LGAD development for CMS & thoughts on ePIC TOF R&D

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TOF-PID WG weekly meeting

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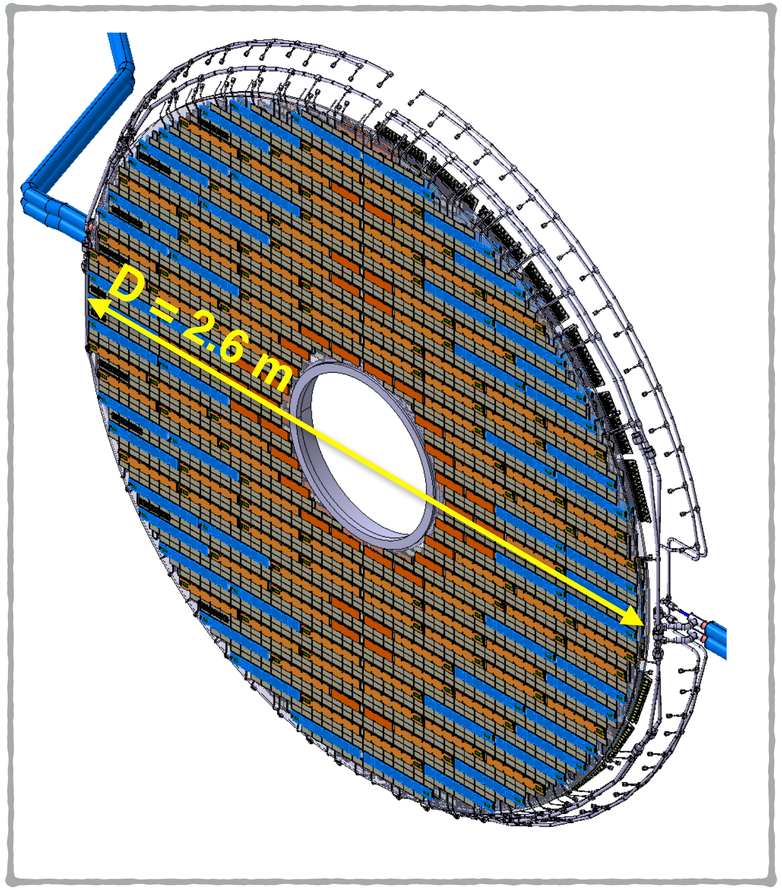
CMS LGAD sensor R&D

- CMS Endcap Timing Layer (ETL) will provide 30-40 ps timing for HL-LHC, covers $1.6 < \eta < 3.0$

- At time of ETL conceptual proposal, LGADs existed at proof-of-concept level, but significant need for R&D within project.

- Some of the key LGAD R&D questions for ETL:
  - Ensure gain layer uniformity
  - Radiation hardness (up to 1.5×10^{15} neq/cm^2)
  - Minimize interpad gaps
  - Production yield & uniformity (correlated with cost)

Endcap timing layer



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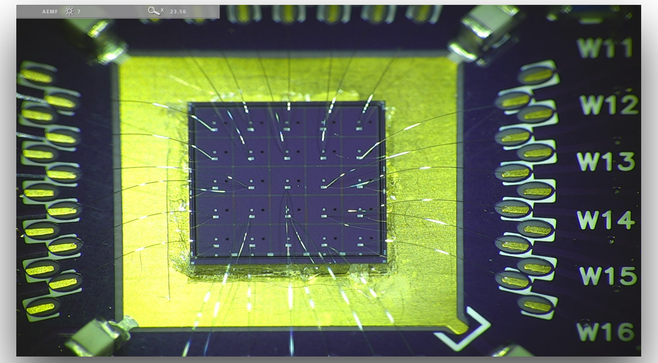
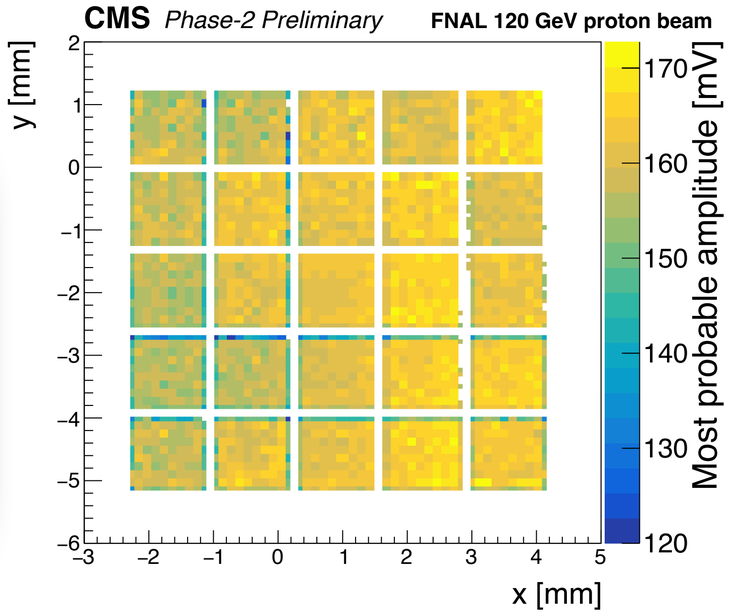
Demonstrating uniformity

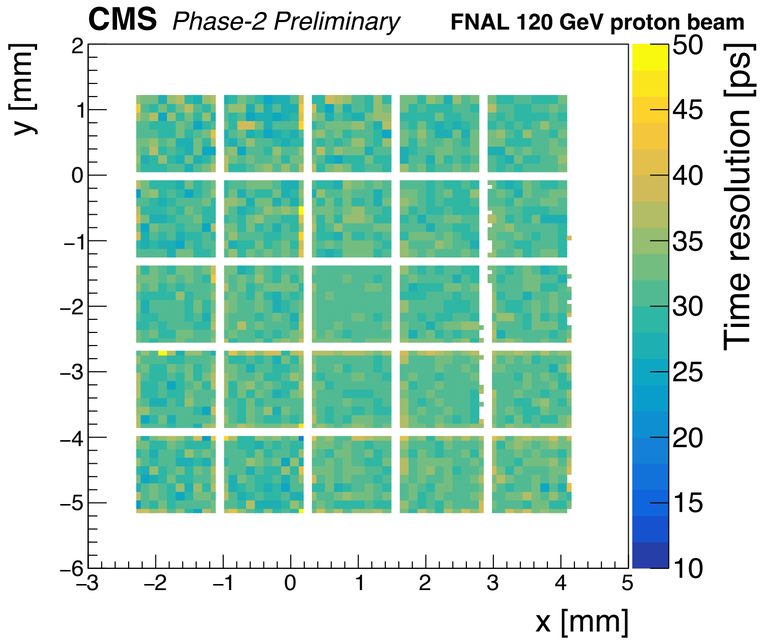
- Over time, iterated with foundries to improve uniformity
- In parallel, developed strategy to verify uniformity with simple probe tests

