Performance of highly irradiated pixel sensors for the CMS HL-LHC upgrade

corrinne mills (UIC+FNAL)

On behalf of the CMS Tracker group

TREDI in Vienna

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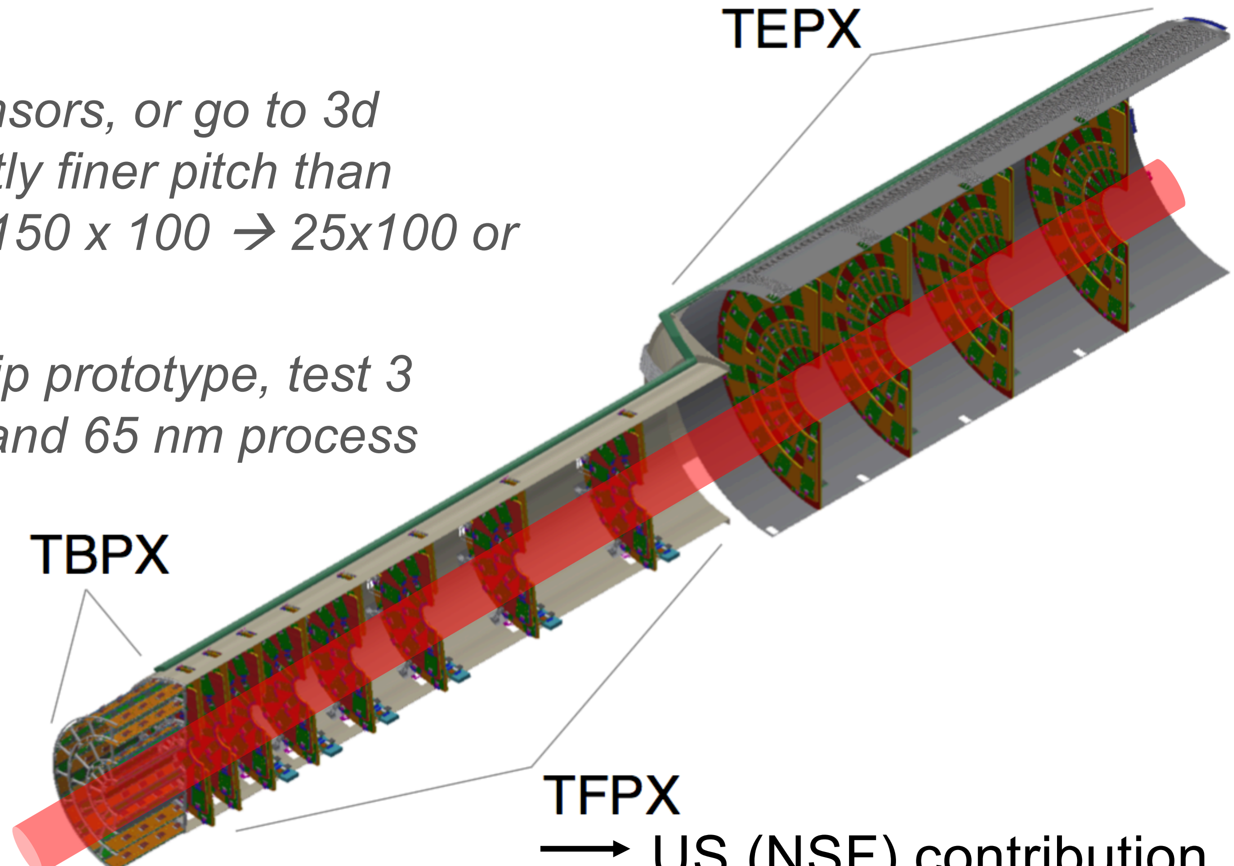
CMS HL-LHC pixel upgrade

- CMS Phase-2 pixel detector for the HL-LHC must withstand an unprecedented radiation environment: **2 x 10^{16} n_{eq}/cm^2**
  → *Barrel innermost layer ~3 cm from beam*
- Years-long program of sensor, ROC R&D for designs that can tolerate this
  → *Thinned planar sensors, or go to 3d sensors, significantly finer pitch than current detectors (150 x 100 → 25x100 or 50x50 μm^2)*
  → *RD53A readout chip prototype, test 3 analog front-ends and 65 nm process*



Approximate region of > 1 x 10^{16} n_{eq}/cm^2: TBPX layer 1 and innermost TFPX ring

¼ of final detector

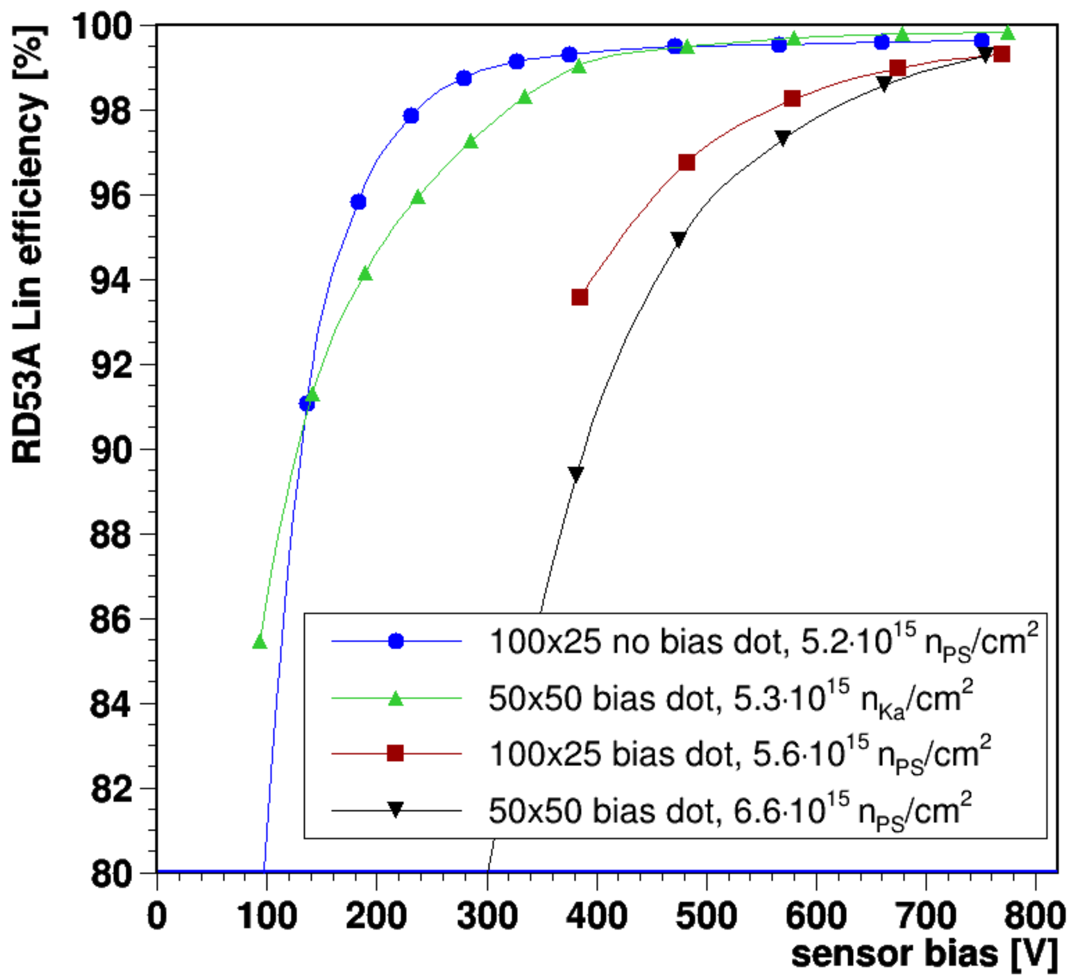
TFPX ⟶ US (NSF) contribution

Planar sensor studies

- Performance of planar sensors designed for the CMS Phase-2 pixel detector upgrade have been studied at a fluence just above 5 x 10^{15} n_{eq}/cm^2
- Sensor with no bias dot reaches full efficiency first

→ *Motivation to omit bias dot*

sensor	threshold	angle
● (blue circle)	1300 e	34°
▲ (green triangle)	1200 e	18°
■ (dark red square)	1500 e	34°
▼ (dark green inverted triangle)	1400 e	30°

