Steady-state Confinement of Anisotropic Hot Ion Plasma in the Gas Dynamic Trap

A.A.Ivanov[1,2], A.V.Anikeev[1,2], P.A.Bagryansky[1,2], A.D.Beklemishev[1,2], A.S.Donin[1,2], A.V.Kireenko[1], K.Yu.Kirillov[2], M.S.Korzhavina[2], A.A.Lizunov[1], V.V.Maximov[1,2], S.V.Murakhtin[1,2], E.I.Pinzhenin[2], V.V.Prikhodko[1,2], V.Ya.Savkin[1,2], E.I.Soldatkina[1,2], A.L.Solomakhin[1,2], Yu.A.Tsidulko[1,2]

[1] *Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russian Federation*

[2] *Novosibirsk State University, 630090 Novosibirsk, Russian Federation*

Abstract. The paper summarizes recent results obtained in the gas dynamic trap experiment. Gas dynamic trap (GDT) is a mirror device where Maxwellian plasma component and fast anisotropic ions are confined in the axially symmetric central cell with outboard MHD anchor cell. The GDT NB heating system is capable of providing six focused 20-25 keV hydrogen or deuterium beams. The total beam power delivered to the central cell plasma reached 4 MW in the 5 ms pulse. Two additional focused 25 keV beams provide up to 1.2 MW in the compact mirror cell attached at the end of the GDT central cell.

Comparison of the experimental data on global energy and particle balance with the results of the Monte-Carlo modeling of the plasma equilibrium parameters indicates that the two-component plasma in GDT reaches steady-state within 5ms shot. The characteristic plasma lifetimes are 4 - 5 times shorter than the pulse duration. In these experiments peripheral gas-puff near the end mirror is used to maintain plasma radial profile during the NB injection. Peak density of anisotropic ions with the mean energy of 10 keV exceeded $4x10^{19}$ m^{-3} near their turning points, that is close to main plasma density in the reported experiments. Accordingly, in these experiments the maximal beta value was increased from 0.4, which was reported previously, to about 0.6. Electron temperature of plasma was also significantly increased from ~100eV up to about 160 eV in the steady state regime and exceeded 200eV in transient regimes with somewhat smaller density. The stability against MHD interchange modes was established using the set of biased radial limiters and segmented end wall.

The new results of experiments with the compact mirror cell attached to the GDT central cell are be also presented in the paper. In particular, micro-instability limits in extremely anisotropic hot ion plasmoid were studied.

1. Experimental Setup

The gas dynamic trap (see Fig. 1) is a long axially symmetric magnetic mirror system with a high mirror ratio variable in the range of 12.5-100 that confines a two-component plasma [1].

One of the components is a collisional background (or “target”) plasma with ion and electron density of about $5x10^{19}$ cm^{-3} produced by arc-discharge source installed inside end tank. The ion mean free path of scattering into the loss cone is less than the mirror-to-mirror distance for this component, so that it is confined in The plasma contains anisotropic fast ions with energies of of 20-25 keV which are produced by neutral beam injection at the centre of the device at 45° to the axis collisional or a gas dynamic regime [2]. . The fast ions are confined in the central cell between the turning points in strong magnetic field near the end mirrors where the mirror ratio is 2.

Parameter	Value
Mirror to mirror distance	7 m
Magnetic field at midplane in mirrors	≤0.28 T 2.5–15 T
Target plasma density radius at the midplane electron temperature	(3–6) × 10^{19} m^{-3} 6–7 cm ≈ 200 eV
Energy of deuterium neutral beams	≈ 20 keV
Pulse duration	5 ms
Total injection power	3.9–4.0 MW
Injection angle	45°
Fast ion density in turning point regions	≈ 3 × 10^{19} m^{-3}
Mean energy of fast ions	≈10 keV
Maximal local plasma β	0.6

