X-rays from the DRAGON Facility

1 Introduction

The high-voltage electrodes of the electostatic dipoles can act as a generator of x-rays (bremsstrahlung, not characteristic) at levels which are hazardous. Especially during conditioning of the electrodes, voltage will be above normal operating levels and currents of 10's of micro-amps are common. The key factors are: how x-rays cause dose; absorbing materials between the x-ray source and personnel; energy and intensity of the electron current, and the anode material.

The need for, and usefulness of, additional shielding material will be examined.

2 Dose

For x-rays the quality factor Q $\approx$ 1 and 1 sievert (Sv) is produced by an absorbed energy of 1 J/kg [TRIUMF Kinematics Handbook, IV-16]. Thus the x-ray dose in Sv is the product of the energy flux of the x-rays (J/m^2) times the inverse attenuation length λ (m^2/kg) in the body (taken as water in the following calculations). In the following table the attenuation lengths are calculated from the "energy absorption cross sections" tabulated by Israel and Storm [Nuclear Data Tables **A7**(1970)565].

E_γ (keV)	Water (cm)	Ti (cm)	Fe (cm)	Pb (cm)
10	0.2	0.002	0.001	0.0007
20	1.9	0.014	0.003	0.0013
50	25.0	0.21	0.078	0.013
100	30.0	1.56	0.58	0.040
200	34.5	5.5	2.6	0.14
500	33.7	7.2	4.3	0.93

It is evident that x-rays of energy below 20 keV can cause a large dose to the surface of the body. Above 50 keV the maximum dose is lower, but a greater volume of the body is irradiated.

3 Attenuation by electrodes and tank walls

In order to accelerate the electrons to significant voltages, the electrodes must be in vacuum, and thus enclosed by the stainless steel vacuum tank. The minimum tank thickness is 0.5" (1.27 cm). From the above table it is seen that 1.27 cm of Fe will attenuate 20-keV x-rays by a factor 10^{184}, 50-keV x-rays by 10^7, 100-keV x-rays by a factor 9, and 500-keV x-rays by only a factor of 1.34. The conclusion is that only the more energetic x-rays - above 50 keV -

are likely to pose a radiation hazard, provided one does not look through any "window" in the tank.

From most directions the source of x-rays, electrons accelerated from cathode to anode, is shielded also by the 2.6-cm thick titanium electrodes. They afford attenuation factors of 10^5 at 50 keV, 5 at 100 keV, and 1.4 at 500 keV.

4 X-ray production rates

For most of DRAGON operations the electrode voltages will be at 50% or less of the maximum design, ±200 kV on ED1 and ±160 kV on ED2. Voltage conditioning of electrodes would go 10–20% above the intended operating voltage. Worst case will be when DRAGON is to be conditioned for ±200 kV. Assuming the highest conditioning voltages to be ±250 kV, the end-point energy for bremsstrahlung would be 500 keV.

The dependence of total x-ray production on anode material and accelerating voltage is reasonably well known [H.Koch and J.Motz, Rev. Mod. Phys. **31**(1959)920]. There is a reasonable model for how that total yield is distributed as a function of x-ray energy, but rather less is known about the x-ray angular distribution at energies of interest here. According to tables in *Handbook of Radiological Protection*, by the Radioactive Substances Advisory Committee, U.K. 1971, there should be about 2.5 keV bremsstrahlung energy yield per 500 keV electron hitting a Ti anode. This is consistent with an estimate using EGS4. Figure 3.3(3) of the same source gives the x-ray energy distribution. Combining these estimates with the energy absorption cross sections allows the calculation of transmission through the tank walls and dose at 1 m (see Figure 1).

5 Additional shielding

The FMA dipoles at Argonne have 1/4" of lead around the electrostatic dipole tanks. The transmission and dose when the absorber is 1/4" of Pb instead of 1/2" of Fe is shown in Figure 2. Pb is much more effective than Fe between 100 and 250 keV, and the dose per μA of electrons is reduced by an order of magnitude.

With absorption by both the tank walls and 1/4" of Pb, the estimated dose from a 1-μA current of 500 keV electrons is 0.2 μSv/sec at 1 m, or 0.7 mSv/hr/μA. This should be compared to the 0.3 mSv per quarter limit for non-ARW's.

