Radiation issues in the single tunnel environment

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for LLRF team

Agenda

- XFEL radiation environment
  - gamma
  - neutrons
- influence of radiation on electronic devices
  - TID (Total Ionizing Dose)
  - DDD (Displacement Damage Dose)
  - SEE (Single Event Effects)
- countermeasures
  - shielding
  - SEE-tolerant circuits and algorithms

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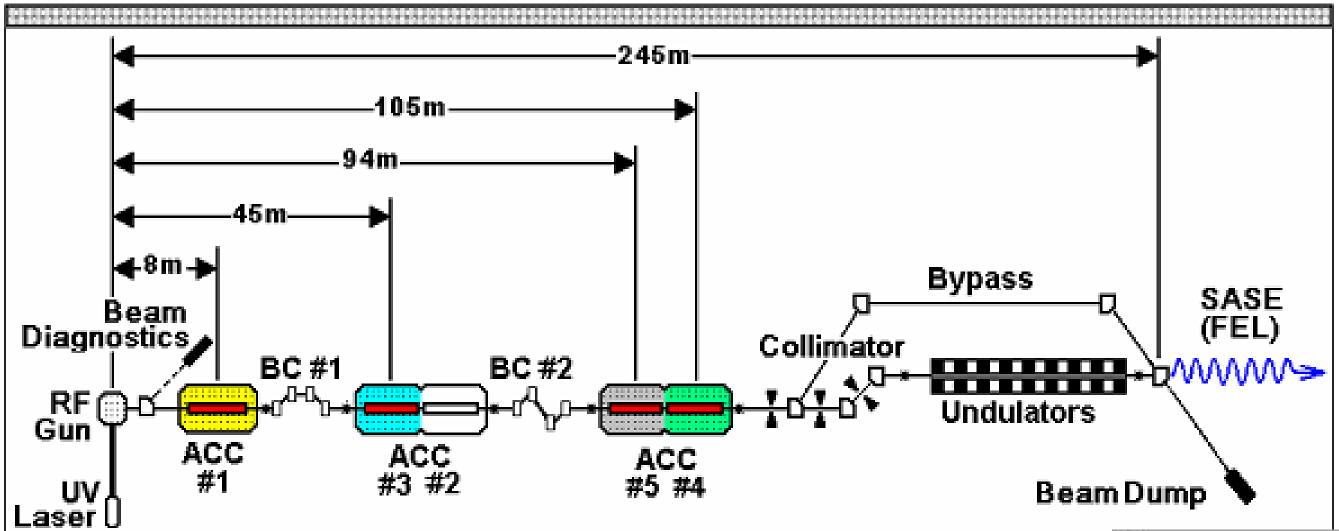
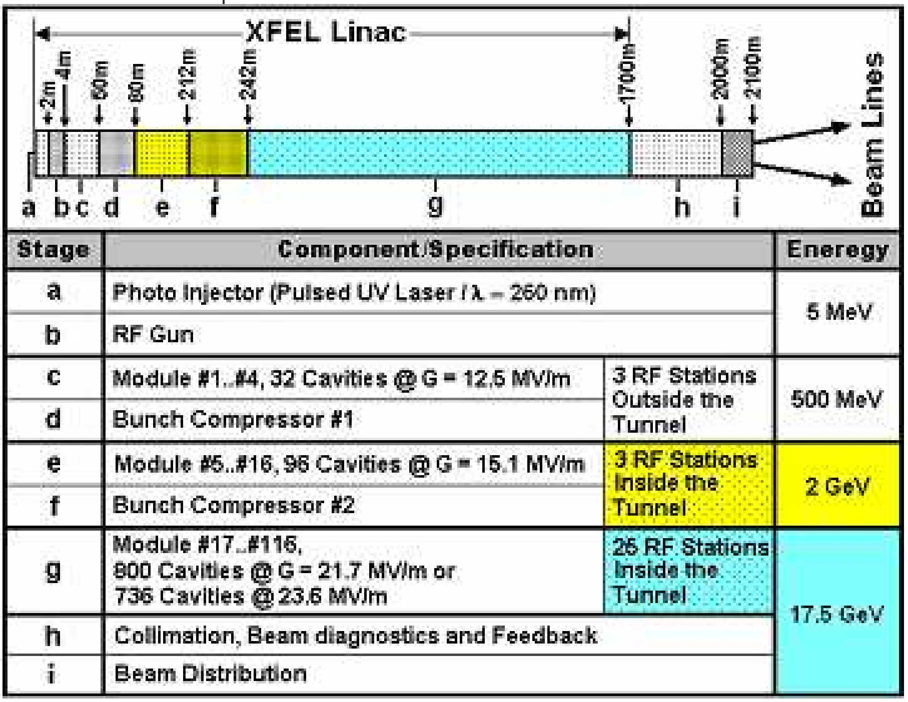
FLASH – the Pilot Project for XFEL



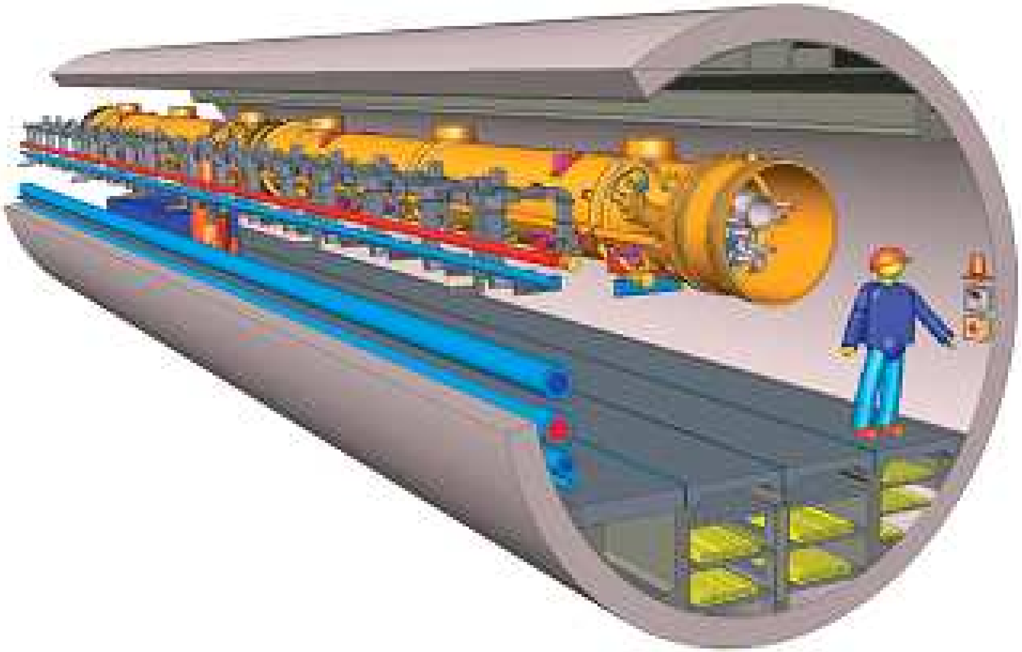
Highlighting the locations of dose measurement at FLASH

