

Use of pipe-like plasma targets for the production of gamma-beams using high power lasers

This study surrounds certain aspects of the production of gamma -beams using the interaction between a laser pulse and a plasma medium with a predesigned structure. To be more specific, we simulate the passage of a simple Gaussian pulse through a pipe-like overdense carbon plasma structure using a Particle-in-Cell code (EPOCH). The plasma pipe consists of a cylindrical bulk region, with the density $100\ n_{crit}$, surrounding a cylindrical channel, with the density $20\ n_{crit}$ (see figure 1). The channel diameter is comparable with the laser beam waist radius, such that most of the energy transferred from it to the plasma goes into the channel region. The propagation of the laser through the channel drives a longitudinal electron current (see figure 4), which in turn generates and sustains a quasistatic azimuthal magnetic field. By deflecting the highly energetic electrons, this field induces the production of synchrotron photons. The result is a gamma-beam with a relatively small divergence.

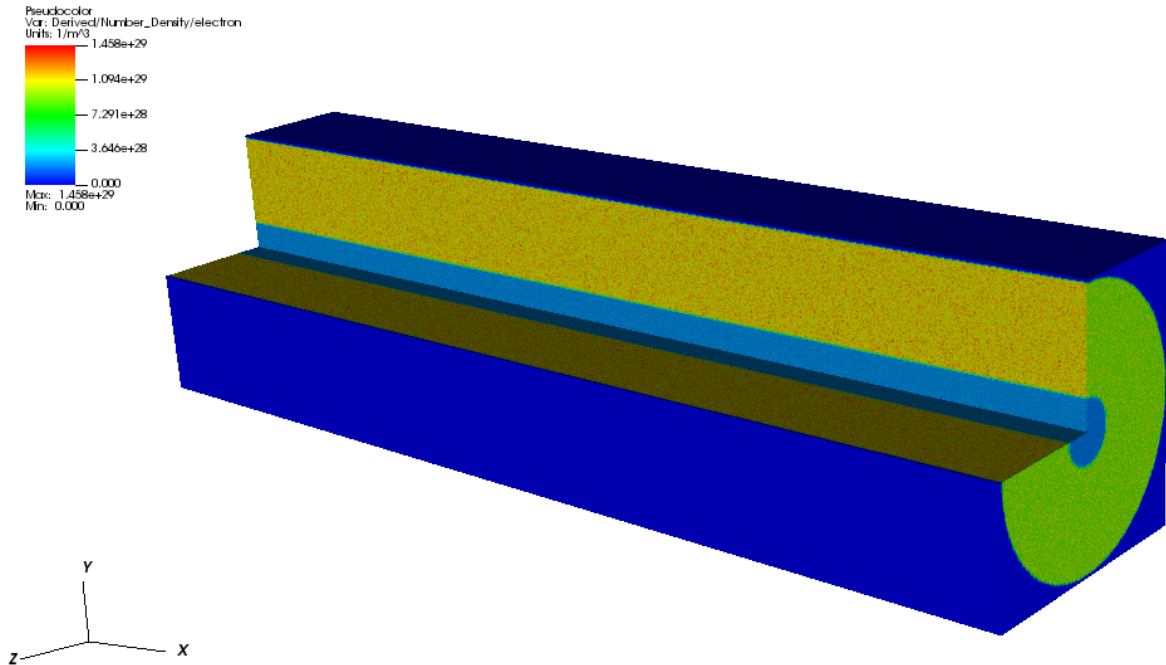


Figure 1: A plot of the electron number density at the beginning of the simulation showcasing the structure of the carbon plasma used for the numerical experiments.

