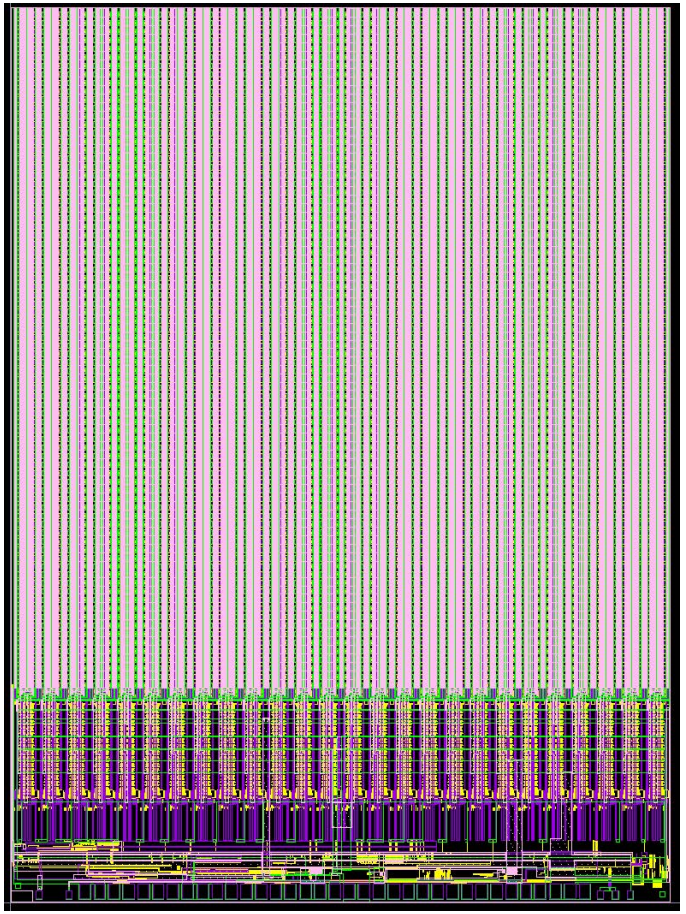
High rate capability and radiation tolerance of the **PROC600** readout chip for the CMS pixel detector



P. Berger, M.Meinhard, A. Starodumov

ETH Zurich, Switzerland

on behalf of the CMS Pixel Collaboration

Pixel 2016 Workshop

5-9 Sept 2014, Sestri Levante (Italy)

Outline

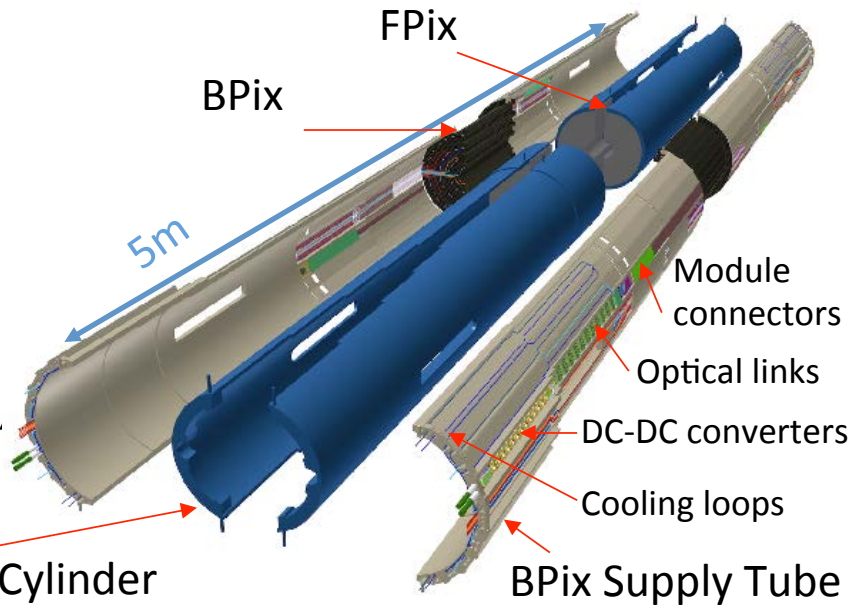
- Phase I upgrade CMS pixel detector
  - conditions: rates, radiation levels
- PROC600 design
  - Dynamic Cluster Column Drain mechanism
- High rate performance
  - Xrays: test in the lab
  - High rate proton beam at PSI proton irradiation facility
- Radiation hardness
  - irradiation at KIT
  - performance at 60-480MRad
- Summary

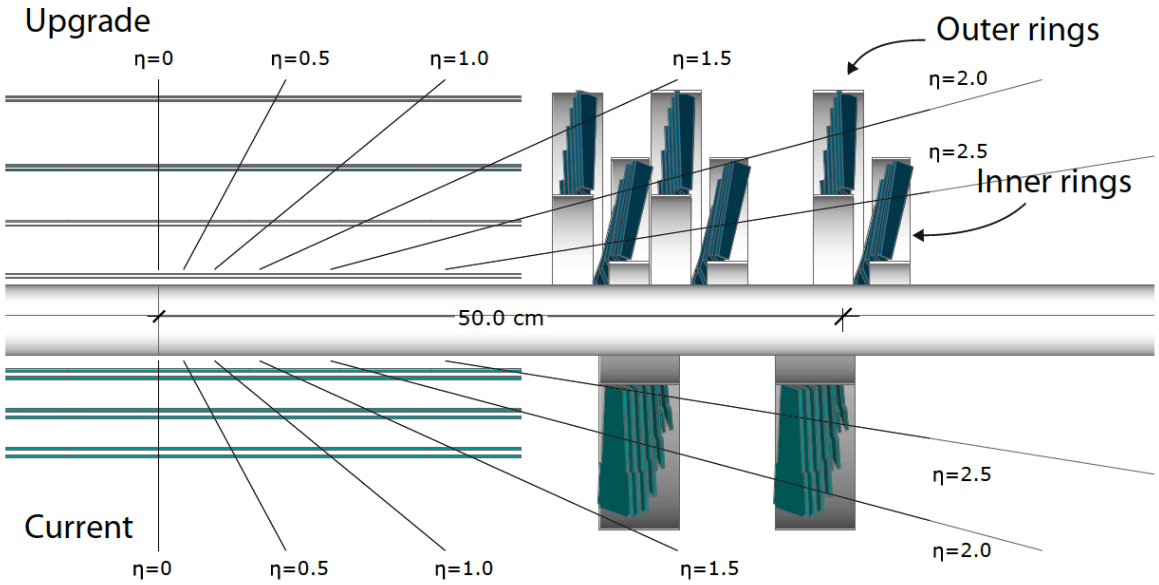
Phase I Upgrade CMS Pixel Detector

CMS Phase 1 Upgrade Pixel Detector

New in CMS pixel detector

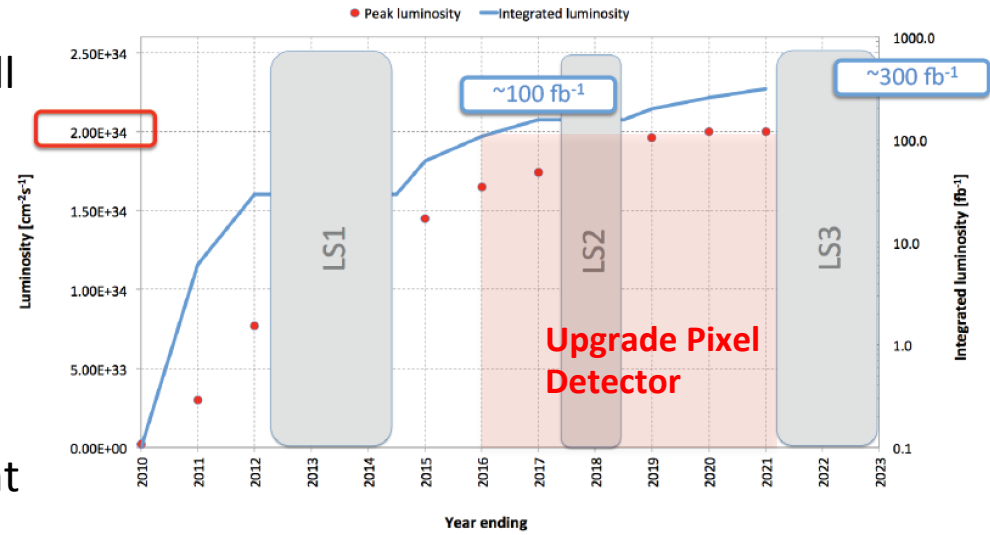
- mechanics: 4 Barrel Layers (BPix), 6 Forward Discs (FPix)
- cooling system: two-phase CO2
- power system: DC-DC converters
- DAQ system: based on microTCA
- readout chips: psi46digv2.1-respin (L2-4 BPix, FPix) and **PROC600v2 (L1)**

