Introduction to PIONEER's Active Target

Adam Molnar

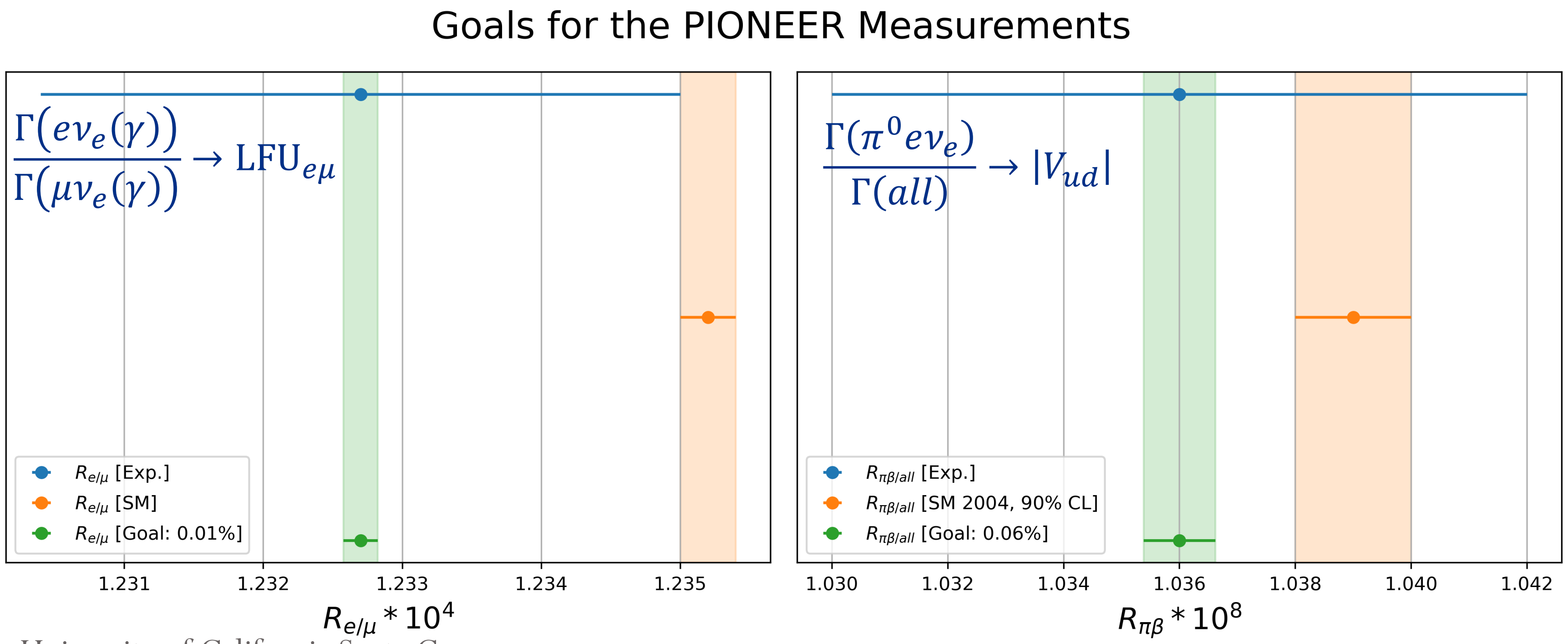
PIONEER Experimental Motivation

Phase I

- Measure $R_{e/\mu} = \frac{\Gamma(\pi^+ \to e + \upsilon(\gamma))}{\Gamma(\pi^+ \to \mu + \upsilon(\gamma))}$ to unparalleled sensitivity (10^{-4})
- Unprecedented test of Lepton Flavor Universality (LFU) of which there has been hints of violations such as in the g-2 experiment

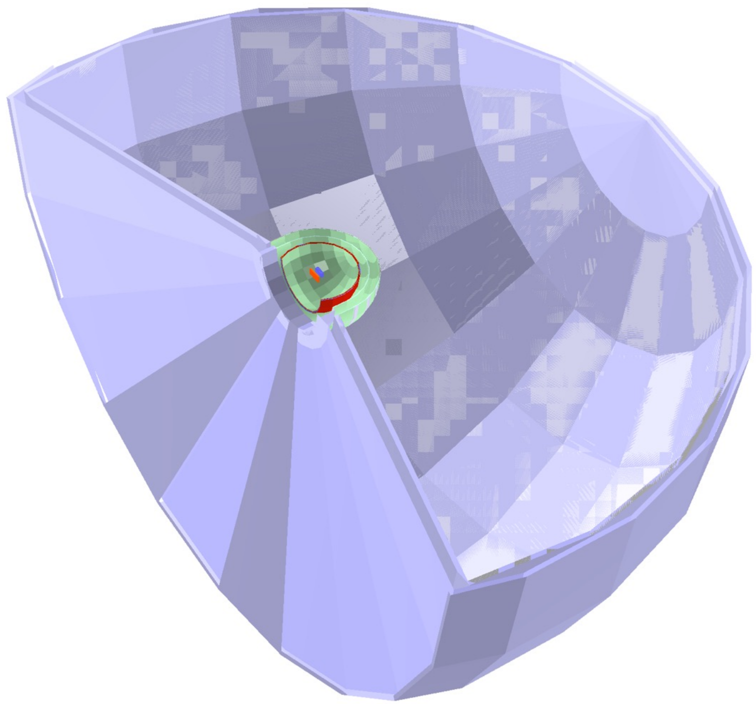
Phase II + III

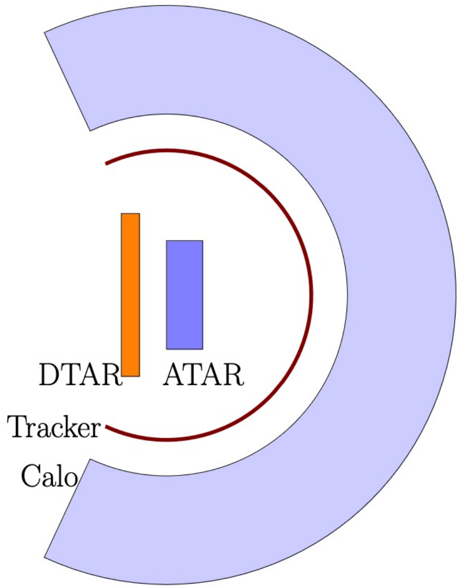
- Measure the branching fraction of Pi beta decay $\frac{\Gamma(\pi^+ \to \pi^0 e^+ \upsilon)}{\Gamma(\text{total})}$ to a higher experimental precision
- Phase II will increase the precision 3x and phase III will increase 10x
- II: Will allow for CKM unitarity test via $\frac{|V_{us}|}{|V_{ud}|}$ currently limited by this branching ratio
- III: Will allow for $|V_{ud}|$ extraction in the theoretically cleanest way



PIONEER Experiment at a Glance

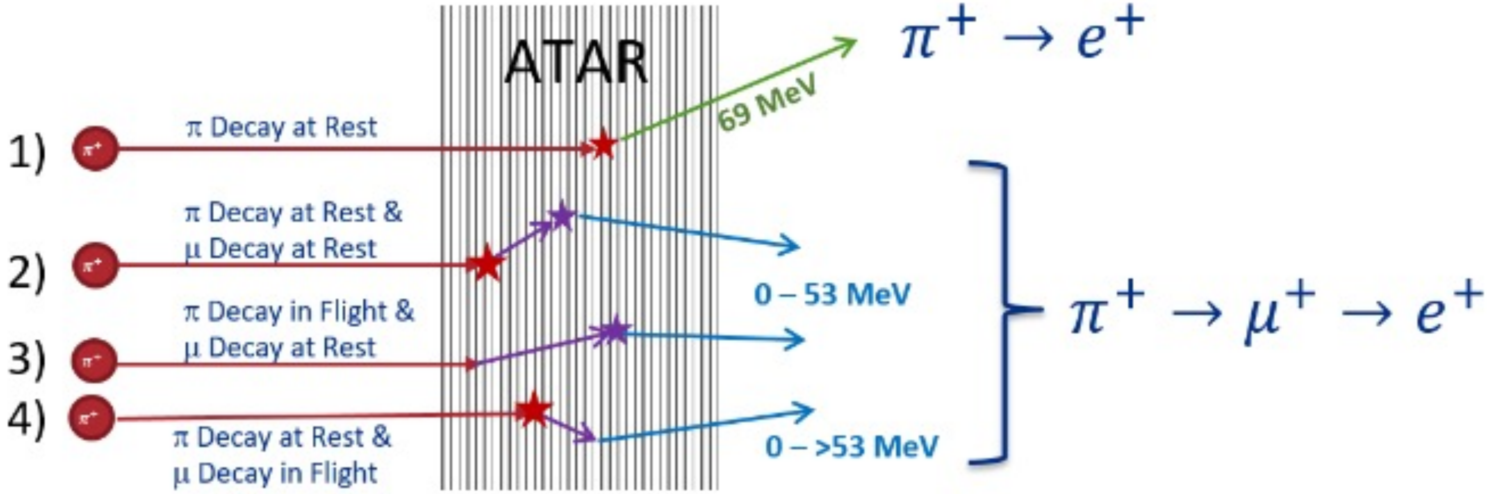
- PIONEER will run in the PiE5 beam line the world's most intense pion beam
- The pions will be degraded by an active likely silicon based Degrading TARget (DTAR)
- In the center of the experiment a silicon based Active TARget (ATAR)
- MPGD based tracker???
- Calorimeter either LYSO or Liquid Xenon





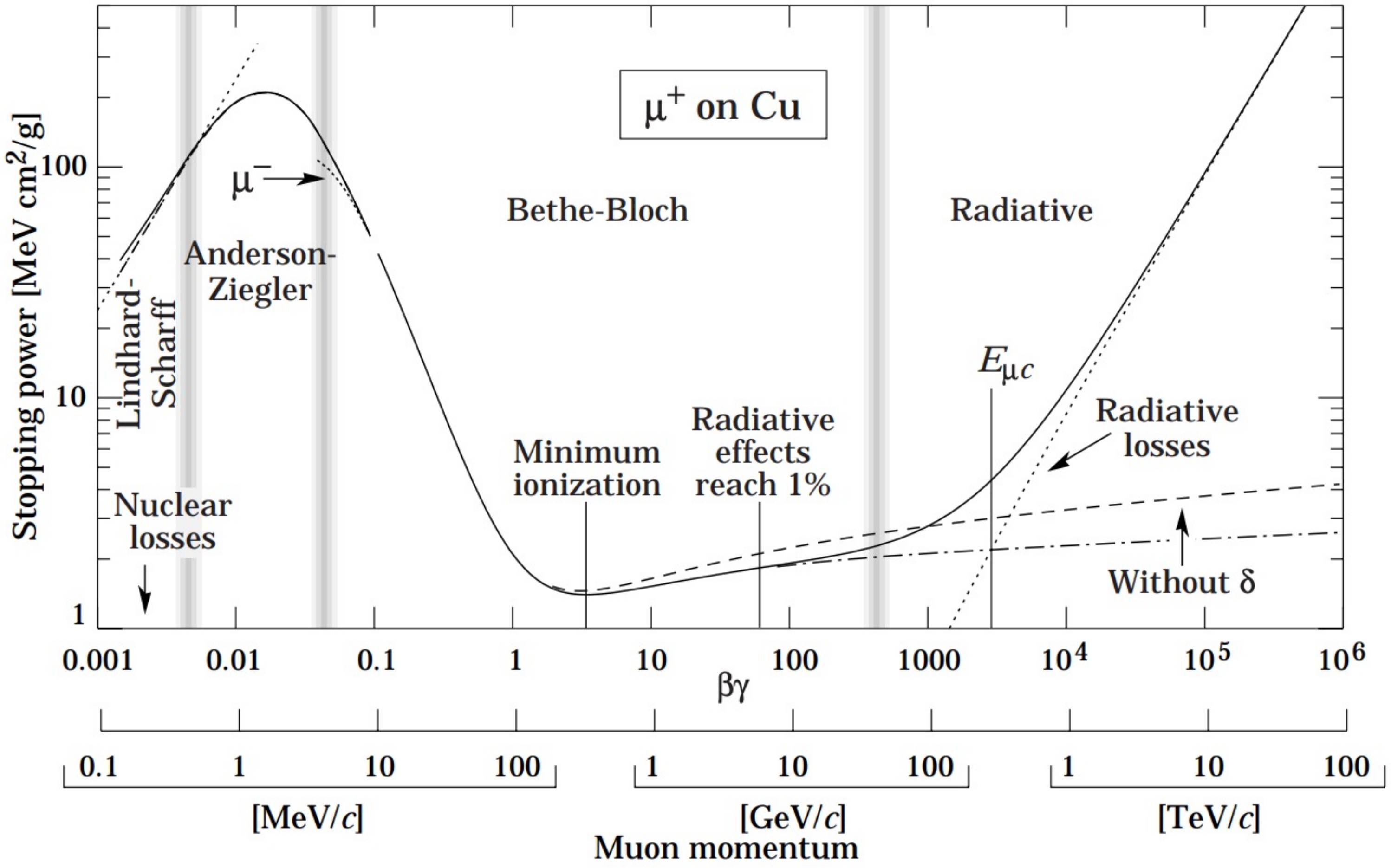
PIONEER's ATAR

- The center of the PIONEER experiment will be instrumented with a highly granular active target that will be used primarily for event identification
- ATAR will differentiate the two-stage dominant kinked decay of the pion to muon background from the monoenergetic single stage decay of the pion to an electron
- 5-dimensional tracking (3 dimensions of space, time, and energy) will be necessary to instrument the ATAR
- High rate and large dynamic range environment going from 1 MIP (e^+) to 100s of MIPs (μ^+ and π^+)