We aim to study the variation of the gamma yield with the change in the internal radius of the pipe (*i.e.* the channel radius), while keeping the external radius fixed. For the parametrization of the laser we chose the defining parameters to be: $a_0 = 190$, $\lambda_0 = 1 \mu\text{m}$, which lead to a peak intensity of $5 \times 10^{22} \text{ W/cm}^2$. We remark that this value of laser peak intensity is in general relevant for the new Petawatt laser infrastructures around the world. We also chose the beam waist radius to be $w_0 = 1.3 \mu\text{m}$, which sets the power of our laser to 1 PW. The laser was focalized at $x = 0.0$ and the pulse duration was 35 fs. The exterior radius of the pipe was fixed to $4 \mu\text{m}$, while the interior radius was given the values: $0.5w_0$, $0.7w_0$, $1.0w_0$, and $1.2w_0$. The total length of the pipe was set to $33 \mu\text{m}$ and the total simulation time was chosen to be 110 fs. In all simulations the plasma was initialized as being fully ionized, since studies in the literature suggest that at the intensity and the power we work with the initially neutral medium would become fully ionized almost instantly. For the grid, we used a distretization of $30/\mu\text{m}$ in all three spatial directions. Since we are only interested to look at the energy of the produced photons, we have set them in the simulation to not propagate in time (that is, after they are produced, they are registered and not used further in the simulation), thus reducing greatly the simulation time. The average simulation time was 26 hours.

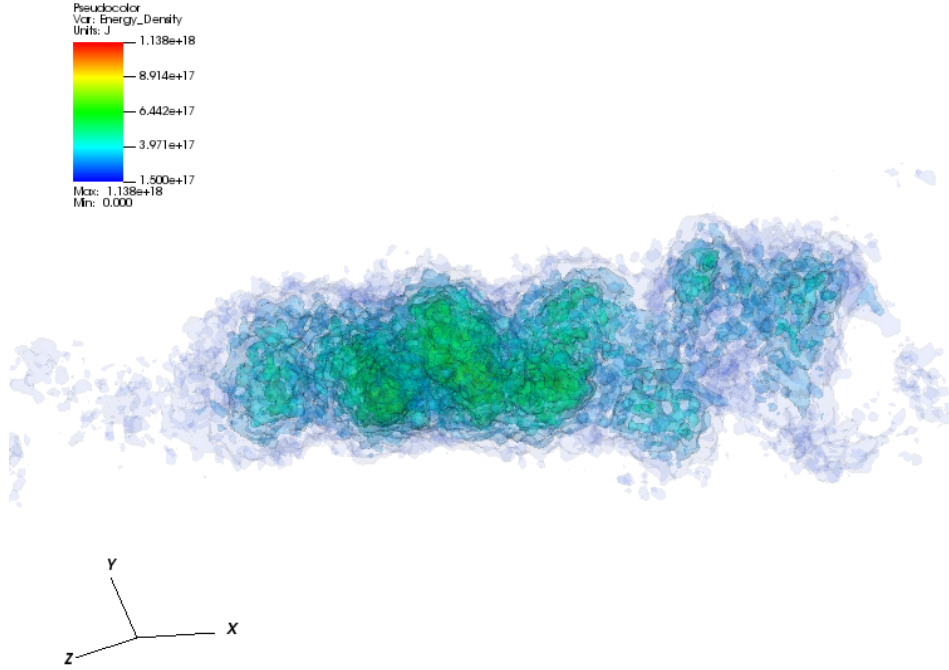


Figure 2: A plot of the electron energy density (average electron energy multiplied by the number density) that showcases the electron current generated in the channel.

In figure 3 we show the energy distribution in volume of the photon energy for the photons generated up to 100 fs into the simulation. By analyzing the data, we find that photons are generated, as expected, predominantly inside the channel region. From the transversal section we can observe better the internal structure of the photon bulk.

