Radiation Environment

1 MeV Neutron Equivalent Fluence

>20 MeV Hadrons Fluence

Total deposited dose

---> Lifetime and health of detector and surrounding FPGAs

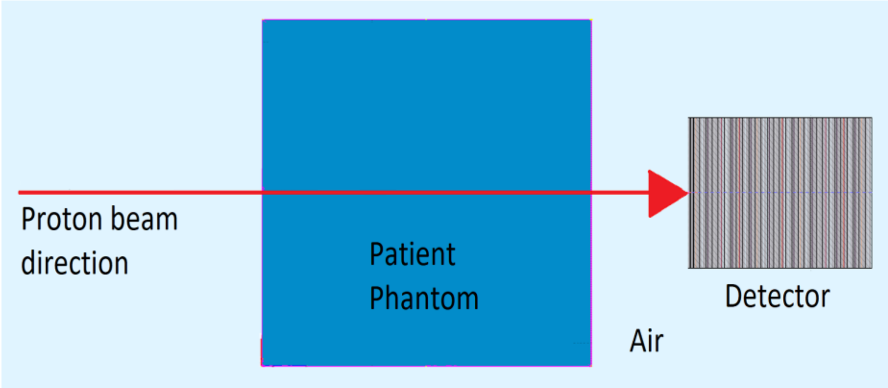
Contents

- Simulation setup (FLUKA)
  - Proton CT and Proton Therapy setting
  - Scoring quantities offered by FLUKA
    - Dose (Total dose, energy per unit mass) [rad]
    - HADGT20M (Fluence of hadrons with energies > 20 MeV) [cm^{-2}]
    - SI1MEVNE (Silicon 1 MeV neutron equivalent fluence) [cm^{-2}]
- Radiation hardness and some typical numbers
- Normalization of results (clinical setting)
- Results
  - Two dimensional fluence plots of Hadrons and Neutrons around detector (top-down view)
  - HADGT20M and SI1MEVNE fluence with respect to distance from center of the detector
  - Total dose to detector chips
  - Table of results and expected lifetimes and health of the detector and FPGAs

Simulation setup 1

Proton CT

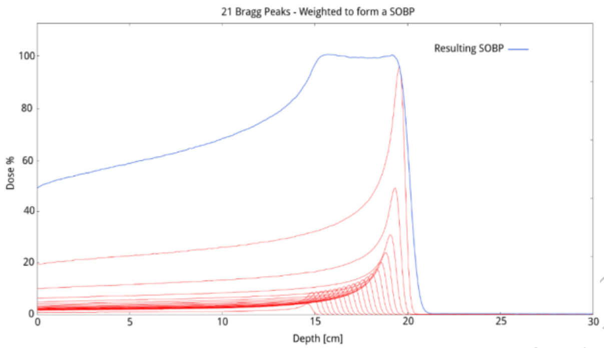
- $230\ MeV$ proton beam
- Proton beam has a cross-section of $22\ x\ 14\ cm^2$
- Detector cross section is $28\ x\ 18\ cm^2$
- $30\ cm$ thick water phantom



Top-down view of the simulation geometries

Proton Therapy

- $147 - 174\ MeV$ Proton beams
- Proton beam has a cross section of $5\ x\ 5\ cm^2$
- $30\ cm$ thick water phantom with a $5\ x\ 5\ x\ 5\ cm^3$ target volume located at $15 - 20\ cm$ depth.

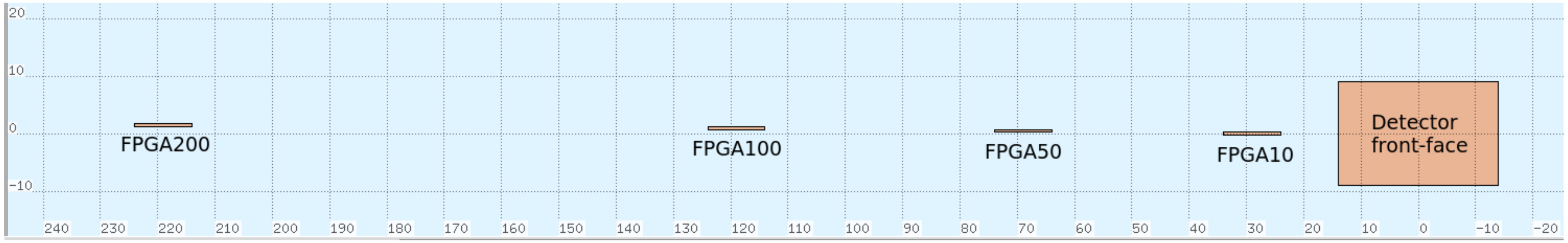


Spread-out Bragg peak (SOBP) covering the target volume

Simulation setup 2

FPGAs (Field-Programmable Gate Arrays)

- **Dimension of the FPGA is** $10\ cm\ x\ 0.5\ cm\ x\ 18\ cm$
- **Located next to the detector at** $10\ cm$, $50\ cm$, $100\ cm$ **and** $200\ cm$ **distance relative to the edge of detector**



Wide view of the simulation geometries along the beam-axis

Fluence quantities

HADGT20M

«Fluence of hadrons with energy > 20 MeV $[cm^{-2}]$, unstable hadrons of lower energies are also counted»

SI1MEVNE

«Silicon 1 MeV neutron equivalent fluence $[cm^{-2}]$» Hadron fluence folded with a displacement damage function (D(E)) and normalised to the displacement damage by 1 MeV neutrons in silicon.

