Outline

- Introduction
  - Scope
  - Quick summary of radiation damage
- FLUKA simulations
  - Simulation setup
  - Results: expectations for
    - Total ionizing dose
    - Displacement damage
    - Single event effects
- Conclusions

Background and scope

- At the Centro Nazionale di Adroterapia Oncologica (CNAO) in Pavia, an in-beam PET module named **INSIDE** is being installed in 1 of the 3 treatment rooms
  - Planar PET system (2 LYSO planes of 10 x 25 cm^2)
  - Behind the LYSO: Hamamatsu Silicon Photomultipliers (SiPMs)
- CNAO is a hadron therapy treatment center where patients are treated dayly with protons or carbon ions (typical fraction: 2 Gy)
- The INSIDE PET system enables to monitor whether the treatment is performed as expected by:
  - Day-by-day comparisons
  - Monte Carlo vs data comparisons
- In 2018, patient tests will be done during 3 months. If successfull, PET system will stay in treatment room
- **Goal of this study: get quickly a rough idea whether the SiPMs resist for a while to this kind of environment…**
- Use FLUKA with very simplified setup to simulate what typical dose levels etc we can expect

Quick summary of radiation damage

Cumulative effects

Three types of damage

1. **Total Ionization Dose (TID)**, for electronics also called surface damage:
   - Effects caused by long term exposure to *ionizing radiation*.
   - Induces changes in the mechanical and electrical properties of materials that may cause them to operate incorrectly or even fail.
   - An important effect for insulators (charge build-up), cabling, electronics (surface charge effects), optical elements (lenses, filters) and cryogenics.
2. **Displacement Damage Dose (DDD)** also called NIEL:
   - Effects due to long term exposure to interactions with *non-ionizing energy transfer*
   - Originates displacement defects in semiconductor materials (introduction of deep band-gap levels, traps,...)
   - Important effect in all semiconductor bulk-based devices.

SEE

3. **Single Event Effects (SEE):**
   - Effect due to a single interaction, wherein a *large ionization* gives a temporary or permanent damage to many electronically live devices or systems.
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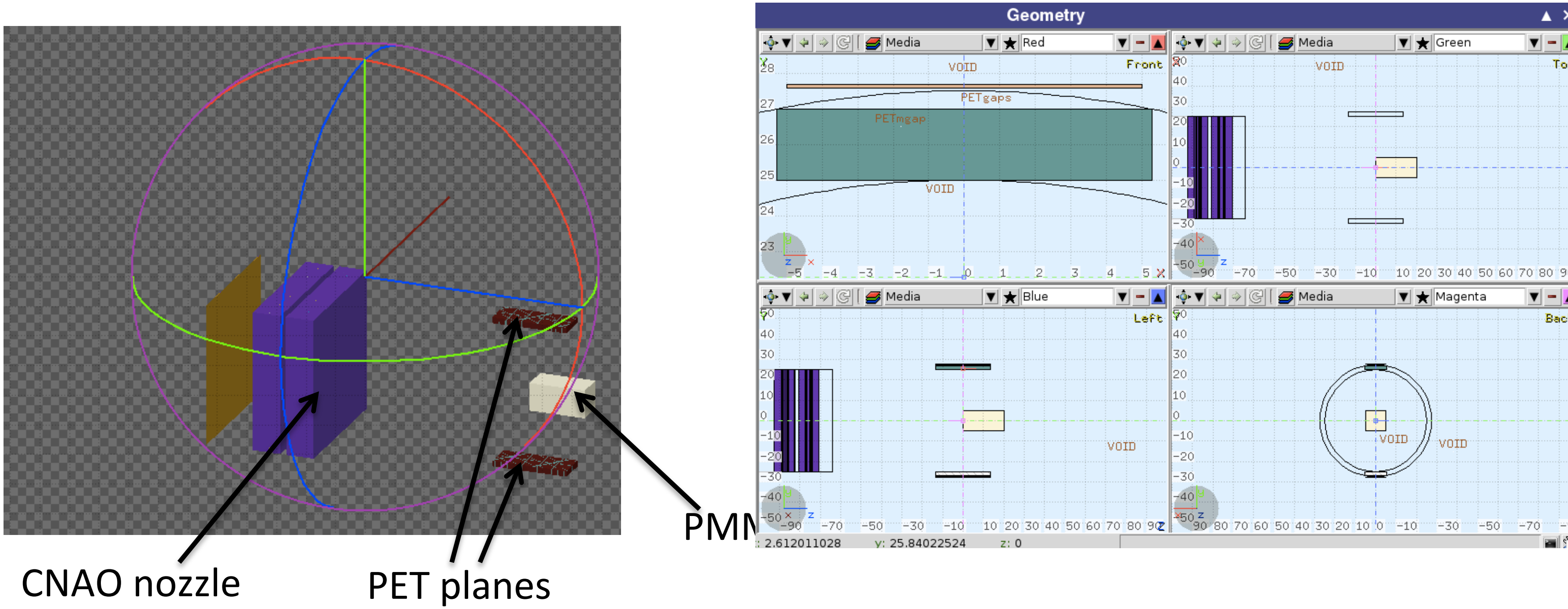
   - Induces errors, undesired latch-ups and may lead to system failure.

FLUKA simulation setup



- CNAO nozzle (Mairani) and beam structure (spills) taken into account
- PET system created by using FLUKA PET-tool (Garcia, Cuccagna, …)
- Behind LYSO: a 1 mm layer of silicon (SiPM)
- Treatment plan for protons: 2 Gy on 3 x 3 x 3 cm^3, at 4-7 cm depth: energies 62 to 91 MeV
- Protons shot on a PMMA target (4 x 4 x 20 cm^3)
- Statistics simulated: 5 x 10^7

Remember from last time…

Cumulative effects

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USRBIN:

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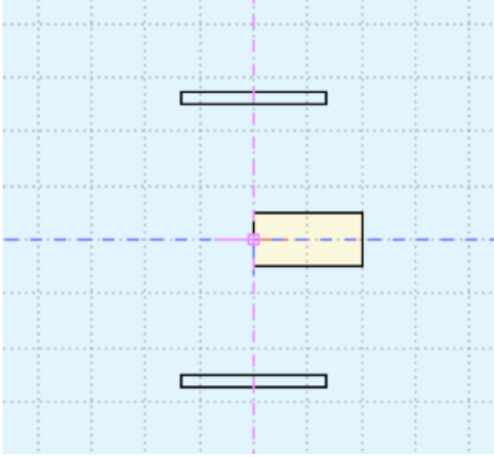
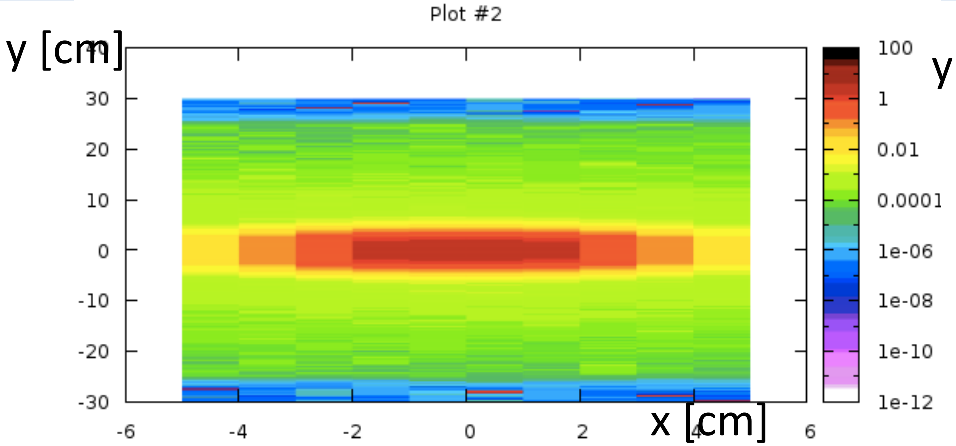
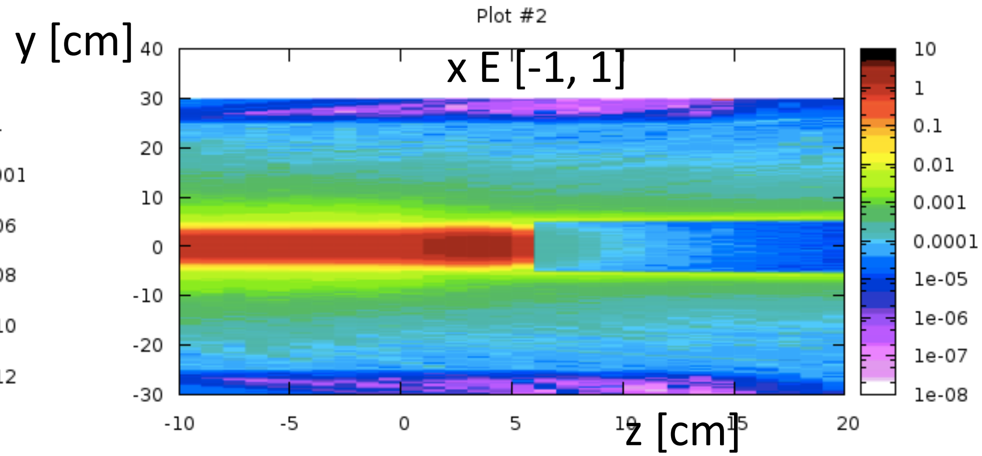
Total ionizing dose (TID)

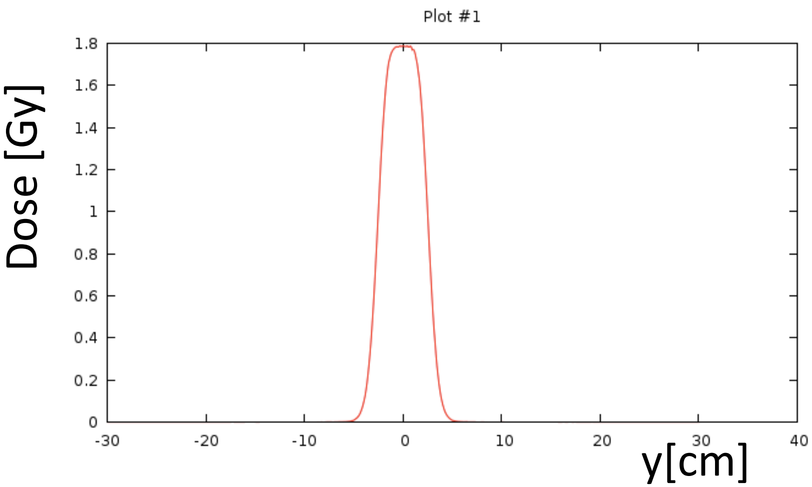
FLUKA allows to score total ionizing dose (USRBIN scoring)

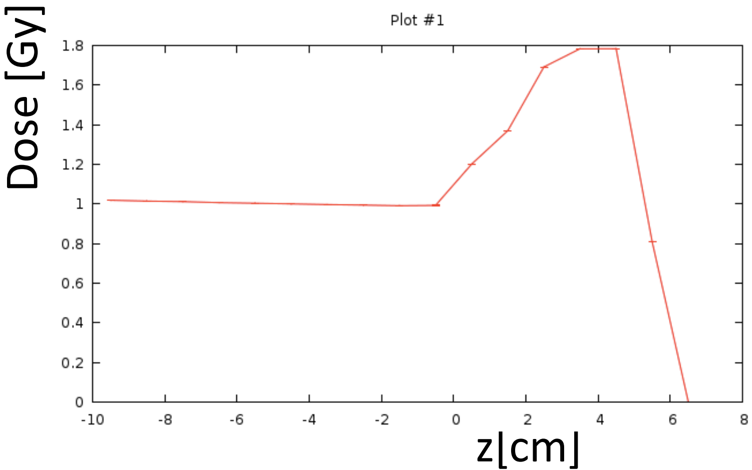
- Dose is 3D distribution
- FLUKA gives dose in GeV/g per primary in a given location (typically a bin in x,y,z)
- **1 Cross check** to confirm that the prescribed dose was 1.8 Gy (2E10 primaries)











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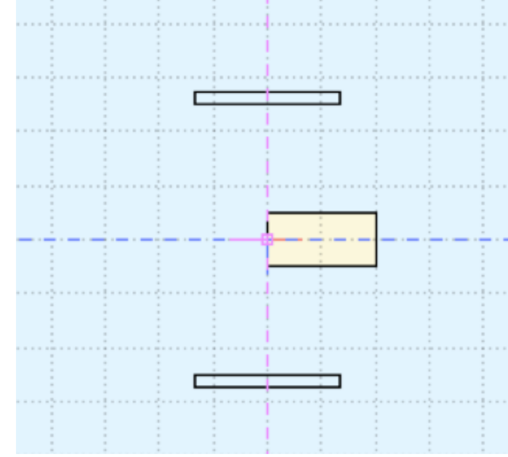

