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Gas Dynamic Trap as a High Power Neutron Source for Accelerated Tests of Materials.

A.A.Ivanov, E.P.Kruglyakov, Yu.A.Tsidulko

Budker Institute of Nuclear Physics, Novosibirsk, Russia

At present, the development of the world fusion reactor program is concentrated on the ITER project. However, even in the case of successful execution of this project it cannot fulfill the required function of high power neutron source for candidate materials testing of future fusion power plant. The fusion reactor cannot be built without performing extensive program dedicated to qualify the materials to be used in the reactor core under high power irradiation by $14\,MeV$ and secondary neutrons. Among the problems to be solved can be mentioned the following ones: H, He, *dpa* production rates, neutron activation of materials, degradation of conductivity of metals, etc. These materials either existing or to be created, should be of high mechanical endurance and should retain adequate electrical properties before the reactor shutdown. Besides, it is desirable to use low activated materials with mentioned above properties. Among the main currently available materials for the first wall there are ferritic-martensitic steels and vanadium alloys which have sufficiently long operating time. But even in this case one should replace the first wall segments after a few years. If such segments will be irradiated within 10 years with a neutron wall load of $2\,MW/m^2$ the level of radiation damages will achieve $200\,dpa$. The ITER will provide only about $2\,dpa$ per year. Therefore it becomes clear that the requirement of material scientists to have separate high power dedicated neutron source with a flux density even more than $2\,MW/m^2$ is absolutely necessary. The program of materials testing cannot be fulfilled without such a source. Compared to other proposed schemes plasma based neutron source which produces nearly monochromatic $14\,MeV$ neutrons look the most attractive. One should pay attention that in sprite of the fact of appearance of large number of secondary neutrons produced in matter surrounding the plasma of fusion reactor, the most substantial effects in a radiation modification of materials are caused by the neutrons of high energy. Besides, one can add, that calculated neutron spectra of ITER and plasma based neutron source are similar to each other. From the other side, D-T reactions don't produce neutrons with energies more than $14\,MeV$. Accelerator based neutron sources have such neutrons. As a result undesirable effects can be obtained in the irradiation process. Besides, the testing zone area is too small and cannot solve many problems of materials testing. Thus, one can conclude, that the program of material testing cannot be fulfilled without plasma based dedicated neutron source. At present, such a source can be built on the basis of mirror machines or compact tokamaks with low aspect ratio (like START). Taking into account that minimum area of irradiated wall of a tokamak can not be done $20 \div 27\,kg$ of tritium. If one tries to increase the neutron flux density, say, two times, this will be absolutely unreal because of the fact that commercially available amount of tritium in the world is less than 5 kg/yr. In the case of mirror based neutron source the area of the zone with intensive neutron flux can be done of the order of $1\,m^2$. At the moment the most well studied project of the mirror-based neutron source exists in the Budker Institute of Nuclear Physics (Novosibirsk, Russia) [1, 2]. This project uses the idea of oblique injection of fast atoms into a warm plasma confined in so called Gas Dynamic Trap (GDT), — a mirror machine with a high ($R > 10$) mirror ratio. Fast atoms passing through the plasma will convert into fast ions. The population of the energetic ions appears in the trap. In the vicinities of the turning points the longitudinal velocity of energetic ions is close to zero. At the same time the transversal velocity will achieve its maximum. If one injects fast atoms of tritium into deuterium plasma or deuterium and tritium atoms even into hydrogen plasma, $14\,MeV$ neutron flux will be created mostly in the ranges of turning points. This concept has been already presented earlier [1, 2]. The accumulation of sloshing ions was demonstrated experimentally [3]. Estimations showed that GDT based neutron source can produce uncollided neutron source with flux density of the order of $2\,MW/m^2$. Taking into account recent progress in production of strong (up to $20\,T$) magnetic field with the aid of usual superconductors [4], so as in the technique of neutral beam injectors we revised the results of our calculations. One of the aim of the revision was to study the conditions where the GDT based neutron source is capable to generate power flux density of the order of $3 \div 4\,MW/m^2$. In Fig.1 a dependence of $14\,MeV$ neutron flux on the injection energy of D-T mixture is presented ($n_t/n_d = 1.28$). The electron temperature of the order of $10^{-2}E_{inj}$ is assumed (it is rather well established that under this condition microturbulence does not excite in a plasma). Maximal flux density can be achieved in this case for the injection energies (shown in Fig.2) of the order of $250\,keV$. As it is seen in Fig.2 even more than $4\,MW/m^2$ can be achieved with smaller injection energy of D-T mixture if the electron temperature will be a little more than $10^{-2}E_{inj}$. It is significant to note that the tritium consumption does not exceed several hundred grams even for $4\,MW/m^2$ in the case of the discussed scheme.

