Modelling the synchrotron emission of RMHD AGN Jet simulations with the PLUTO particle module

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Introduction

Radio-loud Active Galactic Nuclei (AGN) are associated with the production of relativistic jets. The spectral energy distribution (SED) of these jets can extend from radio to very high energy γ-rays and exhibit a characteristic double bump structure [1]. The emission at the lower wavelengths (radio-optical) is dominated by synchrotron radiation from a population of non-thermal electrons. Based on the properties of their emission AGN are subdivided into different classes which depend on both the morphology (e.g. FRI and FRII dichotomy) as well as the viewing angle with respect to the jet (e.g. Radio galaxies vs Blazars) [2]. To investigate how the kinematics and evolution of the relativistic jet influence the properties of the AGN, numerical simulations have been employed. In the past these simulations have been limited either to large scale computational fluid dynamic simulations (e.g. [3]), which do not consider micro-scale physics (such as the evolution of the non-thermal particles), or smaller scale particle in cell simulations, which become too computationally expensive to simulate the large-scale morphology of the jet [4]. To obtain a more complete emission model of large-scale fluid dynamic simulations of AGN jets, we have employed the new fluid-particle hybrid module of the PLUTO code [5].

RMHD Simulations

A three dimensional (3D) Relativistic magneto-hydrodynamic simulation was created using the grid based hydrodynamic code PLUTO ver 4.4 (http://plutocode.ph.unito.it/) [6]. The simulation consisted of a Cartesian domain with 512x512x1024 cells. A stratified background medium was initially assigned to the domain and a lower density jet fluid was injected through a nozzle on the lower *z* boundary. A resolution of 4 cells/jet radius was used. The jet was injected at a constant rate with a force-free helical magnetic field (see [3]). The injection parameters are given in Table 1. Figure 1 shows the resulting structure that was produced.

Table 1 : Jet injection parameters

Parameter	Value
Lorentz factor	10
Jet/ambient density ratio	10^{-4}
Mach number	10
B-field	10 μG