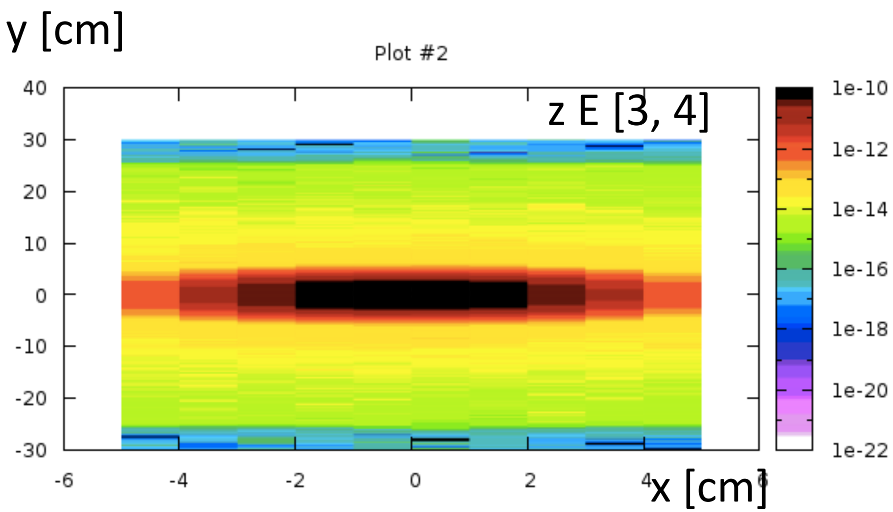

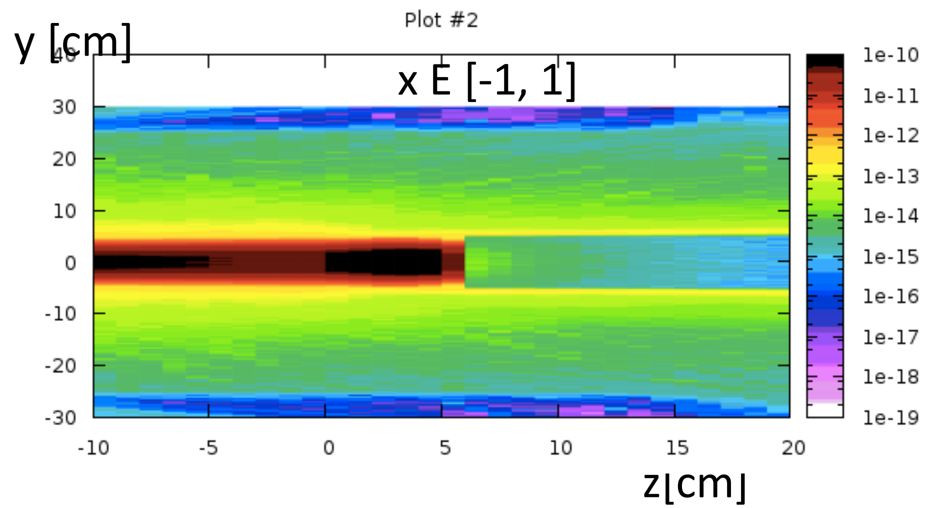

From this logarithmic plot it is already clear that dose levels at SiPM would be about 5-6 orders of magnitude below target dose levels

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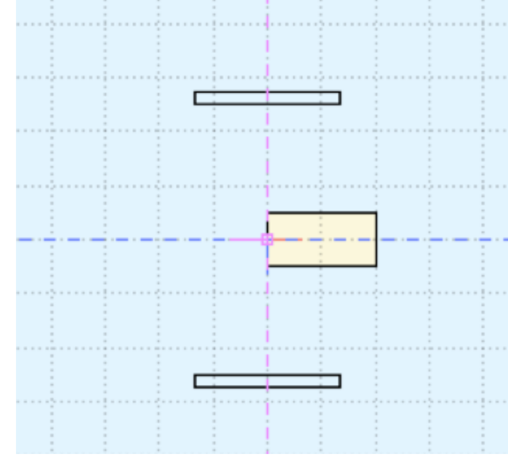

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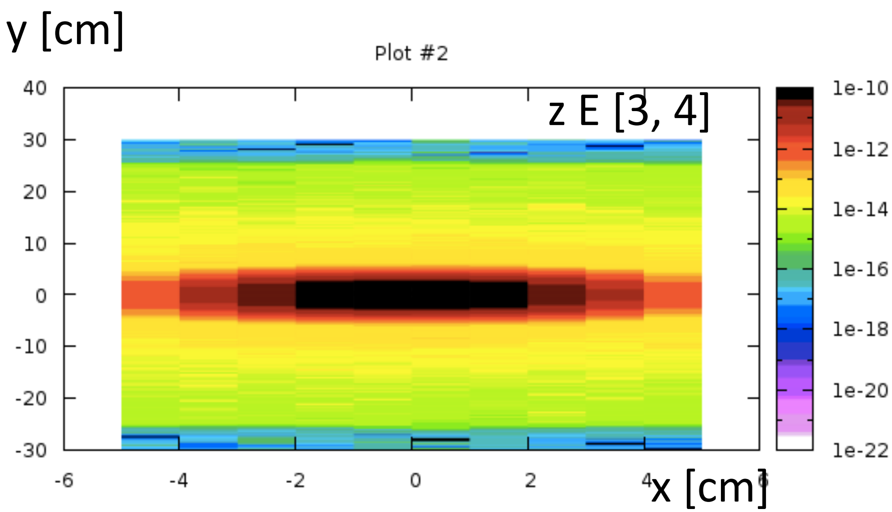

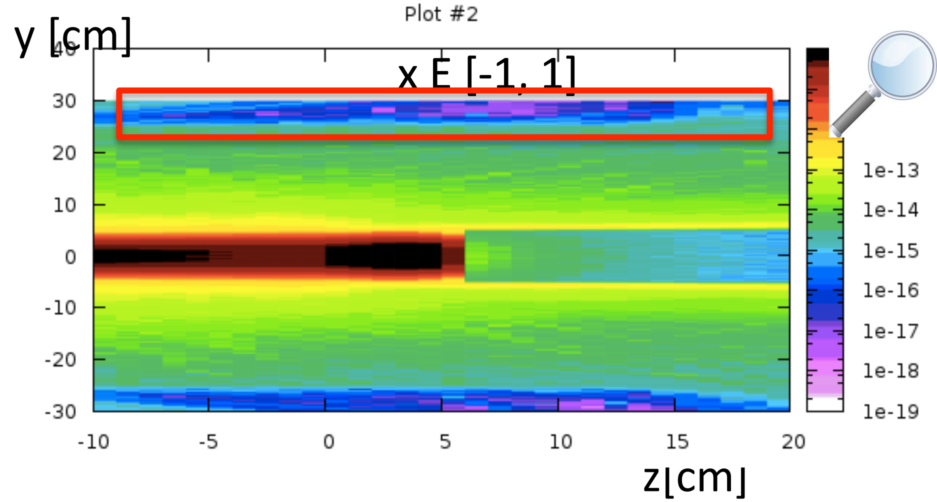

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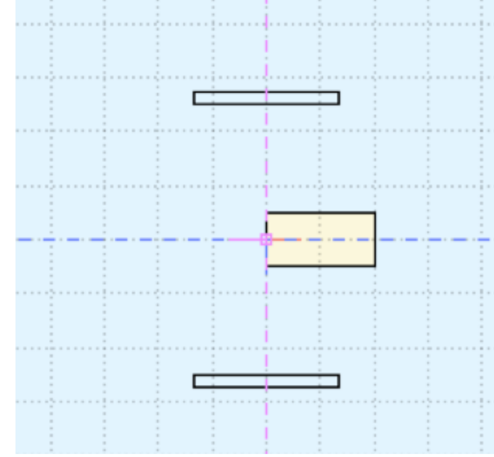
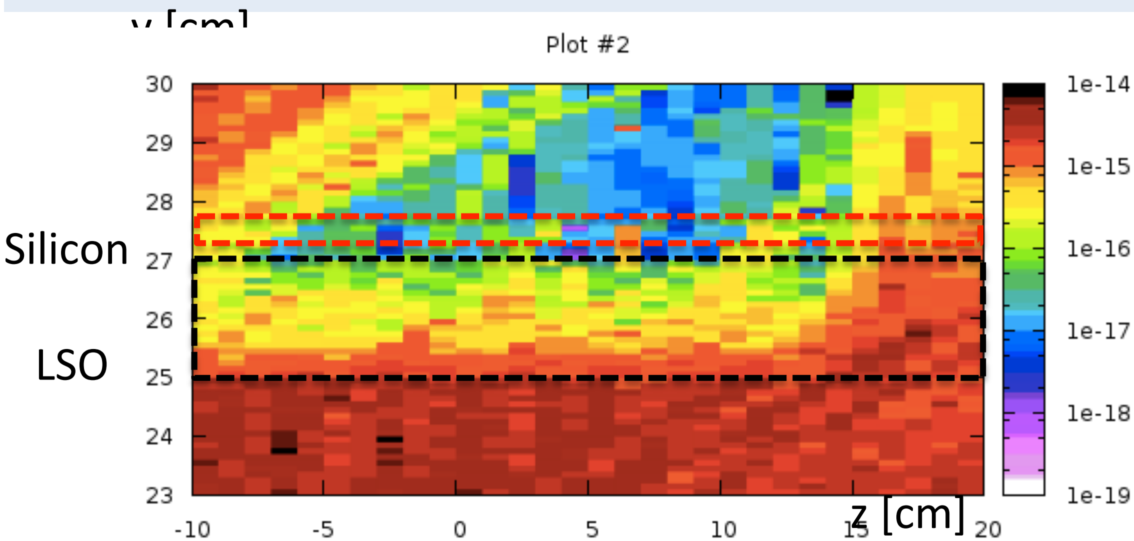
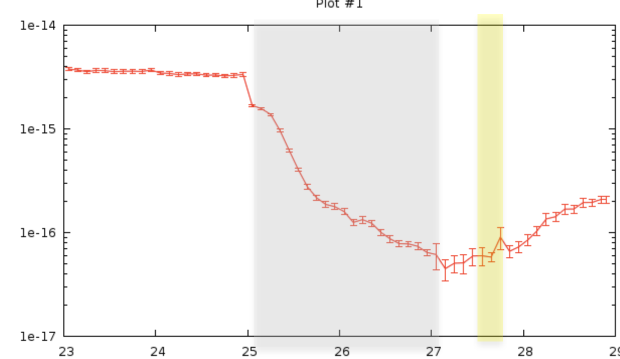




dose average in x,z per primary [Gy]



y [cm]

MAX Dose levels inside Silicon about 10^{-15} Gy per primary
AVERAGE Dose levels (av in x and z) at most order 10^{-16} Gy per primary

- 5 proton treatments per day with INSIDE
- each treatment 1 liter tumor
- 1 liter tumor with 2 Gy: 2E11 protons (see Kraan, Med. Phys. 45 (1), January 2018)
- 200 days per year operation (1000 treatments pretty big tumors with INSIDE…)

→ Total nr of protons per year is: 5*2E11*200=2E14 protons per year→ FROM NOW ON SAY **10^{14}!**

→ MAX local dose in Silicon about 0.1 Gy [conservative and VERY rough]

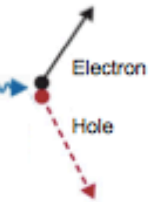
→ AVERAGE dose in Silicon about 0.01 Gy [conservative and VERY rough]

E.Garutti, DESY lecture

Surface effects

Effects on SiPMs

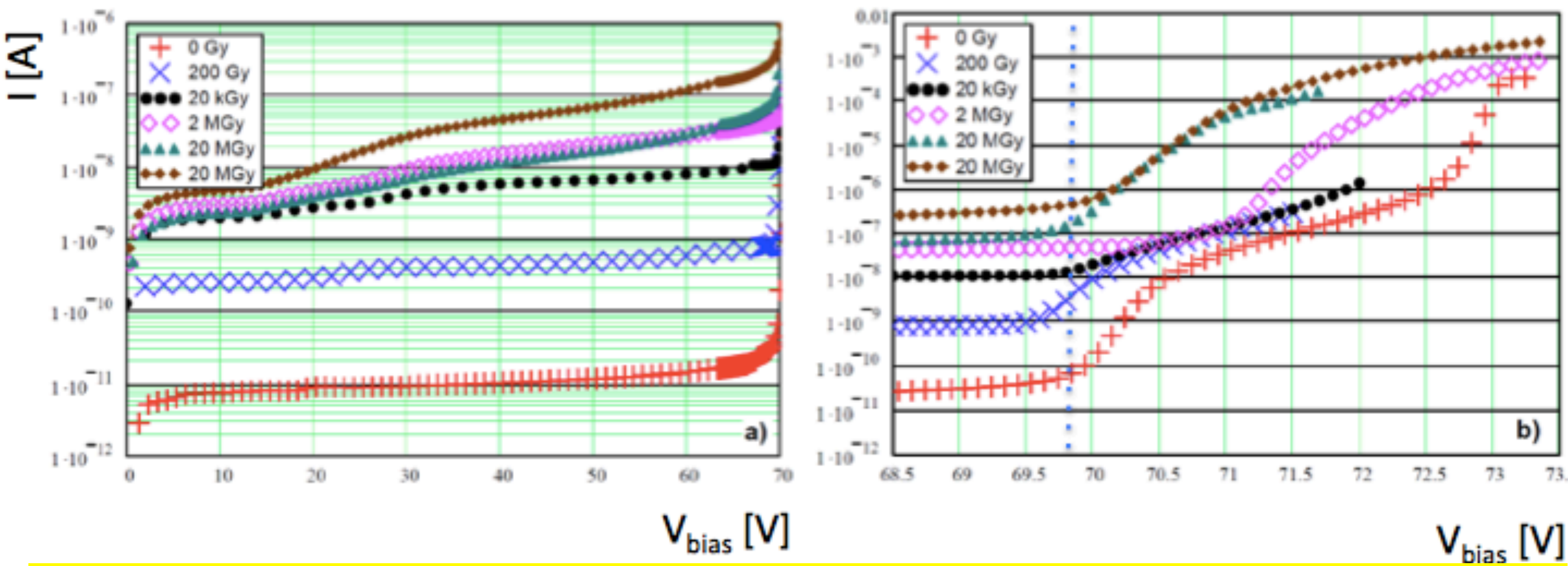
Effects of X-rays: Dark Current



Hamamatsu SiPM (MPPC 50um pixel) irradiated, not biased:

- 200 Gy and 20 kGy at X-ray tube (Mo target)
- 2 and 20 MGy at PETRA III

X-ray < 300 keV only surface damage ➔ N_{ox} and J_{surf}



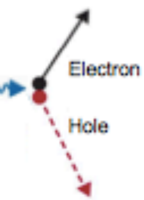
We are in the zone MUCH below 200 Gy!

