Passive and real-time radiation monitoring at FEL facilities using radiochromic films, bubble detectors and thermoluminescent dosimeters

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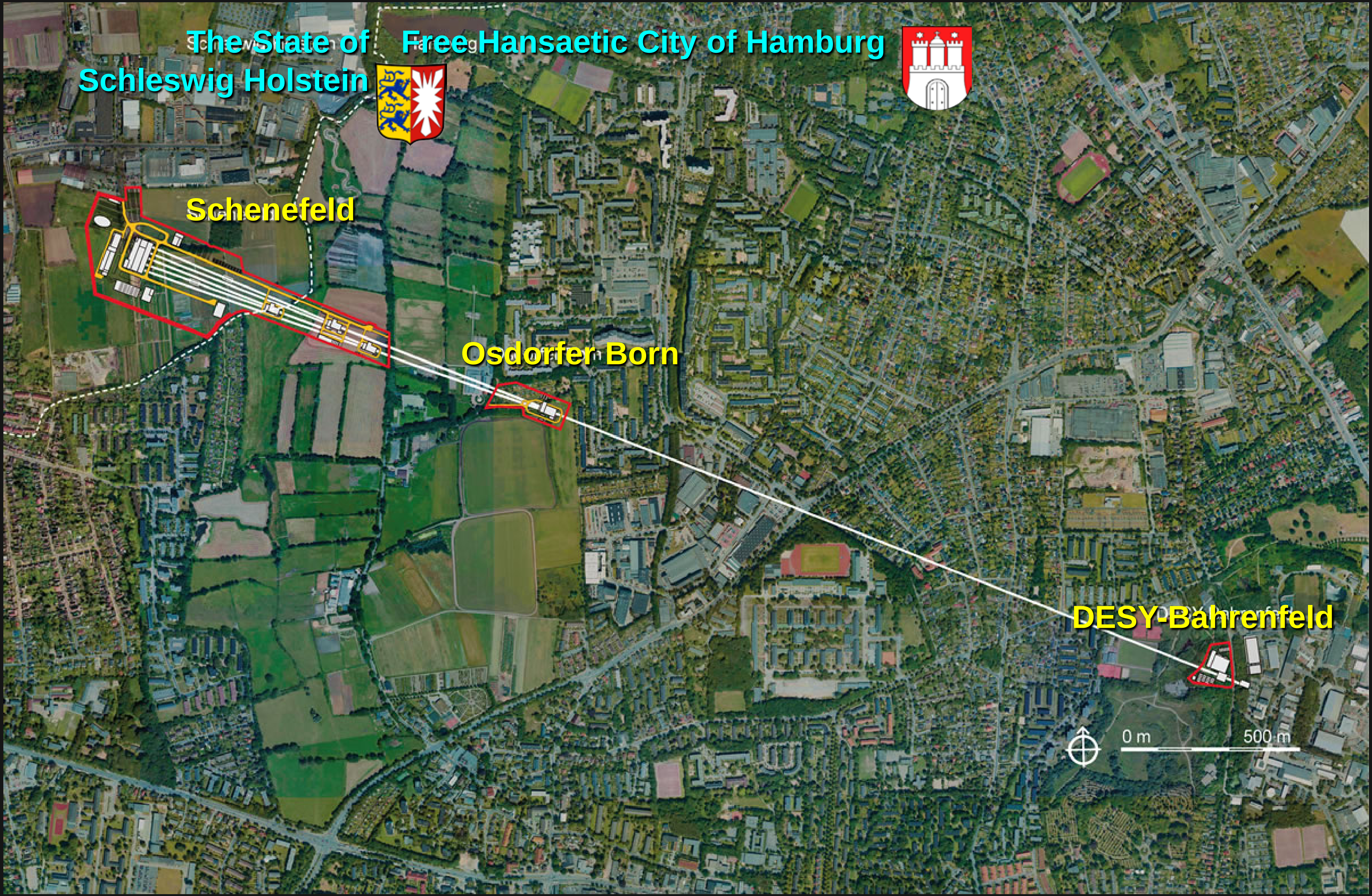
Deutsches Elektronen-Synchrotron (DESY), Hamburg, GERMANY

Light Sources Operating in DESY Compound

European XFEL- Layout



Motivation of our Research

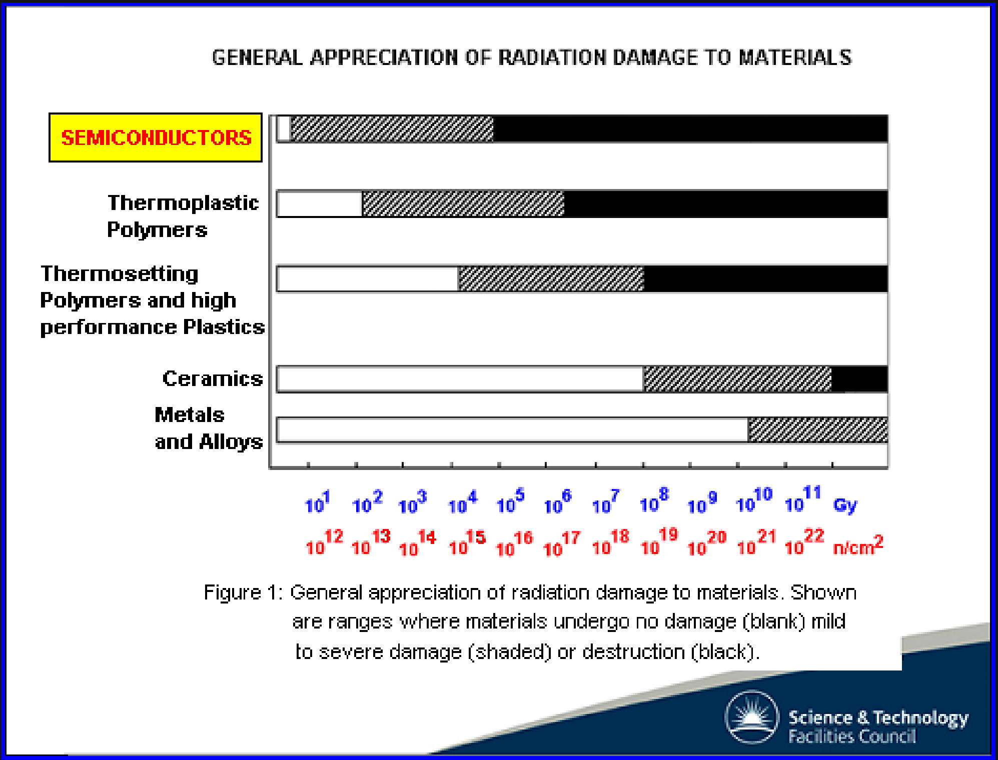
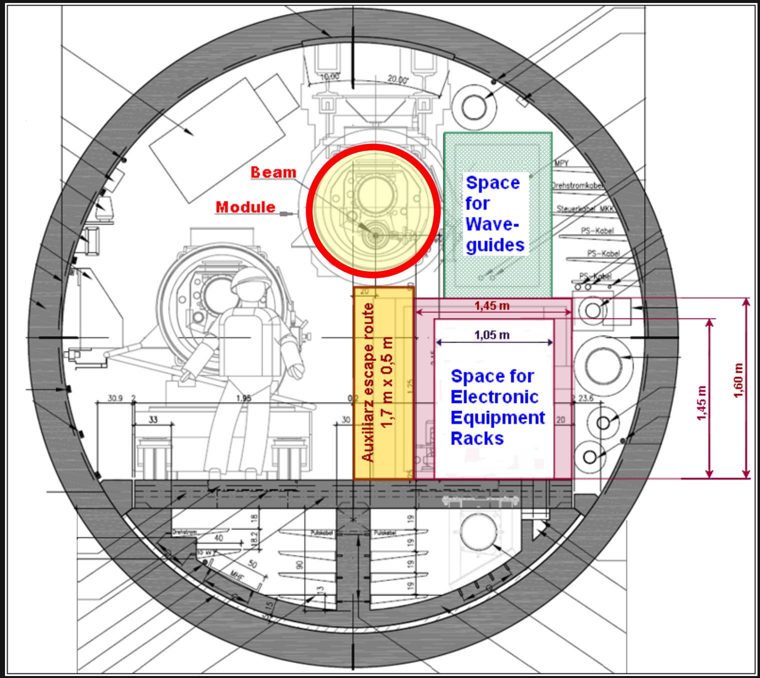


