Si Based Sensor R&D and High-Intensity Electron Beamline at DESY

22st Sep. 2023,

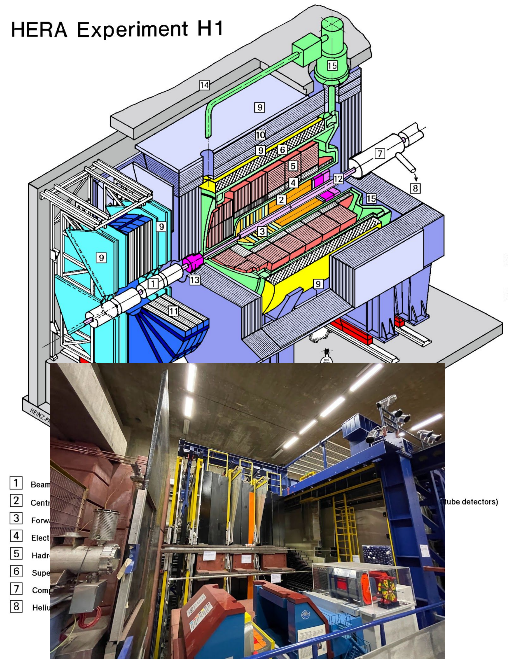
Dohun Kim

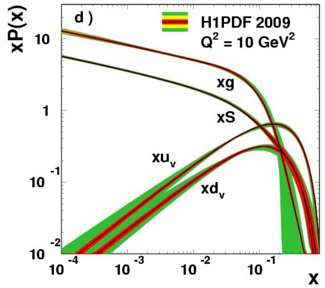
HELMHOLTZ

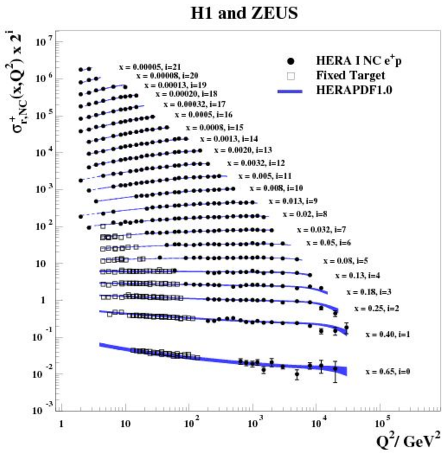
DESY.

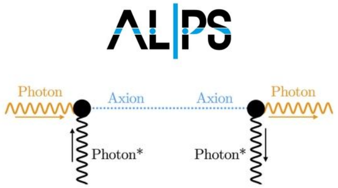
Introduction - DESY

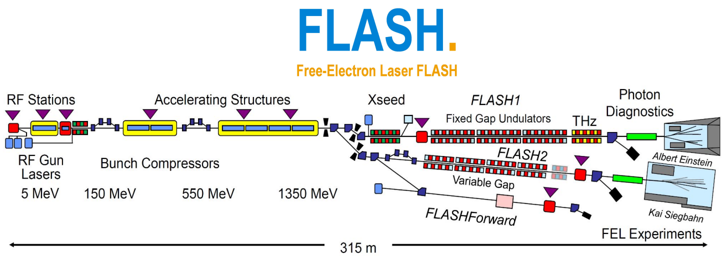
About FH at DESY

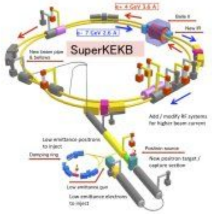


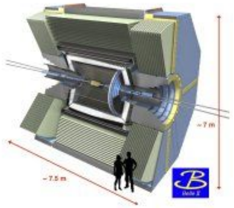


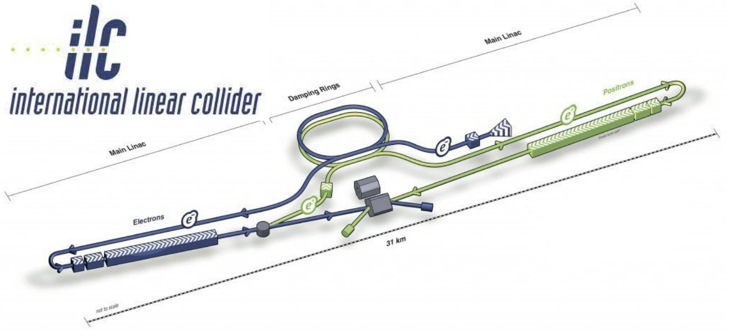


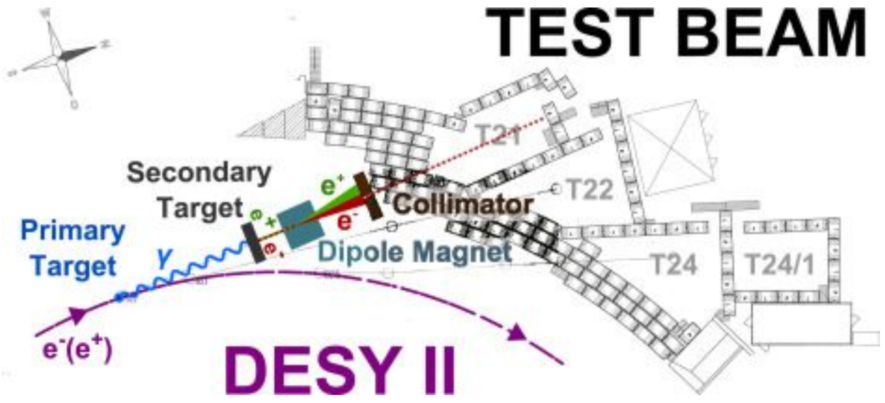


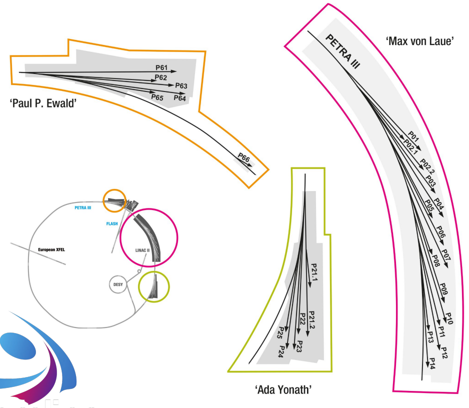


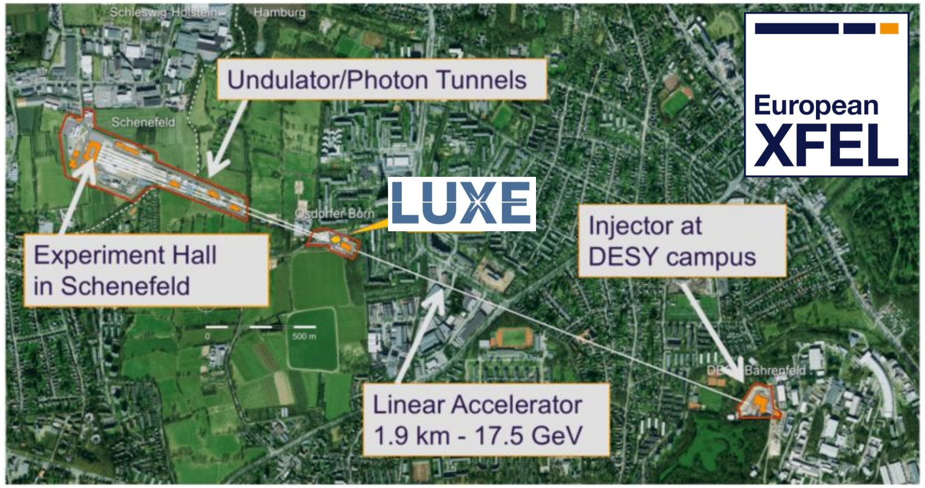












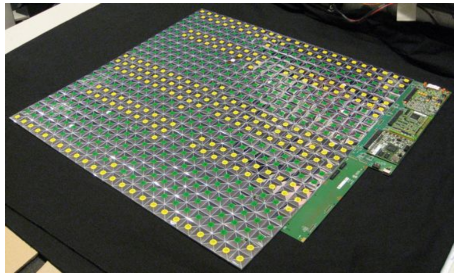
DESY.

Introduction - Group

FTX | Research and Technologies for Future Particle Physics Experiments

- Doing research in 5 subgroups
  - SLB: Science with Lepton Beams
    - Study on Higgs factory and LUXE
  - SFT: Software for Future experiments
    - Simulation & analysis software development
    - Machine learning
  - DTA: Detector Technologies - Calorimeters
    - SiPM based HCAL & ECAL development
  - TBT: Test Beam and Telescopes
    - Detector R&D infrastructure development
  - AST: Accelerator Science and Technology
    - FLASH, ALPS II and accelerator R&D

LUXE



Introduction - Group

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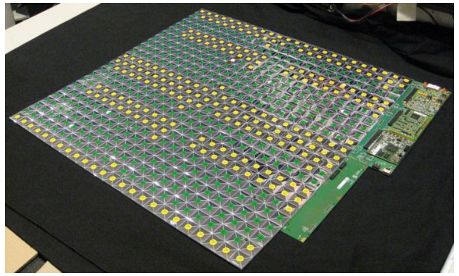


Motivation

European Strategy Update for Particle Physics, 2020

European Strategy Update

3

High-priority future initiatives

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

- ***the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;***

- ***Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.***

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

B. Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. ***The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.***

....

C. The success of particle physics experiments relies on innovative instrumentation and state-of-the-art infrastructures. To prepare and realise future experimental research programmes, the community must maintain a strong focus on instrumentation. ***Detector R&D programmes and associated infrastructures should be supported at CERN, national institutes, laboratories and universities. Synergies between the needs of different scientific fields and industry should be identified and exploited to boost efficiency in the development process and increase opportunities for more technology transfer benefiting society at large. Collaborative platforms and consortia must be adequately supported to provide coherence in these R&D activities. The community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels.***

Motivation

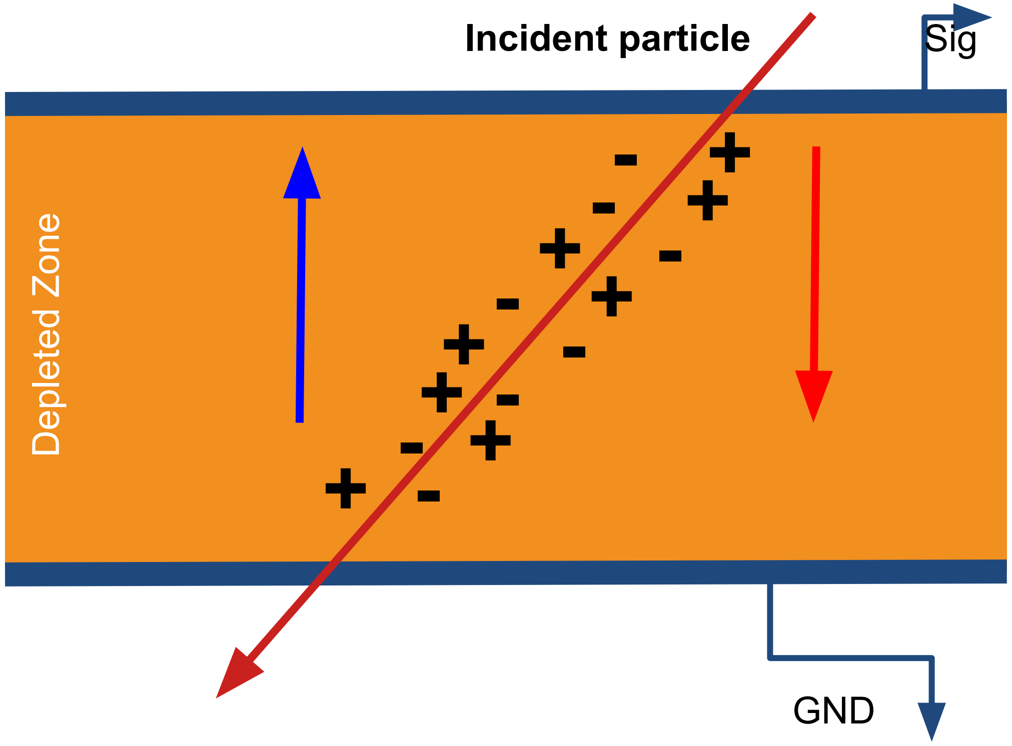
Future Lepton Collider & HL-LHC Upgrade

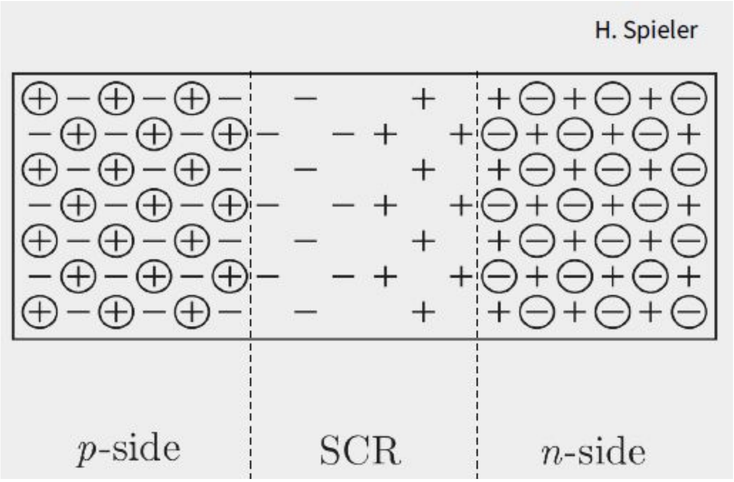
Silicon Detector Requirement

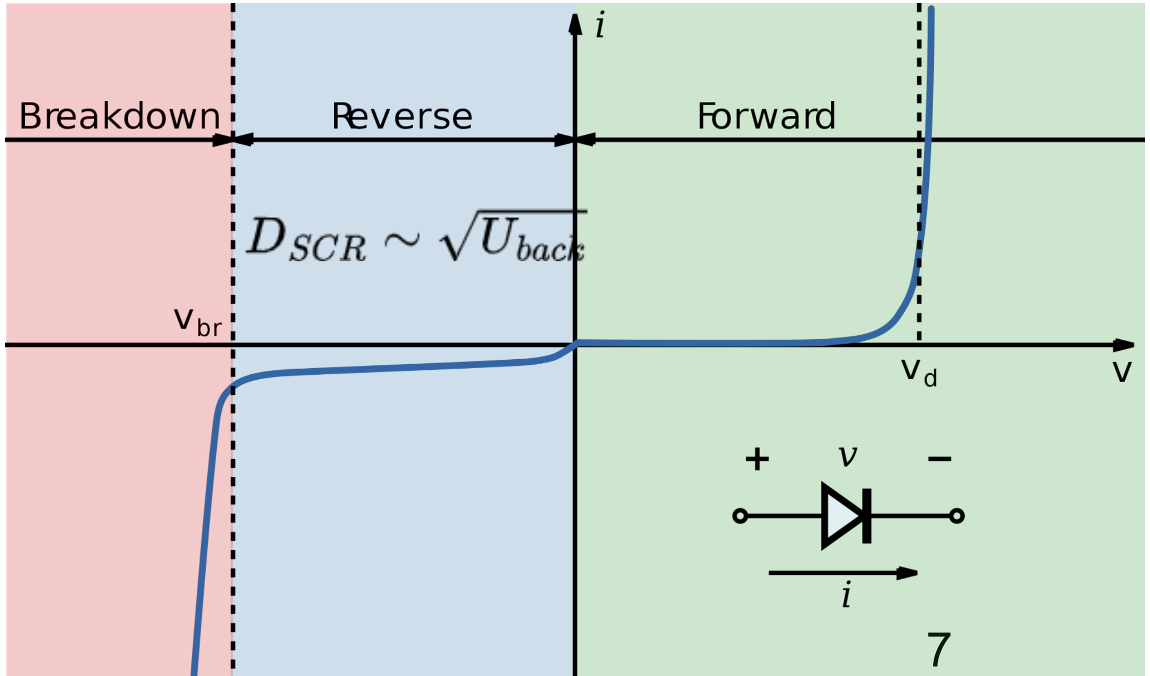
	Lepton Colliders	(HL-) LHC (ATLAS/CMS)
Material budget	< 1 % X_0	10 % X_0
Single-point Resolution	3 µm	~ 15 µm
Time Resolution	~ps - ns	25 ns
Granularity	< 25 µm x 25 µm	50 µm x 50 µm
Radiation Tolerance	< 10^{11} n_{eq}/cm^2	$0(10^{16}$ $n_{eq}/cm^2)$

Si Based Sensor

Introduction







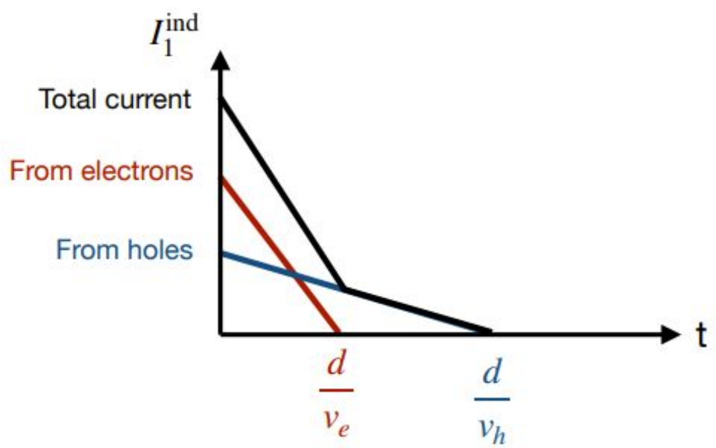
- **To reduce hole-electron recombination**
  - **Large signal**
- **To collects charges faster via E-field**

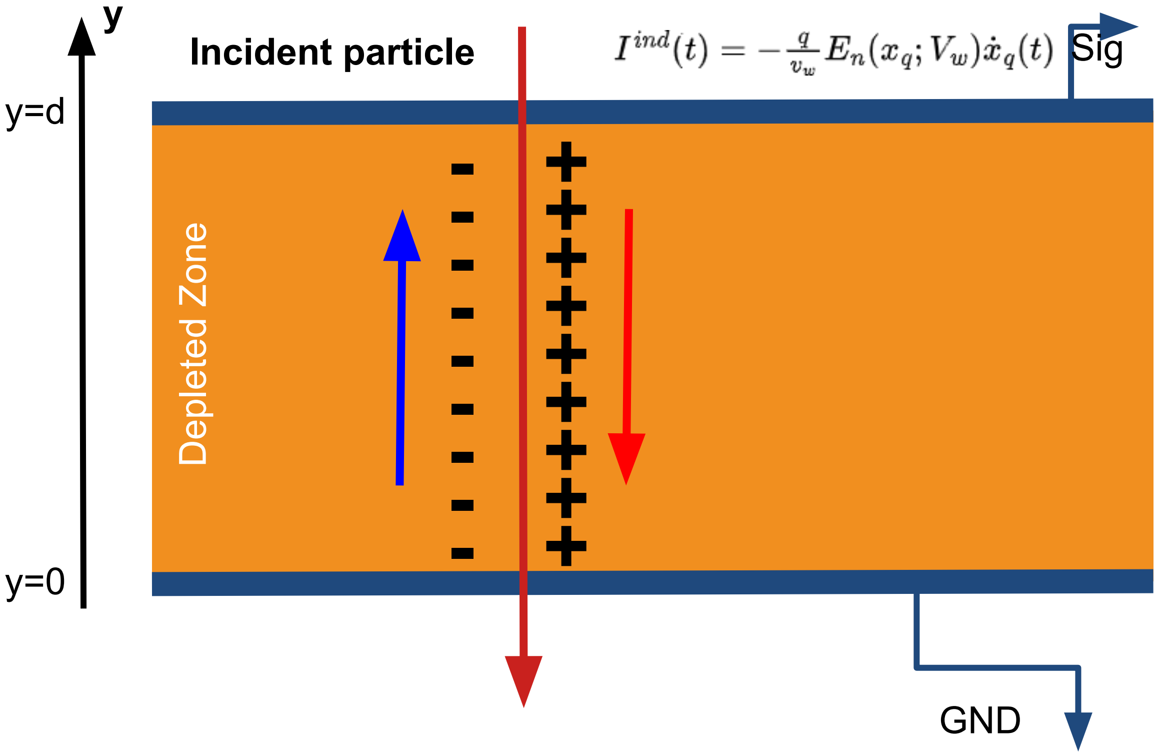
Ramo-Shockley Theorem

Signal - Simple Example

- Signal is proportional to weighting field of electrode and trajectory of the incident particle
  - Geometry of electrodes
  - Drift trajectories
  - Avalanche multiplication
    - LGAD, ELADs etc.
- A simple example : Diode
  - Weighting field for electrode

