RADIATION HARDNESS TESTING OF ELECTRONICS

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DEPARTMENT OF RADIATION RESEARCH AND PROTON RADIOTHERAPY

PRESENTATION PLAN

1. Radiation environments
2. Radiation damage to electronics
3. Testing conditions and irradiation facilities
4. RD50 intercomparison

RADIATION ENVIRONMENTS

- cosmic environment
- high energy physics experiments
- nuclear phission and fusion
- medical
- millitary
- ...

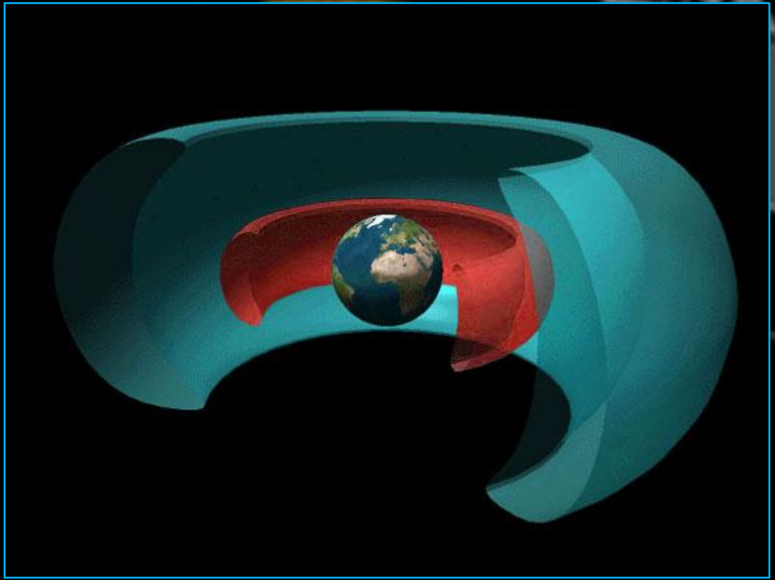
COSMIC RADIATION ENVIRONMENT

- Van Allen belts – protons (up to hundreds MeV) and electrons (up to a few MeV) trapped by Earth’s magnetic field, anisotropic
  - satellites on a low Earth orbit (LEO) pass several times a day through them
  - other planets also can have them!
- Solar flares – electrons, protons and heavy ions for a few days
- Galactic radiation – isotropic, low flux, high energy (tens MeV – hundreds GeV) – causes mainly SEE
- Radiation from artificial sources
  - radioisotope thermoelectric generators
  - scientific equipment, i.e. X-ray diffraction and fluorescence spectrometer containing ^{55}Fe (ExoMars ESA mission)
  - high altitude nuclear weapon tests, i.e. Telstar satellite irradiated by an electrons belt

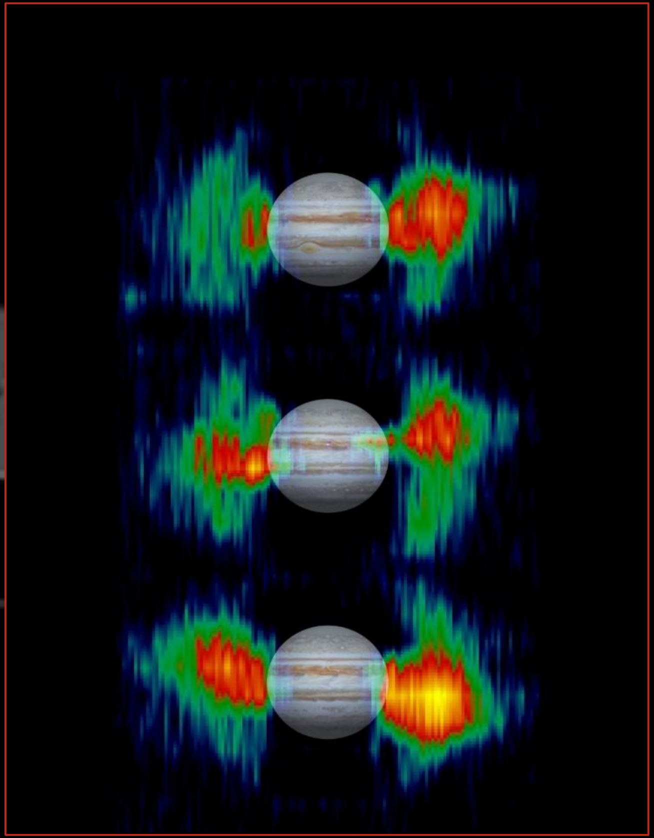
How much dose?

- gamma rays polarimeter POLAR-2 **(300 km altitude, 42° inclination)** is supposed to get **4,96 Gy within 78,1 years (or 5,04 years if it wouldn’t have the case)**

COSMIC RADIATION ENVIRONMENT



By JHUAPL, NASA, recoloured by cmglee - http://www.nasa.gov/content/goddard/van-allen-probes-reveal-zebra-stripes-in-space, Public Domain, https://commons.wikimedia.org/w/index.php?curid=37587765



