R-Weg : A New High-Intensity Electron Beamline at DESY II

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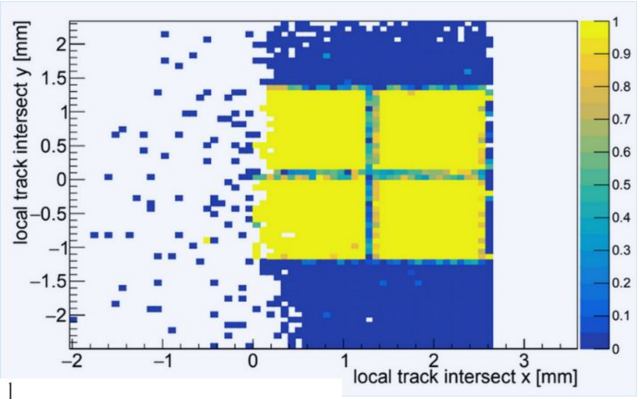
HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

DESY.

Testbeam Campaign

- Testbeam
  - To verify the performance of sensors or devices using high energetic particle beam
  - Tracking using beam telescope
    - Enable to distinguish particle and noise
- Why to require high rate beam?
  - A lot of tracks for precise measurement
  - To verify readout performances of sensors with high rate beam
    - E.g. beam monitor, beam counter
  - To irradiate sensors



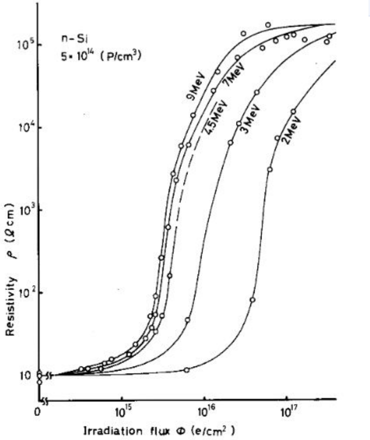
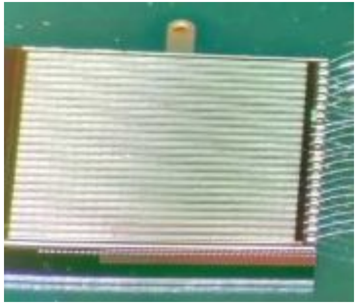


FIG. 5. Variation of the resistivity as a function of irradiation flux at different electron energies for the irradiated n-type silicon sample.

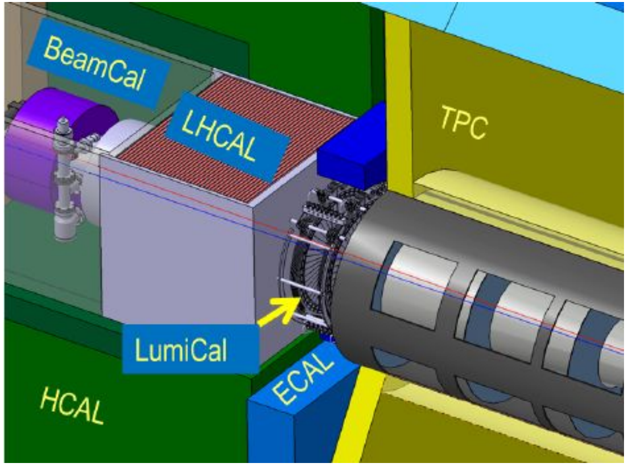
https://doi.org/10.1063/1.324032

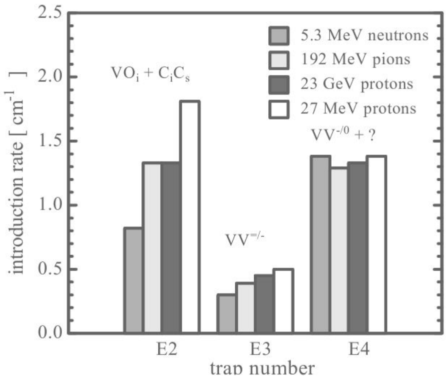


A prototype of HVMAPS, HitPix for beam monitor with high rate beam at HIT
Dissertation of Alena Larissa Weber

Motivation of Irradiation Campaign

- A lot of experiments plant to use high rate beam
- LumiCal
  - Precise measurement of the ILC's luminosity via Bhabha scattering
  - High energetic incident electrons penetrate into Si/W sensors
  - High statistics at low angle => $N_{Bha} \sim 1/\theta^3$
- HL-LHC upgrade for ATLAS
  - Max. fluence of Layer 1 will be 1.4 x 10^{16} n_{eq}/cm^2
  - 99% of all hits at a bunch spacing of 25 ns requires a time resolution about 5 ns during experiment
- General question
  - Different effects from the different type of particles
    - In case of electron beam?





Rate of single defects obtained from neutron, pion and proton radiation

Prior Electron Irradiation Studies

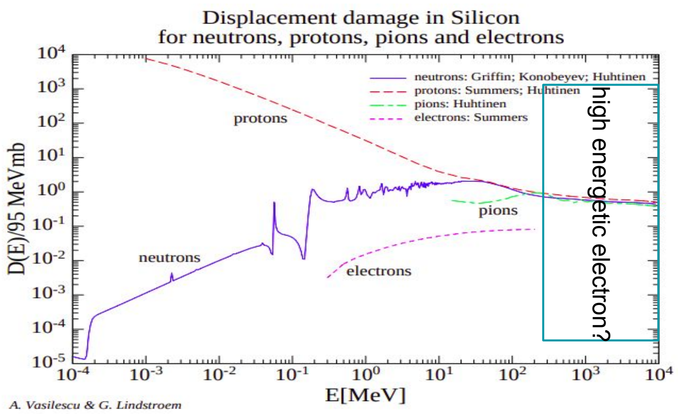
- There were few prior irradiation studies of Si-based sensor with electron beam
  - 1 Grad with 2 MeV electron beam
    - 36 times less damage than expected from classic NIEL

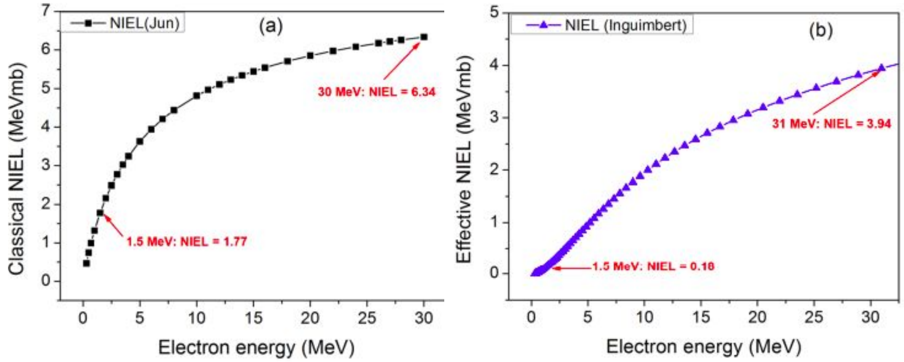
    J.M. Rafi et al, NIM A 604 (2009) 258
  - 150 Mrad with 900 MeV electron beam
    - 2 times less damage

    S. Dittongo et al, NIM A 546 (2005) 300
  - 270 Mrad using electron beam with energy between 3.5 - 13.3 GeV

    P. Anderson et al, arXiv:1703.05429v1

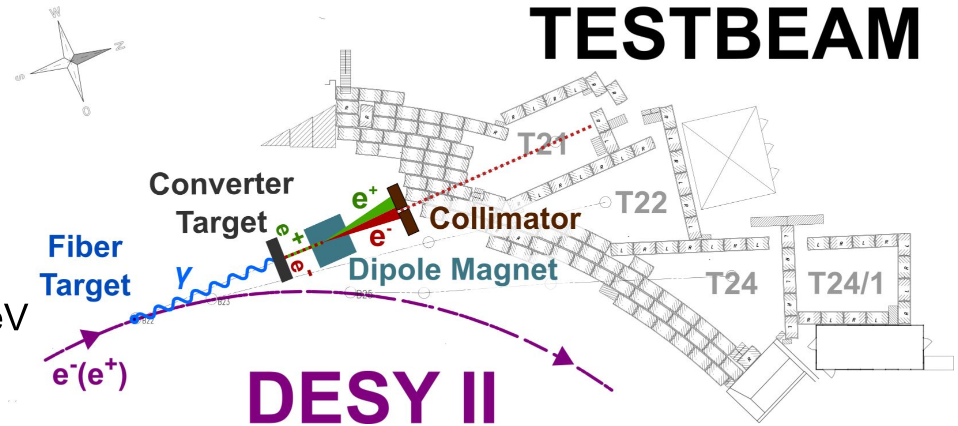
- Effective NIEL in case of GeV scale beam?





The DESY II Testbeam Facility

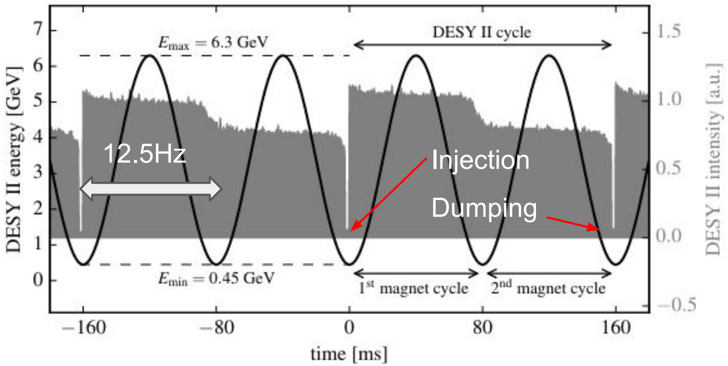
- DESY provides three testbeam lines (T21, T22 and T24) with single electrons
- Beam is generated by two targets
- Enables choice of momentum between 1 and 6 GeV
- Limits rate to a few 10 kHz
- How to increase the beam rate?

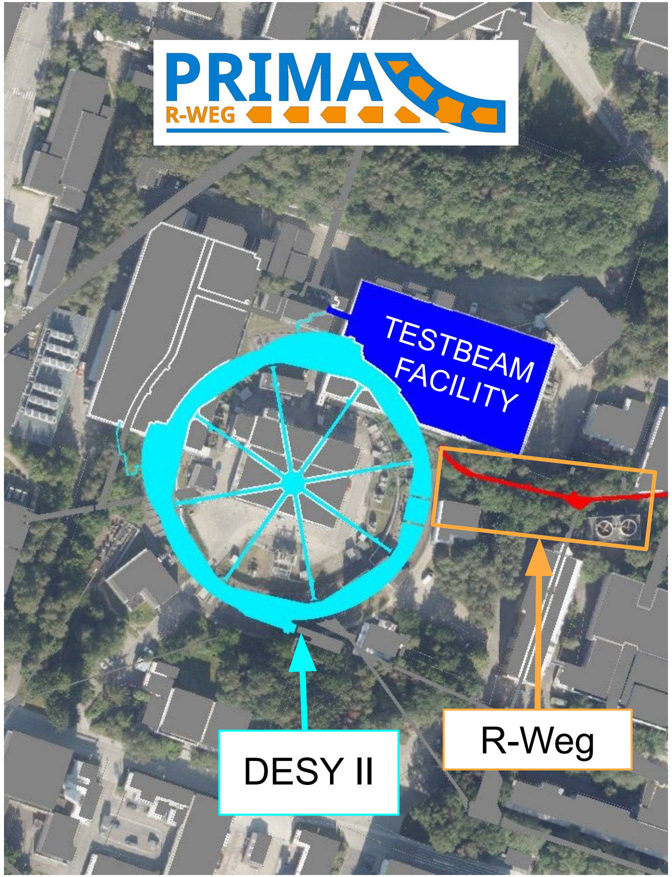


arXiv:1807.09328v2

PRIMA at the R-Weg

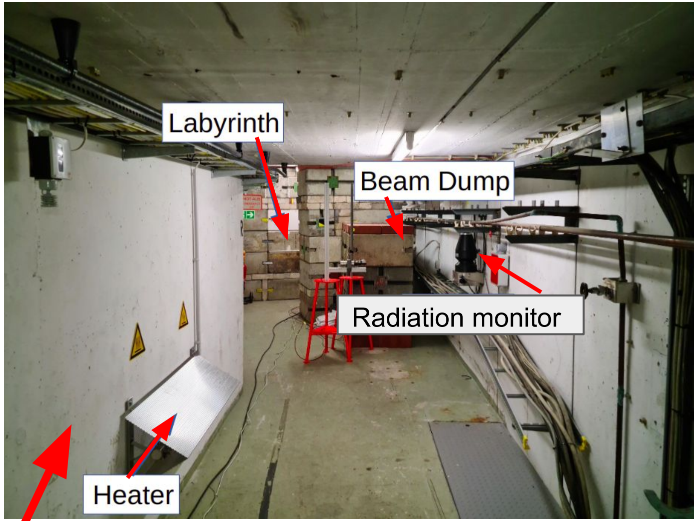
- PRIMary-beam test Area (PRIMA)
- Former transfer beamline from DESY II to DORIS
- Beam is transferred to PETRA or dumped after the 2nd magnet cycle in DESY II
- Feasibility studies in order to test usability as a new test beam line with high rates
- Installation of equipment in 2021