Vital design parameters and dimensions of the XFEL



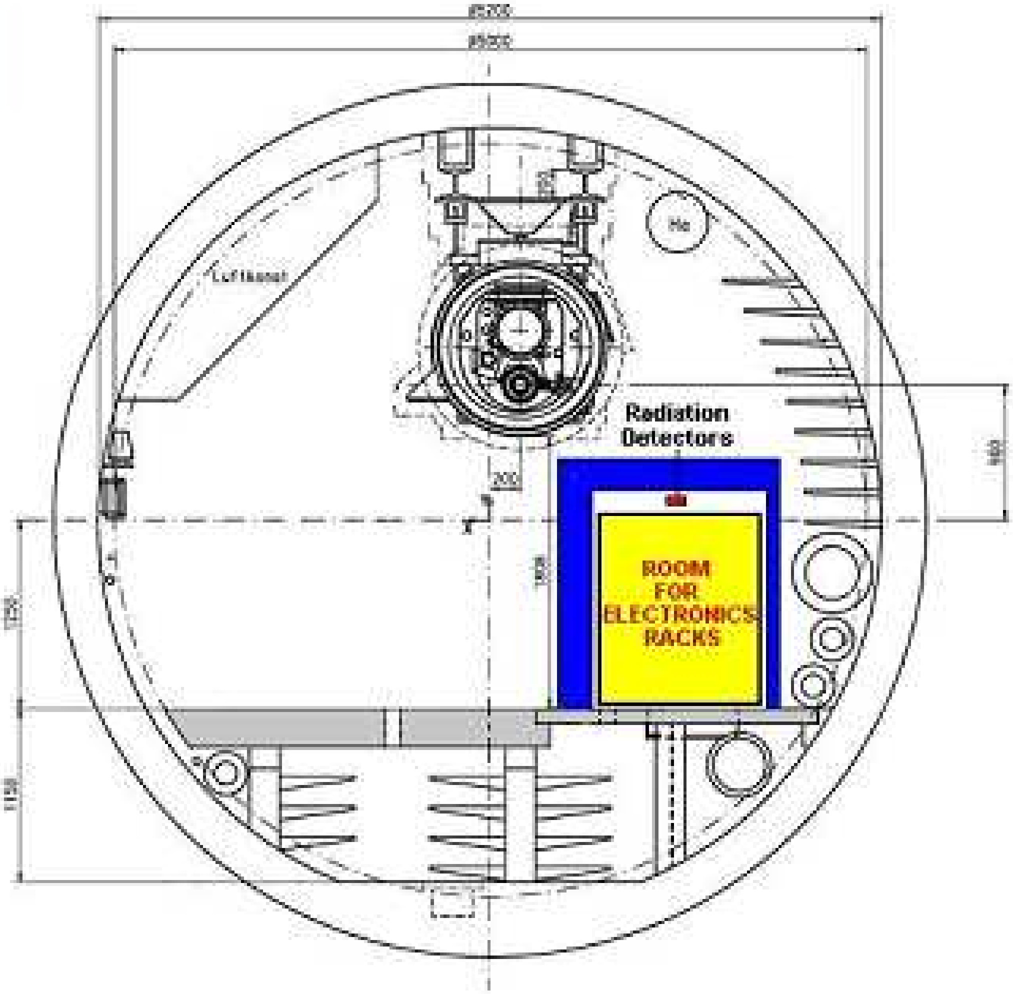
Stage	Component/Specification		Eneregy
a	Photo Injector (Pulsed UV Laser / λ = 260 nm)		5 MeV
b	RF Gun		
c	Module #1..#4, 32 Cavities @ G = 12.5 MV/m	3 RF Stations Outside the Tunnel	500 MeV
d	Bunch Compressor #1		
e	Module #5..#16, 96 Cavities @ G = 15.1 MV/m	3 RF Stations Inside the Tunnel	2 GeV
f	Bunch Compressor #2		
g	Module #17..#116, 800 Cavities @ G = 21.7 MV/m or 736 Cavities @ 23.6 MV/m	26 RF Stations Inside the Tunnel	17.5 GeV
h	Collimation, Beam diagnostics and Feedback		
i	Beam Distribution		

XFEL Tunnel Layouts

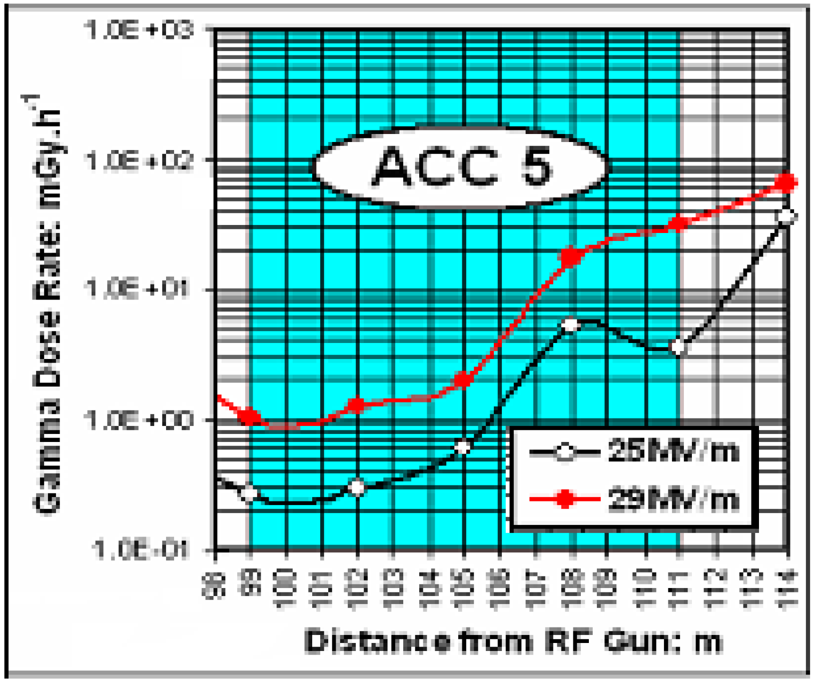


Panoramic view of the XFEL Tunnel showing the Cryomodule, Utility ducts and Electrical cable trays

