Low Power Sensor Concepts

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Introduction

- **The Silicon Pixel Tracker (SPT):**
  - **The main driver is low detector mass**
  - **Low mass is enabled by low detector power**
  - **Benefits the forward tracker from the reduced cooling, cables and mechanical structure**
  - **Could equally well be called "low mass pixel tracker"**
  - **The concept includes barrel and forward trackers using the same technology**
- **Low power, low noise, large pixel sensors**
  - **Large pixels with low noise are challenging in principle**
  - **Prompt charge collection and efficient data sparsification with high detection efficiency**
  - **Low average and peak power**

Low Power Sensor Concept

- Integrating tracker
  - Binary readout - only hit pixels are read out, flagged by in-pixel logic
    - In-pixel electronics should be very power efficient
  - All detector readout
    - Just a source follower in pixel, but has on-chip sparsification
- Rough calculation:
  - 30 Gpixels
  - 1 μA operating current per pixel @1.8V
  - 1% duty factor
  - Average power = 540W (but could be lower)
- For the SPT the idea is to make the signal as large as possible
  - Simplifies the in-pixel electronics, gain and power are reduced
  - Electronic noise becomes less of an issue if the signal is very large

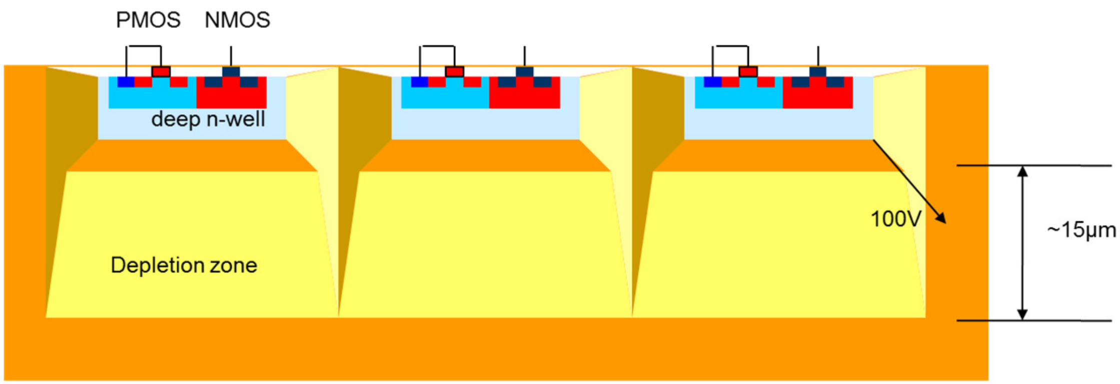
How Signal is Usually Detected in HEP

- Signal is immediately converted to voltage at the place of collection
  - Microstrips, hybrid pixels, monolithic active pixel sensors
  - The voltage is developed across the capacitance of the collecting element (a diode)
  - $\Delta V = \Delta Q / C$
  - If C is large, ΔV is small -> can increase ΔQ by making the sensor thicker (≈80 e-/µm)
- Separating the charge collection from the voltage conversion has benefits:
  - Charge-to-voltage conversion factor (CVF) does not depend on the size of the collecting element
  - The collecting element can be very large, or very small – the choice is yours
  - The sense node must be kept small to generate high voltage from small signal
- The downside:
  - Charge transfer from the collecting element to the sense node is required
  - Adds complexity

