3D Silicon Pixel Detectors for the Forward Physics Experiments

PRELIMINARY Results

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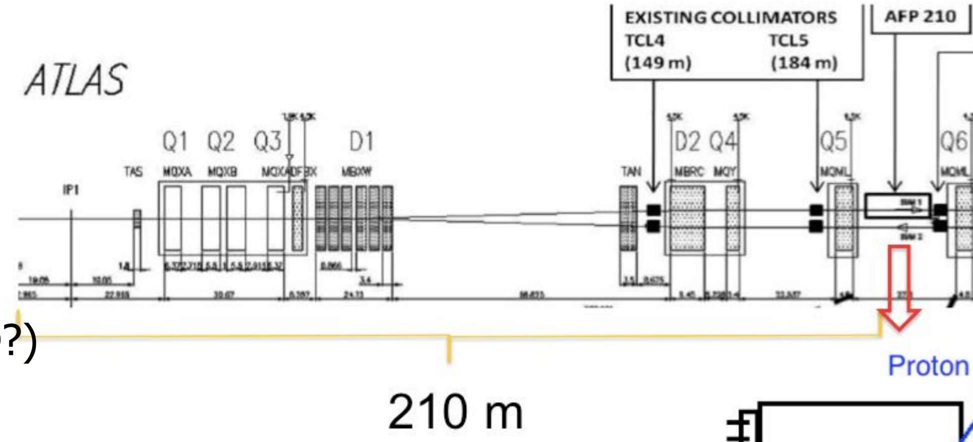
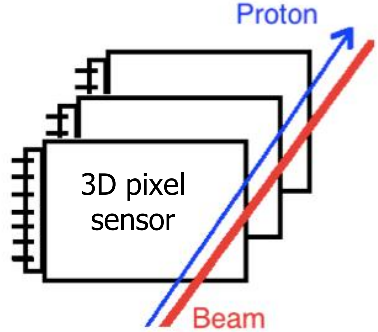
Introduction

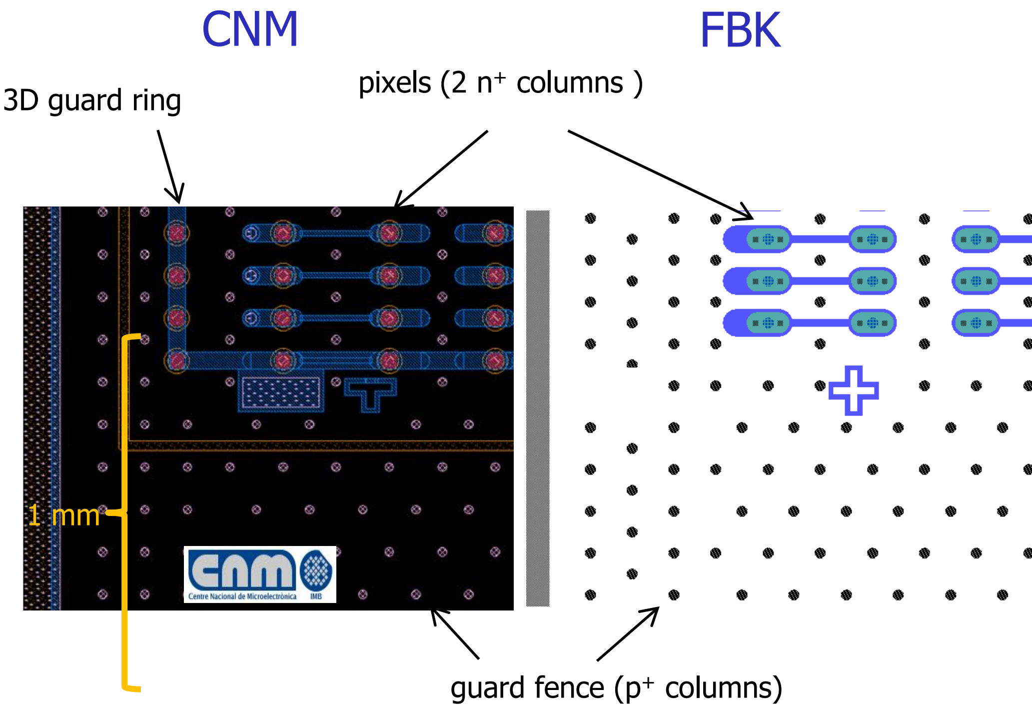
- Atlas Forward Physics (AFP)
  - Diffractive physics: protons leave pp interaction intact
    → very forward protons
  - Combination of
    3D pixel tracker and fast timing (UFSD?) detectors for pile-up removal
  - Detectors close to the beam (2-3 mm) for good acceptance
- → Requirements:
  - Slim edge of side facing beam: ~100-200 µm
  - Highly non-uniform irradiation
- Status of the proposal
  - AFP conditionally approved for dedicated low-lumi runs
  - Possible high-lumi upgrade later
  - Installation planned for end of 2015
    → second use of 3D silicon sensors in HEP experiment!





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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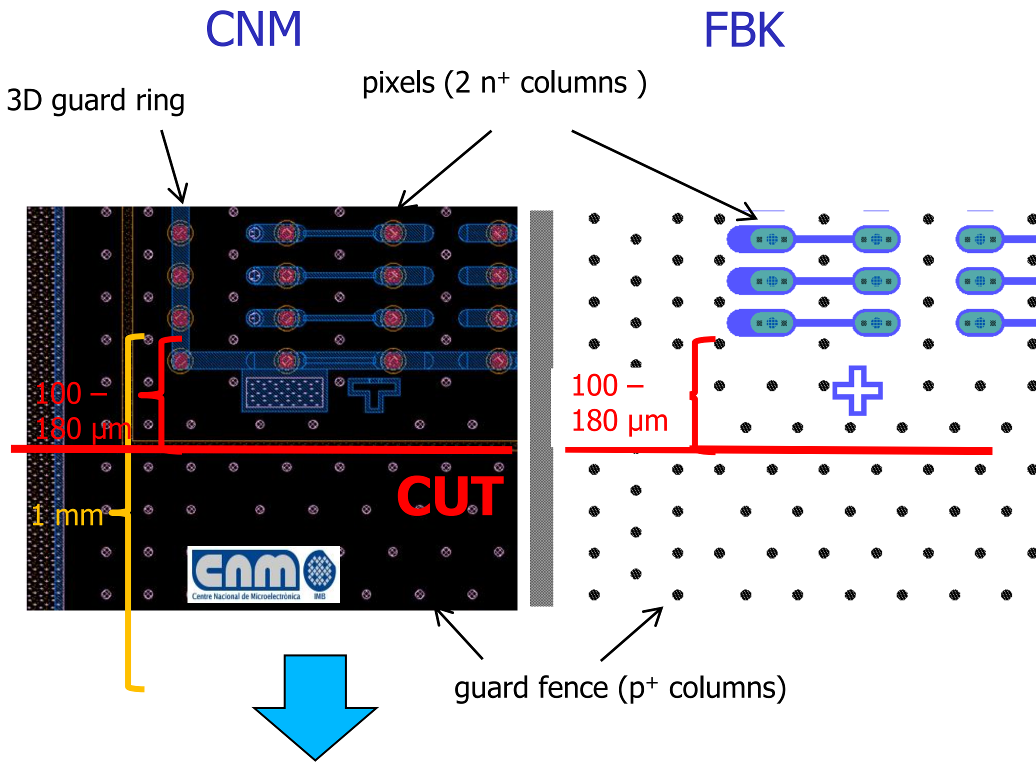
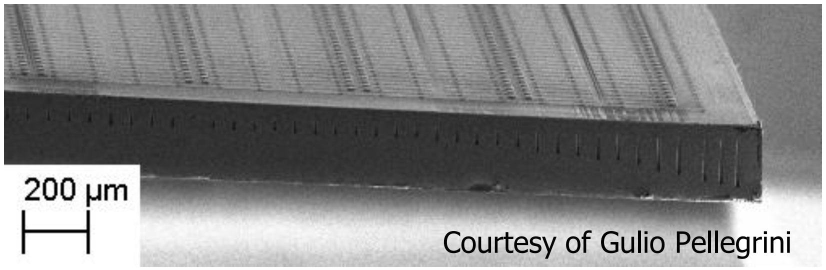
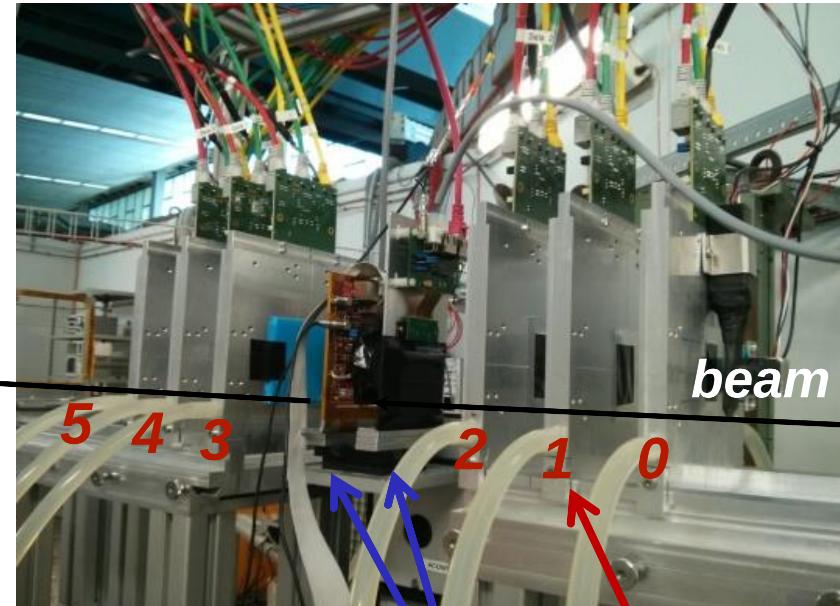


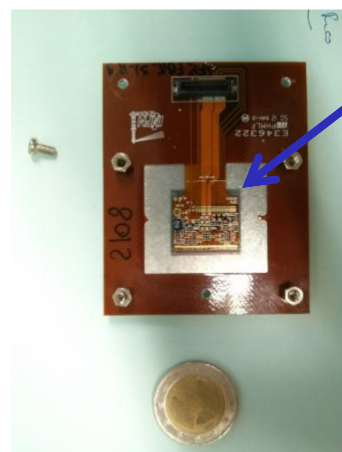
- Edge slimming:
  - Cut IBL sensors' inactive bottom edge down to 100-180 μm (FE-I4 chip: 80 μm dead region)
  - Technique here: standard diamond-saw cut