Damage categories:

Category		Effect	Scales with simulated/measured quantity
Single Event effects (Random in time)	***Single Event Upset (SEU)***	Memory bit flip (soft error) Temporary functional failure	HADGT20M $[cm^{-2}]$ (+/or HEHAD-EQ, THNEU-EQ)
	Single Event Latchup (SEL)	Abnormal high current state Permanent/destructive if not protected	HADGT20M $[cm^{-2}]$ (+/or HEHAD-EQ)
Cumulative effects (Long term)	***Total Ionizing Dose (TID)***	Charge build-up in oxide Threshold shift & increased leakage current Ultimately destructive	DOSE [GeV/g] -> stricly IONIZING only!
	Displacement damage	Atomic displacements Degradation over time Ultimately destructive	SI1MEVNE $[cm^{-2}]$ {NIEL}

Radiation hardness

Total Ionizing Dose (TID) and Non-Ionizing Energy Loss (NIEL)

- Detector chip (ALPIDE MAPS) [3]
  - TID radiation hardness $2.7E6\ rad$
  - NIEL radiation hardness $1.7E13\ n_{eq}/cm^2$
- Typical FPGA [4]
  - TID radiation hardness $10\ krad$ (conservative number)

Single Event Upset (SEU) – bitflips in FPGA

- Typical FPGA has a sensitivity between 10^{-14} and $10^{-15} cm^2/bit$ (Single Event Upset cross section)
- # SEU = Cross section * Hadron fluence * configuration memory

[3] M. Mager. ALPIDE, the Monolithic Active Pixel Sensor for the ALICE ITS upgrade.
[4] H. Quinn. Radiation effects in reconfigurable FPGAs.

Normalization

Proton CT

- Number of protons used for a single image [1]:
  $3.15E8$
- Yearly workload (clinic):
  25 images per day, 235 days per year
- Number of protons involved in a year:
  $3.15E8\ x\ 25\ x\ 235 = \underline{\underline{1.851E12}}$

