# Neutron Shielding of the GDT (Novosibirsk) Neutron Generator Project a Feasibility Study

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## ABSTRACT

The paper presents results of extensive neutronic studies of the neutron source test facility based on the Novosibirsk Gas Dynamic Trap (GDT). The facility is to provide $10^{18}$ DT-neutrons/s (over a continuous 10-year period) for material-test studies. The paper examines the protective-shield capacity to ensure survival of GDT vital parts and suggests design modifications when survival is in jeopardy. The numerical studies used the 3D-AMC-VINIA Monte Carlo code with a precise computer representation of the sensitive parts of the facility. Intensity maps were plotted for neutron fluences, displacements, heat deposition, etc. Shielding feasibility has been ascertained, and the lifetime of consumable components ensured beyond the recommended values. A modification is suggested to extend the irradiation space at HARD neutron energy spectra to increase the volume to 1 $m^3$ with damage gradients <5%/cm. The design achieves neutron fluences close to $10^{14}$ $n/cm^2s$ ($3.10^{22}$ $n/cm^2$ end-of-life) in a >100 $\ell$ test space.

## 1. INTRODUCTION

Fusion reactor planning implies an exhaustive safety testing program aimed at identifying reliable materials capable of safely surviving about three decades in the hostile intense 14.MeV neutron degrading environment. Such a campaign is essential for any DT-based fusion facility - be it magnetically or inertially confined. The ITER project and the future DEMO facilities will involve fluences of the order of 2-4 $MW/m^2y$ on the first wall. To obtain this greatly needed resistance-to-damage information, accelerated tests at 1-5 $MW/m^2y$ fluences, with duty cycles of not less than 50%, are required. It is with this aim that the Gas Dynamic Trap (GDT) Neutron Source (NS) has been proposed [1]. The GDT-NS (Figs.1) is a plasma mirror-machine (mirror ratio=26T/1.8T=14.4, 10 m inter mirror distance, 15 cm diameter cylindrical neutron emitting zone), dynamically stabilized by constant plasma outflow into a controlled cusp magnetic field of the expander chambers, experimentally demonstrated to be stable [2] against MHD and kinetic plasma instabilities, and with no sloshing ion instabilities.

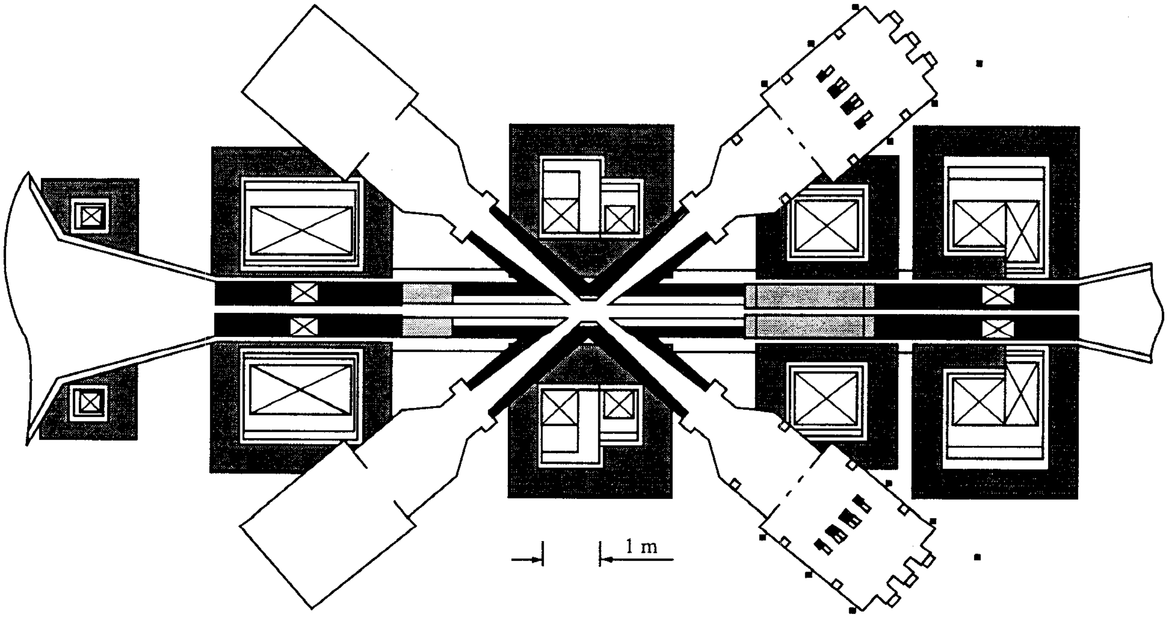

Fig.1a- GDT facility model as 'seen' by the computer: (slant cut through both the GDT and the injector-2 axes). Note the different shades of gray indicate: Dark=W shield, Medium= SS shield; Light= parts under investigation