DESY Test Beam

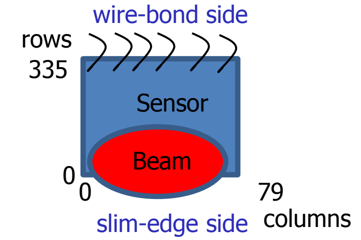
- Check performance in test beam
  - DESY II 4 or 5 GeV electrons
  - ACONITE telescope (EUDET type)
    - 6 planes of MIMOSA-26:
      660k Si pixels (18.4 µm pitch)
    - Trigger: 4 scintillators
  - Thanks to AIDA support

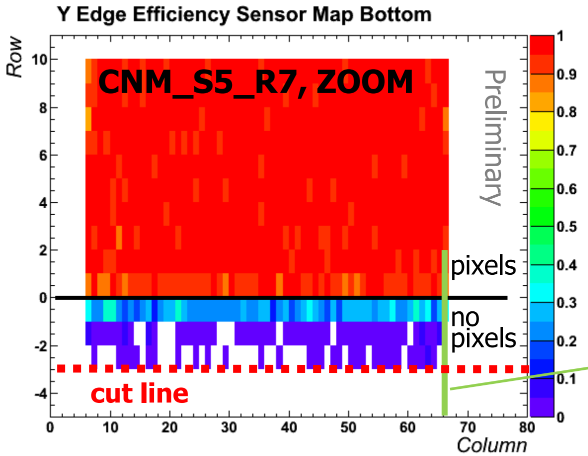


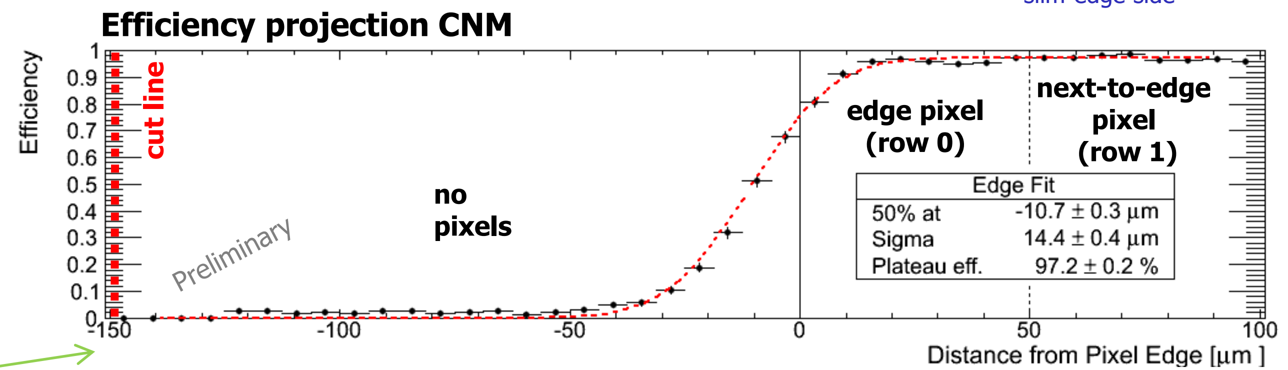


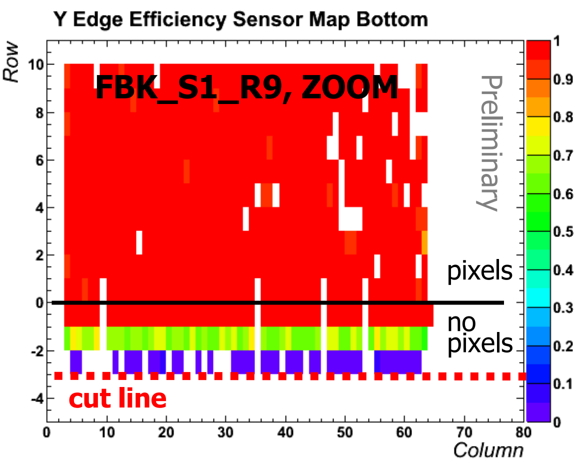
Thanks to all test beam participants,
esp. I. Rubinskiy (DESY), D. Pohl (Bonn),
O. Korchak (Prague), Sh. Hsu (Washington),
A. Micelli (IFAE)

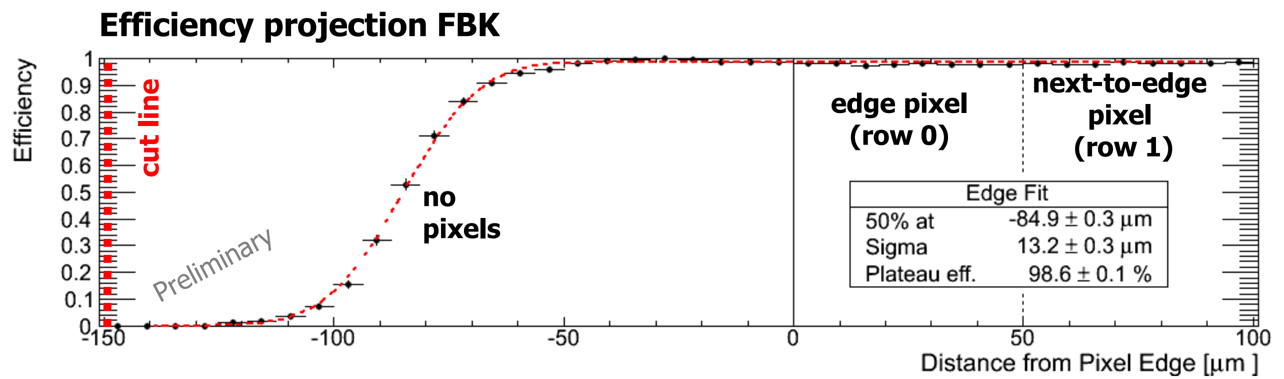
Slim-Edge Efficiency in DESY Test Beam









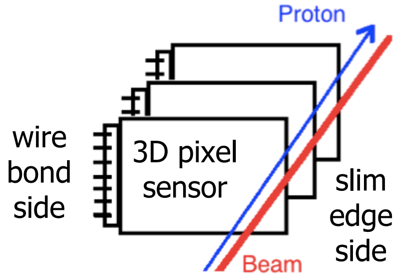


20 V bias

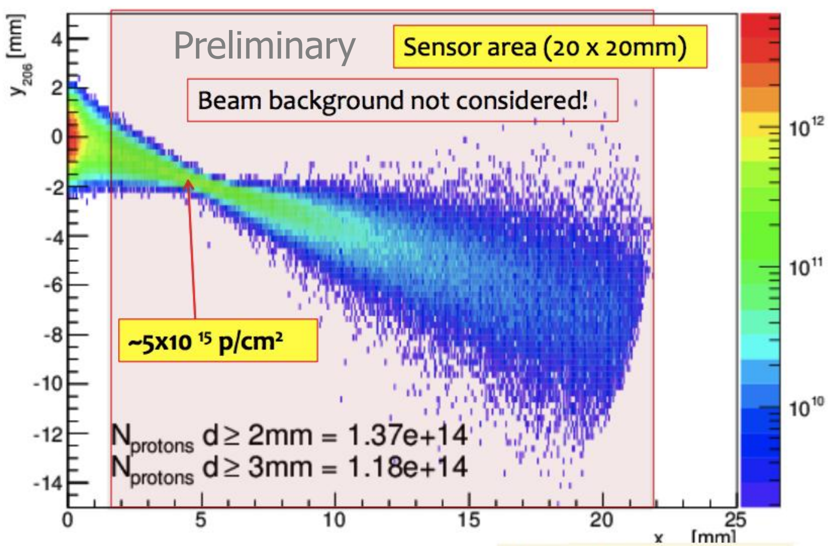
- Efficiency stable up to last pixel (Bug fixed compared to last RD-50 WS)
- For FBK even ~80 µm beyond: Efficient edge due to absence of guard ring (but implications on resolution/alignment if edge pixel is different)
- In both cases: AFP slim-edge requirements fulfilled (<180 µm dead area)

Radiation Hardness Requirements

- Highly non-uniform irradiation
  → high fluence gradient between neighbouring pixels
- Integrated fluence depends on run scenario
- Low-μ run scenario (approved AFP scenario for start)
  - Only dedicated runs → ~100 pb^{-1}
  - Fluence peak: 5×10^{12} p/cm^2 (~7 TeV p)
    → should be manageable
- High-μ run scenario (possible future scenario)
  - In the beam for large parts of run 2 → ~100 fb^{-1}
  - Fluence peak: 5×10^{15} p/cm^2 (~7 TeV p)
    → studied in the following
- To check:
  Can detector be operated to give
  high efficiency in all regions?
  - Unirradiated: Low V_{BD} → $V<V_{BD}$ needed
  - Irradiated region: High V needed ($V>V_{dep,irr}$, E field)

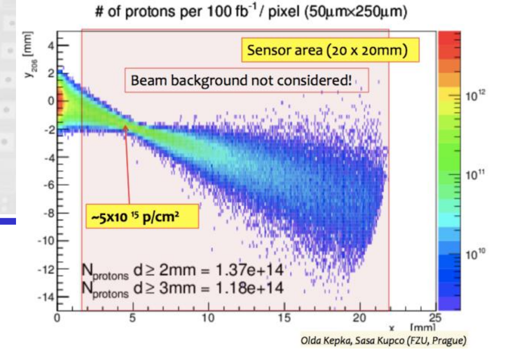


Estimated Fluence for high-μ run:
# of protons per 100 fb^{-1} / pixel (50μm×250μm)



Olda Kepka, Sasa Kupco (FZU, Prague)

Non-Uniform Irradiation



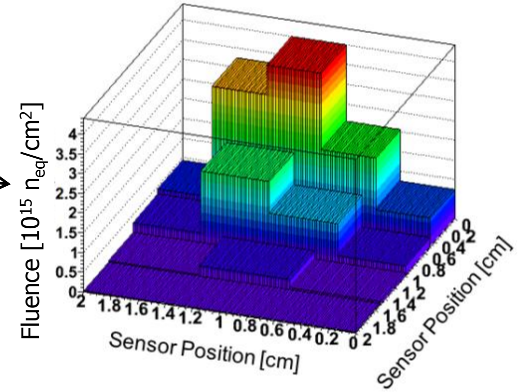
- No 7 TeV irradiation facility available yet…
  - Radiation damage of 7 TeV p not yet calculated. Similar to GeV p? Maybe should be studied within RD50? (important for all forward exp.)