HV-CMOS for HL-LHC

HV-CMOS sensors – the structure

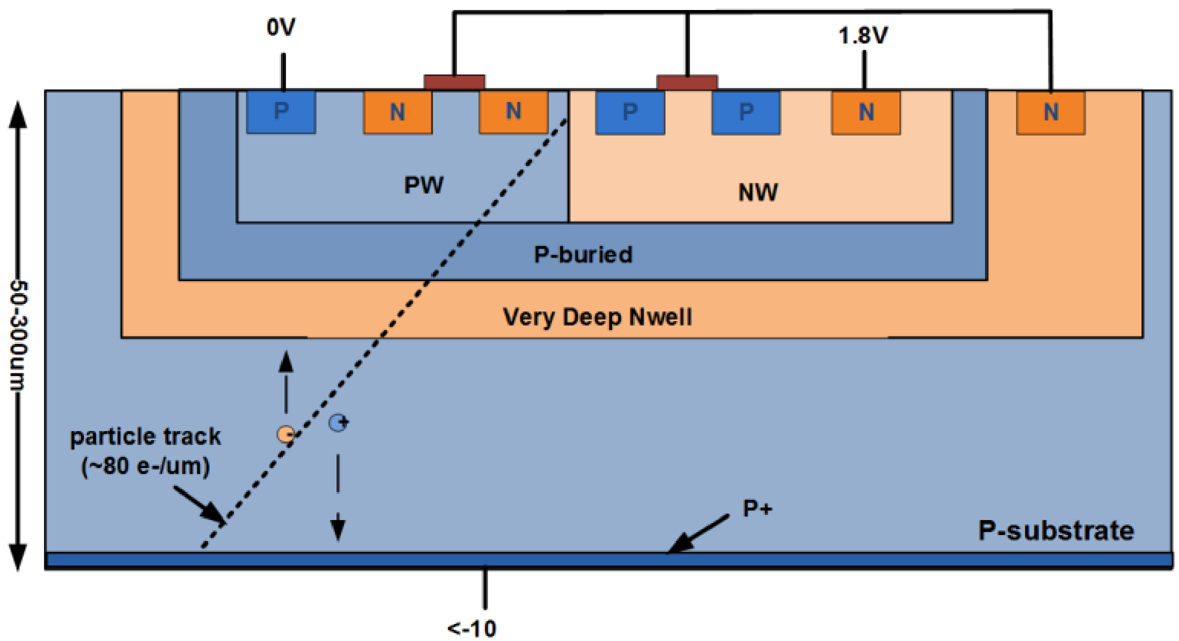
- Example AMS 350nm AMS HV: Typical reverse bias voltage is 60-100 V and the depleted region depth ~15 μm.
- 20 Ωcm substrate resistance -> acceptor density ~ 10^{15} cm^{-3}.



- **The electronics is inside the collecting diodes**
