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Health Physics Aspects of Nuclear Radiations from Deuterium Beam Injectors

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DEUTERIUM BEAM INJECTORS

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ABSTRACT

Estimations are made for X-ray generation from the accelerator column of various neutral beam injectors. For the case of deuterium beam operation where 2.5-MeV D-D neutrons pose a serious health physics concern, neutron and tritium production rates from beam targets are calculated for different beam energies. Biological doses from these radiations and shielding requirements are discussed.

1. INTRODUCTION

Neutral beam injection experiments with upcoming magnetic fusion devices require increasingly higher beam power and in some cases deuterium beams rather than hydrogen beams. As the required beam energy increases beyond 100 keV, X-ray generation from accelerator columns becomes a health physics concern even for the hydrogen beam injectors. With deuterium beams, however, there are additional health physics problems associated with 2.5-MeV D-D neutrons from $D(d, n)^3\text{He}$ and tritium generation via $D(d, p)\text{T}$ reactions. Even at low energies (say ~ 40 keV), the D-D neutron generation is appreciable enough to yield serious radiation doses around an unshielded test facility. The 14-MeV neutrons from D-T reactions will not be considered since the tritium concentration in the target due to D-D reactions is negligible compared to the deuterium concentration. High energy deuterium beam test facilities are naturally being built inside a shielded housing (e.g., LLL 200-keV Neutral Beam Test Facility)¹.

Not only for the future high energy injectors, but also for the current low energy (≤ 60 keV) injectors, an estimation of radiation intensities from the injector facilities as a function of injector power is very much needed. A typical neutral beam injector structure is illustrated by the Princeton Large Tokamak (PLT) neutral beam injector design in Fig. 1. The ion source with an acceleration column is the source of X-radiation due to inevitable backstreaming electrons hitting metal surfaces. The gas cell, the neutral beam target, and the ion beam dump are the sources of D-D neutrons and tritons. The line density of deuterium molecules in the gas cell is maintained high for neutralization and thus acts as a thin gas target for incoming deuterium particles. Energetic deuterium particles, on the other hand, are implanted into the solid targets when they are stopped, and the deuterium particle concentration builds up and so does the neutron yield.

In this report, we will estimate neutron (and triton) production rates from various parts in a beam line mentioned above and the X-ray generation rate from an accelerator column. These calculations cover a wide energy range of significance to neutral beam injectors.

ORNL/PLT BEAMLINE AND ORNL TEST FACILITY TARGET BOX.

Fig. 1. A schematic of the ORNL/PLT Neutral Beam Injection System.

2. YIELD CALCULATION OF NEUTRONS AND TRITONS

Three places can be identified from Fig. 1 as the source of D-D reactions, i.e., $D(d, n)^3\text{He}$ for the neutron generation and $D(d, p)\text{T}$ for the triton generation. These are the gas cell, the ion beam dump, and the beam target. Since the two branch reactions have about equal reaction cross sections, the triton yield will be approximately equal to the neutron yield.

The total number of neutrons per second (Y) can be calculated by the following expression for a drive-in target:

$$Y = \frac{I_b C_D}{e} W_{DD} ,$$

$$W_{DD} = \sum_{k=1}^3 k f_k V_D(E_b/k) , \text{ and} \quad (1)$$

$$V_D = \int_0^R \sigma[E(x)] dx ,$$

where V_D is the integrated total reaction cross section up to the stopping range (R) in the unit of cm^3 , W_{DD} is the sum of the contribution of each deuterium ion species (D_1^+ , D_2^+ , and D_3^+) weighted by its fraction (f_k) and the number of nuclei per ion (k), I_b is the total beam current (ampere), C_D is the equilibrium deuteron concentration in a target (cm^{-3}), and e is the electronic charge.

