Inverse Compton Emission and Cooling of Relativistic Particles Accelerated at Shear Layers in Relativistic Jets

Tej Chand & Markus Böttcher

CSR, North-West University, Potchefstroom

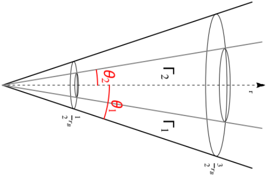
Fermi Summer School June 3, 2023

Outline:

1. Relativistic Jest & Shear Boundary Layers (SBLs)
2. Particle Anisotropy
3. Angle-independent Radiation Spectra
4. Angle-dependent Radiation Spectra
5. Effect of Radiation Drag on Particle Spectra
6. Conclusions

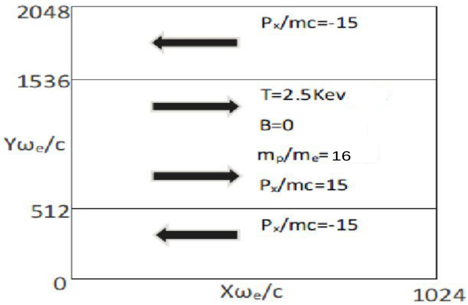
Spine-Sheath Morphology of Jets:

- Relativistic jets are **collimated outflows** of matter from the **accreting black holes** residing at the centre of the active galaxies (AGN) that can travel undisrupted over kpc scales.
- Both observational evidence, as well as theoretical considerations from MHD simulations of jets, suggest that they are **radially stratified with a fast inner spine surrounded by a slower moving outer sheath** (e.g. Ghisellini et al. 2005, Walg et al. 2013).
- The shear layers formed in the relativistic jets are promising sites for particle acceleration (Alves et al. 2012, Liang et al. 2013).



Where Do We Simulate?

- We perform 2.5 D Particle-in-Cell simulation of E- and B- field generation and particle acceleration at relativistic SBLs. For this, we used the TRISTAN-MP code developed by Spitkovsky (2005).

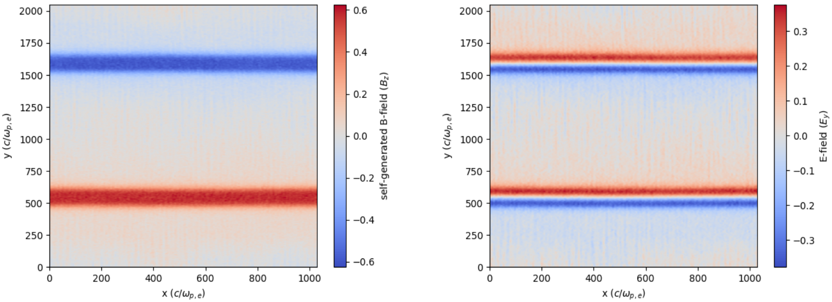


ion-electron mass ratio, $m_i/m_e = 16$

Simulated in the Equal-Lorentz-Factor (ELF) frame

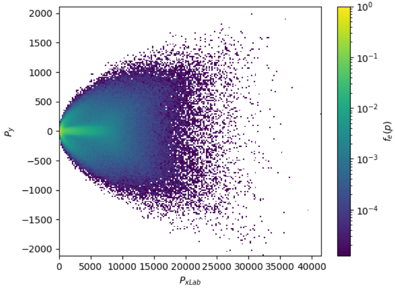
Self-generation of E- & B- Fields.

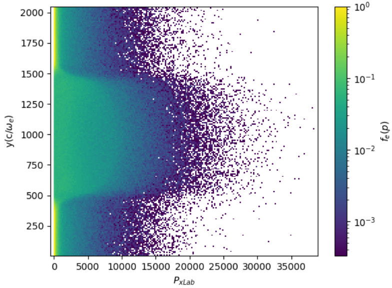
Self-generated B- & E-fields in the case of **pure e^-ion plasma**



Particle anisotropy.

P_y vs. P_{xLab} plot for electrons:

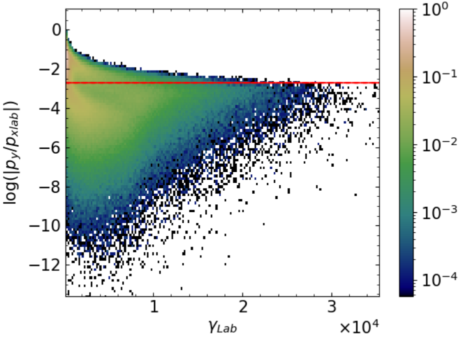




- P_x is Lorentz boosted to the laboratory frame.
- Diffusion of some of the spine electrons into the sheath region takes place.

