QIE & potential use in EB VFE

Jim Hirschauer
Tom Zimmerman
(Fermilab)

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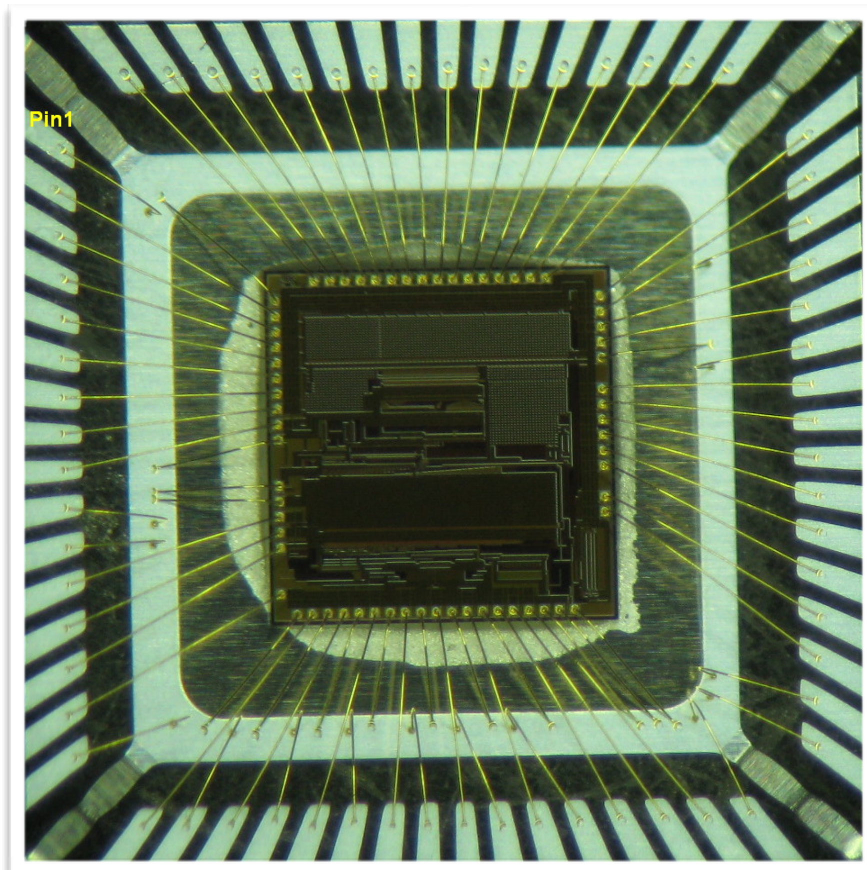
Introduction

- QIE **overview**
  - operation, response, performance, usage in HCAL, radiation tolerance
- Considerations for **EB usage**:
  - many EB channels ➔ available space on detector
  - excellent EB resolution ➔ digitization precision and dynamic range
  - timing requirements
  - radiation tolerance
- **Summary**

QIE11 overview

- **Gated charge integrator**
  - operation tested from 40-100 MHz
- **17-bit dynamic range** with **8-bit readout** (emphasis on economy of bits)
  - 4 ranges and 6-bit ADC
- **6-bit TDC** (500 ps resolution)
- **350 nm SiGe BiCMOS** process (AMS)
  - sufficient TID/neutron tolerance for HCAL barrel front-end
  - potential advantage for SEE
  - 5V @ 40 mA analog, 3.3V @ 35 mA digital (320 mW total)
- Internal **charge injection**
- Internal clock **phase adjustment**
- Input **current shunt** allows tuning of photosensor gain.

3.2mm



10mm

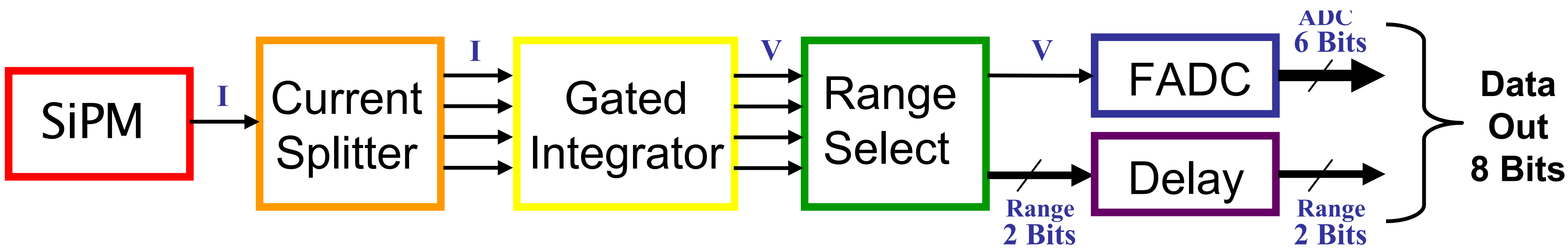
QIE history

- Designed by Tom Zimmerman since before 1995.
  - A short history of development:
    - 1989: Originally conceived by Bill Foster for **SDC @ SSC**
    - 1995: 1st fully-functional chip designed by [Tom Zimmerman]() for the **KTeV experiment @ FNAL**
      - 2 μm Orbit "Bi-CMOS", 3000 ch.
    - 1996: Front-end for calorimeters of **CDF @ FNAL**
      - 2 μm Orbit "Bi-CMOS", 10,000 ch.
    - 2002: Front-end for **MINOS Near Detector @ FNAL**
      - 2 μm Orbit "Bi-CMOS", 10,000 ch.
    - 2003: Front-end for **CMS HCAL @ CERN**
      - 0.8 μm AMS BiCMOS, 10,000 ch.
    - 2013: Front-end for **CMS HCAL** upgrade, and a ***candidate*** for **ATLAS TileCAL** upgrade
      - 0.35 μm AMS SiGe, 17,000 ch. → 27,000 ch.

Joint Development

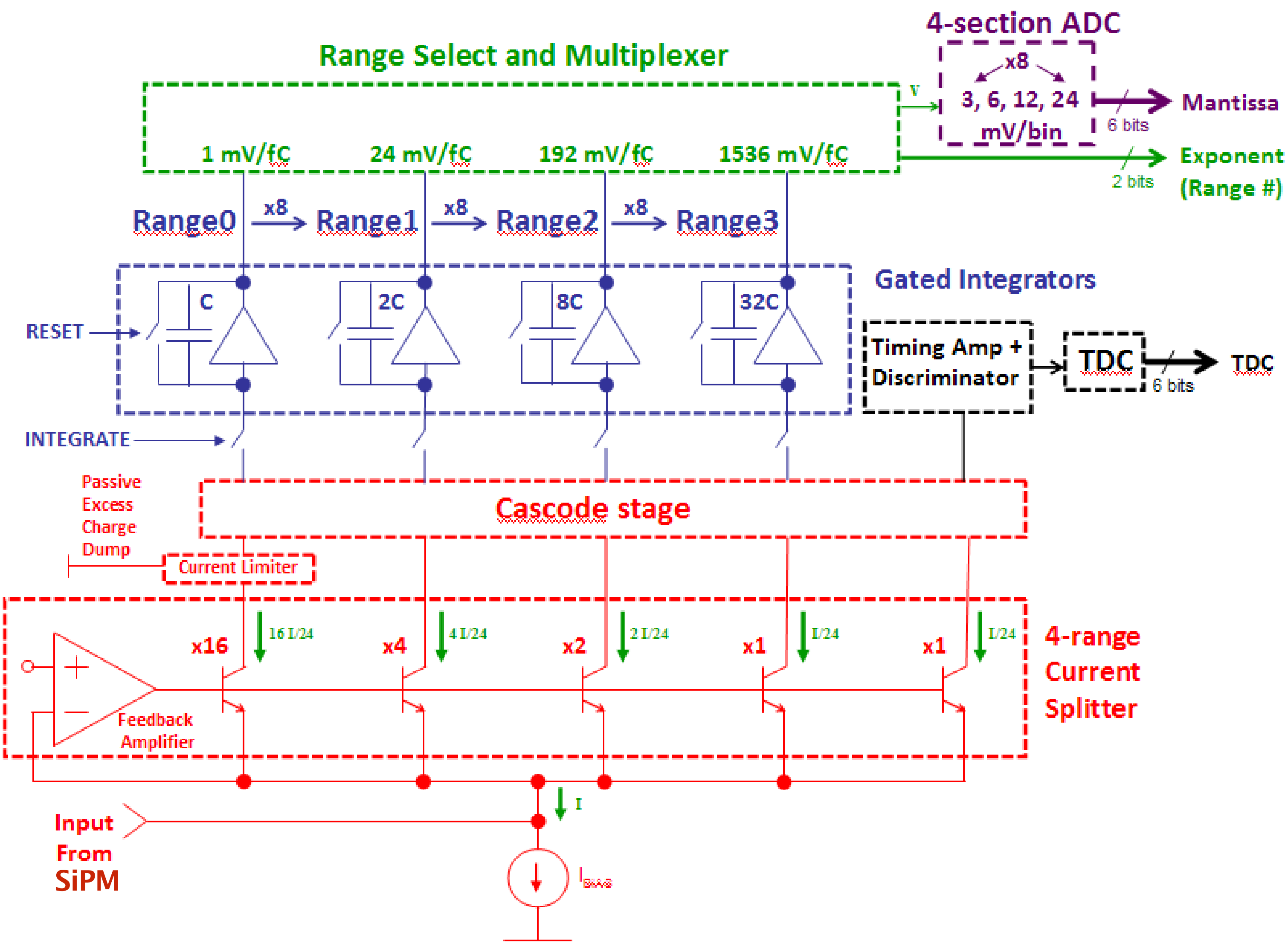
QIE11 operation

- Receive charge from photosensor
- **Split** current into 4 logarithmically weighted ranges
- **Integrate** currents on separate capacitors
- **Select** lowest range capacitor that is not saturated
- **Digitize** voltage on selected capacitor with FADC