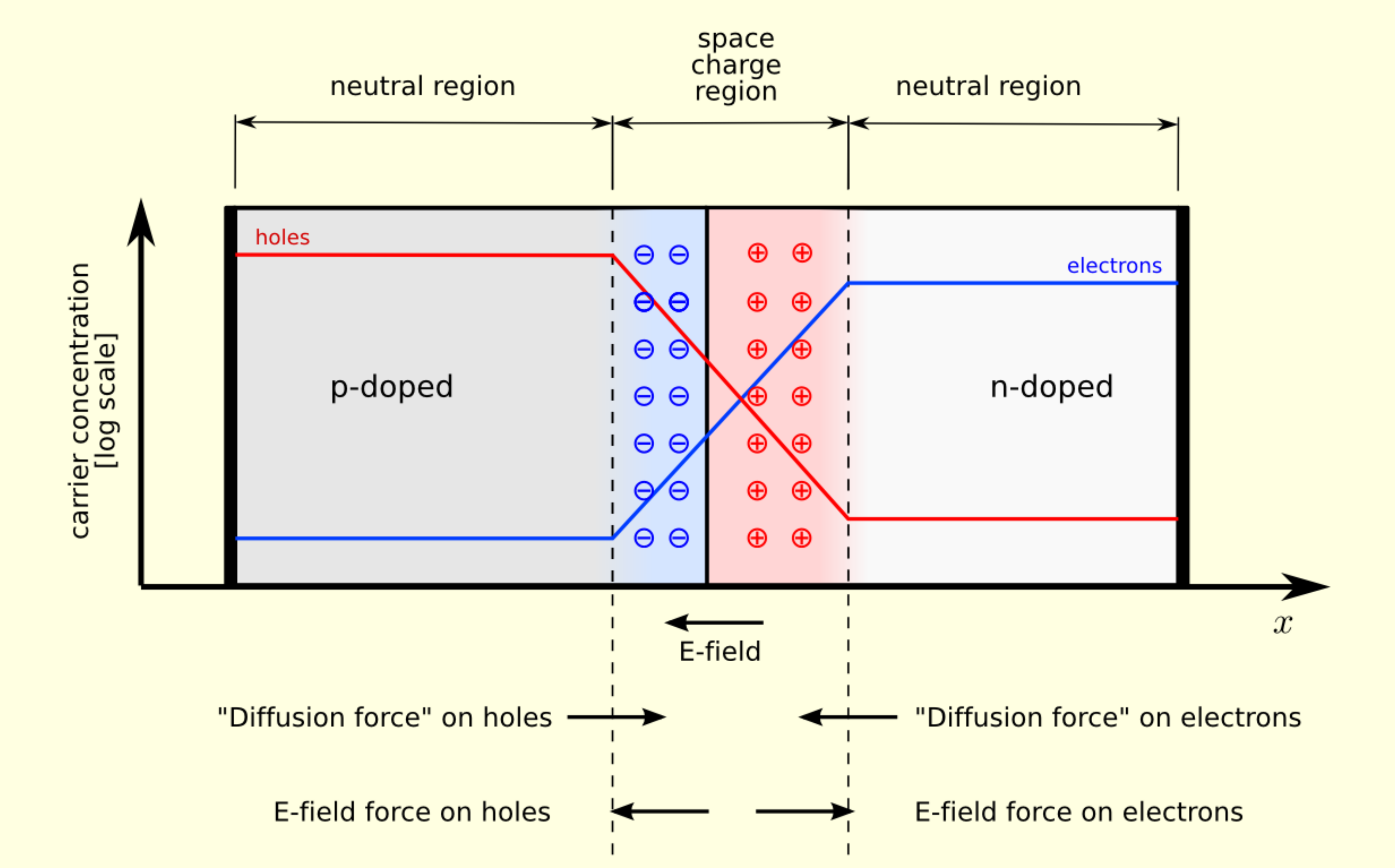
PIONEER's Four Dominant Decay Modes (3 of background 1 of signal)

Introduction to Silicon Detectors: Ionizing Radiation

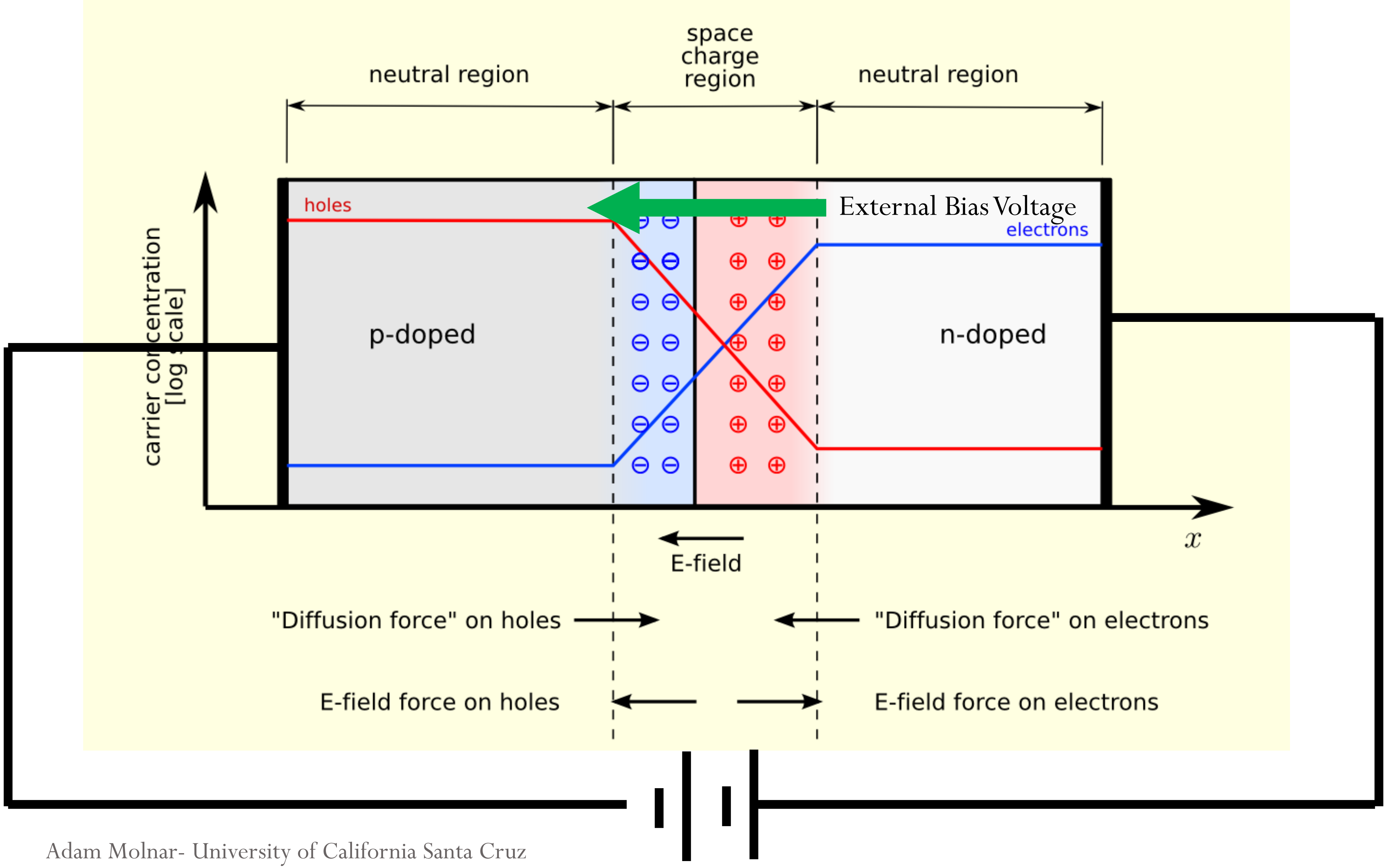


When charged particles (ionizing radiation) go through a material they lose energy and in turn excite electron hole pairs in the material. This is true in semiconductors where the stopping power is governed by the Bethe-Bloch equation above. Most silicon detectors deal with minimum ionizing particles or MIPs.

Traditional Silicon Detectors and PN Junctions



Traditional Silicon Detectors and PN Junctions Adding a Reverse Bias



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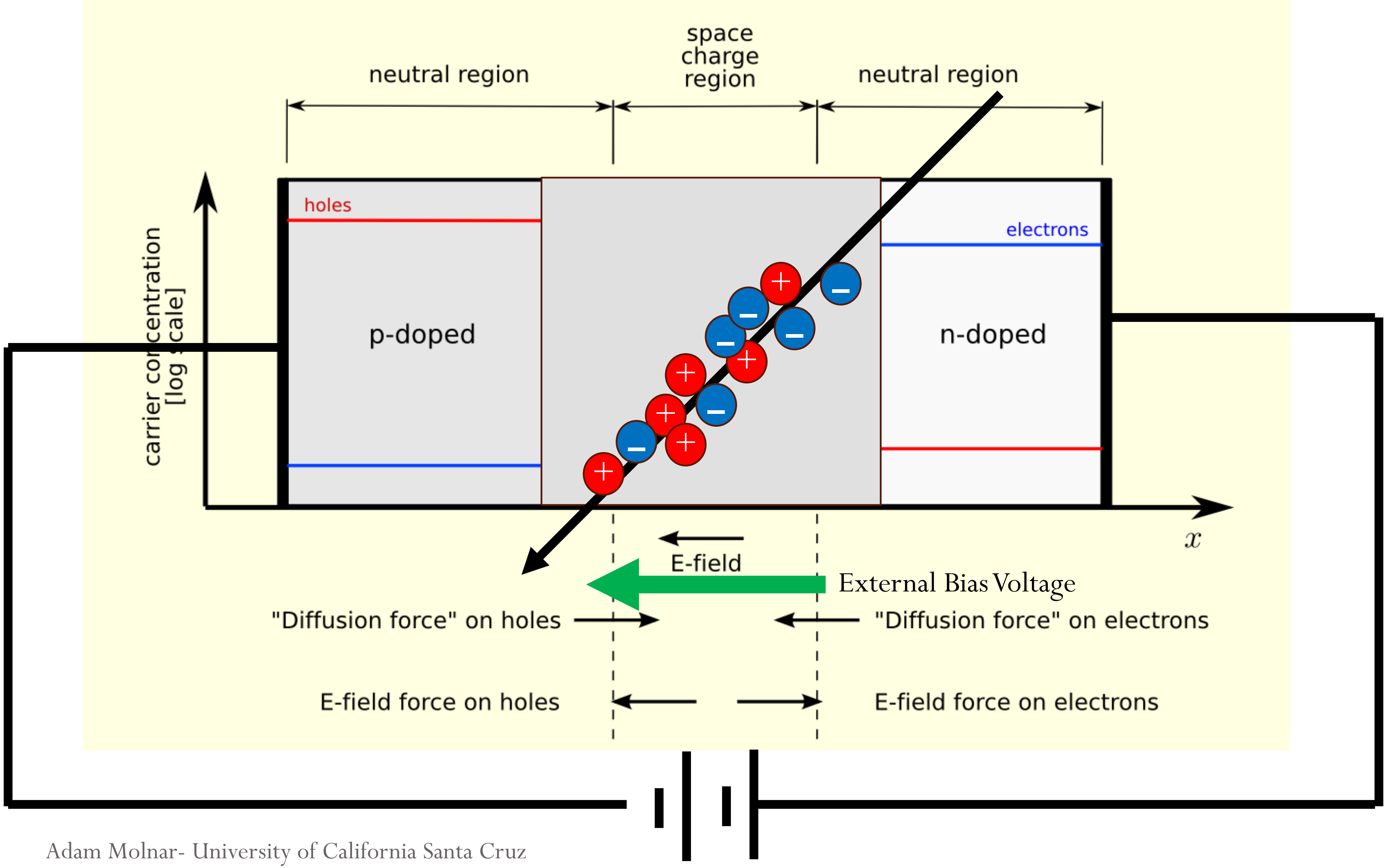