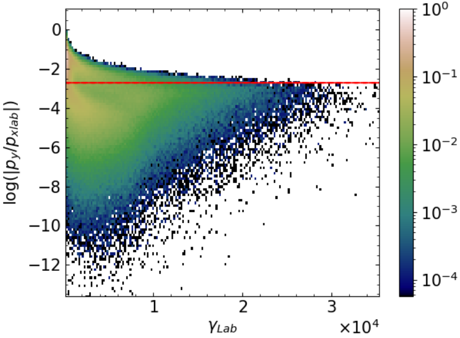
Particle Anisotropy

Beam angle vs. γ_{Lab} plot for electrons:



Particle Anisotropy

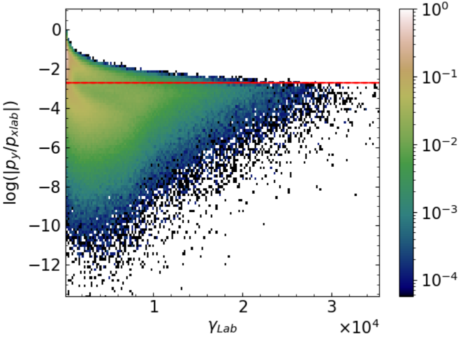
Beam angle vs. γ_{Lab} plot for electrons:



- High energy spine electrons are observed with beam angles much smaller than $1/\Gamma$.

Particle Anisotropy

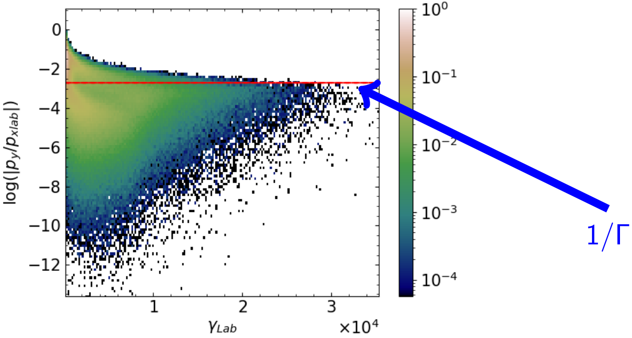
Beam angle vs. γ_{Lab} plot for electrons:



- High energy spine electrons are observed with beam angles much smaller than $1/\Gamma$.
- There exists an anticorrelation between beam angle and e^{-}-energy.

Particle Anisotropy

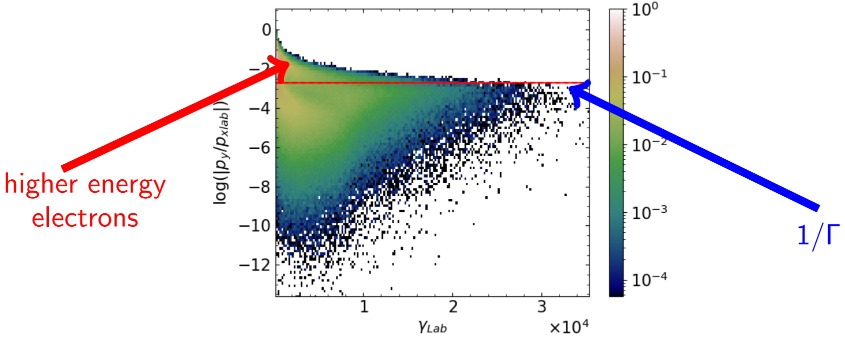
Beam angle vs. γ_{Lab} plot for electrons:



- High energy spine electrons are observed with beam angles much smaller than $1/\Gamma$.
- There exists an anticorrelation between beam angle and e^{-}-energy.

Particle Anisotropy

Beam angle vs. γ_{Lab} plot for electrons:



- High energy spine electrons are observed with beam angles much smaller than $1/\Gamma$.
- There exists an anticorrelation between beam angle and e^--energy.

Angle-independent Radiation Spectra

- Radiation spectra are evaluated using a simple delta-function approximation for the monoenergetic target photon field.