Table 1: The main parameters of GDT plasma confinement experiment

The GDT NB heating system was substantially upgraded last year. After upgrade it is capable of providing six focused 20-25 keV hydrogen or deuterium beams. The total beam power delivered to the central cell plasma reaches 4 MW in the 5 ms pulse and further increase upto 6MW is foreseen. During the beam injection, target plasma density is maintained by peripheral gas puff. Two additional focused 25 keV beams deliver up to 1.2 M W in the compact mirror cell attached to the GDT central cell at one of the ends. The setup for the experiment with the external compact mirror cell is also shown in Fig. 1. Major idea of the experiment is to provide hot ion plasmoid in the external mirror cell with strongly focused neutral beams. According to preliminary estimates, fast ion density in the plasmoid could exceed that of the target plasma giving rise to development of considerable ambipolar potential and plugging of axial plasma losses. Table 1 shows major parameters of the GDT experiment.

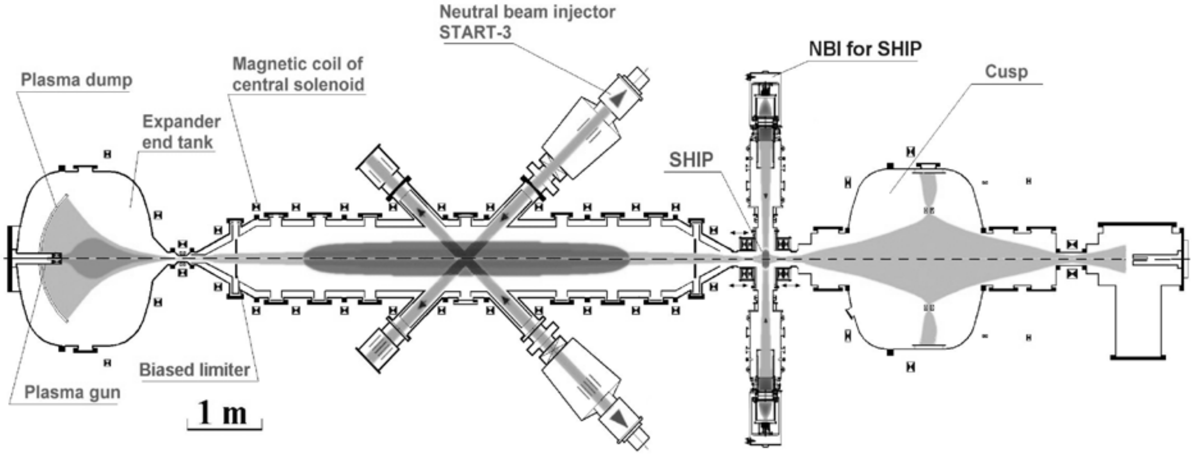

Fig.1 General layout of the GDT experiment.

2. Steady state confinement of anisotropic high-β plasma

The characteristic time of target plasma losses through end mirrors and injected ion slowing down time are significantly (4-5 times) smaller than the duration of beam injection pulse (5 ms). Therefore a steady-state regime of plasma confinement was realized in the experiments. Temporal variation of plasma energy in this regime is shown in Fig.2. The total energy stored in the fast ion component, exceeded 1 kJ for the maximal density near turning points of up to $4x10^{19}$ m^{-3}. This value is close to the target plasma