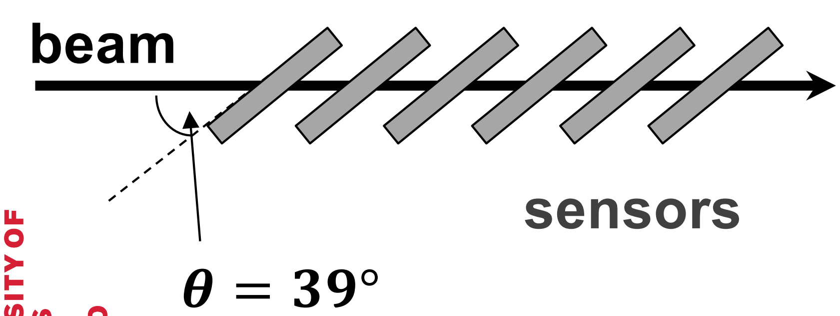


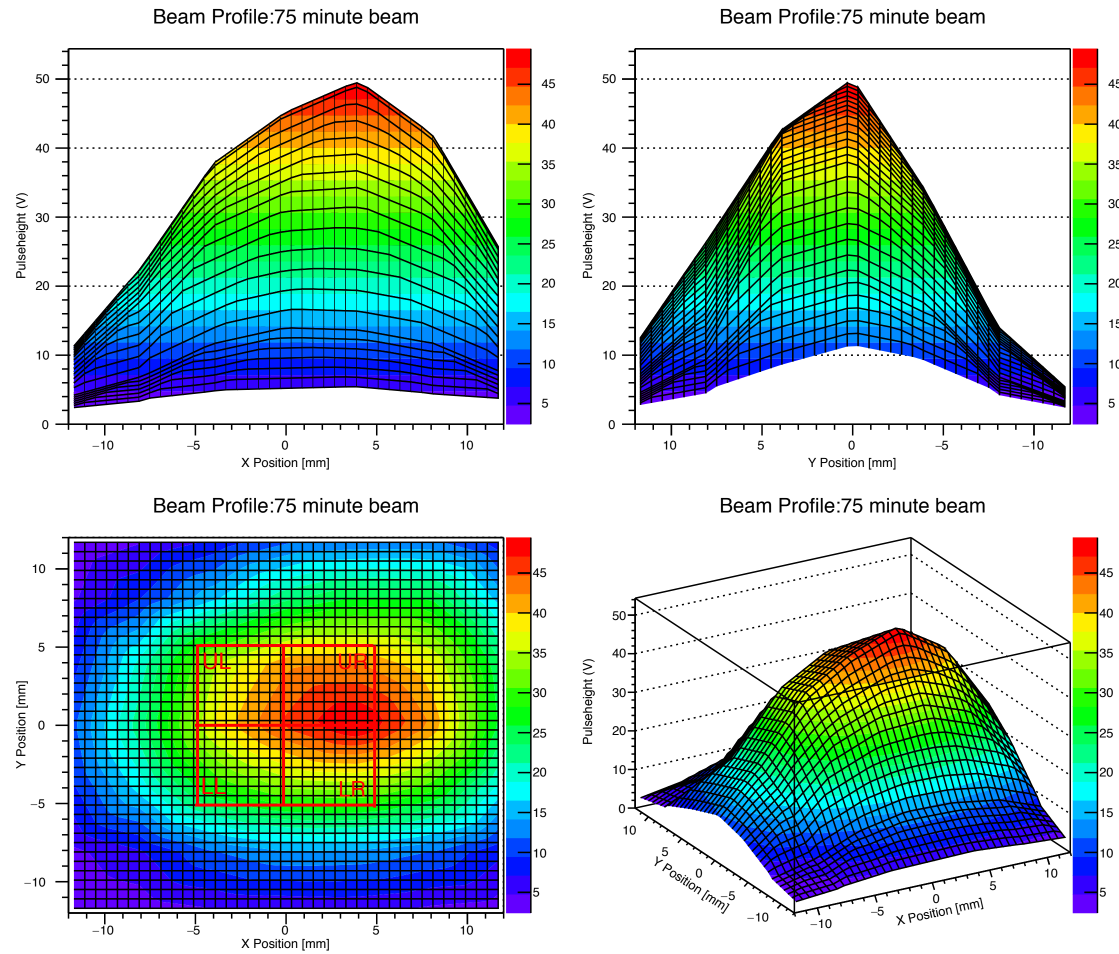
plot: J Sonneveld

Irradiation at Los Alamos

- **LANSCE facility: 800 MeV protons**
- Profile monitored by PIN diode: a beam spot (1 σ) of ~6.5 mm (x) and ~8.5 mm (y)
- Beam centered on the Linear front-end
- Sensors tilted in the beam

→ *ellipsoidal irradiation spot*





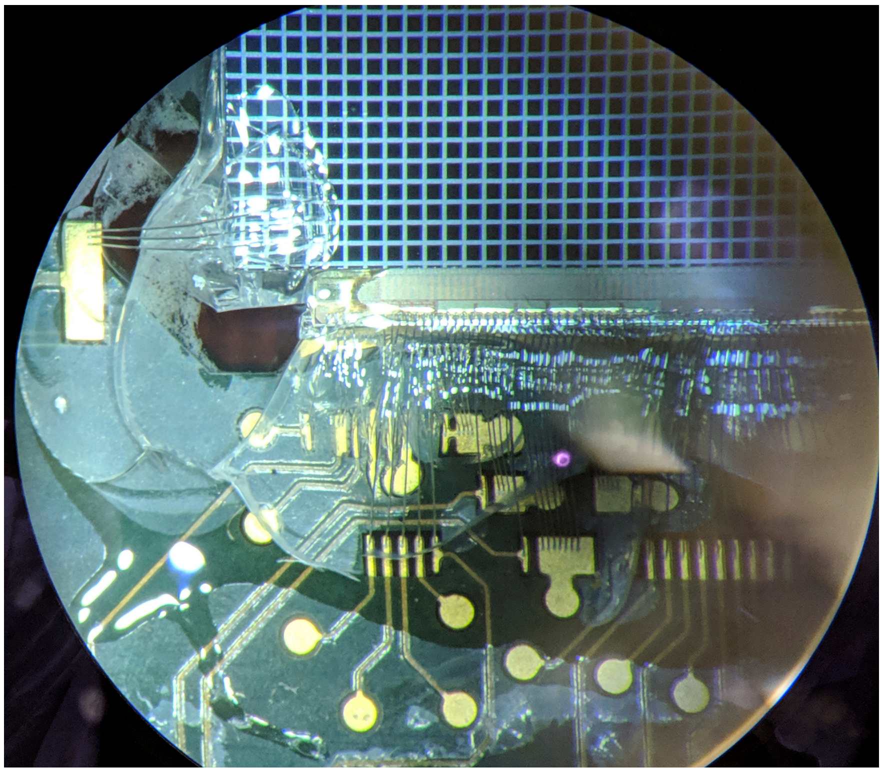
Pin Diode Array analysis of the LANL beam profile during the November 2019 irradiation courtesy Martin Hoeferkamp and Sally Seidel, University of New Mexico.

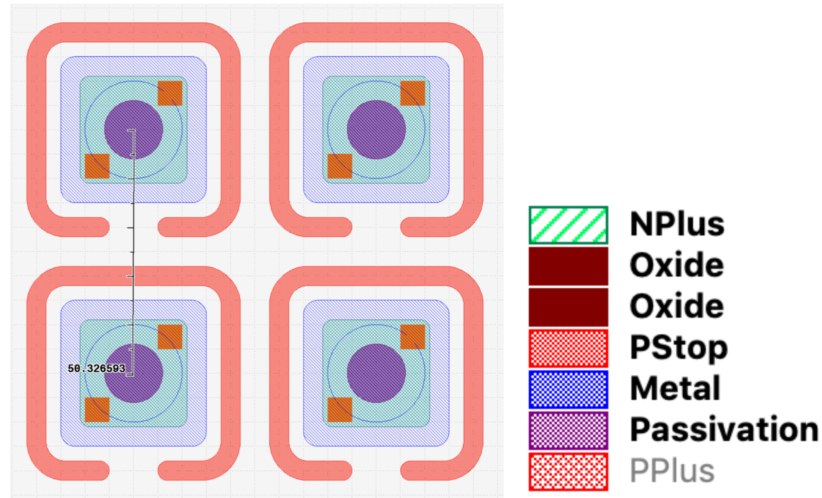
Irradiation at Los Alamos

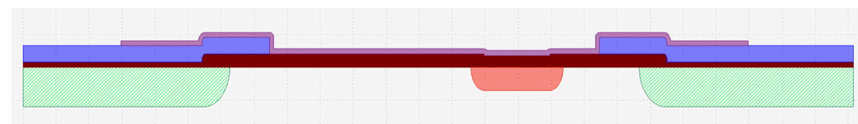
- Planar pixel sensors bump-bonded to the RD53A prototype chip were irradiated for CMS in late 2018
  - → *Half to full layer-1 ($2x10^{16}$ n_{eq}/cm^2) fluence, rest to $1x10^{16}$ n_{eq}/cm^2*
- Estimate of **peak fluence** of "$1x10^{16}$ n_{eq}/cm^2" batch was more like **$1.3x10^{16}$ n_{eq}/cm^2**.
  - → *Measured through activation of Al foils*
  - → *Relatively little information exists on pixel sensors at this fluence*
- Wirebonds encapsulated with sylgard for mechanical protection prior to irradiation
  - → *Fine at lower doses (2 MGy) but **hardens & cracks** with this amount of radiation (5-7 MGy)*
- This talk: results from a sensor in the 1.3×10^{16} n_{eq}/cm^2 batch
  - → *One other device from this batch partially functional: problems synching with external clocks but sensitive to beam and radioactive sources with similar efficiency*