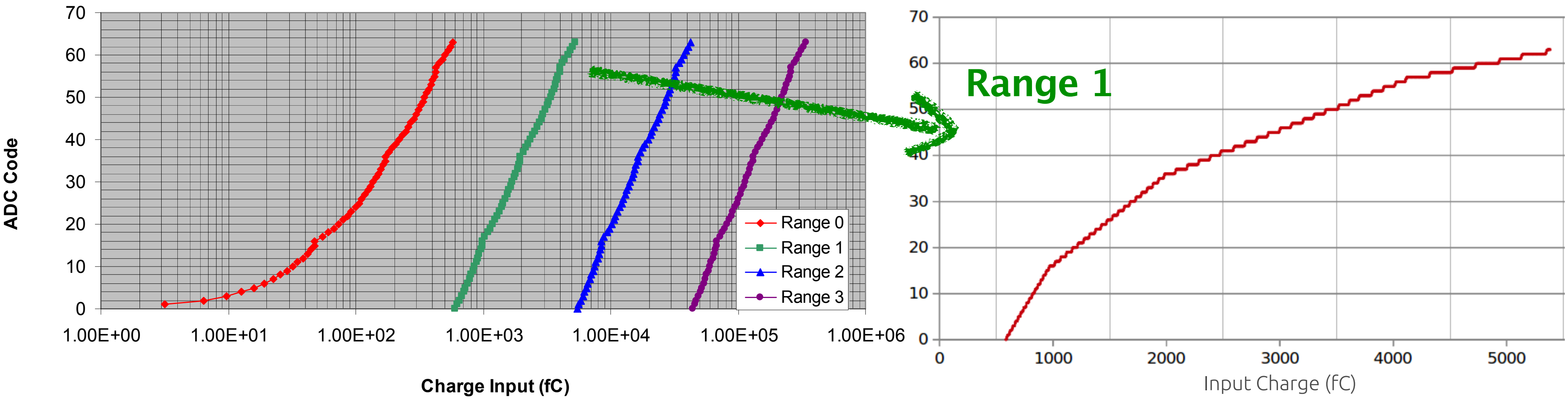


QIE11 operation (2)

- **Split** ratios: 16, 4, 2, 1, 1 (for TDC)
- **Integration** capacitor ratios: 1, 2, 8, 32
- **Select**
- **ADC** sub-range ratios: 3, 6, 12, 24

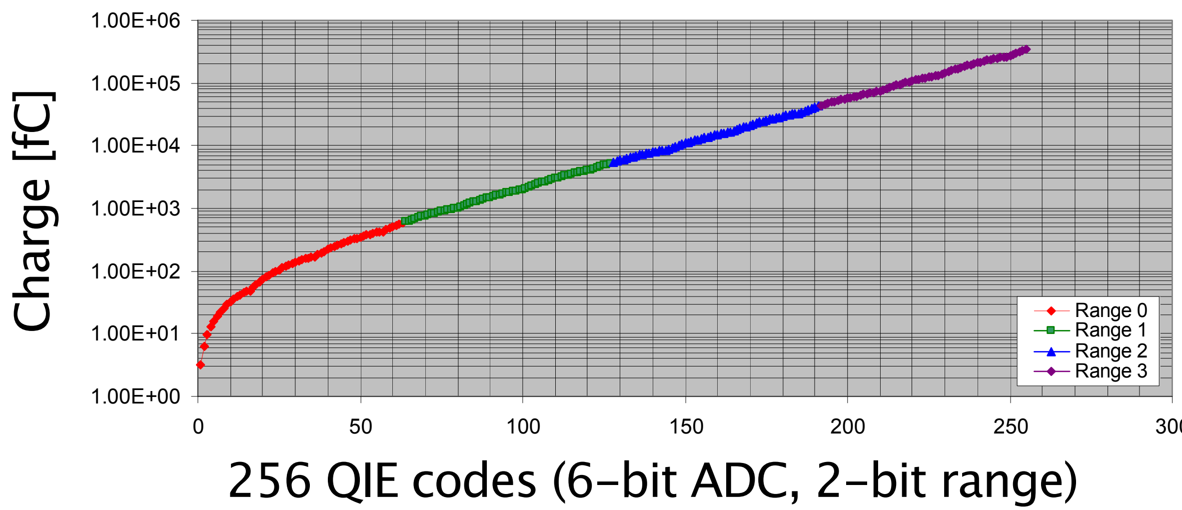


QIE11 response



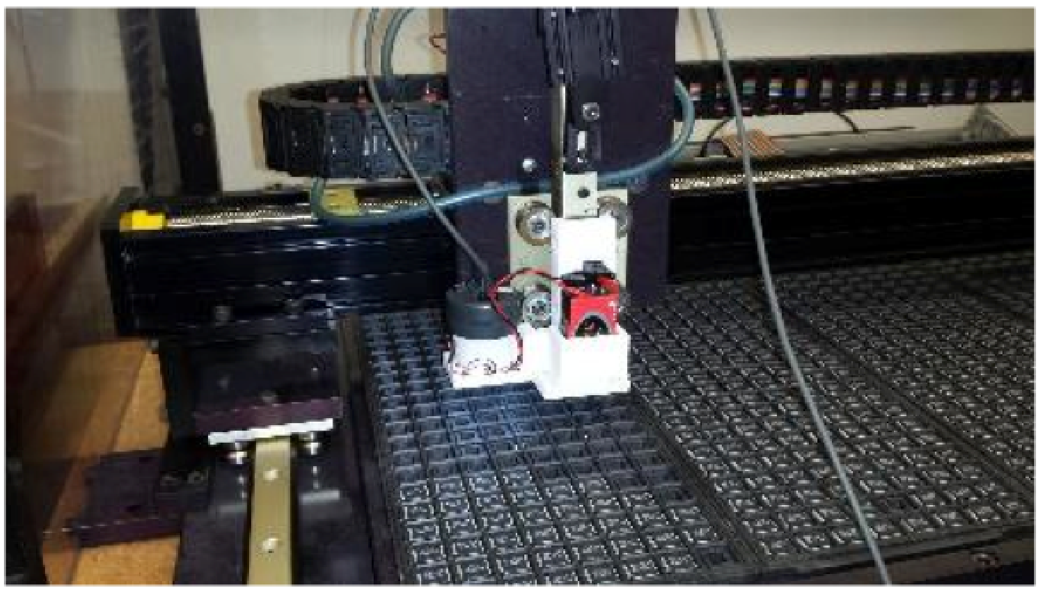
LSB = 3 fC

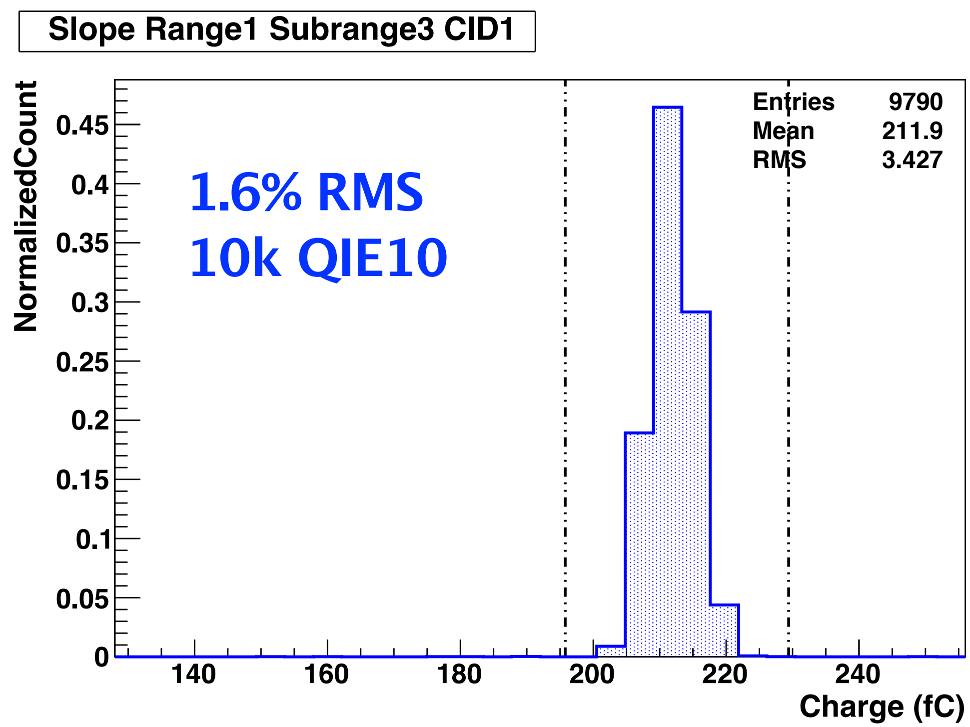
Maximum ~ 350 pC



QIE11 performance

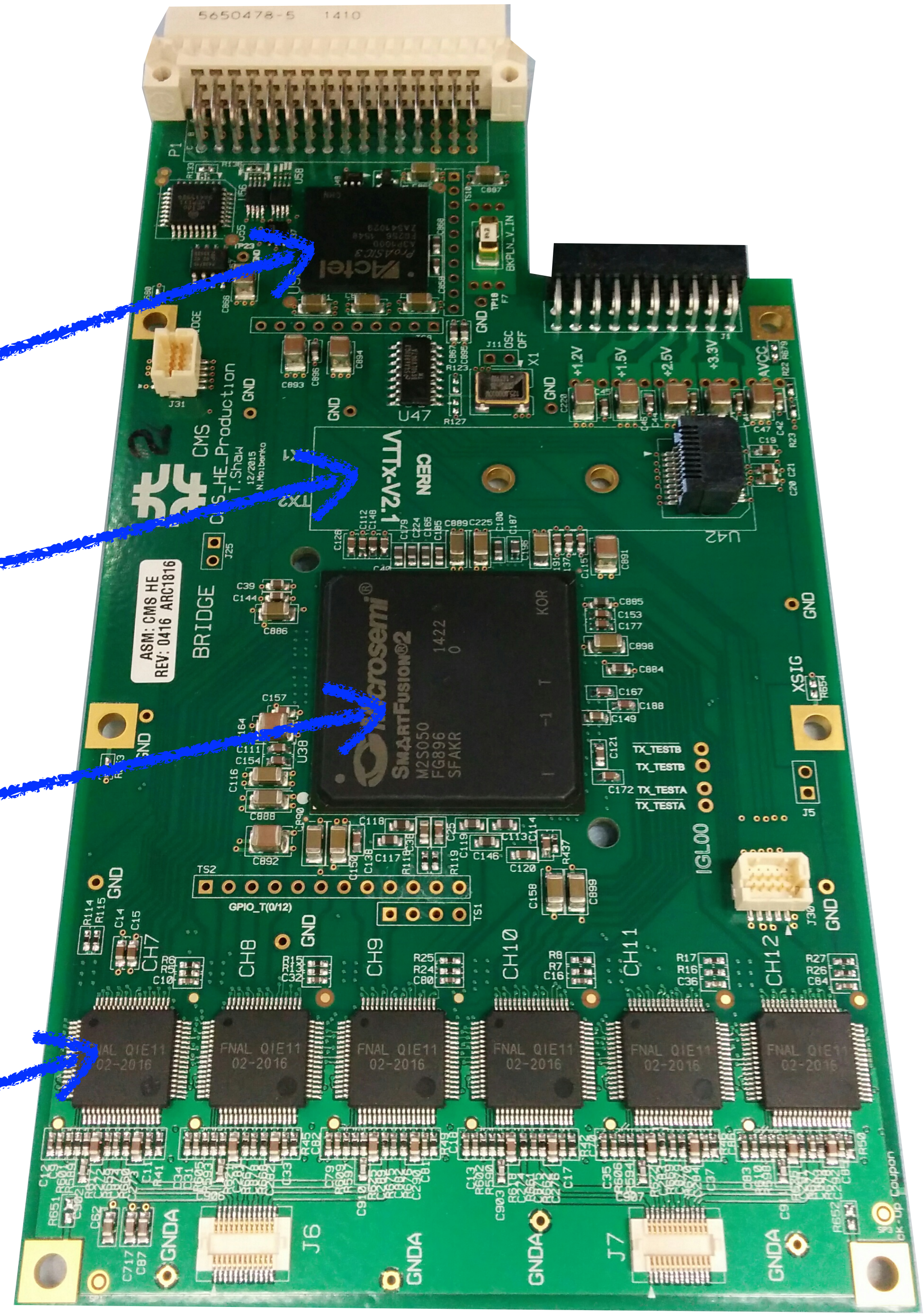
- Tested ~200 quantities for 12k QIE11 in April 2016 using ASIC test robot.
- Yield for basic functionality is ~98%.
- Yield for uniformity requirements is ~85%.
- Response variation acheived by **precision of bipolar current splitters ~1.5%**.