The 2.6 cm Ti electrodes provide additional shielding (comparable to that of the stainless steel walls), the shielding factor being very large in certain direction and negligible in others.

6 Expected dose during conditioning

Currents drawn during conditioning may be many orders of magnitude greater than those drawn during normal operation of conditioned electrodes. During conditioning it is not uncommon to have currents of 10's of μA. If the current were entirely due to electrons drawn

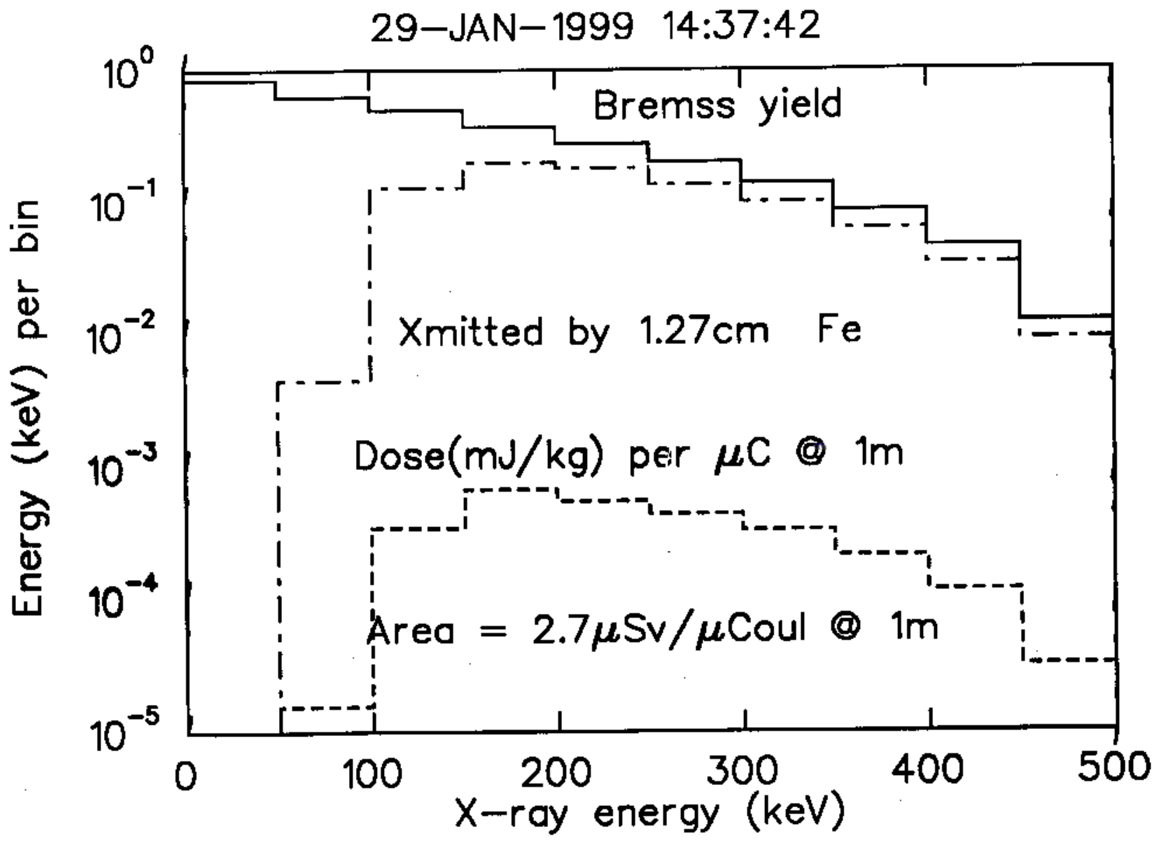

Figure 1: Transmission through the tank walls and dose at 1 m.