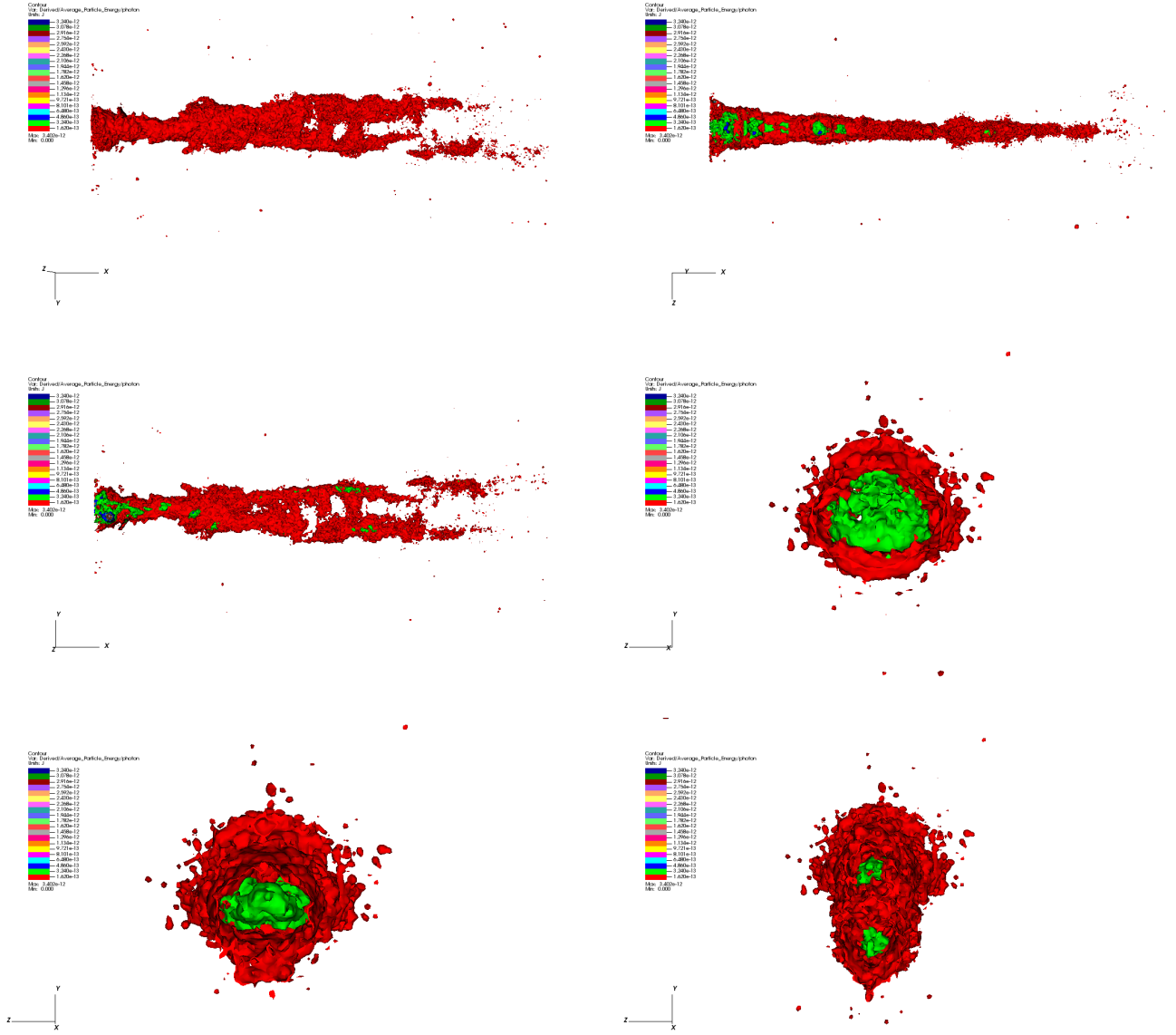


Figure 3: A series of contour plots of the average photon energy showcasing all the photons produced up to 100fs into the simulation. Different plots show different clips of the photon bulk. They are displayed in the following order: top left - uncut view; top right - cut through the middle in the x-z plane; middle left - cut through the middle in the x-y plane; middle right - transversal cut 1 μm in from the entry plane of the laser; bottom left - transversal cut 3 μm in from the entry plane of the laser; bottom right - transversal cut 6 μm in from the entry plane of the laser.