  → Here: Proof-of-principle tests at usual irrad. facilities with lower p energy
- First test beam study in 2012 with focussed CERN-PS 23 GeV irradiation

  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)

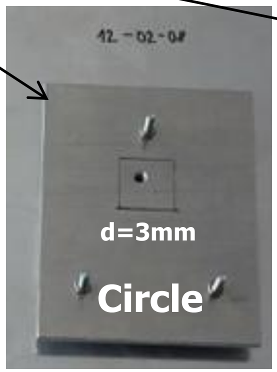
Fluence map of CERN-PS irradiation:

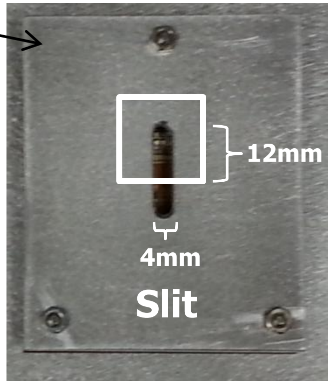


Thanks to Felix Bögelspacher (KIT) for irradiation and Petr Sicho (CERN) for help

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

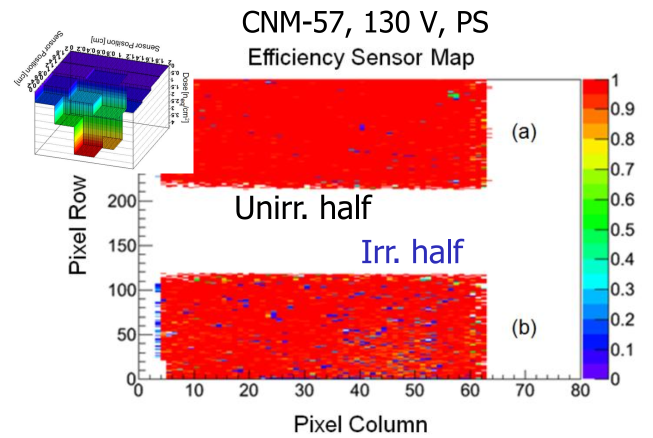
Al shields at Karlsruhe:





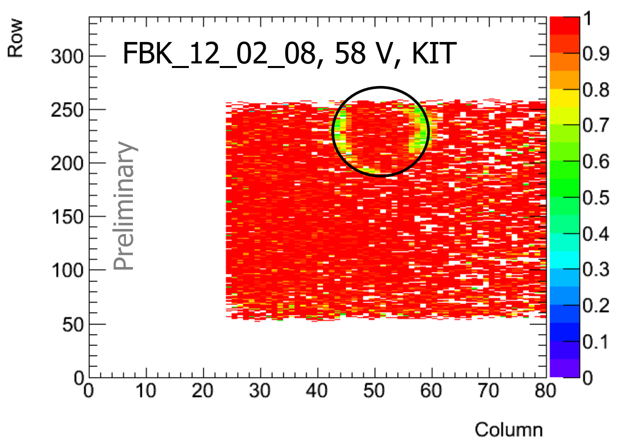
Efficiency of Irradiated Devices

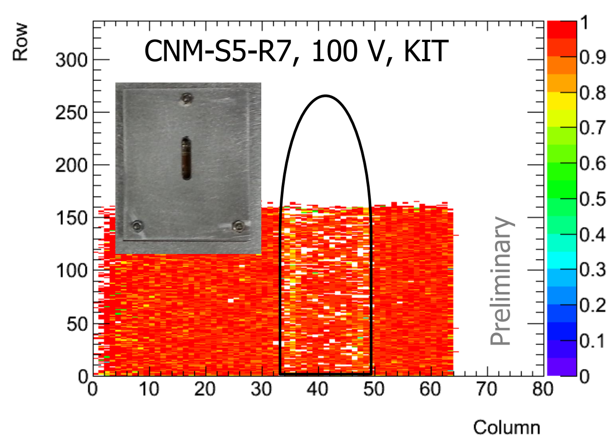
- Test beam: DESY (KIT irr. devices), CERN (PS irr. device), normal incidence, T < -20 °C
- Different runs at different bias voltages of irradiated sample (V limited by high I_{leak})
- Irradiated area (only centre for KIT) almost as efficient as unirradiated region
- Ring of lower efficiency at edge of hole at KIT
  - Not seen for focussed PS beam
  - Under investigation (see slides later)

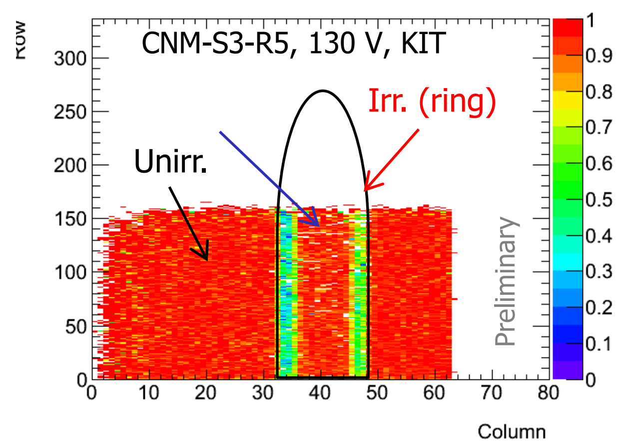


Efficiency Sensor Maps

Noisy and dead pixels masked



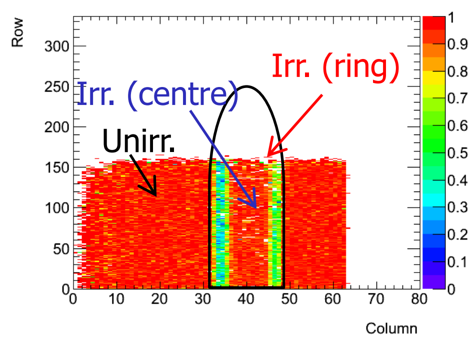




Measurement Summary and Efficiency Results (Absolute Values)

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	2	3
ToT at 20 ke	10	10	~11	~5	~8
SingleSmall Hits Rejected	No	No	No	Yes	Yes
Eff_{max}(unirr) [%]	99	99	98	95	94
Eff_{max}(irr,centre) [%]	-	98	97	94	93
Eff_{max}(irr,ring) [%]	-	-	70	90	58

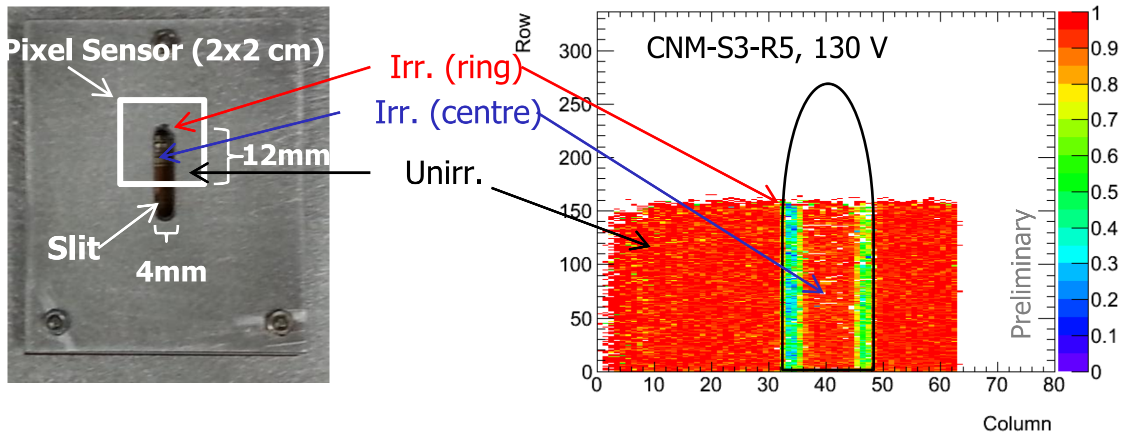
Device types, irradiation and measurement conditions vary!



- 3-4% lower efficiency of 2 CNM devices irrad. at KIT (both unirr. and irr. area) is **artifact**!
  - Chip register HitDiscCnfg =2 (0 for other meas.) → Single small hits (ToT<3) rejected (good for time-walk correction, but usually test beam analyses take all hits into account)
  - Especially large effect in combination with low ToT tuning (verified with source scans: 5-20% eff. loss possible)
- Despite partly unfavourable settings: ≥ 93% in irr. part (centre) achieved (≥ 97% for favourable settings)
- Irradiated part (centre) within 1% as efficient as unirrad. part
- Significantly lower eff. in ring of irr. part