Latest sensor production: good uniformity

5x5 FBK LGAD array on 26-ch board (2022)







(Improved tracking—now resolve interpad gaps)

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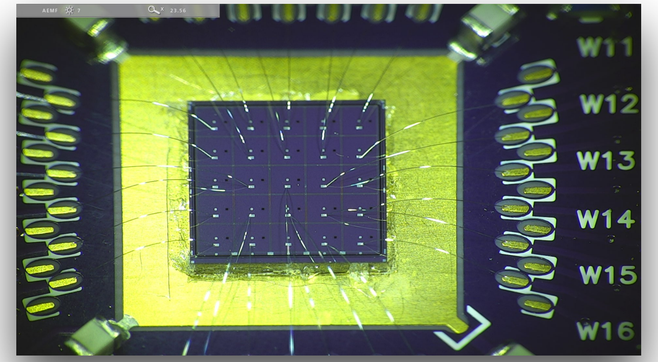
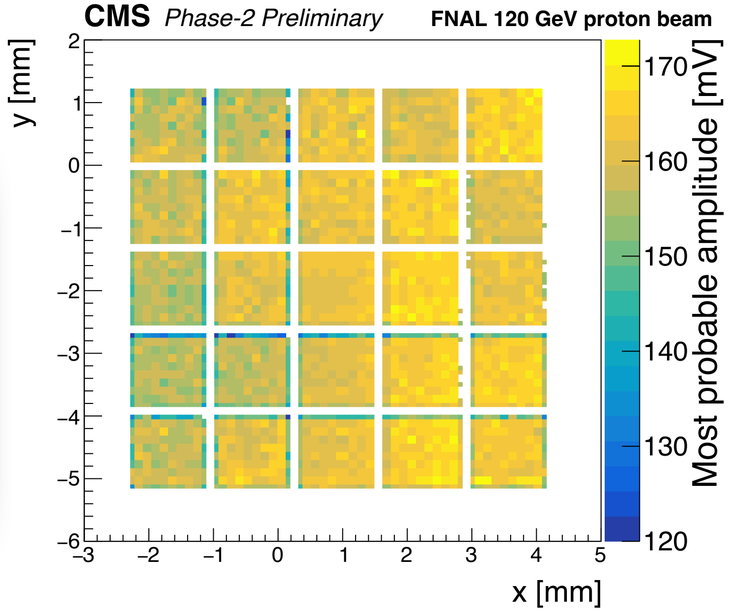
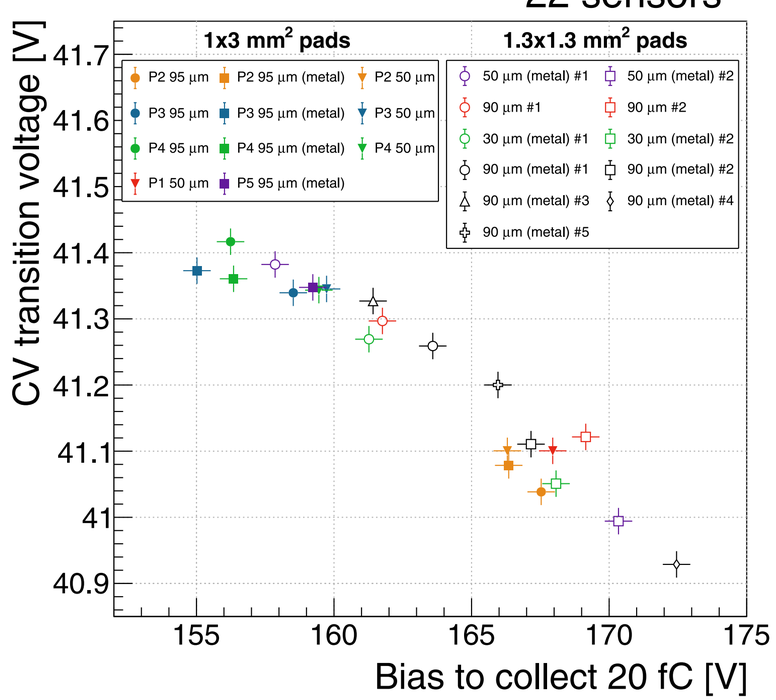




Correlate probe measurements (passive) with gain (active)



Nucl. Inst. Meth. A 1018 (2021) 165828

- Uniformity issue resolved, and procedure established for production QA/QC.

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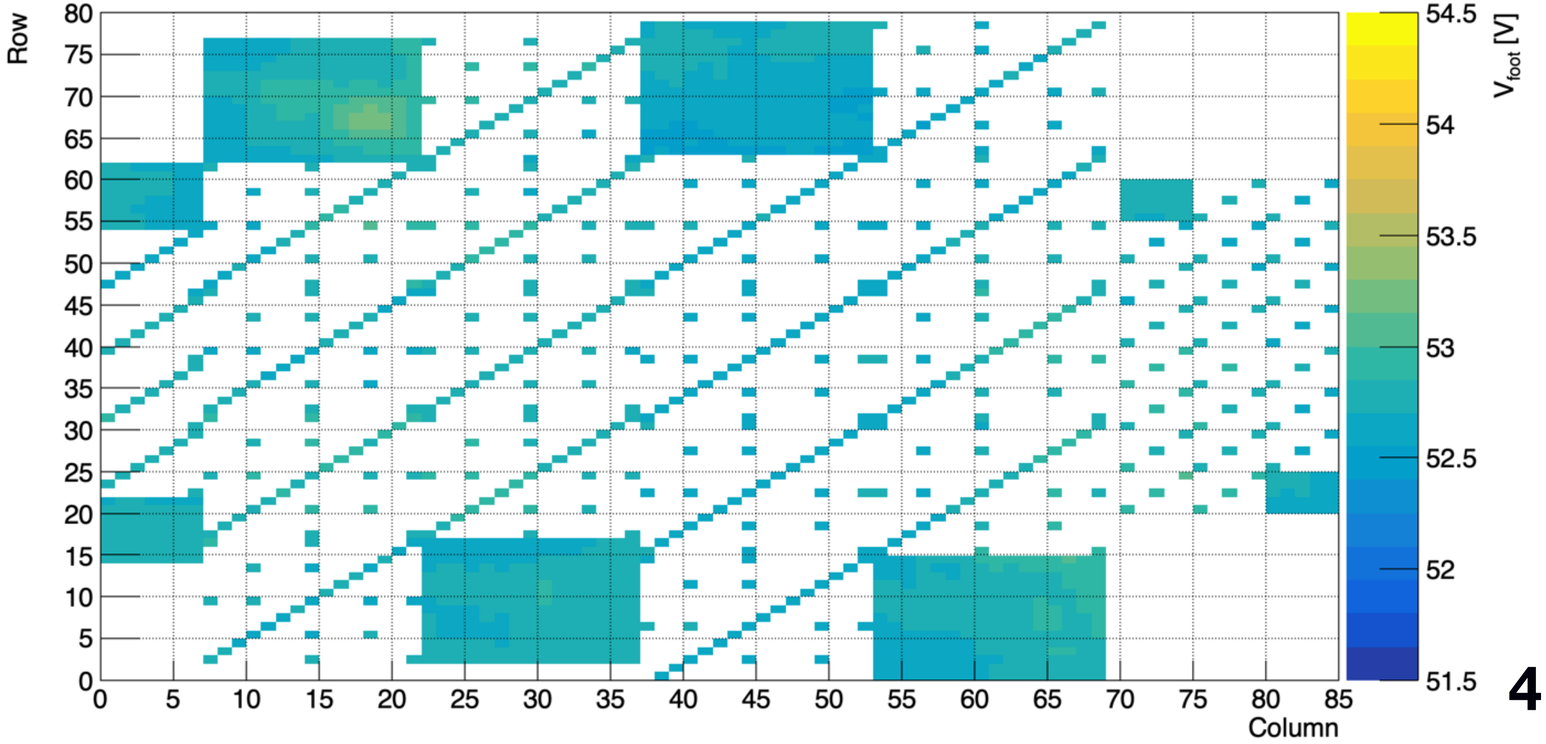
HPK gain uniformity