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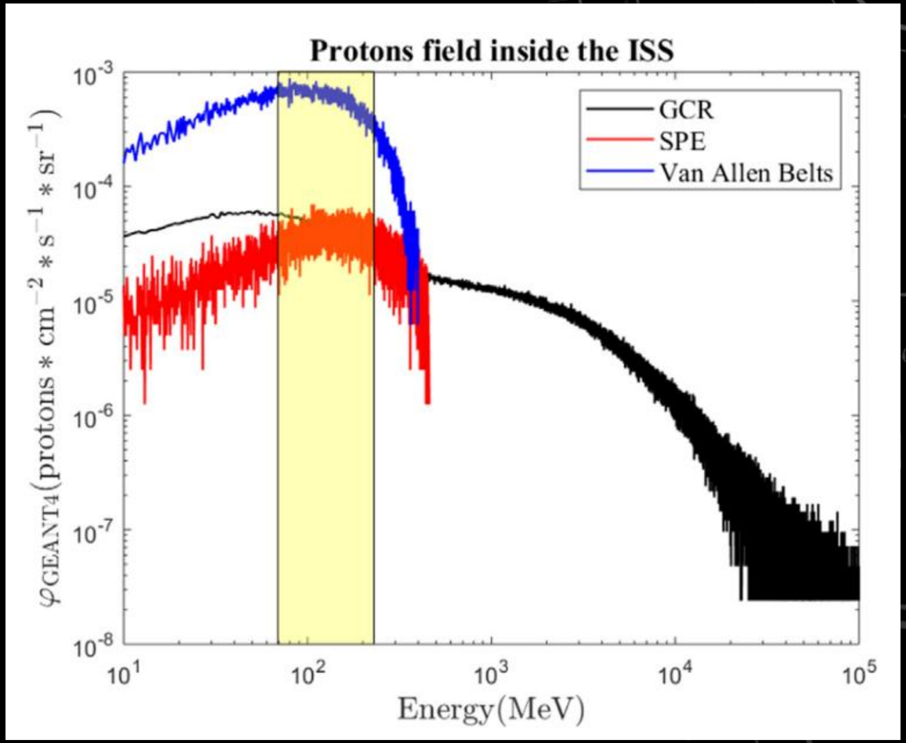
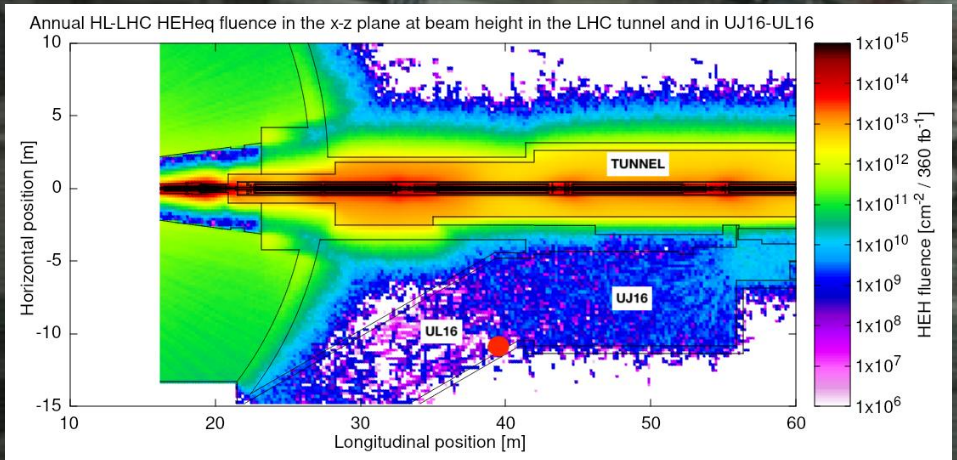


S. Peracchi et al., Advances in Space Research 67 (2021) 2534–2543

ACCELERATOR RADIATION ENVIRONMENT



https://r2e.web.cern.ch/about-radiation/radiation-environment-lhc

- Radiation damage caused mainly by gamma and neutrons (Belousov, 2014)
- Expected total fluence neutron equivalent is 1.6×10^{14} cm^{-2} (Claeys & Simoen, 2013)

RADIATION DAMAGE TO ELECTRONICS (SEMICONDUCTORS)

- single event effects (SEE)
- total ionizing dose (TID) effects
- displacement damage - deffects caused by radiation can generate, recombine or trap electron-hole pairs, cause donors and acceptors compensation and tunnelling

enhanced low doserate effects sensitivity (ELDRS) –in case of higher flux, crystal lattice defects can be partially repaired- when testing, doserate must be below 0,1 mGy/s

SINGLE EVENT EFFECTS

- upset – a particle leaves a wake of electron-hole pairs, causing removable errors, i.e. bit flips; can also have a persistent form (stuck bits)
- latchup – turning on a parasitic transistor (can be turned off only by removing power supply, otherwise thermal runaway and melting can occur)
- burnout – similar to SEL – localized high-current state
- transient – voltage peak, can destroy elements connected to that voltage if they can't handle it
- functional interrupt
- gate rupture
- dielectric rupture
- snapback

https://radiationtestsolutions.com/blogs/single-event-effects-in-aerospace-applications/

WHAT CAN BE TESTED WITH PROTONS?