V_D is calculated by using the stopping power of a metal, dE/dx , to determine $E(x)$, and by obtaining the value of the reaction cross section (σ) at $E(x)$ at depth x . V_D is thus a function of only target material and the energy per nucleon, E_b/k . In deriving Eq. (1), we have assumed: (1) C_D is independent of depth and beam energy, and (2) the incoming particle flux is constant with respect to penetration depth into a target. W_{DD} has been calculated for several target materials for varied beam composition and energy.² The deuteron concentration in a target is a property of target material, and in general it decreases as the target temperature increases.³

For the neutralizer gas cell region, the line density is not high enough to degrade the energy of incoming ions. Therefore, $E(x) = E_b$ and R is simply the gas cell length (L), and thus Eq. (1) becomes

$$\gamma = \frac{2 n_0 L I_b}{e} \sum_{k=1}^3 k f_k \sigma(E_b/k), \quad (2)$$

where n_0 is the average molecular deuterium gas (D_2) density in the gas cell.

In Fig. 2, the total number of neutrons per ampere of beam from a copper target is plotted as a function of beam energy and beam composition. The value of C_D used in the calculation is $\approx 1.7 \times 10^{22} \text{ cm}^{-3}$, which was obtained experimentally for a dc beam by Hilton et al. for the target temperature below $\approx 200^\circ\text{C}$.³ In the case of pulsed operation as in the neutral beam injectors, C_D depends on the beam flux density and the duty cycle. It takes only a few seconds to fill a fresh target to a concentration of 10^{22} cm^{-3} with a beam whose current density is a quarter ampere per cm^2 . In general, the loss rate due to diffusion out of the target surface is rather slow. If the duty factor is relatively higher ($\gtrsim 10\%$), the target concentration may well be maintained close to the dc value. Calculations given in Fig. 2 can be viewed as the upper limit for pulsed beams. Figure 3 shows the total neutron yield from a gas cell normalized to a line density of 10^{16} cm^{-2} and to 1 A of beam current.

Neutron yields and tritium activities are calculated in Table 1 for four injector systems including those of PLT, PDX, ISX-B, Doublet-III, and TFTR. Copper targets are assumed for both the neutral beam calorimeter and the ion beam dump. Neutron yields from other target materials will not deviate too much from the one for copper. Values of the gas cell line density are assigned for each deuterium beam energy such that the cell thickness is 90% of the equilibrium cell for D_1^+ . The instantaneous neutron flux is estimated in the absence of shielding at a location of 100 cm from a virtual point source whose intensity is the sum of all three sources. The actual time-averaged fast neutron flux is then obtained by multiplying the instantaneous flux by the duty factor. The total tritium activity produced in the system is the product of the production rate shown in the table,

Fig. 2. D-D neutron yield per ampere of deuterium beam from copper target as a function of beam energy ($C_D = 1.7 \times 10^{22} \text{ cm}^{-3}$ assumed).

ORNL/DWG/FED-771001

Fig. 3. Neutron yield from gas cell per ampere of beam current per thickness of 10^{16} molecules/cm² as a function of beam energy.

Table 1. Neutron yields and dose rates for various neutral beam injector systems

	PLT (40 kV/60 A)	ISX-B (40 kV/100 A)	PDX/D-III ^d (60 kV/100 A)	TFTR ^e (3/120 kV/60 A)
Gas cell ^a line density (D ₂ /cm ²)	3×10^{15}	3×10^{15}	4×10^{15}	8×10^{15}
Neutralization efficiency	72%	72%	65%	38%
Neutron yields (number/sec)				
N.B. target	1.1×10^{11}	1.9×10^{11}	5.7×10^{11}	4.0×10^{12}
Ion dump	4.5×10^{10}	7.4×10^{10}	3.0×10^{11}	6.6×10^{12}
Gas cell	4.7×10^9	9.4×10^9	3.5×10^{10}	3.6×10^{11}
Tritium yield (μ Ci/sec)	7.6×10^{-3}	1.3×10^{-2}	4.4×10^{-2}	0.53
Neutron flux ^b at 1 m (number/cm ² sec)	1×10^6	1.7×10^6	5.8×10^6	7×10^7
Biological dose ^c (mrem/sec)	40	68	230	2.7×10^3
1% duty cycle (mrem/hr)	1.4×10^3	2.5×10^3	8.3×10^3	9.7×10^4

^aLine densities giving 90% of the equilibrium fraction for a D⁺ particle are used.