Wafer	V_foot [V]	Sigma V_foot [V]	Ratio V_foot [%]
1	55.2974	0.159749	0.29
2	55.2488	0.128252	0.23
7	54.3802	0.113994	0.21
8	54.3587	0.117354	0.22
14	52.7301	0.101182	0.19
16	52.2769	0.0793503	0.15
19	52.0818	0.0804609	0.15
21	51.4057	0.195995	0.38

Map of probe measurements across HPK wafer



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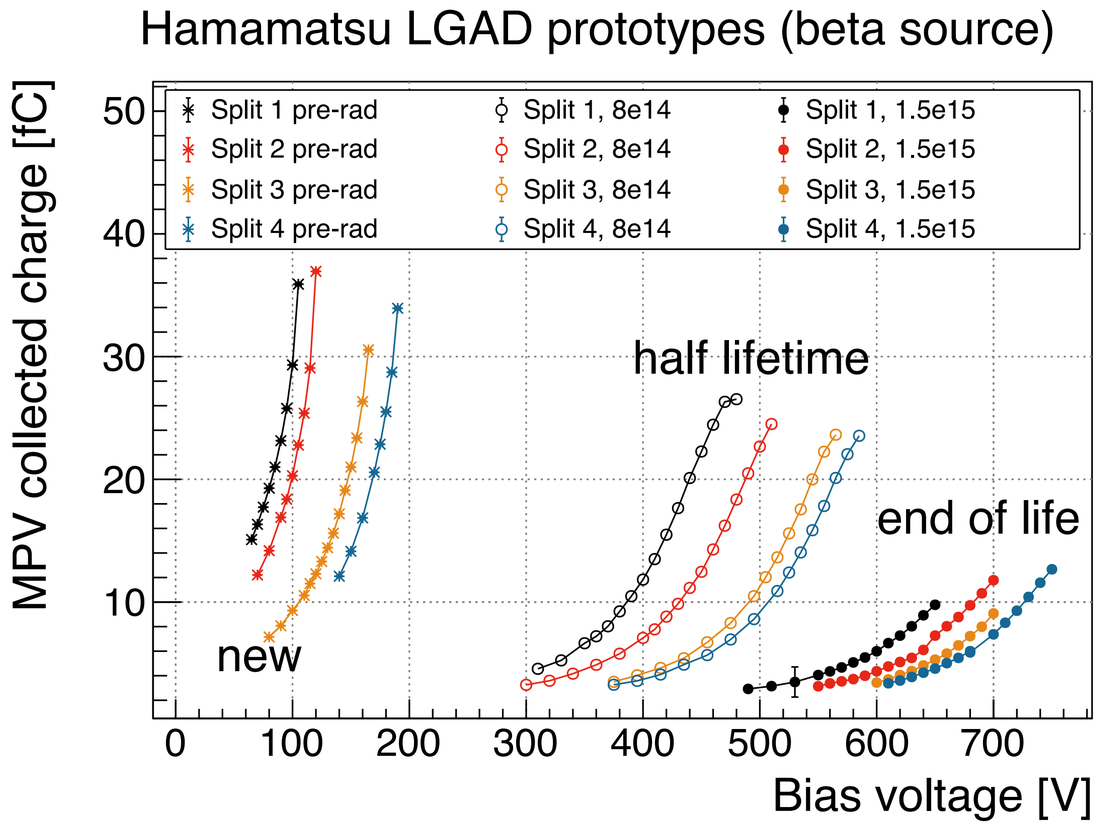
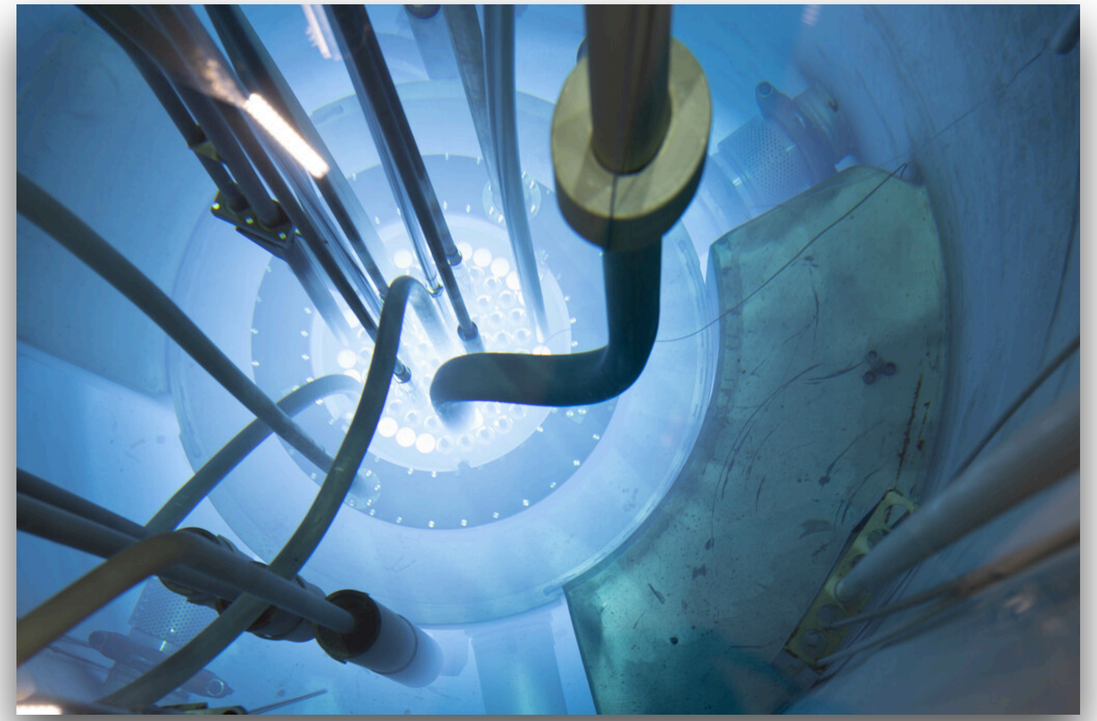
- Production QA strategy will rely on probe measurements at foundries.
- **N.B.** not trivial to apply to AC-LGADs — gain layer is not finely segmented

