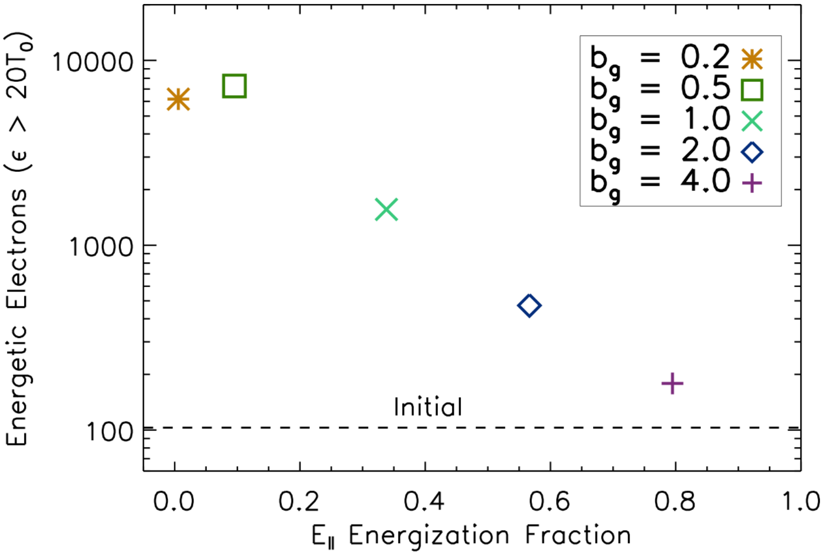


The guide field controls the dominant mechanism



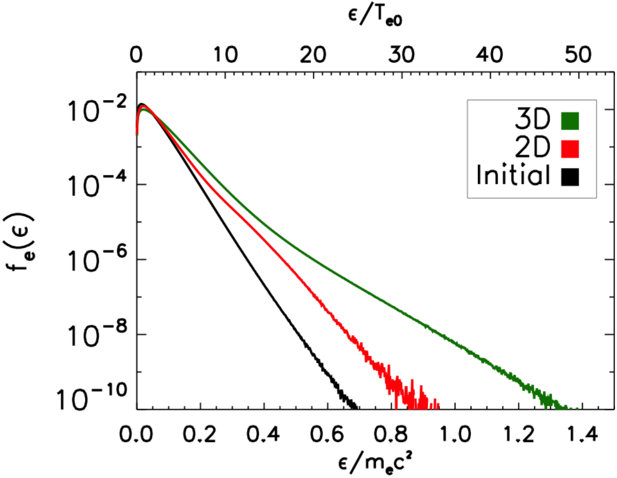
- $b_g \ll 1$: Fermi reflection dominates energy conversion
- $b_g \gg 1$: $E_\parallel$ dominated energy conversion

$E_\parallel$ is an inefficient electron accelerator



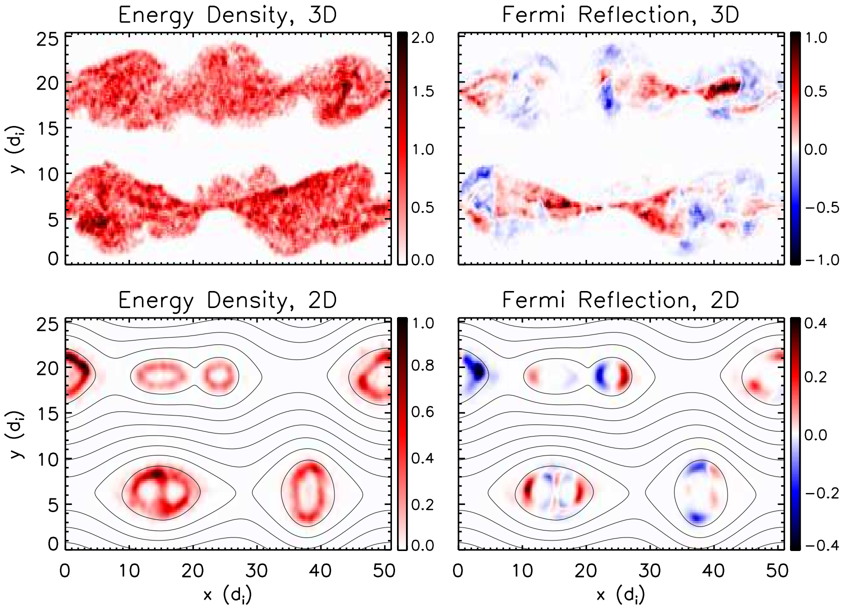
- $b_g \gg 1$: $E_\parallel$ dominates but energizes few electrons