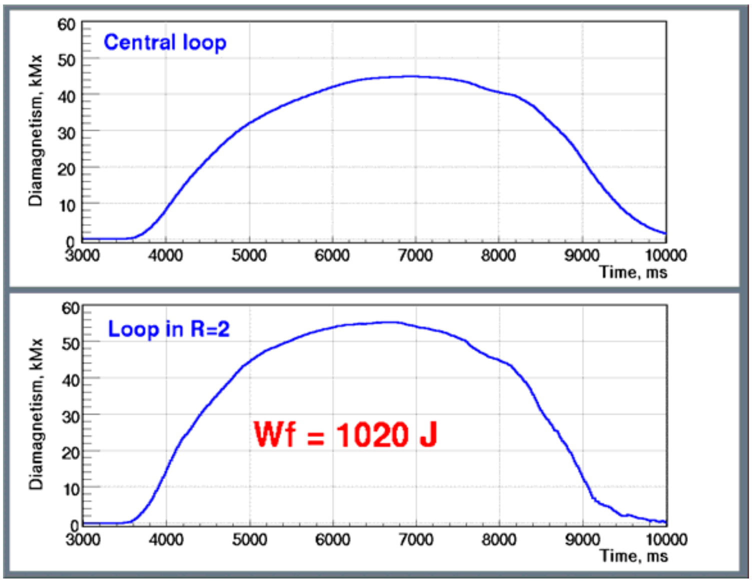

Fig 2. Diamagnetism of plasma and fast ions in GDT.

density. These parameters are considerable higher than that obtained in the previous experiments [1,3] in which maximal anisotropic plasma beta was 0.4. Local measurements of magnetic field reduction due to finite plasma beat are still in progress, but preliminary results and comparison of the stored plasma energy indicate that in this regime plasma beta is close to 0.6.

In Fig. 3 results of measurements of the plasma electron temperature during 4 MW deuterium beams injection are shown. For this series of plasma shots there was no gas puff, so that plasma density considerably decreases to the end of the pulse down to $\sim 1.5\ 10^{19} m^{-3}$. It is seen that the maximal T_e reached exceeds 200 eV. In the Fig.3 also shown are temporal variation of electron temperature in the regime when plasma density was sustain by gas puff and result of simulation of 10MW beam injection in the same conditions. In the regime when the density was sustain with 3.5MW injection electron temperature was about 160eV. The calculated curve corresponding to 10 MW of heating beam power, is also plotted to illustrate the predicted T_e growth with increase of injection power.

Measurements of axial density profile of anisotropic fast ions in turning point regions, indicated formation of density peaks. Radial profile of the fast ion density was narrow, as it was in the previous experiments with shorter injection pulse. Its characteristic width was measured to be ≈7 cm, which is close to ion Larmor radius, and did not considerably change during 5 ms beam injection. The measured characteristics of fast ions were found to be in good agreement with estimations and numerical calculations based of pair Coulomb scattering theory.

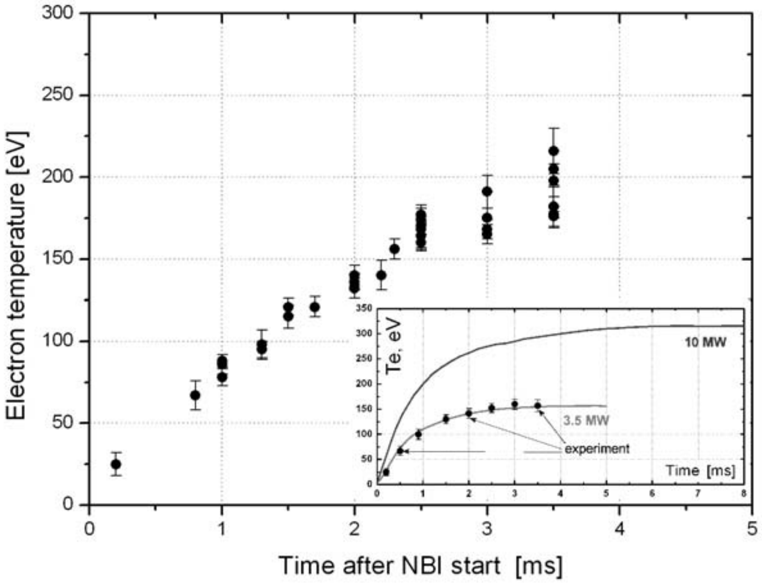

Fig. 3: Electron temperature in shot with 4 MW NB heating. Also shown are measurements of electron temperature in experiments with 3.5 MW compared with Monte-Carlo simulations (solid curve). Simulation result for 10 MW injection is also shown.