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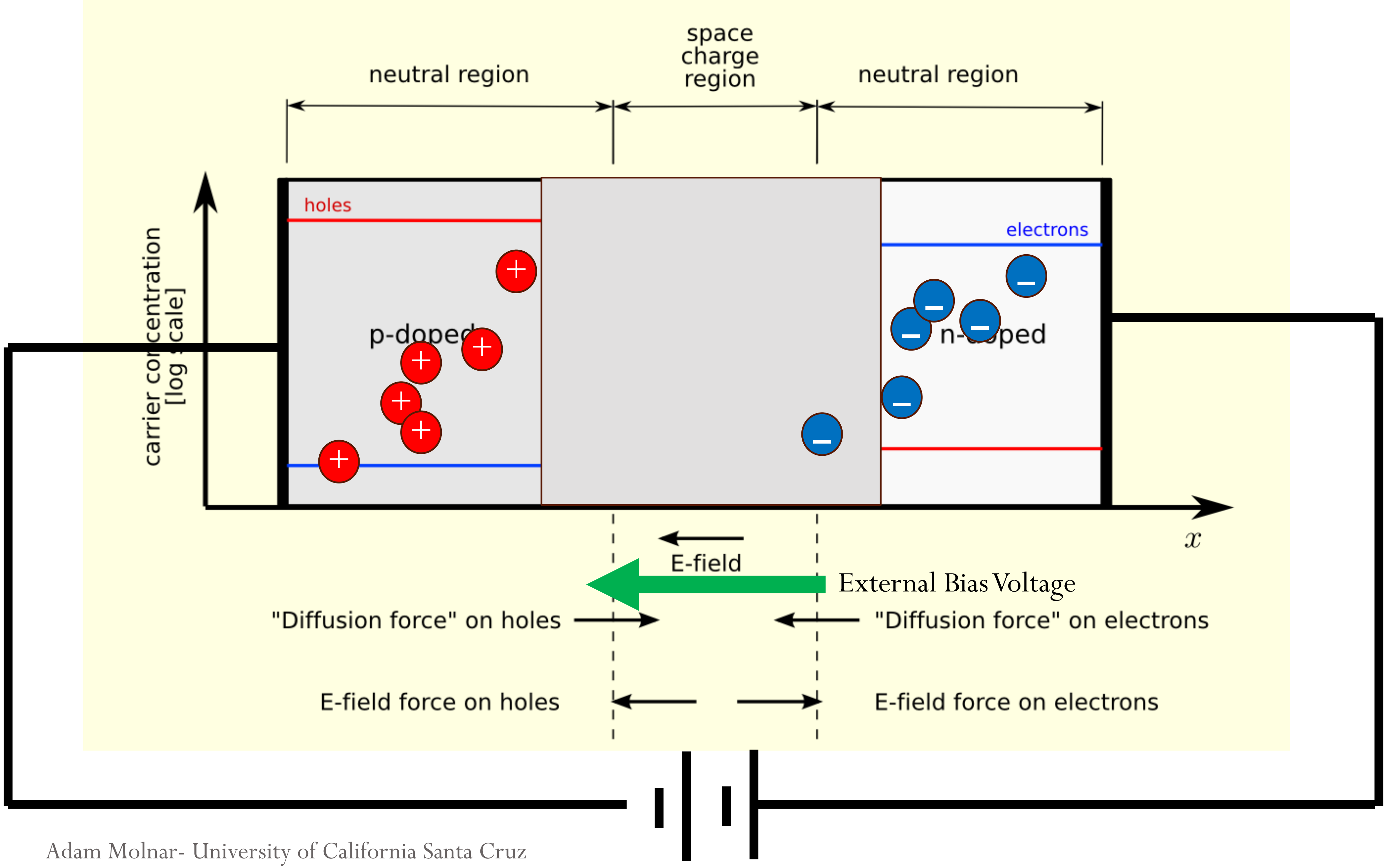
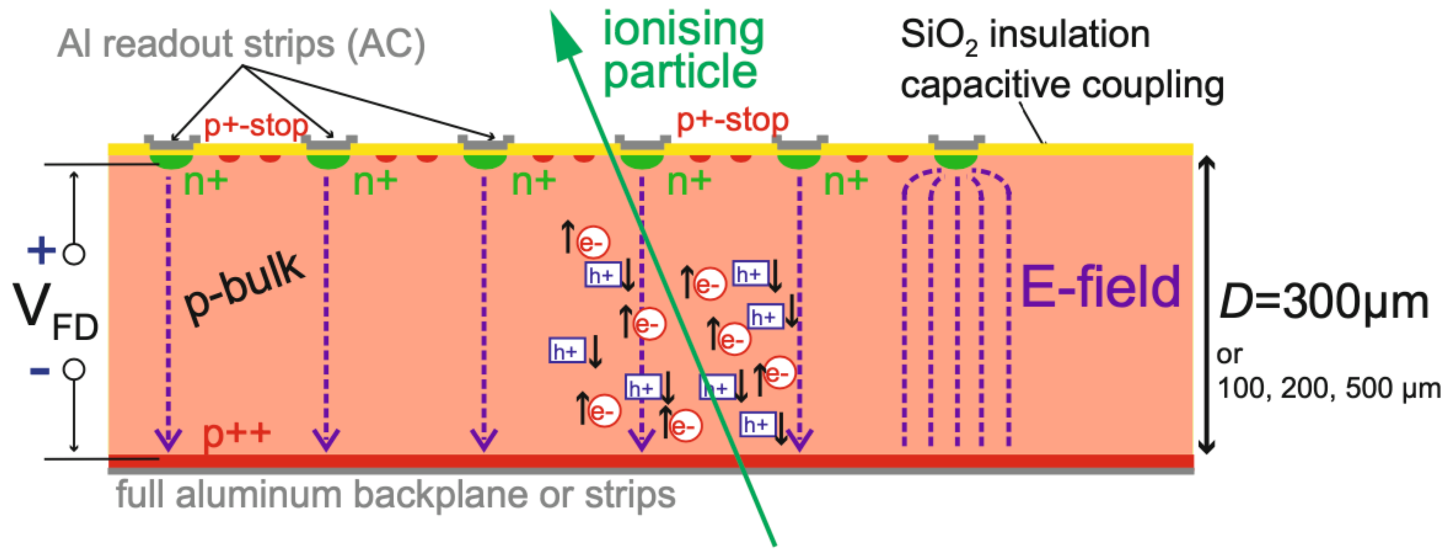
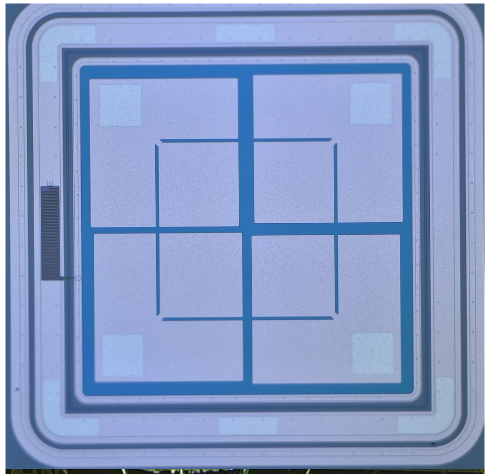


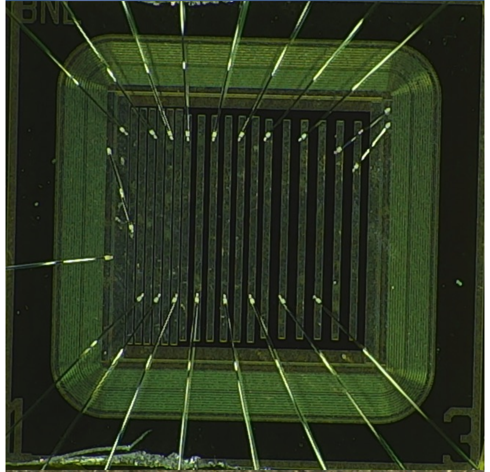
Position Measurement/Standard Silicon Sensor



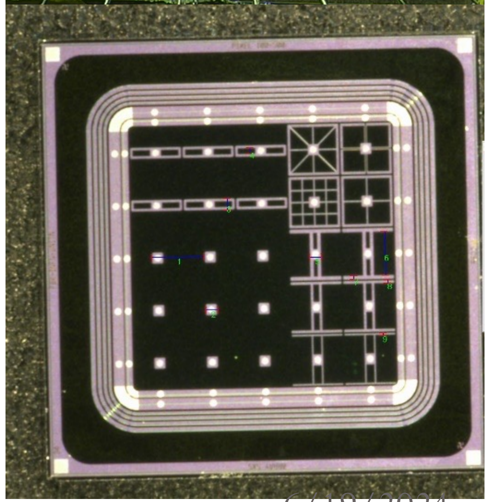
Silicon Pixels



Silicon Strips

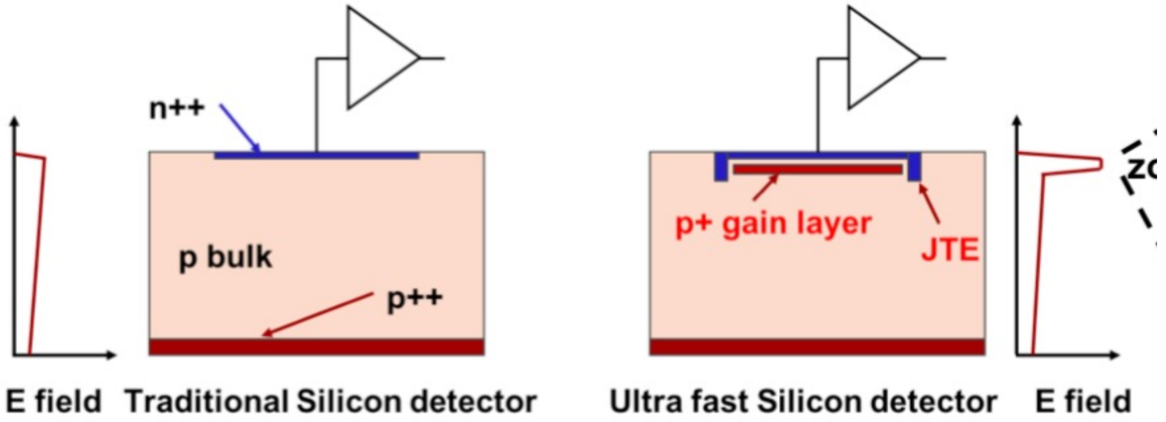


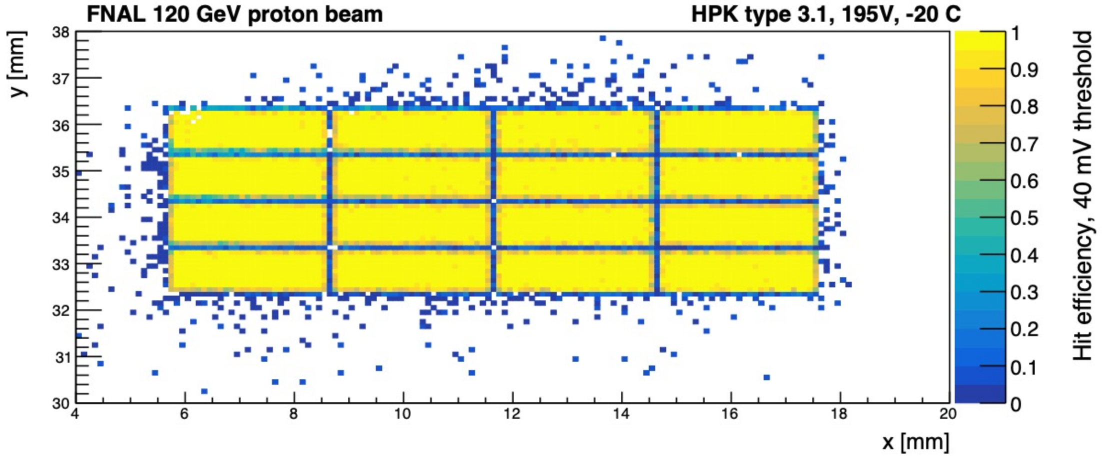
Novel Geometries (Microstrips)



What if I also want timing? Low Gain Avalanche Detectors (LGADs)

- LGADs or Low Gain Avalanche Detectors are a next generation silicon detector technology that improves the timing capability of silicon detectors by adding a region of high gain amplifying intrinsically fast but small signals
- Timing resolution of O(10ps) and spatial resolution (10μm)
- Major downfall of traditional LGADs is the necessity of terminating junction extensions for the high field implants reducing fill factor

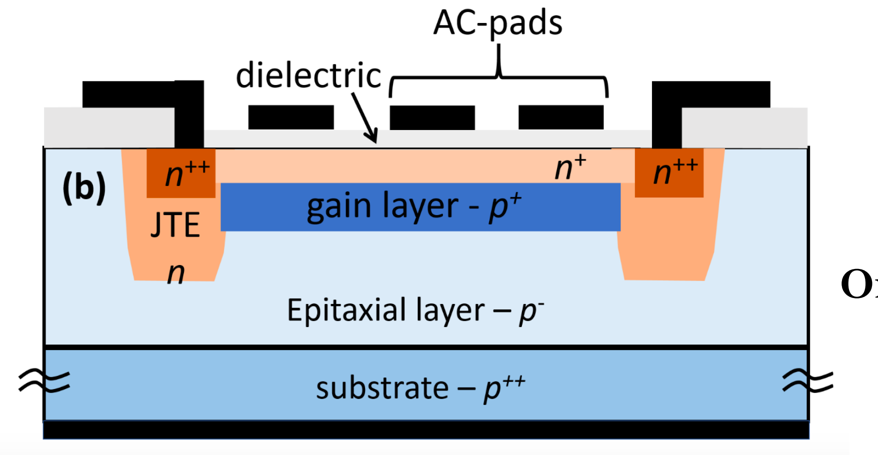




Efficiency plot showcasing LGAD fill factor

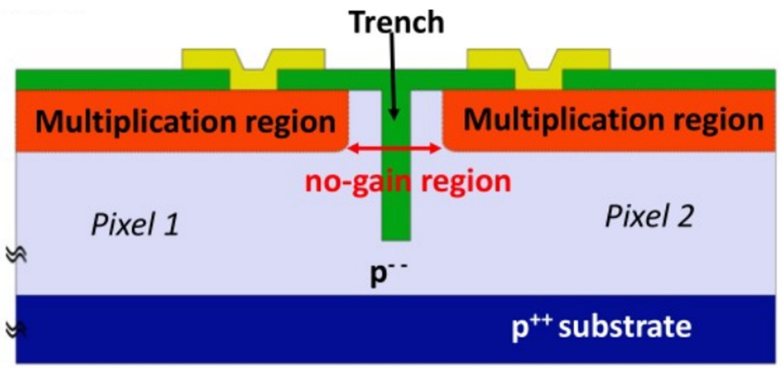
Silicon Sensor Breeds and Challenges for PIONEER

