Planar n^+-in-n pixel sensors for the ATLAS IBL upgrade

Daniel Muenstermann

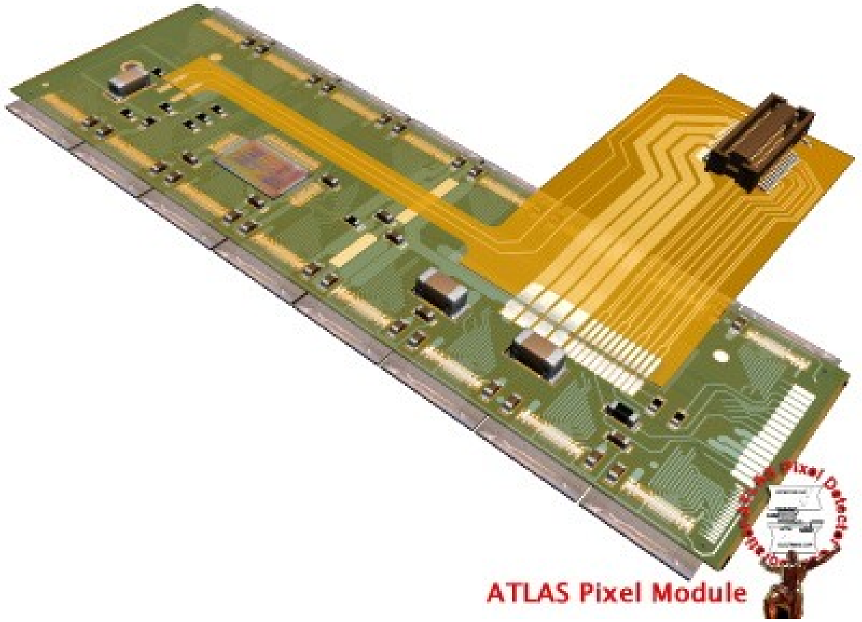
deeply indebted to many people from the ATLAS IBL and PPS communities whose work I present

Disclaimer: neither p-type nor 3D,

but I hope I will be able to show that
also n-type sensors can be advanced...

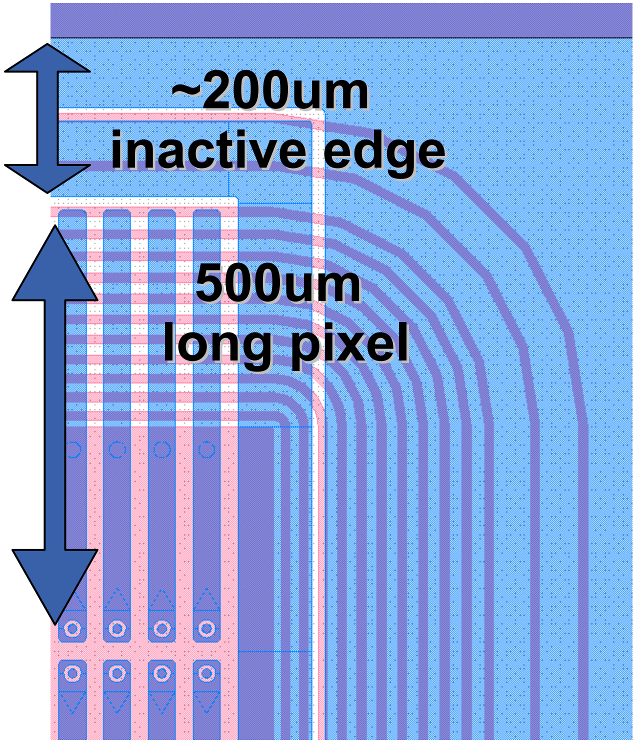
Planar Pixel Sensors in ATLAS: past

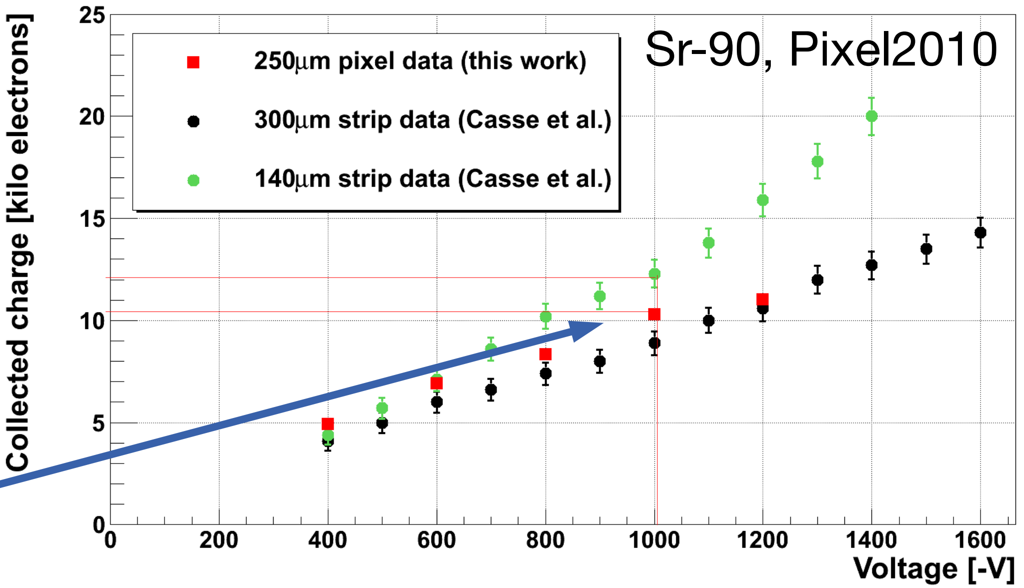
- The current ATLAS Pixel detector is based on planar sensors
  - much production and operation experience
  - proven to be rad-hard up to at least $1 \cdot 10^{15}\ n_{eq}/cm^2$ at 600V bias voltage
  - ongoing HL-LHC R&D for the phase 2 upgrade: ATLAS PPS R&D Project
- Several planar sensor flavours were proposed for IBL:
  - n-in-n conservative design
    - as close to the current sensor as possible
  - n-in-n slim-edge design
    - significantly reduced edge inefficiencies
  - thin n-in-p designs
    - 150 µm thin, very promising candidates for future upgrades → why not now?



Planar Pixel Sensors in ATLAS: present

- Chosen sensor: semi-thin n-in-n slim-edge
  - identical to the proven and reliable sensors of the current detector *as far as reasonable*
  - produced by one of the two sensor vendors of the original production
  - bump-bonded by one of the two bump vendors of the original production
- Modifications:
  - fit to the FE-I4 footprint
    - 250 μm long pixels
    - large sensor: 80 columns and 336 rows
  - reduction of the inactive edges
    - were 1100 μm before
    - are now 200 to 250 μm
  - thickness:
    - was 250 μm, now 200 μm
      - acceptable yield
      - save radiation length
      - improve collected charge after irradiation by 1-2 ke^-





IBL Sensors: requirements

- Production readiness:
  - reliability and experience
  - sufficient yield
  - be able to keep to the schedule
- IBL specifications to qualify:
  - Inactive edges < 450 μm (i.e. geometric efficiency > 97.4%)
  - Thickness between 150 and 250 μm
  - Power dissipation < 200 mW/cm^2 at 1kV
  - Leakage current < 100 nA/pixel
  - Operation possible at -15°C on sensor
  - Hit efficiency > 97%
    - after a benchmark fluence of $5 \cdot 10^{15}$ n_{eq}/cm^2
    - at a bias voltage of 1 kV
- All specifications met, but...

Sensor Review

- ...alternative option: 3D sensors → review

Sensor Review: outcome

- Panel recommendations:

> **Recommendation**
> **The Panel believes the lowest risk option to meet the IBL schedule is the 100% planar option.**
>
> **The Panel notes that there is an opportunity to use the 3D technology to populate the forward region where the tracking could take advantage of the electrode orientation to give a better z-resolution after heavy irradiation.**
>
> **The Panel recommends that the IBL investigate a mixed scenario proposed by the IBL project management. The IBL should proceed to full production of the planar sensors required to build 100% of the IBL, and the current production of 3D should be completed (3 batches from each of CNM and FBK). If the yield is sufficient, then up to 50% of the modules (in the forward regions) can be made using 3D sensors.**

- i.e. planar sensors to be produced for 100% of IBL (in fact, 200% to have spares and contingency)
- performance at high eta values to be studied

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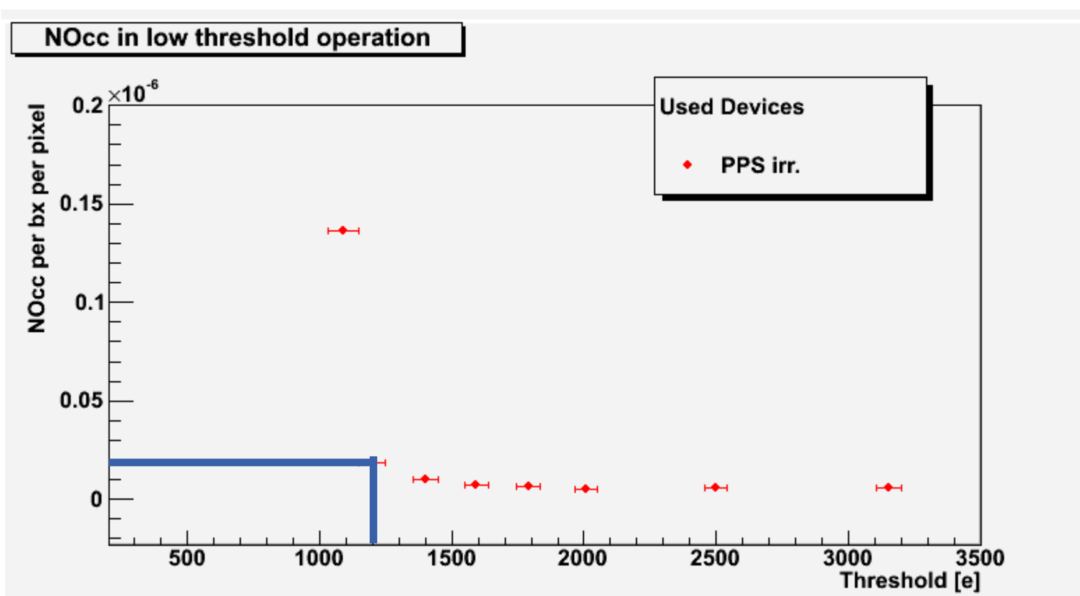
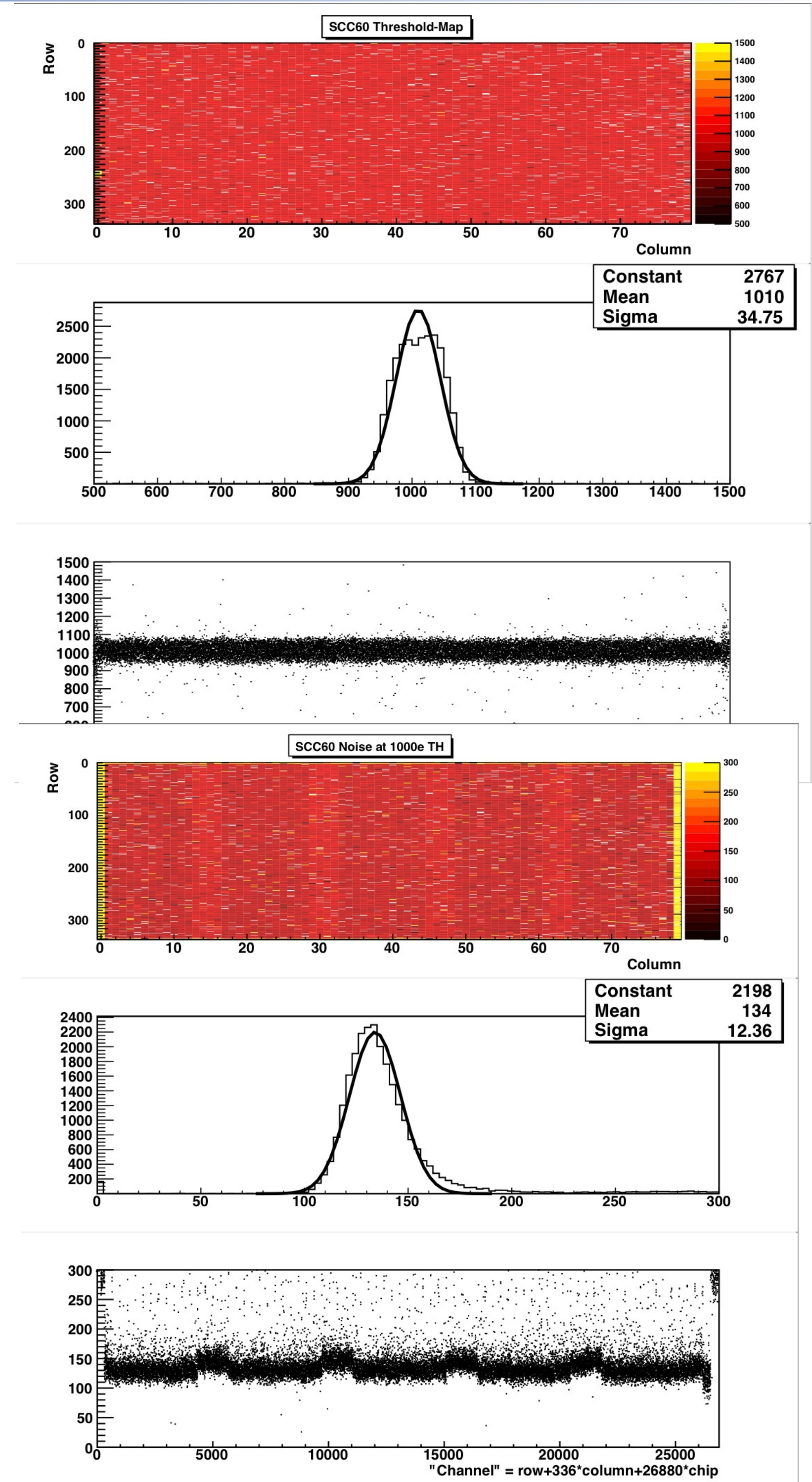
Some Highlights

