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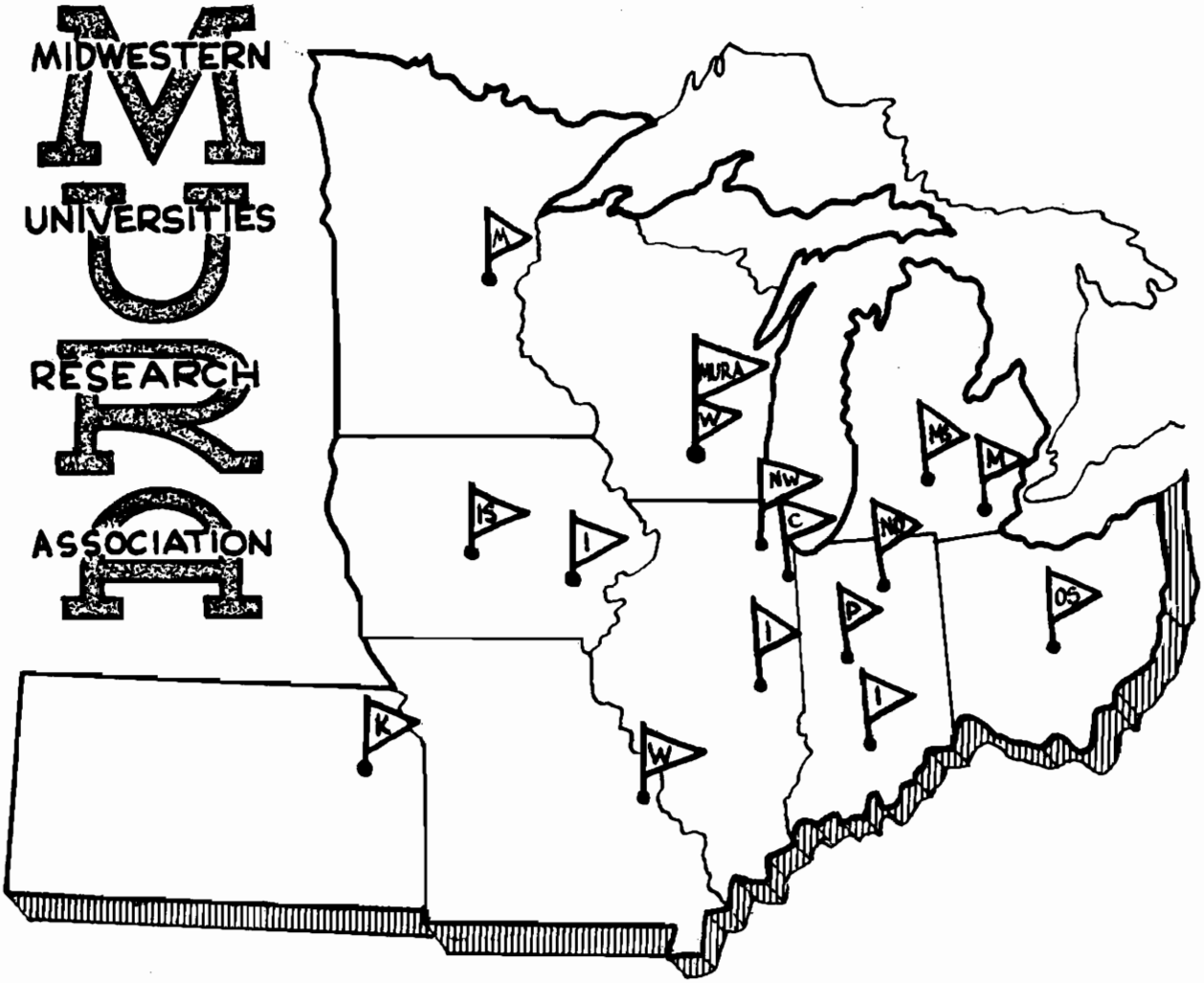


# REPORT ON SHIELDING THE MURA HIGH INTENSITY 50 MEV ELECTRON ACCELERATOR

James H. Smith

**REPORT** **NUMBER** 408

MURA-408
Internal

MIDWESTERN UNIVERSITIES RESEARCH ASSOCIATION*

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# REPORT ON SHIELDING THE MURA HIGH INTENSITY 50 MEV ELECTRON ACCELERATOR

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June 2, 1958

## ABSTRACT

Shielding requirements against the gamma rays and neutrons which will be radiated by the MURA 50 Mev electron accelerator now being constructed are calculated.

