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FINAL REPORT ON THE
START PROGRAMME

Collection of fast ions in reactor plasma during neutral beam injection

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Abstract

This study focuses on a computational observation of ions exchange processes in a magnetically confining thermonuclear plasma using fully kinetic Particle-in-Cell (PIC) code. The experiment was conducted to observe the dynamic of ions exchange after injecting a neutral beam into a plasma. As a result of the work, the dynamics of fast ions collection after neutrals injection was calculated for an infinite plasma column. The applicability of this approach and future development of the method are discussed in the conclusion.

1. MAIN PART

Introduction

One of the problems with fusion reactors is heating the plasma components to make them hot enough to ignite. For this purpose, high-energy neutral beams are injected into the plasma. Fast neutrals exchange electrons with plasma ions and become fast ions held by the magnetic field. At the same time, thermal ions become neutral and leave the plasma. On average, the temperature of the ions increases and the plasma becomes hotter. The dynamics of the collection and movement of fast ions in plasma is difficult to predict analytically, taking into account all the parameters of the facility and the injector, so we can observe it experimentally or calculate it using plasma simulation tools. This study focuses on the second option using the kinetic Particle-in-Cell (PIC) method to simulate the behavior of plasma particles.

Theory

PIC methods divide into different categories depending on the approach for particles simulation. Kinetic, fluid and hybrid (kinetic ions and fluid electrons) approaches exist. In this study, we used the fully kinetic PIC software “ef” [1] (originally developed at VBLHEP in C++ and then rewritten in Python), which makes it possible to simulate the behavior of charged particles in self-consistent and external electric and magnetic fields in the nonrelativistic case. The self-consistent electric field is calculated as a potential gradient, which is calculated from the Maxwell equation using a finite difference scheme. The charge density for the equation is calculated at the grid nodes by distributing the particle charges over the nearest nodes. The program considers the behavior of particles in 3 dimensions; therefore, it has strong restrictions on the total complexity of the computational domain. The number of particles, cells in the grid, time steps, and some other parameters in the domain must be chosen consistently, in accordance with the physics of the observation process, and minimized in order to have an acceptable computation time. The basic rules for choosing experimental parameters are discussed in [2, p. 404].

Kinetic PIC allows simulation of particle collisions such as ion-neutral exchange processes. Ion exchange is determined by the relative velocity of the reactants and the cross section of the process, which also depends on the relative velocity. The number of exchanged pairs per unit time and per unit volume is found by formula 1:

$$N = n_a n_b \langle \sigma v \rangle, \quad (1)$$

where n_b and n_b are the reactants densities, $\langle \sigma v \rangle$ is an average reaction cross-section to a reactants' relative velocity.

For a large number of particles, the probabilistic approach is accessible. The probability calculates for each pair of reagents in the domain and, if it reaches some definite value, then the exchange occurs. So as the energy of neutrals are much higher than of plasma ions, the assumption was made that a relative ion-neutral speed is constant and equals to a neutral velocity. It allows to reduce the calculations only to defining the densities on the domain mesh and do not compute relative velocities for each reacting pair.