- Tuning of FE-I4-based assemblies to thresholds as low as 1000 electrons still works after 6e15 neq/cm2 and ~1GRad (!!)
- Noise occupancy going up only below ~1200 electrons

→ operation at 1500 electrons seems to be pretty much on the safe side

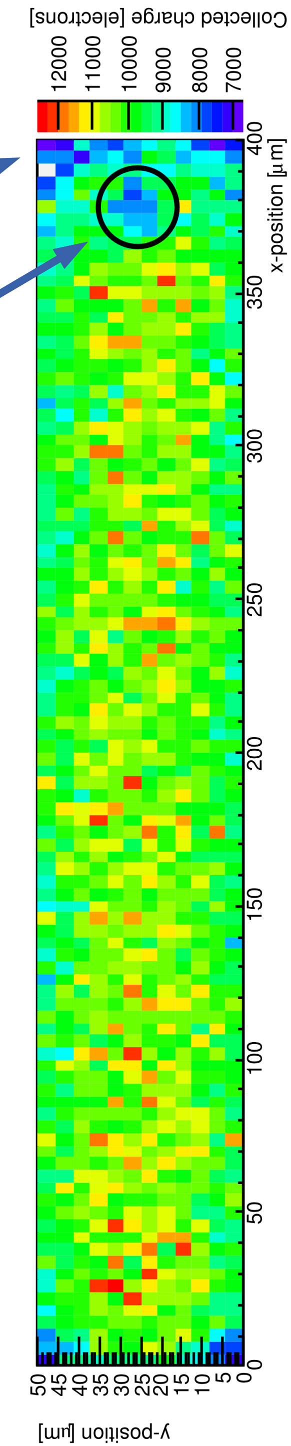
  - where are we with 1500 electrons threshold?

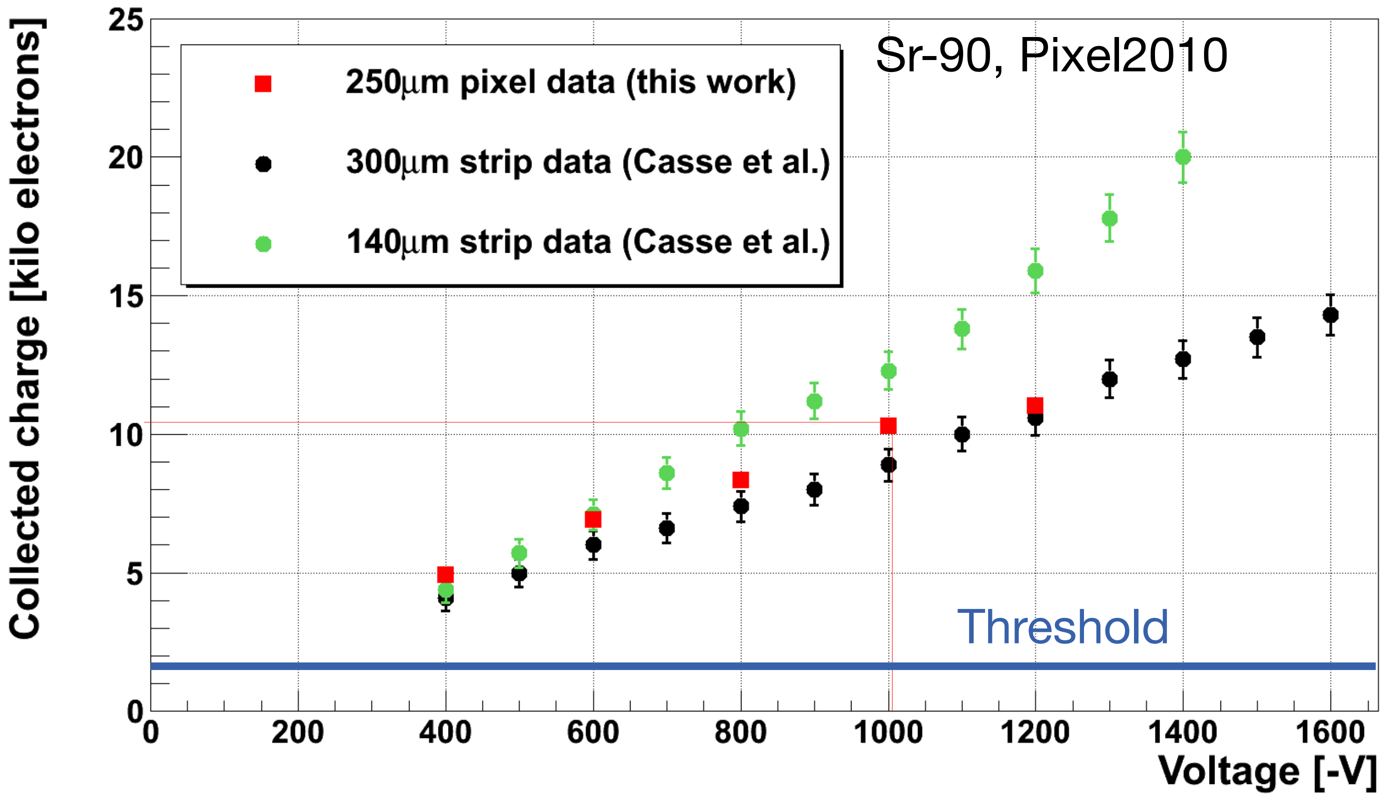




Where are we with ~1500 electrons?

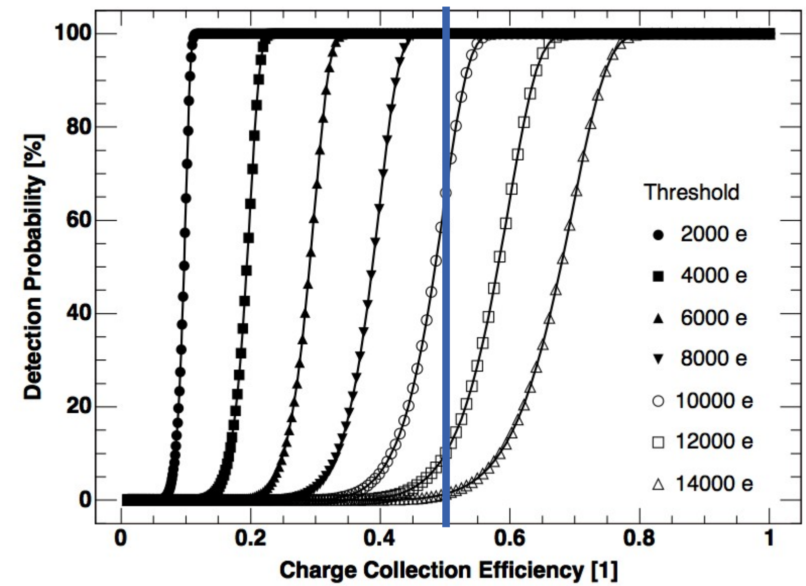
- A signal of ~10 ke$^-$ with a threshold of 1500 electrons implies
  - a Signal/Threshold ratio of >6
  - a Signal/Noise ratio of >45
- Charge losses due to charge sharing, bias rail and bias dot
  - charge sharing and bias dot smeared out by angles in both r-phi and eta
  - bias rail (most important source of inefficiency) smeared out by eta (already at center of the FE-I4 closest to middle of stave!)





Requirements after irradiation

- most important parameter: Hit efficiency (must remain high)
- can be addressed by
  - increasing the signal (collecting more charge) → higher bias voltage
  - decreasing the threshold
    - S/T should be better than 2-2.5
    - sensible noise occupancy limit might be 10^{-6}
    - w/o charge loss, even a threshold of ~6000 electrons likely good enough



- low threshold might enable the use of low(er) bias voltages
  - only use the voltage necessary to reach an acceptable efficiency
  - less power dissipation
- Status:
  - thresholds of ~1100 to 1600 electrons were used in the testbeam
  - noise occupancy is still of the order of 10^{-7} at 1100 electrons
  - reliability of absolute calibration of FE-I4 (in particular also after irradiation) is still looked into