SINGLE-EVENT EFFECTS TEST MATRIX FOR VARIOUS COMPONENTS

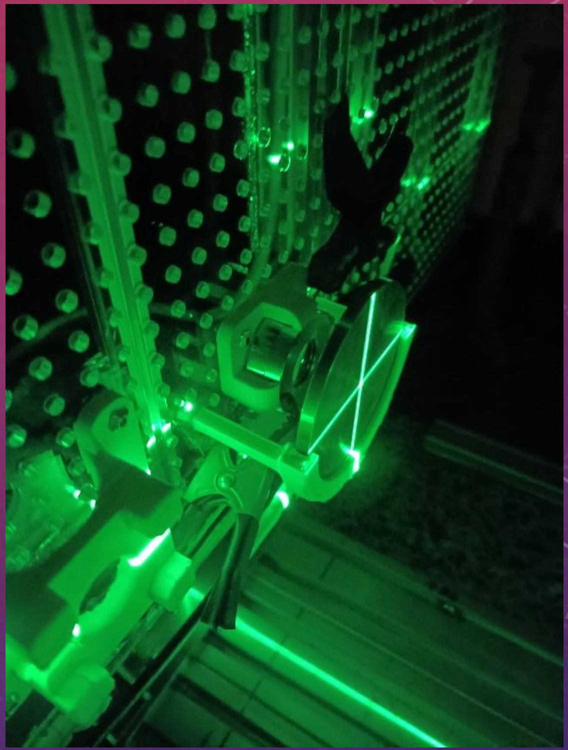
Component	SEU Proton	SEU Heavy Ion	SEL Proton	SEL Heavy Ion	SEGR Heavy Ion	SEB Heavy Ion	SET Heavy Ion	SE Microdose
discrete MOS	no	no	no	no	yes	yes	no	yes
CMOS ICs	yes	yes	yes	yes	yes	yes	yes	yes
discrete power MOS	no	no	no	no	yes	yes	no	yes
discrete bipolar	no	no	no	no	no	yes	no	yes
bipolar linear ICs	yes	yes	yes	yes	yes	yes	yes	yes
discrete MEMS	no	no	no	no	no	no	no	no
MEMS ICs	yes	yes	yes	yes	yes	yes	yes	yes
discrete III-V	no	no	no	no	no	yes	no	no
III-V ICs	yes	yes	no	no	no	yes	yes	no
discrete optoelectronics	yes	yes	no	no	no	no	no	no
optoelectronic ICs	yes	yes	yes	yes	yes	yes	yes	yes

- Protons of energy less than 180 MeV cannot be used for SEL testing (Schwank et al., 2013), but TID testing is possible

TESTING FACILITIES AROUND THE WORLD

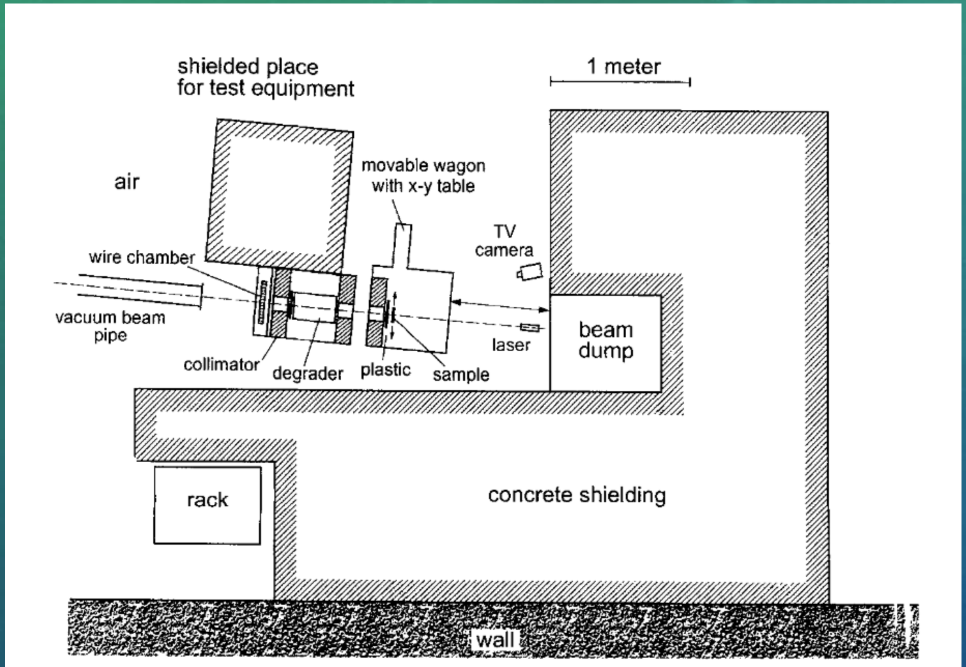
- Proton beams of different energies
- Other beams: heavy ions, neutrons, muons, gamma etc.

AIC-144 (IFJ)



- Energy: 60 MeV
- Current: 1 nA – 80 nA
- Available doses: up to 100 kGy
- Beam can be scattered by metal foils (i.e. Pb, W) and limited by collimators of different shapes and diameters
- XY scanner , 40x40 cm movement ranges