Figure 1: General appreciation of radiation damage to materials. Shown are ranges where materials undergo no damage (blank) mild to severe damage (shaded) or destruction (black).

Semiconductors (microelectronics) are in general highly susceptable to ionising radiation.

Instrumentation and control devices of modern particle accelerators are solely based on microelectronics.

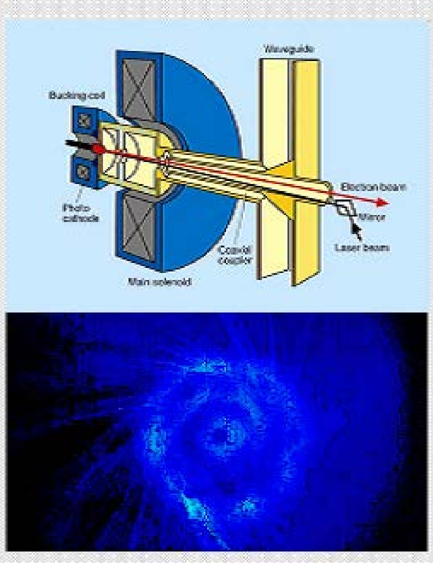
In jam packed FEL tunnel (i. e. European XFEL@ DESY) electronic equipment racks are installed in close proximity of the accelerator modules producing <u>parasitic (gamma and neutron) radiation</u>.



Hence, for a safe and uniterrupted operation of the FEL facilities monitoring of this parasitic radiation and impementation of suitable radiation shielding for the racks housing sensitive electronic devices become mandatory.

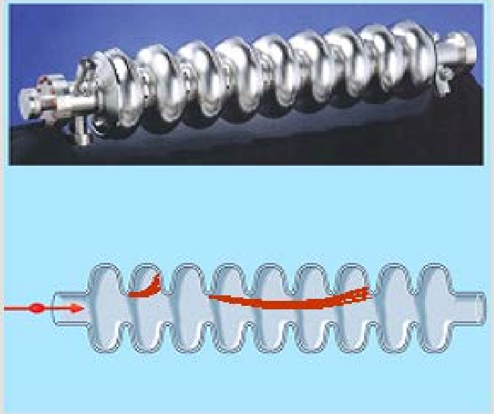
Parasitic Radiation Sources in FEL

Dark current



Typical Dark Current Distribution

Field emission



Fowler Nordheim Theory

Beam losses

Bunch Compressors and Injector

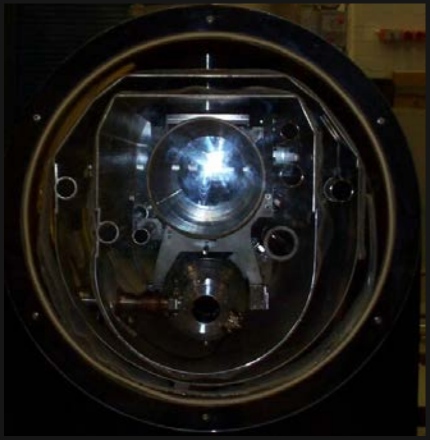
Valid for FLASH as well as European XFEL

Impression of the Free Electron Laser in Hamburg (FLASH) operating since April 2006 at DESY

a) Superconducting modules

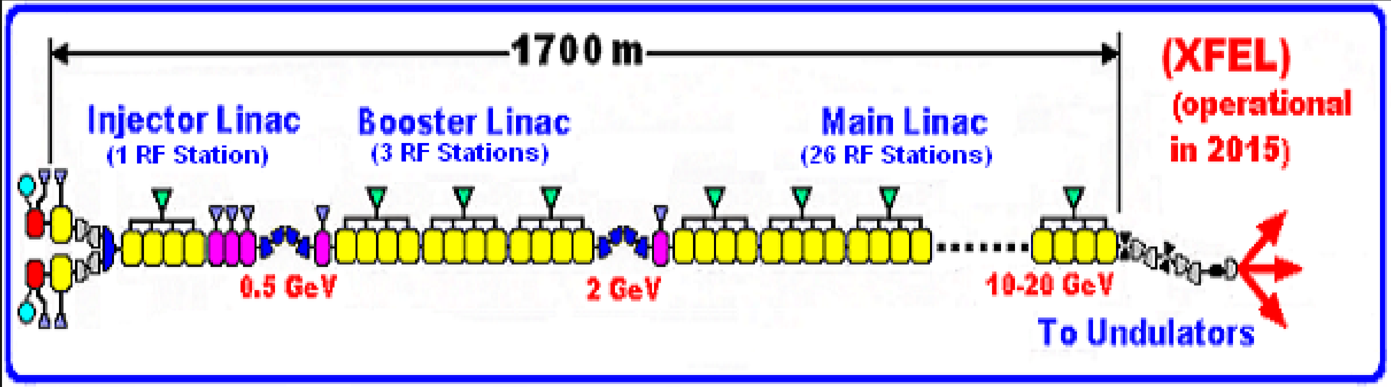
b) Beam line with diagnostic system

c) Undulator- array (SASE FEL)



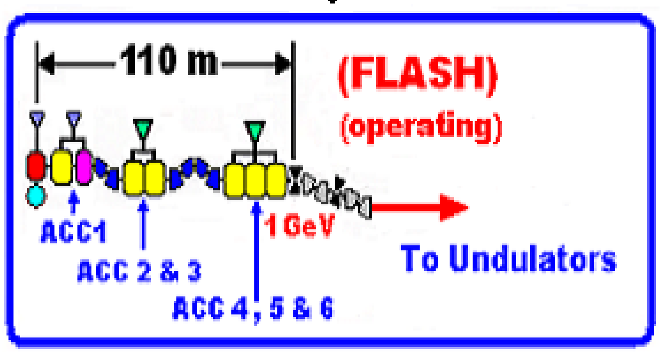
d) TESLA Module cross section

FLASH and XFEL an Intercomparison



Dark current induced gamma dose in XFEL will be much less than that of FLASH

Field emission electron induced gamma dose in XFEL will be 2.15 times higher than that of FLASH