- 1.25 fc (7800 e^-) for the minimum ionizing particle (MIPs) traveling through 120μm thick silicon
- Nominally, the ATAR will have 48 layers of 120μm thick 200μm pitch silicon sensors
- Each LGAD type has its own challenges and advantages
- Additionally, a traditional Silicon PiN diode sensor is being considered as an alternative design to an LGAD sensor



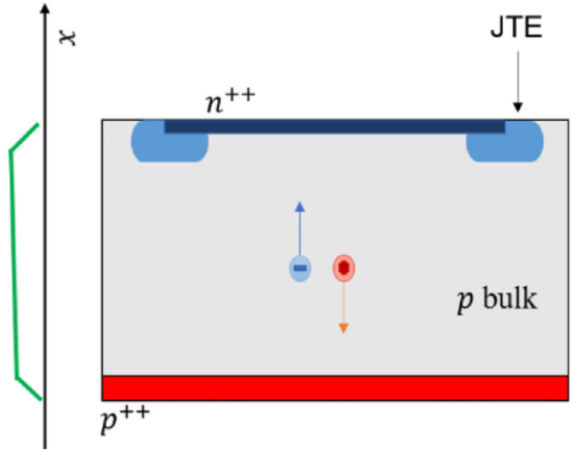
AC-LGAD

Or



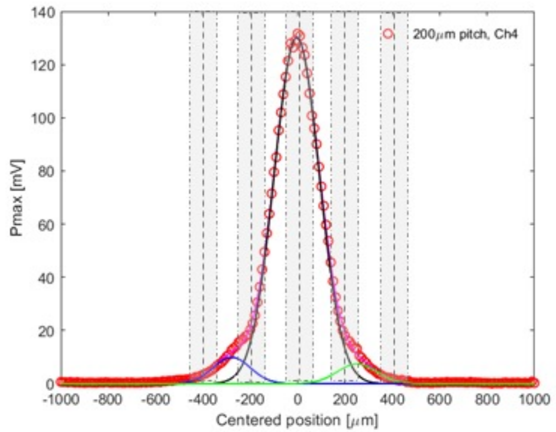
TI-LGAD

Or

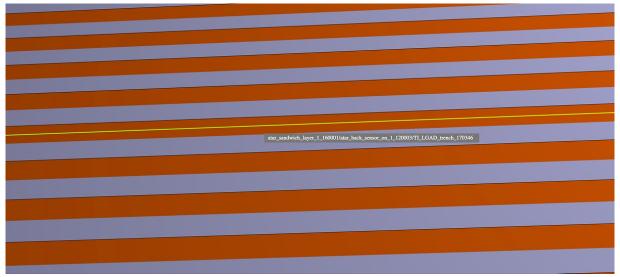


PiN

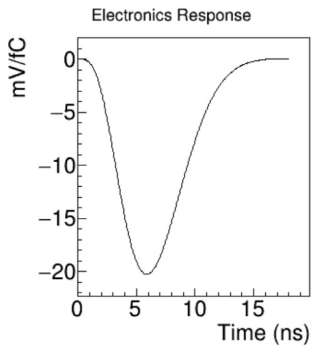
Detector Response



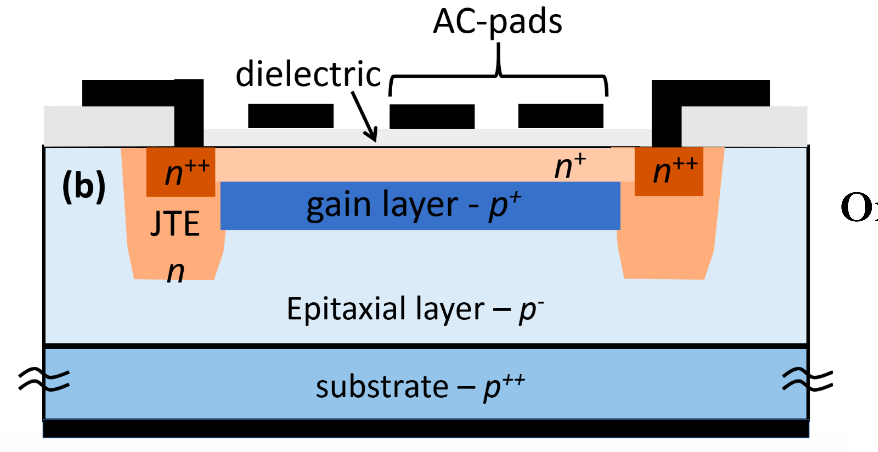
AC-LGADs exhibit a mechanism known as charge sharing. Currently implementing a charge sharing model in the simulation.



Implemented TI-LGADs into the PIONEER simulation by a geometry only approach. Trench regions considered dead material.

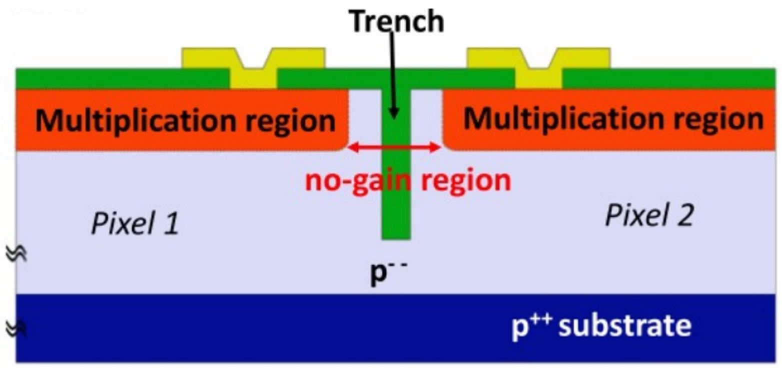


PiN Sensors have intrinsically very fast signals, but without gain are quite tiny. To make PiN sensors feasible for the ATAR experiment dedicated cold electronics research and development would be necessary.



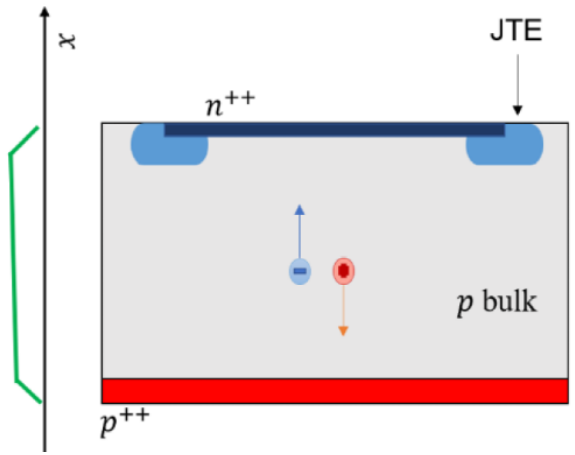
AC-LGAD

Or



TI-LGAD

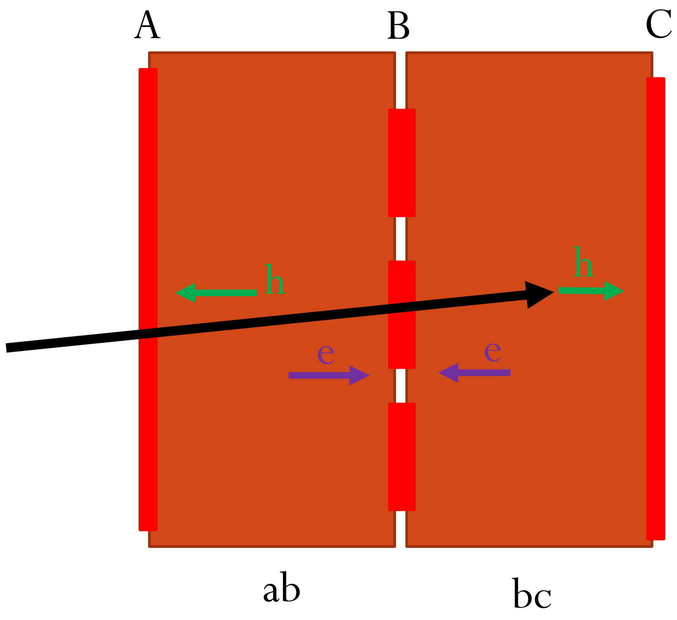
Or



PiN

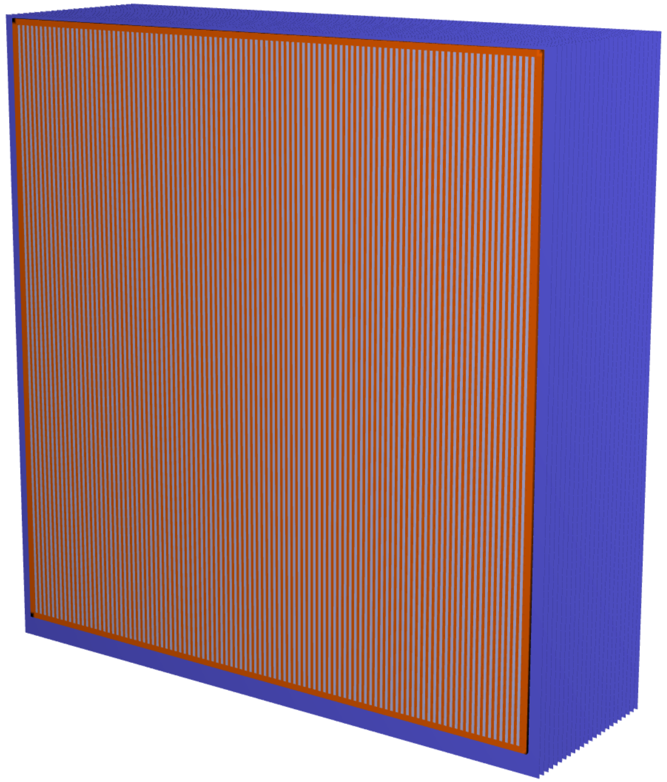
Double Sided Variant PiN Sensors

- Another technology being considered for the PIONEER experiment are double sided silicon detectors (developed at BNL) can either be LGADs or PiN type sensors
- This would allow for x and y directionality in one layer of the ATAR and minimization of dead material
- First prototype Sensors from BNL are being studied at SCIPP
- Reduction of nominal 25μm air gap (aiming to be below 5μm)



ATAR Active Region Basics

- PIONEER's nominal ATAR will consist of 48 layers of LGAD silicon sensors
- The bulk thickness of the sensors are 120μm
- Each layer will have 100 strips per layer each of these are considered as independent active volumes in the simulation
- At this point of time there is no nominal LGAD choice, but TI-LGADs and AC-LGADs are being investigated



Adam Molnar- University of California Santa Cruz

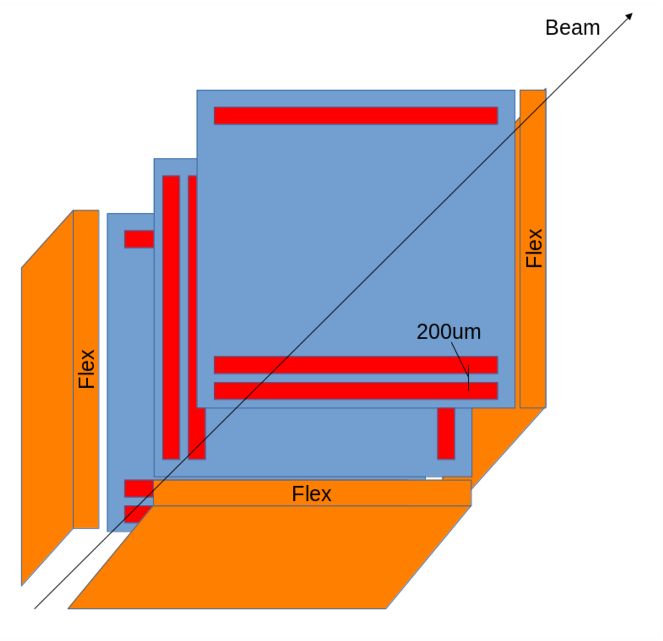
Why the Nominal* Values

120µm Bulk Thickness	200µm Pitch	LGAD	48 Layers	2x2cm
Thinnest self supporting sensor, also want the sensor thin for granularity and repetition rate	Balance between getting enough points of the muon track, but keeping overall channel count low along with having a geometry that can easily be matched to a flex/PCB	Better S/N ratio than standard PIN, better timing resolution, and allows the use of a fast amplifier for an increased, fast repetition rate	From the beam profile, the pions stop on average after 24 layers (dependent on bulk thickness)	From the beam parameters this is the shape that fits the "supposed" pion beam

