Radiation from accelerated particles in relativistic jets with shocks and shear-flow

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PIC simulations of relativistic electron-positron (electro-ion) jets injected into a stationary medium show that particle acceleration occurs within the downstream jet (Choi et al. PhPl, 21, 072905 2014). The Weibel instability is responsible for generating and amplifying highly non-uniform, small-scale magnetic fields. These magnetic fields contribute to the electron's transverse deflection behind the jet head. Recently, reconnection in jets has been proposed for additional particle acceleration mechanism for AGN jets and gamma-ray bursts. Various reconnection simulations have been performed; RPIC simulations, resistive relativistic MHD, and two-fluid simulations. Besides reconnection, kinetic Kelvin-Helmholtz instability (kKHI) is also responsible for particle acceleration. Moreover, the additional particle acceleration and electromagnetic fields generated by kKHI contribute to radiation (Nishikawa et al. 2013a,b, 2014). It is noteworthy to mention that the radiation from deflected electrons has different properties than synchrotron radiation which is calculated in a uniform magnetic field. This radiation obtained self-consistently may be important to understanding the complex time evolution and/or spectral structure in gamma-ray bursts, relativistic jets, and supernova remnants. Recently we have started to investigate shocks and kKHI simultaneously injecting jets in an ambient plasma, shown in this poster. Here you see that the current filaments structures are different between electron-positron and electron-proton jets.

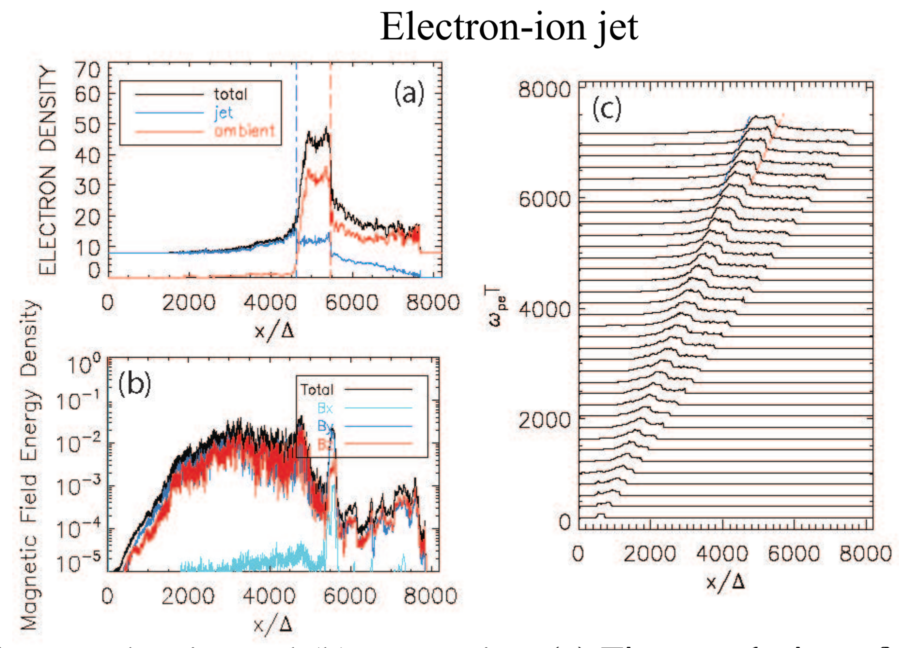
Key Scientific questions

- **How do shocks in relativistic jets evolve?**
- **How magnetic fields affect shocks and reconnection?**
- **How are particles accelerated?**
- **What are the dominant radiation processes?**
- **How do 3-D relativistic particle simulations reveal the dynamics of shock fronts and transition regions?**
- **How do shocks in relativistic jets evolve under various ambient plasma and magnetic fields?**
- **How do magnetic fields generated by the Weibel instability contribute to radiation?**
- **How the Electron-Scale Kelvin-Helmholtz instability (ESKHI) (kKHI) grows.**

*** For some answers see Nishikawa et al. 2006, ApJ, 642, 1267**
Ramirez-Ruiz, Nishikawa & Hededal, 2007, ApJ, 671, 1877
Nishikawa et al. 2009, ApJ, 698, L10
Nishikawa et al. 2014, ApJ, 793, 60