LGAD radiation hardness

- Gain implant de-activates with irradiation at LHC
- Emulate by exposure at nuclear reactor (up to 1.5 x 10^{15} neq / cm^2)





TRIGA reactor at JSI, Ljubljana, Slovenia

- Compensate by increasing bias.

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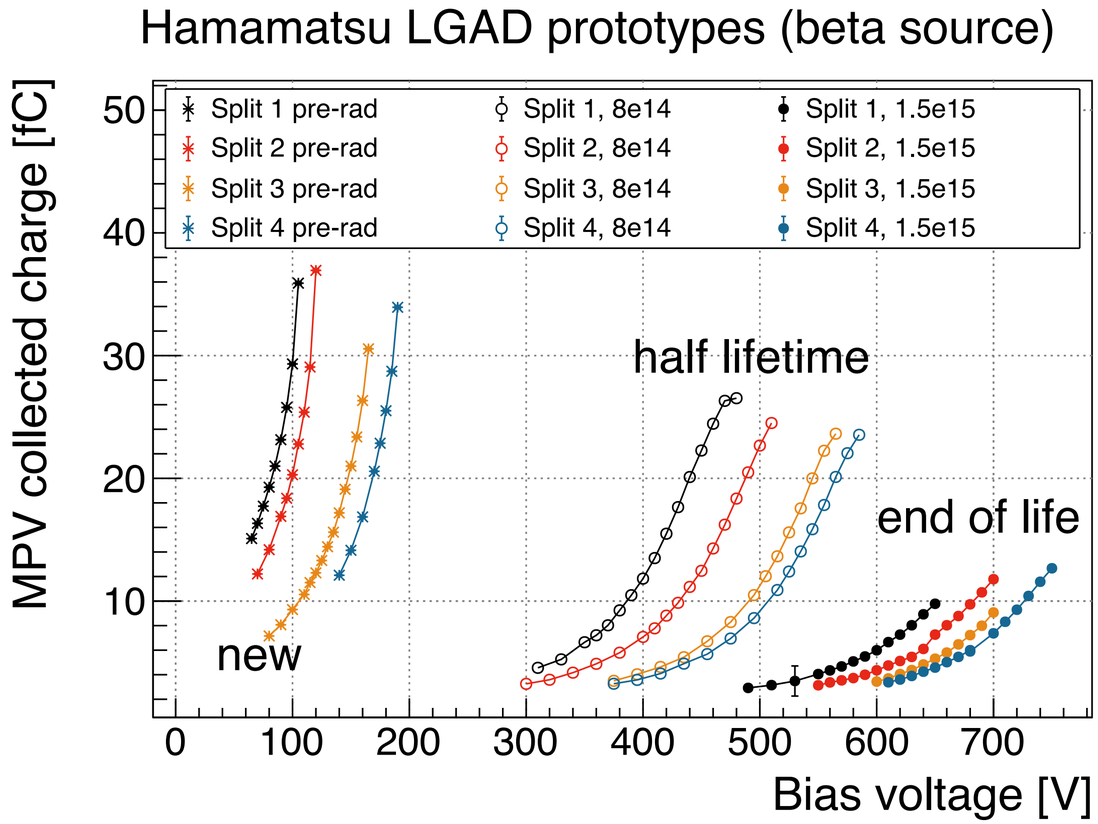

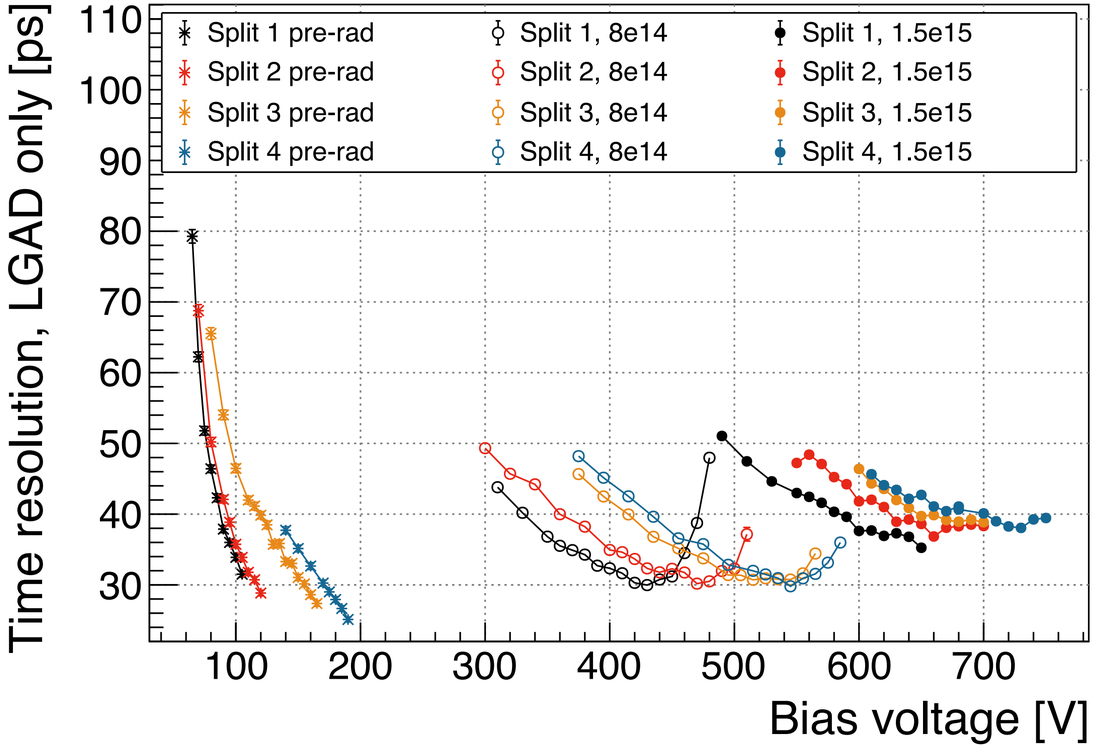

- HPK sensors need > 550 V for highest fluence regions—too high.