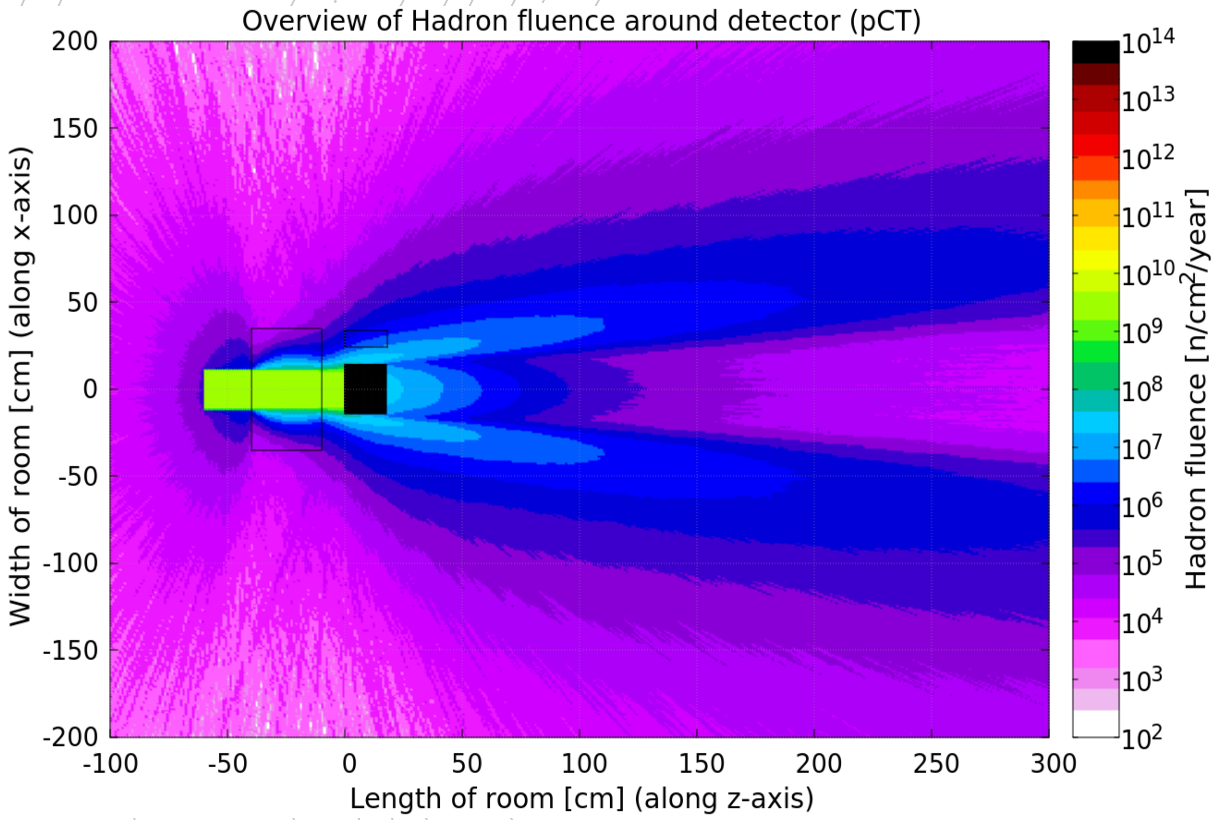
Proton Therapy

- Number of protons in a single 2Gy treatment fraction [2]:
  5.815E10
- Yearly workload (clinic):
  25 treatments per day, 235 days per year
- Number of protons involved in a year:
  $5.815E10\ x\ 25\ x\ 235 = \underline{\underline{3.416E14}}$

[1] R. P. Johnson, et al. A Fast Experimental Scanner for Proton CT: Technical Performance and First Experience With Phantom Scans.
[2] J.R. Sølie. A Comparative Study of Radiation Environment and Secondary Dose Production in a Particle Therapy Treatment Room Applying Proton, Helium and Carbon Ion Beams.

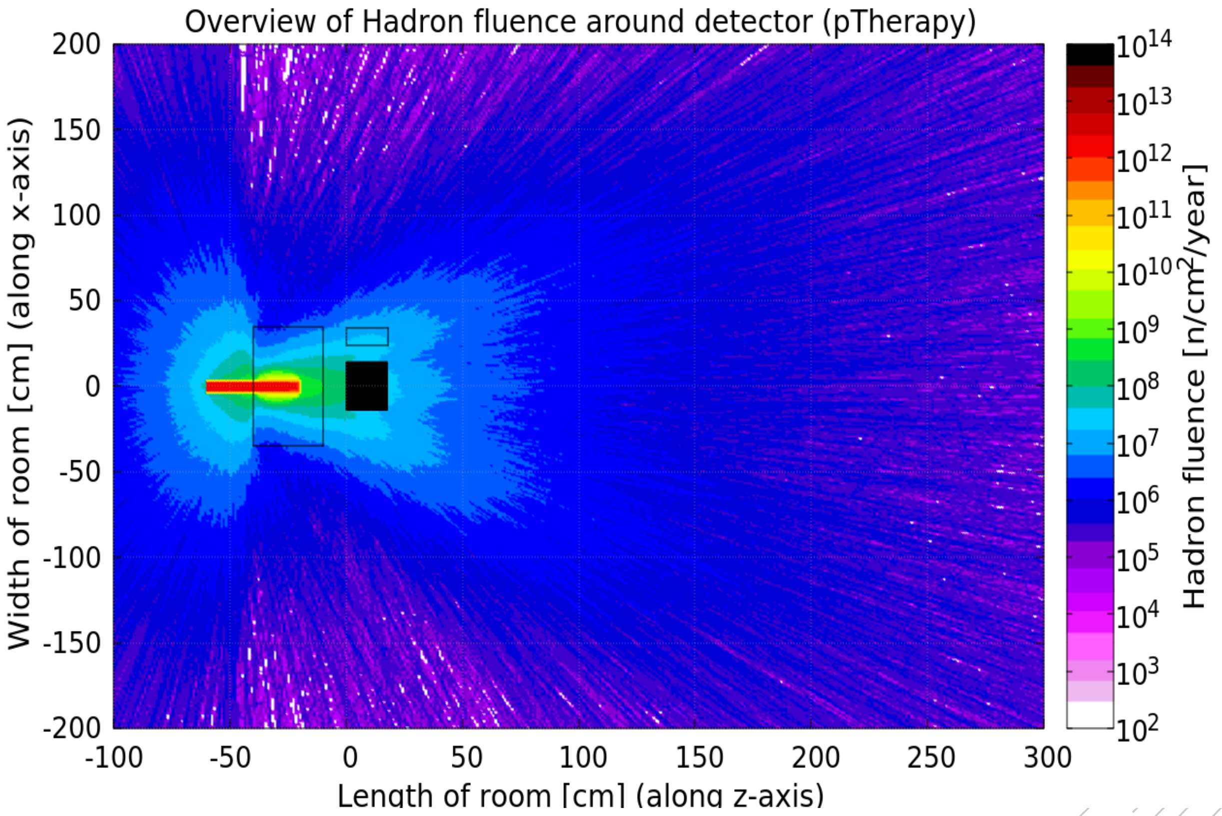
Hadron Fluence Overview plots

Proton CT (normalized to per year)



