Experiments in support of the GDT-based facility for plasma-material interaction testing project

A.S. Arakcheev[1,2], P.A. Bagryansky[1,2], E.I. Soldatkina[1,2]

[1] *Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia*

[2] *Novosibirsk State University, Novosibirsk, Russia*

Introduction

The steady state heat flux along the magnetic field lines in the scrape-off layer of future burning plasma experiments (tokamaks and stellarators) is in the range of 1 GW/m^2 at temperatures in range of 30-100 eV [1]. For stationary operation of the reactor (hundreds of seconds), such a power flux leads to the irreversible destruction of almost any material. This power can be decreased when placing the divertor plates at an acute angle to the incident flux of plasma to the order of 10 MW/m^2. A realistic plasma source with a comparable heat flux along the magnetic field impinging at an angle of up to a few degrees will be required to predict the erosion and deposition of plasma-facing materials, including mixed materials, nano-structured materials, and materials with continuous replenishment of the surface coating. It seems that a Gas Dynamic Trap (GDT) might be well suited for this purpose due to adequate level of the power density which is predicted at the magnetic mirror throats of the GDT device. The GDT device at the Budker Institute of Nuclear Physics is an axially symmetric magnetic mirror machine [2]. The main component of the GDT device is a 7m long solenoid, with a magnetic field at the midplane up to 0.35 T and a mirror ratio R = 35 (Fig.1). The GDT facility is intended for the confinement of plasmas with two ion components [3]. One component is deuterium plasma with an isotropic Maxwell velocity distribution, its electron and ion temperatures of up to 250 eV, density of $\sim 1\text{–}3\cdot10^{13}$ cm^{-3}. Confinement of such plasma in the GDT is similar to that of a gas in a vessel with a small hole. The other component consists of fast deuterons with an average energy of ~10 keV and density up to $5\cdot10^{13}$ cm^{-3} and is produced by intense deuterium neutral beam injection (NBI) with a duration of 5 ms. The energy of injected neutral particles is 22–25 keV, and the total NBI power up to 5 MW. The plasma beta in the mirror system reaches a value $\beta = 8\pi n\langle\varepsilon\rangle/B^2 = 0.55$, where n and ‹ε› are the density and average transverse energy of fast ions, respectively, and B is the magnetic induction.

MHD stabilization of the GDT plasma is provided by “vortex confinement” mechanism [4].

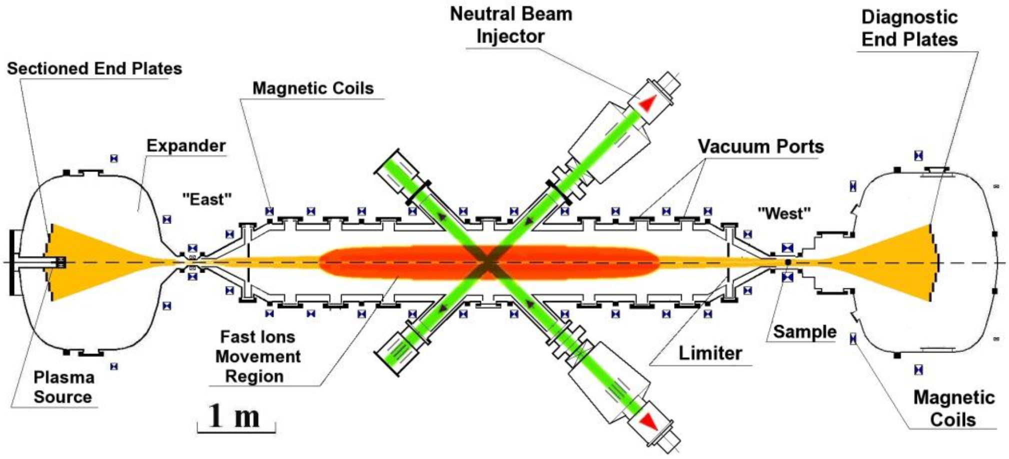

Fig.1. GDT device layout.

The paper presents an experimental study of the plasma heat flux in the mirror throat of the GDT device.

Experimental data

The maximal power flux density is obviously in the mirror throat of the GDT. Therefore we placed a metal body in the centre of “western” mirror in order to maximize the heat flux.

The sample was made of molybdenum and had a cylindrical shape with a diameter of 16 mm and a length of 20 mm. The plasma diameter in the mirror was about 45 mm. The sample was equipped with a copper-constantan thermocouple probe to measure the temperature jump during the pulse. Based on data of secondary emission probes system and calorimeters one could conclude that the average absorbed power in a typical shot was about 2 MW, therefore there was about 1 MW reaching each mirror, equivalent to a power density in the mirror of about 0.5 GWm^{-2} in the case of steady-state operation.

The temperature increase of the sample was measured by a thermocouple with the tip located 6 mm below the surface. In these experiments we also measured the time evolution of the plasma temperature and density profiles (fig. 2, fig. 3) by means of a Thomson scattering diagnostic placed in GDT central cross section.

