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

PRELIMINARY Results

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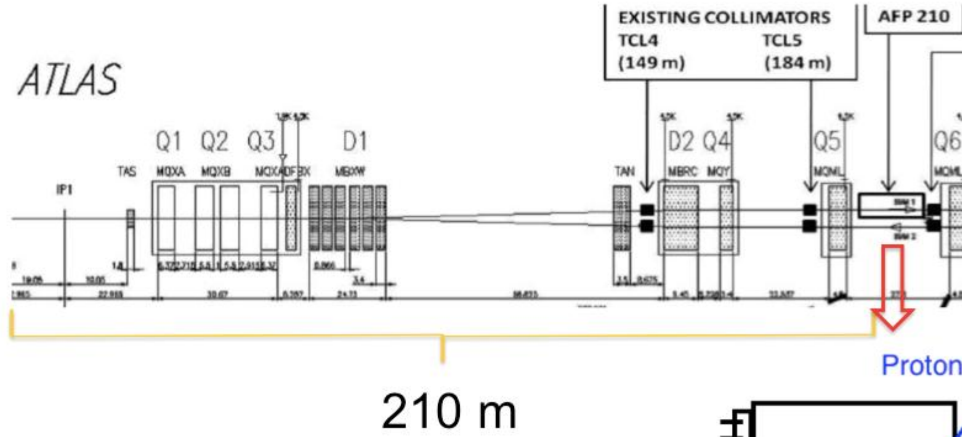
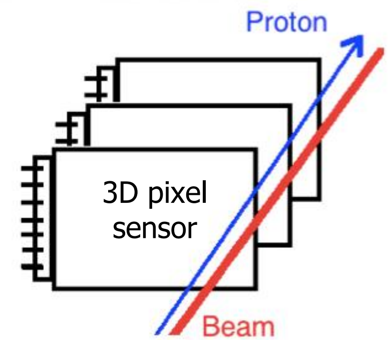
Introduction

- Atlas Forward Physics (AFP)
  - Diffractive physics: protons leave pp interaction intact
    → very forward protons
  - Combination of
    3D pixel tracker and fast timing detectors (pile-up removal)
  - Detectors close to the beam (2-3 mm) for good acceptance

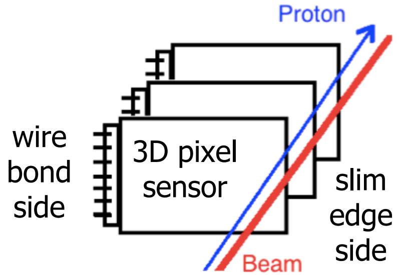




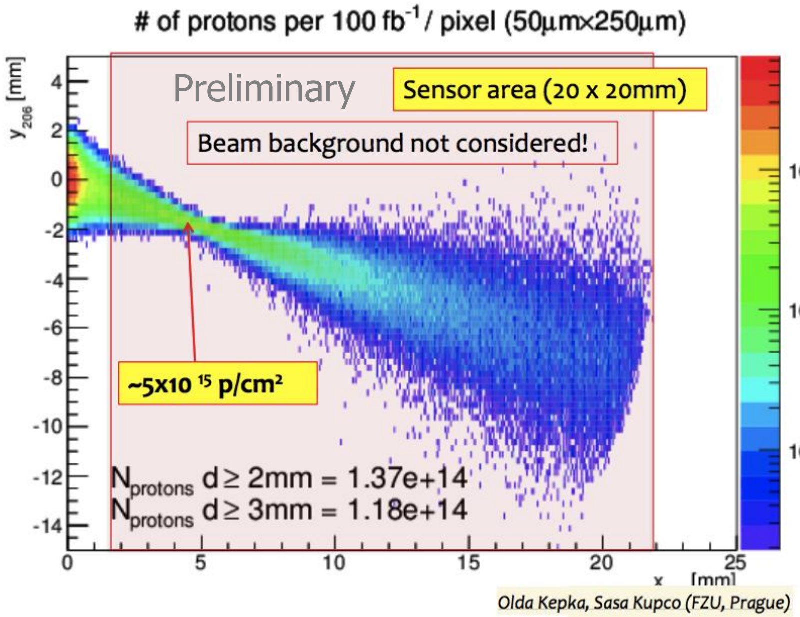
- Status of the proposal
  - AFP passed ATLAS Physics review (24.01.)
  - Installation planned for end of 2015
    → second use of 3D silicon sensors in HEP experiment!

Pixel Requirements

- Pixel detector requirements
  - ~10 μm tracking resolution in one direction
  - 2x2 cm^2 active area
  - Slim edge of side facing beam: ~100-200 μm
  - Highly non-uniform irradiation
    $5x10^{15}$ p/cm^2 (7 TeV p!) to several orders of magnitude lower on one sensor (preliminary, depends on final specs)

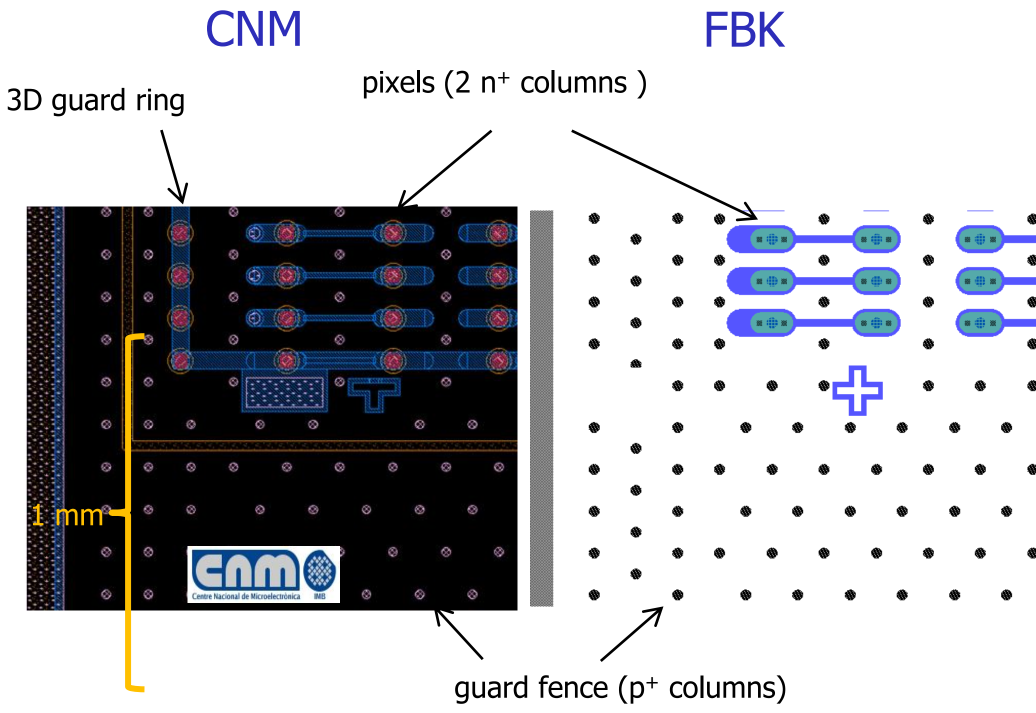


→ Baseline:
3D FE-I4 sensors with slimmed edge



Sensors and Edge Slimming

- FE-I4 3D IBL sensors (CNM and FBK)
  - 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 already 200 µm slim edge
    - Bottom: >1 mm bias tab (not needed!)
  - IBL spares (not always best quality)