- **Modest depletion due to low resistivity silicon**
- **Far from ideal, as it stands**
  - **Large diode capacitance**
  - **Higher resistivity substrate required to deplete deeper**

Ivan Perić, Heidelberg

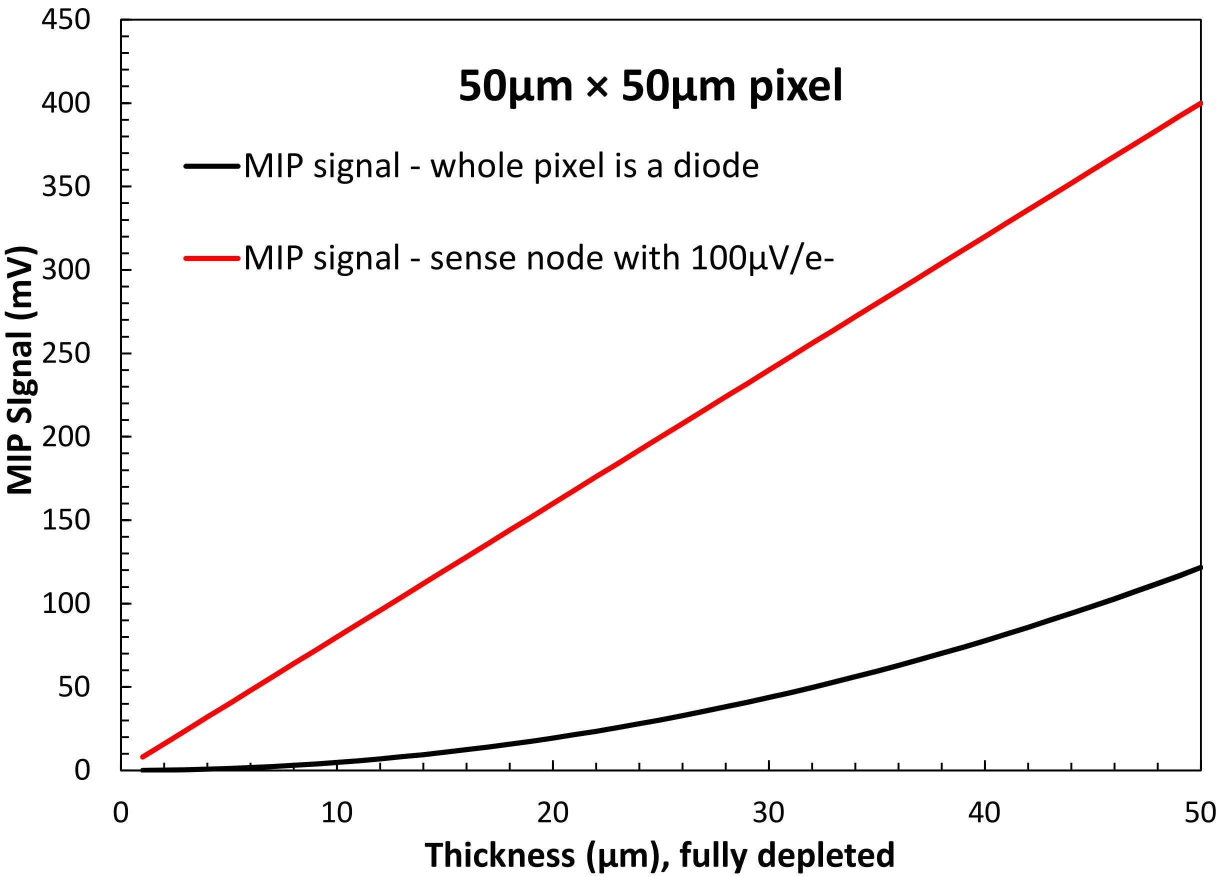
PEGASUS - Depleted MAPS (180nm)



