THE SHIP EXPERIMENT AT THE GDT FACILITY: CONCEPT AND RESULTS OF CALCULATIONS

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1. Introduction

The Gas Dynamic Trap (GDT) experimental facility 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" or “target” plasma with ion and electron temperatures up to 130 eV and a density up to $1.8 \times 10^{14}$ 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 SHIP (Synthesised Hot Ion Plasmoid) 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 [3] 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 plasma-$\beta$ 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 [4]. It consists of modules which allow the calculations of neutral gas, background plasma and of the fast ion component considering their mutual interactions.

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

2. Technical description

The experiments will be performed in a small, additional mirror section which is installed at the end of one side of the GDT. Figure 1 shows a schematic view of this arrangement. The magnetic field on the 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 may be varied by extending/shortening the distance between the coils. The SHIP mirror is filled with a hydrogen background plasma streaming in from the central cell of the GDT. This plasma component is maxwellised and will have an

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electron temperature of about 100 eV. It is pre-heated up by the standard neutral beam injection system of the GDT. Two neutral beam injectors, which have been newly developed, 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 a ramp-like pulse with a duration of at least 1 ms. So, the injection power will be variable in the range of 1-3 MW. Ionisation of the beams generates the high-energetic ion component. The density of the resulting hot ion plasmoid is expected to be substantially 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 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 should 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 $\beta$-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.

Fig. 1: GDT facility with the SHIP experiment.

3. Scientific objectives

The SHIP plasma will have some peculiarities which are of particular interest from the point of view of plasma physics:
- The ions will be divided into two energetically very different components of which the high-energetic one has the majority.
- The distribution of the flight directions of the fast ions will be highly non-isotropic.
- The non-isotropic movements of the fast ions will result in azimuthal currents which will distort the paraxial external magnetic field so that the effective magnetic field will become non-paraxial.
- Because of their high energy the fast ions will move on relatively large gyro-radii.
- In the case of a high-power injection (3 MW) and of low magnetic field a high value of $\beta$ is expected for the whole 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 equilibrium states of two-component plasmas with high parameters under the condition that the high-energetic ion component represents the majority.
• 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-\( \beta \) threshold to instability of any kind in the attainable parameter range.
• To explore the influence of non-paraxiality of the effective magnetic field on the equilibrium density distribution of high-energetic ions. Regarding the neutron source the question whether a longitudinal quenching will appear or not is of special interest because this effect could remarkably raise the maximum of the neutron production density.

4. Physical considerations

Several physical facts, which are of importance when comparing GDT and SHIP experiments, are to be briefly discussed. Considering target plasma and neutral gas as known distribution functions, in GDT experiments hitherto performed, the transport of the fast ions could be considered as a linear transport process. Substantial effects resulting from the interaction of a fast ion test particle with the population of the other fast ions were not observed. Results of measurements and of calculations which were done just in the frame of this approximation well agreed [5]. This is a result of the fact that the fast ion density is too low to produce non-linear effects. In the SHIP experiments 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 and will reach such values leading to several non-linear phenomena. This is because the fast ion population itself now considerable contributes to various interaction processes of a fast particle. Those are: the ionisation of the neutral beams, the angular scattering and the high-\( \beta \) effect which can result in a spatial redistribution of the fast ions as consequence of magnetic field deformations by strong azimuthal fast ion currents.

The question of main interest is whether the desired high parameters of the fast ions, which have been estimated on the basis of classical plasma theory, may be actually achieved with two injectors of the new type. These results are to check by means of more accurate numerical methods. The main resistance against high fast ion parameters comes from the fact that a strong fast ion density will produce a high electrostatic potential which will lower the ion density of the target plasma. The lowering of the warm ion density then results in a reduction of the ionisation rate of the neutral beams. This is because the charge-exchange (CX) with warm ions gives the highest ionisation rate for the injection energy in the range of 20-25 keV. The loss of this rate might not be compensated by an increase of the electron or ion impact ionisation. So, this feedback strongly acts against the built-up of the fast ion population. In an approximate model the relation

\[
n_w = \left( \sqrt{n_f^2 + 4 \cdot n_0^2} - n_f \right) / 2
\]  

may be derived, where:
- \( n_w \) - density of the so called “warm” ions of the target plasma,
- \( n_f \) - density of the fast ions,
- \( n_e \) - electron density, \( n_e = n_w + n_f \).

In equation (1) all densities are in their radial (\( r \)), axial (\( z \)) and time (\( t \)) dependencies and \( n_0(r,t) \) is a fixed radial profile of the target plasma at the entrance into the SHIP chamber. The assumptions of the model are: the fixed profile \( n_0 \) for electrons and warm ions at the entrance,
their distribution according to the law of Boltzmann with the same temperatures $T_w$ and $T_e$ in the region of sloshing fast ions and the neutrality condition.

Another feedback effect connected with the densities of warm and fast ions is caused by the neutral gas. For SHIP one may expect a strong interaction between fast ions and the gas. The charge-exchange ionisation of the neutral beams with the warm ions of the target plasma produces a strong source of neutral gas just in the vicinity of the centre. Other possible source terms should be negligible. Since the central gas source is proportional to the warm ion density an increase of the fast ions will be supported by a thinner gas, which will reduce their charge-exchange losses.

5. Pre-Calculation

5.1. Calculation model

It was the main interest of the first calculations to get to know about the time behaviour of the fast ion density considering the feedback by the target plasma ions via equation (1) and by the neutral gas. This was done by means of an iteration cycle. The iteration was terminated when the changes of the fast ion density between subsequent calculations were in the range of the statistical error, i.e. about a few per cent. Unfortunately, the effect of the neutral gas could be taken into account by a rough approximation only.