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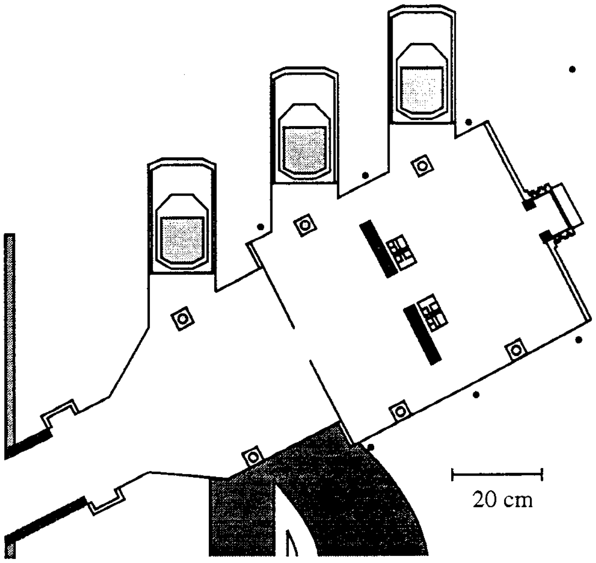


Fig. 1b - GDT head-2 He cryogenic system (as 'seen' by the computer): vertical cut through the axes of its three He containers: the three He toroidal pumps with their respective fins are also shown. The different shades of gray indicate: Dark=W shield, Medium= SS shield; Light= parts under investigation.

The reacting dense plasma ($2\times10^{14}$ $D^+/cm^3$, $T_e$=1.1 keV, $T_d$=0.3 keV) is sustained by neutral ion beams: the 94 keV $T^0$ (6.5 MW) beam produces the 14 MeV-neutron emission, while the 80 keV $D^0$ (8.5 MW) beam enhances the neutron production by reducing the electron drag, thus keeping the tritons within an energy range close to the peak cross section while they are circulating in the deuterium plasma. Damage to the super-conducting coil of the GDT-NS, simulated recently with a "brutal" shield, appear to be acceptable [3]. Results presented here are done with a model conforming to and compatible with the engineering-design.

In the course of the present studies neutron migration is followed to neutron energies down to 16 eV (in [1] the energy cut-off was 64 eV).

## 2. 3D-AMC-VINIA CODE - A BRIEF DESCRIPTION

All simulations use the 3D-AMC-VINIA subroutine complex, which is a 3-D analogical code that, like MCNP, MORSE, TRIPOLI, TARTRAN, etc, implements all the standard techniques, such as biasing, splitting, forced-collisions, flux-at-a-point, etc. It treats energy and space (position and direction) in a continuous representation. The code is flexible and easy for

(i) material and geometry structural design input or alterations,

(ii) extraction of required outputs both directly or for post-processing.

Nuclear cross section data are used in a pointwise form (resonances naturally included) "in extenso" with no truncations, approximations, or group-smearing. The ENDF/B6 nuclear data library is used for neutrons, and EPDL in ENDF/B format for gamma random walk. Data of nuclides not available in the ENDF/B6 library are taken from EFF-2 and JEF-2.2, all in ENDF/B-format.

The merit of 3D-AMC-VINIA in tasks like the present is that in contrast to the other above mentioned 3D-Monte Carlo codes, which probe space POINTwise, 3D-AMC-VINIA probes space LINE- or RAY- wise using the Drizzle & Shower splitting technique [4,5]. Indeed, the Drizzle-Shower technique, with its analogical smooth collection of estimator contributions, leads to a strong reduction of the variance, thereby fast convergence, and subsequent CPU-time economy estimated conservatively to be a factor of 20. The efficiency of the technique is amply demonstrated by the efficient simulation and interpretation of experimental measurements on ASDEX and TEXTOR tokamak neutronic diagnostics (sample activations, nuclear emulsion plates...) [6]. The technique allows a direct analogical in-depth access to heavily shielded regions in intense neutron and gamma environments, such as super-conducting coil shielding [3]. The present calculations have been done on IBM-3090/28T and Risk-6000 ENEA computers at Frascati.

