A Fusion Neutron Source for the Incineration of Radioactive Waste Based on the Gas Dynamic Trap

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Abstract. The paper presents a 3D numerical model of the neutron source for the transmutation of long-lived radioactive waste in spent nuclear fuel. The projected plasma type neutron source is based on the Gas Dynamic Trap (GDT) which is a special magnetic mirror system for the plasma confinement. A new improved version of the GDT type fusion neutron source is numerically simulated by use different numerical methods. New physical phenomena such as a vortex confinement, improved axial confinement, low radial transport, high β etc. were included in these simulations. The experimental and theoretical foundations of these phenomena were obtained in the GDT-U experimental facility in the Budker Institute. In result the proposed neutron source has two n-zones of 2 m length with a neutron power of 1.6 MW/m and a neutron production rate up to $1.5x10^{18}$ n/s each. This source can be used for application to a fusion driven system for the burning of MA in spent nuclear fuel. One plasma-fusion GDT driver can operate for two sub-critical burners placed around the neutron emission zones.

1. Introduction

To become a long-term sustainable option for the world energy supply fission reactor technology has to solve the high-level waste repository problem. For this purpose, great R&D effort is made worldwide to develop new closed fuel cycle options and their technical solutions for minimizing the high-level waste that finally must be disposed [1]. Long-lived fission products and, in particular, minor actinides (MA) are the components of the spent nuclear fuel which cause the most concern. Regarding the incineration of minor actinides, nuclear devices producing high-energetic (fast) neutrons by nuclear fissions and confining them without substantial energy moderation have the highest efficiency. Such devices can be built as fast reactors and as sub-critical nuclear fuel systems, the so-called driven systems, which are fed with neutrons from an external neutron source. As it is follow from the physical and technological solutions for the safe and effective sub-critical MA burner, the external driver should produce ~ 10^{18} neutron/sec in steady state operation. And electricity consumption of such system must be indemnified by nuclear power production with relevant energy multiplication factor $Q > 1$ [2]. Currently the accelerator driven spallation neutron source (ADS) [2,3] is favored for this purpose because of the high neutron emission intensity achievable.

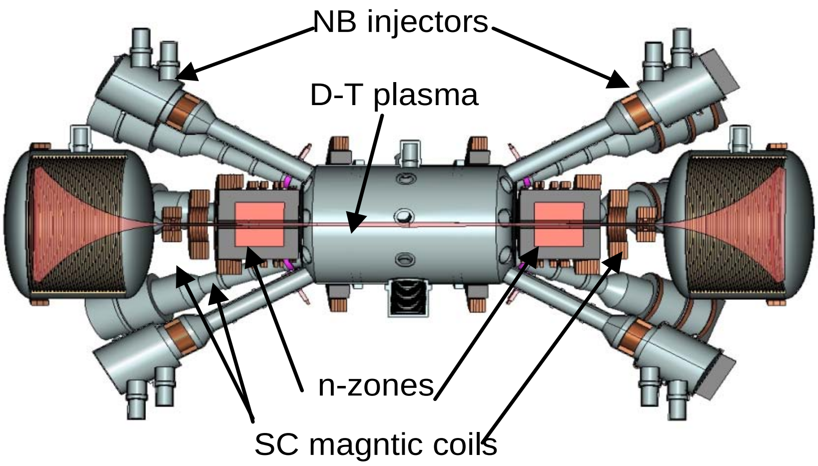
Recently, the idea of coupling a sub-critical fission reactor and a DT-plasma device generating 14 MeV neutrons for the incineration and transmutation of long-lived isotopes has attracted increasing interest. Such DT-plasma surrounded by fission blanket provides some advantages as compared to ADS. Firstly, one has to notice, that from a physics point of view, presence of 14 MeV neutrons in the generated spectrum provides additional flexibility with regard to the generation of additional neutrons via (n,2n), and (n,3n) reactions, as well as from ^{238}U fission, which is a threshold reaction. Moreover, the 14 MeV neutrons provide also greater incineration/transmutation capabilities of the system, since this permits even lower k_{eff}-regimes. Finally, the variable dimension of the neutron source (i.e., of the plasma) in a fusion-fission system opens new design possibilities for the sub-critical fission blanket, ultimately leading to more efficient incineration/transmutation machines. It is assumed that such a device could be more cost efficient due to its compactness, simplified maintenance, reduced operating costs, etc.

