Conceptual Design Studies of GDT-based Neutron Source

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ABSTRACT

An analysis shows that the existing nuclear technology data bases are not sufficient to arrive at a DEMO with reasonable confidence in achieving target availability levels [1]. In order to provide these data, a testing facility capable of simulating neutron environment in a fusion reactor is needed.

A number of proposals for plasma-type neutron sources have been made recently to meet the testing requirements. In comparison with the other proposed schemes, which exclusively capitalize the advanced tokamak concepts, the neutron source based on gas-dynamic trap (GDT) concept [2] has rather attractive design features stemming from its axial symmetry. Recently, significant progress in the pre-conceptual design of the source has been made. Firstly, application of up-to-date technology reduced the power consumption of the magnets also providing its longer lifetimes; secondly, the plasma parameters were revised using a self-consistent numerical model which, in particular, in contrast to that initially used, accounting for the collisions between the fast ions. Further development of the model was supported by experiments on the GDT facility at Budker Institute.

INTRODUCTION

GDT is a high mirror ratio magnetic mirror with a length greatly exceeding ion mean free path of scattering into the loss cone. To generate 14MeV neutrons, 80-100keV D-T neutral beams are obliquely injected at the midplane of the device into a relatively cold (0.8-1.1keV) deuterium target plasma confined in gas-dynamic regime.

For the given plasma parameters, the trapped fast tritons and deuterons are slowed down by electron drag much faster than scattered over the pitch angles due to ion-ion collisions. Thus, their angular spread keeps rather small during the lifetime period inside the plasma which results in a strong ion density increase towards the ion turning points located near the mirrors. The neutron yield is then peaked in these regions housing the test zones.

Pre-conceptual design study reviewed in [1] adopted the performance guidelines established by a number of IEA workshops as well as the physics constrains consistent with the existing magnetic mirror data base. It provided the following parameters of the source: power consumption - 60MW, neutron flux-$2.5 MW/m^2$, annual tritium consumption - 0.16kg. Fig.1 shows elevation view of the GDT-based neutron source of Efremov's design referred to as IN-1 neutron source [3].

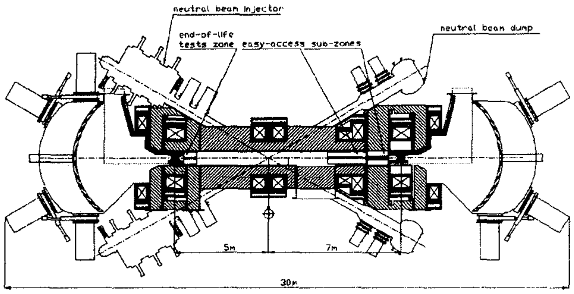

Fig.1 Schematic of GDT-based neutron source.

The facility has two zones for tests. One of these is 1.9m long and 12cm in diameter. It is divided into easy access and end-of-life tests sub-zones. Oppositely housed is 0.4m long end-of-life tests zone. Neutron load in the test zones approaches $2.5 MW/m^2$ on the first wall and then falls down outward to about $0.25 MW/m^2$.

Pre-conceptual design revealed intrinsic potentialities of the concept which, if realized, could significantly improve the source performance. A few issues were also recognized as being quite critical for its feasibility. One of the major issue of concern addressed here is how could the mean time between failures of the 26T mirror magnet, which incorporates SC-magnet and a water cooled insert, be increased to achieve reasonable availability level of the system as a

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whole? According to technological as well as economical reasons the resistive coil lifetime should be increased at least up to 2-3 years instead of about 300 hours achieved for KS-250 magnet of similar design [4]. The principal solution to this problem was find in mirror field reduction to a value achievable without use of a resistive choke coil. The results of the electromagnetic calculations of SC mirror magnet without a resistive part are presented in the Section I. In Sec.II we examine possible set of the neutron source parameters under more conservative assumption about achievable electron temperature.

I. MAGNET SYSTEM OF THE SOURCE

The overall magnet configuration of the IN-1 neutron source [3] is shown on Fig.1. To produce the required 26T mirror field, the combined magnet incorporating SC-coil and a resistive water-cooled insert is used. The SC-coil provides 9-10T contribution to on-axis field. The resistive part adds another 16-17T consuming maximally of 30MW from the grid. This design is similar to that of KS-250 magnet [4]. The magnetic field at superconductor was also limited to 11T as in KS-250.