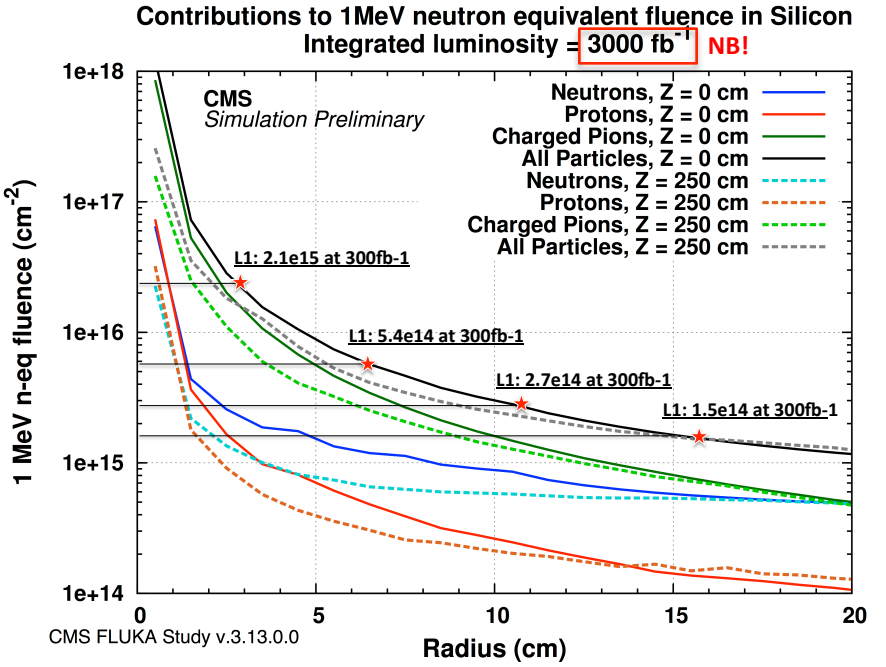




Operating conditions of Pixel Detector

- The detector should be fully operational till LS3 (2022) at L=2×10^{34} cm^{-2}sec^{-1}
- Integrated luminosity: 500fb^{-1} (TDR-2012), 300fb^{-1} (LHC plans-2014)
- Fluence (L1): 2.1x10^{15} 1MeV neq/cm^2
- Dose (L1): 102MRad
- Pixel hit rate:
  - based on cluster multiplicity in current detector: 420 MHz/cm2 with R$^{-1.53}$
  - based on PYTHIA simulations: 580MHz/cm^2 with R$^{-1.9}$





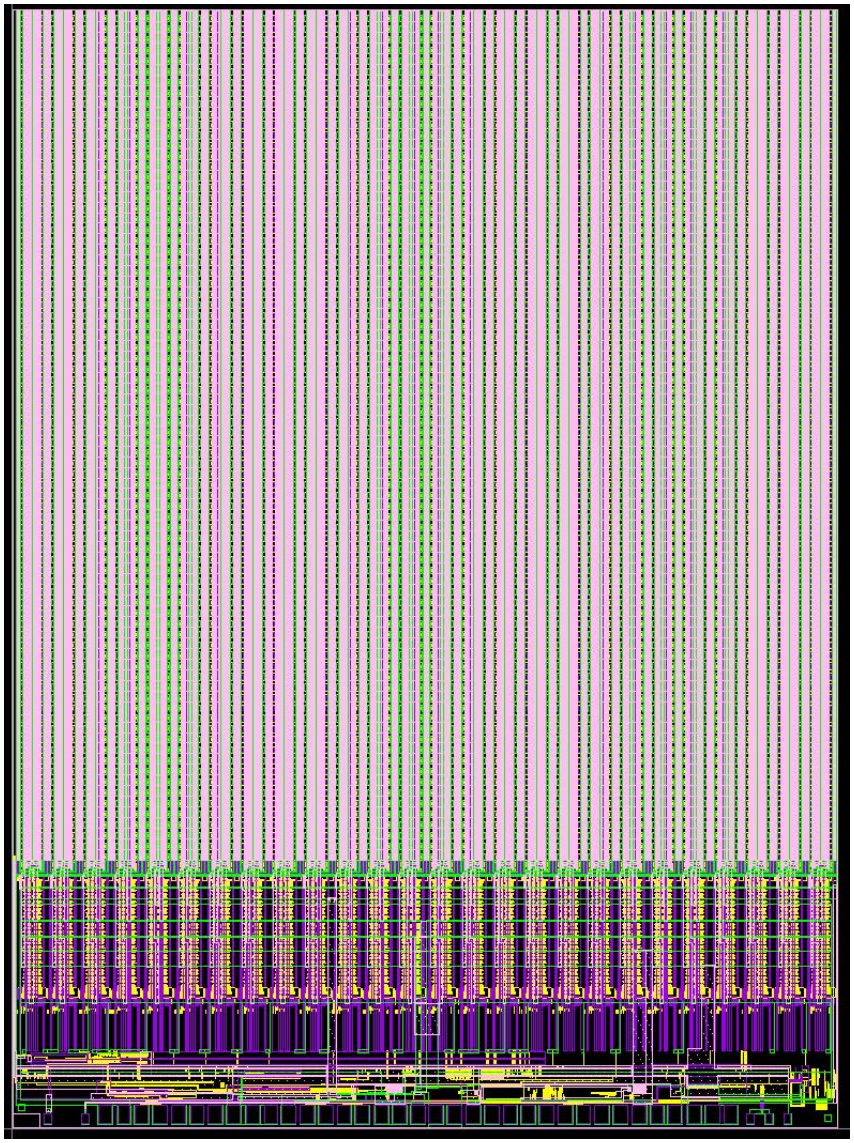
Layer	R, cm	300fb-1 Fluence, 10E15 1MeVneq/cm2	300fb-1 Dose, Mrad	500fb-1 Fluence, 10E15 1MeVneq/cm2	500fb-1 Dose, Mrad	Rate, MHz/ cm2
1	3.0	2.1	102	3.5	170	420-580
2	6.8	0.54	29	0.9	48	120
3	10.9	0.27	14	0.45	24	58
4	16.0	0.15	8	0.25	13	32

PROC600 design

PROC600 parameters

Design parameters

- chip size: 7860µ x 10500µ
- 339 transistor/pixel
- pixel arrangement: 52 x 80
- DCCD transfer in DC at 40MHz
- Data Buffer Cells: 4 x 56
- Timestamp Buffer Cells: 40
- ROC Read-out Buffer Cells: 64
- total # of transistors: 2.2M
- analog pulse height: 8 bit ADC
- pixel hit rate : 600MHz/cm^2
- expected rad. hardness: ~500MRad
- power consumption: 200mW/cm^2

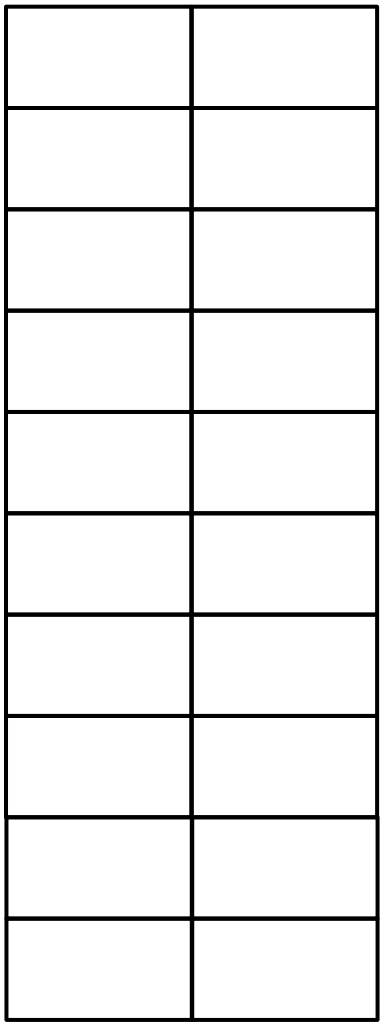


PROC600 features

- Main idea: readout cluster of 4 pixels instead of single pixels
  - Dynamic Cluster Column Drain mechanism (DCCD) introduced
  - major circuit redesign
- DCCD vs individual pixel readout
  - mean size of 2x2 cluster in double column is 1.95 pixels
  - mean number of clusters per event per double column is 1.2 at 600 MHz/cm^2 hence 2.34 pixels per column drain (CD)
  - Single pixel (psi46dig chip): needs ~2n+3 clocks per CD (n=#pixels): 7.7 clocks per CD
  - DCCD (PROC600): needs m+2 clocks per CD (m=#clusters): 3.2 clocks per CD
  - gain of factor 2.4 in speed
  - new logic design of up to 7 pending CDs gives overall factor of 3
- Data Buffer:
  - trigger verified DB check-out for up to 4 pending read outs
  - no reset after read out

