Radiation from electrons in magnetic field turbulence astrophysical scenarios

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http://golp.ist.utl.pt/
**OSIRIS 2.0**

**osiris framework**

- Massively Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST

**New Features in v2.0**

- Bessel Beams
- Binary Collision Module
- Tunnel (ADK) and Impact Ionization
- Dynamic Load Balancing
- PML absorbing BC
- Optimized higher order splines
- Parallel I/O (HDF5)
- Boosted frame in 1/2/3D

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http://cfp.ist.utl.pt/golp/epp/  
http://exodus.physics.ucla.edu/
Determining radiation spectral features

Spectrum calculation from particle trajectories

\[ \frac{d^2 I}{d\omega d\Omega} = \frac{e^2}{4\pi c} \left| \int_{-\infty}^{+\infty} \hat{n} \times \left[ (\hat{n} - \beta) \times \beta \right] e^{i\omega(t + R(t')/c)} \frac{1}{(1 - \beta \cdot \hat{n})^2} \right|^2 \]

Jackson, J.D., Classical Electrodynamics

plasma dispersion from Razin* effect

\[ \beta \rightarrow \beta n_r = \beta \left( 1 - \frac{\omega_p^2}{\omega^2} \right)^{1/2} \]

Particle tracking in OSIRIS

Relevant physics associated with small subset of particles

Record detailed 7D phase-space of “interesting” particles

Technically challenging

- Subset of \( \sim 10^3 \) particles in \( \sim 10^9 \)
- Storing information for every particle not feasible
- \( 10^4 \) iter. \( \times \) \( 10^9 \) part. \( \Rightarrow \) \( \sim 500 \) TB

Radiation from Weibel turbulence is an open question

Evolution through wide range of wiggler strengths $aW$

- Early times [first stage of the instability]: $aW << 1$
- @ Saturation: $aW > 1$ [high $k$, small $B$]
- Later times: $aW << 1$ [small $B$ to 0]

Radiation spectrum of Weibel turbulence will be a combination of the different regimes

typical signature to be assessed via numerical simulations

3D simulation setup

**moving plasma**

- **e+ e- fluid**
  - $u_{fl} = 20$
  - $u_{th} = 0.01$
  - # ppc = 4
  - $n_{\text{norm}} = 1$
  - $L = 16 \times 80 \times 80 \, c/\omega_p$

**background**

- **e+ e- fluid**
  - $u_{fl} = 0$
  - $u_{th} = 0.01$
  - # ppc = 4
  - $n_{\text{norm}} = 1$

**general**

- **3D simulation box**
  - $L = 16 \times 80 \times 80 \, c/\omega_p$
  - $\Delta t = 0.0609$
  - # cells = $200 \times 600 \times 600$
3D results confirm 2D evolution of filamentation

- B field energy [a.u.]

- Electron density parallel plane

- Electron density perpendicular plane

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3D results confirm 2D evolution of radiation spectrum

B-field energy perp plane

B-field energy parallel plane

$B_{\perp}(k)$ [a.u.]

$B_{\parallel}$ [a.u.]

$|B|^2 = (m_e c^2 \omega_p e)^2$

$\propto \omega^0$

$\propto \omega^{2/3}$

with dispersion

no dispersion

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Decrease in B strength prevents further significant radiation

Spectrum remains unchanged for long times

B-field energy
perp plane

B-field energy
parallel plane

\[ B \perp (k) \text{ [a.u.]} \]

\[ B \parallel \text{energy} \]

with dispersion
no dispersion

\( \propto \omega^{2/3} \)

\( \propto \omega^1 \)

\( \propto \omega^{2/3} \)
e-p beam: later filamentation of protons sustains B

protons lead to larger filaments at later times
Early stages similar to e-e+ case

Further evolution of spectrum due to significant B strength at small scales

- B-field energy

- B-field energy [a.u.]

- $\propto \omega^0$

- $\propto \omega^1$

- with dispersion

- no dispersion

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Physical processes underlying the KHI dynamics

2D PIC Simulations

- Density structure formation
- Magnetic field generation

2D longitudinal dynamics

2D transverse dynamics

<table>
<thead>
<tr>
<th>plasma left</th>
<th>general</th>
<th>plasma right</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u_{fl} = -0.5 )</td>
<td>\textbf{2D simulation box}</td>
<td>( u_{fl} = 0.5 )</td>
</tr>
<tr>
<td>( L = [0,100] \times [0,50] \ c/\omega_p )</td>
<td>( L = 100 \times 100 \ c/\omega_p )</td>
<td>( L = [0,100] \times [50,100] \ c/\omega_p )</td>
</tr>
<tr>
<td></td>
<td>( \Delta t = 0.03359 )</td>
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<tr>
<td></td>
<td># cells = 2000 \times 2000 \ p e- fluid</td>
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</tr>
<tr>
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<td>( uth = 0.001, # \ ppc = 4 )</td>
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<td>( n_L = n_R = 1 )</td>
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</tbody>
</table>

See also poster E.Alves et al., Magnetic field generation via the Kelvin-Helmholtz instability.
2D Kelvin-Helmoltz: longitudinal vs transverse geometry

Density asymmetry leads to wave drifting

\[ n^+ + n^- = 1 \]
\[ n^+ / n^- = 10 \]

\[ \text{Im}(\omega) = \omega_p + \omega \]
\[ \text{Re}(\omega) = \omega_p + \omega \]

Wave propagation

Density symmetric scenario (\( n^+ / n^- = 1 \))

\[ x_0 = x_1 = x_2 \]

Density asymmetric scenario (\( n^+ / n^- = 10 \))

\[ x_0 = x_1 \]

See also poster E. Alves et al., Magnetic field generation via the Kelvin-Helmholtz instability.
B-field structure different than in Weibel scenario

Sequence of events

Shearing flows

KH

Development of vortices

KH signature

leads to

Bulk interpenetration between flows

Weibel

Development of filaments

Weibel signature

See also poster E. Alves et al., Magnetic field generation via the Kelvin-Helmholtz instability.
Spectrum peak independent of geometry

2D longitudinal

2D transverse

similar peak position

slope $\propto \omega^{-2}$ at intermediate to late times

$\propto \omega^{-2}$
2D KH longitudinal spectra

\[ \theta = 0^\circ \]

\[ \theta = 90^\circ \]

similar peak position

radiation associated with B3 perturbation at the shear surface
Radiation spectra is approximately isotropic due to similar B field amplitude in all directions at shear region.
Weibel vs Kelvin-Helmoltz spectra in propagation direction

2D KH longitudinal

3D Weibel

\( \propto \omega^{3/4} \)

\( \propto \omega^{-3.7} \)

\( \propto \omega^{-2} \)

\( \propto \omega^{1} \)

\( \propto \omega^{-6} \)

\( \propto \omega^{-1} \)

\( \propto \omega^{-3/2} \)
Conclusions

**Weibel**

- Spectrum is not pure synchrotron or jitter. [B field strength/length scale extend over wide range during instability].
- Growth of filaments at onset of instability promotes emission at low $\omega$.
- At saturation, B structures with $k \sim \omega_{pe}/c$ and high field amplitude lead to synchrotron type spectrum.

**Kelvin-Helmoltz**

- Spectrum is similar in orthogonal viewing angles, with ‘synchrotron’-like peak. [B field strength similar in all components at saturation].
- Longitudinal spectra at high $\omega$ presents features associated with BI perturbations at shear surface.
- Slopes at low and high $\omega$ less steep than in Weibel case due to different field structure.