Normalization: 1.851E12

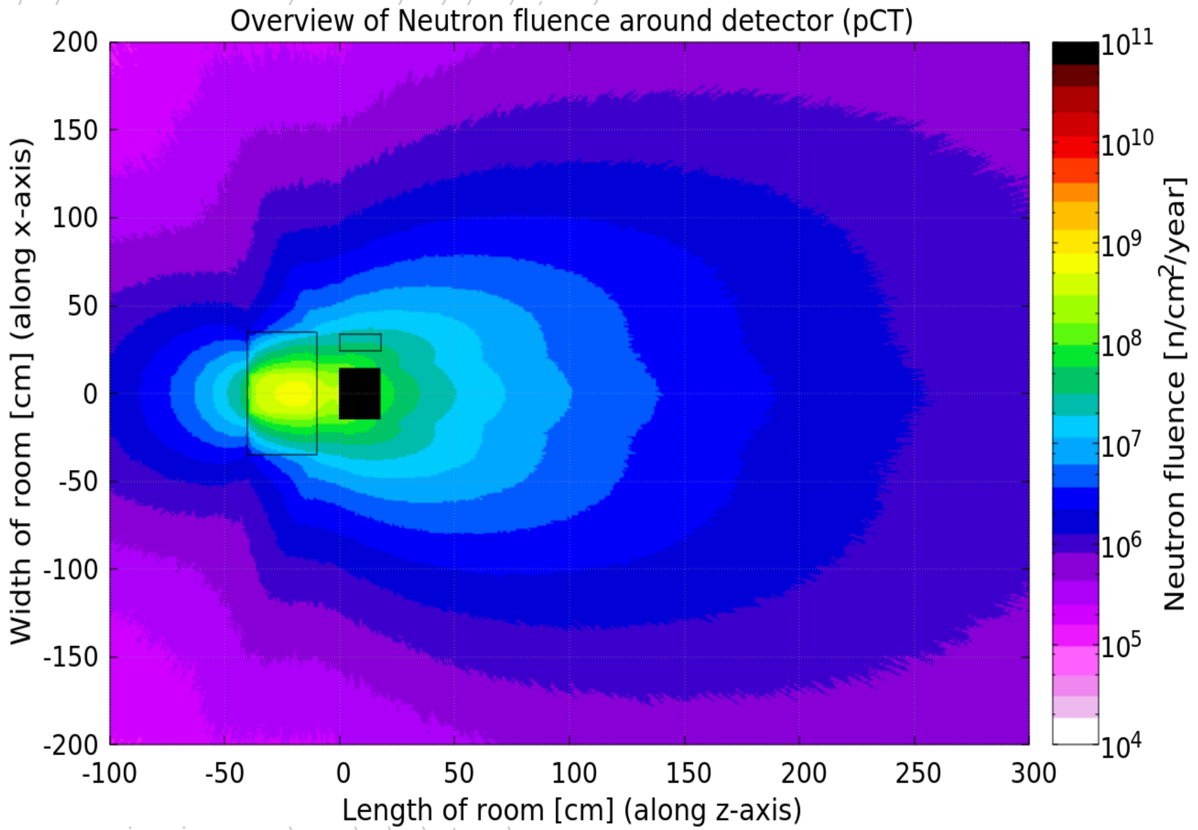
Proton Therapy (normalized to per year)