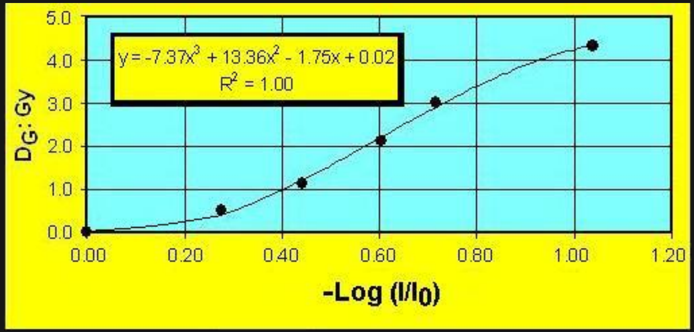


PARAMETERS	FLASH	XFEL
Length(m)	110	1700
End Energy (GeV)	1	20
Number of Modules	6	116
Number of Cavities	48	928
Cavity Type	TESLA	TESLA
Number of RF Stations	4	30
Location of RF Stations	Outside	In Tunnel
Gradient (MV/m)	16-21	23.6-30
QF (unloaded)	5.0E09	1.0E09
Repetition Rate (Hz)	5 - 10	10
RF Pulse Length (ms)	1.33	1.40
Beam Pulse Length (ms)	0.80	0.65
Wavelength (nm)	10	0.1
Peak Power (kW)	208	600

Passive-Gamma Dosimetry (TLD and Radiochromic Films)

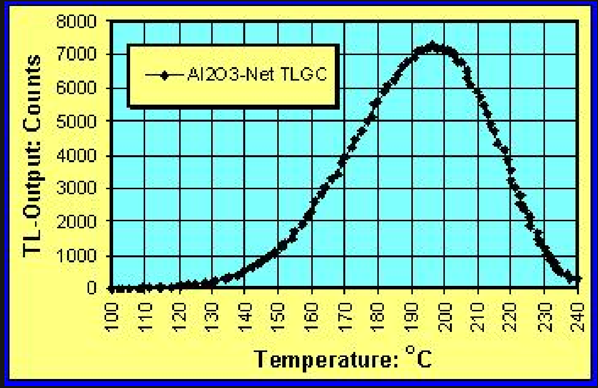
(a) Radiochromic Films (GaF-EBT)

Photograph of ^{60}Co gamma irradiated radiochromic films



Calibration curve of radiochromic film dosimeters

(b) Thermo-Model 3500 TLD-Reader



TL- Glow curve of a Al_2O_3 (TLD-500) chip

Radiochromic films were used for long term, simultaneous assessments of gamma doses at various locations in FLASH tunnel.

TLD chips were used for precise short-term assessments of gamma and fast neutron Fluence (kerma) at contact with the accelerator modules.

Passive-Neutron Dosimetry (bubble detectors)

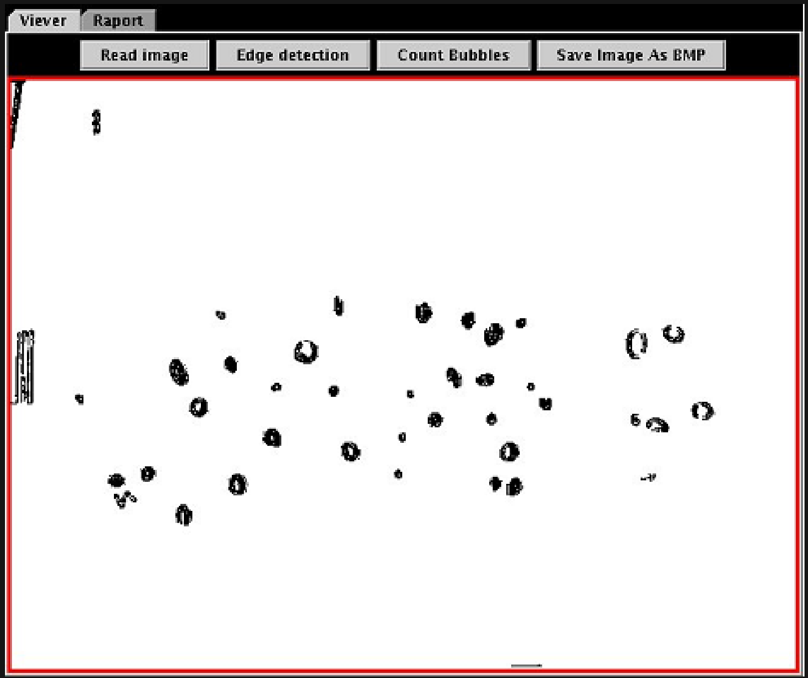
(Ideally suited for neutron detection in a strong gamma background)

(a) Input: Digital photograph of the bubble dosimeter after neutron exposure

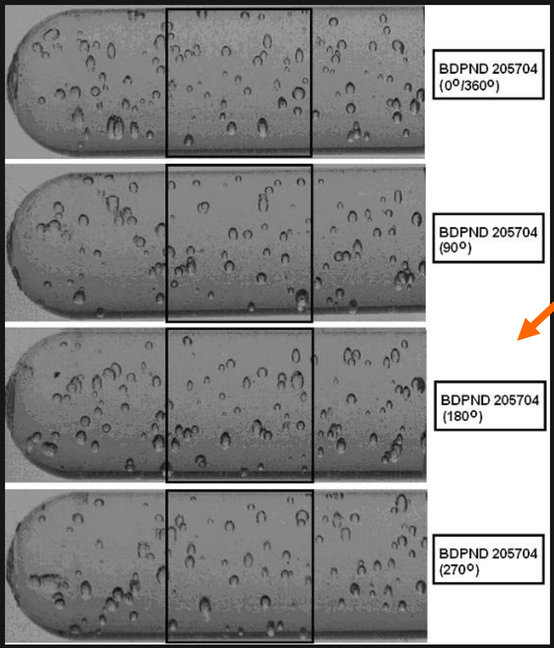
(b) Edge Detection

(c) Image counting

(d) Data output

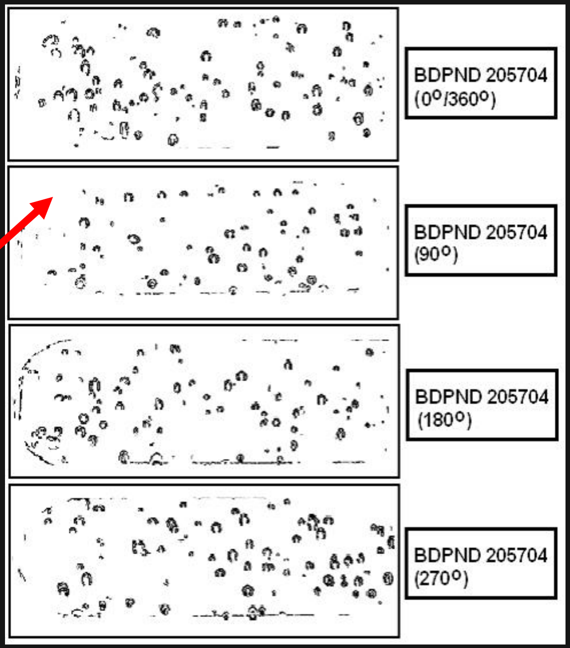


Automatic Bubble Counting Algorithm (ABCA)