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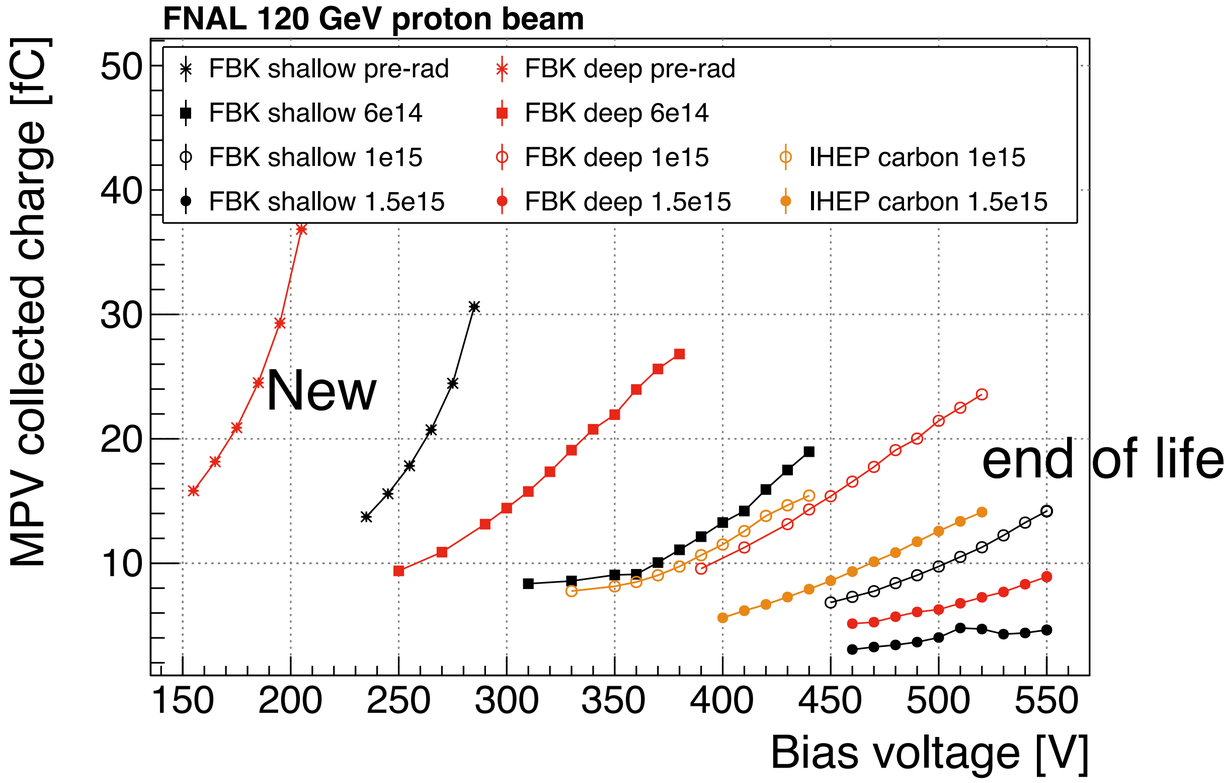
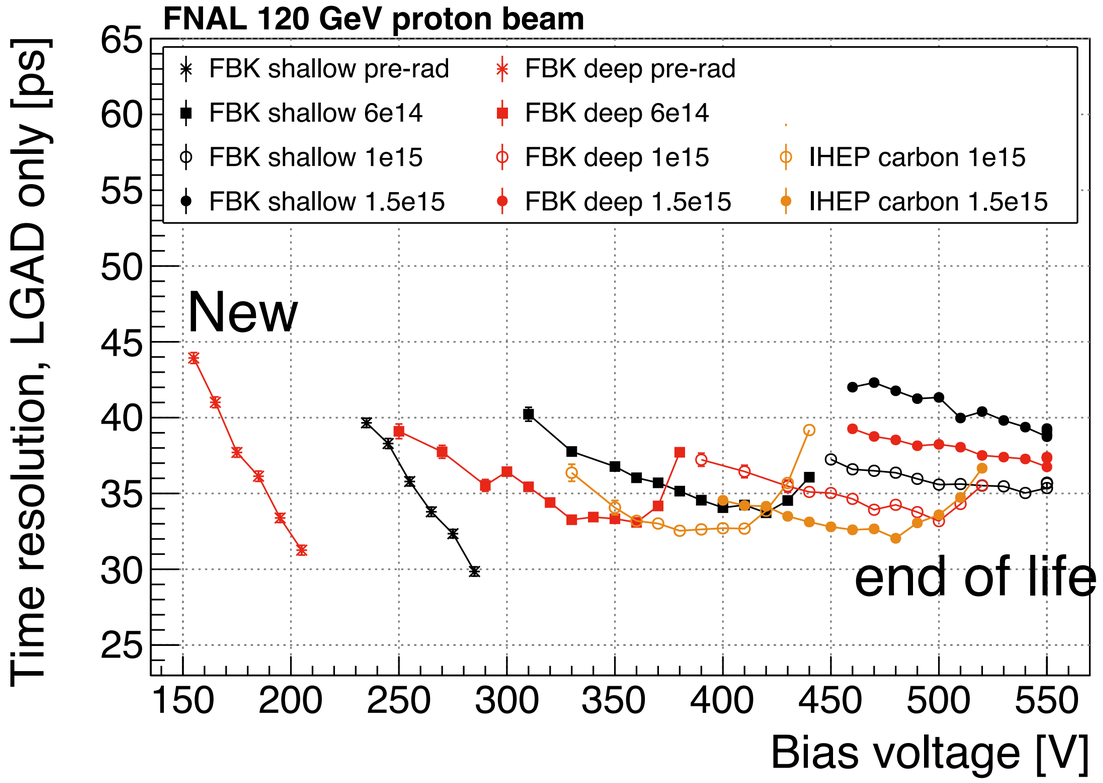
LGAD radiation hardness