E.Garutti, DESY lecture

Surface effects

Effects on SiPMs

Effects of X-rays: Gain and V_{bd}



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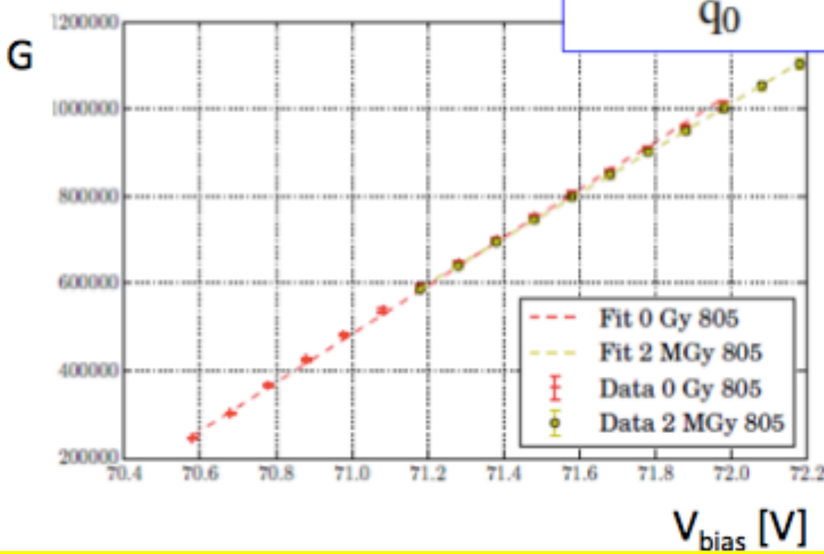
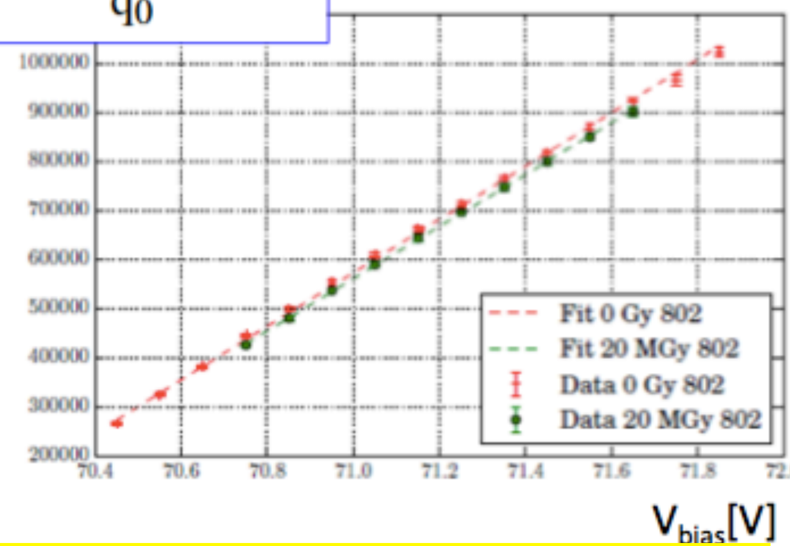
$$G = \frac{Q_{out}}{q_0} = \frac{C_{pix} \cdot (V_{bias} - V_{bd})}{q_0}$$



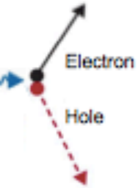


We are in the zone MUCH below 2 MGy!!!

Surface effects

Effects on SiPMs

Effects of X-rays: DCR and correlated noise



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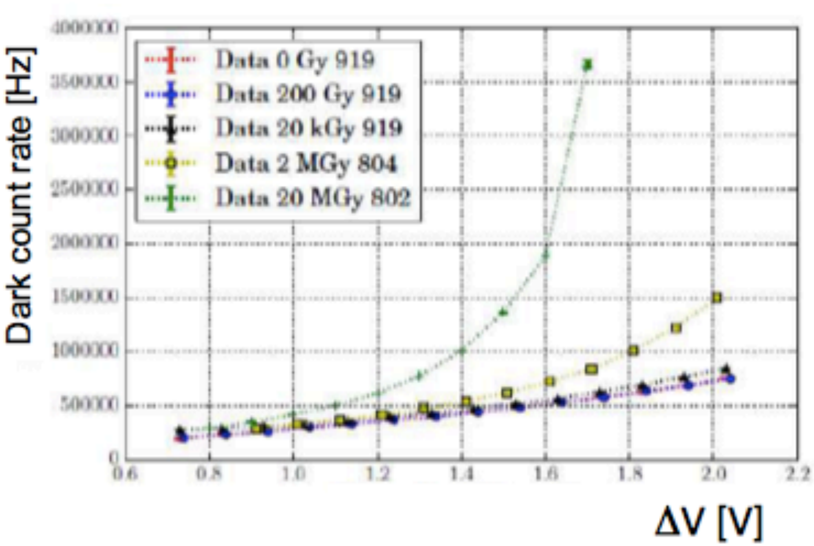

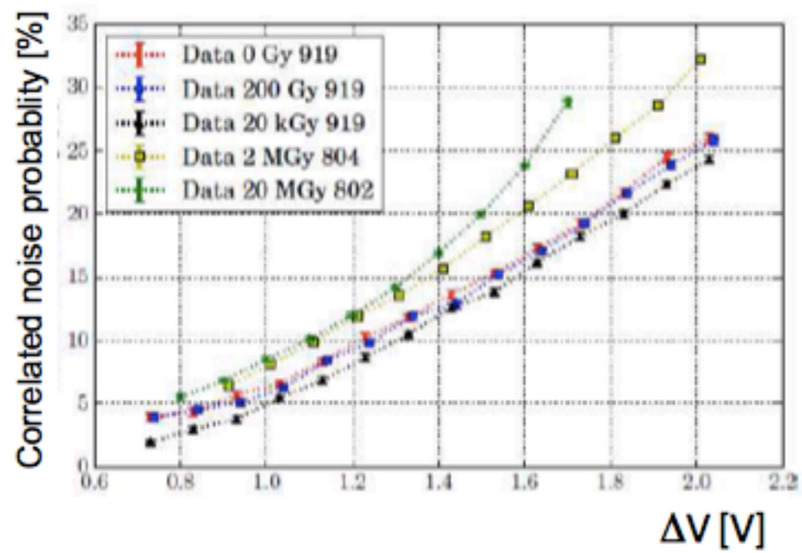

- small increase ~10% for 0-20 kGy
- increase by x3 for V_..>1.5V and 20 MGy

- negligible change for 0-20 kGy
- unexpected increase for > 2 Mgy

We are in the zone MUCH below 200 Gy!!!

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USRBIN:
- **DPA-SCO: displacement per atom**
- **SI1MEVNE: fluence of Si 1MeV equilavent particles**
- **NIEL-DEP: non-ionizing energy loss**

SEE

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Displacement Per Atom: DPA

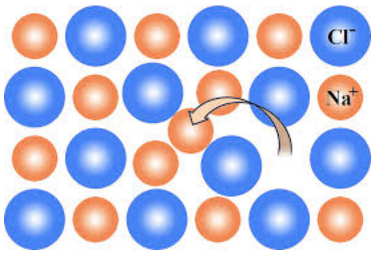
- Measure for amount of radiation damage in irradiated materials
- Example: 3dpa: each atom in material has been displaced on average 3 times

$$\mathrm{dpa} = \frac{M_A}{N_A \rho} N_F$$

$$[\mathrm{dpa}] = \frac{[\mathrm{g\ mol}^{-1}]}{[\mathrm{nr\ of\ atoms\ mol}^{-1}][\mathrm{g\ cm}^{-3}]}[\mathrm{nr\ frenkel\ pairs}] = \frac{[\mathrm{nr\ frenkel\ pairs}]}{[\mathrm{nr\ of\ atoms}]}[\mathrm{cm}^3]$$

$$[\mathrm{dpa\ per\ bin}] = \frac{[\mathrm{dpa}]}{[\mathrm{bin\ volume}]} = \frac{\frac{[\mathrm{nr\ frenkel\ pairs}]}{[\mathrm{nr\ of\ atoms}]}[\mathrm{cm}^3]}{[\mathrm{cm}^3]} = \frac{[\mathrm{nr\ frenkel\ pairs}]}{[\mathrm{nr\ of\ atoms}]}$$

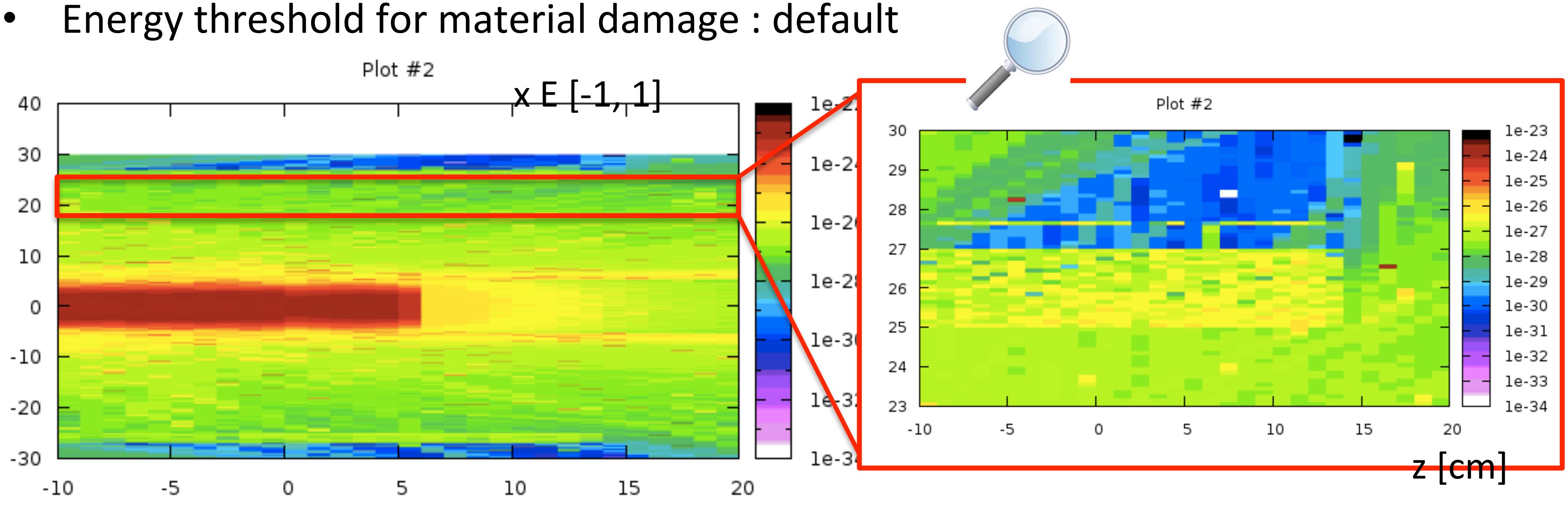
- M_A=molar mass [g mol^{-1}]
- N_A=number of Avogradro [nr atoms mol^{-1}]
- N_F=number of defects (Frenkel pairs)
- ρ=density [g/cm^3]



- In FLUKA: scoring per bin, so what we get is an **average number of displacements per atom per bin per primary**

Displacement Per Atom: DPA

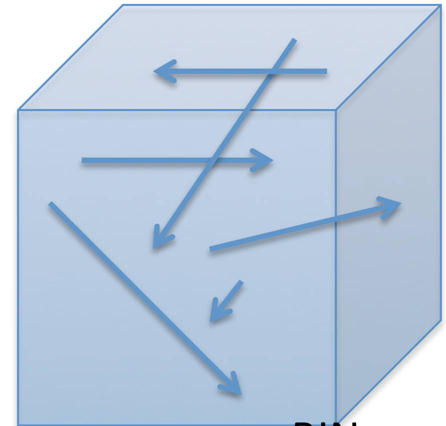
- Measure for amount of radiation damage in irradiated materials
- Locally up to max about 1E-26 **per atom per bin per primary**
- Energy threshold for material damage : default



- **average number of displacements per atom per bin per primary is** 1E-26
- With 1E14 primaries per year: 1E-12 per atom
- How many atoms are there in total?
  - Volume of 1 side silicon=1 mm* 10cm * 25 cm = 25 cm^3
  - About 2.3 g cm-3→ ~ 50 g silicon on each PET module side
  - M_A=28 g mol-1 → about 2 mol=2 *N_A ~ 10^{24} atoms
- →Interpretation not quite clear, generally not reported in radiation damage studies in Si

Si1MeV neutron equivalent fluence

- USRBIN scoring
- What is it? What unit?
  - USRBIN scoring of SI1MEVNE: a particle fluence [cm-2], again per primary
  - In reality it's more a density of particle tracks
- Formula:



$$\frac{\sum_{i=0}^{N_{\text{tracks in bin}}} \left|\vec{l}_i\right| [cm]}{V_{bin}[cm^3]}$$

