Measurement of Critical Radiation Levels at FLASH and their Relevance to XFEL

BHASKAR MUKHERJEE

Deutsches Elektronen-Synchrotron (DESY)

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Motivation and Goal of this Talk

During 2004-2006 we have carried out numerous radiation measurements at FLASH and gathered important radiation dosimetry and spectrometry related data

Like FLASH the future XFEL will be made of superconducting TESLA cavities operating at about same gradient level (~ 24 MV/m)

Hence, this talk will focus on the applicability of radiation measurement data evaluated at FLASH to predict radiation levels at critical locations of interest at XFEL

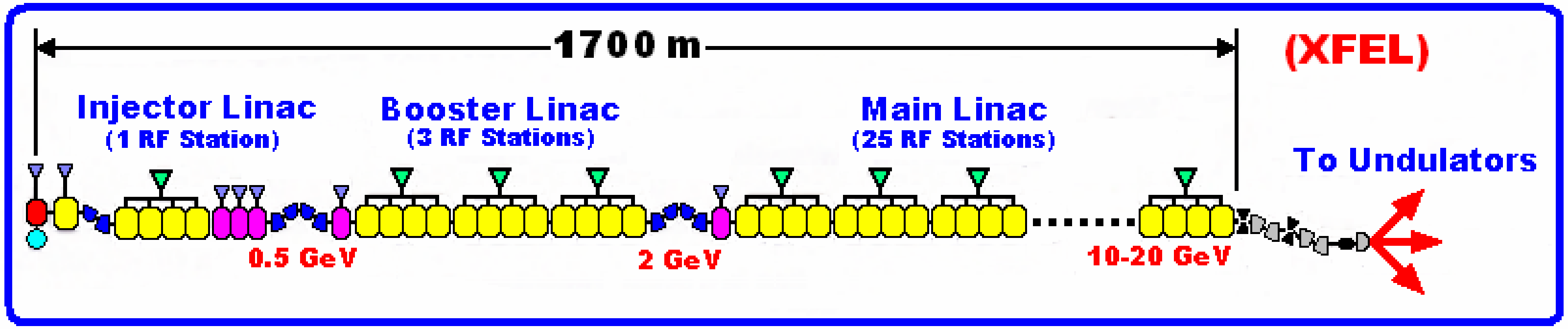
The data will be used to serve for three major objectives at XFEL:

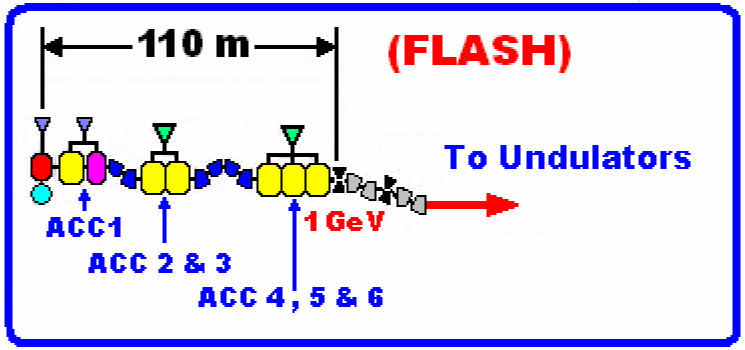
(a) Source term for radiological shielding (mitigation) calculation

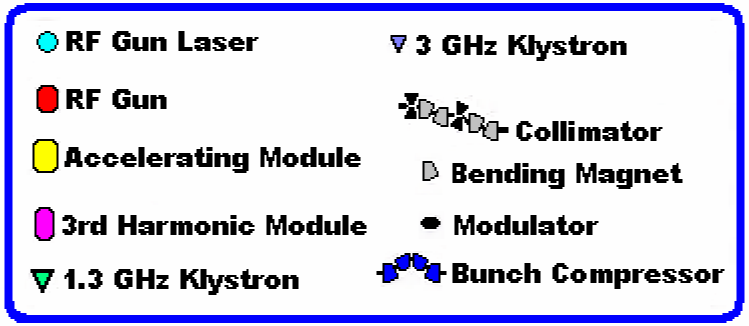
(b) Prediction of radiation induced damage in semiconductors (electronics) and Optoelectronics

(c) Selecting the radiation monitoring criteria at XFEL

Linac sections of XFEL and FLASH : Intercomparison







PARAMETERS	FLASH	XFEL
Length(m)	110	1700
End Energy(GeV)	1	20
Number of Modules	6	116
Number of Cavities	48	928
Cavity Type	TESLA	TESLA
Number of RF Stations	4	29
Location of RF Stations	Outside	In Tunnel
Gradient (MV/m)	16-21	23.6-30
QF (unloaded)	5.0E09	10E10
Repetition Rate (Hz)	5 - 10	10
RF Pulse Length	1.33	1.40
Beam Pulse Length (ms)	0.80	0.65
Wavelength (nm)	1	0.1
Peak Power (kW)	208	600