Normalization: 3.416E14

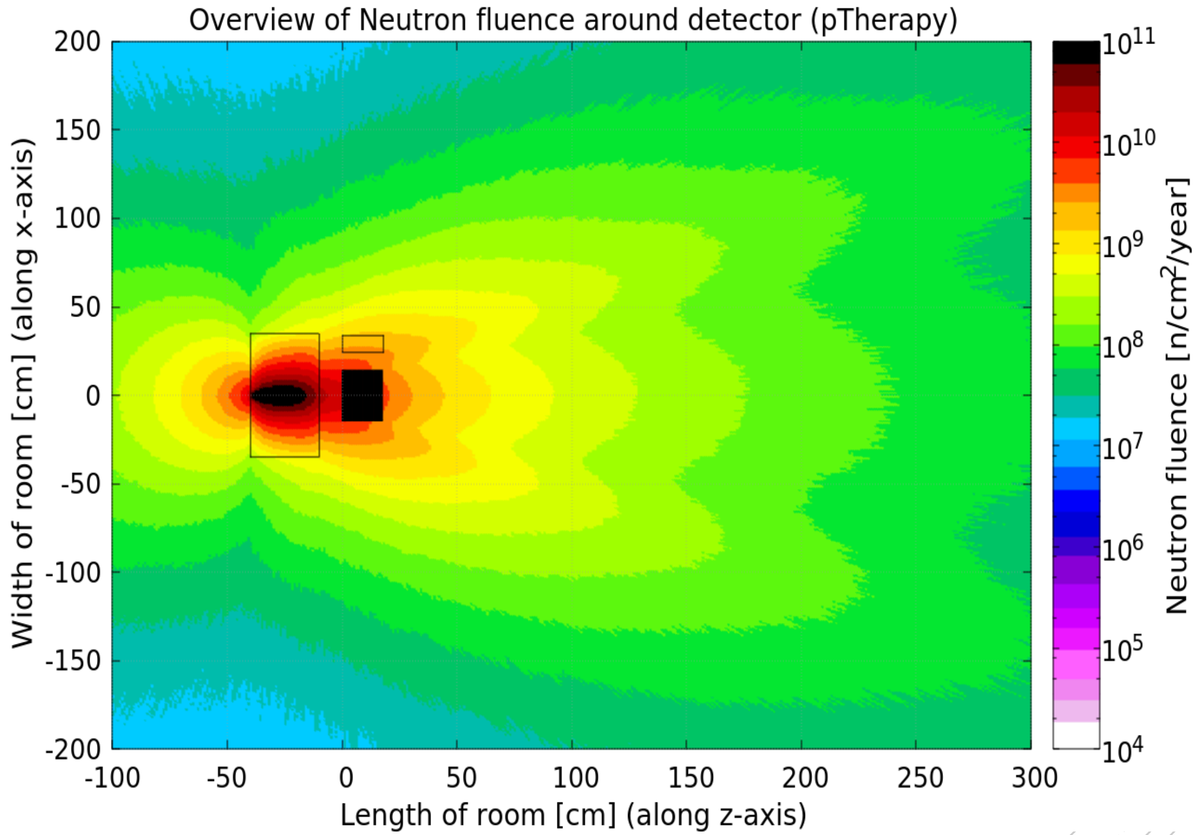
Neutron Fluence Overview plots

Proton CT (normalized to per year)



Normalization: 1.851E12

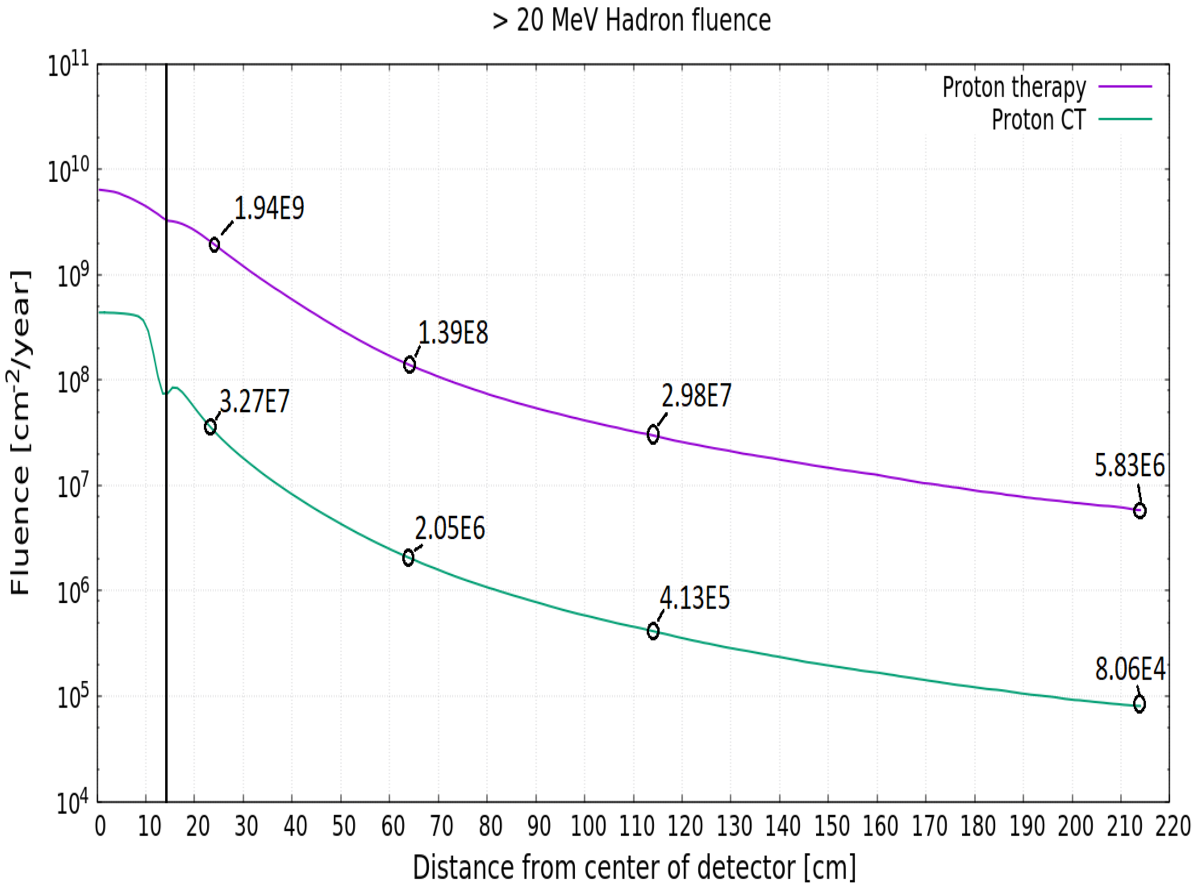
Proton Therapy (normalized to per year)