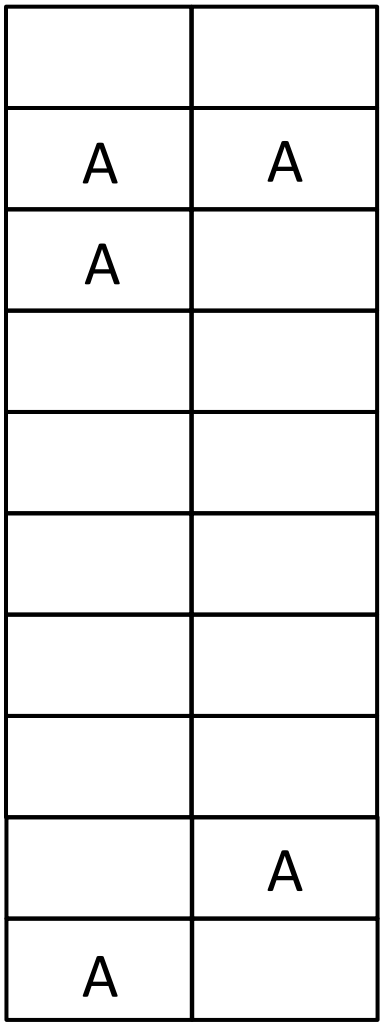
Dynamic Cluster Column Drain mechanism

- Empty Double Column



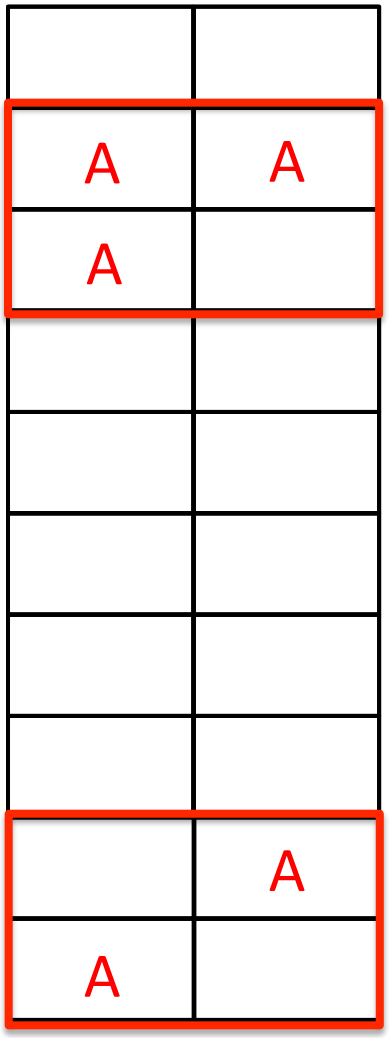
Dynamic Cluster Column Drain mechanism

- First event with time stamp „A“ and 2 clusters



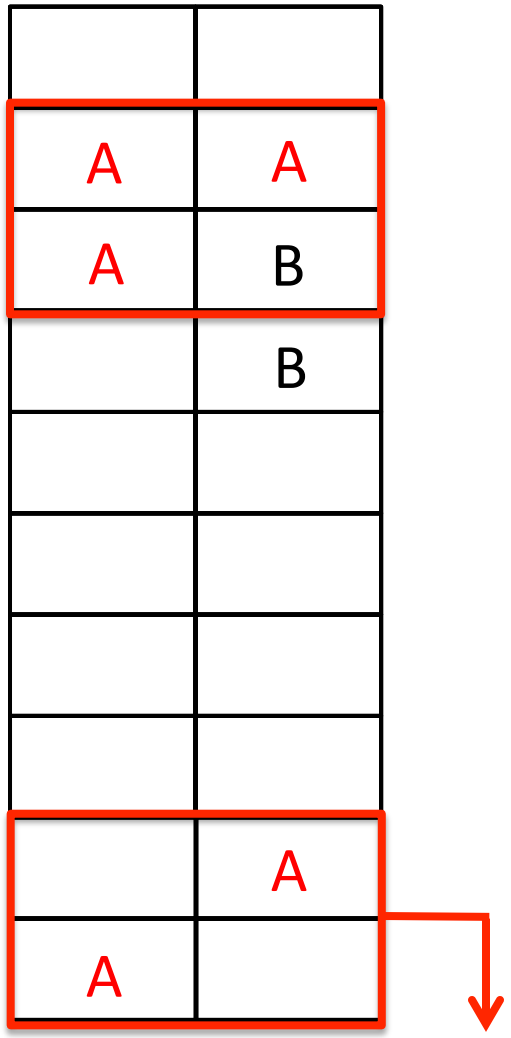
Dynamic Cluster Column Drain mechanism

- First event with time stamp „A“ and 2 clusters
- Dynamic search for “A” clusters. Dynamic means not at fixed address boundaries



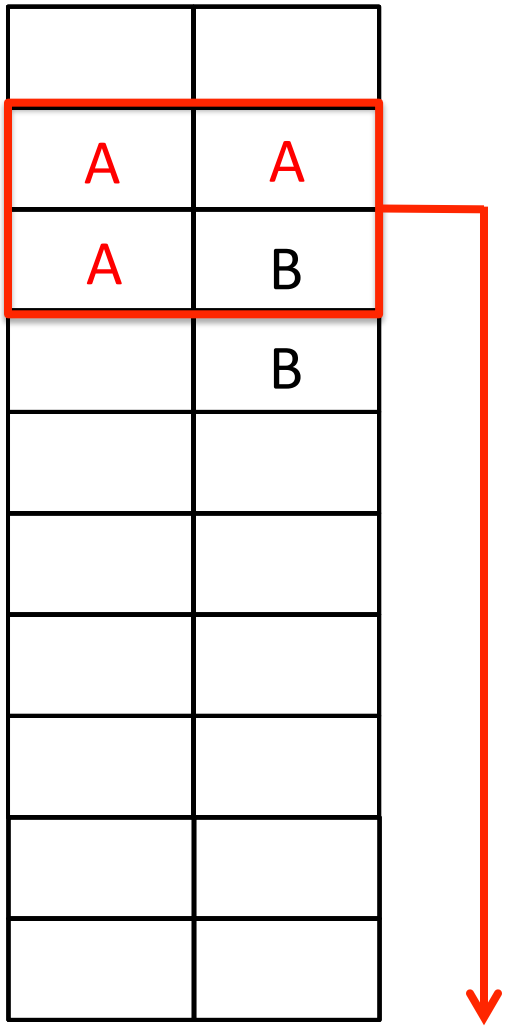
Dynamic Cluster Column Drain mechanism

- First event with time stamp „A“ and 2 clusters
- Dynamic search for “A” clusters. Dynamic
- means not at fixed address boundaries
- Transfer of first “A” cluster. At the same time new event with time stamp “B”



Dynamic Cluster Column Drain mechanism

- First event with time stamp „A“ and 2 clusters
- Dynamic search for “A” clusters. Dynamic
- means not at fixed address boundaries
- Transfer of first “A” cluster. At the same time new event with time stamp “B”
- Transfer of 2nd “A” cluster. “B”-hits are preserved



Dynamic Cluster Column Drain mechanism

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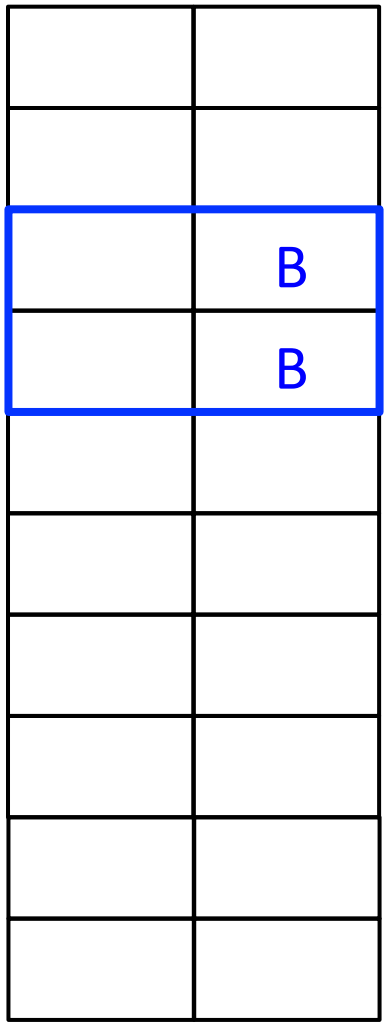
- Transfer of first “A” cluster. At the same time new event with time stamp “B”
- Transfer of 2nd “A” cluster. “B”-hits are preserved
- Dynamic search for “B” cluster



Dynamic Cluster Column Drain mechanism

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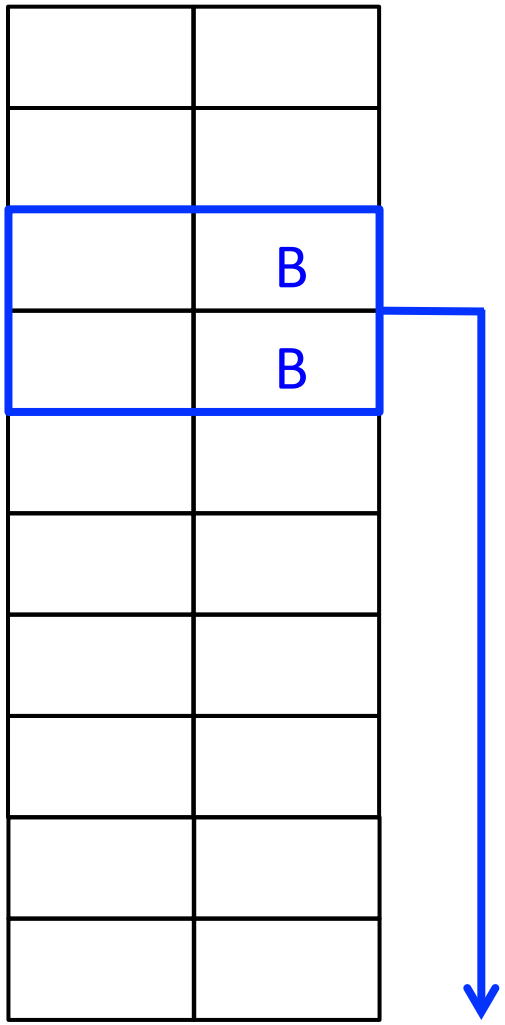
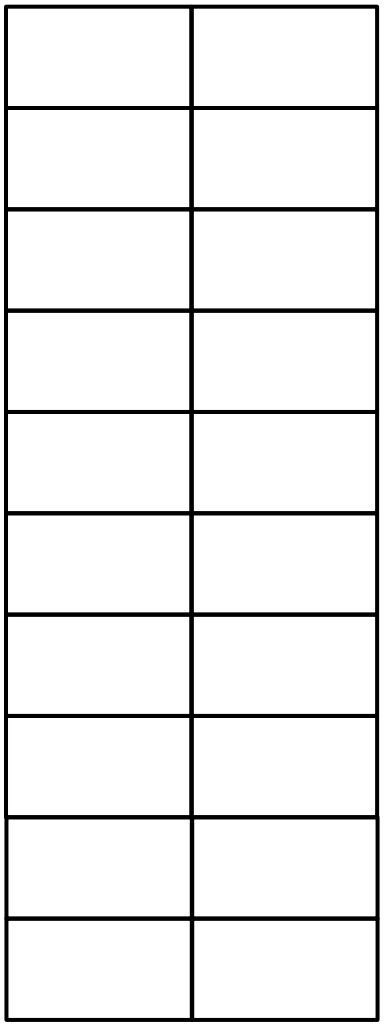
- Transfer of 2nd “A” cluster. “B”-hits are preserved.
- Dynamic search for “B” clusters
- Transfer of “B” cluster