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Fig.1

Radiation Measurements conducted at FLASH

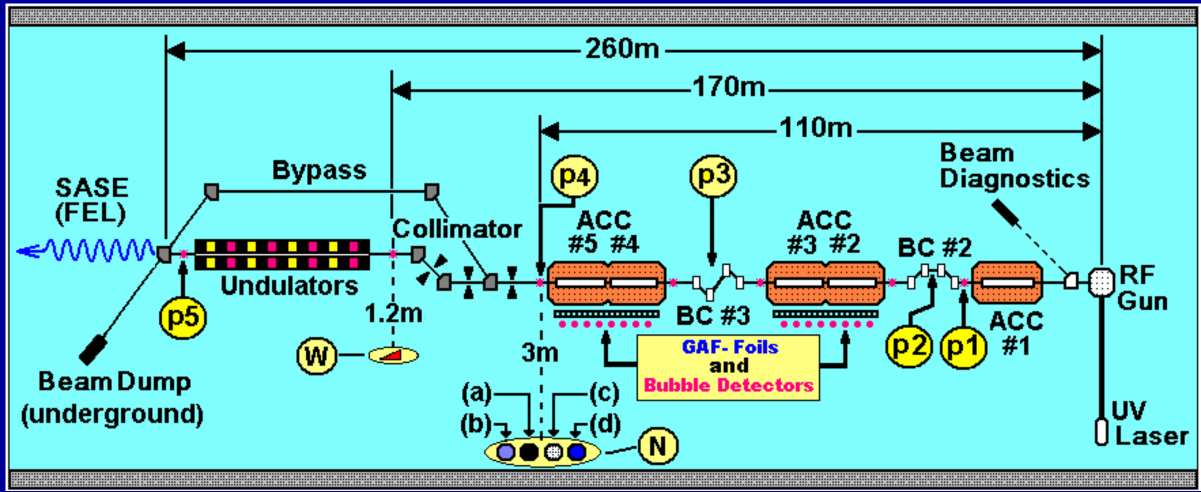


Fig. 2

Exp #1: In-situ gamma dose measurement along accelerator modules ACC1 – ACC5 using radiochromic (GAF) Films and Bubble Detectors

Exp #2: In-situ neutron and gamma dose measurement at accelerator module ACC 5 operating in "Field Emission Mode" using PorTL TLD bulbs and Bubble Detectors

Exp #3: In-situ Photo-Neutron spectrum evaluation near accelerator module ACC 5 (position N) using Bubble Detectors

Exp #4: In-situ unfolding of bremsstrahlung (photon) spectrum near the collimator (position W) using TLD chips embedded in a lead wedge

Exp #5: In-situ measurement neutron dose/fluence at critical locations along the beam pipe (positions p1, p2, p3, p4 and p5)

Exp # 1: Results

Gamma does rates along FLASH during Routine Operation at a gradient of ~ 21 MV/m

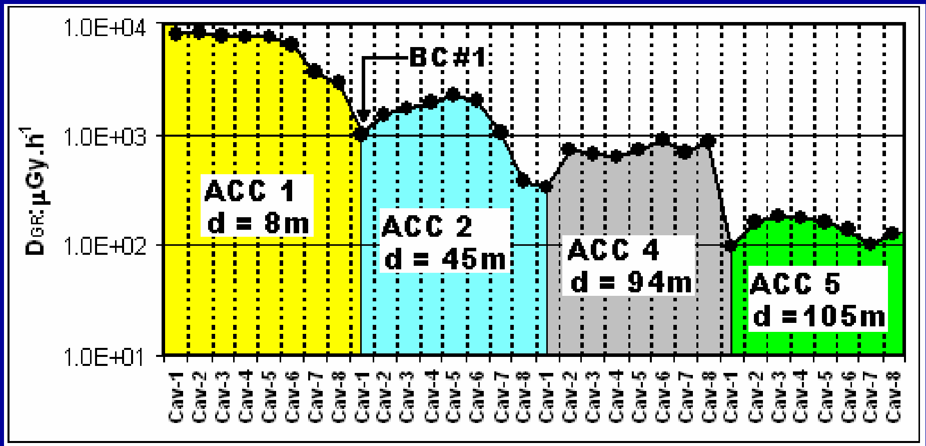


Fig. 3

(R1.1) Accelerated dark current from RF gun is the prime source of gamma dose.

(R1.2) Gamma dose rate drops strongly with the distance from the RF gun.

(R1.3) Gamma dose rate at the cryomodule (ACC 1) near bunch compressor (BC #1) is two orders of magnitude higher than the distant module ACC 5.

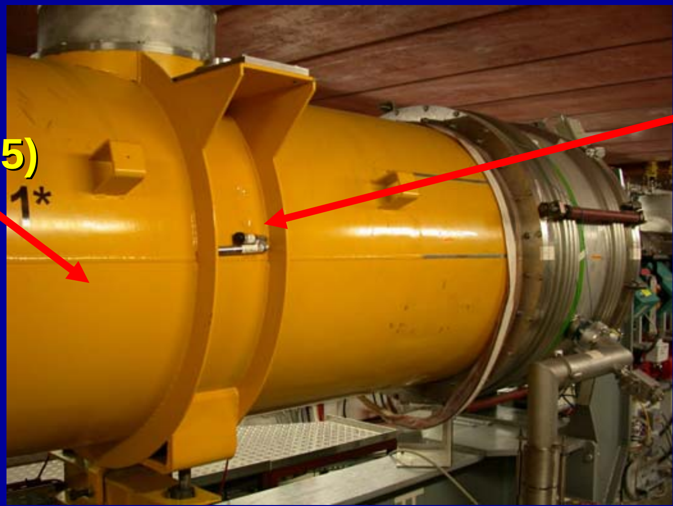
(R1.4) The radiation dose at modules, far away for the RF gun mainly contributed by the accelerated field emission electrons inside cavities.

(R1.5) The radiation doses (both gamma and neutron) depends on “locally produced” accelerated (~ MeV) field emissions, “NOT ON” the main Electron Beam (~ GeV).