The average temperature increase of the molybdenum sample was about (12.9±1.6) K corresponding to an energy deposition of (132±16.5) J. Dividing by the effective NBI duration (4 ms) and the sample surface area (2 cm^2) we find that the power density was about (165.5±20.7) MWm^{-2} which is 3 times smaller than the maximal estimated value mentioned above. Using data from fig. 2 one can estimate the temporal dependence of power density reaching the sample assuming the gas dynamic plasma flow type which can be described in the mirror as [5]

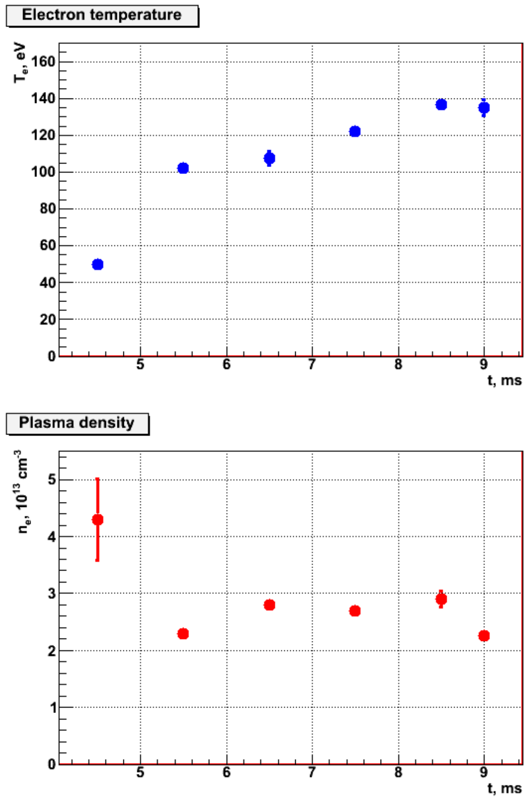

Fig.2. Plasma temperature and density vs. time at the plasma axis. Neutral beams injection starts at 3.6 ms with duration of 5 ms.

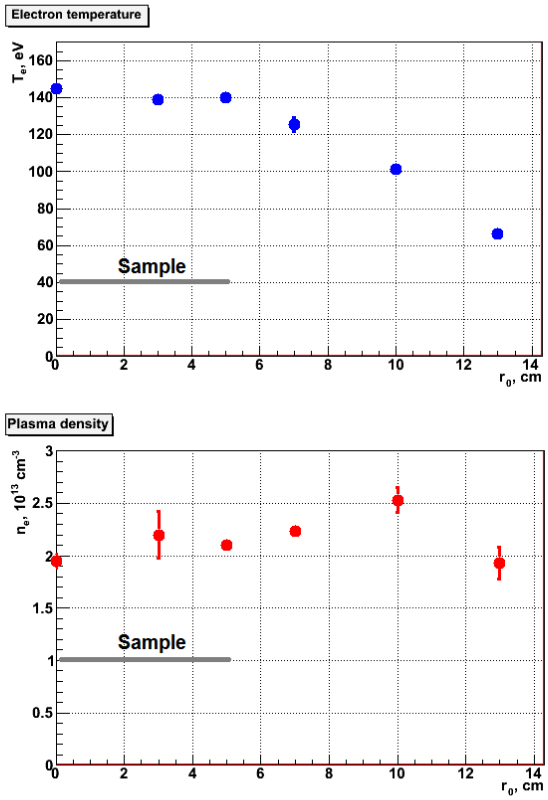

Fig.3. Plasma temperature and density vs. radius in moment of 8 ms. Projection of molybdenum sample to the central cross section is 5cm (solid line).

$j_{GDT} \approx 1.53n\sqrt{\dfrac{T_e}{2\pi m_i}}$, where n is plasma density, T_e the electron temperature and m_i the ion mass. Previous considerations [5] and experiments on GDT showed that each electron-ion pair carries energy of about $8T_e$. Hence the time dependence of the power density is

$$P_{GDT}(t) \approx 12n(t)T_e^{3/2}(t)\sqrt{\frac{1}{2\pi m_i}}. \qquad (*)$$

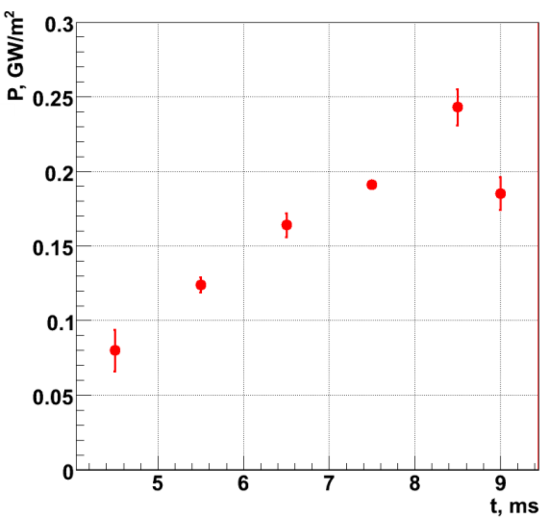

Fig.4. Temporal evolution of the power density in the mirror estimated by formula (*). NBI stops at 8.5 ms.

The temporal evolution of P_{GDT} is plotted in Fig. 4. It shows that the maximal power density is obtained at the end of the neutral beam injection pulse and reaches a value of about 0.25 GWm^{-2}. The calculated total energy agrees with the measured value of 160 J to an accuracy of a few percent.

Conclusions

Our results show that the maximal power flux density in the GDT mirror is about 0.25 GW/m^2 with a plasma electron temperature of about 140 eV at a density of $2 \cdot 10^{13}$ cm^{-3}. The energy density deposited on the surface of a probe installed in the mirror throat during a 5 ms plasma shot was 0.8 MJm^{-2}.

The greatest extrapolation from current experience with GDT device is the a 100000-fold increase in pulse length, from 5 ms to 500 s, needed for an adequate testing of the divertor components for ITER, Wendelstein 7-X, NSTX-U etc., and in general for developing plasma-facing components since high-fluence operation is not a critical issue for such systems. The most important part of a prospective facility for PMI studies based on the Gas Dynamic Trap is the neutral beam system. Reliable neutral beam modules with adequate power and operation time of few hundred of second are currently available (see for example [6]) as well as required pumping systems and superconducting magnetic coils [7, 8].

Experiments carried out allow one to conclude that there are no fundamental objections for considering the GDT type system as a facility for PMI testing.

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