Energization is enhanced in 3D systems

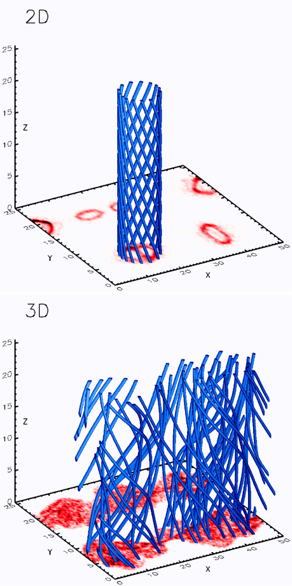


- Comparable magnetic energy release in 2D, 3D
- Factor of ≈ 10 increase in high-energy electrons in 3D.
- **Why does a larger energy fraction go into energetic electrons in 3D?**

Energetic Electrons (> 0.5 $m_e c^2$)



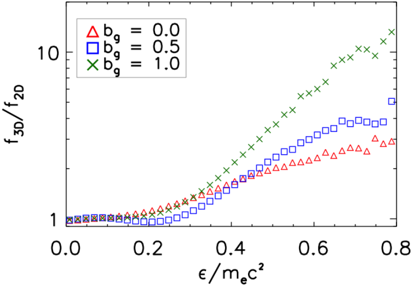
3D transport (chaotic field lines) is key

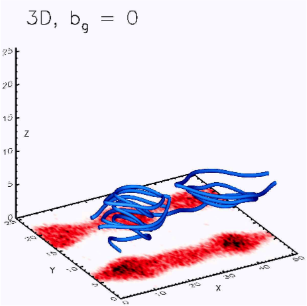


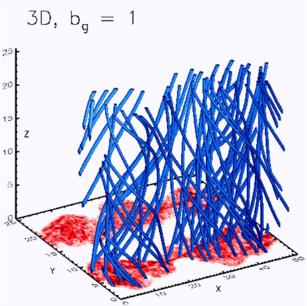
- Particles follow field lines
- 2D: Single acceleration period then ejection into closed island. Limited energy gain.
- 3D: Stochastic fields allows particles to escape islands and continuously accelerate.

The guide field controls 3D transport

- **3D enhancement increases with guide field**
- $b_g \sim 0$: quasi-2D field (island trapping)
- $b_g \gtrsim 1$: stochastic field (strong transport)