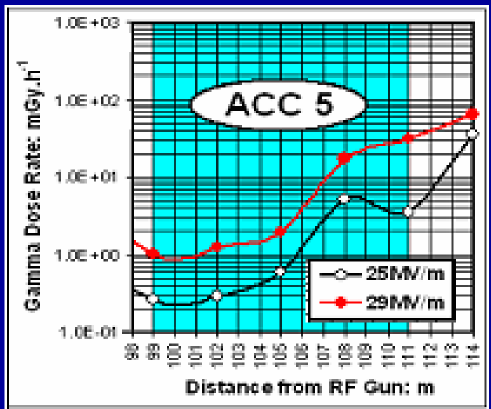
Exp #2: Results

In-situ Gamma/Neutron Dosimetry at FLASH Module

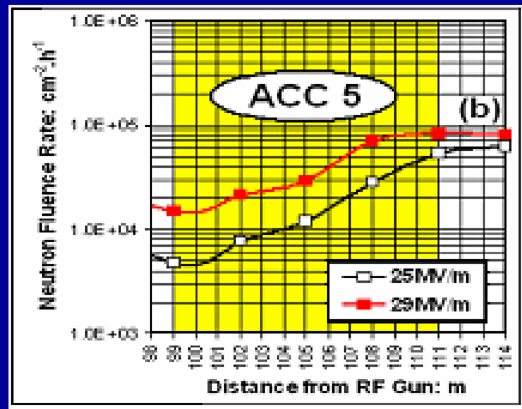
Accelerator
Module (ACC 5)



Neutron/Gamma
Dosimeter pairs



Field Emission Mode
(RF Gun OFF)



Gamma Dose Rate along the module tank, estimated using TLD and GAF-Dosimeters.

Neutron Fluence Rate along the module evaluated with Bubble dosimeters.

Exp #2: Results (continued)

Neutron kerma and Gamma Dose Rates along the Module

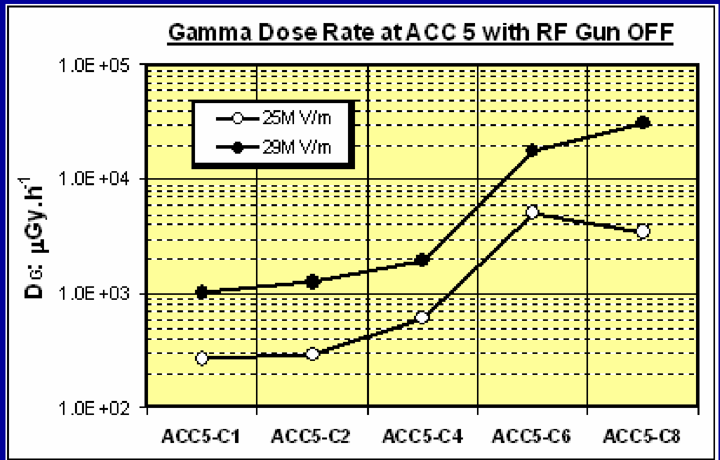


Fig. 4a

Gamma dose rate along ACC 5 running in Field-Emission mode

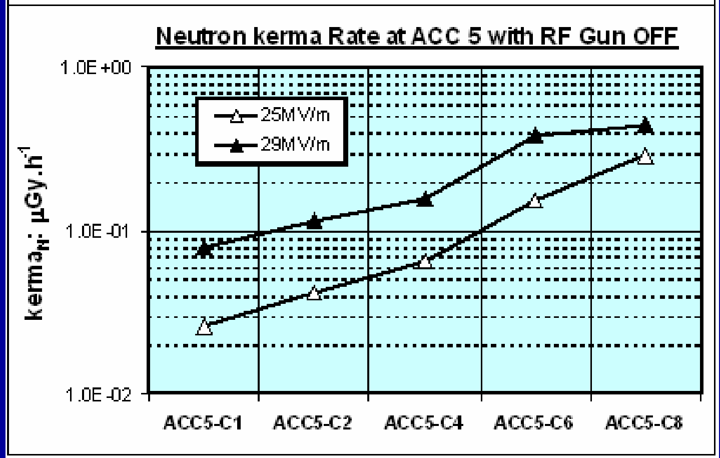


Fig. 4b

Neutron kerma rate along ACC 5 running in Field-Emission mode

- **(R2.1) Gamma Dose rate is 4 orders of magnitude higher than neutron kerma (Si) rate.**

Exp #2: Results (continued)

Gamma Dose Rates evaluated at different Gradient

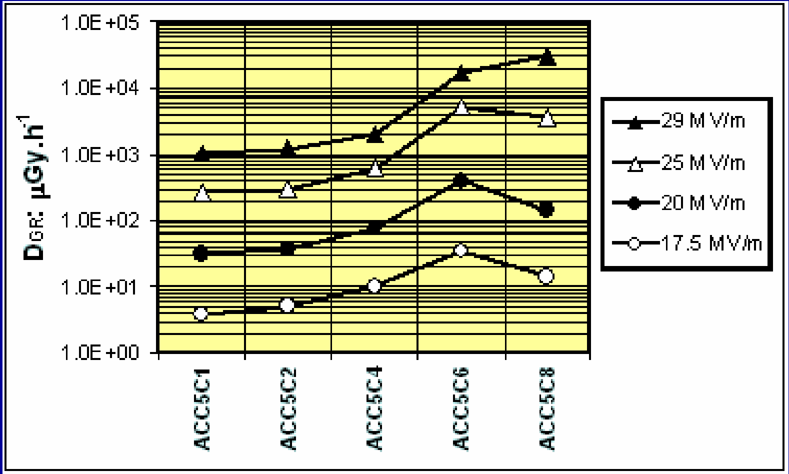


Fig. 5a

Gamma dose rates along ACC 5 estimated using radiochromic films while running in field emission mode (RF gun off).