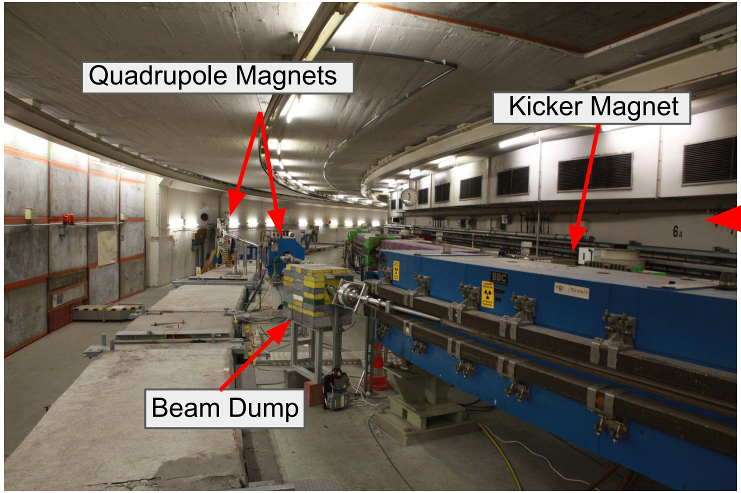


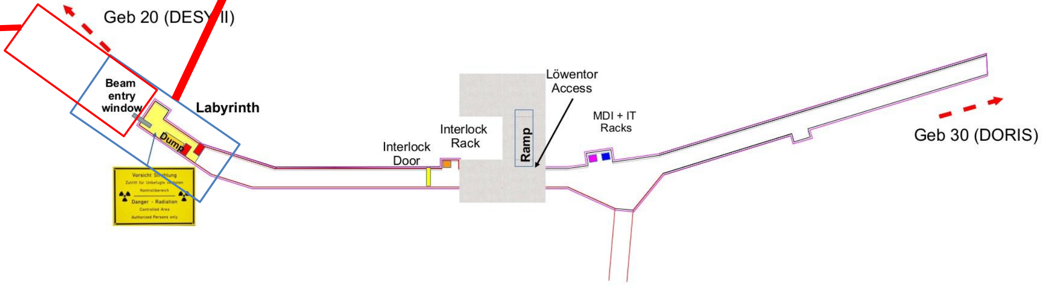


Installed Instrumentation

- Radiation safety calibrations
  - Interlock door is located far from beam dump
  - Heater removes humidity
  - Labyrinth with two walls
  - Radiation monitors

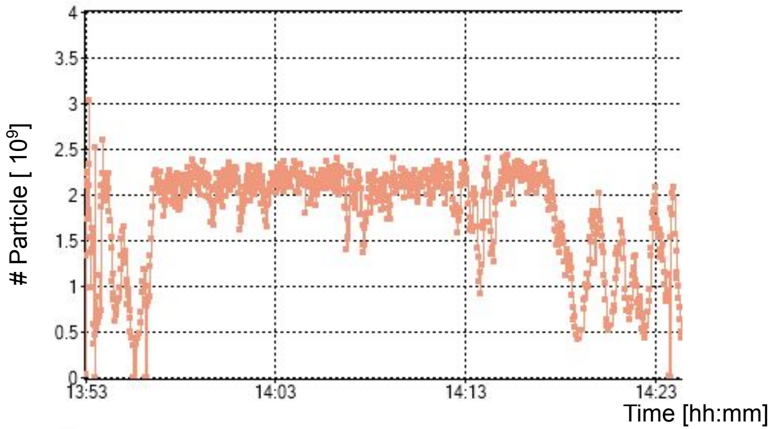


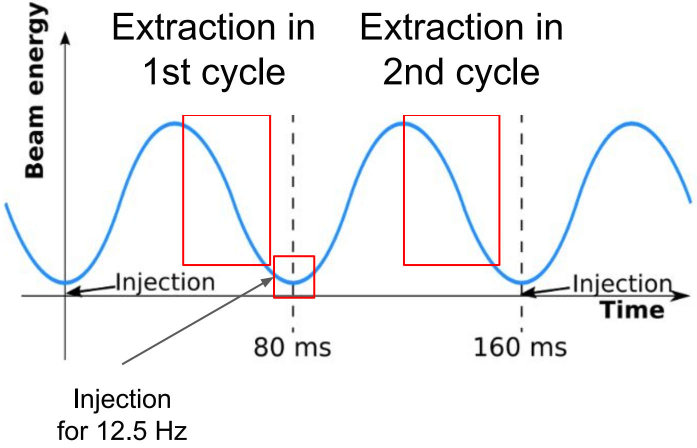




Beam Operation in PRIMA

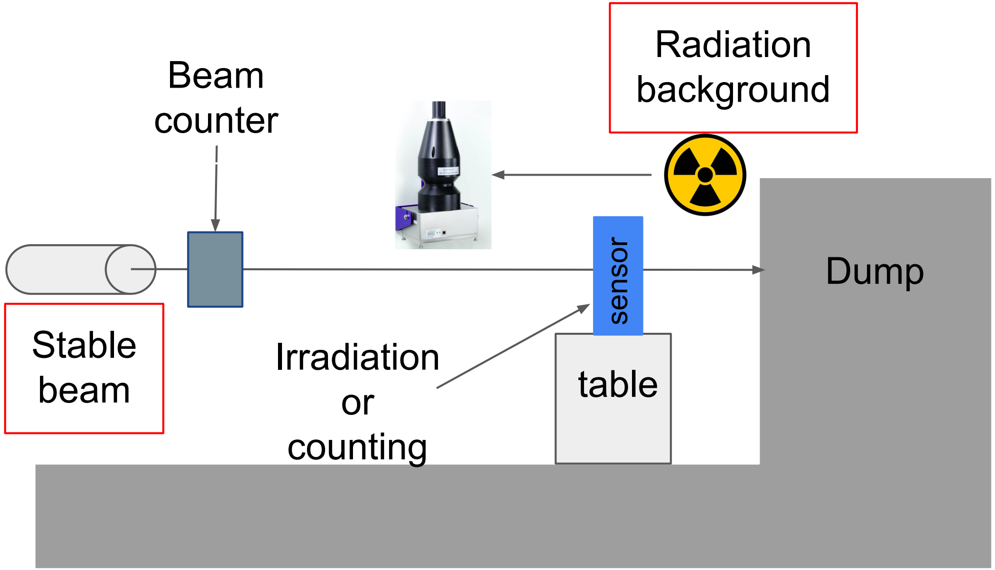
- # Particles
  - Possible < $1x10^5$ e / bunch
  - Max. : $3x10^{10}$ e / bunch
- Bunch length < 100 ps
- Energy of beam between 0.45 GeV and 6.3 GeV
  - Current beam with energy of 500 MeV
- Rate of extraction
  - Current extraction frequency of 6.25 Hz
  - Concerns with frequency upgrade of 12.5Hz





Necessary preparations and Possibilities

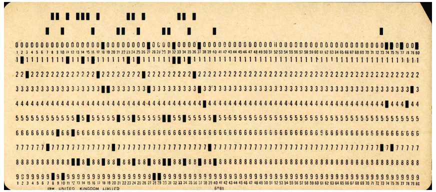
- Requirements
  - Radiation backgrounds for safety
  - Reducing background effects
  - Electron dose over time
  - Beam stability
  - Beam counter
  - Control of beam intensity
    - High for irradiation campaign
    - Very low for tracking

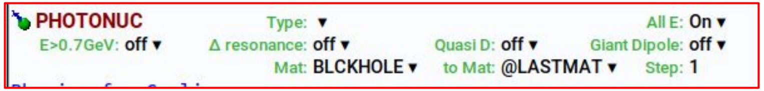


Simulation

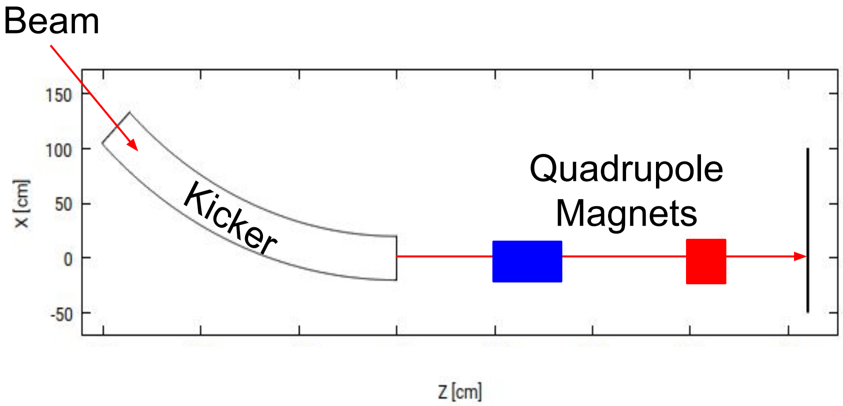
https://fluka.cern

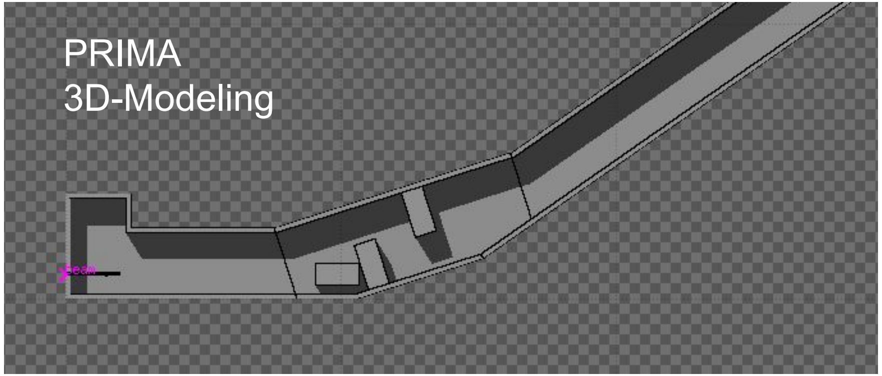
- MC framework for the interaction and transport of particles in materials
  - Based on card system originated from punched cards
  - Photon interactions > 100 eV
  - Electron interactions > 1 keV
  - Thermal and high energy neutron interaction
- Using FLUKA
  - Radiation protection to measure dose
  - Magnetic field to study beam stability
  - Radiation damage to estimate irradiation





FLUKA's physics card





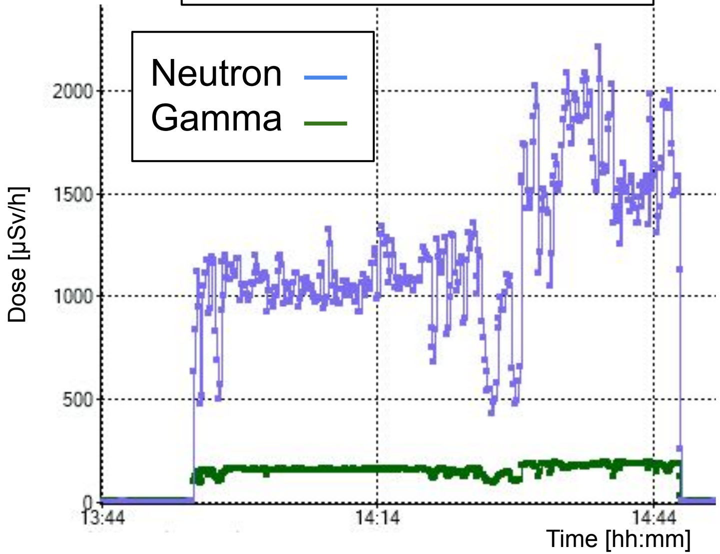
Radiation

- Radiation background
  - How many neutrons and gammas
    - Resonance of photonuclear reaction
    - Mostly from beam dump
  - Measurement
    - Radiation monitor : PANDORA

- PANDORA
  - Scintillator
    - Gamma > 50 keV
    - Low energetic neutron < 20 MeV
  - Moderated ^{3}He tube
    - High energetic neutron > 20 MeV