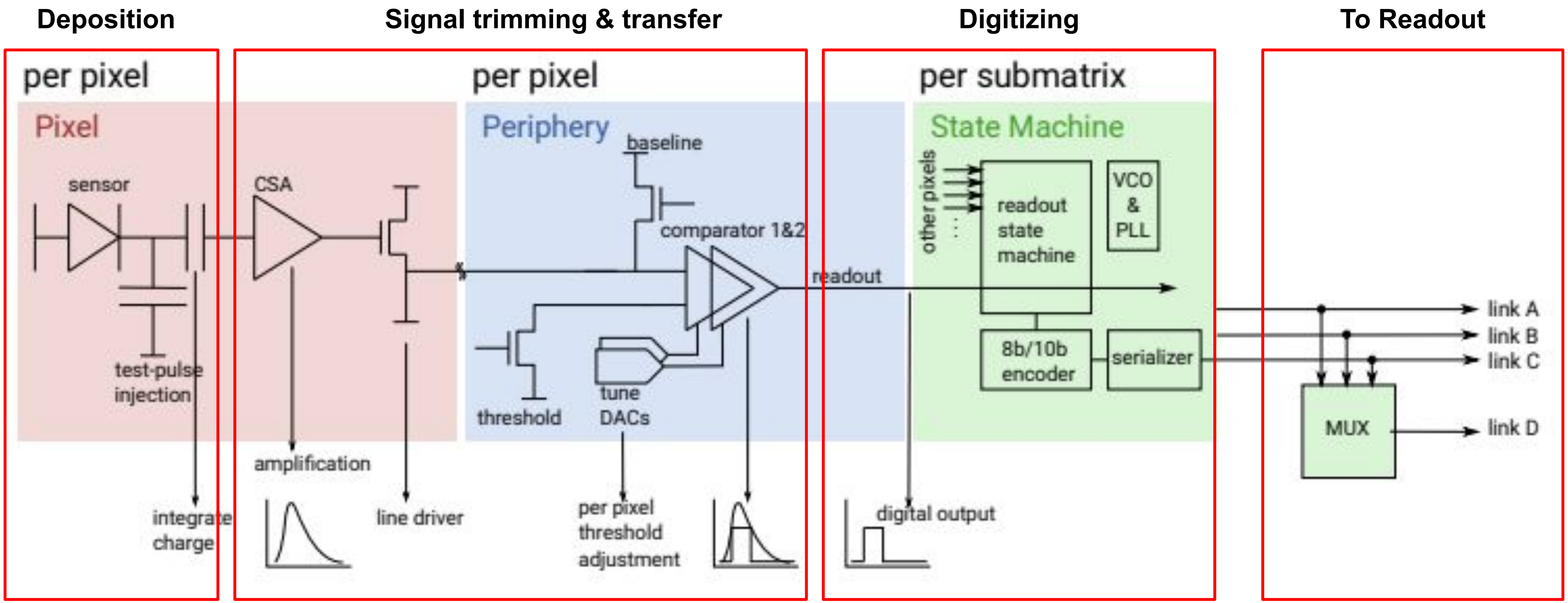
$$E = \frac{V_w}{d}\hat{y}$$





Data Acquisition Process

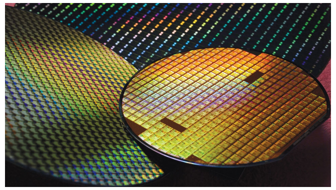
Signal Transfer and Digitizing



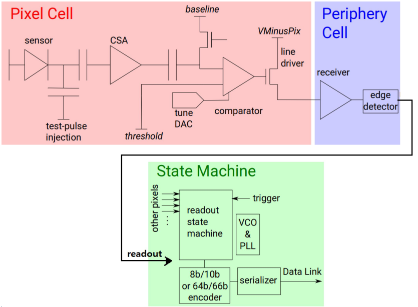
One of examples : MuPix10 Schematics

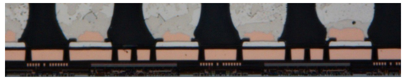
Si Based Tracker

Pixel Detector



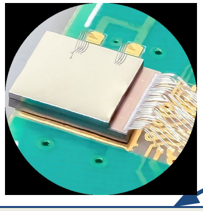
Silicon Pixel

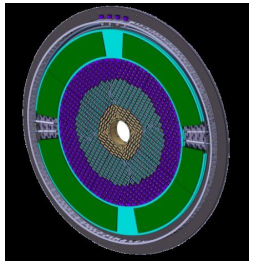


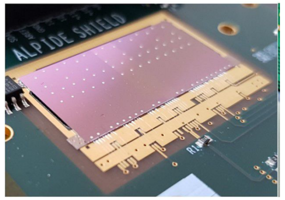


Hybrid Detectors

Monolithic Detector







Concentrate on Deposition

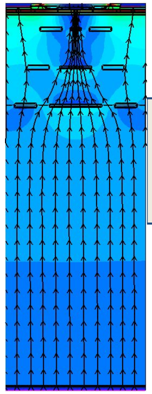
Concentrate on Devices

Planar Sensor

LGADs

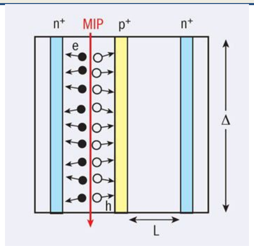
HV-CMOS

Low- Capacitance



ELADs

3D Sensor



Monolithic LGADs

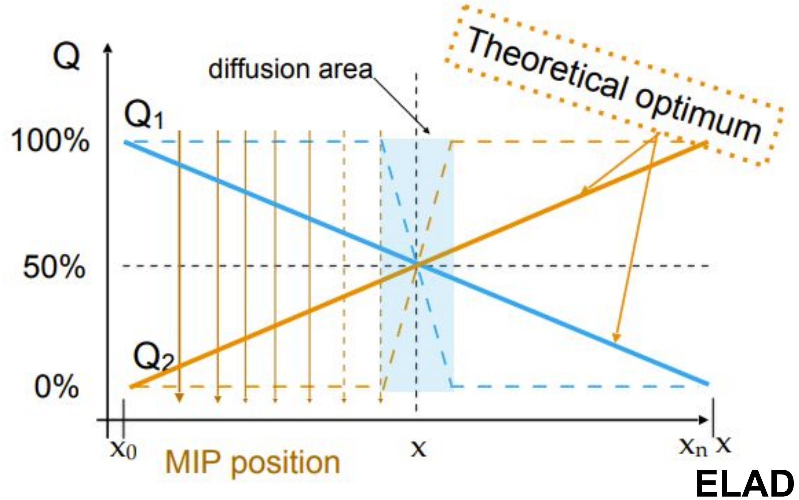
Main Goals

1. Spatial resolution
2. Time resolution
3. Low noise
4. Low material budget
5. Radiation hardness

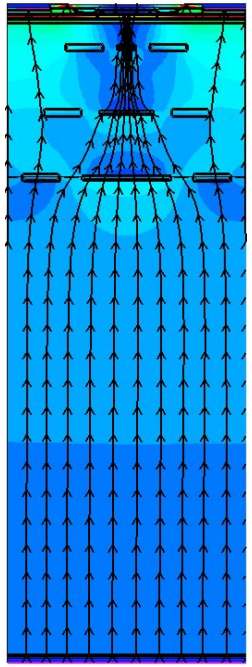
Charge Deposition

Concerning Large Signal and Electric Field

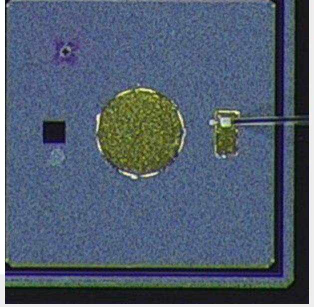
- Gain layer
  - High electric field causes impact ionization
  - Sub-nanosecond time resolution
  - Radiation hardness 2.5 x 10^{15} N_{eq}/cm^2 and 2 MGy
- Charge sharing
  - Position resolution in thin sensor limited to $\frac{\sigma_{pitch}}{\sqrt{12}}$
  - Enhance charge sharing
- Short drift time
  - Not reduce signal
  - High radiation tolerance

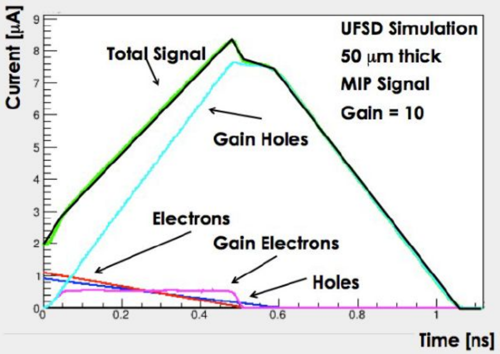


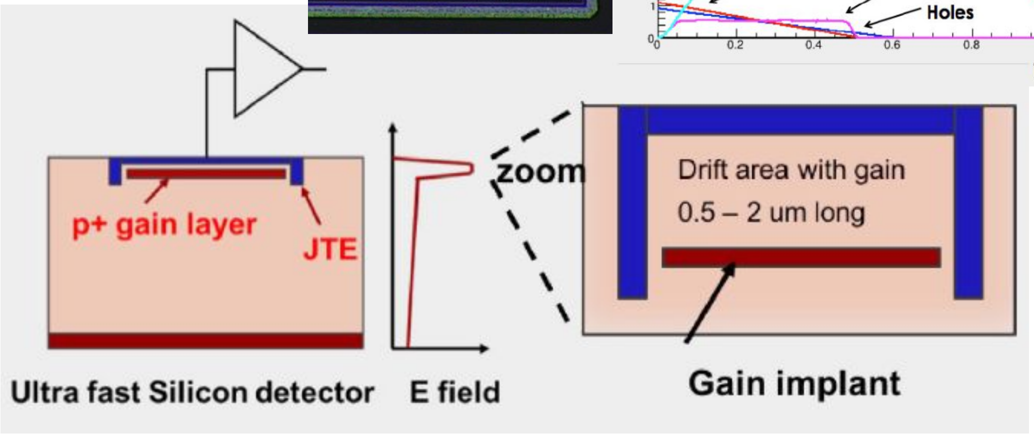
ELAD



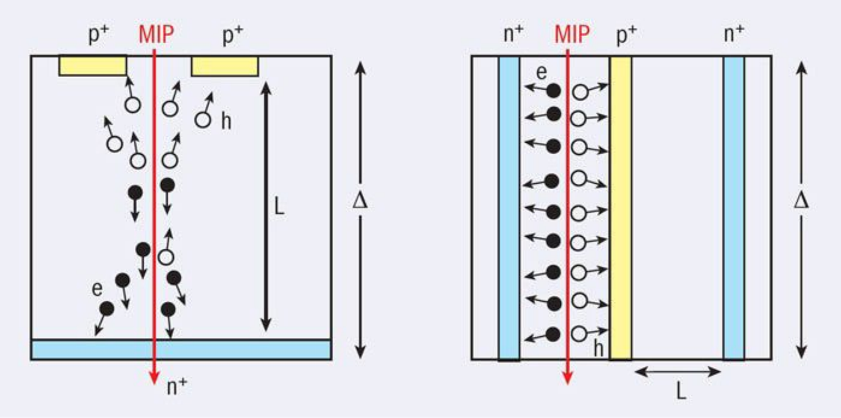
LGAD







3D Sensor

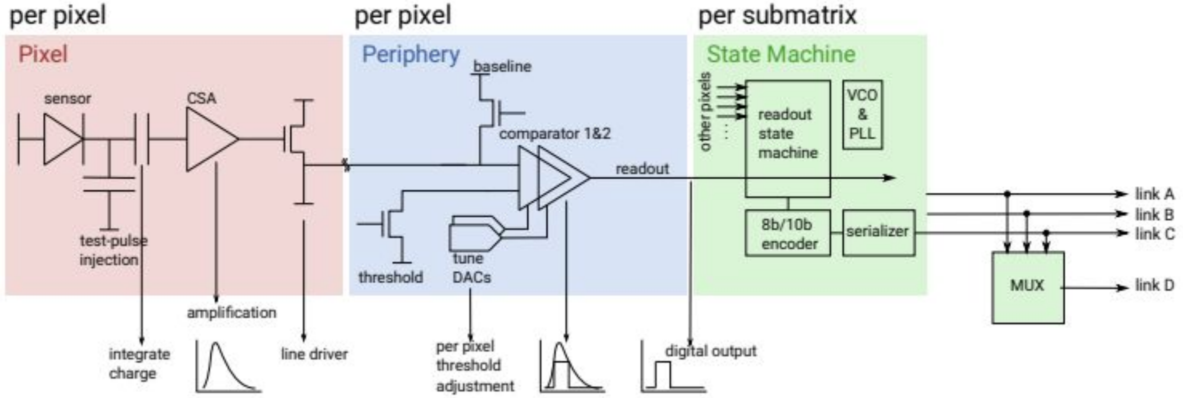


In-Pixel Devices

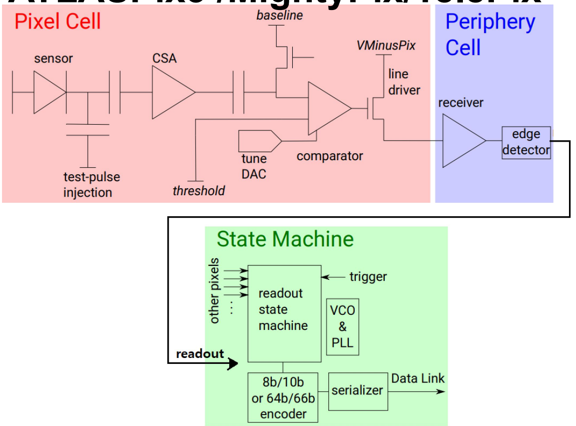
Concerning Material Budget and Capacitor

- Monolithic Active Pixel Sensor (MAPS)
    - Low capacitance : Low noise
    - Using high resistivity material for depleted zone
    - Standard CMOS imaging process
    - Possible small pitches
- High Voltage MAPS (HVMAPS)
    - High voltage extends depleted zone and increase drift
    - Nanosecond time resolution
    - Standard HV-CMOS imagine process
- Low material budget
    - Thin to 50 µm or much thinner
    - Small Multiple scattering
    - Possible to bend sensor

MuPix 10



ATLASPix3 /MightyPix/TelePix



HitPix

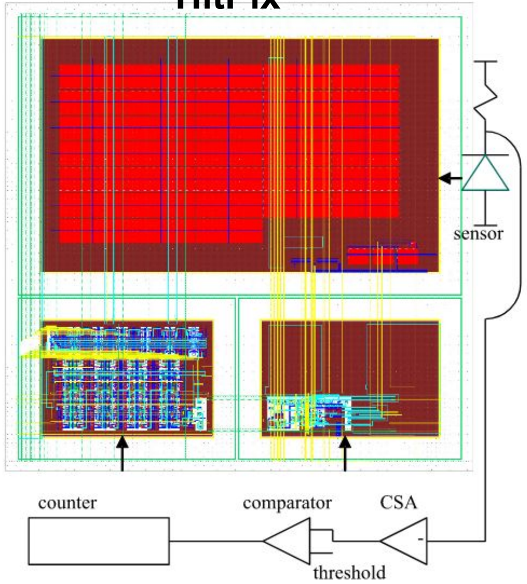
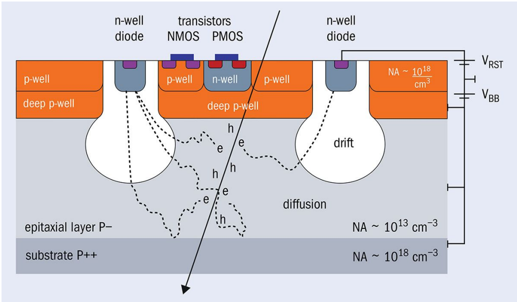
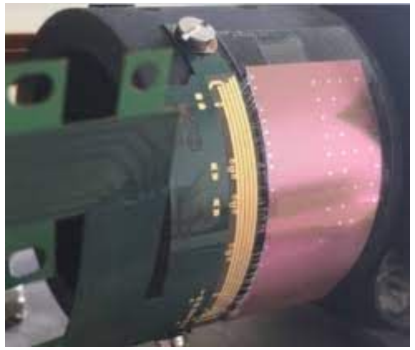


Fig. 3. Layout of the pixel with the three different parts, the sensor electrode (top), the digital (bottom left), and analog electronics (bottom right).

ALPIDE ITS 3

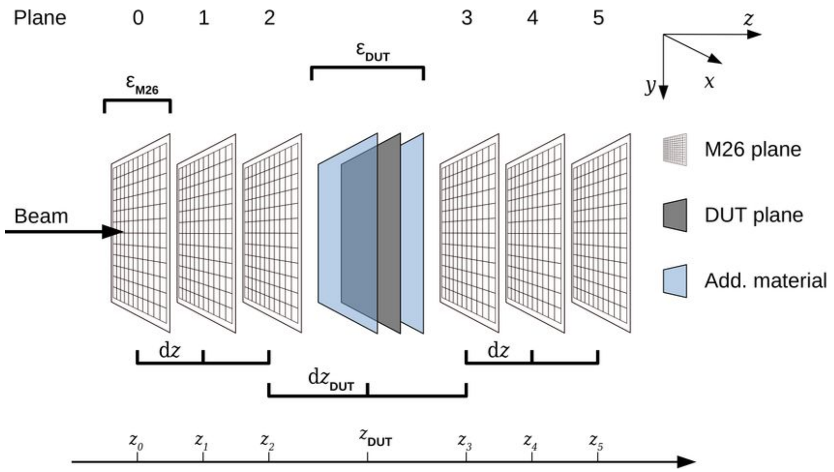




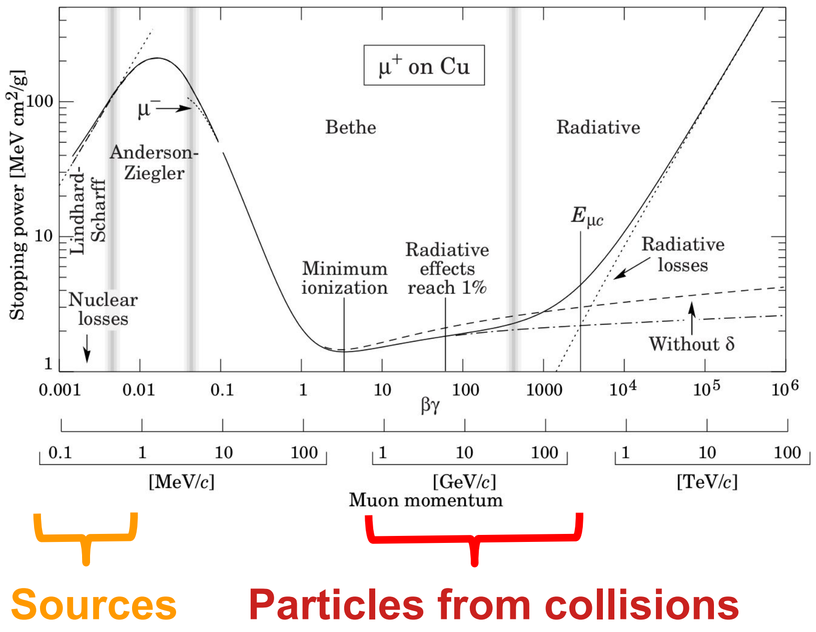
Introduction - Test Beam

Why a Test Beam?

- What is test beam campaign?
  - To verify the performance of sensors or devices using high energetic particle beam
  - Tracking using beam telescope
    - Enable to distinguish particle and noise
- In all above steps tests and evaluations are necessary of:
  - Performance: efficiency, noise, rate capability, stability …
  - Resolution: position, energy, time, …



- Energy has to be in the GeV range



- Sources: not enough energy
- Comics: too low rate per area (1/cm²/min)

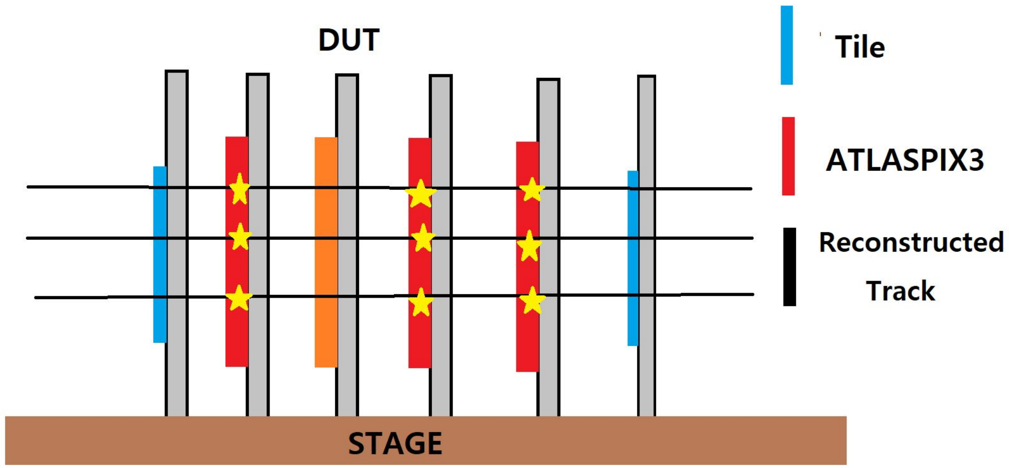
Introduction - Test Beam

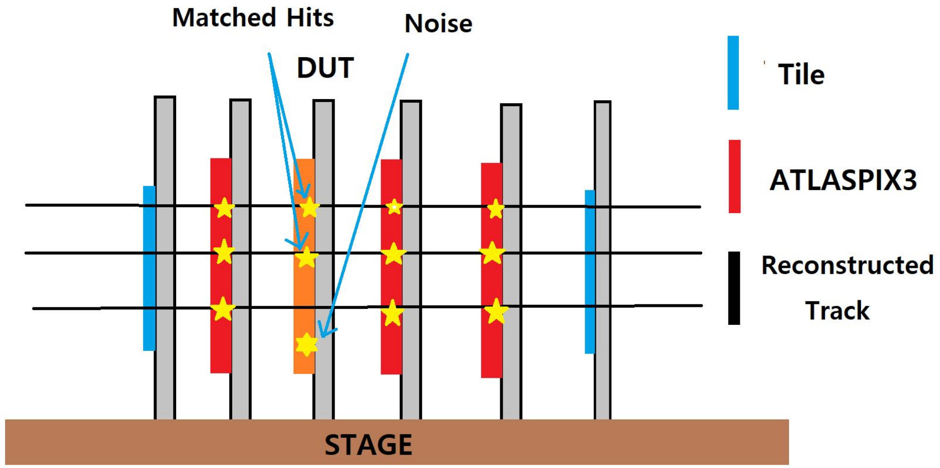
Telescope - Efficiency measurement

- Beam telescope
  - Consist of 3 or more reference layers, Device Under Test (DUT) layer and time reference layers optionally
  - Tracks are reconstructed only using reference layers
- Track efficiency
  - Linear fit using hits in reference layers
  - Reconstructed tracks are compared to hits in DUT layer
    - If matched : count as matched hit
    - If not matched : count as noise
  - Definition of efficiency

$$\epsilon = N_{\text{tracks associated with a hit}} / N_{\text{total tracks}}$$

  - Noise
    - Electric noise, scattering and inefficiency of telescope etc.