Efficiencies

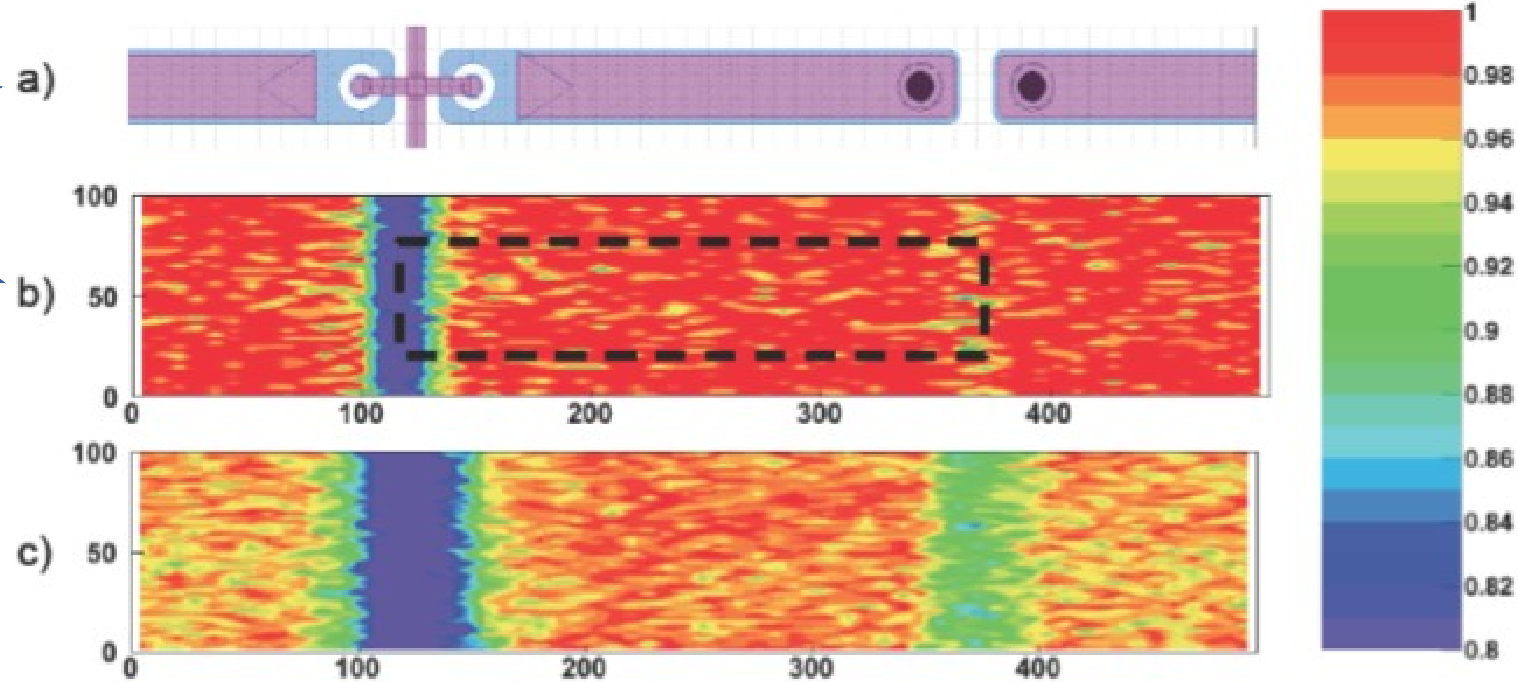
- Testbeams in April at DESY and in June at CERN yielded the following efficiencies at 1kV:

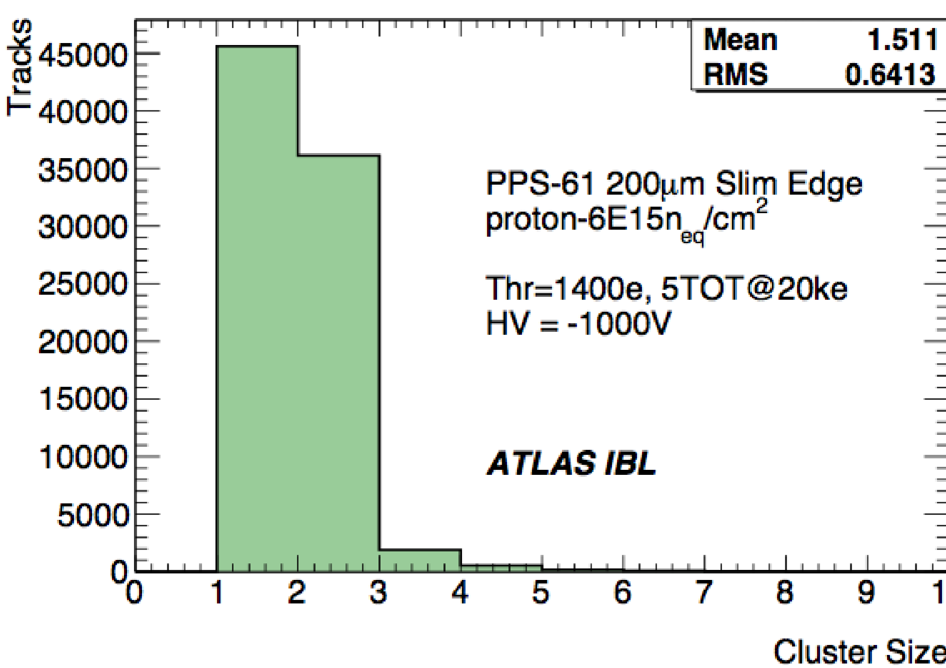
Device	Testbeam	Fluence	Angle	irrad.	Efficiency
LUB1	DESY	4e15	15°	neutrons	99.1%
LUB2	DESY	4e15	0°	neutrons	99.4%
LUB3	DESY	4e15	0°	neutrons	98.4%
SCC61	CERN	6e15	15°	protons	96.9%
LUB2	CERN	4e15	15°	neutrons	99.0%

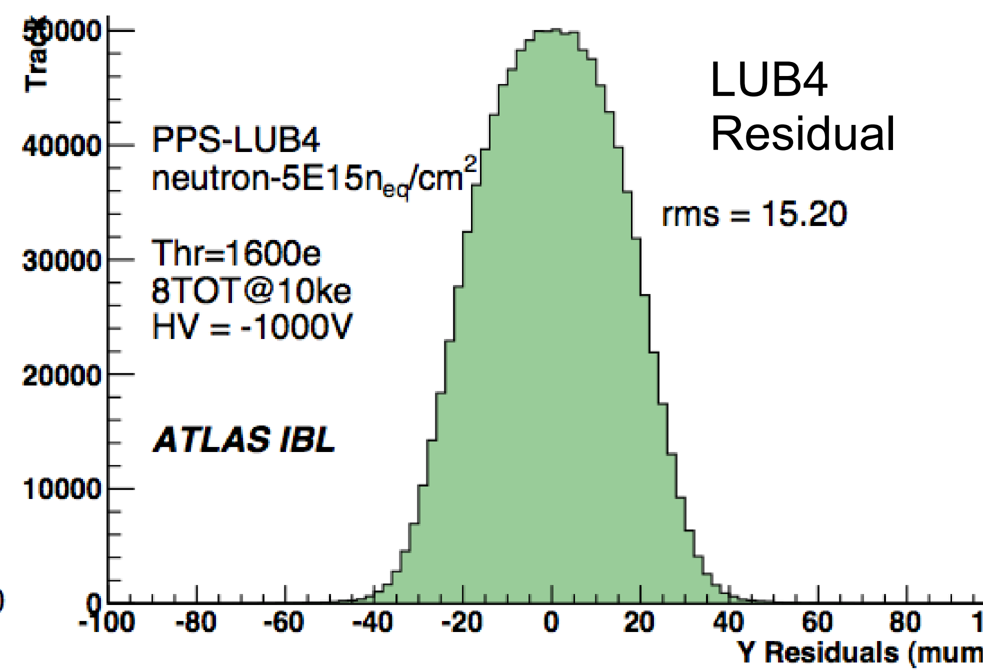
- All neutron-irradiated assemblies work as expected
- SCC61 has received 6e15 neq/cm^2 and a dose of roughly 1GRad (!)
  - specification for FE-I4: 250MRad
  - working hypotheses:
    - threshold might be higher than assumed – would explain many effects with proton-irradiated sensors
    - 1GRad does change things in FE-I4, still learning what to do about it
  - efficiency nevertheless still compatible with requirement (>97%)

