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Numerical Studies of Neutron Distributions in GDT Experiments

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1. Introduction

The Budker Institute of Nuclear Physics has proposed a Neutron Generator on the base of a Gas-Dynamic Trap (GDT) dedicated to fusion material research [1]. Currently, at the GDT facility of the Budker Institute an experimental research program is running to establish the physical data base of this project proposal. In experiments with high-power neutral beam injection of hydrogen the following global parameters were achieved: mean energy of the fast ions in the range of 5-8 keV, their maximum density almost 10^{13} cm^{-3} and total plasma-ß up to 30% [2].

In recent experiments DD fusion regimes were realised with a high power D^0 beam injection [3]. In these experiments, by monitoring the 2.45 MeV neutrons and 3.02 MeV protons produced in DD fusion reactions the axial distribution of the fast ions may be directly deduced what is not possible otherwise. Under these conditions, the direct comparison of experimental data with results of numerical simulation (especially the axial distributions) is possible.

In the Forschungszentrum Rossendorf the Fast Ion Transport code FIT has been developed on the base of the Monte Carlo method. It allows a detailed analysis of the fast ion field dynamics during GDT experiments [4]. Recently, the code has been extended to enable not only the computation of the ion phase space distributions but also that of neutron distributions generated by various fusion reactions.

By means of FIT calculations the dependences of the total neutron yield and of the ion densities on several plasma parameters and operating regimes have been studied. In this report the results of numerical study of the fusion products spatial distribution in DD experiment on Gas-Dynamic Trap are presented. Also the comparison with experimental data for neutron and proton fluxes is made. Additionally for comparison, the neutron production was calculated for D^0-T^0 beam injection instead of D^0 beams for the same experimental conditions.

2. Calculations of neutron production

The fusion neutron productions were calculated by means of the updated Fast Ion Transport code (FIT) that has been developed in the frame of a collaboration agreement between the Budker Institute Novosibirsk and Forschungszentrum Rossendorf. The code simulates the transport of energetic ions in given magnetic field and target plasma. It uses the Monte Carlo method and has been developed under the requirements:

- to simulate the fast ion transport in the frame of the classical transport and to consider the three-dimensional space, energy and time dependencies of the relevant phenomena involved,
- to take into account a maximum of detailed information on the GDT system and
- to produce a maximum of results per run.

The general scheme of the code is of standard Monte Carlo type: statistically independent fast ion histories are generated in course of which the scoring of results is performed by summing up contributions to well-defined estimators for each quantity of interest. Having simulated N particle histories a final result for each quantity is computed as the average of the estimates scored by each of them and the statistical error of the result is calculated from the mean quadratic deviation of the individual estimates from their mean value. The main disadvantage of the method is the slow convergence of the statistical errors according to $N^{-1/2}$. The main components of the code are:

- generation of neutral atoms on the emission surfaces of neutral beam injectors;
- ionisation of the NBI atoms by charge exchange, electron and ion impact;
- flight of ions in a given magnetic field;
- their interaction with the target plasma (energy loss and angular scattering);
- their interaction with the neutral gas and generation of fast atoms;
- their interaction with the fast ions and generation of fusion neutrons and protons.

In addition to magnetic field, neutral gas and warm plasma the fusion component of FIT demands the input of the target fast ions (deuterons) inside the volume of the fast ion transport (deuteron for DD or triton for DT fusion). The space and energy distribution of the target fast ions during a shot were preliminary calculated by means of FIT.

FIT offers a great spectrum of physical quantities that may be calculated. The results represent the quantities of interest as discrete distributions over a user-defined phase space grid over a sequence of time intervals. The main of them are: the fast ion energy content, NB trapped power, charge-exchange loss power, electron drag power, distribution of the fusion neutron, neutron flux to given detectors, energy and pitch angle distribution functions of the fast ions in a magnetic flux tube defined by a radial interval at the GDT midplane. A detailed description of the FIT code is given in [4].

3. Simulation results

The numerical studies of DD fusion experiment in GDT was made for the basic regime of GDT-facility [2,3]. The experimental data of warm plasma and NBI system were used as input parameters for the calculations. Both fusion reactions were take into account:

$$D + D = He^3(0.82\ \mathrm{MeV}) + n(2.45\ \mathrm{MeV})$$

$$D + D = T(1.01\ \mathrm{MeV}) + p(3.02\ \mathrm{MeV})$$

The distributions of fast deuteron density along the Z-axis for several times during the experiment are presented by Fig.1. The zero time is associated to the start of neutral beam injection. The maximum density appears in the region of the turning points of the sloshing fast deuterons, where the mirror ratio R is about 2. The ratio between maximum D^+-ion density and that in the midplane is estimated as 3-4.