Operating parameters of two point designs (those for IN-1 source are marked by stars) the first of which is discussed in this paper are given in Table 1.

Table I

The neutron source parameters

Parameter	Value
Power consumption	47.1/50* MW
Trapped NB-power	22/15* MW
Neutron flux density	1.8/2..5* MW/m^2
Specific neutron yield	0.49MW/m
D^0 beam energy	65/80* keV
T^0 beam energy	65/94*keV
Electron temperature	0.65/1.1*keV
Cold ion temperature	2.23/0.3*keV
Mirror-to-mirror	11.4/10*m
Test zone axial extent	1.0m
Plasma radius	8.0cm
Injection angle	30^0
Mirror field	13T
Mirror ratio	10
Test zone mirror ratio	3.7
Plasma $\beta_\perp$ at midplane	0.36
Electron density, n_e	1.73/2*× 10^{14} cm $^{-3}$
Cold ion density at midplane,	0.17 ×10^{14} cm^{-3}
at test zone	0.13 ×10^{14} cm^{-3}
D^+/T^+ density in test zone,	2.24 ×10^{14} cm^{-3}
Cold ion lifetime	0.6ms
D^+ slowing down time	8.0 ms

The technology developed for ITER magnets allows the critical magnetic field to be significantly increased from 11T assumed in IN-1 design. The ITER project will build a central solenoid model operated with a peak field strength of 13T in a 1.6m bore [5]. Using this achievement, the power consumed by the mirror magnet can be reduced from 15 to 3MW thereby providing higher lifetime [6]. As it was above mentioned, the higher figure of merit can be achieved if the mirror field is limited to 13T thereby allowing use of purely superconducting magnet. The Lagrange optimization algorithm was applied to minimize the volume of the SC 13T on-axis field mirror magnet [6]. Current density distribution over radius was approximated by three subcoils with a constant current density in each for the maximum field of 13,10,7T. The calculated parameters of the coil are given in Table 2.

Table II

The parameters of the optimized SC mirror magnet

N	r, m	Δr, m	Δz, m	$J_{0,\ MA/m^2}$	Steel fraction	σ_τ, MPa	σ_τ, MPa
1	0.5	0.2	1.6	14	0.56	161	25.1
2	0.675	0.15	1.45	22	0.42	333	41.4
3	0.785	0.07	1.45	35	0.4	450	71
4	0.855	0.07	1.35	35	0.4	375	42
5	0.945	0.11	1.25	35	0.4	-175	47.1

Here σ_τ and σ_z stand for the maximum hoop stress and maximum compressive stress, respectively. It was assumed that the subcoils are not mechanically connected to each other. The maximum hoop stresses in the subcoils are then below tolerances for the stainless steel envelope, and compressive stresses do not exceed those for epoxy compound at 4.5K as well.

II. OPERATIONAL PARAMETERS OF THE NEUTRON SOURCE

The neutron flux in the test zone is sensitive to the attainable plasma performance, notably electron temperature and allowable beta. Capability to operate at high beta has been already demonstrated in many mirror experiments. At the same time, the maximum electron temperature for relevant experimental conditions was limited to 260eV [7] which is still significantly smaller than that assumed in IN-1. A positive finding in mirror experiments is rather long electron-energy confinement time approaching 0.45-0.9ms [7] that is quite close to that needed (~ 0.5ms). Moreover, according to the data presented in [7] there is some indication that electron confinement even improved for higher temperatures. Nevertheless the present data does not provide a satisfactory basis for direct extrapolation to the neutron source without intermediate steps [8]. Therefore, the source versions with lower electron temperatures allowing more direct extrapolation from existing database are to be studied. Here we consider the source version with the electron temperature reduced to 650eV which is about 2.5 times of that already achieved.

In order to simulate the neutron source plasma we have developed a self-consistent numerical model which incorporates fast ion-ion collisions. This model enables us to re-adjust magnetic field profile to keep the same position of the test zones as in IN-1. Calculated parameters of the source are given in Table 1. Figures 2, 3 show distribution of the magnetic field and neutron flux profile along the device.