Shock formation, forward shock, reverse shock

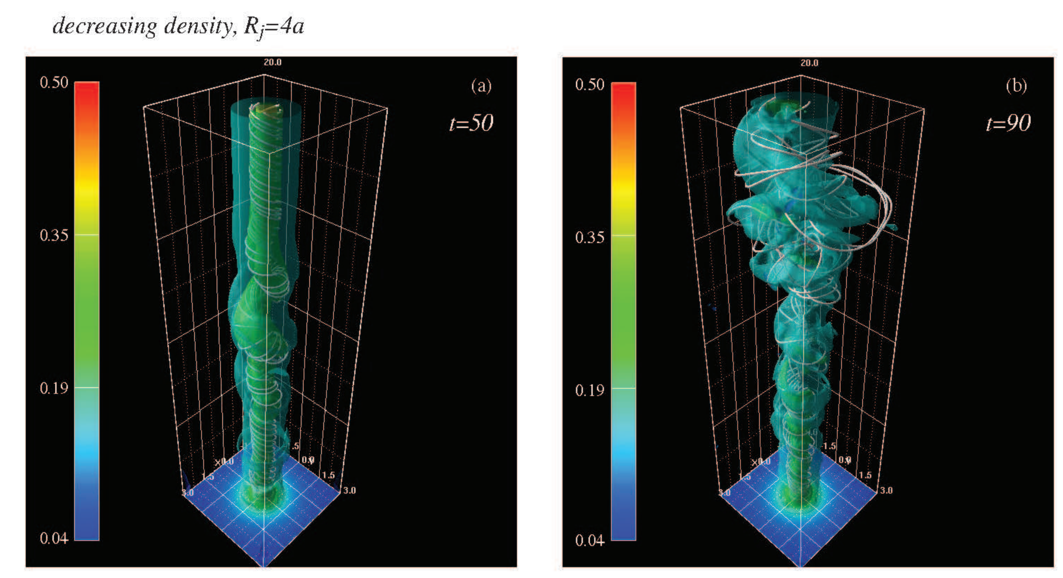
Electron-ion jet



(a) electron density and (b) magnetic field energy divided by the total kinetic energy at $t = 7372\omega_{pe}^{-1}$. (c) Time evolution of the electron density profile.

(Choi et al. PhPl, 21, 072905, 2014)

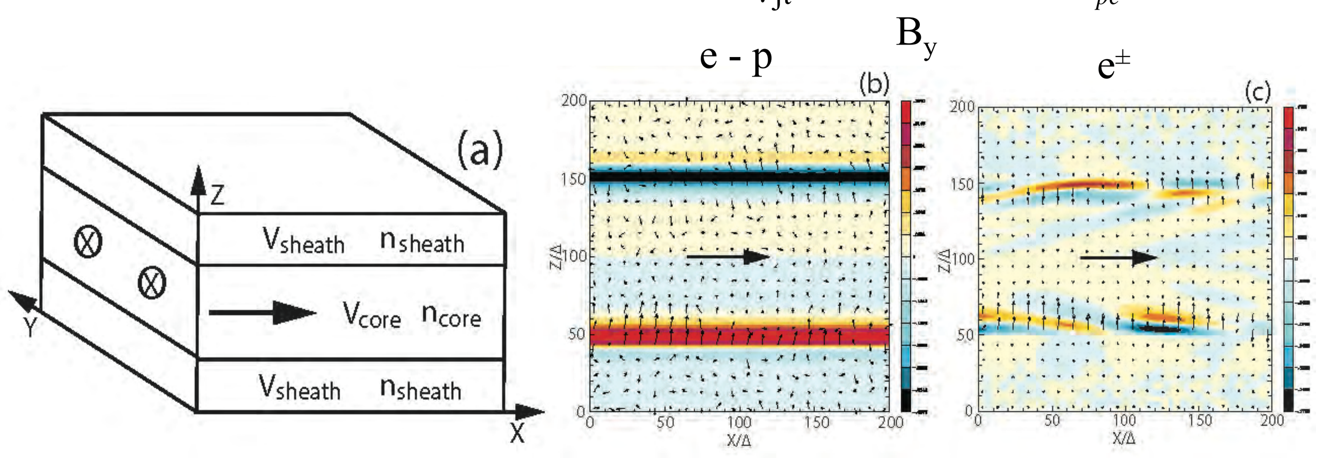
3-D kink instability with helical magnetic field