- R&D at different foundry (FBK) → significantly improved rad. hardness
- Co-implantation of carbon yields significantly improved radiation hardness
  - Can be performed FBK and IHEP-IME, but not HPK





- Best designs keep 30—40 ps resolution at end of life, with bias < 550 V

CMS LGAD Market Survey

LGAD Market Survey parameters

		Parameter (from MS table)
	Step 0	Preparation of samples for irradiation (0.6E15; 1e15; 1.5E15)
New	1	Breakdown voltage due to gain
	2	Bulk depletion voltage
	3	Number of pads with leakage current higher than 5 x I_leak Mode
	4	Spread of the gain layer depletion voltage within a large-size sensors
	5	micro discharge noise at Vbias < V(20 fC)
	6	Maximum leakage currents for the large-size sensor at V(8 fC)
	Step 1	Q-V measurement
	7	Time resolution at V(8 fC), measured in small-size sensors, in a β−telescope
	8	time jitter at V(8 fC) < 50 ps, measured in small-size sensors
	9	Pad isolation
	10	No-gain distance between pads
Irradiated	11	Breakdown voltage due to gain
	12	micro discharge noise at the V(8 fC) working point
	13	Bias to reach 8 fC(V)/active thickness(μm) V(8 fC)/D
	14	Time resolution at V(8 fC), measured in small-size sensors, in a β−telescope
	15	Pad isolation

- CERN procurement process solicits samples from any interested vendors
  - Many vendors considered, at least 3 likely to be qualified for CMS
  - No official decisions on vendors yet.
- Involvement of multiple vendors was extremely advantageous.
  - Each vendor pushed different R&D frontiers
    - FBK: Radiation tolerance, interpad gaps
    - HPK: Uniformity, yield
  - Not obvious who would qualify, though strongly correlated with participation in past R&D
  - Significant cost and risk reductions with multiple qualified vendors
    - Unlikely any 1 vendor could cover entire detector (due to large size, but also technical constraints)
    - Facilitates in-kind and international contributions

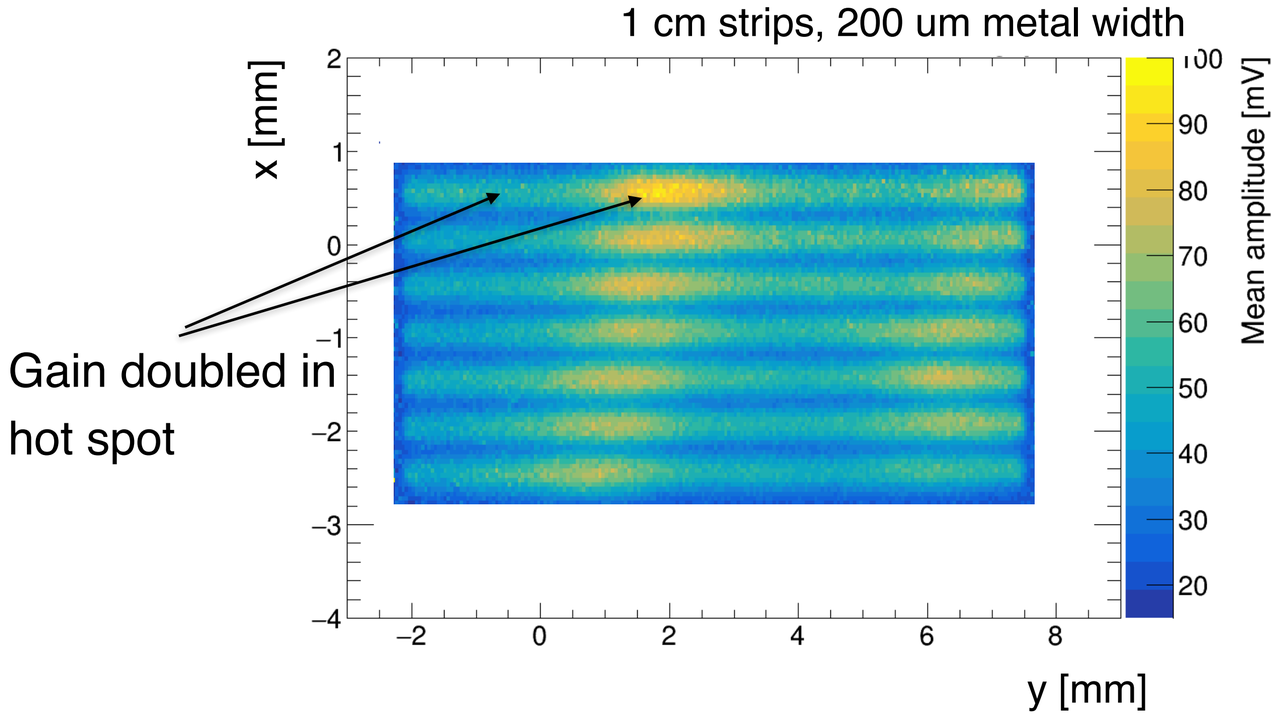
ePIC TOF sensor R&D

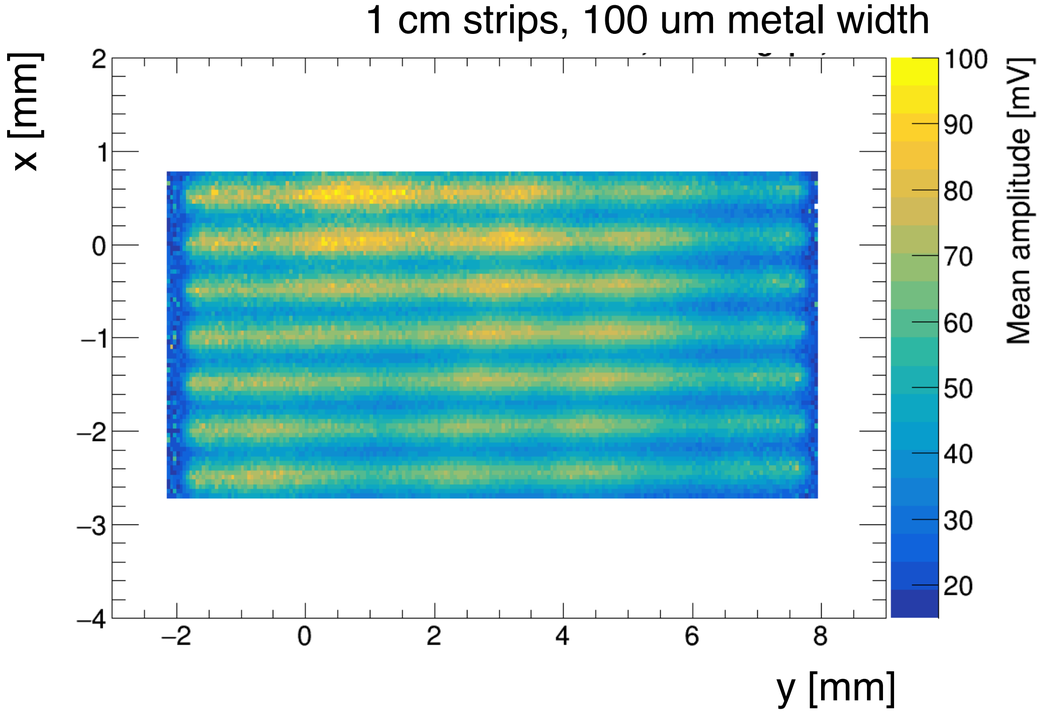
- AC-LGADs appropriate for EPIC ToF have been demonstrated at beam tests, certainly capable of delivering 30 ps and 10-20 um resolution
  - 500 μm x 0.5 to 2.5 cm strips (arXiv 2211.09698)
  - 500 μm x 500 μm pads (2022 JINST 17 P05001)