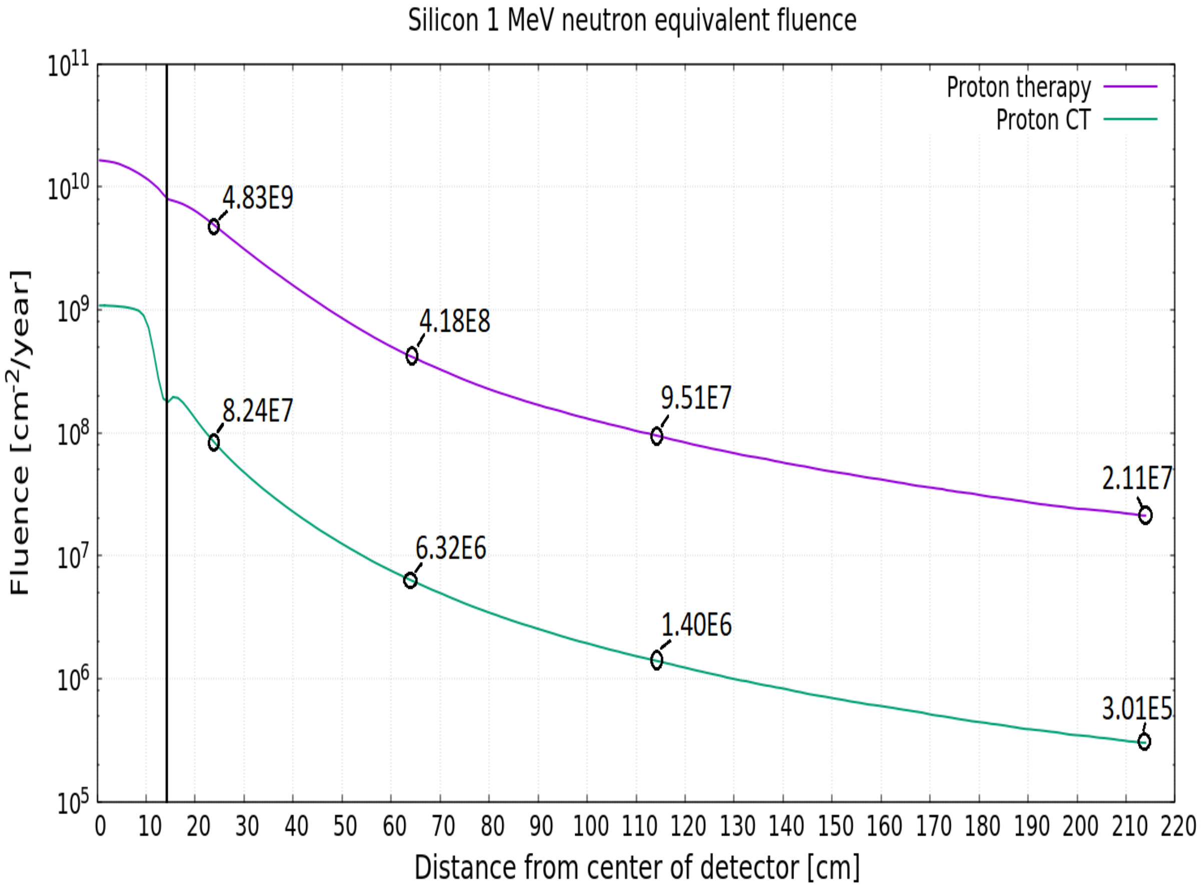
Normalization: 3.416E14

Fluence with respect to lateral distance from detector