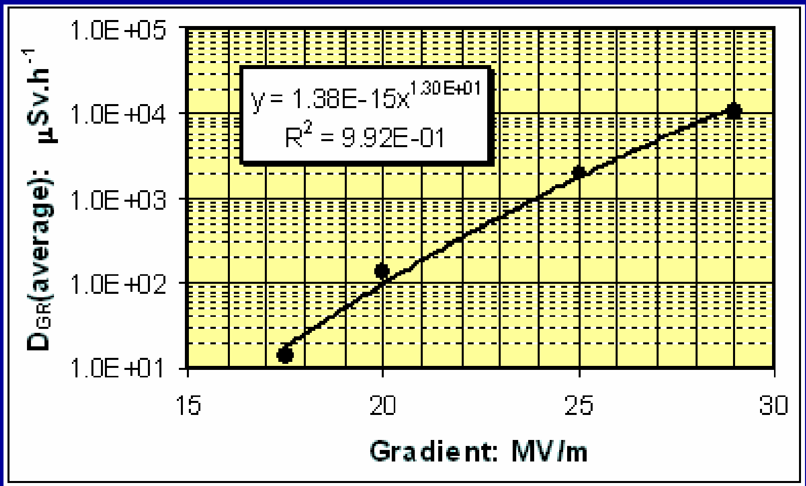


Fig. 5b

Average Gamma dose rate plotted as a function of the Gradient across the module.

- **(R2.2) Gamma Dose Rate skyrockets with the Gradient**

Exp #2: Results (continued)

Radiation induced Cryogenic Loss

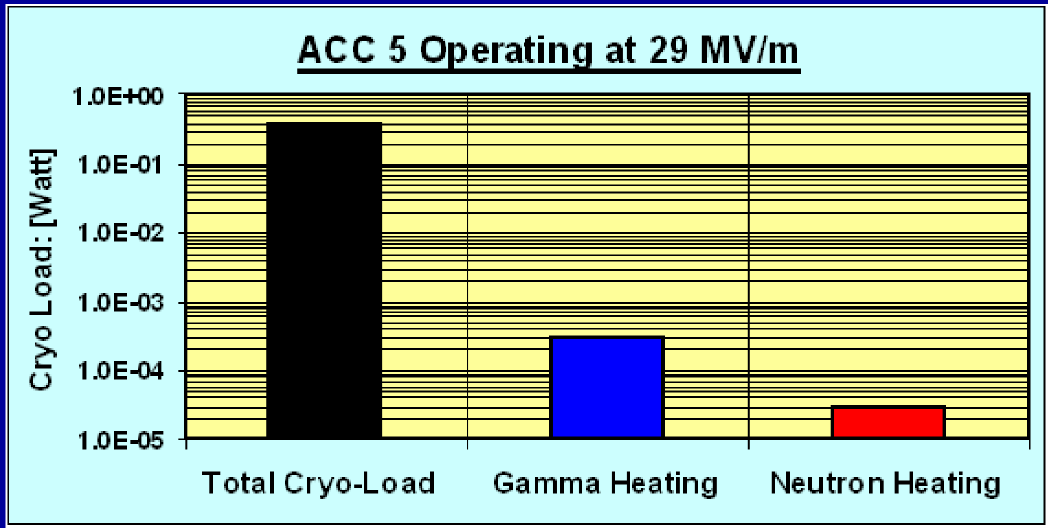


Fig. 6

(R2.3) TLD bulbs (gammas) and Bubble detectors (Neutrons) were used to assess radiation doses (kerma) and then used to derive the Cryogenic Losses (nuclear heating).

(R2.4) Neutron and gamma radiations are produced when high- energy electrons strike the superconducting Niobium cavities.

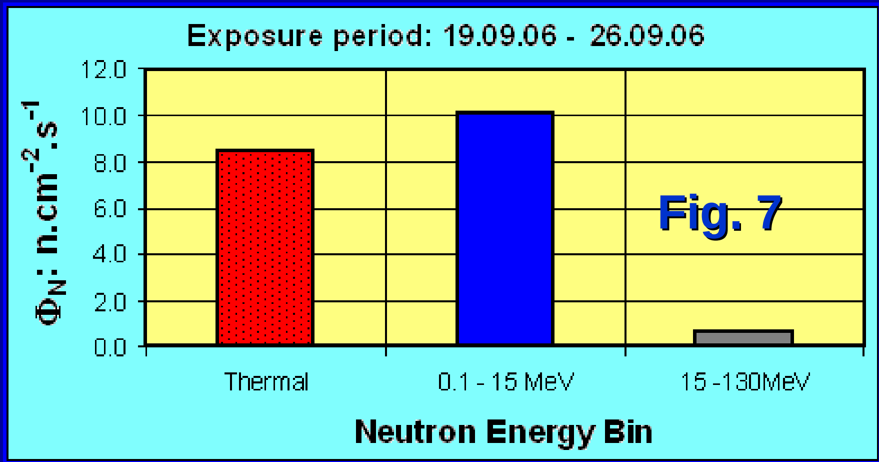
(R2.5) At 2 K, Niobium is superconducting, hence, Ohmic- heat loss is nil. Neutrons and gamma rays interact with liquid He causing Cryogenic Loss.

(R2.6) Radiation induced Heat Generation is more than THREE ORDERS OF MAGNITUDE lower than the loss produced by other sources (???).