^bAn isotropically emitting point source is assumed, whose strength is the sum of all three sources and a 20% removal of fast neutrons through ~1.5-cm-thick iron vacuum wall.

^cFlux-to-dose conversion factor of 4×10^{-5} mrem per neutron/cm² is used.⁴ Instantaneous gamma contribution is neglected.

^dThe beam energy is tentative.

^eThree sources per beam line.

the total operation time, and the duty factor. It should be noted again that the values are very likely upper limits and the health physics considerations based on these calculations will be conservative ones.

The equilibrium concentration of deuterons in a target generally decreases with target temperature. Therefore, it is expected that if a thermal inertia target ($\sim 1000^\circ\text{C}$) is employed, the neutron yield could be reduced substantially. As mentioned already we used a semi-empirically determined saturation concentration in a copper target, where the target temperature was maintained approximately below 200°C .

3. X-RAYS FROM ACCELERATOR COLUMN

In an accelerator column, electrons are produced primarily through two mechanisms: (1) ionization of background gas by the primary ions passing through and (2) secondary emission from electrode surface either by stray ion particles or by field emission. While process (1) depends on the background pressure, process (2) depends on the optical and voltage-holding properties of the accelerator column. These electrons are accelerated backwards and stopped by electrodes or ion source walls, where X rays are generated in a way similar to an X-ray tube. The ion beam is also stopped by metal targets, but the efficiency of X-ray production is negligible compared to that for electrons in the energy range of interest to neutral beam injectors.

Figuring out the backstreaming electron current is extremely difficult in practice. One could estimate the electron production rate through process (1) in a column, but process (2) depends on the operating condition. In fact, the amount of X-radiation via process (2) can be used as a diagnostic tool to indicate the degree of tuning of an ion source, the minimum X-ray generation being the best beam optics condition.⁵ Here we will make an *ad hoc* estimation based on the power loading data on the first electrode defining the discharge plasma and the ion beam (or plasma electrode). The power loading to this electrode (minus the contribution from the discharge plasma) is attributed to the backstreaming electrons. Not accounted for here is the portion of electrons passing through extraction apertures and hitting the ion source walls. We will approximate this

fraction of electron current to be roughly equal to the one hitting the plasma electrode, simply based on a 50% geometrical transparency of a typical neutral beam injector design. We also assume that all the electrons get accelerated to the full potential, although this is not true for those electrons born by ionization collisions (process 1). Then the total backstream electron current is $I_e \approx 2\epsilon_1 I_b$, where ϵ_1 is the fraction of total accelerator power that appears on the first (plasma) electrode. From test stand experiences, ϵ_1 is, typically, ~ 0.03 .

There are two types of X-ray generation by electron excitation: the continuous spectrum of radiation (or bremsstrahlung) and the characteristic X rays. Although dose rate calculation is an extremely complicated problem with the complex geometry and the wide X-ray spectrum, we will attempt to obtain rough estimations using the simplest model as follows. Let $F(E)$ be the energy spectrum of X-ray photons from a point source in terms of keV per electron per one-keV energy interval. Assume an isotropic emission of photons and a shield of spherical shell with thickness x . Then the dose rate at a distance r from the source can be written approximately as

$$D = \frac{10^8 I_e}{4\pi r^2} \int_0^{E_0} F(E) \exp[-\mu(E)x] \frac{\mu_k(E)}{\rho} dE, \quad (3)$$

where the dose rate (D) is in unit of rad/sec, I_e is the backstreaming electron current in ampere with an energy E_0 (keV), $\mu(E)$ is the linear attenuation coefficient, and $\mu_k(E)/\rho$ is the mass energy transfer coefficient of human body in terms of cm^2/g .

The attenuation coefficient and the energy transfer coefficient are well documented for a number of materials.⁶ The attenuation coefficients of metals are in general a sharply decreasing function of energy up to a few hundred keV, above which they decrease more slowly. For example, attenuation through a 1-cm-thick aluminum vacuum wall is as follows: $e^{-\mu x} \approx 10^{-30}$ for 10-keV photons, $\approx 10^{-4}$ for 20 keV, and ≈ 0.6 for 100 keV. Therefore, most of low energy X-ray photons (say ~ 20 keV) are essentially stopped by the vacuum chamber wall of an injector. Table 2 shows some values of μ/ρ and μ_k/ρ for a few materials of interest at various photon energies taken from Ref. 6.