*AEC Research and Development Report. Research supported by the Atomic Energy Commission, Contract No. AEC AT (11-1) 384.

**University of Illinois

Report on Shielding the MURA High Intensity
50 Mev Electron Accelerator

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1. Allowed levels of radiation.

This report will consider the shielding of the M.U.R.A. 50 Mev electron accelerator under the assumption that it will be run at full intensity, i.e. $4.8 \times 10^{13}$ electrons a second, for 40 hours each week. It will consider allowable radiation doses of 300 milliroentgens per week of gamma rays and 300 milliroentgen-equivalent-man per week of neutrons for MURA workers. (Note that this is higher by a factor of three than current good practice and higher than that allowed by AEC for young radiation workers. This figure was used only because the installation is a temporary one and presumably will not actually average anything close to 40 hours of operation per week and will not be operated as a long term device). Allowable radiation levels at the house next door will be considered 8 milliroentgen equivalent man per week. (2.5 m rem/wk is a rough figure for natural background).

Protection of the sidewalk area has not been specifically considered. I do not believe that any practical shield will actually bring it down to 8rem/wk. If necessary I can consider it further.

2. References.

References referred to in the report are:

1. Protection Against Betatron-Synchrotron Radiations up to 100 Million Electron Volts. Handbook 55, U.S. Dept. of Commerce, National Bureau of Standards (1954)

2. Reactor Shielding Design Manual, Ed. by J. Rockwell III, D. Van Nostrand 1956.

3. TID-7545 Conference on Shielding of High Energy Accelerators, Held at New York, April 11 to 13, 1957

4. L.H. Lanzl and A.O. Hanson, Phys.Rev. 83, 959 (1951)

3. Sources of radiation.

A. γ-rays

All calculations have been made under the assumption that 50 Mev electrons are incident on iron. Iron has a radiation length of 14.1 gms/cm² or 1.8 cm and a critical energy of 24.3 Mev. Therefore no reasonable shower theory can be applied. I have made a very rough shower type analysis using a critical energy 17 Mev (for convenience in calculation) to estimate the source of radiation. This shows that after 2.7 radiation lengths (4.85 cm) 72% of the initial electron energy is still present in the shower. After 2.7 radiation lengths we assume that the minimum absorption for iron holds.

The geometry of the accelerator makes it reasonable to suppose that the resulting γ-rays must go through about 8" of iron. In most cases they will penetrate closer to 16". I have assumed only 8". It might be worth noting that if the beam scallops are in any way peculiar it might be possible to get a beam out through much less iron.

After the 2.7 initial radiation lengths the remainder of the iron attenuates by a factor of 38 leaving .72x38 = 19% of the initial energy leaving the machine as γ-rays. They will be very broadly distributed in energy around 7.5 Mev. This is

$$50 \text{ Mev} \times 4.8 \times 10^{13} \text{ electrons} \times 0.019 = 4.56 \times 10^{13} \text{ Mev/sec}$$
$$= 0.61 \times 10^{13} \ 7.5 \text{ Mev } \gamma\text{-rays/sec.}$$

B Neutrons

The $\gamma$-rays in the iron produce a non-negligible number of photoneutrons. The mean free path for an interaction in iron of density 7.8 is

$$mfp = \lambda = \left(0.847 \times 10^{23}\, \sigma_{Fe}\right)^{-1}.$$

The probability for a photon of energy k to interact in $dx$ is

$$\frac{dx}{\lambda}\, N(k)\, dk$$

where $N(k)$= number of photons per Mev and dk is the photon energy interval in Mev. The probability for producing a neutron in is then

$$\int \frac{dx}{\lambda} N(k)\, dk$$

$$= 0.847 \times 10^{23} \int dx\, \sigma(k)\, N(k)\, dk$$

Since most of the reactions will be produced in the giant resonance region where $\sigma$ is strongly peaked at 17.5 Mev we may remove $N(k)$ substituting N(17.5). The remaining integral is just the integrated cross section which may be written $.12\, \frac{NZ}{A} \times 10^{-24}$ Mev cm$^2$ (Ref. 3 p 202). The probability for making a neutron in dx is then

$$0.847 \times 10^{23}\, dx\; N(17) \times 0.12\, \frac{NZ}{A} \times 10^{-24}$$
$$= 0.847 \times 10^{-1} \times 0.12 \times \frac{30 \times 26}{56}\, \cancel{x}\, N(17)\, dx$$
$$= 0.14\, N(17)\, dx \text{ (in cm)}$$