PAUL SCHERRER INSTITUTE – PROTON IRRADIATION FACILITY

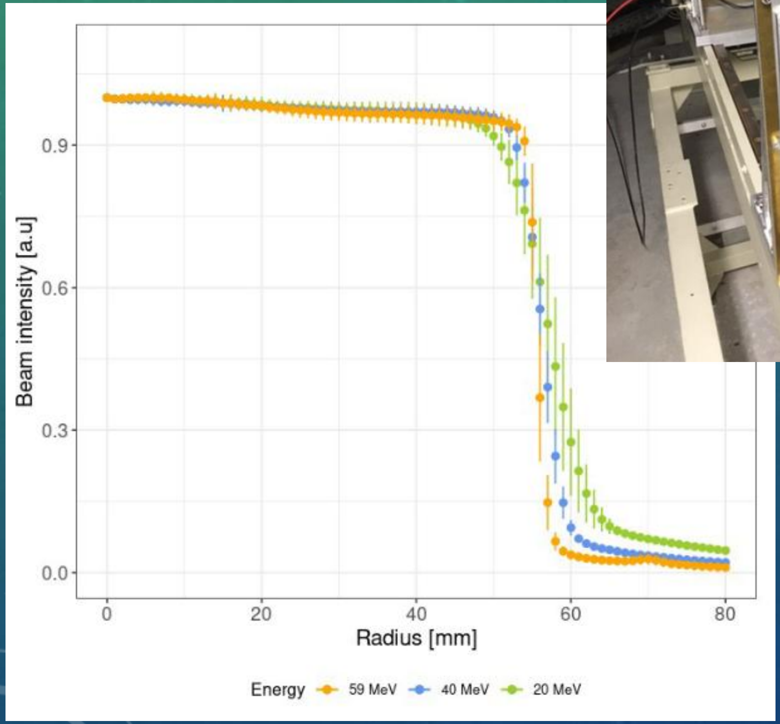


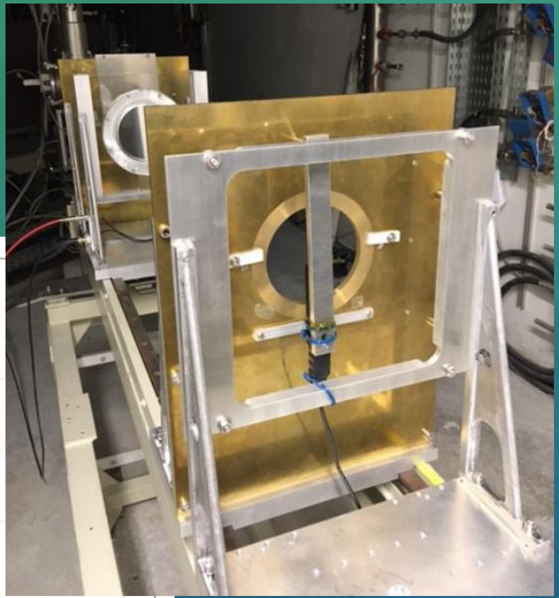
W. Hajdas et al./Nucl. Instr. and Meth. in Phys. Res. B 113 (1996) 54-58

- Energy: 30-300 MeV
- Maximum current at test facility: 3 nA
- Maximum field: 10 x 10 cm
- XY scanner with 30 cm range
- Neutrons background: less than 10^{-4} neutrons / cm^2 / proton

https://www.psi.ch/en/pif

CENTRE NATIONAL D'ETUDES SPATIALES (CNES)

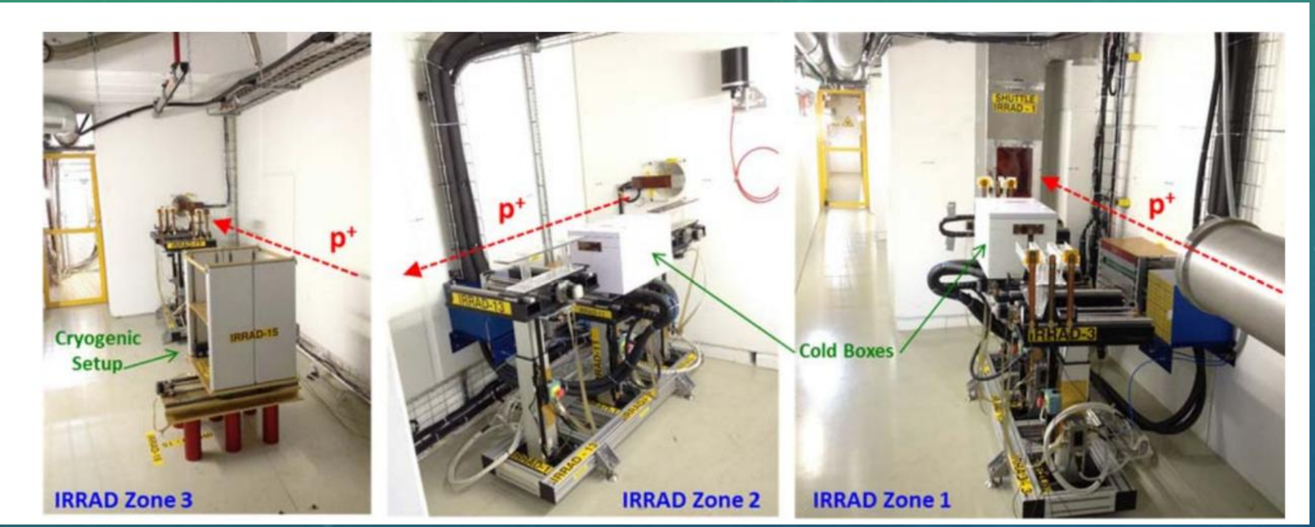




Validation of a new 60 MeV proton beam-line for radiation hardness testing, DOI: 10.1109/RADECS55911.2022.10412420

- Energy (59.0 ± 0,5) MeV
- Current 10 pA – 10 µA
- Delivered flux: $2*10^5 – 2*10^{10}$ p/cm²/s
- Circular field of about 100 mm diameter – inhomogenity less than 5% - prepared by:
  - 2 tantalum foils of 0.15 mm thickness:
    1. at beam nozzle
    2. 120 cm after beam nozzle
  - double ring occluder inside collimator 2.