Lucky Number 13

- HPK, 50x50 μm^2, 150 μm thick, FDB
- Open p-stop design
  → *Reduced active area*
  → *Not baseline for CMS HL-LHC*

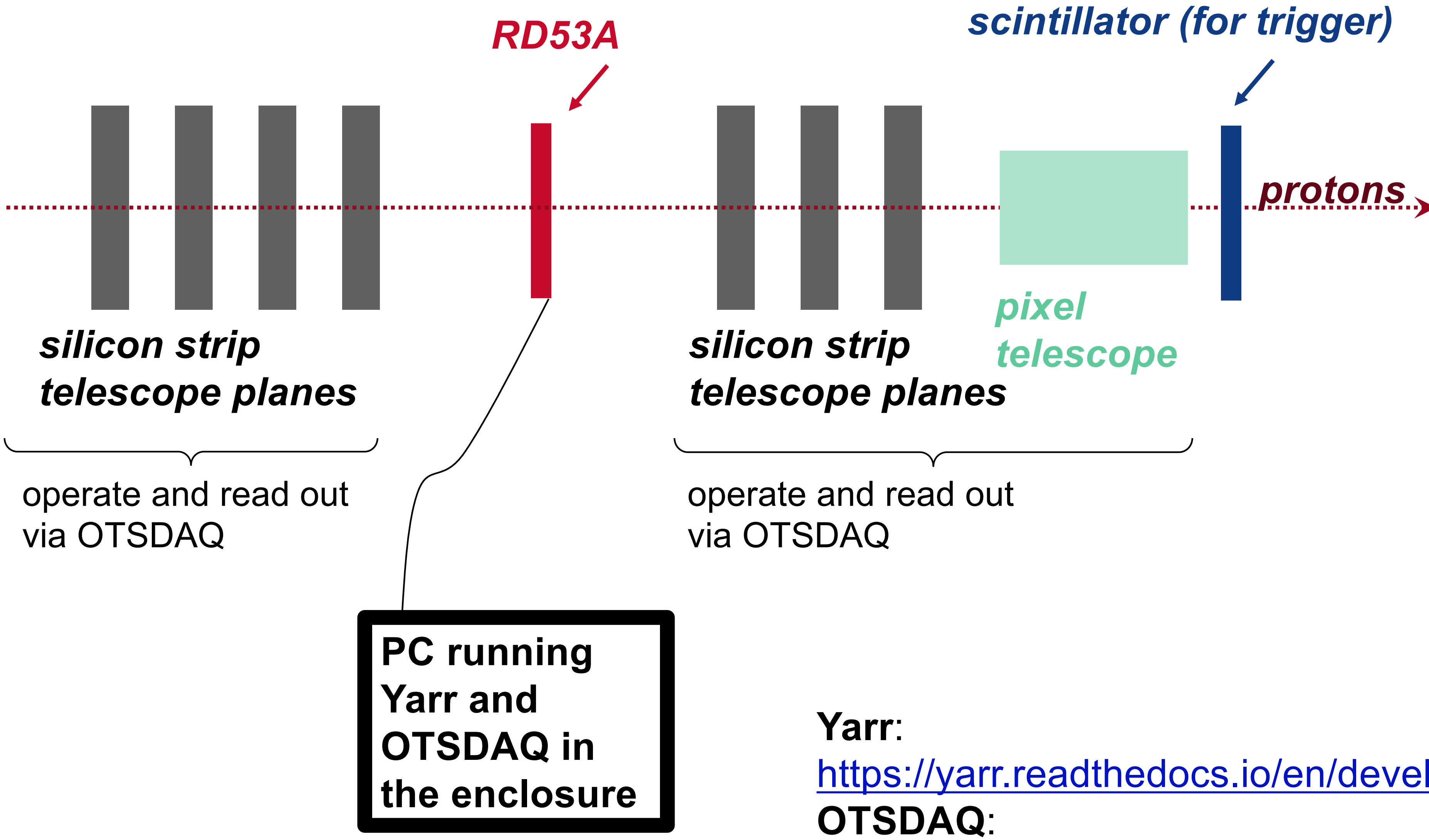






- Sylgard pulled back from sensor and took the wirebonds with it
- Inspection and repair of HV wirebonds at Fermilab recovered sensor