Exp #3: Results

Estimation of Photoneutron Energy Distribution (Spectrum) using Bubble Detectors

Bubble detectors are Ideally suited for Pulsed Neutron Dosimetry with a strong gamma background, such as in FLASH/XFEL tunnel.



The 3 bin Neutron Fluence spectrum estimated near ACC 5 (Gradient = 25 MV/m).

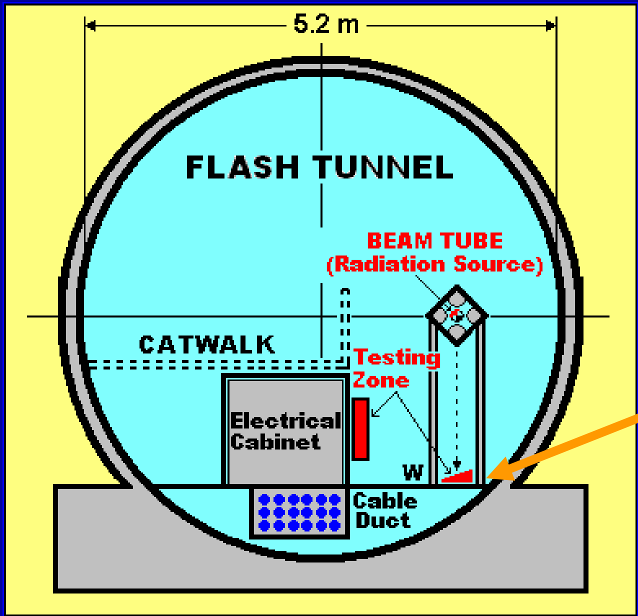
(R3.1) Giant Dipole Resonance neutrons of energy 0.1- 15 MeV are most predominant

(R3.2) Thermal neutrons are produced by room scattering of photoneutrons (s. above) and may trigger SEU in some microelectronic memories.

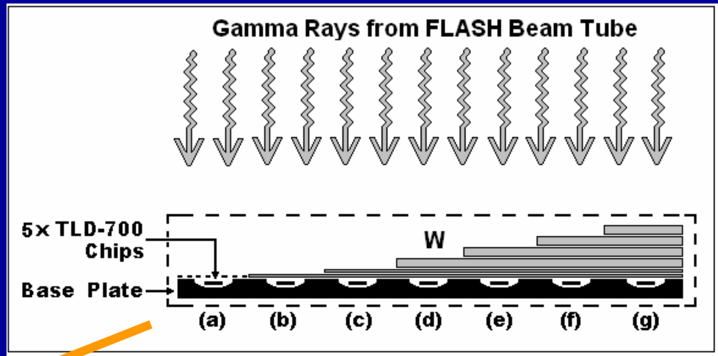
(R3.3) Number of high-energy (> 15 MeV) neutrons are significantly low.

Exp #4: Results

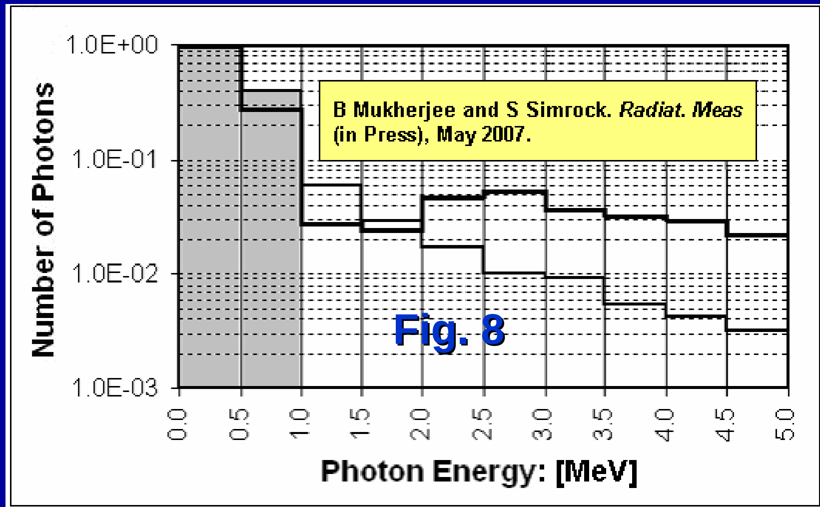
Unfolding of the Bremsstrahlung Spectrum



Location of the Lead Wedge in the FLASH Tunnel



The Lead wedge embedded with TLD Chips



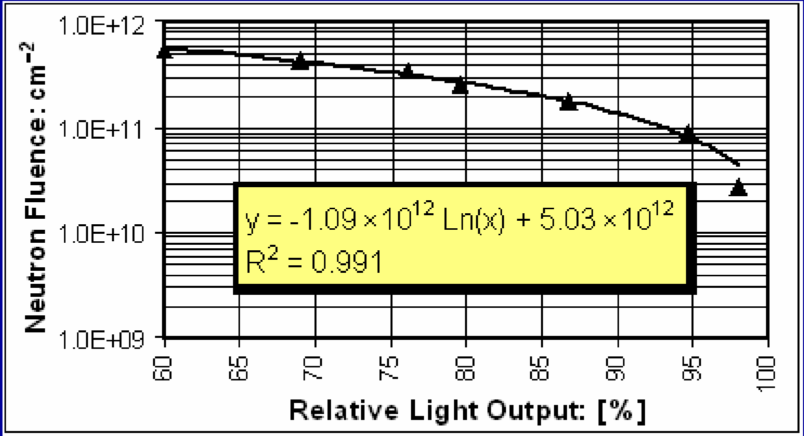
The unfolded bremsstrahlung spectrum

(R4.1) The peak and average bremsstrahlung (BS) photon energy were calculated to be 0.5 and 0.9 MeV respectively

