Status of 3D silicon pixel detectors for the ATLAS Forward Physics experiment (AFP)

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IFAE Barcelona

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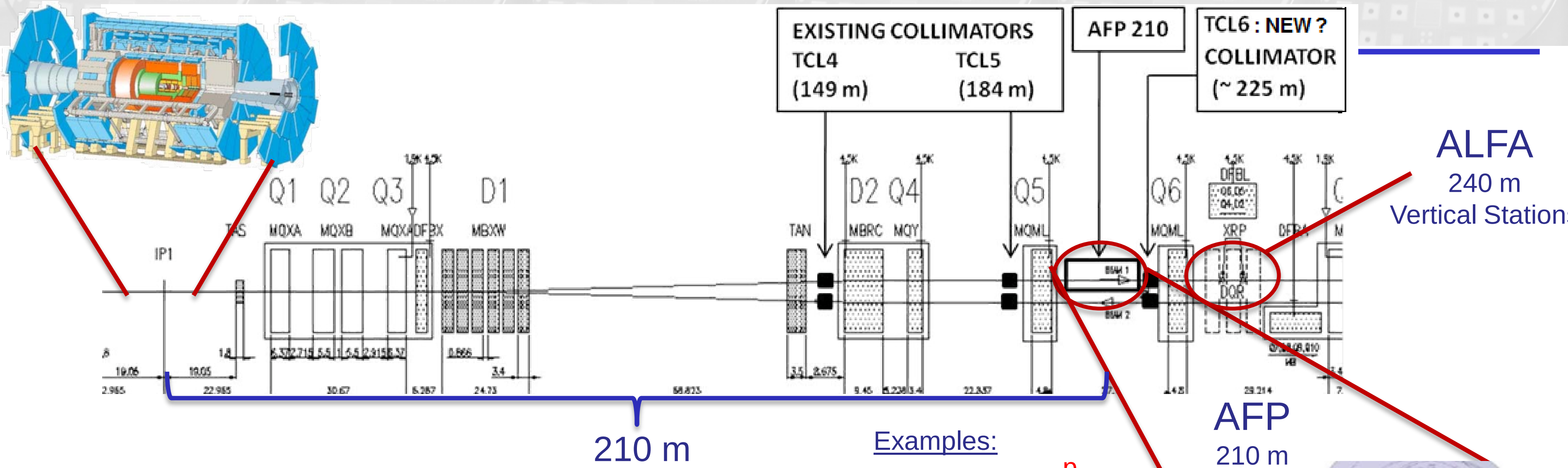
Trento, 18 Feb 2015

EXCELENCIA
SEVERO
OCHOA

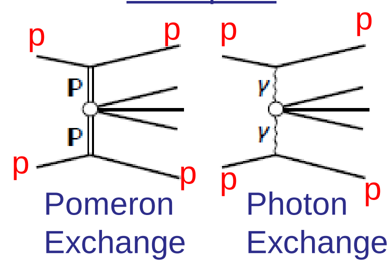
AFP Introduction

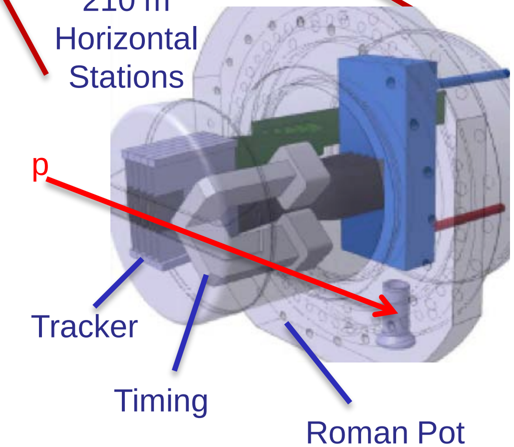


- AFP intends to study **diffractive processes**: protons leave inelastic pp interaction intact, small scattering angle
  → tag very forward protons
- Tracking and timing detectors very close to the beam (2-3 mm)
- **AFP is approved by ATLAS EB (6 Feb)!** (CB/LHCC approval to follow)
  - Dedicated short runs at low lumi in initial phase (μ~1)
  - High lumi program (μ~50) under study, revisited later
  - Installation in staged approach: first two stations ("0+2")

    - Could aim to install in 2015/16 shutdown!

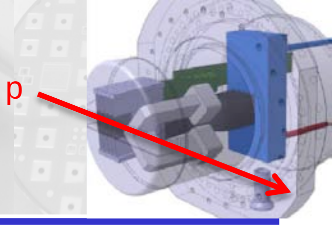
Examples:





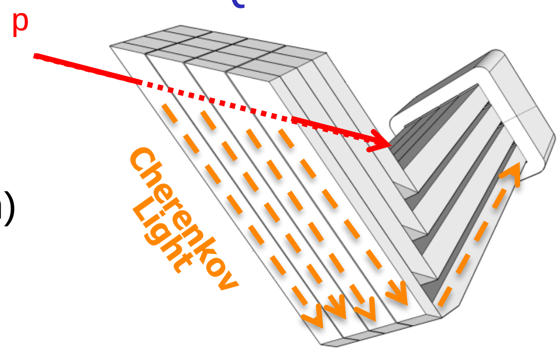
2 stations on each side of IP
- 206 m: tracking only
- 214 m: tracking+timing

AFP Detectors



- **Timing**
  - Task: Constraint on primary vertex for pile-up background rejection
    - → 10 ps resolution for high-μ runs (2 mm PV constraint)
    - → 30 ps for initial low-μ runs (not needed for 0+2 option)
  - Baseline: QUARTIC (Quartz Cherenkov)
  - In R&D phase: Si LGAD or Diamond

4x4 LQbars



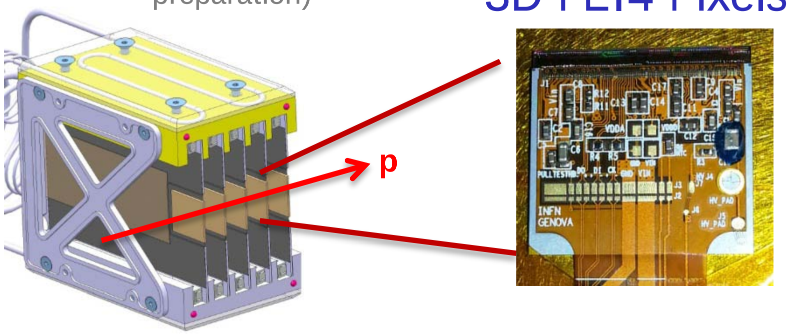
AFP TDR (in preparation)

- **Tracking**
  - Task: Tag p and measure its momentum (together with LHC magnets)
  - Requirements
    - Good position resolution: 10 μm (x), 30 μm (y)
    - Slim edge of side facing beam: 100-200 μm
    - Highly non-uniform irradiation (up to 3×10^{15} n_{eq}/cm^2)

    } Main topic here
  - Solution
    - 4 layers of slim-edge 3D FE-I4 pixel detectors (telescope configuration)

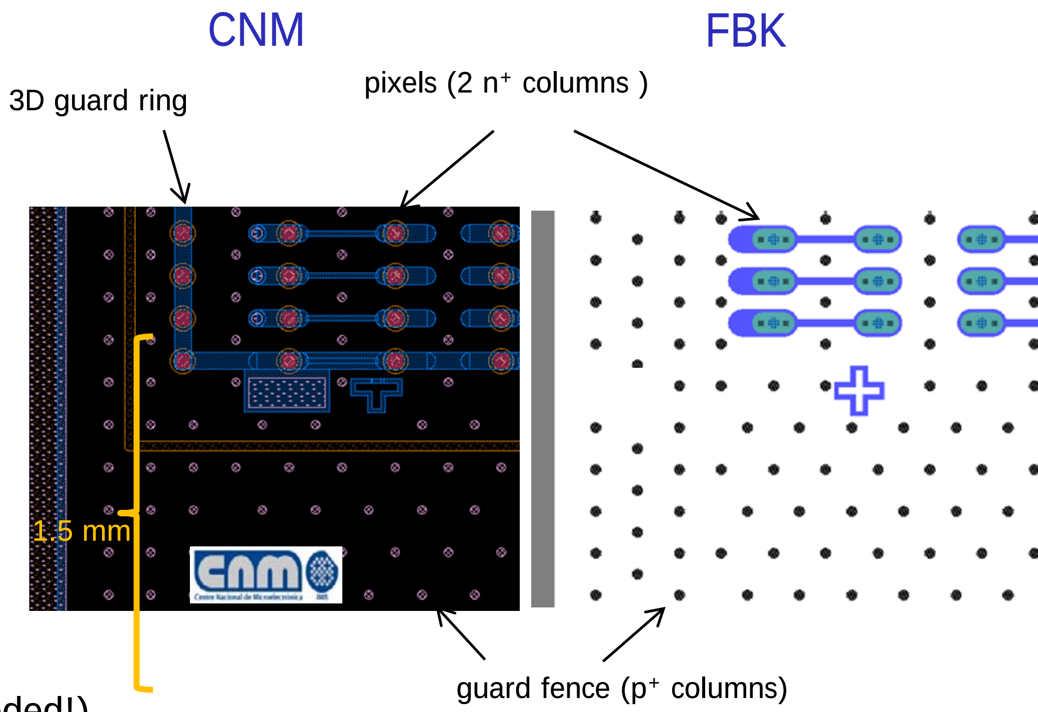
      → **second use of 3D silicon sensors in HEP experiment!**

3D FEI4 Pixels



Sensors and Edge Slimming

- FE-I4 3D IBL sensors (CNM and FBK)
  (more details in A. Gaudiello's talk at this workshop)
  - 336x80 pixels of 50x250 μm^2
  - p-type bulk, 2 n$^+$ columns per pixel
  - Edge termination:
    - CNM: 3D guard ring of n$^+$ columns
      + p$^+$ ohmic-column fence
    - FBK: p$^+$ ohmic-column fence
    - Left/right edge:
      already 200 μm slim edge for IBL
    - Bottom (should be slim for AFP):
      1.5 mm bias tab in IBL production (not needed!)