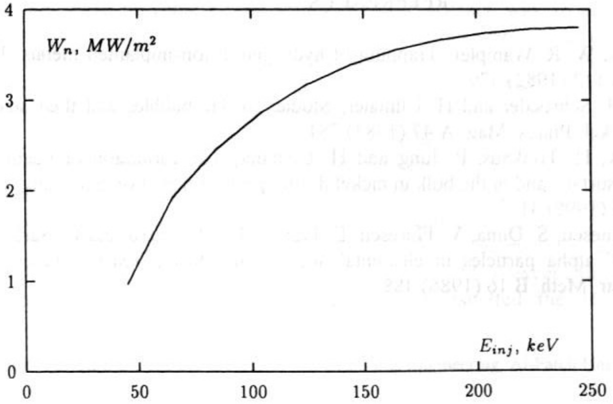

Figure 1:

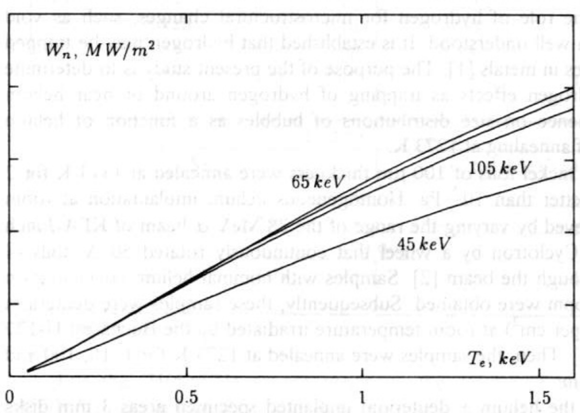

Figure 2:

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Fast Heating of a Dense Plasma by High-Power Electron Beam at the GOL-3-II Facility

A.V. Arzhannikov, V.T. Astrelin, A.V. Burdakov, V.S. Koidan,
K.I. Mekler, P.I. Melnikov, S.V. Polosatkin,
V.V. Postupaev, A.F. Rovenskikh, S.L. Sinitsky

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia.

One of possible approaches to a fusion energy problem is a concept of a pulsed multi-mirror fusion reactor [1]. The proposed pulsed fusion reactor with dense (n ~ 10^{17} cm^{-3}) high-β-plasma is based on a long (L ~ 200 m) solenoid with strong (B ~ 15 T) magnetic field. Plasma confinement along the magnetic field is provided by a large number of magnetic mirrors (multi-mirror trap). The radial equilibrium is maintained by the chamber walls (non-magnetic confinement), while the only role of the magnetic field is to suppress the plasma heat conductivity.

The crucial problem for the development of the pulsed multimirror fusion reactor concept is producing of hot dense (~ 10^{17} cm^{-3}) plasma.

The fast heating of the plasma with $10^{15} \div 10^{17}$ cm-3 density during the injection of a microsecond electron beam with an energy content over 100 kJ is being investigated at the GOL-3-II facility [2]. In this facility the plasma column has a diameter 6 cm and 12-m length, longitudinal magnetic field is up to 5T in the homogeneous part of the solenoid and up to 10T in its end mirrors. There is a possibility to change the magnetic field configuration from uniform to multimirror one. The plasma density can be varied in $10^{14} \div 10^{17}$ cm^{-3} range. For the beam-plasma heating experiments the high-power electron beam generator U-2 is used with possible beam energy content up to 0.3 MJ.

The main goal of the experiments on the GOL-3-II facility is obtaining the dense ($10^{16} \div 10^{17}$ cm^{-3}) and hot (~ 1 keV) plasma and achieving $\beta \geq 1$. Under these conditions, the experiments on the "wall" and multimirror confinement of a plasma become feasible.

In the paper recent results achieved at this facility are presented.

It is experimentally shown that macroscopically stable transportation of the 200 kJ-electron beam (1 MeV, 30 kA, 8μs) through the 12m-plasma column is possible under conditions close to total current neutralization. At injection of such beam into plasma with density $(1 \div 2) \cdot 10^{15}$ cm^{-3} the very strong collisionless beam relaxation is observed due to development of the two-stream instability. The efficiency of deceleration of the beam electrons is 30÷40% according to measurements of their energy spectrum. Energy content of the plasma and its electron temperature increases with growth of the beam energy content. The measurement of distribution function of plasma electrons by Thomson scattering has shown that characteristic temperature of the electrons is ~ 2 keV at density $(1 \div 2) \cdot 10^{15}$ cm^{-3}. Note, that such an electron temperature was reached in open traps for the first time. An anisotropy of the distribution function of hot plasma electrons is observed. The average energy of particle movement along the beam direction is few times higher then transverse one. The electron distribution function during heating is formed due to turbulent fields excited in a plasma by the beam. Abnormally high (compared to the classical) electron collision frequency caused by the same fields leads to decrease in the plasma longitudinal thermal conductivity, and hence increases the temperature and lifetime of electrons [3]. Under these experimental conditions, the ion temperature is 20÷30 eV.

For substantial increasing the ion temperature and obtaining plasma with $\beta \geq 1$ the method of a two-stage heating of a dense plasma is developed [4]. New experiments in this direction are also performed at the GOL-3-II facility. To do so, in the beginning of the 12-m device the deuterium cloud with a density of up 10^{17} cm^{-3} of a few meters length is formed. On the rest of the device the density of the plasma is ~ 10^{15} cm^{-3}. The hot electrons of this "rare" plasma transfer their energy to electrons and ions of the dense cloud by binary collisions. In this case, the plasma with a ~10^{16} cm^{-3} density has the electron temperature of 0,3÷0,5 keV, and the ion temperature increases up to 0,1÷0,2 keV.

In order to improve parameters of a dense plasma it is planned not only to optimize the conditions of its heating but also to improve the dense plasma confinement. For this, the dense plasma bunch is placed in a short (~1m) region with lower magnetic field ("magnetic pit") where the dense plasma should be confined as in "gasdynamic" trap. Such experiments are started. As the calculations show under the conditions of the GOL-3-II facility it is possible to obtain the dense ($10^{16} \div 10^{17}$ cm^{-3}) and hot (~ 1 keV) plasma with $\beta \geq 1$. This will enable to start the experiments on the "wall" and multimirror plasma confinement. Feasibility of such experiments at the GOL-3-II facility are discussed.

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