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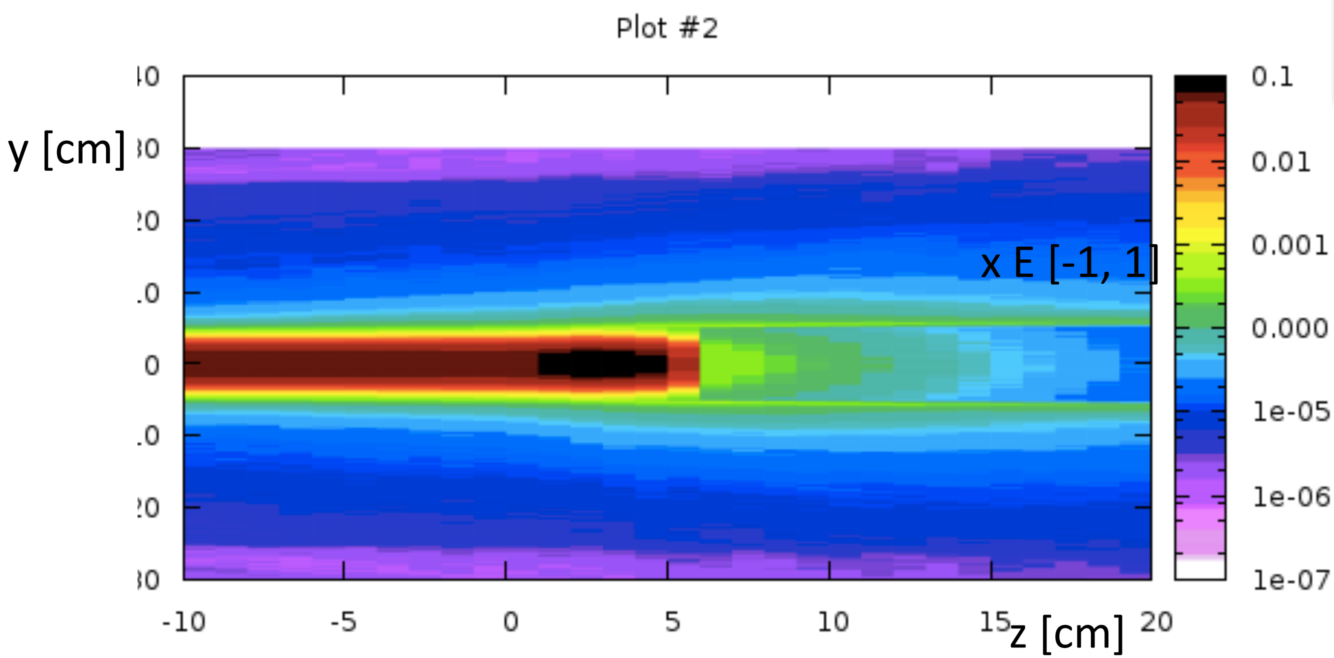

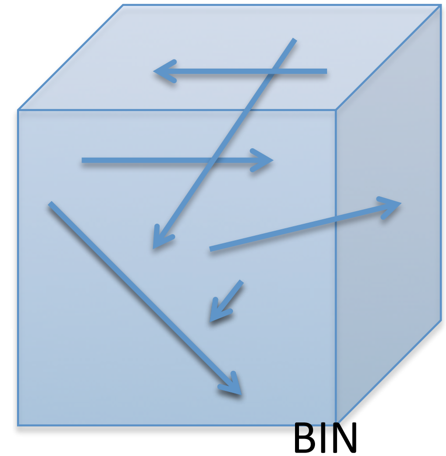

At most about:

- 10^{-5} 1MeV neutron equivalent particles cm^{-2} per primary
- With 1E14 primaries: 1E9 1MeV neutron equivalent particles cm^{-2} per year
- Interpretation see later

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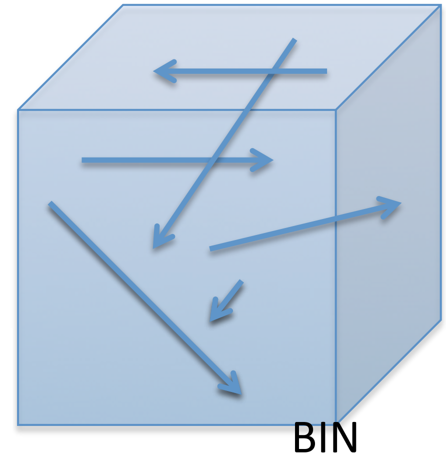

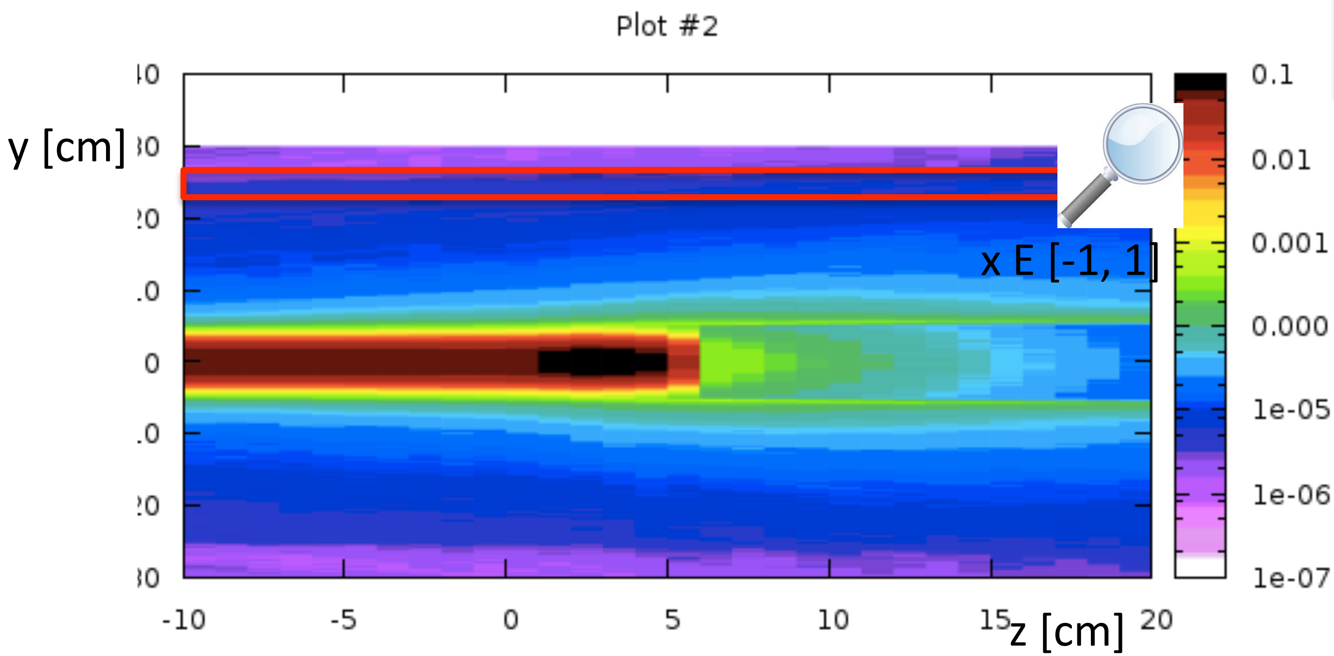

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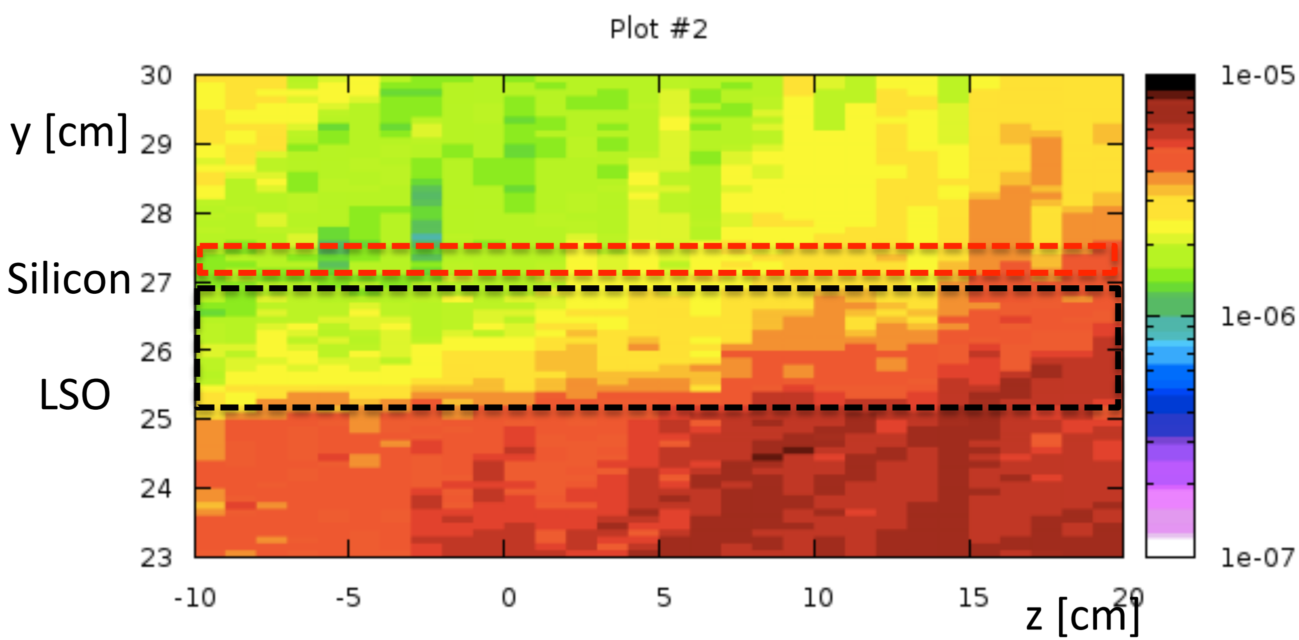
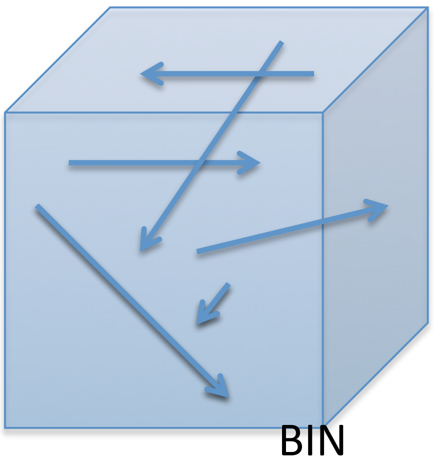


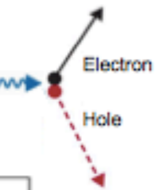


At **most** about:

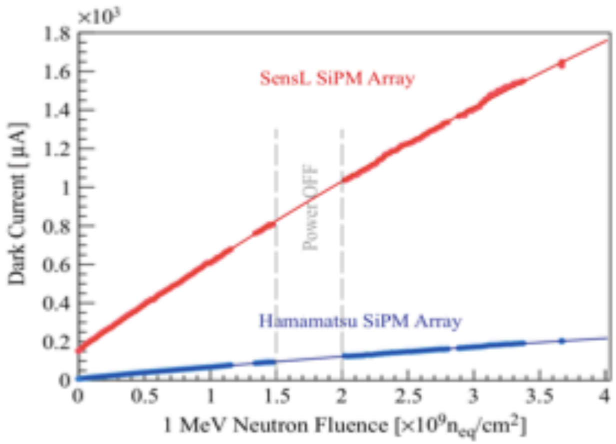
- 10^{-5} 1MeV neutron equivalent particles cm^{-2} per primary (average ~ 1E-6)
- With 1E14 primaries per year: 1E9 1MeV neutron equivalent particles cm^{-2} per year
- Interpretation see later

Bulk effects

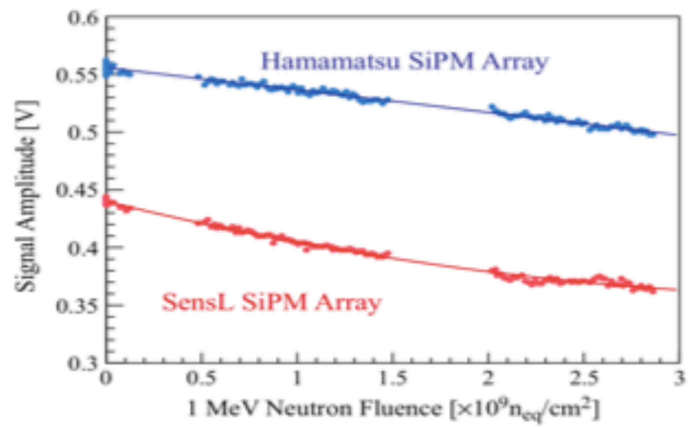
Effects of neutrons: DCR and response



Increase Dark Count Rate

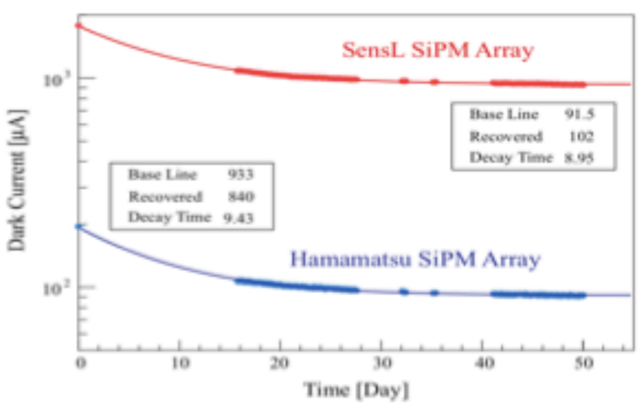


Signal loss

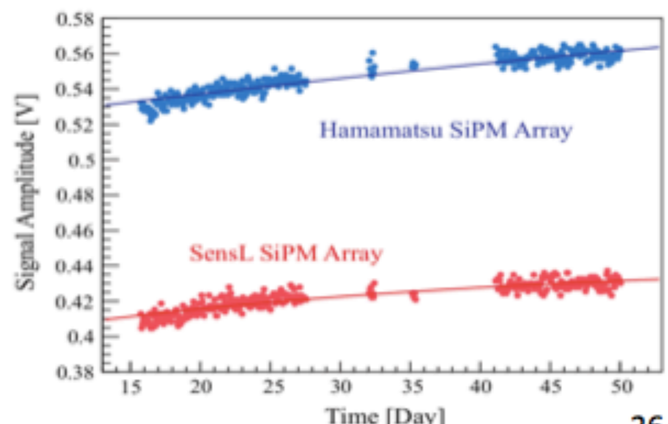


R.T. annealing

~50% recovery



~100% recovery



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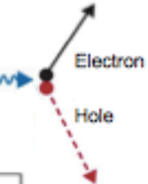
Bulk effects