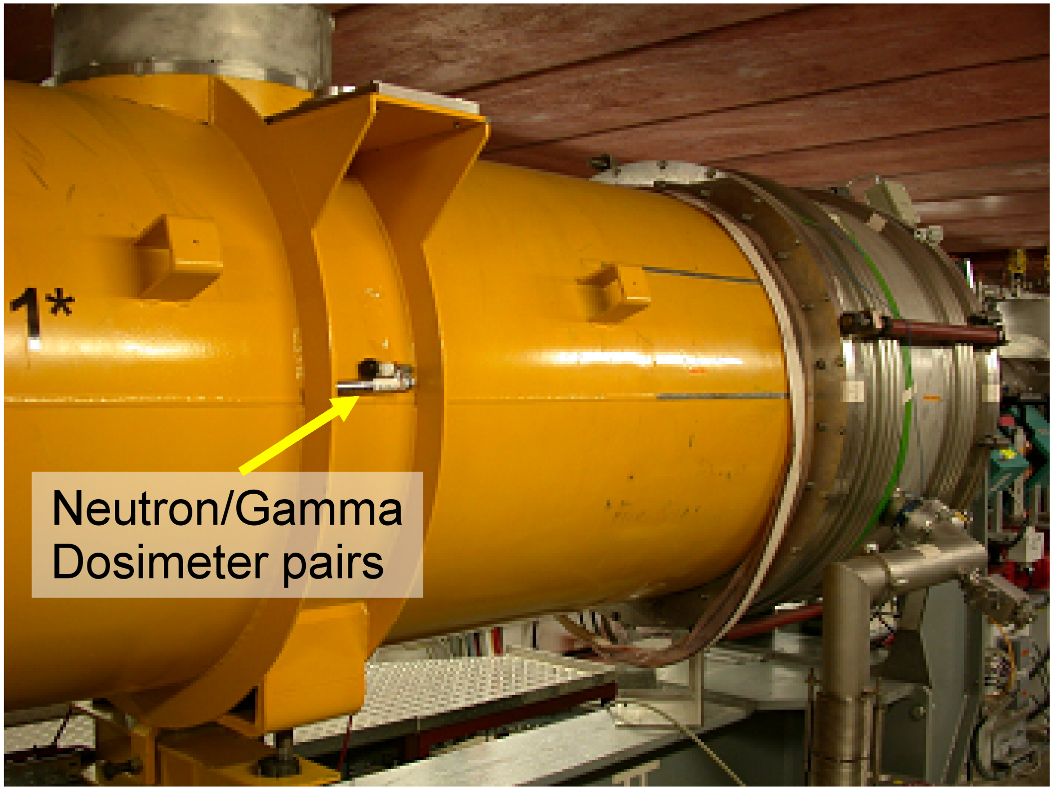
Shielded Space for LLRF-Electronics



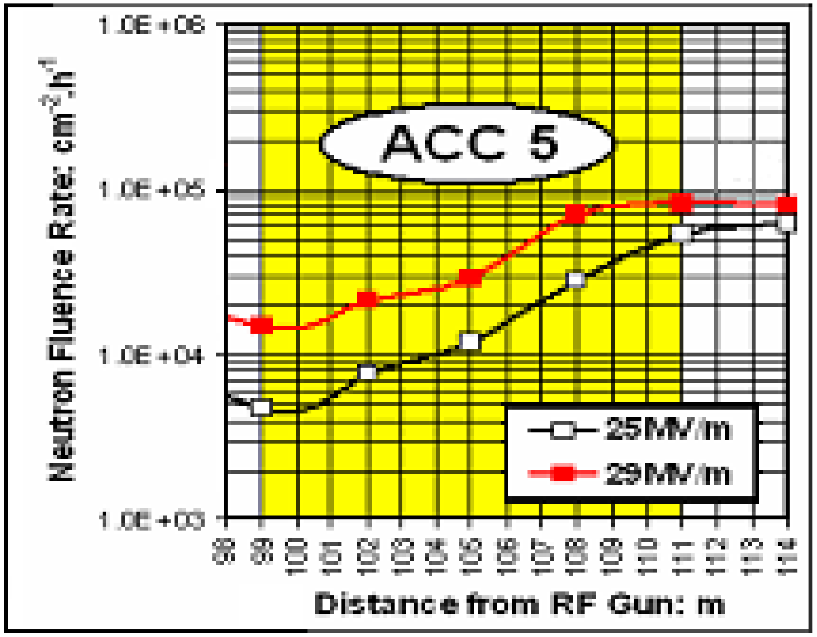
In-situ Radiation Dosimetry at FLASH Module



Gamma Dose Rate along the module tank

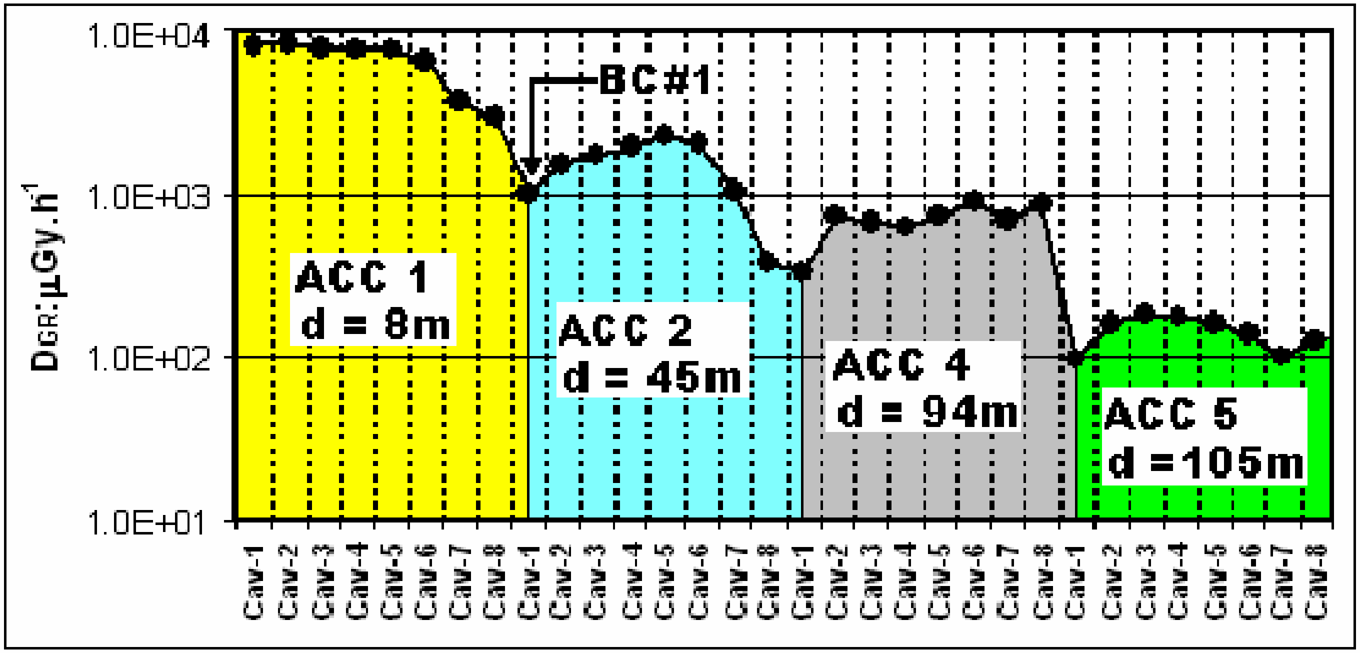


Neutron/Gamma Dosimeter pairs



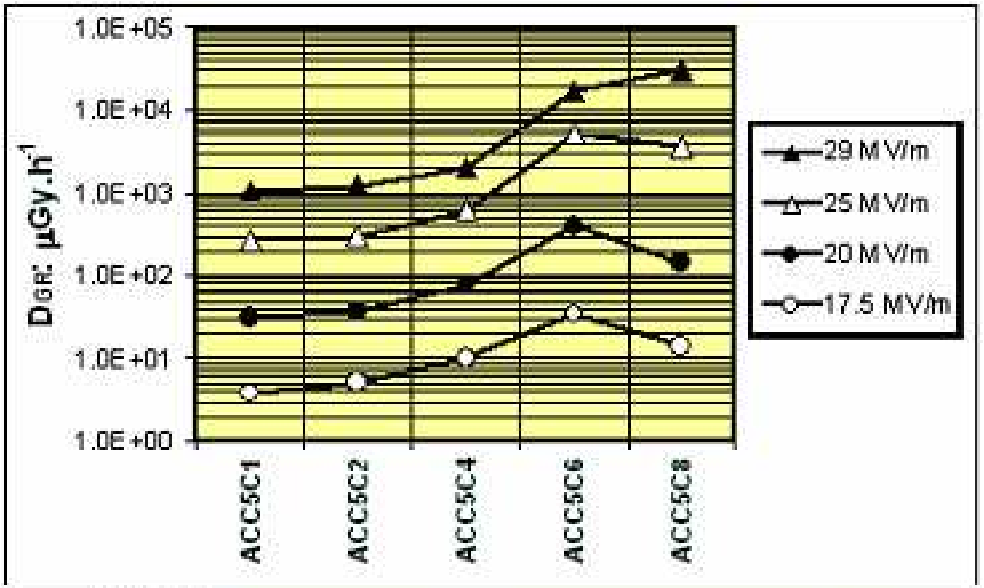
Neutron Fluence Rate along the module tank

Gamma Dose Measurement along FLASH during Routine Operation at a gradient of ~21 MV/m