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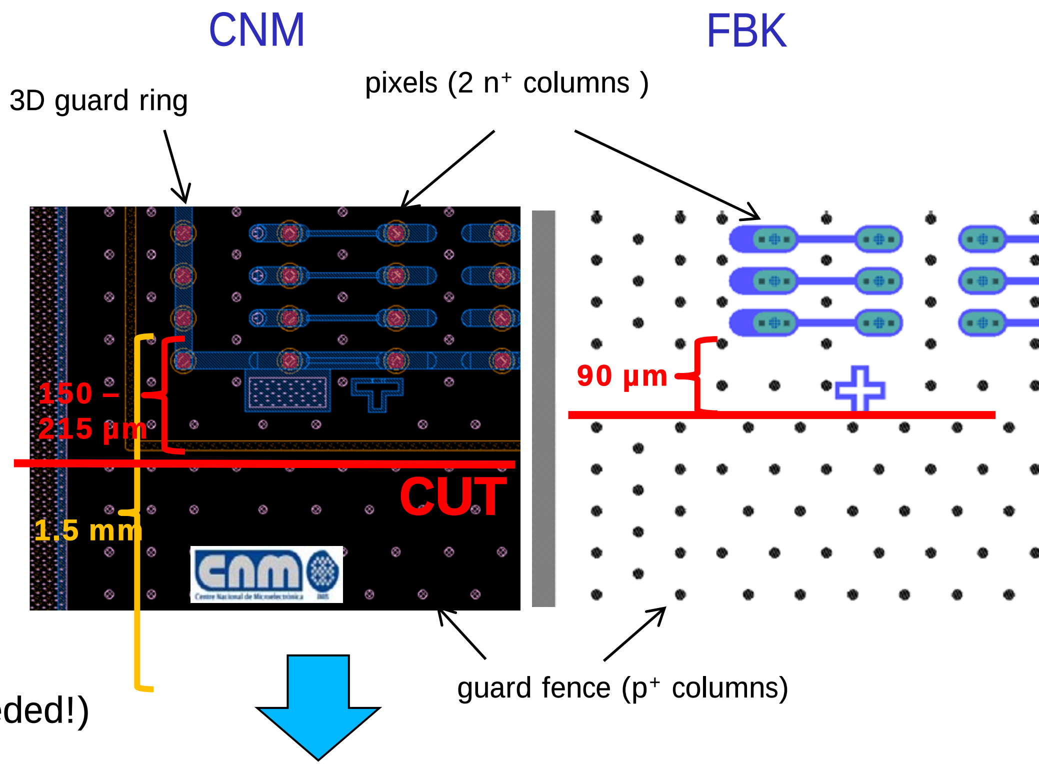
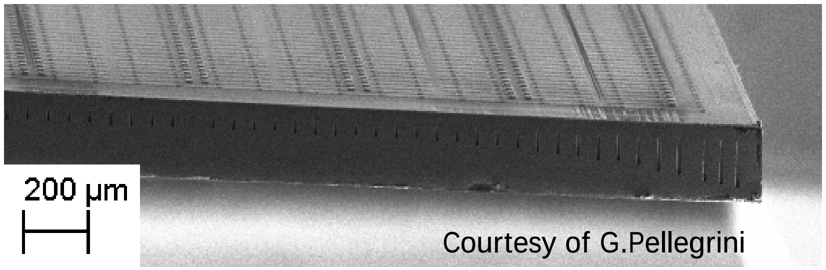
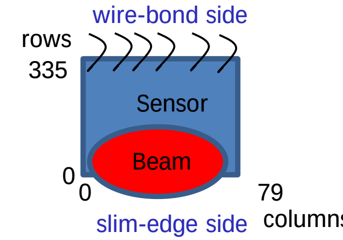


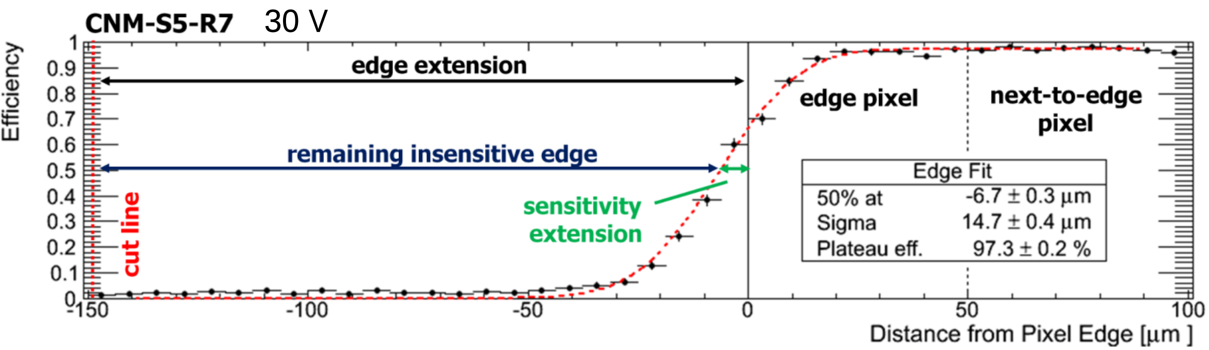
- Edge slimming of bottom
  - Cut IBL sensors' inactive bottom edge down to 90-210 µm (FE-I4 chip: 80 µm dead region)
  - Technique here: standard diamond-saw cut

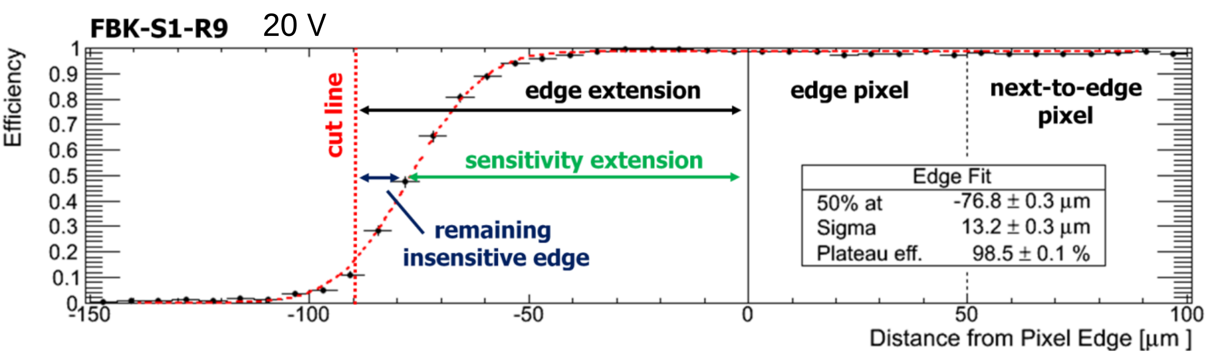


Note: IBL spares used for these studies (not always best quality)

Slim-Edge Efficiency at Bottom



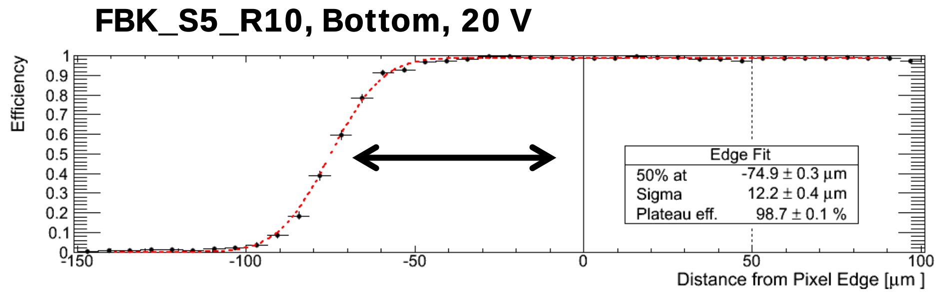


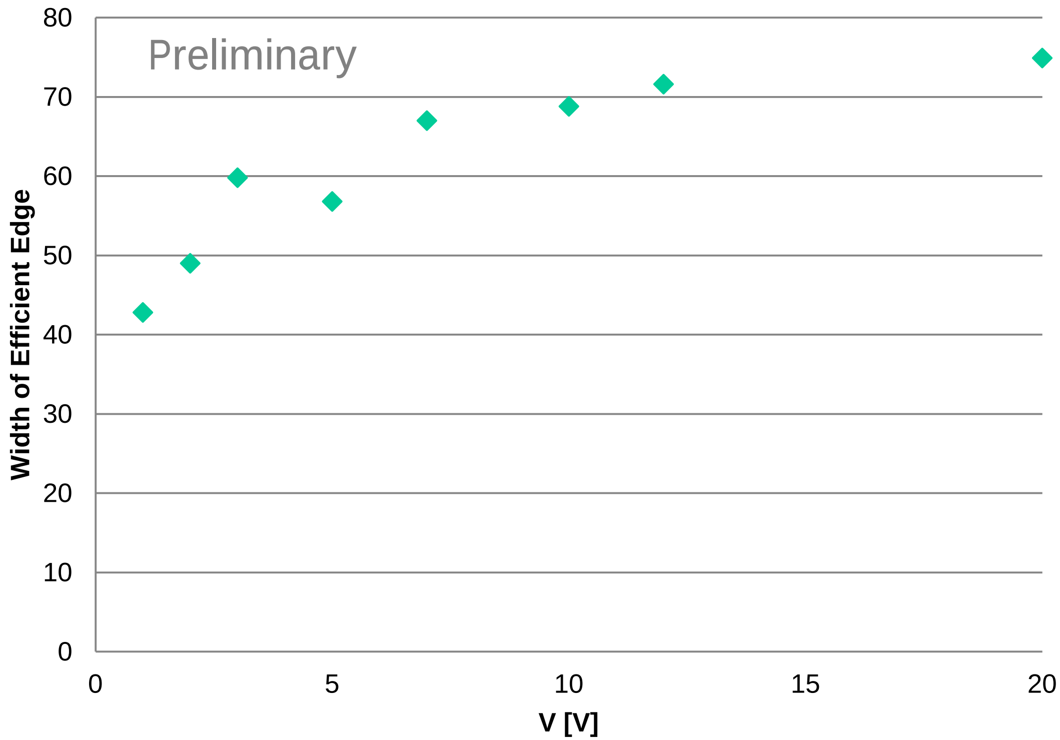


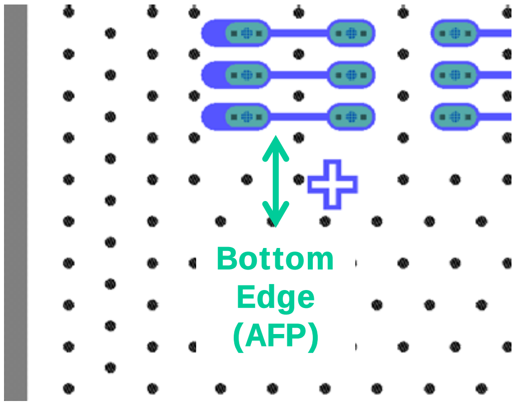
- DESY testbeam (4-5 GeV e^-) with EUDET-type telescope
- Efficiency stable up to last pixel (smeared by telescope resolution)
- For FBK even ~75 μm beyond: Efficient edge due to absence of guard ring
  → <15 μm insensitive edge!
  → Slimmest edge apart from fully active edge technology
  - But implications on resolution/ alignment if edge pixel is different
- For both CNM and FBK: <150 μm insensitive edge possible
  → AFP slim-edge requirements fulfilled

Sample	FBK-S1-R9	FBK-S2-R10	CNM-S3-R5	CNM-S5-R7
Edge extension after cut	91 μm	87 μm	215 μm	150 μm
Sensitivity extension beyond last pixel	77 μm	75 μm	1 μm	7 μm
Remaining insensitive edge	14 μm	12 μm	214 μm	143 μm

Development of Edge Extension in FBK Sensor with Voltage



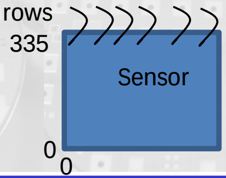


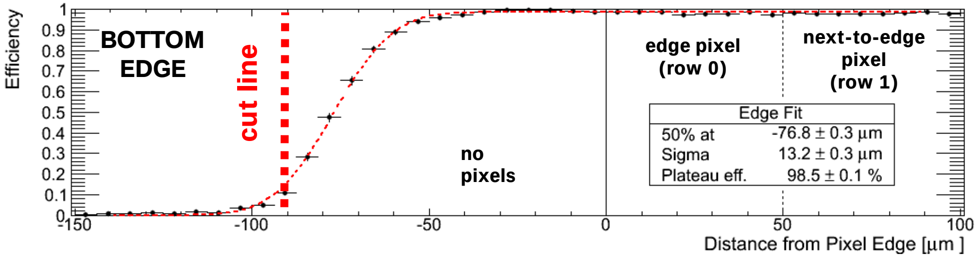


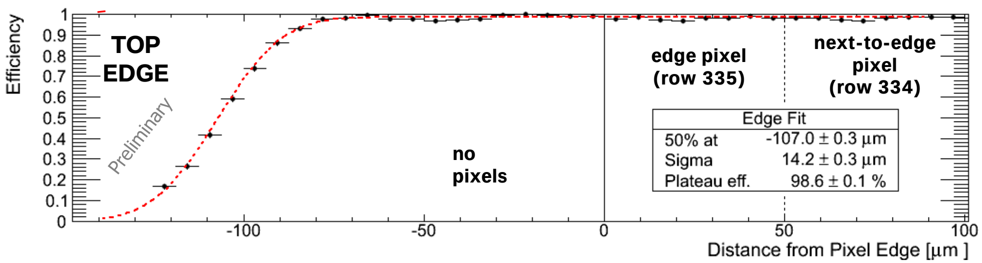
- Width of efficient edge increases with voltage (depletion zone increases)
- Saturation between first and second guard line beyond last pixel

Edge Extension - Comparison Top-Bottom

FBK_S1_R9, 20 V



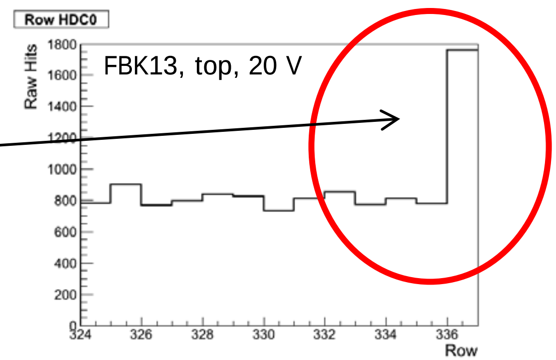




- FBK sensitivity extension at top (107 µm) 30 µm larger than at bottom (77 µm)
  - Although symmetric geometry
  - Top sensitivity extension would surpass cut line (at 90 µm) at bottom!