Effects on SiPMs

Effects of neutrons: DC AV MAX sponse



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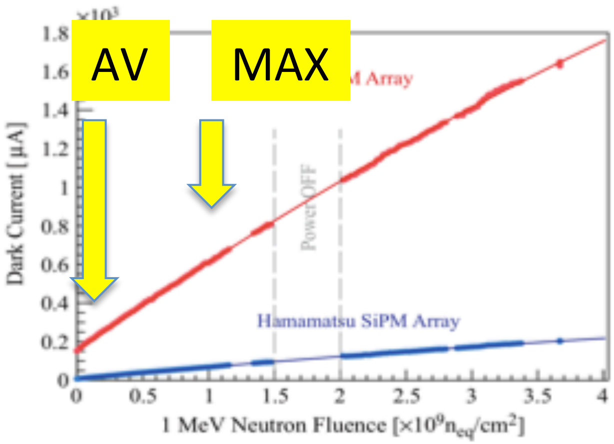
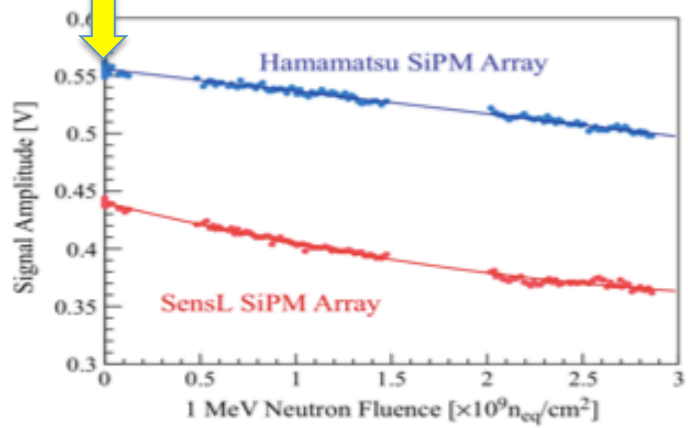
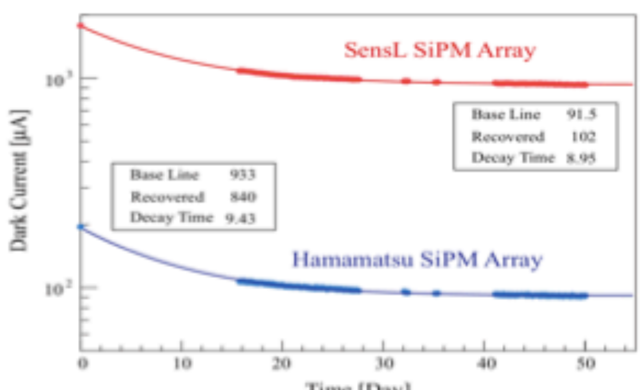


Signal loss

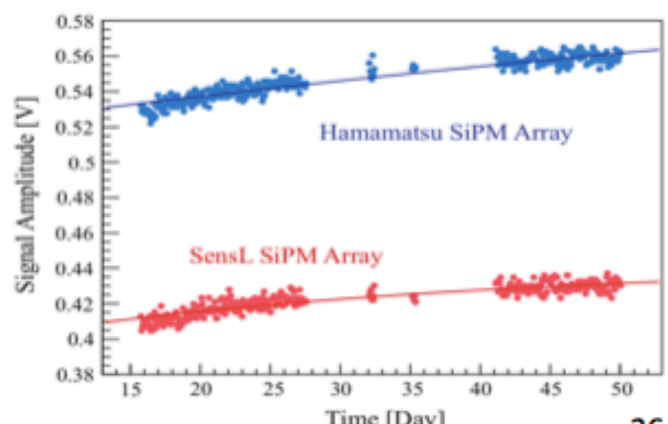


R.T. annealing

~50% recovery



~100% recovery



Remember from last time…

Cumulative effects

Three types of damage

1. **Total Ionization Dose (TID)**, for electronics also called surface damage:

USRBIN:
- **DOSE**

2. <u>**Displacement Damage Dose (DDD)** also called NIEL:</u>

USRBIN:
- **DPA-SCO: displacement per atom**
- **SI1MEVNE: fluence of Si 1MeV equilavent particles**
- **NIEL-DEP: non-ionizing energy loss (not needed)**

SEE

3. **Single Event Effects (SEE):**
   - Effect due to a single interaction, wherein a *large ionization* gives a temporary or permanent damage to many electronically live devices or systems.
   - Important effect for digital circuits such as memories or microprocessors.
   - Induces errors, undesired latch-ups and may lead to system failure.

Remember from last time…

Cumulative effects

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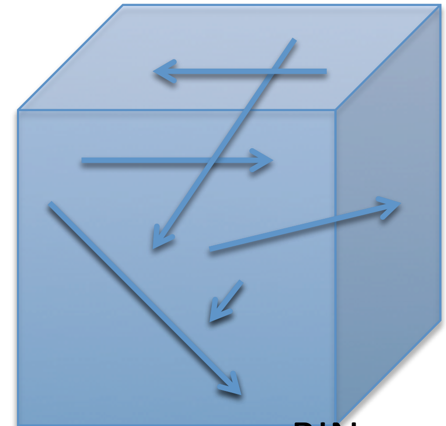
SEE

3. **Single Event Effects (SEE):**

USRBIN:
- **HEHAD**

Integrated high-energy hadron equivalent fluence



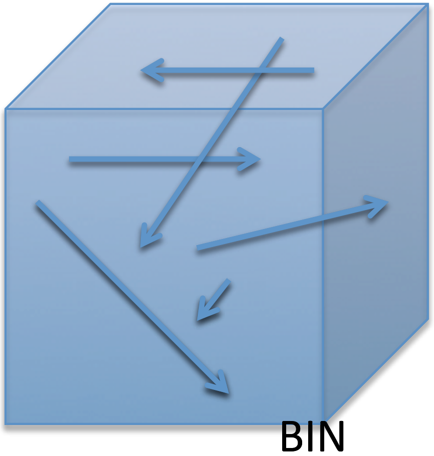
- To predict single event effects
- FLUKA can score the "**integrated high-energy hadron equivalent fluence**" in a given position: HEHAD-EQ
- What is it? What unit?

> - USRBIN scoring of HEHAD-EQ: fluence of particles >20MeV in a bin per primary [cm-2 per primary]
> - Again more a density of particle tracks

- Formula (Ntracks are here the number of particles with energy >20 MeV):

$$\frac{\sum_{i=0}^{N_{\text{tracks in bin}}} \left|\vec{l}_i\right| [cm]}{V_{bin}[cm^3]}$$

Integrated High Energy Hadron Equivalent Fluence



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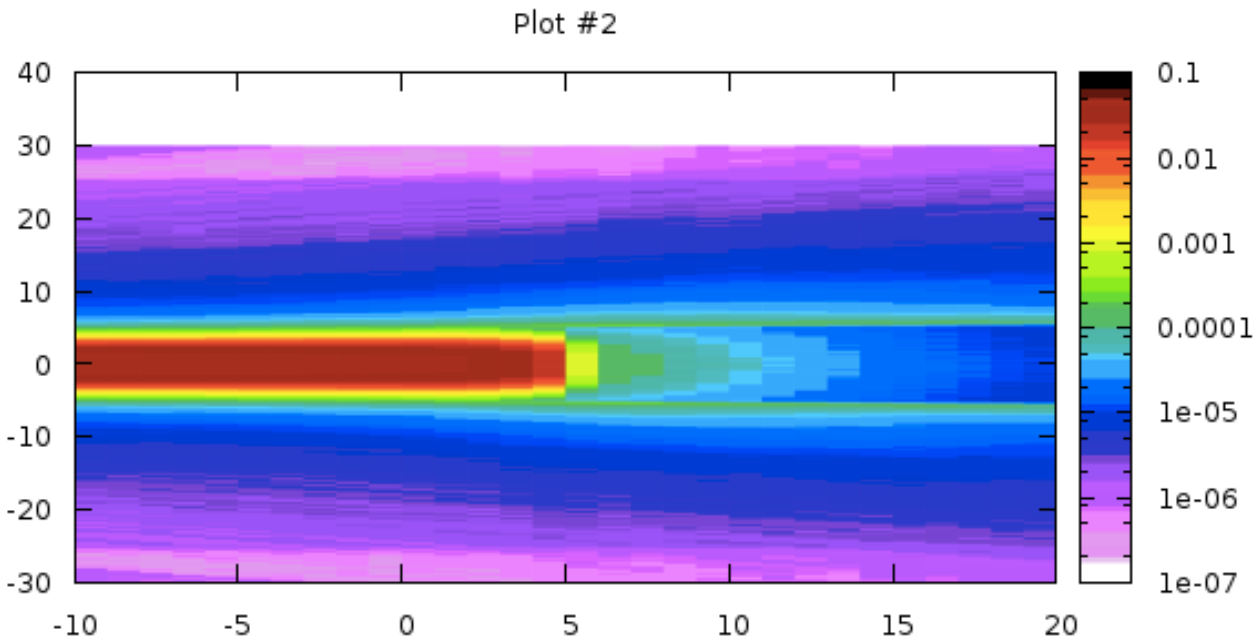

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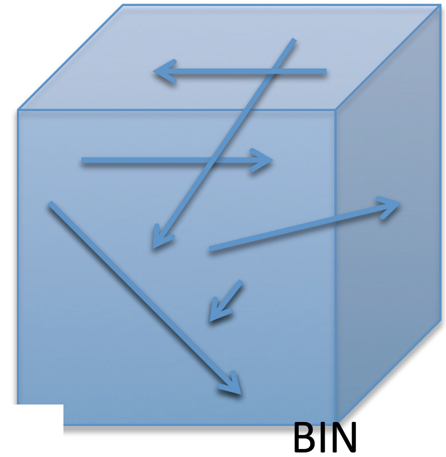