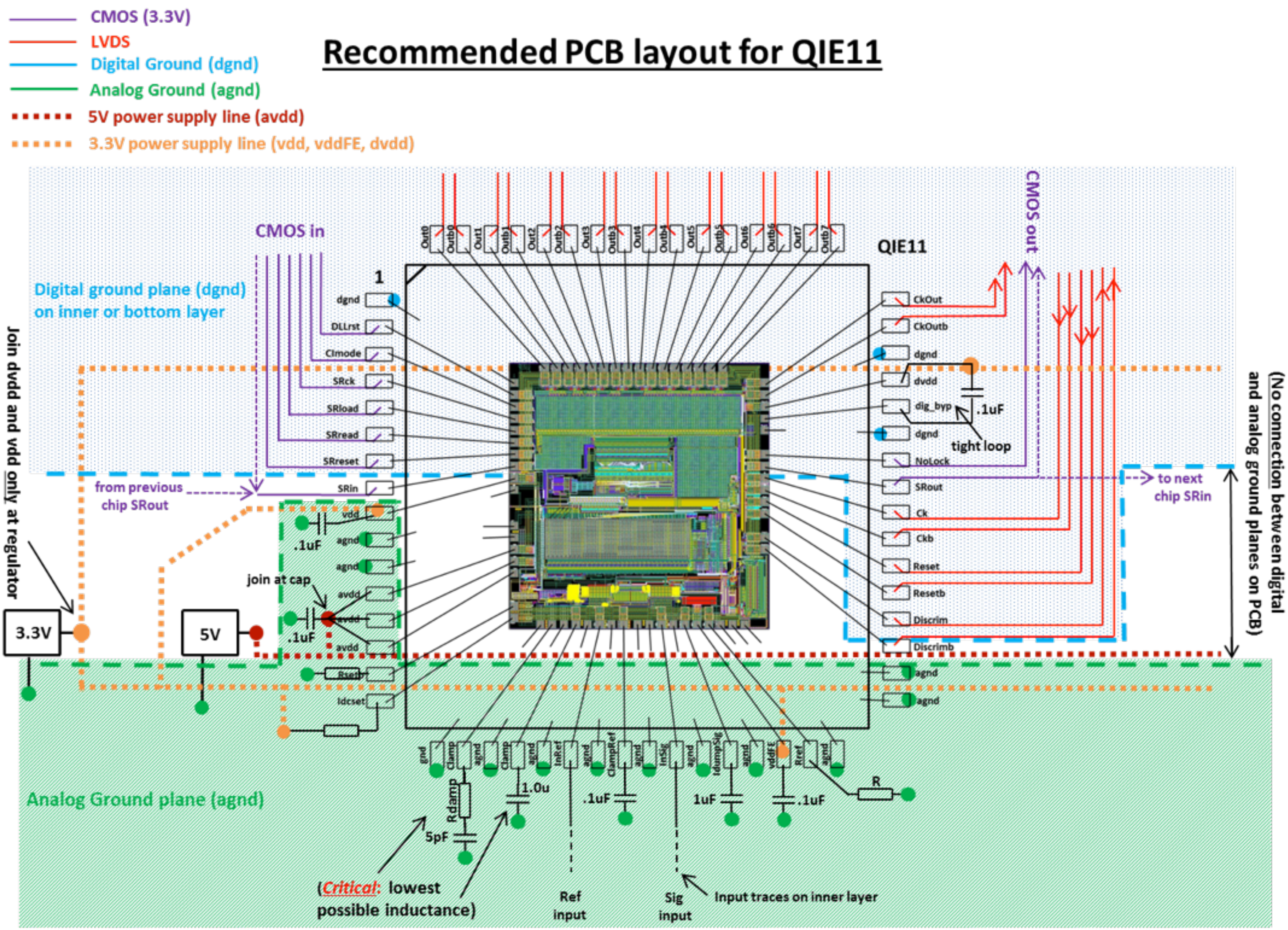


Usage on HCAL frontend card

- Microsemi **ProASIC3** FPGA
  - slow control via I2C, Igloo programming
- CERN **VTTx** (not stuffed in photo)
  - data transmission
- Microsemi **Igloo2** FPGA
  - alignment/clock, serialization, formatting, encoding
- 6 **QIE11** (6 on other side)
  - signal digitization

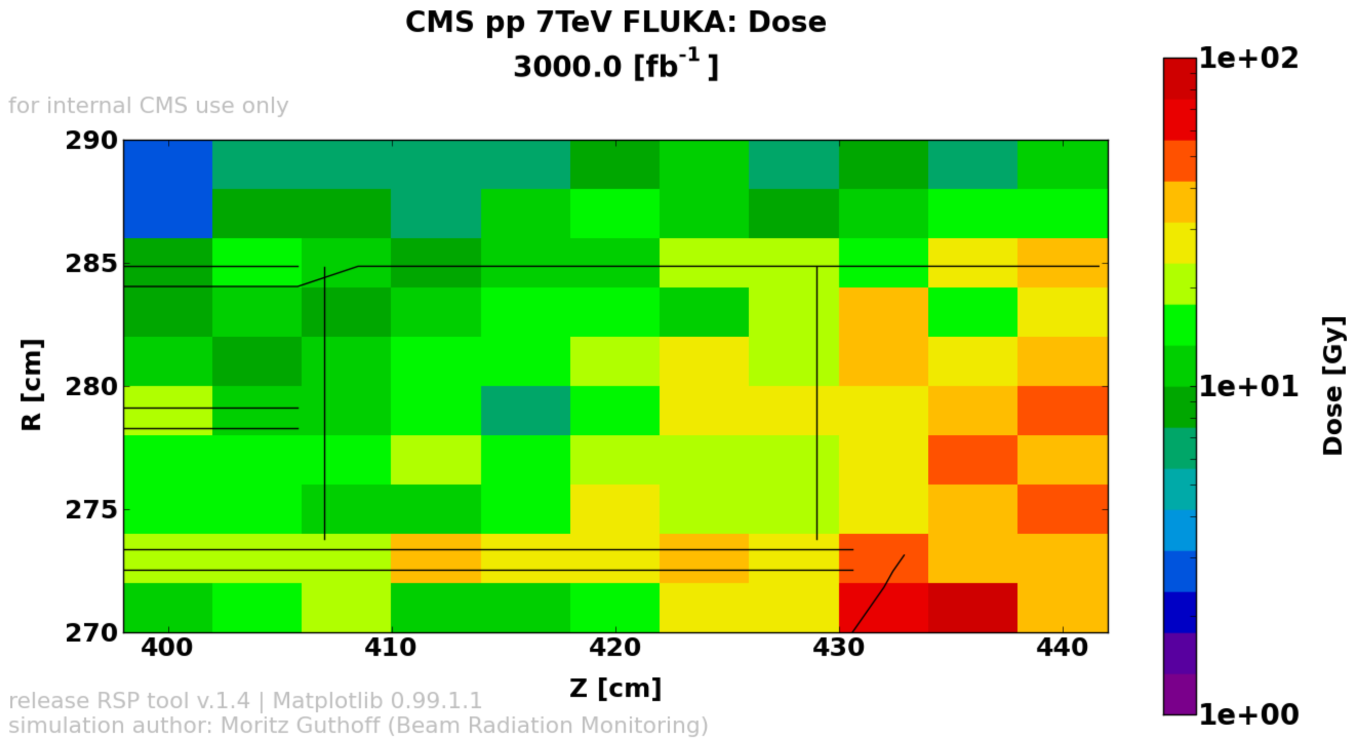


Recommended PCB layout for QIE11



HCAL radiation tolerance requirements

	TID (krad)	1 MeV neutron (cm^{-2})	>20 MeV hadron (cm^{-2})
HB	3.1±0.7	(1.1±0.1)E+12	(2.0±0.3)E+11
HE	0.9±0.1	(9±2)E+10	(1.6±0.6)E+10
HF	4.1±2.7	(7±0.7)E+11	(1.8±0.3)E+11



Potential radiation effects

Cumulative effects

- **Total ionizing dose** (**TID**) in CMOS and SiGe bipolar components.
- **Displacement damage** (**DD**) in SiGe bipolar components.

Single event effects (SEE)

- **Digital SEU** in CMOS.
- **Analog SEU** in current splitters, integrators, etc.
- **Catastrophic SEE**: burnout (SEBO), gate rupture (SEGR), and latchup (SEL).