Three-dimensional density isosurfaces with a transverse slice at z = 0 for the decreasing density cases B2 (Rj = 4a) at t/t_c = 50 and 90. Representative solid magnetic field lines are shown, and the color scales with the logarithm of the density. (Mizuno et al, ApJ, 784:167, 2014)

Kinetic Kelvin-Helmholtz instability (kKHI)

$\gamma_{jt} = 15$ $t = 300\omega_{pe}^{-1}$

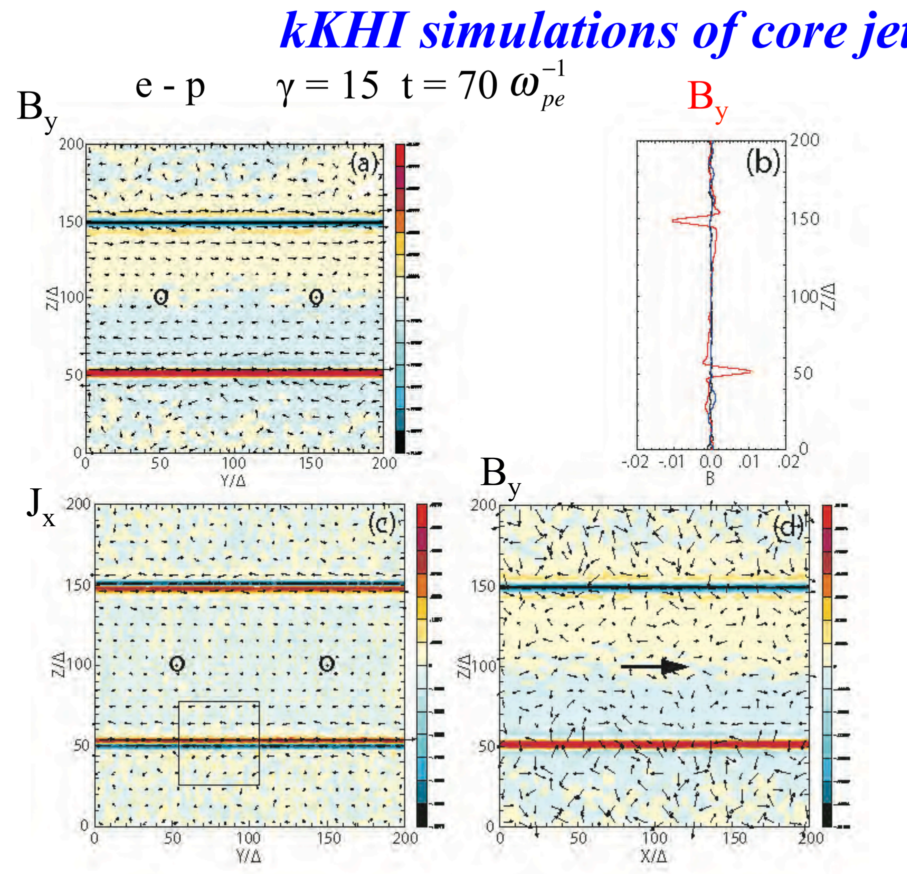


Panel (a) shows our simulation model where the sheath plasma can be stationary or moving in the same direction as the jet core. Panels (b) & (c) show the magnetic field component $\mathbf{B}_y > 0$ (red) and $\mathbf{B}_y < 0$ (blue) plotted in the $\mathbf{x} - \mathbf{z}$ plane (jet flow indicated by large arrows) at the center of the simulation box, $\mathbf{y} = 100\Delta$ at $\mathbf{t} = 300\ \omega_{pe}^{-1}$, (b) for the $\mathbf{e}^-$- $\mathbf{p}^+$ case and (c) for the $\mathbf{e}^{\pm}$ case, both with $\gamma_{core} = 15$. The smaller arrows indicate the magnetic field direction in the plane. Panels (b) & (c) cover one fifth of the simulation system length in the **x** direction.