- But, significant sensor R&D needed for realistic detector
  - Gain layer uniformity
    - Builds upon CMS/ATLAS R&D, but not solved universally, and requires new QA strategy.
  - Optimization of signal sharing in resistive layer
  - Readout of large electrodes & interface with electronics
  - Sensor active thickness
  - High yield production demonstration
- Need to approach questions from multiple foundries.

Gain uniformity, BNL 500 um strips

- Very large active area: sensitivity to non-uniformity in gain layer
  - Stripe patterns of high gain observed in most sensors of this production
  - High gain regions limit operating voltage → other regions remain underbiased



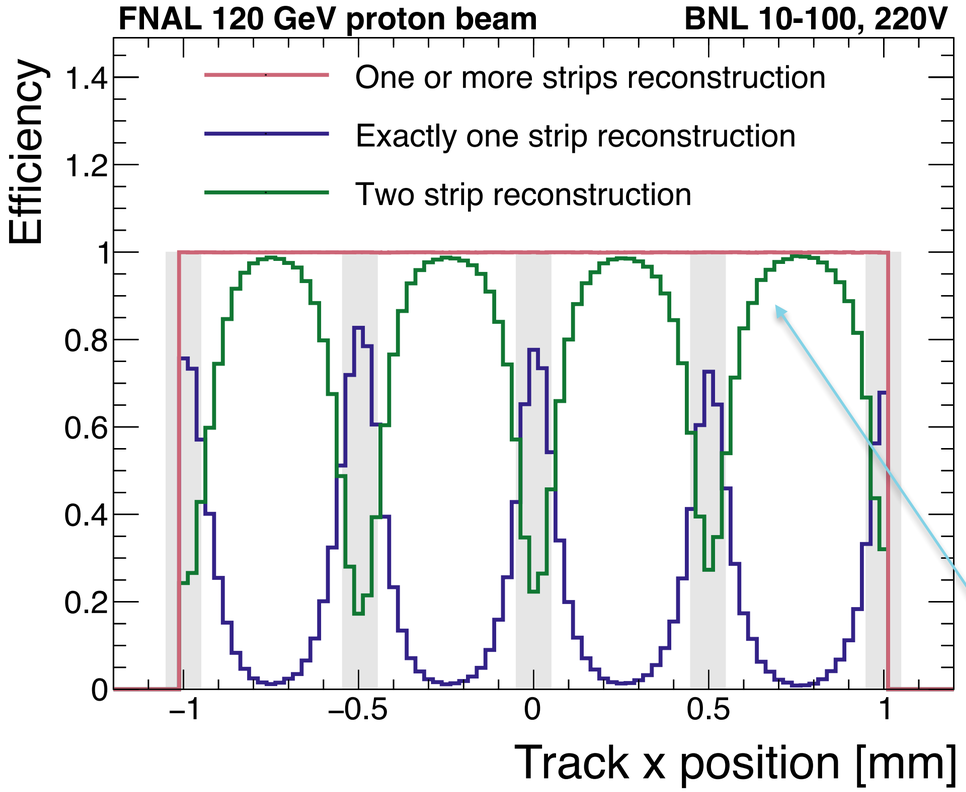


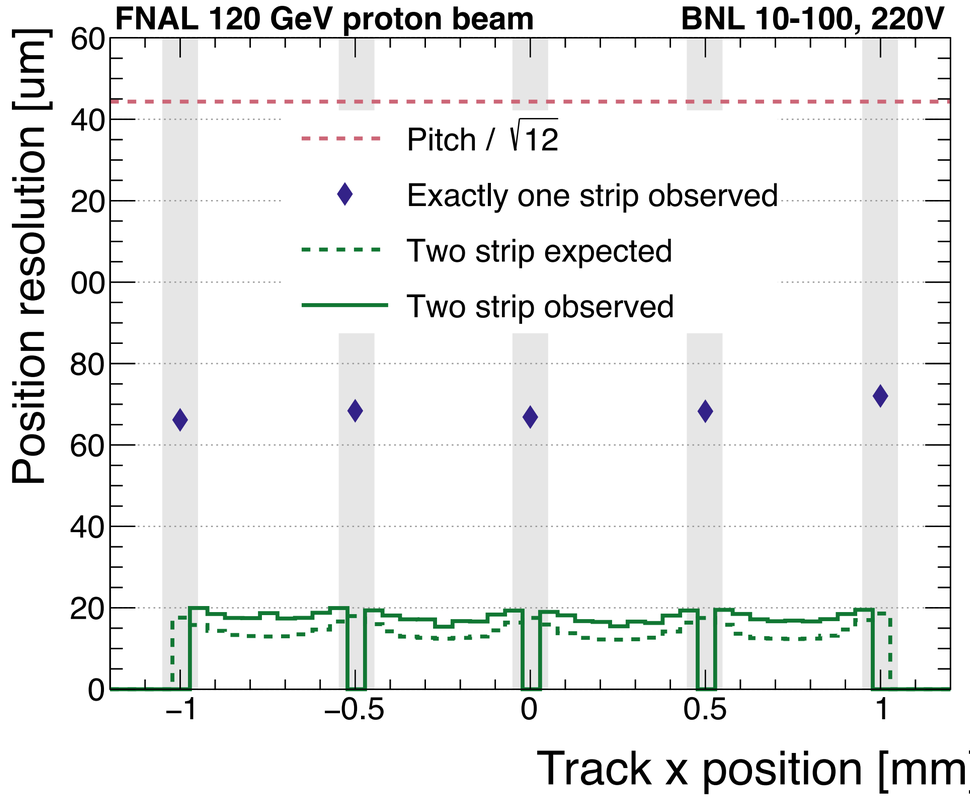
- Expect improved uniformity in next prototypes
  - Uniform 2x2 cm^2 LGADs for ATLAS/CMS already demonstrated
  - Still extract useful lessons despite non-uniformity!