- Effect already visible at hit level from ratio
  $R = N^{last\text{-}row} / N^{next\text{-}to\text{-}last\text{-}rows}$

  → indicator for sensitivity extension
  - $R_{top} > R_{bottom}$ for slim-edge devices (from TB and ^{90}Sr)
  - $R_{top} = R_{bottom}$ for regular-edge devices (from ^{90}Sr)



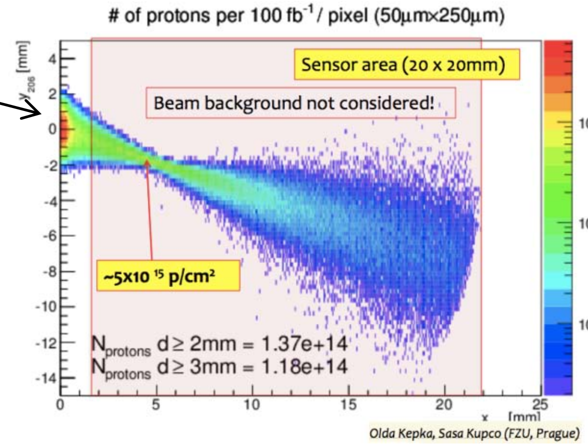
^{90}Sr source scan

Sensor	Edge	BOTTOM		TOP	
		<Hit Mult>	R	<Hit Mult>	R
FBK_S1_R9	Slim bottom	2.05	1.64 ± 0.05	2.04	1.92 ± 0.04
FBK13	Regular	2.45	2.14 ± 0.08	2.42	2.14 ± 0.07

- Possible reason:
  cut-related defects might restrict depletion-zone growth

Non-Uniform Irradiation

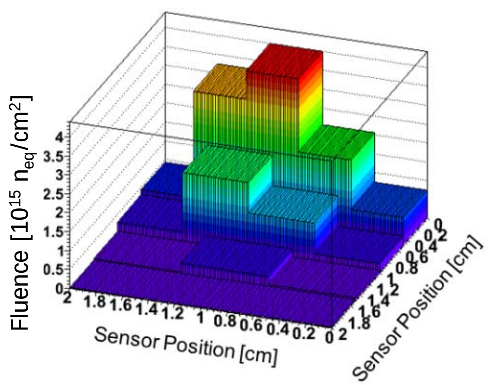
- Highly non-uniform fluence from diffractive p
  - Future high-lumi runs: max. 5×10^{15} p/cm^2 (~7 TeV p)
    → focus of studies here
  - Initial low-lumi runs: most of the time retracted to parking position
    → lower and more uniform fluence → less demanding

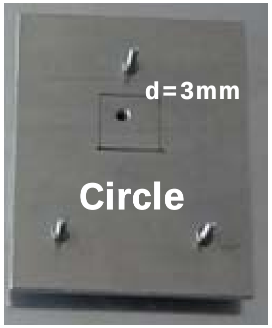


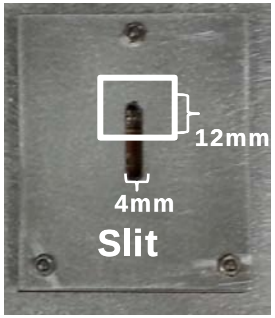
- 2 irrad. campaigns with different non-uniformity scenarios
  - No 7 TeV irradiation facility available yet
    → Proof-of-principle tests at usual irrad. facilities with lower p energy

1) Focussed 23 GeV p irradiation (CERN-PS)
   → fluence spread large, gradual transition

2) 23 MeV p (KIT) through hole in 5mm Al plate
   → very localised fluence with abrupt transition







1.8-3.6 x 10^{15} n_{eq}/cm^2

Thanks to Felix Bögelspacher (KIT) for irradiation

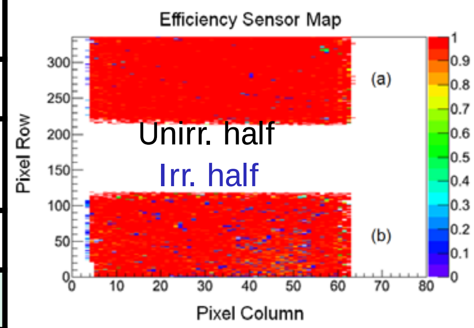
- To check: Can detectors be operated to give high eff. in all regions?
  (Irrad. side → high V_{bias} needed; but unirr. side → low V_{BD})

Efficiency Results

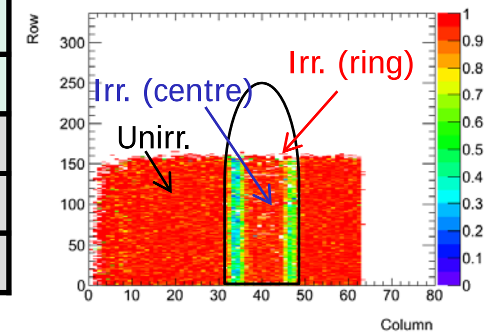
DESY and CERN Testbeams

Group	Non-Uniform Irradiation	Unirr. Reference	PS Focussed	KIT Hole (circ.)	KIT Hole (slit)		
Device + Irrad	Φ [10^{15} n_{eq}/cm^2]	Unirr.	4.0 (max)	1.8	3.3		3.6
	Sample	CNM 55	CNM 57	FBK 12_02_08	CNM S5-R7		CNM S3-R5
	Edge	Regular	Regular	Regular	Slimmed		Slimmed
Meas. Settings	V_{bias} [V]	30	130	58	90	100	130
	Threshold [ke]	3	1.7	2	2	2	3
	ToT @ inj.charge [ke]	10@20	10@20	~11@20	6@10	~5@20	~8@20
	SingleSmall Hits Reject	No	No	No	No	Yes	Yes
Results	Eff_{max}(unirr) [%]	99	99	98	99	95	94
	Eff_{max}(irr,centre) [%]	-	98	97	96	94	93
	Eff_{max}(irr,ring) [%]	-	-	70	93	90	58

PS focussed, CNM-57, 130 V



KIT hole, CNM-S3-R5, 130 V



- Irradiated part (centre) within few % as efficient as unirradiated part
- Significantly lower eff. in ring of irr. part at edge of hole (KIT)
  - Seems not to be due to effectively larger fluence (from position-resolved dosimetry)

Dependence on FE-I4 chip parameters

HitDiscCnfg, PrmpVbnLcc

	Non-Uniform Irradiation	Unirr. Reference	PS Focussed	KIT Hole (circ.)	KIT Hole (slit)		
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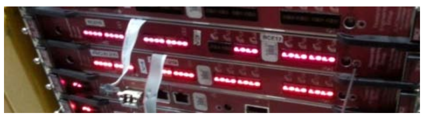
	Eff_{max}(irr,centre) [%]	-	98	97	96	94	93
	Eff_{max}(irr,ring) [%]	-	-	70	93	90	58
					New TB	Previous TB	

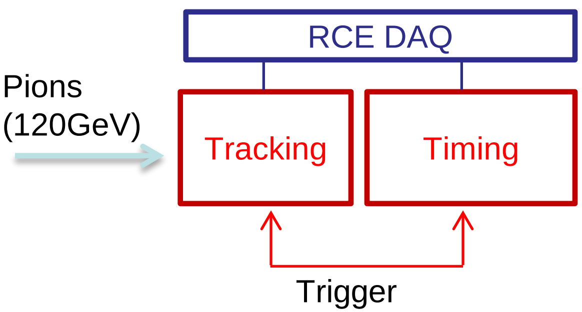
- 3-4% lower efficiency for last two columns
  (both unirr. and irr. area) due to FE-I4 chip setting in previous testbeam (TB)
  - HitDiscCnfg=2 → Single small hits (ToT<3) rejected (to avoid time-walk effects, but usually TB analyses take HitDiscCnfg=0)
- Higher efficiency in new testbeam in October 2014 with HitDiscCnfg=0
- No dependence on leakage-current compensation parameter PrmpVbnLcc (0, 100, 200) found

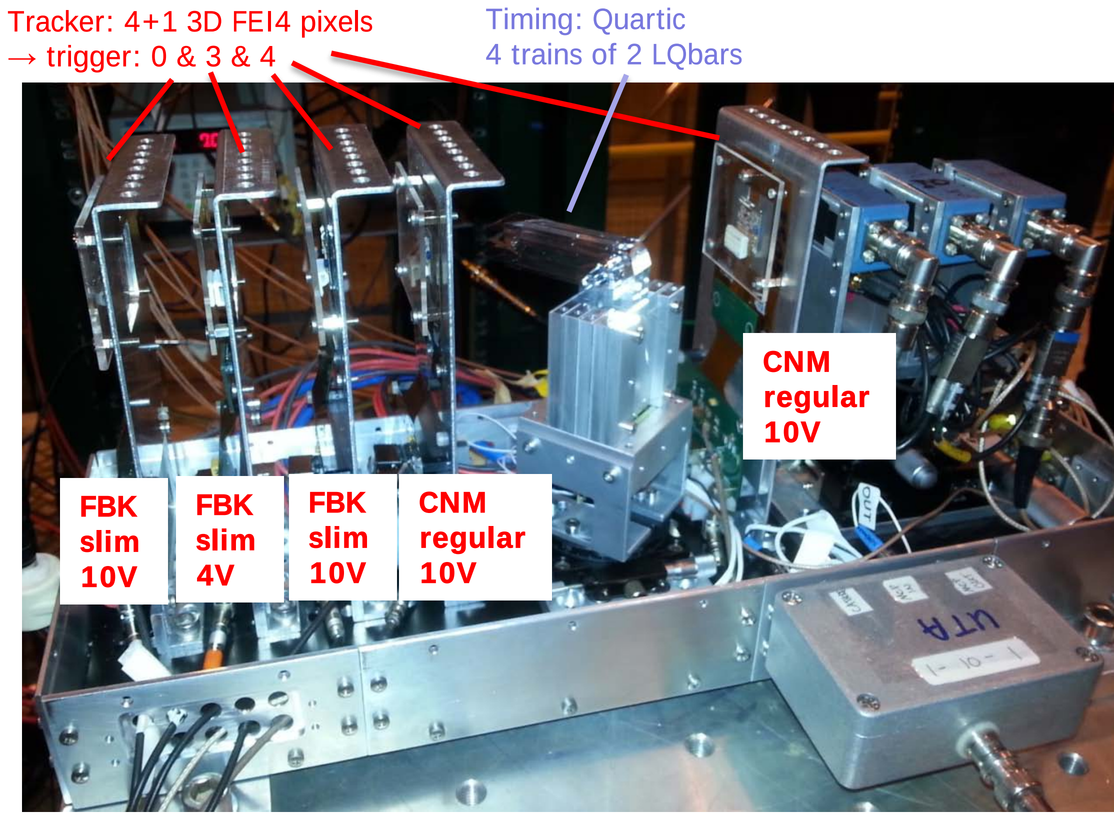
AFP Integration Testbeam

November 2014

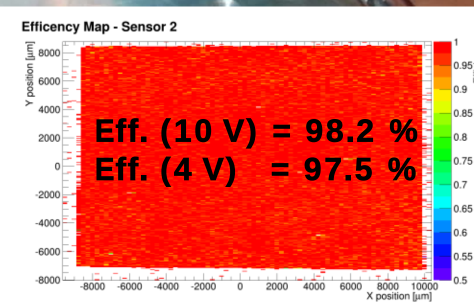
- AFP system-integration test
  Tracking + Timing (Quartic+HPTDC)
  - Common trigger
  - Common readout (RCE) → 1 data format