(Nishikawa et al. ApJ, 793, 60, 2014)

kKHI simulations of core jet- stationary sheath plasma

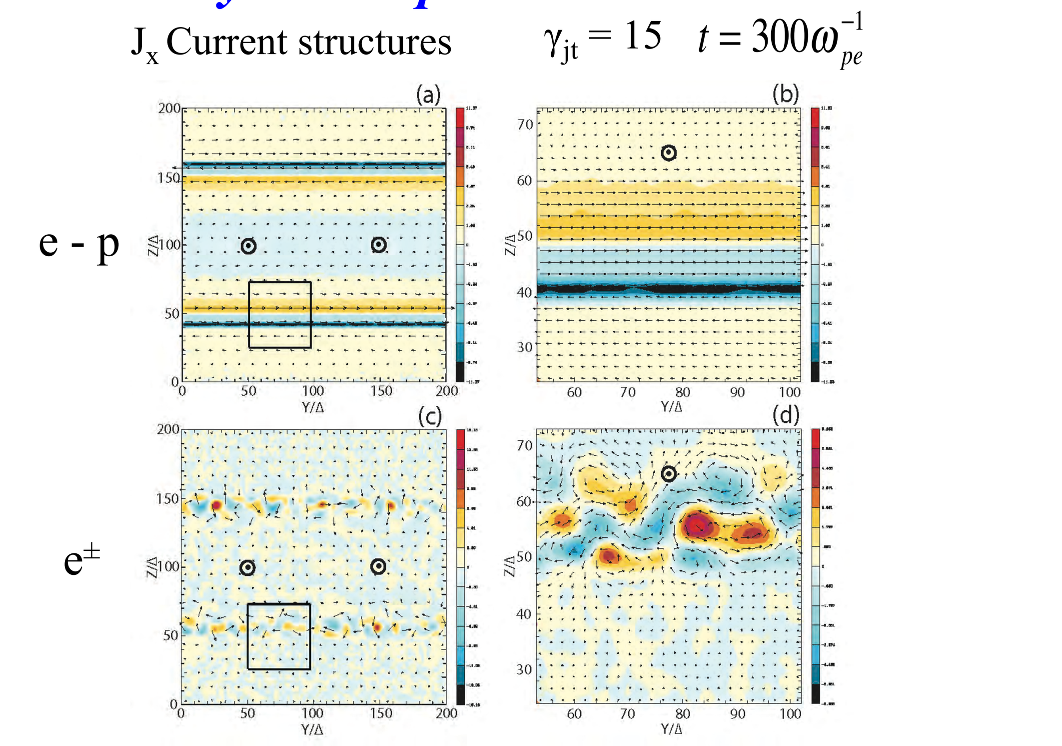
e - p $\gamma = 15$ $t = 70\ \omega_{pe}^{-1}$



Kinetic KHI generates current filaments J_x (c) at the velocity shear which creates the magnetic field B_y ((a), (b), and (d)).