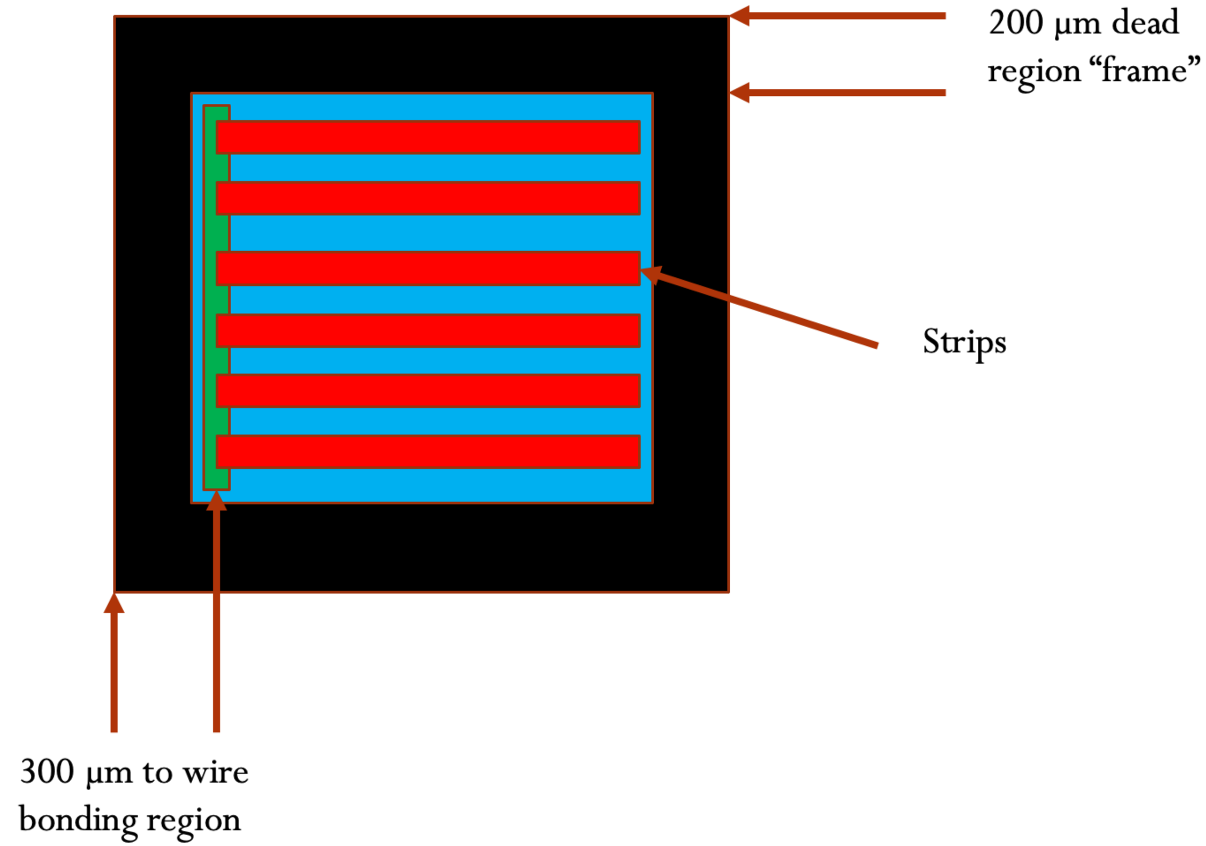
Asterisk, as these parameters are the initial stab at a design but will likely change as our ATAR simulation campaign begins

Tour Through the Nominal (Single sided) ATAR

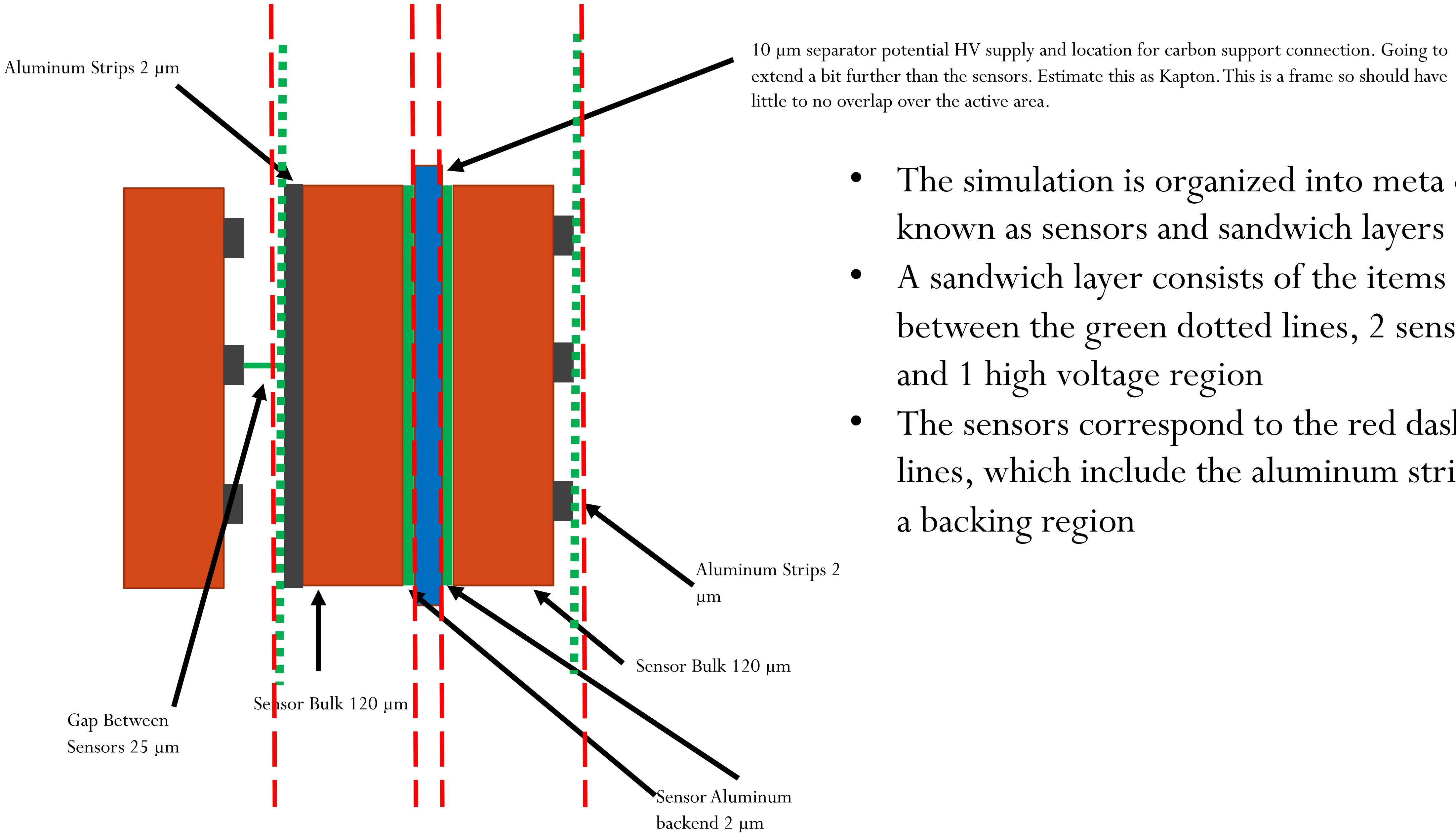
Sensors staggered for readout. Each layer has 2 sensors. Each layer will oscillate but only the "front" and "back" sensors. For example layer 1 sensor 1 will be read out on the right and layer 1 sensor 2 the bottom. Then layer 2 sensor 1 will be read out left and layer 2 sensor 2 top.



Staggering by 300 μm total 200 for dead region than an extra 100 μm



Tour Continued - ATAR Meta Objects

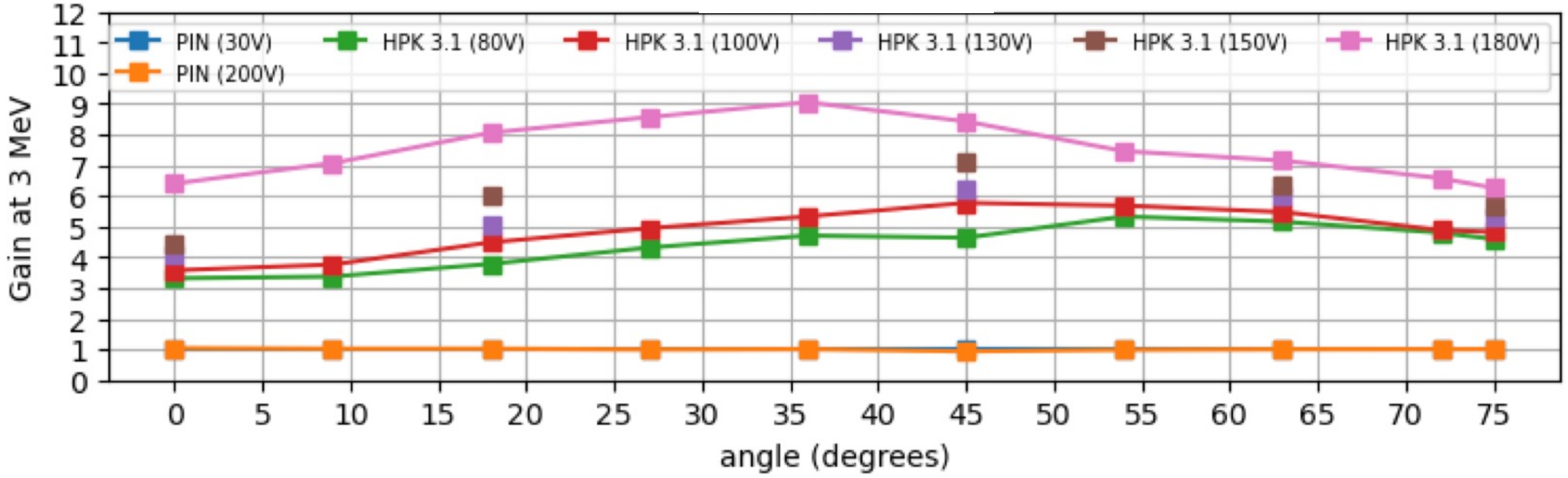


- The simulation is organized into meta objects known as sensors and sandwich layers
- A sandwich layer consists of the items in between the green dotted lines, 2 sensors and 1 high voltage region
- The sensors correspond to the red dashed lines, which include the aluminum strips and a backing region

ATAR Other Issues: Gain Saturation (LGADs Only)

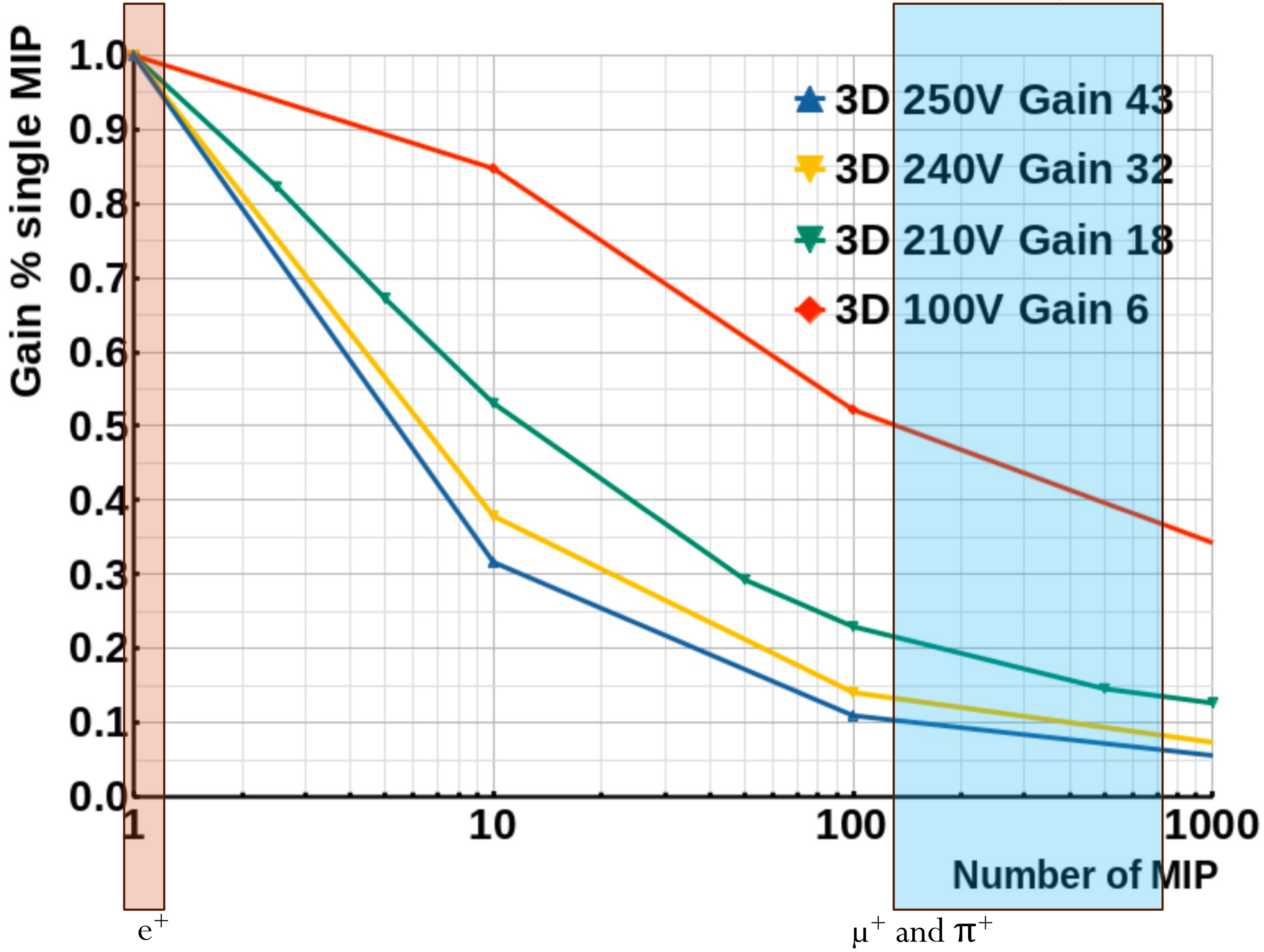
- For the PIONEER experiment it will be critical to differentiate the ionization deposit differences of positrons, muons, and pions
- LGADs exhibit the behavior of gain suppression where the space charge cloud reduces the amplification field
- It is crucial that PIONEER is able to unfold the non linear gain saturation response of the LGADs in the ATAR