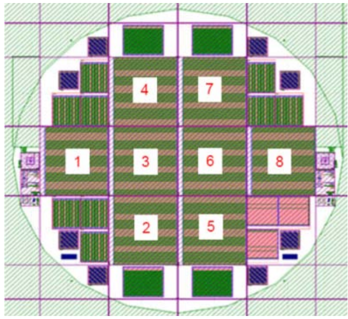




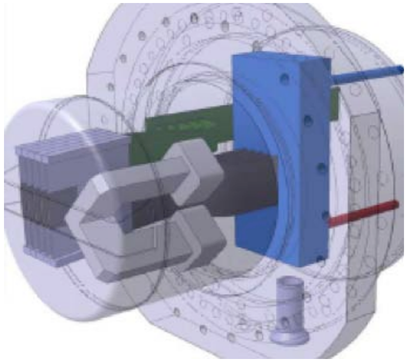
- Integration successful
  - Good performance of tracking and timing detectors
- Simultaneous test of alternative timing systems (Si LGAD and diamond)



AFP Pixel Module and Station Production



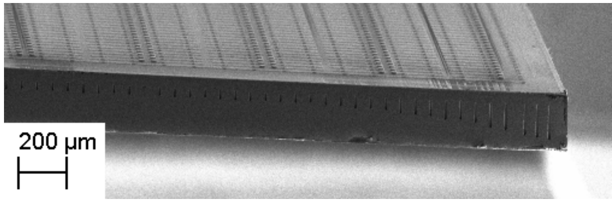
- AFP run 6682 at CNM finished
  - Lost wafers due to machine malfunctions
  - 5 wafers finished (40 sensors) → UBM at IZM
    ~9 good sensors after slim-edge dicing (estimated from IV on UBM side)
    Preliminary!!!
    → Yield of good sensors ~23%
    → Hope to have enough good sensors!
    - 8 needed for 0+2 stage in 2015 (need excellent flip-chipping/assembly yield)
- Flip-chipping (bump-bonding) to FE-I4 to be done at IFAE
- AFP flexible circuit being designed
- Module assembly incl. wire-bonding and QA to be done by IFAE
- Simultaneous production of Roman Pots and Stations
- Timing detectors partially produced, but installation no priority for 0+2 (but desirable to gain experience/study backgrounds)



→ Aim to have pixel modules for first two stations (2x4 3D FE-I4) ready by the end of 2015 (tight!)

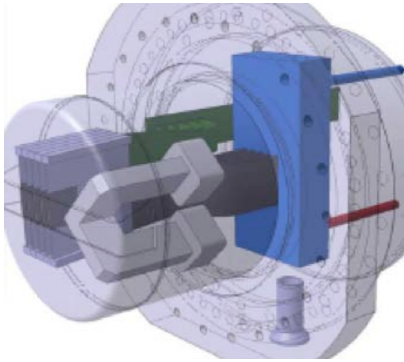
Conclusions

- Slim-edge and non-uniformly irradiated 3D AFP sensors studied
  - Insensitive pixel-sensor region highly reduced
    - With guard ring (CNM) insensitive edge down to 143 µm
    - Without guard ring (FBK) even efficient beyond last pixel: ~15 µm insensitive edge!
  - High efficiency achievable after non-uniform irradiation at high-lumi fluence (100 fb^{-1})



→ Slim-edge 3D pixel detectors qualified for AFP

- AFP November 2014 integration testbeam successfully finished
- AFP 3D-pixel-module, Roman Pot and station production ongoing
- Aim to have pixel modules for first two stations ready by the end of 2015 (tight!)

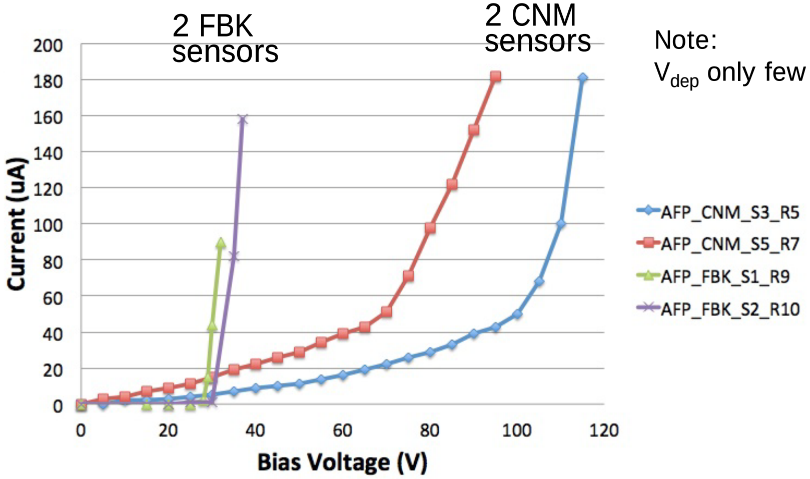


→ Second use of 3D silicon sensors in HEP experiment!

BACKUP

Current and Noise

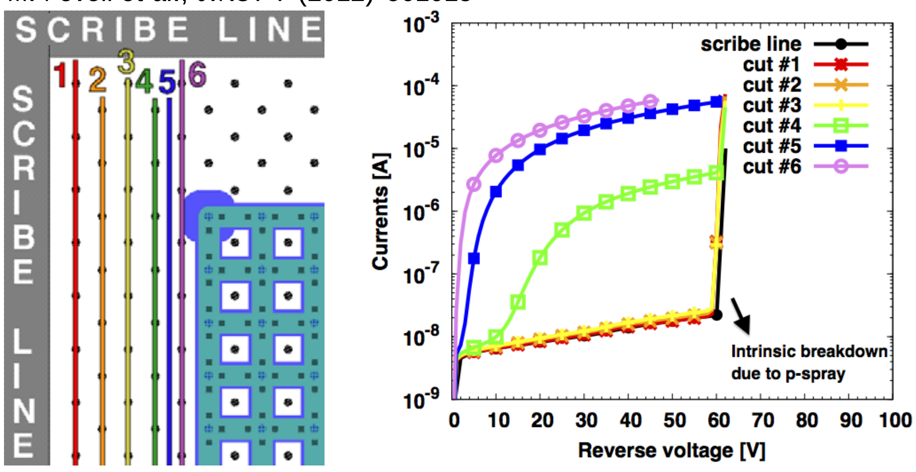
IV of sensors after slimming:
normal for sensor-quality class used



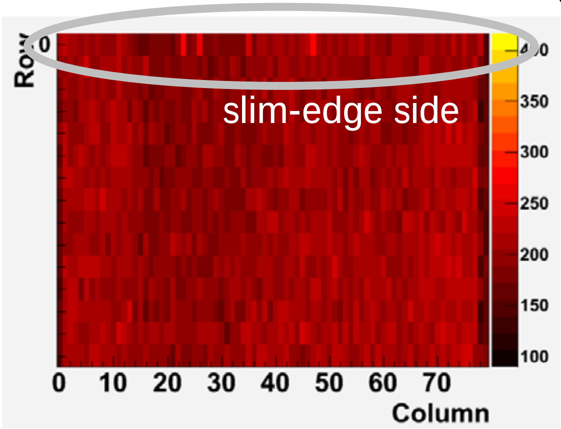
Note:
V_{dep} only few V (3D!)

Previous study on FBK sensors:
IV unaffected up to 100 µm cut line

M. Povoli et al., JINST 7 (2012) C01015



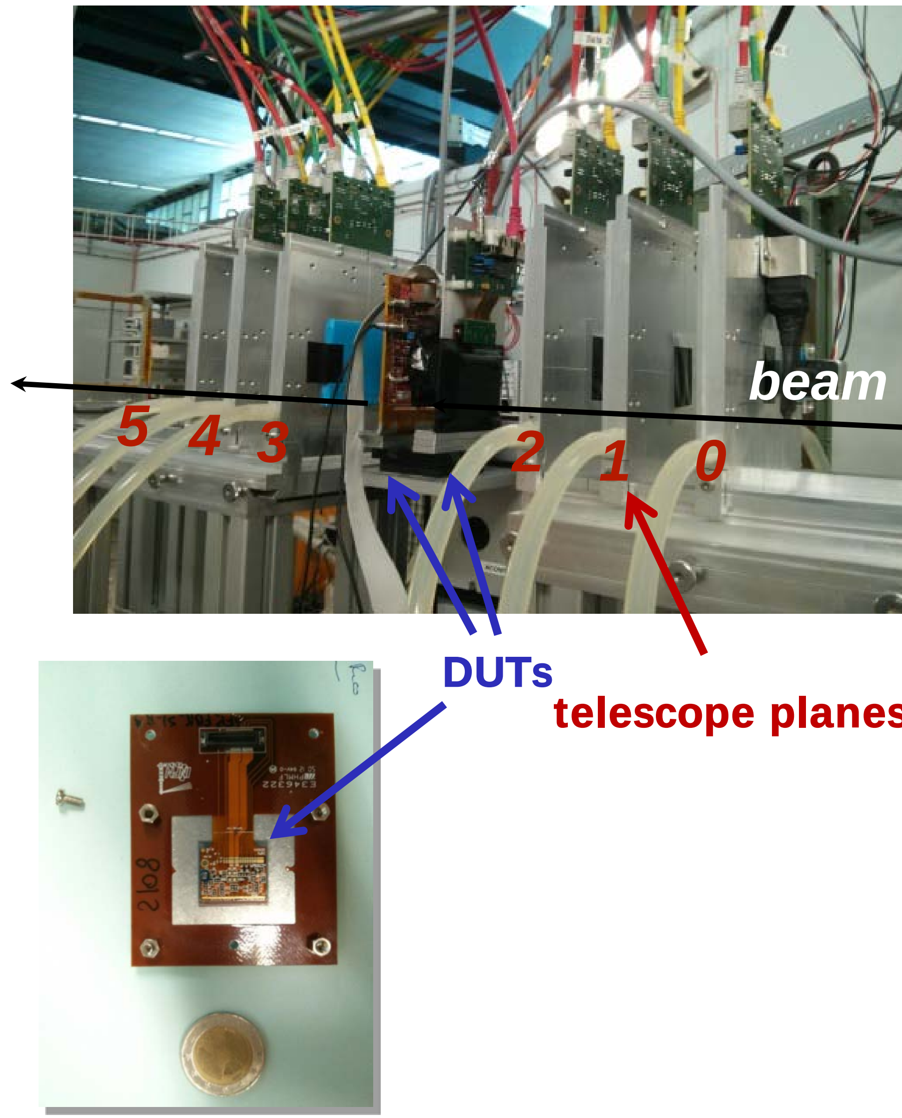
Noise of CNM device near edge



- No anomalous current and noise after edge-slimming to 100-180 µm

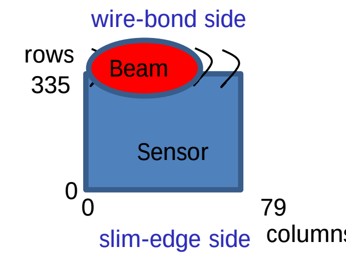
Test Beam

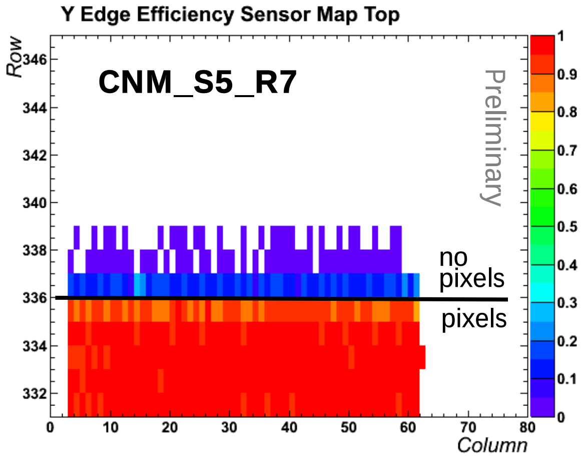
- Check performance (hit efficiency) in test beam
  - DESY II 4 or 5 GeV electrons
  - ACONITE telescope (EUDET type)
    - 6 planes of MIMOSA-26:
      660k Si pixels (18.4 µm pitch)
    - Trigger: 4 scintillators
  - Thanks to AIDA support