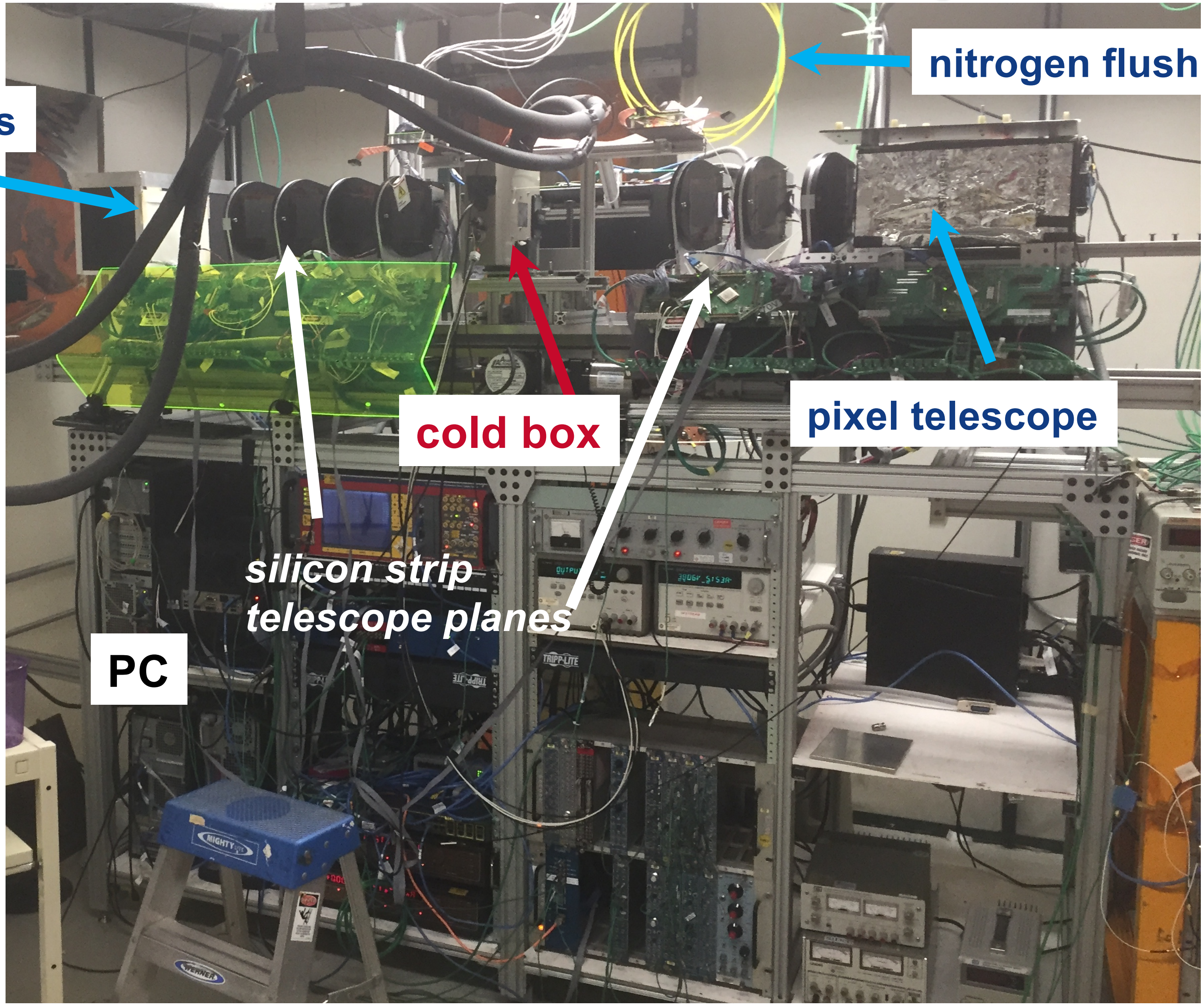
Test beam schematic



Yarr: https://yarr.readthedocs.io/en/devel/

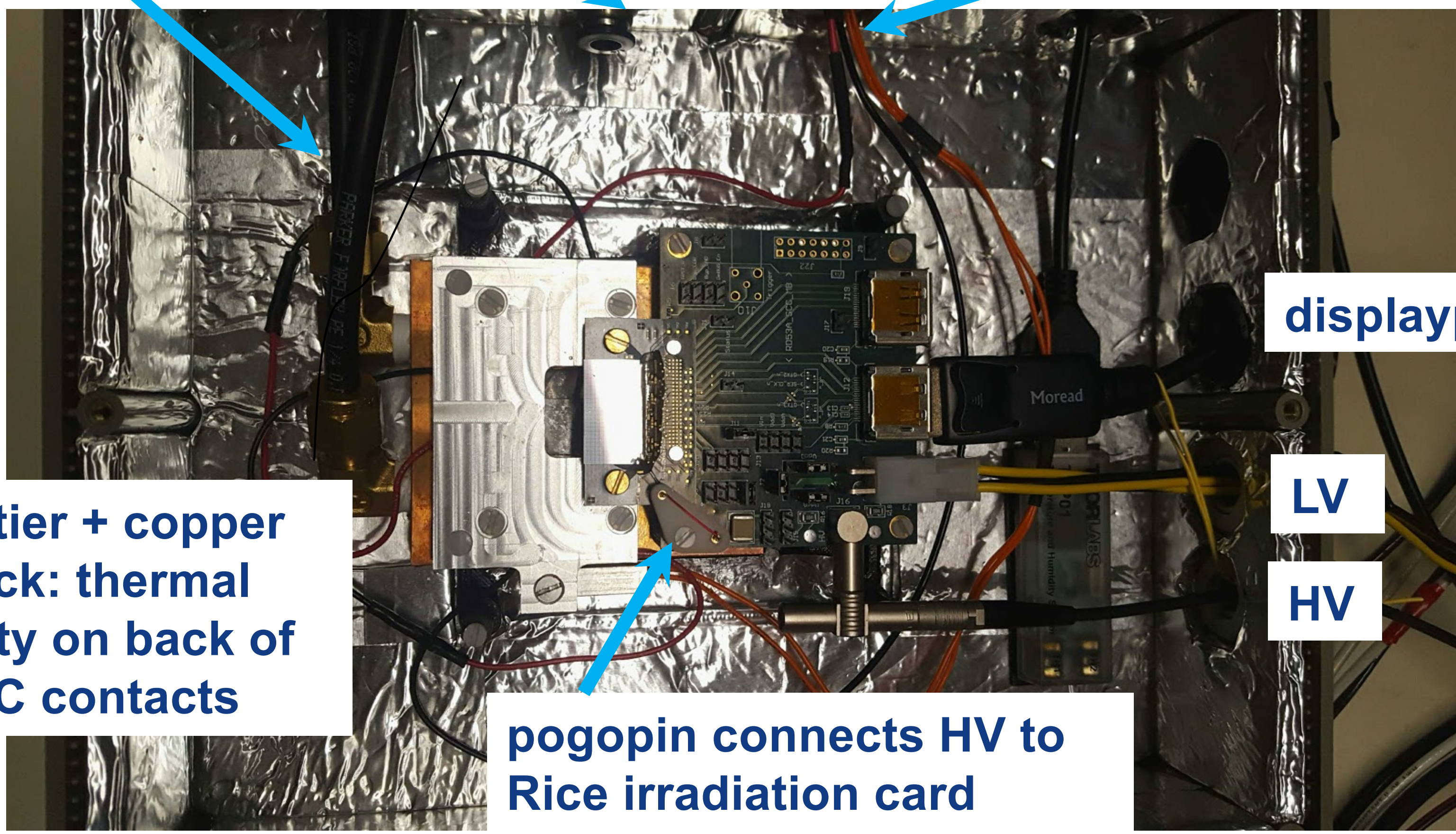
OTSDAQ: https://arxiv.org/abs/1806.07240

FNAL test beam setup

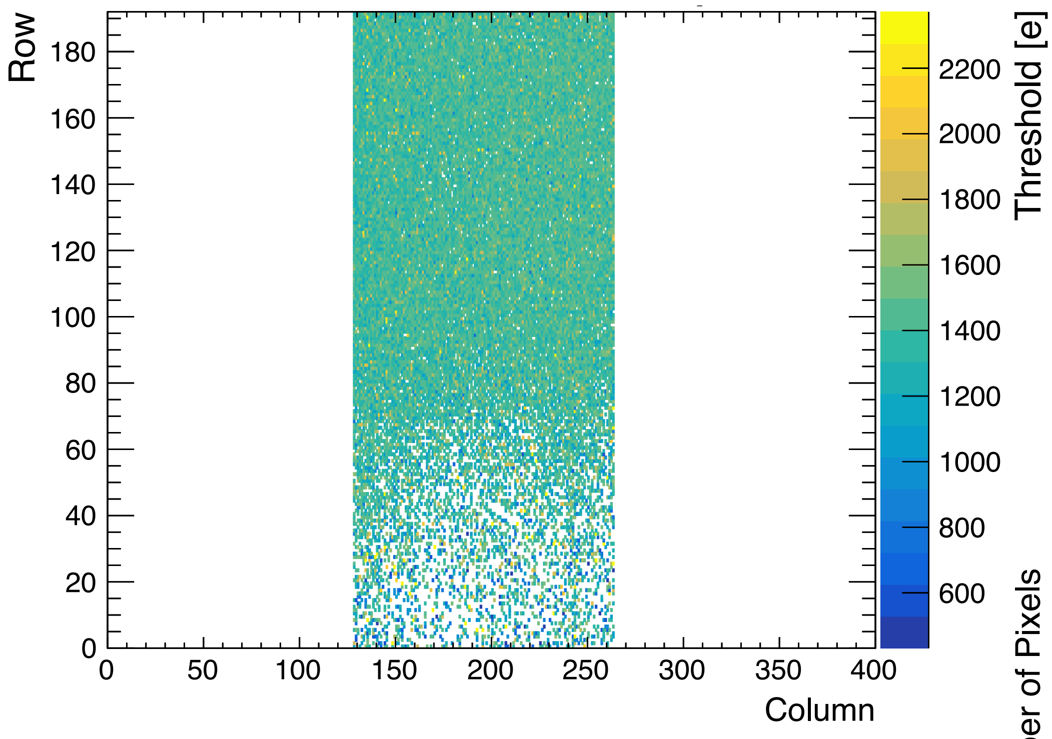


DUT in coldbox

- Run devices cold (-25C – -35C) to control leakage current during operation of irradiated devices
- Grateful to Mauro Dinardo, Luigi Moroni for loan of their coldboxes