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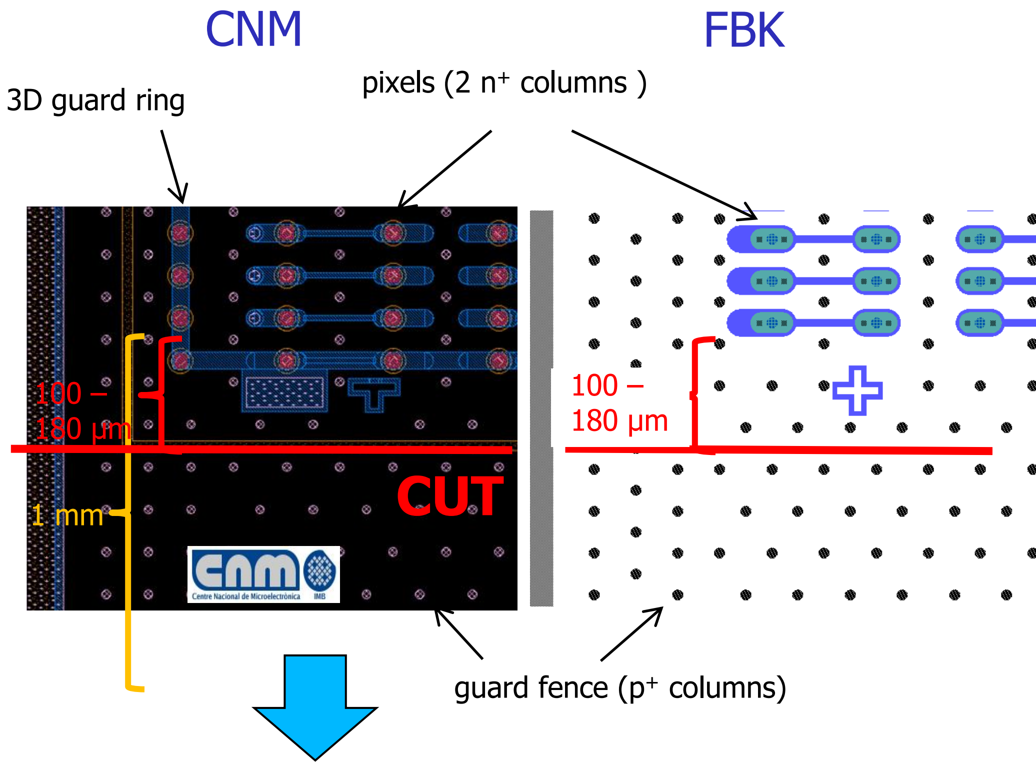
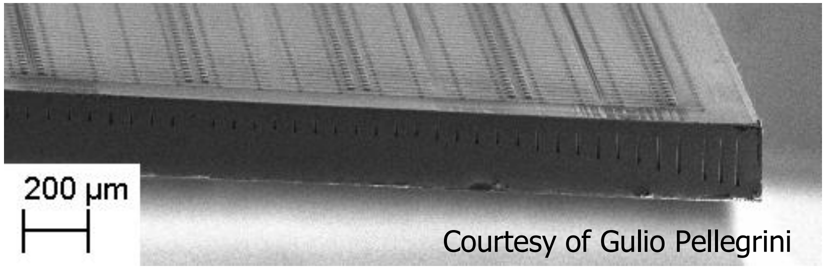
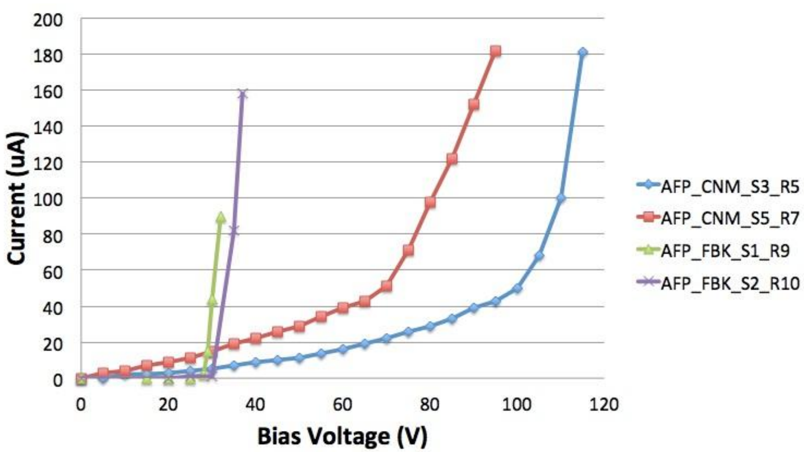


- Edge slimming:
  - Cut IBL sensors' inactive bottom edge
    down to 100-180 µm (FE-I4 chip: 80 µm dead region)
  - Technique here: standard diamond-saw cut
  - Previously also investigated: sensors with
    SCP slimming with promising results
    see A. Micelli, 21st RD50 workshop Nov 2012; S. Grinstein, 8th Trento workshop 2013



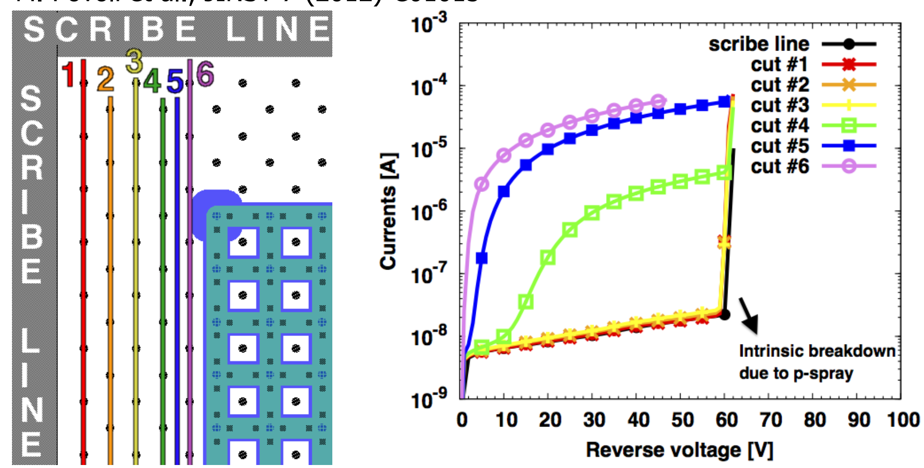
Current and Noise

IV of sensors used here (2 FBK, 2 CNM):
normal for used sensor-quality class

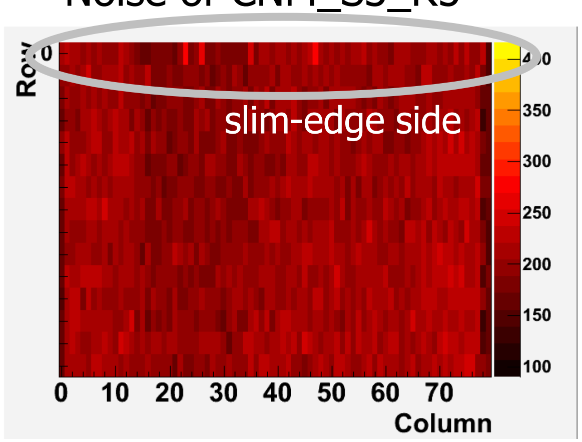


Previous study on FBK sensors:
IV unaffected up to 100 μm cut line

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



Noise of CNM_S3_R5

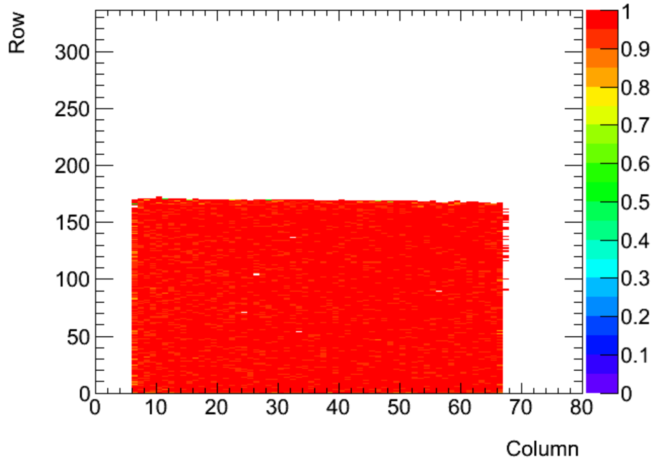


- No anomalous current and noise after edge-slimming to 100-180 μm

Efficiency of Slim-Edge Sensors in Test Beam

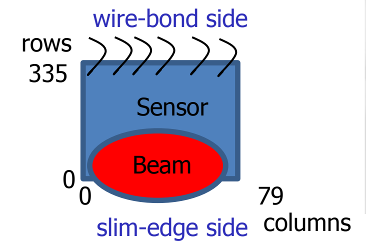
- DESY II Test beam: 4 or 5 GeV electrons
- ACONITE telescope (EUDET type)
- Normal incidence
- 1 reference IBL sensor,
  4 slimmed-edge AFP sensors
- Average efficiency after slimming (97-99%) comparable to IBL reference
  → what about edges?