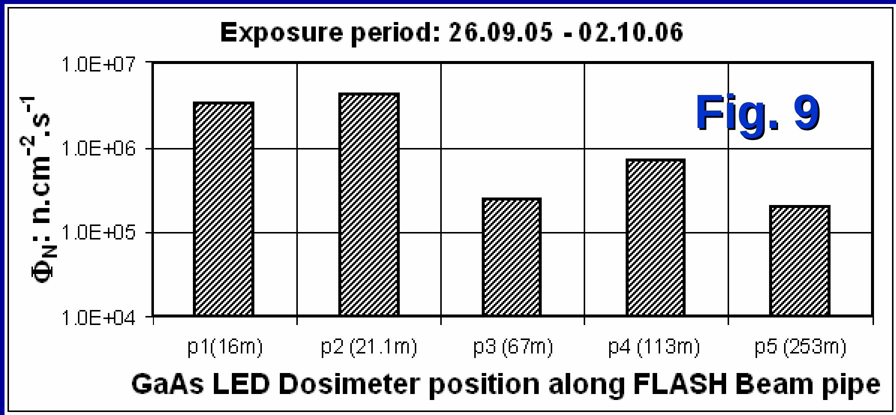
(R4.2) Major (92%) part of the BS is contained within 1 MeV band (shaded area)

Exp #5: Results

Fast Neutron Dose Rates along the FLASH Beam pipe Estimated in-situ using GaAs LED (COTS)



Calibration curve of the GaAs dosimeters evaluated using a ^{241}Am/Be Neutron Source.



Fast neutron fluence along the FLASH beam pipe estimated with tiny GaAs Dosimeters.

(R5.1) Significant levels of neutron fluence are produced at critical areas (bunch compressors, collimator, injector) due the interaction of "transversally diverted" electrons with the beam tube wall locations p1, p2, p3, p4 and p5 in Fig. 2)

(R5.2) These neutrons are generated in small areas, intensity drops significantly with distance from the production spots (i.e. beam interaction regions), "NIL"effects on LLRF electronics.

Applicability of FLASH Radiation Data for the prediction of Radiation Levels in XFEL

Based on the following grounds

(1) Radiation fields are locally produced by the accelerated field emissions in the cavities itself, not by the primary high-energy electron beam (*Fig. 3*).

(2) The Gamma dose (kerma) outperforms the neutron kerma by excess of 4 orders of magnitude (*Fig. 4a* and *4b*), also be valid for XFEL

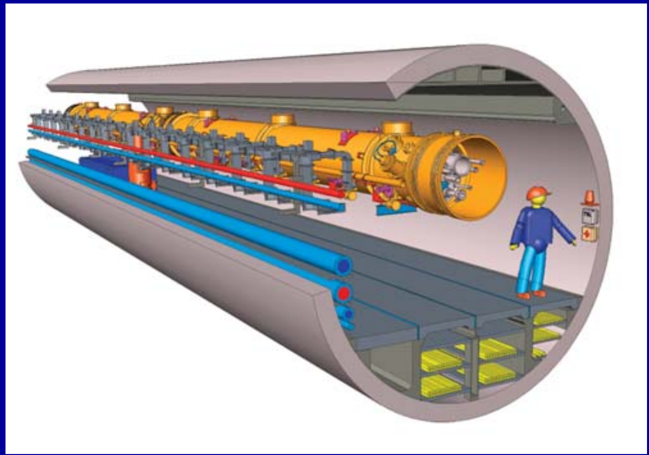
(3) For both FLASH and XFEL the major radiation component are photons, the relevant photon dose depends solely on the gradient across the cavity (*Fig. 5a* and *5b*) and the surface quality (polishing) of the cavities.

(4) Same type of superconducting TESLA cavity presently used at FLASH will be deployed in XFEL project (*Fig. 1* and *2*). Hence, we can predict the radiation induced cryogenic loss will also be very low for XFEL (*Fig. 6*).

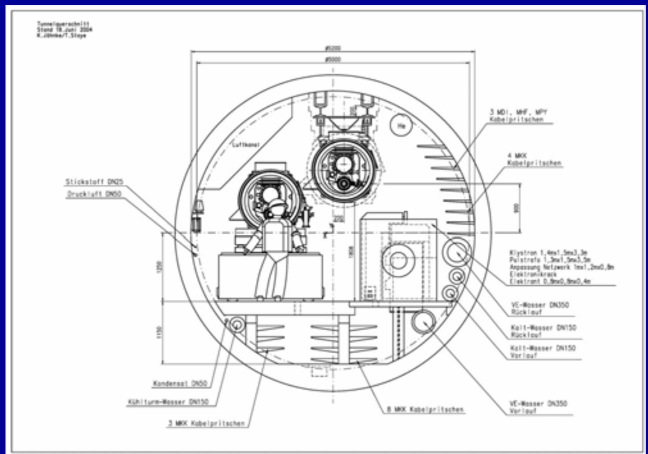
(5) The energy spectra (*accelerated field emission electron generated*) of the photoneutrons (*Fig. 7*) and bremsstrahlung (*Fig.8*) for both FLASH and XFEL will be quite similar.

(6) The electron energy at bunch compressors of FLASH and XFEL (*Fig.1*) will be within the 0.5 – 2 GeV band, hence, the characteristics of the stray neutrons produced in the beam pipe will be the same (*Fig. 9*).

Application: Shielding for LLRF Electronics in XFEL Tunnel



Panoramic view of the XFEL Tunnel showing the Cryomodule, Utility ducts and Electrical cable trays.