Original Photos

Filtered Photos (ABCA)

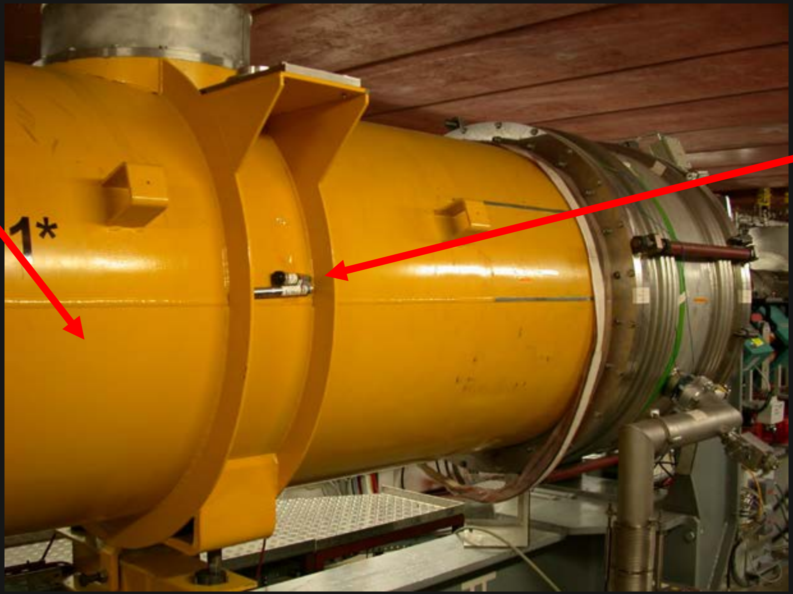


Bubble Count Results: (Manual vs. ABCA)

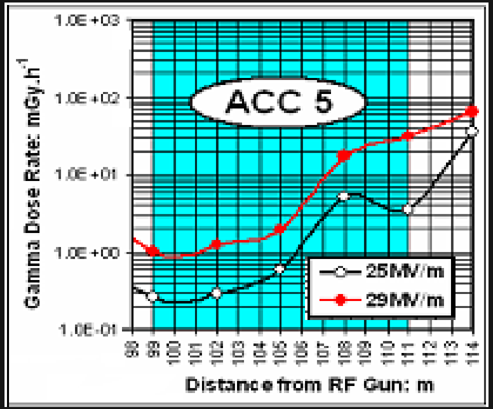
	BDPND205704
Neutron DE(micro Sv)	50.6
Average Nr. of Bubbles (ABCA)	118.8
Average Nr. of Bubbles (Manual)	118.5
Sensitivity/ABCA (micro Sv/bubble)	0.426
Sensitivity/Manual (micro Sv/bubble)	0.427
Sensitivty/Supplier (micro Sv/bubble)	0.455

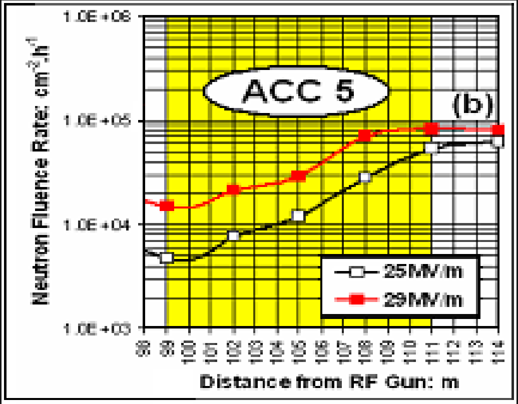
In-situ Radiation Dosimetry at FLASH Cryo Module

Accelerator Cryo Module



Neutron/Gamma Dosimeter pairs

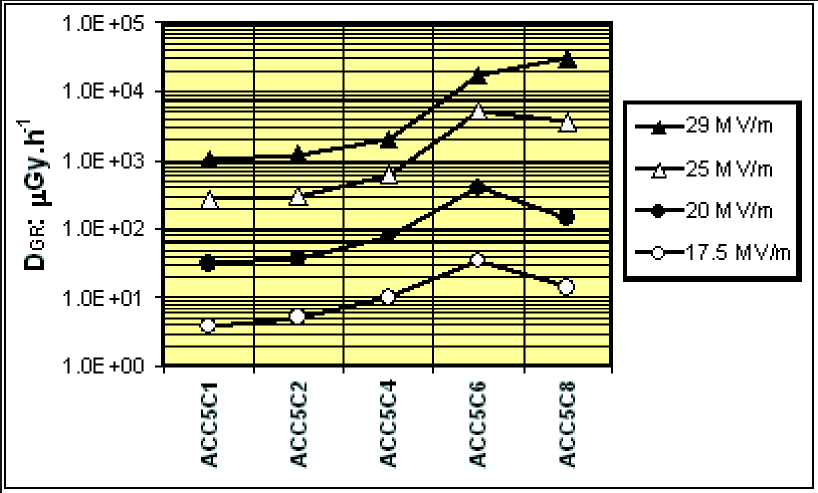




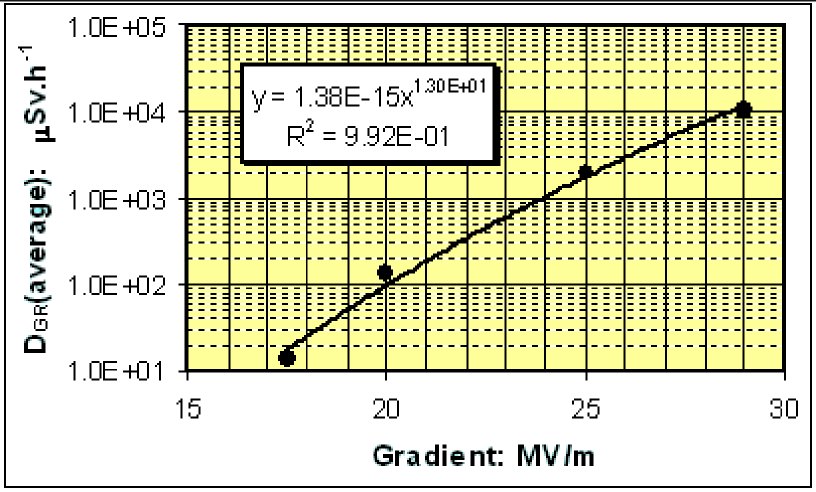
Gamma Dose Rate along the module tank, estimated using TLD and RCF-Dosimeters

Neutron Fluence Rate along the module evaluated with Bubble dosimeters

Gamma Dose Measurement along the Accelerator Cryo Module 5 (electron beam off) at different Gradient