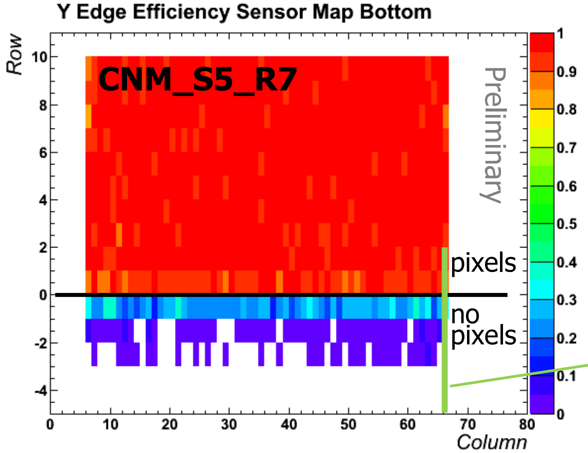
Thanks to all test beam participants, esp. I. Rubinskiy (DESY), D. Pohl (Bonn), O. Korchak (Prague), Sh. Hsu (Washington)

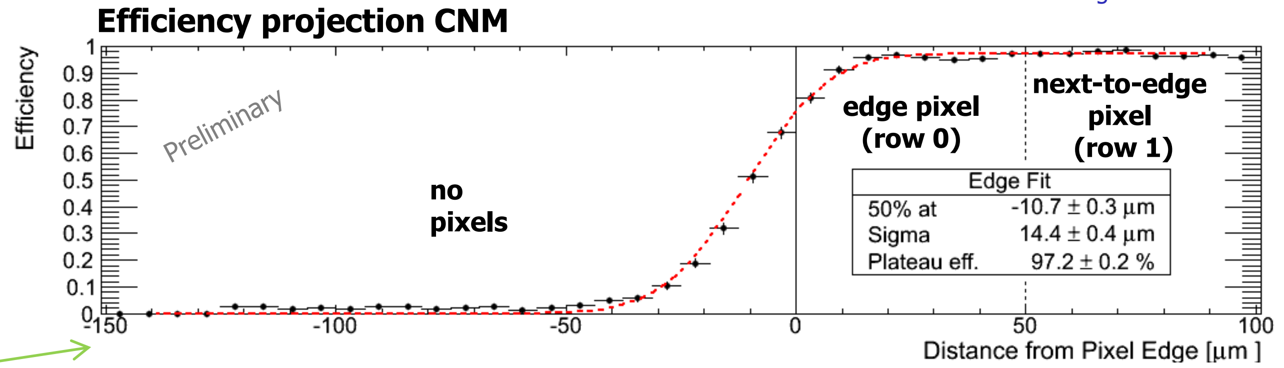


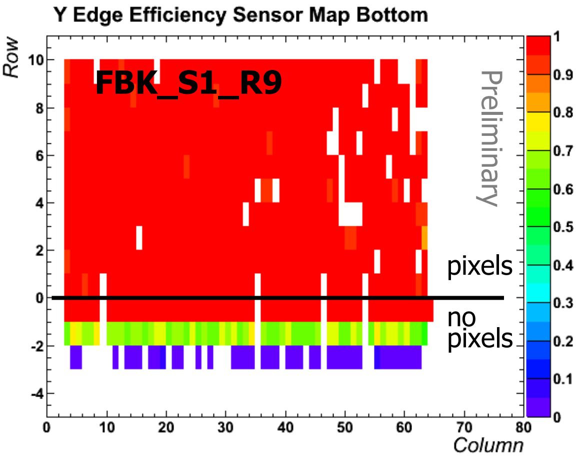
	DUTs				
Sample	CNM-55 (Refer.)	CNM_S3_R5	FBK_S5_R10	CNM_S5_R7	FBK_S1_R9
Edge	Regular	Slimmed	Slimmed	Slimmed	Slimmed
Bias [V]	30	30	20	30	20
Threshold [ke]	2.8	1.9	2.0	2.0	2.0
Efficiency	98-99%	98.3%	98.6%	96.9%	98.0%

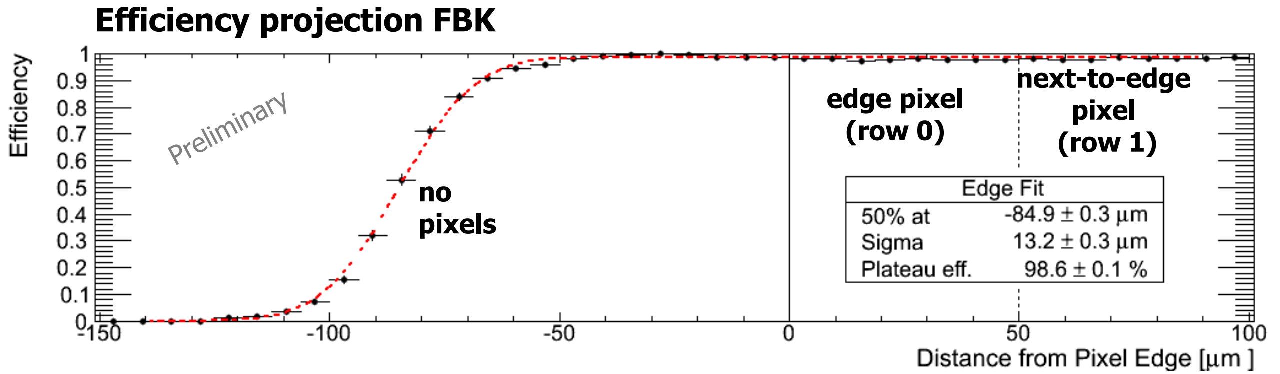
Edge Efficiency (Slim Edge Bottom Side)









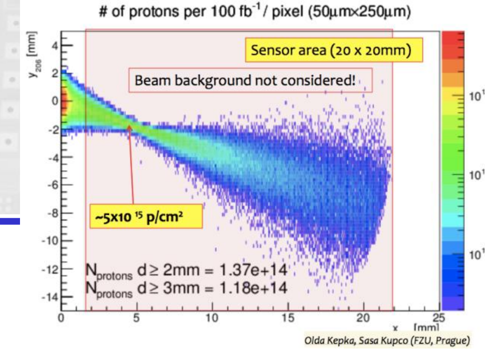


- Efficiency stable up to last pixel
  - For FBK even ~80-85 µm beyond (efficient edge due to absence of guard ring)

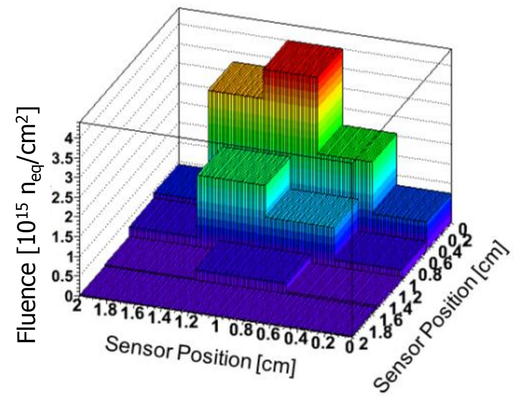
→ same behaviour as for non-slimmed edge!

Non-Uniform Irradiation

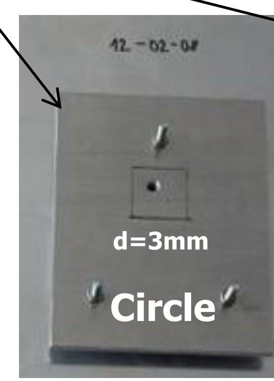
- Non-uniform irradiation:
  Can detector be operated to give high efficiency both in unirradiated region ($V<V_{BD}$ needed) and in irradiated region ($V>V_{dep,irr}$ needed)?
- First test beam study in 2012 with focussed CERN-PS 23 GeV irradiation promising: 98% efficiency
  see A. Micelli, 21st RD50 workshop Nov 2012; S. Grinstein, 8th Trento workshop 2013
- But fluence spread was large
- Another irradiation with more localised fluence:
  23 MeV protons (KIT) through hole in Al plate (5 mm thick)
  → focus of following slides

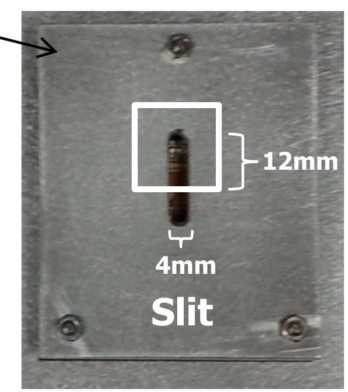


Fluence map of CERN-PS irradiation:



Al shields at Karlsruhe:





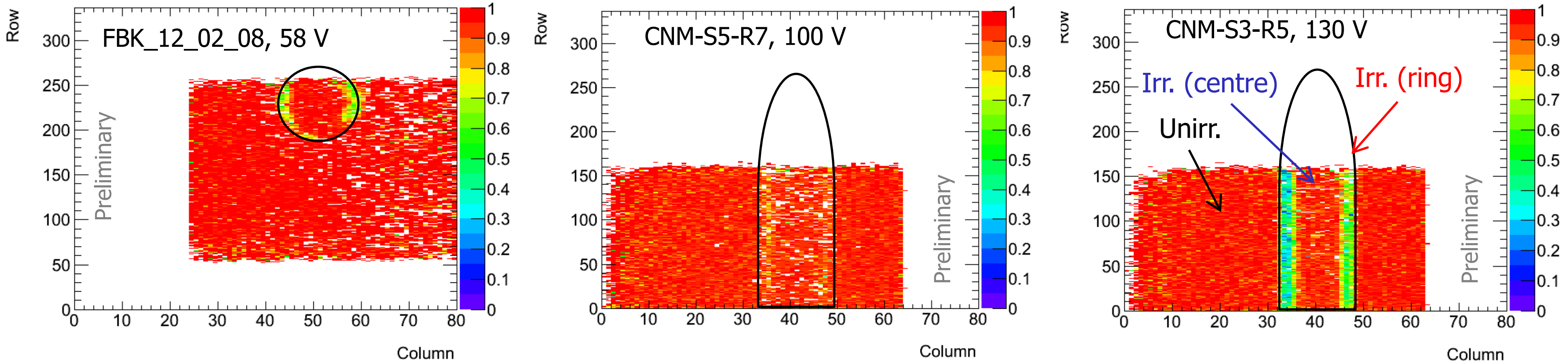
Non-Uniform Irradiation	PS 23 GeV p Focussed beam	KIT 23 MeV p Hole (circle)	KIT 23 MeV p Hole (slit)	
Φ [10^{15} n_{eq}/cm^2]	4.0 (max)	1.8	3.3	3.6
Sample	CNM 57	FBK 12_02_08	CNM S5-R7	CNM S3-R5
Edge	Regular	Regular	Slimmed	Slimmed

Thanks to Petr Sicho (CERN)/Felix Bögelspacher (KIT) for irradiation

Efficiency of Irradiated Devices

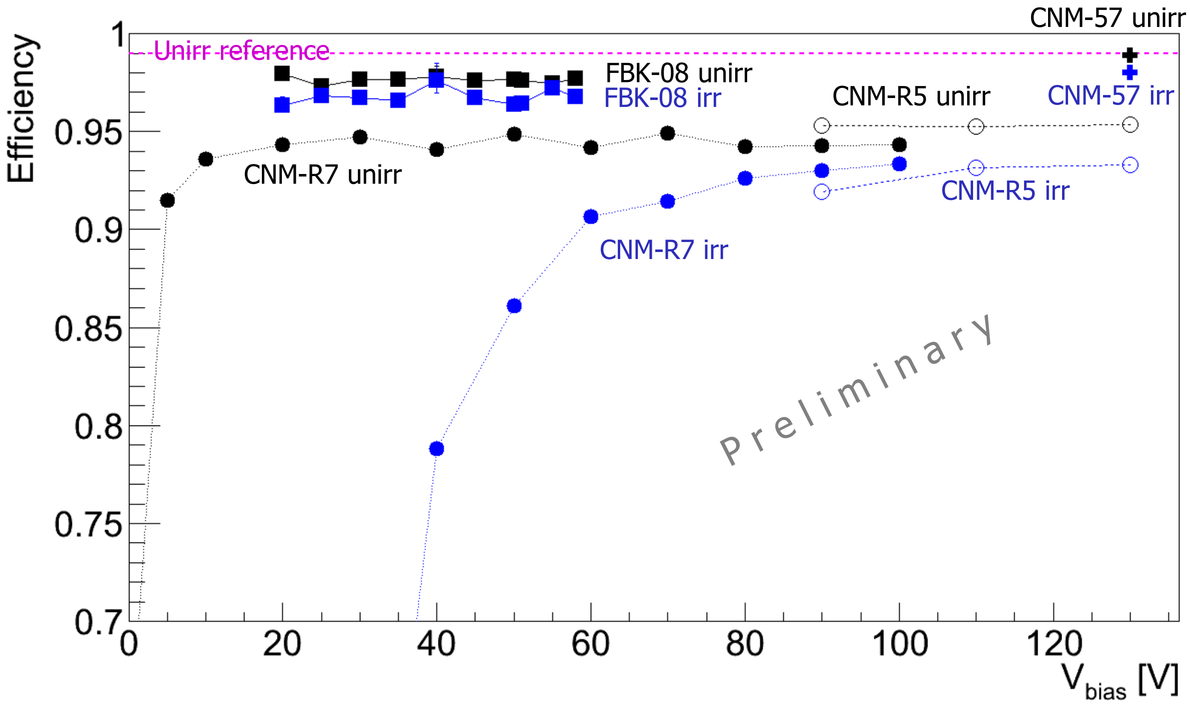
- Test beam: DESY (KIT irr. devices), CERN (PS irr. device), normal incidence, T < -20 °C
- Different runs at different bias voltages of irradiated sample (V limited by high I_{leak})
- Challenging to tune threshold in such non-uniformly irradiated sensors
- Noisy and dead pixels masked
- Irradiated hole (centre) almost as efficient as unirradiated region
- Ring of lower efficiency at edge of hole
  - Probably due to scattering of p at edge of Al shield -> loose energy -> much more damaging

Efficiency Sensor Maps



Efficiency

for unirradiated and irradiated (centre) area



- Irradiated part (centre) almost as efficient as unirrad. part
- Irradiation through hole (KIT): offset for CNM devices
  - Both unirr. and irr. area
  - Note different fluence, irr. area, threshold, edge
  - Threshold of 2 ke gives 1% more
  - Problem with tuning? Non-uniform eff. even in unirr. area

Non-Uniform Irradiation	Unirr. Reference	PS Focussed	KIT Hole (circ.)	KIT Hole (slit)	
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
Threshold [ke]	3	1.7	2	3	3

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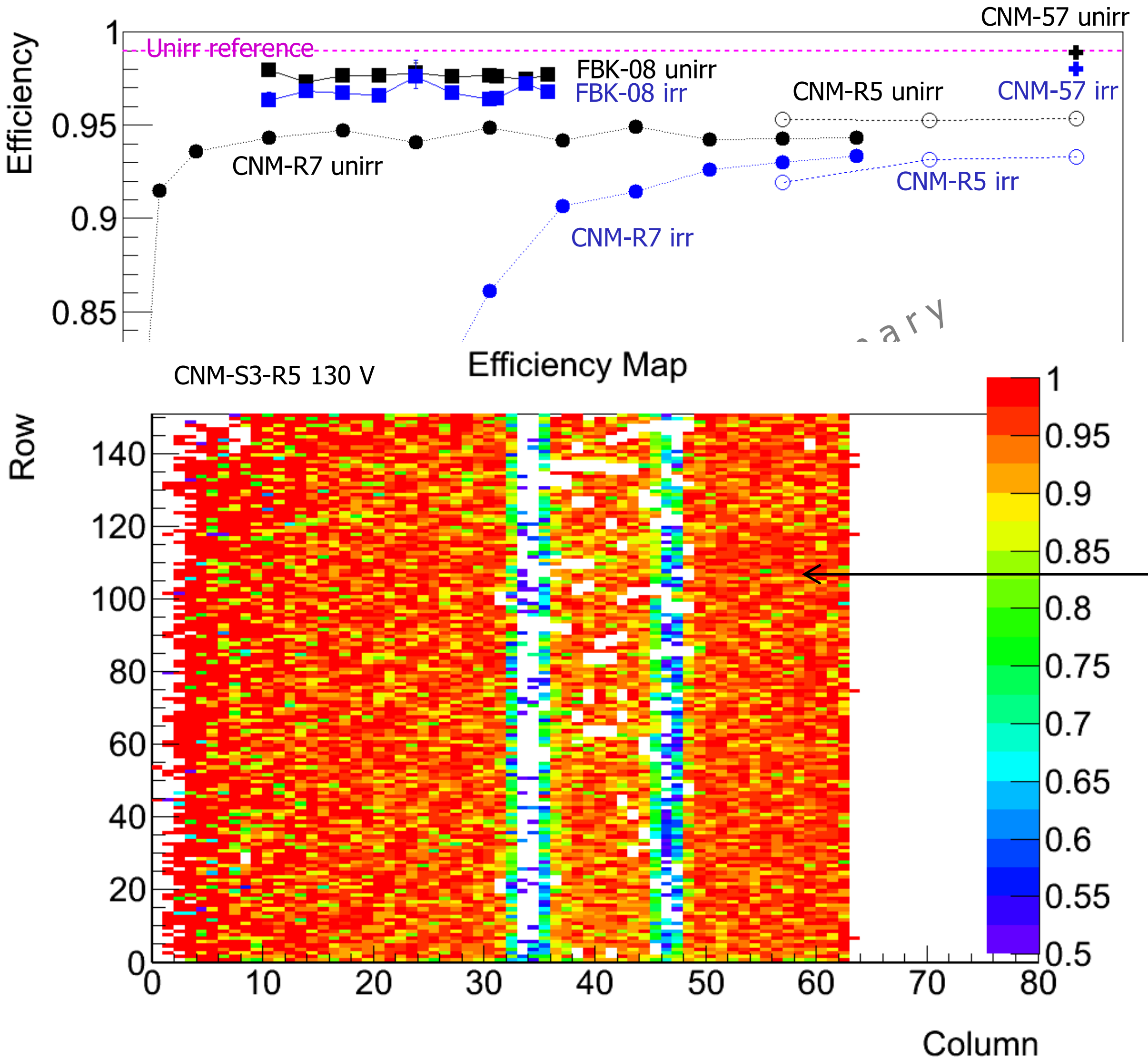