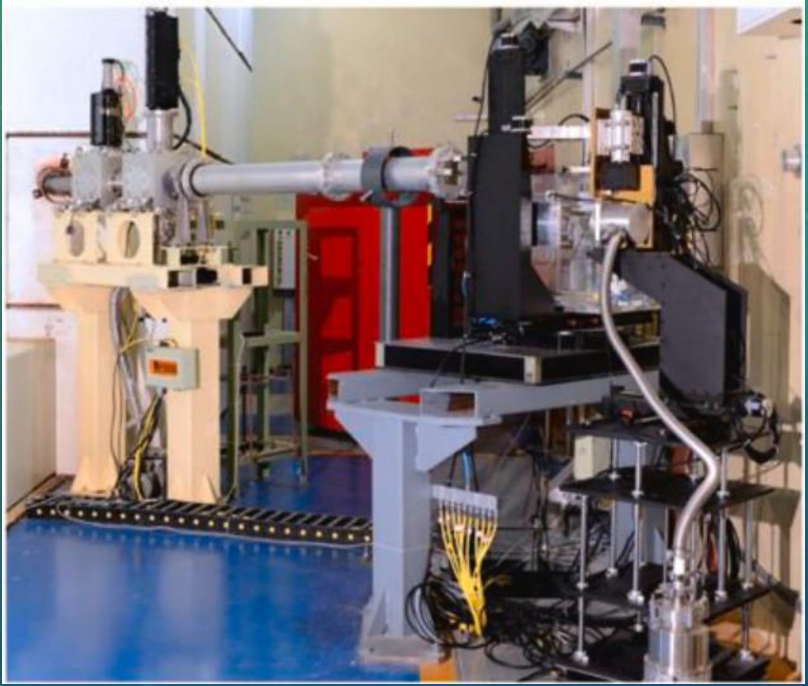
IRRAD (CERN)



Allport et al., *Experimental determination of proton hardness factors at several irradiation facilities*

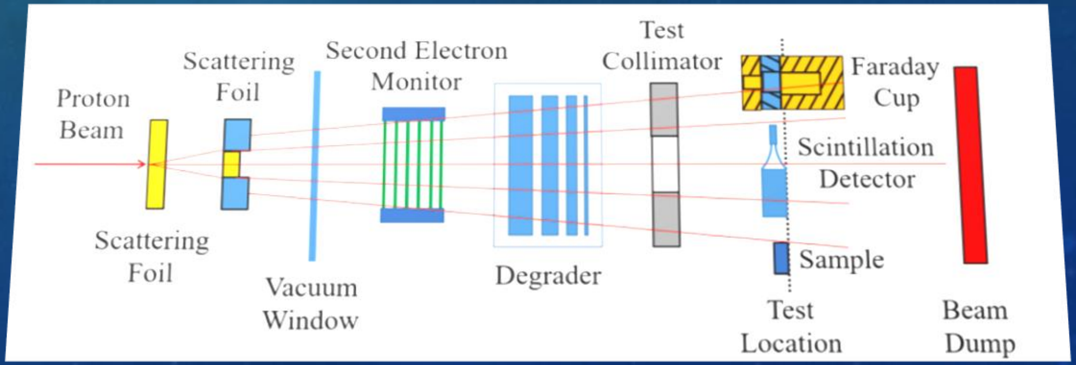
- Energy: 23 GeV
- Spot dimensions (FWHM): $5 \times 5 - 20 \times 20\ mm^2$
- Robotic scanner with climate chamber

CHINA INSTITUTE OF ATOMIC ENERGY (CIAE)

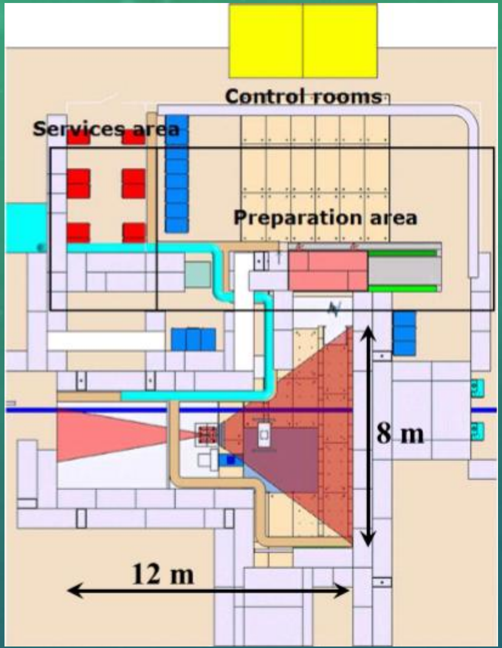


Y.-W. Zhang et al., Nuclear Inst. and Methods in Physics Research, B 517 (2022) 43–48

