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The SHIP Experiment at GDT: Physical Concept and Pre–Calculations

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1. Introduction

The Gas-Dynamic Trap (GDT) of the Budker Institute Novosibirsk is a long axisymmetric mirror system with a high mirror ratio to confine a two-component plasma [1]. The mirror ratio can be varied in the range of 12.5-100. One component is a collisional "background" plasma with ion and electron temperatures up to 130 eV and a density up to 1.8×10^{14} cm^{-3}. Its ion mean free path of scattering into the loss cone is much less than the mirror-to-mirror distance what results in the gas-dynamic regime of confinement. The second component is the population of fast ions with energies of 2-17 keV and a density up to 10^{13} cm^{-3}. They are produced by a 45° neutral beam (NB) injection into the central cell. The fast ions are confined in the mirror regime having their turning points at the mirror ratio of 2. To provide MHD stability of the entire plasma axisymmetric min-B cells are attached to both ends of the central cell.

At present, the GDT facility is being upgraded. The first stage of the upgrade is the **S**ynthesised **H**ot **I**on **P**lasmoid (SHIP) experiment [2]. It aims, on the one hand, at the investigation of plasmas which are expected to appear in the region of high neutron production in a GDT based fusion neutron source proposed by the Budker Institute and, on the other hand, at the investigation of plasmas the parameters of which have never been achieved before in magnetic mirrors. The expected record values of plasma parameters and several peculiarities of the plasma, like the composition of two energetically very different ion components where the high-energetic part represents the majority, strong non-isotropic angular distribution of the high-energetic ions and non-linear effects as non-paraxial effective magnetic field and high value of β offer a great field for interesting investigations.

In order to simulate the particle fields inside the GDT device and later in a GDT based neutron source an Integrated Transport Code System (ITCS) is being developed in collaboration between Forschungszentrum Rossendorf and Budker Institute. It consists of modules which allow the calculations of neutral gas, background plasma and of the fast ion component considering their mutual interactions [3].

This contribution explains the concept of the SHIP experiment and presents the results of first calculations by means of the ITCS modules.

2. Technical Description and Scientific Objectives

The experiments will be performed in a small, additional mirror section which is installed at the end of one side of the GDT. Fig. 1 shows a schematic view of this arrangement. The magnetic field on axis will be in the range of 0.5-5 Tesla and the mirror ratio will amount to 1.2-1.4. The magnetic field strength will be varied by extending/shortening the distance between the coils. The SHIP mirror is filled with background plasma streaming in from the central cell of the GDT. This plasma component is maxwellised and will have an electron temperature about 100 eV. It is pre-heated up by the standard neutral beam injection system of the GDT. Two newly developed neutral beam injectors will perpendicularly inject into the SHIP mirror a total current up to 120 eq. Amperes of hydrogen atoms with an energy up to 25 keV as pulse with a duration up to 3 ms. Ionisation of the beams generates the high-energetic ion component. The density of the resulting Hot Ion Plasmoid is expected to be higher than that of the target plasma. For the given experimental conditions, the lifetime of the synthesised plasma is essentially determined by the target plasma cooling rate and might

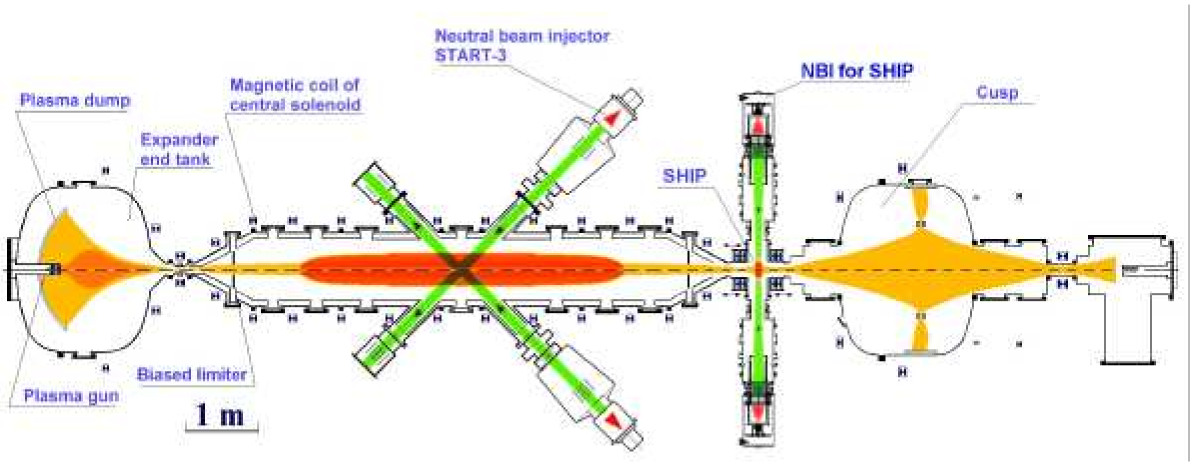

Fig. 1: GDT facility with the SHIP experiment.

be of the order of one millisecond. Since the energy loss of the fast ions by a background plasma with high electron temperature is negligible in the millisecond time-scale the averaged energy of the trapped ions is expected to be not much lower than the injection energy, i.e. in the range 15-20 keV. It was estimated that their density will reach 10^{14} cm^{-3} in a volume of about 500 cm^3 even in the case of low magnetic field what will result in high β-values between 20-40 per cent. The SHIP device will be equipped with several diagnostic methods which are successfully used in GDT experiments. The construction of the SHIP experimental cell will soon have been finished.