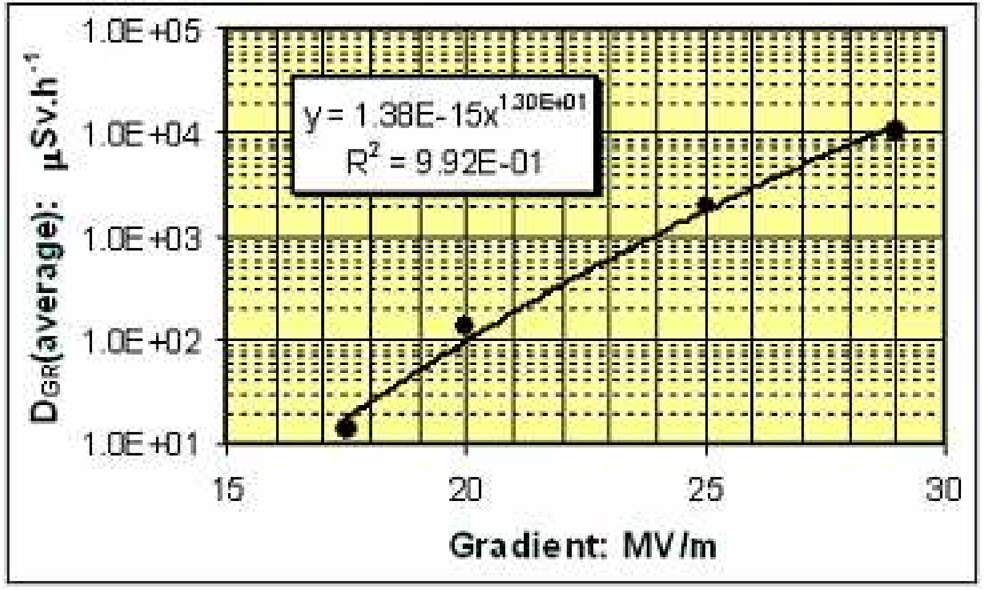


- Accelerated dark current from RF gun is the prime source of gamma dose
- Gamma dose rate drops with the distance from the RF gun
- Gamma dose rate at the cryomodule (ACC 1) near bunch compressor (BC #1) is two orders of magnitude higher than the distant module ACC 5
- The dose distribution pattern along the module surface is non-homogeneous
- The radiation dose at modules far away for the RF gun caused by the accelerated field emission electrons

Gamma Dose Measurement along the Accelerator Module 5 at different Gradients (RF Gun off)



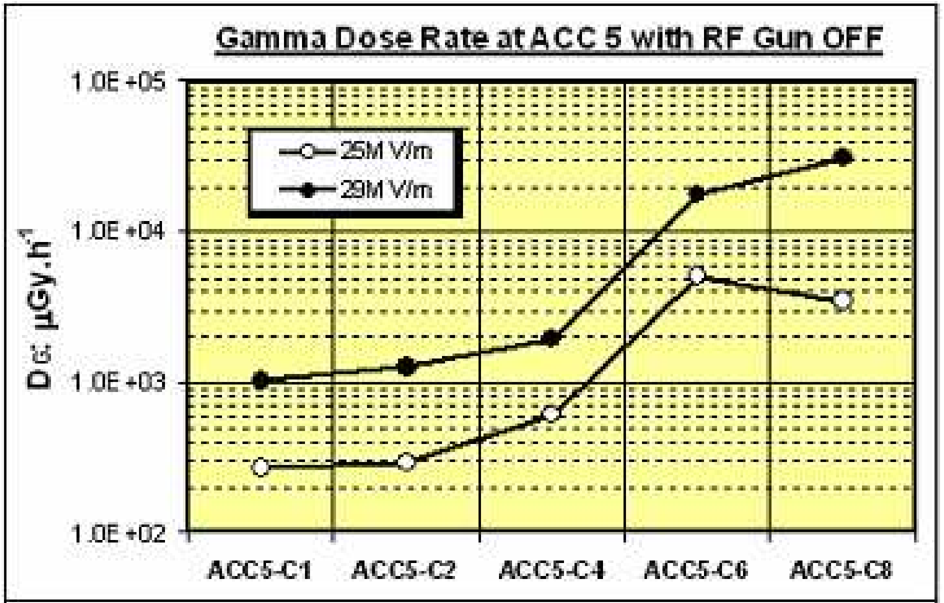
Gamma dose rates along ACC 5 running in field emission mode (RF gun off)



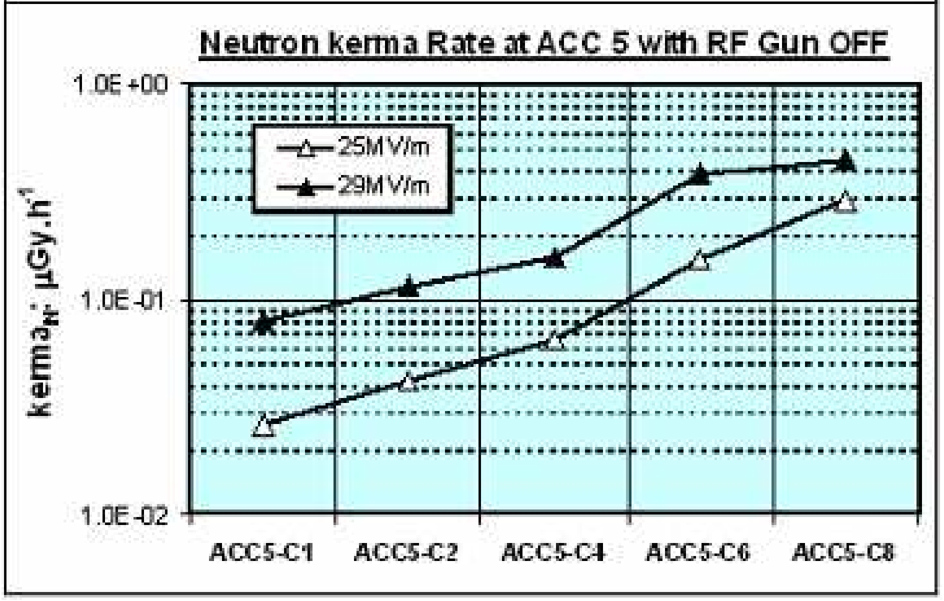
Average Gamma dose rate as a function of Gradient

Gamma Dose Rate skyrockets with the Gradient across the accelerator module

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



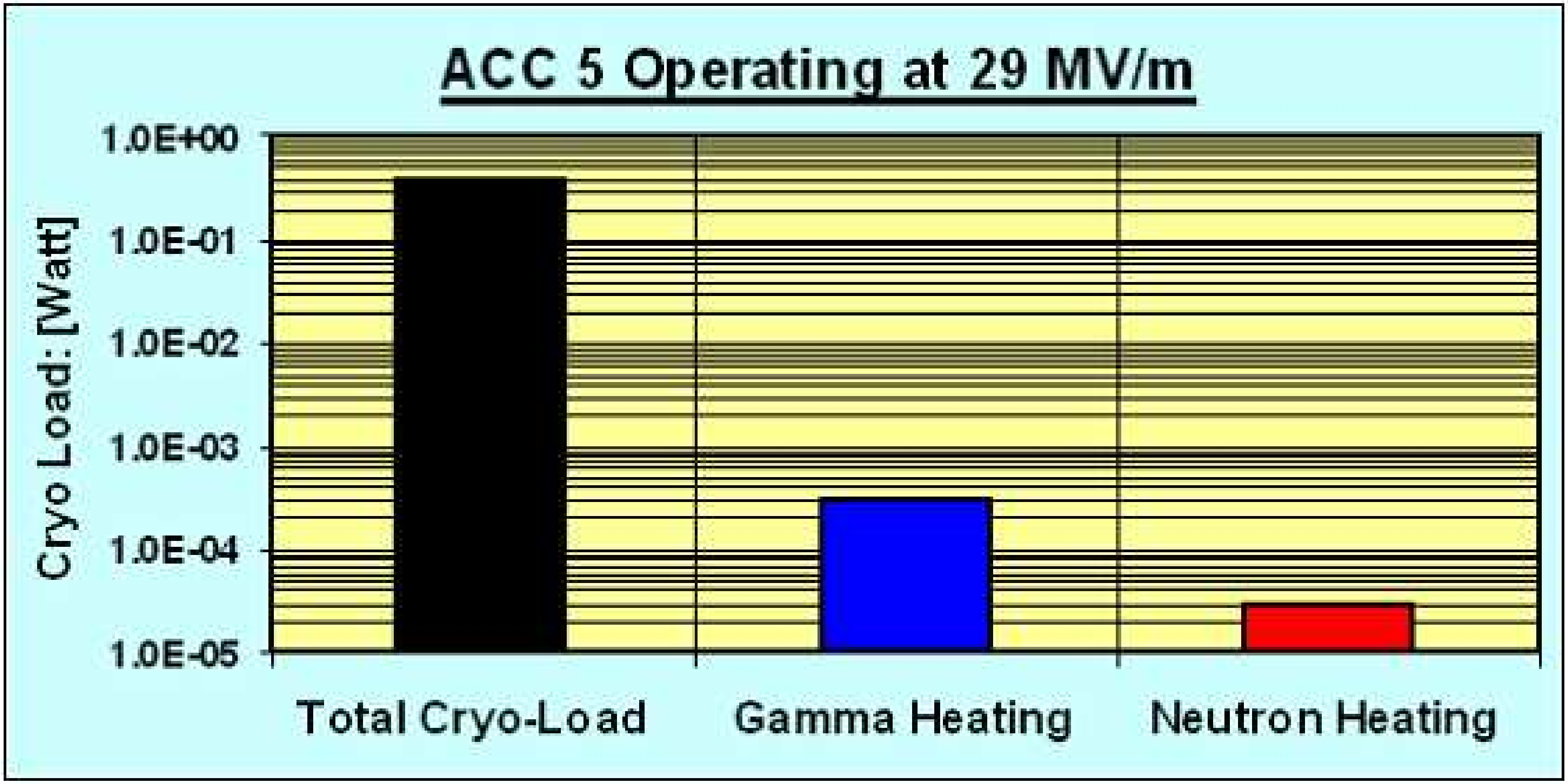
Gamma dose rates along ACC 5 running in field emission mode (RF gun off)