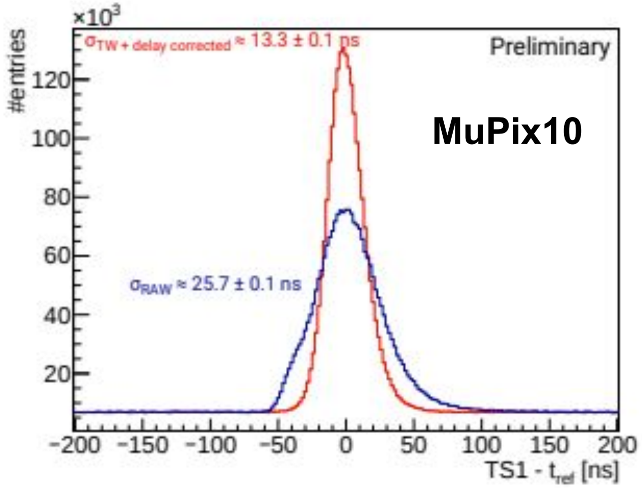
Characterizing

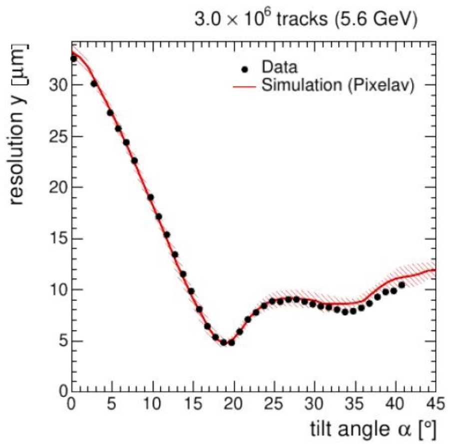
Spatial and Time Resolution

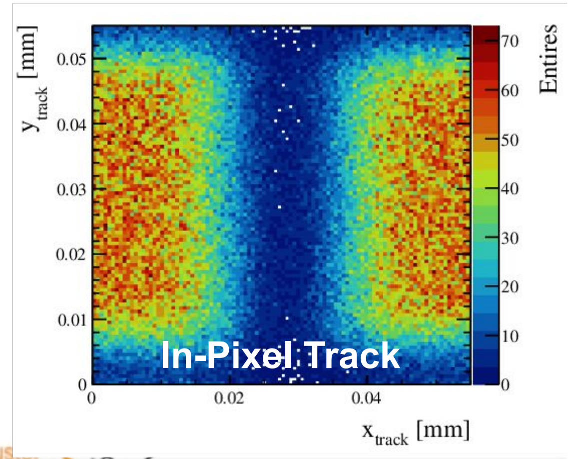
- Devices performance test
  - Amplifier, comparator, signal trimming etc.
  - It affects track efficiency, time resolution
- Time resolution is measured using Time reference layer
  - It contains a lot of parameters

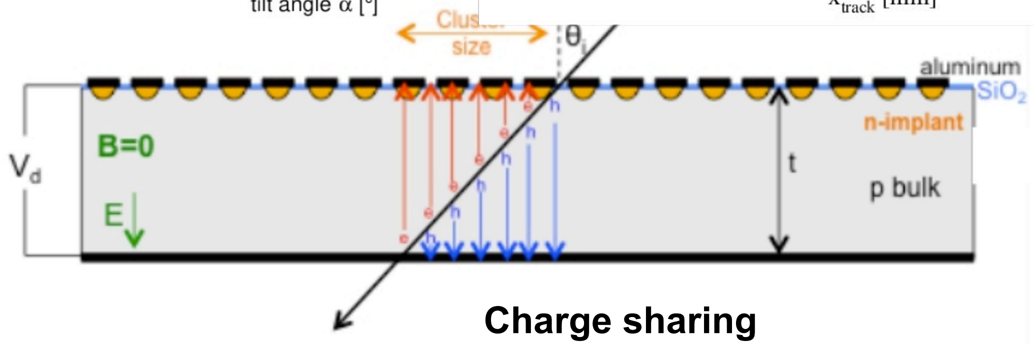
$$\sigma_t^2 = \sigma_{Jitter}^2 + (\sigma_{Noise} + \sigma_{total\ ionizing})^2 + \sigma_{distortion}^2 + \sigma_{TDC}^2$$

- Charge sharing improves spatial resolution
- Required in-pixel efficiency measurement
  - It depends on geometry, electric field

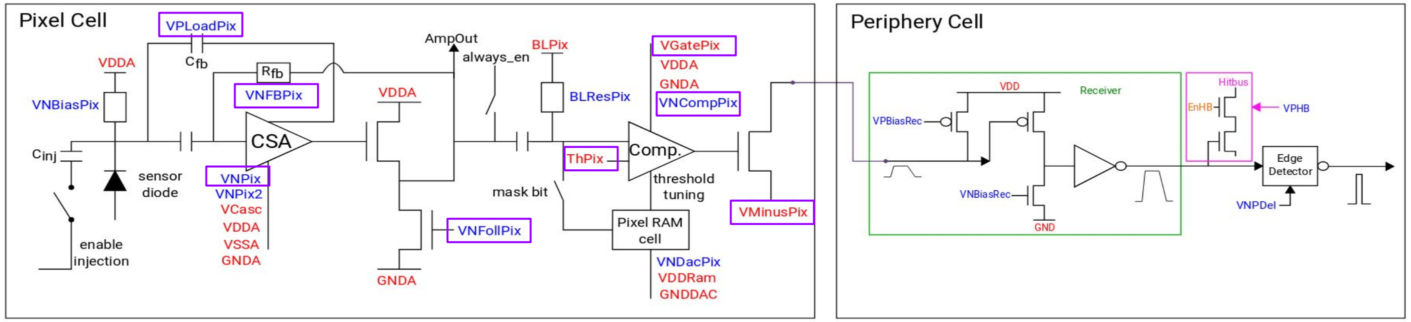








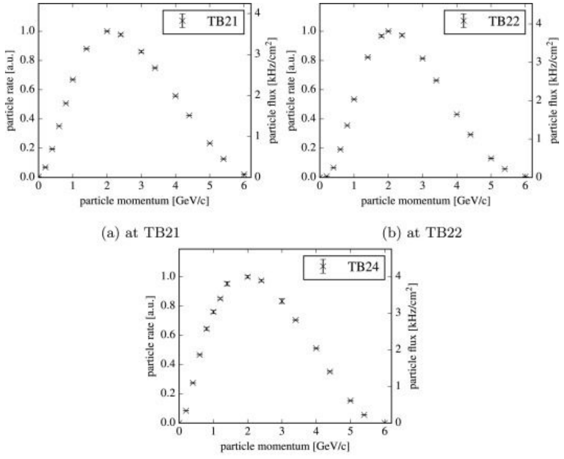
Charge sharing



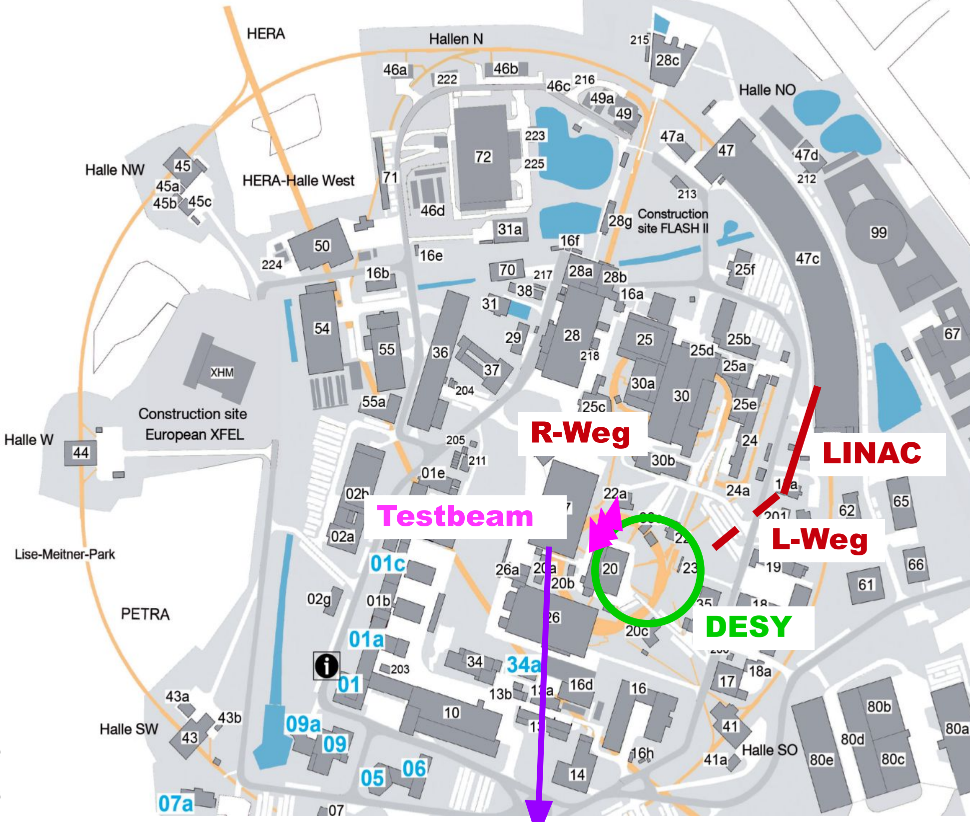
Facility

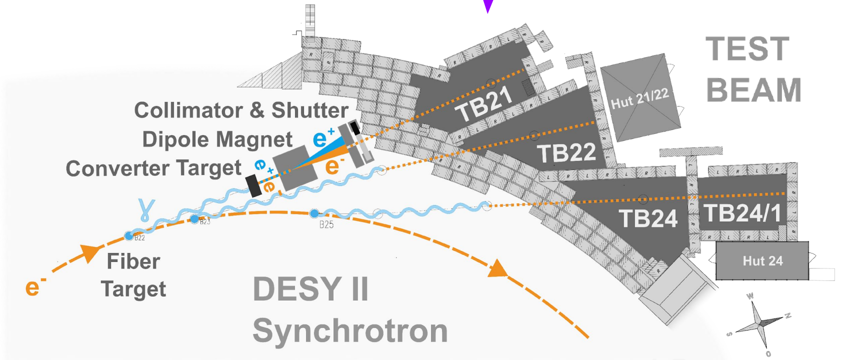
Overview and Beam Generation

- Testbeam facility parasitically uses beam for PETRA III
  - LINAC filles bunches to pre-accelerator DESY II
  - 1 MHz circulation frequency
- Target based beam generation at DESY II
  - Fiber target in the ring generates Bremsstrahlung photons
  - Gamma is converted to electron-positron pair
  - Dipole magnet selects beam type & energy
- Single electron energy up to 6 GeV selectable
  - Beam rate depends on beam energy
  - Limits rate to a few 10 kHz



(a) at TB21 (b) at TB22 (c) at TB24

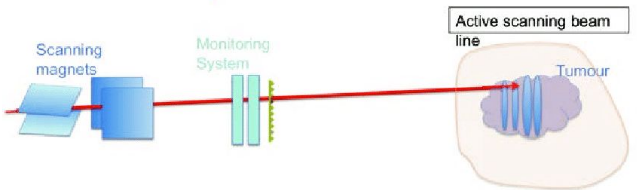


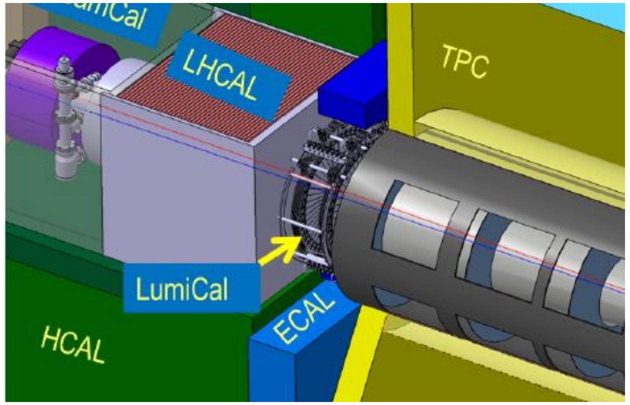


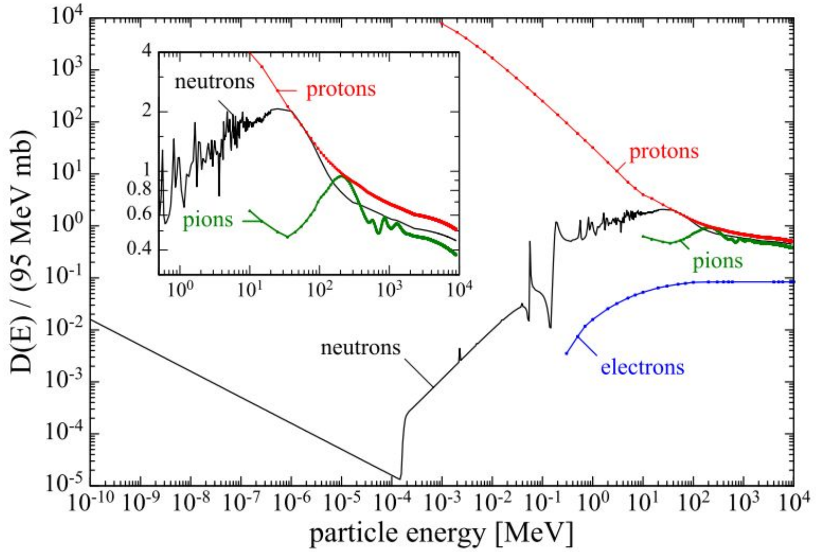
Motivation of High Rate Beam

More Powerful Beam & Irradiation

- A lot of tracks for precise measurement
  - In-pixel spatial resolution & pixel timing, material budget etc.
- To verify readout performances of sensors with high rate beam
  - A lot of experiments plant to use high rate beam
  - E.g. beam monitor, beam counter
- To irradiate sensors
  - LumiCal for ILC experiment
    - 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
    - e.g) ATLAS : Max. fluence of Layer 1 will be 1.4×10^{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 damages from the different type of particles



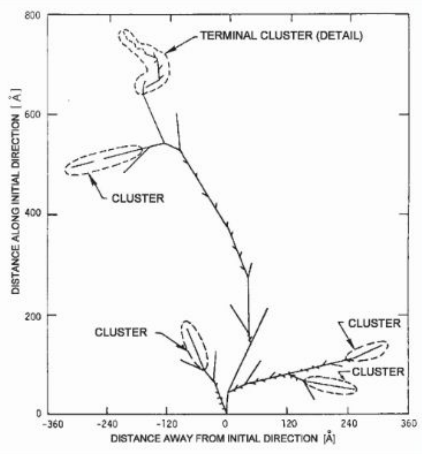




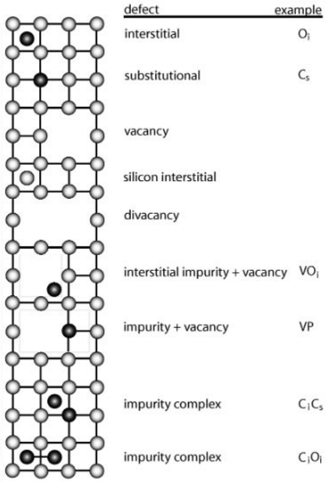
Irradiation Study

Bulk Damage

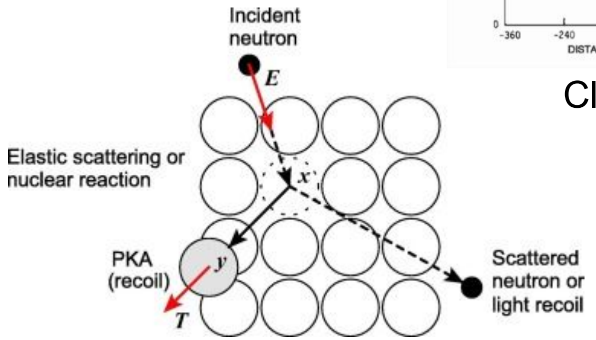
- Bulk damage
  - Non Ionizing Energy Loss (NIEL) or Total Ionizing Dose (TID)
  - Hadrons, higher energetic Leptons and gammas
  - Displacement in a pair of a Si interstitial
  - A vacancy in Si-lattice
- Bulk damage impact on detector
  - Determined by Shockley-Read-Hall statistics

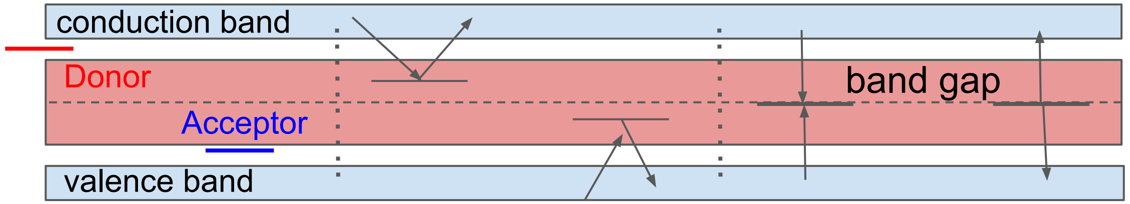


Cluster defect

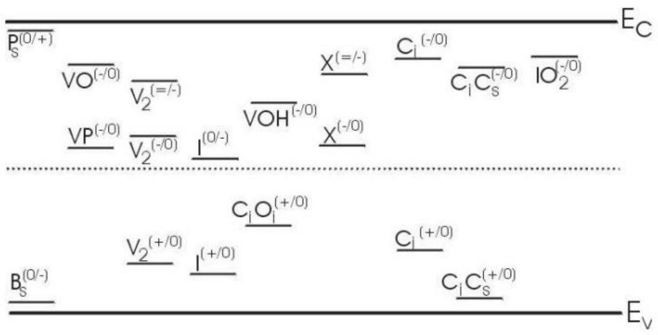


Single defects





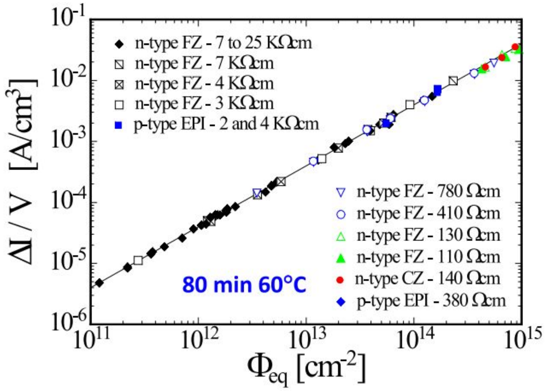
Donor & acceptor generation	Trapping	Generation & Recombination
■ Charged defects ■ Change of E-field	■ Deep defects ■ Signal drop	■ Current increase ■ Cooling helps to reduce

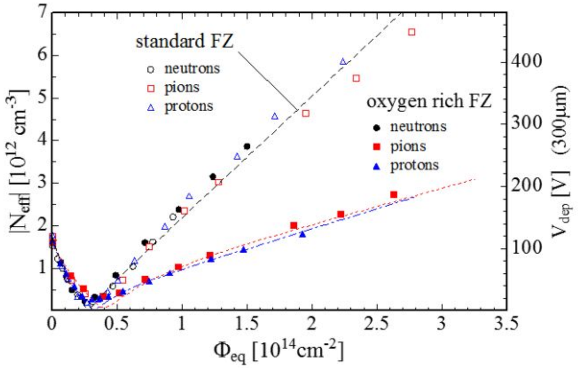


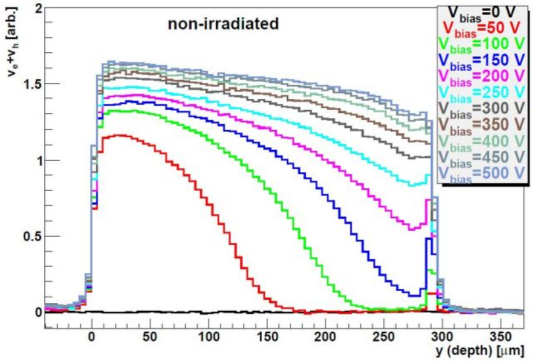
Irradiation Study

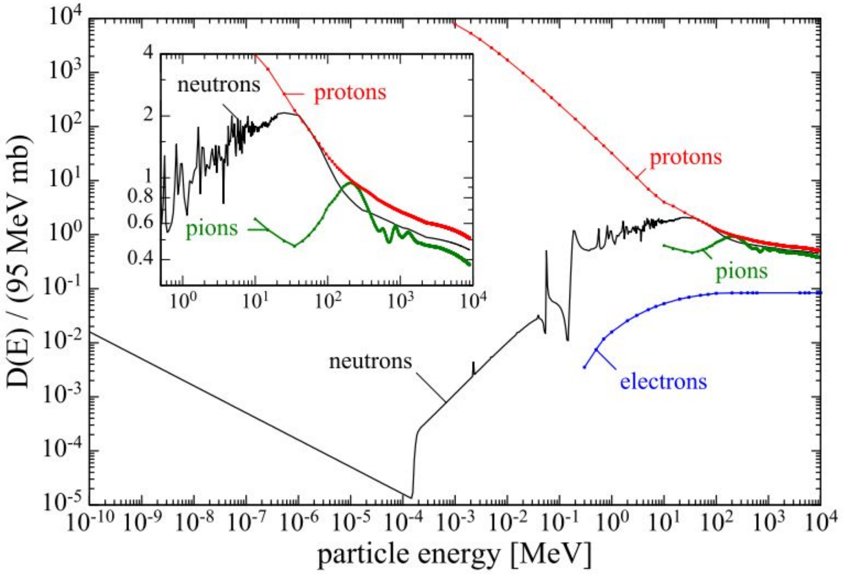
Effects

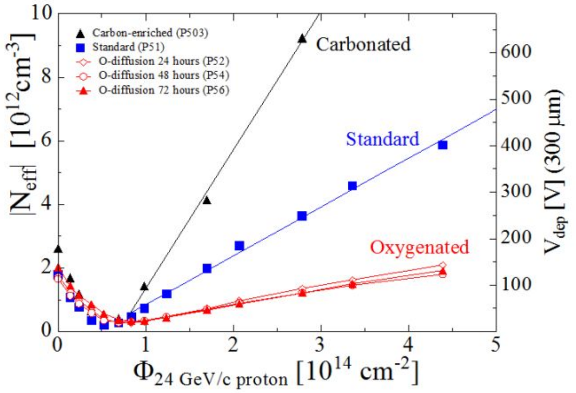
- Increase leakage current
- Conversion of effective Doping concentration
  - Depends on radiation particle
  - Depends on doping type and material
- Drift velocity in charge collecting diode is changed
- What happens in case of electron beam?