The SHIP plasma will have some peculiarities which are of particular interest from the point of view of plasma physics:

- The ions are divided in two energetically very different components of which the high-energetic one has the majority.
- The distribution of the flight directions of the fast ions is highly non-isotropic.
- The non-isotropic movements of the fast ions result in azimuth currents which distort the paraxial external magnetic field so that the effective magnetic field becomes non-paraxial.
- Because of their high energy the fast ions move on relative large gyro-radii.
- The high β of the total plasma to which the fast ions contribute by far the greatest part.

These peculiarities and the envisaged record parameters of the SHIP plasma offer the opportunity to investigate the following objectives which are of interest from the point of view of fundamental plasma physics and at the same time of high importance regarding the neutron source project:

- To study the contribution to MHD-instability and to explore the influence of non-paraxial effective magnetic field on this issue.
- To investigate the level of micro-fluctuations in the high-energetic ion component and its dependence on the background plasma.
- To determine high-β threshold to instability of any kind in the attainable parameter range.
- To explore the influence of non-paraxiality of effective magnetic field on the equilibrium density distribution of high-energetic ions. Regarding the neutron source the question whether there will appear a longitudinal quenching or not is of special interest because this effect could remarkably raise the maximum of the neutron production density.

3. Pre-Calculations

3.1. Changes of the MCFIT Code

The linear version of the Monte Carlo code MCFIT simulates the transport of neutral beam produced energetic ions interacting with a given magnetic field, a background (target) plasma and with neutral gas. The code stochastically generates independent ion histories which during their lifetimes contribute to the estimations of the quantities of interest. The main disadvantage of the method is the slow convergence of the statistical error according to $N^{1/2}$ where N is the number of simulated particle histories. On the other side the code describes the relevant transport processes with a minimum of approximations. The assumption of a linear fast ion transport was a good approximation for the experiments which were performed up to now at the GDT. Results of measurements and of calculations were in good agreement [4].

In the SHIP experiment the situation will be substantially different from that in the GDT. Here, the fast ion density is expected to be remarkably higher than that of the target plasma ions. In contrast to that in GDT experiments the target plasma ion density was about one order of magnitude higher than that of the fast ions. This fact has the consequence that several interactions of the fast ions become non-linear, that means, that the "interaction partners" - i.e. magnetic field, background plasma and neutral gas – now depend on the fast ion field too. To meet such requirements in the simulation a Monte Carlo code offers only the possibility to do this by means of iterations: the first simulation is done with pre-defined start values of the "partners" and gives the first approximation of the fast ion field. After calculating new values of the "partners" the next fast ion simulation follows. To prepare the MCFIT code for that purpose it was necessary to introduce the following modifications.

- *Splitting of the ion density:*
  n_w - density of the so called "warm" ions of the target plasma.
  n_f - density of the fast ions.
  n_e – electron density, $n_e=n_w+n_f$.
  As input for MCFIT the density field $n_w(r,z,t)$ in its radial, axial and time dependencies is to calculate for a given n_f according to

$$n_w = (\sqrt{n_f^2 + 4 \cdot n_0^2} - n_f)/2 \,, \tag{1}$$

  where $n_0(r,t)$ is the profile of the target plasma streaming into the SHIP chamber from the GDT central cell. The newly introduced fast ion density n_f gives now a contribution to the ionisation process of the neutral beams and to the angular scattering of the fast ions. At present, only the ion impact is considered in the ionisation process.
- *Calculation of the azimuth fast ion currents in the high-*β *case:*
  To give the possibility to consider the effect of a high β-value the earlier version of MCFIT proposed to correct the effective magnetic field acting on a fast ion on the base of the perpendicular pressure field of the fast ions which is a standard result of MCFIT. Numerical difficulties resulting in steep gradients of the effective magnetic field let to the improved method to calculate the azimuth fast ion currents by MCFIT and to use them to modify the magnetic field according to the Biot-Savart law.