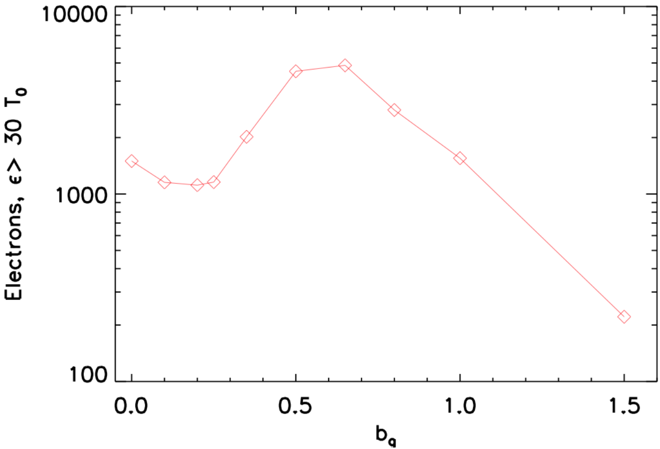




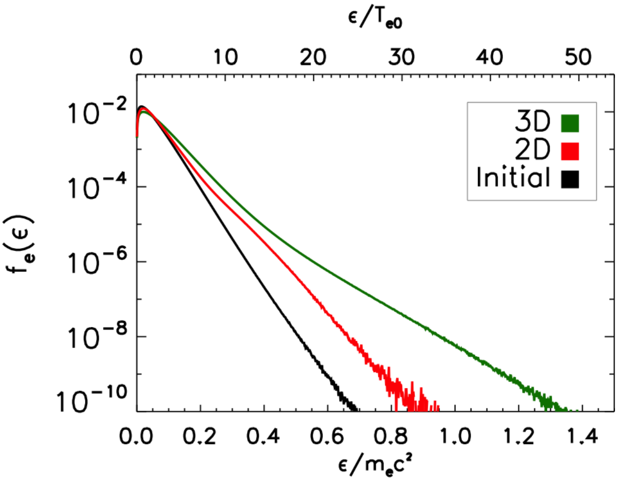


Putting it all together

- Efficient Fermi acceleration requires $b_g \lesssim 1$
- 3D transport requires $b_g > 0$
- Simulations: **peak electron energization for** $b_g \sim 1$



Power Laws?



- Many groups get power laws in relativistic reconnection. Much harder in the non-relativistic case.
- See posters by Xiaocan Li, Fan Guo, Patrick Kilian, Yingcaho Lu + talk by Dmitri after lunch

The Payoff: A New Computational Model

See Jim Drake's poster

If $E_{||}$ is unimportant for particle energization, we can ignore the physics behind it

- Eliminate kinetic scales
  - Do not control production of most energetic particles
  - Particle production controlled by the dynamics of macro-islands

A self-consistent MHD/guiding-center kinetic model

- An MHD backbone with macro-particles evolved with the guiding-center equations
  - Energetic component evolved in the MHD fields
  - Energetic particle feedback on the MHD fluid through the pressure-driven currents
  - Total energy of system (MHD plus energetic component) is conserved

Basic equations

- MHD momentum equation with MHD pressure and energetic particle current ($\mathbf{J}_h$).

$$\rho \frac{d\mathbf{v}}{dt} = \frac{1}{c}\mathbf{J} \times \mathbf{B} - \nabla P - \frac{1}{c}\mathbf{J}_{ehT\perp} \times \mathbf{B} + en_i E_{\|}\mathbf{b}.$$

- With

$$\mathbf{J}_{ehT\perp} = \frac{c}{B}\mathbf{b} \times \left(P_{eh\perp}\nabla \ln(B) + T_{eh\|}\boldsymbol{\kappa}\right) - \left(\nabla \times \frac{cP_{eh\perp}\mathbf{b}}{B}\right)_{\perp},$$

RHS: gradient B drift, curvature drift, magnetization current

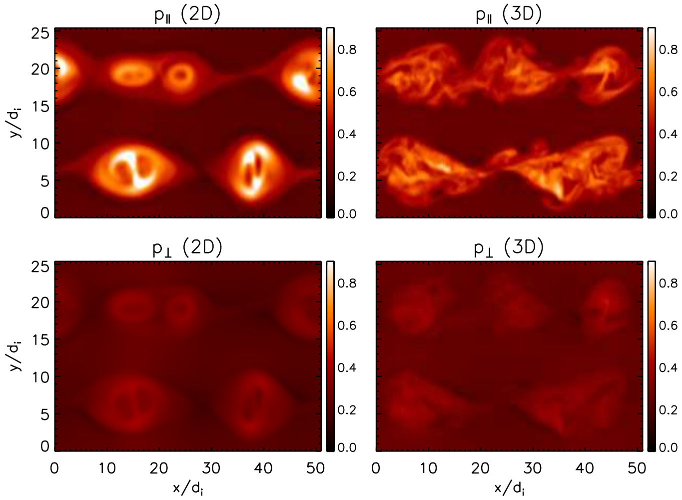
- Ohm's Law is unchanged

$$\mathbf{E} = \frac{1}{nc}(n_{ec}\mathbf{v}_{ec} + n_{eh}\mathbf{v}_{eh}) \times \mathbf{B} = \frac{1}{nec}\mathbf{J} \times \mathbf{B} - \frac{1}{c}\mathbf{v} \times \mathbf{B} \simeq -\frac{1}{c}\mathbf{v} \times \mathbf{B},$$

