

Radiation Shielding for Electronic Devices Operating in XFEL Environment: Monte Carlo Simulations and Radiation Measurements at FLASH

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MOTIVATION

High- energy electron linear accelerators generate parasitic radiations (mainly **bremsstrahlung photons** and to a much lesser extent **photo-neutrons**) via the interaction of accelerated field emission electrons with accelerator cavity walls.

The future XFEL will be housed in a single 5 m diameter underground tunnel. All LLRF Electronic Devices, made of radiation sensitive COTS microelectronics will be installed in close vicinity of the radiation producing accelerator modules (cavities).

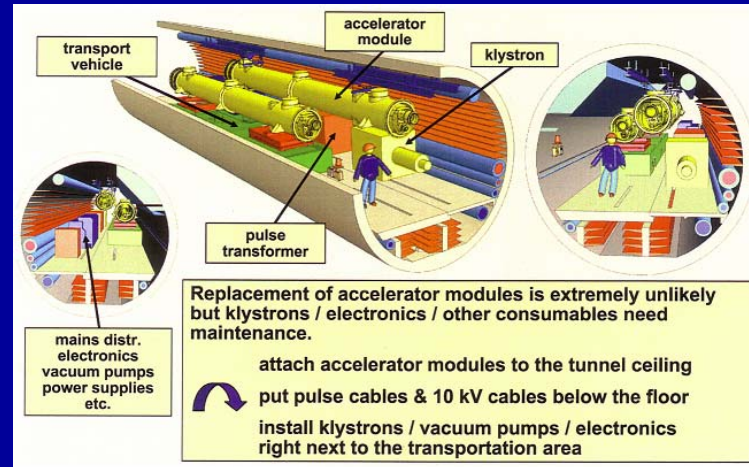
The **bremsstrahlung** induced total ionising dose (TID) is the prime source of detrimental radiation effect.

The single event upsets (SEU) triggered by scattered **thermal neutrons** pose no permanent damage to electronics, however, could cause serious functional disturbance of the microelectronics.

This talk highlights the design principle of the dedicated radiation shielding for the electronic devices to be operating in XFEL tunnel.

MAIN GOAL

Radiological Shielding Design for Electronic Equipment Racks to be located at the Cold Side of the XFEL Linac Tunnel



Critical Shield Design Criteria

Adequate: prolong the operational life of the electronics (COTS) up to 10 y

Compact: shall fit in the 5 m diameter linac tunnel, whereas keeping enough space for the passage of personnel and transport of equipments

Low Material Cost: using commonly available, non toxic, low cost materials

Low Fabrication Cost: off line, modular construction (IKEA philosophy)

Easy to upgrade: easy and cost-effective upgrade of the existing shielding

PROJECTED RADIATION DOSE FIGURES FOR XFEL

For the total XFEL operation time of 80000h (10 y)

Extrapolated from FLASH Radiation Measurement Data

Gradient : 22.5 MV. m⁻¹ (Routine operation)

Gamma Dose (unshielded): 120 Gy

Neutron kerma (unshielded): 0.031 Gy

*Number of SEU in 1 MB bq4017MC-70 SRAM (unshielded): 8.0×10^4

Gradient : 30 MV. m⁻¹ (Worst Case Scenario)