Table 2. Values of the mass attenuation coefficient, μ/ρ (cm²/g) and the mass energy transfer coefficient, μ_k/ρ (cm²/g)

$h\nu$ (keV)	μ			μ_k/ρ	
	¹³ Al	²⁶ Fe	⁸² Pb	Water	Muscle (striated)
10	26.2	172.6	136.6	4.79	4.78
15	7.90	56.3	114.7	1.28	1.32
20	3.39	25.5	85.5	0.512	0.533
30	1.12	8.11	29.1	0.149	0.154
40	0.565	3.61	13.8	0.0677	0.0701
50	0.367	1.94	7.71	0.0418	0.0431
60	0.277	1.20	4.87	0.0320	0.0328
80	0.201	0.490	2.37	0.0262	0.0264
100	0.170	0.370	5.78	0.0256	0.0256
150	0.138	0.197	2.07	0.0277	0.0275
200	0.122	0.147	1.014	0.0297	0.0294
300	0.104	0.110	0.406	0.0312	0.0317

The characteristic X rays are emitted when the incoming electron knocks an electron from one of inner shells of the target atoms and an outer shell electron makes a quantized radiative transition to fill the hole in the inner shell. The probability of producing characteristic X rays is the product of the inner shell ionization probability and the probability of the radiative transition (the fluorescence yield). The energy required for this process corresponds to the binding energy of the electron in the shell, which represents the characteristic line spectrum. For example, $E_K \approx 9$ keV and $E_L \approx 1.1$ keV for copper. The energy distribution of characteristic X rays is then $F_K(E) \propto \delta(E - E_K)$, and so on. The number of K-series photons emitted from a bulk copper specimen per electron per steradian according to the measurements by Birks et al.⁷ goes as follows:

8×10^{-6} for $E_0 = 10$ keV, 2×10^{-4} for $E_0 = 25$ keV, 4×10^{-4} for $E_0 = 40$ keV, and 2×10^{-3} for $E_0 = 120$ keV (extrapolated) which scales⁸ roughly as $(E_0/E_k - 1)^{1.67}$. As pointed out in the previous paragraph, however, the characteristic X rays lie in the low energy region and are thus mostly shielded by a vacuum chamber wall.

The continuous spectrum of radiation is produced as a result of transitions of energy levels of incoming electrons in the fields of the nuclei of the target atoms. Dyson⁹ showed that to a close approximation, the energy distribution of the bremsstrahlung radiation may be written (in terms of keV per electron per keV energy interval) as

$$F_B(E) = 2.76 \times 10^{-6} Z(E_0 - E), \quad (4)$$

where Z is the atomic number of the target. The total number of continuous quanta whose energy is greater than E_c is then given as

$$\begin{aligned} N(E_0, E_c) &= \int_{E_c}^{E_0} \frac{F_B(E)}{E} dE \\ &= 2.76 \times 10^{-6} Z E_c [U_0 \ln U_0 - (U_0 - 1)] \end{aligned} \quad (5)$$

where $U_0 = E_0/E_c$. For the sake of comparison with the K X rays at $E_0 = 40$ keV from copper ($Z = 29$), the number of bremsstrahlung photons is estimated (in terms of number per electron per steradian) as: 3×10^{-4} for $E_c = 5$ keV and 5×10^{-5} for $E_c = 20$ keV.

Table 3 summarizes sample calculations for some actual injector systems using Eq. (3) for an idealized geometry. The source of X rays is copper, and the chamber wall (which is the only shield) is 1.5-cm-thick iron. For low energy beams ($\lesssim 100$ keV), most X rays are contained by chamber walls and do not pose serious health physics problems.

Table 3. X-ray dose rates^a due to backstreaming electrons at a location of 1 m from a fictitious point source (a 1.5-cm iron vacuum chamber wall is the only shield)

	PDX/D-III (60 kV/100 A)	TFTR (3/120 kV/60 A)	200-kV Test stand
per ampere (mrem/sec)	5.4×10^{-6}	13	620
0.03 I _b (mrem/sec)	1.6×10^{-5}	70	—
1% duty cycle (mrem/hr)	6×10^{-4}	2.5×10^3	2.2×10^4 ^b

^aAssuming rem = rad for X rays.