- We **studied these effects simultaneously** with 230 MeV protons for which 1e11/cm2 fluence ~ 5.8 krad TID in silicon.

Chip Monitoring

1) Operate chip in beam and **count five error types:**

- Capacitor ID (should cycle 0,1,2,3)
- Exponent errors (should be 0)
- TDC errors (should be 63)
- DLL NoLock (should be locked)
- TDC discriminator (should be low)
- change in rad hard shadow register

Zero occurences, as expected

2) Use these raw counts to determine expected **SEE rate** assuming:

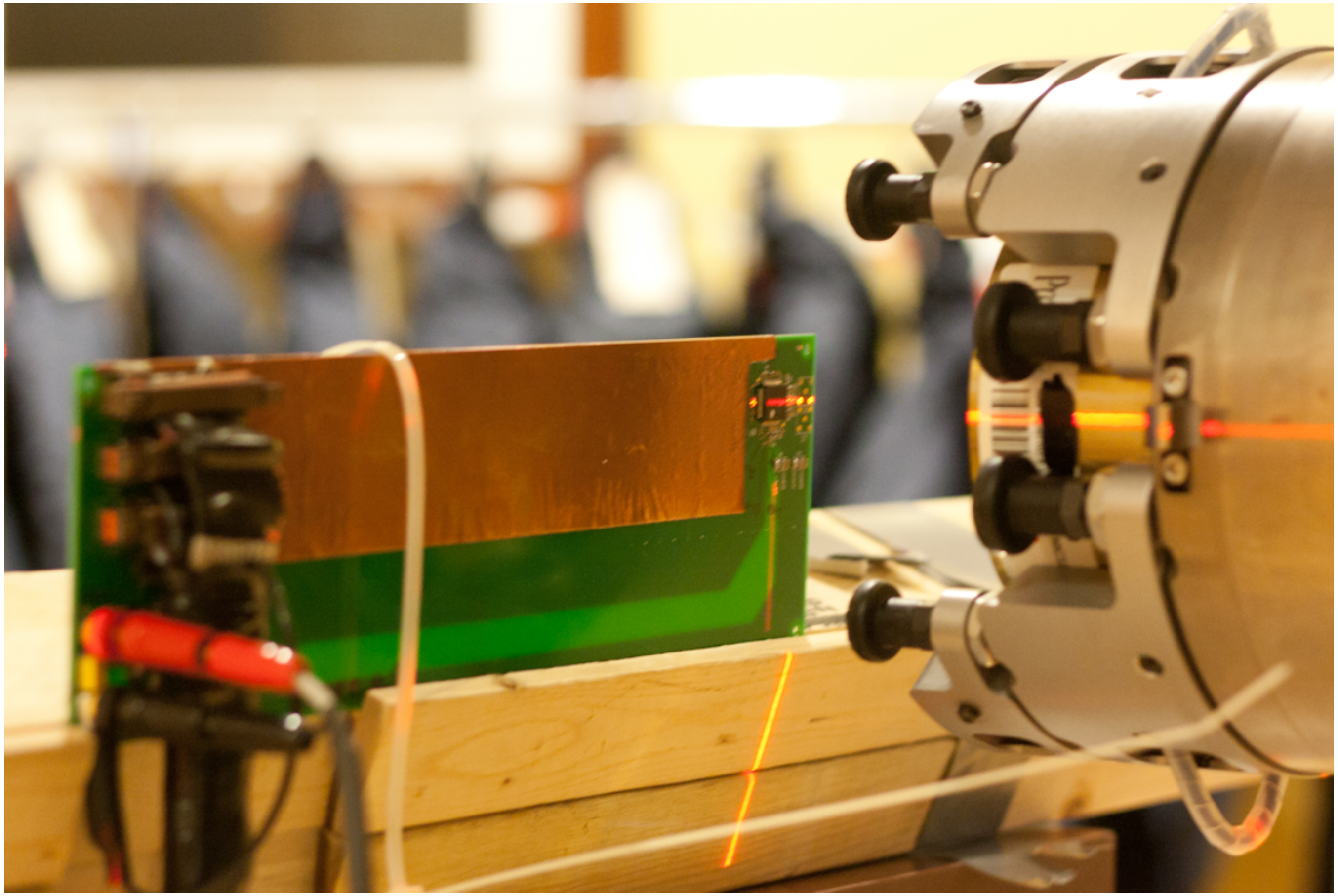
- 7000 HE channels
- 1.6e10/cm2 fluence for 20 MeV hadrons
- integrated luminosity of 3000/fb
- instantaneous luminosity of 5e34/cm2/s

3) Monitor **pedestal** vs. TID and nucleon fluence.

4) Monitor **response** vs. nucleon fluence.

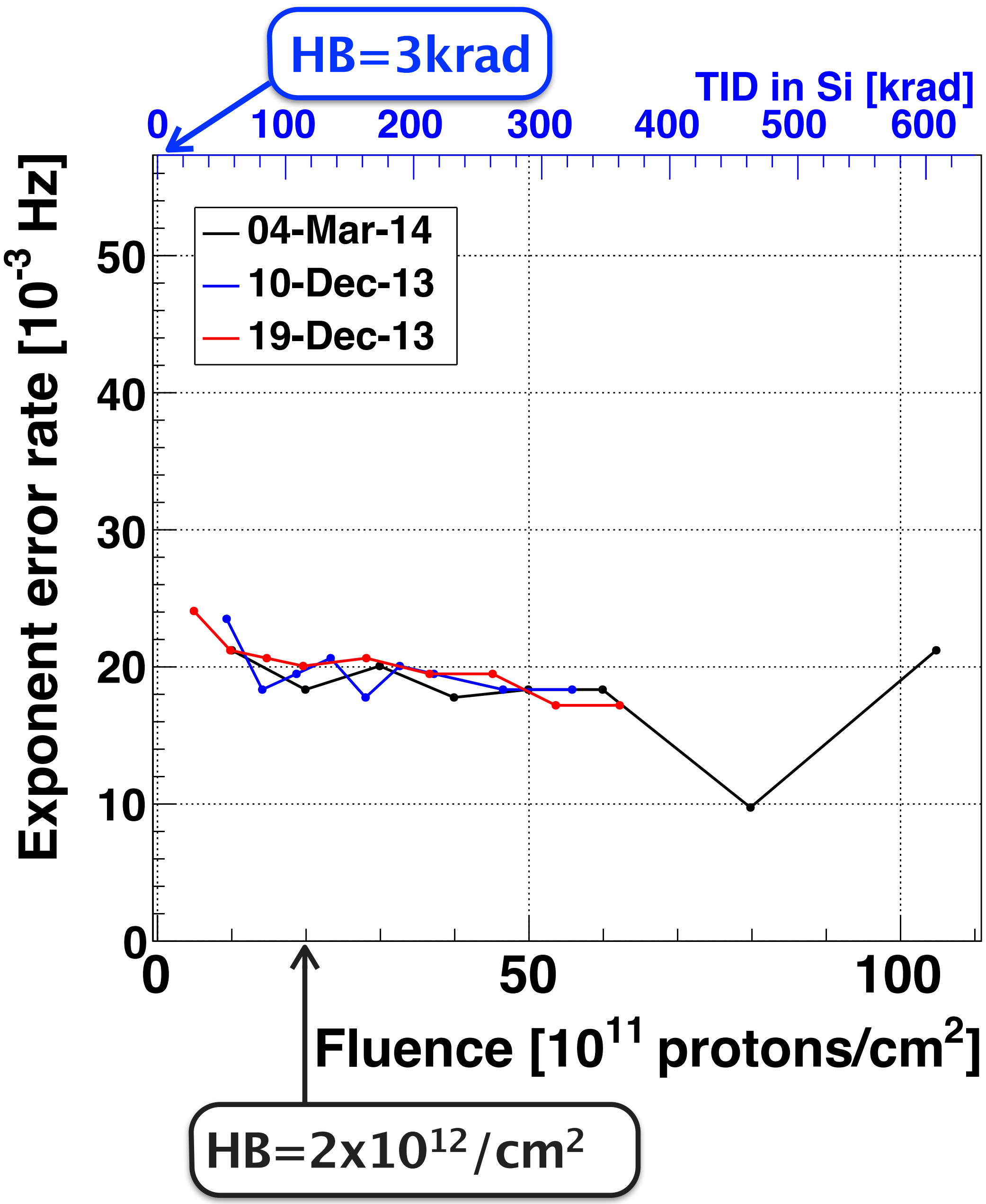
Test configuration

- Tested QIE10 in **230 MeV proton beam** at Central Dupage Hospital near Fermilab
- Operated chip with **full power, clock, and 40MHz readout**.
- Three different days/ chips: 10–Dec–14, 19–Dec–14, 04–Mar–14
- **Flux** ~5×10^9 protons/ cm^2/s
- **Dose rate** ~300 rad/s