- The radiation cooling term for inverse Compton scattering of relativistic electrons in the angle-integrated external photon field in the Thomson regime is:

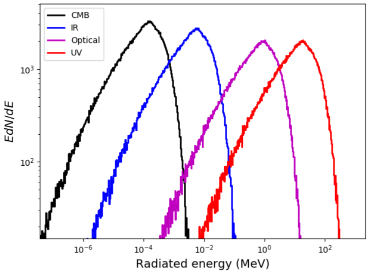
$$\left(\frac{d\gamma}{dt}\right)_{rad} = \frac{\pi^4}{15}\, \sigma_T \; c \; K \; \gamma^2 \; \theta^4 \quad , \qquad K = \frac{8\pi}{\lambda_c^3}$$

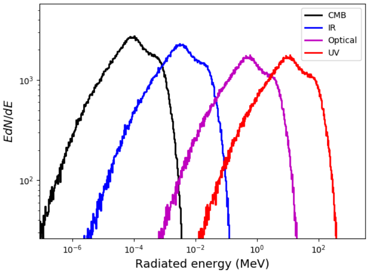
$$\sigma_T = \frac{8\pi}{3}\left(\frac{e^2}{m_e c^2}\right)^2 \implies \text{Thomson cross-section}$$

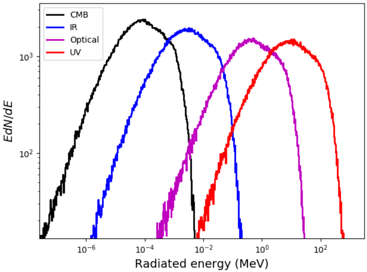
$$\lambda_c = \frac{h}{m_e c} \implies \textit{Compton wavelength}$$

$$\theta = \frac{K_B T}{m_e c^2} \implies \text{normalized photon temperature}$$

- Angle-averaged radiation spectra for different radiation temperatures obtained from the PiC simulations:

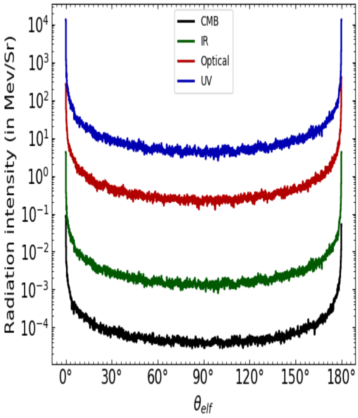




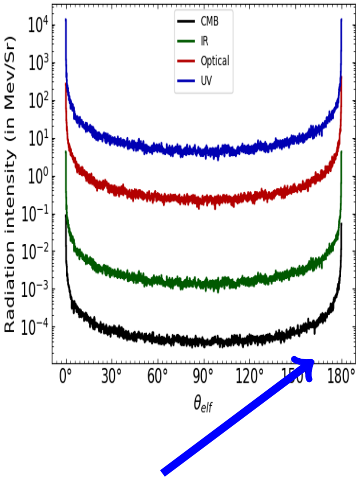


NWU

Observation of Angle-averaged Radiation Spectra

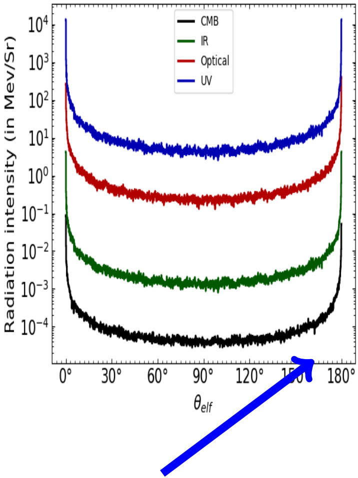


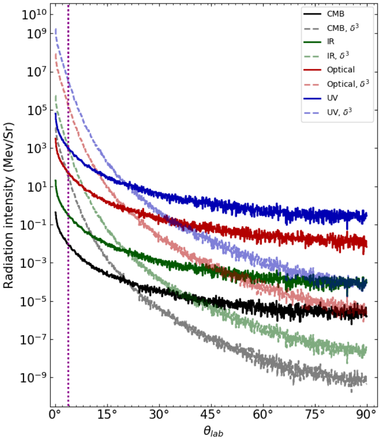
Observation of Angle-averaged Radiation Spectra



in equal Lorentz factor frame

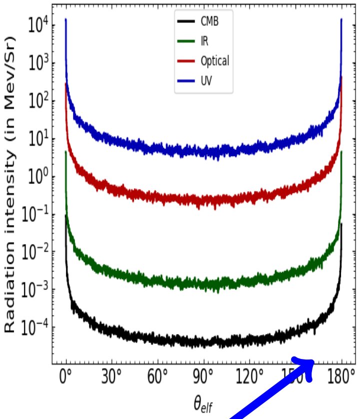
Observation of Angle-averaged Radiation Spectra