Some testbeam highlights

- PPS 61
  - design sketch
  - 1000V
  - 600V
  - cluster sizes



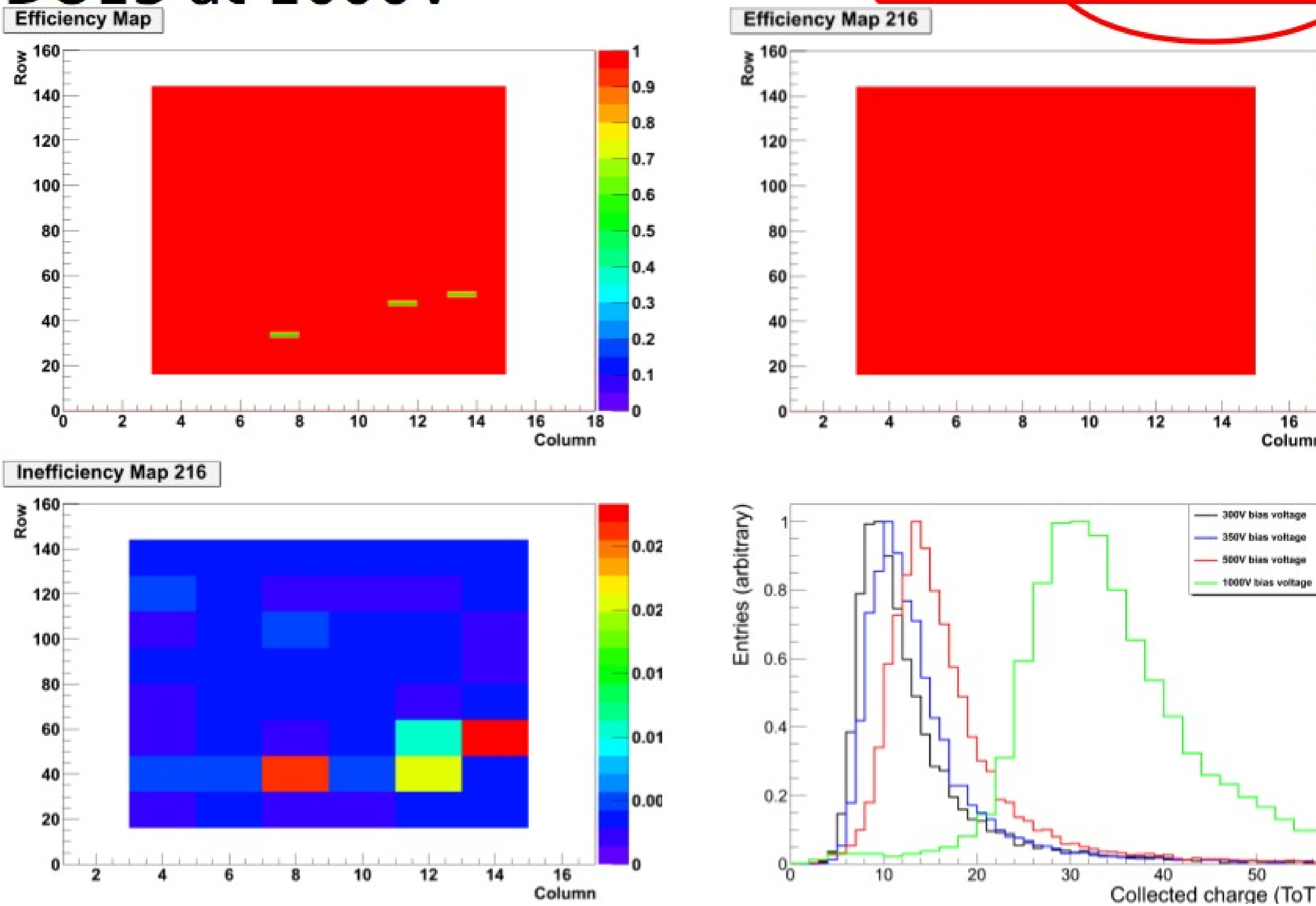




Crosscheck: FE-I3-assembly after $5 \cdot 10^{15}$ n_{eq}/cm^2

DO13 at 1000V

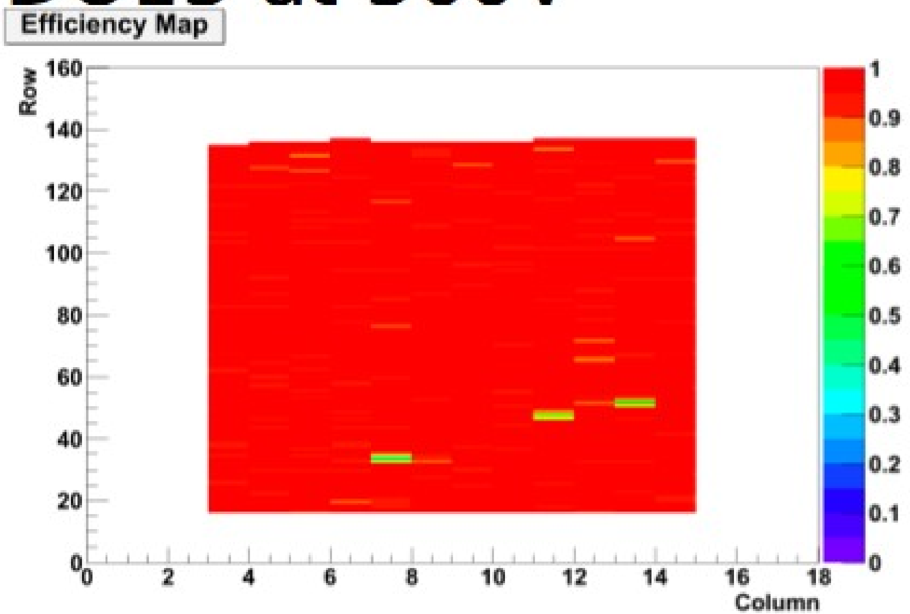
Efficiency: 99.6%±0.1%

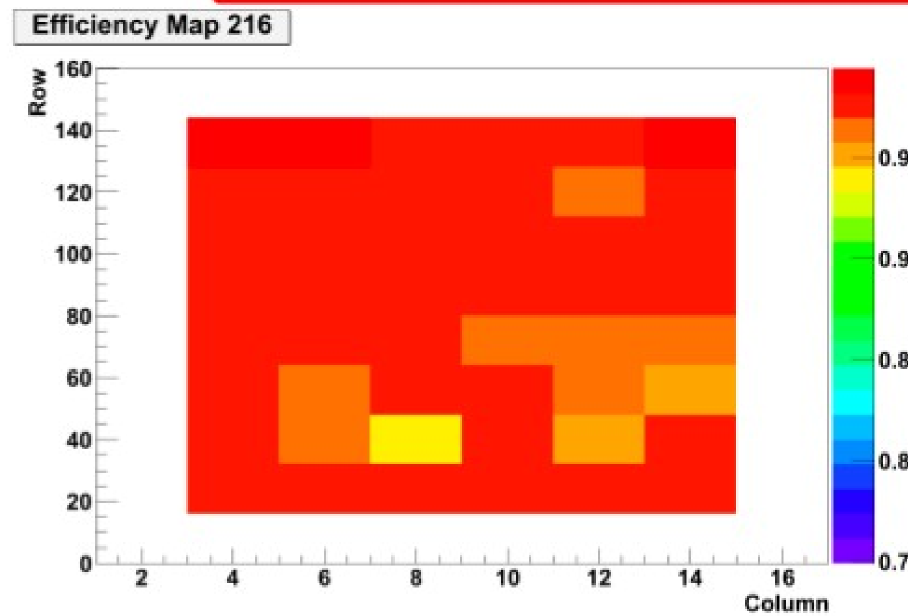


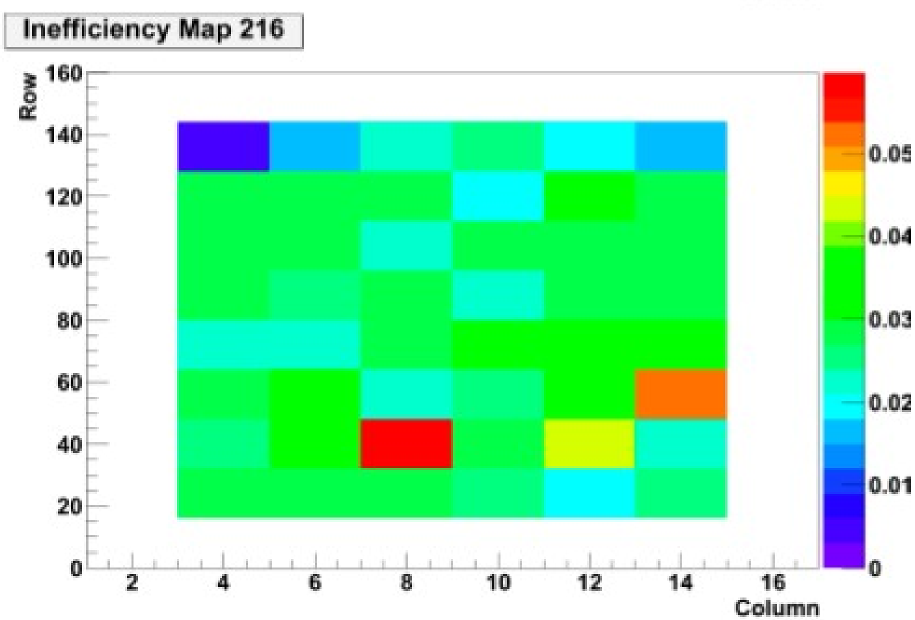
Crosscheck: FE-I3-assembly after $5 \cdot 10^{15}\ n_{eq}/cm^2$