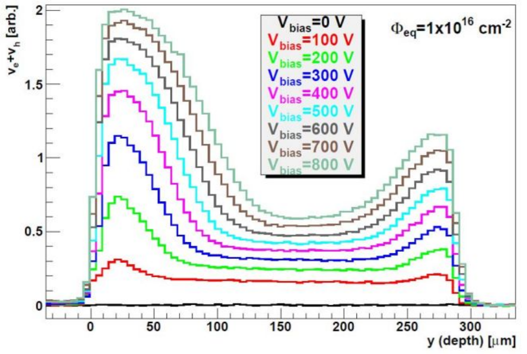








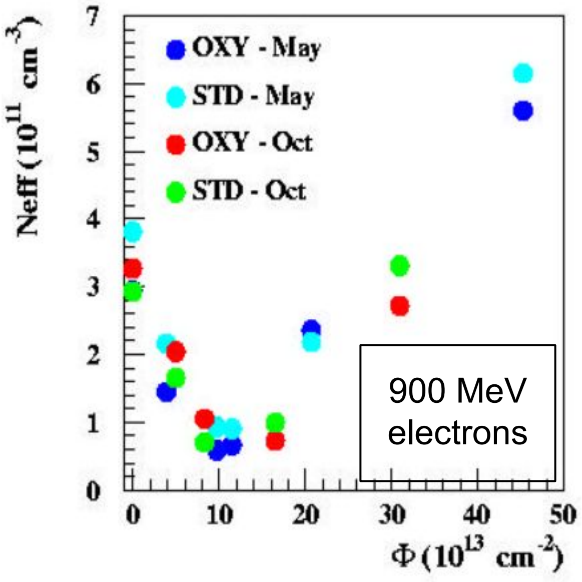




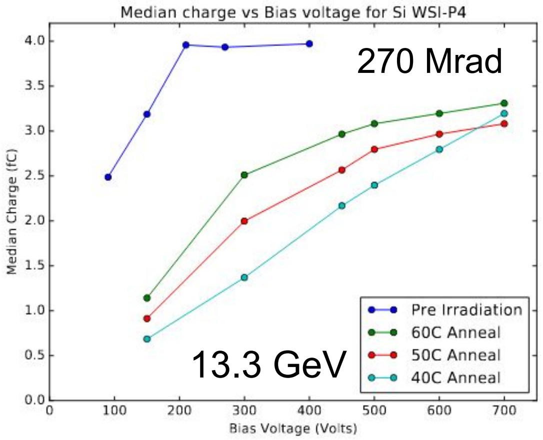
Irradiation Study

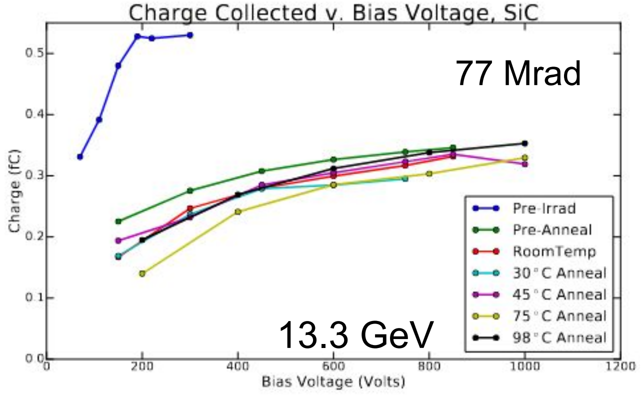
Electron

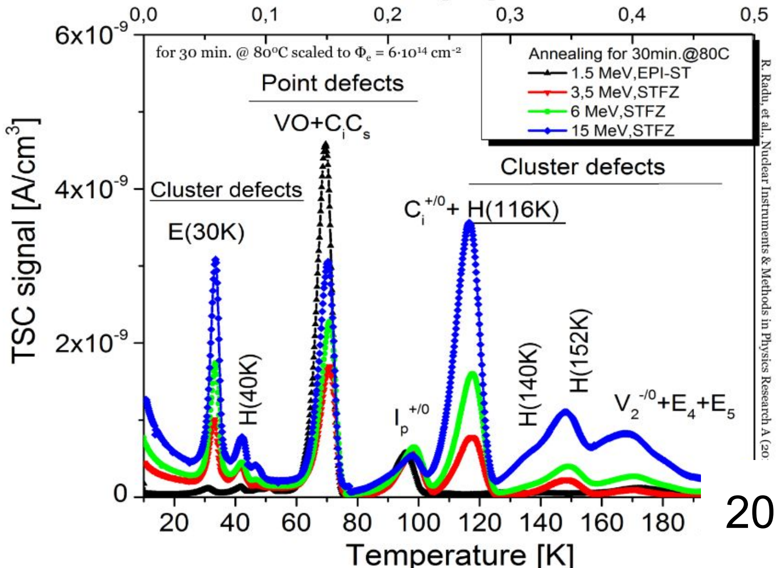
- There were few prior irradiation studies of Si-based sensor with rel. low energetic electron beam
  - There is no significant difference between oxygen riched and standard Si sensors
  - Cluster defects are increased by higher energetic electrons
- A irradiation campaign at SLAC for development of BeamCal
  - Si diode and SiC sensors are tested
    - ^{90}Sr source are used to measure the amplitude of deposited charges
  - Irradiation damages were observed
    - Amplitude of signal decreased after irradiation
    - Leakage current increases
  - But, there are any details



[S. Dittongo et al, NIM A 546(2005) 300]



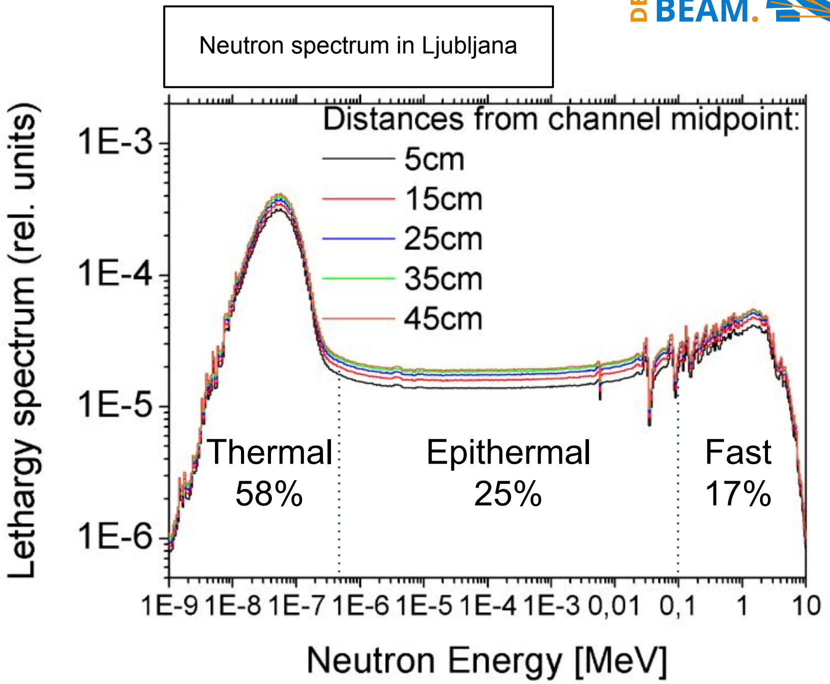


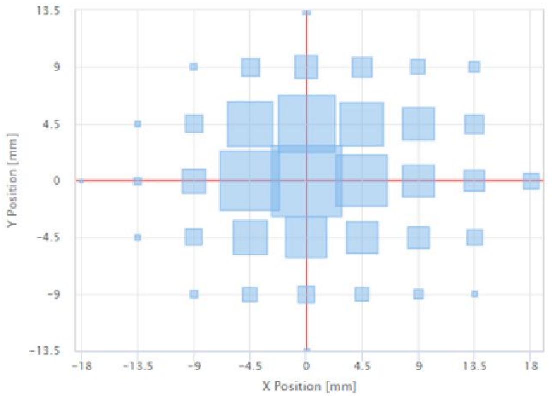


Irradiation Facilities

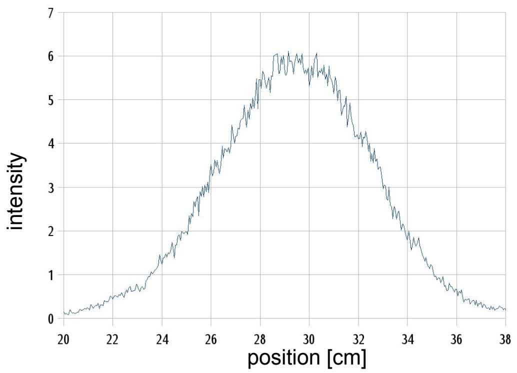
Neutron and Proton

- Neutron Irradiation facility in Ljubljana
  - Neutrons are generated by a reactor
  - ~ 10^{15} n_{eq}/cm^2 in 1 h 30 min.
  - Only Non-Ionizing Energy Loss (NIEL)
- Proton irradiation facilities using synchrotron
  - 24 GeV Proton beam at IRRAD, CERN
    - ~ 5 x 10^{11} p/spill (~400 ms)
  - 23 MeV Proton beam at KIT
    - ~ 5 x 10^{15} n_{eq}/cm^2 in 1h 30 min.
  - NIEL and Ionizing Energy Loss (IEL)
- Photon source or low energetic electron only for IEL
  - Photon with energy smaller than 300 keV
  - Electron with energy smaller than 255 keV





Beam profile at IRRAD

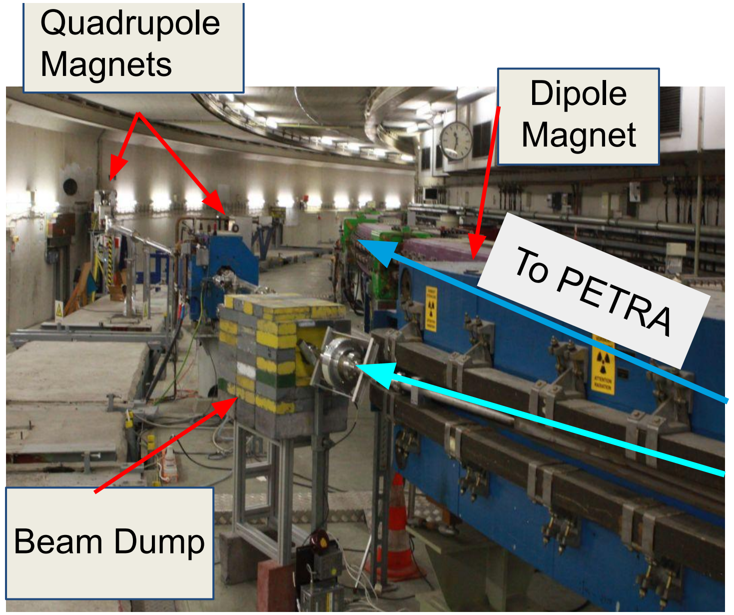


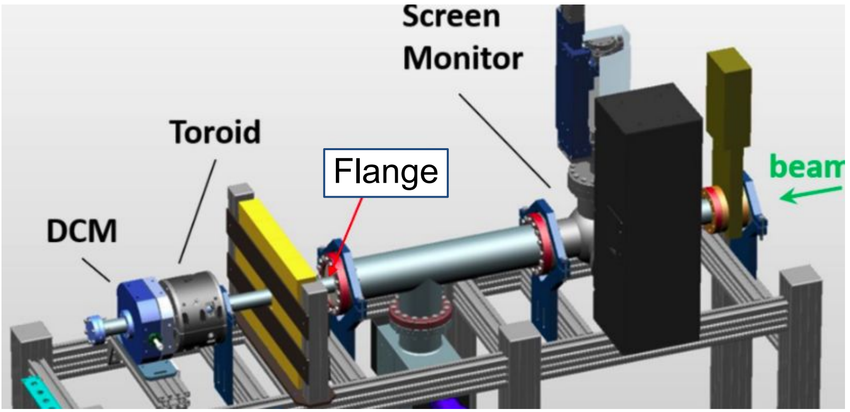
Beam profile at KIT

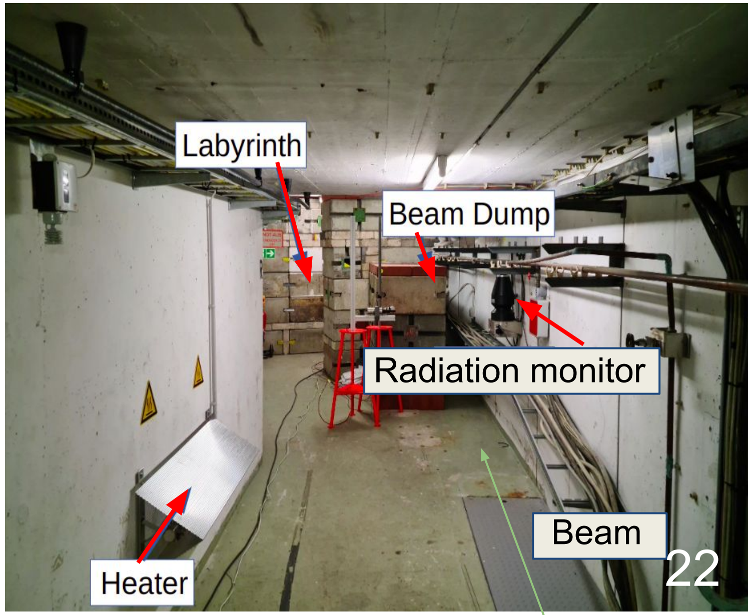
Irradiation Facility

PRIMary-beam test Area : PRIMA

- New facility, PRIMary-beam test Area(PRIMA), for irradiation using electron beam
  - Beam is filled into PETRA
  - If not, beam is dumped in DESY II
    - Dumped beam could be upcycled
- Important instrument in PRIMA facility
  - Dipole magnet extracts beam from DESY II into PRIMA
  - Quadrupole Magnets(QMs) to focus or defocus on beam
  - Toroid measures the number of beam through the beam pipe
  - Beam dump and Labyrinth
  - Radiation monitors : at beam dump and next to beam pipe
  - Heater to remove humidity



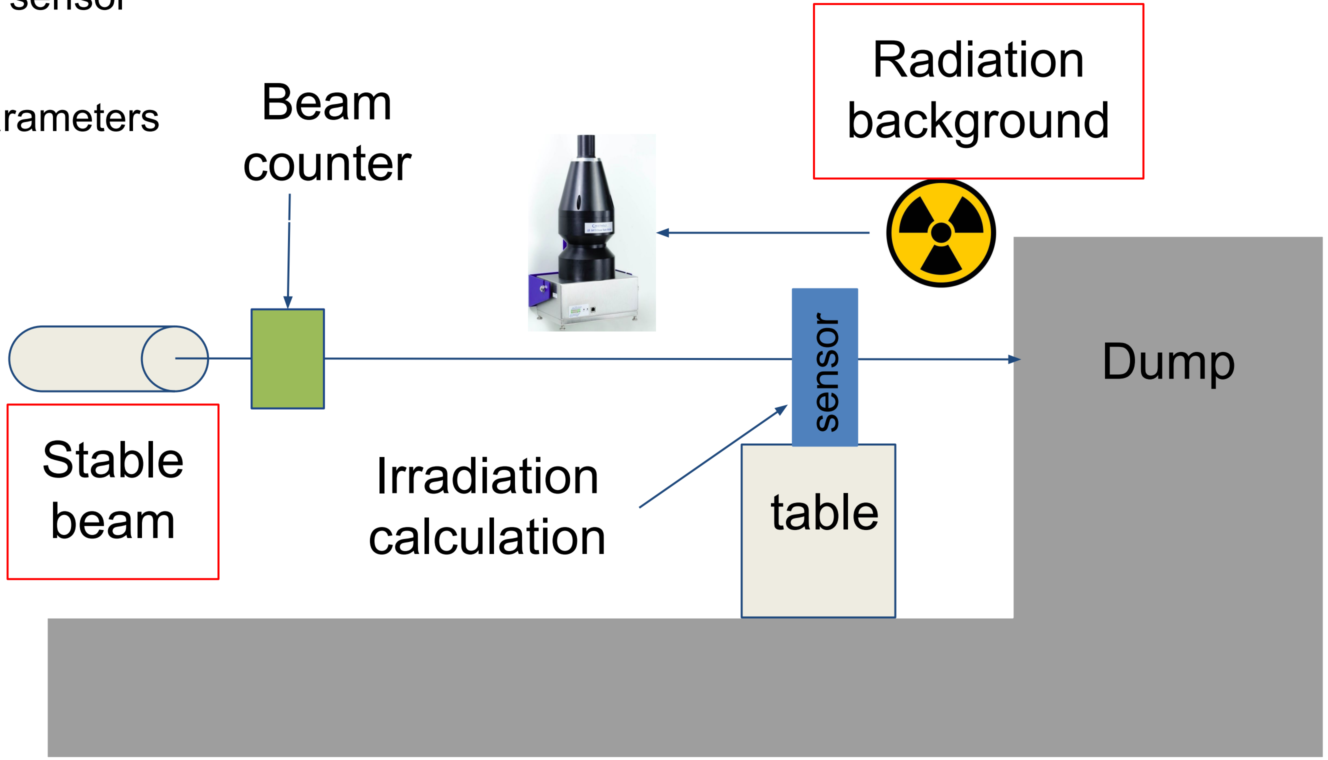




Required Study

For User

- Radiation background
  - For safety
    - Number of Neutron and Photon after extraction
  - Estimation of number of beam at the dump as beam counter
  - To reduce radiation damage to devices except the sensor
- Beam stability
  - Fluctuation of mains Frequency changes beam parameters
  - Beam size, position and divergence
  - Quadrupole magnets have to be optimized
- Beam counter
  - Using Toroid



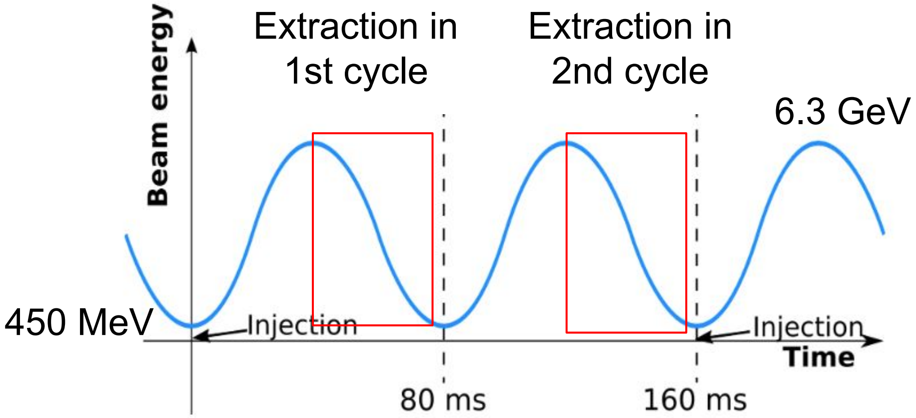
Beam Operation in PRIMA

Beam Profile

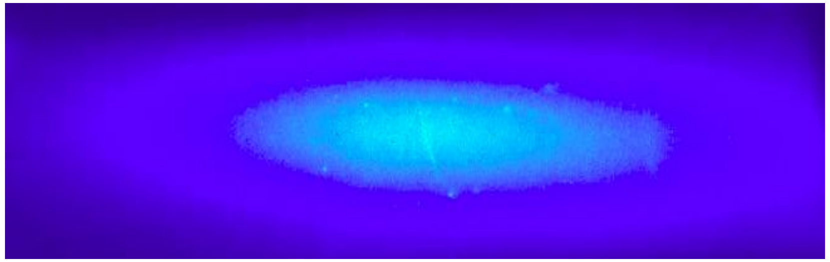
- Beam
  - Number of electrons in bunch depends on the injection
    - Up to 3×10^{10} e / bunch
    - Possible < 1×10^{5} e / bunch
    - Bunch length smaller than 100 ps
    - Repeated frequency of 6.25 Hz
      - It can be upgrade to 12.5 Hz
    - Beam energy oscillates like sin(x) between 450 MeV to 6.3 GeV

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

  - Beam size is expected smaller than 1 cm x 1 cm in DESY II ring



Current beam with energy of 500 MeV measured with beam camera

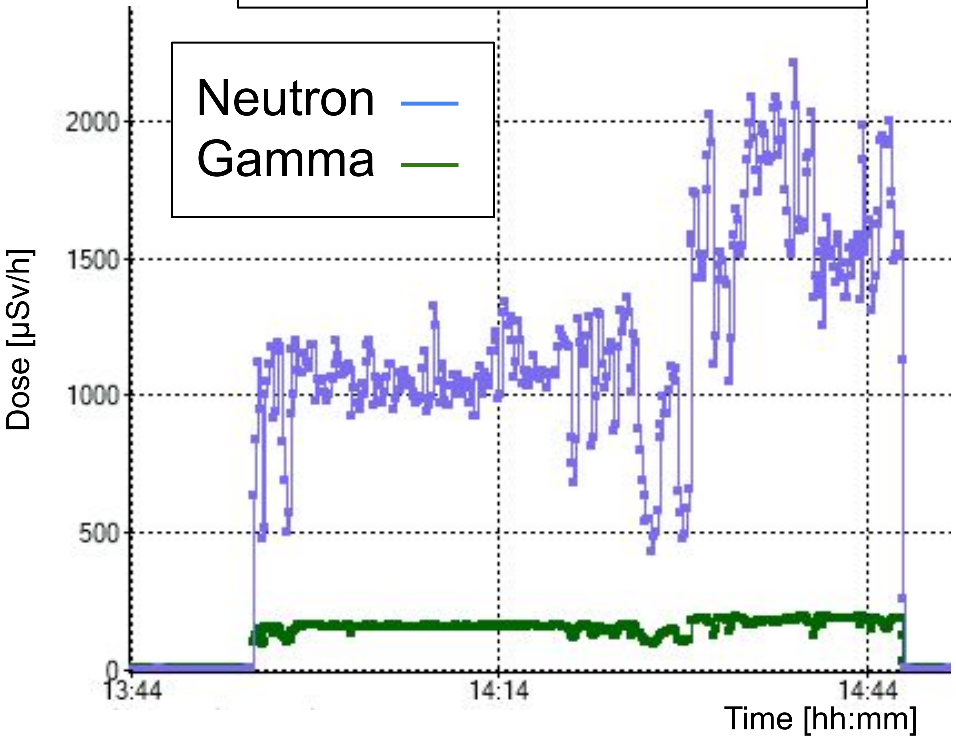


Measurement

PANDORA - Radiation Monitor

- Radiation background
  - Neutron and photon are generated
    - Resonance of photonuclear reaction
  - Mostly from beam dump
  - Large size of beam and unstable beam generate background too
  - Not only safety, but also to shield devices to neutrons
  - Beam stability can be estimated
    - Dose is proportional to # electrons
- PANDORA
  - Scintillator
    - Gamma > 50 keV
    - High energetic neutron > 20 MeV
  - Moderated ^{3}He tube
    - Low energetic neutron < 20 MeV

PANDORA Measurement



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 → ^{12}C + β + ν
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

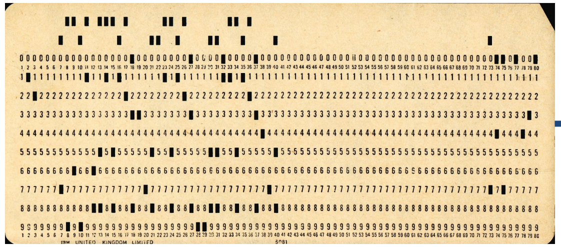
Table 1 – Overview of the LB 6419 responses due to neutron radiation.