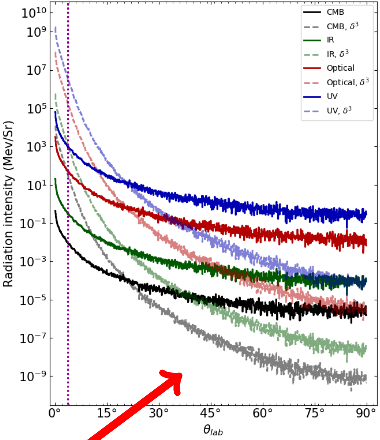




in equal Lorentz factor frame

Observation of Angle-averaged Radiation Spectra





in equal Lorentz factor frame

in lab. frame

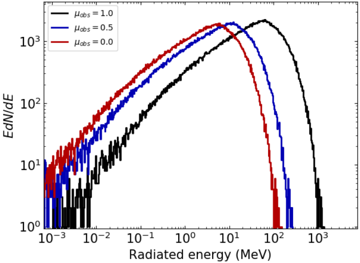
Angle-dependent Radiation Spectra

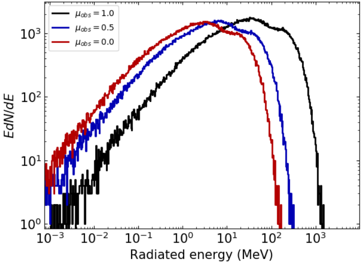
- The cooling term for inverse Compton scattering of relativistic electrons in angle-dependent photon field in the Thomson regime is:

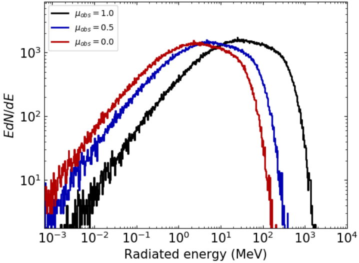
$$\frac{\mathrm{d}\gamma}{\mathrm{dt}}(\mu,\gamma,\theta) = \frac{2.4\times 3c\sigma_T K\theta^2}{2.7\times 8\gamma^2}\Bigg[\left(\epsilon_{s_{max}}^2-\epsilon_{s_{min}}^2\right)+\frac{\epsilon_{s_{max}}^4-\epsilon_{s_{min}}^4}{4\gamma^2}+ \frac{\epsilon_{s_{max}}^5-\epsilon_{s_{min}}^5}{5\gamma^3}-\frac{2}{2.7\theta(1-\beta\mu)}\left\{\frac{\left(\epsilon_{s_{max}}^3-\epsilon_{s_{min}}^3\right)}{3\gamma^2}+\frac{\epsilon_{s_{max}}^4-\epsilon_{s_{min}}^4}{4\gamma^3}\right\} + \frac{1}{\gamma^4}\frac{1}{(2.7\theta)^2(1-\beta\mu)^2}\left\{\frac{\epsilon_{s_{max}}^4-\epsilon_{s_{min}}^4}{4}+\frac{2\left(\epsilon_{s_{max}}^5-\epsilon_{s_{min}}^5\right)}{5\gamma}+ \frac{\epsilon_{s_{max}}^6-\epsilon_{s_{min}}^6}{2\gamma^2}+\frac{4\left(\epsilon_{s_{max}}^7-\epsilon_{s_{min}}^7\right)}{7\gamma^3}\right\}\Bigg]$$

- $\epsilon_{s_{max}} = \frac{5.4\gamma^2(1-\beta\mu)\theta}{1+5.4\gamma\theta(1-\beta\mu)}$ and $\epsilon_{s_{min}} = \frac{2.7\theta(1-\beta\mu)}{2}$ and $\mu = \cos\psi$. ψ is the angle between the direction of propagation of interacting photons and electrons.