Dynamic Cluster Column Drain mechanism

- First event with time stamp „A“ and 2 clusters
- Dynamic search for “A” clusters. Dynamic
- means not at fixed address boundaries
- Transfer of first “A” cluster. At the same time new event with time stamp “B”
- Transfer of 2nd “A” cluster. “B”-hits are preserved.
- Dynamic search for “B” clusters
- Transfer of “B” cluster
- Cluster ID „A“ or „B“ a 3-bit word that stored in each pixel of cluster



PROC600 features (cont.)

- Main idea: readout cluster of 4 pixels instead of single pixels
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  - major circuit redesign
- DCCD vs individual pixel readout
  - mean size of 2x2 cluster in double column is 1.95 pixels
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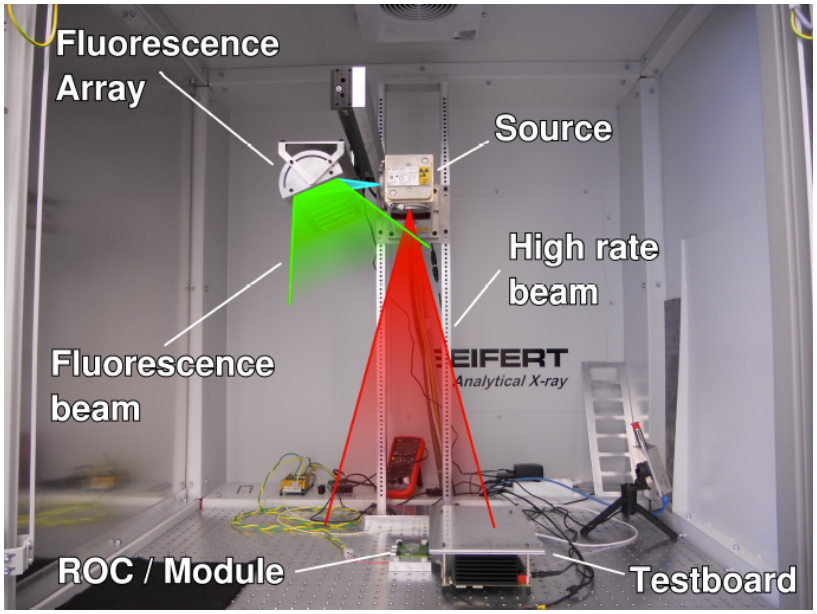
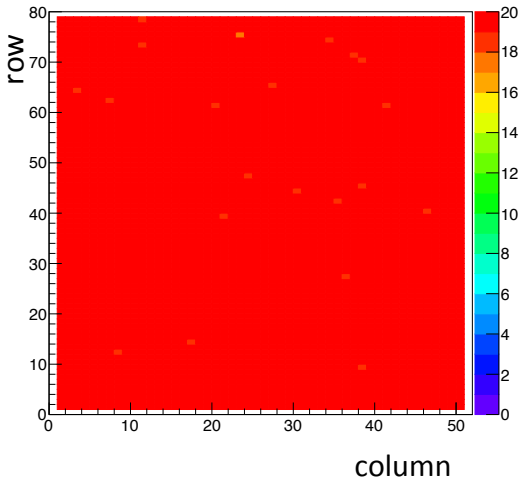
High rate tests

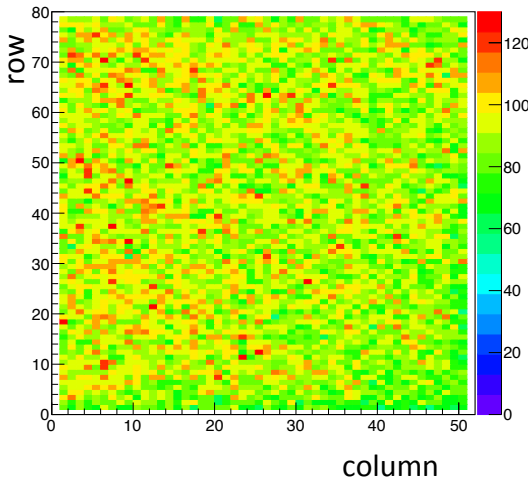
High rate efficiency test with X-rays



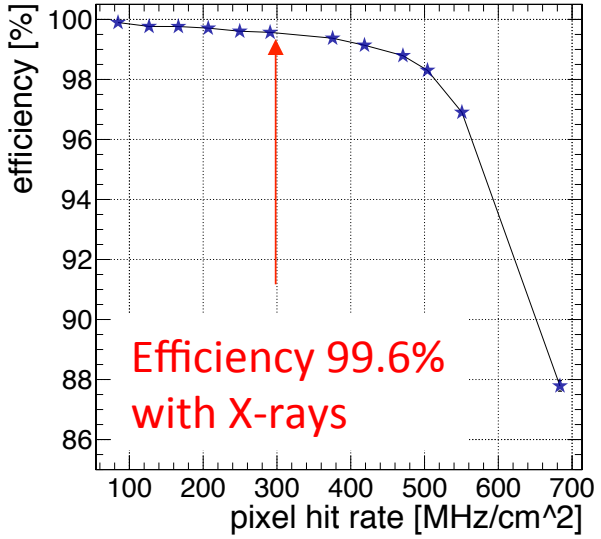
Internally generated calibrate signals



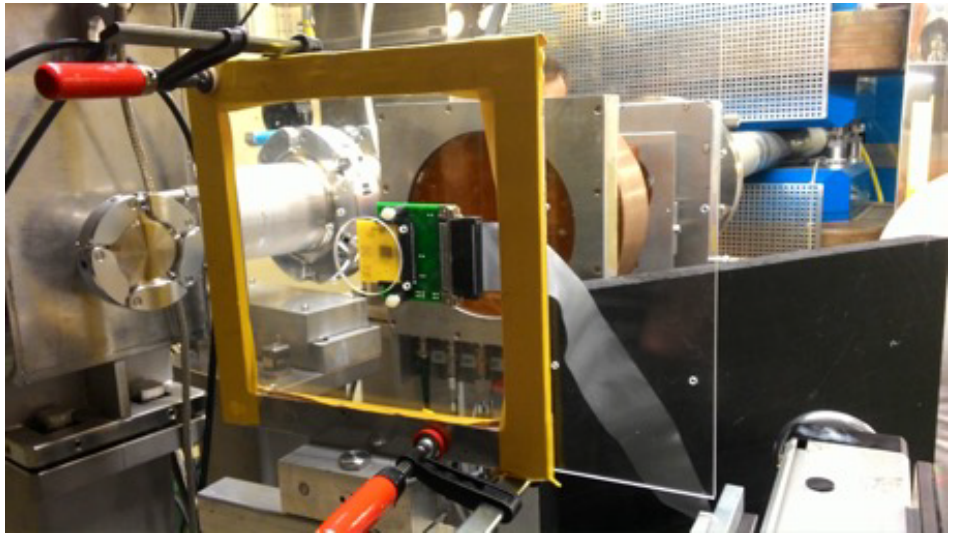
X-ray hits

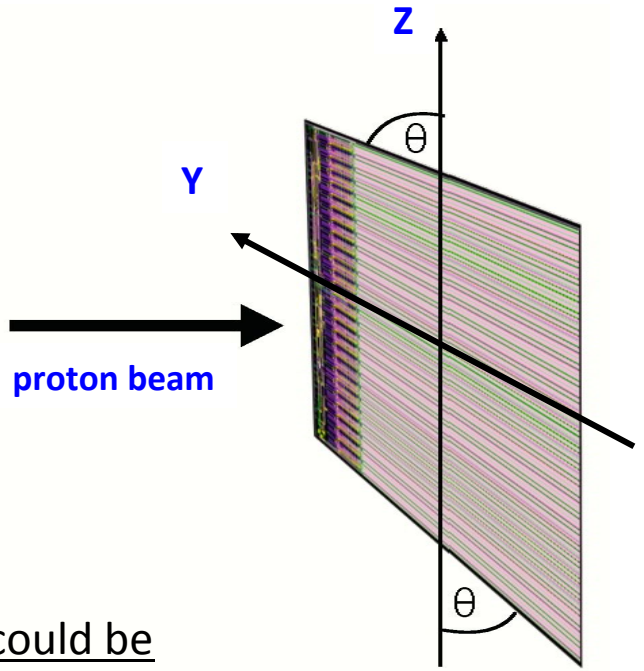


- Data traffic generated by high rate X-rays
- Efficiency measured with internal calibrate signals
- X-rays produce single pixel hit cluster: such test verified the functionality only of DC time stamp buffer
- On average one expects 1.9 hits per cluster in DC at LHC conditions
- Hence 300MHz/cm^2 X-rays rate correspond to 600MHz/cm^2 hit rate from particles
- next step measure efficiency with charged particles