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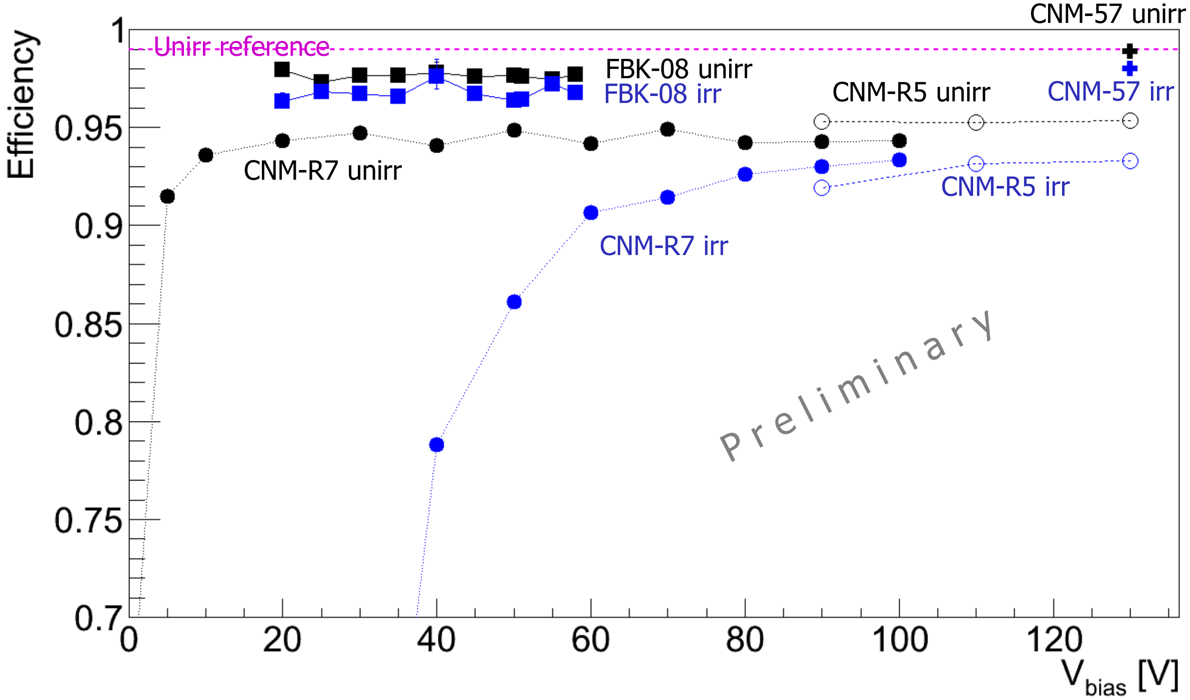

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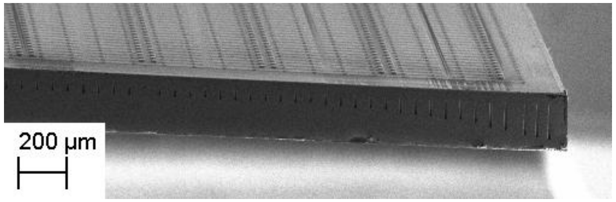
  - Threshold of 2 ke gives 1% more
  - Problem with tuning? Non-uniform eff. even in unirr. area
- For all devices: eff. ≥ 93% (≥ 94% for 2 ke threshold)
- Highest eff. for focussed-beam irradiation with CNM-57: 98% in irr. area
- Possibly improvable by tilting sensor (15° under study)

Conclusions

- Slim-edge and non-uniformly irradiated 3D AFP sensors studied
- Good performance despite low sensor quality
- Slim edge:
  - IV, noise and efficiency in test beam unaffected by edge-cutting with diamond saw (FBK: efficient edge)
  - Inactive pixel-sensor region highly reduced (from >1 mm to 100-180 µm)



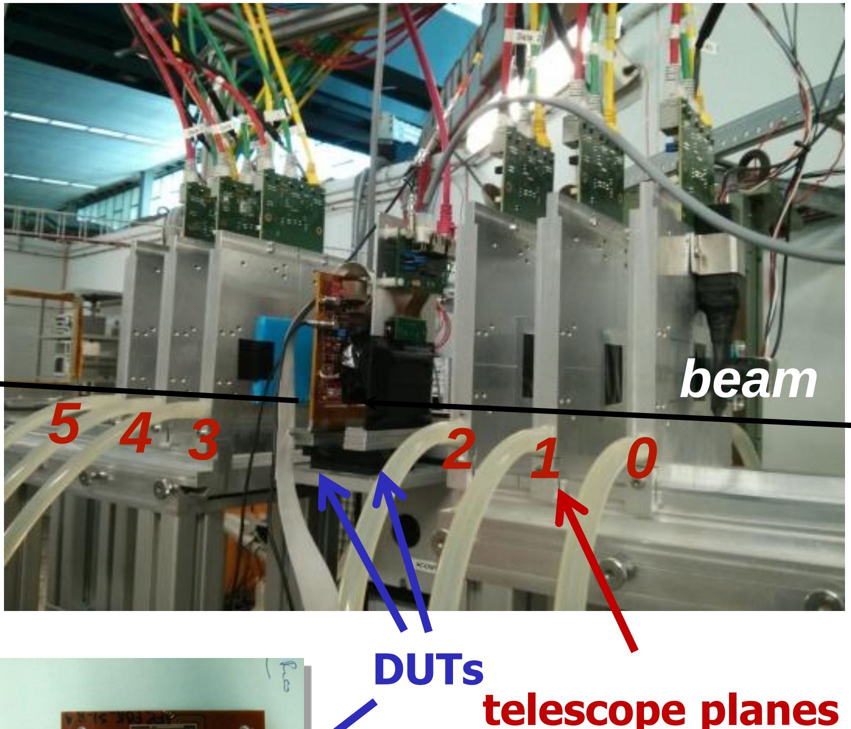
- Non-uniform irradiation:
  - High efficiency of 94-98% achievable in irradiated part (for thr ≤ 2 ke)
- Outlook:
  - CNM AFP production run with 12 wafers expected to end in April
  - Module production by IZM (UBM, flip-chip), IFAE (wirebonding) and Oslo (flex design)
  - Test beams at the end of the year with a first system of tracking and timing detectors
  - AFP planned to be installed end of 2015
    → second use of 3D silicon sensors in HEP experiment!

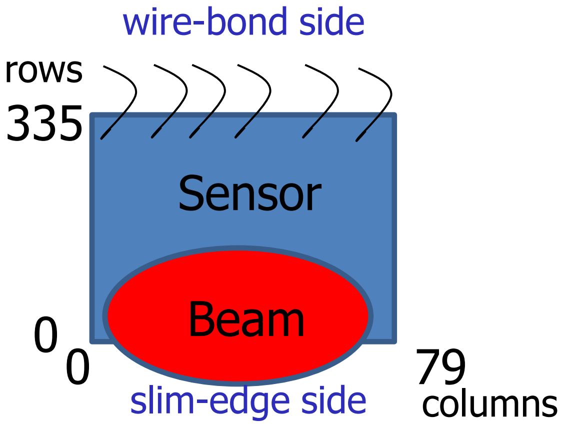
BACKUP

DESY Test Beam

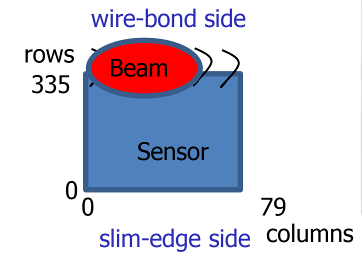
- Check performance in test beam
  - DESY II 4 or 5 GeV electrons
  - ACONITE telescope (EUDET type)
    - 6 planes of MIMOSA-26:
      660k Si pixels (18.4 µm pitch)
    - Trigger: 4 scintillators
  - Special study of edge efficiency of first rows (slim-edge side)

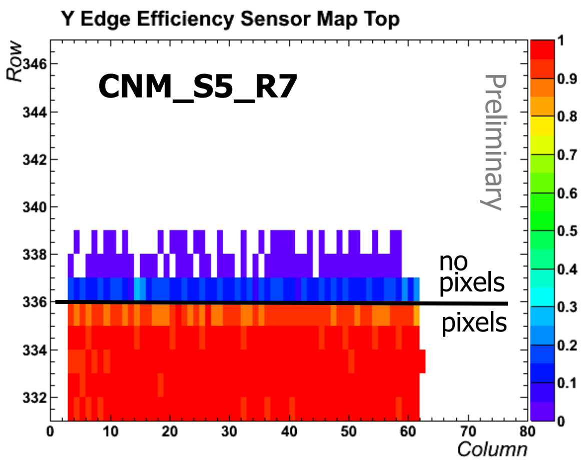
Thanks to all test beam participants,
esp. I. Rubinskiy (DESY), D. Pohl (Bonn),
O. Korchak (Prague), Sh. Hsu (Washington)