## 3. GDT UPDATED MODEL

The initial round of simulations aimed at establishing whether the GDT could survive in the hostile radiative environment used a "brutal" shield and rough model. Now that the feasibility of the facility has been ascertained [3], a more refined model is used:

A. Neutron emission profile. Neutron-emission R,Z-profiles (Figs.2) consider a realistic space distribution of the

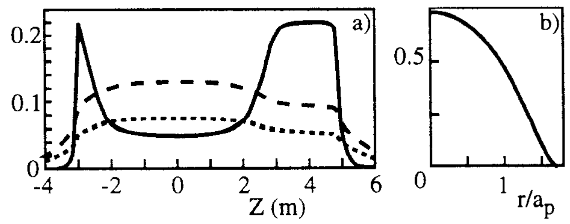


Fig.2- Characteristics of GDT neutron emission: a)- Axial (Abscissea Z in meters):intensity profile (full line), $a_p(Z)$=radial (m) extent of emission (dotted line), maximum radial (m) excursion of injected tritons (dashed line). b)- Radial neutron emission profile

magnetic field [7] that determines the T-D plasma shape and neutron energy distribution accounting for injection of hydrogen (94.keV-$T^0$ and 80.keV-$D^0$) into the background of the "cold" deuterium plasma confined in the magnetic trap. The neutron emission direction is isotropic, with a Gaussian energy spectrum ($E_0$=14.7 MeV, FWHH=1.2 MeV).

B. Plasma shape. From the shape of the neutron emission profile as defined above, the expected plasma boundary has been extended to allow space for the injected 94 keV-triton revolution in the axial magnetic field of the GDT.

C. Sample irradiation zones. Two hollow cylindrical spaces ($R_i$ = 0.125, $R_o$ = 0.5 m) are considered for sample irradiation [1] (Fig.1a). They are referred to as SIZ-S (small: h = 0.4m, Vol = 0.29 $m^3$) and SIZ-L (large: h = 1.9 m, Vol = 1.4 $m^3$). The space adjacent to the two SIZs is also being investigated: they have each been extended xially by 20 cm on both sides and then characterized as regards fluence intensity and spectral hardness for two representative materials, to check whether the extra volumes are also suitable for use as SIZs.

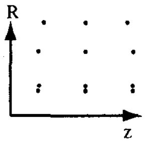
D. Ion-source head, sweep magnet, and injector duct are modeled as for the engineering design (Fig.1b).

## 4. RESULTS OF SIMULATIONS

Fluences and spectra have been calculated at several monitoring positions for each zone/wing, selected at four radial positions (Table 1 and Fig.3).

TABLE 1
Large SIZ neutron fluence variation across the LARGE SIZ.
Z refers to in ZONE points, 1 & 2 (left & right) are WING points.

| | Position(cm) | | Fluence(n/cm$^2$s) | |
|---|---|---|---|---|
| | | | Sample Material | |
| | R | Z | Structural: 90%SS+10%$H_2O$ | Ceramic: 100%-$Al_2O_3$ |
| | Back | | | |
| $1_b$ | 49.50 | 300.0 | $.13\times10^{10}$ ± 56% | $.28\times10^{11}$ ±28% |
| $Z_b$ | | 395.0 | $.81\times10^{10}$ ±33% | $1.5\times10^{11}$ ±42% |
| $2_b$ | | 490.0 | $.60\times10^{10}$ ±48% | $.31\times10^{11}$±44% |
| | Center | | | |
| $1_c$ | 33.75 | 290.0 | $.13\times10^{13}$ ± 30% | $.25\times10^{13}$ ±21% |
| $Z_c$ | | 395.0 | $.34\times10^{12}$ ±31% | $.27\times10^{13}$ ±35% |
| $2_c$ | | 500.0 | $1.1\times10^{13}$ ±36% | $.04\times10^{13}$ ±62% |
| | Front cm depth | | | |
| $1_a$ | 13.50 | 291.0 | $.56\times10^{14}$ ±18% | $.43\times10^{14}$ ±20% |
| $Z_a$ | | 395.0 | $.58\times10^{14}$ ±22% | $.38\times10^{14}$ ±9% |
| $2_a$ | | 500.0 | $.13\times10^{14}$ ±15% | $.20\times10^{14}$±27% |
| | Front | | | |
| $1_f$ | 12.50 | 290.0 | $.38\times1014$ ±17% | $.59\times10^{14}$ ±42% |
| $Z_f$ | | 395.0 | $1.1\times1014$ ±34% | $.78\times10^{14}$ ±31% |
| $2_f$ | | 500.0 | $.19\times1014$ ±44% | $.14\times10^{14}$ ±29% |



Point scheme

(fluences followed by the corresponding 1-sigma %-distribution bars)