Tomasz Hemperek, Bonn U

- Designed by Strasbourg
- 18 µm thick substrate
- Back-side biased to -20V for full depletion
- 25 µm x 25 µm pixels
- Noise ≈15 e-
- Will not scale well towards larger pixels

Small Sense Node vs. Large Diode

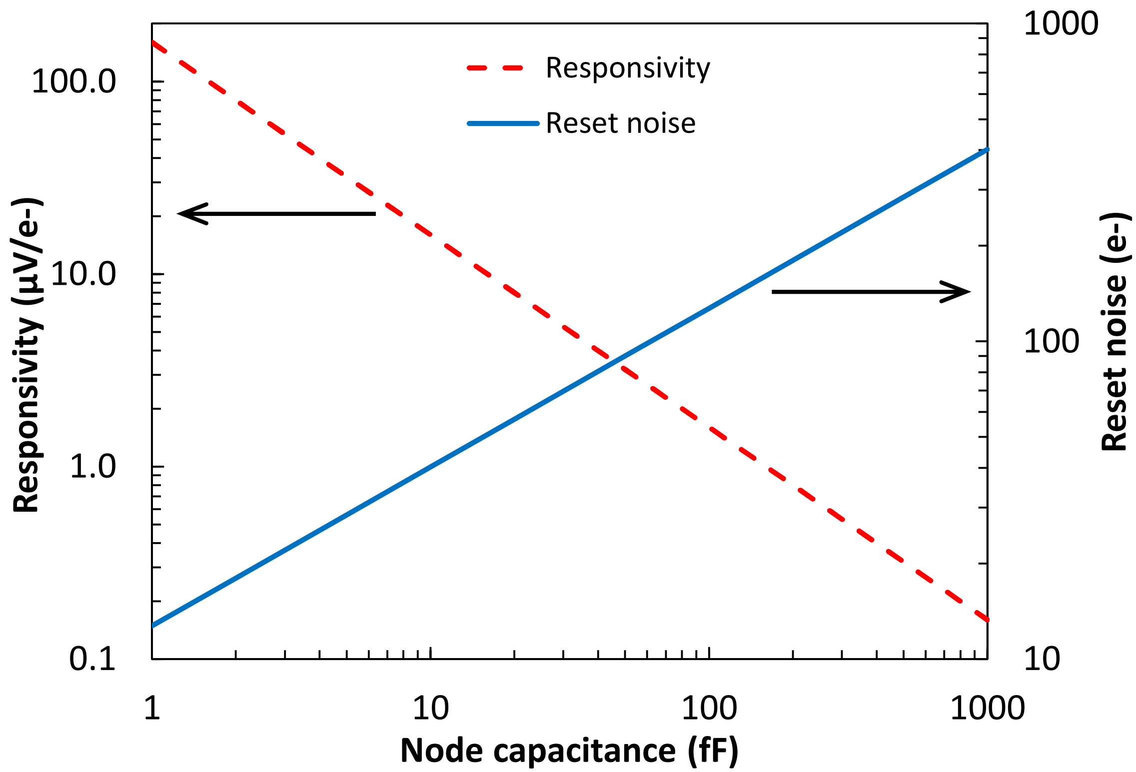


- High sensitivity node offers much higher voltage signal
- Large collecting diodes or multiple small diodes are no match
- Assuming full depletion (reduces diode capacitance)
- Larger signal requires less gain (e.g. ×3 could be fine) and less power
- Low power, noisy electronics could be OK.
- The equivalent for single photon imaging, but for MIPs

Reset Noise

Reset noise in electrons RMS: $N = \frac{\sqrt{kTC_n}}{q}$

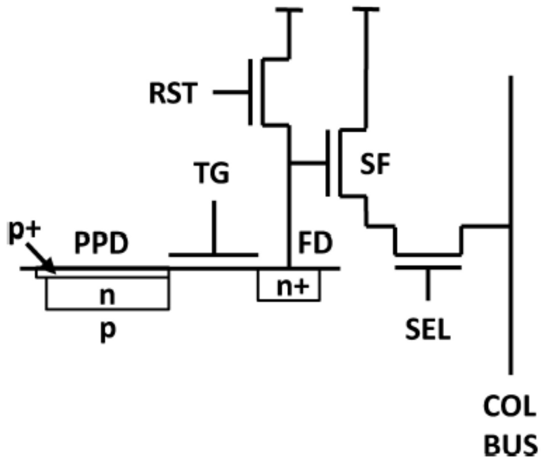
C_n (fF)	Responsivity (µV/e-)	Reset noise (e-)
1	160	12.72
2	80	17.98
5	32	28.44
10	16	40.21
20	8	56.87
50	3.2	89.92
100	1.6	127.17
200	0.8	179.84
500	0.32	284.36
1000	0.16	402.14