- The radiation spectra due to inverse Compton scattering of relativistic electrons in an angle-dependent UV-photon field:

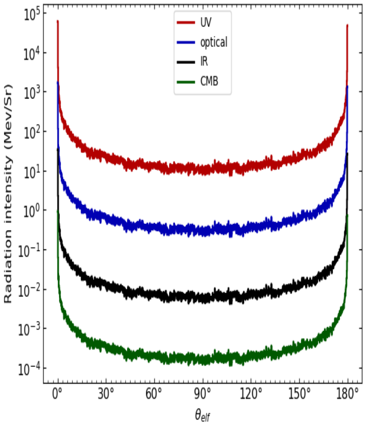




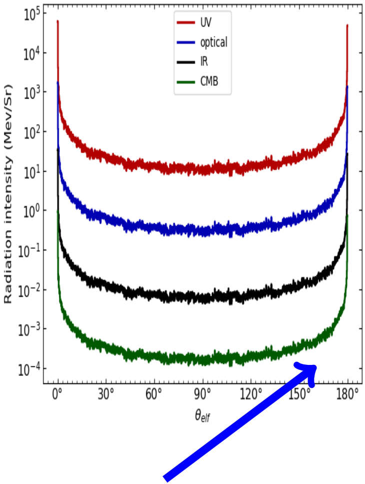


NWU

Observation of Angle-dependent Radiation Spectra

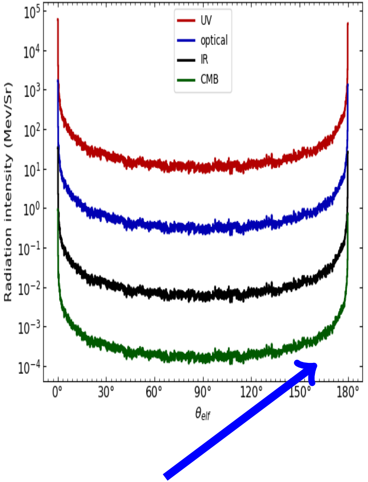


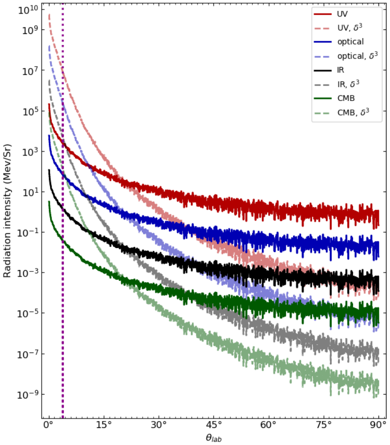
Observation of Angle-dependent Radiation Spectra



in equal Lorentz factor frame

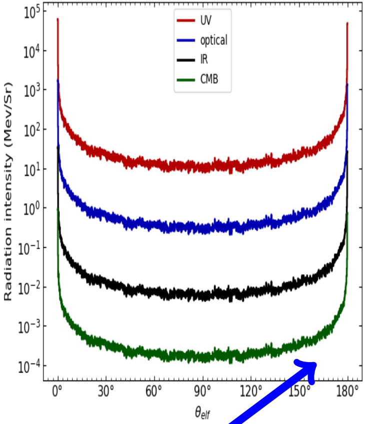
Observation of Angle-dependent Radiation Spectra

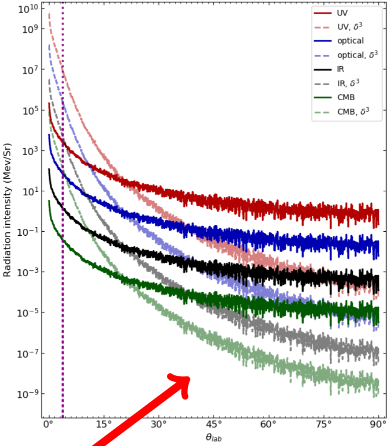




in equal Lorentz factor frame

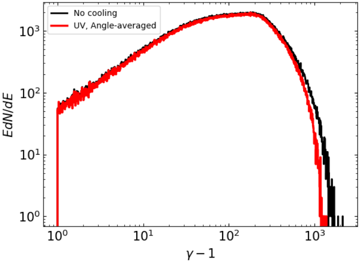
Observation of Angle-dependent Radiation Spectra