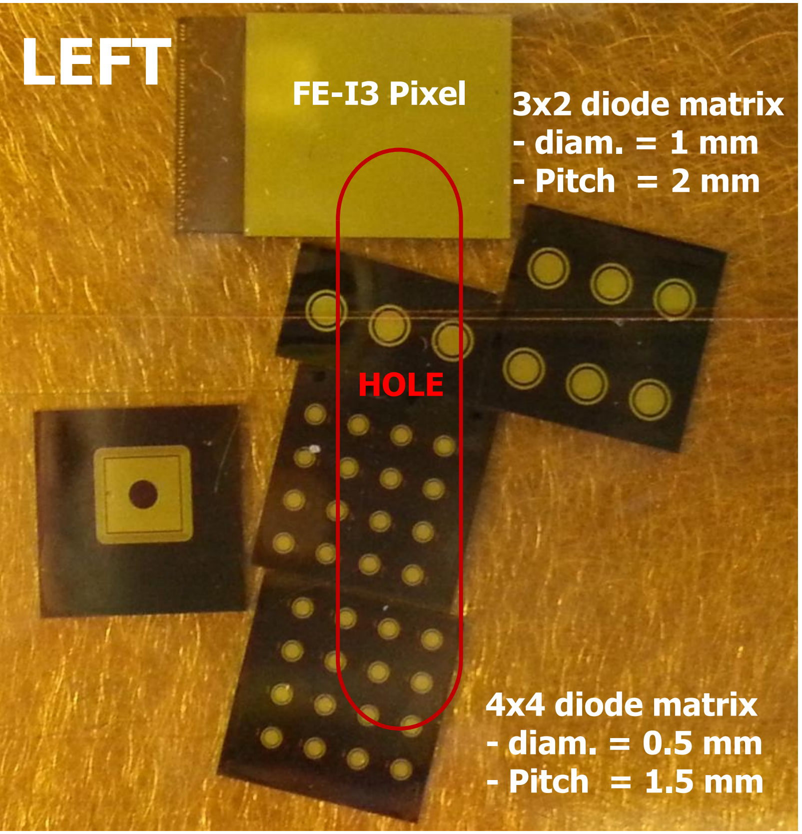
Investigation of Low-Efficiency Ring

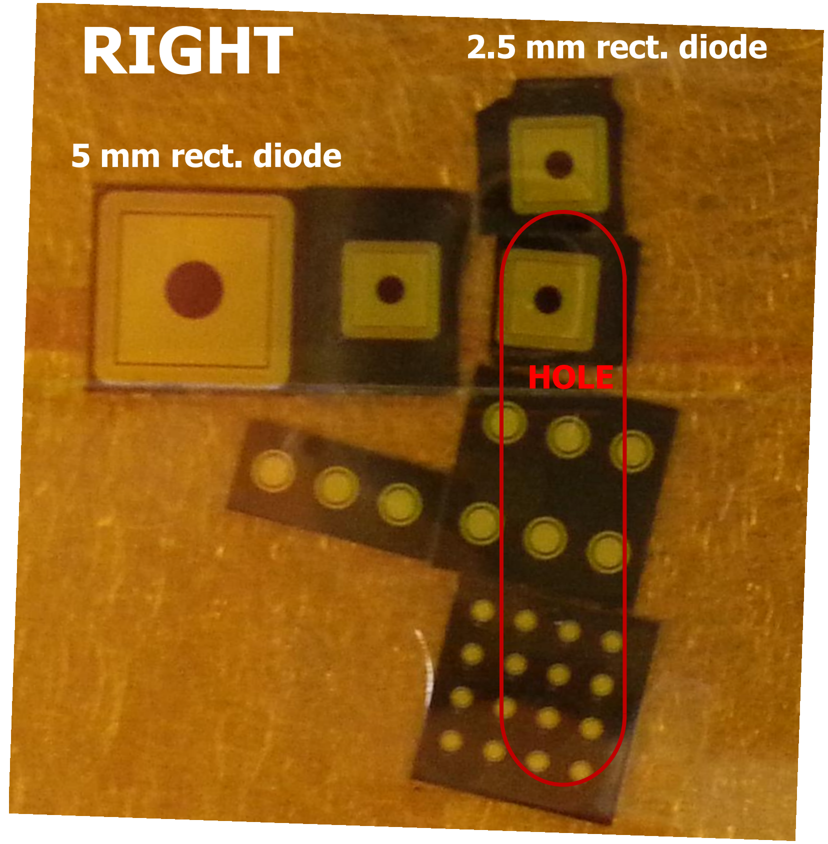
5 mm Al shields: **Pixel-Sensor Efficiency Map**



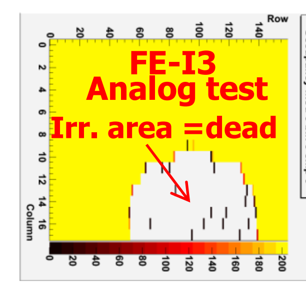
- Effect of irradiation method with Al shield (possibly higher effective fluence)?
  - Discussed at last RD50 workshop
  - Scattering of p at edge of Al shield → loose energy → much more damaging
- Or real effect of sharply non-uniformly irradiated devices?
  - Sensor effect?
    - Transition region 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



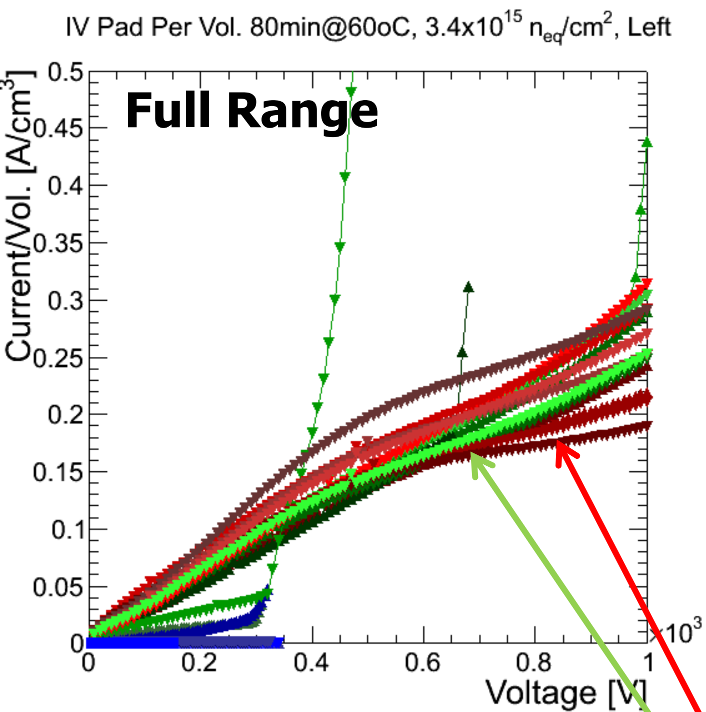


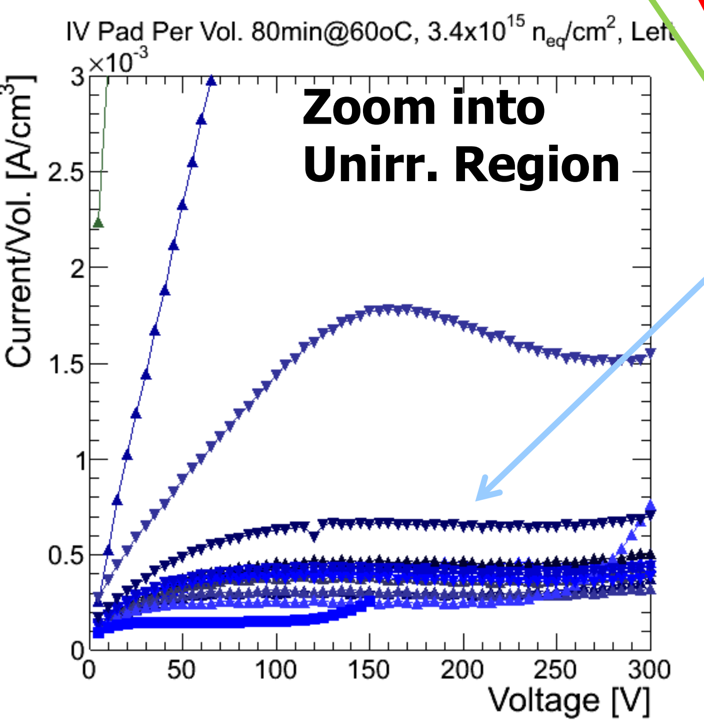
Thanks to CNM (Giulio, Marta, Virginia) for providing diodes, setup and help!

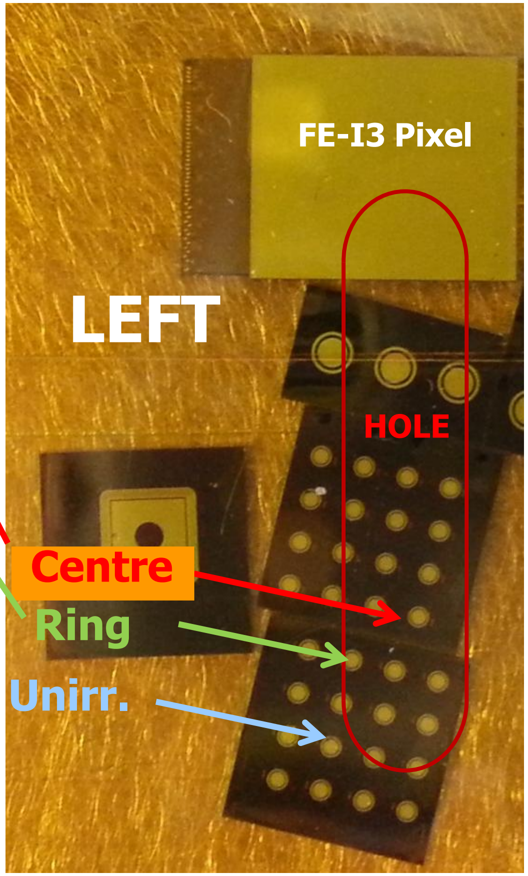


- Multi-device approach (diodes: n-type STFZ, d=300 μm)
- Irradiation under same slit-like Al masks ("left" and "right") as pixel irradiation at KIT
  - Intended: 5-10 x 10^{13} n_{eq}/cm^2 (FE-I3 only specified up to <10^{15} n_{eq}/cm^2 , reliable plateau for CV/IV)
  - Obtained: 3.4 x 10^{15} n_{eq}/cm^2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