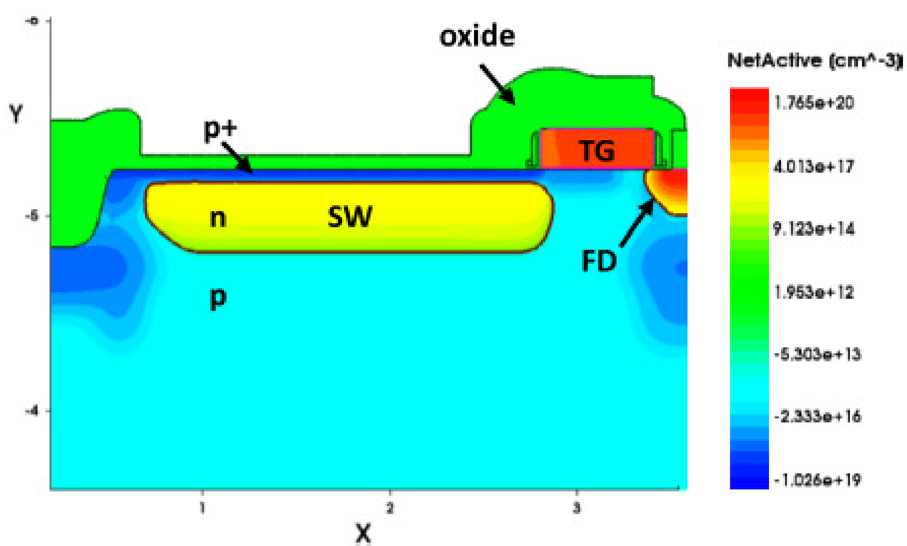
Noise Issues

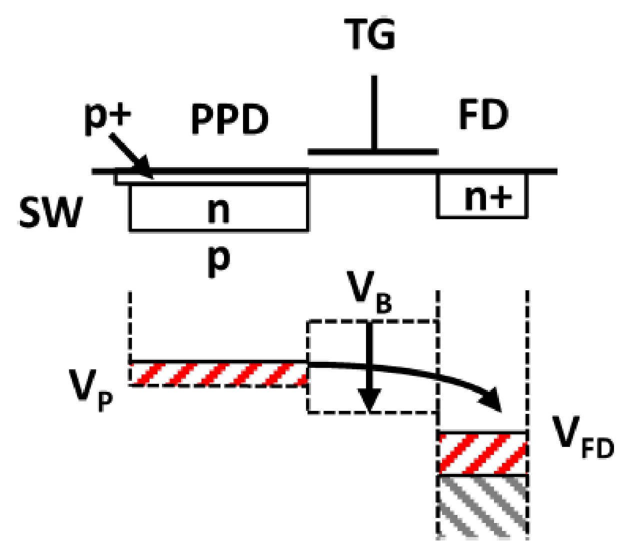
- Average signal should be 2000-4000 e- (Landau-distributed)
  - Beware of lower side tail and charge sharing
  - Many real signals will be smaller than this
- As the CVF increases reset noise becomes small
  - 16 e- RMS for 100 µV/e- sense node
  - Correlated double sampling (CDS) still required for suppression of external interference, crosstalk, supply variations, etc.
- Transistor noise (white and 1/*f*) adds another ~10 e- RMS
- Very high SNR required
  - Low amplification
  - Threshold for MIP detection should be large, e.g. > 15σ
  - Even 10σ threshold in a 30 Gpix system would produce 1.4 million fake hits

Pinned Photodiode (PPD)



- Also known as 4T pixel
- Widely used in imaging CMOS sensors with excellent performance
  - Noise could be <1 e-
  - CDS comes naturally
  - Fast enough for HD video
- Not used in HEP (yet)

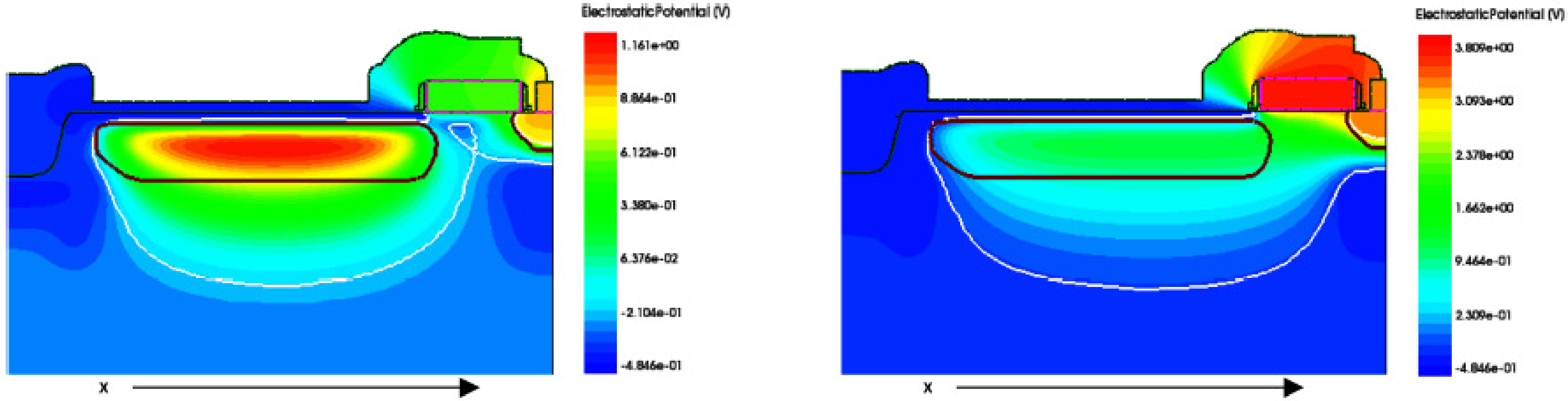




Eric Fossum, IEEE Journal of the Electron Devices Society (2014)