3.2. Results

Up to now one regime with minimum parameters was considered: electron temperature – 100 eV, plasma in-stream density n_0 – 0.5x10^{14} cm^{-3}, injection power – 1 MW as ramp, injection energy – 20 keV, duration of injection – 1 or 2 ms. The interest was focused on the iteration procedure between n_f and n_w via equation (1). As approximation the neutral gas was prepared only once by special calculations for the steady state and not included in the iteration. The MCFIT calculation were performed for 2 milliseconds after the NBI start. It turned out, that the fast ion population reached its steady states very quickly, already in about 1 ms. After four iteration steps the maximum of the fast ion density distribution remained in the range of the statistical error of few percent. Figures 1 and 2 show the steady state radial (in the midplane) and axial distributions (on the axis) of the various densities. The density will reach the value of 0.8x10^{14} cm^{-3}, the mean energy will be about 9 keV. Therefore the maxi-

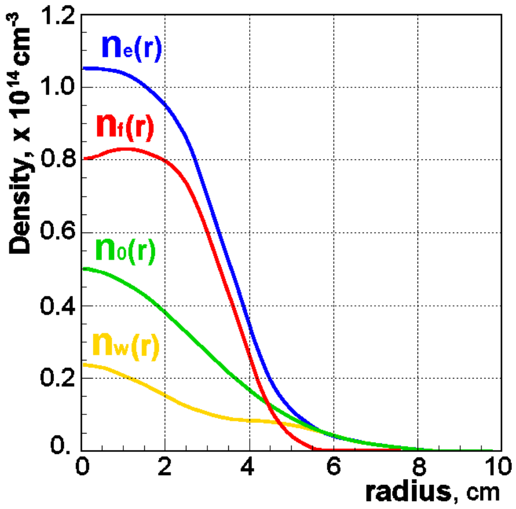

Fig. 2: Radial distributions of densities.

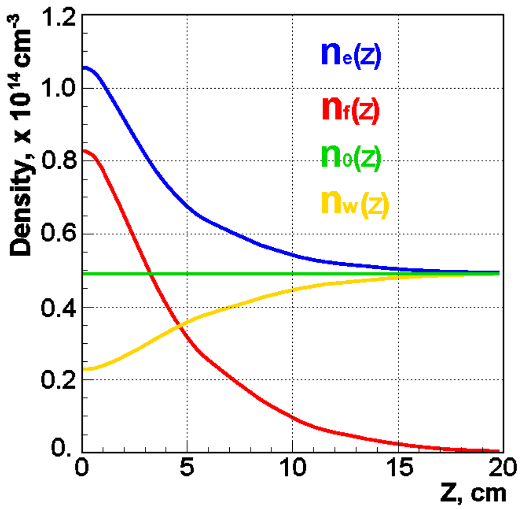

Fig. 3: Axial distributions of densities.

mum β-value of the fast ions will not exceed 8%. Figure 4 shows the power balance for the fast ions. In the iteration electron drag and charge exchange loss powers remarkably varied in their relation. To estimate the energy confinement time of the fast ions τ_E under steady state conditions a special calculation was performed: The neutral beam injection was switched off after 1 ms but neutral gas, electron and the "partner" ion fields remained unchanged. Figure 5 shows the calculated energy content W_f of the fast ions. The fit of the drop by an exponential function gives the value $\tau_E = 225$ μs.

The calculations for a high-power regime with 3 MW injection power and 25 keV injection energy are under way.

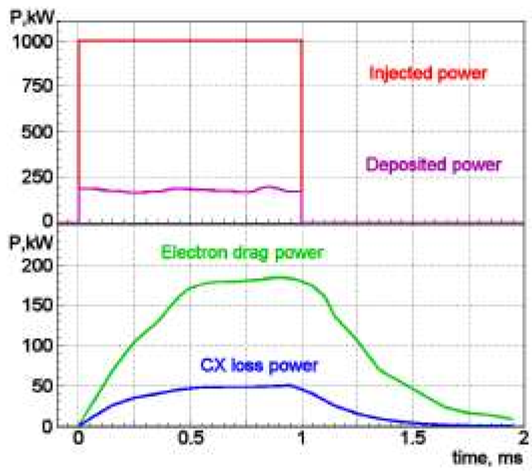

Fig. 4: Power balance of fast ions.

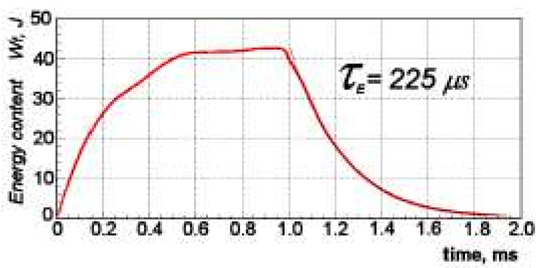

Fig. 5: Model calculation of the fast ion energy content.

4. Conclusions

- The construction of the SHIP experimental cell will soon have been finished.
- The fast ion Monte Carlo transport code MCFIT has been extended to offer the possibility to include several non-linear transport effects.
- MCFIT fast ion calculations of a regime with minimum parameters of the NBI gave the results that the steady state is already reached in 1 ms, then the density will be 0.8×10^{14} cm^{-3}, the mean energy 9 keV and β about 8%.

References

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