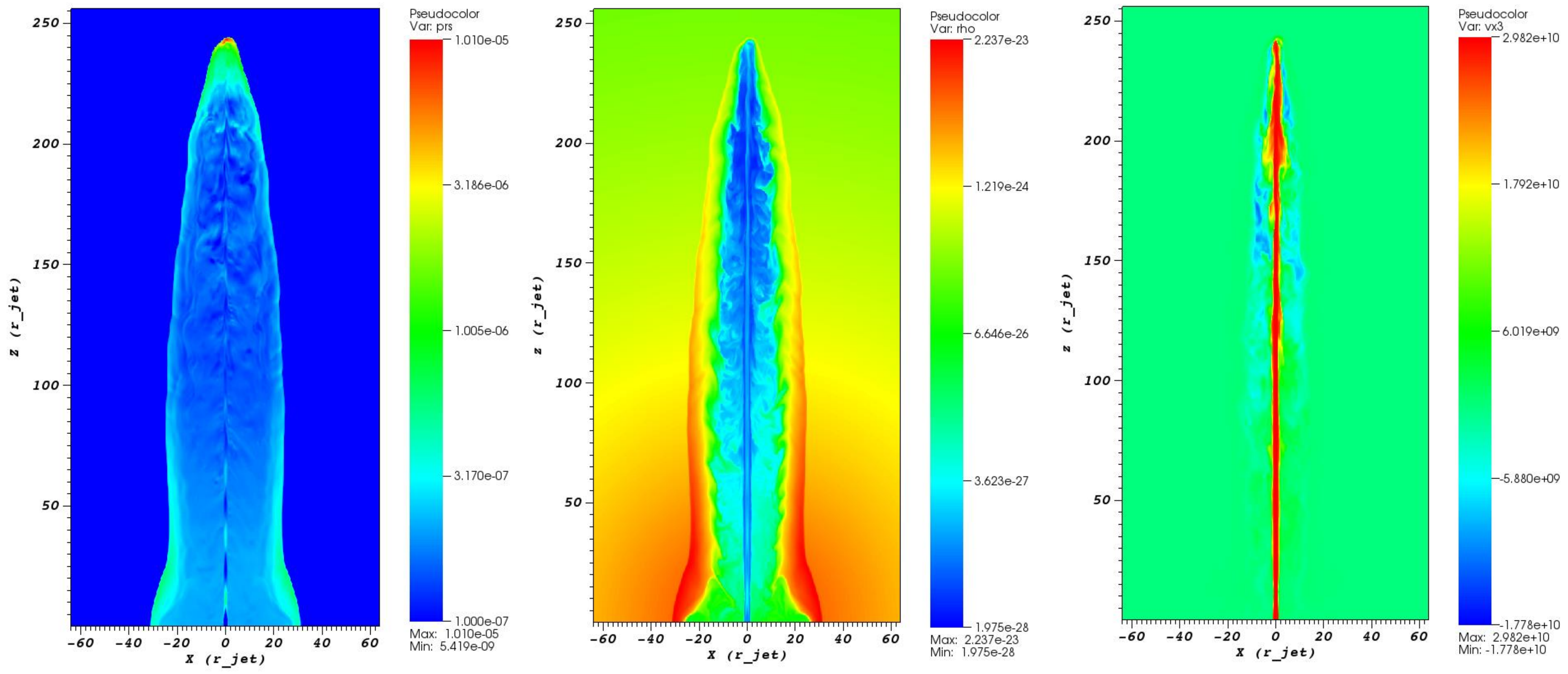

Figure 1: Pressure (left), Density (middle) and velocity (right) slices through the y-axis of the jet.