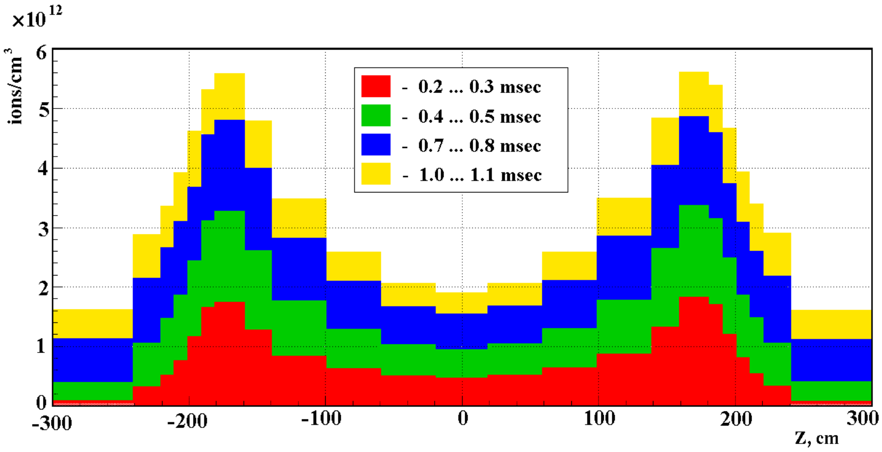

Fig.1 *On-axis density of fast deuterons for several time intervals.*

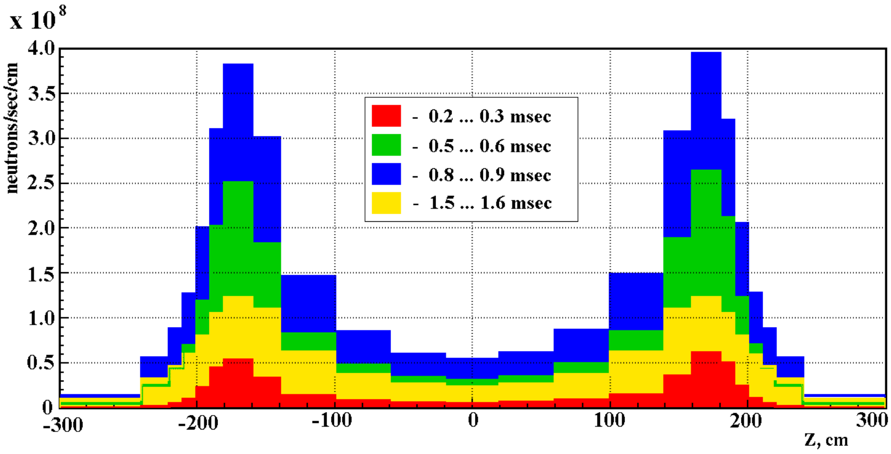

Fig.2 *The linear specific yield of DD fusion neutron for several time intervals.*

The axial distributions of the linear specific yield of 2.45 MeV neutrons for different moments are shown on Fig.2. The unit on the figure corresponds to the number of fusion neutrons born in cross section plasma disk with 1 cm width per second. The ratio between the values in midplane and in turning point regions is about 10-12 what corresponds to the square of the density ratio. The total neutron production rate is shown on Fig.3b.

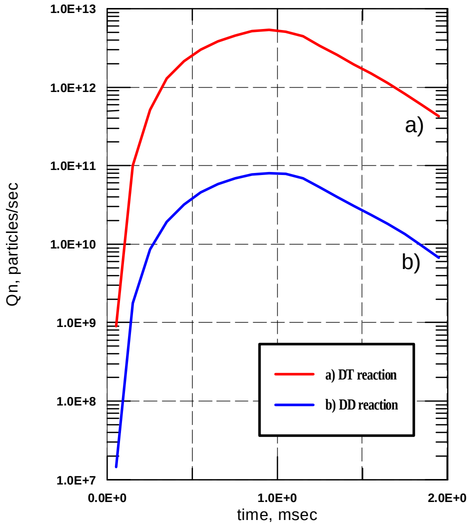

Fig 3*: The total neutron production rate.*
a) DT reaction, b) DD reaction

The spatial distribution of the fusion reaction rate was used for calculation of neutron (or 3.02 MeV proton) flux to the surface of first wall or on test plates. The simulation results can be compared with experimental data of 3.02 MeV proton and 2.45 MeV neutron measurement [3] to directly examine the capabilities of the physical models that have been incorporated in the Fast Ion Transport code.

