Project of the GDT-Based Steady-State Experiment

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Abstract. In recent years, significant success in a plasma stabilization, heating and confinement in Gas Dynamic Trap (GDT) has been acheived. However, transition processes such as fast ions buildup, ion and electron temperature growth, etc., are still underway until the end of plasma heating. Thus, heating sources worktime (around 5 ms) is too short for plasma parameters to become stationary. In this work we propose a project of GDT-based stationary plasma experiment with pulse length long enough to finish all transition processes. The implemetation of the project will allow us to test GDT stabilization, heating and confinement methods to stationary conditions and to scale the methods to reactor-sized devices. Features of the project include a superconducting magnetic system with 15 T magnetic mirror field, 30 ms plasma pulse and mixed neutral particle and ECR heating. Results of numerical simulations of such experiment using DOL code are also presented.

INTRODUCTION

The Gas Dynamic Trap (GDT) [1] facility is an axisymmetric mirror trap with high mirror ratio (up to 35) and two plasma components. The warm (target) component, which is confined in the collisional regime, has an isotropic Maxwellian velocity distribution. This component is initially created by the plasma generator and heated up by neutral beams and ECR. The hot component, which is represented by the high-energy (fast) ion population, is formed due to the trapping of powerful neutral beams on the target plasma. The fast ions are confined in the regime with rare collisions. The relative plasma pressure β (the ratio of plasma pressure to the pressure of the magnetic field) in the turning points of the fast plasma component was demonstrated to achieve maximum values of about 0.6 in the experiments with deuterium plasmas [2].

Recently, significant advance was achieved both in plasma stabilization [3] and electron component temperature [4, 5]. Currently, plasma confined in GDT is MHD-stable and electron temperature is high enough (up to 900 eV) for prolonged confinement of fast ions. Microinstabilities (in particular AIC) of fast component do exist in GDT, but demonstrated no significant impact on fast ions confinement [6]. Those issues are critical for projects of GDT-based neutron source and fusion reactor.

However, duration of neutral beam and ECR heating (5 and 3 ms correspondingly) is too short for transitional processes such as temperature growth and fast ions buildup to finish and plasma confinement in GDT is, at best, quasistationary. As can be seen from Fig. 1 fast particles buildup continues almost until the end of neutral beam injection and electron temperature is changing with typical time around 3 ms (which is comparable with 5 ms time of neutral beam injection).

Any further movement in direction of GDT-based neutron source or fusion reactor requires testing of current concepts of plasma confinement and stabilization in GDT with plasma lifetimes long enough to finish all transitional processes. This article is dedicated to description of project of such new device with provisional name GDT2.

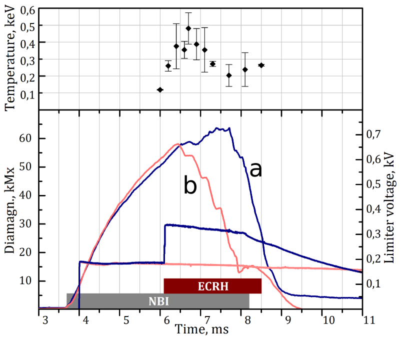

FIGURE 1. Typical time dependencies of diamagnetism (defined mostly by fast ions) and electron temperature in GDT. Lina a) and line b) corresponds to MHD-stable and MHD-unstable limiter voltage scenarios (see [4, 5] for details).

BASIC PARAMETERS OF GDT2 PROJECT

Basic layout of the device is planned to be the same, with two plasma components - fast sloshing ions and warm collisional target plasma confined in an axisymmetric mirror trap with high mirror ratio.

Neutral Beam Injection System

In order to reach steady-state, plasma discharge time in new device must be much longer than 3-5 ms which is the characteristic time of processes in GDT. As a reasonable compromise between physical requirements and Budker Institute technical and financial capabilities 30 ms neutral beam injection duration was chosen. Four new high power neutral beam injectors [7] are expected to be used in the project, with total neutral beams power up to 12.5 MW.

Magnetic System

High injection power creates bigger plasma pressure and current GDT magnetic system is too weak to confine such plasma. At the moment, magnetic field in GDT is 0.35 T at the center of the device and around 10 T at the mirrors. With total injected neutrals beam power around 5 MW relative plasma pressure can be as high as 60%. Thus, much stronger magnetic field is required for new device. Magnetic field strength equals to 1 T at the midplane and 15 T at the mirrors was found to be sufficient after simple estimates. Due to combination of longer plasma discharge time and high magnetic field superconducting coils were found to be optimal for magnetic system.