High rate test setups

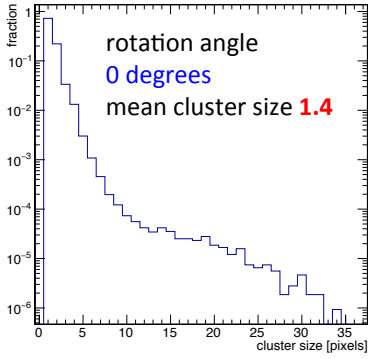


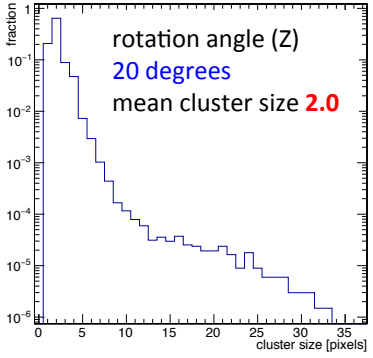


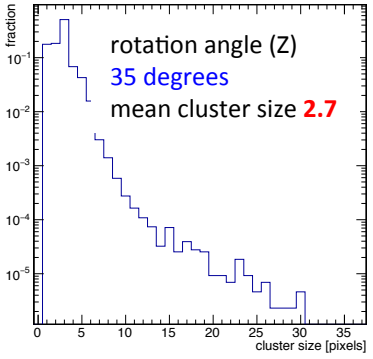
- Efficiency dependence on cluster size (included Data buffer inefficiency) studied with p-beam
- PIF (Proton Irradiation Facility) at PSI provides beam of 200MeV protons with rate of 70MHz

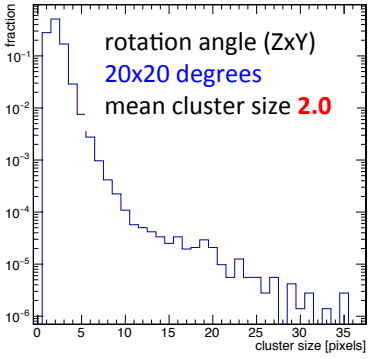
Sample could be

- rotated about z axis: clusters along DC
- rotated about y axis: clusters across DC