Tunnel Cross Section.

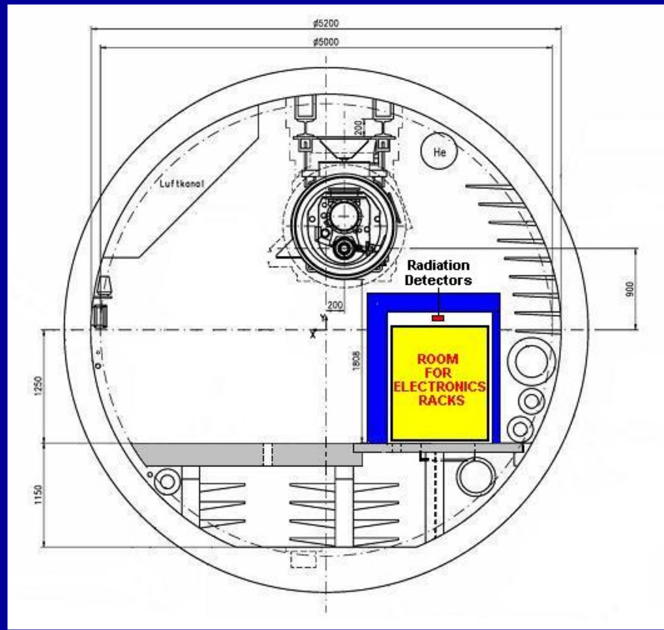


Fig. 10

Shielded Space allocated for the LLRF-Electronics and associated Radiation detectors.

(1) Data from FLASH studies was used as source terms for MCNP simulation

(2) Heavy concrete (ρ = 3.8 g.cm^{-3}) with 10 % B_4C additive was found to be most suitable

Application of FLASH data to predict the Radiation Effects in Electronic Components to be placed in XFEL Tunnel

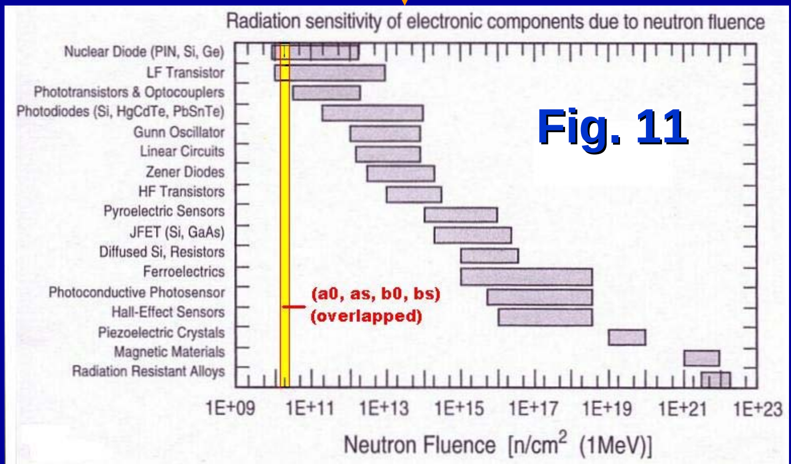
Radiation Data	G = 30 MV/m		G = 23.6 MV/m	
D_G (no shield): [μGy.h^{-1}]	2.2×10^4		9.72×10^2	
D_G (no shield)/10y: [Gy]	1.76×10^3	(a0)	7.78×10^1	(b0)
D_G (shield)/10y: [Gy]	33.4	(as)	1.48	(bs)
Φ_N (no shield): [cm^{-2}h^{-1}]	6.91×10^5		5.54×10^5	
Φ_N (no shield)/10y: [cm^{-2}]	5.53×10^{10}	(a0)	4.32×10^{10}	(b0)
Φ_N (shield)/10y: [cm^{-2}]	4.42×10^{10}	(as)	3.46×10^{10}	(bs)

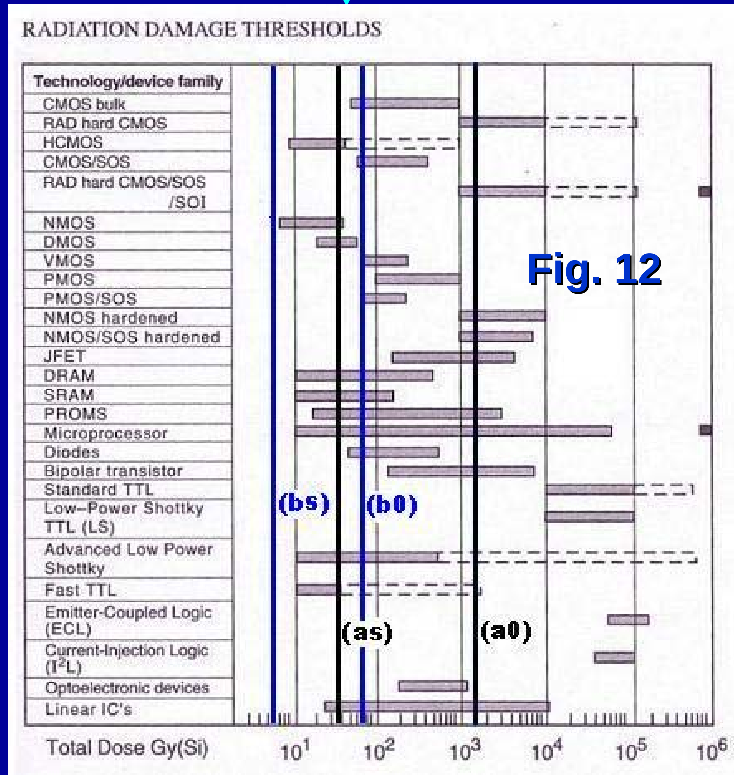
Shielding: 20 cm Heavy Concrete
Dose reduction factor: 0.019

Neutrons

Table 1

Gammas





Reference: A W Cho and M Tigner (Eds): *Handbook of Accelerator Physics and Engineering*, World Scientific, Singapore, London, 3rd Edition, 2006.