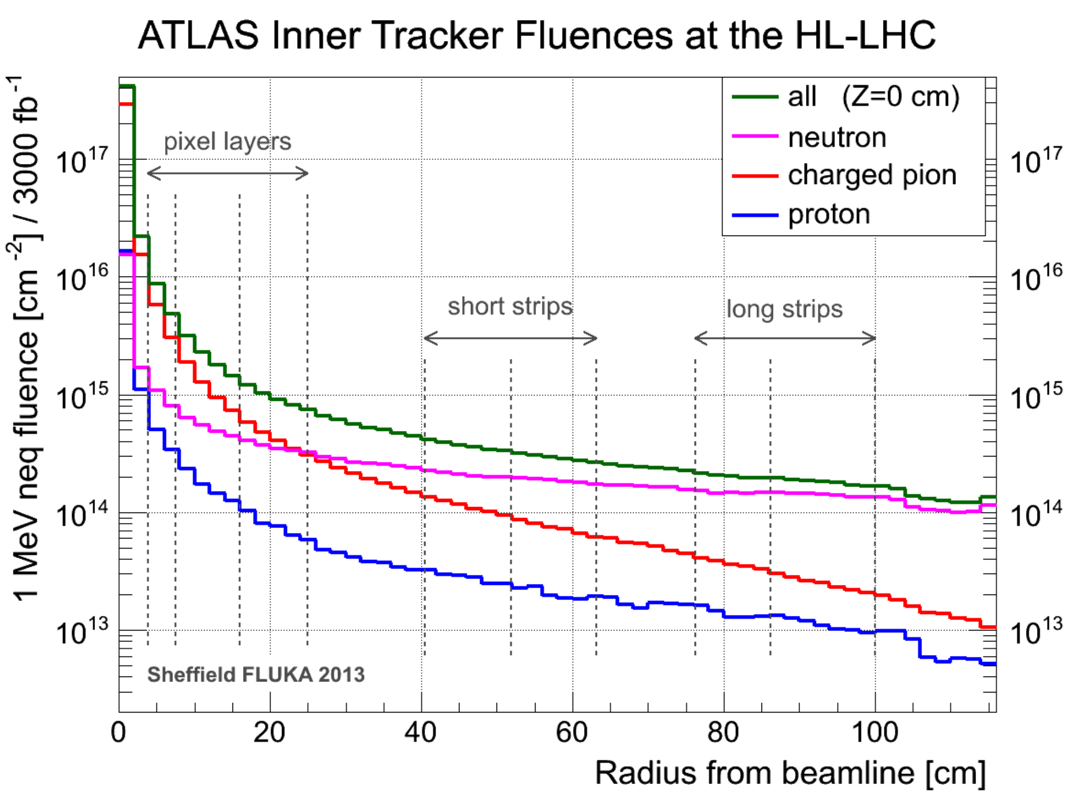
PPD Operation

Eric Fossum, IEEE Journal of the Electron Devices Society (2014)



- **Similar charge transfer happens in CCDs, but here without much electric field**
- **Charge transfer is slow (few µs)**
  - **Not a problem for an integrating tracker**
- **Photogate collection also possible – higher dark current, but charge transfer could be much faster**
- **Large pixels (50 µm) are a solvable challenge (common interests with X-ray detection)**
- **Full depletion possible too**
- **Large PPD pixel enabling integrating tracker could be a very strong proposition**

Similar Technology for HL-LHC?



- Synergies with HL-LHC could help fund detector development for ILC
- However, the radiation environment is much harsher: neutron fluence 10^{14} cm^{-2} is predicted
  - For ILC it is 5×10^{9} cm^{-2}
- Full depletion for prompt charge collection is a must, unlike for ILC
- Integrating tracker will not work for LHC, single bunch timing required
  - Power will be higher
- How to get LHC support (funding) for this?

Conclusions

- Unique features of the integrating SPT
  - Low mass enabled by low power dissipation
  - Charge transfer from a large diode to a small sense node
  - High sensitivity required to reduce power consumption
  - Binary readout
- Challenges to work on:
  - Much more detailed study required on pixel and sensor architectures
  - Pattern recognition with different degrees of integration to be proven
  - Mechanical support structure
- An opportunity for international leadership by UK institutions
- I have now a 1-year project to develop fully depleted PPD pixels – large overlap with SPT
- Could be seeking support from CERN for HL-LHC