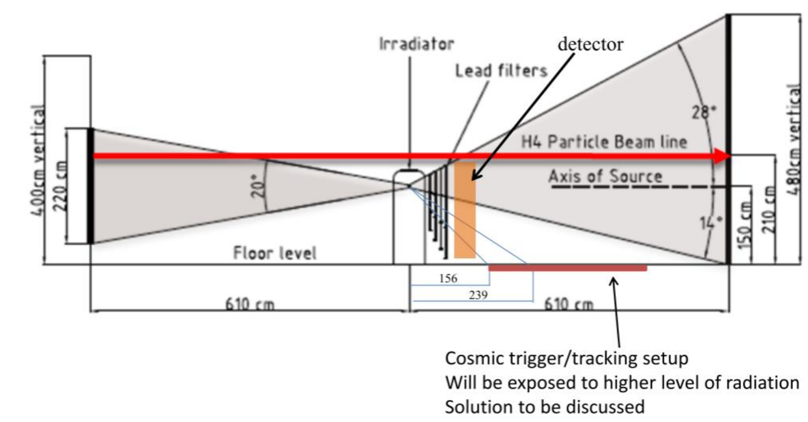
- Energy: 75-100 MeV
- Flat dose distribution formed by double scattering
  1. tantalum foil 0.46 mm thickness – Gauss distribution
  2. 500 mm after:
     - tantalum disk – radius 16.5 mm, thickness 1.08 mm
     - aluminum ring – thickness 4.35 mm
- Sample is placed 1900 mm after the 2nd target



GAMMA IRRADIATION FACILITY (GIF) AND GIF^{++}



- Simultaneous irradiation by accelerator and ^{137}Cs (662 keV photons)
- GIF: 0.5 TBq (2004) + particles from X5 line in SPS West Area
- GIF^{++}: 14 TBq + particles from H4 line in EHN1 (mainly muons, max. 100 GeV)
  - muons fluence delivered in 1 spill: 10^4



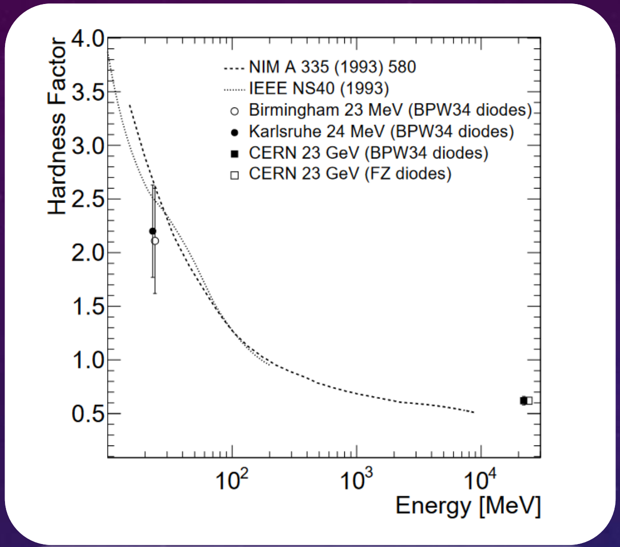
GIF ++ The new CERN Gamma Irradiation Facility, R. Guida, R. Fortin, D. Pfeiffer, F. Ravotti on behalf of the GIF++ working group
RD51 mini week, December 5th 2012

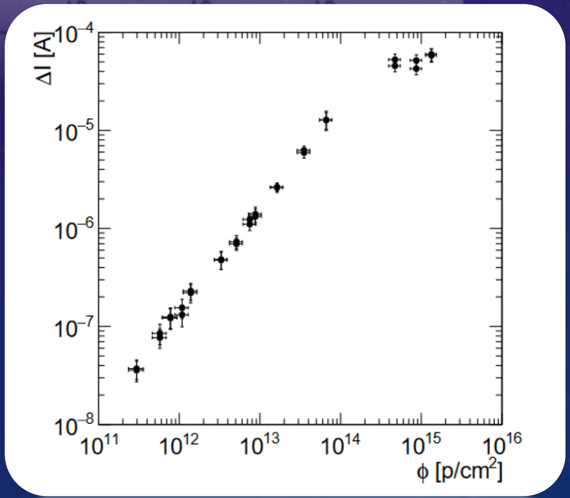
Distance from source	GIF++	Old GIF
1.5 m	58.7	1.8
3.0 m	14.7	0.4
4.5 m	6.5	0.2

Gamma flux ($\cdot 10^6$ s^{-1} cm^{-2})

(dose rate @ 6.10 m of ~45 mSv/h)