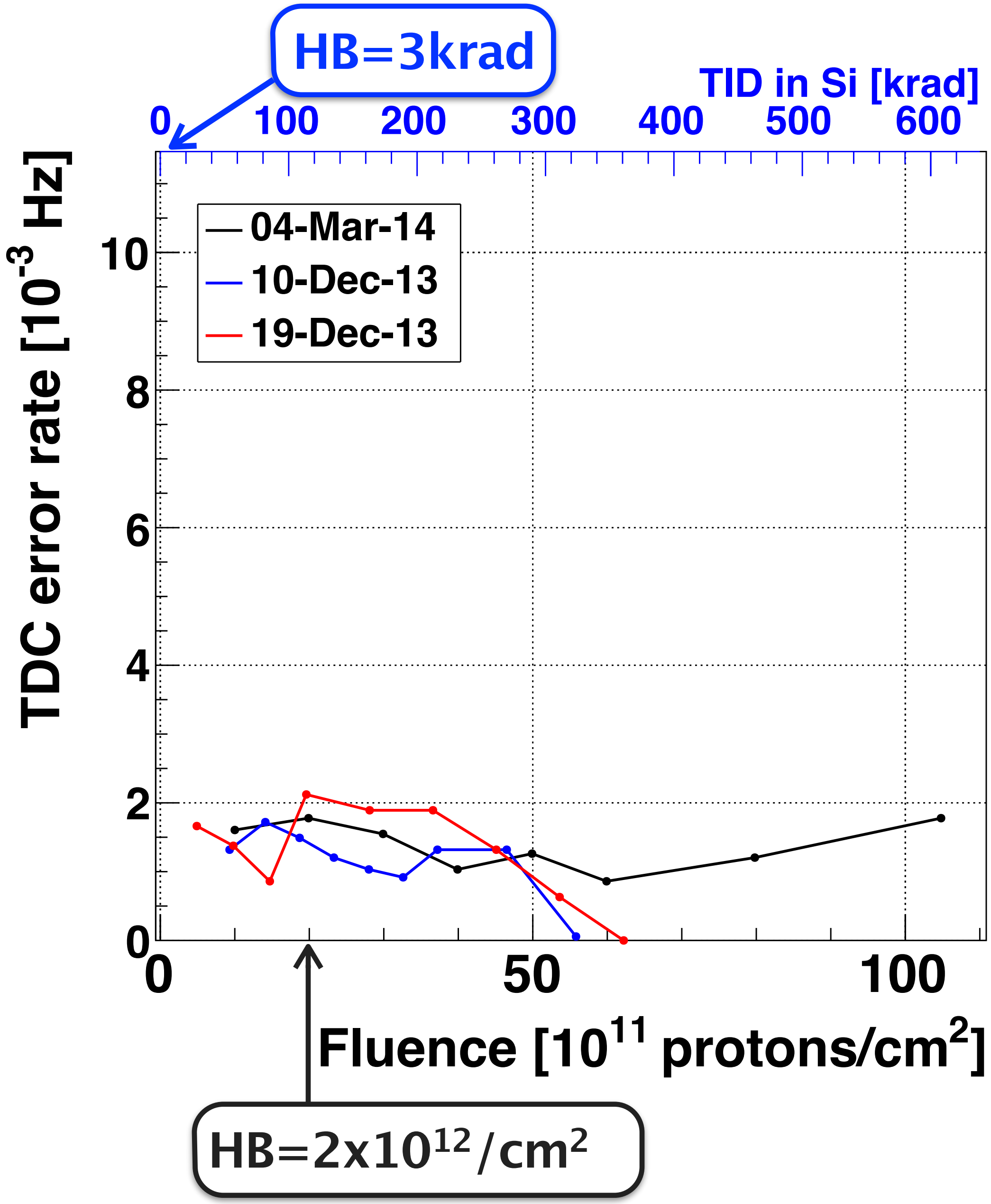
SEE: Exponent error rate

- One exponent **error every ~minute on entire detector (16k channels).**
- Frontend runs without interruption — zero intervention required.
- Uncorrelated with physics events.
- Potential trigger deadtime and signal inefficiency is 1e–9.
- **Acceptable for HCAL**



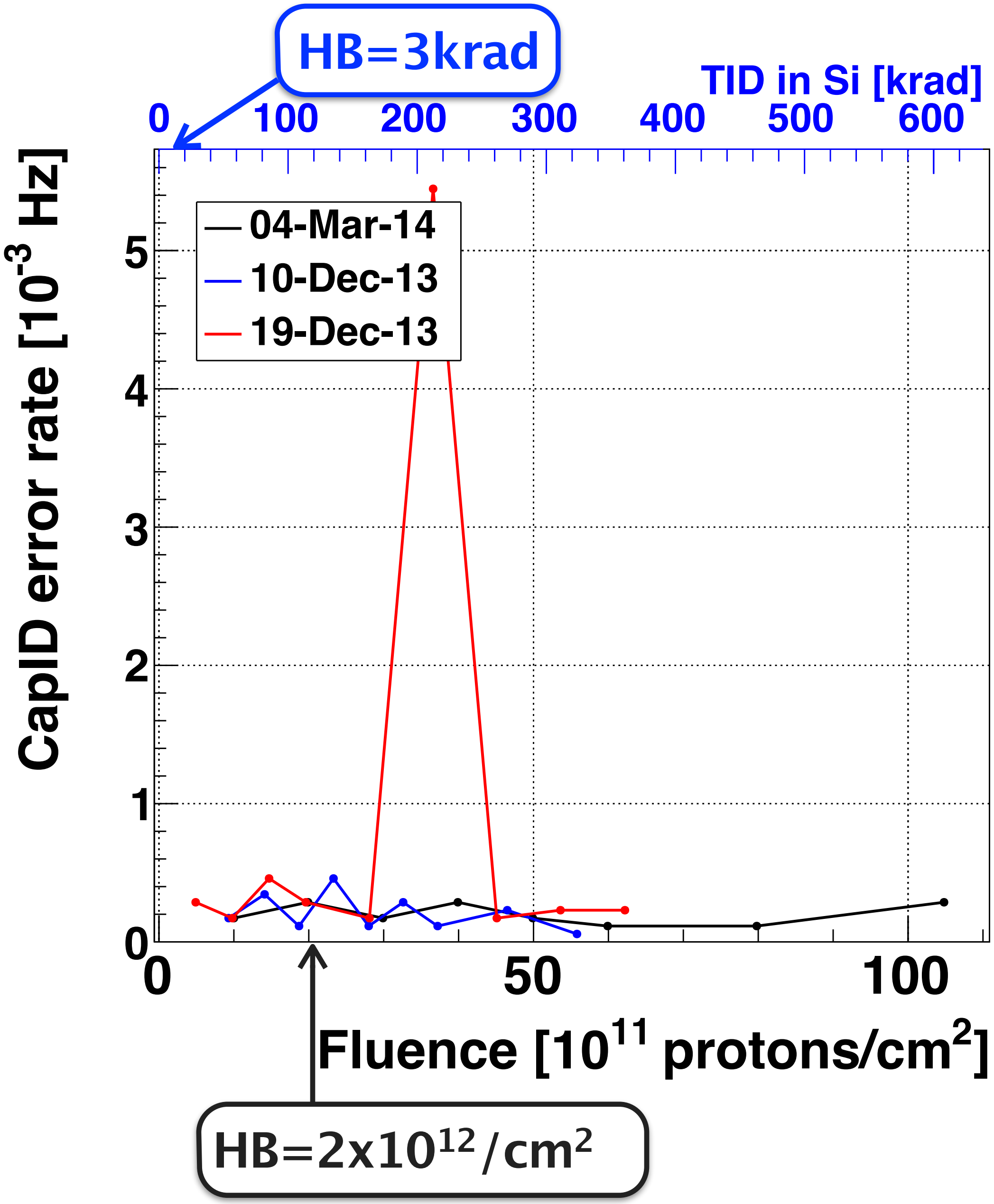
SEE: TDC error rate

- One TDC **error every 10 minutes hours on entire HBHE detector.**
- **Acceptable for HCAL**



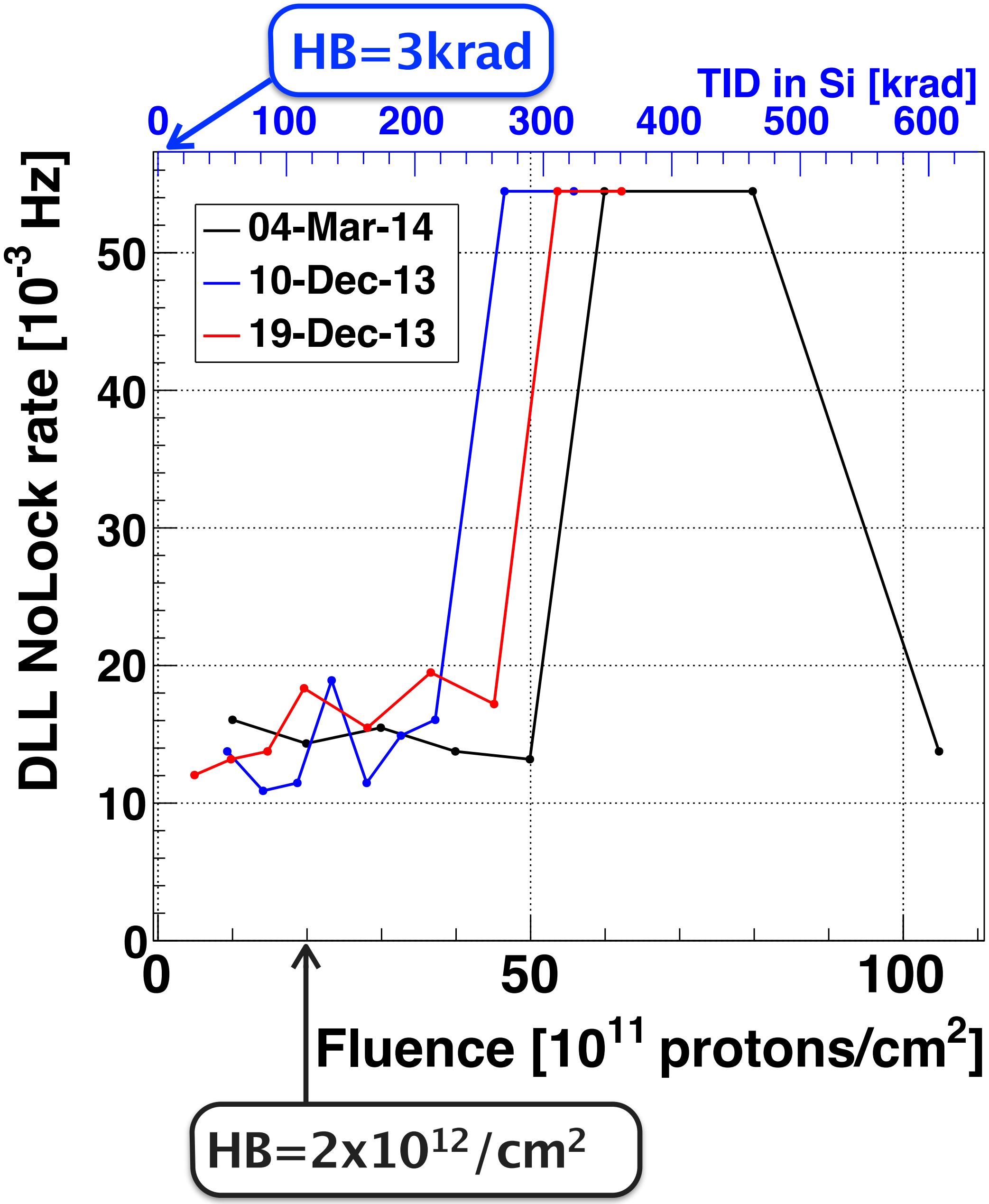
SEE: CapID error rate

- On Dec19, CapIDs stopped rotating at about 200 krad (40e11/cm^2), but **recovered after QIE reset**.
- QIE reset occurs every orbit in normal operations.
- **Acceptable for HCAL**