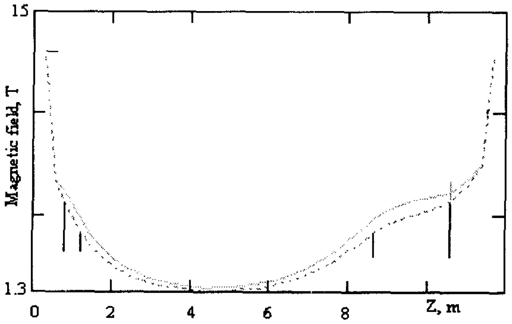

Fig.2 On axis magnetic field profile. Solid line represents vacuum magnetic field; dashed line corresponds to the magnetic field reduced due to finite plasma beta. Horizontal bar indicate the mirror field magnitude.

Vertical bars on Fig.2 indicate the position of the testing zones inside of which the field variations amount to ± 15%.

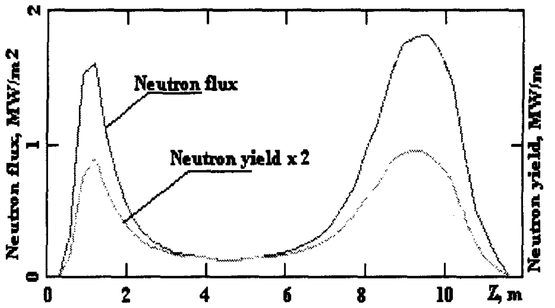

Fig.3 Profiles of the 14MeV neutron flux and neutron yield along the axis.

III. NEUTRON SOURCE SIMULATIONS

The major physics issues in the reaction chamber for the neutron source are MHD equilibrium and stability, microstability of the energetic sloshing ions, start-up, cold ion fueling, and electron heat conduction onto the end walls. Startup, MHD stability, equilibrium control, and microstability were all demonstrated in GDT experiment for moderate plasma parameters. The transverse plasma losses were measured be small compared to the losses through the mirrors at least for mirror ratios less than 25. Strong reduction of the longitudinal electron heat flux was also observed. Electron temperatures up to 70eV were measured in the regimes with 3MW, 14keV neutral beam injection. Further increase of the temperature was limited by the available beam power and pulse duration. In these regimes, the plasma energy balance was determined essentially just by classical mechanisms of energy losses. It was confirmed by comparison of the measured energy content in sloshing ions with that predicted by the numerical code. Fig.4 shows temporal variation of the energy stored in the sloshing ions averaged over a few plasma shots.

The experimentally measured plasma parameters were find to be in reasonable agreement with the code predictions. This gives reasonable level of confidence in applicability of this concept to the neutron source design. However, further verification and generation of the relevant database at plasma parameters maximally close to that expected in the neutron source are necessary before its construction. For this purpose, the Hydrogen Prototype of the GDT-based Neutron Source (HPNS) is now under construction at Novosibirsk. Operating point parameters of HPNS is given inTable 3.

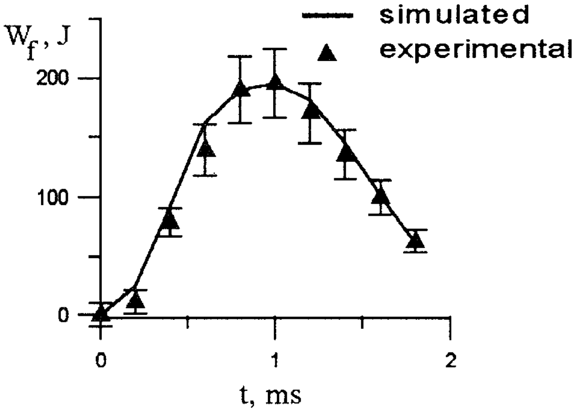

Fig.4 Temporal behavior of the sloshing ion energy content in GDT experiment.

Table III
The HPNS parameters

Parameter	Value
Power consumption	40MW
Pulse duration	2sec.,eq.
Magnetic field at midplane	1T
Repetition rate	1 pulse/20min
Neutral beam energy	20-60 keV
Injected power	7-9MW
Electron temperature	0.2-0.6keV
Cold ion temperature	0.2-0.6keV
Mirror-to-mirror	10m
Mirror ratio	8-20
Plasma radius	10cm
Max. energetic ion density	$0.8-1.1\times10^{14}\mathrm{cm}^{-3}$
Electron density at midplane	$0.4-0.6\times10^{14}\mathrm{cm}^{-3}$
Injection angle	40^0

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