Scintillator

^{3}He Tube

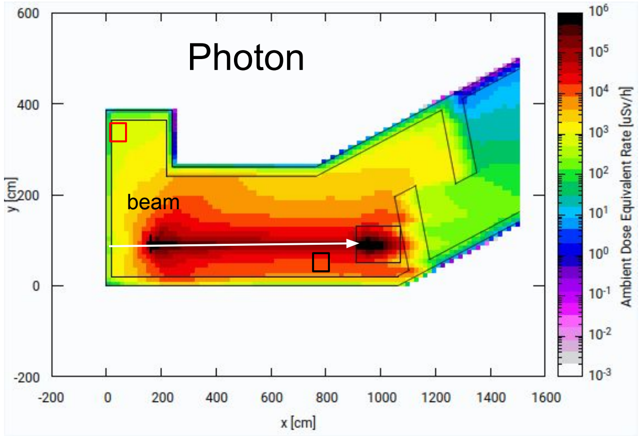


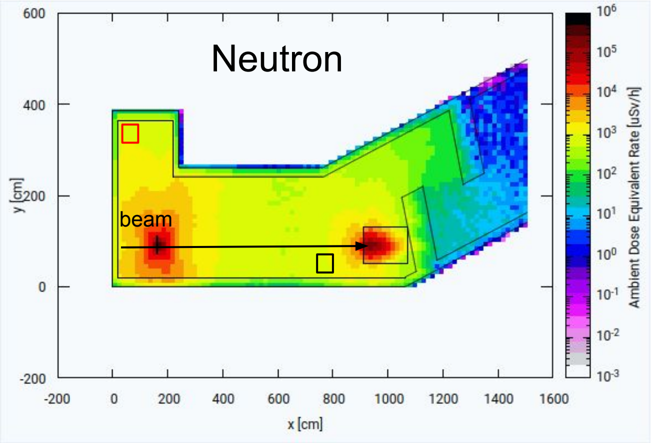
Time structure / Type of radiation	Continuous Total response, no pileup	Burst Delayed response only
High energy neutrons > 20 MeV	Scintillator: H(n,n)H → recoil protons	Scintillator: $^{12}C(n,p)^{12}B \rightarrow {}^{12}C + \beta + \nu$
Low energy neutrons < 20 MeV	Moderated ^{3}He – tube: $^3He(n,p)^3T$	Moderated ^{3}He – tube: $^3He(n,p)^3T$ delayed by TOF

Table 1 – Overview of the LB 6419 responses due to neutron radiation.

Nuclear Science Symposium Conference Record, 2007.
Volume: 3, Pages: 1982 - 1983

Compare to Doses During Beam Time for 500 MeV





Beam loss of 10% at the flange 6.25 Hz, 2×10^9e / bunch		At the corner □ (red)	At the Dump □ (black)
Simulated Dose [μSv/h]	Photon	530 ± 2	7935± 15
	Neutron	805 ± 35	1000 ± 40
Measured Dose [μSv/h]	Photon	~70	~160
	Neutron	~800	~1000

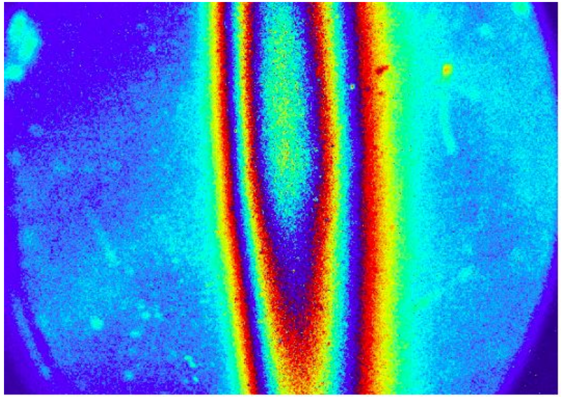
Dose at Dump with Reduced Beam Rate

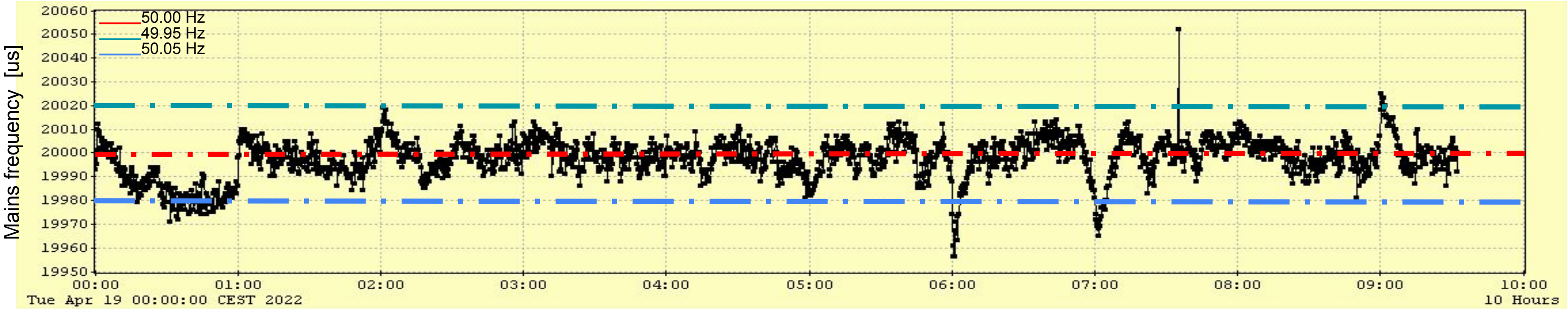
500 MeV Electron Beam		
Beam loss of 10% at the flange 6.25 Hz, $1x10^7$e / bunch	Measured dose [μSv/h]	Simulated dose [μSv/h]
Photon	~30	39.7 ± 0.1
Neutron	~60	5 ± 0.2

6 GeV Electron Beam		
Without beam loss 6.25 Hz, $2x10^7$e / bunch	Measured dose [μSv/h]	Simulated dose [μSv/h]
Photon	~30	39.8 ± 0.3
Neutron	~60	60.9 ± 2.1

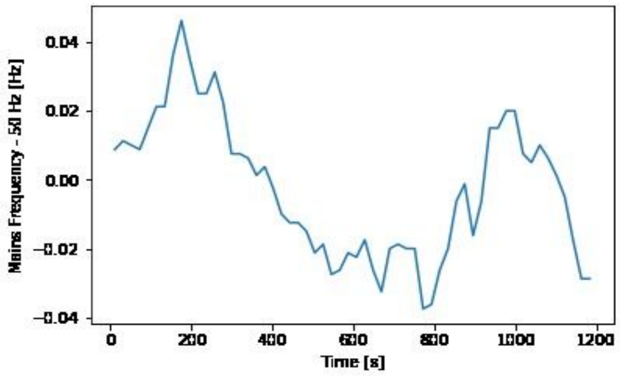
Beam Stability

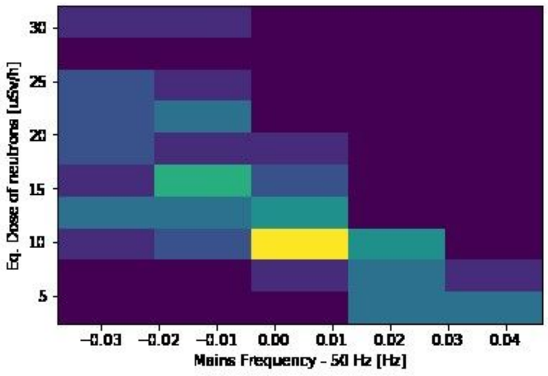
- Beam stability
  - Fluctuation of mains frequency causes fluctuation of extraction timing
  - $\Delta t_{\rm ext} \sim \Delta E \sim \Delta\theta$
    - Fluctuation in the beam position
    - Deformation of the beam shape

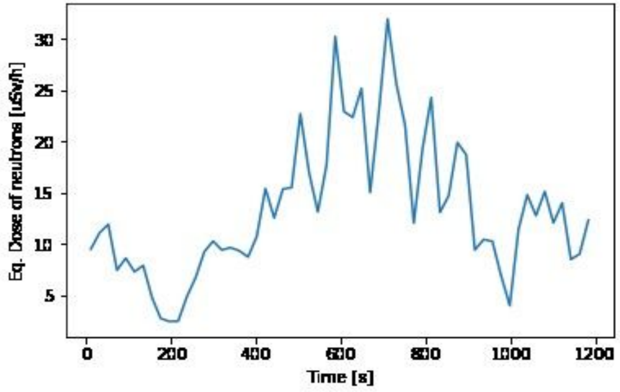


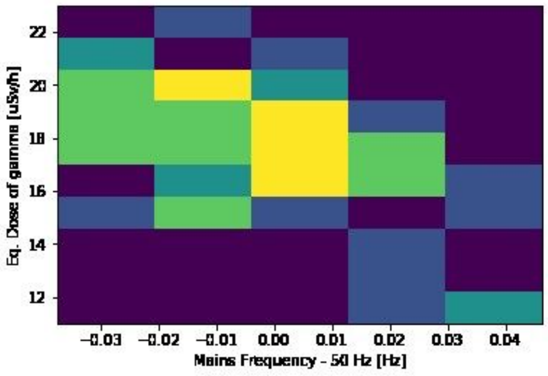


Correlation between fluctuated Mains Frequency and Doses at Beam Dump for 500 MeV Beam

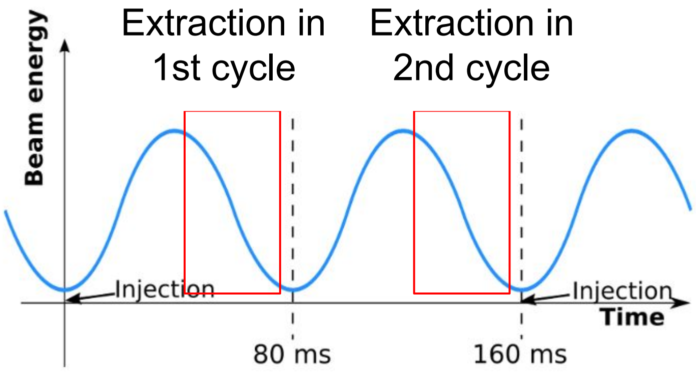


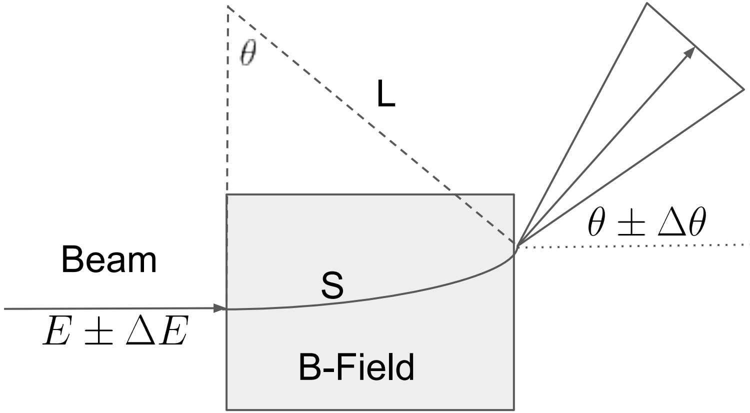






Error Calculation





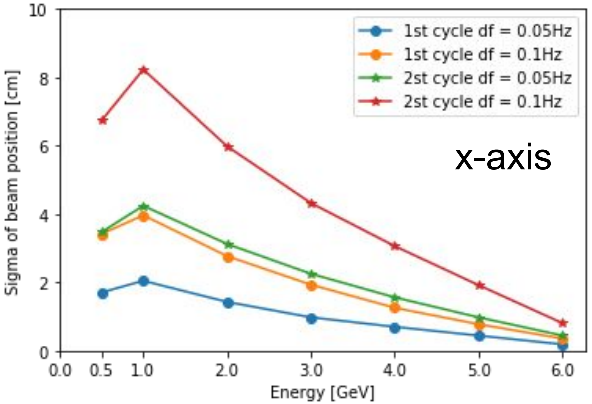
$$E(t) = \frac{E_{max} - E_{min}}{2} sin(2\pi f_m t_{ext} + \phi) + \frac{E_{max} + E_{min}}{2}$$

