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The goal of this project is to investigate several interesting and poorly understood physical processes taking place in relativistic plasma. Plasma is sometimes described as the fourth state of matter after solid, liquid and gaseous, it is a combination of ionized gas (concucting electric current) and magnetic field. In our project, we will focus on the simplest type of plasma - electron-positron gas consisting of elementary particles of the same mass and opposite electric charges. Relativistic plasma means that either the kinetic energy of the particles is comparable or greater than their rest mass energy (mc^2), or when the magnetic energy density is comparable or greater than the energy density of the particles. Numerical simulations of relativistic plasma can be peformed with the technique called "particle-in-cell", in which the simulation space is divided into small cells, and each cell contains average magnetic and electric field, as well as a certain number (dozens - scores) of particles. Our simulations will be performed with the numerical code Zeltron created by Dr. Benoit Cerutti, this code is publicly available at [http://benoit.cerutti.free.fr/Zeltron/]. Running even a small simulation requires using multiple processor units simultaneously, therefore we also need access to large supercumputers consisting of thousands of processors. Fortunately, there is a rapidly growing computational infrastructure in Poland. We plan to work on the best national supercomputers within the PLGrid network [http://www.plgrid.pl/], but also to utilize computational resources in USA that will be accessible via international collaboration. We will collaborate with researchers from the Stanford University and the University of Colorado.

What particular plasma processes do we plan to simulate? Relativistic plasma contains large amounts of magnetic energy. In certain situations, a fraction of this energy may be locked in a temporary equilibrium. If the system is kicked away from the equilibrium, instabilities may arise, for example the plasma begins to move and its kinetic energy grows rapidly. Motions of the plasma induce electric fields, but also they may lead to collisions between regions of opposite direction of magnetic field. This leads to the so-called magnetic reconnection, in which magnetic field lines reconnect. Here, a number of poorly understood processes take place. A fraction of the magnetic energy is converted to the particle energy, and part into the plasma motions. After a while, the instability becomes non-linear, and plasma motions become increasingly chaotic, it is a sign of developing magnetic turbulence.

Why is this interesting, and what is the main application? We can deduce the existence of relativistic plasma for the most extreme phenomena in the Universe. This primarily concerns the cosmic sources of gamma-ray emission, in which the photon energy is billions of times higher than the energy of photons seen by the human eye. The production of gamma-ray radiation requires the existence of highly energetic (relativistic) particles of non-thermal distribution. A natural question arises - what mechanism of particle acceleration can explain them? Roughly speaking, today researchers focus on two possibilities - shock waves and magnetic reconnection. Relativistic shock waves have been studied quite extensively, including also particle-in-cell simulations. It appears shock waves face serious obstacles for efficient particle acceleration in the relativistic regime. On the other hand, relativistic magnetic reconnection is still a poorly understood process, however, recently published numerical simulations suggest highly efficient particle acceleration.

In the proposed project, we would like to study the mechanism of relativistic magnetic reconnection triggerred by plasma instabilities. We would like to understand how efficient is particle acceleration in this case, and what is the role of magnetic turbulence. The Zeltron code will allow us to calculate the spectral, temporal and angular distribution of high-energy radiation produced during the simulations. We expect a lot of interesting results that may contribute to solving some fundamental mysteries of astrophysics.