Gamma Dose (unshielded): 1520 Gy

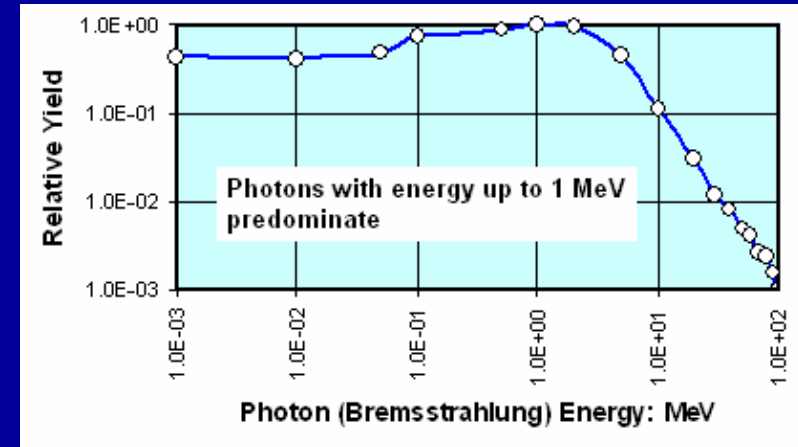
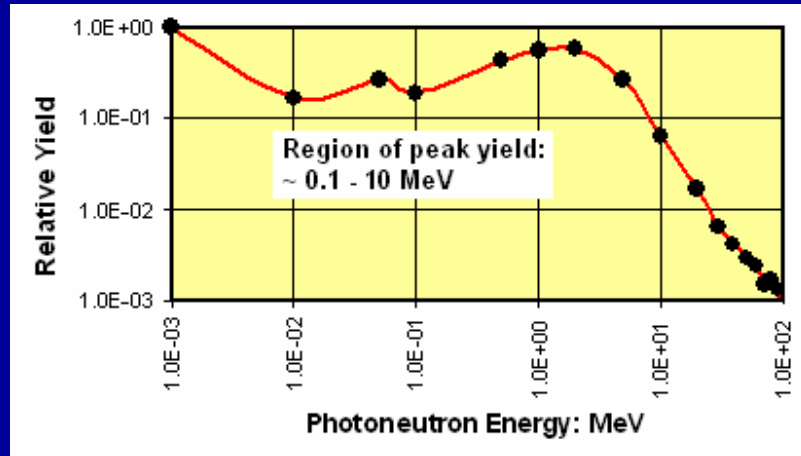
Neutron kerma (unshielded): 0.050 Gy

*Number of SEU in 1 MB bq4017MC-70 SRAM (unshielded): 1.02×10^5

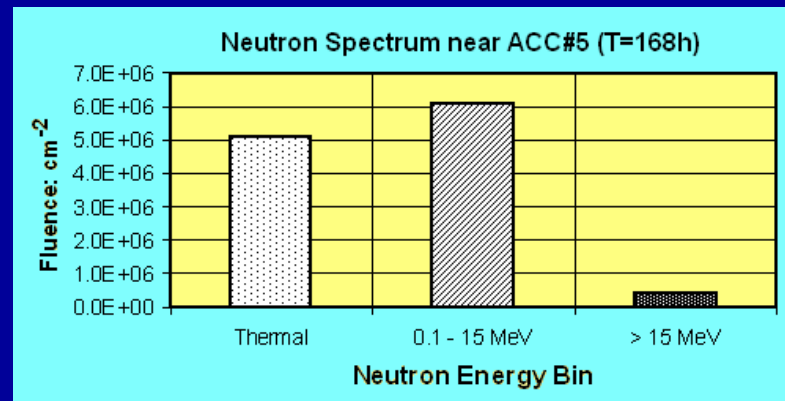
* Using the SEU Cross Section of $2.3 \times 10^{-13} \text{ cm}^2 \cdot \text{bit}^{-1}$ (D Makowski, PhD Thesis, 2006, DMCS, TU Lodz, Poland).

FLUKA SIMULATION OF NEUTRON AND GAMMA FIELDS

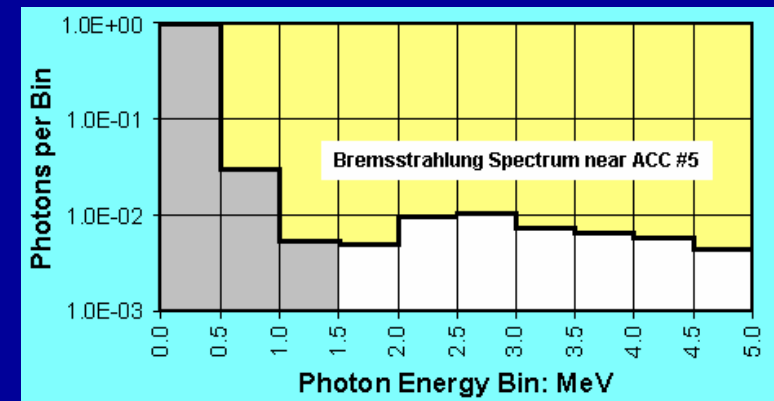
1 GeV Electron on 2 mm thick Nb Target : H S Lee, Pohang Lab, Korea