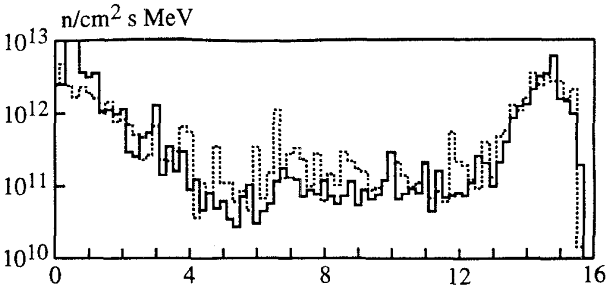


Fig.3- Comparison of the hardness of neutron energy spectra in sample irradiation zone SIZ-L for a structural material (90%-SS+10%$H_2O$) at the first wall (full line) and 1 cm within it (dotted line). Histogram statistical precision at the level of 40%.

### *4.1. SIZ characteristics and capacities - fluences, spectra, volumes*

The two SIZs are characterized successively for:

a) structural material - stainless steel (with 10% by volume of cooling water),

b) ceramic material - $Al_2O_3$ insulator.

The neutronic characteristics at the selected points are shown in Fig.3, Table.1.

### *4.2. Damage to injector insulators: Ion sources and sweep magnets*

In a first version of the model calculations regarding sweep-magnets and ion sources, insulators are unscreened (as given in the design). The extreme irradiation dose of 1.7±0.6 Grad/d at the sweep magnet epoxy insulator was beyond tolerances as it implied a <4-8>days life, close to, yet short of the prescribed <10-100>days. Hence, the necessity for some extra shielding of the direct flux. The second model, restricting to a minimum neutron access to the injector tube by a shield (leaving free just the space for the three injected neutral-ion beams (Fig.1b)) reduced the dose to 0.67±0.1 Grad/d on the sweep magnet (<12.6-17>day life), and 0.33±0.15 Grad/d to the ion-source alumina insulator (<17-43>day life), both conforming to the specifications. As insulator damage is a LOCAL deterioration, the direct flux has to be attenuated. A third simulation, with the insertion of LOCAL shields (Fig.1b), led to extreme dose to the ion-source alumina of 2.7±0.5 Grad/y (a life >300 days); the dose to the sweep magnet will be higher as its shield shades the ion source, while the inverse is not true. Now that tolerances are widely respected and the cure is defined, one can at leisure optimize.

## 5. CONCLUSIONS

Although the results presented and discussed here all derive from the unoptimized shield, the simulations already show that the GDT operation at the level of the present concept of design and shielding is viable. The simulations suggest some modifications to improve the GDT properties and some have been quantified. The following conclusions can be drawn at this stage:

1. Feasibility is demonstrated for the critical central SC coil situated at the crossing of the injection ducts. The situation will improve with the in-injector-tube W shield.
2. Coil B1 in the vicinity of the Small-SIZ is adequately shielded in spite of the presence of the SIZ (even void) and the dump tube in its unshielded-tube version.
3. Fluences and spectra within the two pairs of wings of both zone-S and zone-L are similar and the volume of the SIZ-S allocated to irradiation can be increased. One should consider extending the SIZs axially as this enhances the irradiation volume with a near-to-zero damage gradient axially.
4. Injector insulator damage complies with the project imposed tolerances of substitution rates of <10-100>days. Indeed, in the unshielded version the sweep-magnet insulator received 1.7±0.6 Grad/d, i.e., a <4-7.8>day life short of the imposed tolerance. However, in the "restricted" injector version the dose had already fallen to 0.67±0.1 Grad/d, (<12.6-17>day life), while the ion-source alumina received 0.33±0.15 Grad/d (<17-43>day life), both observing the imposed restriction. The local shielding of the direct flux led to a strong reduction with a dose to the ion-source alumina of 2.7±0.5 Grad/y (a life >300 days). With such a margin, optimization is a must.
5. GDT delivers a fluence of up to $10^{14}$ n/cm.s, i.e., by end of life $3.10^{22}$ n/cm$^2$, onto a SS first-wall.
6. Within its first 1-cm inner shell (20 liter volume) the irradiation spectrum hardness is conserved (Fig.3), while the fluence remains sensibly constant, particularly axially, thus ensuring that the samples have an axial damage gradient << 10%/cm (ECC commission specifications for material test facilities).
7. Estimated damage to the B1 coil indicates that the fluence arriving at the coil through the "brutal" W shield is lower than the fluence that leaks through the injector, even with the corresponding SIZ-S void. Thus, the shielding should be relaxed by reducing its thickness from the INSIDE, in contrast with shield economy, to allow more irradiation space at about 1%/cm damage gradients.

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