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

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

Radiation Induced Cryogenic Loss



The TLD (gammas) and Bubble detectors (Neutrons) were used to assess radiation doses (kerma) and then used to derive the Cryogenic Losses

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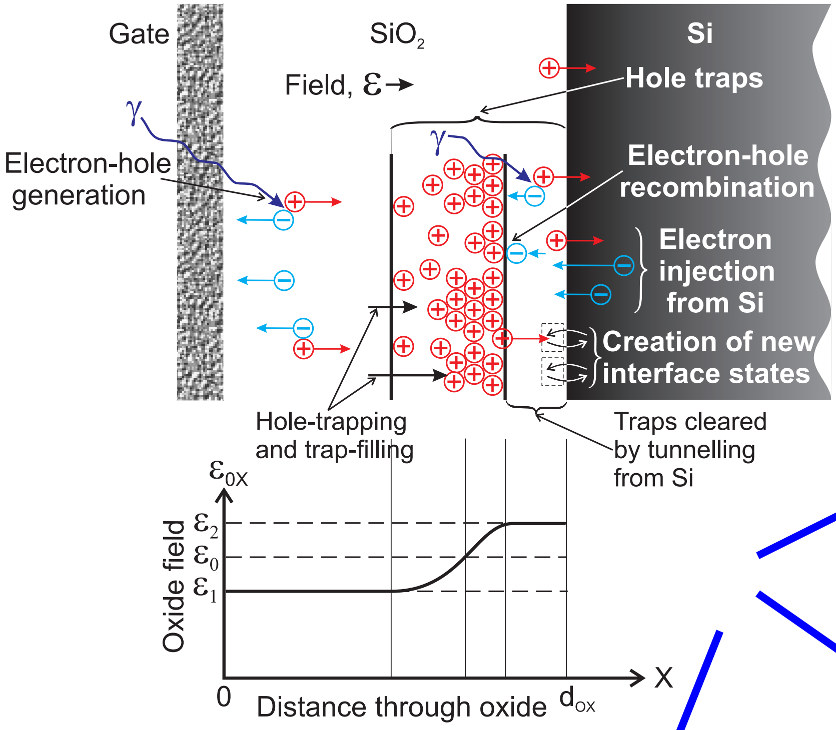
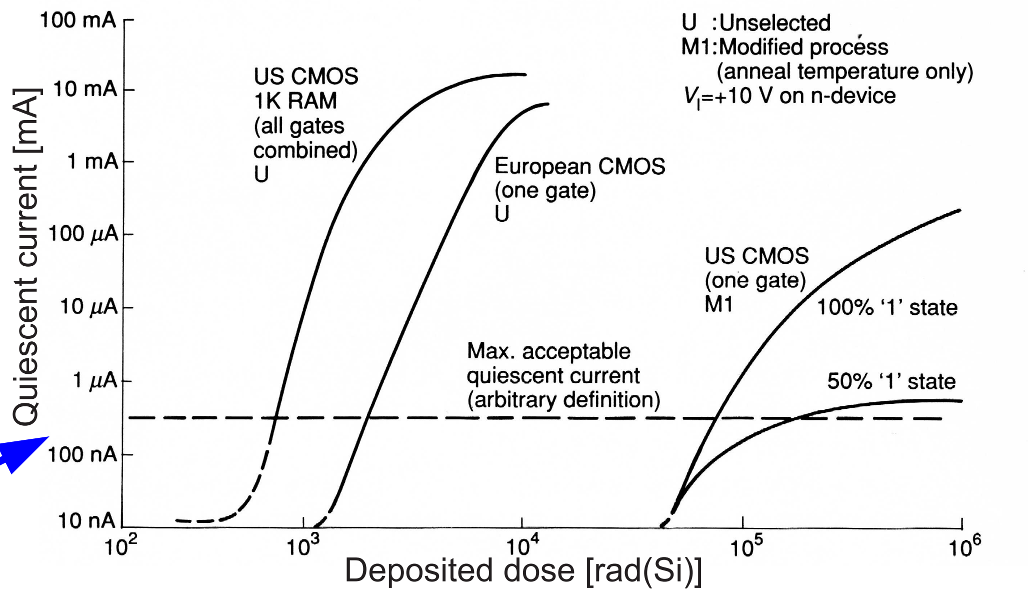
The influence of radiation on electronic devices

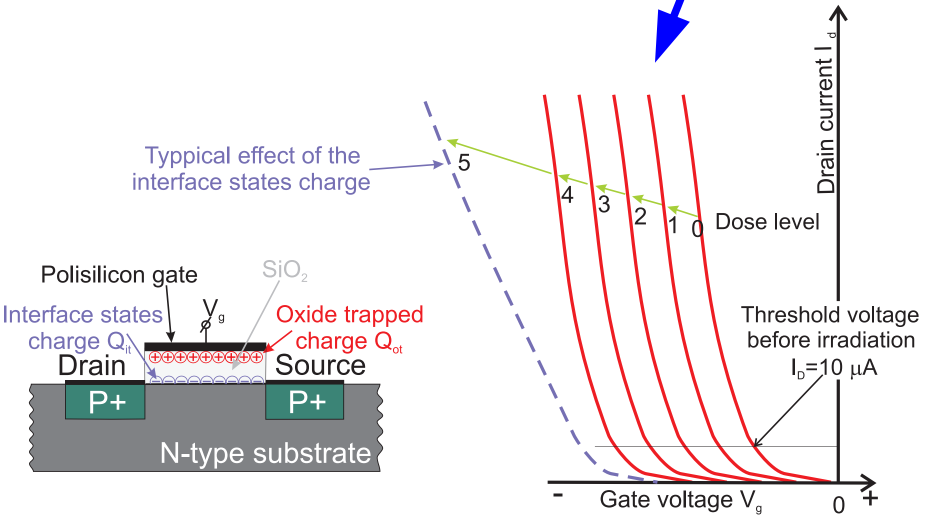
Photons and particles in a form of radiation can basically generate following types of effects in silicon components:

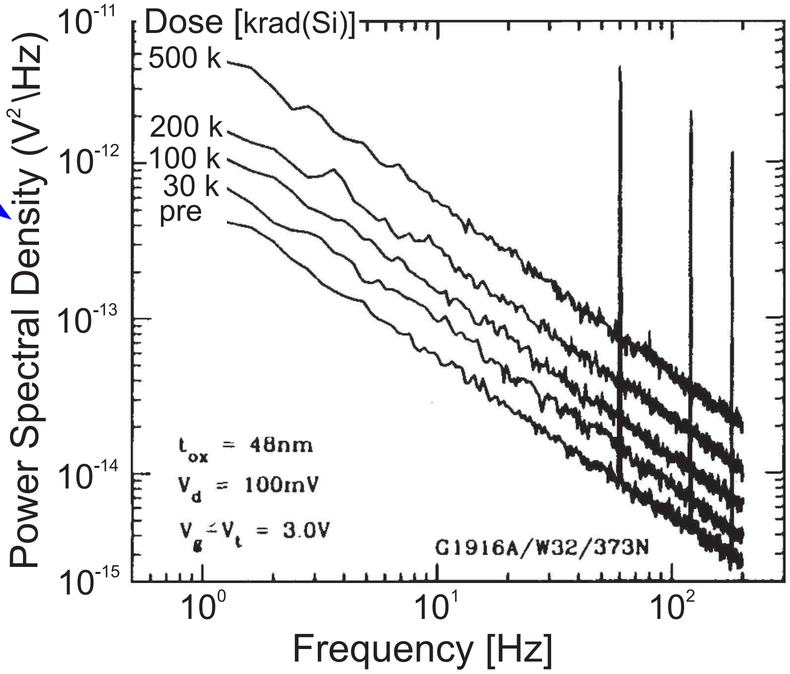
- permanent
  - ionizing effect (TID)
  - displacement damage (DDD)
- transient (SEE - Single Event Effect)
  - non-destructive (SET, SEU, SEFI)
  - destructive (SEL, SEB, SEGR)

Ionization effects in MOS transistor





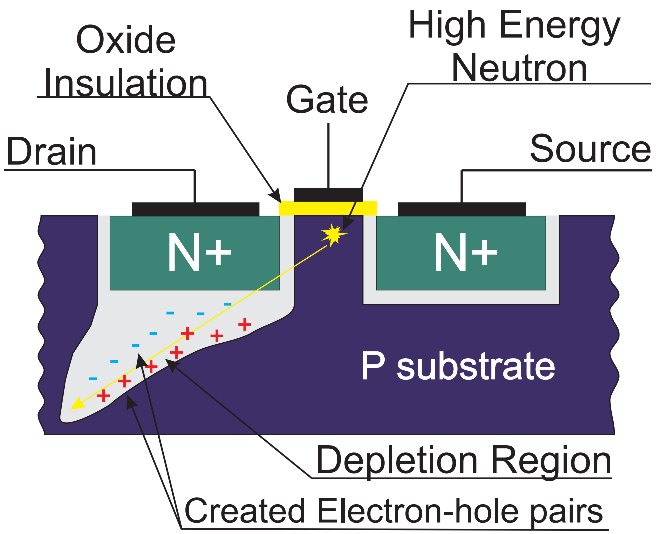


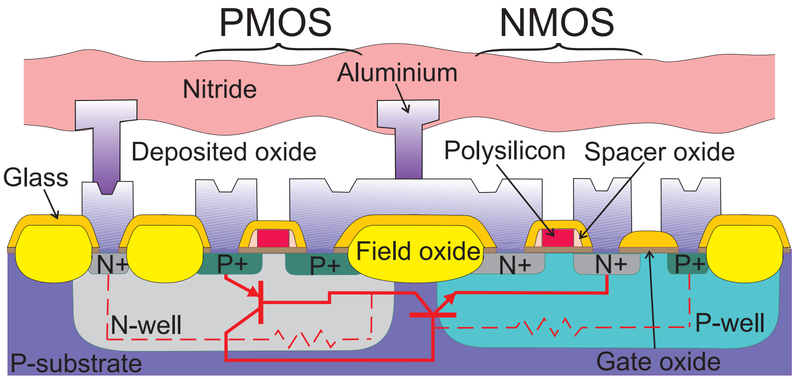


Degradation of MOS transistor parameters

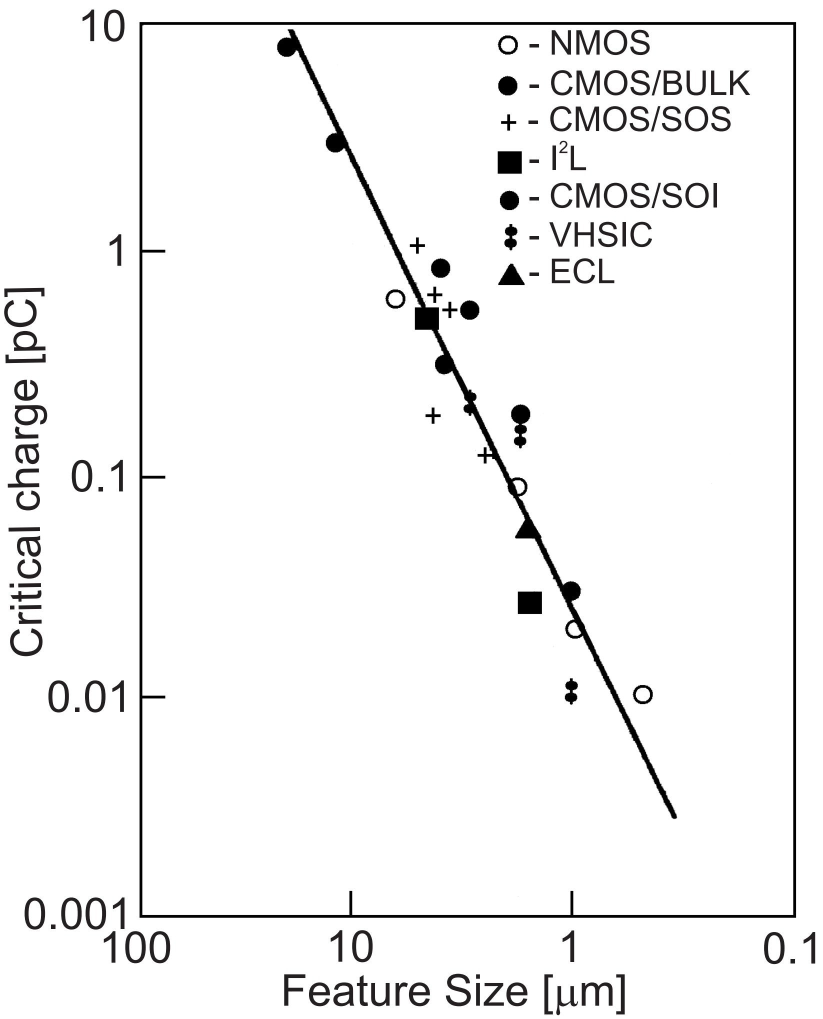
- modification of the threshold voltage V_t
- decrease of transconductance
- increase of leakage currents
- reduction of drain-source breakdown voltage
- deterioration of noise parameters
- reduction in surface mobility
- increase of the surface recombination rate

Single Event Effects (SEE)