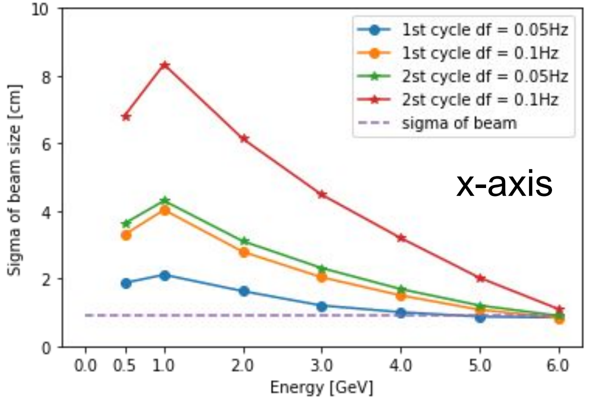
$$\Delta E(t) = \frac{E_{max} - E_{min}}{2} [sin(2\pi f_m (t_{ext} + \Delta t_{ext}) + \phi) - sin(2\pi f_m t_{ext} + \phi)]$$

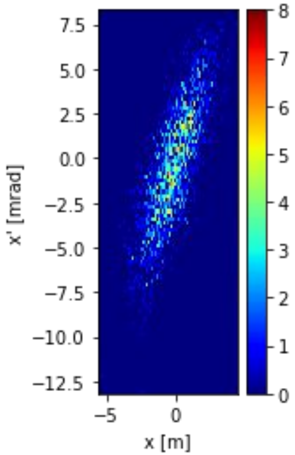
$$B[T] = \frac{E[GeV]}{0.3S[m]}\theta \rightarrow \frac{\Delta\theta}{\theta} = \frac{\Delta E}{E}$$

Beam Size for Δf = 0.05 Hz after Kicker Magnet

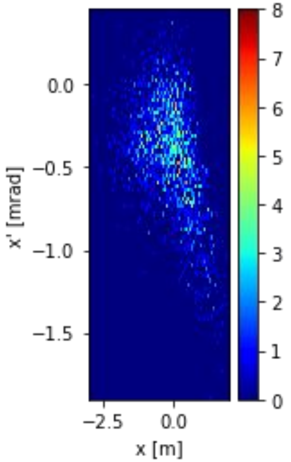
Front of the first quadrupole magnet



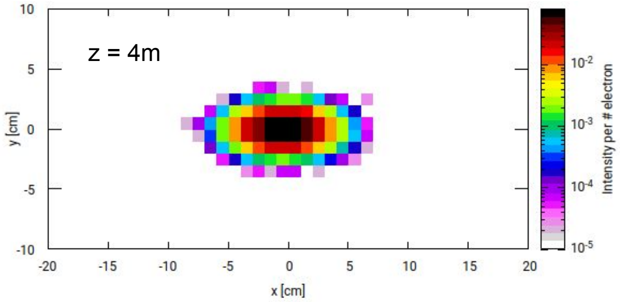


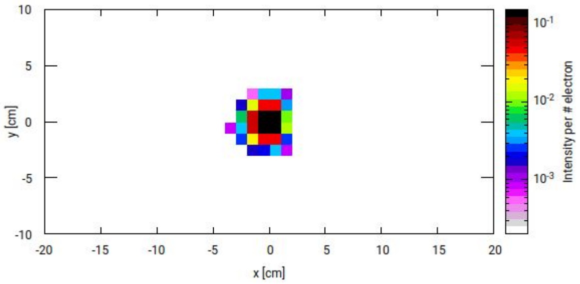


1st cycle 500 MeV for Δf = 0.05 Hz



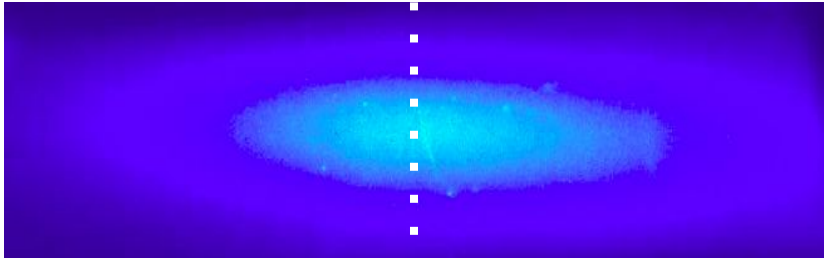
1st cycle 6 GeV for Δf = 0.05 Hz

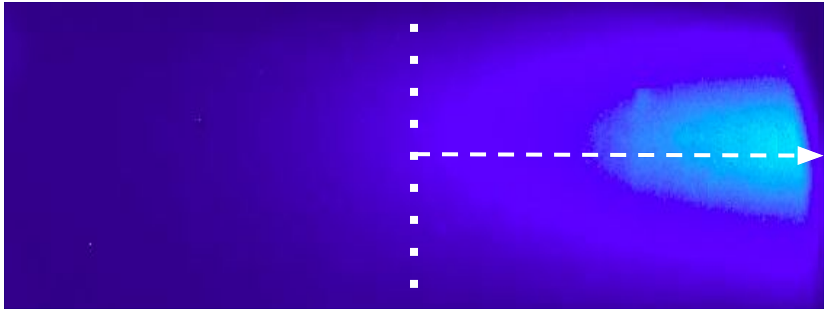


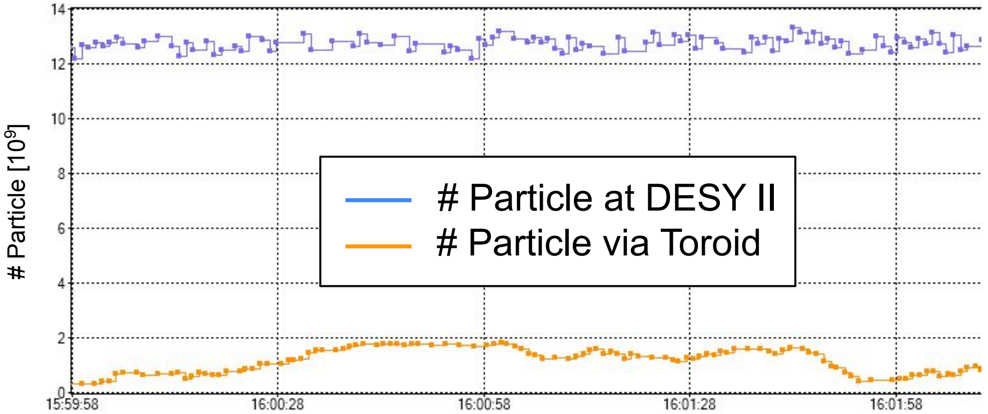


Measured Current 500 MeV Beam

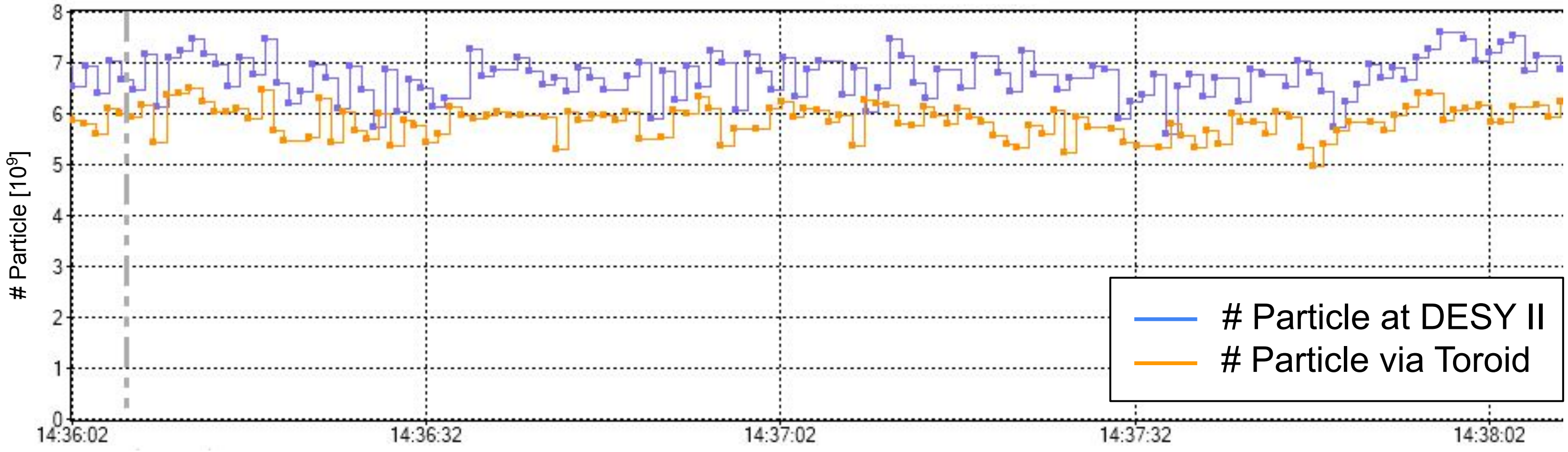
Current beam with energy of 500 MeV
measured with beam camera







Beam Rate Measurement for 6 GeV Without Quadrupole Magnets

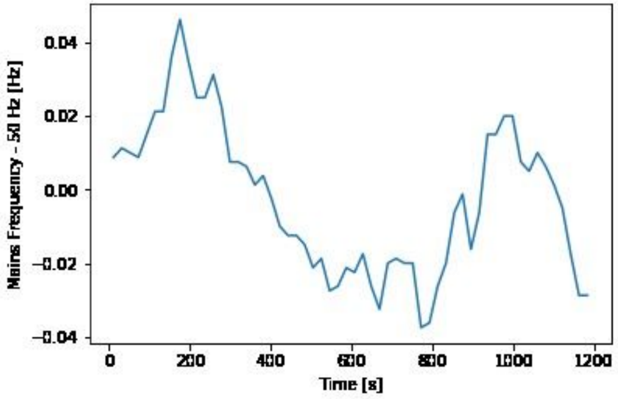


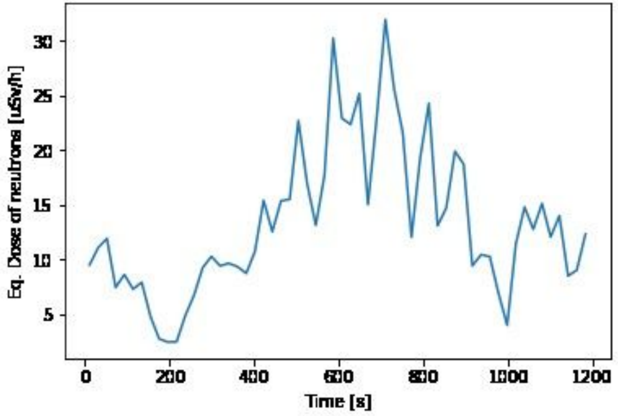
Summary

- Radiation
  - Doses in PRIMA are estimated well using FLUKA
  - Beam instability changes a lot of dose in PRIMA

- Beam stability
  - The simulation result shows the current unstable beam in PRIMA
  - The beam with energy of 6 GeV is more stable
  - Require to study quadrupole magnets

6 GeV Electron Beam		
Without beam loss 6.25 Hz, 2x10^7e / bunch	Measured dose [μSv/h]	Simulated dose [μSv/h]
Photon	~30	39.8 ± 0.3
Neutron	~60	60.9 ± 2.1

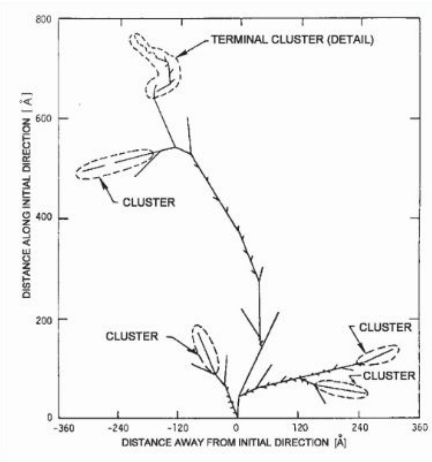




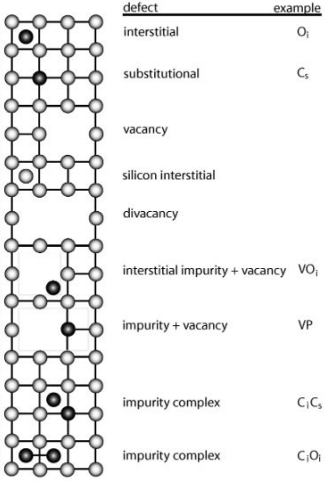
Backup

Irradiation Campaign

- Bulk damage
  - Non Ionizing Energy Loss (NIEL)
  - Hadrons, higher energetic Leptons and gammas
  - Displacement in a pair of a Si interstitial
  - A vacancy in Si-lattice

