INTEGRATED TRANSPORT CODE SYSTEM FOR MULTICOMPONENT HIGH-β PLASMAS IN THE GAS-DYNAMIC TRAP

A.N.Karpushov, A.V.Anikeev, K.Noack[1], S.L.Strogalova[2]

Budker Institute of Nuclear Physics, Prospect Lavrent eva 11, 630090, Novosibirsk, Russia
[1] Forschungszentrum Rossendorf, Postfach 51 01 19, D-01314, Dresden, Germany
[2] Novosibirsk State University, Pirogova 2, 630090, Novosibirsk, Russia

INTRODUCTION

The report is focused on the development of theoretical and numerical models of multicomponent high-β plasma confinement and transport in the Gas-Dynamic Trap (GDT) [1]. The Gas-Dynamic Trap is an axisymmetric open trap with a high mirror ratio for the confinement of collisional plasma. Based on this type of plasma device a high-power source of 14 MeV neutrons dedicated to fusion material irradiation and other applications has been proposed [2].

In order to simulate the plasma behaviour in the existing GDT experiment as well as that in the GDT-based neutron source the Integrated Transport Code System (ITCS) has been developed. Existing stand-alone codes calculating the target plasma, the fast ions and the neutral gas in the GDT were coupled by an appropriate file transfer. The purpose of the ITCS is the calculation of physical effects connected with these particle fields. It considers the full dependence of the transport phenomena on space, time, energy and angle variables as well as the interactions between the fields. To check the capabilities of the physical models that have been incorporated in the ITCS the overall comparison between numerical and experimental results from the GDT has been made.

A possibility to achieve both a high electron and a high ion temperature of the dense plasma, as required for the GDT-based neutron source, has not yet been demonstrated experimentally in the GDT. Therefore, the development of approaches enabling the study of plasma physics issues related to plasma confinement in the GDT at conditions relevant for the neutron source is mandatory [3]. To this end the ITCS was used for numerical investigations of the possibility to achieve the high plasma parameters in the GDT experiment.

1. PHYSICAL MODEL OF THE MULTI-COMPONENT GDT PLASMAS

The multicomponent GDT plasmas consist of the target plasma isotropic Maxwellian electrons and ions, fast (sloshing) ions and neutral components. The warm background plasma (target) with electron temperature 3-120 eV and density of (1-20)$\times10^{13}$ cm^{-3} produced by a plasma gun and (or) by gas-puffing. The different methods of cold-gas fuelling was proposed and experimentally tested on the GDT. The fast ions are created by the injection high energy neutral beams into the GDT central cell. The six neutral beams with the injection energy of 12.5-17.5 keV are used. The duration of the NB pulse is 1.0-1.2 ms; total injected power exceeds 4 MW. The neutral beams in the GDT are trapped as a result of charge-exchange and ionisation by target plasma ions and electrons, and transformed into the fast ion population. Fast ion relaxation is determined by electron and ion drag, charge-exchange on the neutrals and angular scattering in the Coulomb collisions with plasma ions. The target plasma storage and decay is described by longitudinal losses (classical gas-dynamic or additional heat losses on limiters and plasma gun), cross-filed transport, radiated losses, neutral gas ionisation [1]. The neutral component in the GDT consists of the slow molecules and atoms, Frank-Condom neutrals and fast charge-exchange atoms. The neutral gas transport described by an interaction with target plasma and fast ions, plasma-wall and neutrals-wall processes.

2. FAST INTEGRATED TRANSPORT CODE (FITC) FOR MULTI-COMPONENT PLASMAS

The code FITC has been developed to simulate the GDT target plasma transport under NBs heating [6]. It allows to calculate the target plasma temperature and density radial profiles over time and the radial profiles of the power deposited by fast ion drag. The code includes the following processes in the target plasma:

- the particle source from the plasma gun or another sources (cold-gas fuelling, pellet injection; etc.);
- the longitudinal losses through the mirrors, losses to limiters and losses to the plasma gun;
- the cross-field transport: plasma thermal conductivity and diffusion;
- the heating of target plasma ions and electrons by fast ions;
- energy exchange between ions and electrons.

The code based on the combined numerical solution of the MHD equations for target plasma and kinetic equation for fast ions. The fast ion model includes:

- conversion of neutral beams to fast ion population by charge-exchange, electron and ion impact ionisation;
- interaction of fast ions with target plasma (electron and ion drag);
- charge-exchange losses.