IV

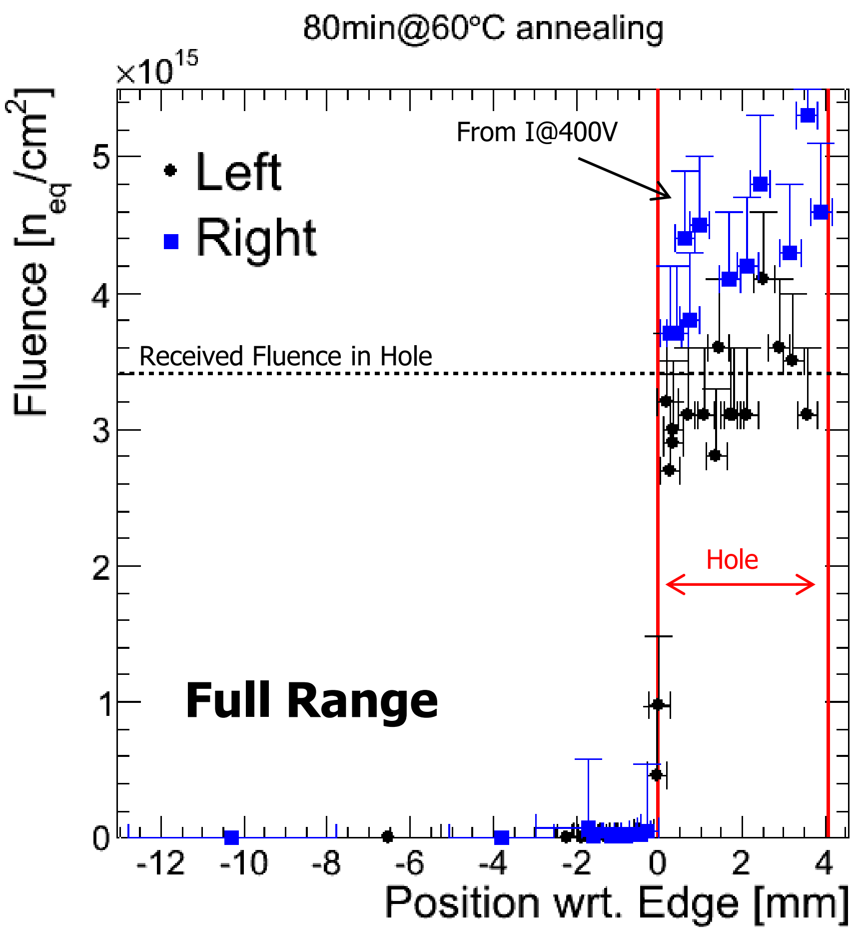


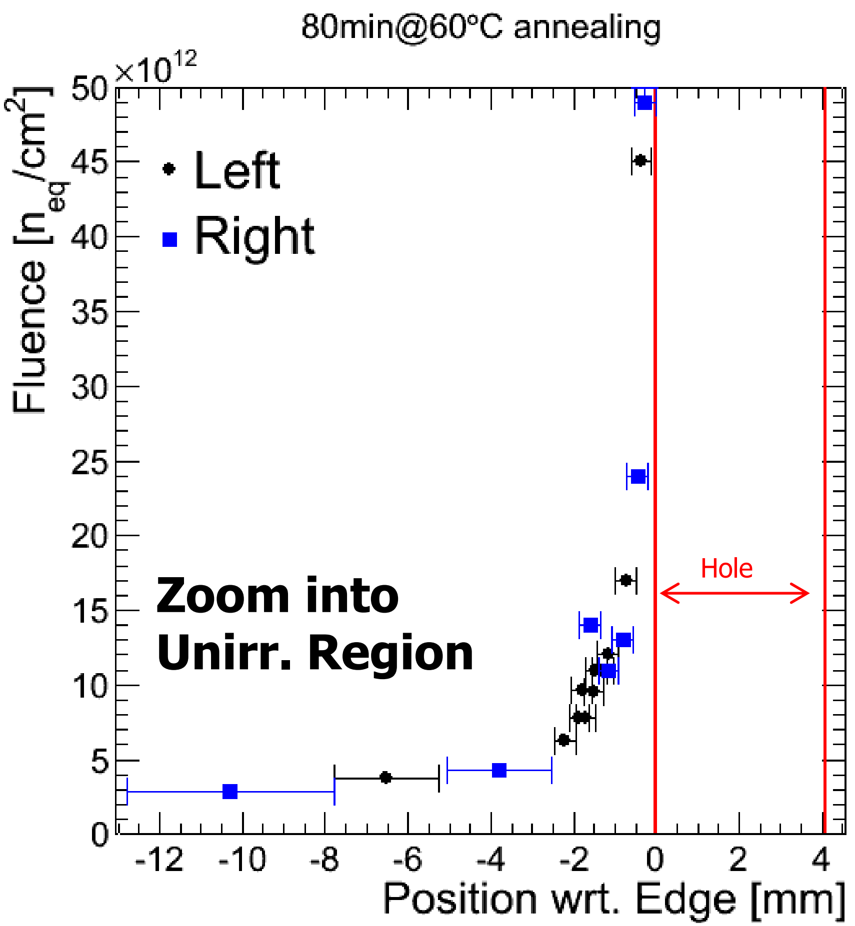




- Measrued at 20 °C
- 3x2-matrix diodes excluded (GR not contactable)
- No real plateau for irradiated diodes, but kink at 400-600 V → in the following I/V(400 V) for fluence calculation
- Plateau for most unirr. ones
- No significant difference between centre and edge of irr. region
- If only fraction of area has been irradiated, leakage current scales approx. with same fraction

Fluence vs. Position wrt. Edge

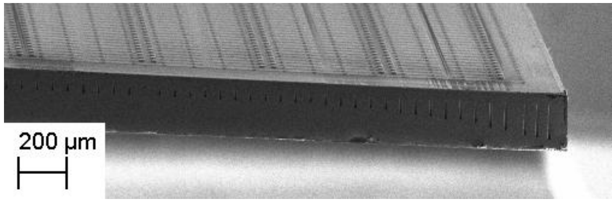




- x error bars = extension of diode; upper y error bar to indicate lack of plateau; α = 4x10^{17} A/cm
- No significant difference between centre and edge of irr. region; consistent with received fluence
- Substantial fluence (~10^{12} – 10^{13} cm^{-2}) also under Al mask; higher the closer to the hole

Conclusions

- Slim-edge and non-uniformly irradiated 3D AFP sensors studied
  - Inactive pixel-sensor region highly reduced (to 100-180 µm) without impact on efficiency
    - Without guard ring even efficient beyond last pixel
  - High efficiency achievable in centre of irradiated part at high-µ fluence (100 fb^{-1})
    - ≥97% for all devices with optimal tuning and parameter setting
  - Low efficiency at edge of irradiated hole
    - Position-resolved dosimetry shows no hint of higher fluence at edge (at least not from I_{leak})
  - For approved low-µ run (100 pb^{-1}): 3 orders of magnitude less → relaxed conditions

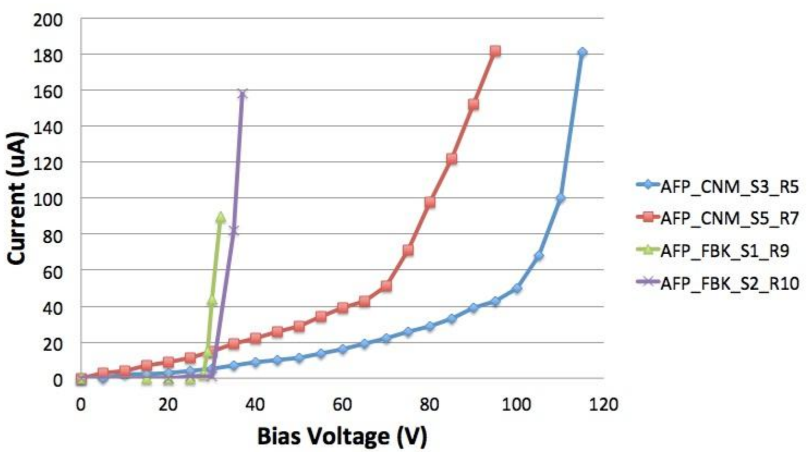


- Outlook:
  - Charge-collection measurements on dosimetry-diodes
  - New non-uniform irrad. at KIT with lower fluence and bare sensor/chip + planar FE-I3
  - Simulation of non-uniformly irradiated sensor
  - CNM AFP production run with 12 wafers expected to end soon

BACKUP

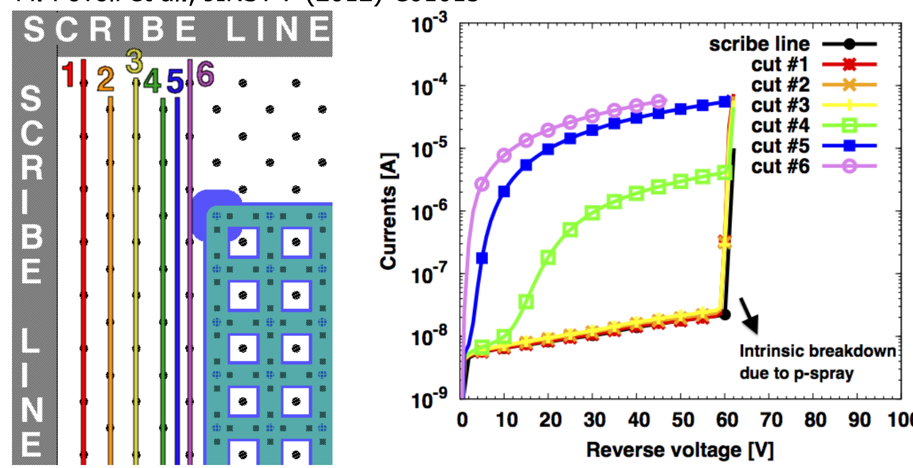
Current and Noise

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

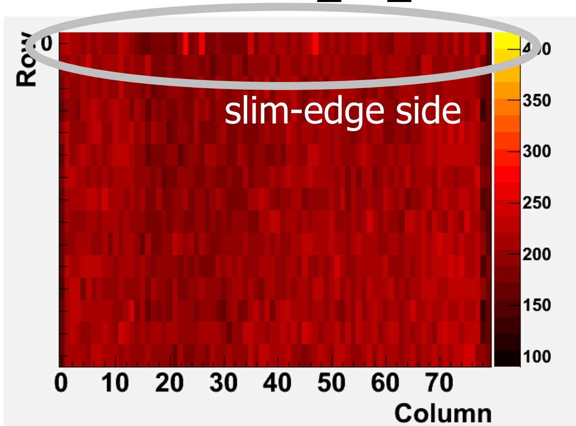


Previous study on FBK sensors:
IV unaffected up to 100 µm cut line

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



Noise of CNM_S3_R5

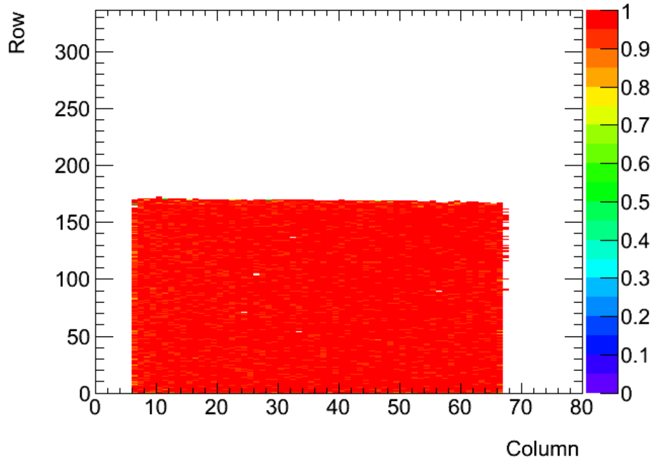


- No anomalous current and noise after edge-slimming to 100-180 µm

Efficiency of Slim-Edge Sensors in Test Beam

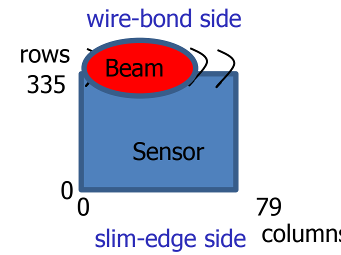
- DESY II Test beam: 4 or 5 GeV electrons
- ACONITE telescope (EUDET type)
- Normal incidence
- 1 reference IBL sensor,
  4 slimmed-edge AFP sensors
- Average efficiency after slimming (97-99%) comparable to IBL reference
  → what about edges?