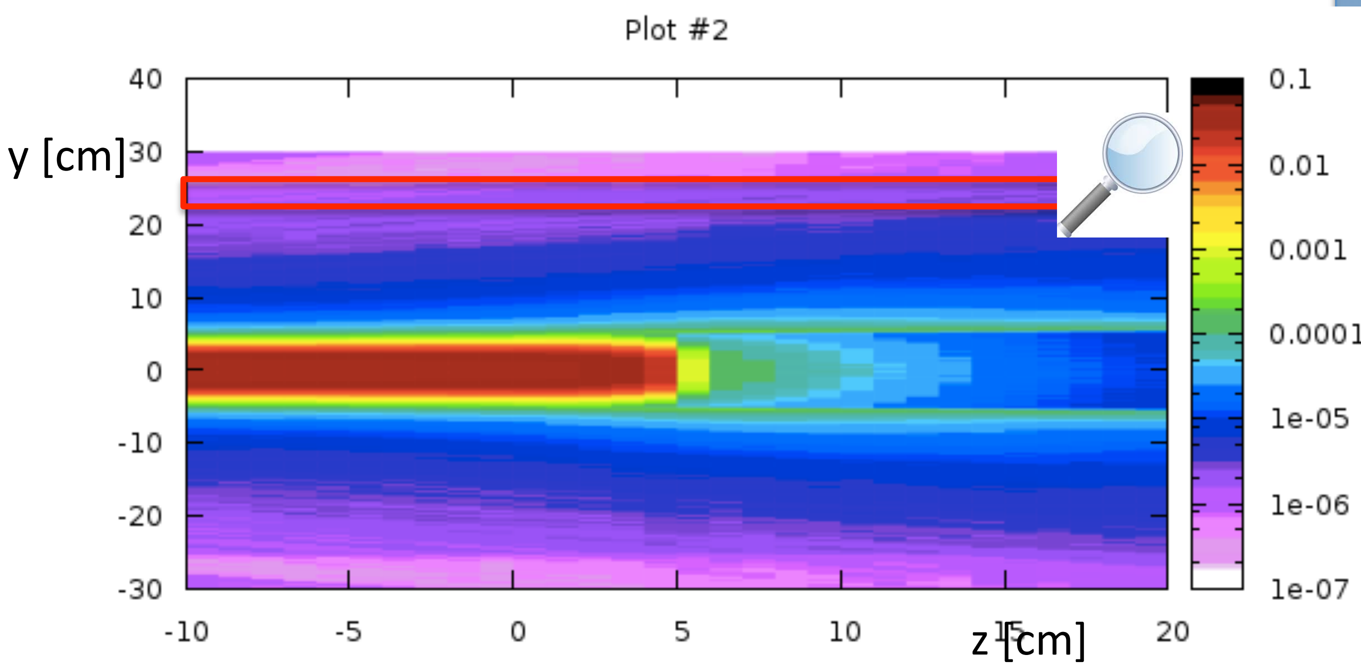

Integrated High Energy Hadron Equivalent Fluence

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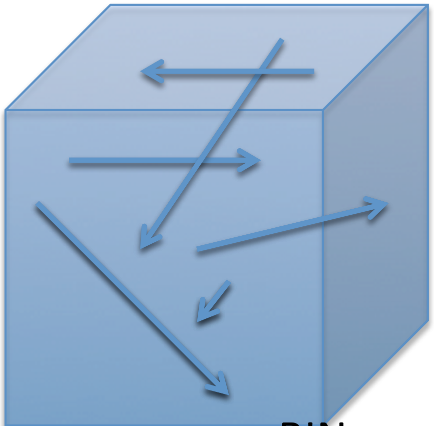
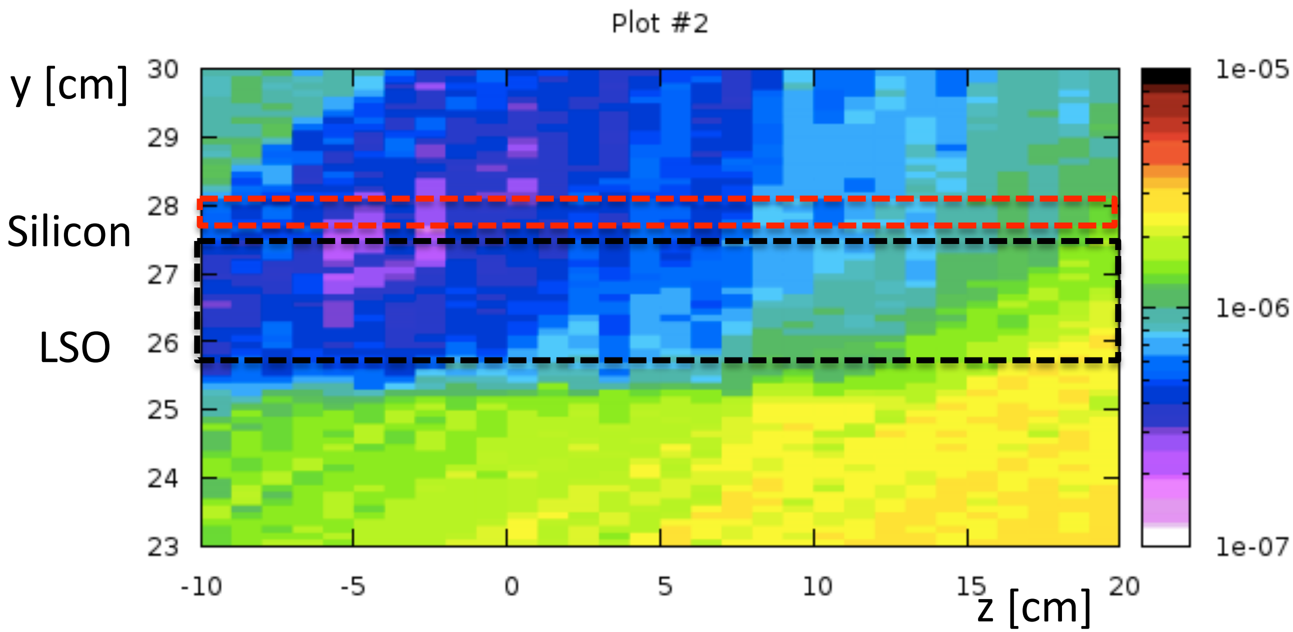




At most 1E-6 per primary → 1E8 cm^{-2} per year (given 1E14 protons/year)

Remember from last time…

Cumulative effects

Three types of damage

1. **Total Ionization Dose (TID)**, for electronics also called surface damage:

USRBIN:
- **DOSE**

2.

USRBIN:
- **DPA-SCO: displacement per atom**
- **SI1MEVNE: fluence of Si 1MeV equilavent particles**
- **NIEL-DEP: non-ionizing energy loss**

SEE

3. **Single Event Effects (SEE):**

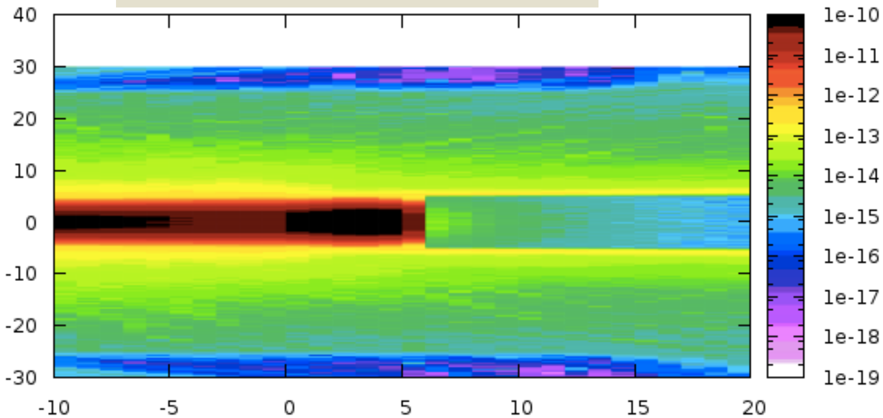
USRBIN:
- **HEHAD-EQ: fluence of high energy (>20MeV) particles**

Compare and interpret…

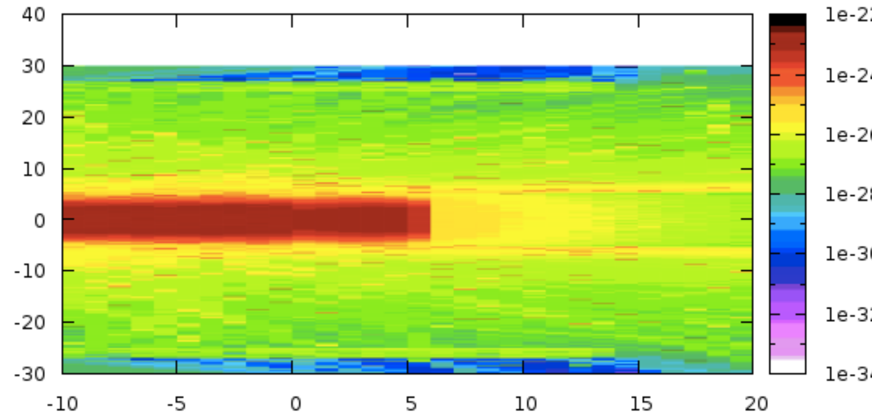
Quick comparison (1)

Y vs z, x-region is [-1, 1] (central region), so highest density of particles

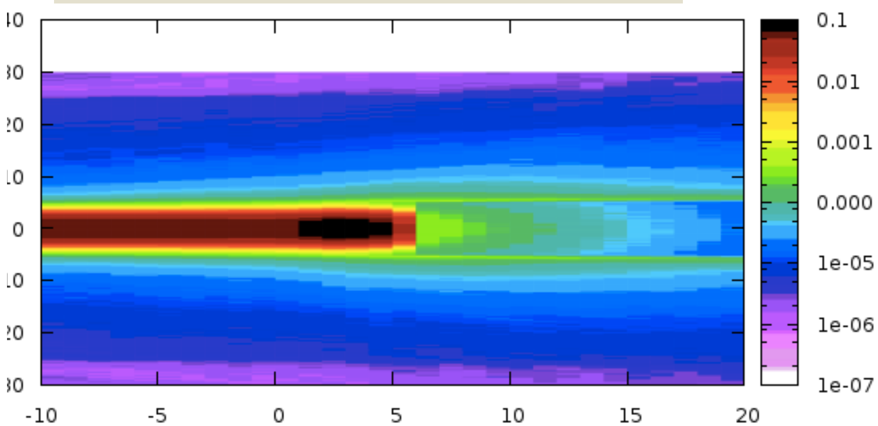
DOSE per primary [Gy]



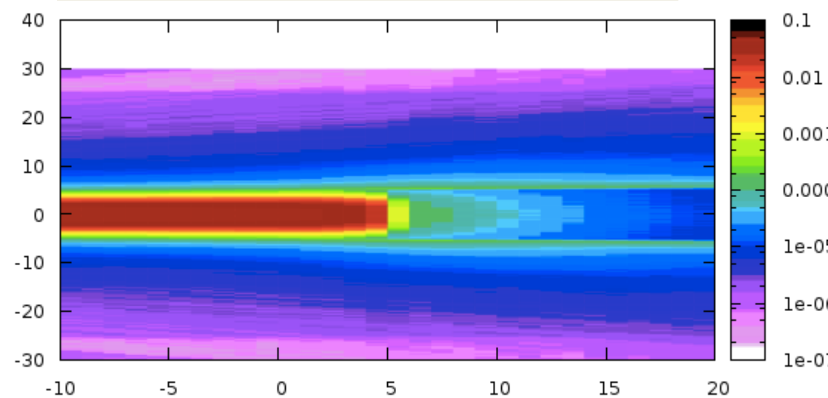
DPA per primary per atom [ ]



Si1MeVEQ per primary [cm^{-2}]



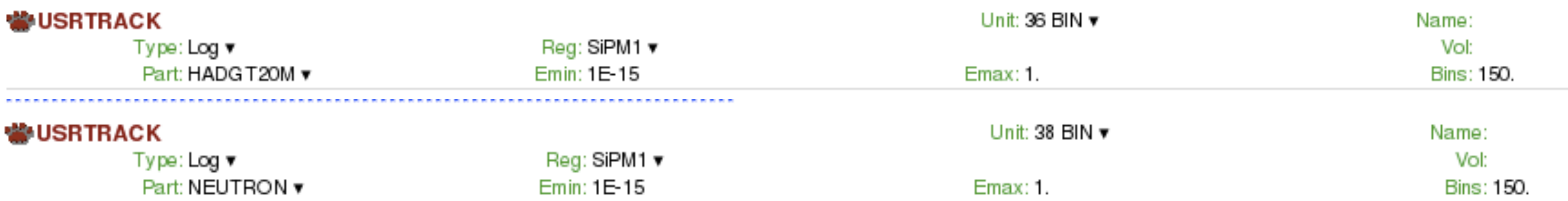
HEHAD-EQ per primary [cm^{-2}]

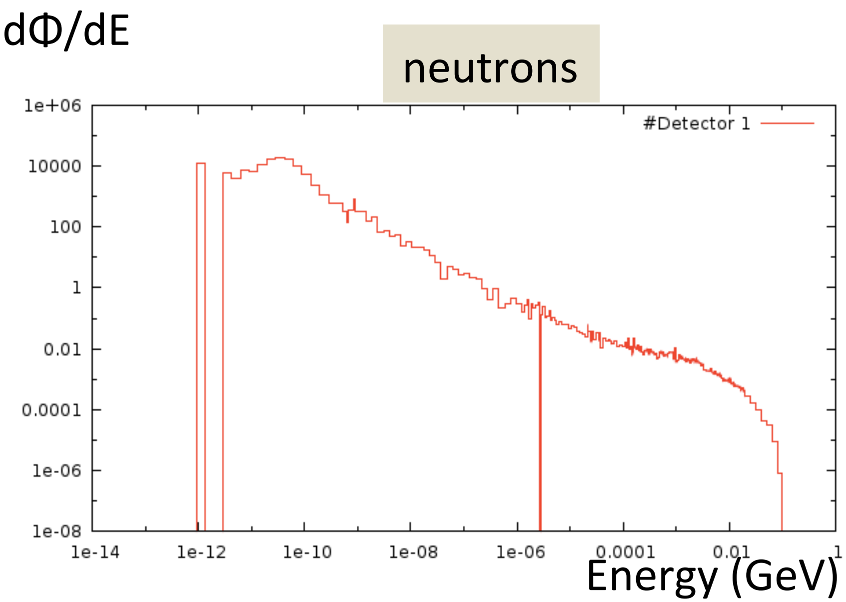


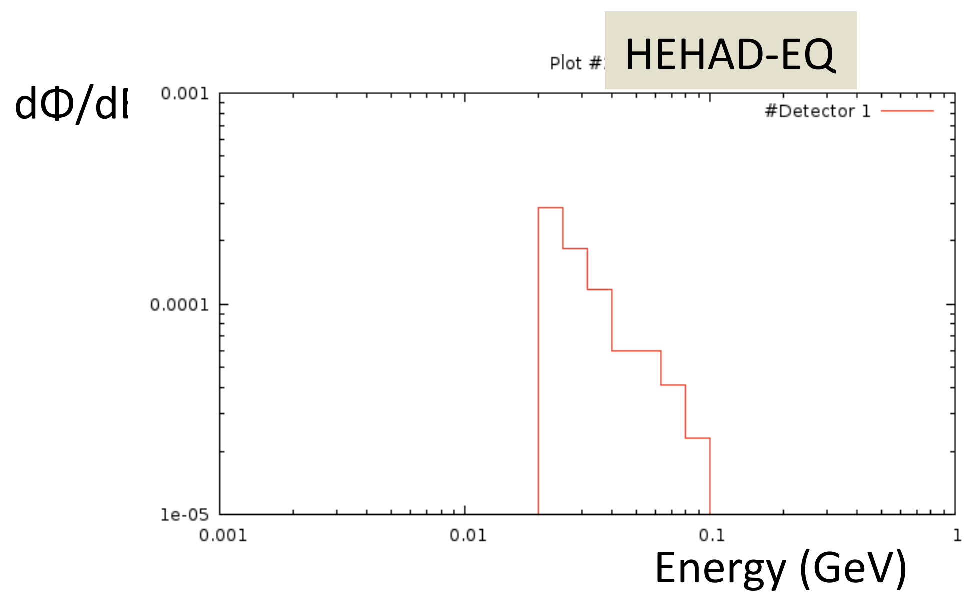
Remember that the energy of the protons wasn't so high (<100 MeV)