Radiation Effects on Various Materials: Summary

Radiation Data	G = 30 MV/m		G = 23.6 MV/m	
D_G (no shield): [μGy.h^{-1}]	2.2×10^4		9.72×10^2	
D_G (no shield)/10y: [Gy]	1.76×10^3	(a0)	7.78×10^1	(b0)
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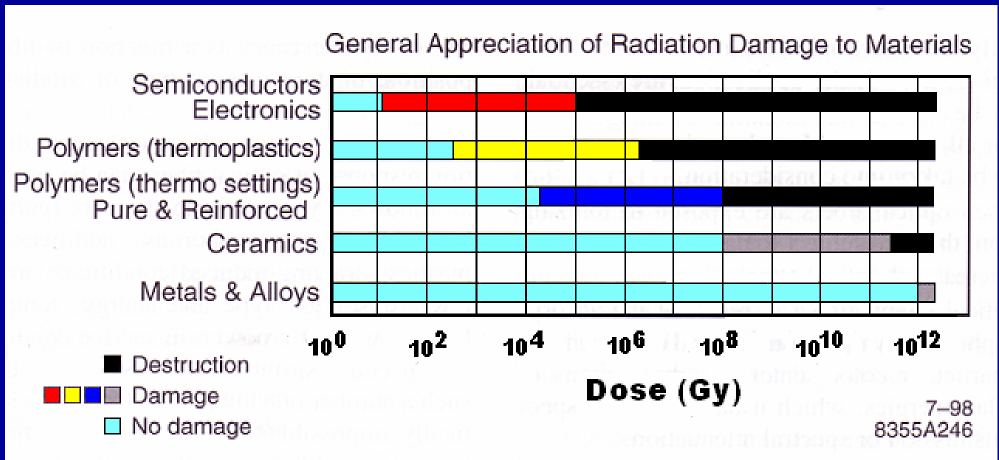

Semiconductors are most vulnerable

Followed by Polymers, i.e. optocouplers, Optical fibre etc.

Example:

Gamma Dose Rate near ACC 1 (Figure 3): 0.01 Gy/h

Hence,
Damage threshold for semiconductors will reach after: 1000 hours

Damage threshold for optical devices will reach after: 50000 hours

Reference: A W Cho and M Tigner (Eds): *Handbook of Accelerator Physics and Engineering*, World Scientific, Singapore, London, 3rd Edition, 2006.

Radiation Sources and Mitigation Strategies

Sources:

1) Primary source: Bremsstrahlung (Photons) causing TID
2) Negligible fast neutrons (4 orders of magnitude lower than photons, considering the Silicon kerma
3) Wall scattered thermal neutrons, causing SEU (non detrimental)

Mitigation:

1) Use radiation hard electronics (military standard) => Very expensive
2) Use COTS components with adequate shielding made of heavy concrete or lead (*please note TMR and other software based techniques are irrelevant to eliminate the TID*)
3) Use thick lead shielding around CCD cameras and optoelectronic devices
4) Use a Borosilicate glass filter to prevent the creation of “Hot Pixels” in CCD cameras

Radiation Monitoring Criteria for XFEL

Photons are the prime source of detrimental effects.

Photon sensors with a wide dynamic range, immune to "pulsed" nature (PW) of radiation at XFEL shall be used.

The photon detectors will be of small size and located inside the concrete vault situated in XFEL tunnel housing the LLRF and Power electronics devices.

The detectors will be capable to respond a wide range of gamma dose rate from the accelerator modules and provide warning signals enabling to limit the "module gradient", thereby reducing the gamma dose at the location of interest.

Summary and Conclusion (1)

We have carried out extensive radiation measurements projects at FLASH during the period 2004-2006

At superconducting electron linac driving FLASH/XFEL gamma and neutron radiation fields are predominantly produced by accelerated field emission electrons: (a) inside the cavity itself (b) not influenced by main electron beam, accelerated to several GeV.

The XFEL will be made of similar type of superconducting TESLA cavity currently used at FLASH (Fig. 1). Hence, experimentally estimated radiation parameters of FLASH could reliably be used for radiation dose predictions at XFEL.

The FLASH radiation data was used as "source term" for Monte Carlo Shielding calculations. 20 cm thick heavy concrete slabs found to be most optimum to protect the LLRF electronics, to be installed in the XFEL tunnel (Fig. 10).

Summary and Conclusion (2)

10 years (projected XFEL operation) integrated gamma dose (causing TID) and neutron fluence (causing NIEL) in LLRF electronics, under shielded as well as un-shielded conditions have been calculated (Table 1).

Semiconductor and Optoelectronic devices near RF Gun/Injector could be exposed to high levels of gamma radiation resulting in irreversible damage.

Radiation effects of neutrons (Fig. 11) and gamma rays (Fig. 12) in various COTS electronic components have been investigated.

At XFEL the Total Ionising Dose (TID) found to be the main source of radiation damage in electronics, whereas the role of displacement damage (NIEL) from neutrons predicted to be very low (Table 1).

The Single Event Upset (SEU) poses no long term “detrimental effects” in electronics, hence, not included in this presentation.

Bhaskar thanks you for your Patience