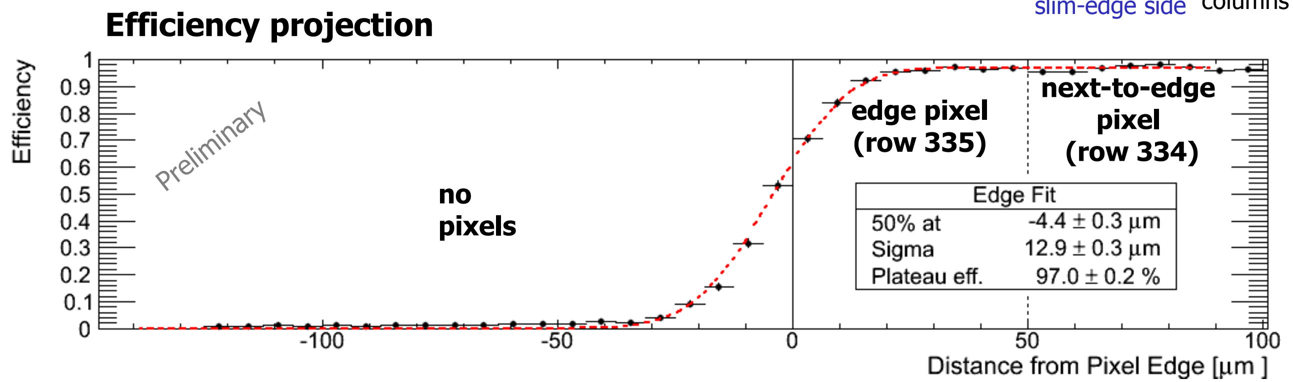


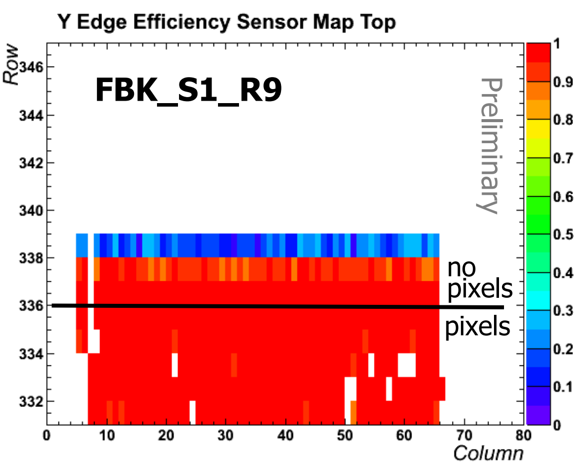


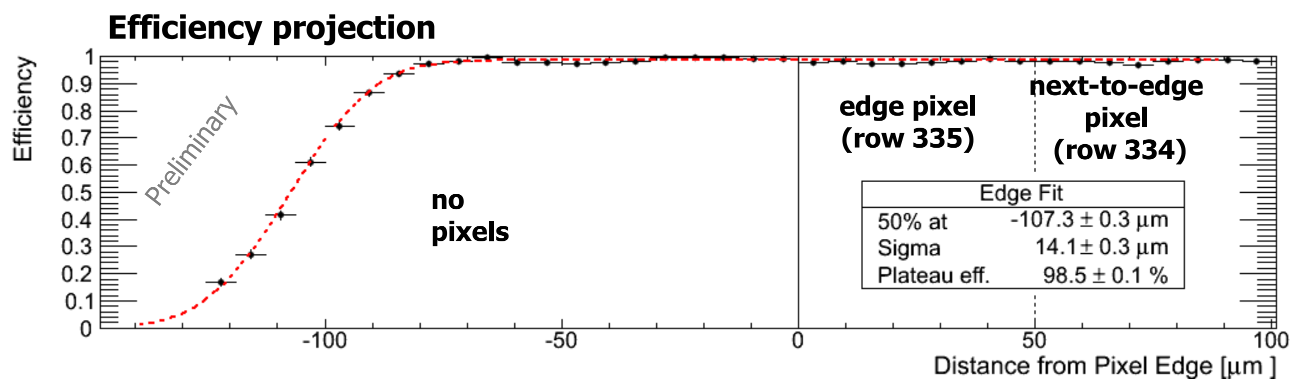
Regular Unslimmed Edge (Top Side)





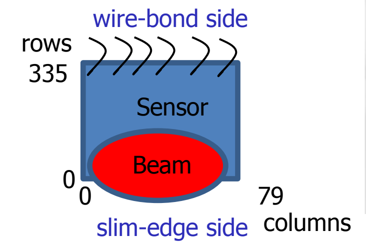


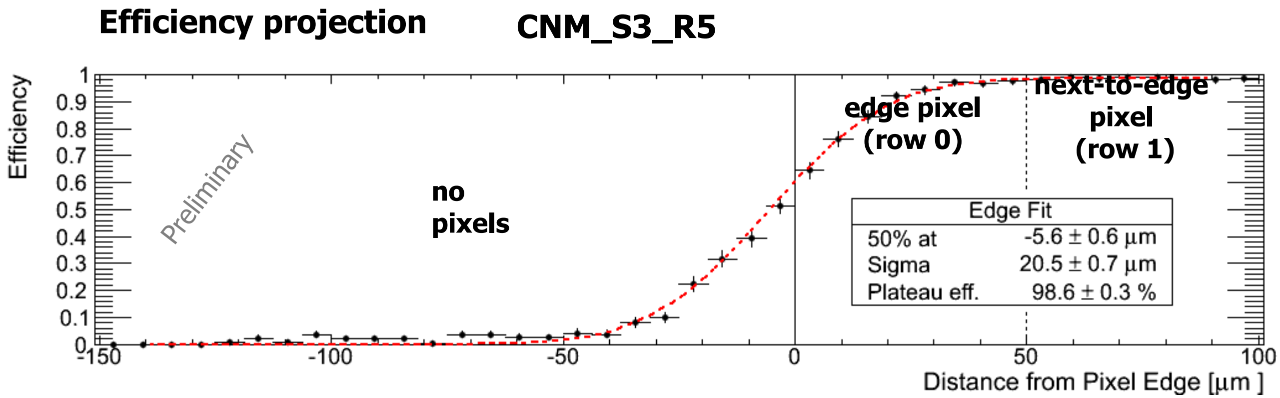


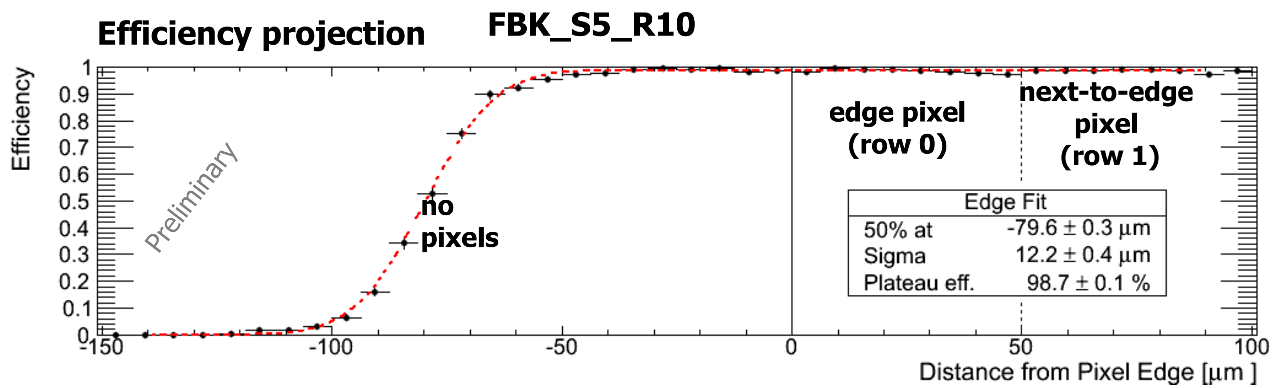


- Efficiency stable up to last pixel
  - Smearing due to beam telescope resolution
  - For FBK even ~100 µm beyond (active edge due to absence of guard ring); a bit noisy/hot pixels → masked