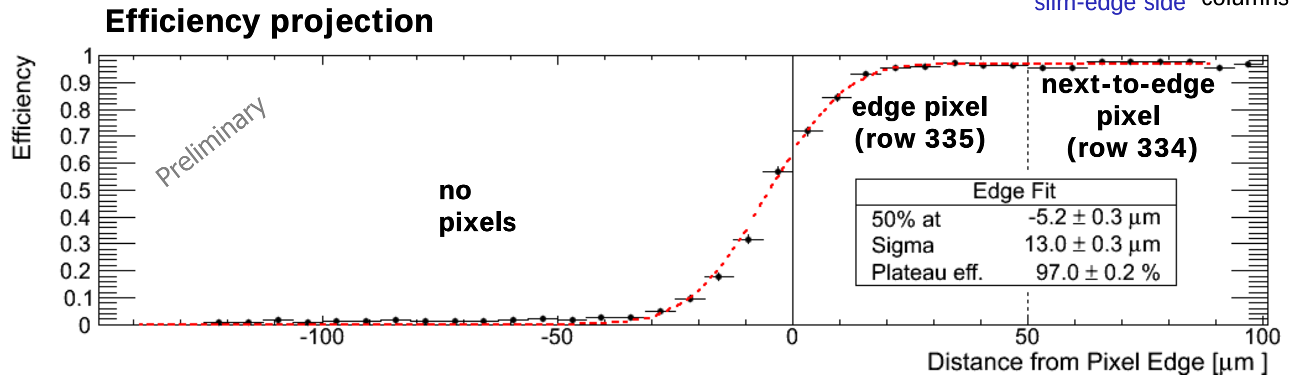


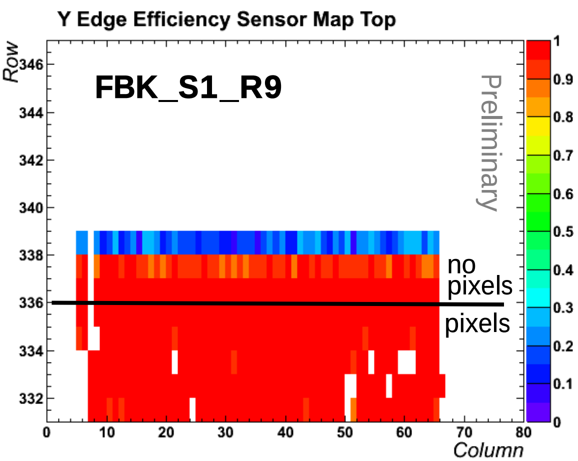
Thanks to all test beam participants,
esp. I. Rubinskiy (DESY), D. Pohl (Bonn),
O. Korchak (Prague), Sh. Hsu (Washington),
A. Micelli (IFAE)

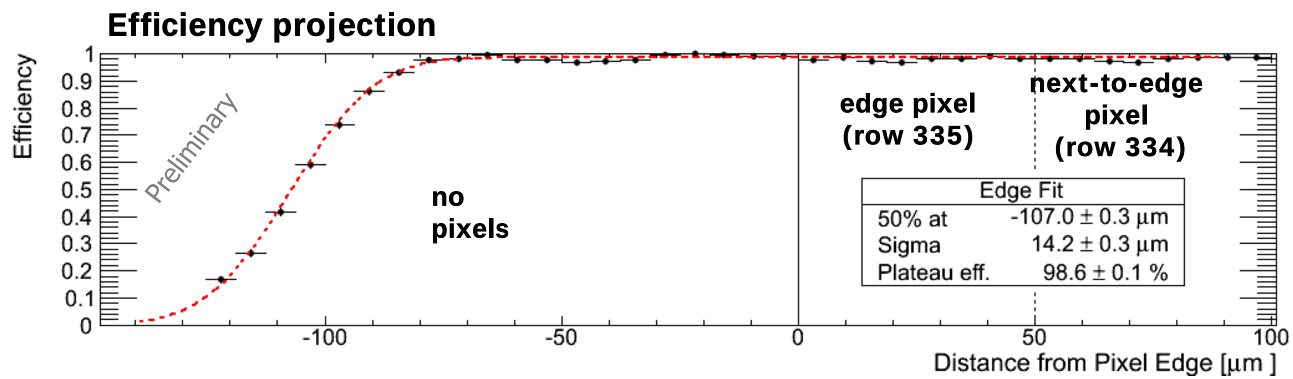
Regular Unslimmed Edge (Top Side)





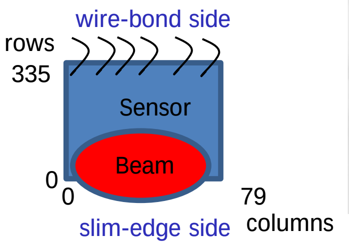


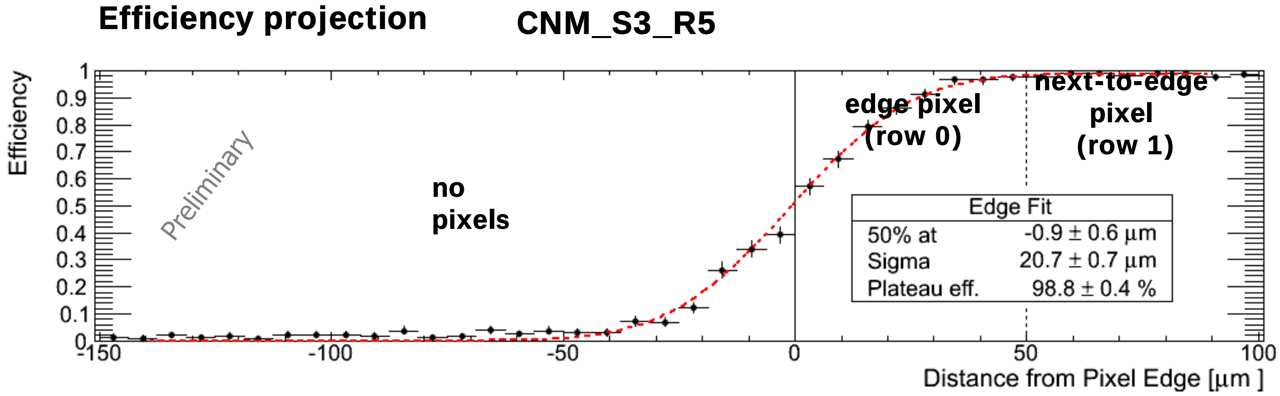


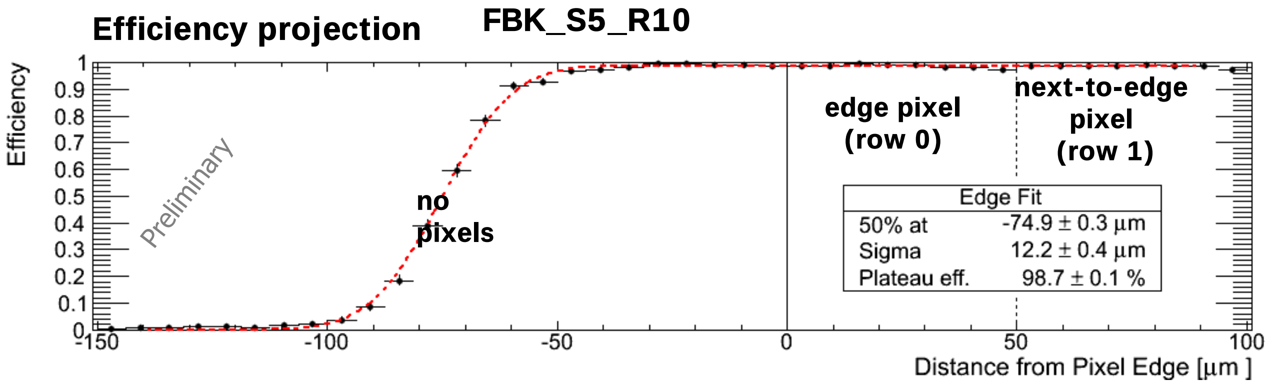


- Efficiency stable up to last pixel
  - Smearing due to beam telescope resolution
  - For FBK even ~100 µm beyond (active edge due to absence of guard ring); a bit noisy/hot pixels → masked

Slim Edge (Bottom Side)
Other devices





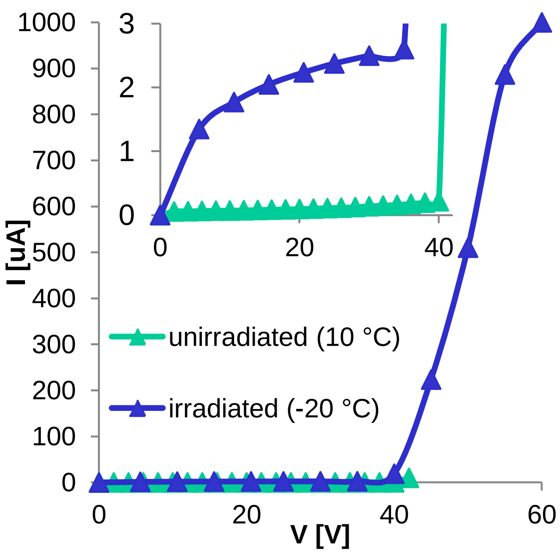


Electrical Characteristics

- Not optimal sensors from beginning (IBL spares)
  - Merged/disconnected bump bonds, partly low V_{BD}