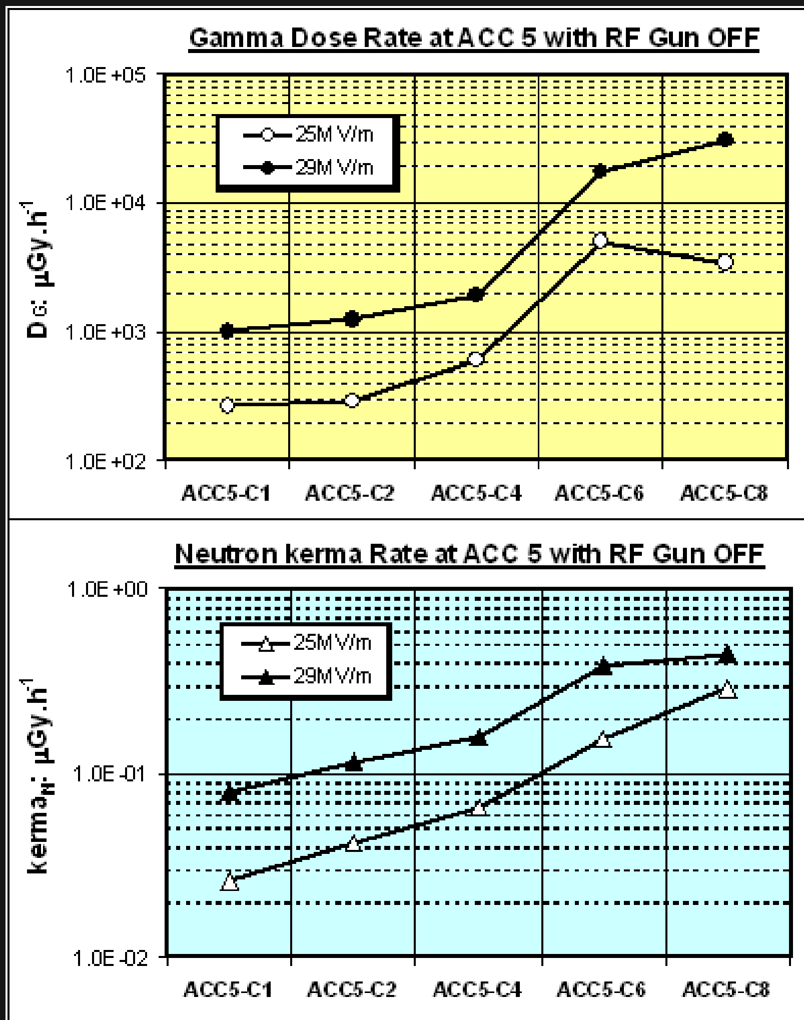
Gamma dose rates along ACC 5 estimated using radiochromic films running in field emission mode (beam off).



Average Gamma dose rate plotted as a function of Gradient.

Gamma Dose Rate skyrockets with the Gradient across the accelerator module.

In situ Dosimetry of Neutron and Gamma Radiation Fields in FLASH Environment

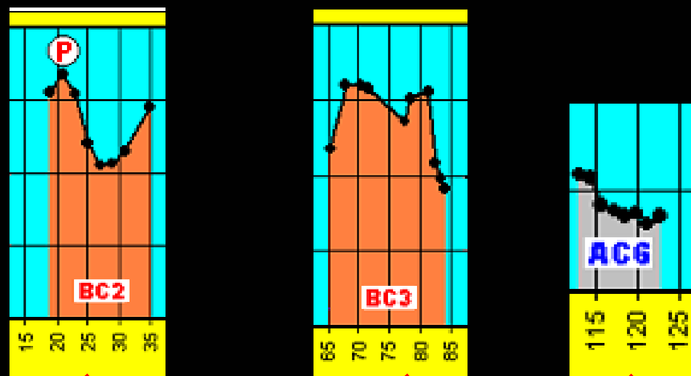


Gamma dose (kerma) rate along ACC 5 running in Field-Emission mode

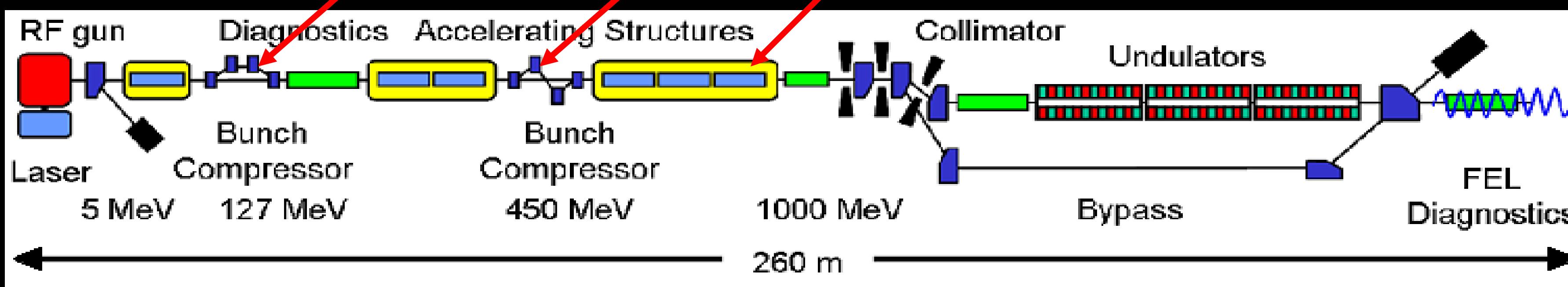
Neutron dose (kerma) rate along ACC 5 running in Field-Emission mode

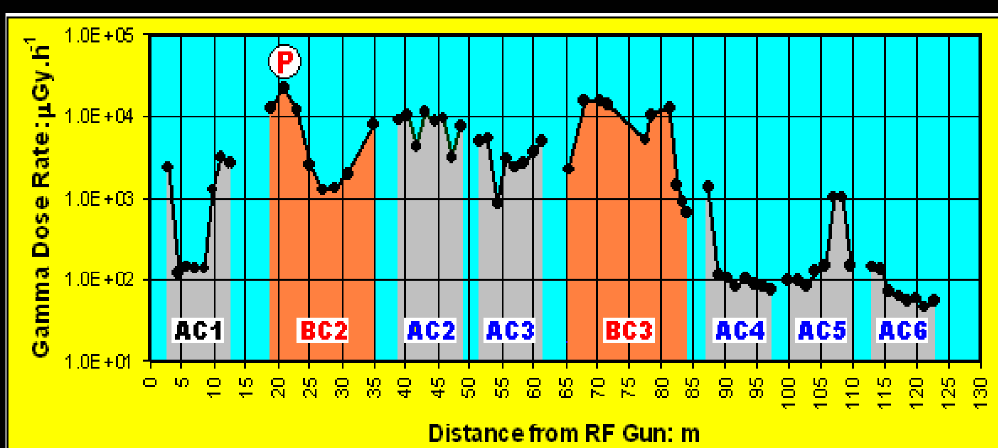
Gamma Dose rate is 4 orders of magnitude higher than the neutron kerma (Si) rate.

Radiation Measurement along FLASH Linac



Gamma dose rates along FLASH were evaluated using Thermo-luminescence Dosimeters (TLD) and radiochromic films.