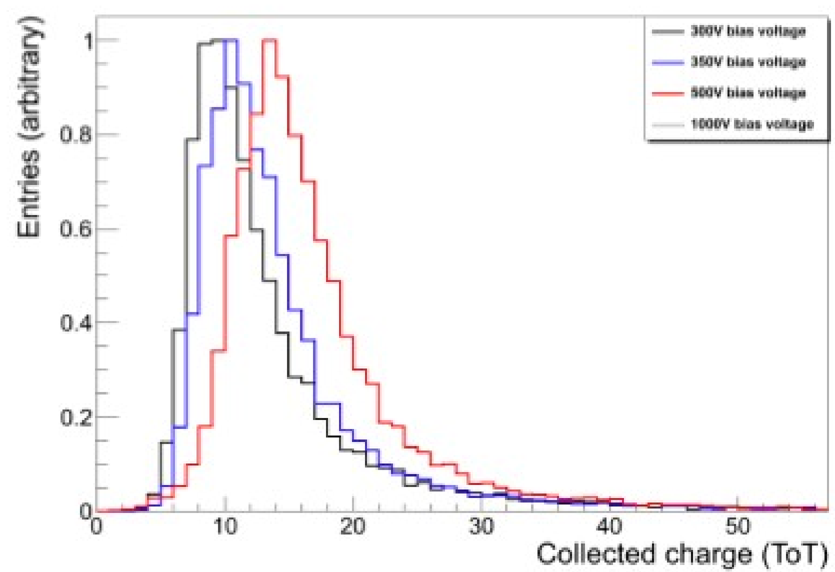
Efficiency: 97.3%±0.1%

DO13 at 500V







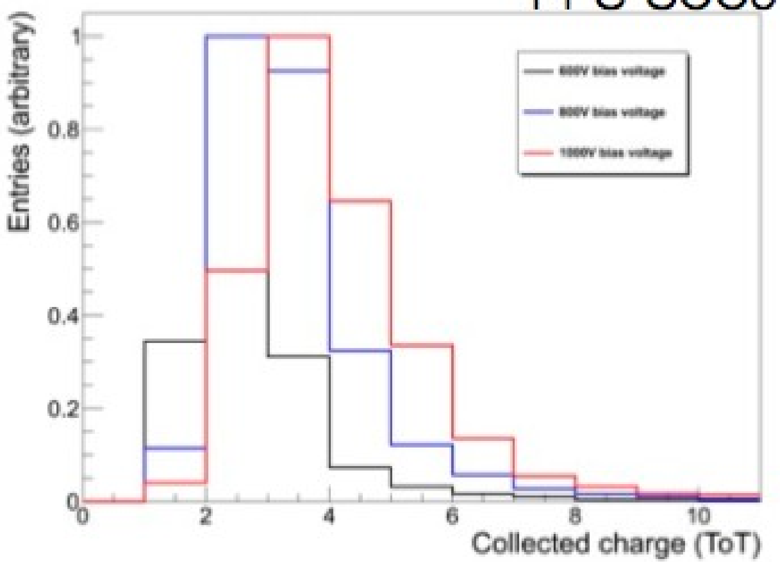


Crosscheck: ToT spectra

- ToT spectra look reasonable and rise with increasing bias voltages

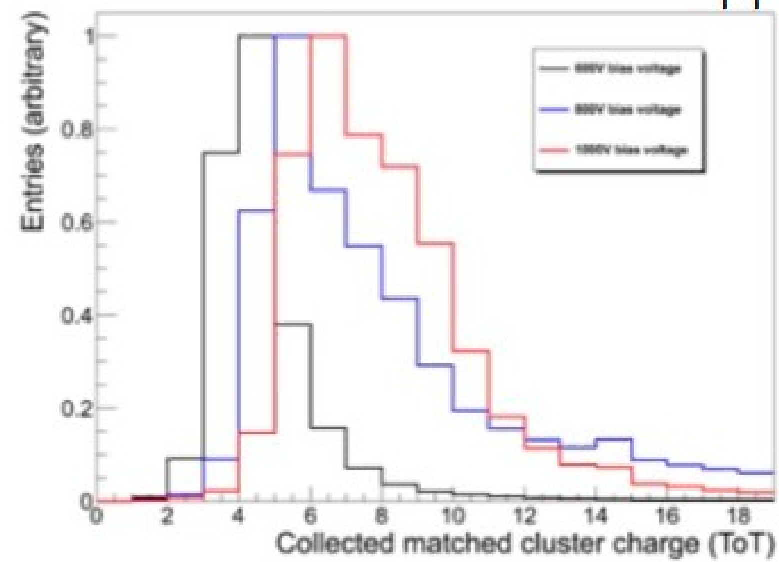
6e15 neq/cm² protons

PPS-SCC61



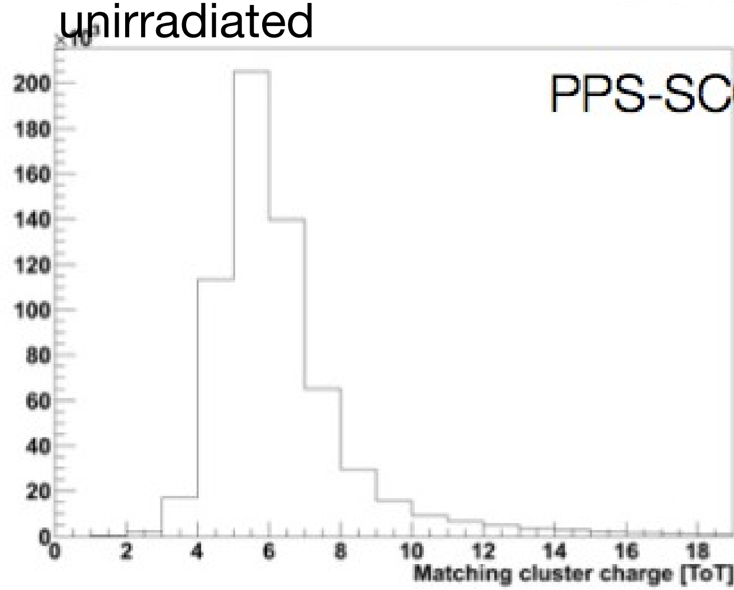
4e15 neq/cm² neutrons

PPS-LUB2



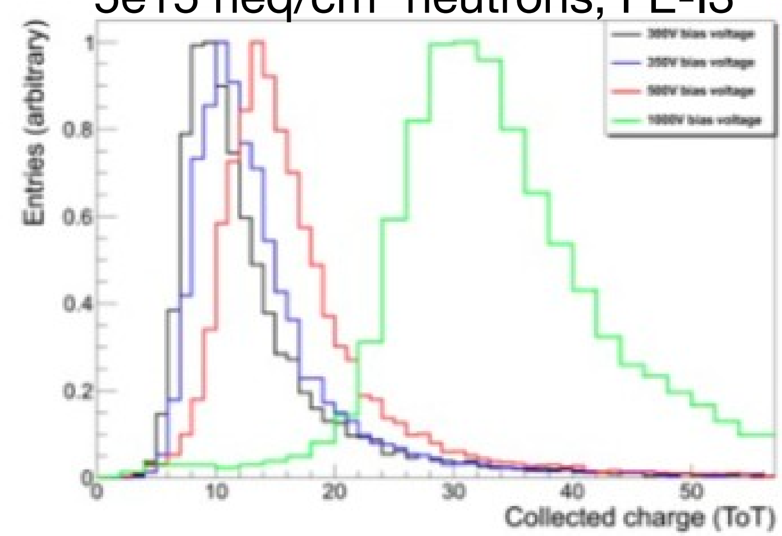
unirradiated

PPS-SCC41



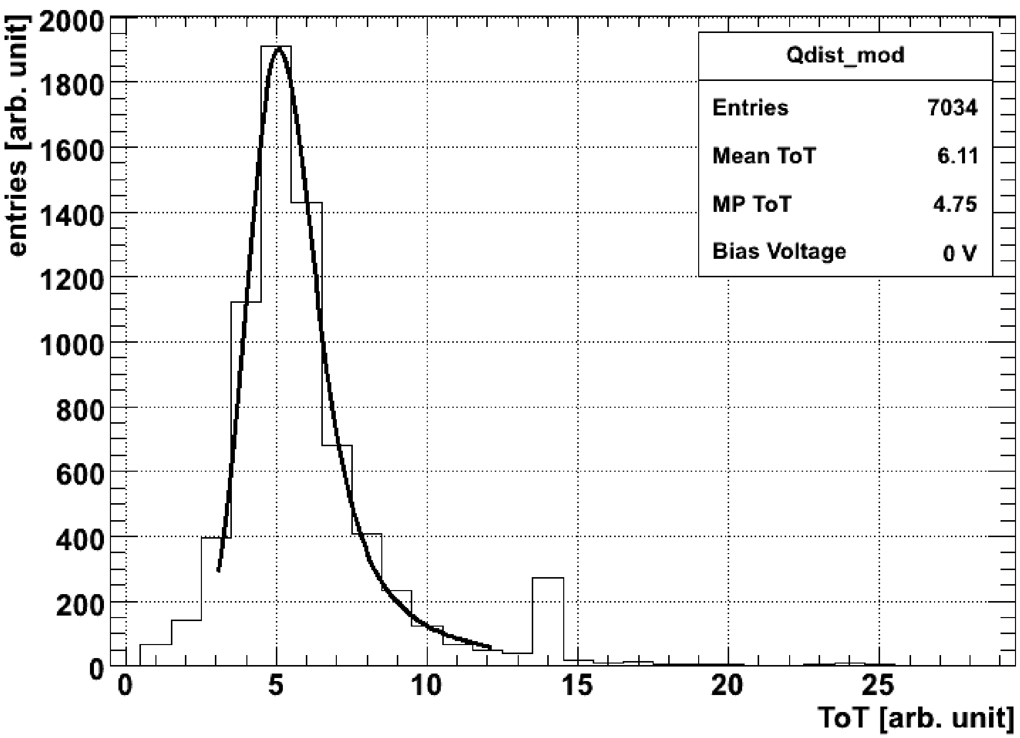
5e15 neq/cm² neutrons, FE-I3

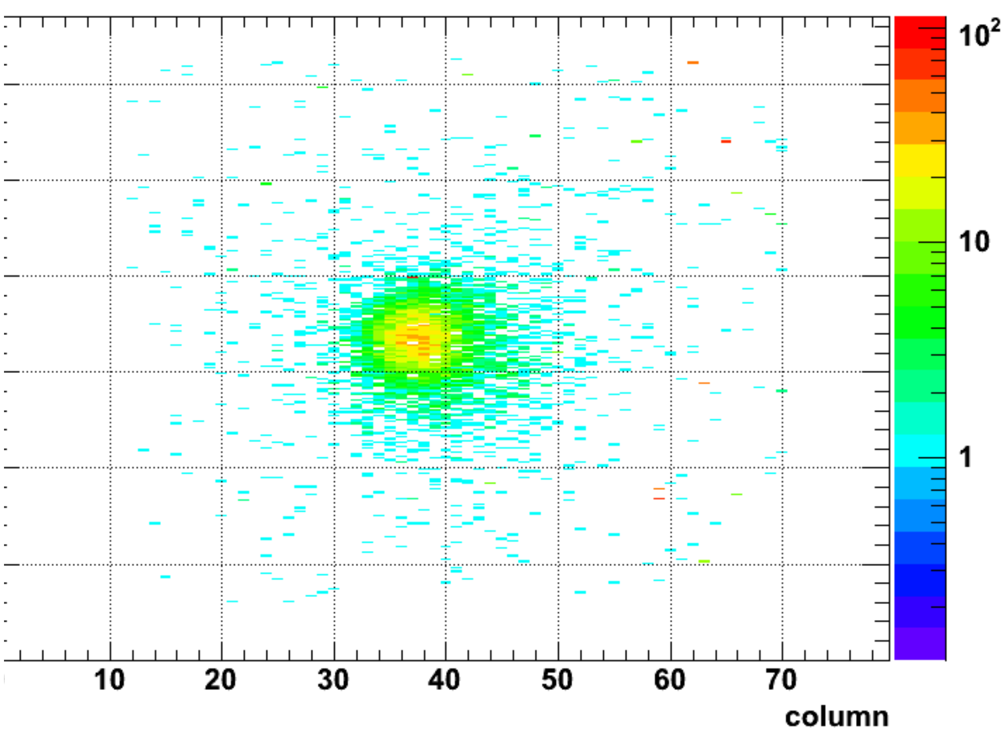
PPS-DO13



Crosscheck: Lab measurements

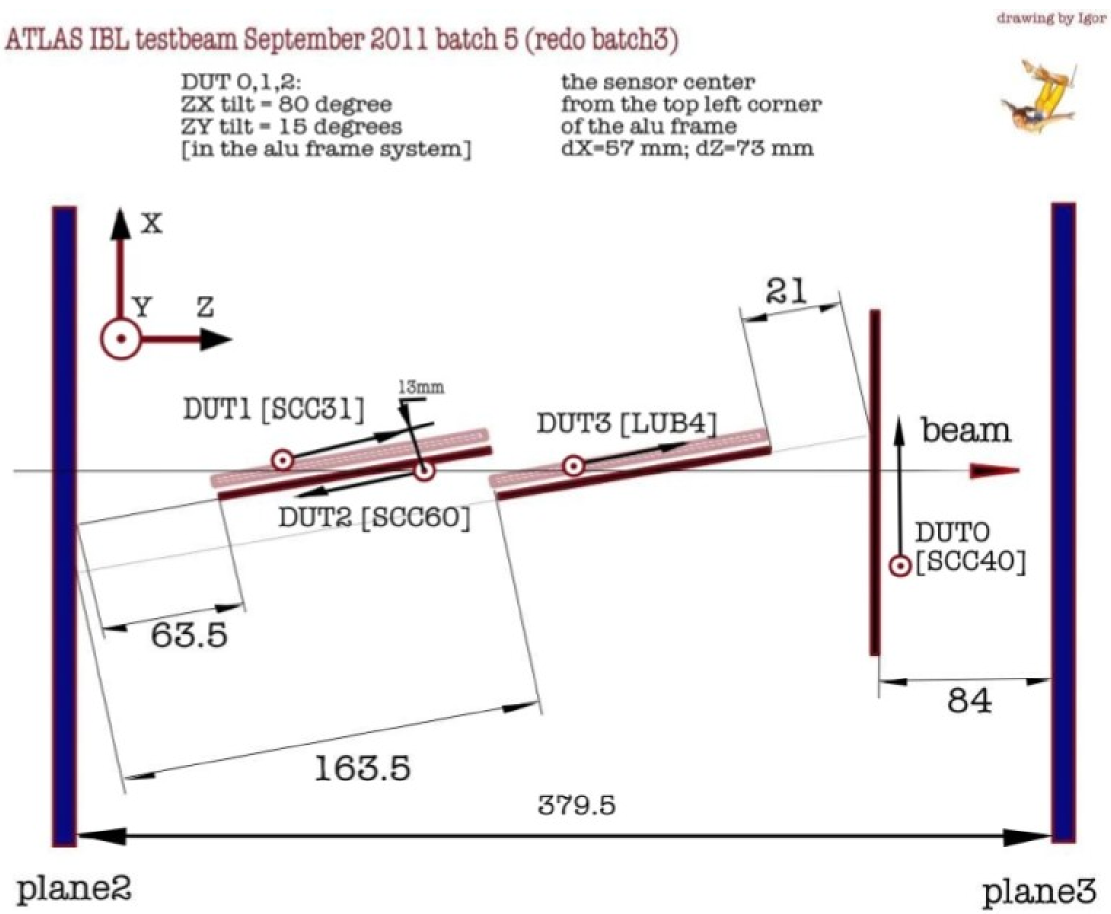
- Lab measurement with SCC24 (6e15 neq/cm^2 23MeV protons)
- Collimated Sr-90 beta-electron source
- Tuning
  - threshold of 1600 e$^-$(?)
  - 5ToT@10ke$^-$ (?)
- Stable long-term operation at 1100V
  - → stable operation possible also outside of specified region