Differential fluence (1)

- With USRTRACK can score the differential fluence as function of energy in a certain region
- No Volume provided, so unit here is GeV^{-1} cm per primary

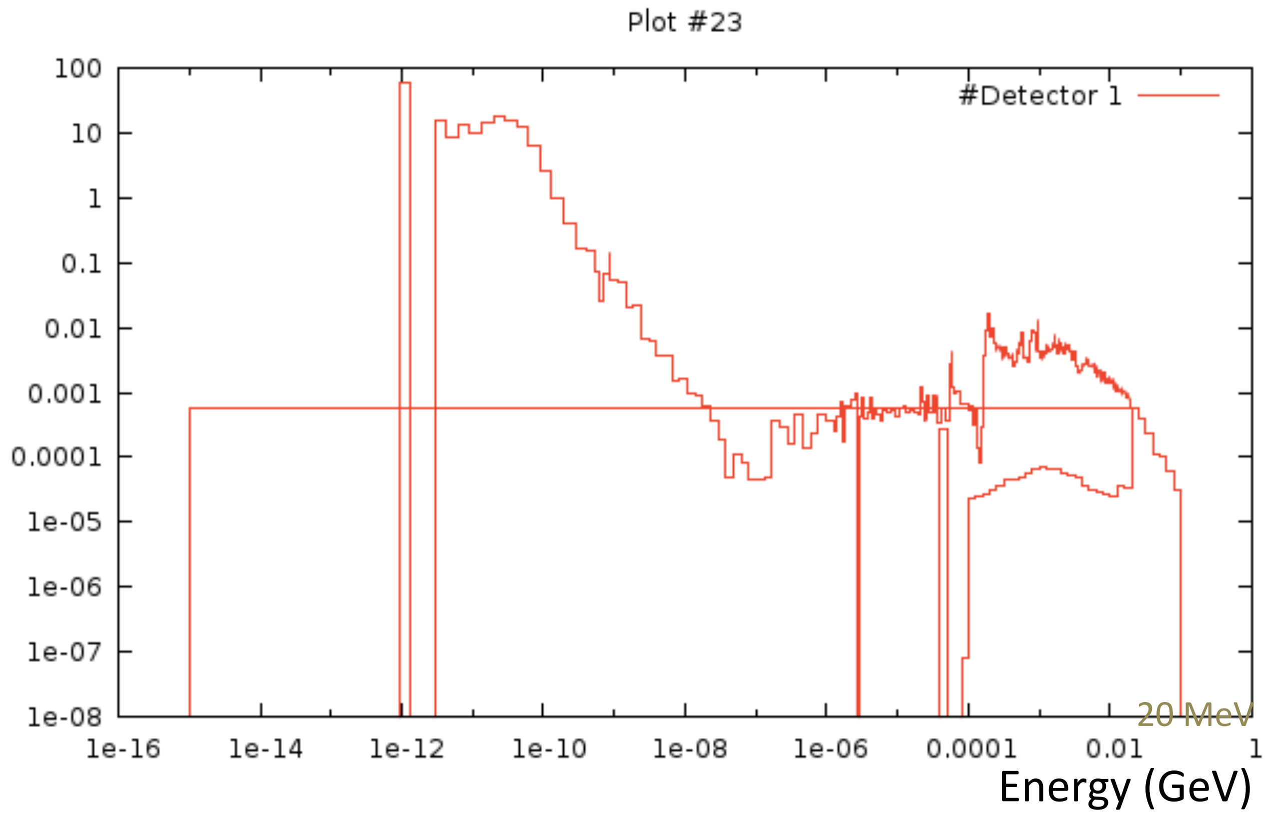






Differential fluence (2)

- With USRTRACK can score the differential fluence as function of energy in a certain region
- No Volume provided, s unit here is GeV^{-1} cm pe primary
- Plot is ugly in FLAIR/ GNUPLOT.



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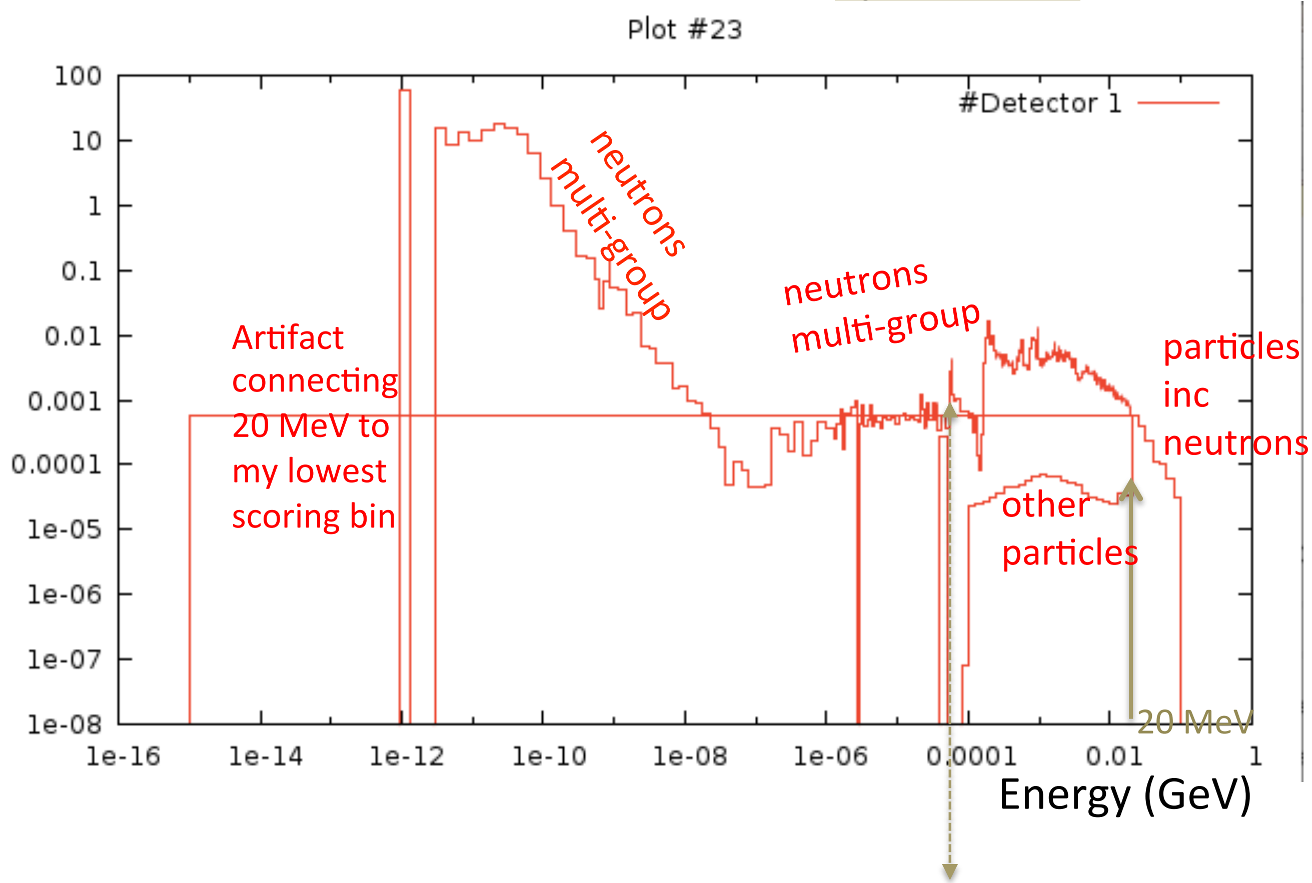
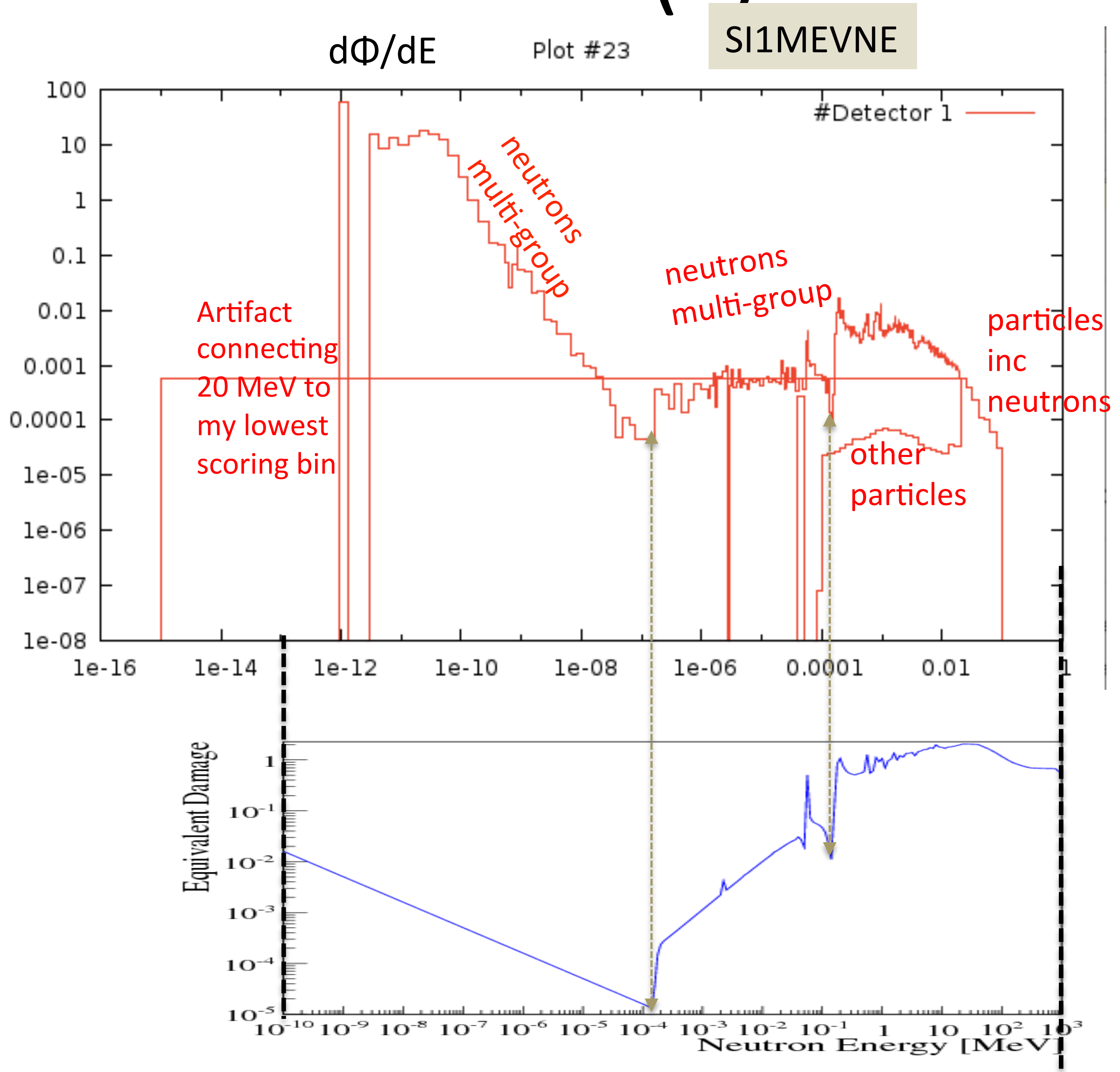


Differential fluence (3)

- With USRTRACK can score the differential fluence as function of energy in a certain region
- No Volume provided, s(unit here is GeV^{-1} cm pe primary