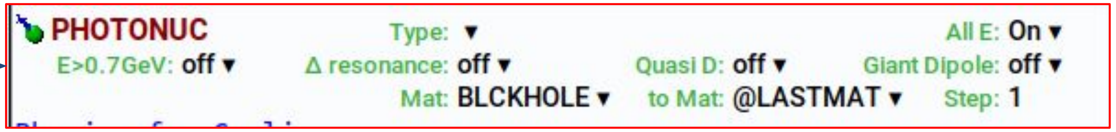
Nuclear Science Symposium Conference Record, 2007.
Volume: 3, Pages: 1982 - 1983

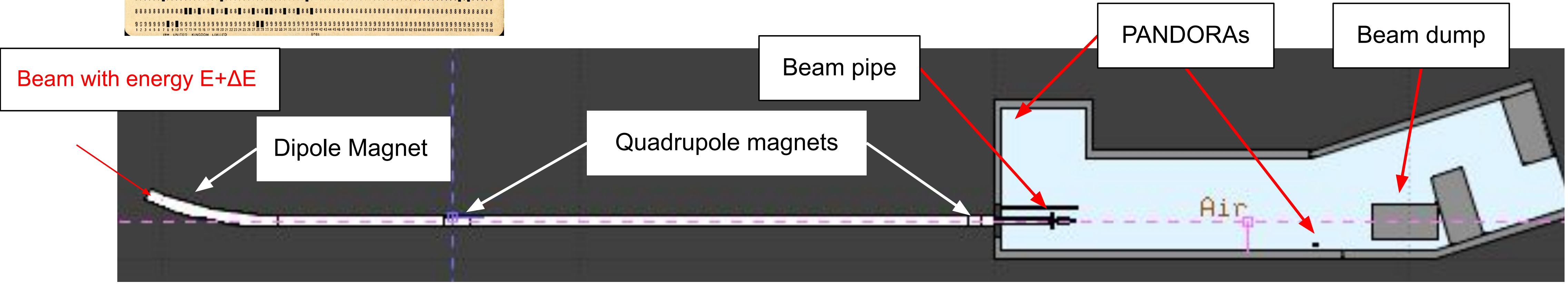
Simulation and Model

FLUKA

- FLUKA is MC framework for the interaction and transport of particles in materials
  - It is based on punching card system and Fortran
  - Eq-Dose of generated Photon and Neutron can be calculated
  - Movement of Particles passing through magnets is observable
- Extraction Magnets, Beam line and facility are integrated into the FLUKA geometry
- Beam Extraction model
  - Δt_{ext} is proportional to error of mains frequency
  - Current of dipole magnet depending only on beam energy is constant
    - Extracting angle depends on the beam energy due to Lorentz force



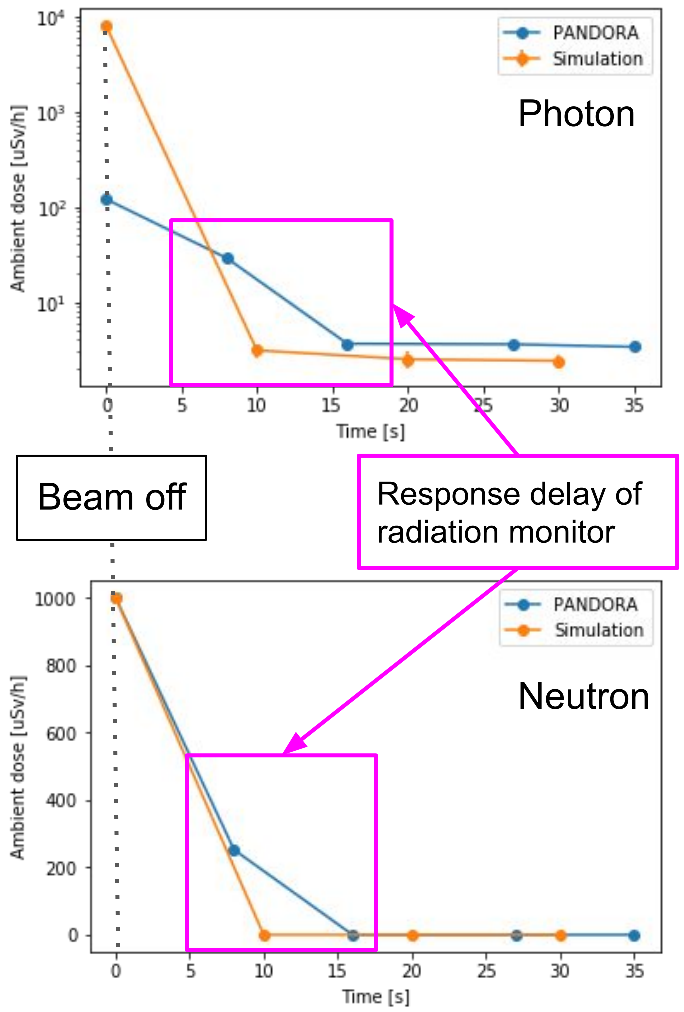




Radiation Background

Simulation and Measurement

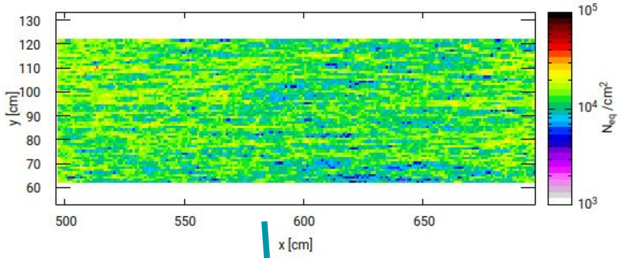
- Detectability of Photon is saturated
  - Too high rate
- For safety
  - Beam-time : Not allow to enter into the area
  - After beam time
    - Electron and Neutron disappear immediately
    - Activated material emits gamma
  - User should take a dosimeter

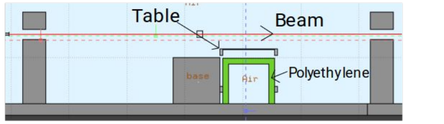


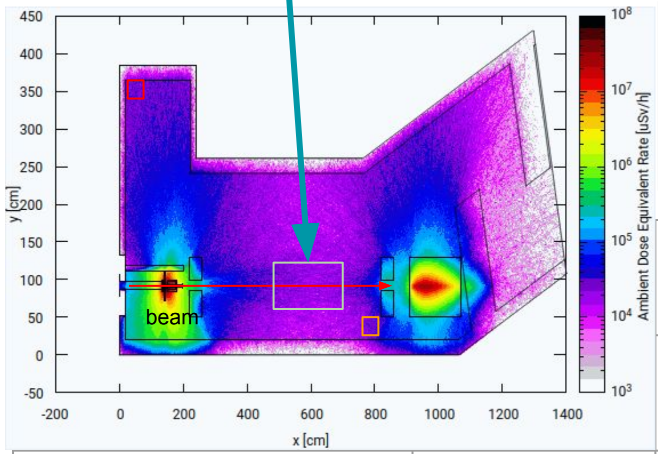
Radiation Background

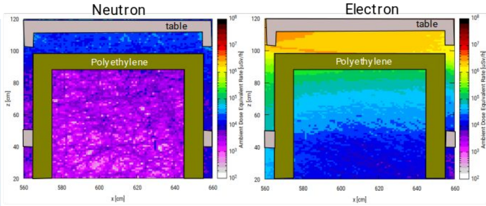
Simulation and Measurement

- Detectability of Photon is saturated
  - Too high rate
- For safety
  - Beam-time : Not allow to enter into the area
  - After beam time
    - Electron and Neutron disappear immediately
    - Activated material emits gamma
  - User should take a dosimeter
- To reduce neutron damage in DUT
  - Labyrinth is installed between beam pipe and dump
- To reduce damage in devices
  - Safety zone is found using simulation







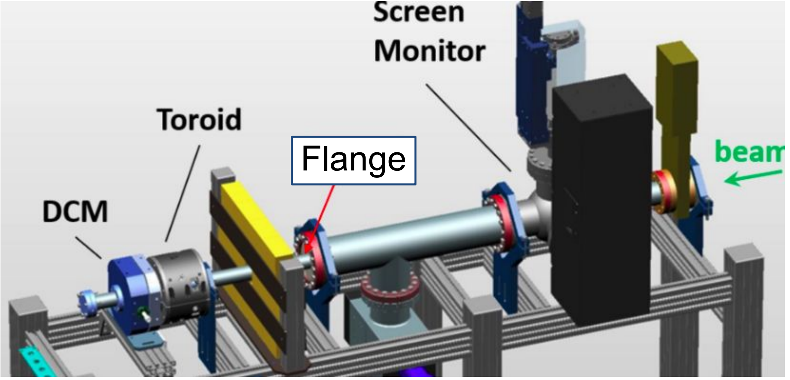


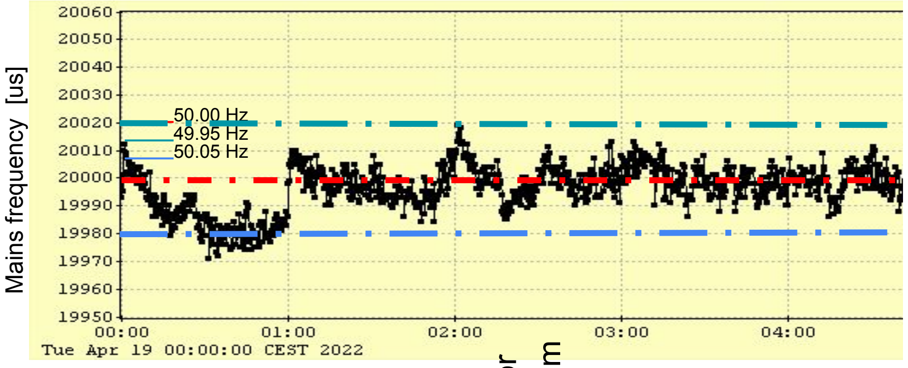
12E9 per bunch with 6GeV

		Beam loss of 10% at the flange 500 MeV Beam	Without beam loss 6 GeV Beam
		6.25 Hz, 2×10^9e / bunch	6.25 Hz, 7×10^9e / bunch
Simulated Dose [μSv/h]	Photon	7935± 15	13930 ± 105
	Neutron	1000 ± 40	21315 ± 735
Measured Dose [μSv/h]	Photon	~160	~900
	Neutron	~1000	~22000

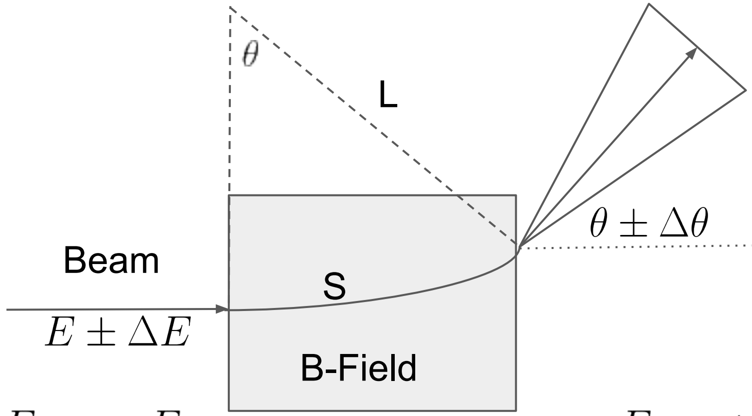
Beam Stability

Beam Position and Size





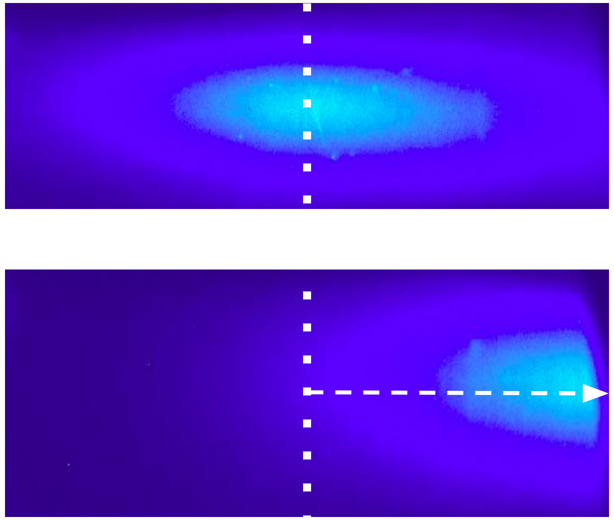
- Mains frequency synchronizes all magnet system at DESY II
  - Its fluctuation correlates beam stability
  - Uncertainty of extracting time ~ extracting angle
    - It causes change of beam position and beam size
    - Increases unexpected hit to materials at beam pipe
    - Radiation background is changed



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

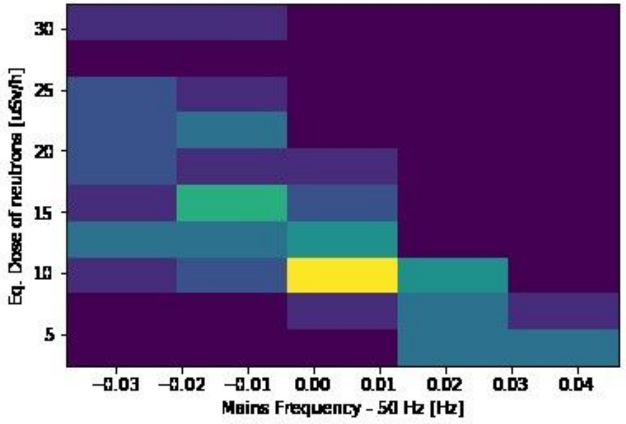
$$B[T] = \frac{E[GeV]}{0.3S[m]}\theta \rightarrow \frac{\Delta\theta}{\theta} = \frac{\Delta E}{E}$$

Current beam with energy of 500 MeV measured with beam camera



Correlation for 500 MeV beam

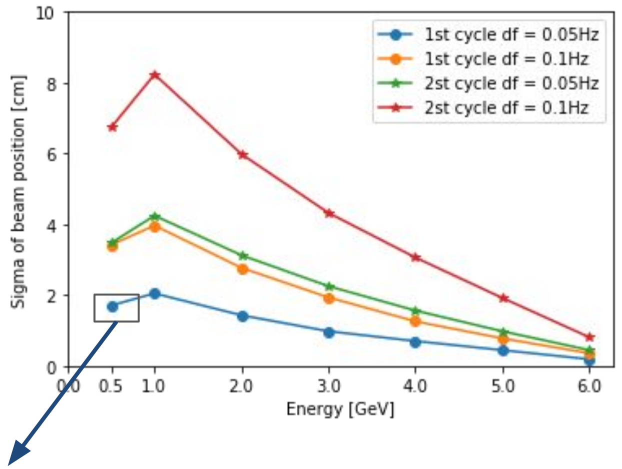
$\Delta t_{ext} \sim \Delta E \sim \Delta\theta$

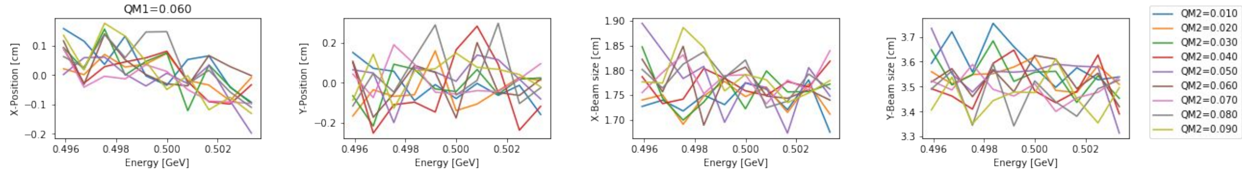


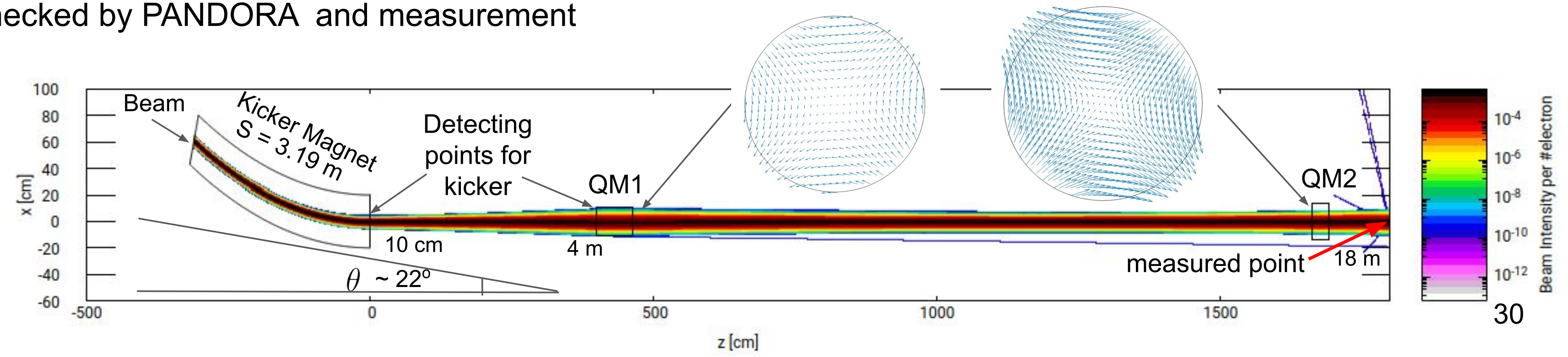
Beam Stability

Beam Position and Size

- Mains frequency synchronizes all magnet system at DESY II
  - Its fluctuation correlates beam stability
  - Uncertainty of extracting time ~ extracting angle
    - It causes change of beam position and beam size
    - Increases unexpected hit to materials at beam pipe
    - Radiation background is changed
- Quadrupole magnets would make beam stable
  - Beam position offset depends on extracting energy
    - 6 GeV is stable
  - A example : 500 MeV
    - QM1 could correct the beam position
    - It can be checked by PANDORA and measurement

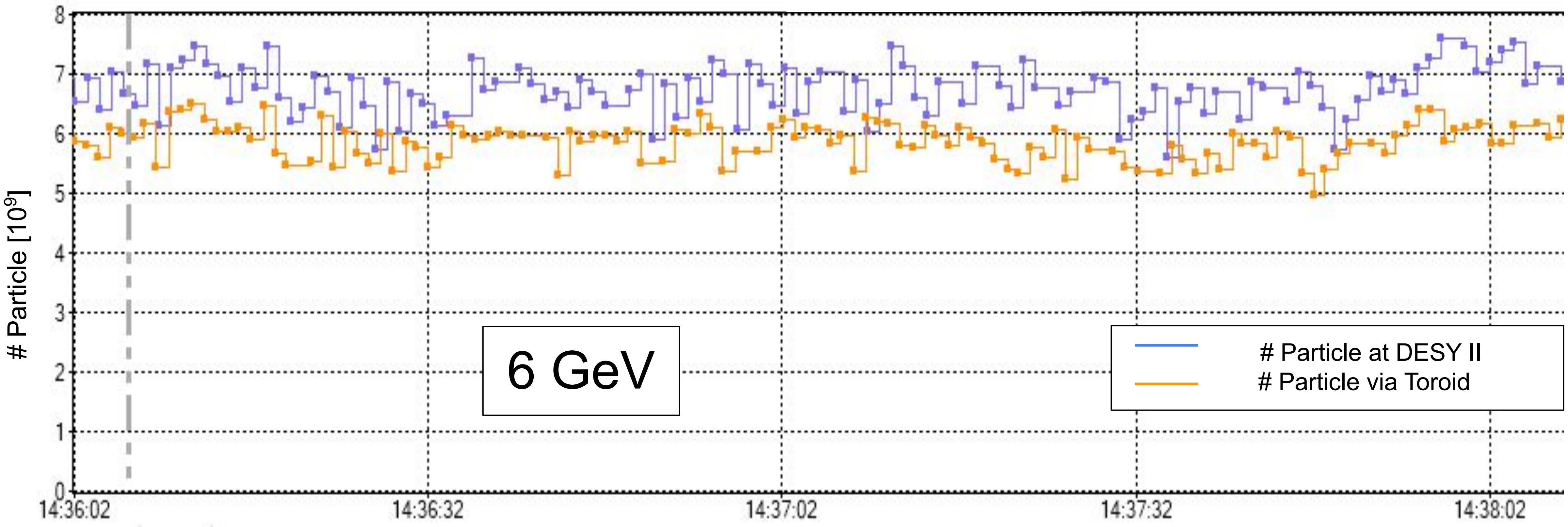






Beam Stability

Beam Position and Size



Summary

FuTure Experiment

- Si sensor R&D as tracker for Future experiments
  - For Timing, spatial resolution : 4D Tracker
  - Low material budget
  - Electronics and Readout
- Test beam is an important campaign for sensor R&D
  - DESY is one of big facilities
  - New test beam facility will be open for users
    - High rate beam
    - Irradiation
  - New facility could provide other particles to users

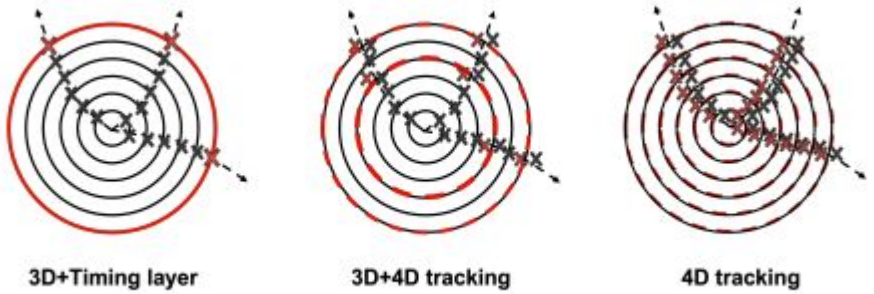
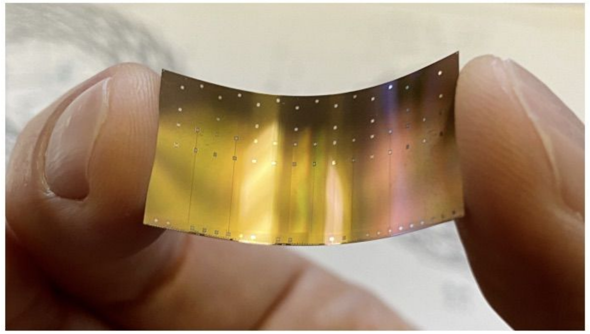
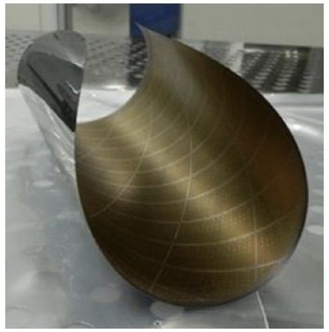
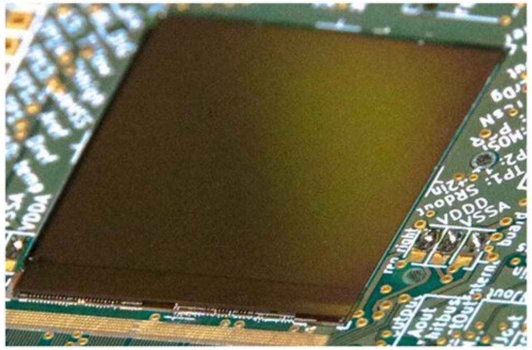


Figure 2: Possible implementations of a tracker system with timing capability.