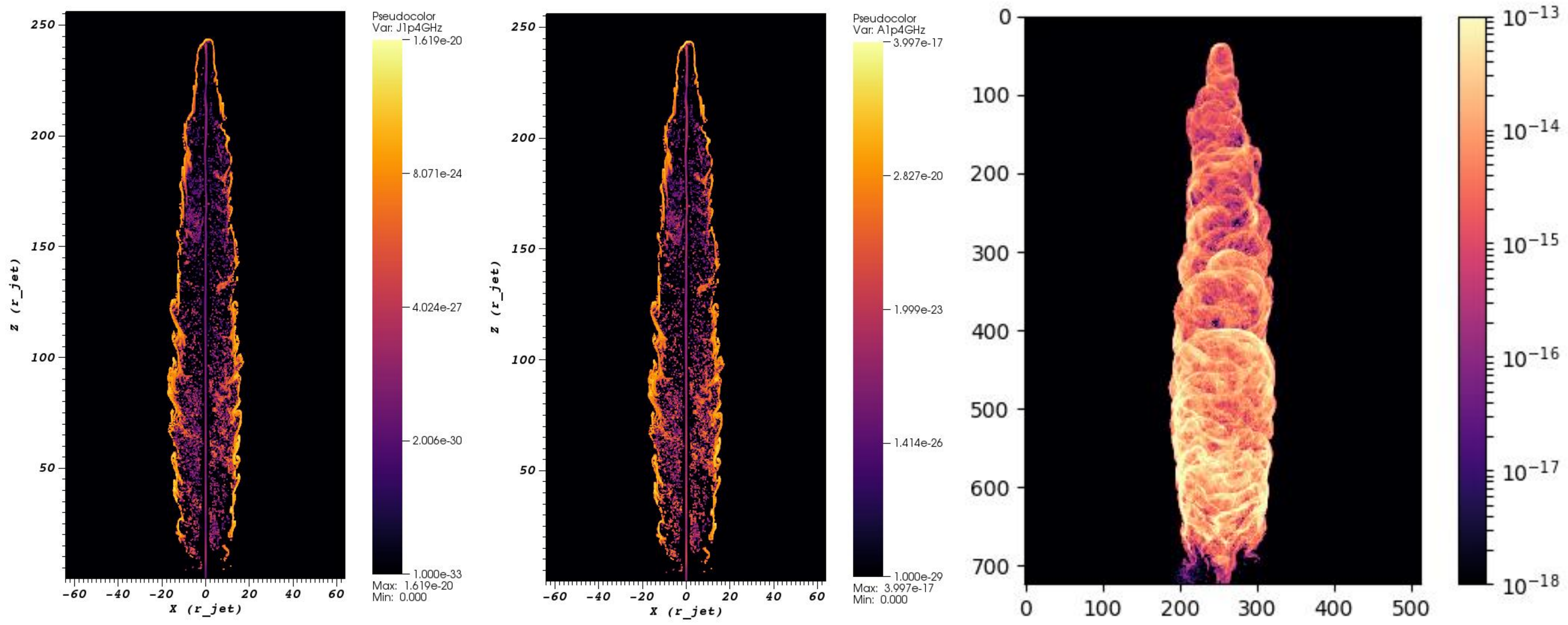

Figure 3: Slices of the emission (left) and absorption (middle) coefficients through the y-axis of the jet along with the intensity map (right) at 1.4 GHz for a viewing angle of 45°.

Particle-hybrid module

Using the PLUTO hybrid framework [5], a sample of Lagrangian particles was continuously injected at the jet nozzle, with a random spatial distribution. Each Lagrangian particle represents an ensemble of non-thermal electrons, with a finite power-law energy distribution. The parameters for the initial nonthermal distribution is listed in Table 2. As the particle propagates with the fluid the spectrum is updated considering processes such as adiabatic expansion and radiative cooling. Figure 2 shows a rendering of the Lagrangian particles in a segment of the jet.