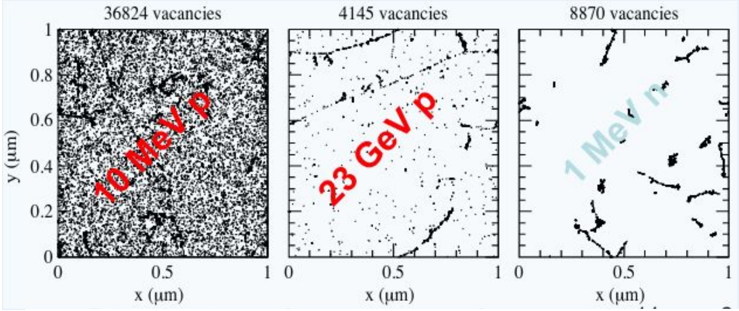


Cluster defect



Single defects

	Gamma	Electron	Proton	Neutron
Interaction	compton electrons	Coulomb	Coulomb & elastic nuclear	elastic nuclear
Single defects	300 keV	255 keV	185 eV	185 eV
Cluster defects	-	8 MeV	35 keV	35 keV

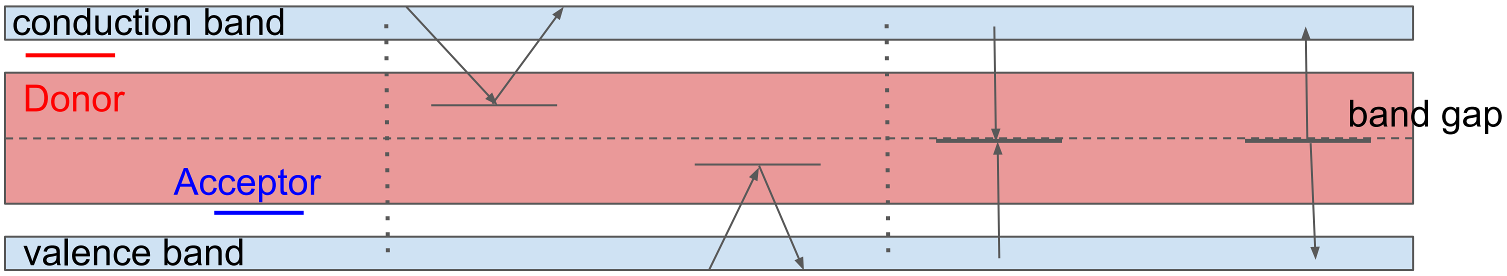


Vacancies distribution after $\Phi eq=10^{14}\ cm^{-2}$

[Mika Huhtinen NIMA 491(2002) 194]

Irradiation Campaign

- Bulk damage impact on detector
  - Determined by Shockley-Read-Hall statistics



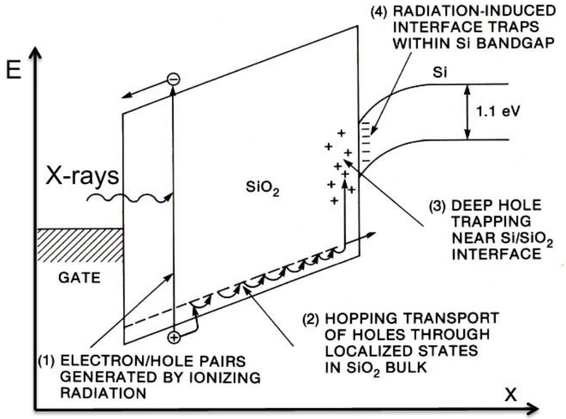
Doner & acceptor generation
- Charged defects
- Change of E-field

Trapping
- Deep defects
- Signal drop

Generation & Recombination
- Current increase
- Cooling helps to reduce

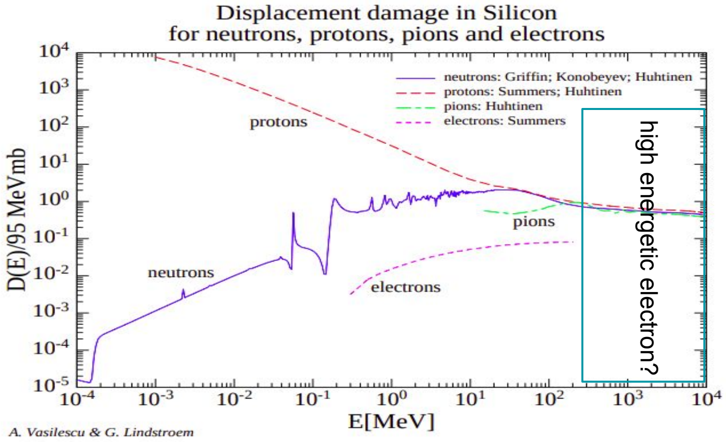
Irradiation Campaign

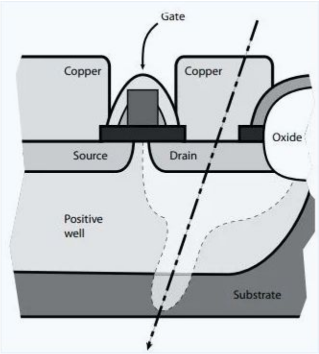
- Surface damage
  - Ionizing Energy Loss (IEL)
  - Most sudden generated hole-electron pair in the oxide recombine immediately
  - If generated holes arrive between Si and oxide, where many deep hole traps exist, they may be kept there permanently
    - Increase of the capacitive coupling between pixels
      Increase of leakage currents, etc.
  - Fe-55 (50 keV gamma) is used to test commonly

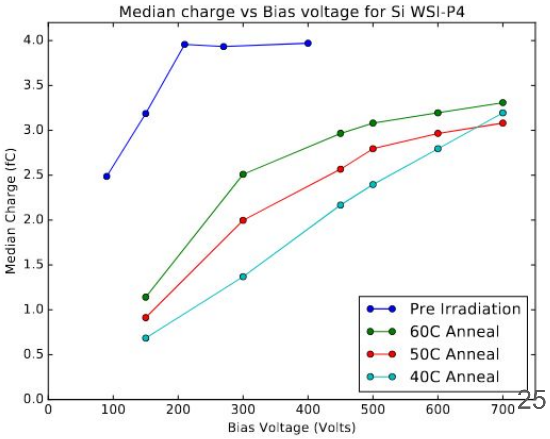


Motivation of Irradiation Campaign

- 1 Grad with 2 MeV electrons
  - 35 times less damage than expected from non-ionizing energy loss (NIEL)
- 150 Mrad with 900 MeV electrons
  - Degree of damage as small as one fourth that expected from NIEL
- 270 Mrad using electron beam with energy of 13.3 GeV
  - Measured deposited charges before and after irradiation and annealing

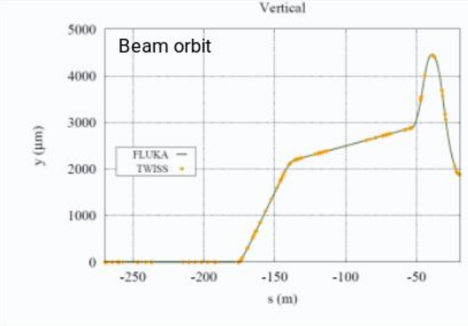


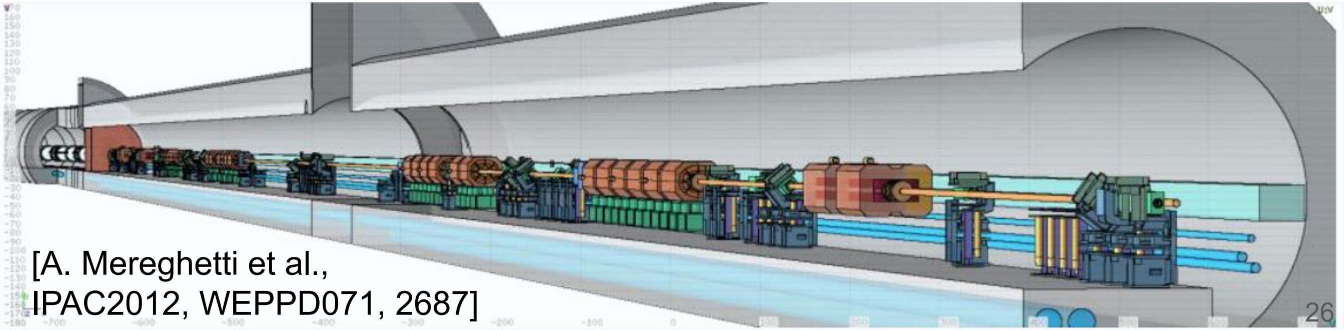




FLUKA

- MC framework for the interaction and transport of particles in materials
  - Based on Fortran
  - Photo interactions > 100eV
  - Electron interactions > 1 keV
  - Low energy neutron interaction < 20 MeV
- Applications
  - Accelerator design
  - Radiation protection (shielding, activation)
  - Radiation damage or electronics effects
  - etc.

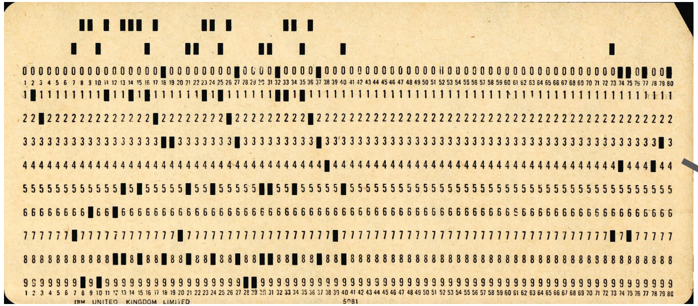


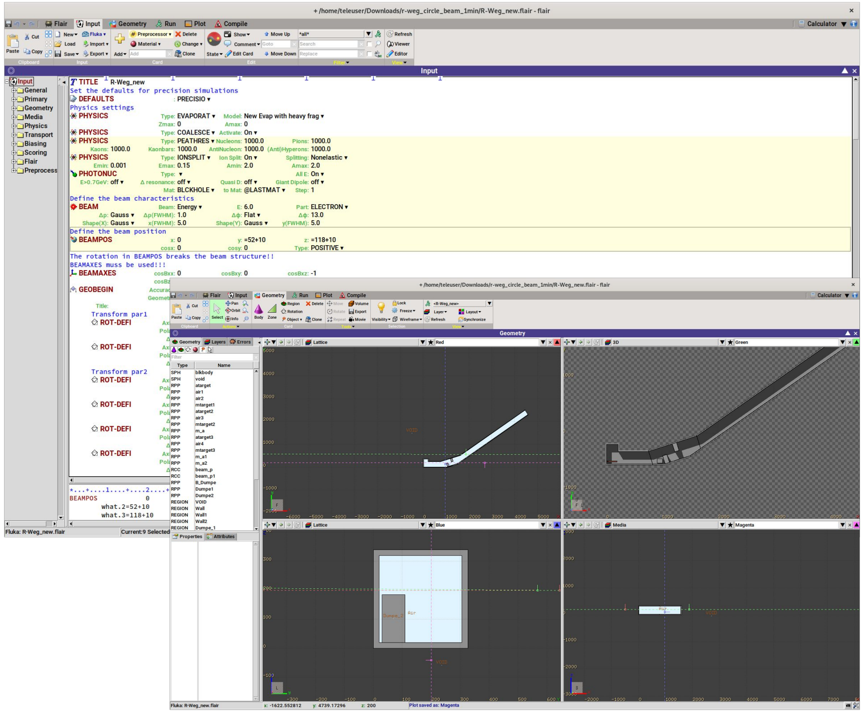


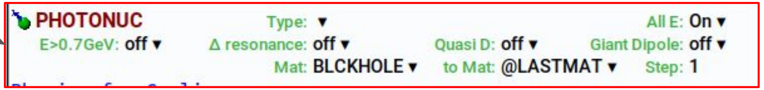
[A. Mereghetti et al., IPAC2012, WEPPD071, 2687]

FLUKA

- FLUKA
  - Input file of FLUKA based on “cards”
    - “Cards” originate from punched cards
    - Choose function cards
      - Geometry, Physics, Scoring, Magnet, etc.
  - Possible to link to user defined codes
    - Language : Fortran
  - Provides the 3D view of geometry