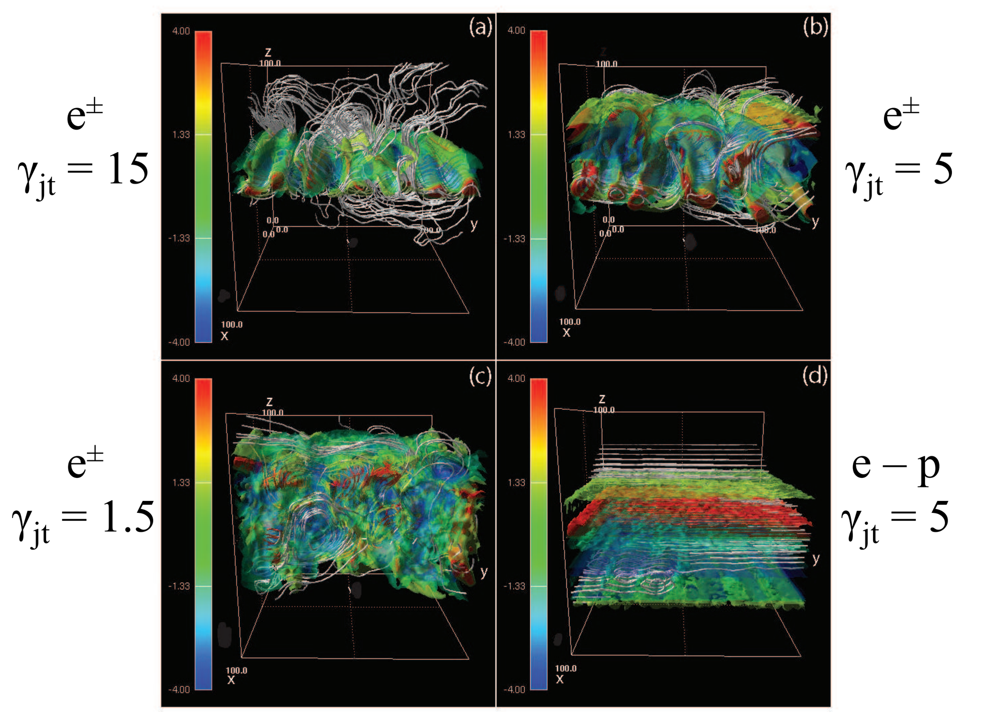
(Nishikawa et al. 2013a,b)

J_x Current structures $\gamma_{jt} = 15$ $t = 300\omega_{pe}^{-1}$



Magnetic field structure transverse to the flow direction for jt = 15 is shown in the **y −z** plane (jet flows out of the page) at the center of the simulation box, **x** = 500 for the $\mathbf{e}^-$- $\mathbf{p}^+$ case (upper row) and the $\mathbf{e}^{\pm}$ case (lower row) at simulation time $t = 300\omega_{pe}^{-1}$ (Nishikawa et al. ApJ, 793, 60, 2014)