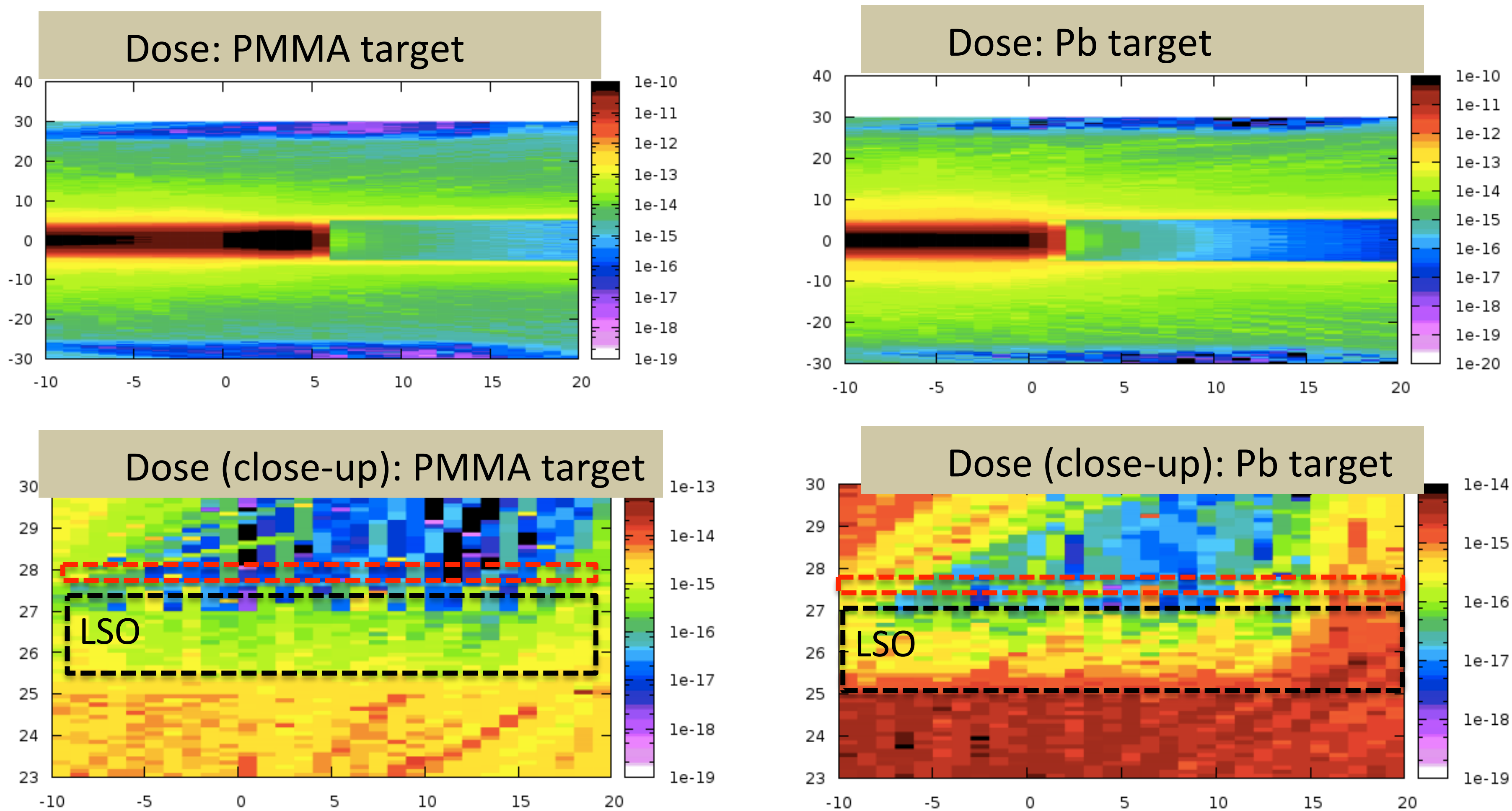


Simulations on lead

- Motivation:
  - Would like to test the SiPMs under more severe conditions than previous tests.
    - with a lead target instead of a PMMA target the expected particle flux is much higher!
    - How much higher?
- Score same quantities:

1. Dose
2. Si1MevEq
3. HEHAD-EQ

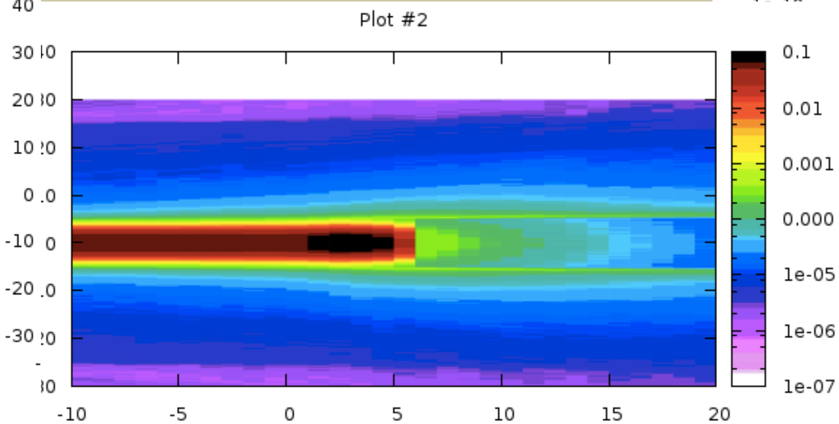
Simulations on lead



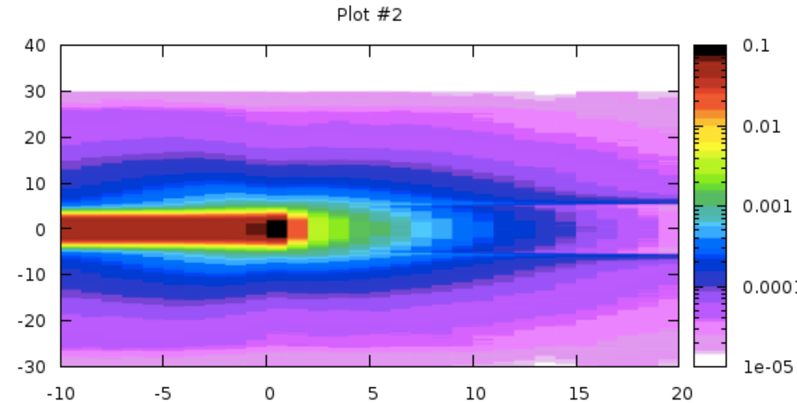
By irradiating a Pb target, the MAX local dose in Silicon is a factor 3-5 (guess!!!) PMMA target (max dose 10^{-15} Gy per primary)

Simulations on lead

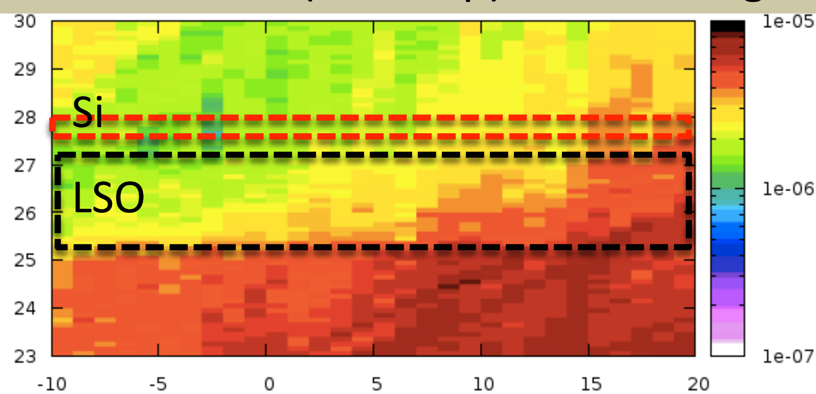
Si1MeVEq: PMMA target



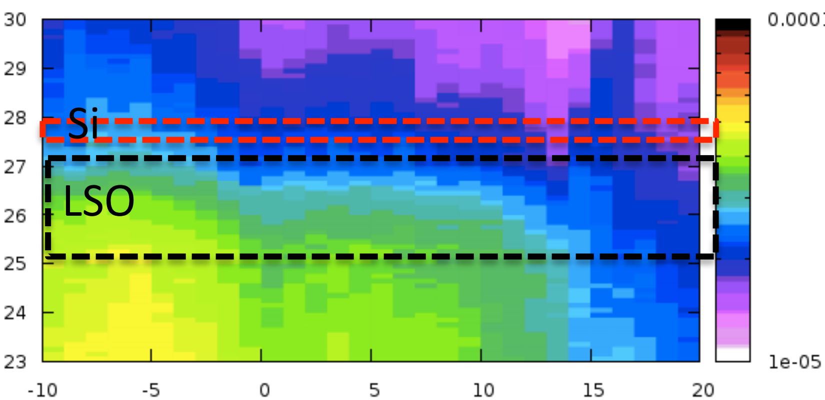
Si1MeVEq: Pb target



Si1MeVEQ (close-up): PMMA target



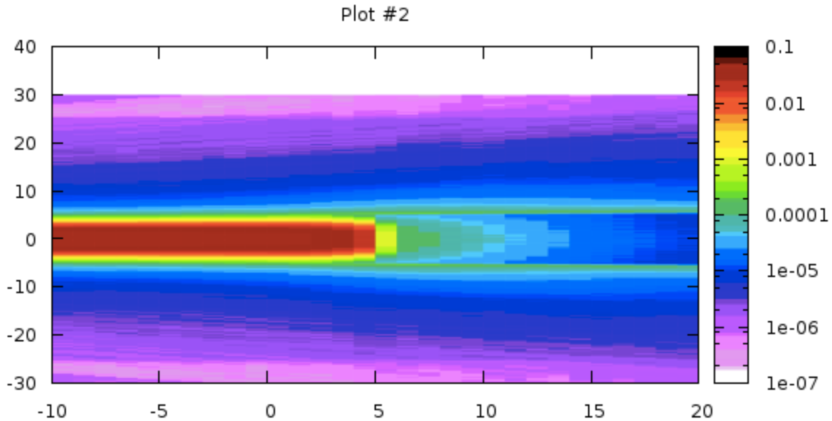
Si1MeVEq (close-up): Pb target



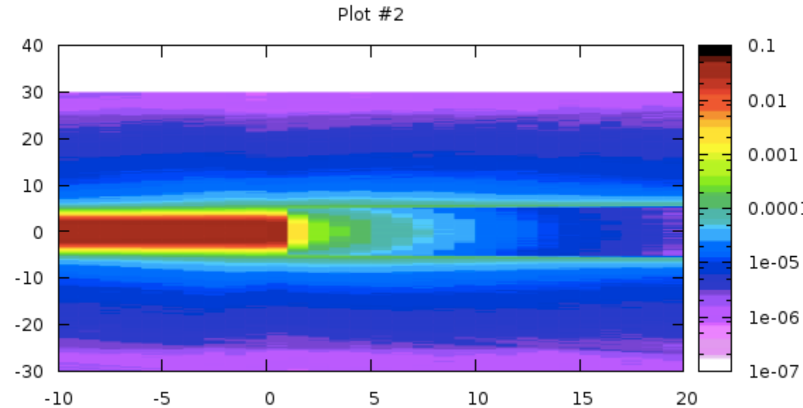
- By irradiating with a Pb target Si1MeVEq flux in Silicon MAX about 5E-5, about a factor **10-50 (rough guess…) higher** than PMMA target
- With 1E14 primaries per year: max 10^{10}-10^{11} 1MeV neutron equivalent particles cm^{-2} per year (with PMMA 10^{9})

Simulations on lead

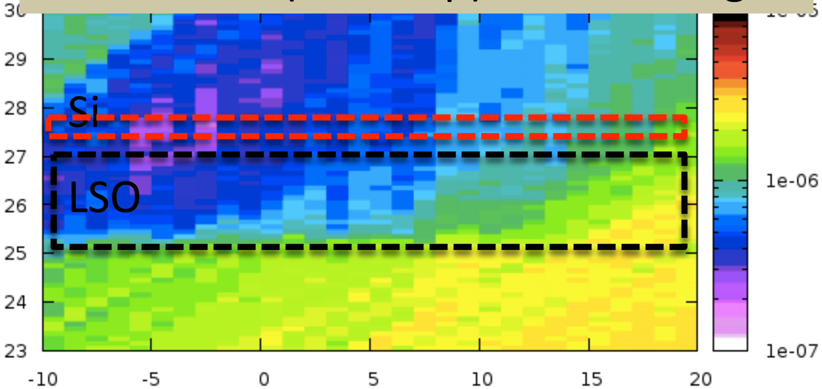
HEHADEq: PMMA target



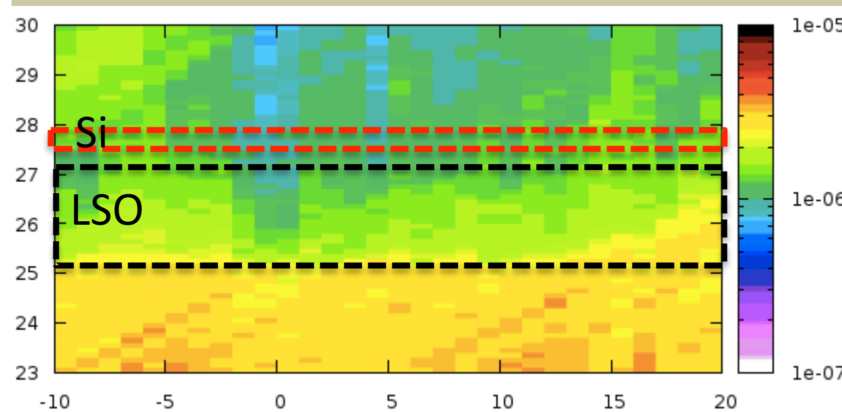
HEHAD: Pb target



HEHAD (close-up): PMMA target



HEHAD (close-up): Pb target



- By irradiating with a Pb target HEHAD-EQ flux in about a factor 5 **(rough conservative guess…) higher** than PMMA target (5E-6 rather than 1E-6)
- With 1E14 primaries per year: max 5×10^{8} HEHAD particles cm^{-2} per year (with PMMA 10^{8})

Conclusions

- **First attempt** made to estimate quantities relevant for radiation damage of silicon and electronics
- FLUKA scoring more or less under control
- Seems we are in low exposure zone and SiPMs are expected to function for a while…
- Could test the SiPMs under more severe irradiation circumstances: Pb target
- Remember that energies used of order 100 MeV
- Findings checked with FLUKA experts:
  - **Giuseppe Battistoni**
  - **Silvia Muraro**
  - **Luigi Esposito**
  - **Markus Brugher**
  - **Anna Ferrari**