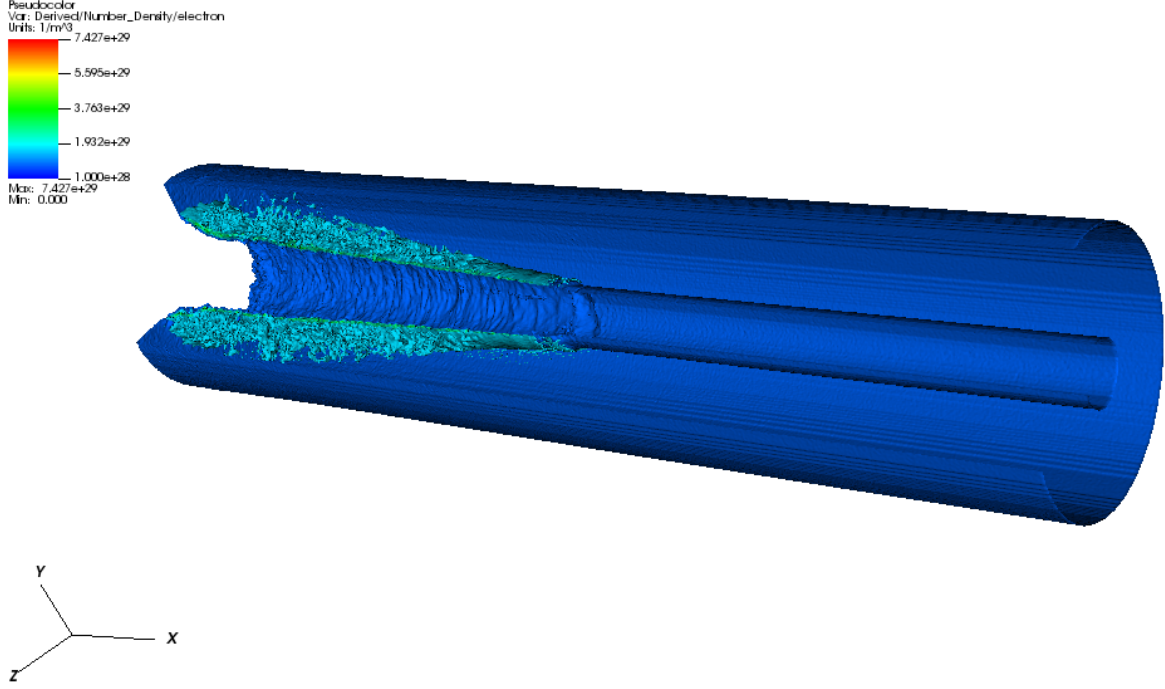


Figure 4: A plot of the electron number density 100 fs into the simulation that showcases how the passage of the laser through the plasma affects the structure of our plasma pipe. Some channel electrons spread inside the bulk region.

In order to compare the photon production as a function of channel radius, we look at the average particle energy per grid cell. We count all the cells that contain an average energy larger than a certain lower limit. The results are shown in figure 5. In this plot, by efficiency we actually mean the number of grid cell with average energy above a certain value divided by the total number of grid cells that contain non-zero values of photon energy. This is used as a way to estimate the fraction of photons above certain energies from the total number of photons produced in the simulation. We can see that both graphs show an increase with the increase of the channel radius. This trend is more pronounced in the low energy samples. We also note that the curves are concave, which suggests that further increase of the channel radius will not continue to increase the synchrotron photon yield. This is expected, since further increase in the radius would make the channel much thicker than the laser beam.