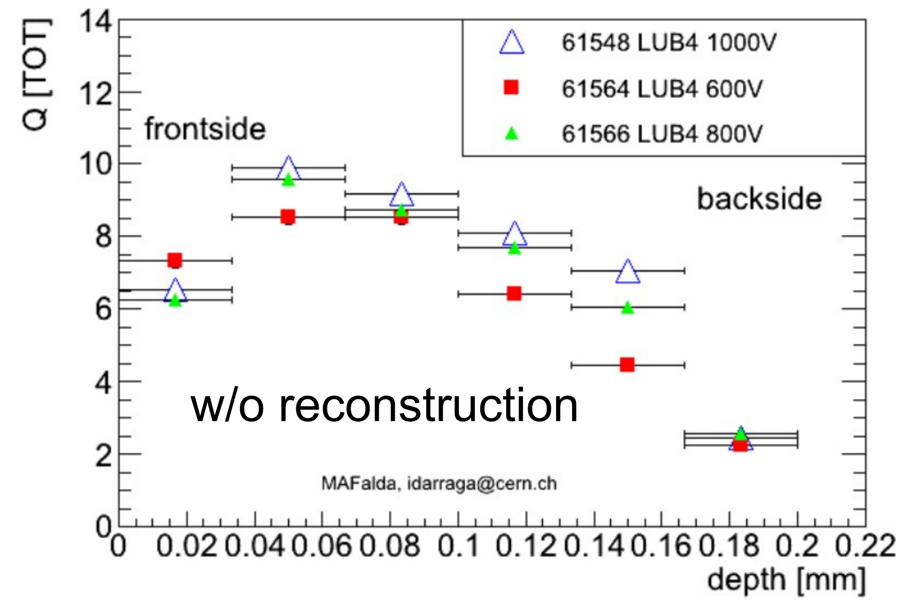
High-eta behaviour

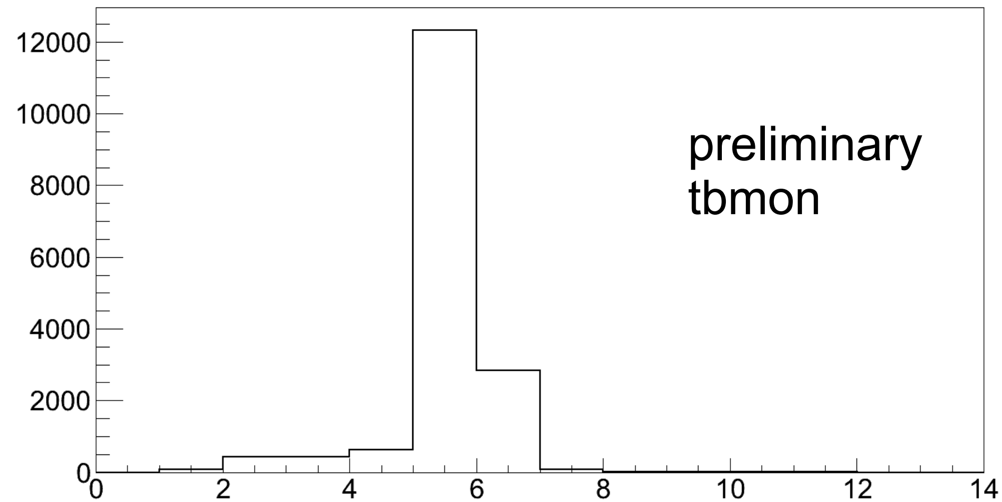
- Took testbeam data at an angle equivalent to eta=2.5
- Many changes necessary in the reconstruction
  - still waiting for “final” results from reconstructed data including the determination of the incidence angle from reconstrution (main source of uncertainty)
  - first preliminary impressions w/o reconstructed angle available

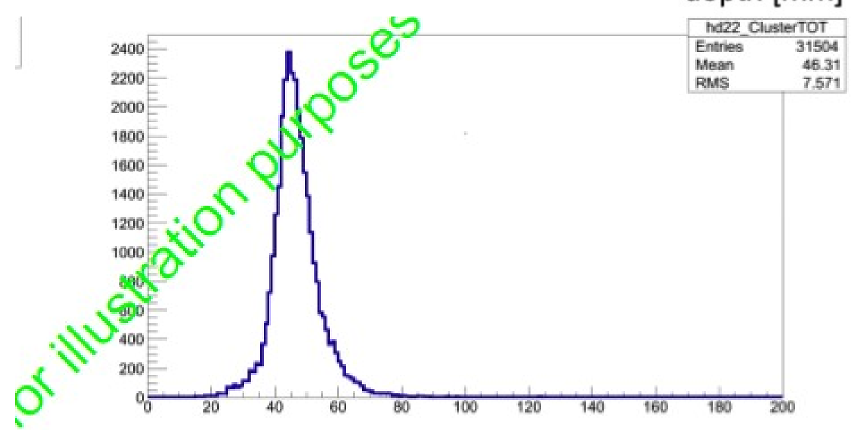


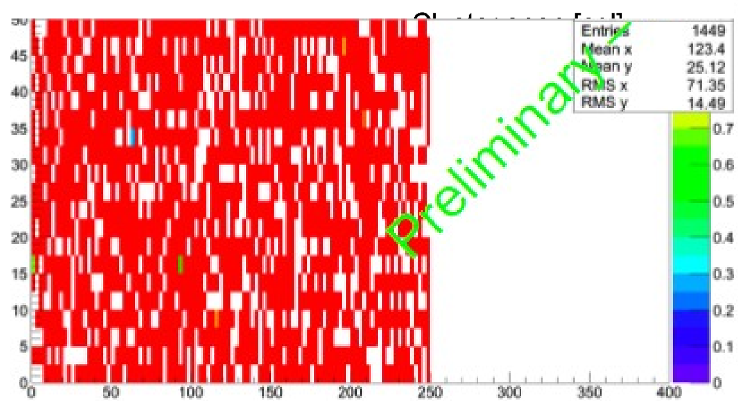
High-eta behaviour

- extremely preliminary
- for illustration only
- stay tuned





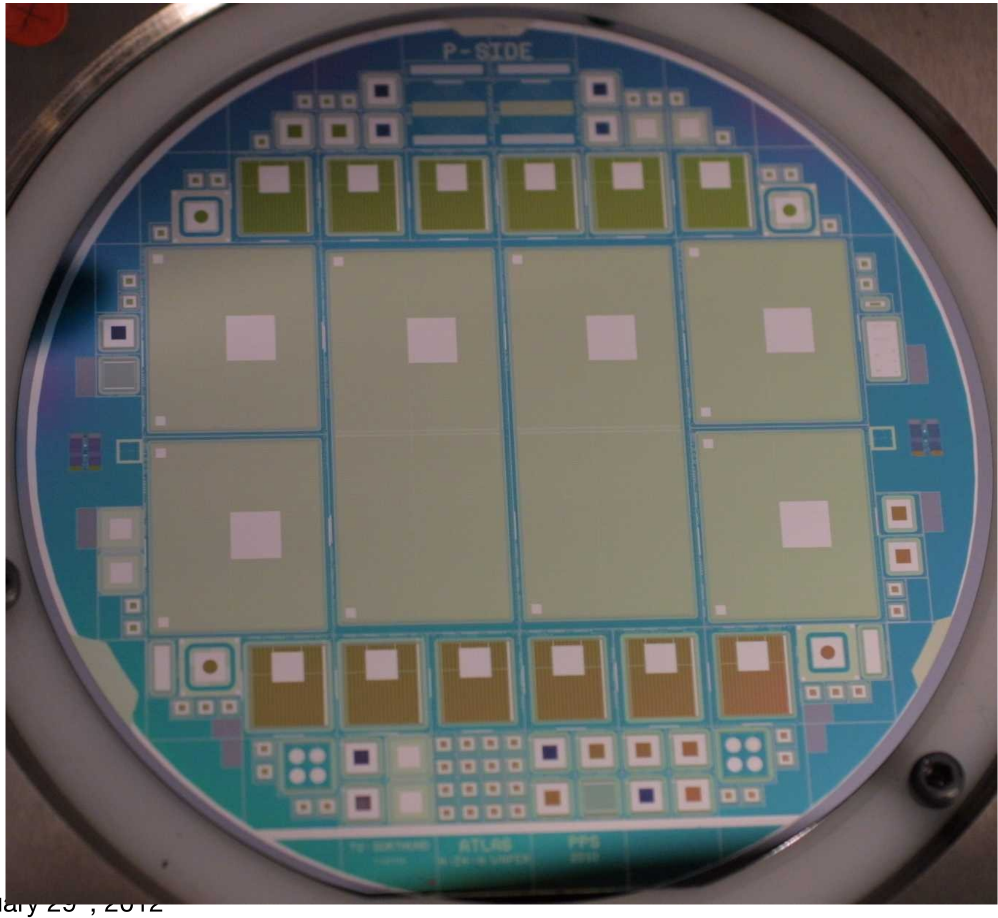




99.68% efficiency
only a preview (done with TbTupleAna, working on realisation with tbmon)

Gaining experience: n-bulk qualification wafer

- 6 FE-I4 sensors:
  - conservative and slim edge designs
  - one 2-chip and two 1-chip sensors of each design
- 12 FE-I3 SCs
  - various guard ring designs
- diodes, test structures…
- produced in 5 thicknesses:
  - 150, 175, 200, 225 and 250 μm
- studies of
  - production yield
  - charge collection

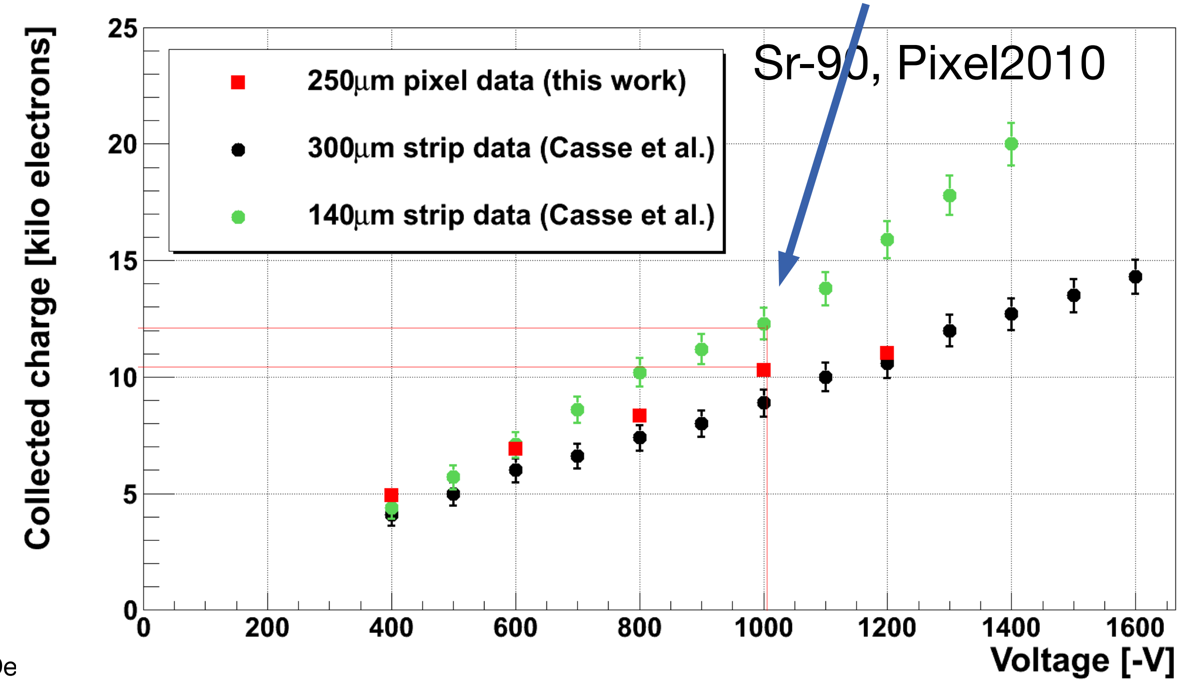


Wafer thickness

- Thinner sensors
  - generate about 1-2 ke⁻ more charge after $5 \cdot 10^{15}$ n_{eq}/cm^2 at 1 kV
  - have less radiation length
- "Wafer yield" (# of started wafers/# of delivered wafers)
  - 200 µm: ~90% (mean for 175, 200, 225µm)
  - for comparison: 250 µm: ~97%
- Bump-bonding
  - only down to 200 µm w/o handling wafer
- **Compromise: 200 µm → chosen as IBL candidate**

thickness	wafers ordered	wafers started	wafers received
250um	12	19	18
225um	6	12	11
200um	6	12	10
175um	6	12	11
150um	6	18	8