FLUKA’s physics card

Geometry using FLUKA

- Principle of combinatorial Geometry
  - Complex objects are made using boolean operations
  - Possible to modularize the bodies
    - Easier to design complex parts
    - Modules can be transformed easily using cards
  - There are disadvantages
    - It is not easy to convert CAD to FLUKA
    - FLUKA provides simple bodies
      - Planes, boxes, sphere, cylinders, cones ..
- Material cards
  - Material property of bodies are defined using cards
    - density, interaction, ionisation etc.
  - A lot of materials are included in FLUKA already
  - User can define a material too
  - Special material : blackbody
    - all absorbing material
    - The region where is simulated has to be surrounded by blackbody

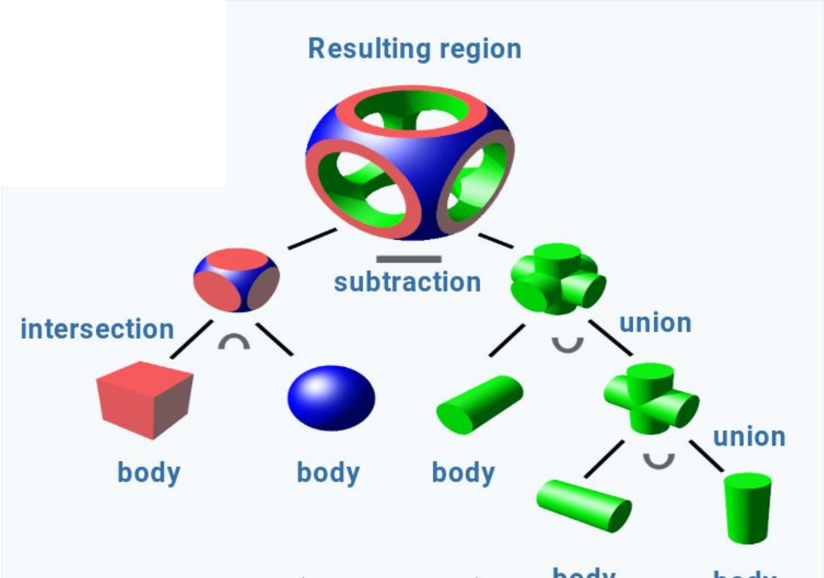
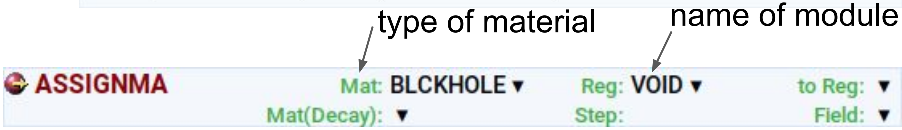


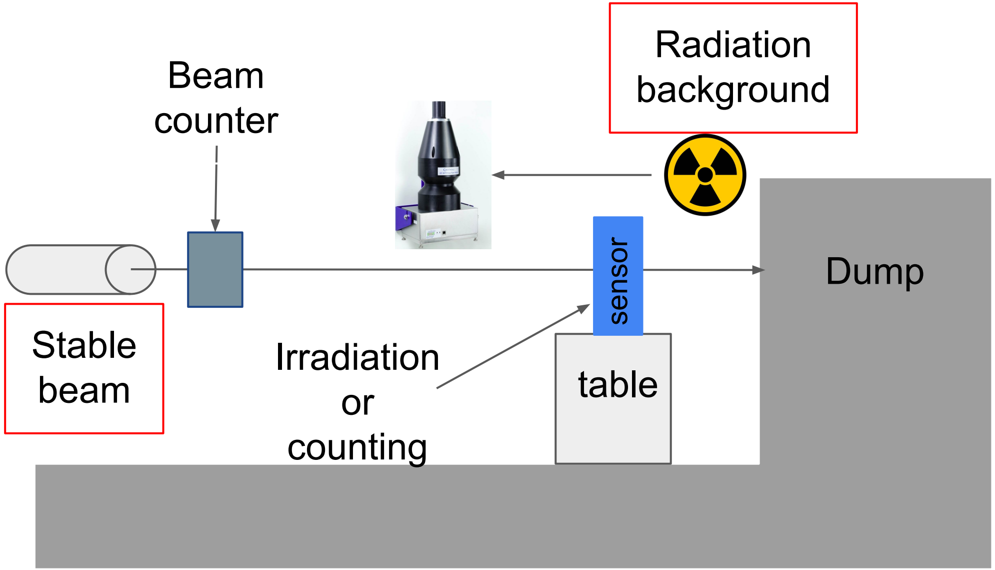
Image from Wikipedia (CC BY-SA 3.0)



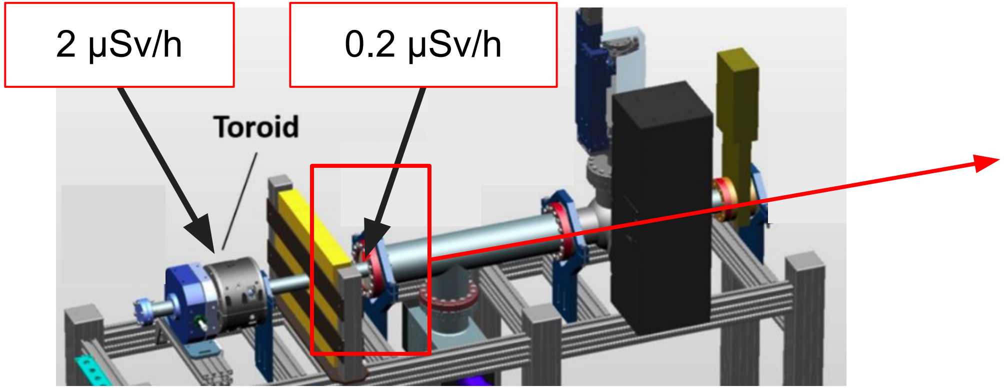
Material card

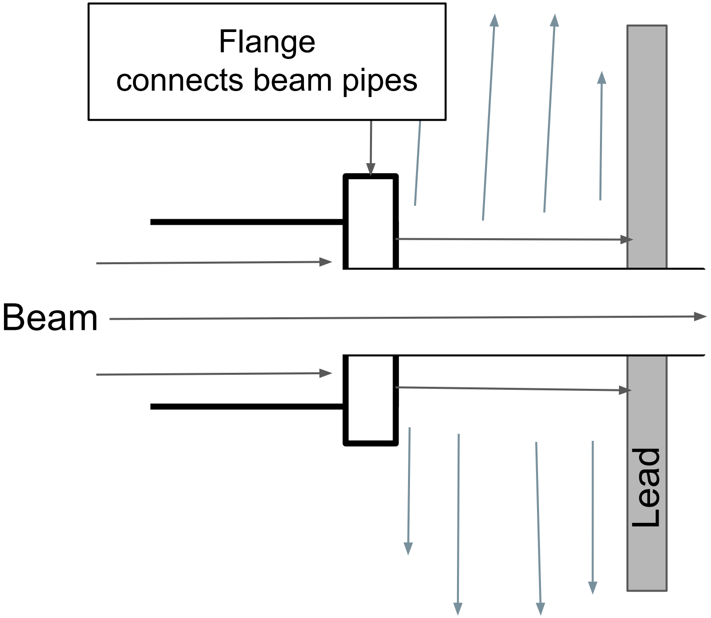
What is Necessary for PRIMA?

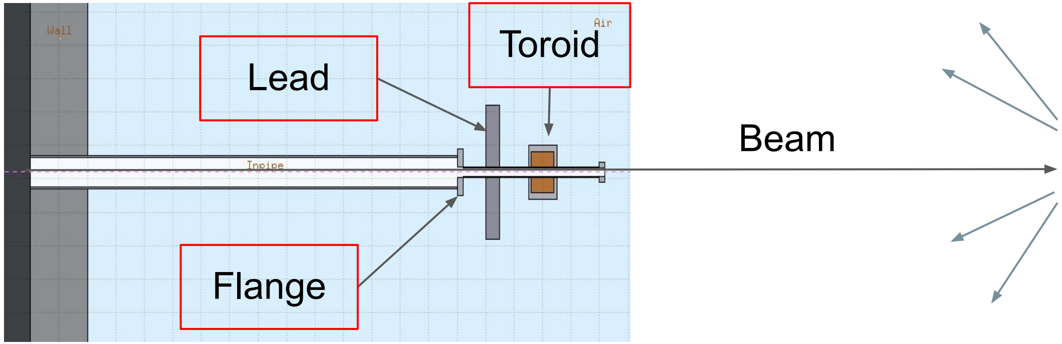
- Precise references for
  - Radiation backgrounds
  - Beam stability
  - Electron dose over time
  - Number of particles