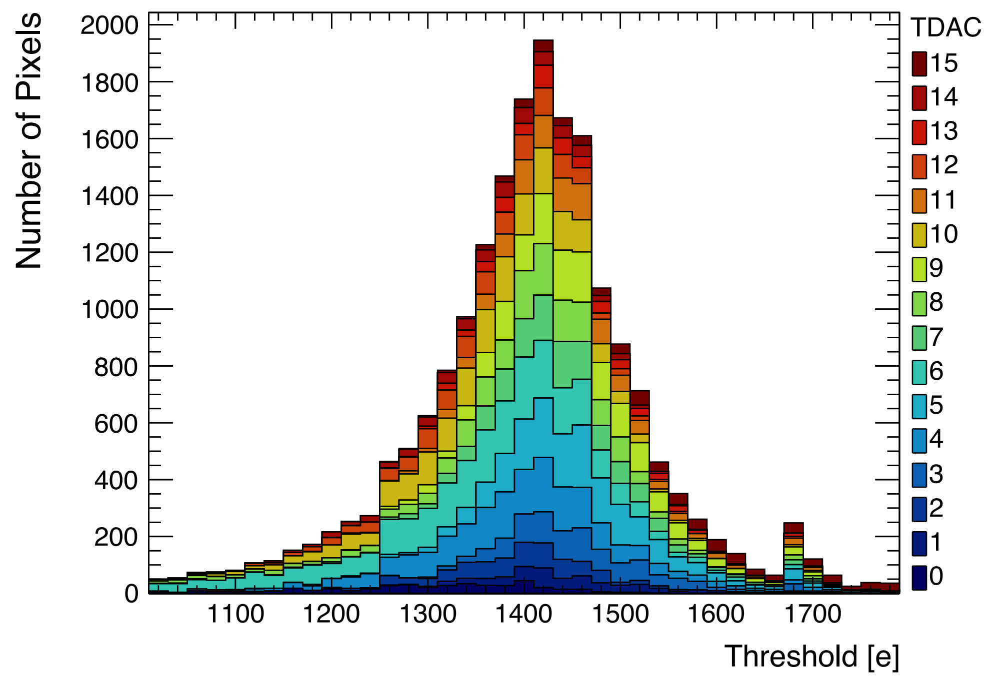


Tuning irradiated module



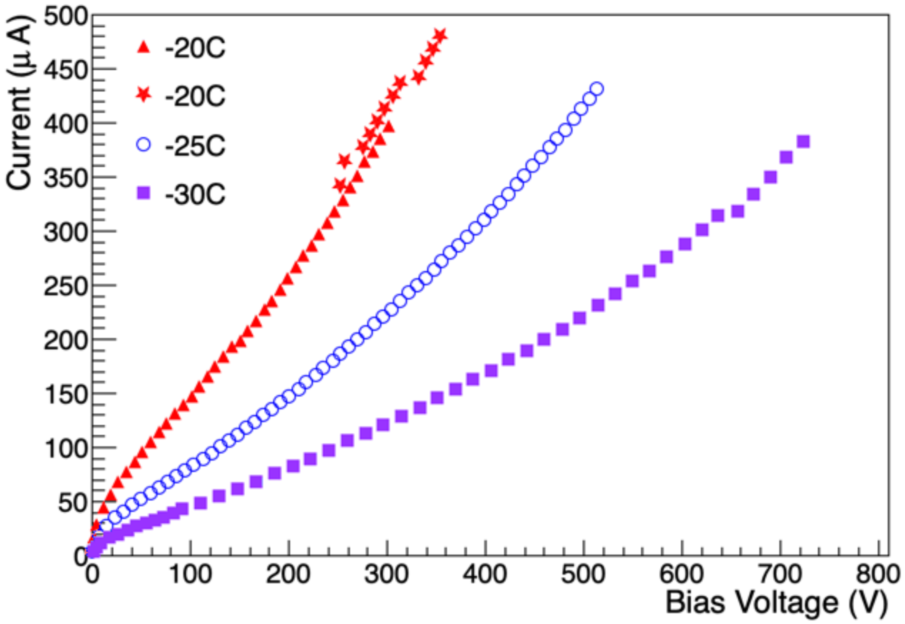
Lowest threshold we could tune to was 1400e, with parameters:

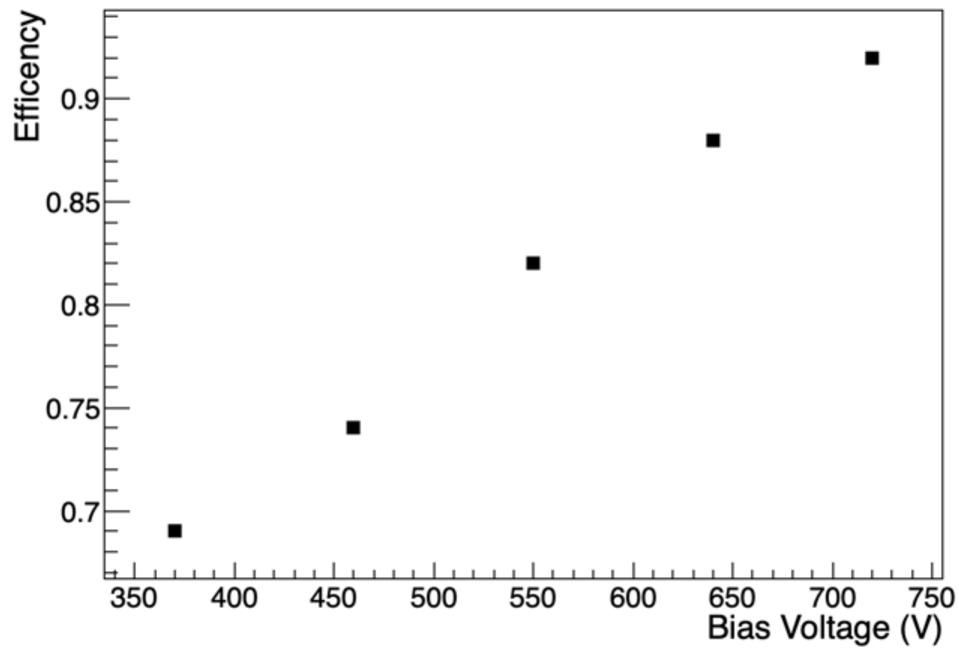
LinKrumCurr: 30
LinLdac: 135
LinRefKrum: 300
LinVth: 385



- About 25% pixels noisy and/or untunable
  - → *Wirebonds at the top of the plot*
  - → *Can be recovered with higher threshold, but charge collection efficiency correspondingly reduced*

Bias and Efficiency



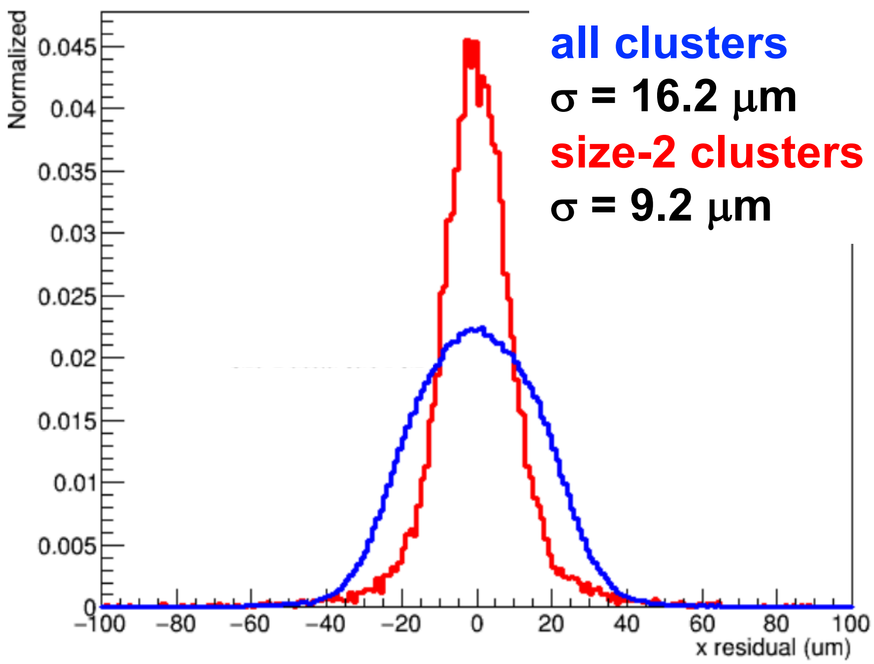


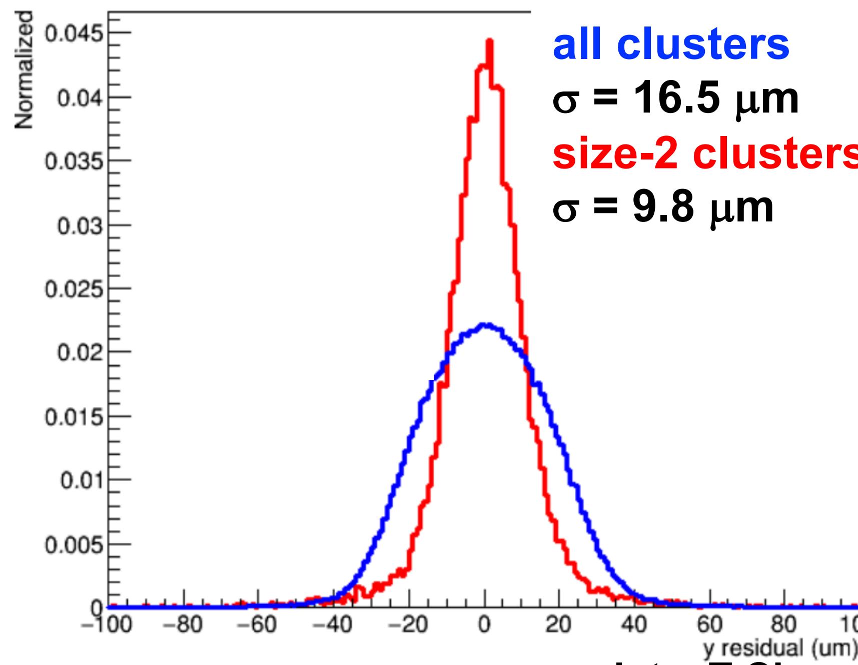
- I-V for sensor used in beam depends on temperature as expected
  → *Purple curve (-30C) is our operating point*
- Bias voltages at the sensor (corrected for resistors on adapter card)
- Efficiency vs bias voltage does not seem to plateau