The probability for a single electron to make a neutron in some $dx$ is then

$$0.14 \int N(17)\, dx = 0.14 \times \text{"track length" of 17.5 Mev } \gamma\text{-}s$$

A numerical integration of my simple shower curve gives $\int = 0.2858$. Or there are

$$0.14 \times 0.29 = 0.0404 \text{ neutrons per electron.}$$

B Neutrons

The $\gamma$-rays in the iron produce a non-negligible number of photoneutrons. The mean free path for an interaction in iron of density 7.8 is

$$mfp = \lambda = \left(0.847 \times 10^{22}\, \sigma_{Fe}\right)^{-1}.$$

The probability for a photon of energy k to interact in $dx$ is

$$\frac{dx}{\lambda}\, N(k)\, dk$$

where $N(k)$= number of photons per Mev and dk is the photon energy interval in Mev. The probability for producing a neutron in is then

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$$0.14 \int N(17)\, dx = 0.14 \times \text{"track length" of 17.5 Mev } \gamma\text{-}s$$

A numerical integration of my simple shower curve gives $\int = 0.2858$. Or there are

$$0.14 \times 0.29 = 0.0404 \text{ neutrons per electron.}$$

(This is a reasonable number in that we usually assume 0.01 neutrons per electron from our 22 Mev machine and the number should go like the energy squared).

The machine thus becomes a source of

$$4.8 \times 10^{13} \times 0.0404 = 1.94 \times 10^{12} \text{ neut/sec.}$$

These neutrons will be considered to have 1 to 3 Mev energy. I do not believe that the few fairly high energy neutrons will be a problem. Furthermore, the neutrons will be assumed isotropic to be produced at the electron orbit, and to escape between iron yokes since this can happen in certain directions and is the worst case.

4. γ-ray shielding requirements.

A. Beams

If the electron beam strikes a target of some sort, a highly directed beam results. If the direction of these beams is known then local shielding will take care of the beam problem. If beams can arise by accident, then the general shielding should take care of a beam in the equatorial plane.

A rough calculation of Lansl and Hanson's data shows that for each γ-ray total there are 13.5 γ's per steradian at the center of the beam. Since this is for 17.5 Mev electrons we may assume $13.5 \times (\frac{50}{17.5})^2 = 110$ γ's per steradian at center per γ-beam.

Since there are $0.61 \times 10^{13}$ γ's per sec. the central beam intensity will be

$$0.67 \times 10^{15} \text{ 7.5 Mev } \gamma\text{-s/sec ster.}$$

At 12 feet from the beam source 1 $cm^2 = 0.746 \times 10^{-5}$ steradian or there will be a γ flux of

$$0.5 \times 10^{10} \text{ 7.5 Mev } \gamma\text{'s/sec cm}^2$$

Since a flux of 1-7.5 Mev $\gamma$/sec cm$^2$ makes a dose of $0.85 \times 10^{-5}$ r/hr or $3.4 \times 10^{-4}$ r/40 hr wk (Ref. 2 p.19), this is a dose of

$$1.7 \times 10^6 \text{ r/40 hr wk.}$$

(This is a central intensity of 8100 r/min at 1 meter which sounds a little high when compared with the output of our 22 Mev machine of 80 r/min at 1 meter).