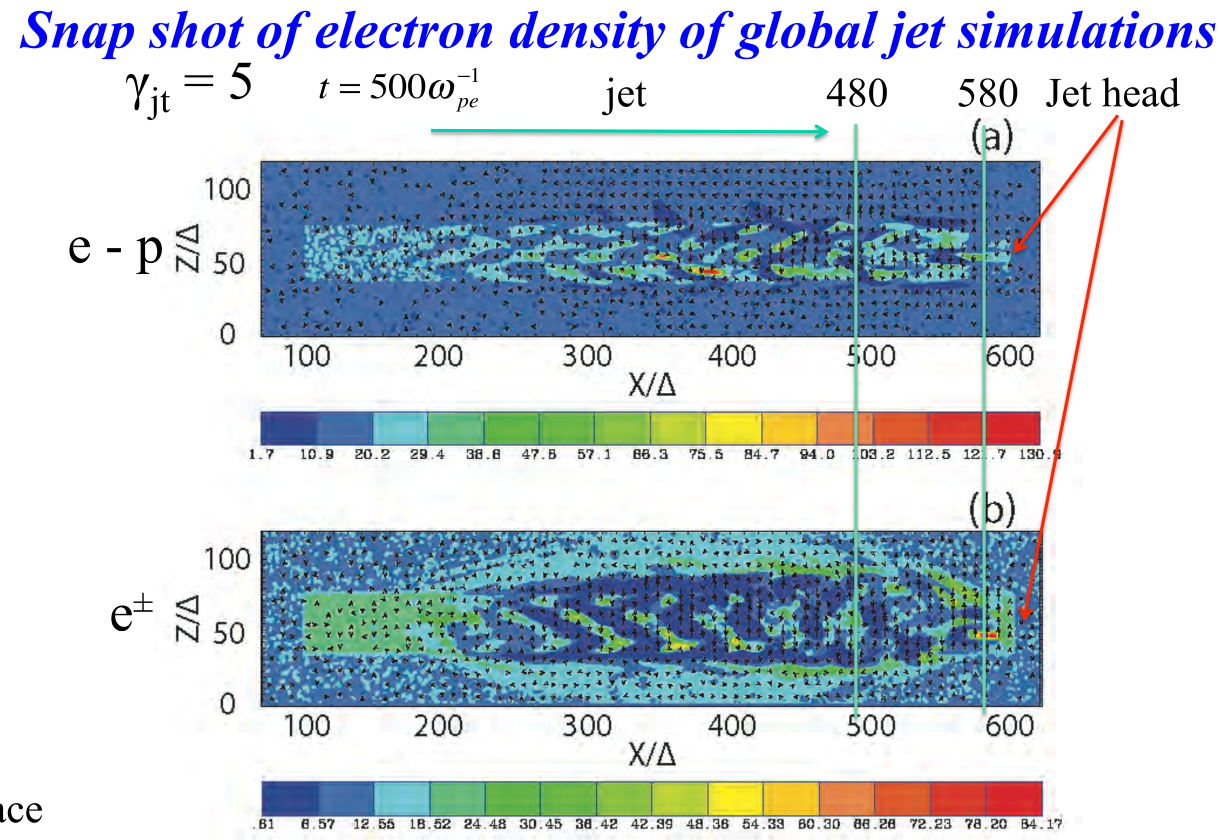
Currents and magnetic fields



Currents and magnetic fields at the velocity shear surface displayed as isosurfaces of the x component of current density with white magnetic field lines for $e^{\pm}$ cases with (a) $\gamma_{jt} = 15$, (b) $\gamma_{jt} = 5$, and (c) $\gamma_{jt} = 1.5$ at $t = 300\omega_{pe}^{-1}$. Panel (d) shows the currents and magnetic fields for the e−- p+ case with $\gamma_{jt} = 5$ at $t = 300\omega_{pe}^{-1}$.

(Nishikawa et al. ApJ, 793, 60, 2014)

Snap shot of electron density of global jet simulations



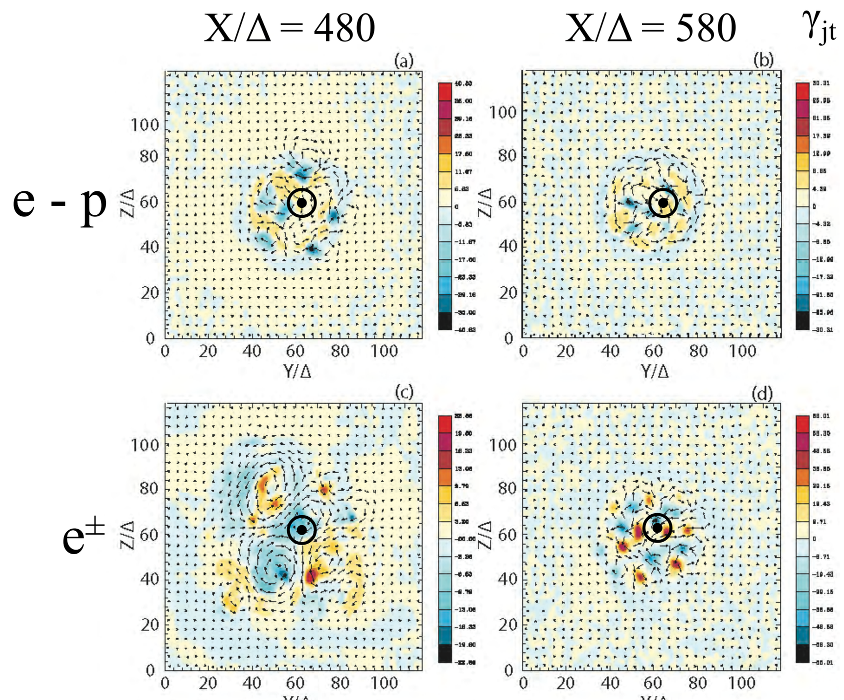
Mid-plane slices of the electron density for jet Lorentz factor $\gamma_{jt} = 5$ at simulation time $t = 500\omega_{pe}^{-1}$. The jet is injected at $\mathbf{x}/\Delta = 100$, propagates to the right, and the jet front is located at $\mathbf{x}/\Delta = 600$. The upper panel shows that the electron density structure for mass ratio $\mathbf{m}_i/\mathbf{m}_e = 1836$ is rather confined within the jet. On the contrary, the lower panel for an electron-positron case shows that the jet expands transversely.