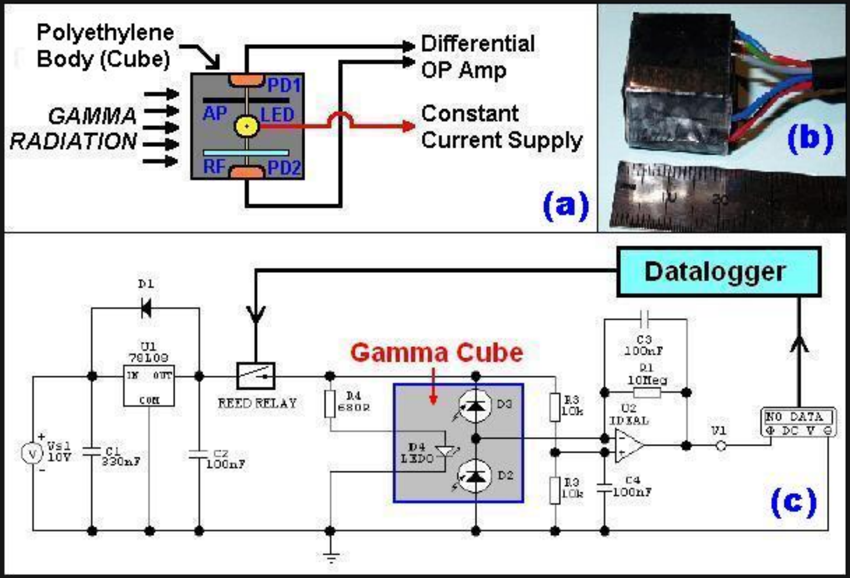




The region of high gamma doses found to be in the vicinity of Bunch Compressors (BC2 , BC3).

The lowest gamma dose prevailed at the furthest accelerator cryo module (AC6).

A real-time Gamma Dosimeter using Radiochromic Film



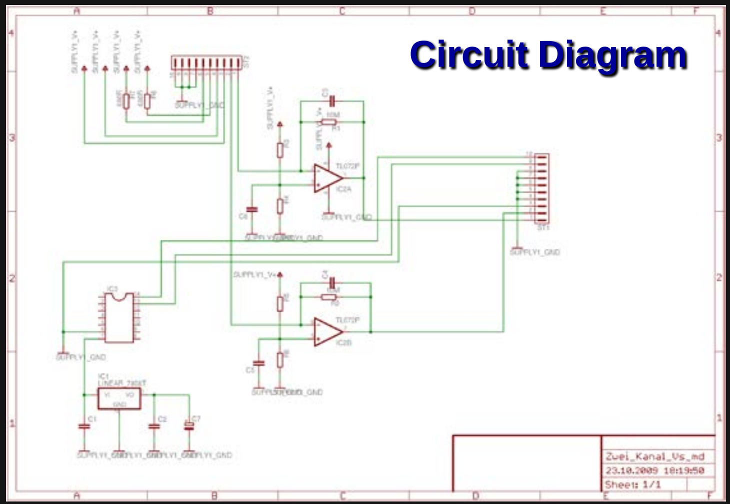
Based on common radiochromic film we have developed a real time gamma detector (GAMMACUBE) as depicted above (a). An aluminium aperture and a piece radiochromic film (Gaf EBT3) were mounted inside a 2cm x 2cm x 2cm opaque (black) polystyrene cube.

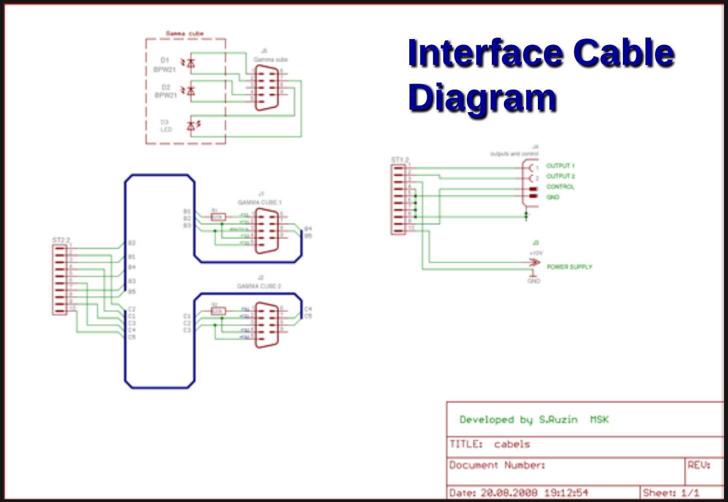
Two PIN photodiodes were mounted facing the aperture (PD1) and EBT3 film (PD2) and a high-power red LED placed in between. The diodes were connected to a high-gain differential OP AMP and the LED was powered by a constant current supply.

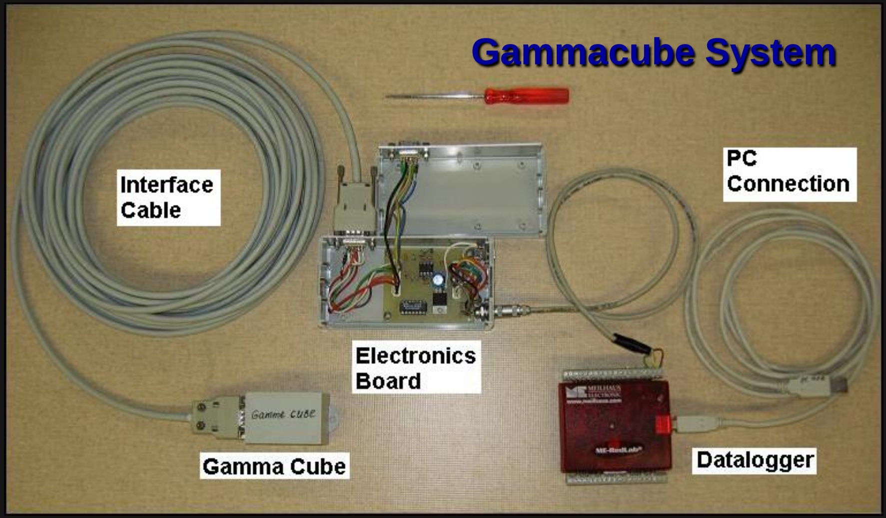
While exposed to gamma radiation, the radiochromic film strip decolours (turns darker) causing a change of illumination level detected by the photodiodes, resulting in a voltage difference across the photodiode pairs, which is further enhanced by the high-gain OP Amp. The output is multiplied by the „calibration factor“ to give the integrated gamma dose.

The first prototype of the GAMMACUBE detector (b) and light detection system and power supply (c) embodying the gamma dosimeter are depicted above.

Gammacube Hardware Development

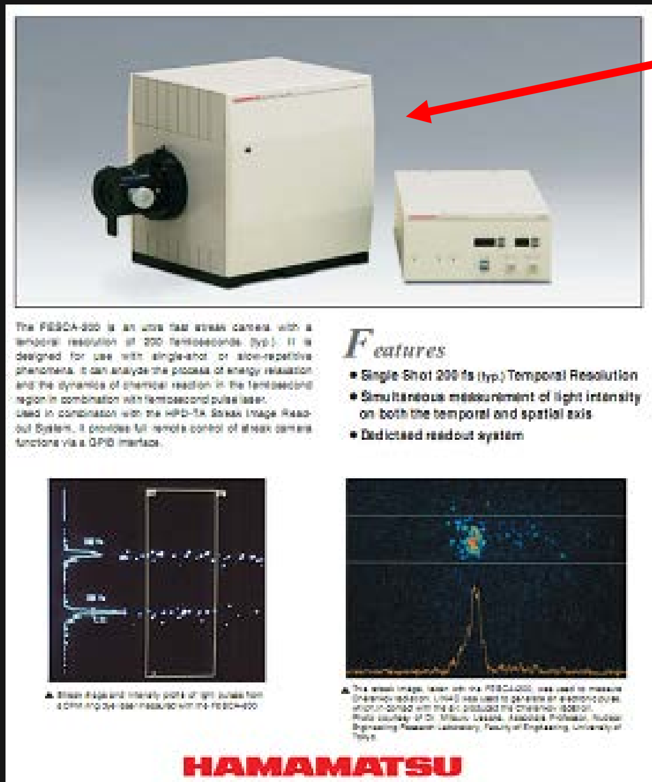






B Mukherjee, S Simrock. S Ruzin, T Lipka. Vorrichtung und Verfarhren zur instanten Erfassung von Gammastrahlendosen. Bundesrepublik Deutschland, Patent Nr. 10 2007 056989, München 2010.