^bPer ampere of backstreaming electron current.

4. BIOLOGICAL DOSES AND SHIELDING REQUIREMENTS

Neutrons and X or γ rays interact with human tissue in different ways. There have been 33 possible neutron interactions identified with soft tissue whose composition can be expressed as $(C_5H_{40}O_{18}N)_n$. Neutrons impart their energy primarily in the form of recoil protons, which in turn do the damage to the cells. Gammas, on the other hand, impart their energy to the medium through electrons in most cases. For neutrons whose energies are in the vicinity of 2.5 MeV, about 83% of the energy loss occurs through the elastic collision of neutrons with protons.¹⁰ $O(n, n)O$ contributes about 5%, and $H(n, \gamma)D$ about 6%.

Biological dose rates at a reference location (100 cm from a radiation source) are estimated in Table 1 for 2.5-MeV neutrons and in Table 3 for bremsstrahlung X rays. The last column in Tables 1 and 3 shows the time-averaged doses (mrem/hr) for the continuous operation of pulsed beams with a duty cycle of 1%. Both the instantaneous doses, i.e., (dose rate) $\times$ (beam pulse length), and the time-averaged doses for these systems are high enough to warrant a biological shielding. Table 4 illustrates some key features of federal regulations on the maximum permissible doses in different cases. Neutron shielding for the systems such as PLT, ISX-B, and PDX should provide a neutron attenuation on the order of 10^4 (i.e., four ten-folding lengths).

Table 4. Maximum permissible dose levels

	Occupational			Unrestricted area
	rem/13 week	rem/year	accumulated ^a (rem)	
Whole body or important organs	3	5	5(N-18)	0.5 rem per year 100 mrem per week 2 mrem per hour
Skin or thyroid	8	30	30(N-18)	
Feet, hands, etc.	25	75	75(N-18)	

^aN is the age of a worker (N > 18).

Some of common neutron shielding materials have ten-folding attenuation lengths as given approximately as follows:¹¹ water ~ 13 cm, iron ~ 14 cm, concrete ~ 27 cm, and Pb-loaded borated polyethylene ~ 13 cm. Neutron activation of the shielding materials does not seem to pose a serious problem in the energy range of D-D neutrons. However, special attention is needed for shielding of the instantaneous gamma rays generated from shielding material itself (e.g., capture gammas from thermal neutrons). Therefore, the composite shielding method is commonly employed to effectively shield the instantaneous gammas as well as the fast neutrons and to remove the thermalized neutrons. For a composite shield of lead, boron, and polyethylene, Santoro and Alsmiller¹² estimated that the gamma dose is less than a half percent of the neutron dose for varied shielding thickness. This result implies that with a proper shielding arrangement we can neglect the instantaneous gammas.

The dose due to X rays from the accelerator column becomes significant at energies higher than ≈ 100 keV. A neutral beam injector test facility with a 60-A/120-keV source, for example, would yield $\approx 10^3$ mrem/hr at 1 m from the accelerator column and $\approx 10^2$ mrem/hr at 3 m away, if the duty cycle is 1%. The estimated dose at the location of 3 m, which is an easily accessible distance, is still far above the permissible dose, although the real geometry will likely yield less dosage than the idealized geometry. The health physics consideration of X-radiation is to be noted especially for the ordinary hydrogen beam test facilities for which no neutron shielding is anticipated.

5. CONCLUSIONS

Expressions for the source intensities of both D-D neutrons and X-ray photons from the neutral beam injector were derived as a function of beam energy. Sample calculations are made for actual injector systems for PLT, PDX, ISX-B, Doublet-III, and TFTR. The X-ray dose from the accelerator structure becomes a health physics concern at beam energies above 100 keV. The 2.5-MeV, D-D neutron yields from the systems considered warrant a hefty biological shielding in order to perform a full-scale D-beam operation in a test stand mode.

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