The code was used in two modifications:

1. self-sufficient calculations for the system of target plasma and fast ions. It was used for preliminary or 0-step calculation of the GDT plasma parameters and
2. calculations with internal data source of plasma drag. This calculation regime was used as a part of the ITCS. The output data of the FIT code on the drag of fast ions on target ions and electrons are used in this case.

3. APPLICATION OF THE INTEGRATED TRANSPORT CODE SYSTEM

For the calculation of plasma parameters in the GDT-upgrade regimes the codes FITC, FIT [4], TUBE [7] and NEUSI [5] were used in the following steps:

Step I, FITC Pre-Calculation:

A preliminary FITC calculation was used to produce the initial approximation of the target plasma parameters ($\boldsymbol{n(r,t)}$, $\boldsymbol{T_e(r,t)}$ and $\boldsymbol{T_i(r,t)}$) for FIT, TUBE and NEUSI codes. It performed on the base of the following information:

- Data of the magnetic field and vacuum chamber geometry.
- Data of the NBI system.
- Data on the plasma gun operational regime.
- The neutral gas distribution $\boldsymbol{n_O(r,z,t)}$ in the vacuum chamber was estimated from the foregoing regimes or was set to zero.

Step II, FIT Pre-Calculation:

The preliminary FIT calculation was applied to produce the following outputs:

- The source distribution of slow atoms generated by the NB-plasma interaction in the near-axis region. The data was used as a volume source by TUBE and NEUSI.
- The fast ion field, which use by NEUSI for calculation of the charge-exchange fast neutrals.

The calculations use the following inputs:

- Detailed data of the NBI system:
- Data of the target plasma $\boldsymbol{n(r,t)}$, $\boldsymbol{T_e(r,t)}$ and $\boldsymbol{T_i(r,t)}$

- Data of the magnetic field ***B(r,z,t).***
- The neutral gas components: slow atoms and molecules. This data for preliminary FIT calculation was taken from the calculations for the foregoing calculations or was set to 0.

Step III, TUBE and NEUSI neutral gas calculations:

The neutral gas calculations include the two steps the calculations of the neutral sources on the vacuum chamber first wall (TUBE [7]) and calculation of the neutral component distributions into the GDT plasma (NEUSI [5]). The detail description of the neutral gas package was given in [4].

Step IV, FIT calculations of the fast ion field, radial profiles of electron and ion drag depositions:

A long-time FIT calculation was performed differing from that in *step II* by a neutral component used, all component of the neutrals computed by NEUSI (step III) were take into account. The FIT code calculate:

- The radial profiles of electron and ion drag deposition $P_{Fi}(r,t)$ and $P_{Fe}(r,t)$ (which are the inputs for target plasma calculation *(Step V)*.
- The fast ion distribution in time and phase space $f_F(^3r,^3v,t)$. The construction of a wide spectrum of outputs for energy, pitch angles and spatial distributions is allowed on the base of the f_F integration.
- The FIT output include global time functions: energy content $W_F(t)$, trapped power $P_{tr}(t)$, drag-loss power $P_{Fe}(t)$ and $P_{Fe}(t)$, power of the charge-exchange losses $P_{ex}(t)$, particle content $N_F(t)$; energy distributions $F(E,r,t)$; pitch angle distribution $F(\Theta,E,r,t)$; and other [4]. All outputs listed in *Step II* are also allowed.

Step V, target plasma calculations:

The FITC target plasma calculation performed for the target plasma parameters $n(r,t)$, $T_e(r,t)$ and $T_i(r,t)$. It based on the following information:

- Data of the magnetic field and vacuum chamber geometry (see *Step I*).
- Radial distribution of plasma heating $P_{Fi}(r,t)$ and $P_{Fe}(r,t)$.
- Data on the plasma gun operational regime.

Steps I and II used ones per run of code system. III-V steps arrange the main loop of the ITCS. The exit from the loop occurred when the differences in the outputs of two successive iterations become neglectable small.