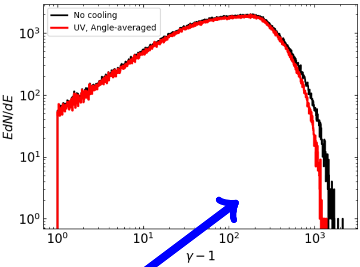


in equal Lorentz factor frame in lab. frame

Effect of Radiation Drag on Particle Spectra

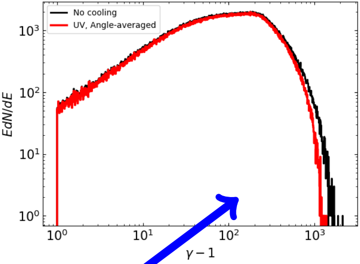


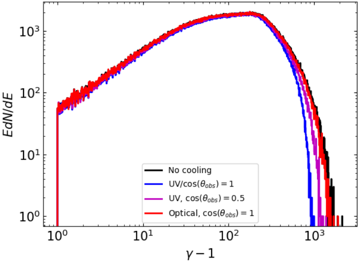
Effect of Radiation Drag on Particle Spectra



cooled by angle-averaged
BB photons

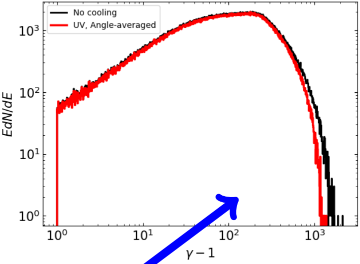
Effect of Radiation Drag on Particle Spectra

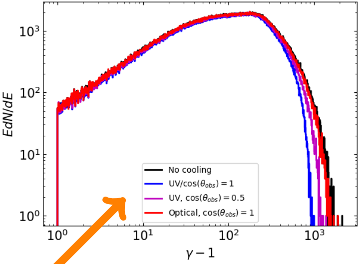




cooled by angle-averaged
BB photons

Effect of Radiation Drag on Particle Spectra





cooled by angle-averaged BB photons

cooled by angle-dependent BB photons

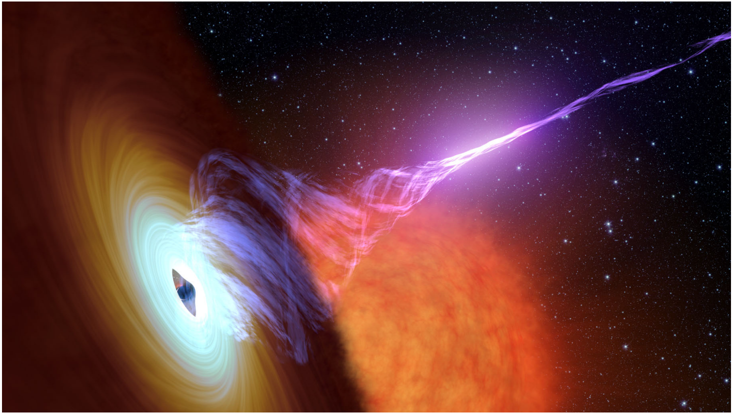
Conclusion:

- PIC simulations of relativistic SBLs can demonstrate efficient generation of E- & B-fields and particle energisation from initially unmagnetized plasma.
- Particle distribution in SBLs at relativistic jets is anisotropic.
- The emitted radiation is strongly beamed in the forward direction, with a characteristic opening angle $\approx 1/\Gamma$
- The inverse-Compton cooling affects electron spectra at higher electron energies.
- The spine-sheath morphology of the relativistic jet can provide a potential resolution of the bulk Lorentz factor crisis in blazars.

Thank You!

Relativistic Jets:

- Relativistic jets are **collimated outflows** of matter from the accreting black holes (BH) residing at the centre of the active galaxies (AGN).



Artist's concept of a black hole with an accretion disk.