Table 2: Injected Non-thermal electron distribution

γ_{min}	γ_{max}	p
10^2	10^7	2.1

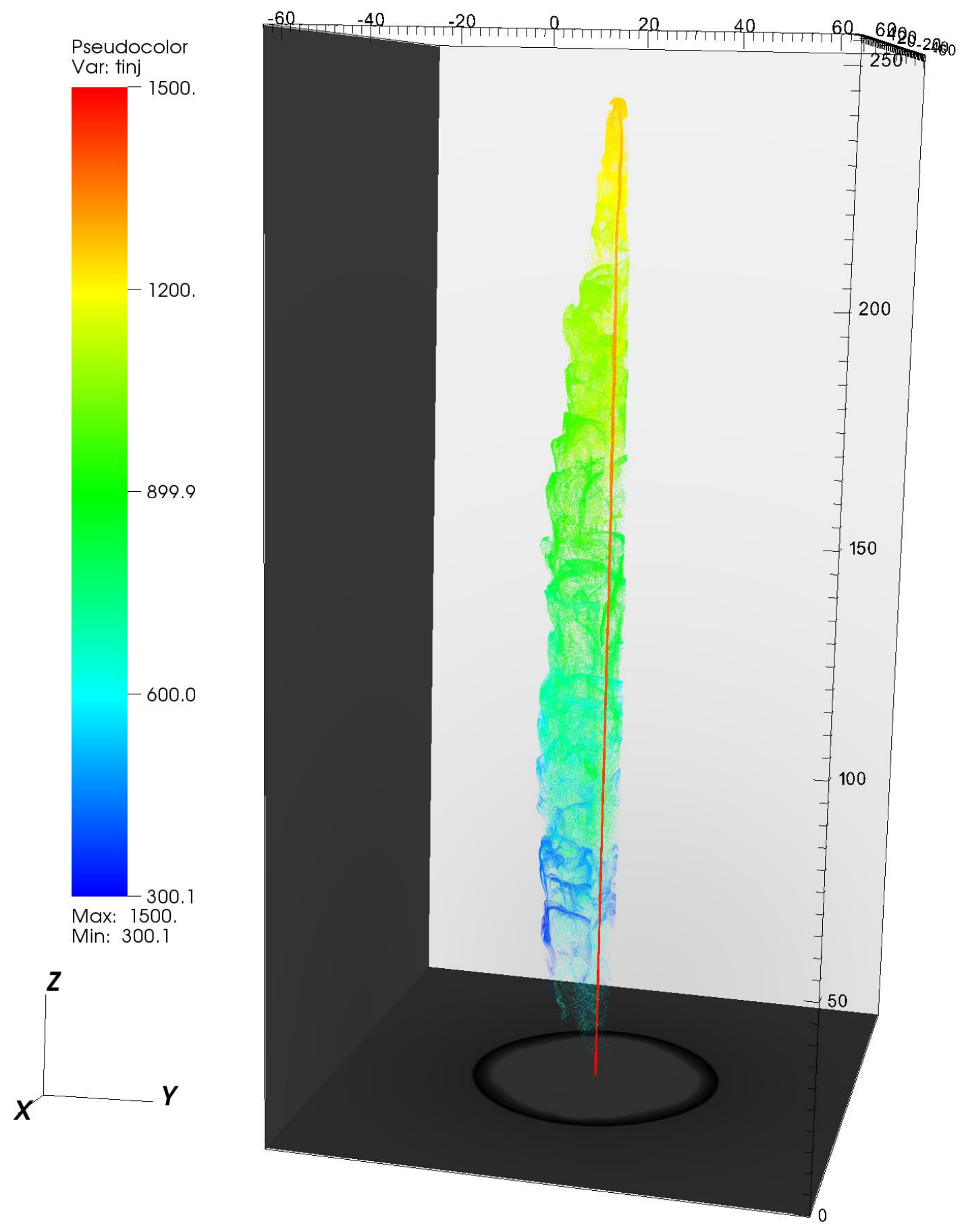

Figure 2: Distribution of Lagrangian particles in the simulation, the colour represents the time of injection

Emission modelling

Using the spectral information of the particles the synchrotron emissivity is calculated during runtime by [5],

$$j'_{syn}(\nu', \hat{\boldsymbol{n}}'_{los}, \boldsymbol{B}') = \frac{\sqrt{3e^3}}{4\pi m_e c^2} |\boldsymbol{B}' \times \boldsymbol{n}'_{los}| \int_{E_i}^{E_f} N'(E') F(x) dE', \qquad (1)$$

where $F(x) = x\int_x^\infty K_{\frac{5}{3}}(z)dz$ and $x = \frac{\nu'}{\nu'_{cr}} = \frac{4\pi m_e^3 c^5 \nu'}{3eE'^2|\boldsymbol{B}' \times \boldsymbol{n}'_{los}|}$

In addition, we have added the calculation of absorption coefficients to the module using [7],

$$\alpha'_{syn}(\nu', \hat{\boldsymbol{n}}'_{los}, \boldsymbol{B}') = \frac{\sqrt{3e^3}}{8\pi(m_e c\nu')^2} |\boldsymbol{B}' \times \boldsymbol{n}'_{los}| \int_{E_i}^{E_f} \frac{N'(E')}{E'} \frac{d}{dE'}\left(E'^2 F(x)\right) dE', \qquad (2)$$

Relativistic transformations are incorporated into the calculations of the coefficients. These coefficients are integrated along a line of sight using ray tracing to produce intensity maps from the simulations at different radio frequencies. Figure 3 shows the resulting emission and absorption coefficients at 1.4 GHz as well as the resulting intensity map for a viewing angle of 45° with respect to the axis of the jet.

Discussion & Conclusion

The RMHD simulations reproduce a collimated relativistic beam surrounded by a turbulent backflow and cocoon region. For the magnetic field strength considered the jet remains kinetically dominated and, therefore, we do not obtain magnetically driven instabilities. The Lagrangian particles were injected with the jet fluid and flowed along the beam of the jet, after which they were deposited in the backflow and cocoon. The slice of the emissivity shows extended emission from the cocoon region as well as the collimated beam. The highest intensity emission occurs along the edges of the cocoon close to the shock front produced by the jet. The extended cocoon dominates the integrated intensity map and obscures the beam of the jet at the chosen viewing angle.

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