FLASH Experimental Results

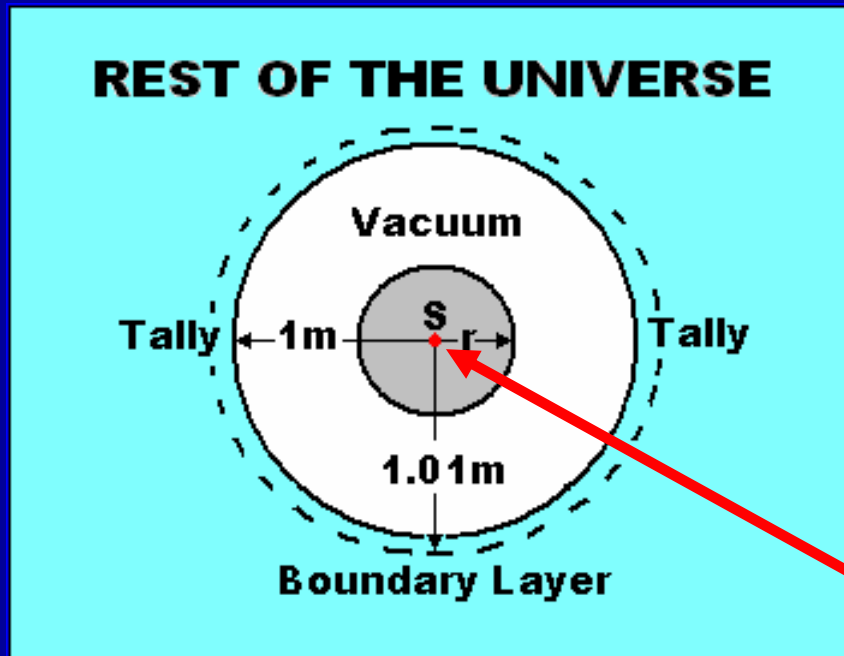


Neutron Spectrum evaluated using Bubble Detectors.



Bremsstrahlung Spectrum deconvoluted using a Pb-Wedge (Bleiorgel).

Monte-Carlo Simulation of a Spherical Polyethylene Shield



The point source **S** is located at the centre of the spherical Poly. (s. Table) shield of radius **r**

The neutron fluence and dose equivalent were evaluated on the spherical tally of radius 1.0 m

The upper boundary of the tally surface was set at 1.01m

The neutron energy spectrum of the source **S** was considered to have the characteristics of a "Fission" spectrum:

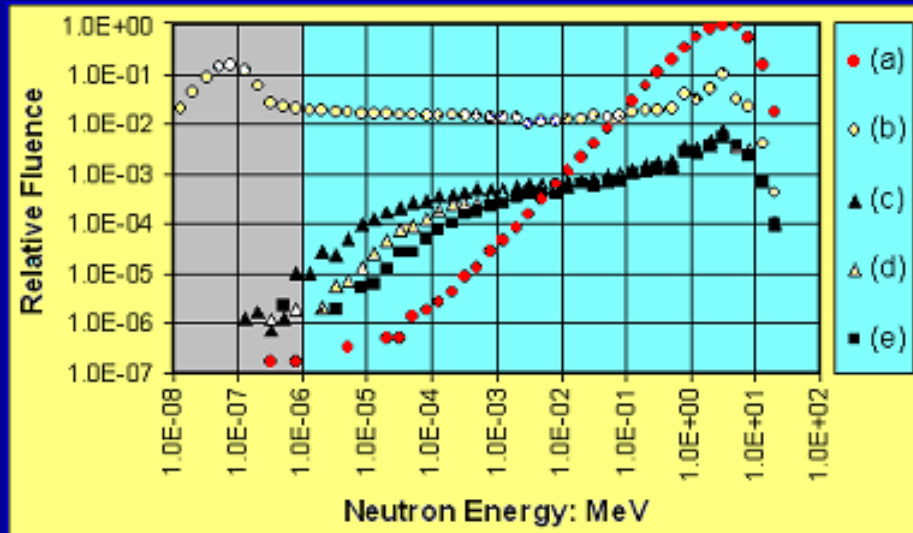
$$f(E) = 0.30033 \exp(-E/1.025) \sinh(2.926)^{0.5}$$