Slim Edge (Bottom Side) Other devices





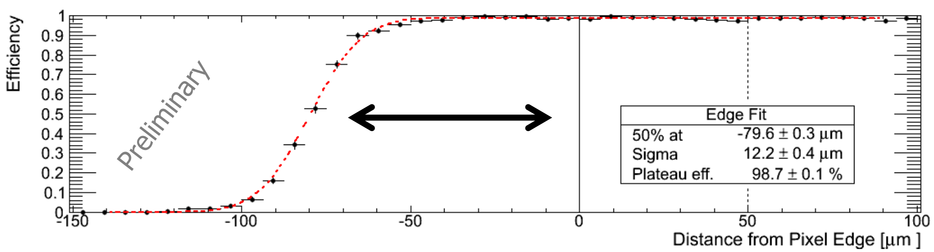


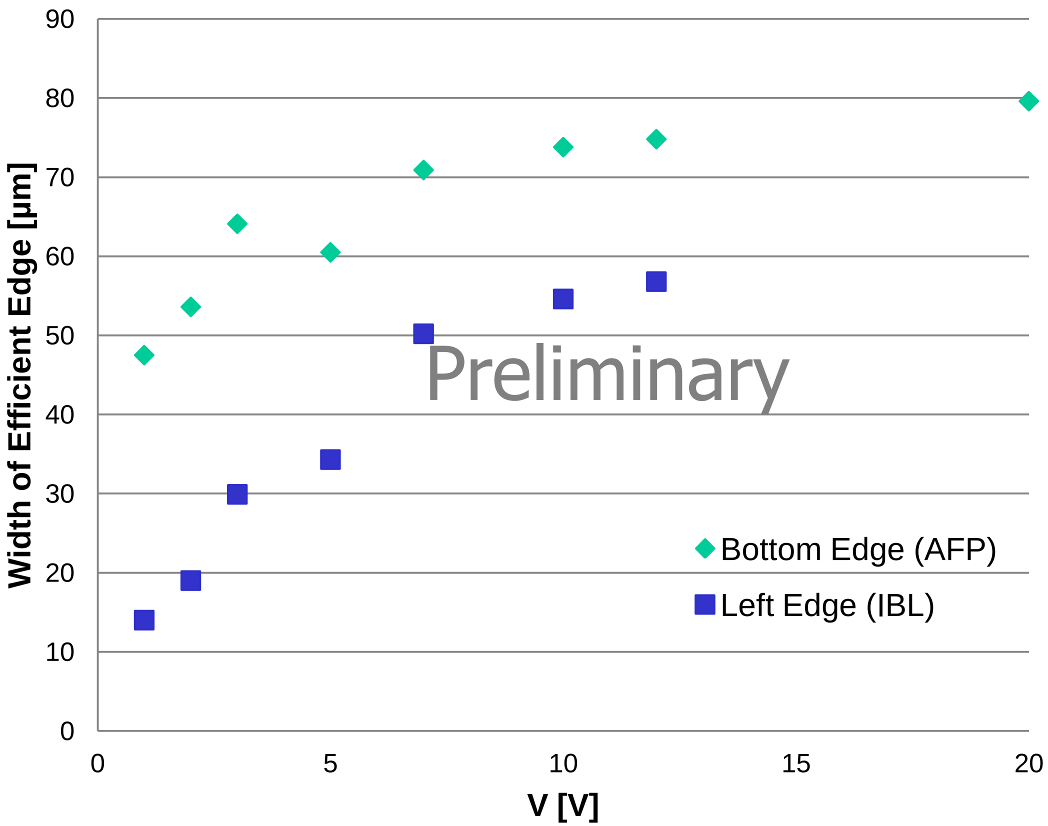
- Efficiency stable up to last pixel
  - For FBK even ~85 µm beyond (active edge due to absence of guard ring); a bit noisy/hot pixels → masked

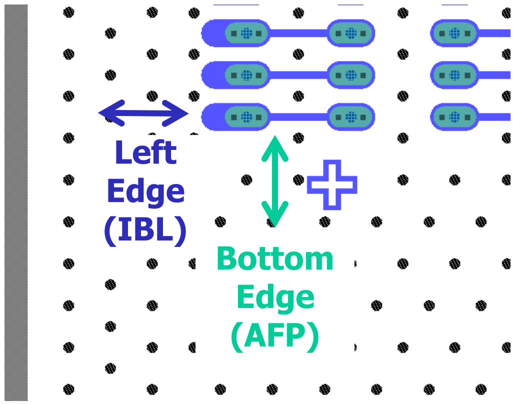
→ same behaviour as for non-slimmed edge!

Development of Efficient Edge in FBK Sensor with Voltage

FBK_S5_R10, 20 V







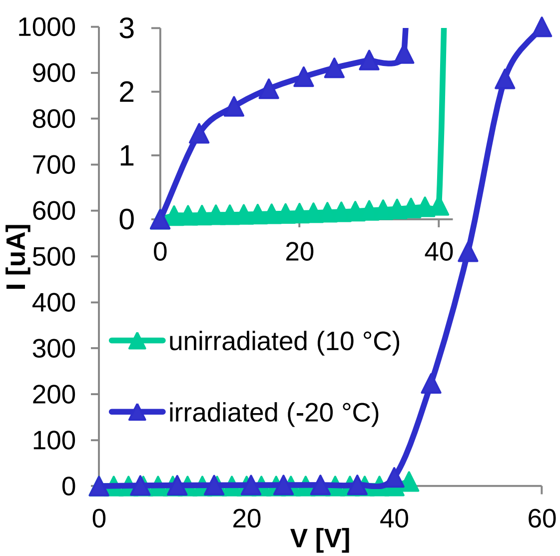
- Width of efficient edge increases with voltage (depletion zone increases)
- Saturation between first and second guard line beyond last pixel
- Bottom edge has larger width of efficient edge than left edge