voltage (V)	370	460	550	640	720
efficiency	0.69	0.74	0.82	0.88	0.92

Residuals

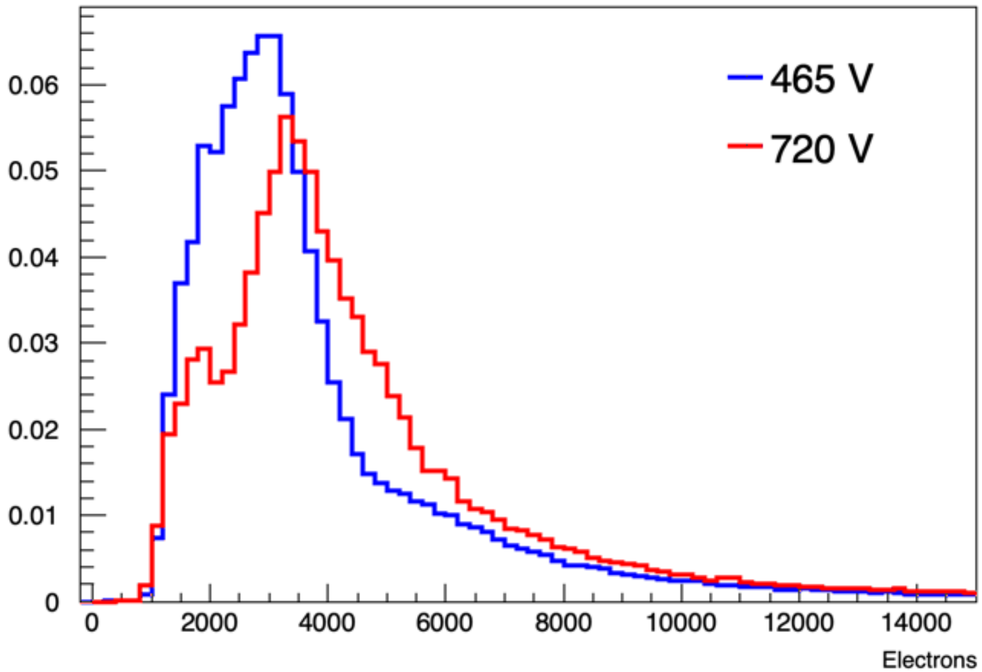
- Reconstruction and alignment with Monicelli software (INFN-Milano Bicocca)
- Current best alignments: 16-17 μm resolution
  - → *Normal incidence*
  - → *~90% single-pixel clusters and 50/sqrt(12) = 14; difference mostly attributable to telescope resolution (5-7 μm)*

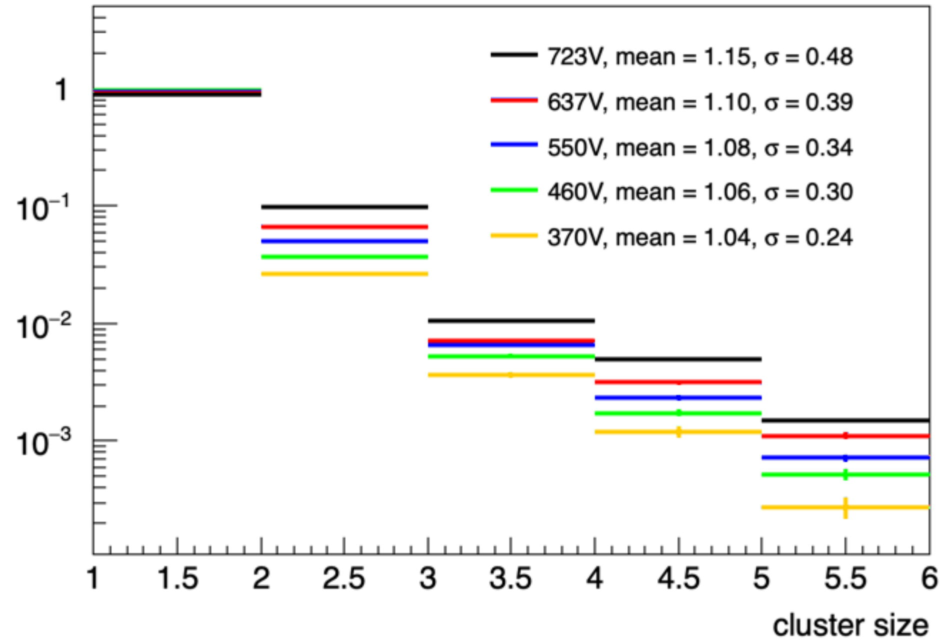




plots: T Cheng

Charge and clusters



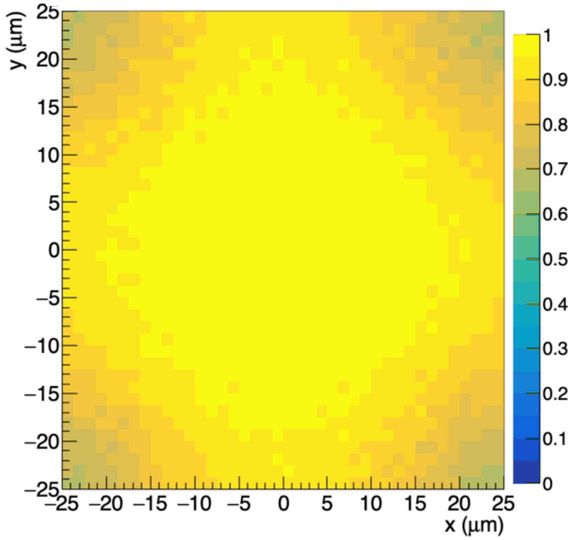


- Internal charge-injection calibration converts ToT -> electrons
- Distributions sculpted by 1400e threshold
  - → *Still a clear trend of increased charge collection at higher bias voltage*
  - → *Same temperature and configuration otherwise*
- About 90% single-pixel clusters, shift to higher values with V_{bias}

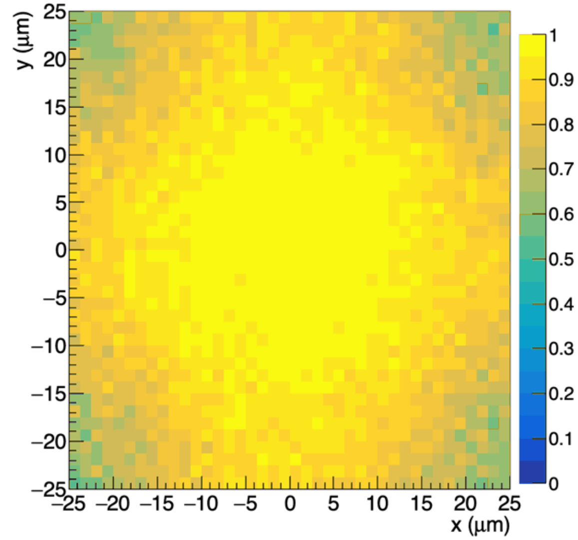
plots: S Dittmer (left), J Reichert (right)

Bias scan: cell efficiency

720 V

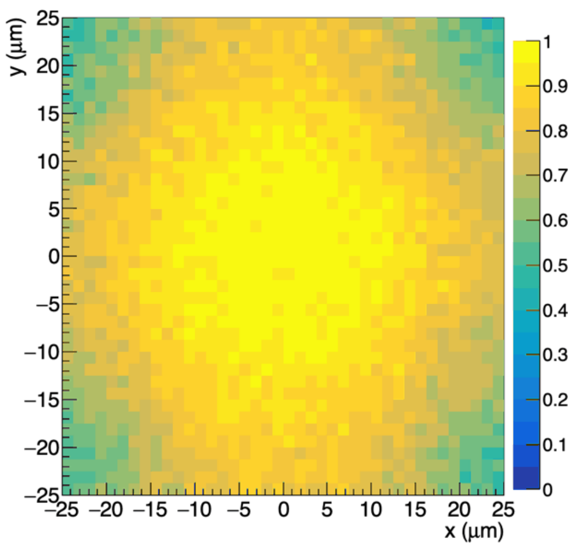


640 V

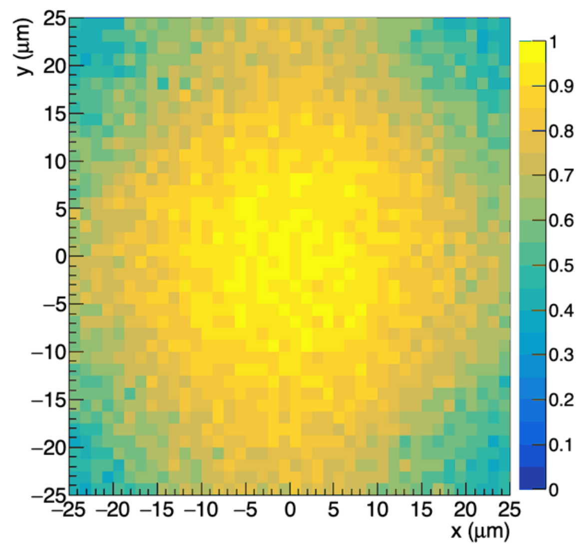


- Looking at single pixel
- 1400e threshold
- -30C
- linear FE only
- Reduced efficiency at edges: charge sharing, inactive area around pixel