For a number of years the Budker Institute of Nuclear Physics (Russia) in collaboration with the Russian and European organizations developed the project of a 14 MeV neutron source for fusion material irradiation and other applications [4,5]. The projected plasma type neutron source is based on the Gas Dynamic Trap (GDT) which is a special magnetic mirror system for the plasma confinement [6]. The main concept and conclusions about the potential of the GDT-based neutron source as driver of a sub-critical device dedicated to the transmutation of spent nuclear fuel from nuclear reactors were presented in [7]. The current work builds on those results and further elaborates the concept of a GDT-based neutron source for nuclear applications.

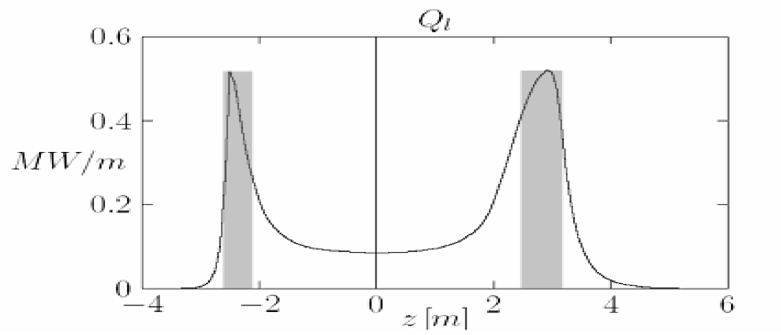
2. The GDT-based Neutron Source

The powerful 14 MeV neutron source on the base of the gas dynamic trap plasma device that confines deuterium-tritium plasma has been primarily developed as irradiation test facility for fusion material studies and for other application [4,5]. A research project of the Budker Institute aims at completing the database of the GDT in the high plasma parameter range, which is essential for the neutron source project. Figure 1 shows a schematic 3D representation of the GDT-based neutron source.

The version of the source dedicated for fusion material studies is an axially symmetric mirror



a)



b)

FIG. 1. (a) Schematic representation of the GDT-based neutron source and (b) example of neutron power production per length for "basic version".

machine of the GDT type, 10 m long and with a mirror ratio of 15. The plasma confined in the GDT includes two ion components with very different energies. One of the components is the collisional target plasma with an isotropic Maxwellian distribution function. The temperatures of its electrons and ions are in the range of 0.2-1 keV and their densities about $2–5 \times 10^{20}$ m $^{-3}$. This component is characterized by a gas-dynamic regime of confinement because the mean free path of the ion scattering into the loss-cone is smaller than the mirror-to-mirror distance. So-called “fast” ions with energies within the thermo-nuclear range represent the second plasma component. It is built up by a powerful neutral beam injection into target plasma. This component is collisionless, and it is confined due to conservation of magnetic moment and energy of the ions. The fast ions are deuterons and tritons, which generate neutrons via the fusion nuclear reaction. The energy of the injected particles is supposed to be 65 – 75 keV and the electrical power for the neutral beam injection is 60 MW in the basic variant of the neutron source.

Density and temperature of the warm plasma as well as the energy of injected atoms are in such relation, that the characteristic slowing down time of the fast ions appears to be much smaller than their characteristic time of scattering. The neutral beams are injected under an angle of 30^{o} to the axis of the device. Therefore, the fast ions retain a small angular spread close to that of the injected neutral beams when oscillating between the turning points near the end magnetic mirrors. Under these conditions the longitudinal profile of the fast ion density and, consequently, also the profile of fusion neutron flux in case of a D-T mixture of fast ions are strongly peaked in the regions of particle reflection near to the magnetic mirrors. Because of that the absolute values of fast ion density and neutron flux in these regions are also much greater than in the rest of the device. So, the oblique injection of neutral beams allows one to spatially separate the regions of beam trapping and neutron generation.

The technical idea would be to surround both neutron production zones (n-zones) of the GDT by a sub-critical system (see FIG.1). A first study of this question [7] has shown that the GDT neutron source as projected for fusion material research cannot compete with a spallation neutron source with respect to both to intensity and efficiency. However, it has some principal advantages, which could be used in a new GDT source project optimized as driver of a sub-critical system. One of them is the essentially harder neutron spectrum, which allows to increase the neutron intensity by (n,2n) reactions with nuclei of certain elements. Another is the prolongation of the rod-like neutron production volume, which offers the option to increase the total neutron emission without exceeding limitations of material parameters by high neutron and temperature loads.

By modifying the external magnetic field the ratio of the emission intensities of both neutron production volumes can be varied. Moreover, these zones can be longitudinally extended, and, even certain axial profiles of the neutron intensity could be adjusted. The calculations show that for the “basic version” neutron source the additional one meter of the “test zone” produces 0.5 MW neutron power and “costs” 16 MW of electric power supply. According to this estimation the “basic version” was newly optimized. A “new version” has two 2 m long n-zones on each side and under 100 MW of total electric power consumption.