Electrical Characteristics

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

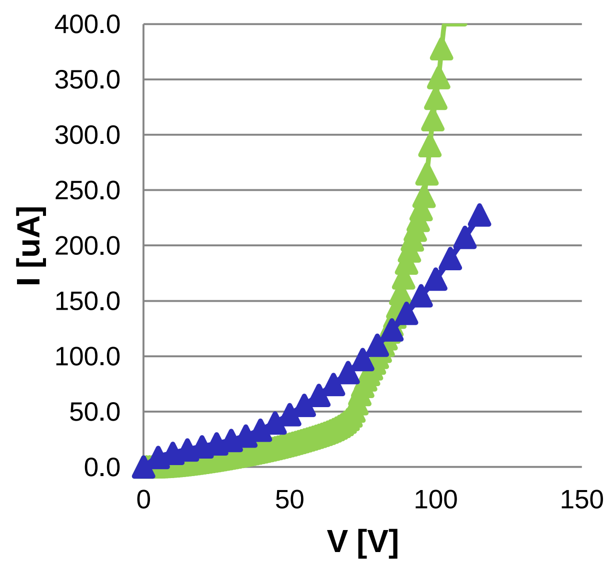
FBK_12_02_08

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



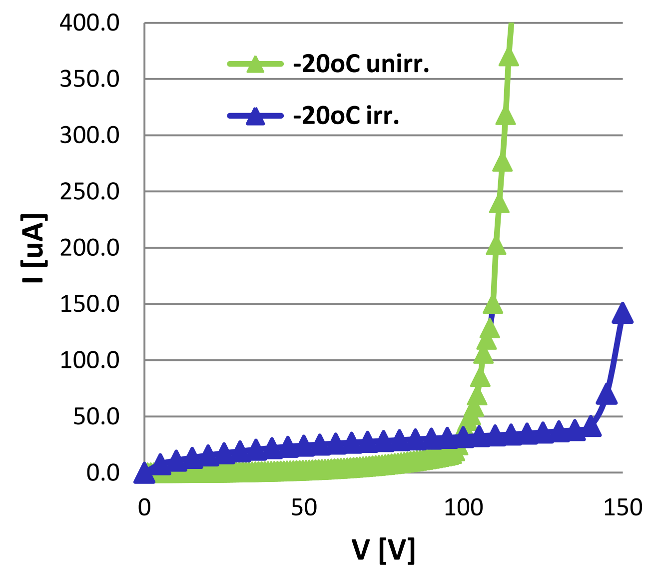
CNM_S5_R7

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



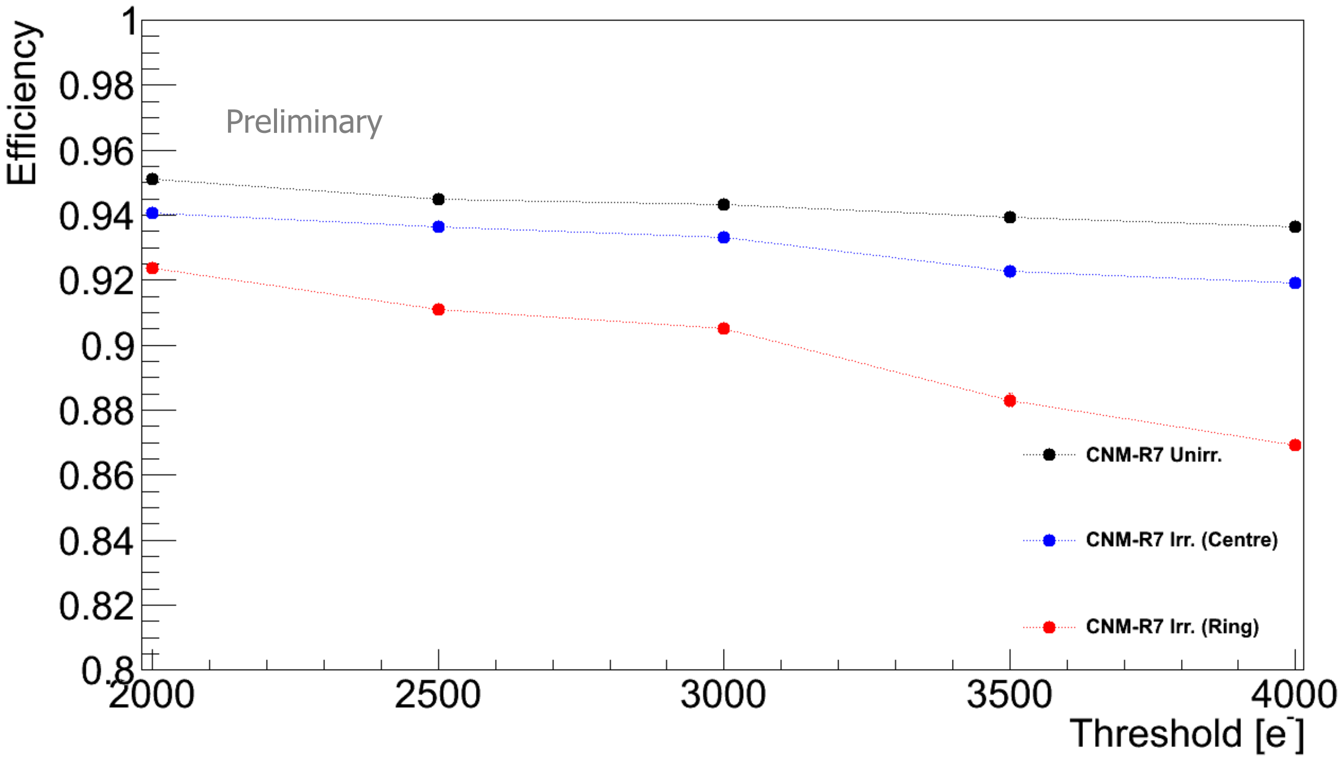
CNM_S3_R5

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



Efficiency vs. Threshold

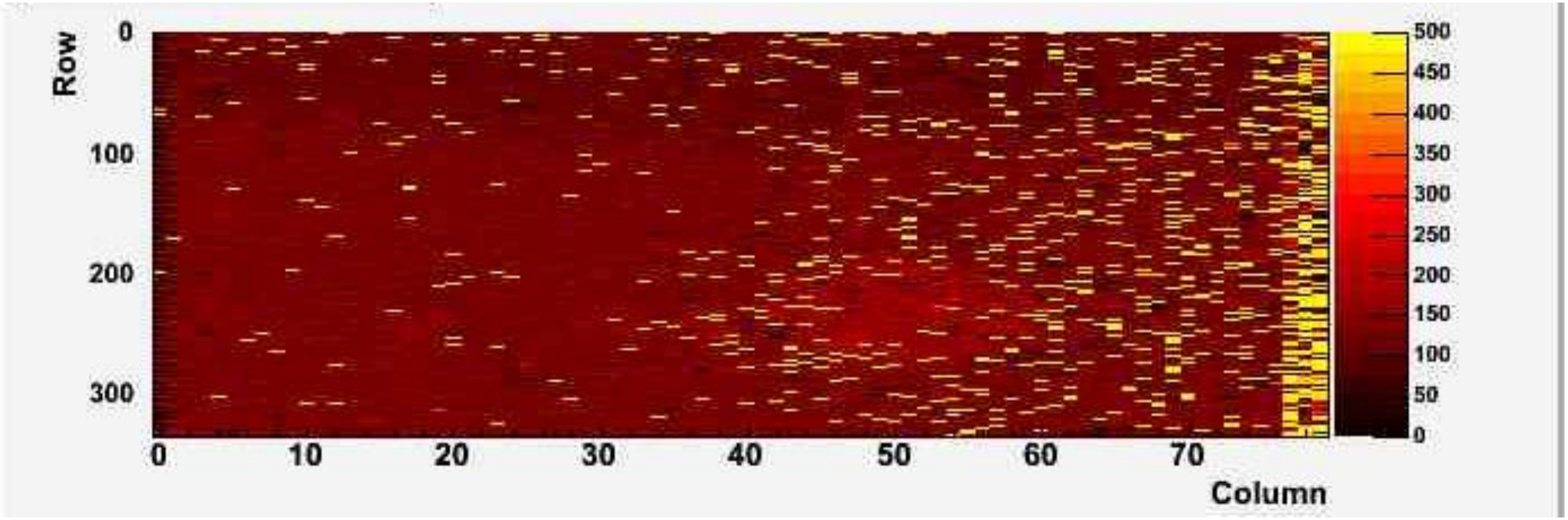
- Improvement of 1% per 1000e reduction of threshold for unirr. and irr. (centre) area
- Even more for higher irradiated ring



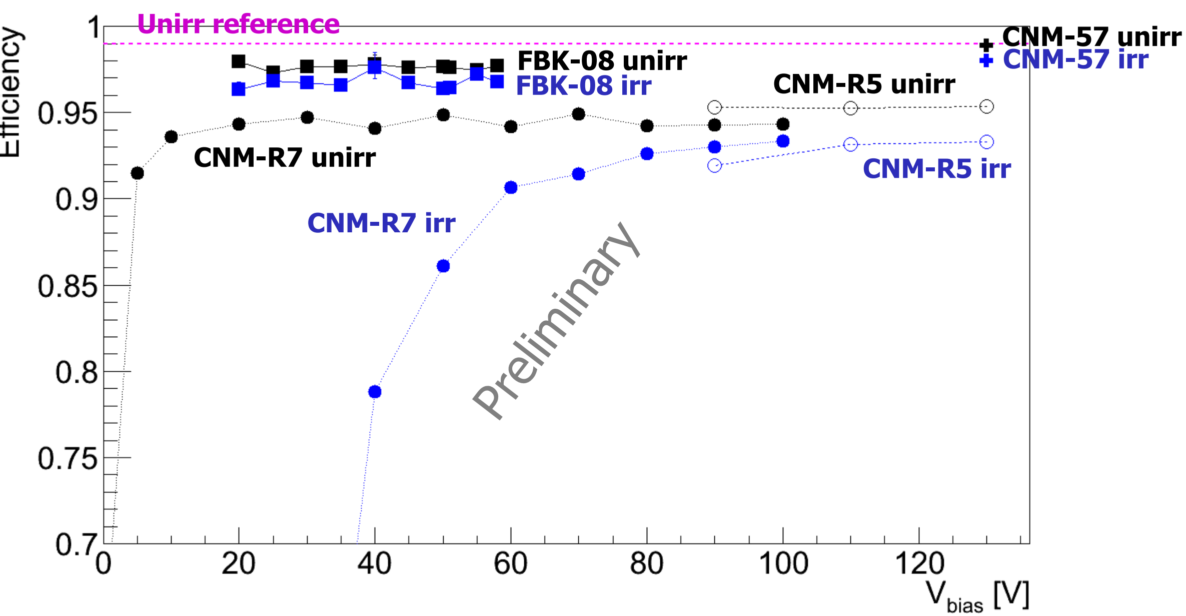
Noise of irradiated sensor

- Noise outside irradiated region ~ 130 e
- Noise inside irradiated region slightly higher (by about 10-20e)

FBK-12-02-08, 50 V



Efficiency



Non-Uniform Irradiation	Unirr. Reference	PS Focussed	KIT Hole (circ.)	KIT Hole (slit)	
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
Threshold [ke]	3	1.7	2	3 (2)	3
Eff_{max}(unirr) [%]	99	99	98	94 (95)	94
Eff_{max}(irr) [%]	-	98	97	93 (94)	93

- Irradiated area (centre) almost as efficient as unirrad. area
- Irradiation through hole (KIT): offset for CNM devices
  - Both unirr. and irr. area
  - Note different fluence, irr. area, threshold, edge
  - Threshold of 2 ke gives 1% more
  - Problem with tuning? Non-uniform eff. even in unirr. Area
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