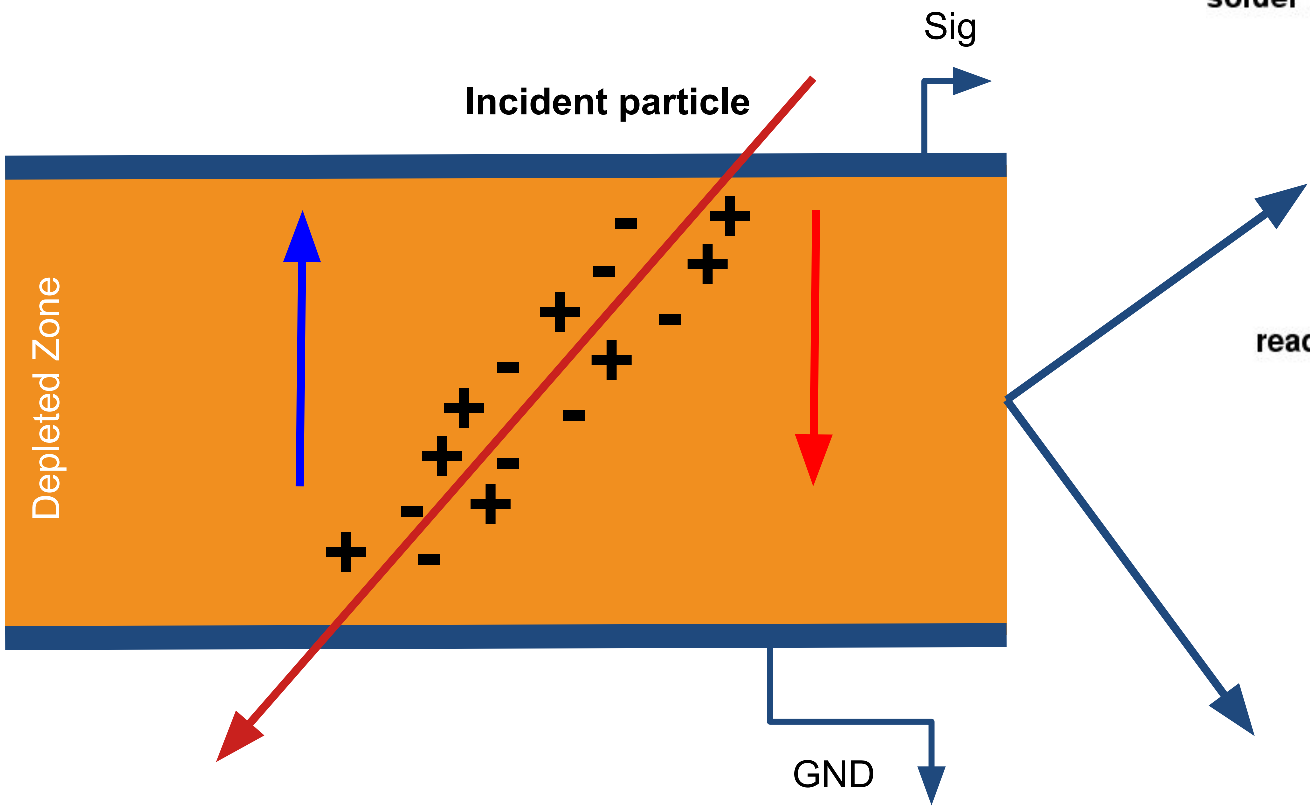


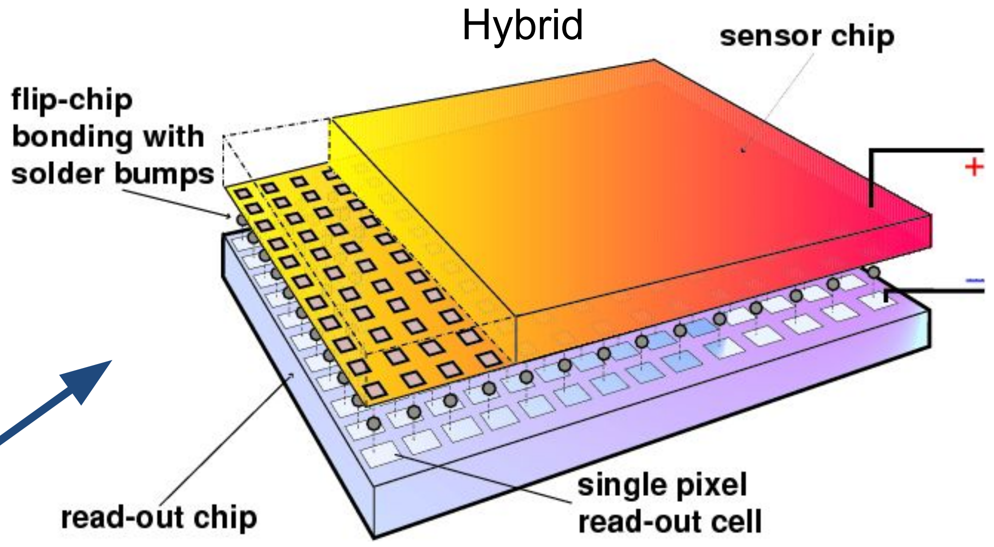
Vielen Dank für Ihre Aufmerksamkeit

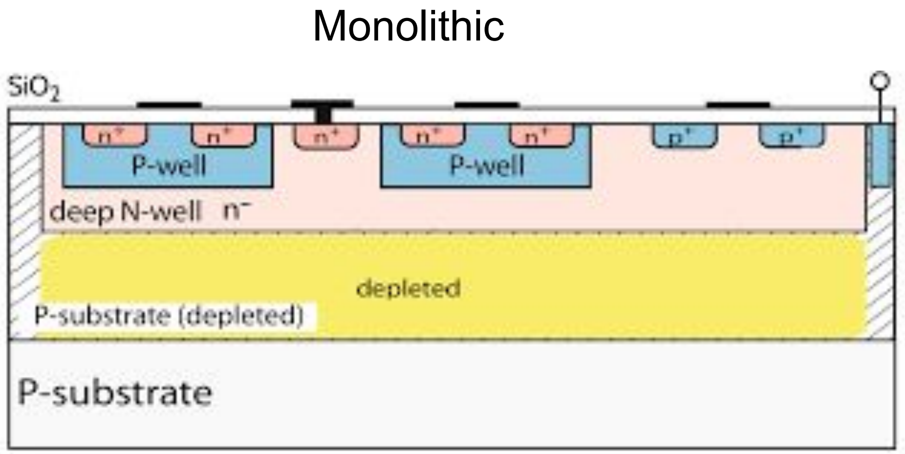
Back up

High Voltage Monolithic Active Pixel Sensor

Introduction







Noise

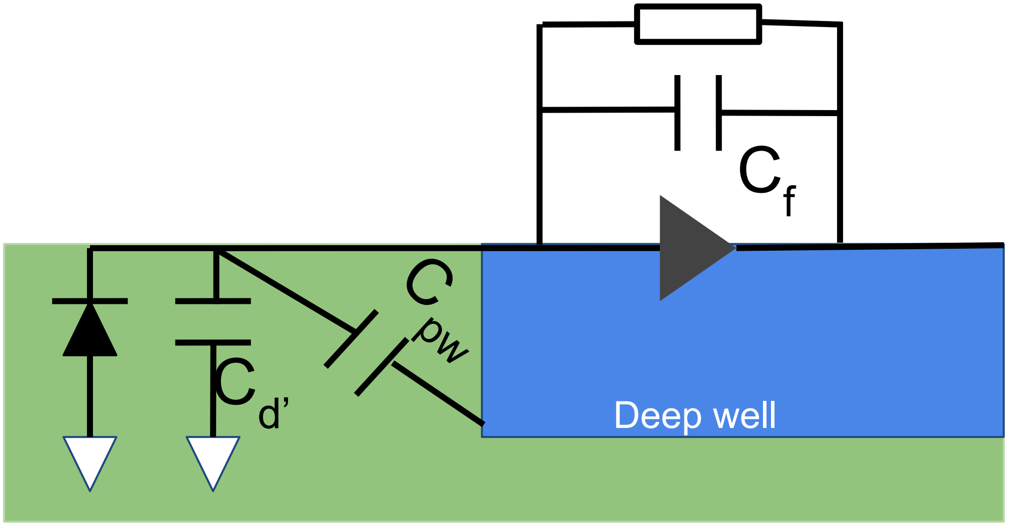
Capacitance

$$< N_n >= \frac{<\Delta v_0>}{q_{elec}\ g} \ \text{where, g is gain}$$

$$C_d = C_{d'} + C_{pw}$$

$$ENC^2 \sim \frac{4}{3}\frac{kT}{g}\frac{C_d^2}{\tau}$$

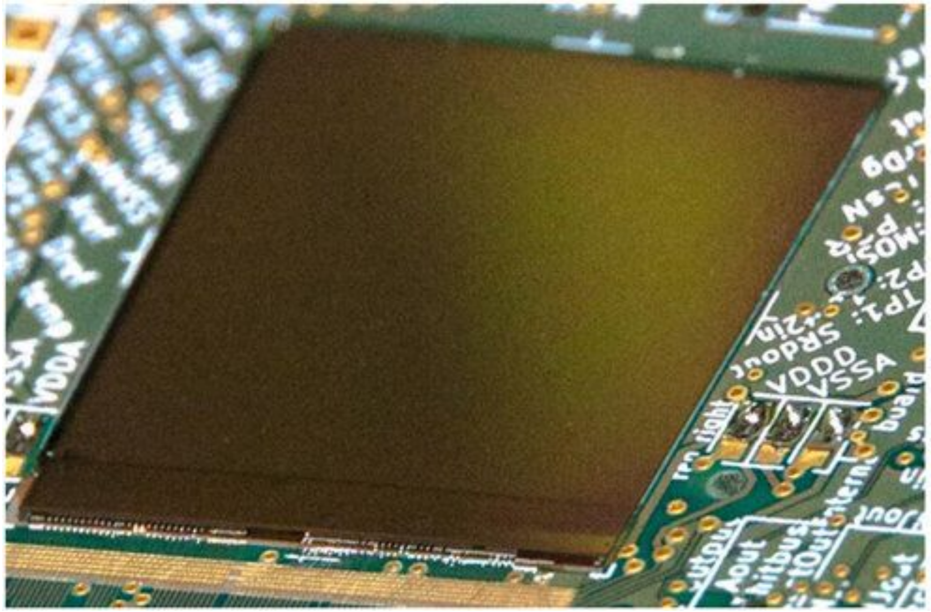
$$\tau_{CSA} \sim \frac{1}{g}\frac{C_d}{C_f}$$

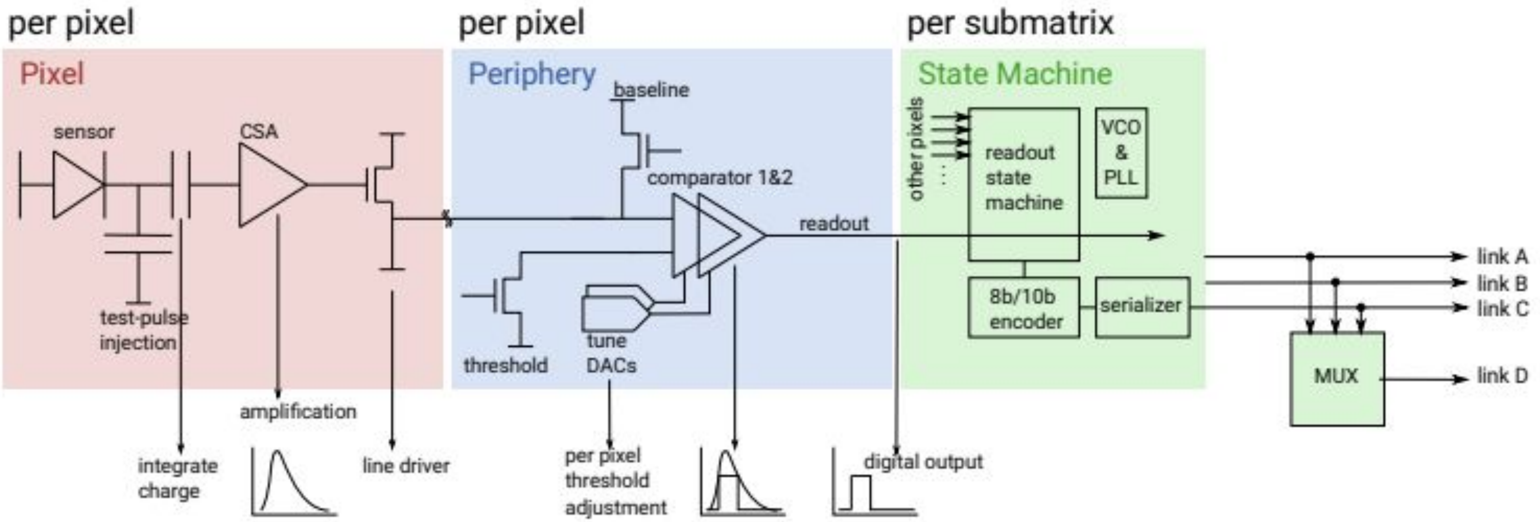


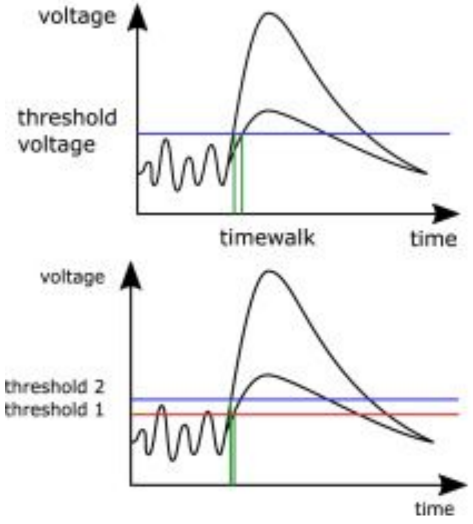
High Voltage Monolithic Active Pixel Sensor

One of Examples : MuPix 10

- MuPix10 is a full size HV-MAPS prototype
  - Detection and signal processing with just 50µm silicon
  - 180nm HV-CMOS process
  - 2cm x 2cm with 256 x 250 pixels
  - Pixel size of 80 x 80µm^2
  - ToA + ToT have 11 + 5 bits
  - LVDS links of 3+1
  - Resistivity of 200Ωcm
- It is developed for Mu3e experiment at PSI
  - Low material budget





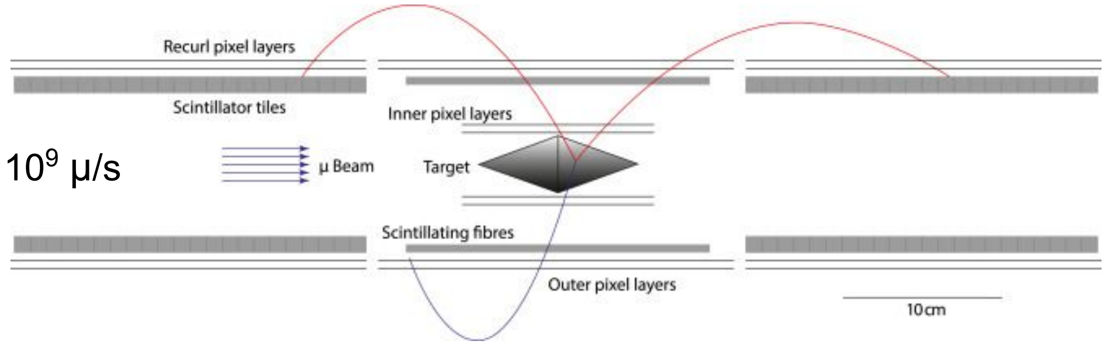


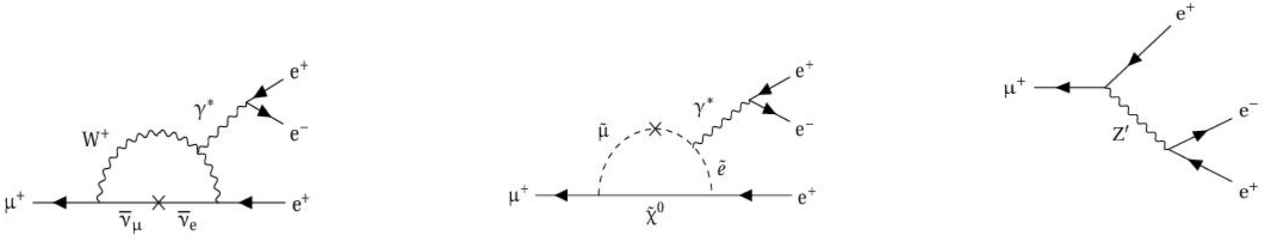
Mu3e Experiment

Introduction

- Search for μ decay into eee
  - Standard model : BR < 10^{-54}
- Current limit
  - BR < 10^{-12} from SINDRUM, 1988
- Aimed measurements
  - Phase I < 2 x 10^{-15}
  - Phase II < 10^{-16}
- Requirement and Challenges
  - High rates
  - Good timing ~100ps
  - Good vertex resolution 100μm
  - Good momentum resolution ~0.5 MeV

  => Low material budget 10^{-3} X_0



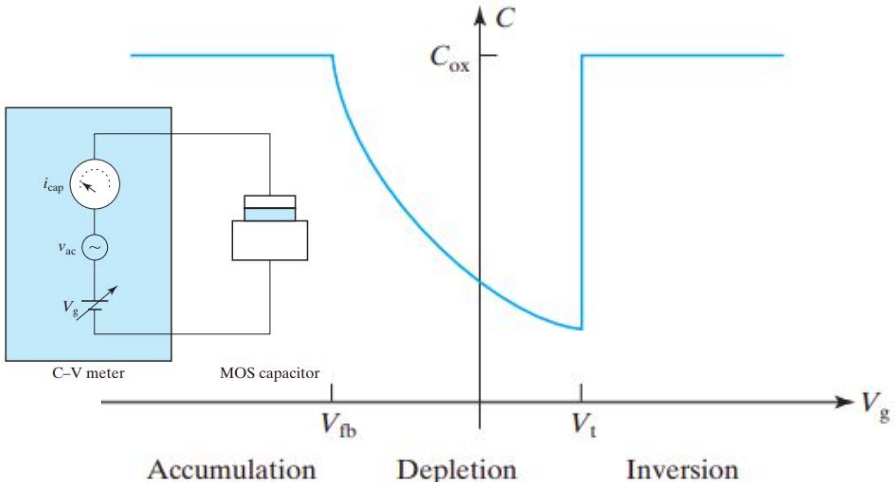


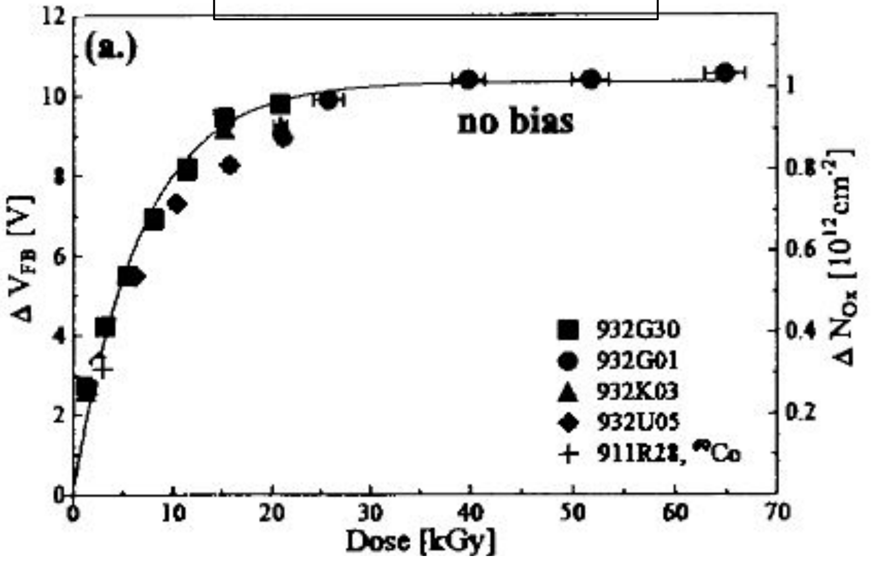
(a) Neutrino mixing. (b) Supersymmetric particles in a loop diagram. (c) At tree level via a Z'.

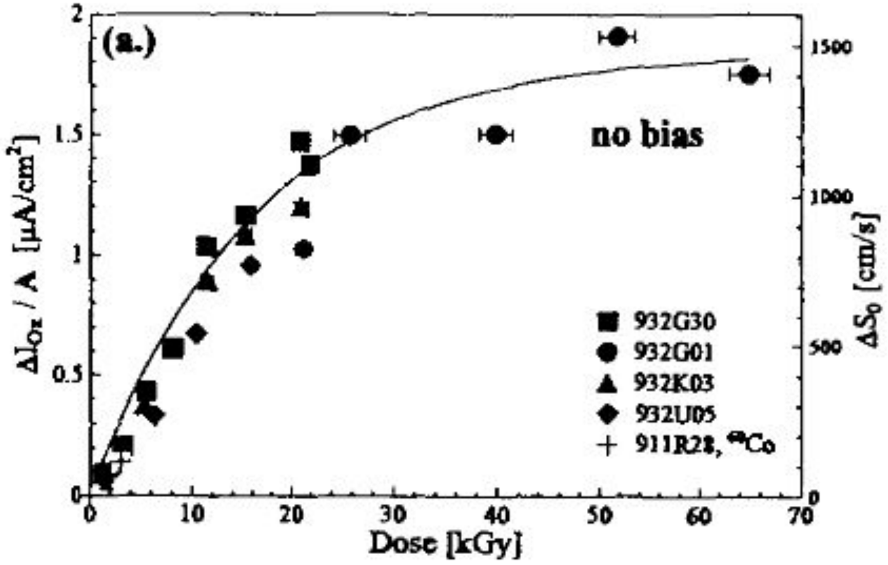
Estimation of Surface Damage

20 keV electrons

- Measuring Flatband voltage
  - V_{FB} can be measured using C-V measurement
- Measuring leakage current
- However, it is not simple to measure surface damage in case of charged particles
  - Bulk damage changes V_{FB} and leakage current too
- E.g. Monolithic sensors are difficult to be studied too
  - A lot of surfaces made by N-/P-wall to shield devices







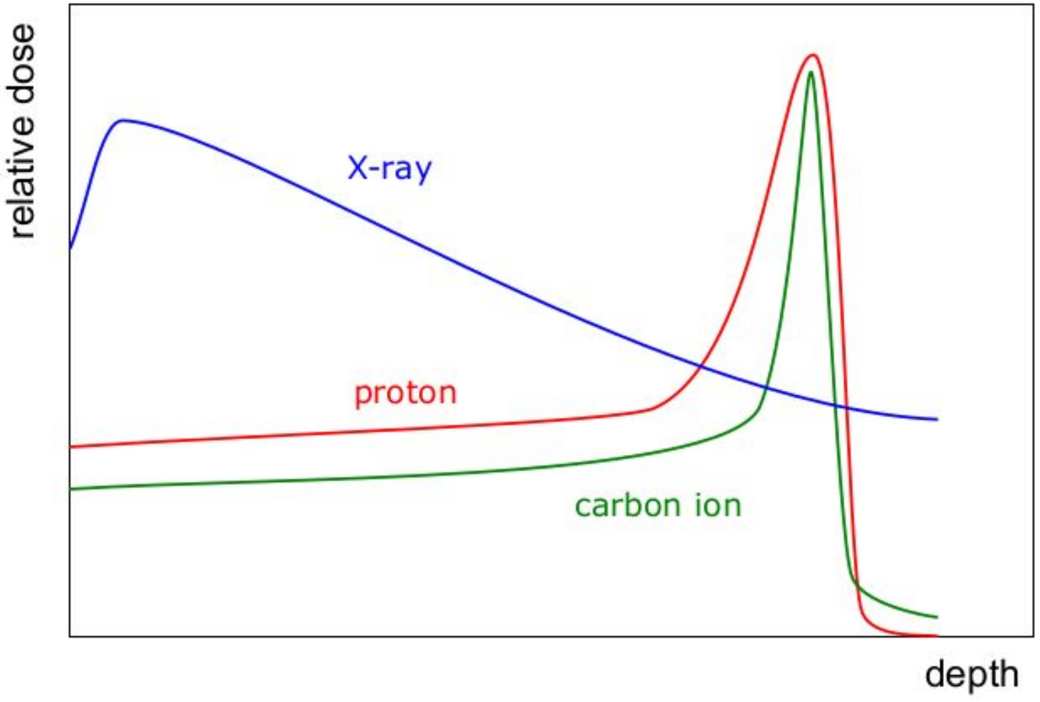
[R. Wunstorf et al. / Nucl. Instr. and Meth. in Phys. Res. A 377 (1996) 290-297]

Single Upset Event

- Measuring Flatband voltage
  - V_{FB} can be measured using C-V measurement
- Measuring leakage current
- However, it is not simple to measure surface damage in case of charged particles
  - Bulk damage changes V_{FB} and leakage current too
- E.g. Monolithic sensors are difficult to be studied too
  - A lot of surfaces made by N-/P-wall to shield devices