Magnetic Field:
In the calculations the time independent, standard magnetic field was used, i.e. both coils produce 5.1 Tesla on the axis which gives 2.4 Tesla in the centre of the SHIP chamber. The field did not vary in time.

Target Plasma:
As boundary condition for the densities of electrons and of warm ions (protons) a time independent Gauss-like distribution $n_0(r)$ with a maximum of $5 \times 10^{13}$ cm$^{-3}$ and a half-width of 3.25 cm was chosen, see Fig. 2. For the first iteration both densities were constructed along the magnetic field without an electrostatic potential, i.e. assuming $n_f$ as zero. The temperatures were fixed to be $T_w=T_e=100$ eV and were not changed in the iteration. After calculating a fast ion density distribution by means of MCFIT new densities $n_w$ and $n_e$ were determined according to equation (1) for the next fast ion simulation.

Neutral Gas Calculations:
The neutral gas calculations were done by means of the Monte Carlo code TUBE [4]. The distributions of warm and fast hydrogen atoms and of molecules were calculated inside the SHIP chamber. It was modelled as cylinder with height and radius both equal to 25 cm. The inner surface was assumed to be coated by titanium as it is in the central cell of the GDT. Unfortunately, TUBE has not yet been extended to be able to consider the interaction of the neutral gas with the fast ions what in case of SHIP will be a serious approximation. But, it acts into the direction that just in the volume occupied by the fast ions too much gas appears and consequently the fast ion density will be calculated too low. Furthermore, the space dependent gas distribution was calculated only once at the beginning of the iteration. For a next iteration step the amplitude of the gas field was multiplied with a factor that has been determined as relation of the neutral beam ionisation rates of both steps.

Neutral Beam Injection:
Up to now only the calculations of a “minimum” variant were performed and have been analysed. The target plasma was that as described above. For the neutral beam injection system only modest parameters were assumed: injection energy of the hydrogen atoms 20 keV and a ramp-like injection power of 1 MW with a duration up to 1 or 2 ms.
Fast Ion Calculations:
The calculations of the fast ion field in each iteration step were done by means of the Monte Carlo code MCFIT [4]. The code simulates test particles starting as high-energetic neutrals from the injectors, being ionised by several interaction partners and moving as fast ions in the magnetic field and interacting with reaction partners in various processes. Recently, the code was modified to be able to consider the interactions between fast particles too. Especially:
- MCFIT now considers the three densities $n_w$, $n_f$ and $n_e$ and the corresponding particles as interaction partners, see section 4.
- Now, the fast ion density $n_f$ gives a contribution to the angular scattering of a fast ion test particle too.
- Moreover, $n_f$ also contributes to the ionisation of the neutral beam particles. The ionisation by charge-exchange has not yet been implemented. This process would not have a direct effect on the particle balance of the fast ions.

Special MCFIT calculations were performed to determine fast ion energy and particle confinement times $\tau_E$ and $\tau_n$, respectively. In the final iteration step, after reaching the steady state (in about 1 ms) the injection was switched off, gas, target plasma and the background fast ions were hold in their current states. Fitting the drops of the energy and particle contents by exponential time functions gave the time constants.

5.2. Results

Up to now, only the calculations for the “minimum” regime could be finished and analysed in detail. It turned out, that the fast ion population reached its steady state 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 a few percent. Figures 2 and 3 show the steady state radial (in the mid-plane) and axial distributions (on the axis) of the various densities. The density will reach the maximum value of $8 \times 10^{13}$ cm$^{-3}$. The volume in which the density of the fast ions is greater than that of the warm ions is about 400 cm$^3$.

Figure 4 shows the power balance for the fast ions in the case of a 1 ms injection. The remarkable low CX-loss power is a consequence of the decrease of the warm ion density forced by the fast ion potential, see Figs. 2 and 3. Figure 5 shows the energy distribution of the fast ions for several time intervals in the case of a 2 ms NB injection. One can see that the energy spectrum practically does not change after 1 ms. The resulting mean energy is about 9 keV only. The soft steady state spectrum is the consequence of the increased electron density, see Figs. 2 and 3. Since the soft energy spectrum and the strong magnetic field the maximum $\beta$-value of the fast ions is merely 8%.

![Fig. 2: Radial distributions of densities.](image1)

![Fig. 3: Axial distributions of densities.](image2)
Figure 6 shows the fast ion energy and particle content as calculated by the special calculation for energy and particle confinement times. The fitting of the drop after 1 ms gave the energy confinement time $\tau_E = 225 \, \mu s$. The corresponding fitting of the particle content resulted in two exponential functions: up to 1.6 ms with $\tau_n = 550 \, \mu s$ and with $\tau_n = 270 \, \mu s$ afterwards.

6. Conclusions

From the work that hitherto has been done the following conclusions may be drawn:

- The construction of the SHIP experimental cell and of the new injectors will soon have been finished.
- The fast ion transport code MCFIT has been extended to be able to consider non-linear processes too.
- The neutral gas code TUBE has to be extended to include the interactions of the neutral gas particles with fast ions.

The pre-calculations of a “minimum” regime were performed and analysed. The fast ion density will be substantially greater than that of the warm target plasma ions, it will reach $8 \times 10^{13} \, \text{cm}^{-3}$. The mean energy in the steady state will be about 9 keV and the maximum of the fast ion $\beta$-value will amount to 8%.

References