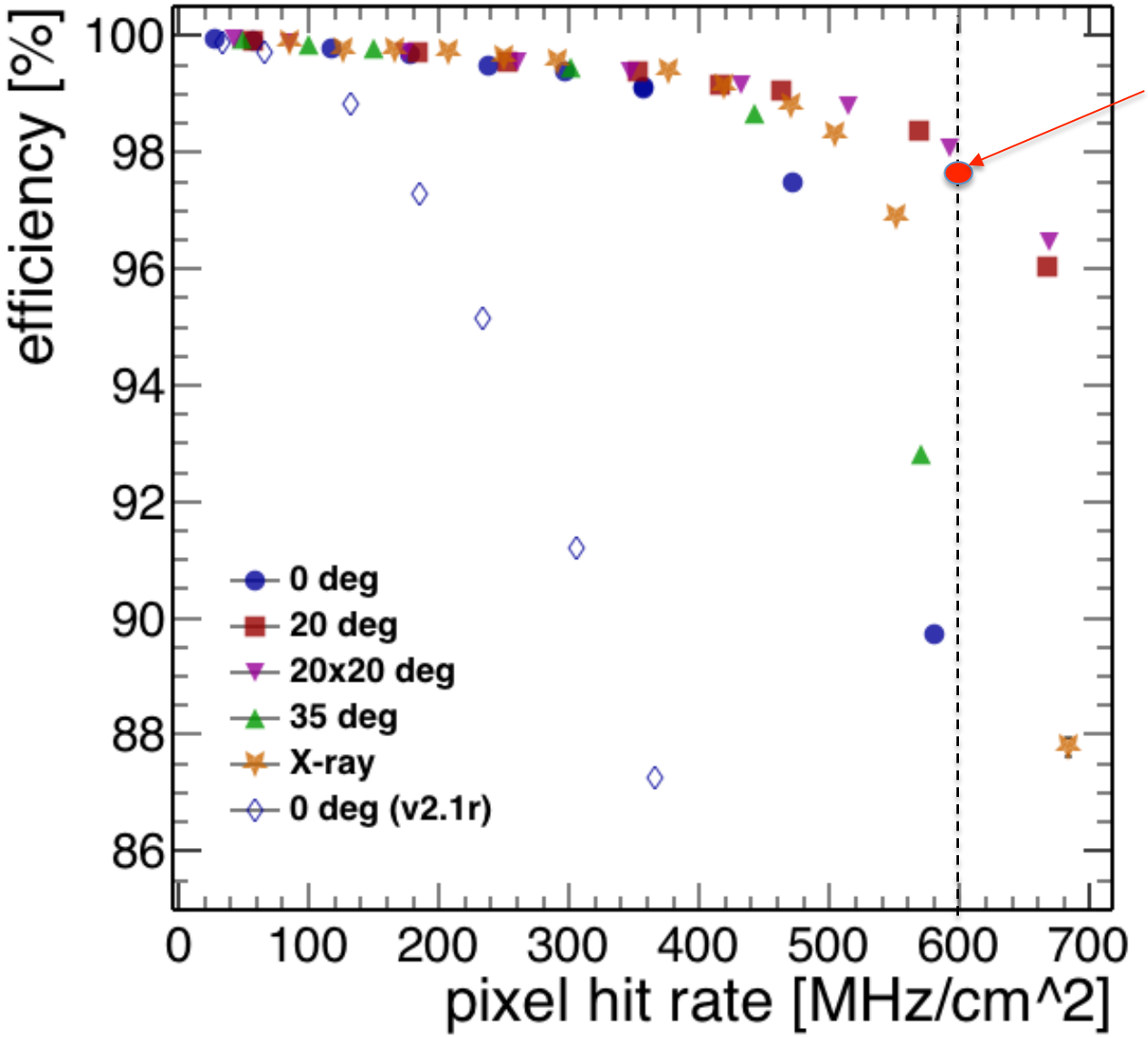








PIF test beam results



Efficiency at 600MHz/cm^2

- 97.6% for 20^0
- 98% for 20^0x20^0

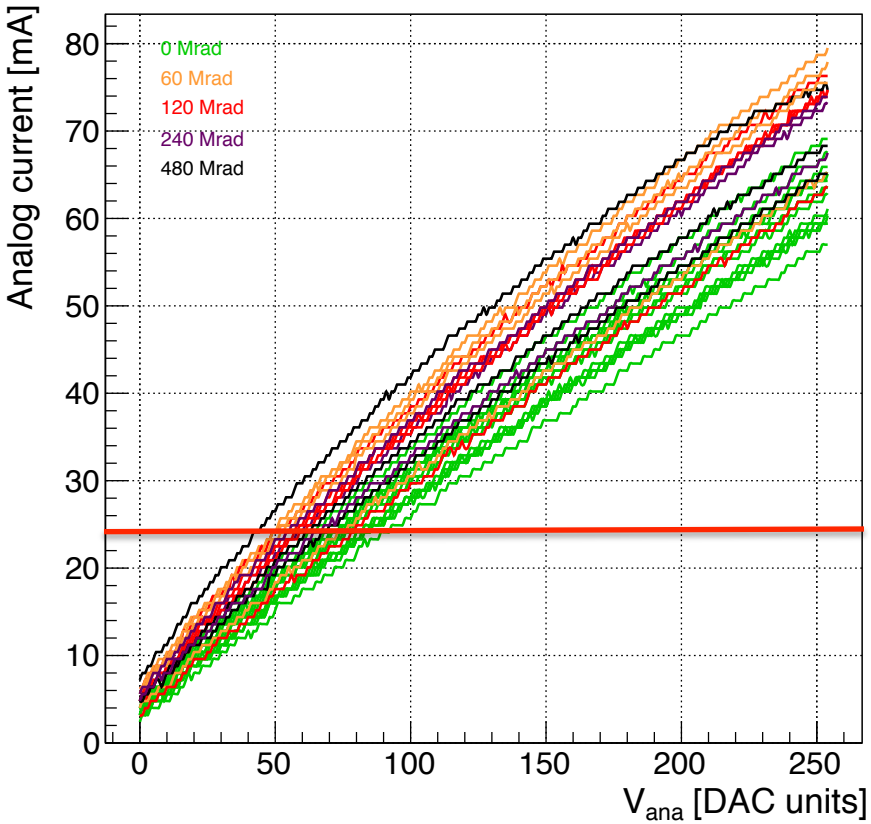
Irradiation studies

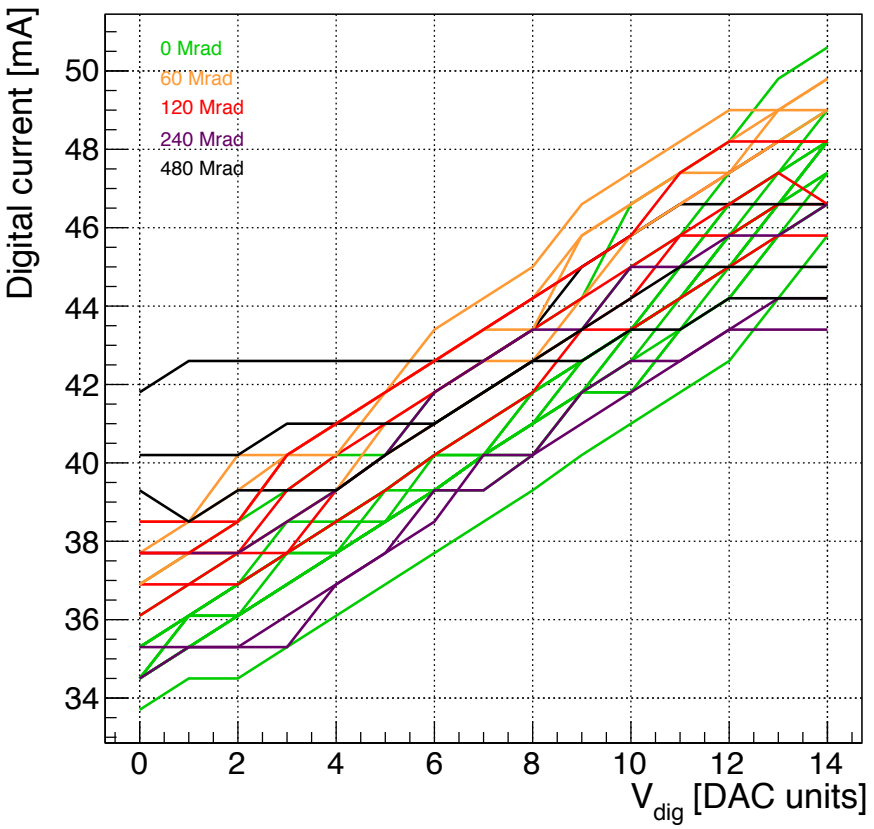
Acknowledgment:
The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project AIDA, grant agreement no. 262025

Irradiation at KIT

- 23 MeV proton beam at Zyklotron AG Karlsruhe
- Target doses:
  - **60** MRad (max expected for psi46dig)
  - **120** MRad (max expected for PROC600)
  - **240** and **480** Mrad (test ROC limits)
- Controlled parameters:
  - dynamic range of DACs (ROC parameters that crucial for operation)
  - threshold and noise
  - trim bit settings (unification of threshold)
  - timewalk (influences an effective threshold)
  - read-back functionality (ability to set ROC power after irradiation)
  - pixel hit efficiency after irradiation

Analog and digital power

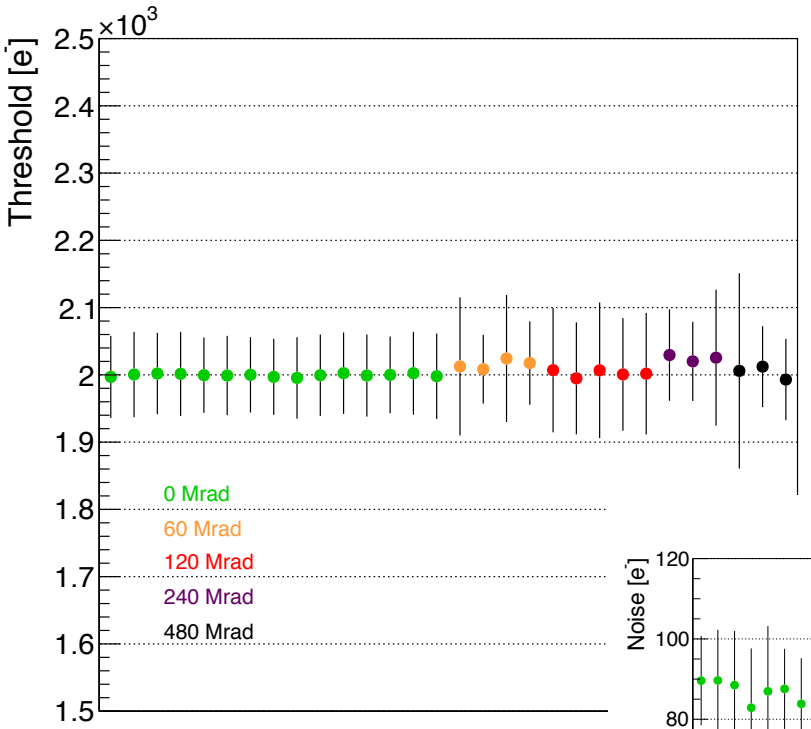




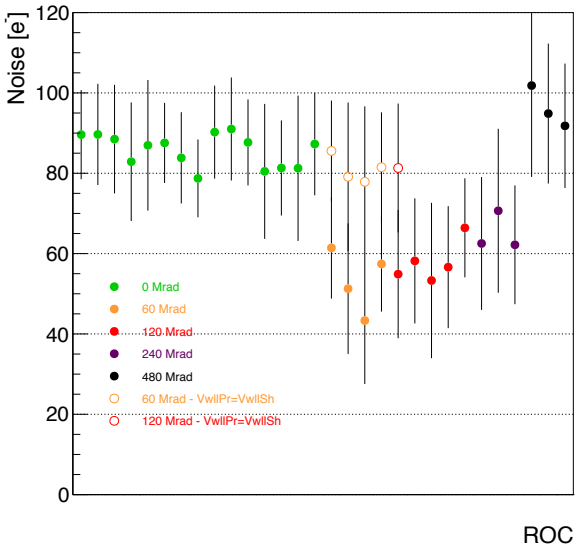
- Analog: default set of Iana = 24 mA
- No saturation observed, tunable up to 480MRad

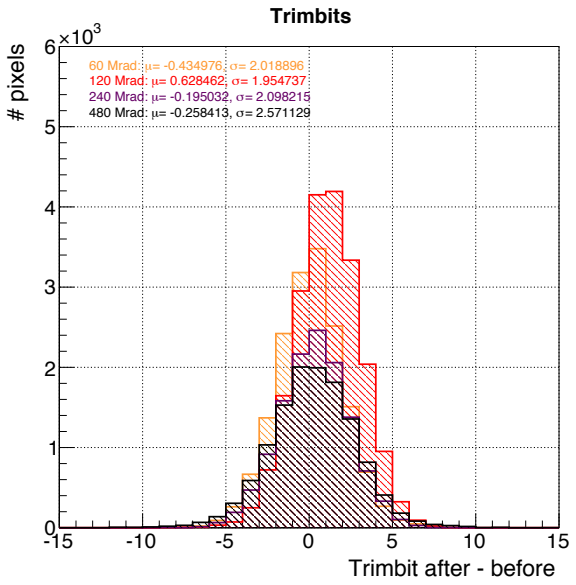
- Digital: set to Vdig=6-10
- No saturation observed, while flattened for higher doses

Trimming: threshold, noise and trim bits



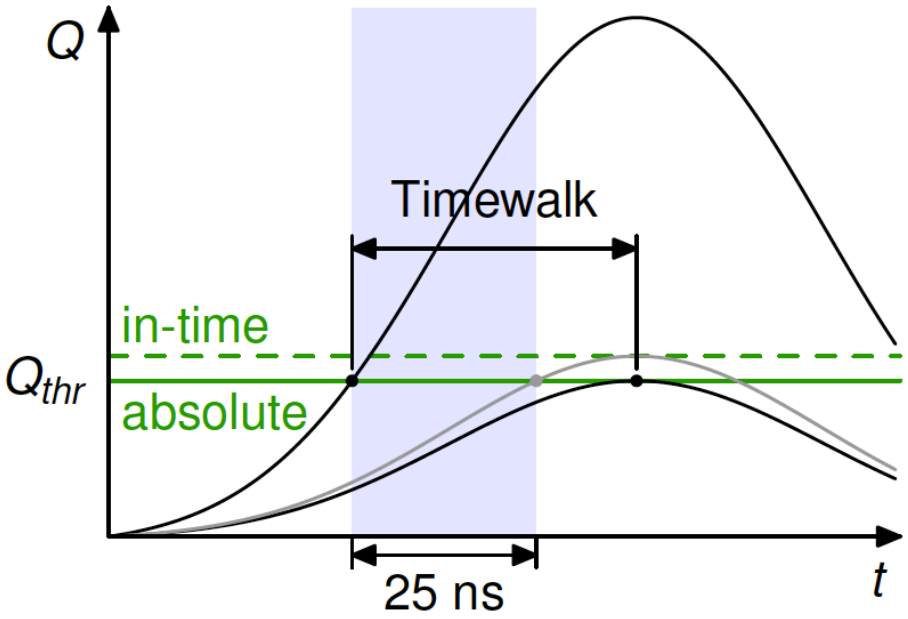
- Before and after irradiation ROC trimmed to (internal calibrate signal) **2000e⁻**
- Noise remains almost the same
- Trimming works well after irradiation
- Trim bit distributions mostly stays the same shifting by ~2 bits