The other opportunity is the increase of the electron temperature T_e of the GDT-plasma. This measure would reduce the energy loss rate of the high-energetic deuterons and tritons and, thereby, increase the fusion reaction rate considerably. For the “basic version” the electron temperature of the order of $10^{-2}E_{inj}$ is assumed (it is well established that under this condition the micro-turbulence is not excited in a mirror plasma). A gas cooling of the electrons down to T_e=0.75 keV has been introduced in the region of expander for increasing of MHD stability effect. In the new GDT-NS improved model we cancel the assumption $T_e \sim 10^{-2}E$inj and permit electron temperature in GDT to reach the self-consistent value. With the input parameters given at the beginning of this section the self-consistent mathematical model of the GDT device [8] yields the electron temperature up to 3 keV. This theoretical prediction is based on gas-dynamic collisionless model of the longitudinal plasma losses in GDT without electron heat conductivity and abnormal transverse losses. The last GDT experiment's results are in agreement with this model and confirm reality of our assumption [9].

Also we take into account improved radial confinement by vortex method [10], reduction of the electron head losses from GDT and maximal plasma $\beta = 0.6$ according to last experimental results at GDT [9]. The next section presents a 3D numerical model of the GDT based neutron source and results of numerical simulation.

3. Numerical Model of Neutron Source and Results of Simulations.

The plasma physics calculations of the neutron source's parameters have been performed by using the MCFIT code, which is a basic module of the Integrated Transport Code System (ITCS) [11]. ITCS was developed for GDT simulations and includes different modules for plasma, particles transport and neutron production modeling. MCFIT code simulates the transport of energetic ions in given magnetic field and target plasma. It uses the Monte Carlo method and has been developed under the requirements:

- to simulate the fast ion transport in the frame of the classical transport and to consider the three-dimensional space, energy and time dependencies of the relevant phenomena involved,
- to take into account a maximum of detailed information on the GDT system and
- to produce a maximum of results per run.

The general scheme of the code is of standard Monte Carlo type: statistically independent fast ion histories are generated in course of which the scoring of results is performed by summing up contributions to well-defined estimators for each quantity of interest. Having simulated N particle histories a final result for each quantity is computed as the average of the estimates scored by each of them and the statistical error of the result is calculated from the mean quadratic deviation of the individual estimates from their mean value. The main components of the code are:

- generation of neutral atoms on the emission surfaces of neutral beam injectors;
- ionisation of the NBI atoms by charge exchange, electron and ion impact;
- flight of ions in a given magnetic field;
- their interaction with the target plasma (energy loss and angular scattering);
- their interaction with the neutral gas;
- their interaction with the fast ions and generation of fusion products.

In addition to magnetic field, neutral gas and warm plasma the fusion component of FIT demands the input of the target fast ions (D and T) inside the volume of the fast ion transport. The space and energy distribution of the target fast ions during a shot were preliminary calculated by means of MCFIT.

MCFIT offers a great spectrum of physical quantities that may be calculated. The results represent the quantities of interest as discrete distributions over a user-defined phase space grid over a sequence of time intervals. The main of them are: the fast ion energy content, NB trapped power, charge-exchange loss power, electron drag power, distribution of the fusion neutron, neutron flux to given detectors, energy and pitch angle distribution functions of the fast ions in a magnetic flux tube defined by a radial interval at the GDT midplane. A detailed description of the MFIT code is given in [11].

MCFIT and ITCS was adopted for GDT neutron source condition. New physical phenomena such as a vortex confinement, improved axial confinement, ambipolar plugging, high β etc. were included in these simulations. The experimental and theoretical foundations of these phenomena were obtained in the GDT-U experimental facility in the Budker Institute. As a result, a new improved version of the fusion neutron source is proposed and numerically simulated. The main parameters of the neutron source are presented in Table I.

TABLE 1: MAIN PARAMETERS OF THE IMPROVED GDT BASED NEUTRON SOURCE (NUMERICAL RESULTS).