RD50 INTERCOMPARISON





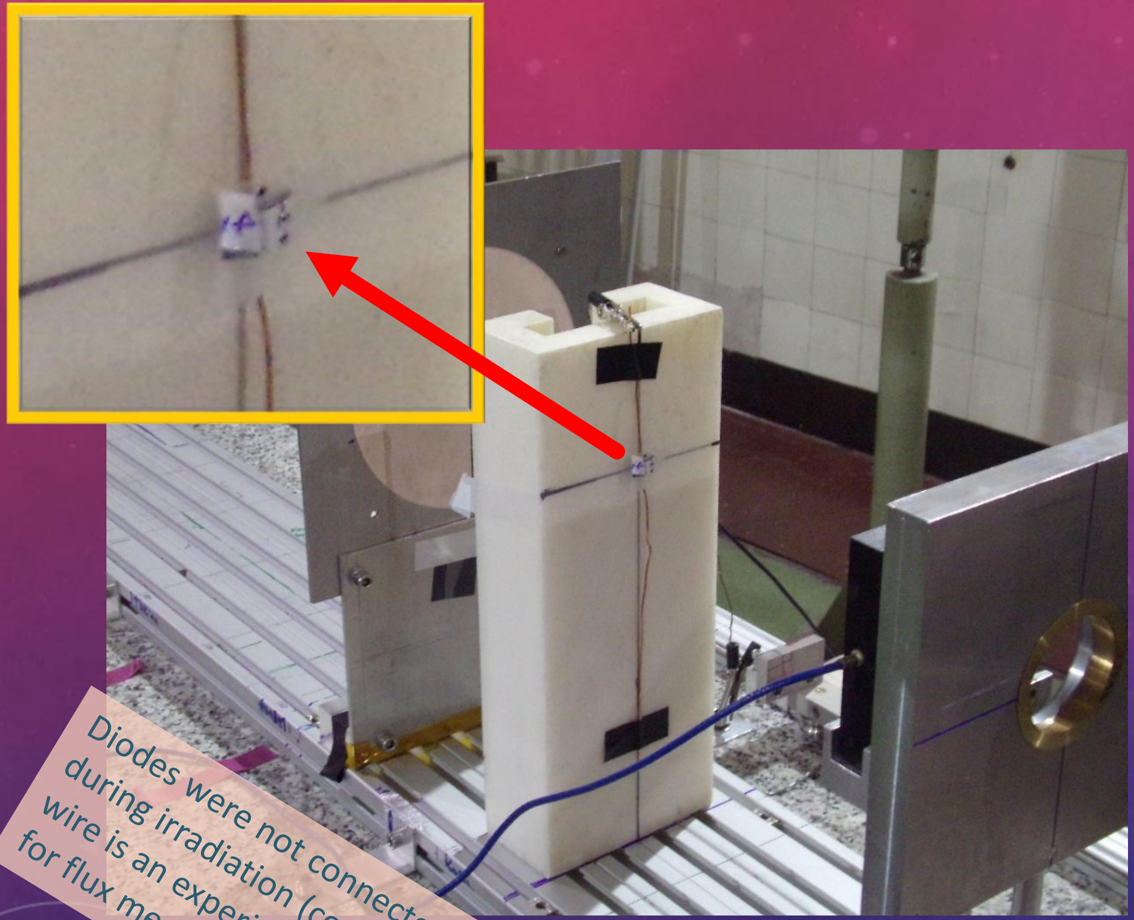
Allport et al.

https://look.ams-osram.com/m/2c4b674435bb90e8/original/BPW-34-F.pdf

- Hardness factor κ – comparison with 1 MeV neutrons
- $\kappa = \frac{\phi_{neq}}{\phi} = \frac{\alpha}{\alpha_{neq}}$
- α, current related damage rate, is derived from measurement of leakage current
- $\Delta I = \alpha l^2 w\phi$, *where* l^2 *- active area of silicon ((0.265 cm)²), w – width of the depletion region (300 µm)*
- ΔI is measured at maximum depletion voltage: $C(V) \sim \frac{1}{\sqrt{V}}$ -> $C(V) = const$

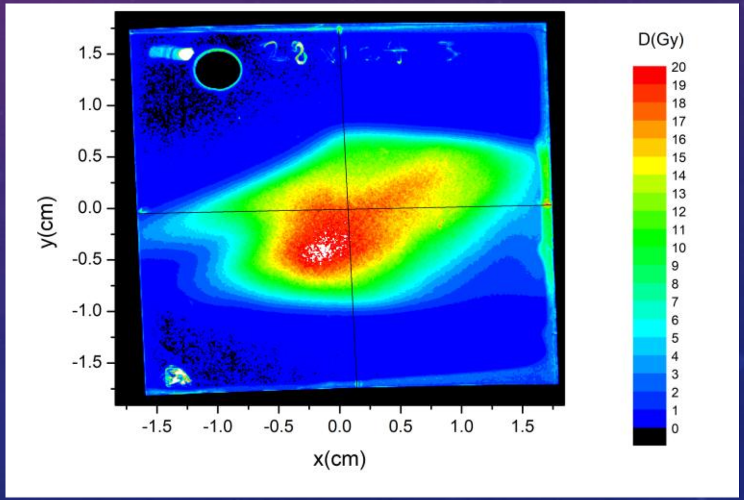
BPW34F IRRADIATIONS AT AIC-144

Diodes 1 and 2 – reached breakdown voltage – excluded from comparison (breakdown might have changed their leakage current).



Diodes were not connected during irradiation (copper wire is an experimental part for flux measurement)!

- Before irradiation, diode 3 has been annealed in 60 °C for 80 min
- Diodes 3 and 4 were irradiated with 403.59 Gy dose, that is **2.34×10^{11} p/cm^2** fluence – similar to the lowest fluence in *Experimental Determination of Proton Hardness Factors at Several Irradiation Facilities*
- Irregular dose distribution (unscattered beam) makes it harder to accurately determine the fluence
- Irradiation time 11.3 s, intensity 16 nA