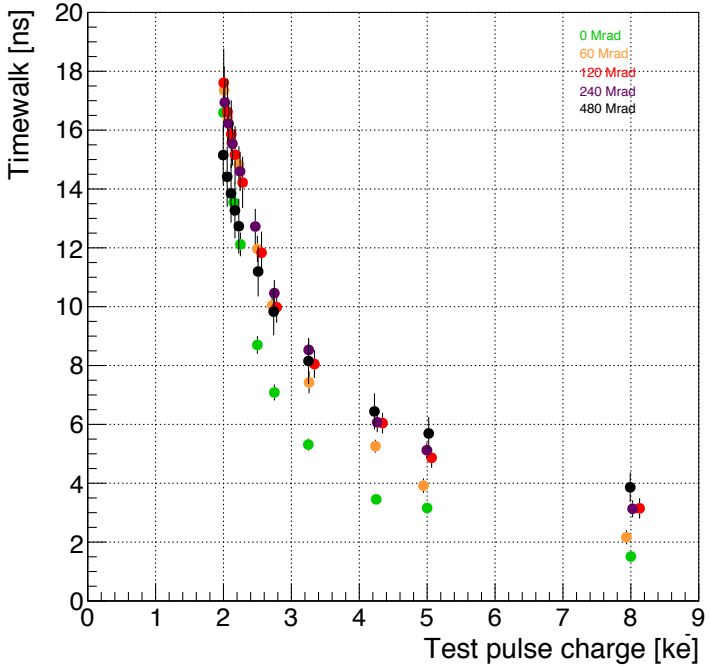




Timewalk and threshold

- Timewalk(T): time difference between moments at which largest and lowest signals cross ROC threshold
  - analog ROC: T>25ns (outside triggered bunch-crossing)
  - PROC600: T<18ns
- Minimum threshold:
  - analog ROC: 3200e^- (high due to timewalk)
  - PROCROC: <2000e^- (also due to reduced x-talk in new ROC layout)
- Low threshold increases detector longevity



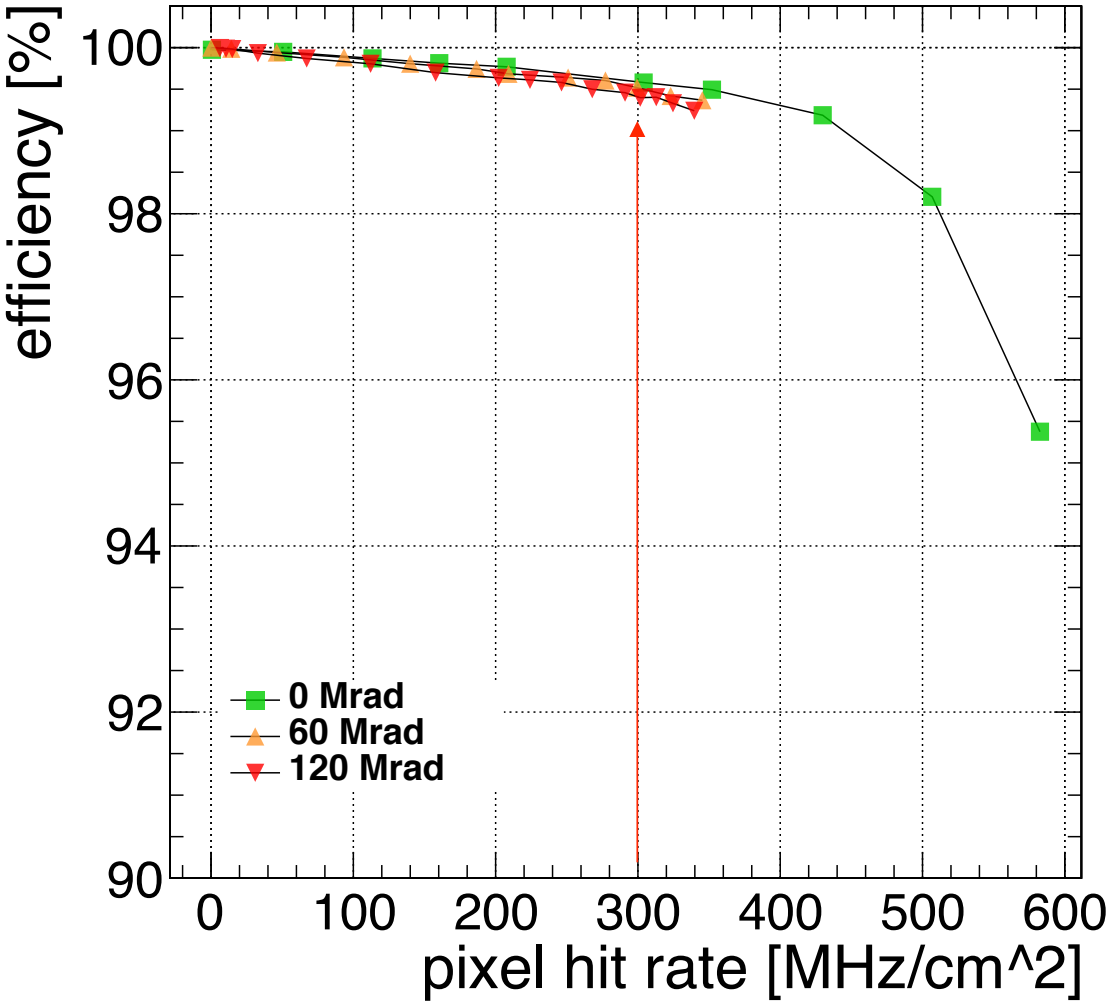


Pixel efficiency with high rate X-rays

Efficiency at 300MHz/cm^2

- measured with X-rays
- higher than 99% event for the highest dose
- only small drop of 0.1-0.2% for irradiated samples up to 120MRad

Dose, MRad	Efficiency, %
0	99.57 ± 0.01
60	99.52 ± 0.02
120	99.40 ± 0.03



Acknowledgment

In this presentation work of many people from the CMS Pixel Upgrade Phase I community is used. I would like to thank all of them. Special thank to

Roland Horisberger (PSI)

Hans-Christian Kästli (PSI)

Beat Meier (PSI)

Tilman Rohe (PSI)

Silvan Streuli (PSI)

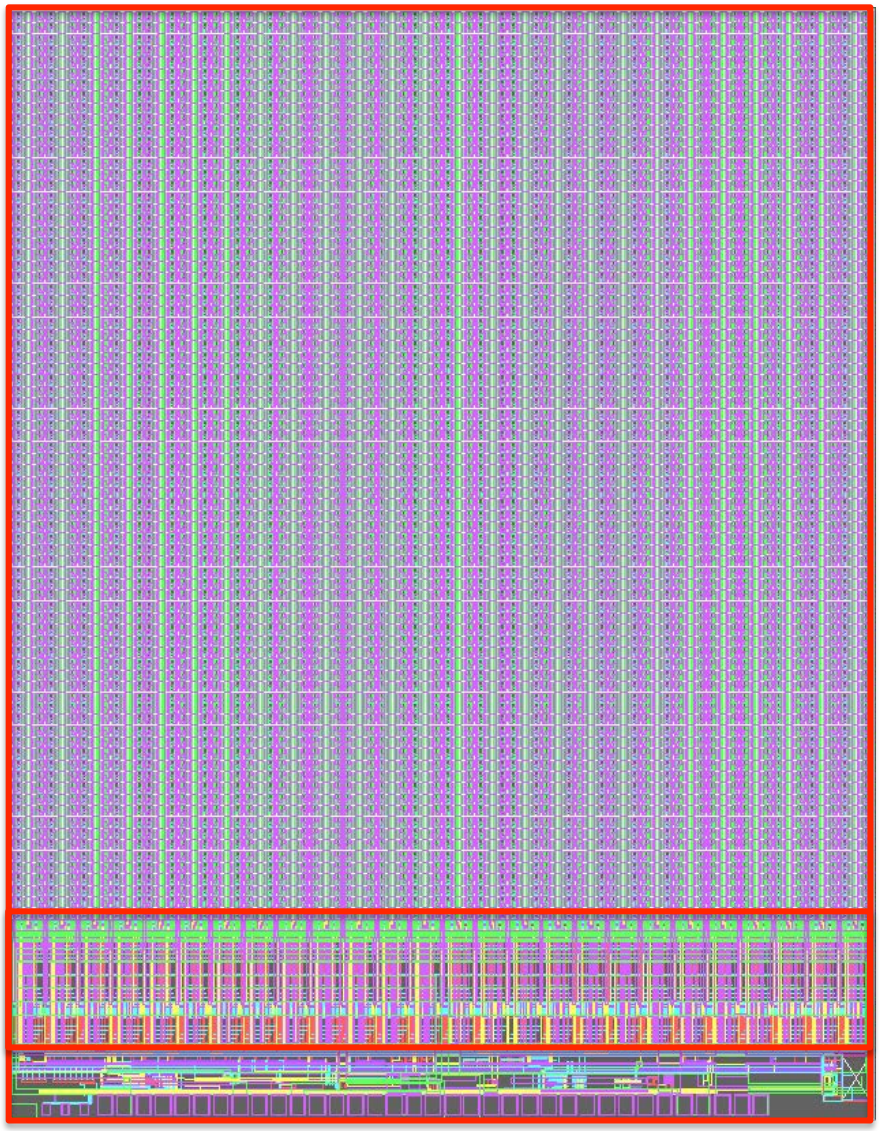
Micha Reichmann (ETHZ)

Summary

- High rate performance of PROC600 matches design goals: 97.6% at 600Mhz/cm^2
- PROC600 fully operational up to 120MRad:
  - DACs dynamic range allows proper tuning
  - low noise of 100e- and low threshold of 2000e-
  - timewalk of 18ns stays within one bunch-crossing
  - pixel hit efficiency remains high >99% at relevant rate produced by X-rays