Experiment

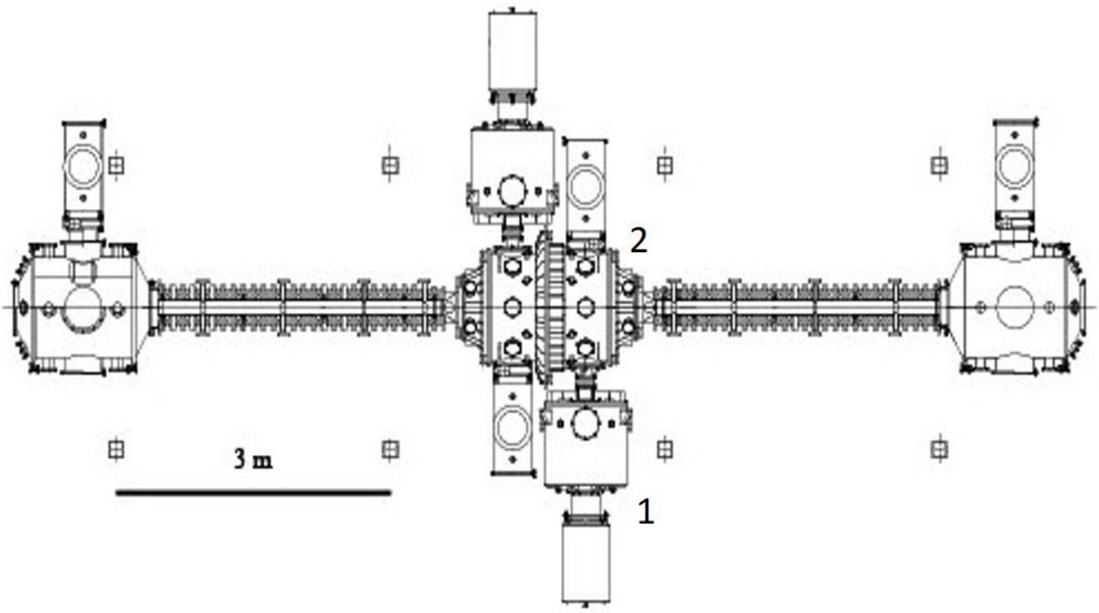

Figure 1. The GOL-NB facility. 1 - injector, 2 - central tank

This experiment is the first attempt of applying computational calculations to the GOL-NB facility (Fig. 1) (Budker Institute of Nuclear Physics, Novosibirsk). The GOL-NB is an axially-symmetric magnetic mirror trap for thermonuclear plasma confinement. It has a neutral injection heating system, which efficiency defines experimentally by measuring the dynamic of fast ions collection. Comparing the results of computational experiment to the real experiment outputs will demonstrate the applicability of the kinetic PIC method (and particularly ef software) to the simulation of exchange processes in the GOL-NB facility.

2. METHODS

This section provides a summary of the experimental set up and development of the code. Two independent blocks of codes were made for applying ions exchange physics and cyclic boundary conditions to the simulation domain. These complements were used for conducting an experiment for ions exchange collection in infinite plasma column in magnetic field.

Experimental set up

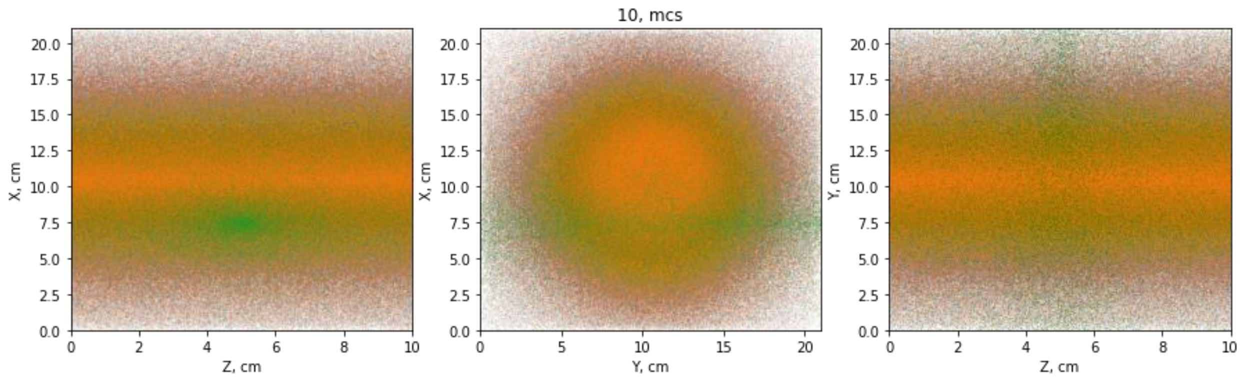

Figure 2 Plasma in the domain at 10 mcs. Projections to XZ, XY and YZ planes. Blue – electrons, orange – protons, green – neutrals.