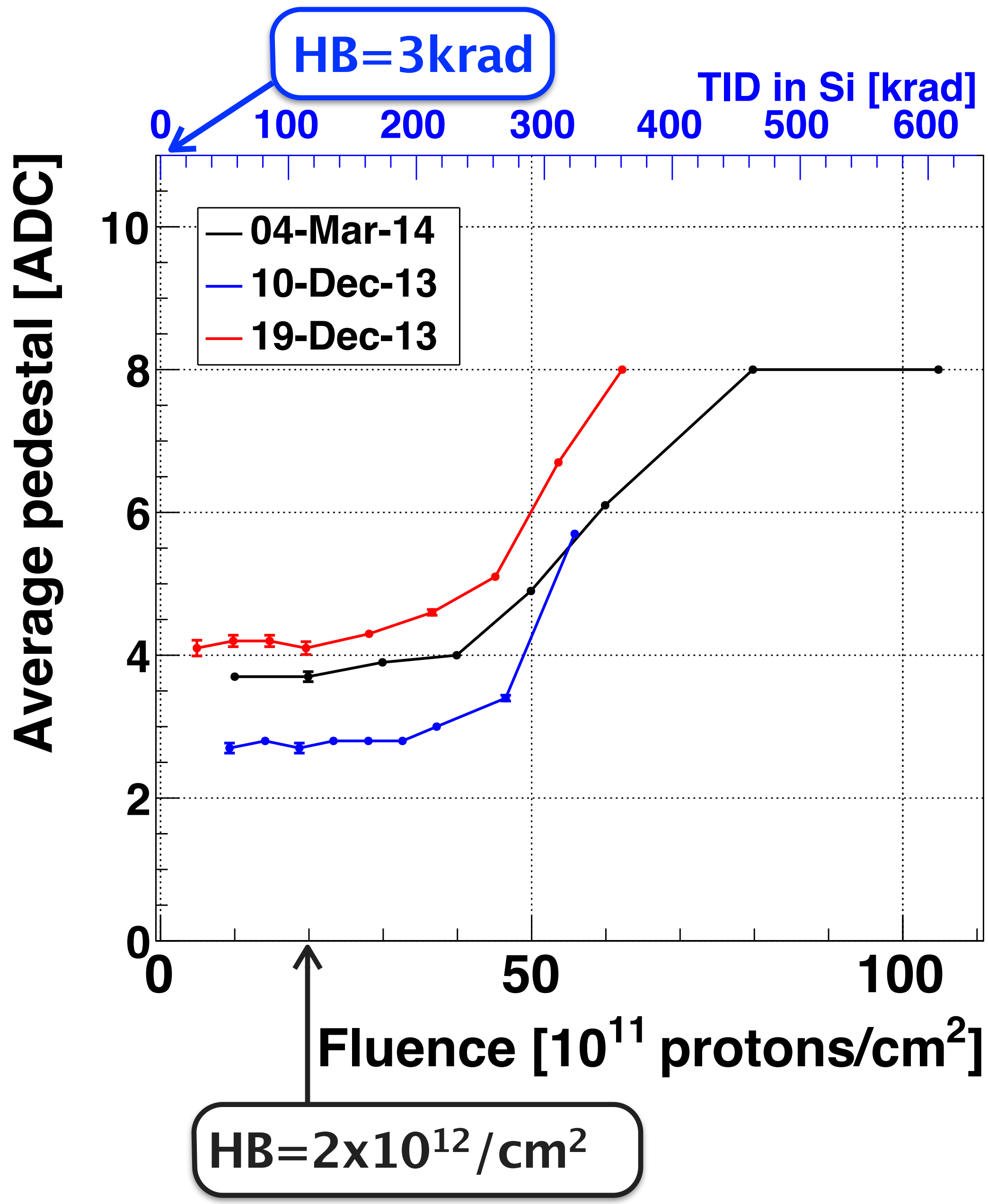
TID: DLL NoLock rate

- **Observed cumulative damage failure mode**: DLL loses ability to lock
- Anneals in 10 days at room temperature ➔ **TID effect**
  - not displacement damage from neutron fluence
- Occurs at **250 krad** or later.
- **Acceptable for HCAL**



TID : Pedestal drift

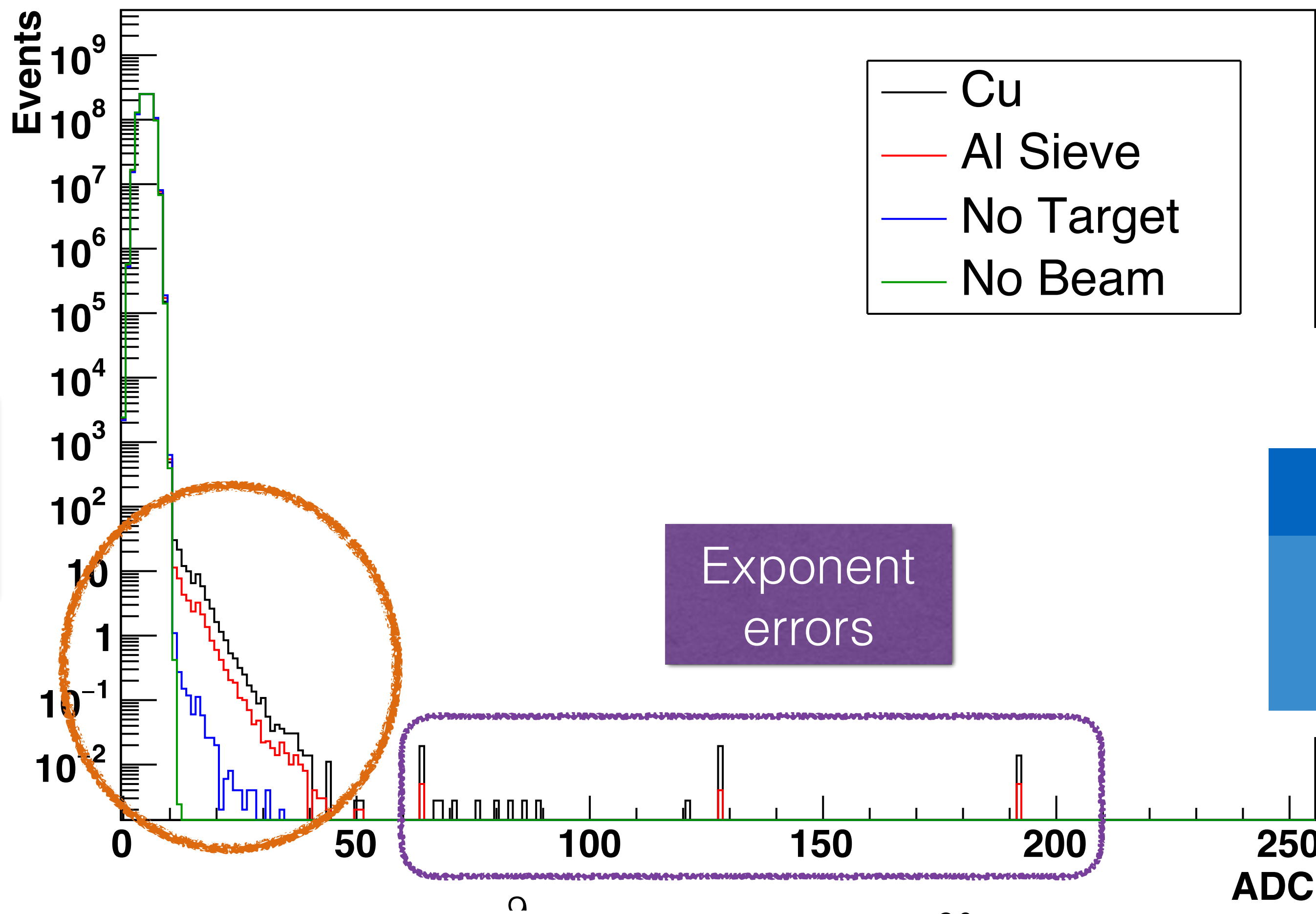
- **Observed pedestal drift**
- Anneals in 10 days at room temperature ➔ **TID effect** (not DD effect)
- Occurs at **150 krad** or later.
- **Acceptable for HCAL**



Analog SEU at CERN CHARM facility

http://charm.web.cern.ch/CHARM/

- Long run shows order 10^{-8} effects
- Rates of 0.5 Hz to 0.006 Hz — uncorrelated with real physics events.
- **Acceptable for HCAL**



Cu target

ADC	Rate (Hz)
15-63	0.5
32-63	6 10^{-3}

Considerations for EB

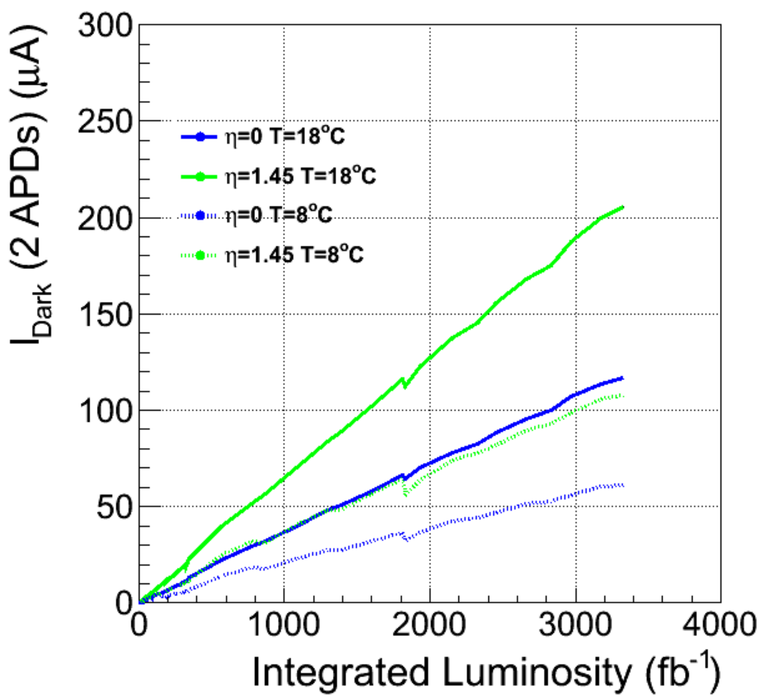
- M. Dejardin*: **Charge integration might outperform pulse shaping** for mitigating effect of APD dark current and out-of-time pileup associated with HL-LHC.