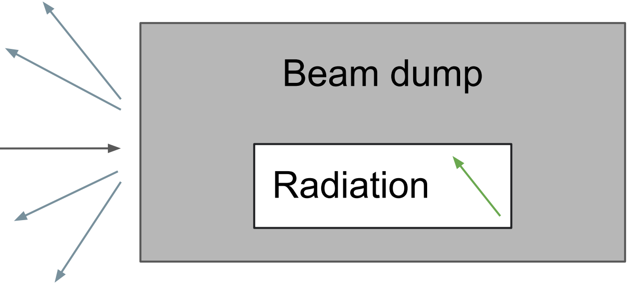


Simulated Beam Line

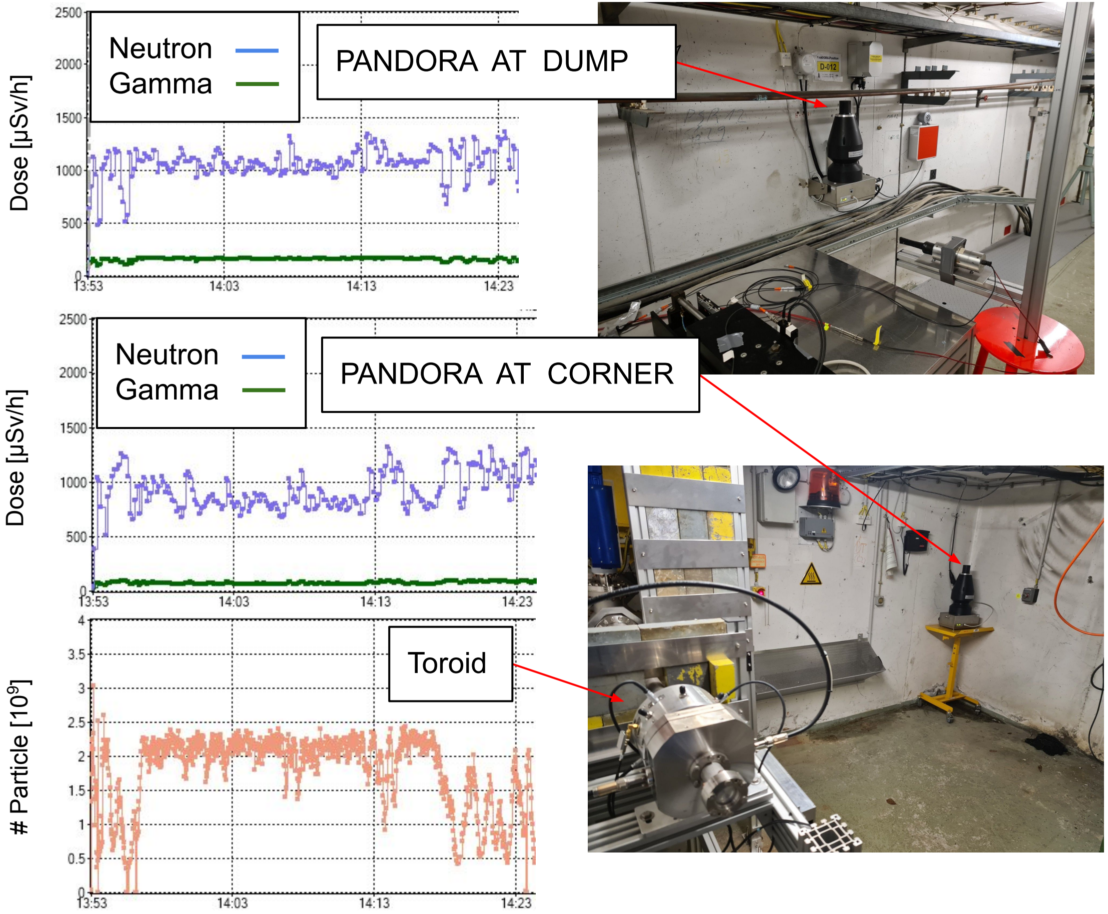




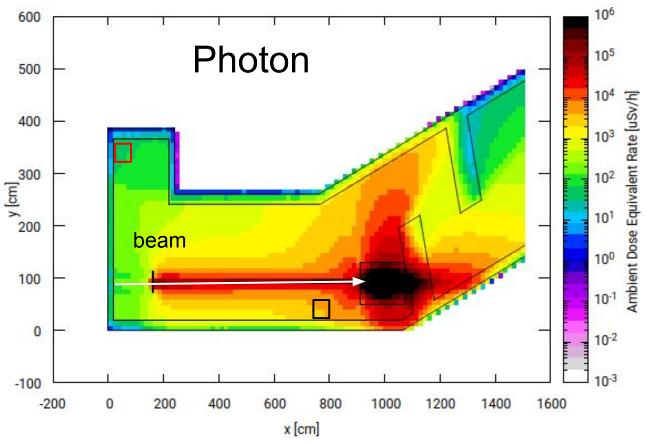


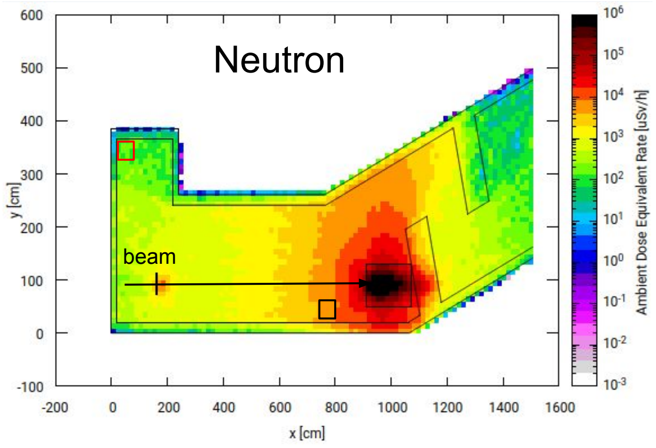


Compare to Doses During Beam Time



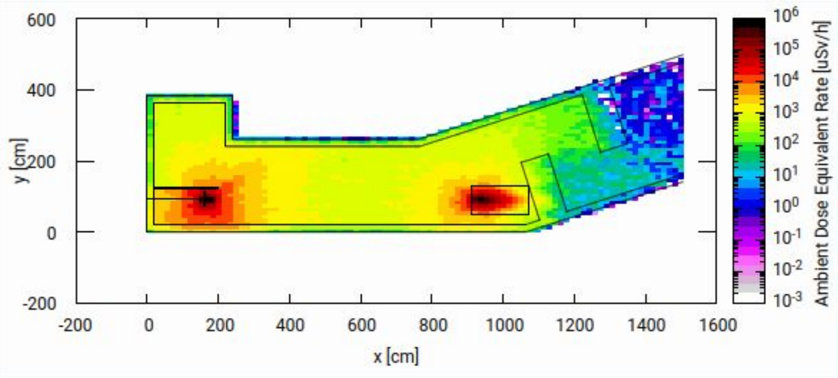
Compare to Doses During Beam Time for 6 GeV

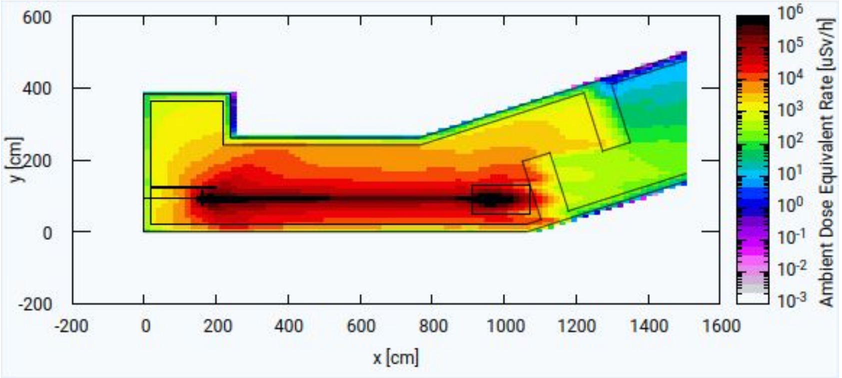


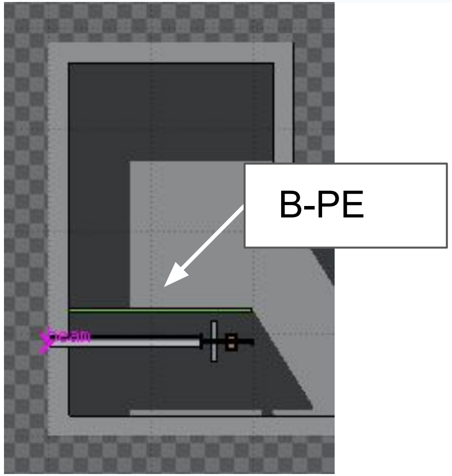


Without beam loss 6.25 Hz, 2x10^{9}e / bunch		At the corner □ (red)	At the Dump □
Simulated Dose [μSv/h]	Photon	35 ± 2	3980 ± 30
	Neutron	130 ± 40	6090 ± 210

Beam Line with Boronated Polyethylene

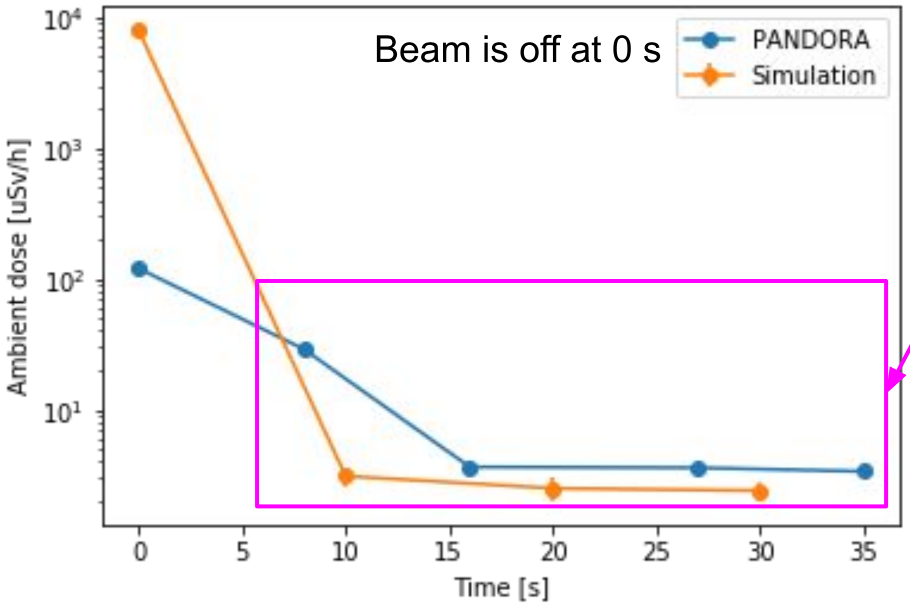






Beam lost of 10% at the flange		With BE-Plate (B of 1%, thickness of 5cm)
		At the corner
Simulated Dose [μSv/h]	Photon	618 ± 10
	Neutron	520 ± 80
Measured Dose [μSv/h]	Photon	~50
	Neutron	~600

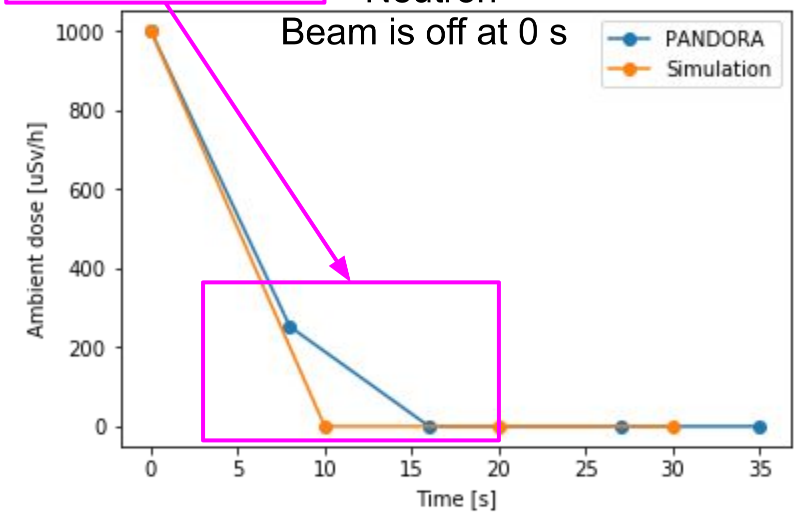
Compared Doses During Cooling Down at the Dump After Beam Dump 1h Long



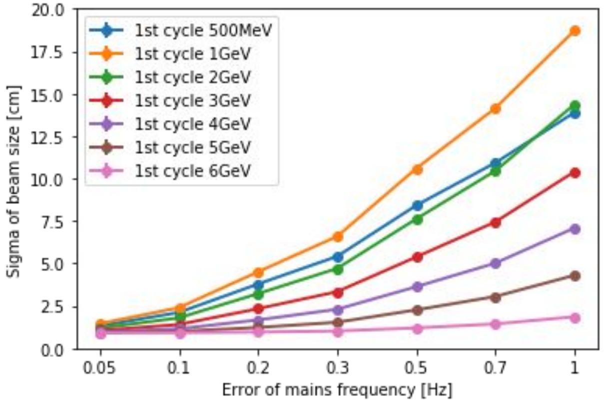
Time structure / Type of radiation	Continuous Total response, no pileup	Burst Delayed response only
High energy neutrons > 20 MeV	Scintillator: H(n,n)H → recoil protons	Scintillator: $^{12}C(n,p)^{12}B \rightarrow {}^{12}C + \beta + \nu$
Low energy neutrons < 20 MeV	Moderated ^{3}He – tube: $^{3}He(n,p)^{3}T$	Moderated ^{3}He – tube: $^{3}He(n,p)^{3}T$ delayed by TOF

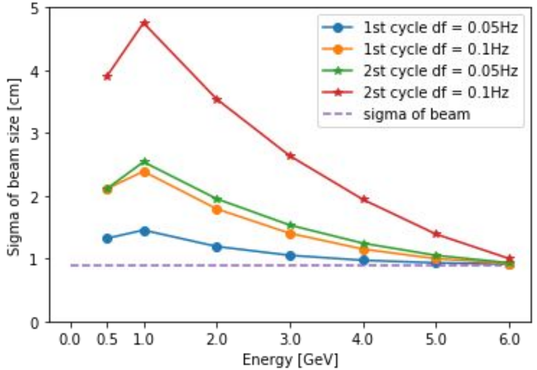
Table 1 – Overview of the LB 6419 responses due to neutron radiation.