Magnetic field and plasma density configurations duplicate those of the GOL-NB facility. The domain consists of a plasma column with a gaussian radial density profile and a temperature of 35 eV, width of a column is 12 cm at half height. To this column, at a quarter of its radius from the center, orthogonally injects a neutral hydrogen beam with energy of 25 keV, gaussian radial density profile, and a width of 7 cm (Fig. 2). The magnetic field is uniform, with a magnitude of 0,35 Tesla. Boundary conditions set as it is a grounded square metal tube was countered the plasma column, and the domain Z-boundaries are self-closing, that simulates an infinite column of plasma. Number of particles in the domain is 1 million of ions and electrons, and at each time step creates a thousand neutral particles.

Time scale was chosen corresponding to the real experiment time of ions exchange saturation (dozens of microseconds). The timestep, as well as the mesh cell size, were chosen to resolve a gyromagnetic rotation of charged particles. Shape of the domain is 21x21x10 cm with a cell shape of 0,35x0,35x0,4 cm. Timestep length equals 1.e-8 seconds. The electron mass was set up equal to a proton mass in order to level off the gyromagnetic periods. Plasma electrons are not participating in the ion-neutral exchange, and are only work as a background charged liquid, providing quasi-neutrality of the plasma.

Particles exchange

In a computational experiment, there is a finite number of discrete timesteps, which is the main difference from real physics. This transforms formula (1) for the exchange probability for one pair of particles into $P = \frac{\langle \sigma v \rangle \, dt}{V}$, where *dt* is the simulation time step and *V* is the volume of the cell in which the probability is calculated. The number of simulated particles is much less than the actual number of particles in the real experiment. Each simulated particle (called a macroparticle) is a large group of real particles (10^9 in this experiment). In this case, the reaction probability should be multiplied by the weight of the macroparticle *W*. For *N* type 1 particles and *M* type 2 particles, the number of reacted pairs in the volume *V* during the time *dt* is *N*M*W*P*. If this number is not an integer, then the random number occupies the interval from 0 to 1, and if it is less than the fractional part, then one more pair reacts in the cell.

This was technically implemented by adding a particle counter to the nodes of the domain mesh. Each node contains information about nearby particles, so the number of reacting pairs can be calculated. Then this number of neutrals changes their charge, and the same happens with ions.

Cyclic borders

The neutrals are injected into the central tank of the facility. Tank’s size is one and a half meters, which is too large to simulate with a kinetic PIC code. The solution is to create a cyclic self-closing boundary, which would simulate plasma in this tank as an infinite column of plasma but would have much lesser longitudinal size to calculate.

The potential on the $Z=0$ surface duplicates the potential $Z=Z_{max}$. The charge density distributed over the nodes of the right Z-edge is added to the left edge, since they are the same in the domain. This provides a cyclic potential (and therefore electric fields) as it is an infinite periodic chain of such domains with particles. When any particle reaches the right or left edge of the domain, it teleports to the other side at the corresponding location. Other boundaries work like grounded metal restraints - they absorb particles that touch them and do not change the potential.

3. RESULTS

The data is written to h5 files, which contain information about the particles (particle type, position, momentum), grid (charge density, particles near nodes), and experiment parameters (time grid, particle sources). We can follow the dynamics of fast ions by counting all the ions with velocities close to the speed of the injector particles. Results shown in figure 3:

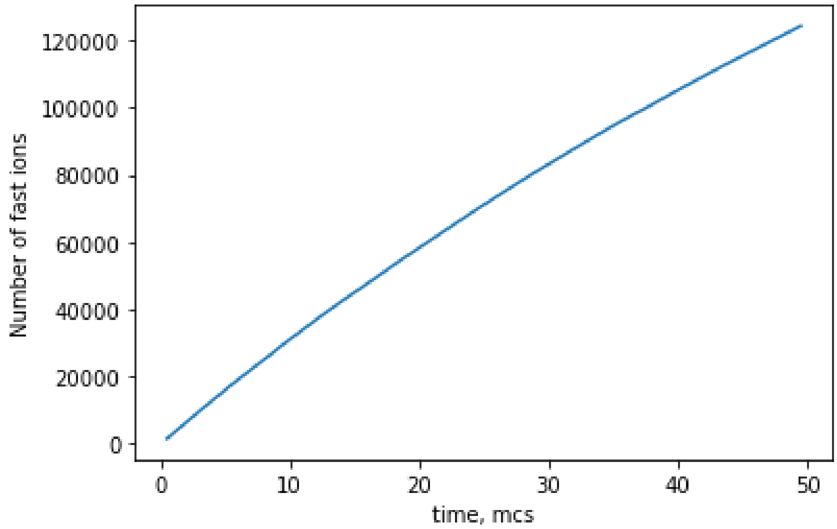

Figure 3. Dynamic of fast ions collection

The graph shows that the saturation is not reached during the simulation, however, the second derivative of the graph is negative. After 50 μs, the proportion of fast ions reached 12% of all ions in the domain and continues to increase. This result is inconsistent with the actual experimental saturation time (30–50 μs).

Fast ions dissemination after 50 mcs of the injection shown in figure 4:

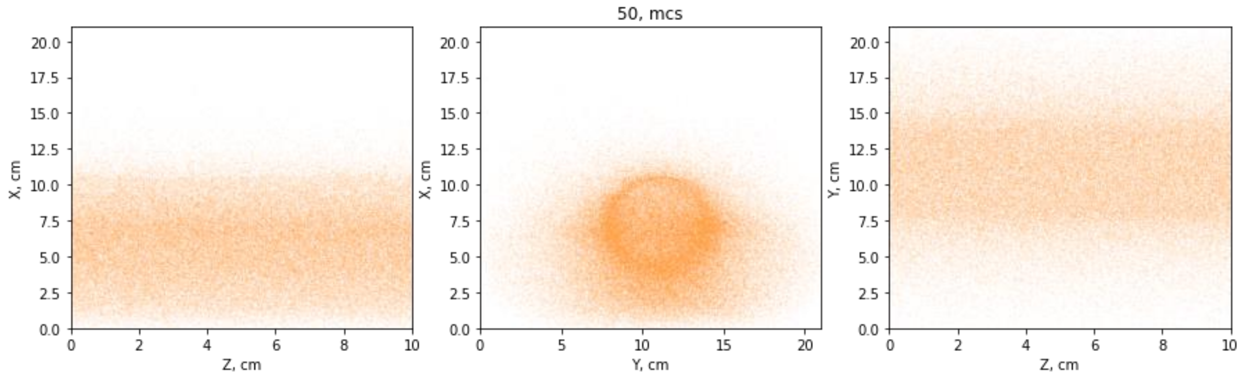

Figure 4. Fast ions positions at 50 μs

The experiment did not resolve plasma waves and the Debye length, so the ions retain their positions in the same orbit in which they occurred after the exchange. In a real plasma, fast ions will propagate across the plasma column due to collisions and instabilities.

Conclusion

The results of computational experiment differ from the real experiment, what can be a result of oversimplifying the model. Nevertheless, such simplification caused by the kinetic PIC method high computational cost. To simulate such long timescales with all physics considered, coarser tools are needed. In future studies, the similar experiment with a hybrid PIC method is to be conducted and compared to the experimental data from the GOL-NB.

The Kinetic PIC software used in this work is still applicable for simulating exchange physics, but the size of the region and the time scales under study should be several orders smaller. The results of experiments with kinetic software can be applied to simulations by hybrid methods that cannot resolve collision physics as precisely.

References

[1] https://github.com/fizmat/ef_python

[2] Hockney, R. W., Eastwood, J. W. (1988). Computer simulation using particles. Bristol: Hilger, 1988.

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