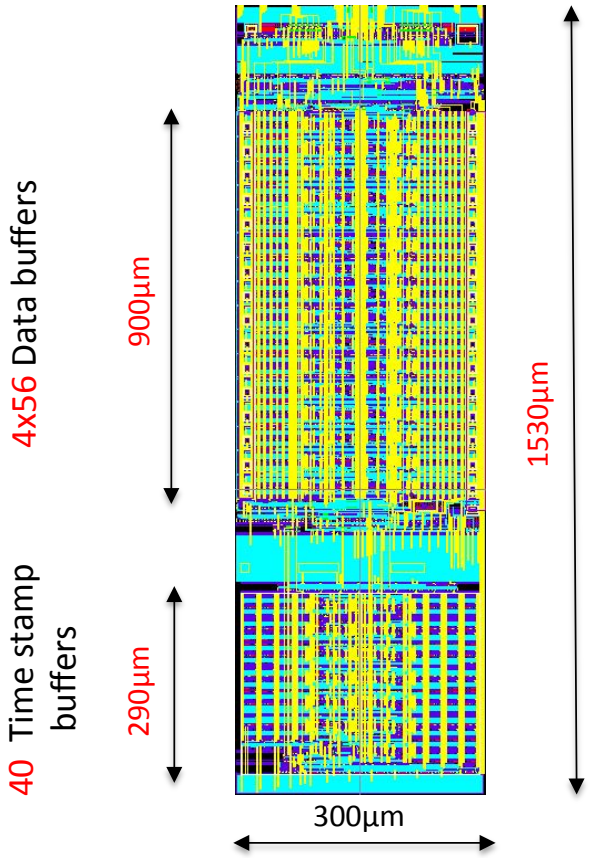
Backup slides

Layout of the PROC600



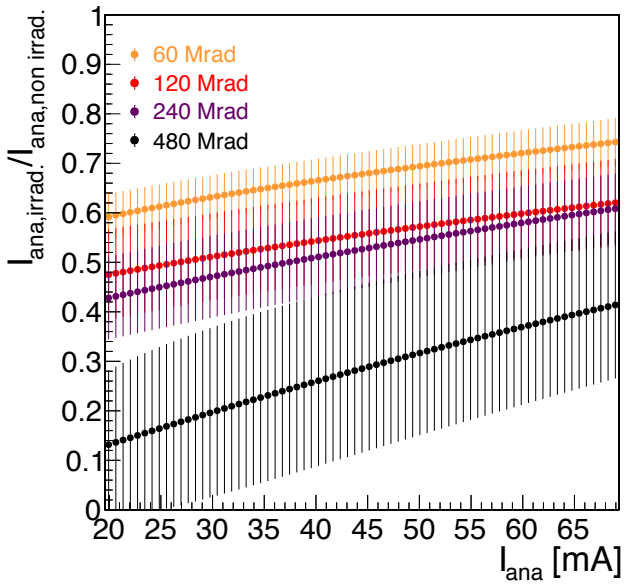
(1) Pixel array: 52 columns and 80 rows arranged in groups of 2 columns (26 double columns)

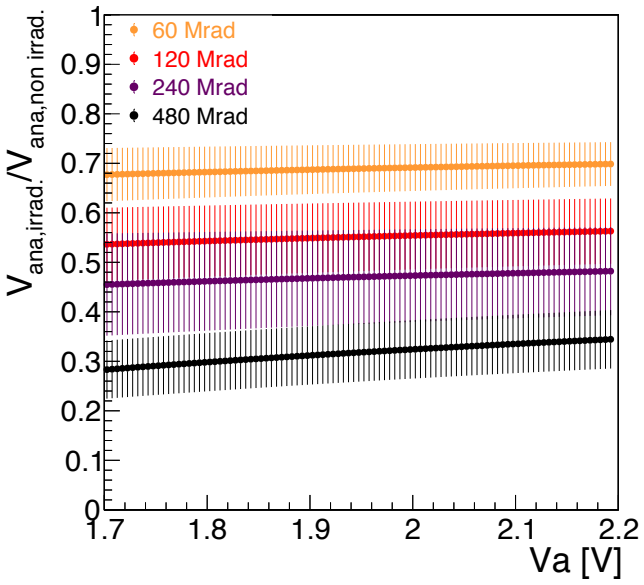
(2) 26 Double Column Interfaces

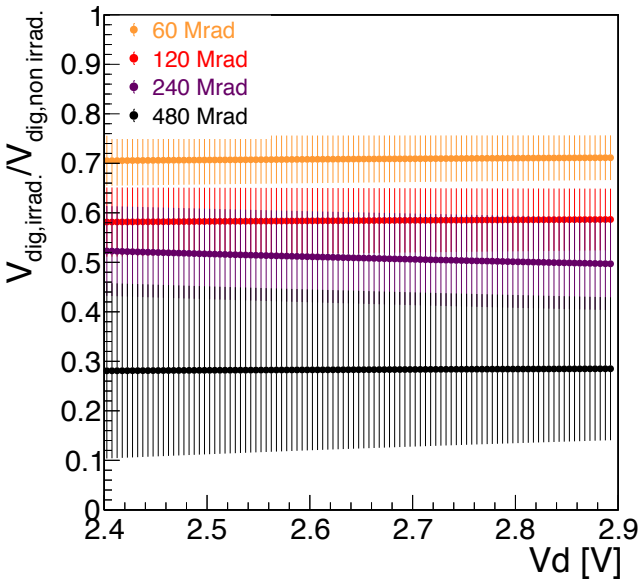


(3) <u>Control Interface Block</u>: readout logic, DACs, I2C interface, voltage regulators, reference and pads

Read-back functionality

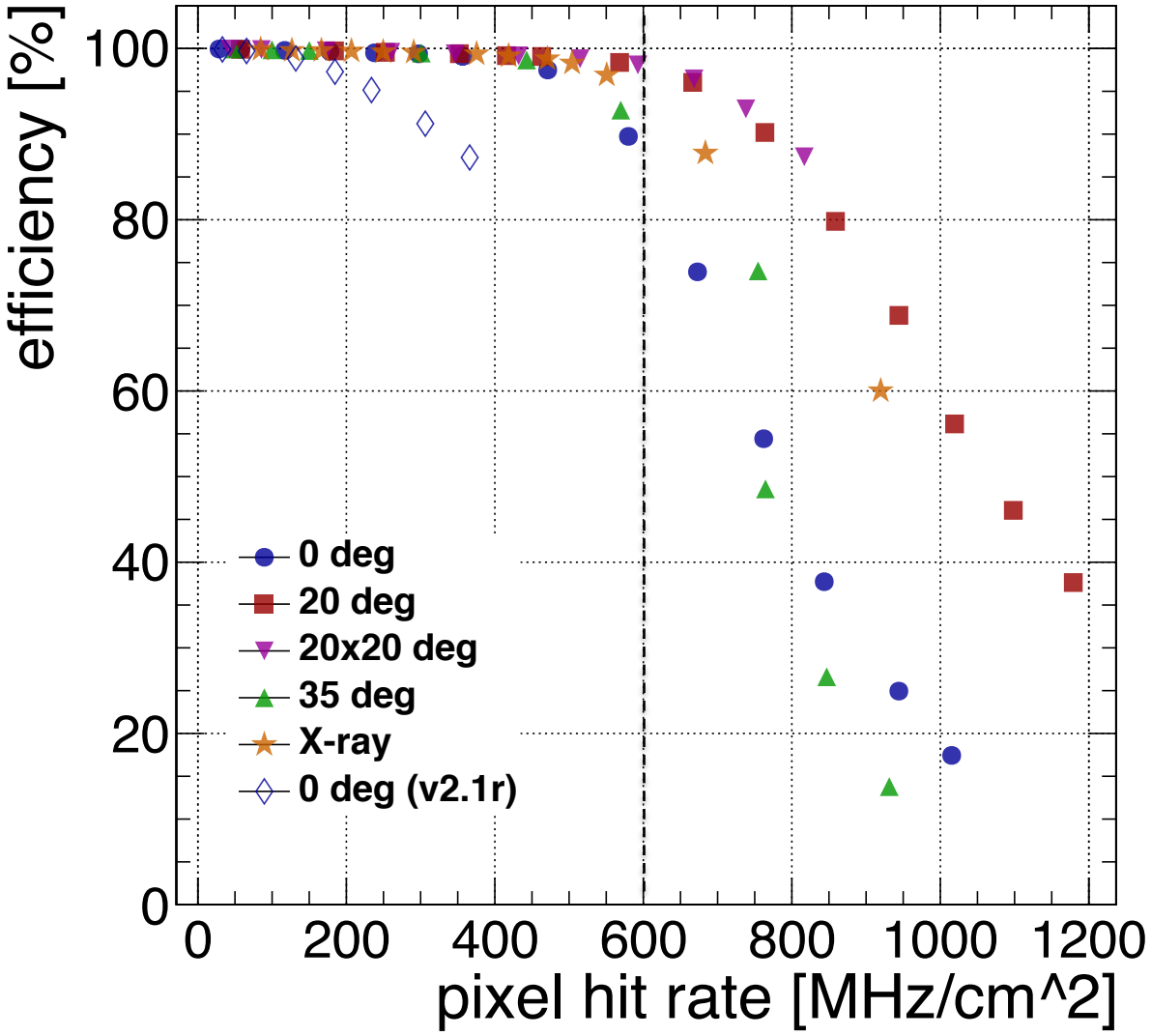






- Read-back mechanism allows to set analog and digital power (voltage and current) during operation
- Current and voltage calibrated during module qualification
- Calibration changes with irradiation but no way to calibrate in situ
- Way to keep read-back functionality still to be found

PIF test beam results



Efficiency at 600MHz/cm^2: 97.6%
Efficiency at 800MHz/cm^2: 90%
Efficiency at 1.0GHz/cm^2: 60%
Efficiency at 1.2GHz/cm^2: 38%