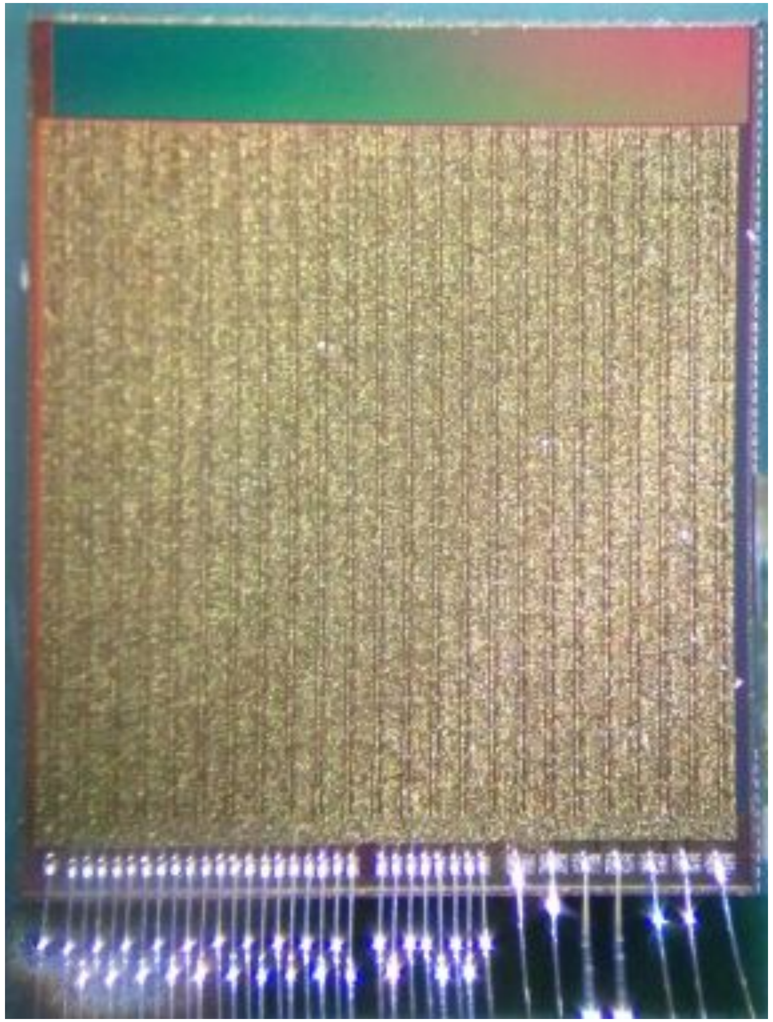
Motivation

- Beam monitoring system at Heidelberg Ion-beam Therapy Center (HIT)
  - Current beam monitor made of gas and multi wire proportional chambers (MWPCs)
    - It cannot provide information on 2D beam shape
    - The resolution is limited by the wire distance typically in the order of 0.5 - 1.0 mm
    - The Strong magnetic field of an MRI might influence the movement of the ionized gas
  - Plan to implemented MRI-guided ion-beam delivery
  - Precise measurement of Position, spot size and dose delivery



HitPix

Requirement	Design decision
Spatial resolution of 200 µm and FWHM resolution of 400 µm	Pixel size is 200 µm × 200 µm prototype with 24 x 24 pixel matrix
Deviation of beam parameters have to be detected within 100 µs after integration time has been completed	Adaptable frame rate, typical values are in the order of 100 kHz for projection readout on-chip
Detector lifetime can not be less than 6 months and should be more than 1 year ~ $1.3 \times 10^{15}\ n_{eq}/cm^2$	HV-CMOS technology and radiation tolerant circuit design are used a 180 nm HV-CMOS technology
Total detector block material budget is 2 mm water equivalent (several sensor layers and mechanical structure)	Thinned sensors are available (100 µm per layer)[1], interconnection via flex PCB, carbon plate for rigidity possible down to 50 µm
Up to 2^{10} particles per second wrong (20 GHz on $0.5cm^2$)	In-pixel counters store the number of events until frame readout.
Sensitive area has to be at least 25 cm × 25 cm, because of spot size and scanning range.	It can be realised by building a sensor matrix from several sensors (max. 2 cm × 2 cm each), stabilised by a carbon plate and connected via flex PCB.



Pixel

- A depletion region of 30-50 μm depth
- Radiation tolerance
  - Fast charge collection and separation improve tolerance to radiation- induced bulk damage
  - For the tolerance to surface damage
    - The radiation-tolerant PMOS circuits
    - All linear NMOS transistors are replaced by enclosed transistors
- Consist of two flavors of HitPix
  - HitPixS
    - Three separated wells in every pixel
    - To assure that the signal charge flows into the CSA
    - Reduce leakage currents
  - HitPixISO
    - The deep n-well used as sensor electrode
    - The isolation to avoid shorting and to prevent capacitive crosstalk of digital signal
- Substrate resistivity : 300 Ωcm

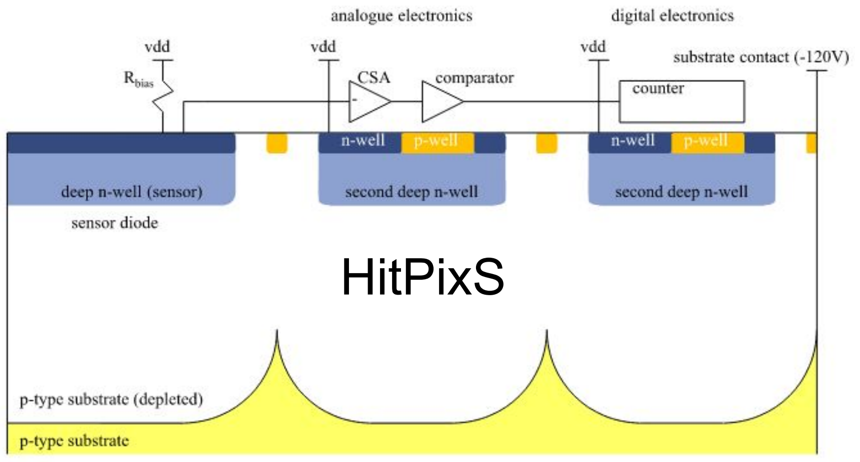


Fig. 4. Cross section of the pixel with separated wells.

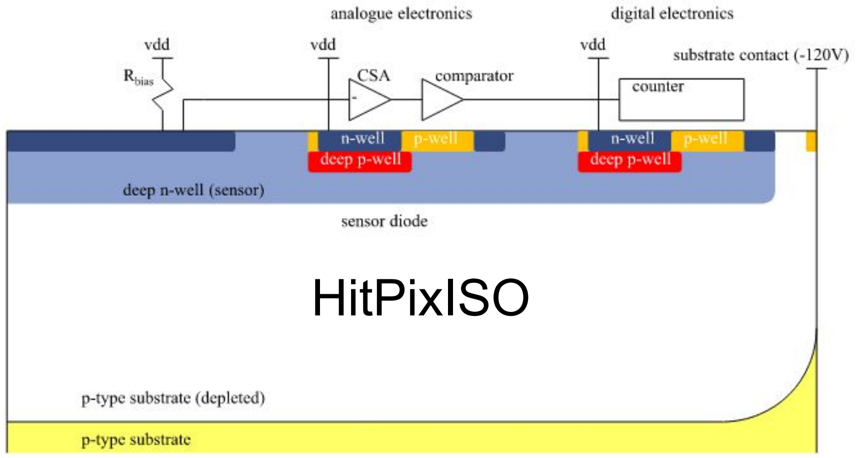
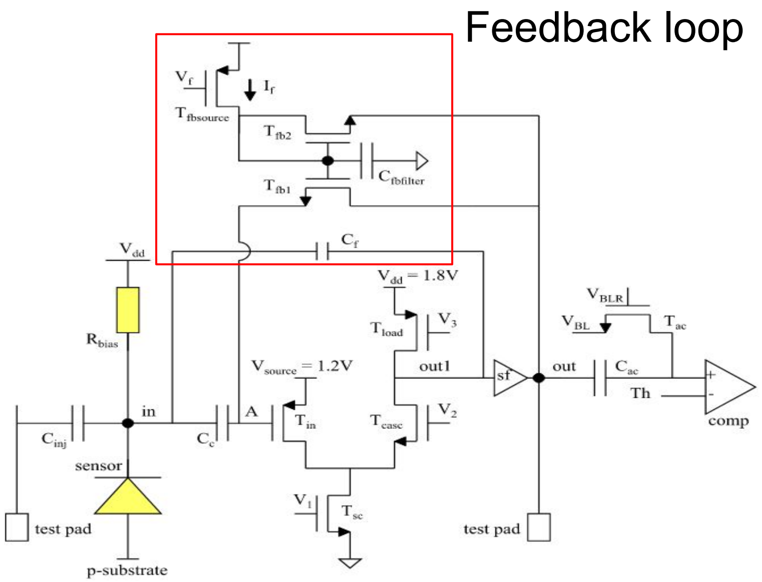
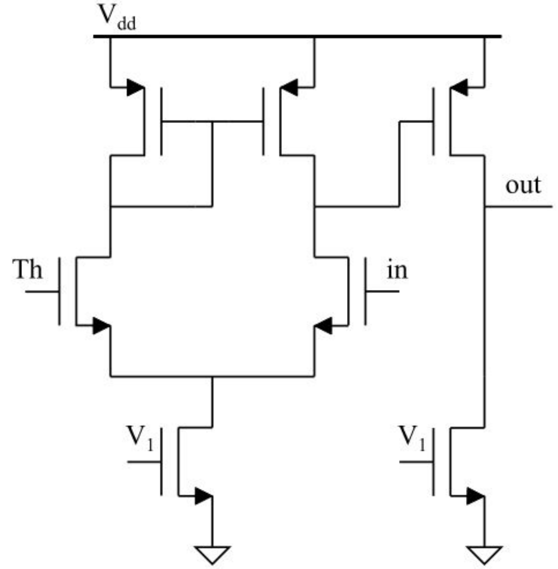


Fig. 5. Cross section of the pixel with large deep n-well and isolated shallow n-wells.

Analog Pixel Electronics

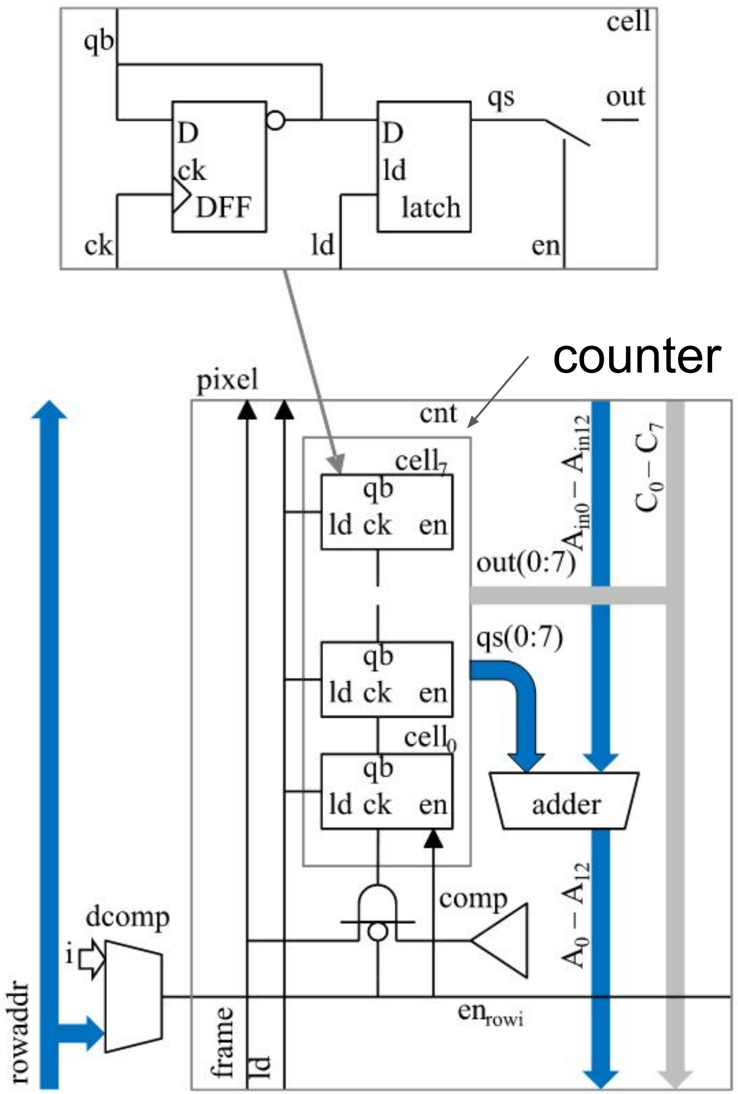
- Charge Sensitive Amplifier (CSA)
  - A folded cascode amplifier with PMOS
  - The charge-to-voltage conversion gain is $\frac{C_f}{C_{sens} + C_f}$
  - C_{sens} capacitance of the sensor diode from simulation
    - HitPixS : 52 fF
    - HitPixISO : 946 fF
  - A small loop gain reduction arises due to the voltage division at C_c and the gate-source T_{in}
- Comparator
  - A standard differential amplifier
  - The threshold (TH) setting is global
  - TH tuning is unnecessary due to the large signal
    - But, plan to implement in the next version
    - The different aging speeds of pixels due to inhomogeneous irradiation
- Power consumption
  - CSA : 4.7 μA
  - Comparator : 10 μA





Digital Pixel Electronics

- The block scheme of the digital part in each pixel
- 8-bit ripple counter is implemented
- Full readout
    - Before reading out the counter states, the bits are stored into D-latches by activation of ld
    - The counters of all pixels in row i are read out by setting the 5-bit signal rowaddr to i
    - The output of the latches qs is connected to the 8-bit bus
    - The row address and counter states are stored in the same register
- Faster readout
    - An asynchronous 13-bit adder is implemented in every pixel
    - The sum of counter states is obtained from the adders in one column
    - In just one readout cycle, the column projection can be read out



Feedback Circuit

- To avoid analog pile-up, the feedback circuit should discharged the capacitances fast enough
- And it should generate as little noise as possible so that smaller signals can be detected
- The discharge current increases with longer pulse duration
  - The dead time does not increase linearly with signal amplitude
- Simulation result for HitPixS in case of 60 MeV protons
  - About 1 MHz counting is possible (dashed line in Fig.14)
  - For stronger feedback current faster rest times can be achieved
- Simulated equivalent noise charge (ENC) with 0.5 nA feedback without leakage current
  - 136 e^- for HitPixS
  - 433 e^- for HitPixIso
  - Leakage current by irradiation damage dominates

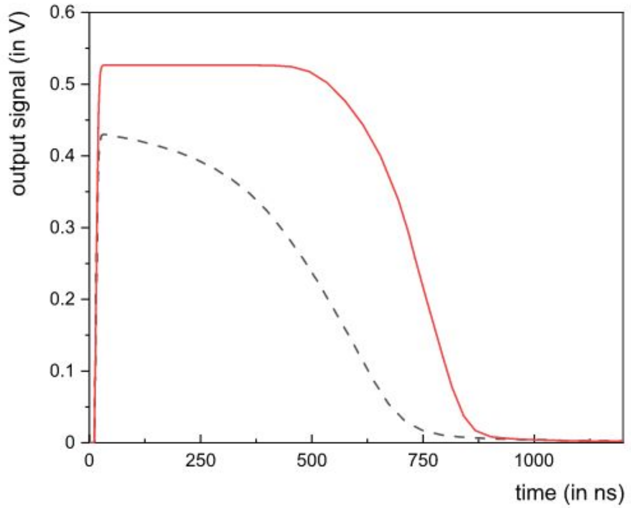


Fig. 14. Simulation of the HitPixS amplifier to an input signal of 27 800 e^- (dashed line) and 3 × 27 800 e^- (solid line).

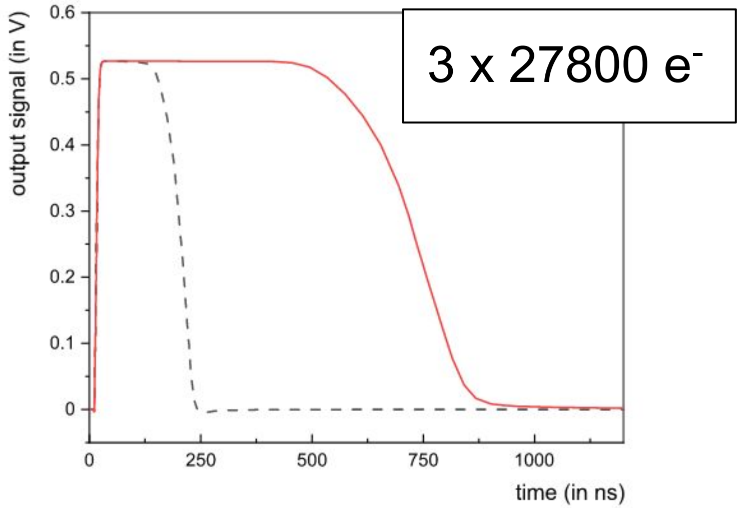


Fig. 15. Simulated signal length for a feedback current of 0.5 nA (solid line) and 2.5 nA (dashed line).

Testbeam Measurement

- Two hitmaps
  - ⅔ of the beam particles have to pass the sensor
  - For low intensities, the counting rate matches the expectation
  - For high intensities, dependence becomes sublinear
    - Due to pile-up of signals at CSA output
    - It could be enhanced, e.q. increasing the feedback current I_f

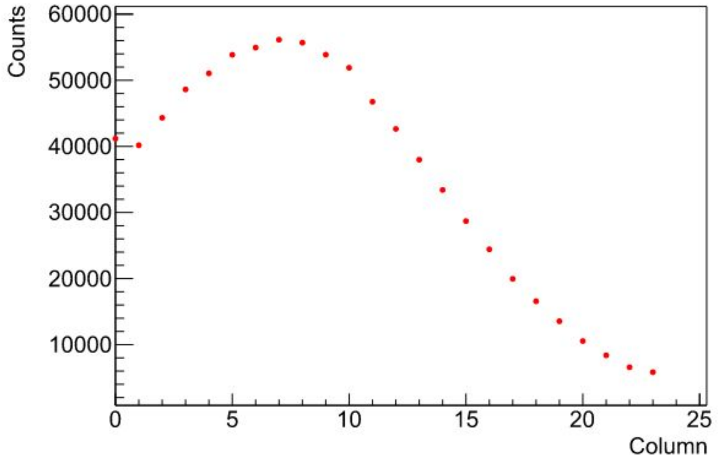


Fig. 25. In the adder readout mode, the sum of all counter states per column is read out. The result is a projection. The graph shows the profile of a carbon beam with 2×10^6 ions/s at an energy of 423.44 MeV/u, measured by HitPixS.

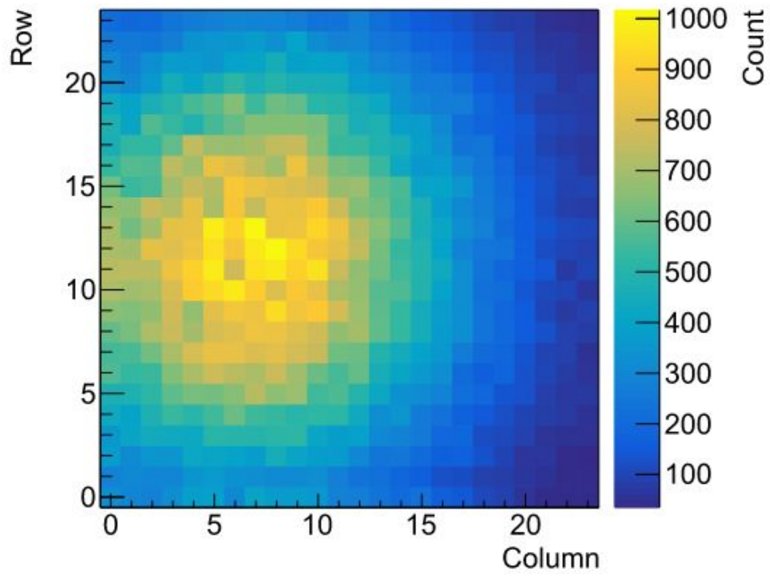


Fig. 24. Integrated counts of the pixels displaying the spot of the carbon beam 2×10^6 carbon ions/s at an energy of 423.44 MeV/u. Measured on HitPixS.