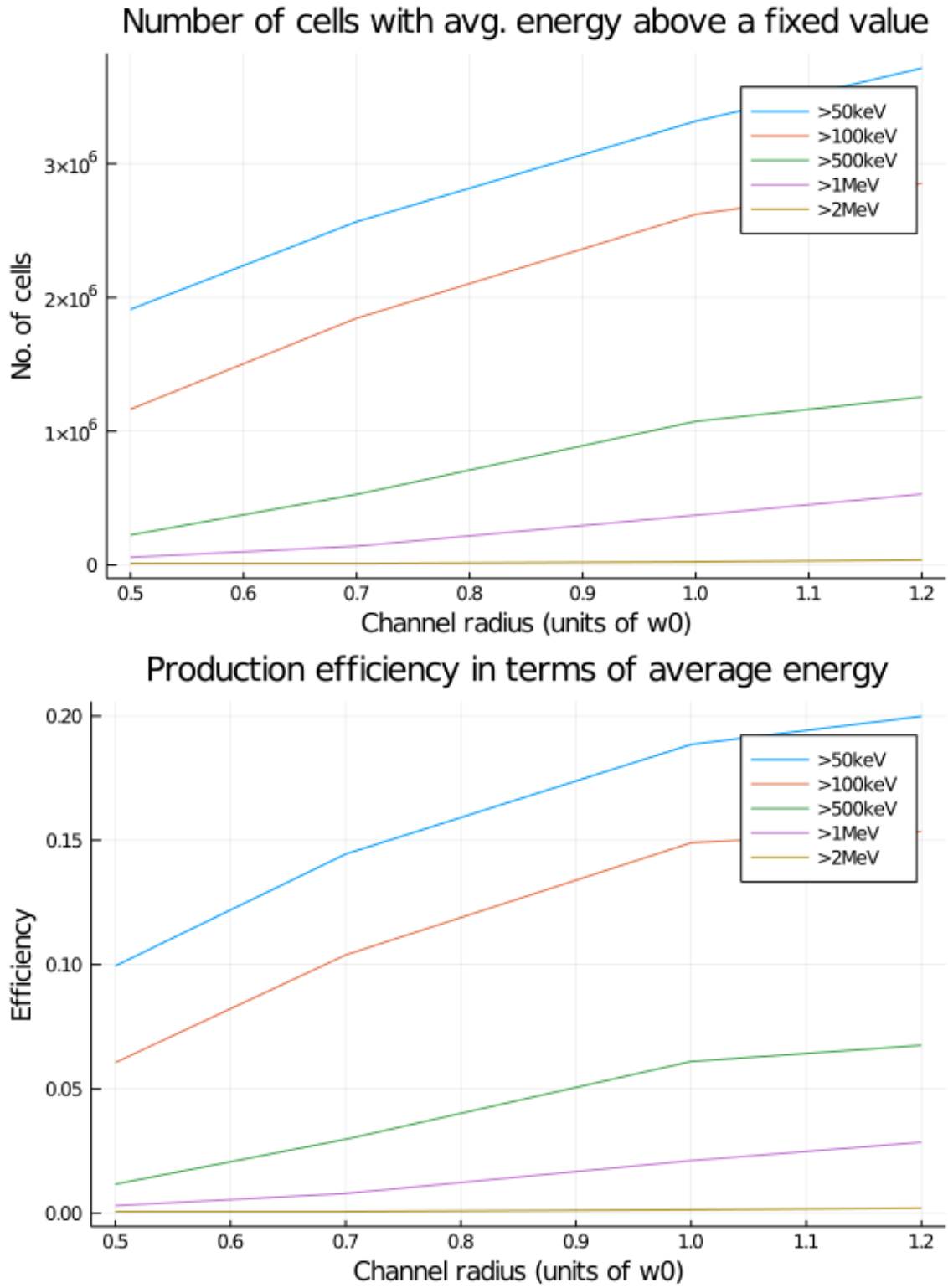


Figure 5: Plots comparing the production yield of different photon energies in terms of the channel radius. Top: the number of cells with average photon energy above 50 keV, 100 keV, 500 keV, 1 MeV, and 2 MeV, respectively. Bottom: the production efficiency for different energies above the same lower limits as in the previous plot.