- Particles are given by guiding-center equations

$$\frac{d}{dt}p_{e\|} = p_{e\|}\mathbf{v}_E \cdot \boldsymbol{\kappa} - \frac{\mu_e}{\gamma_e}\mathbf{b} \cdot \nabla B - eE_{\|}$$

Electron Anisotropy

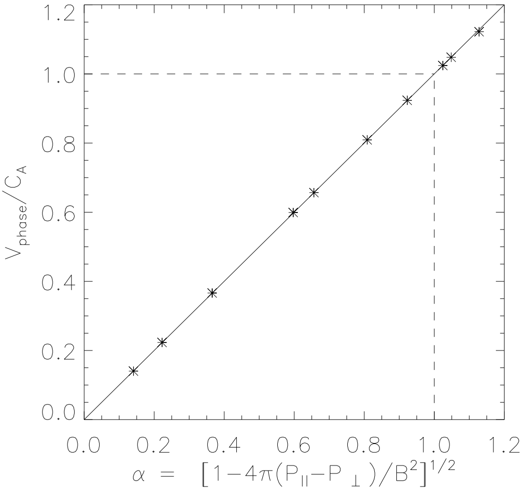


- Fermi Reflection and $E_{\|} J_{\|}$ increase $p_{\|}$.

Code Validation (for more see poster by J. Drake)

- Alfvén wave with $P_{\parallel} \neq P_{\perp}$

$$V_p = V_A \sqrt{1 - 4\pi \frac{P_{\parallel} - P_{\perp}}{B^2}} \equiv \alpha V_A$$



Conclusions

- **Peak electron acceleration requires Fermi acceleration & strong 3D transport ($b_g \sim 1$)**
- b_g controls the mechanism
  - 2D simulations isolate mechanism efficiency
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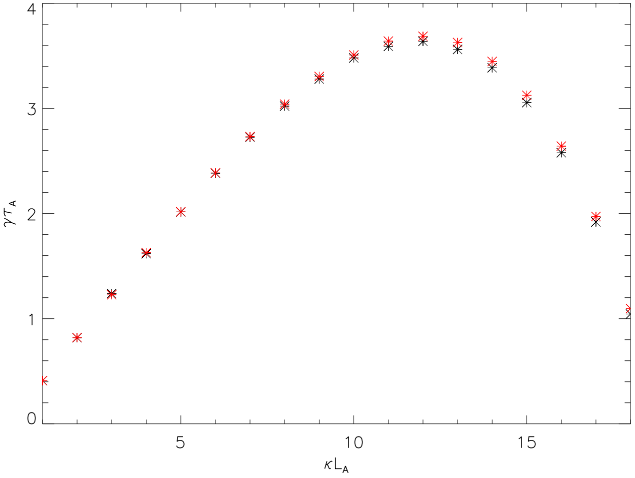
- b_g controls 3D transport
  - Compare 2D & 3D simulations to isolate role of 3D transport
  - Stochastic 3D field enhance electron acceleration
  - Strong 3D transport requires a guide field $b_g > 0$

New computational model based on this work self-consistently describes particle acceleration in macro-scale systems

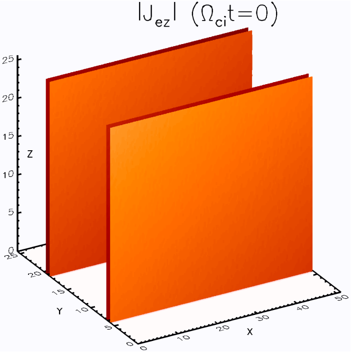
Extra Slides

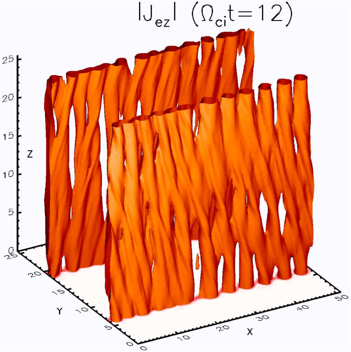
Code Validation II: Linear Growth of Firehose

$$\gamma = kV_A|\alpha| - \nu k^4$$



Initial Conditions





- Periodic Boundary Conditions
- Guide field $b_g = 1$

- Reconnection develops from particle noise

Filamentary Current Structure