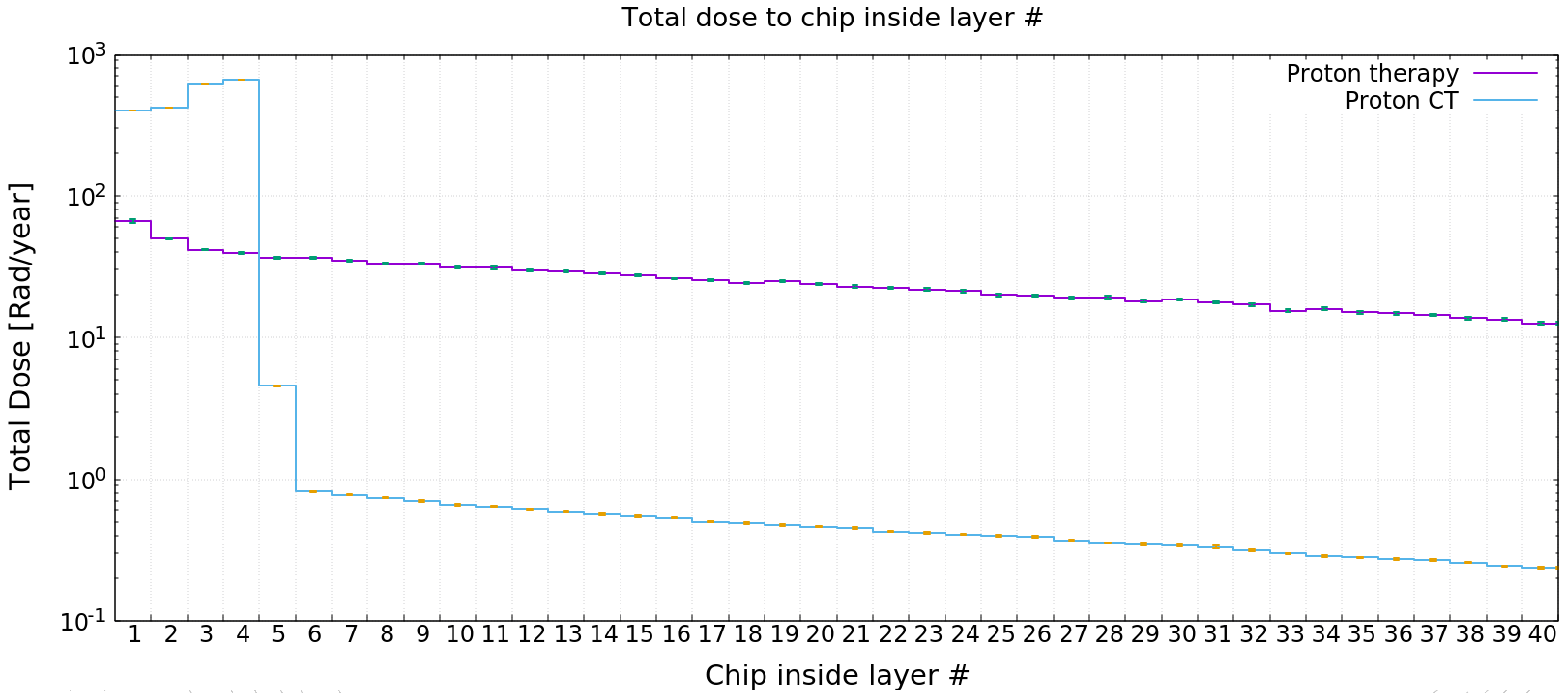
HADGT20M (yearly workload)



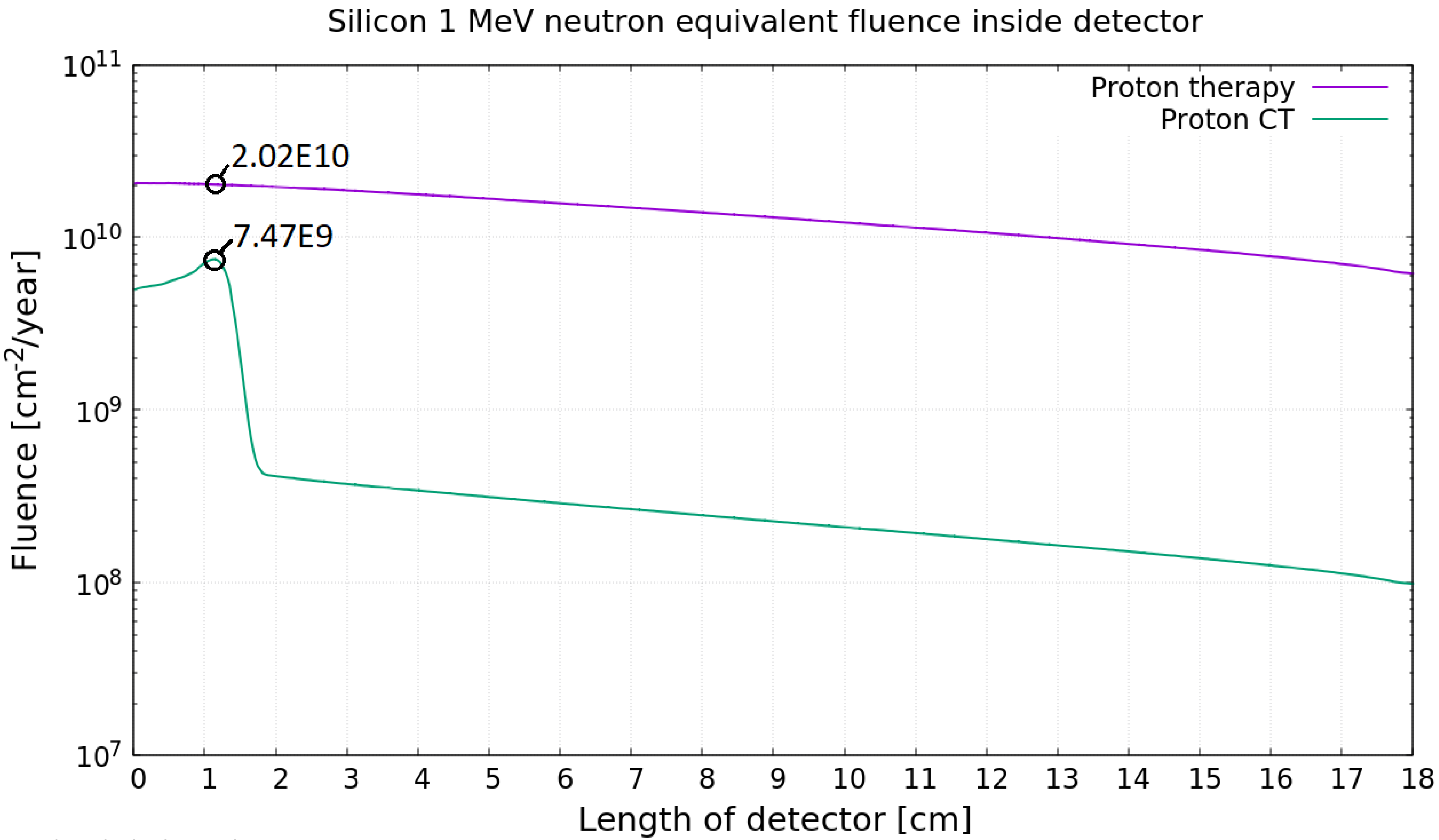
SI1MEVNE (yearly workload)