Where, **E** is the neutron energy in MeV

Physical properties of the Shielding Materials.

Physical Parameters	Polyethylene	Boron Carbide
Formula	CH ₂	B ₄ C
Atomic Wt.	14.027	55.26
Wt. Fraction (H)	0.1437	0
Wt. Fraction (^{nat} B)	0	0.783
Wt. Fraction (C)	0.856	0.217

RESULTS



Showing the relative neutron fluence on the 30 cm radius spherical shield surface as functions of neutron energy:

(a) Input neutron spectrum (fission spectrum)

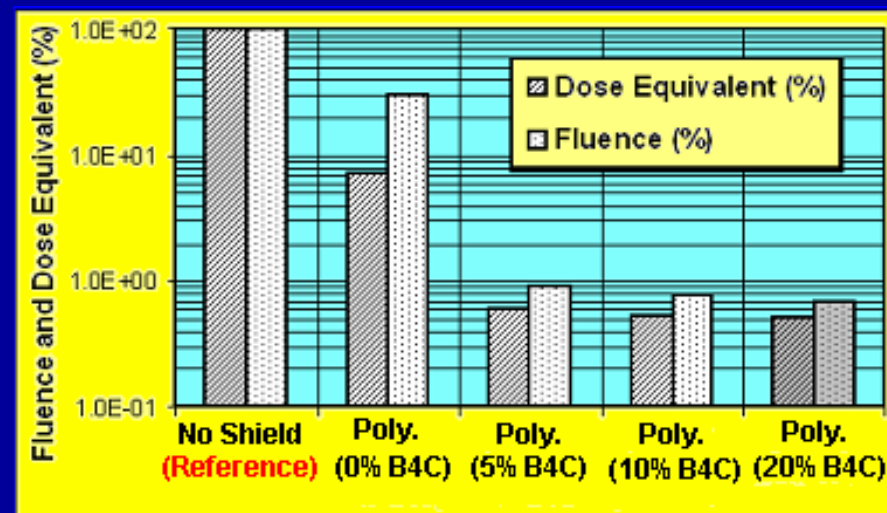
(b) Polyethylene with no B₄C

(c) Polyethylene with 5% B₄C

(d) Polyethylene with 10% B₄C

(e) Polyethylene with 20% B₄C

Showing the integrated (relative) neutron dose equivalent and fluence on the surface of the spherical (30 cm radius) polyethylene shield with different amounts of B₄C additive, calculated using MCNP 4A code.



RESULT SUMMARY

Transmission of bremsstrahlung through 10 mm thick lead shielding

Photon Energy Band	Intensity	HVL (Pb): mm	Transmission (10 mm Pb)
0 - 0.5 MeV	1.00E+00	2.0	3.13E-02
0.5 - 1.0 MeV	5.00E-02	6.5	1.72E-02
1.0 - 1.5 MeV	7.00E-03	11.0	3.73E-03

Net Bremsstrahlung Transmission through 10 mm thick Pb Plate: 5.22E-02

Neutron Attenuation by Borated Polyethylene Spherical Shield

A 30 cm diameter pure polyethylene shield causes the drop of neutron fluence by a factor 0.2

By the same time substantially increase the thermal neutron fluence, enhancing the probability of triggering SEU in microelectronics