Example 1: Streak Camera Radiation Protection



The Femtosecond Streak Camera (Model: C6138(FESCA-200).

A Streak Camera is made of high quality optoelectronic components as well as micro-electronic circuitry susceptable to radiation.

Hence, we housed the Streak Camera in a shielded (neutron and gamma) container. The monitoring dosimeter locations are indicated.

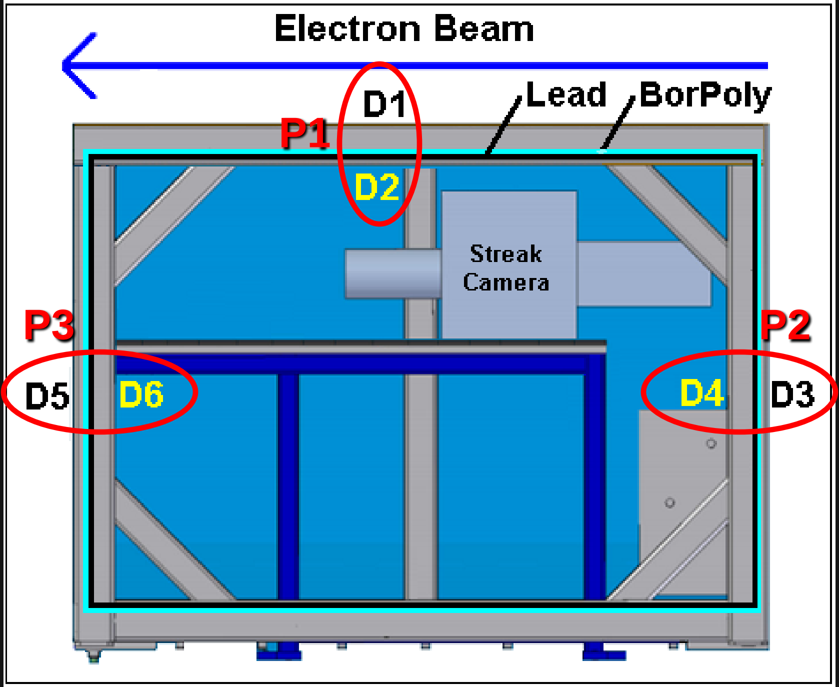
To protect the micro- and optoelectronic components of the Streak Camera (worth: ~ 500k Euro) we have devloped a high-efficacy, compact (neutron+gamma) shielding

Thermoluminescent (passive) dosimeters of type TLD-600 (^{6}LiF: Ti,Mg) were used to confirm the efficacy of the protective shielding containment

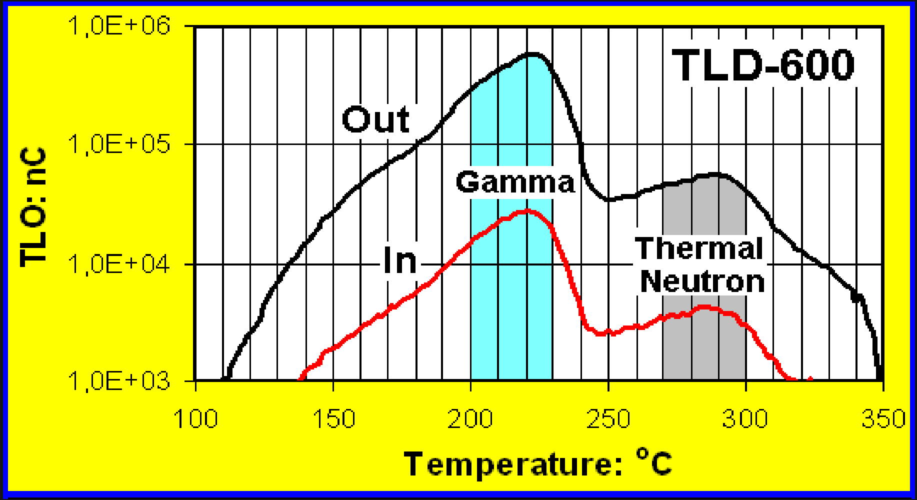
The Gammacube detectors were depolyed to monitor the gamma doses in and outside the shielding container housing he Streak camera in real-time.

Streak Camera Container Dosimetry (shielding efficacy)

Material: 16mm Pb+6mm Boronated Polyethylene



The gamma attenuation and thermal neutron cut-off factor were evaluated by analying the TL-glow curves of TLD-600 (^{6}LiF: Ti,Mg) chips.



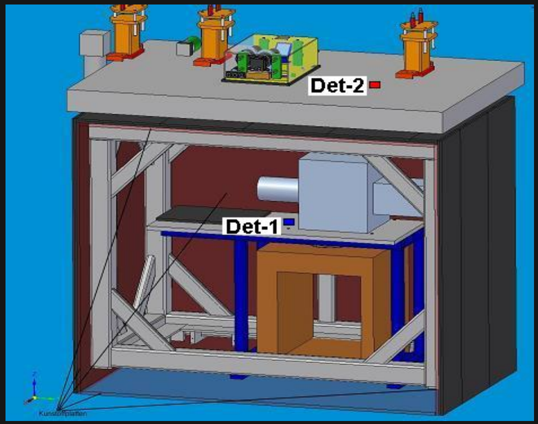
Location at Container	Attenuation§	
	Therm. Neutron	Gamma Rays
D2/D1 (P1)	7.46×10^{-2}	4.80×10^{-2}
D4/D3 (P2)	2.24×10^{-1}	3.59×10^{-1}
D6/D5 (P3)	9.93×10^{-2}	9.27×10^{-2}

§ and Therm. Neutron Cut off Factor

At selected locations (P1, P2, P3) on container pairs of TLD-600 chips (one outside the shielding and other inside) were attached.