A parasitic thyristor structure responsible for SEL in CMOS inverter



Vulnerability to SEE for various semiconductor technologies

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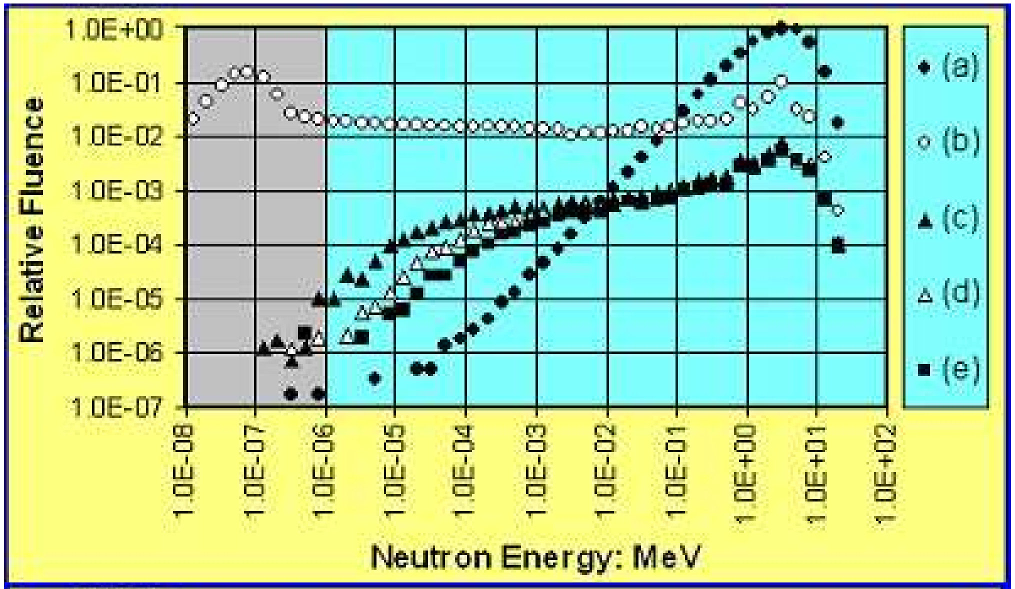
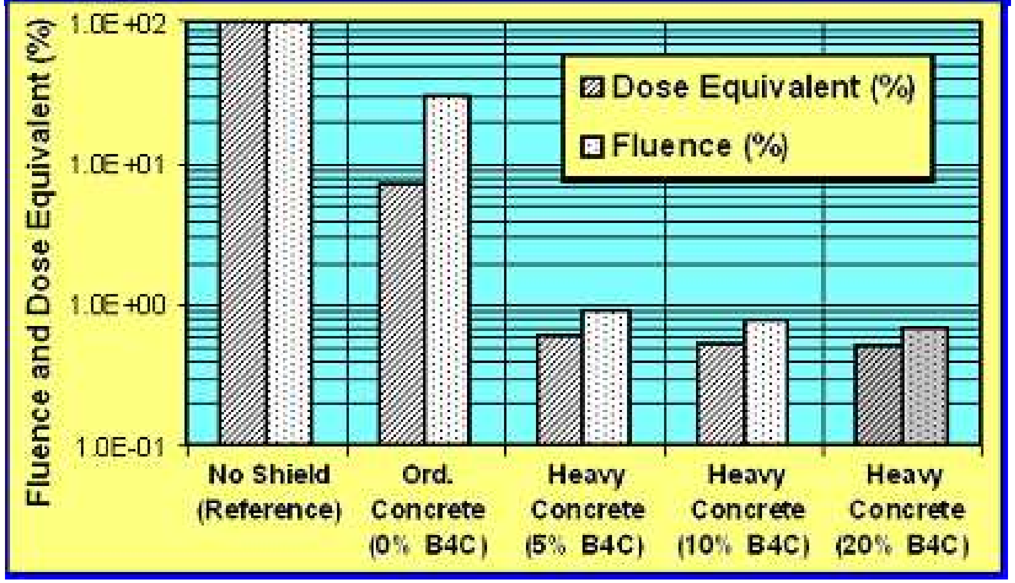
Monte Carlo Simulation of Shielding Concrete





(a) Input neutron spectrum (fission spectrum)
(b) Ordinary concrete with no B_4C
(c) Heavy concrete with 5% B_4C
(d) Heavy concrete with 10% B_4C
(e) Heavy concrete with 20% B_4C

Showing the integrated neutron dose equivalent on the surface of a 50 cm radius concrete shield with different amounts of B_4C

Thin Thermal Neutron Shield

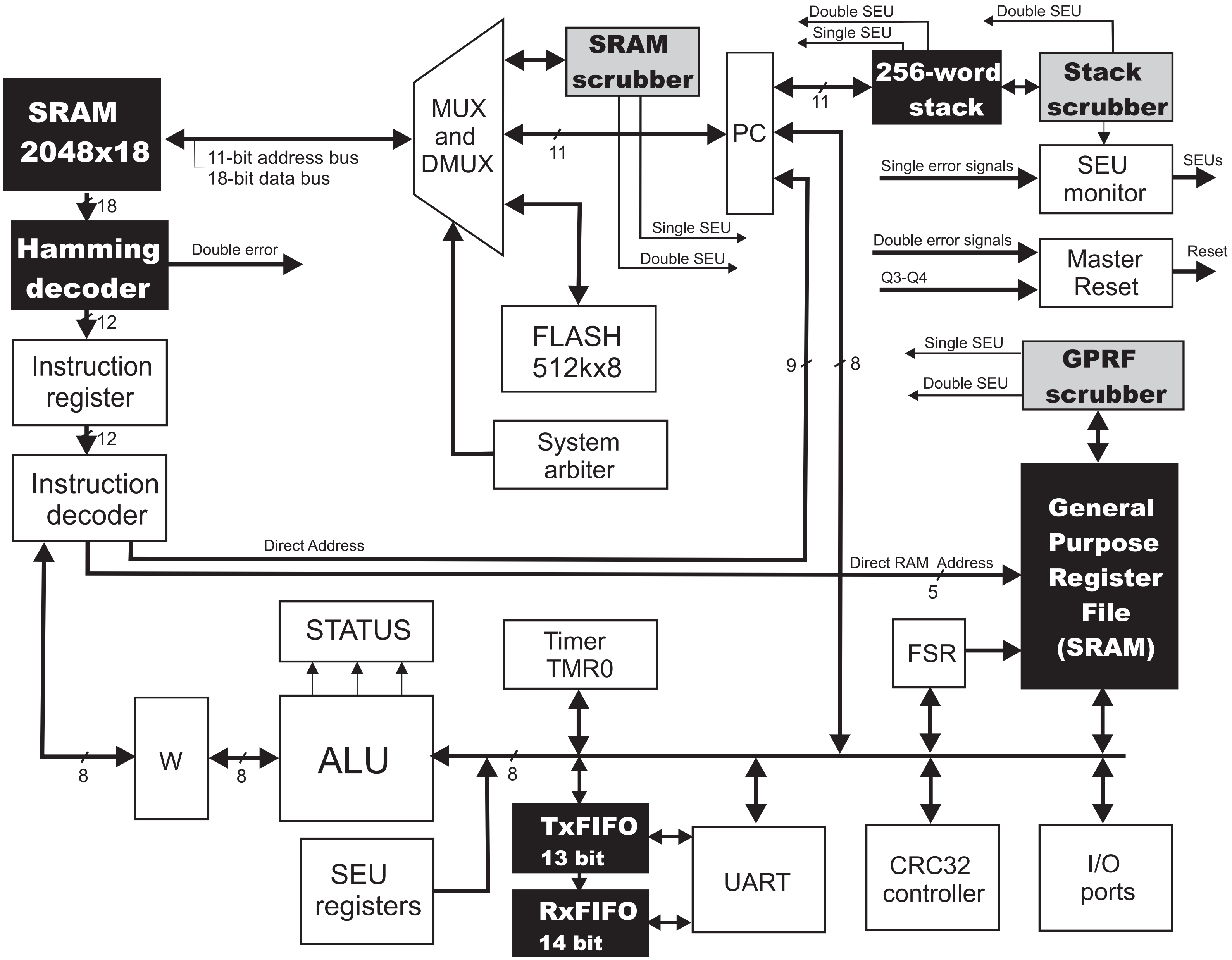
SRAM No	Irradiation Mode	SEU count
1	Am-Be (bare)	40
2	Am-Be (water mod)	275
3	Am-Be (water mod + B shield)	19
4	Linac (bare)	117
5	Linac (Polyeth. mod)	619
6	Linac (Polyeth. mod + B shield)	15

The normalised SEU counts of the bare, polyethylene-moderated and shielded with Borated Polyethylene