Addition of B₄C (ca. 5% wt) in the polyethylene causes the drop of neutron fluence by a factor of 0.01

B₄C additive causes a thermal neutron cut off by 4 orders of magnitude => ideal thermal neutron shield to mitigate SEU in memory chips

Addition of more (> 5%) B₄C yields no extra thermal neutron cut off

SHIELDED RADIATION DOSE FIGURES FOR XFEL

For the total XFEL operation time of 80000h (10 y)

SHIELDING: 10 mm Lead and 3 mm Borated Polyethylene foil

Gradient : 22.5 MV. m⁻¹ (Routine operation)

Gamma Dose (shielded): 6 Gy

Neutron kerma (unshielded): 0.031 Gy (remain unchanged)

*Number of SEU in 1 MB bq4017MC-70 SRAM (shielded): ~ 8.0

Gradient : 30 MV. m⁻¹ (Worst Case Scenario)

Gamma Dose (shielded): 760 Gy

Neutron kerma (unshielded): 0.050 Gy (remain unchanged)

*Number of SEU in 1 MB bq4017MC-70 SRAM (shielded): ~ 10

* Using the SEU Cross Section of $2.3 \times 10^{-13} \text{ cm}^2 \cdot \text{bit}^{-1}$ (D Makowski, PhD Thesis, 2006, DMCS, TU Lodz, Poland and experimentally estimated thermal neutron cut off factor of 10^{-4}).

THE INTERCOMPARISON

Heavy Concrete versus Lead

Parameter	Concrete Slab	Lead Plate
Area	1m ²	1m ²
Thickness	20 cm	1cm
Density	4.8 g.cm ⁻³	13.6 g.cm ⁻³
Volume	0.2 m ³	0.01 m ³
Weight	960 kg	136 kg
Photon Trans. Factor	0.05	0.05

A Lead Shielding outperforms Heavy Concrete Shielding, whereas delivering the same level of Photon Attenuation

RADIATION EXPOSURE OF SRAMS AT FLASH BEAM DUMP



1GeV Electron beam stopped in the water-cooled Aluminium Beam Dump, thereby producing an intense field of parasitic neutrons.

Two pairs of 512 kB non-volatile SRAM, 1st pair kept bare, 2nd pair covered with 3 mm thick borated polyethylene sheet, were placed near beam dump.

7 days exposure during routine FLASH Operation, then read out off-line

RESULTS

**Bare SRAM => 1380 SEU (mean), Shielded SRAM => 80 SEU (mean)
Hence, 3mm Polyboron sheet mitigates the SEU by a factor of 0.06**

SUMMARY AND CONCLUSION

The energy spectra of photoneutrons and bremsstrahlung photons produced by interaction of 1 GeV electrons with 2 mm thick Niobium plate were evaluated using FLUKA simulation code.

The simulation results have been confirmed with the radiation measurement data from FLASH.

Photon (bremsstrahlung) shielding efficacy of Heavy Concrete (Boron additive)/Polyethylene and ordinary Lead was evaluated using MCNP 4A simulation code.

10 years (projected XFEL operation, cold side) integrated gamma dose (causing TID) and neutron fluence (causing NIEL) in microelectronics, under shielded as well as un-shielded conditions have been calculated (predicted) from FLASH radiation measurement data.

Shielding efficacy of Boronated Heavy concrete slab (20 cm thick) and Lead plate (1 cm thick) lined with boronated polyethylene sheet (3 mm thick) were compared

High performance of 3 mm thick boronated polyethylene sheet to mitigate the thermal neutron induced SEU in SRAM (emulating a PC) placed near the main beam dump of FLASH has been demonstrated.

A 20 cm thick heavy concrete slab found to possess the same level of photon attenuation property as a 1 cm thick Lead plate.

Boronated polyethylene lined 1 cm thick Lead plate found to be the most suitable shielding for the microelectronic devices to be located in the COLD SIDE of the XFEL linac.

THANK YOU FOR YOUR ATTENTION