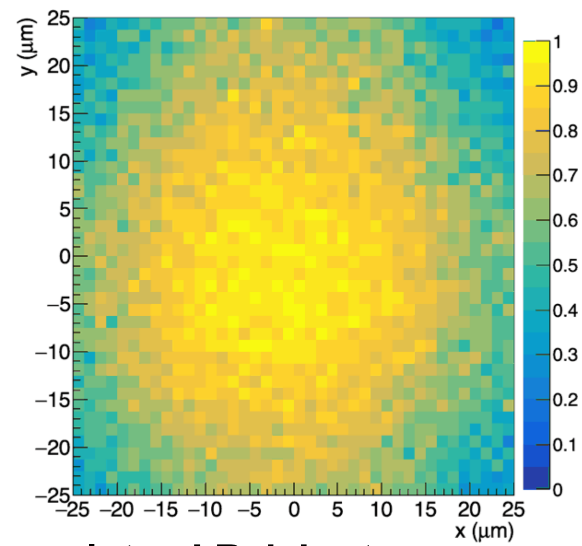
550 V



460 V



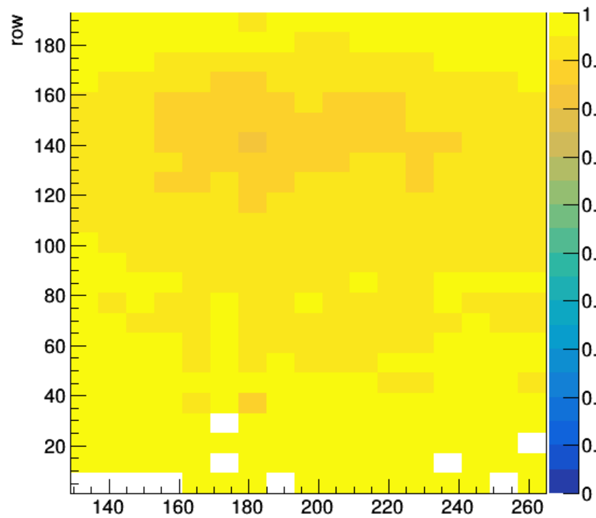
370 V



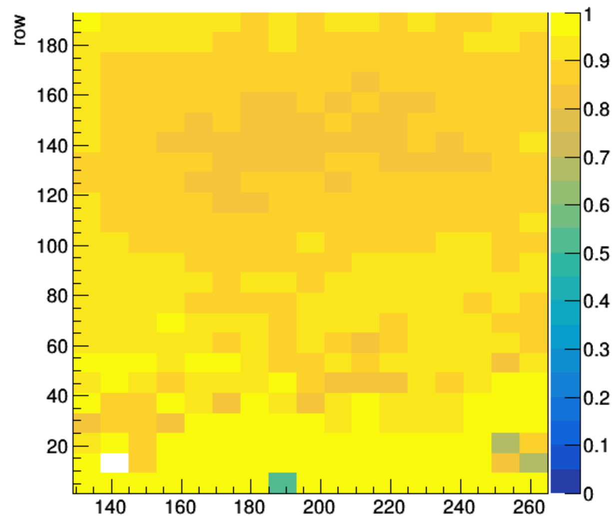
plots: J Reichert

Bias scan: efficiency map

720 V



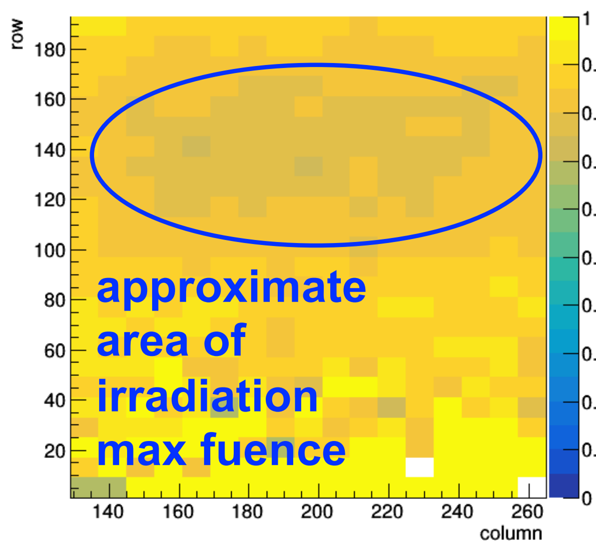
640 V



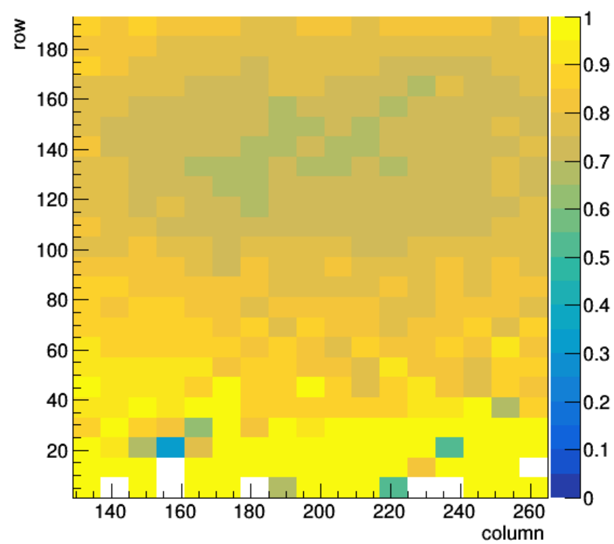
- Looking at linear FE
- 1400e threshold
- -30C
- Pixels grouped in 8x8 blocks – x, y axes are core row and column
- linear FE only