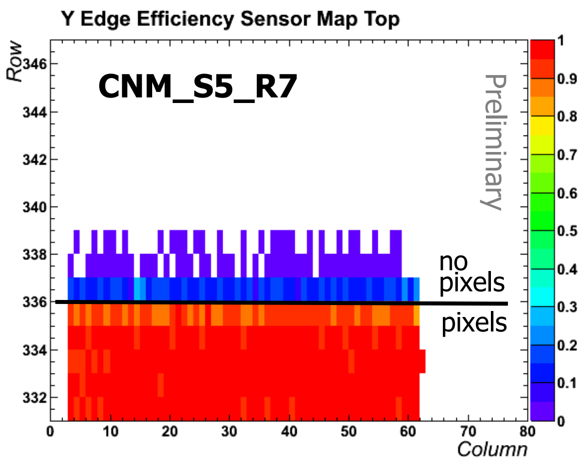
Thanks to all test beam participants, esp. I. Rubinskiy (DESY), D. Pohl (Bonn), O. Korchak (Prague), Sh. Hsu (Washington)

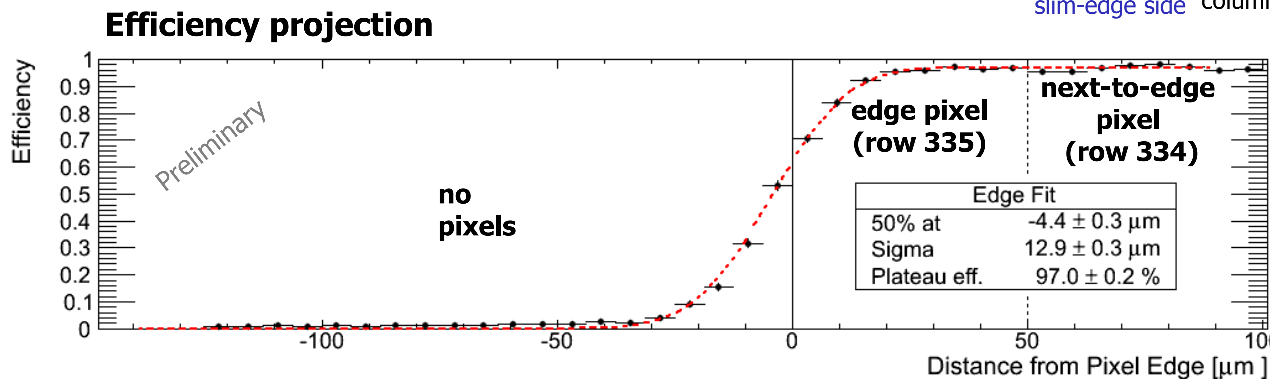


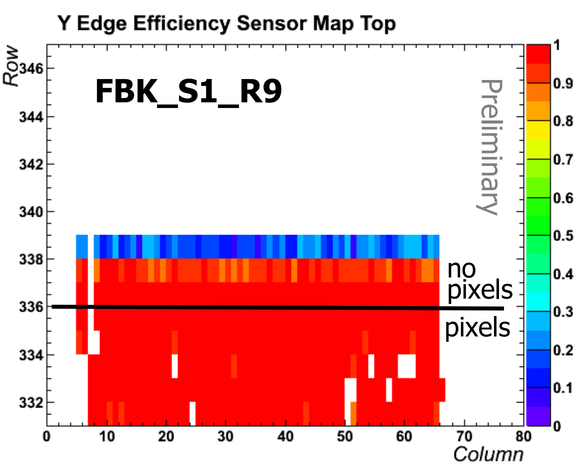
	DUTs				
Sample	CNM-55 (Refer.)	CNM_S3_R5	FBK_S5_R10	CNM_S5_R7	FBK_S1_R9
Edge	Regular	Slimmed	Slimmed	Slimmed	Slimmed
Bias [V]	30	30	20	30	20
Threshold [ke]	2.8	1.9	2.0	2.0	2.0
Efficiency	98-99%	98.3%	98.6%	96.9%	98.0%

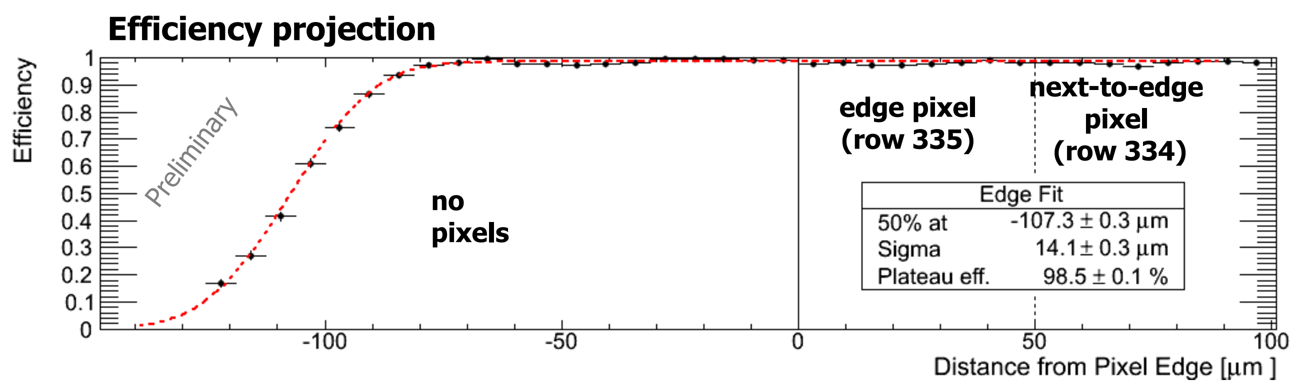
Regular Unslimmed Edge (Top Side)





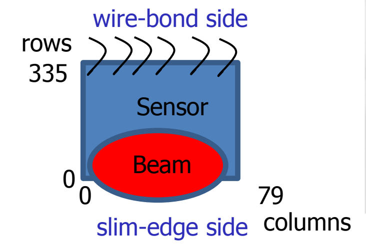




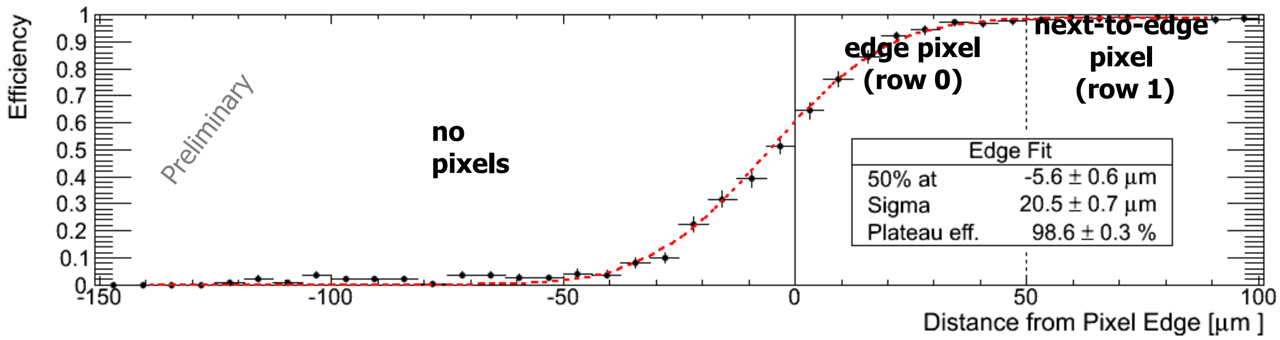


- Efficiency stable up to last pixel
  - Smearing due to beam telescope resolution
  - For FBK even ~100 μm beyond (active edge due to absence of guard ring); a bit noisy/hot pixels → masked