Results

- **The Weibel instability creates filamented currents and density structure along the propagation axis of the jet.**
- **The growth rate of the Weibel instability depends on the Lorentz factor, composition, and strength and direction of ambient B fields.**
- **The electron-ion ambient plasma enhances the generated magnetic fields with the excitation ion Weibel instability.**
- **This enhanced magnetic field with electron-ion ambient plasma may be an origin of large upstream magnetic fields in GRB shocks.**
- **In order to understand the complex shock dynamics of relativistic jets, further simulations with additional physical mechanisms such as radiation loss and inverse Compton scattering are necessary.**
- **Spectra from two electrons are calculated for different conditions.**
- **The magnetic fields created by the Weibel instability generate highly inhomogeneous magnetic fields, which are responsible for Jitter radiation (Medvedev, 2000, 2006; Fleishman 2006).**
- **Numerical approach of calculating radiation from electrons based on simulations self-consistently provides more realistic spectra including jitter radiation.**

Snap shots of current structures

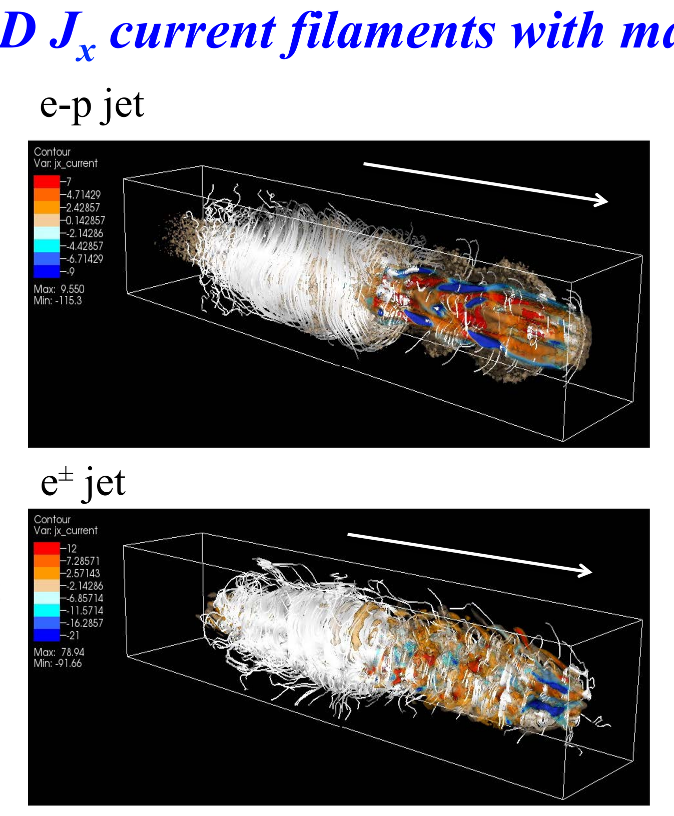
X/Δ = 480 X/Δ = 580 $\gamma_{jt} = 5$ $t = 500\omega_{pe}^{-1}$



⊙Jet center

Slices showing current filaments with transverse magnetic fields. Electron-proton jet contains inside the jet, but $e^{\pm}$ jet expands outside the jet.

3D J_x current filaments with magnetic field lines



3D $\mathbf{J}_x$ current filaments with magnetic filed lines clipped at the center of the jet with $\gamma_{jt} = 5$, $t = 500\ \omega_{pe}^{-1}$. e-p jet has longer continuous current filaments, but $e^{\pm}$ jet has disconnected and twisted current filaments.

(Nishikawa et al. in progress, 2014)

Future plans

- *** Further simulations with a systematic parameter survey will be performed in order to understand shock dynamics including reconnection.**
- *** Further simulations will be performed to calculate self-consistent radiation including time evolution of spectrum and time variability with shocks (Weibel instability) and velocity shear (kKHI).**
- *** Investigate radiation processes from the accelerated electrons and compare with observations (GRBs, SNRs, AGNs, etc).**
- *** Synthetic spectra will be obtained with injected jets including shocks and kKHI simultaneously.**
- *** Simulations of injected jets with helical magnetic field will be performed in order to investigate kink instability with kinetic processes.**

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