Since $1.7 \times 10^6$ r/40 hr wk must be reduced to 0.3 an attenuation of

$$5.7 \times 10^6 = 15.6 \text{ mean free paths must be provided.}$$

B. Average equatorial plane shielding.

If there are no beams, or if beams are in some ways taken care of separately, there will still be a general equatorial plane radiation. In the following we assume it to be spread equally in azimuth and to be confined to 10° up and 10° down from the equatorial plane. We calculate the $\gamma$-ray flux at a radius of 16' from the center of the machine and 7 1/2' from the orbit. The $\gamma$-rays thus cross an area

$$A = 2\pi \times 16 \times 2 \times 7.5 \times \tan 10° \cong 265 \text{ sq.ft.}$$
$$= 2.46 \times 10^5 \text{ cm}^2$$

The $\gamma$-ray flux is then

$$\text{flux} = \frac{0.61 \times 10^{13}}{2.46 \times 10^5} = 0.25 \times 10^8 \qquad \frac{7.5 \text{ Mev } \gamma\text{-rays}}{\text{sec cm}^2}$$

$$\text{Dose} = 3.4 \times 10^{-4} \times 0.247 \times 10^8 = 8{,}400 \text{ r/40 hr wk}$$

Thus the $\gamma$-ray attenuation required in the equatorial plane is

$2.8 \times 10^4 = 10.24$ mean free paths even in the absence of concentrated beams.

A number of simplifications have been made here. Actually there will probably be a narrow much hotter band right at the

equatorial plane. However, there is probably justification for averaging over a fair part of a person's body. Furthermore the radiation will be more nearly targential than radial thereby cutting down the dose. Also most radiation of this type will pass through more than 8" of iron.

C. γ-rays toward the roof.

The number of γ-rays which scatter toward the roof is a hard thing to guess but fortunately the guess is about 0.2% thus requiring an attenuation of about $3 \times 10^3$ to get to 300 mr/wk at a point 8 feet from a concentrated beam. More shielding than this will be needed for neutrons.

D. γ-ray beams toward the basement of the house next door.

The point nearest the source in the basement of the house next door is 24' from that source assuming a tangential beam. The γ-ray dose is then 1/4 that calculated in part A. However the level desired is 8 mr/40 hr wk so that an attenuation of

$$\frac{300}{8} \times \frac{1}{4} \times 5.7 \times 10^6 =$$

$$5 \times 35 \times 10^7 = 17.8 \text{ mean free paths is required.}$$

E. γ-rays to the street

Not considered since the neutron problem is probably worse.

5. Neutron Shielding Requirements

A. General shielding of MURA Ra workers.

The machine produces $2 \times 10^{12}$ neutrons per second. At a point 8 feet from the target the neutron flux is

$$\frac{2 \times 10^{12}}{4\pi \times 240^2} = 2.68 \times 10^6 \text{ neut/cm}^2 \text{ sec.}$$

Reference 2 p.22 gives a dose of 0.12 mrem/hr for a flux of 1 neutron per $cm^2$ per sec in the range 1-3 Mev. This is 4.8 mrem/wk per neutron or

$$4.8 \times 2.68 \times 10^6 = 12.9 \times 10^6 \text{ m rem/wk}$$

An attenuation of

$$4.3 \times 10^4 = 10.66 \text{ mean free paths is thus needed.}$$

B. Basement of house next door.

The attenuation required is 300/8 times that for radiation workers, but again the distance is twice as great, 16' in this case. The attenuation needed is

$$\frac{300}{8} \times \frac{1}{4} \times 4.3 \times 10^4 =$$

$$4.03 \times 10^5 = 12.9 \text{ mean free paths.}$$

C. Neutrons originally going up but scattered from the roof.

Very roughly 1" of hydrocarbon material will scatter 0.4 of all neutrons hitting it.

If we then assume that 1/6 of all neutrons head toward the roof and penetrate 1" of wood, 0.07 of them will scatter. The roof then becomes a source of

$$2 \times 10^{12} \times 0.07 = 1.4 \times 10^{11} \text{ neutrons/sec}$$

--roughly isotropic.

The house is roughly 26' from the center of the roof so there is a neutron flux at the house from this source of about

$$\frac{1.4 \times 10^{11}}{4\pi(26 \times 30.5)^2} = 1.8 \times 10^4 \text{ neut/sec cm}^2$$

At 4.8 mrem/wk per neut/$cm^2$sec this is a dose of $8.65 \times 10^4$ mrem/wk

An attenuation of

$$1.08 \times 10^4 = 9.28 \text{ mean free paths is needed.}$$

One trouble is that such a shield face is then a source of neutrons itself. If we assume a point source of $2 \times 10^{12}$ neutrons and use the Gold integral approximation (Rossi High Energy Physics p. 540) we find a requirement of 10.2 mean free paths.assuming that neutrons emerge from the opposite side of the shield fully isotropic.