Stability of two-component plasma against interchange MHD modes was maintained in an axially symmetric magnetic configuration with the cusp end cell by making use of a set of biased radial limiters (see Fig. 1). With the cusp end cell only and without biasing of the radial limiters plasma energy and beta were limited by growth of MHD activity. The limiter biasing considerably improved plasma stability for higher betas. Formation of the sharp gradient of the electrostatic potential at plasma periphery caused differential rotation with high velocity shear. This effectively suppresses interchange modes with the azimuthal numbers m>1 and large scale drift turbulence. Theoretical consideration [4, 5] also showed non-linear saturation of amplitude of m=1 (rigid displacement) mode and formation in plasma core a region with closed flow lines, so that radial plasma transport become to be small. The nature of this phenomenon is similar to formation of an internal transport barrier in tokamak plasmas.

3. Experiments with internal mirror cell in GDT

Recently, the experiments with injection of focused 25 keV neutral beam into a compact mirror cell located at the end of the GDT central cell have been started (see Fig. 1). These experiments were performed to study confinement of strongly anisotropic hot-ion plasma with density and ion energies approaching those in the regions of high neutron production in the GDT-based neutron source [2]. Specific feature of the experiments with the beam injection in the compact mirror cell is strong anisotropy of fast-ions with $A=W_{\perp}/W_{||}\approx 50$, where $W_{\perp}$ and $W_{||}$ are transverse and axial ion energy, respectively. Note that in the zones of high neutron flux ion anisotropy is relatively small, so these experiments do not fully reproduce conditions in these zones of the neutron source. During injection of the focused neutral beams fast ion density in the local cell reached about $3.8\cdot 10^{19}\,m^{-3}$ so that significant density peak appeared.

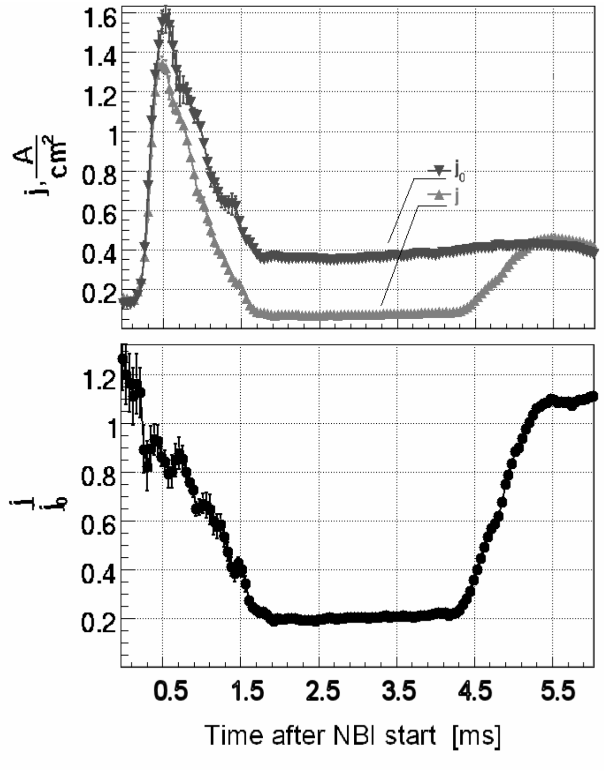

Fig.4 Reduction of axial plasma losses in the experiments with internal mirror cell.

Anisotropic plasma build-up in the local mirror cell was accompanied by development of ambipolar potential barrier, which resulted in a strong suppression of axial plasma losses through this end. Fig. 4 shows ion current density measured on axis near the end wall (upper plot) in the regime with and without injection of two beams into the compact mirror cell. Lower plot, where the relation of j/j_0 is presented, indicates that during the beam injection in the compact mirror cell, the plasma flux out of the end is decreased ~5 times.