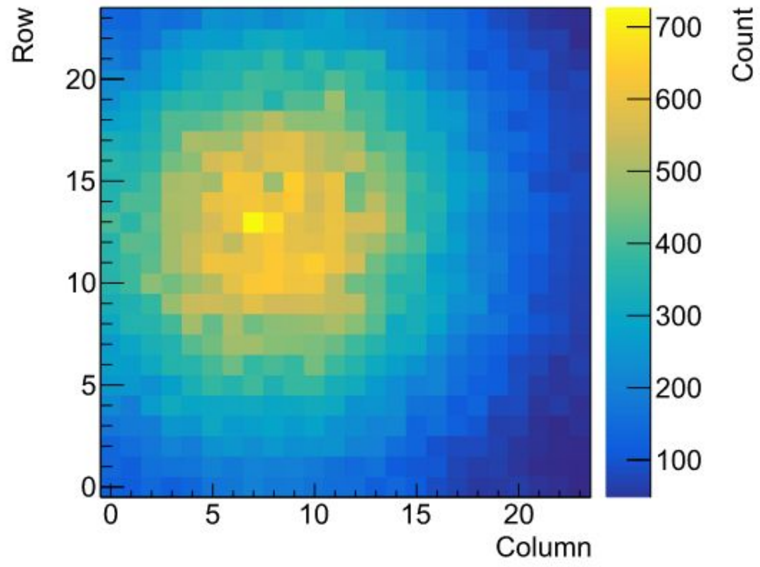
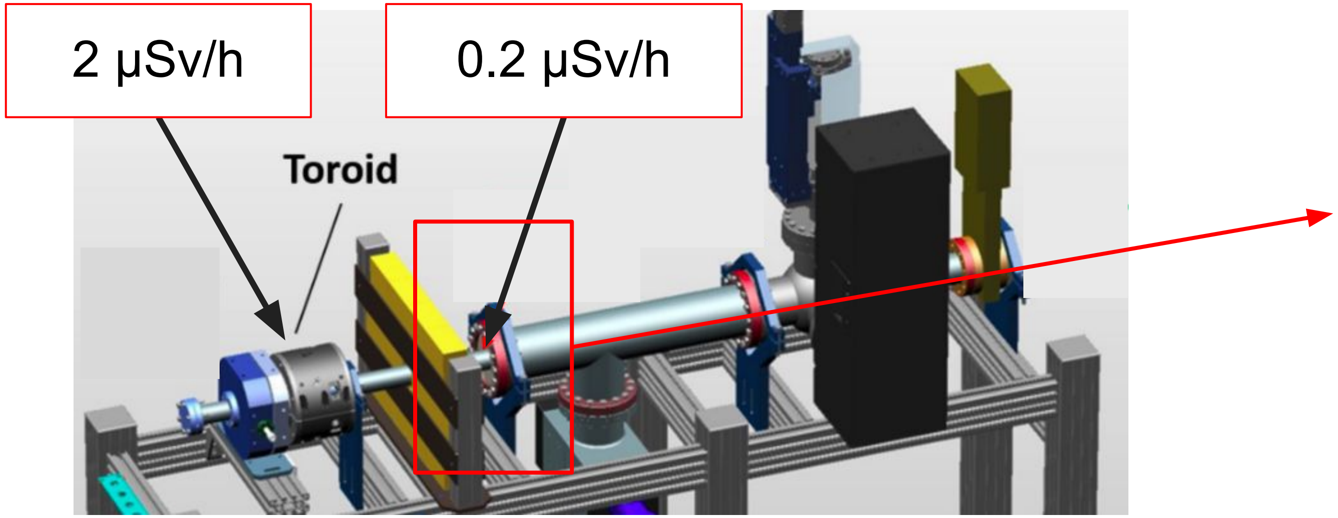
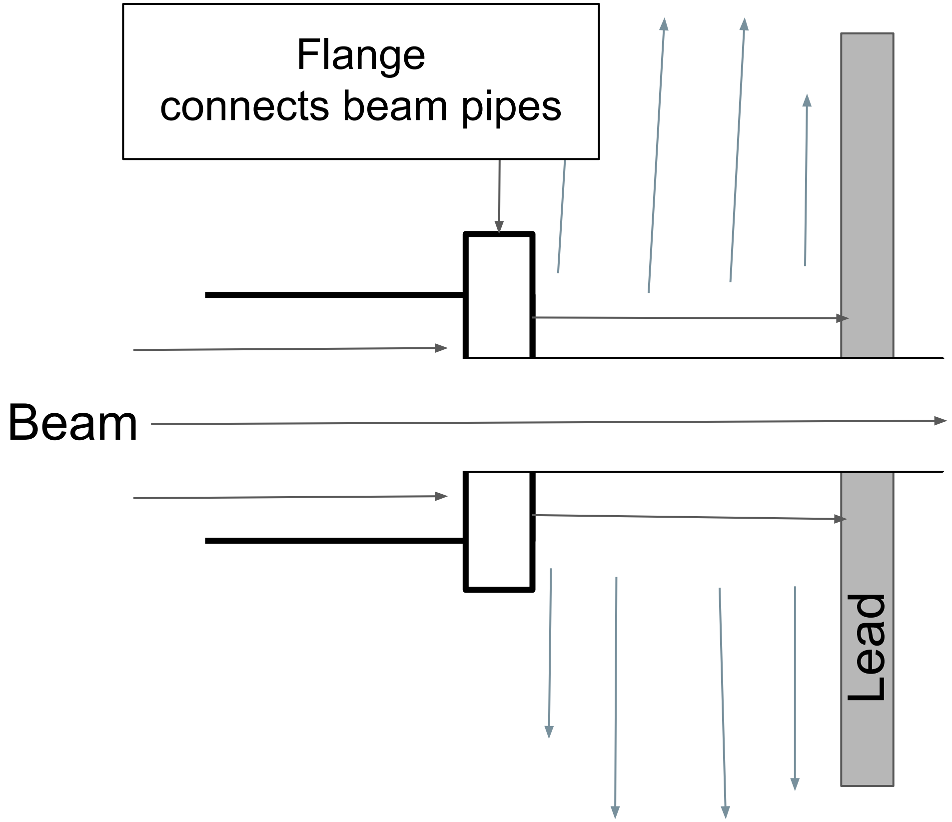
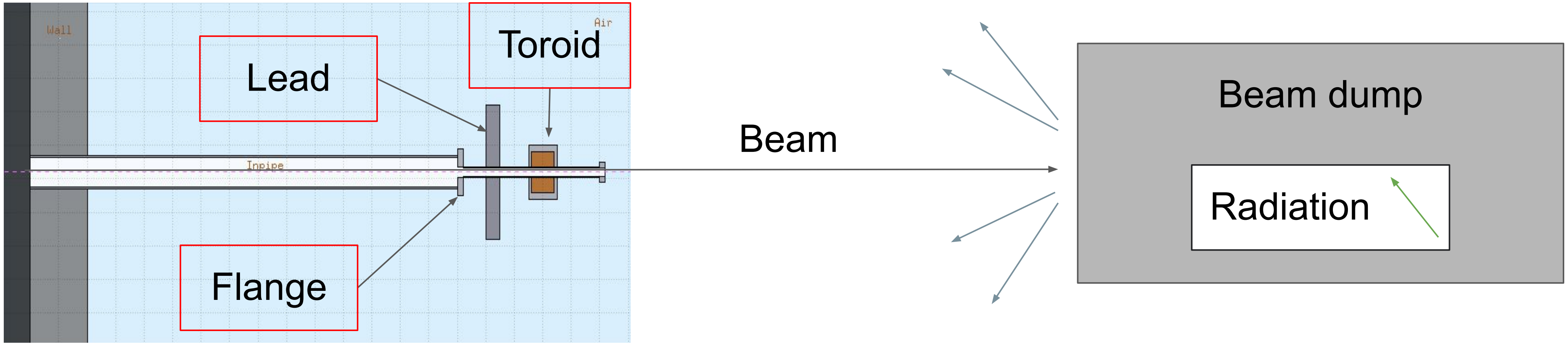


Fig. 26. Integrated counts of the pixels displaying the spot of the carbon beam 2×10^6 carbon ions/s at an energy of 430.10 MeV/u. Measured on HitPixISO.

Simulated Beam Line

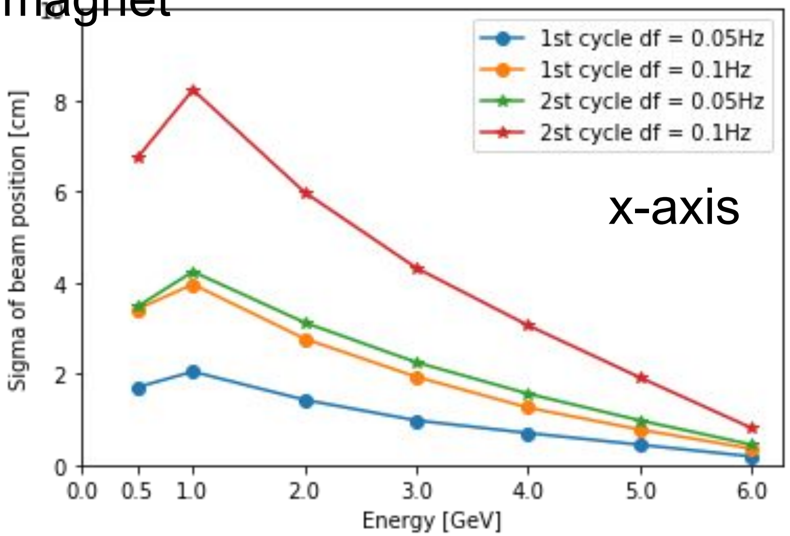


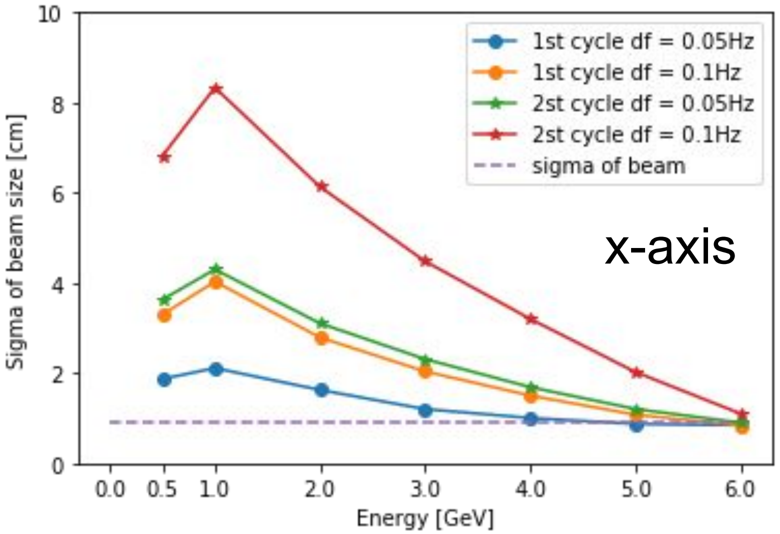




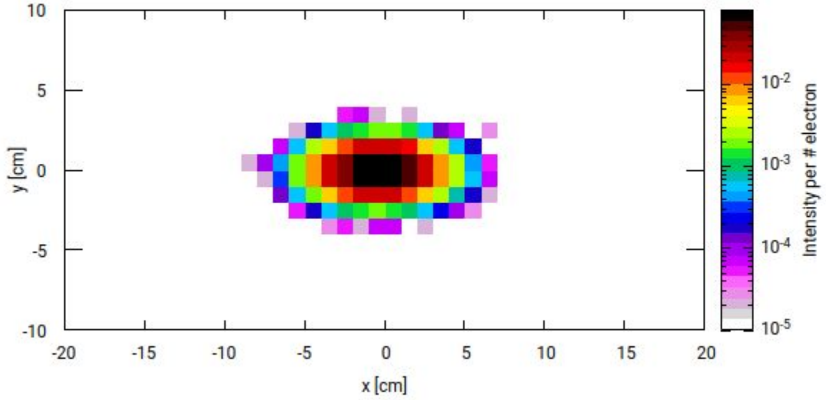
Beam Size for Δf = 0.05 Hz after Kicker Magnet

Front of the first quadrupole magnet

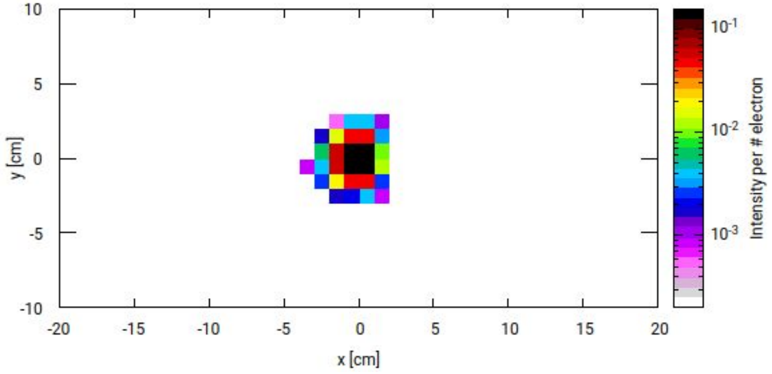




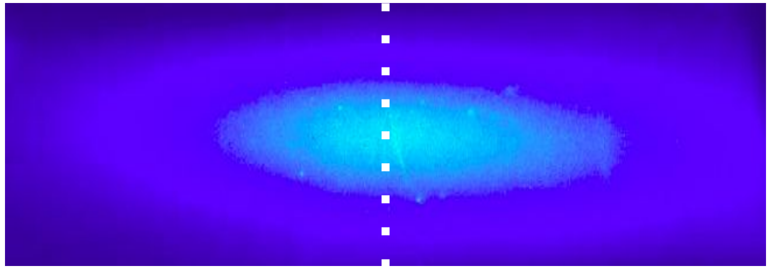
1st cycle 500 MeV for Δf = 0.05 Hz

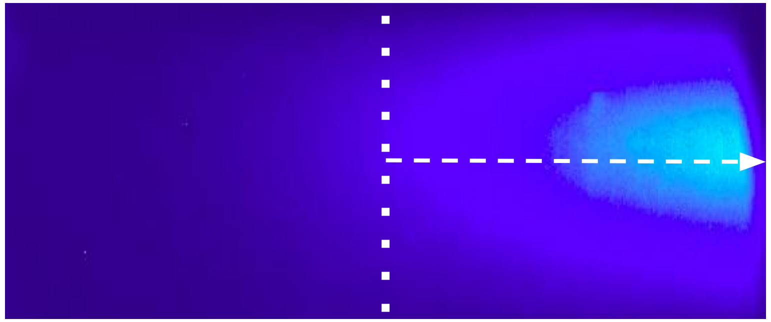


1st cycle 6 GeV for Δf = 0.05 Hz



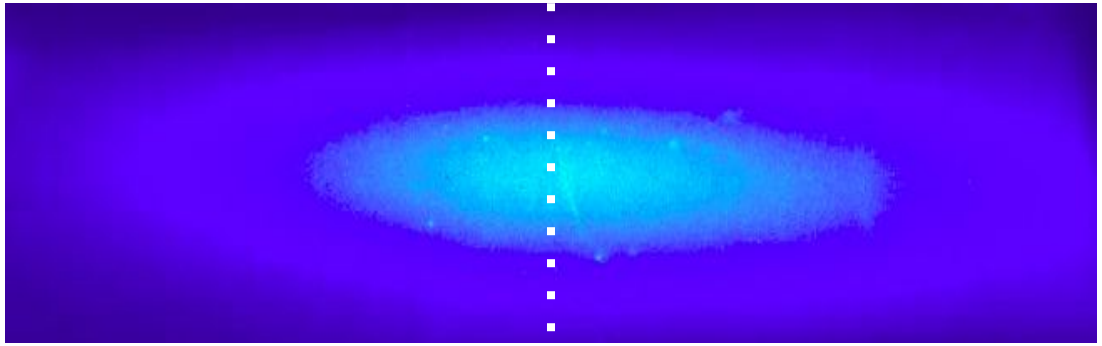
Current beam with energy of 500 MeV measured with beam camera

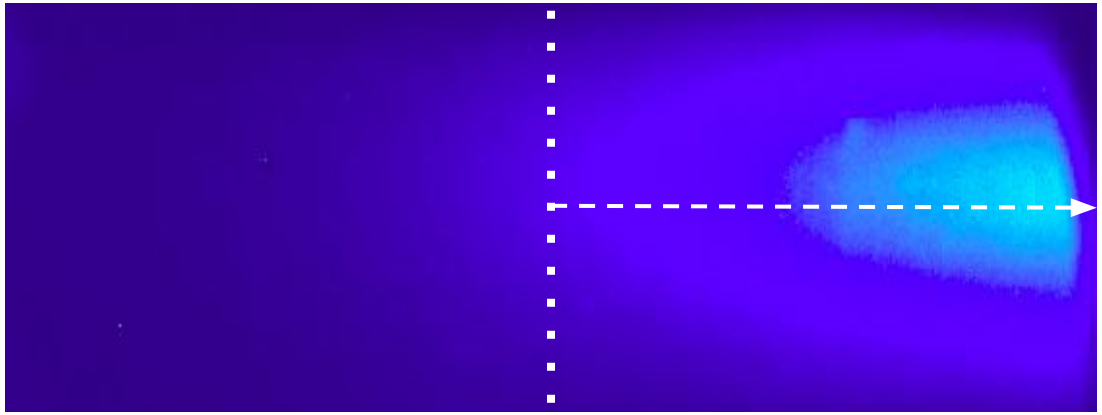


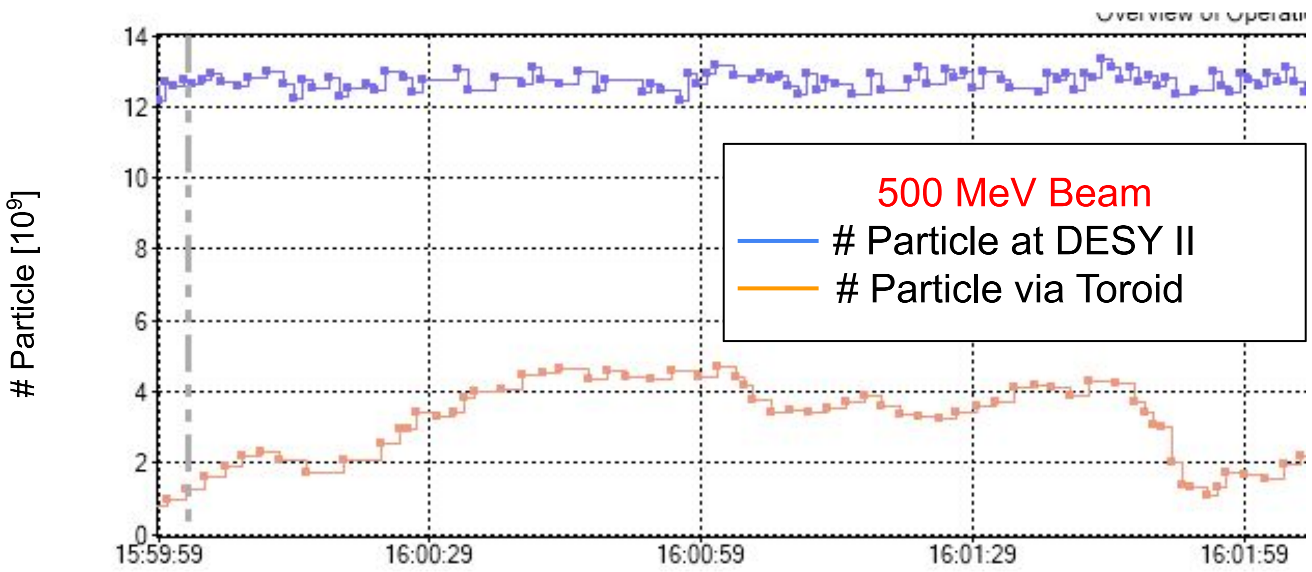


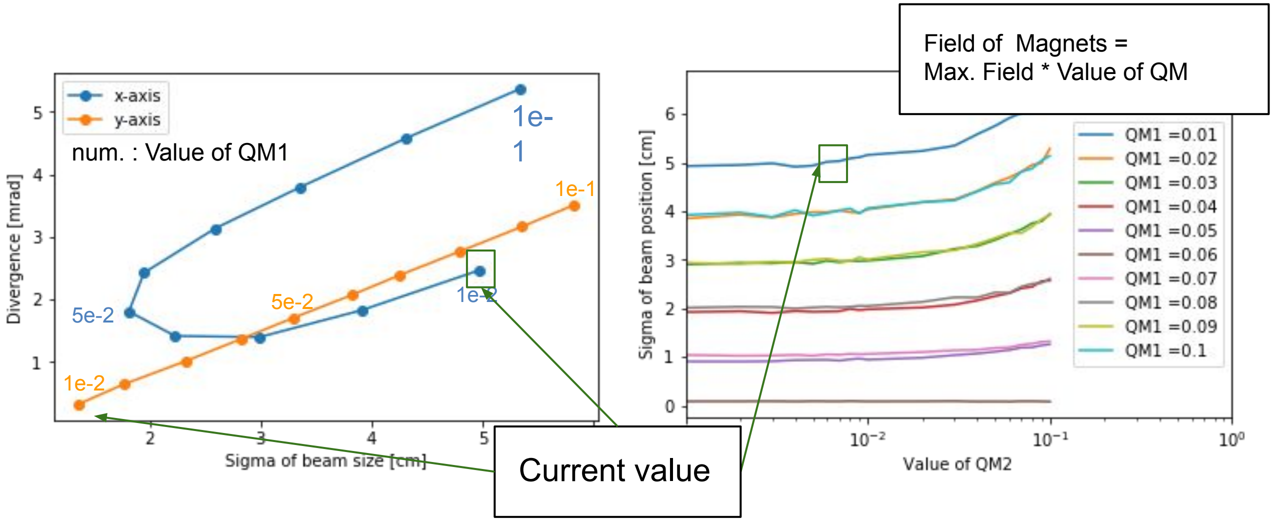
Beam Stability for 500 MeV

Current beam with energy of 500 MeV
measured with beam camera

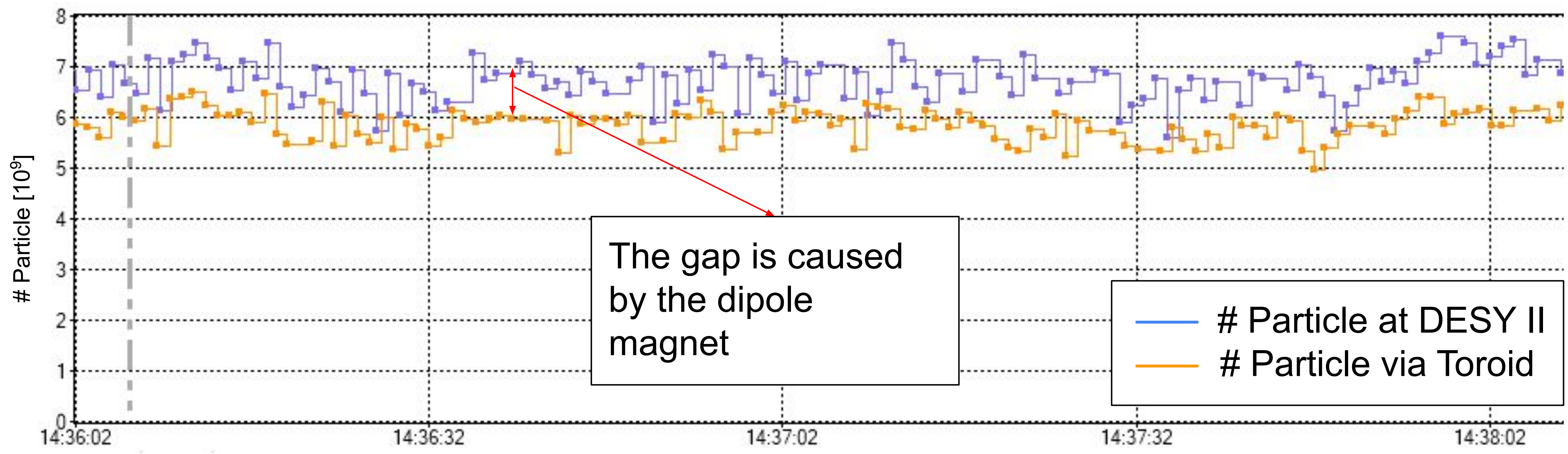


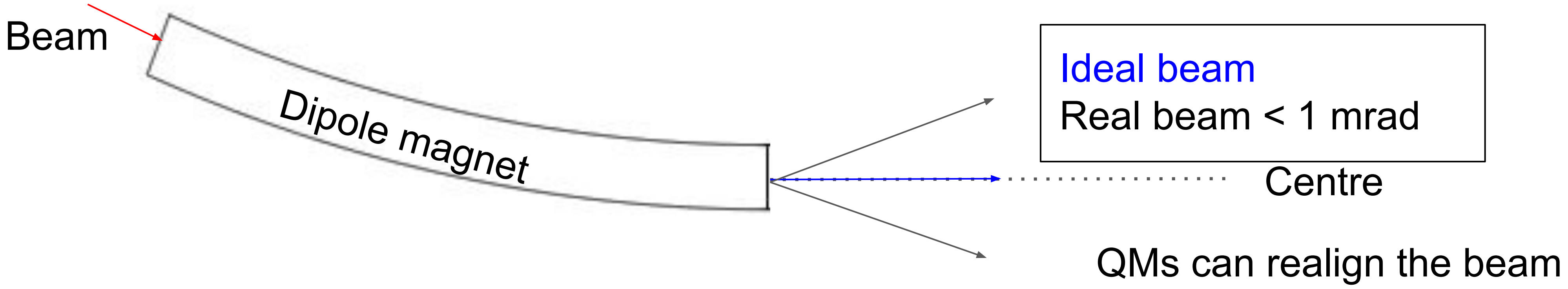






Beam Rate Measurement for 6 GeV Without Quadrupole Magnets





Beam Stability for 6 GeV

- 6 GeV beam
  - Independent of
  - Magnet field scanning for dipole magnet to minimize position offset
  - QMs can realign the beam