D. Neutron shielding of street.

This is a rather complicated structural problem which I cannot consider without more detailed knowledge of the setup.

7. Required Shields

A. Neutron Shields

Reference to section 6 easily leads to the following values of required shielding

| | Earth | Concrete | Heavy Con | Iron |
|---|---|---|---|---|
| MURA (10.66 mfp) | 7.9' | 5.2' | 3.3' | 1.9' |
| House Basement (12.9 ) | 9.6' | ---- | ---- | ---- |
| Roof (10.2 mfp) | 7.6' | 4.9' | 3.2' | 1.8' |

MURA: Five to six feet of ordinary concrete looks like the best solution. For general room shielding I do not believe you will be enough pressed for space to warrant heavy concrete or iron unless it is needed for $\gamma$-rays.

House Basement: Safe with no additional shielding.

Roof: The roof looks like a real problem. A 5' thick slab of concrete will weigh approximately 325 tons. I'm no engineer, but this looks formidable, especially if part of it must be removable. An iron roof would be 400 tons.

The problem might be alleviated somewhat by putting in a thinner roof with a high wall toward the house. This

6. Attenuation of neutrons and 7.5 Mev γ-rays in earth, concrete, heavy concrete, lead, and iron.

| | Mean free path in nuclei for minimum absorption of γ-rays | Reference | Mean free path in for absorption of low energy neutrons | Reference |
|---|---|---|---|---|
| Earth (density 1.5) | 10.4" | 3p201 corrected | 8.9" | 3p179 |
| Concrete (density 2.3) | 6.7"* | 1p38 | 5.8" | 3p179 |
| Heavy Concrete (density 4.25) | 3.77" | 3p201 corrected | 3.7" | 3p179 |
| Iron | 1.74" | 1p38 | 2.1" | 3p179 |
| Lead | .835" | 1p38 | | |

*for 7.5 Mev γ-rays

Note that the attenuation of γ-rays is modified considerably by the build-up factor.

would still irradiate MURA workers upstairs. I understood, furthermore, that you were not anxious to build outside your building and I think this would be necessary unless you severely restrict access to the machine and use iron or heavy concrete.

B. Gamma shielding of the house basement next door.

Section 4D showed an attenuation of $5.35 \times 10^7 = 17.8$ mean-free-paths were needed to shield the house from direct beams. 12 feet of earth (Panofsky may have different earth from yours) is 11.5 mean free paths, hence an additional 6.3 mean free paths must be provided for adequate protection. In addition a buildup factor (Ref. 2 p. 423) of 7.08 = 1.96 mfp's must be provided, or a total of 8.3 mfp's. This is 4.63' of concrete, 1.20' of iron, or 6.9" of lead. This additional shielding should be provided for about $\pm 10°$, of the orbital plane measured from any possible beam spot. Probably lead placed close in is best.

C. General equatorial plane shielding.

Section 4B shows that 10.24 mfp's are needed to reduce the general equatorial beam radiation to tolerance. This is 5.71' of concrete. A six foot concrete wall is recommended. Thus a 6' wall of ordinary concrete will protect from neutrons and the general wash of equatorial gamma rays. There is a buildup factor which has been omitted because of the more stringent requirements of beam protection. For 10.24 mfp's this factor is 4.13 or 9 1/2" of additional concrete.

D. Beams of γ-rays

Section 4A computed an attenuation of 15.6 mfp in the direct γ-ray beam. An additional factor of 6.11 = 1.8 mfp or a total of 17.4 mfp. A six foot concrete wall will supply 10.7 mfp leaving 6.7 mfp additional

6.7 mfp = 3.75 feet of concrete

= .97 feet of iron

= 5.6 inches of lead

I believe it should be possible to install such a belt of lead all the way around the machine and to ± 10° of the orbital plane. This is roughly 8" up 8" down and 6" thick lead just outside the magnet yokes.

I believe the use of such a lead belt is desirable because it is flexible. It need not be in place for low intensity testing and can be thinned, thickened, or made taller or shorter at will.

There will obviously be gaps in this wall. They must be taken care of separately..