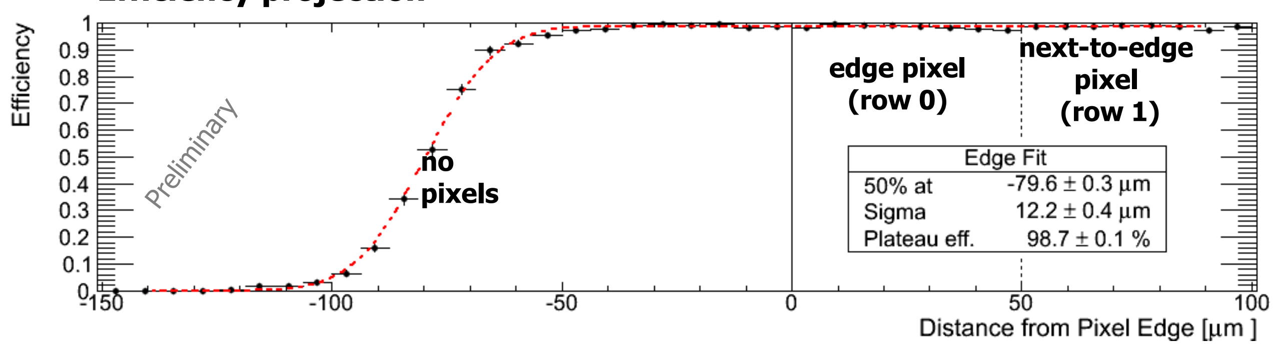
Slim Edge (Bottom Side) Other devices



Efficiency projection **CNM_S3_R5**



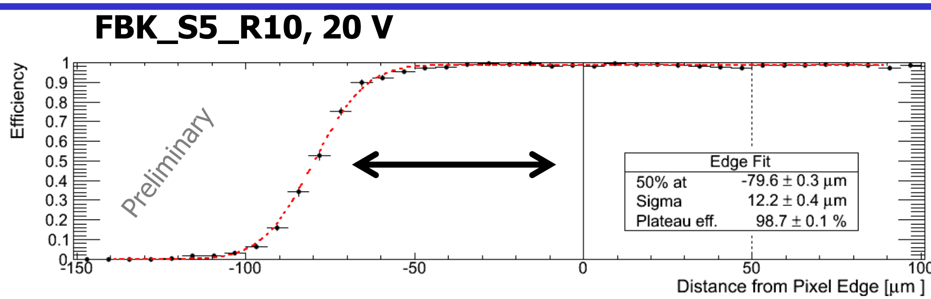
Efficiency projection **FBK_S5_R10**

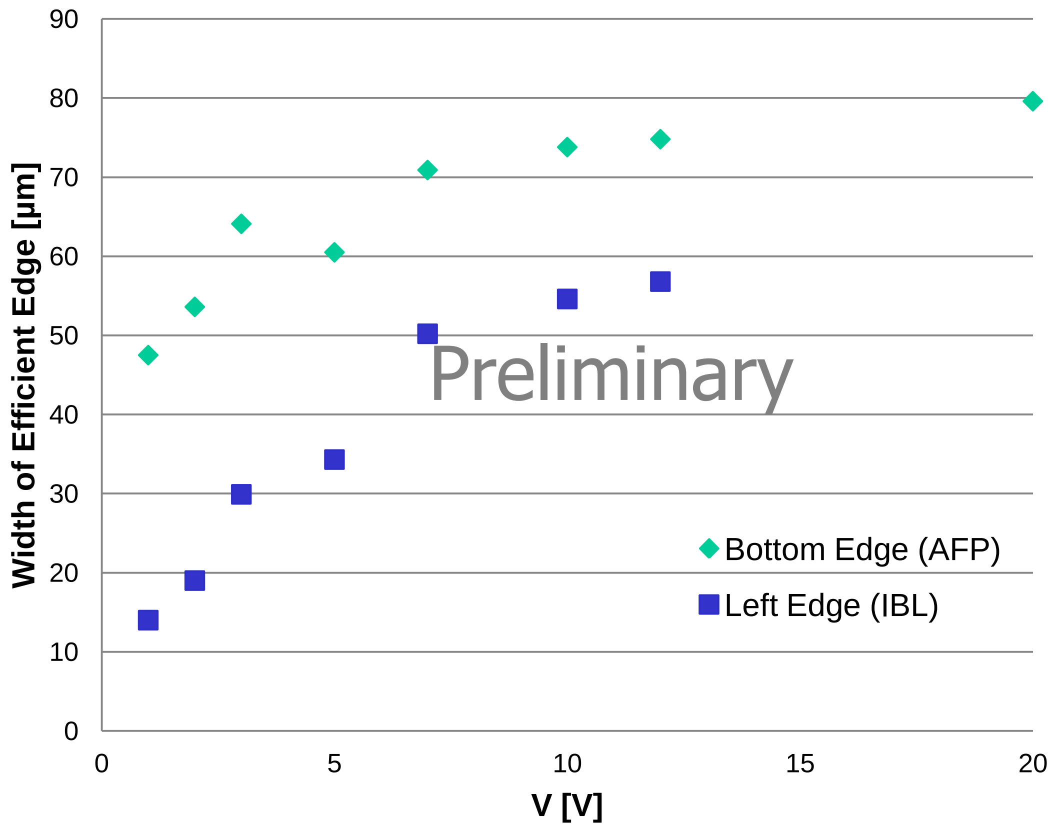


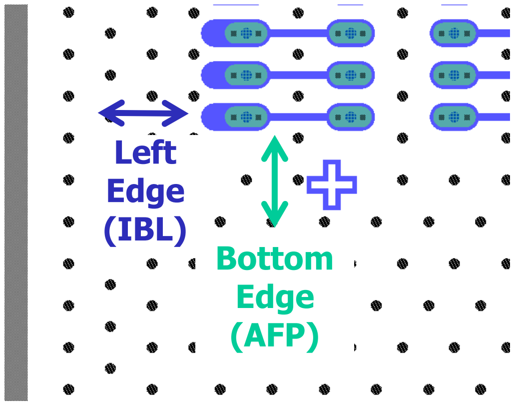
- Efficiency stable up to last pixel
  - For FBK even ~85 µm beyond (active edge due to absence of guard ring); a bit noisy/hot pixels → masked

→ same behaviour as for non-slimmed edge!

Development of Efficient Edge in FBK Sensor with Voltage







- 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

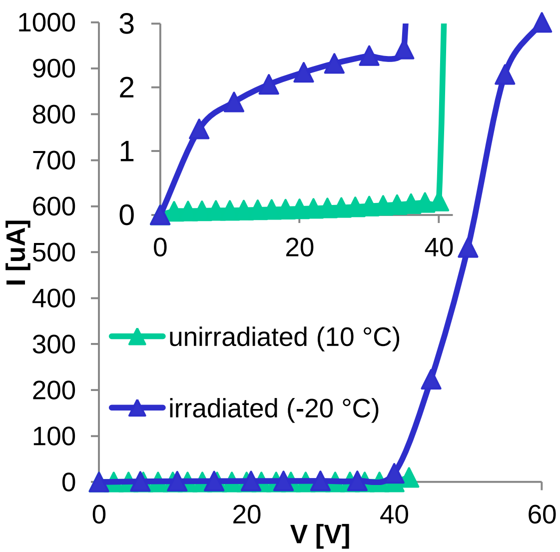
- V_{BD} ~ 40 V before and after irrad.
- Able to bias up to 58 V

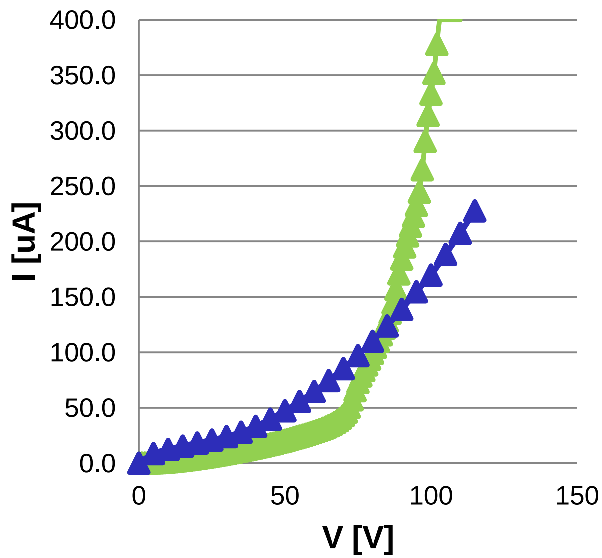
CNM_S5_R7

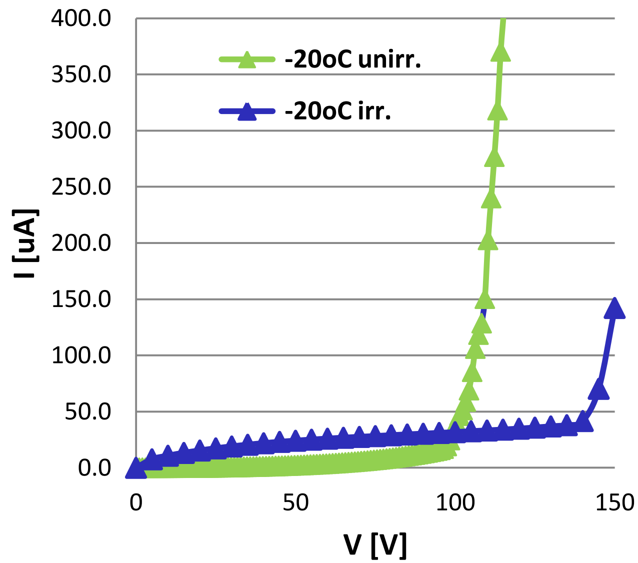
- Soft BD
- Lower I after irr. at high V