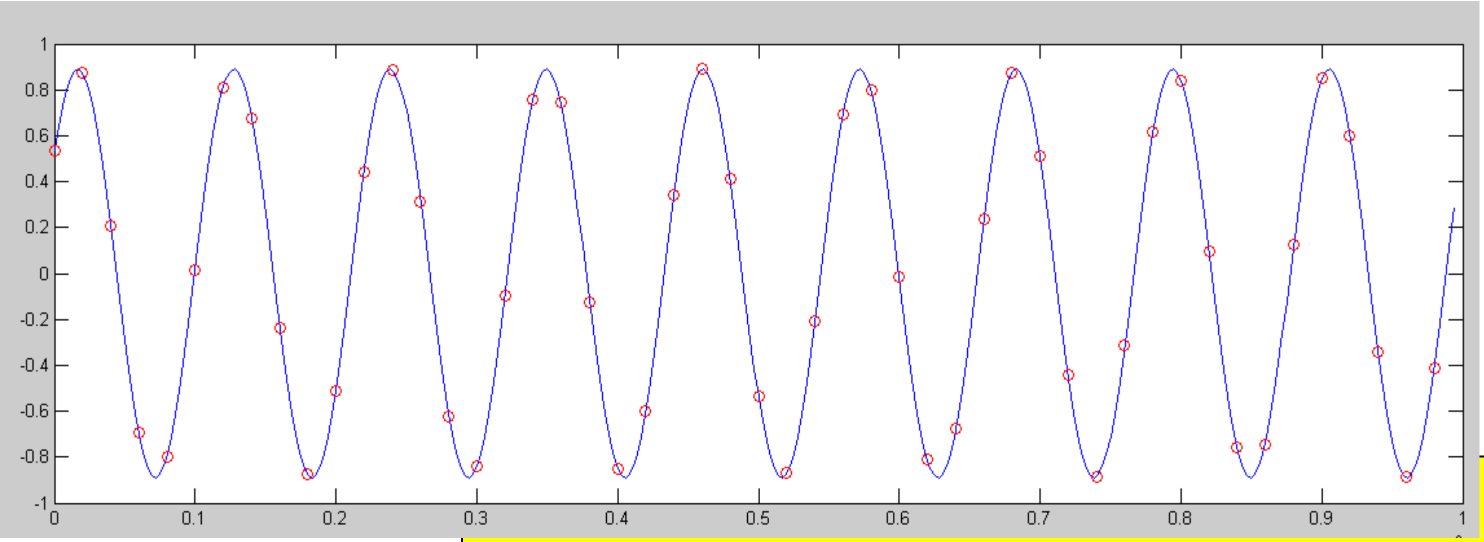
SEU tolerance

- SEU tolerant hardware (microcontroller based on PIC16C57 architecture designed and implemented)
- SEU tolerant algorithms (IQ detection designed and implemented)
- development of SEU-tolerant operating system (sCORE operating system - in progress)

Radiation-tolerant Microcontroller



SEU tolerant IQ detection algorithm



N – number of samples

x_i – signal sample

$\alpha_i = i \cdot \alpha$

α – phase advance

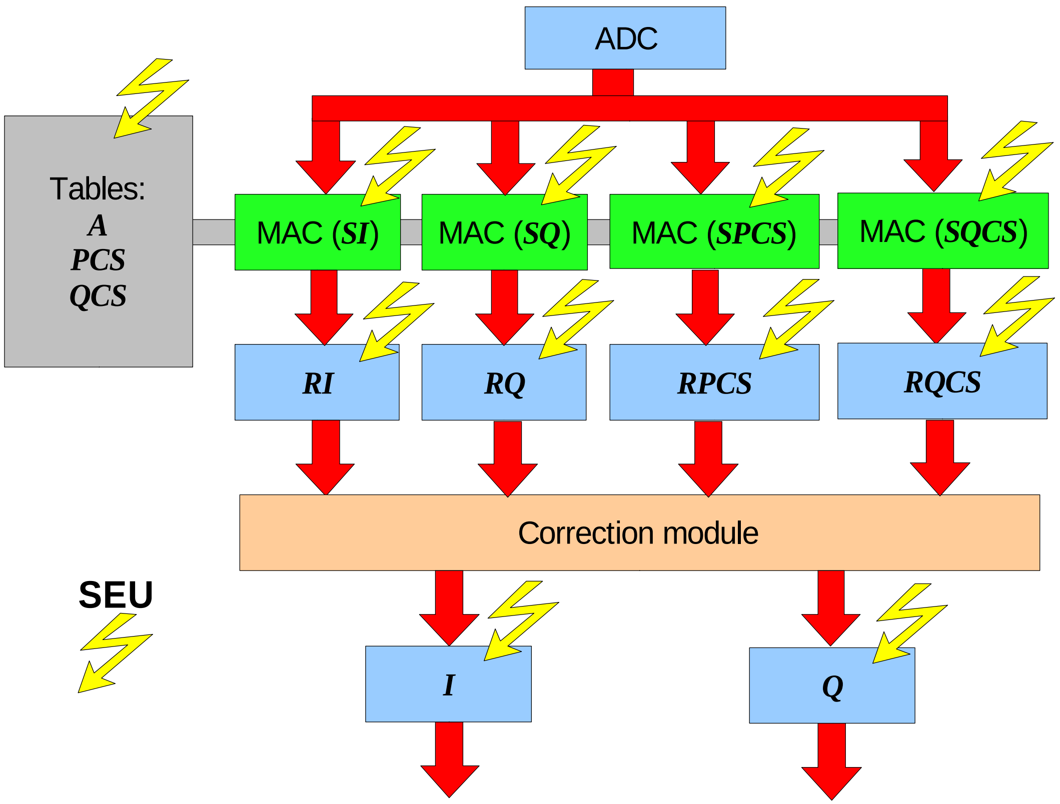
$$\begin{bmatrix} I \\ Q \end{bmatrix} = \frac{2}{N}\begin{bmatrix} \sin\alpha_1 & \sin\alpha_2 & \dots & \sin\alpha_N \\ \cos\alpha_1 & \cos\alpha_2 & \dots & \cos\alpha_N \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ \dots \\ x_N \end{bmatrix} = \mathbf{A}\cdot\mathbf{X}$$

Redundancy

$$\begin{bmatrix} I \\ Q \\ S_1 \\ S_2 \end{bmatrix} = \frac{2}{N}\begin{bmatrix} \sin\alpha_1 & \sin\alpha_2 & \dots & \sin\alpha_N \\ \cos\alpha_1 & \cos\alpha_2 & \dots & \cos\alpha_N \\ pcs_1 & pcs_2 & \dots & pcs_N \\ qcs_1 & qcs_2 & \dots & qcs_N \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ \dots \\ x_N \end{bmatrix} = \begin{bmatrix} \mathbf{A} \\ \mathbf{PCS} \\ \mathbf{QCS} \end{bmatrix} \cdot \mathbf{X}$$

IQ detection algorithm - simulation

- Randomly generated SEUs were affecting all registers
- Almost all errors were corrected (except errors in output registers – application of error correcting codes is required)
- Only double hardware redundancy


ADC

Tables:
A
PCS
QCS

MAC (*SI*)
MAC (*SQ*)
MAC (*SPCS*)
MAC (*SQCS*)

RI
RQ
RPCS
RQCS

Correction module

I
Q

SEU

SI	lcb/IQC4/	05634
SQ	lcb/IQC4/	01622
PCS	lcb/IQC4/	00000
QCS	lcb/IQC4/	00000
Q	lcb/IQC4/	01622
I	lcb/IQC4/	05634

Conclusion

- In the environment of high-energy electron accelerators driving the FLASH/XFEL the Gamma rays predominate over the neutrons
- Total Ionizing Dose (TID) is the main source radiation of effects while Displacement Damage is negligible
- Real-time (on-line) gamma monitoring is imperative to optimize the module gradient in order to reduce the gamma doses, thereby lowering the TID effects to electronics
- The efficient countermeasures can be applied
  - 20 cm thick borated heavy-concrete shield reduces the gamma dose by a factor of 50 (simulation results using MCNP code, the measurements in FLASH are ongoing)
  - 6 mm thick composite material based local shield reduces the SEU probability by a factor 10^{-4}
  - application of the hardware and software redundancy allowing detection and correction SEU driven errors