Total dose to detector chips



Neutron equivalent fluence inside detector



Lifetime of detector

Lifetime (Normalized and cumulated TID and NIEL)

- Roughly $1000\ rad$ inside the Bragg-peak per year
- Assume Bragg-peak is located in the same chip every time
- Radiation hardness of the ALPIDE chip is $2.7E6\ rad$
- NIEL radiation hardness $1.7E13\ n_{eq}/cm^2$

	Number of years before reaching the TID limit
Proton CT	2700 years
pCT+ pTherapy	2450 years

	Number of years before reaching the NIEL limit
Proton CT	2276 years
pCT+ pTherapy	614 years

Lifetime of FPGAs

Total dose deposited in the FPGAs per year [rad/year]

	FPGA10	FPGA50	FPGA100	FPGA200
Proton CT	0.28	9.8E-3	2.2E-3	4.7E-4
pCT + pTherapy	6.033	0.56	0.15	0.04

- Radiation hardness of a typical FPGA is $10\ krad$

	Number of years before reaching the radiation hardness limit [yr]			
	FPGA10	FPGA50	FPGA100	FPGA200
Proton CT	35714	1.02E6	4.54E6	2.13E7
pCT+ pTherapy	1657	17857	66666	250000

FPGAs health (# SEU/year)

Single Event Upsets

- Assume typical FPGA single event upset cross section of $10^{-14}\ cm^2/bit$
- Assume 80 $Mbit$ configuration memory
- # SEU = Cross section x configuration memory x Hadron fluence

	Number of Single Event Upsets per year			
	FPGA10	FPGA50	FPGA100	FPGA200
Proton CT	26	2	0.3	0.06
pCT+pTherapy	1550	110	24	5

Conservatively, every ten bitflip will cause a functional error in the FPGA

Thank you for your time

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Jarle Rambo Sølie
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FPGAs health (Hadron Flux)

>20MeV Hadron flux

	Number of >20 MeV Hadrons per cm^2 per primary proton $[1/cm^2/primary]$			
	FPGA10	FPGA50	FPGA100	FPGA200
Proton CT	1.68E-5	1.09E-6	2.221E-7	4.355E-8
pCT+pTherapy	2.22E-5	1.48E-6	3.07E-7	6.06E-8

- Assume intensity of proton beam to be: $1E9\ protons/sec$

	Flux of >20 MeV Hadrons per cm^2 $[1/s/cm^2]$			
	FPGA10	FPGA50	FPGA100	FPGA200
Proton CT	16751	1085	221	44
pCT+pTherapy	22208	1485	307	61

FPGAs health (# SEU/s)

Single Event Upsets per second

- Assume typical FPGA single event upset cross section of $10^{-14}\ cm^2/bit$
- Assume $80\ Mbit$ configuration memory
- Assume intensity of proton beam to be $1E9\ protons/\sec$
- #SEU/s = Cross section x configuration memory x Hadron flux

	Number of Single Event Upsets per second $[1/s/cm\text{^}2]$			
	FPGA10	FPGA50	FPGA100	FPGA200
Proton CT	0.013	8.7E-4	1.8E-4	3.5E-5
pCT+pTherapy	0.017	1.2E-3	2.5E-4	4.9E-5

Conservatively, every ten bitflip will cause a functional error in the FPGA

Total dose to detector with varying phantoms