CNM_S3_R5

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

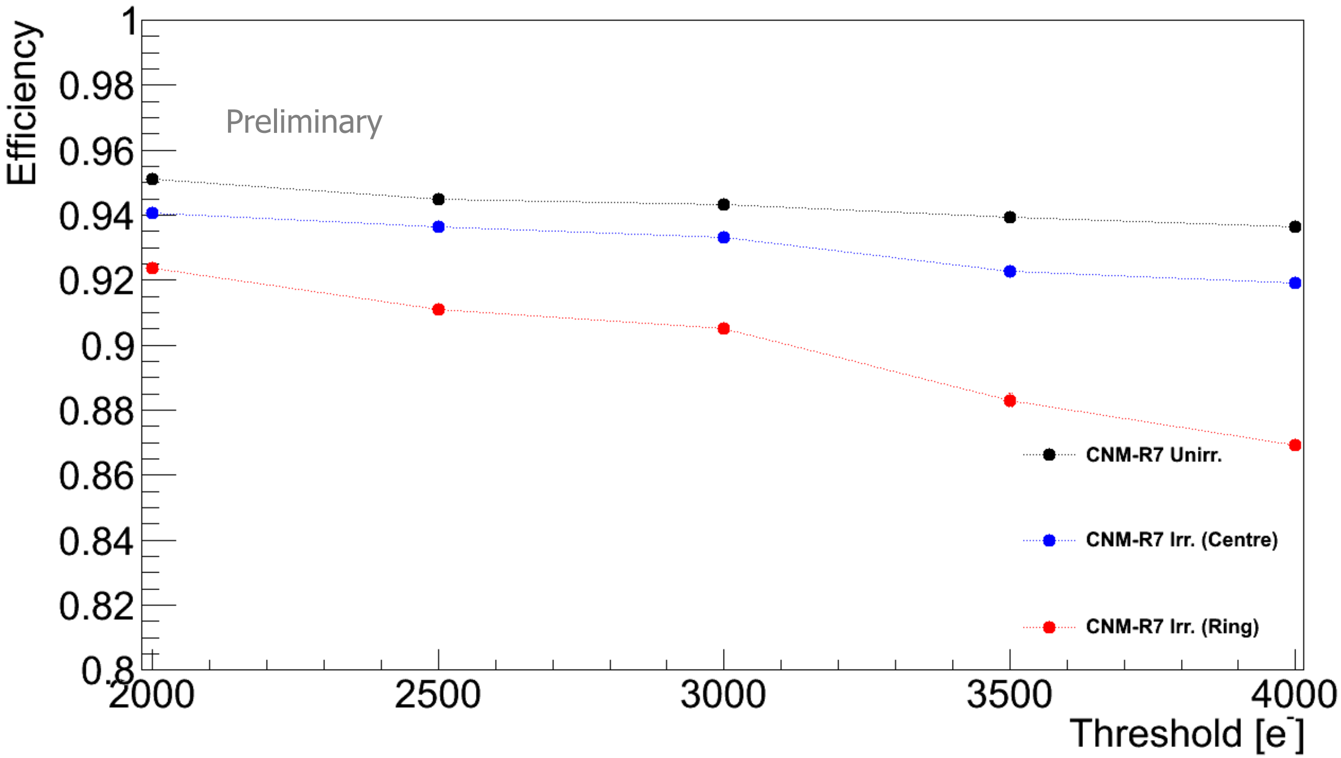






Efficiency vs. Threshold

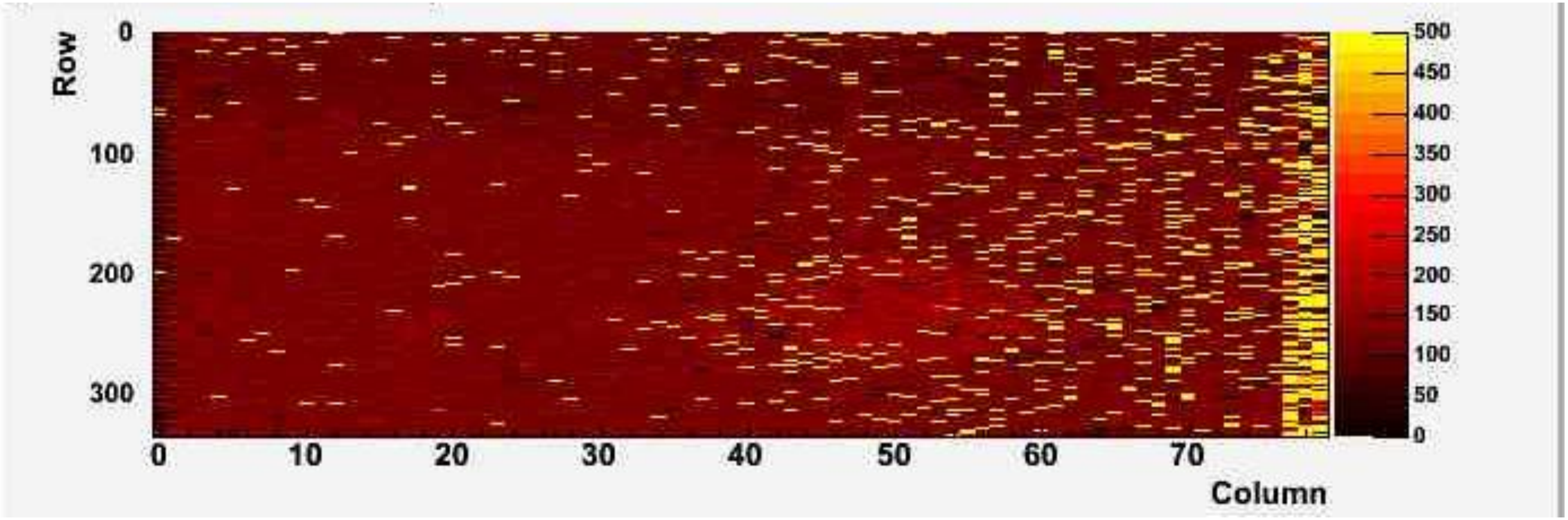
- Improvement of 1% per 1000e reduction of threshold for unirr. and irr. (centre) area
- Even more for higher irradiated ring



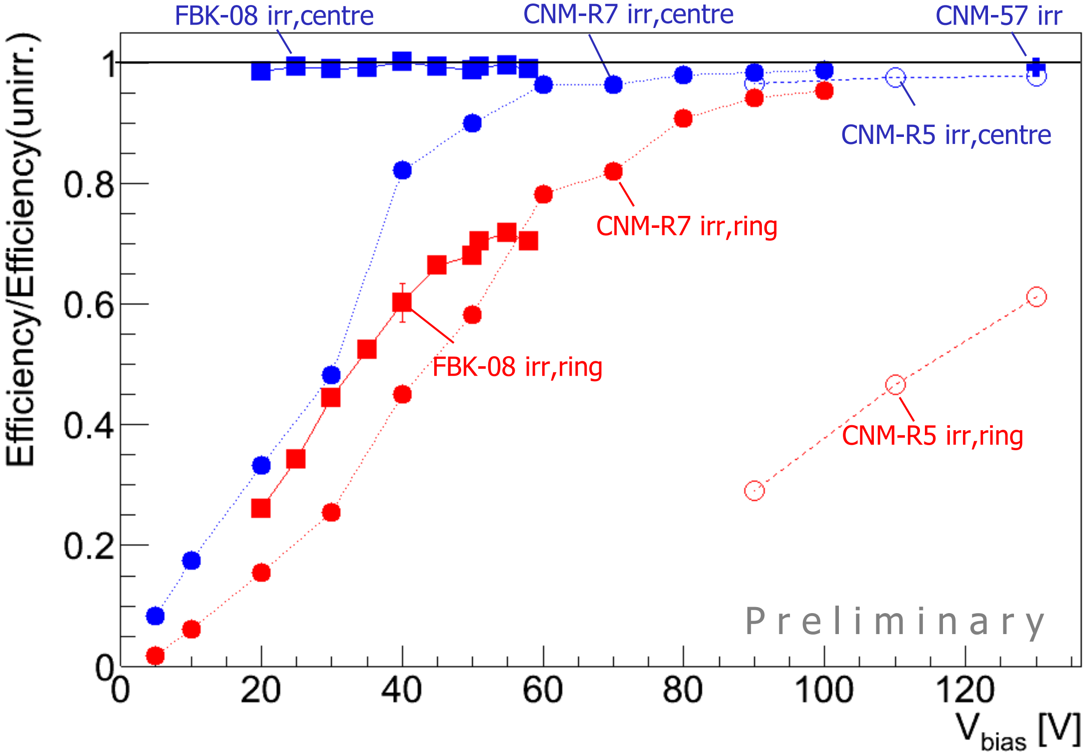
Noise of irradiated sensor

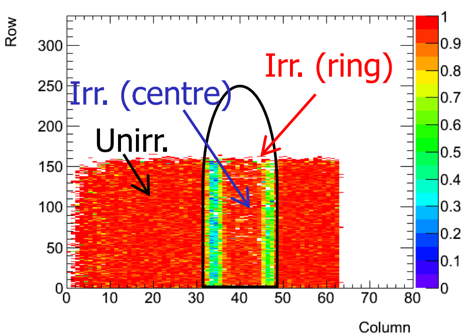
- Noise outside irradiated region ~ 130 e
- Noise inside irradiated region slightly higher (by about 10-20e)

FBK-12-02-08, 50 V



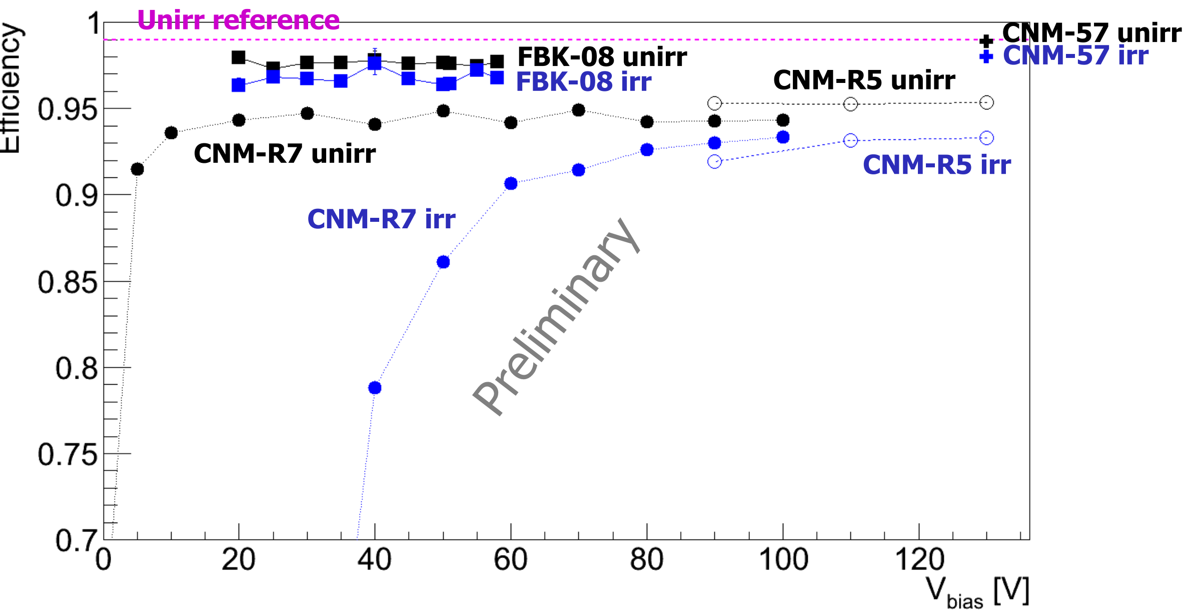
Efficiency/Efficiency(unirr.)





- 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%)

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
- For all devices: eff. ≥ 93%
- Highest eff. for focussed-beam irradiation with CNM-57: 98% in irr. area
- Possibly improvable by tilting sensor (15° under study)