3 MeV Protons from CENPA Tandem Accelerator



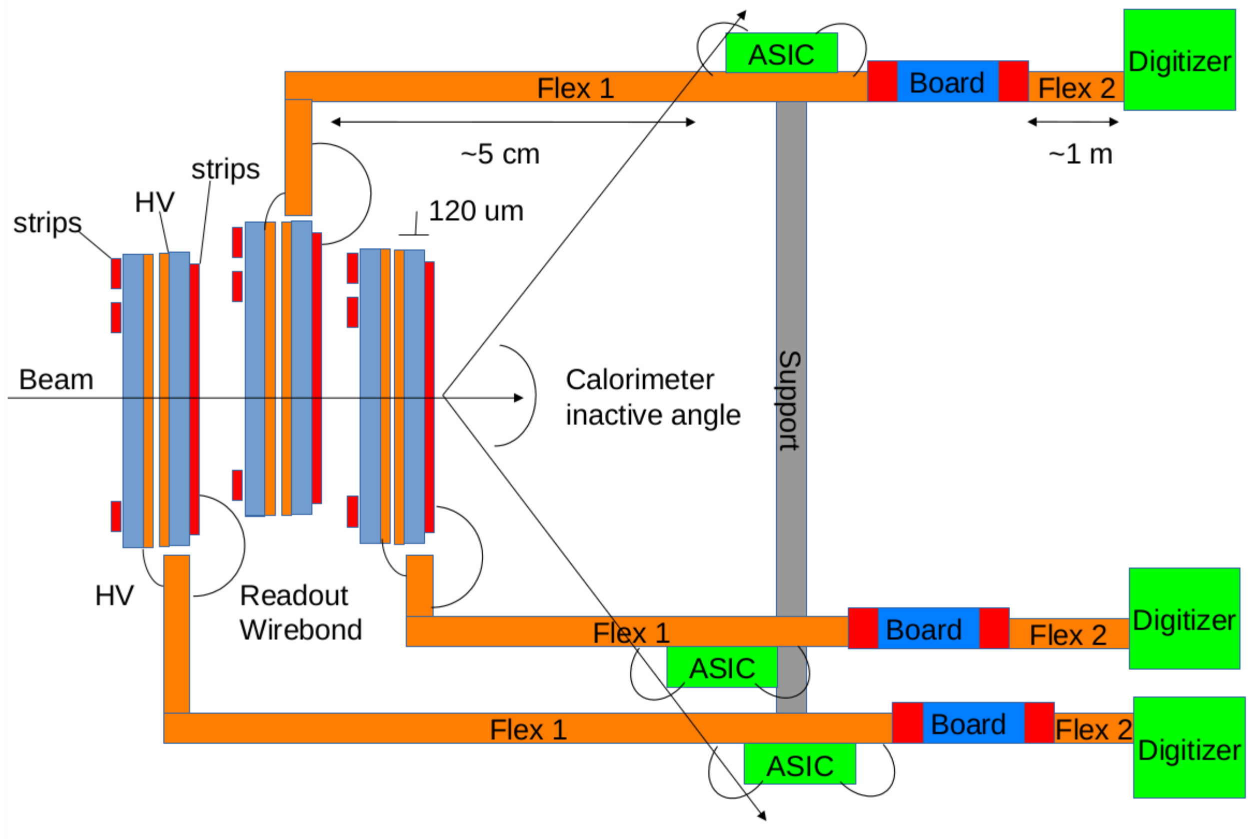
ATAR Other Issues: Gain Saturation (LGADs Only)

- Lower gain reduces the gain saturation effect
- Moving towards lower gain nominal design



ATAR Other Issues: Flex and ATAR Mechanics

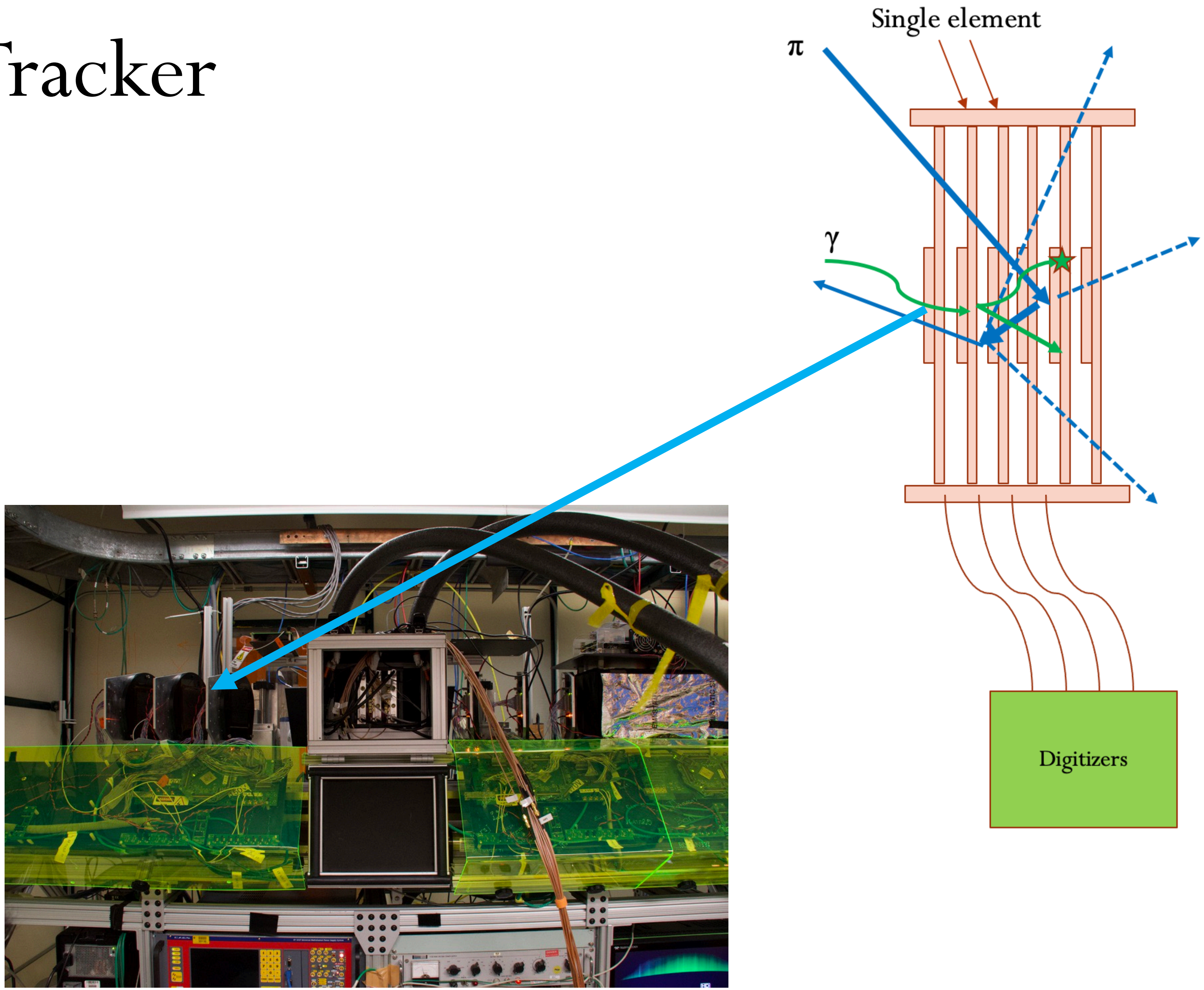
- Dead material is critical to reduce as much as possible in the ATAR
- Subsequently the current plan is to have a flex cable routing the signals out of the ATAR and to a readout board
- From there the read out board will be routed to a downstream digitizer
- There has historically been a lot of issues with crosstalk in the flex this is less of an issue than before
- Much much discussion about how exactly the ATAR mechanics along with the DTAR and Tracker will work



Generalizing to a 5D Tracker

- The future of many fields of physics instrumentation require test beam experimentation
- Growing need for high rate studies with great spatial and timing precision

- The PIONEER ATAR can be straightforwardly generalized to a setup that can be input into dozens of test beams facilities throughout the world
- Giving excellent spatial granularity, spectacular timing response, good energy resolution, and high dynamic range



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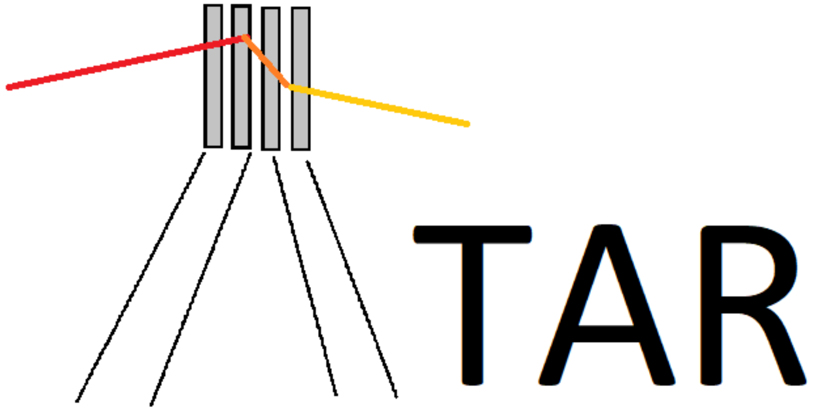
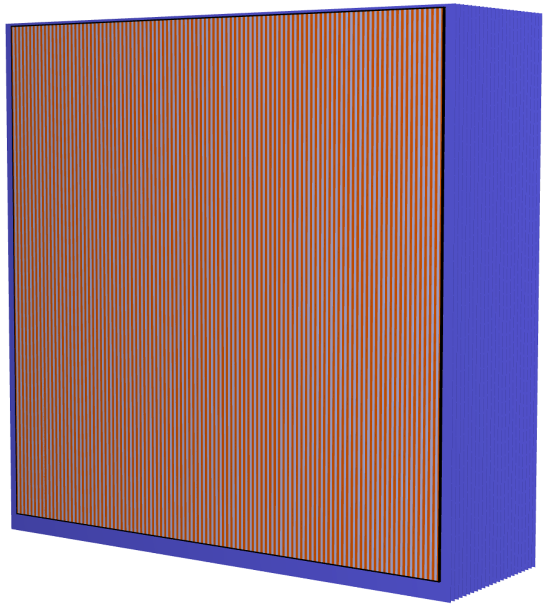
Conclusions

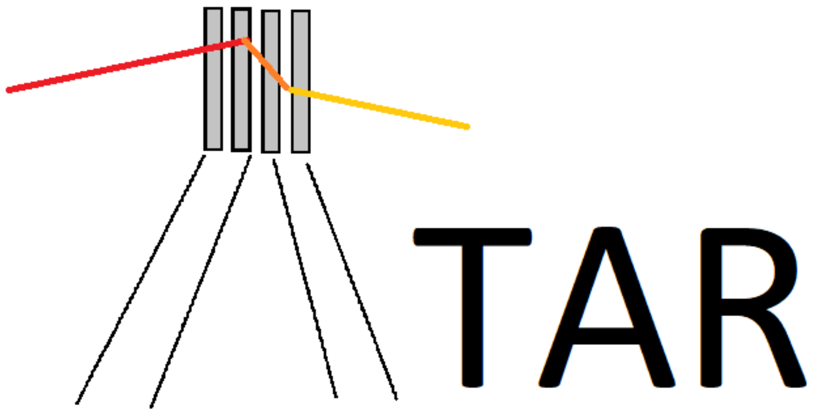
- PIONEER is an exciting experiment probing many hot physics topics to an extreme precision (LFU violation, exotic searches, and PiBeta)
- The ATAR is an ambitious detector requiring much research and development and will be a particularly challenging system integration problem
- ATAR has many design choices that need to be answered through simulation: silicon sensor type, double sided sensors, dead material, etc.
- Once completed the ATAR can be generalized to upgrade existing test beam facilities

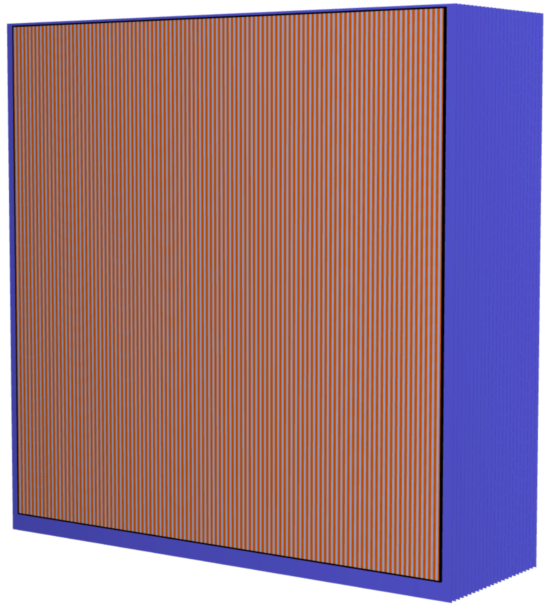




ATAR Takeaways

- 48 layers of 200 micron strip pitch silicon strip detectors
- Minimizing dead material in the ATAR is critical
- ATAR has many design choices that need to be answered through simulation: silicon sensor type, double sided sensors, dead material, etc.
- The optimization space is large and as of now underexplored
- Understanding gain suppression is critical