Parameter	**Value**
Mirror-to-mirror distance	16 m
Maximal magnetic field in mirror, $\boldsymbol{B}_m$	15 T
Mirror ratio, R	15
Estimated energy consumption P_{in}^{el}	≈ 100 MW
Neutral beam injection	D+T
Injection power, P_{inj}	75 MW
Beam energy, E_{inj}	65 keV
Trapped power, P_{tr}	52 MW
...Heating (electon drag) power, P_h	47 MW
Plasma density, n_e	$5x10^{20}$ m^{-3}
Plasma radius, a	10 cm
Electron temperature, T_e	3 keV
Total fusion power, P_{fus}	15 MW

The proposed source is an axially symmetric mirror machine of the GDT type, 16 m long, and having a mirror ratio of 15. The on axis magnetic field profile is sown on FIG.2a. The neutral beams are injected under an angle of 30^o to the axis of the device. The oblique injection of neutral beams thus enables to spatially separate the regions of the beam trapping and the neutron generation. The energy of the injected particles is supposed to be 65 keV and the assumed total injection power is 75 MW. The heating power $P_h = 47$ MW, so the self-consistent electron and ion temperatures of target plasma extend up to 3 keV. Fast ions (D^+ and T^+) with energies of several tens of keV generate neutrons via the (d,t) fusion reaction. The resulting fusion neutron flux is presented on Fig. 2b. It is strongly peaked in the regions of the particle's reflection near the magnetic mirrors (n-zones). The proposed neutron source has two extended (by profiled magnetic field, see Fig. 2a) n-zones of 2 m length with a neutron power of 1.6 MW/m and a integrated neutron production rate up to $1.5x10^{18}$ n/s each.

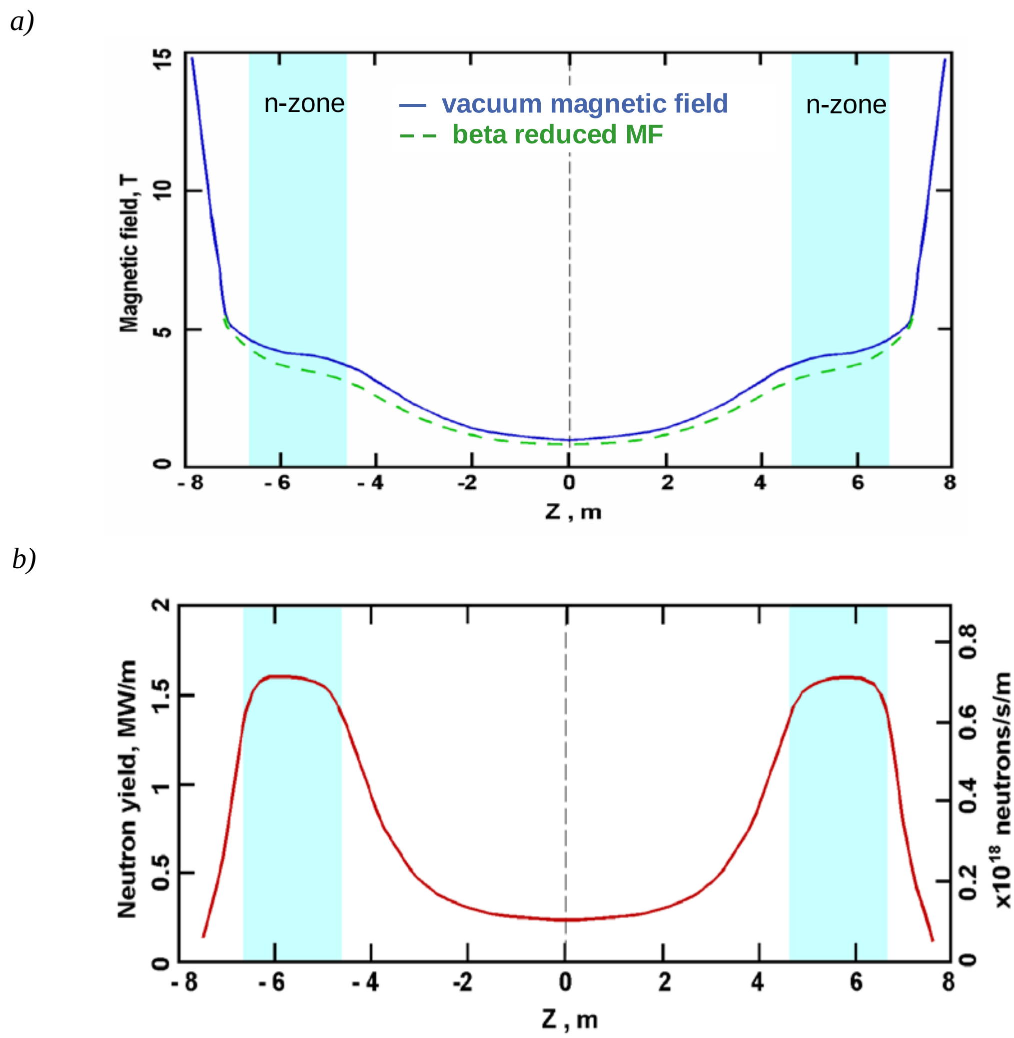


FIG. 2. (a) On axis magnetic field, dash line – beta reduced value. (b) Axial profile of neutron yield.