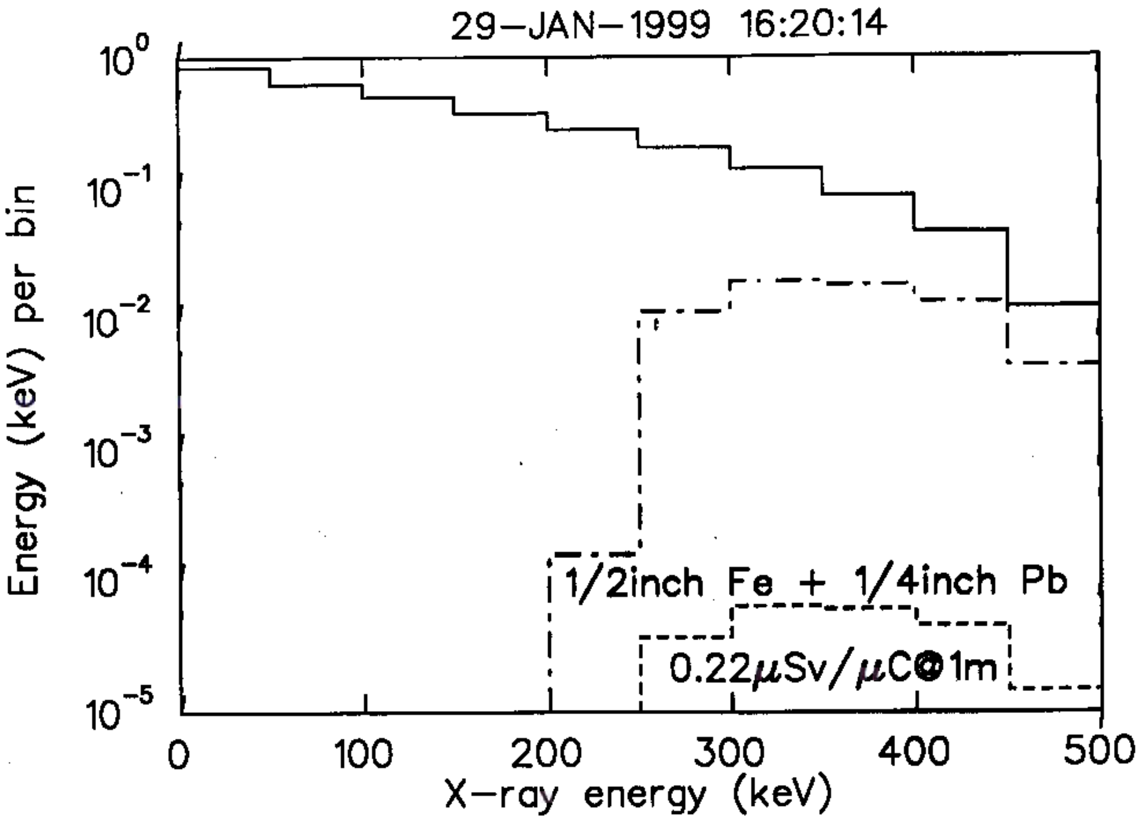

Figure 2: Transmission and does when the absorber is 1/4" of Pb instead of 1/2" of Fe.

from the cathode, the estimated worst-case dose rate at 1 m from the anode would deliver quarterly allowed dose in a few minutes with the shielding described above.

Such dose rates have not been the typical experience for electrostatic dipoles at other facilities. The explanation may be in the nature of the conditioning current. According to unpublished studies [W.Diamond, TASCC], conditioning of large-area, large-gap electrodes is due to gas extracted from the anode, rather than field emission from the cathode; Diamond's measured x-ray yields from small-area, small-gap electrodes at 100 kV were an order of magnitude less than the yield from field emission (when electrons are accelerated all the way from cathode to anode); the data suggested that the factor became even larger as electrode voltage was increased.

It should be noted that the x-ray yield drops sharply as the electrode voltage is decreased, roughly as the square of the electron energy. Even more important, the maximum energy of the x-rays drops into the range where Pb (and even Fe and Ti) are very effective absorbers. Thus, for the vast majority of DRAGON operation 1/4" of Pb shielding should reduce x-ray doses to levels acceptable for working 100 hr per quarter within 1m of the anode.

It is reasonable to expect that 1/4" Pb outside the DRAGON dipole vacuum tanks will provide sufficient screening of x-rays. To deal with the contingency of high x-ray yields, either for operation above 200 kV or if the conditioning process should prove to be dominated by field emission, two extra measures might be taken:

- extend the exclusion zone around the dipoles from 1 m to 3 m during conditioning (perhaps restricting conditioning to times outside normal working hours, if many activities were affected by the larger zone)
- mount additional Pb screens around the dipoles during conditioning (1" of Pb gives a reduction factor of more than 50)

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