Back Up

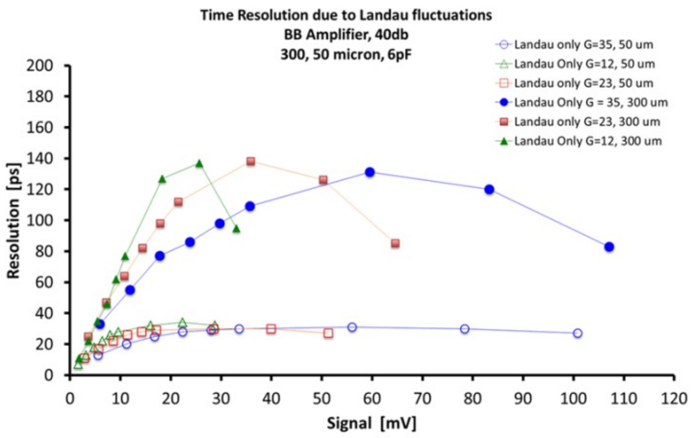
LGAD Timing Resolution

The timing resolution in silicon sensors can be expressed as the sum of four terms time walk σ_{TW}, time jitter σ_J, Landau fluctuations σ_L and TDC binning σ_{TDC}:

$$\sigma_t^2 = \sigma_{TW}^2 + \sigma_J^2 + \sigma_L^2 + \sigma_{TDC}^2$$

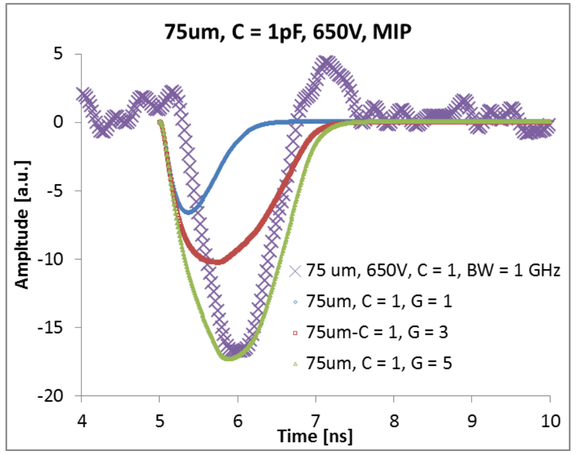
The first two terms are inversely proportional to the slope dV/dt
-> **need fast (i.e. thin sensors) and large pulses (i.e. gain) .**

One reason for thin sensors and low thresholds are the Landau fluctuations seen in beam tests and simulated with WF2:



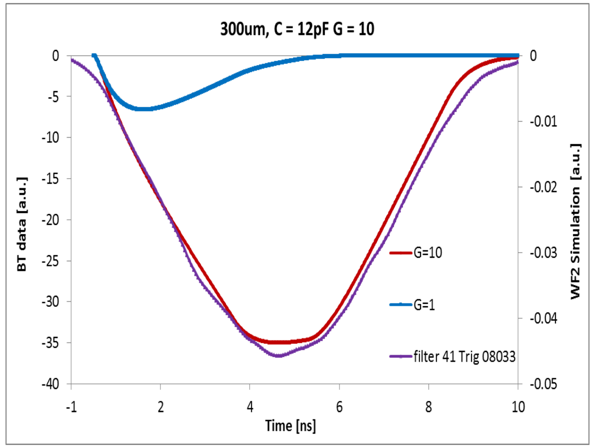
Weightfield2 (WF2) simulations of 75 and 300µm LGAD reproduce the observed pulse shapes

75 µm LGAD, β's



G ~ 5, τ_{Rise} = 500ps

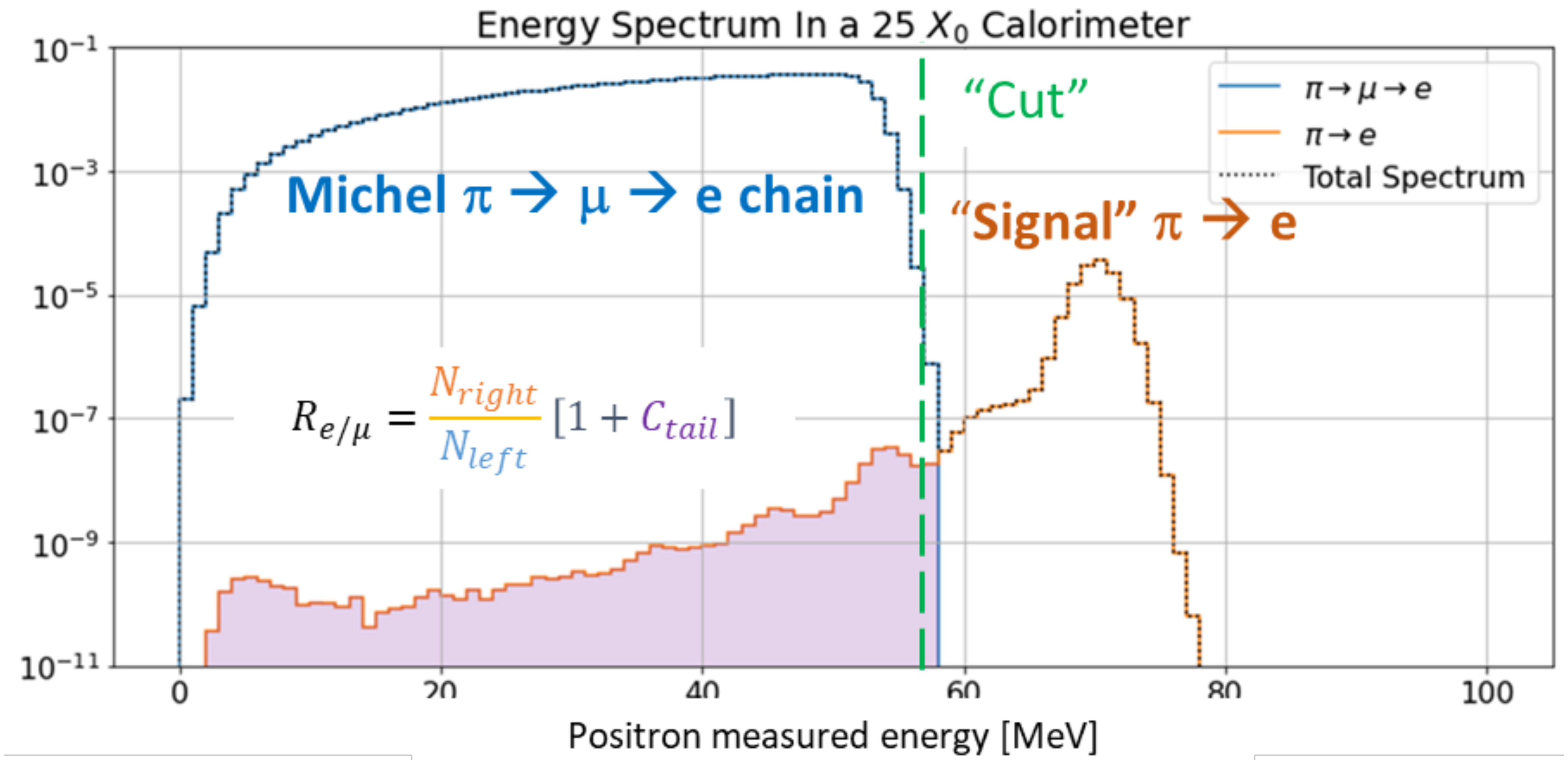
300 µm LGAD, 120 GeV π's



G ~ 10, τ_{Rise} = 5ns

Stolen from Hartmut Sadrozinski

WF2: N. Cartiglia et al,



Energy Spectrum In a 25 X_0 Calorimeter
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
0
20
40
60
80
100
Positron measured energy [MeV]
"Cut"
$\pi \to \mu \to e$
$\pi \to e$
Total Spectrum
Michel π → μ → e chain
"Signal" π → e
$R_{e/\mu} = \frac{N_{right}}{N_{left}}[1 + C_{tail}]$

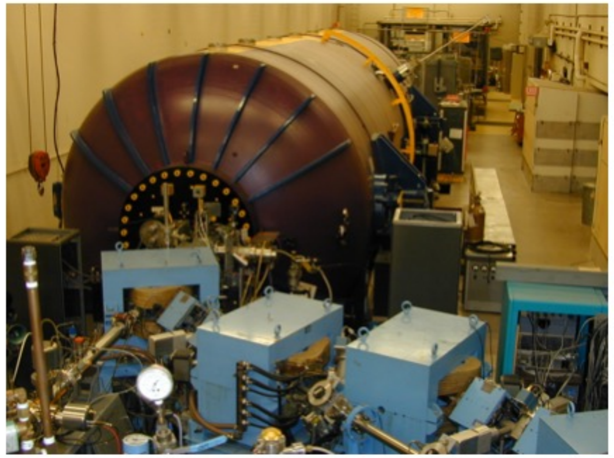
Mode			Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$\mu^+\nu_\mu$	[1]	$(99.98770 \pm 0.00004)\%$		30
Γ_2	$\mu^+\nu_\mu\gamma$	[2]	$(2.00 \pm 0.25) \times 10^{-4}$		30
Γ_3	$e^+\nu_e$	[1]	$(1.230 \pm 0.004) \times 10^{-4}$		70
Γ_4	$e^+\nu_e\gamma$	[2]	$(7.39 \pm 0.05) \times 10^{-7}$		70
Γ_5	$e^+\nu_e\pi^0$		$(1.036 \pm 0.006) \times 10^{-8}$		4
Γ_6	$e^+\nu_e e^+ e^-$		$(3.2 \pm 0.5) \times 10^{-9}$		70
Γ_7	$\mu^+\nu_\mu\nu\bar{\nu}$		$< 9 \times 10^{-6}$	CL=90%	30
Γ_8	$e^+\nu_e\nu\bar{\nu}$		$< 1.6 \times 10^{-7}$	CL=90%	70

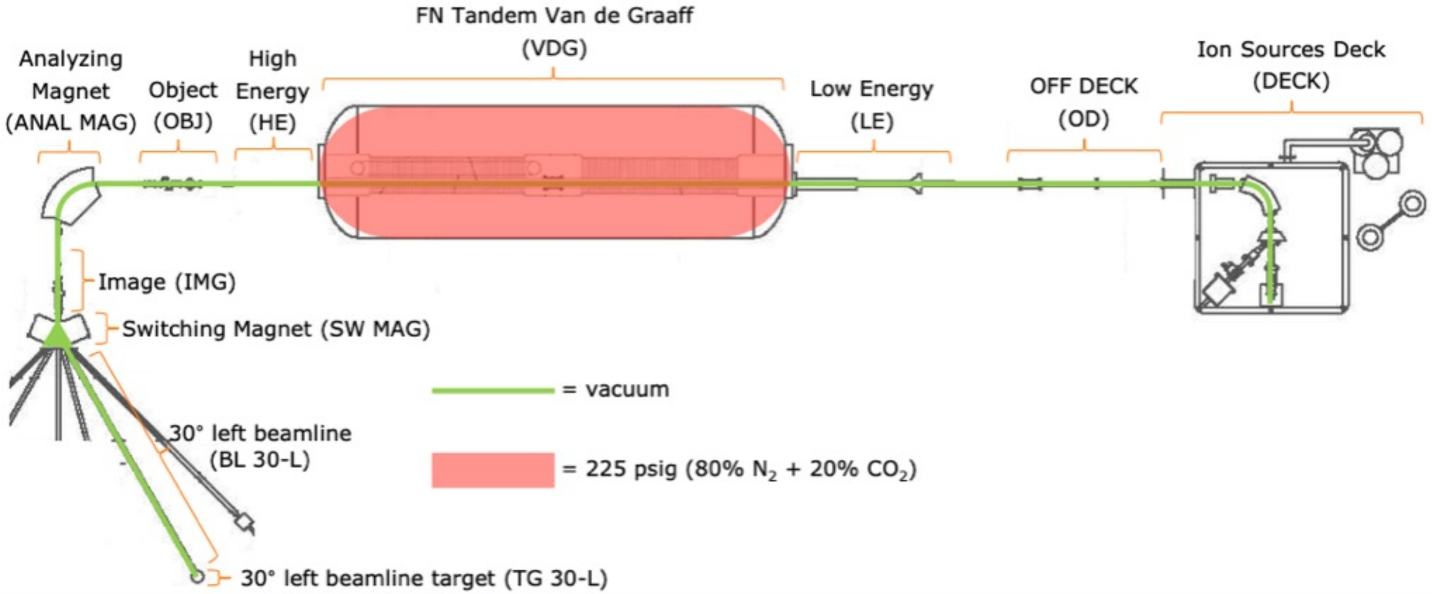
From the PDG

CENPA tandem van de Graaff accelerator

- Negatively charged ions injected from source accelerated by attractive force into tandem accelerator
- High electric potential at center of machine from van de graaff generator
- Stripper foil inside accelerator strips off electrons -> positively charged and accelerated away by repulsive force
- Two accelerations of particles
- Use hydrogen as source for proton beam