NWU

Compton scattered spectra for thermal distribution of photons using delta-approximation:

Thomson cross-section

$$\frac{d\sigma}{d\Omega \ d\epsilon_s} = \sigma_T \ \delta(\epsilon_s \ - \ \gamma^2 \epsilon_0) \ \delta(\Omega_s - \Omega_e) \ H(1 - \epsilon_0 \gamma)$$

The emissivity of Compton-scattered radiation due to the interaction of single electron

$$j_{\epsilon_0}^{head-on}(\gamma) = c \ \sigma_T \ m_e \ c^2 \ \epsilon_s \int_0^{\infty} n_{ph}(\epsilon_0) \ \delta(\epsilon_s - \epsilon_0 \gamma^2) \ \delta(\Omega_s - \Omega_e) \ d\epsilon_0$$

Which on solving gives:

$$j_{\epsilon_s}^{head-on}(\gamma) = \sigma_T \ m_e c^3 \ K \ \delta(\Omega_s - \Omega_e) \ \frac{1}{\gamma^6} \frac{\epsilon_s^3}{e^{\frac{\epsilon_s}{\gamma^2 \theta}} - 1}$$

- The Compton cross section for angle-dependent photon distribution is given by:

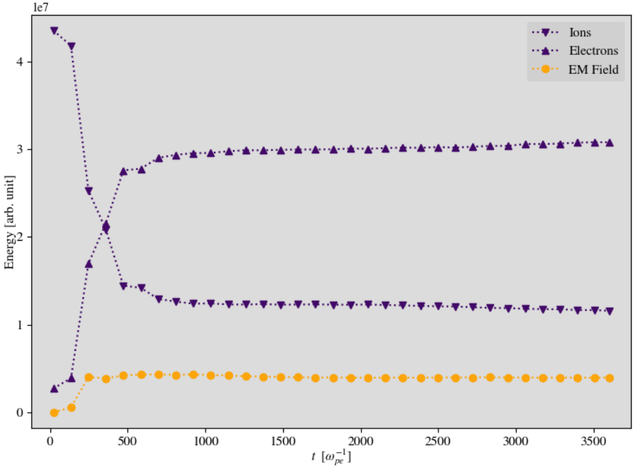
$$\frac{d\sigma_C}{d\Omega_s} = \frac{\pi r_e^2}{\gamma \epsilon'} \left\{ y + \frac{1}{y} - \frac{2\epsilon_s}{\gamma \epsilon' y} + \left(\frac{\epsilon_s}{\gamma \epsilon' y} \right)^2 \right\} H\left(\epsilon_s \; ; \; \frac{\epsilon'}{2\gamma} \, , \; \frac{2\gamma\epsilon'}{1 + 2\epsilon'} \right)$$

- The emissivity for angle-dependent photon distribution using Dirac-delta approximation is:

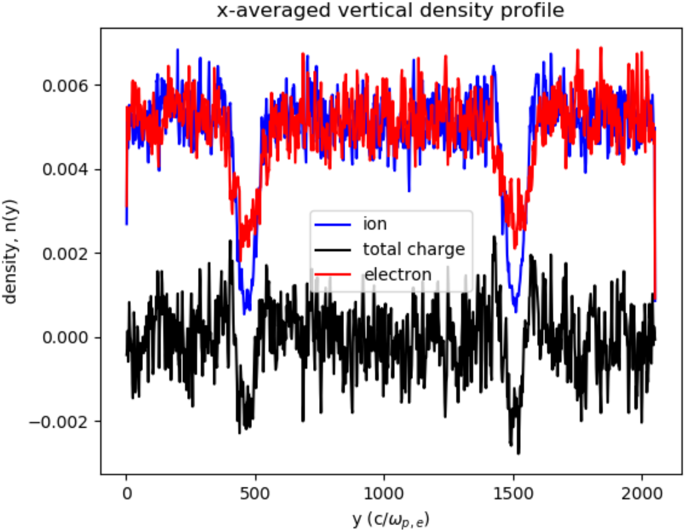
$$\mathrm{j}(\epsilon, \gamma, \mu) = \frac{3 m_e c^3 \sigma_T K \epsilon_s}{8\gamma} \int_0^\infty \frac{1}{\epsilon'} \left\{ y + \frac{1}{y} - \frac{2\epsilon_s}{\gamma \epsilon' y} + \left(\frac{\epsilon_s}{\gamma \epsilon' y} \right)^2 \right\}$$
$$\delta(\epsilon - 2.7\theta) \; H\left(\epsilon_s \; ; \; \frac{\epsilon'}{2\gamma} \, , \; \frac{2\gamma\epsilon'}{1 + 2\epsilon'} \right) d\epsilon$$

Where, $y = 1 - \frac{\epsilon_s}{\gamma}$ and $\epsilon' = \gamma\epsilon(1 - \beta\mu)$. 2.7θ is the mean photon energy of a blackbody radiation field.

Time evolution of particle energies



Vertical density profile



Total charge density