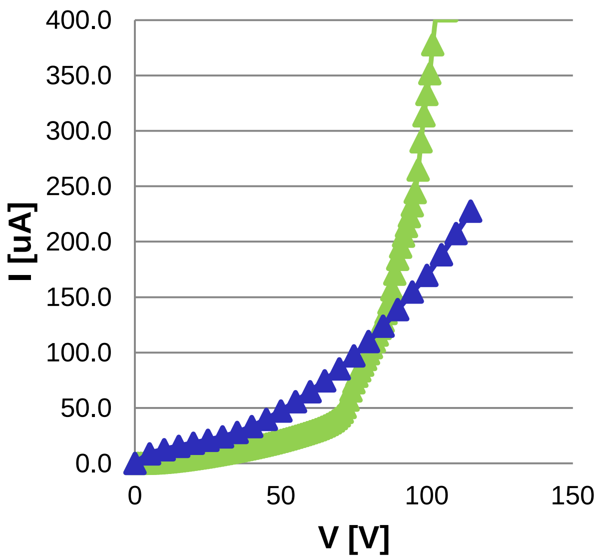
FBK_12_02_08

- V_{BD} ~ 40 V before and after irrad.
- Able to bias up to 58 V



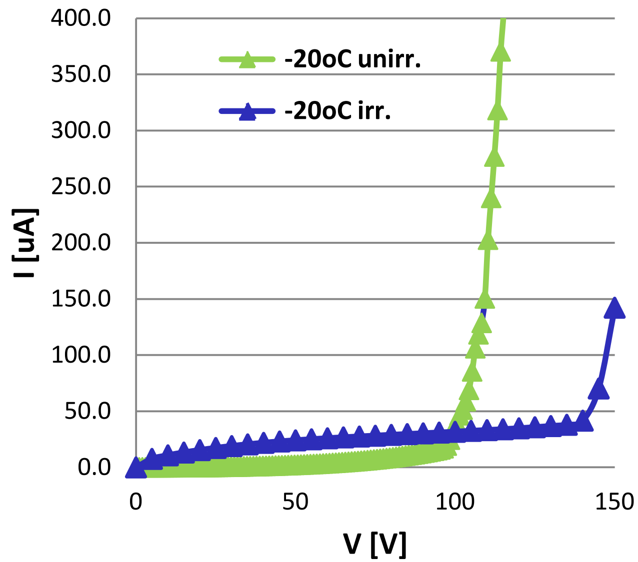
CNM_S5_R7

- Soft BD
- Lower I after irr. at high V



CNM_S3_R5

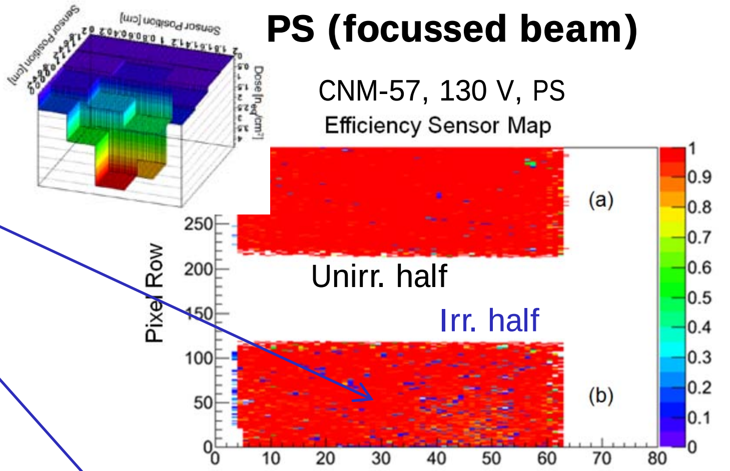
- Shift of V_{BD} to higher V
- Lower I after irr. at high V



Efficiency of Irradiated Devices

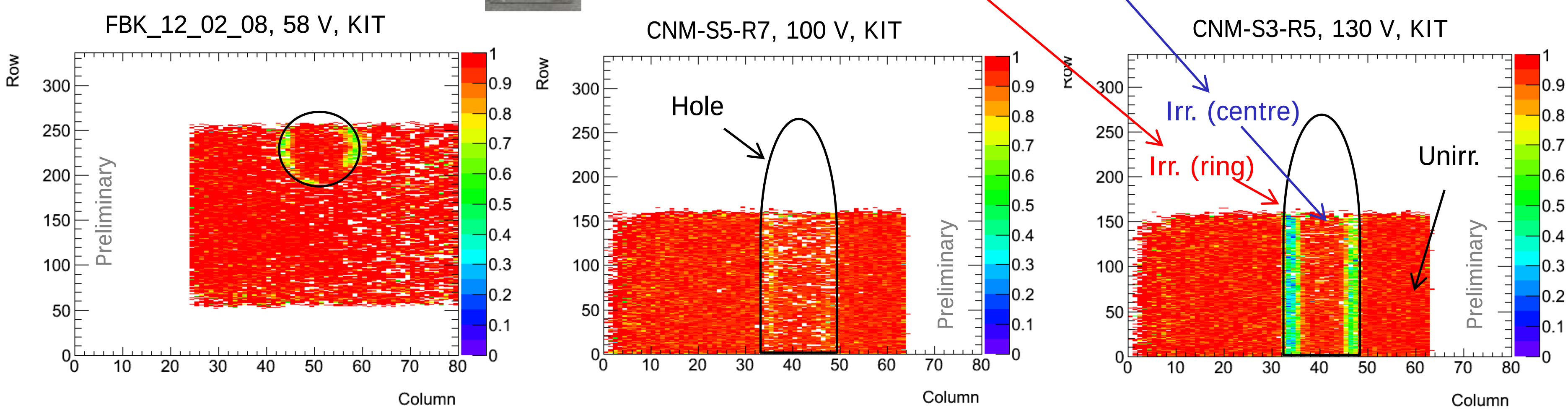
- Test beam:
  DESY (KIT irr.), CERN (PS irr.), T < -20 °C
- Irradiated area (only centre for KIT) almost as efficient as unirradiated region
- Ring of lower efficiency at edge of hole at KIT
  - Not seen for focussed PS beam
  - Under investigation (see slides later)

PS (focussed beam)



S. Grinstein et al., NIM A730 (2013) 28

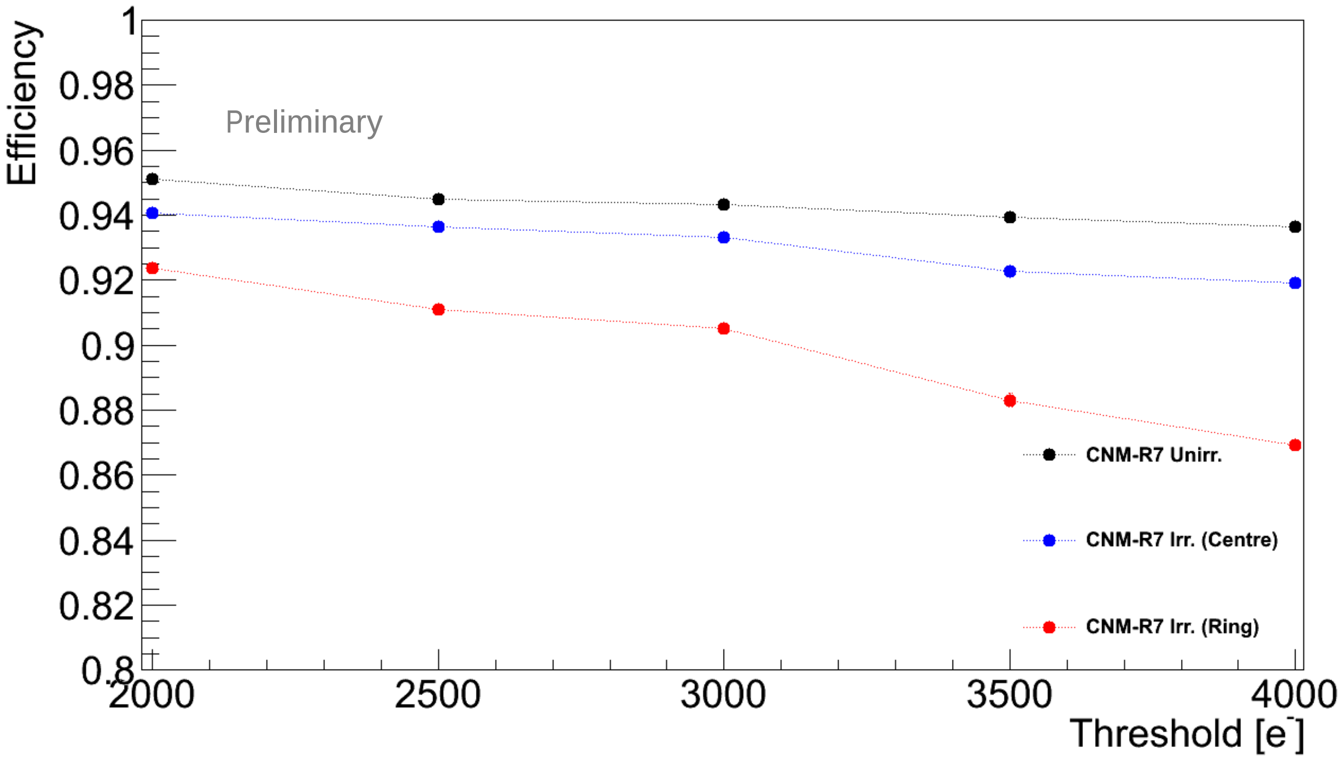
KIT (through hole)



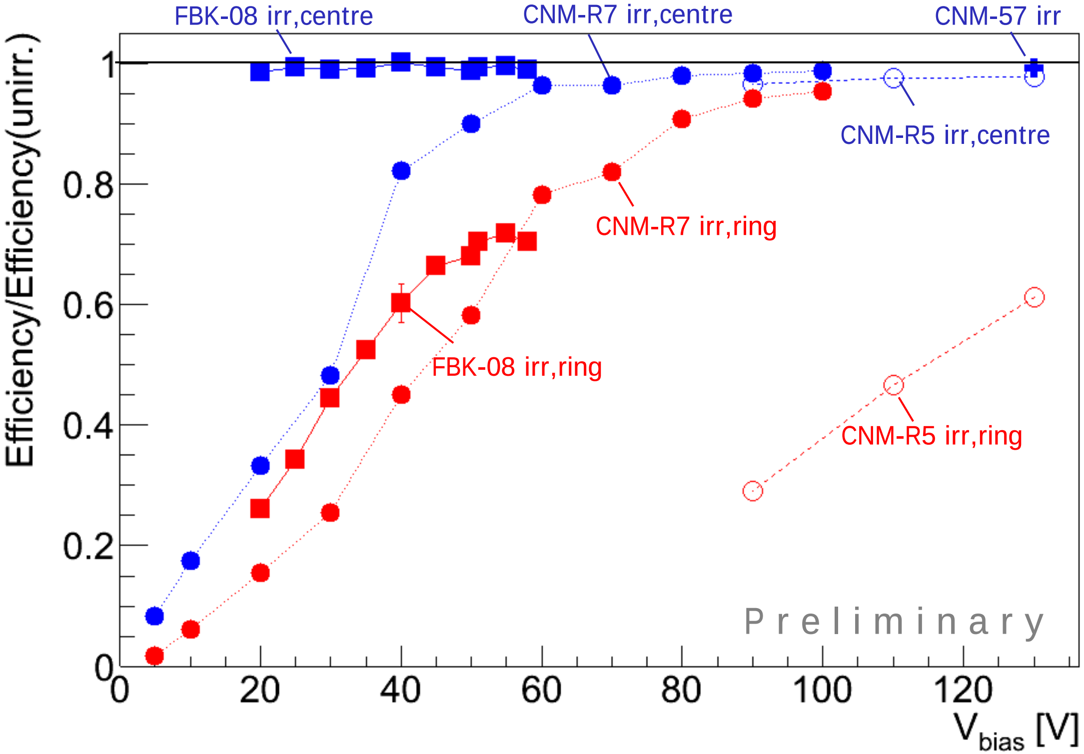
Noisy and dead pixels masked

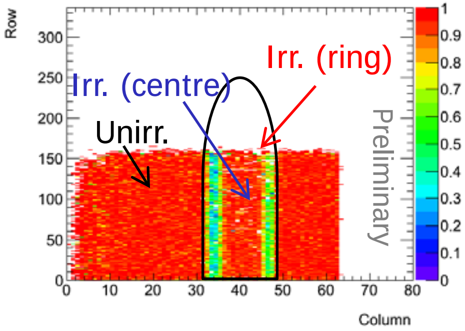
Efficiency vs. Threshold

- Improvement of 1% per 1000e reduction of threshold for unirr. and irr. (centre) area
- Even more for higher irradiated ring



Voltage Dependence of Efficiency/Efficiency(unirr.)