During fast ion build up in the mirror cell, after exceeding certain threshold strong high-frequency oscillations of plasma potential have been observed by RF probes. The main frequency of the fluctuation was about 37 MHz that corresponds to beta decreased ion-cyclotron frequency in the compact cell midplane. The fluctuation started to develop when the fast ion density in the compact mirror cell exceeded $\sim 3\times 10^{19}\,m^{-3}$. Measurements show that high axial k_z and m=1 azimuthal mode dominates in the spectrum of unstable fluctuations [6].

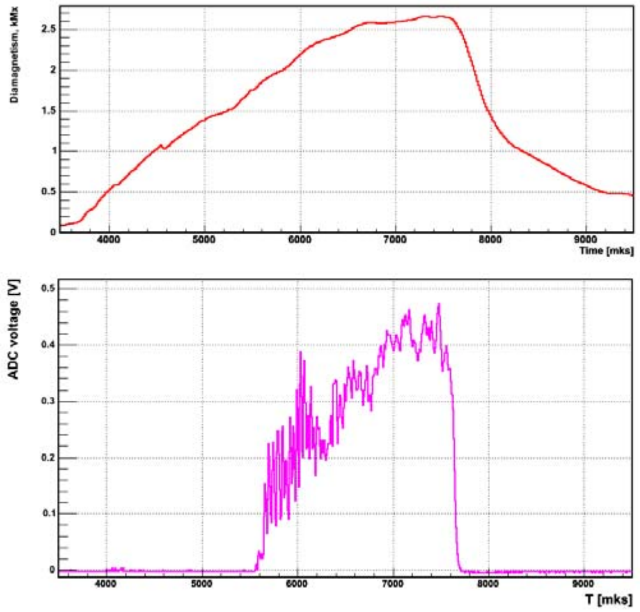

Fig.5 Development of high frequency oscillations during fast ion build up in the compact mirror cell.

Second harmonic is also presented (see Fig.6). The characteristics of the fluctuations which were observed in the compact mirror cell are consistent with Alfven Ion Cyclotron mode [7,8]. The oscillations have not been observed when fast ion density here was small enough. According to [7,8] actual threshold of AIC instability is determined by a parameters βA^2 where $A=\langle E_\perp\rangle/\langle E_{||}\rangle$ is a plasma anisotropy. In the experiments, we observed threshold corresponded to βA^2 ~50 which is considerably larger than that observed in [8]. However, development of these oscillations in our experiment did not considerably alter fast ion confinement or precipitate plasma dumping. Neither limitation of fast ion density with increase of injected power, nor broadening of their angular distribution were observed in the experiments. Further studies are necessary to understand how these oscillations could alter fast ion confinement.

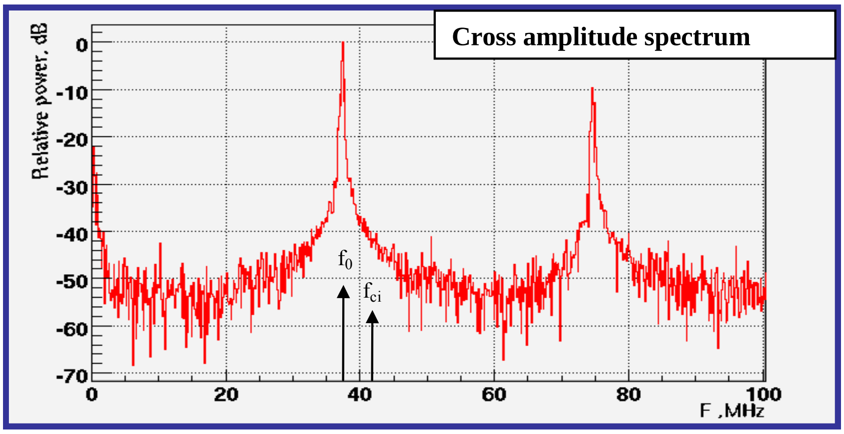

Fig.6 Cross amplitude spectrum of unstable fluctuations.

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