Length of the device was chosen to fit injectors and superconducting magnetic system.

TABLE 1. Main GDT and GDT2 parameters.

	GDT	**GDT2**
Injected power, MW	5	12.5
Injection angle, deg	45	70
Injection duration, ms	5	30
Mirror-to-mirror distance, m	7	10
Midplane magnetic field, T	0.35	1
Mirror magnetic field, T	10	15
Mirror ratio	30	15

Additional parameters, such as neutral beams injection energy, ECR power to neutral beams power ratio, etc, were selected as a result of parameter optimization of a numerical GDT2 model using DOL code.

NUMERICAL SIMULATION

DOL Code

The DOL code [8] was developed by GDT team members and is actively used by GDT team for numerical simulations of GDL-like open mirror systems. The model describes fast ions by solving bounce-averaged Fokker-Plank equation. The confinement of Maxwellian target plasma in magnetic trap is described for all ratios of particle mean free path and trap length.

Multiparametric Optimization Algorithm

The DOL code was used to perform multiparametric optimization using following algorithm:

- The total heating power was fixed at 12.5 MW.
- The ECR heating power was fixed as a part of the total power.
- Injection energy of neutral beams was selected, thus fixing the injection current.
- Additional current I_{mb} to support warm plasma material balance was selected.

Upon fixing input parameters additional conditions were introduced to select optimal configuration:

- Steady-state must be achieved at the end of injection of neutral beams.
- Confinement regime for target plasma must be borderline stable.
- Among those configurations the one with the biggest plasma pressure is selected.

Second condition requires an additional clarification. The DOL code does not describes stability of the plasma, however it is clear, that in kinetic mode (mean free path $\gg$ mirror-to-mirror distance) plasma will be unstable due to empty loss cone of the plasma distribution function. By increasing material balance current I_{mb} one can fill the loss cone and suppress the instability. But at the same time it will increase the plasma density, collisions and loss cone losses thus decreasing overall plasma parameters. That is why borderline regime was selected, then rates of kinetic and gasdynamic losses are equal. This condition is, of course, arbitrary and does not guarantee plasma stability, but it does allow to compare different plasma configurations in similar confinement regime.

Results of Optimization

Some results of numerical simulations are presented at Table 2 and Fig. 2

TABLE 2. Results of numerical simulations.

$\mathbf{E}_{inj}$, **kV**	$\mathbf{n}_{fmax}, cm^{-3}$	$\mathbf{T}_i$, **eV**	$\mathbf{P}_{tr}$, **%**	β , **%**
20	$3 \cdot 10^{13}$	383	40	0.1
25	$2.5 \cdot 10^{13}$	327	34	0.11

Designation: E_{inj} is neutral beam injection energy, n_{fmax} is maximum density of fast ions, T_i is warm ions temperature, P_{tr} is trapped power of neutral beams and β is the ratio of plasma pressure to the pressure of the magnetic field.

Variants with ECR heating power are omitted because they reduced overall parameters in all cases. Higher E_{inj} gives higher β then total power is fixed, however at $E_{inj} > 20$ keV, 30 ms injection duration is not enough to reach steady state.

CONCLUSION

The realization of the project of GDT2 device briefly described in this article will be an important step in advancement to mirror trap-based fusion power.

Key features of the new GDT2 device are:

- Steady-state plasma confinement and heating.

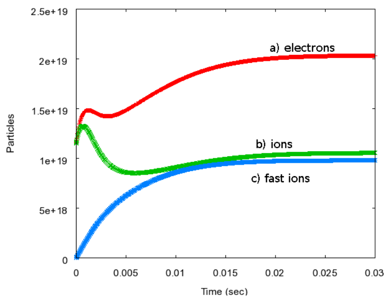

FIGURE 2. Total particle buildup for 20 keV injection energy. Line a)- electrons, line b) - warm ions, line c) - fast ions. Steady state is reached.

- 30 ms high power neutral beam injection heating with total power up to 12.5 MW.
- Injection energy around 20 keV
- Superconducting magnetic system with 15 T mirror field.
- Vortex confinement MHD-stabilization [3].
- Optional ECR heating.

The GDT team has developed new methods of plasma stabilization in axisymmetric mirror traps and mastered the ways of plasma heating. However those methods do require extensive testing in a steady-state conditions. No doubt, new challenges will arise, but significant experience gathered by GDT team allows us to look ahead with an optimism.

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