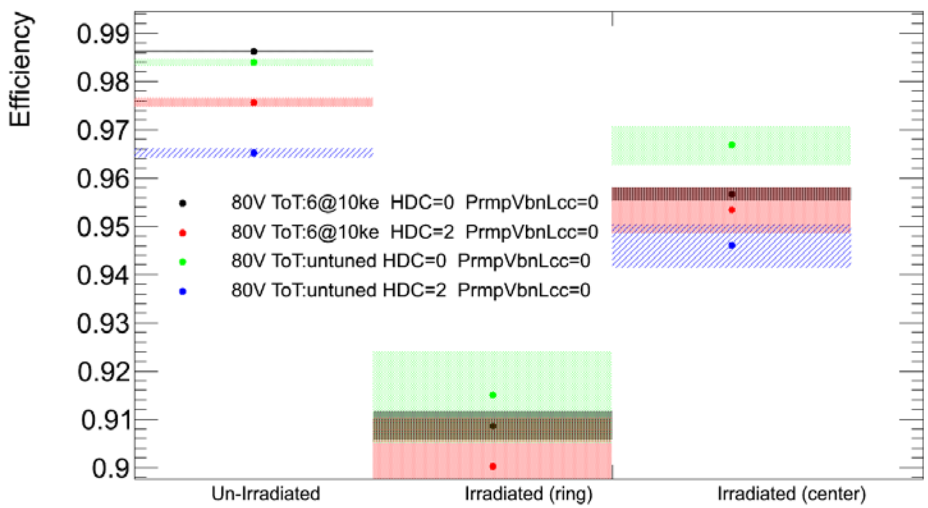


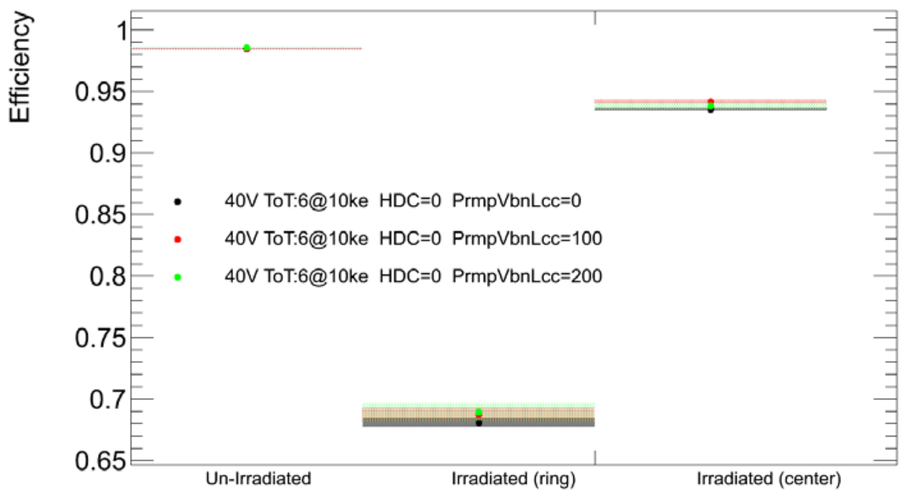
- For better comparison of measurements under different conditions:
  Ratio of efficiency/efficiency(unirr)
- BUT: Curve might change for CNM-R5/7 if measured with HitDiscCnfg =0 (effect on lower eff. is larger)
- Irradiated part (centre)
  - For FBK-08 ($1.8x10^{15}$ n_{eq}/cm^2) plateau reached already below 20V
  - For CNM-R7 (~$3.3x10^{15}$ n_{eq}/cm^2) plateau reached at about 60 V
- Irradiated part (ring)
  - All behave differently
  - FBK seems to saturate at 50 V at ~70%
  - CNM-R7 saturates at 90-100 V at ~90%
  - CNM-R5 much lower, but still steeply increasing at 130 V (60%)

Dependence on FE-I4 chip parameters

HitDiscCnfg, PrmpVbnLcc

CNM-S5-R7 (non-uniformly irradiated, October 2014 CERN TB

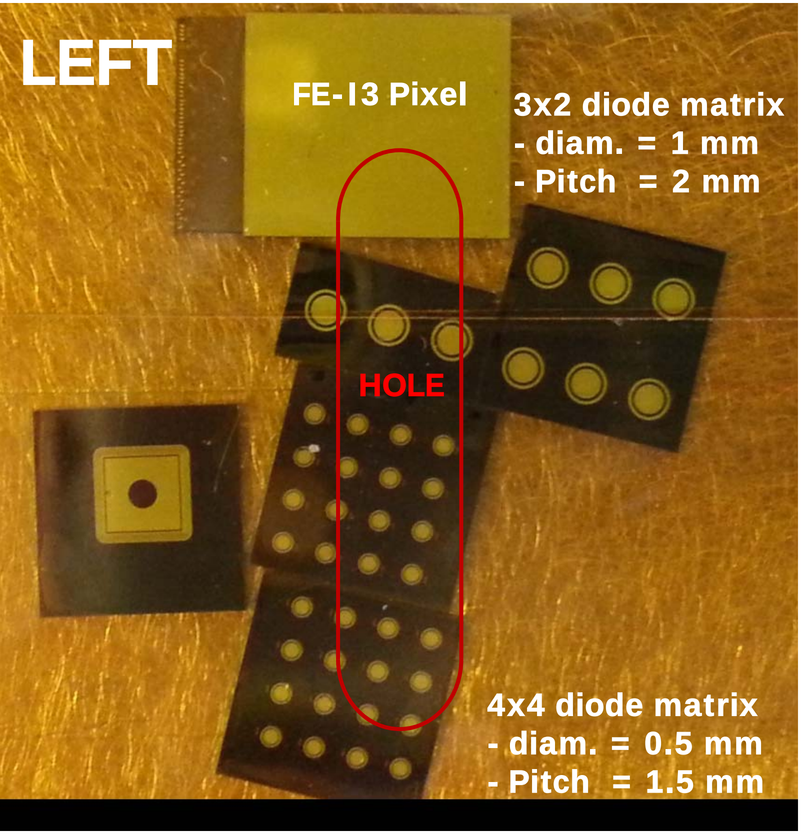


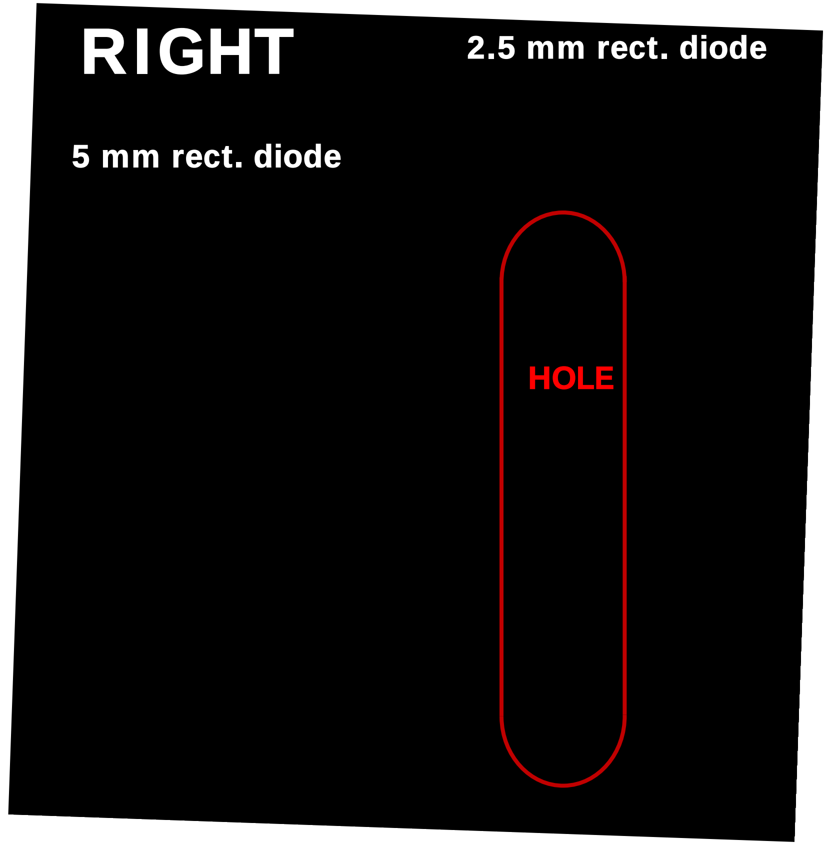


- Efficiency(HDC0) > Efficiency(HDC2)
- For HDC2:
  Efficiency(ToT tuned) > Efficiency(ToT untuned)

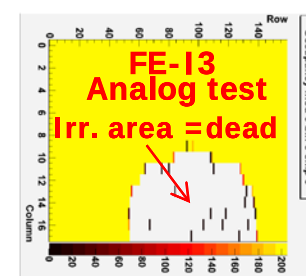
- Efficiencies for different PrmpVbnLcc consistent within uncertainties

Position-Resolved Dosimetry





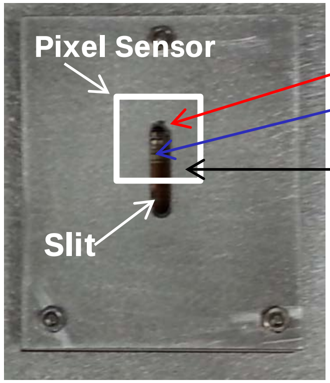
Thanks to CNM (G.Pellegrini, M.Baselga) for providing diodes, setup and help!



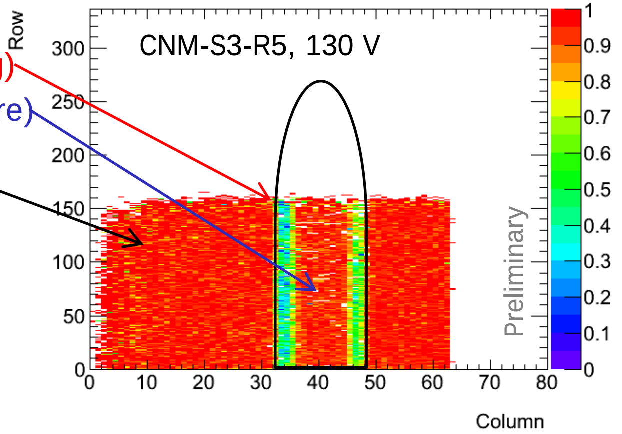
- Multi-device approach (diodes: n-type STFZ, d=300 μm)
- Irradiation under same slit-like Al masks (“left” and “right”) as pixel irradiation at KIT
  - Intended: 5-10 x 10^{13} n_{eq}/cm^2 (FE-I3 only specified up to <10^{15} n_{eq}/cm^2 , reliable plateau for CV/IV)
  - Obtained: 3.4 x 10^{15} n_{eq}/cm^2 (FE-I3 dead in irr. area, no CV/IV plateau in irr. area)

Investigation of Low-Efficiency Ring

5 mm Al shields:

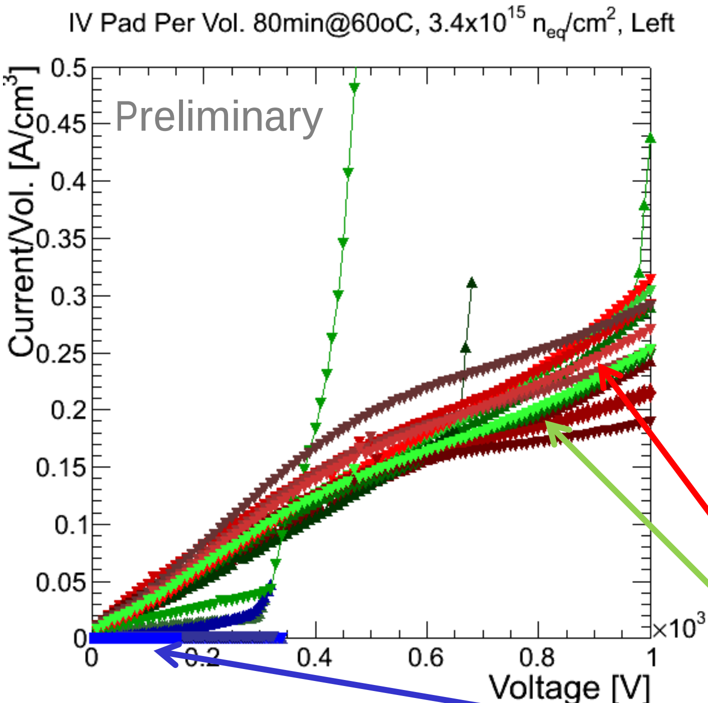


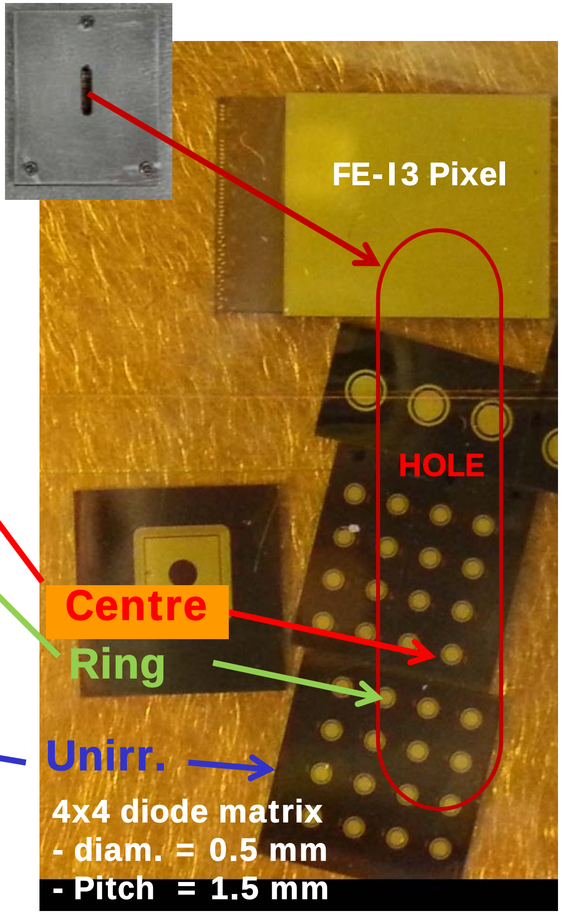
Pixel-Sensor Efficiency Map



- Effect of irradiation method with Al shield (possibly higher effective fluence)?
  - Scattering of p at edge of Al shield → loose energy → much more damaging
- Or real effect of abruptly non-uniformly irradiated devices?
  - Sensor effect?
    - Transition region between highly irradiated Si and unirradiated Si → huge gradient of defect density and current → maybe leads to lower el. field?
  - Chip effect?

Position-Resolved Dosimetry from IV





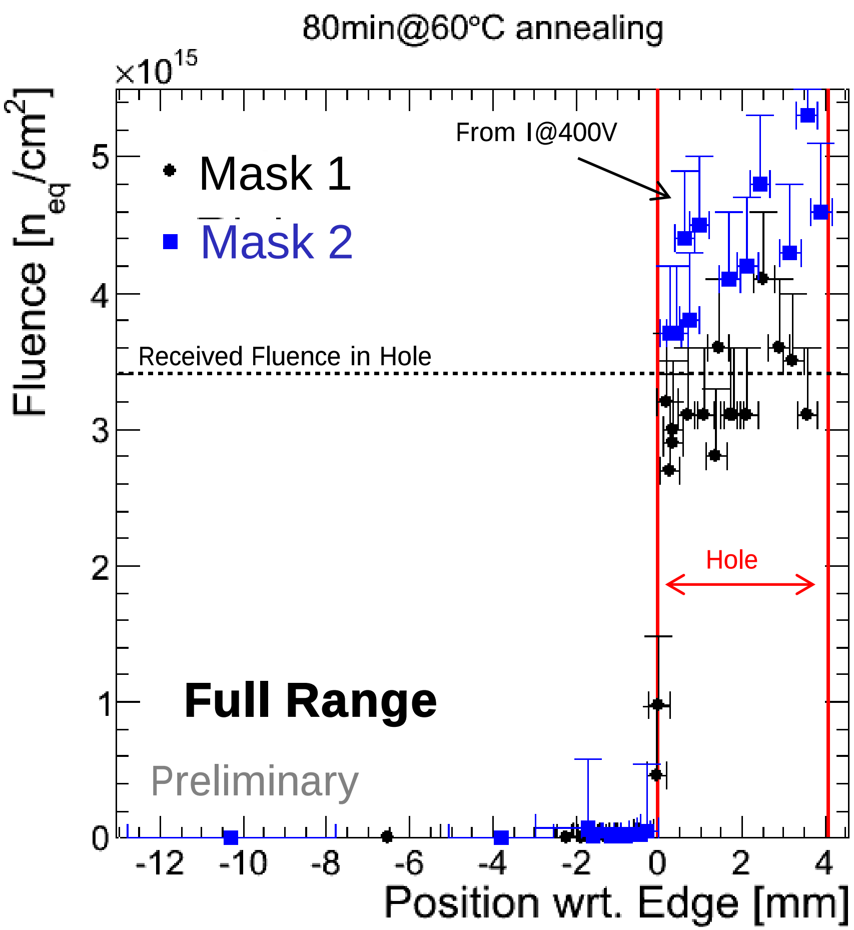
- New irradiation with diode arrays under same slit-like Al masks (left+right) at KIT (3.4×10^{15} n_{eq}/cm^2)
- Dosimetry from IV

$$\Delta I(\Phi_{eq}) = \alpha \Phi_{eq} V$$

- Measured at 20 °C
- No real plateau for irradiated diodes, but kink at 400-600 V → in the following I/V@400 V for fluence calculation taken
- No significant difference between centre and edge of irr. region

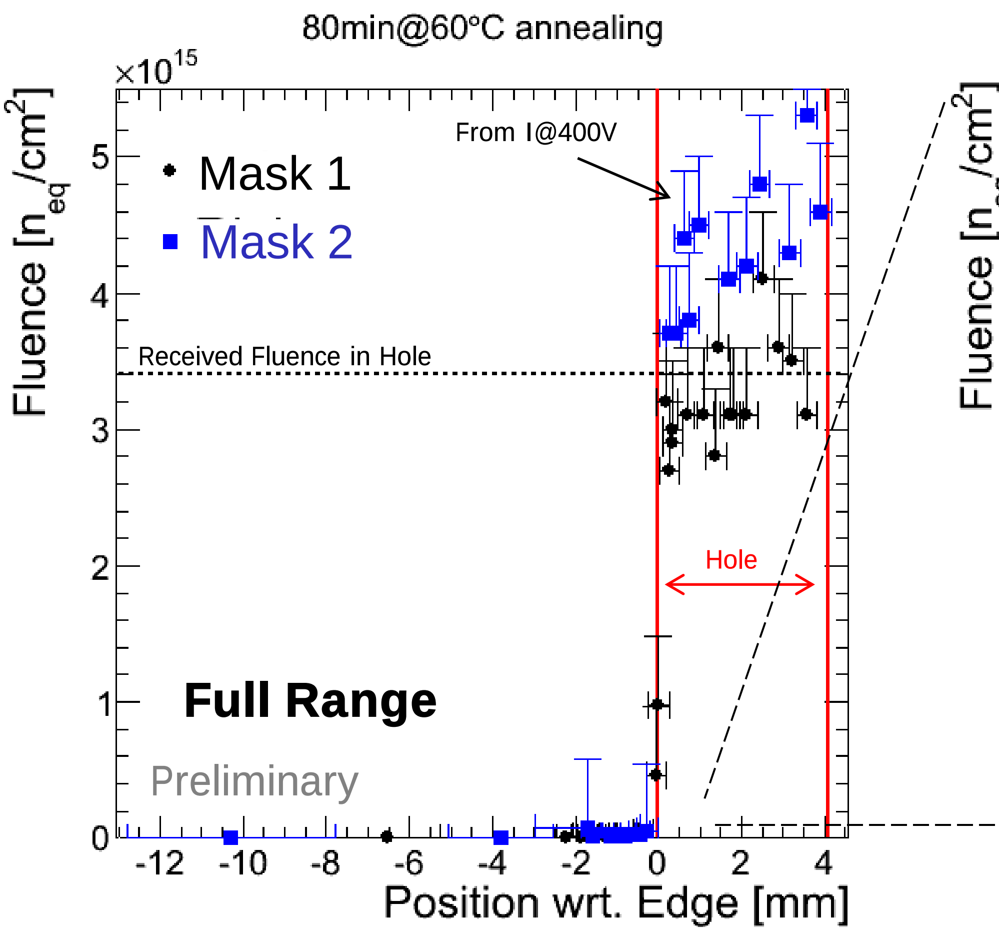
Thanks to CNM (G. Pellegrini, M. Baselga) for providing diodes, setup and help!

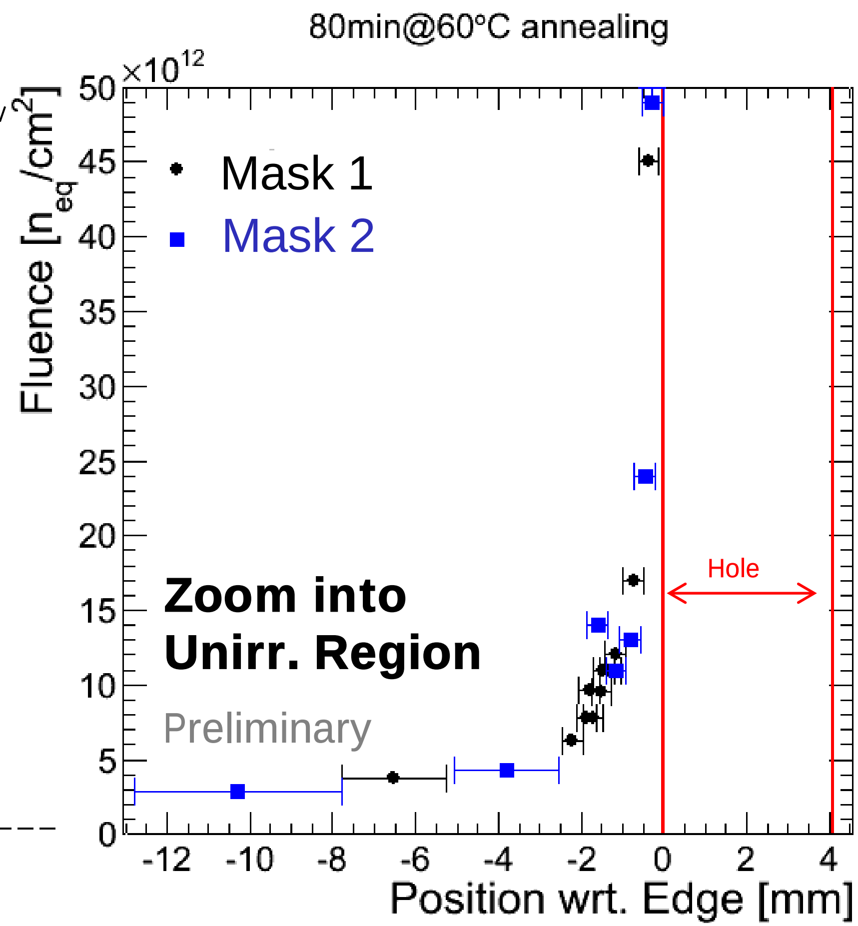
Fluence vs. Position wrt. Edge



- x error bars = extension of diode; upper y error bar to indicate lack of plateau; α = 4x10^17 A/cm
- No significant difference between centre and edge of irr. region; consistent with received fluence

Fluence vs. Position wrt. Edge





- x error bars = extension of diode; upper y error bar to indicate lack of plateau; α = 4x10^{17} A/cm
- No significant difference between centre and edge of irr. region; consistent with received fluence
- Substantial fluence (~10^{12} – 10^{13} cm^{-2}) also under Al mask; higher the closer to the hole