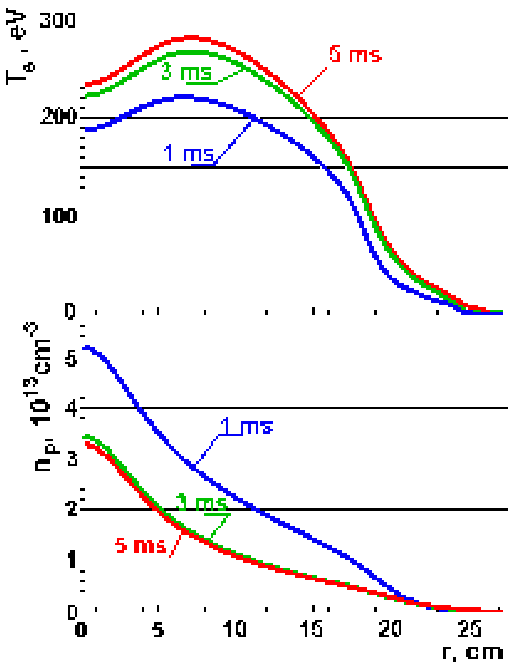

Fig.1: Radial profiles of the plasma density and electron temperature at 1,3,5 ms after start of NBs.

4. RESULTS AND CONCLUSIONS

The possibility to achieve both a high electron temperature and a fast ion density of 10^{13}-10^{14} cm^{-3} were analysed by mean of ITCS. The GDT NB-system consists of six injectors with the beam energy in the range 12.5-17.5 keV. The current of each neutral beam amounts at 48-55 Atom Amperes, the duration of NB pulse is 1.0-1.2 ms, and the total injected power exceeds 4 MW. The new NB-system with beam energy 25-30 keV, beam current up to 80 Atom Amperes, and pulse duration 3-6 ms is proposed for GDT-upgrade. The total injected power about 10 MW estimates. The construction of the magnetic field system allow to increase the magnetic field in the GDT by a factor of ~1.5 (from 0.22 to

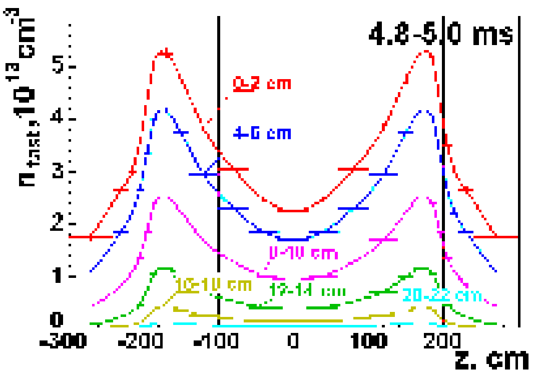

Fig.2: Fast ion density profiles along magnetic field line for various radius intervals.

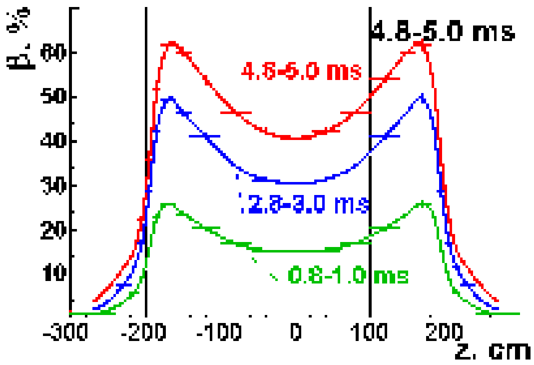

Fig.3: On axis vacuum β for various time intervals.

0.35 T) by increasing the magnetic field capacity batteries.

The neutral gas distribution $n_O(r,z,t)=0$ was use for target plasma pre-calculation (Step I). Then the fields of neutral atom and molecules were calculated by means of FIT, TUBE and NEUSI codes (Step II and III). After 6 iterations the accuracy of electron temperature and density calculations was 5-10 %. The simulated plasma parameters for GDT-Upgrade are presented in Fig. 1-3.

The results of numerical simulations enable us to conclude that the electron temperature of 200-300 eV (Fig.1) will be achieved in the GDT-upgrade with a new NB system (injected power 10 MW, pulse duration 3-5 msec). The density of fast ions at the turning points are estimated as $\sim 5\times 10^{13}$ cm^{-3} (Fig.2), fast ion β will be up to 60 % (Fig.3).

The authors acknowledge Dr. P.A.Bagryansky and Prof. S.Collatz for useful discussions, G.Otto for technical support of ITCS calculations. A.Anikeev and A.Karpuschov are grateful to the Alexander von Humboldt Foundation and German Academic Exchange Service during their working stay at Forschungszentrum Rossendorf (Germany). This work was partially supported by ISTC through research project #492-98.

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