4. MA-Burner Calculation Model

This GDT neutron source can be used for application to a fusion driven system for the burning of MA in spent nuclear fuel. We use one plasma-fusion GDT driver for two sub-critical burners placed around the neutron emission zones. The considered sub-critical burner configuration is based on the reactor design of the European Facility for Industrial Transmutation (EFIT) [12]. The EFIT reactor was designed for the demonstration of the transmutation of minor actinides in an ADS facility on the industrial scale EFIT has a thermal nuclear power of about 400 MW and is cooled by liquid lead. Its fuel is uranium free CERCER fuel 50% MgO +50% (Pu,MAO_2) in volume, containing a large quantity of americium. The plutonium content is ~ 37% leading to k_{eff} ~ 0.97.

In [13] several variations of EFIT design parameters were studied by using ENDF/B-6.5 based 69 group cross sections in the deterministic S_n code TWODANT. In this work the radial and axial dimensions of the EFIT core were varied to increase the H/D ratio from initial ~ 0.3 to ~ 1.1, keeping the active volume and the fuel composition constant, leading to k_{eff} values for source-off condition around 0.975 ± 0.05. The cylindrical system (one half) shown in FIG. 3 served as a basis for the calculation models, which were used for studying the neutron physical characteristics of spallation and fusion driven burners. We used the original flat "pancake" (A) and an extended version (G) of the EFIT reactor for application with the GDT neutron source instead of the ADS lead target. Results of the nuclear analyses based on neutron transport calculations are presented in Table II.

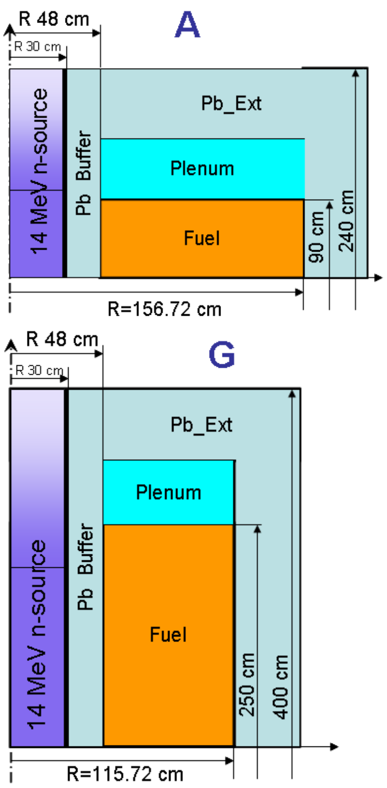


Fig.3 Applied EFIT-like cylindrical geometry with GDT neutron source.

TABLE II: EFFECTS OF DIFFERENT GEOMETRY MODELS AND DIFFERENT SOURCES ON MULTIPLICITY.

Source	ADS		GDT NS	
Geometry	A	G	A	G
Radius (cm)	156.72	115.72	156.72	115.72
Height (cm)	240	400	240	400
Fuel height (cm)	90	250	90	250
Multiplicity source-off, k_{eff}	0.9718	0.9724	0.9733	0.9741
Multiplicity source-on, k_s	0.9329	0.9573	0.9411	0.9577

The most promising variant of a GDT-driven MA burner uses the optimized version of the GDT neutron source with two neutron emission zones that have been elongated to 2 m each and surrounded by two extended subcritical reactors (geometry G). The neutron source requires a power input estimated as 120 MWel (NBI, magnetic system, etc). As a result, the hybrid system with the two MA burners driven by one GDT neutron source can produce more then 1 GW of fission power (~ 550 MWth at each side) with an energy multiplication factor Q^{el}~4. This system incinerates in 1 year about 150 kg MA that corresponds to waste production by 5 LWRs in 1 year.

5. Conclusions

A new improved numerical model of the GDT neutron source based on last experimental results with T_e ~ 3 keV and Q_{fus} ~ 0.3 was proposed and numerically simulated. The two 2 m long n-zones with 1.6 MW/m neutron yield can produce 1.5×10^{18} neutrons per second each. This source can be used for application to fusion driven system for the burning of MA.

The analysis of proposed GDT FDS burner of MA was made on the base of an EFIT reactor design. The elongated version of EFIT with the GDT-NS instead of a spallation target shows considerable promise for the future development of this model.

Acknowledgments

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