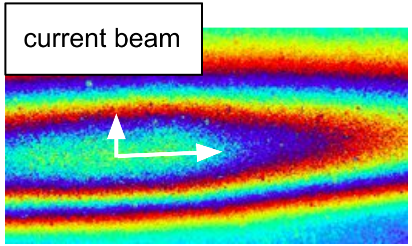
Response delay

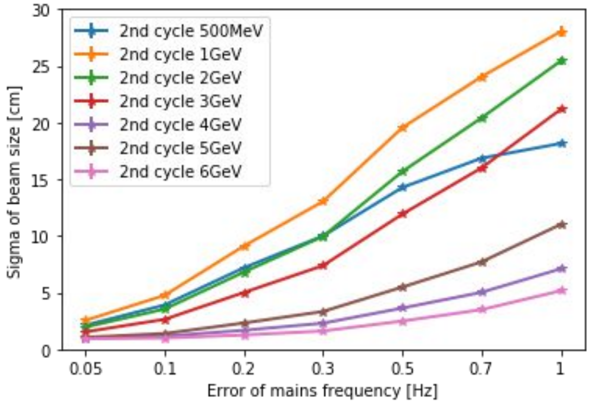


Beam Size

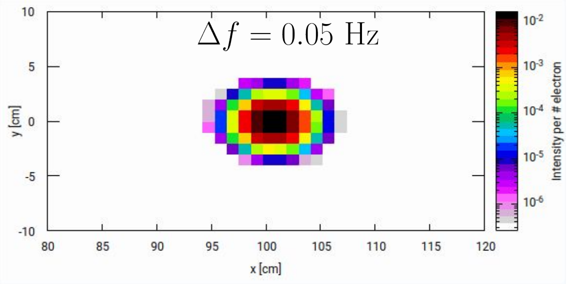




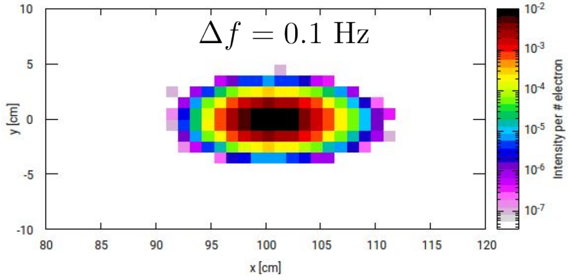




1st cycle 500 MeV

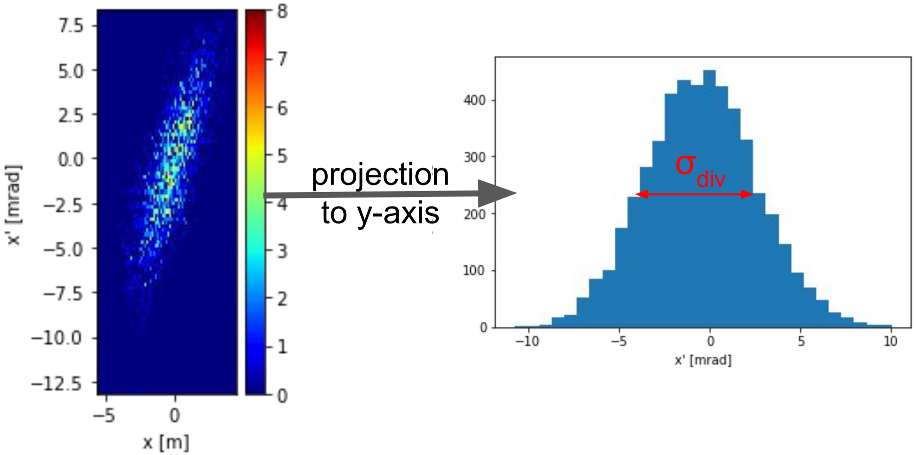


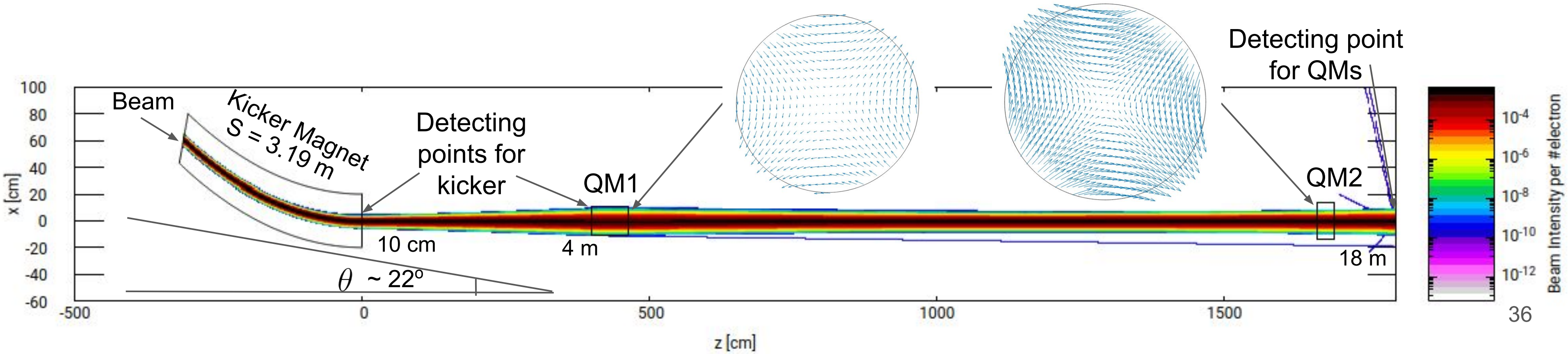
1st cycle 500 MeV



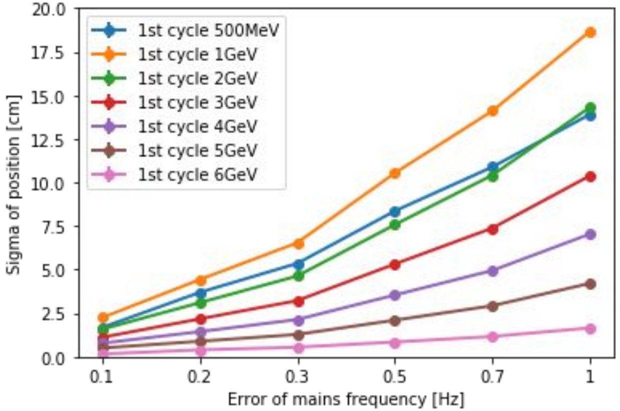
Simulation Setup for Magnets

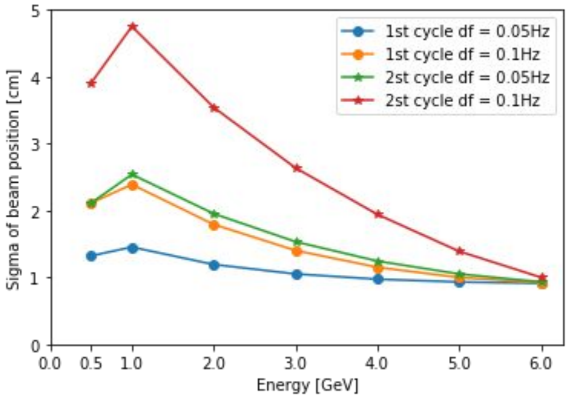
- Measurement
  - Beam size depends on the z-axis
  - Phase space
    - $x' = \frac{dx}{dz} = \frac{P_x}{P_z}$
  - Divergence
- Input parameters
  - Beam size $\sigma_x \text{ x } \sigma_y = 0.9 \text{ x } 0.9 \text{ cm}^2$
  - Spot beam

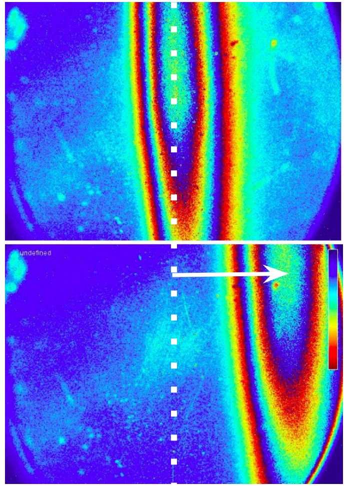


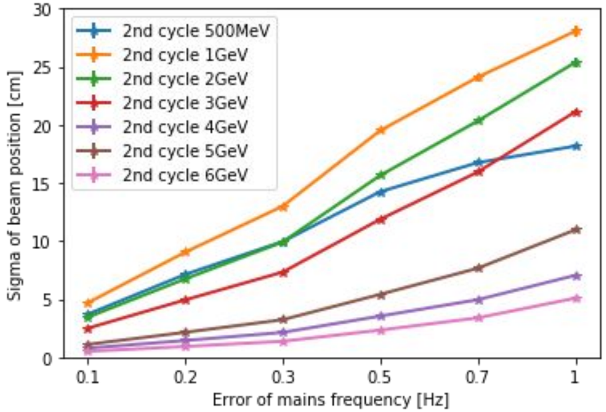


Beam Position

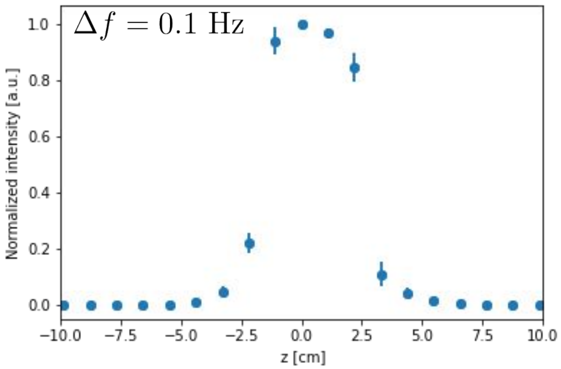




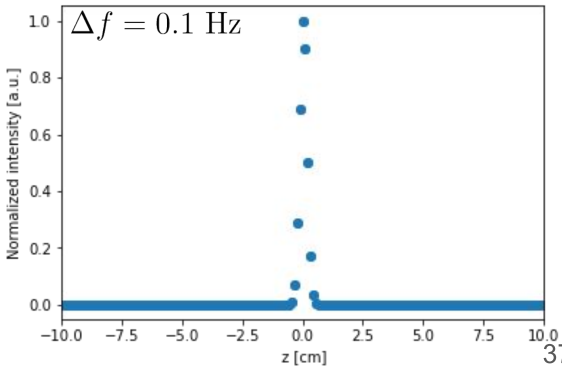




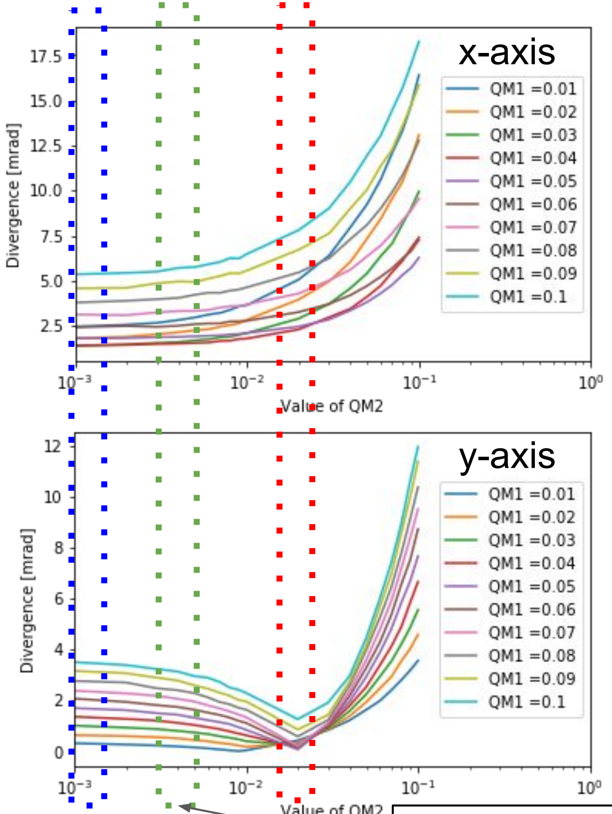
1st cycle 500 MeV



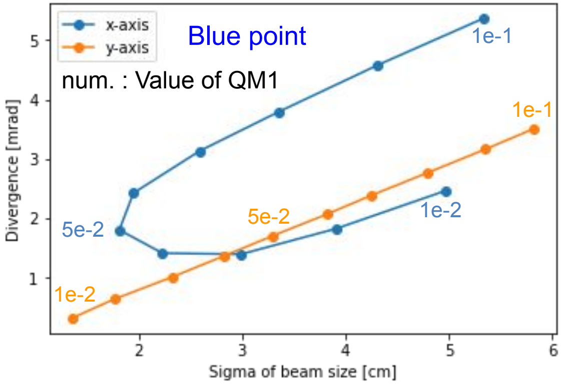
1st cycle 6 GeV

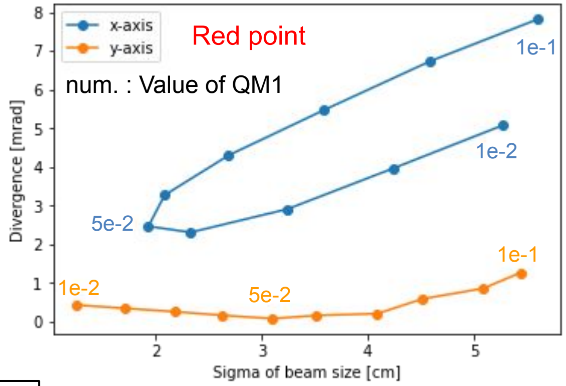


Beam Size & Position for Δf = 0.05 Hz after all Magnets

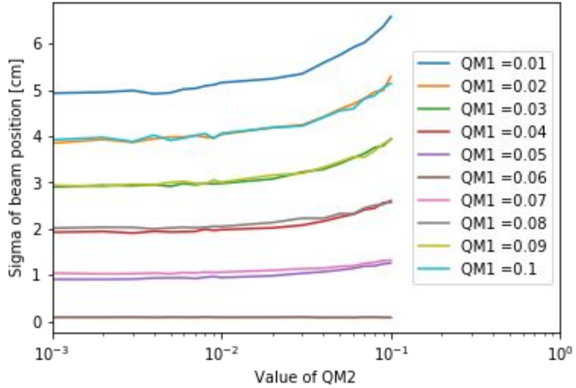


Current value





- Field of Magnets = Max. Field * Value of QM



Next Steps

- Overestimation of photon
  - Reduced beam rate to test PANDORA
- Measuring dose using beam with energy of 6 GeV
- Scanning the quadrupole magnets to compare the simulation results
- Implementing a sextupole magnet into the simulation
- Implementing magnets into the R-Weg geometry