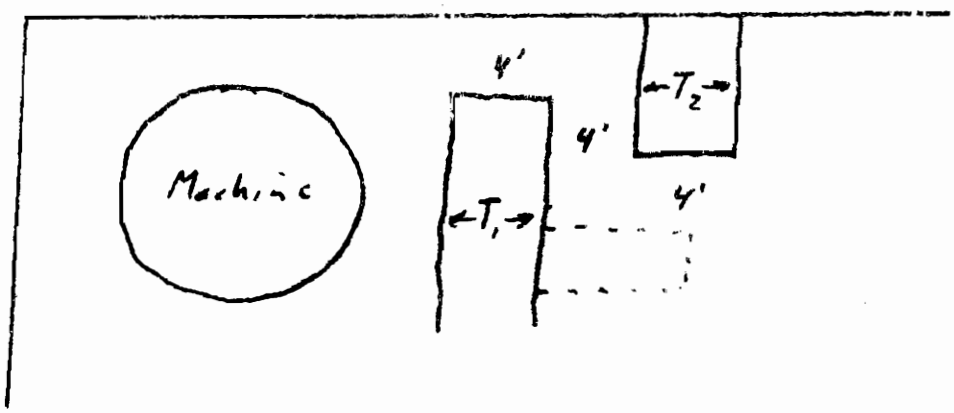
E. Shielding from neutron capture γ-rays

Very simple approximations show that neutron capture γ-s are not a problem.

8. Door to the shielding

I pressume that quick access to the machine is desirable and that therefore a large moving door is undesirable as well as too expensive. Some type of labyrinth is therefore indicated. One possible place for it would be the wall near the house. It

might be built like this




$T_1$ would be the standard wall thickness.

$T_2$ might be somewhat thinner say 2/3 of $T_1$ but it would be safer to make $T_2 = T_1$.

A 4 foot opening is suggested, but should be designed to fit your needs.

Data on the reflection of γ-rays is quite scarce, but there is some on the reflection of 6 Mev γ-rays from iron. Very roughly 2% of the incident dose is reflected from iron. Less will certainly bounce from concrete. Approximately 2 bounces will handle all the γ-radiation except for a directed beam going into the doorway. The indicated design allows some single bounce γ-rays to escape into the room. I recommend, however, that this arrangement be tried. If the measured background should be too high, a concrete block wall shown dotted could easily be built later. It would certainly be adequate.

The neutron scattering through the labyrinth may be more serious than the γ-ray scattering. An adequate calculation

would take an enormous amount of time.

Let us assume that 5.6" is the mfp for absorption. Let us assume that 3" is the mfp for an elastic scattering off a heavy nucleus in concrete. Very roughly, then, each neutron which is scattered back out will be attenuated by a factor 3. In going through the labyrinth about 1/4 of a sphere is available to bounce "out". Thus a wild guess is that there is an attenuation of 10 at each bounce. About 4 bounces are thus needed. This indicates that the dotted wall may well be needed for neutrons. Again I would wait, since it can easily be added later.

9. Final remarks.

The indicated shield--6' of concrete around two walls and a 5' roof plus a lead belt is a rather formidable structure. A roof 5' x 30' x 36' plus walls of 6' thick x 8' high x 57' long indicate 8,100 cubic feet of concrete or 580 tons!

Obviously some kind of concrete block structure must be used. Blocks 18" x 36" x 72" would weigh nearly 2 tons and might be a convenient size. Imbedded iron hook-holders are of course convenient. You have people who know better than I, but this concrete structure looks like about $20 - $40,000.

Even a cursory reading will indicate that I have made many gross assumptions in this report. In most cases I have tried to be conservative. I can only hope there are no mistakes. Compared to our experience here at Illinois I think this shield looks about right order-of-magnitude wise, but a little bit on the conservative side. I suppose if size is a real problem as well as money it might be possible to shave it somewhat with the assumption that when you reach dangerous

beam intensities you measure carefully and buy more iron or concrete as needed.

I have not considered carefully the problem of possible fast neutrons. Therefore you should be prepared to measure these at some early stage. I may as well emphasize here the necessity for very careful surveys as soon as the machine is running. As regards low intensity neutron radiations near the house next door these measurements are difficult and require some thought and care.

A further safety caution: This machine is lethal in a rather short exposure (order 10 seconds) inside the shield and adequate protective devices must be installed to prevent accidental exposure, but these are a different problem.