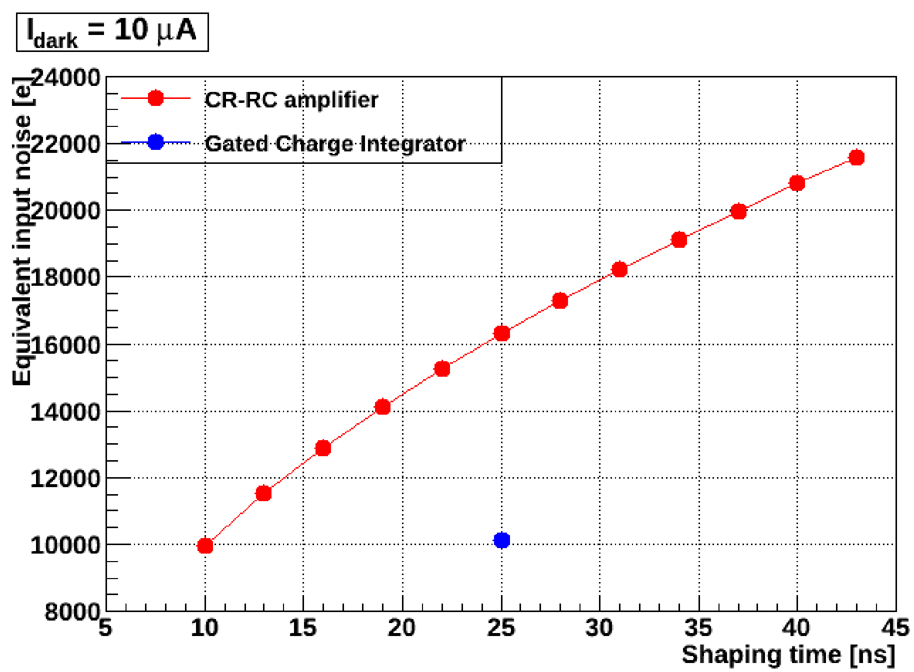
* DN-2015-14

https://indico.cern.ch/event/371835/contributions/881679/attachments/1150997/1652502/MD_Upgrade_20150908.pdf

Important considerations

- More channels / **physical space** on detector
- EB **resolution and dynamic range** >> HCAL resolution and dynamic range
- more precise **timing requirements**
- higher **radiation tolerance requirement**

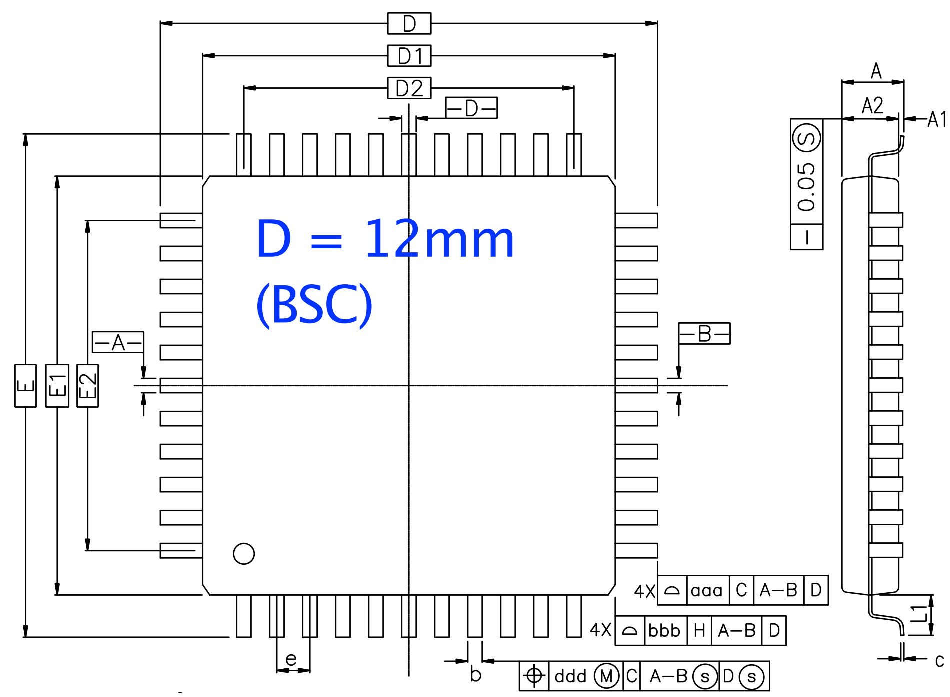




Physical footprint

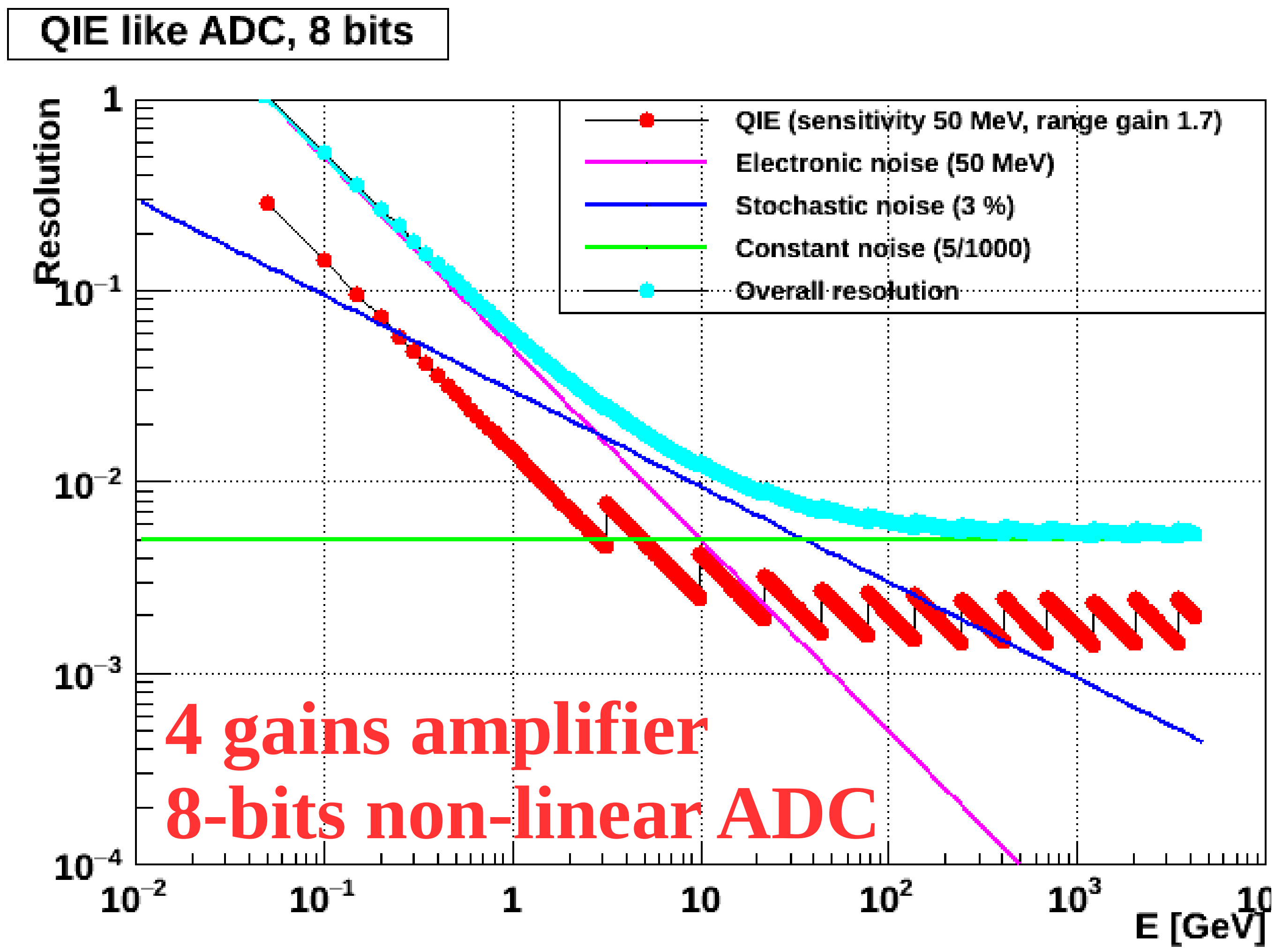
- **64-pin** thin quad flat package is **12x12 mm^2**
- QIE die size is 3.2 x 3.2 mm^2
  - Make better use of space with 4-6 channels chip = **“quad-QIE” chip**.
  - Developed for QIE11, but not needed.

- **20 pins devoted to LVDS output**: 16 data, 2 clock, 2 discriminator.
- QIE13: **on-chip serialization** reduces output pins by factor by 2-4.
  - Implemented for QIE9 (BTeV) but not used.