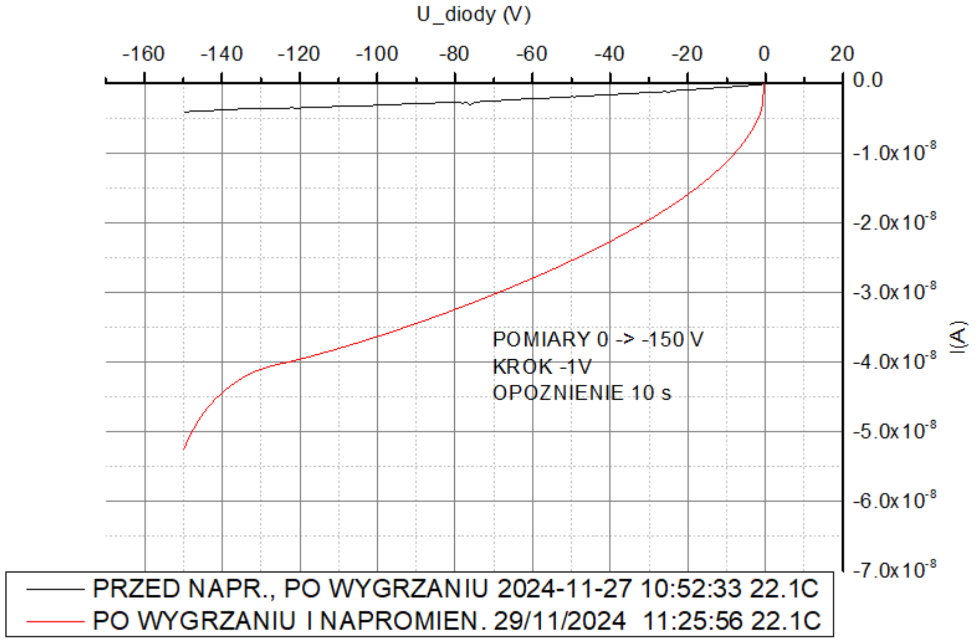


BPW34F CURRENT MEASUREMENTS

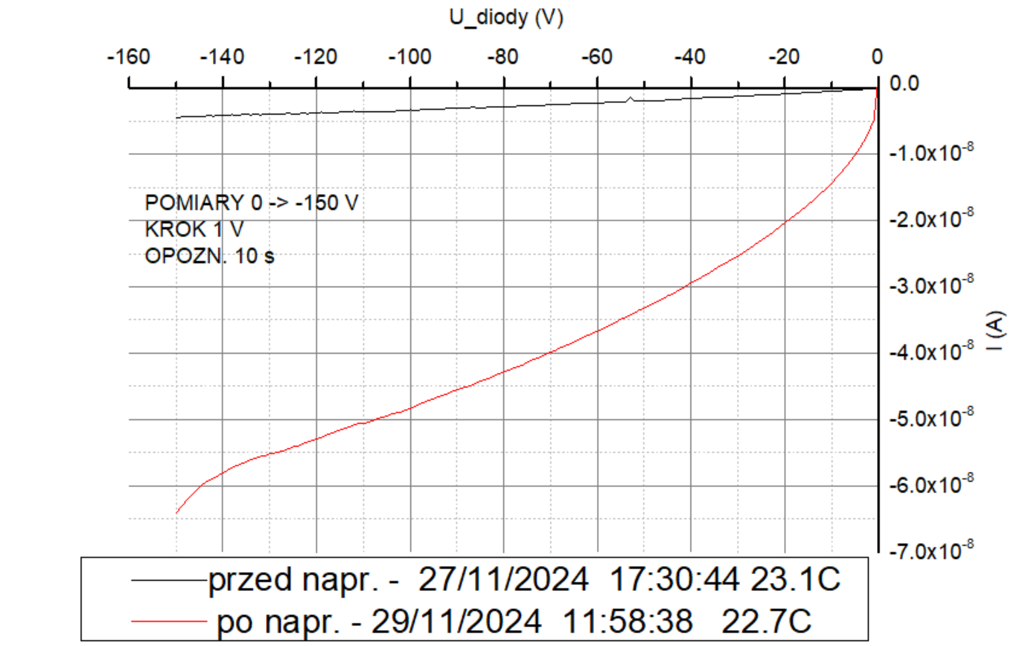
- Diodes were measured using Keithley 6517B electrometer (voltage source and current measurement), in series with a current limiting resistor (10 kΩ)
- Measurement parameters:
  - voltage step: **1 V**
  - maximum voltage: **150 V**
  - delay between voltage change and current measurement: **10 s**
- No device available to measure diode capacitance – full saturation voltage taken from the article: **120 V**

BPW34F CURRENT MEASUREMENTS

DIODE 3 – ANNEALED BEFORE IRRADIATION



DIODE 4 – NOT ANNEALED



- if hardness factor **κ = 1.5** is assumed, delivered fluences for diode 3 and 4 calculated from current change are **2.85×10^{11} and 3.89×10^{11} p/cm^2** respectively
- fluence calculated from current change for diode 3 is **1.22x** higher than from dosimetry with ionization chambers, for diode 4 that is **1.66x** higher

CONCLUSIONS

- Ionizing radiation can cause damage to electronics: single event effects, total dose effects and displacement damage
- Irradiation facility at AIC-144 can be used for some of the tests of radiation hardness – it has proper type of radiation and equipment
- RD50 protocol describes a method of comparison between radiation damage caused by beams available at different facilities, using BPW34F diodes – measuring their leakage current
- Test irradiations of BPW34F diodes have been conducted – obtained results are similar to described in literature, however more precise determination of dose distribution is necessary. On the other hand, some of the results presented there also have quite high error margins.

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THANK YOU FOR ATTENTION