Optimizing signal sharing

- Need two-strip clusters for best performance.
  - Spatial reconstruction— interpolate position with ~ 20 um resolution
  - Time resolution — reduce impact of noise, self-correct delays

Performance for 1 cm strips, 500 um pitch w/100 um metal



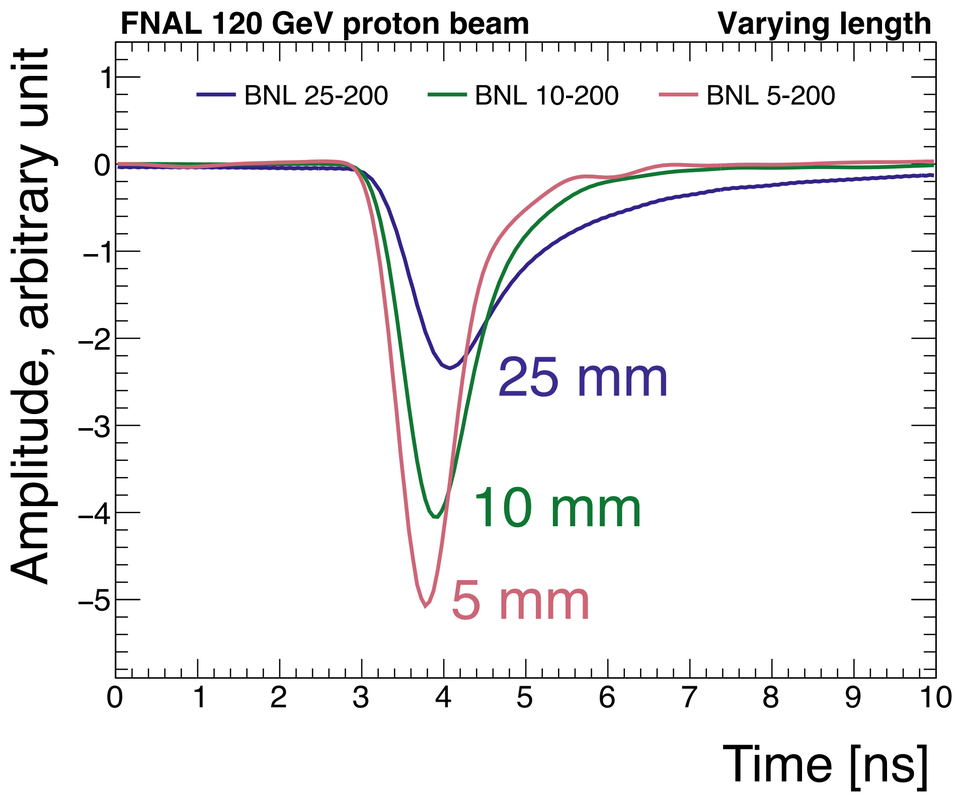


Tune electrode geometry and n++ to maximize 2 strip coverage

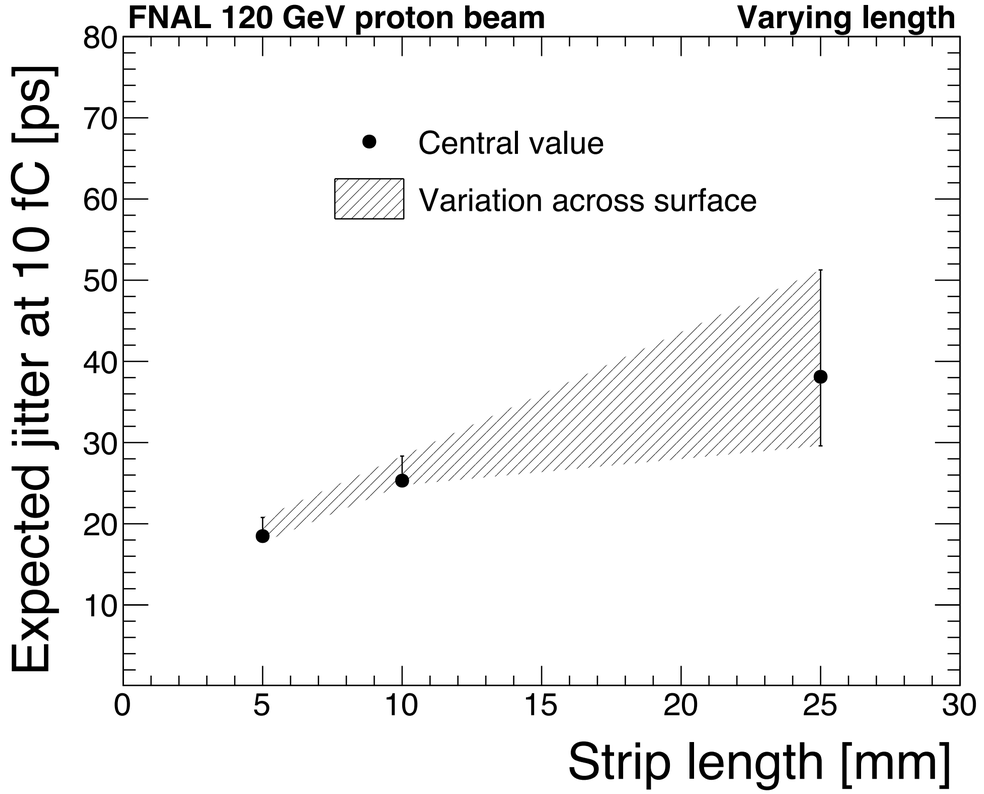
Pulse shapes for precision timing

- Longer strips associated with slower rising edge
  - Likely due to extra capacitance, and transmission line reflection effects

Averaged pulse shapes



Expected jitter for operation at moderate gain



- 1 cm strips: already work well!
- > 2 cm: trying few ideas to improve in next beam test.

Conclusions

- CMS ETL experience—
  - Significant LGAD development undertaken within project
  - Vast benefits to involvement of multiple vendors along the way
    - Push vendors to compete and innovate in R&D phase
    - Safer and cheaper portfolio of suppliers for production

- ePIC ToF is a very promising and exciting detector, but still some work ahead in sensor development.
  - With schedule pressure, should pursue R&D with multiple foundries in parallel
  - Advantageous to maintain relationship with multiple vendors for final sensor procurement.