https://www.npl.washington.edu/cenpa/history#storm



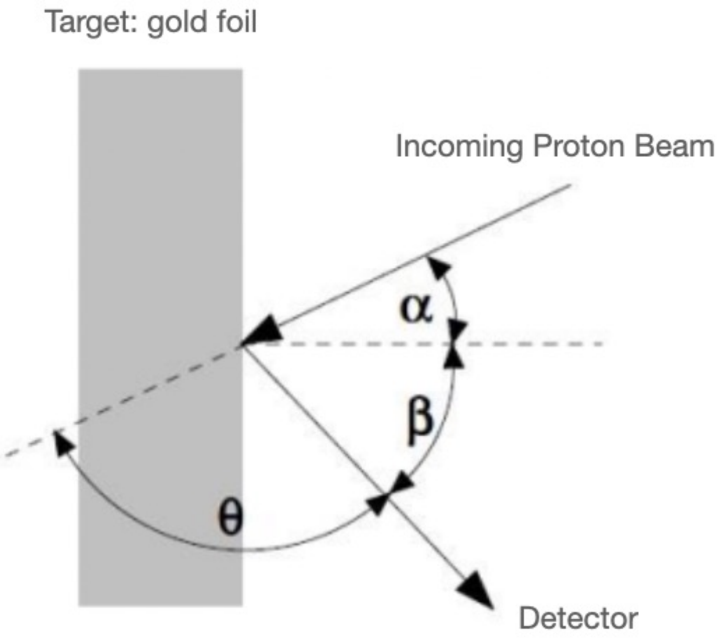


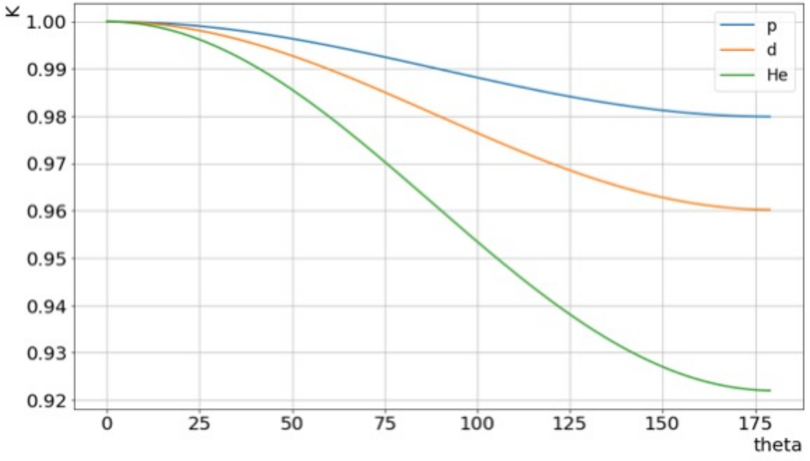
Credit to Svende Braun

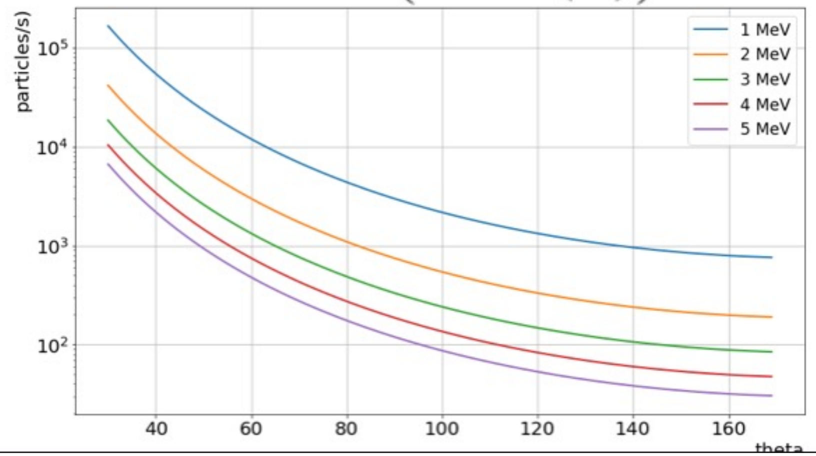
Rutherford Backscattering SpectrometryBS

- Proton beam hits gold foil target, scattering of beam into detector -> to avoid direct beam on target
- Kinematic factor k: $$k = \frac{E_1}{E_o} = \left[\frac{\left(M_2^2 - M_1^2 \sin^2\theta\right)^{1/2} + M_1 \cos\theta}{M_2 + M_1} \right]^2$$
- Scattering cross section:

$$\frac{d\sigma}{d\Omega} \equiv \sigma(\theta) = \left(\frac{Z_1 Z_2 e^2}{4E \ \sin^2\left(\frac{\theta}{2}\right)} \right)^2$$







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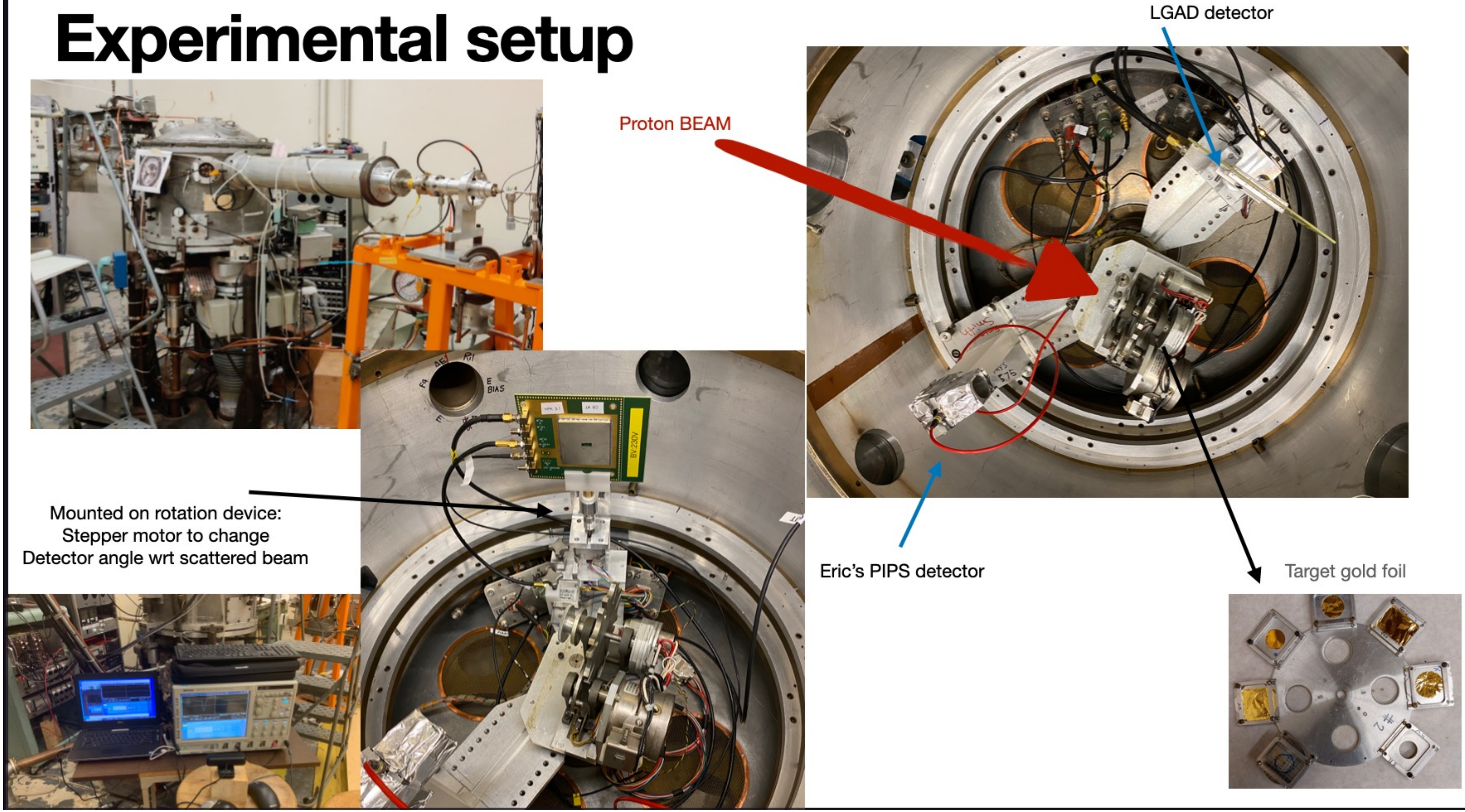
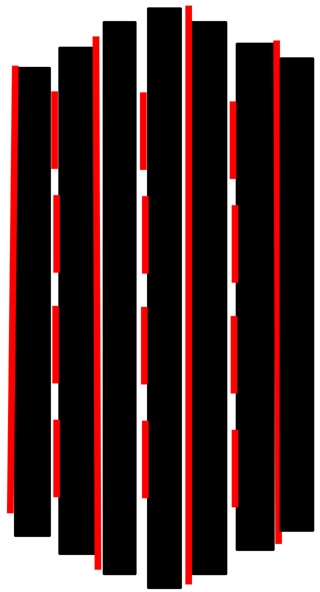
Experimental setup



Credit to Svende Braun

Concept of Alternative Design (v2.0)

- Two adjacent layers shared the same readout strips (N --anode or P -- cathode)
  - 48 layers → 49 x 100 channels (100 channels more than default)
  - 2-sided readout for each layer
  - Minimize both C_{in} and C_{ct}
  - Eliminate the gap/dead materials → 1-2 um?

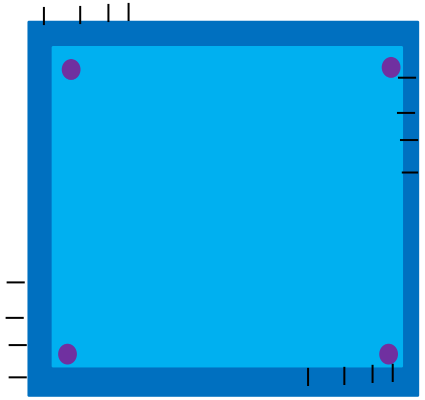


Bulk (120 um)

Readout strip (200 um pitch, 100 width)

Layers are gradually increased/decreased, so that we can readout from the sides

- Each side has about 12 (13) readout cables, separated by ~ 0.5 mm



1f → readout right

1b/2f → readout top

2b/3f → readout left

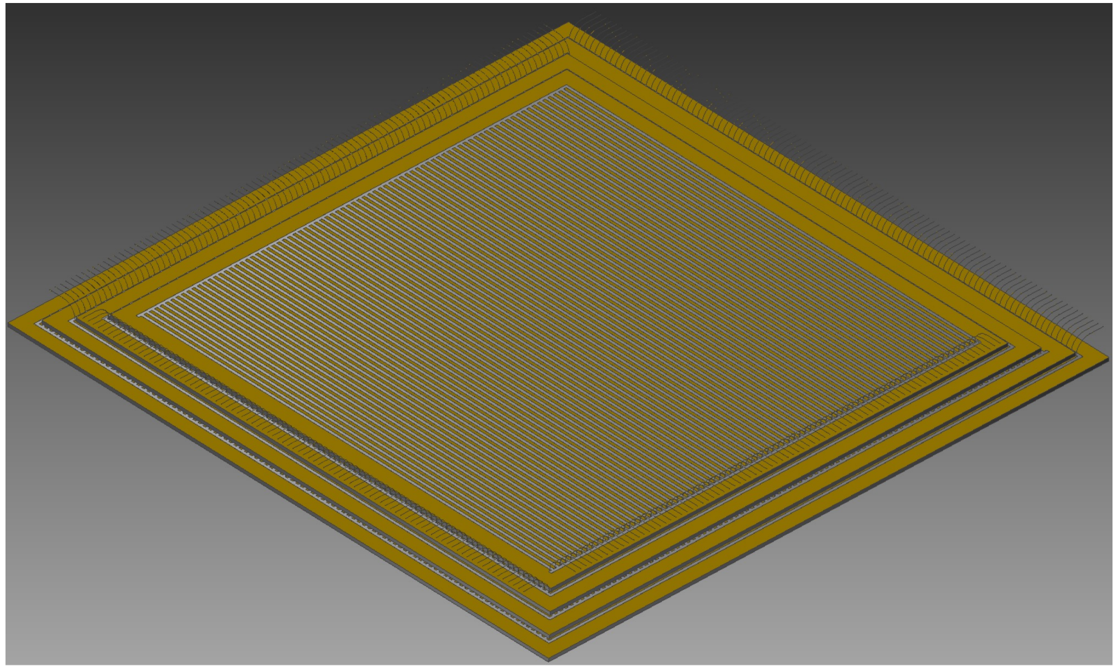
3b/4f → readout bottom

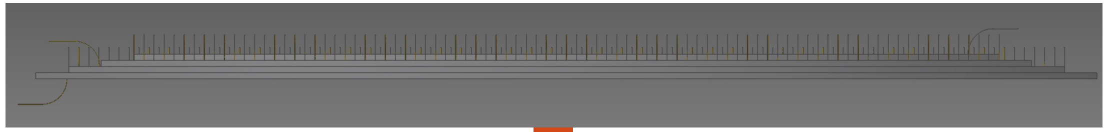
4b/5f → readout right

Anchoring points?

Mini-Unit: Pyramid Shape (Yichen)

- Base substrate size 2.11 cm x 2.11 cm x 120um, metal layer thickness 2um
- Guard ring at the edge: 0.5 mm
- Strip width: 100 um
- Gap between strips: 100 um
- Strip length: 1.99cm, 1.86 cm, 1.73 cm, 1.60 cm
- # of strips: 100, 94, 87, 81
- Strip Readout wire simulated at the end of each strip with 10 um wire size for demo, height ~ 0.5 mm





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