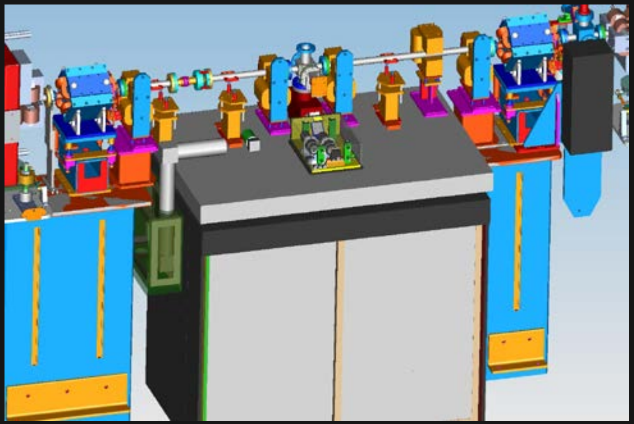
The gamma attenuation and thermal neutron cut off factor were calulated as the ratio of corresponding TL-Glowcurve areas

Streak Camera Monitoring using Gammacube System



The shielding container

Container frame and plates



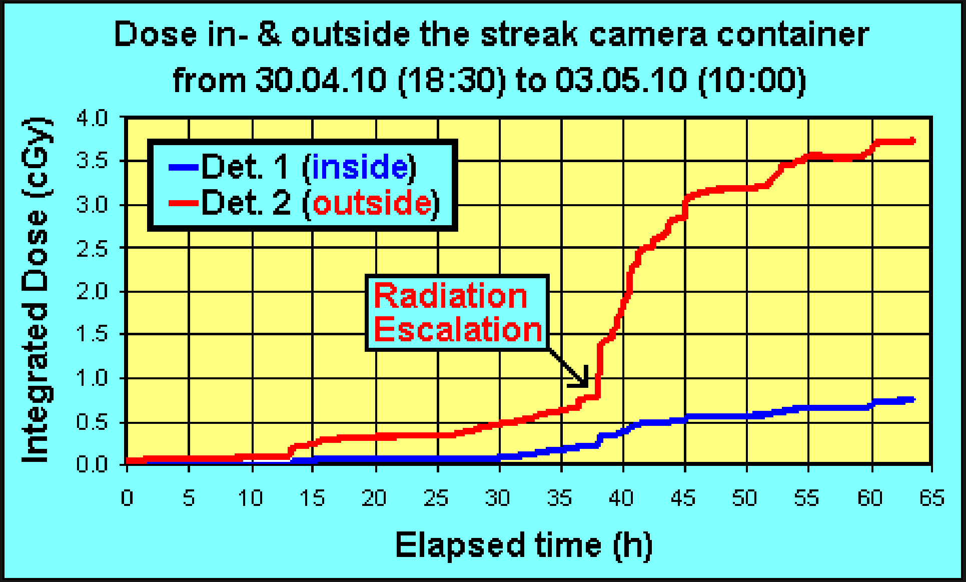
Container Located at beamline

The Gammacube detector-heads were placed inside (Det 1) and outside (Det 2) of the Streak Camera Container.

Detectors were connected to power supply and data acquisition system located in the experiment hut approx. 100m away from the FLASH tunnel.

The system is capable to indicate radiation escalation events.

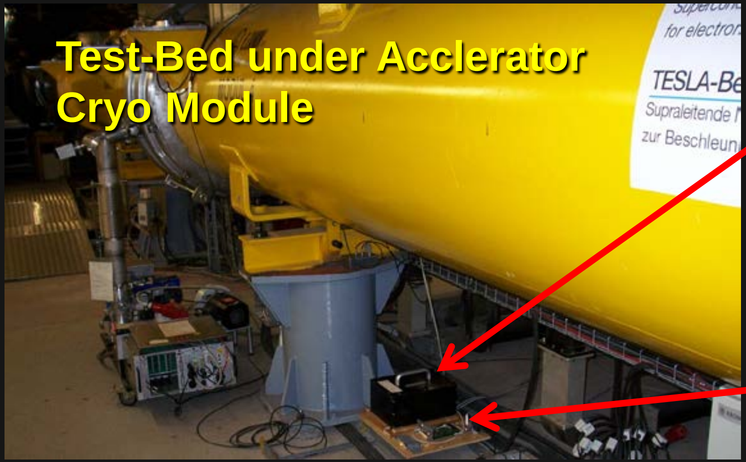
The life-time of Gammacube detector is limited: until the saturation limit (2000 cGy) of the GaF EBT3 radiochromic film is reached => Mandatory Replacement



The plot of integrated gamma doses in- and outside the shielded container housing Streak Camera.

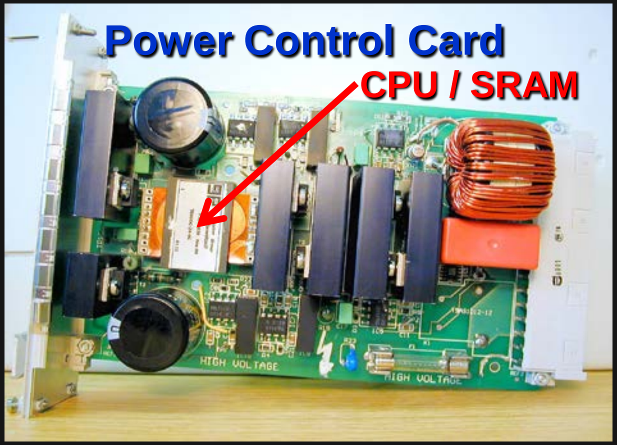
Example 2: Shielding efficacy test for Power Control Devices

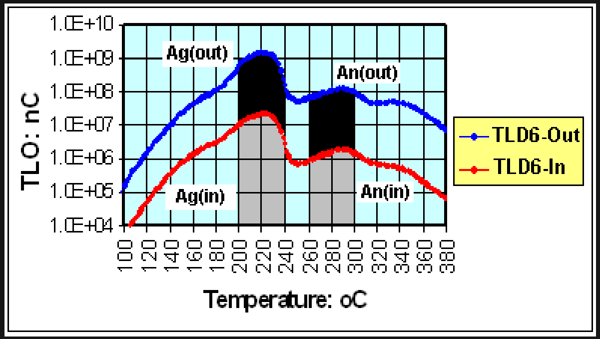
containing highly radio-susceptable SRAM (Static Random Access Memory) chips



Shielded Card
15mm Lead +
6mm Boronated
Rubber

Unshielded Card





TL-Glow Curves of TLD-600 chips:
1st. Chip inside, 2nd. Chip outside

Shielding Efficacy was estimated as the ratio of TLGC areas

Gamma:
Ag(out)/Ag(in) = 0.09

Thermal Neutron:
An(out)/An(out) = 0.01

Both Cards were interfaced to DAC system and continuously monitored over 7 months

Unshielded Card: 2 SEU (Single Event Upset) recorded every week (Total 28 SEU)

Shielded Card: No SEU was recorded

Summary and Conclusion

Research highlights

We presented methods for passive radiation dosimetry in the environment of high-energy electron Linac driving FEL (FLASH & XFEL) using Thermoluminescent Dosimeters, Radio-chromic films and Bubble detectors

We developed a novel real-time gamma dosimetry device (GAMMACUBE) using common Radiochromic Film *(Bundesrepublik Deutschland, Patent Nr. 10 2007 056989, München 2010)*

Major Findings

The gamma radiation originates from the accelerated field emission electrons, resulting gamma dose escalates strongly with the increasing voltage gradient across the accelertor module

In Free Electron Laser environment gamma doses predominate over that of neutrons by more than four orders of magnitude

High radiation levels prevail near Bunch Compressors

Important Applications

High resolution neutron and gamma dose mapping along high-energy electron linear accelerator

Efficacy testing of special purpose shielding assemblies to protect micro and optoelectronic devices placed in the detrimental radiation fields existing in the accelerator tunnel

Remote monitoring of gamma radiation fields (multi location) in real time

Other Prospective applications

Passive and real time radiation monitoring at biomedical and radioisotope production facilities

Acknowledgements

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