plots: J Reichert

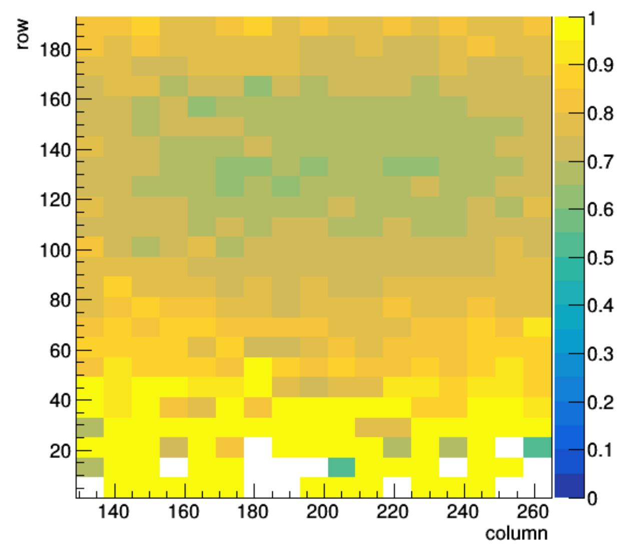
550 V



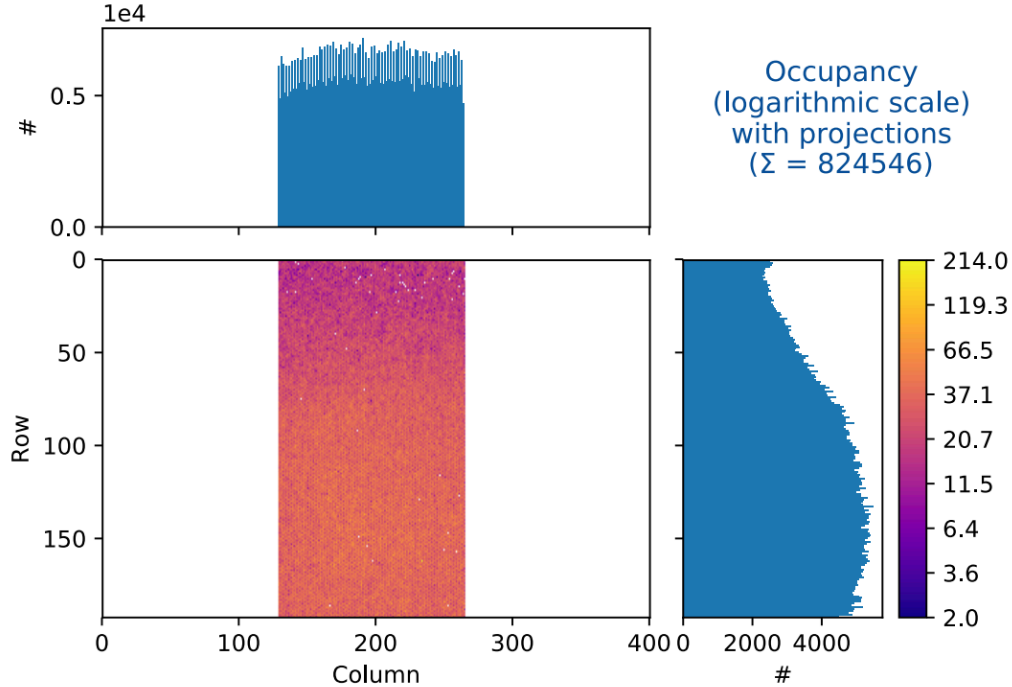
460 V



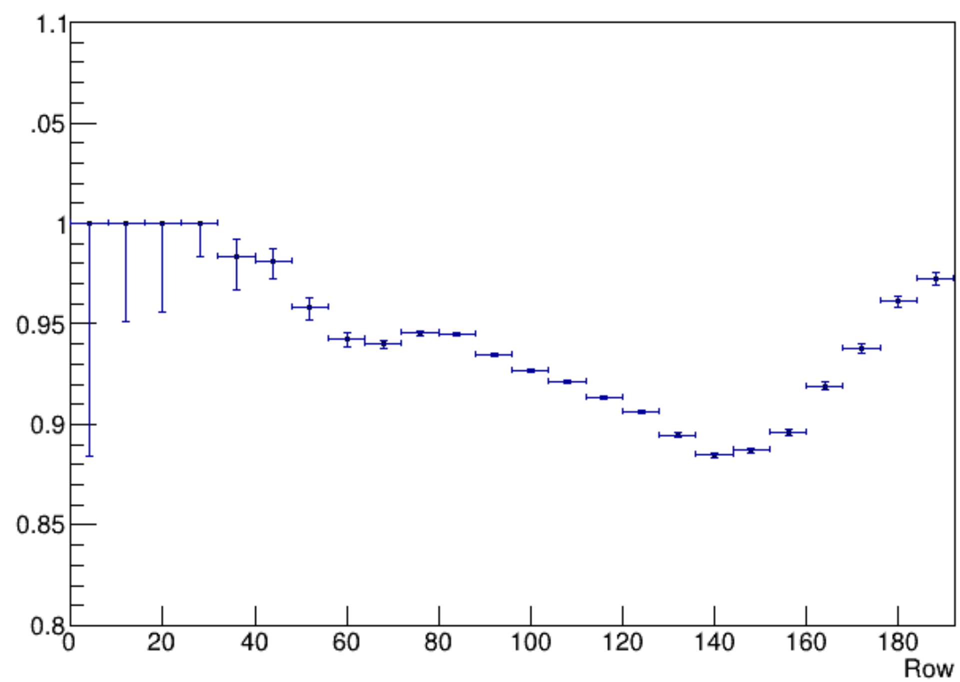
370 V



Efficiency and fluence vs row



- Devices tilted in the irradiation beam → fluence relatively constant within a row
  - → *Efficiency vs. row is a good proxy for efficiency vs. fluence*
  - → *Below: efficiency at 720V*



- Above: occupancy from 10-minute self-trigger scan
  - → *Activation gammas*
  - → *Fluence profile:*
    - flat vs column
    - Peak around row 150

plots: A Hassani & S. Wagner

Conclusion and plans

- **Studied planar sensor with fluence up to 1.3 x 10^{16} n_{eq}/cm^2**
  - → *Encouraging: > 90% efficiency with the irradiated sensor at -800V and -30C, likely some efficiency loss from p-stop*
  - → *Need to understand reproducibility of effects*
- **FNAL Irradiation Test Area under construction**
  - → *400 MeV protons, 10^{14} p/hour*
  - → *First beam expected spring 2020: start with silicon samples (that means us!)*
  - → *Test beam and irradiation integrated in one facility*
- **New round of irradiation testing planned for this year**
  - → *Aim for max fluence 2.0 x 10^{16} n_{eq}/cm^2 again*
  - → *LANSCE request in, will to go to FNAL if it's ready*
  - → *Testing the devices for this campaign in December and upcoming February testbeam runs to establish baseline*
  - → *Systematically understand planar sensor behavior at full HL-LHC fluence, test some 3d sensors as well*

The Test Beam Team

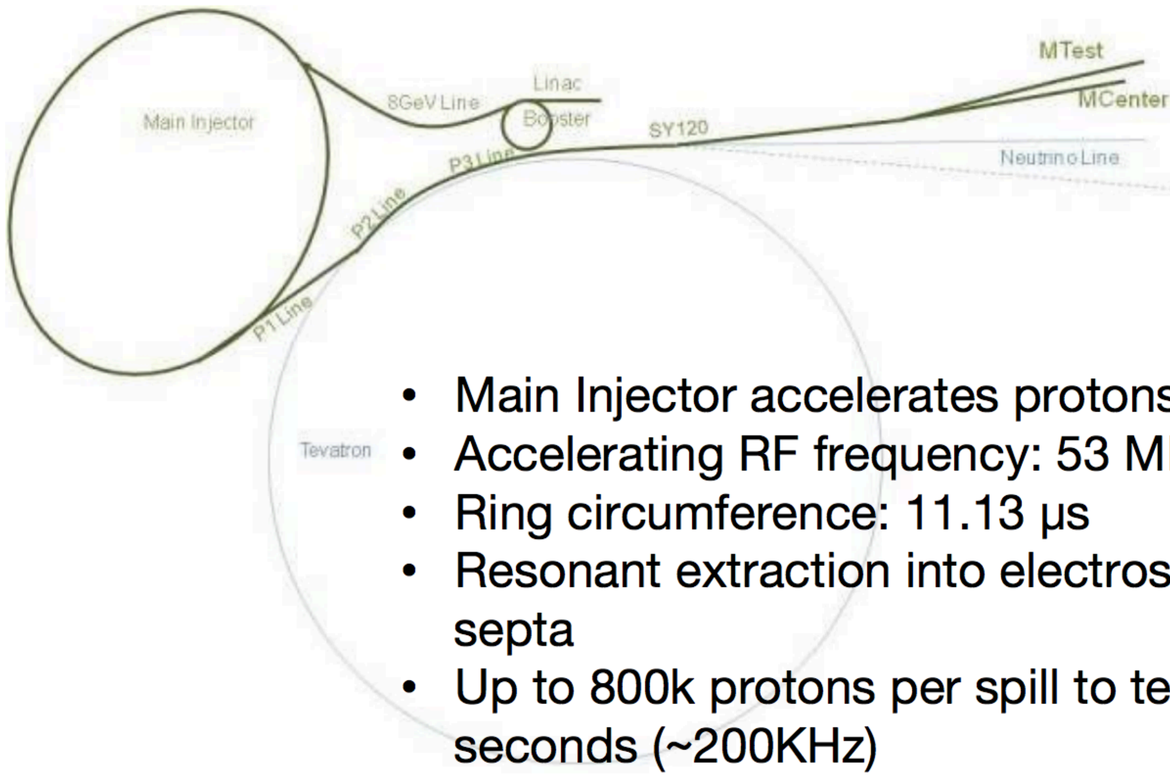
Corrinne Mills, Susan Dittmer, Bryan Cardwell, Titas Roy, Joaquin Siado Castaneda, Joey Reichert, Andre Frankenthal, Stephen Wagner, Stefan Spanier, Julia Thom, Cristina Mantilla Saurez, Frank Jensen, Jason Thieman, Scarlet Norberg, Himal Acharya, Jason Forson, Luke Moore, Duong Nguyen, Tongguang Cheng, Gail Hanson, Ricardo Gonzalez, Alvaro Guerrero, Abbas Hassani, Matthew Jones, Karl Ecklund, Ben Bentele, Chris Hill, Ben Bylsma

Big thanks to Lorenzo Uplegger, Luigi Moroni, Mauro Dinardo, Davide Zuolo, Michael Mocko, John Cumalat, the LANL Blue Room team, Michelle Jonas, Timon Heim

backup

FNAL testbeam

Fermilab Test Beam Facility Overview



- Main Injector accelerates protons to 120 GeV
- Accelerating RF frequency: 53 MHz
- Ring circumference: 11.13 μs
- Resonant extraction into electrostatic and magnetic septa
- Up to 800k protons per spill to test area over 4.2 seconds (~200KHz)
- Repeated every 60 seconds
- Secondary beams including kaons, pions, electrons and muons
- Energies of 1-60 GeV possible (3% resolution)

L. Uplegger

Fermilab