Not a problem for EB

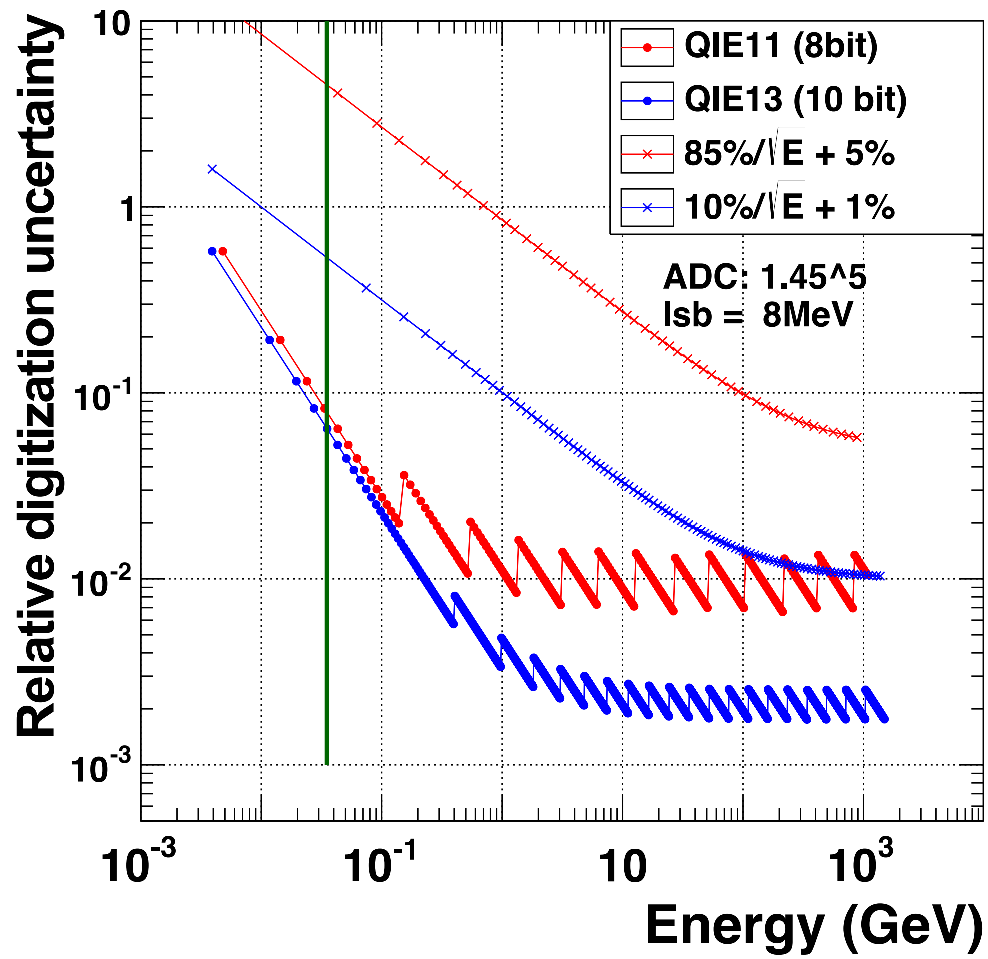
Resolution and dynamic range



- Plot from Marc Dejardin from Ischia matches proposal for QIE13 for Shashlik from 2013 … next slide …

Resolution and dynamic range (2)

	QIE11	QIE13
ADC bits	6	8
ranges	4	4
sub-ranges	4	5
E_{max} [TeV]	1.1	1.5
Gain [fC/GeV]	313	380
LSB [MeV]	10*	8
LSB [fC]	3	3
dyn range [bit]	17	18**
% error in tail	1.5	0.25**



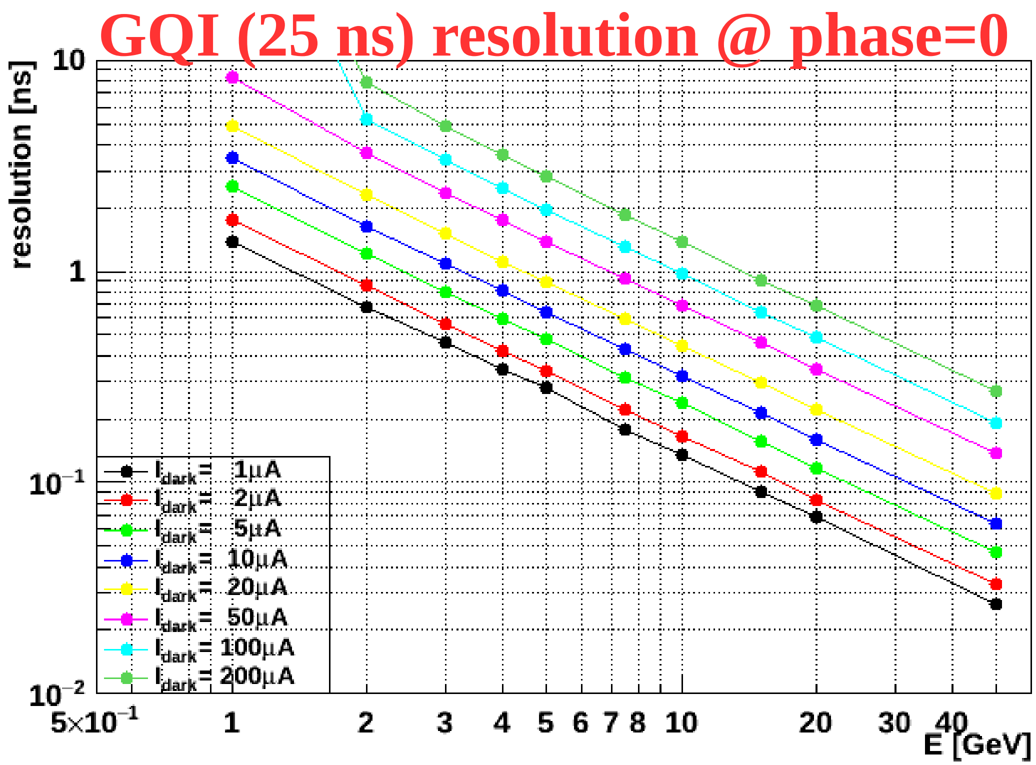
- QIE13 specs for Shashlik
- Add 2 bits to ADC
  - room on chip is sufficient

Not a problem for EB

Timing

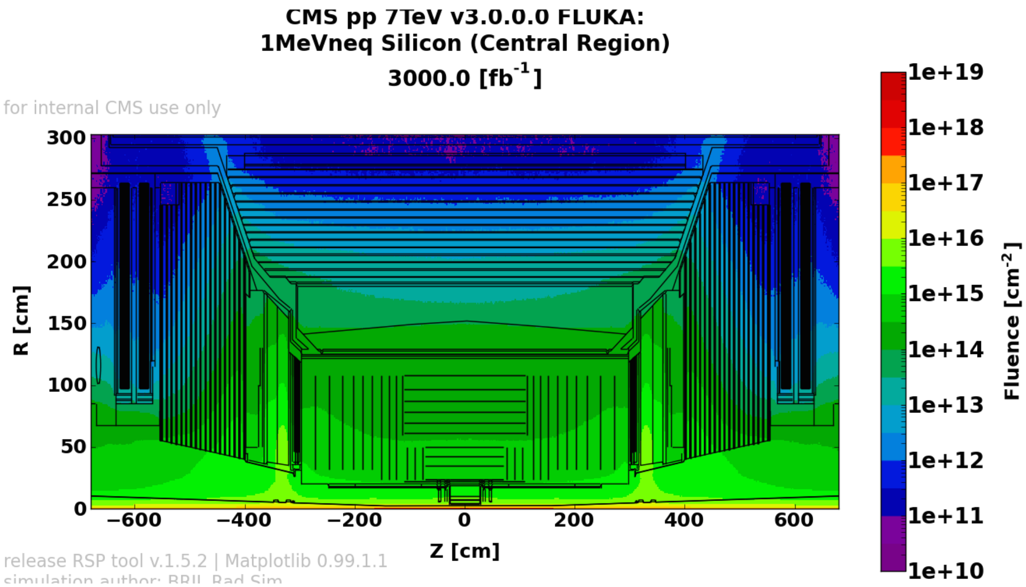
- Require **30 ps resolution** for reasonably sized signals.
  - QIE11 6-bit TDC gives 500 ps resolution over full 25ns bucket using 2 GHz DLL.
- 30ps requires **10-bit TDC** for 40 MHz operation and ~40 GHz DLL.
  - **Technically feasible?** Probably not with current design.
  - Is this **data volume** reasonable with zero suppression on front end?
  - Use restricted range for valid codes? Do we need 30ps resolution for full 25ns bucket?

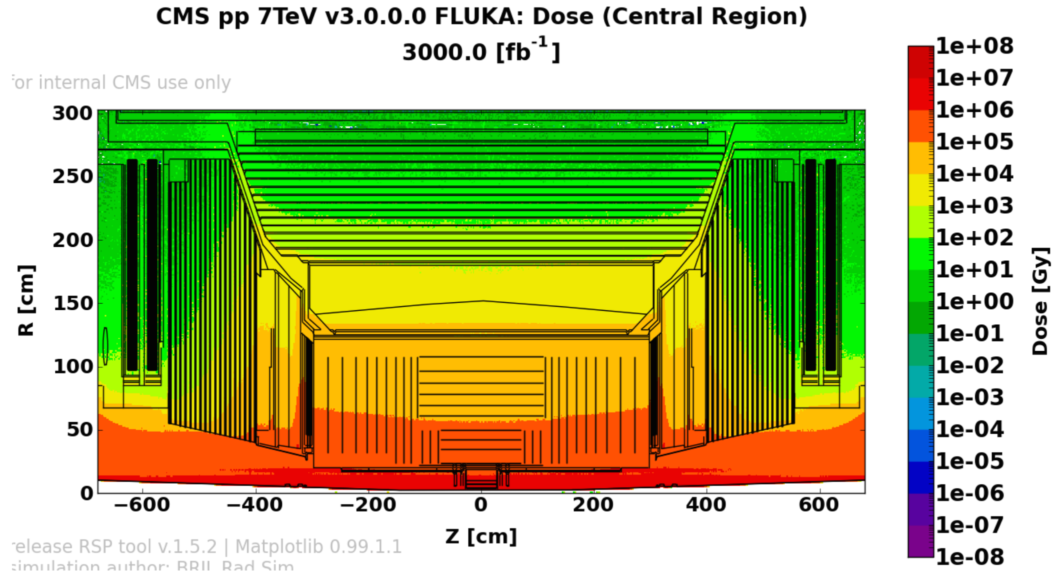
- MD shows **~100 ps resolution** for QIE-like GQI (20uA dark current and 50 GeV signals) using energy measurement with knowledge of pulse shape.
  - Are energy resolution benefits of GQI lost if GQI is run at 160 MHz?



EB radiation tolerance requirement

	TID (krad)	1 MeV neutron (cm^{-2})	>20 MeV hadron (cm^{-2})
EB	1000	1E+14	not considered





- QIE tested to 250 krad and 1e13 1MeV-neutrons/cm^2.
  - TID effects could be dose rate dependent.
- **More studies required for EB use — biggest concern for QIE.**

Summary

- **QIE13 charge digitizing ASIC** would be well suited to EB for **resolution** and **physical size**.

- **Radiation tolerance** requirements for EB are challenging
  - QIE11 are tested to 1e13 1MeV-equivalent neutrons / cm^2
  - Problems observed around TID of 250 krad.
    - Behavior of electronics in high current beam difficult to interpret — more study needed.

- **Timing precision** requirements for EB are challenging
  - Simple TDC requires 10 bits, but more creative options possible.
  - Timing from energy distribution in 25ns bins has ~100ps resolution — problem with GQI in general, not QIE.

Additional Material

QIE11 overview (3)