Fig.4 compares the calculated axial distribution of 3.02 MeV proton flux to test plates located at a radius of 34 cm with measured data. The proton flux was measured and calculated for that moment with maximum D^+ density.

To measure the axial distribution of a DD proton linear specific yield in GDT fusion experiment collimated detectors have been used. The result of this measurement is shown on Fig.5 together with the calculated axial distribution of DD proton sources. The reasonable

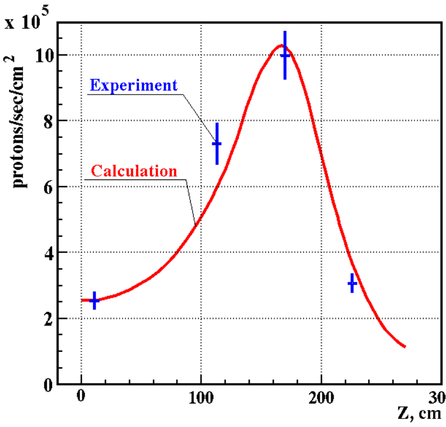

Fig.4 *DD proton flux to test plates without collimator.*

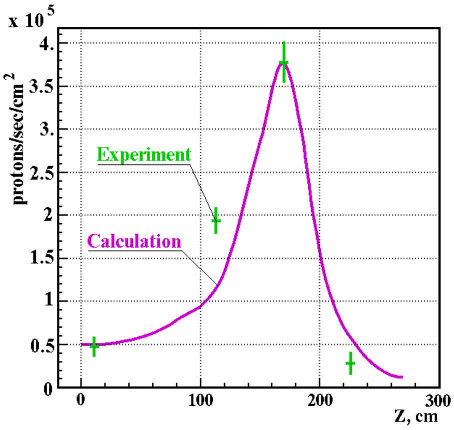

Fig.5 *DD proton flux to test plates with collimator.*

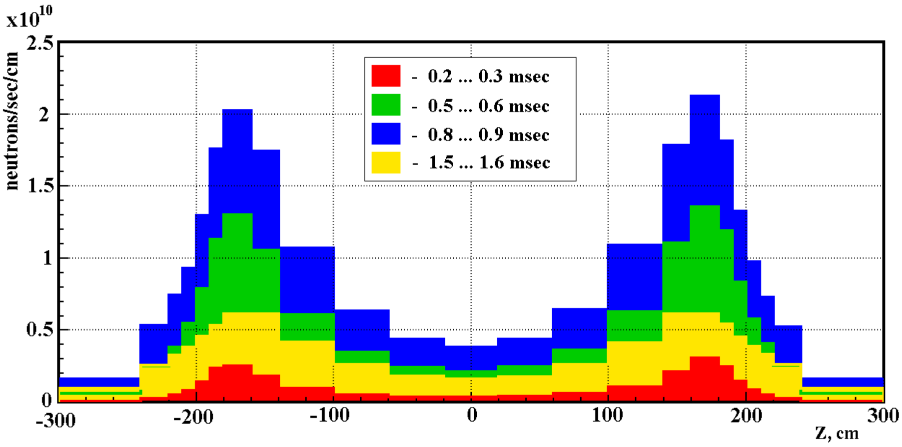

Fig.6 *The linear yield of DT neutrons for different time intervals.*

agreement between experiment and simulation assures that the physical models realised in FIT which are based on two-body Coulomb collisions well describe the fast ions relaxation. This fact feeds the hope that the code may be used for numerical studies on the GDT-based neutron source project.

For illustration of that possibilities the numerical studies of DT fusion in GDT experiment was made. The parameters of target plasma and NBI system in recent DD experiments were used to calculate the DT neutron distribution. It was taken in to account that NBI system would work with D^0-T^0 mixture instead of D gas. The result of this simulation is presented on Fig.3a. The DT neutron linear specific yields for different moments are shown on Fig.6.

4. Conclusions

The simulated spatial and time distribution of neutron and proton production in DD experiment on GDT have been presented and compared with the experimental results. It is shown the reasonable agreement between experimental and simulated data that proves the good description of fast ion transport and relaxation by the physical models of FIT.

Also, the results of numerical DT experiment on GDT have been presented. In case of DT fusion experiment with the same parameters, the total neutron production was calculated to be about 60 times higher than in case of DD experiment.

The presented numerical studies of fusion products spatial distributions and fluxes are a good demonstration that the Fast Ion Transport code may be well used for the calculation of neutron flux distributions in the GDT-based neutron source project [1].

Acknowledgements

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