Expected charge: 10-12 ke⁻



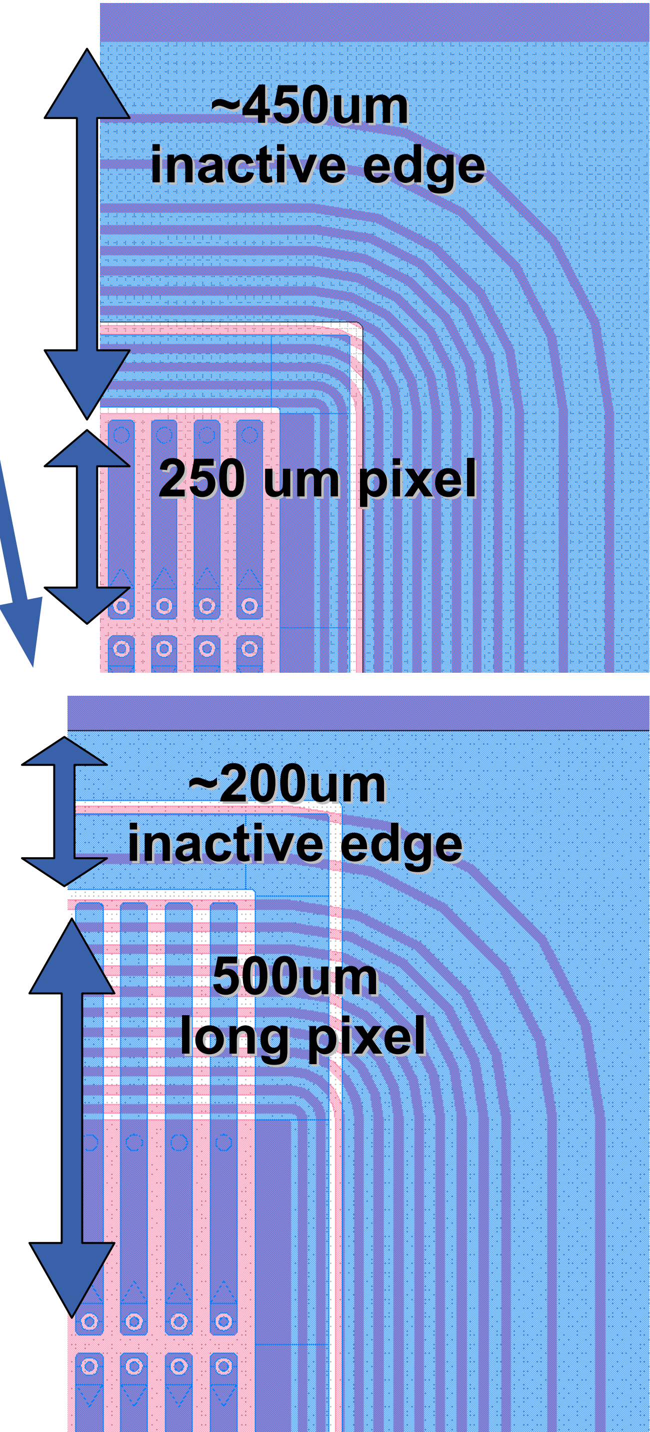
Yields

- Main criterium for a good sensor: $V_{breakdown} > V_{depletion} + Safety$
  - $V_{depletion}$ is typically < 40V for 250 µm and <30V for 200 µm
  - *Safety* was chosen as 30V
  - Sensor yield was measured after production and after dicing
  - Sensor yield includes all FE-I4-structures (1-chip and 2-chip sensors, conservative and slim-edge design) to increase the statistics
- "Sensor yield" (% of good FE-I4 sensors per delivered wafer)
  - 200 µm:
    - 97 ± 3 % were good after production
    - 97 ± 4 % were (still) good after (adjusted) dicing
  - for comparison: 250 µm
    - 94 ± 3 % were good after production
    - 93 ± 3 % were (still) good after dicing

Edge design(s)

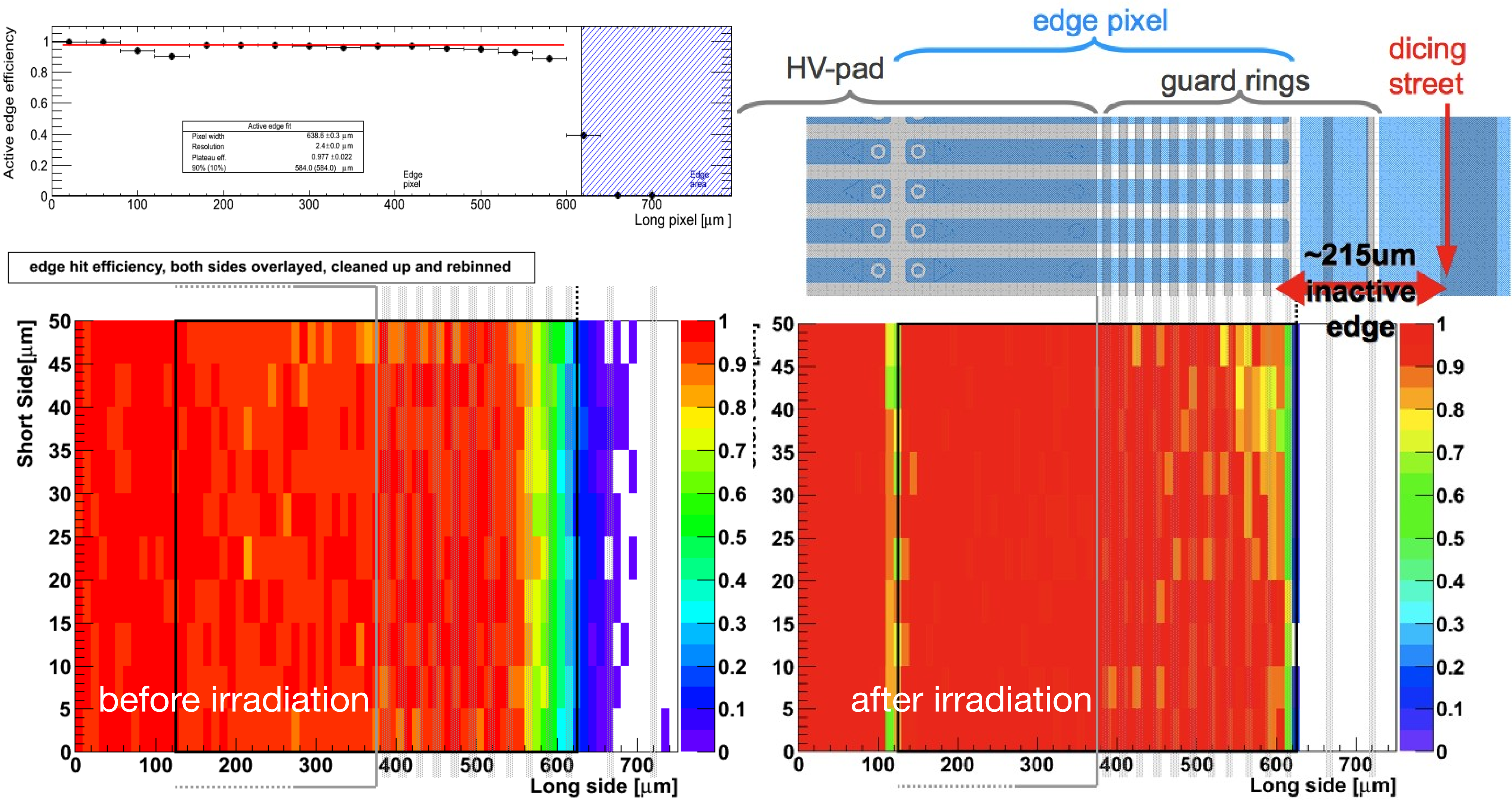
- Conservative design
  - as similar as possible to current ATLAS design
  - ~450 μm inactive edge width
  - electric field at edges homogenious
- Slim edge design
  - guard rings on p-side are shifted beneath the outermost pixels
    → least possible inactive edge (~ 200 μm)
  - less homogenious electric field, but charge collection after irradiation dominated by region directly beneath the pixel implant
    → only moderate deterioration
- Dicing trials result: equal yields

➔ slim-edge design chosen as IBL candidate



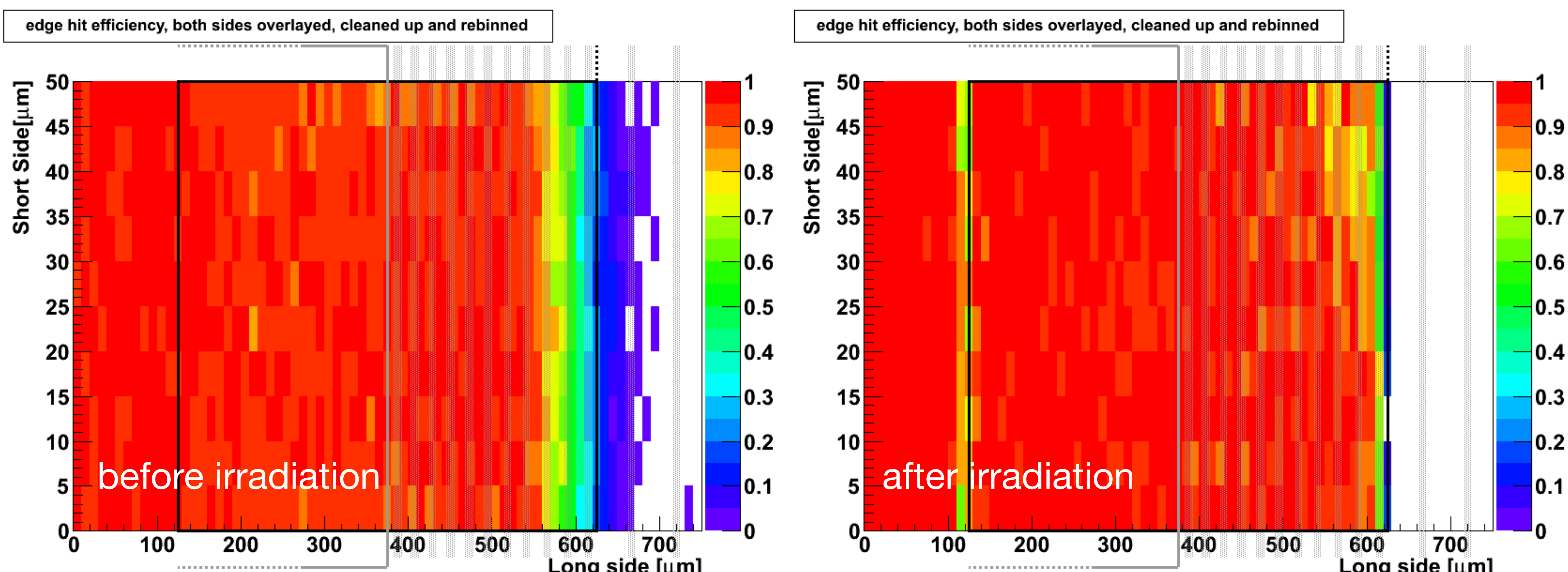
Slim-edge: testbeam results

- Estimation from dedicated test structure and TCAD simulations:
  - ~250 µm inactive edge before irradiation
  - ~200 µm inactive edge after irradiation
- Testbeam results based on FE-I4 slim-edge sensors confirm this:



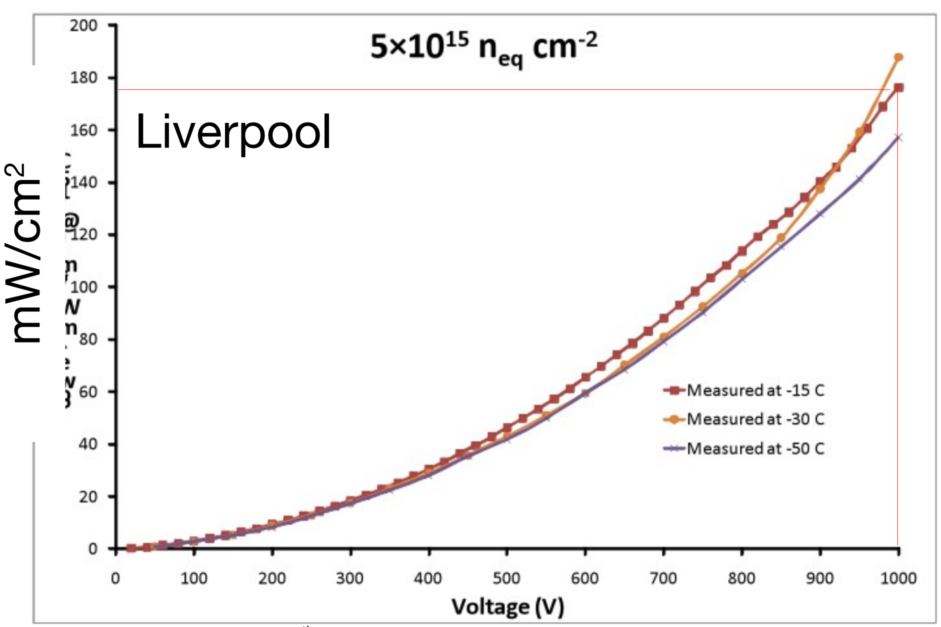
Slim-edge: testbeam results

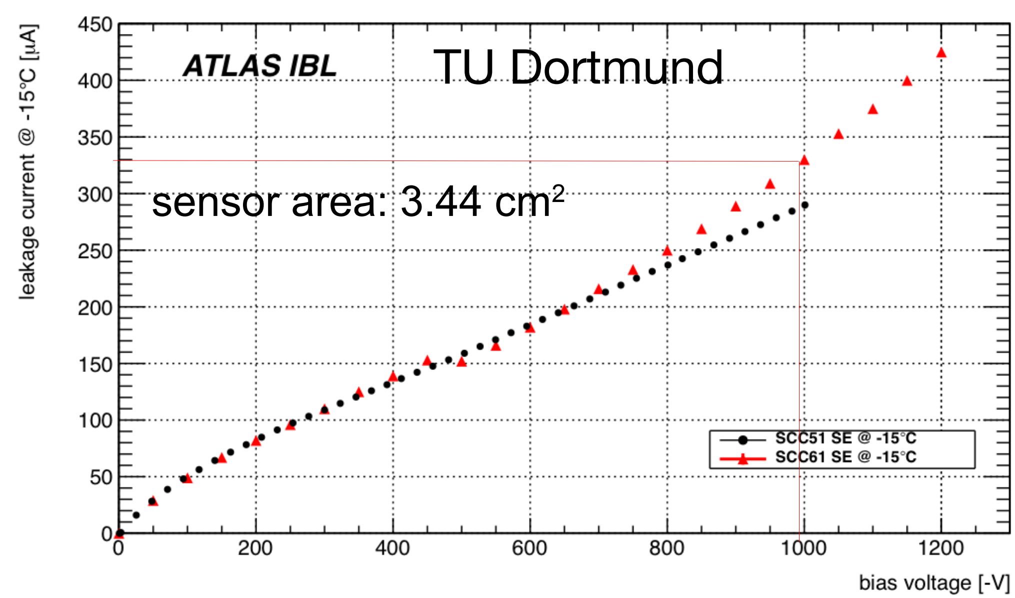
- Estimation from dedicated test structure and TCAD simulations:
  - ~250 µm inactive edge before irradiation
  - ~200 µm inactive edge after irradiation
- Testbeam results based on FE-I4 slim-edge sensors confirm this:
- Edge inefficiency:
  - 200 µm gaps between 2-chip modules
  - 250µm to 200µm inactive edges (before and after irradiation)
    → 98.3% to 98.5% geometric efficiency (compared to 97.4% required)



Leakage current/power dissipation

- Measurements done on few assemblies irradiated to 5-6 $\cdot 10^{15}$ n_{eq}/cm^2 with 23-MeV protons after gluing a Pt-1000 directly to the sensor to have a precise temperature measurement without offset
  - ~100mW/cm², compatible with an annealing factor of ~2
- Comparison to independent measurement from Liverpool on strip sensors in agreement taking into account annealing
- ✓ Power dissipation is safely below 200 mW/cm² at 1 kV and at -15°C
- ✓ Leakage current ~12 nA/pixel at 1kV, i.e. < 25 nA/pixel specification
- ✓ Operation above 1kV possible, no breakdowns observed after irradiation

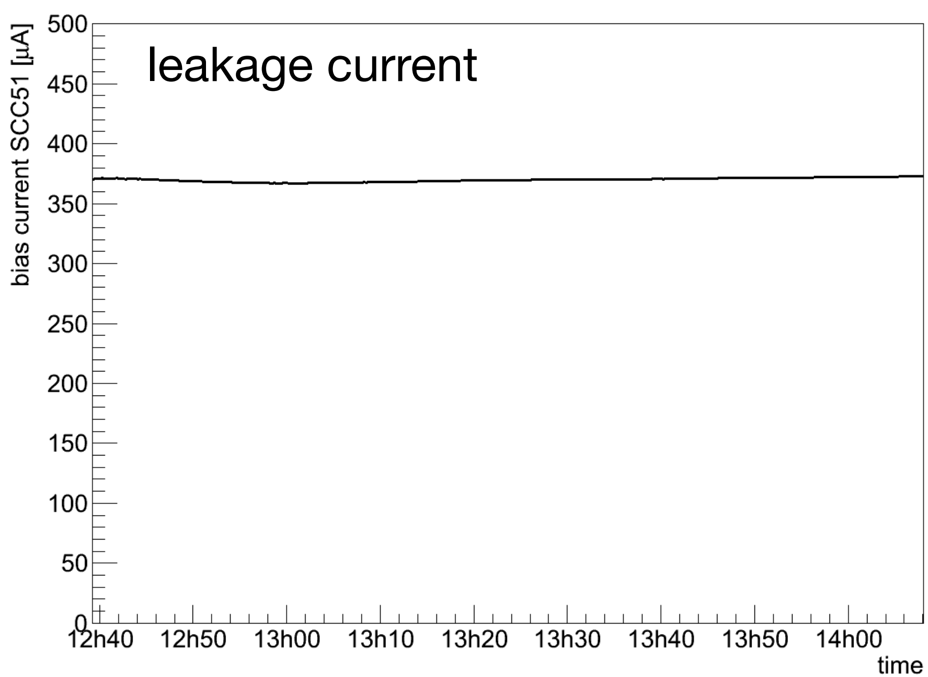


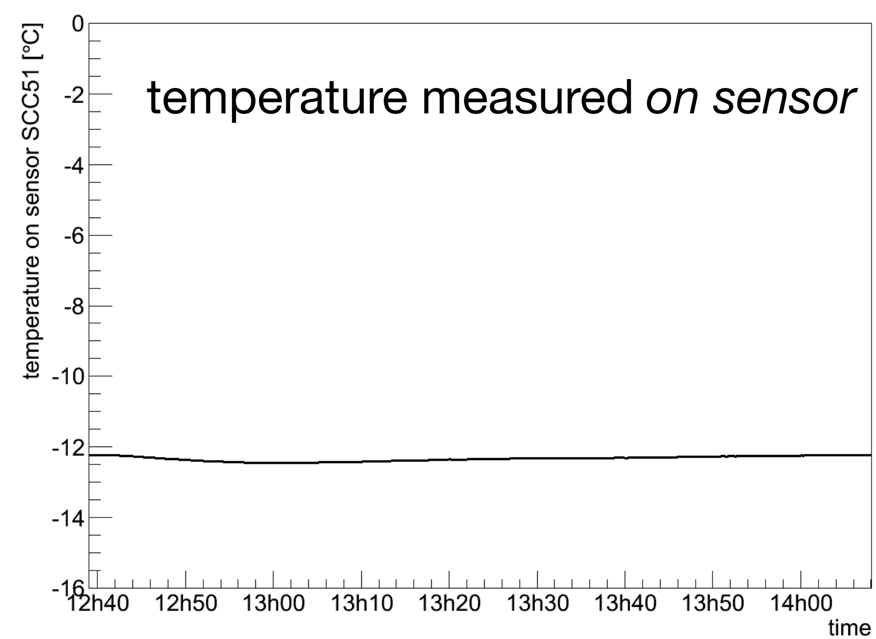


Operation at -15°C

- Uncertainties with respect to the sensor temperature
  - glued a Pt-1000 to the SCC51 sensor (5e15 irradiated in Karlsruhe)
  - operated the assembly (FE configured) using a chiller for 1.5h
- Results:
  - stable temperature at -12.3°C
  - stable operation with 1kV *on the sensor*, no signs of thermal runaway
  - 370µA leakage current, compatible with RD50/Liverpool measurements when taking into account annealing (120 minutes at 60°C)

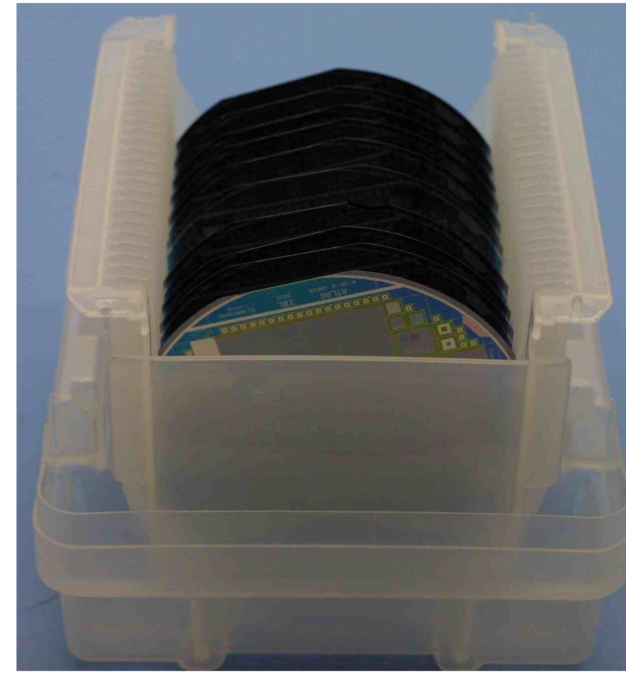
✓ Stable operation at -15°C

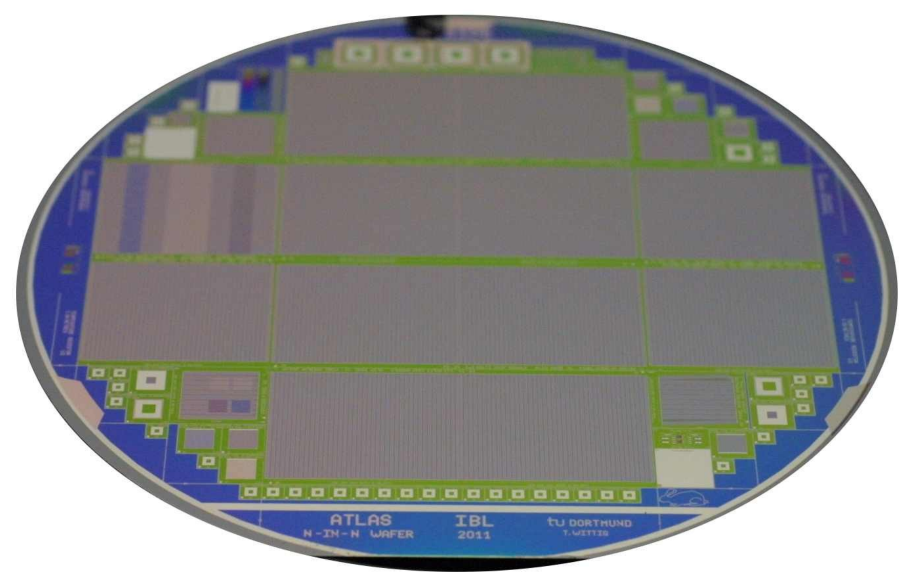




Production status

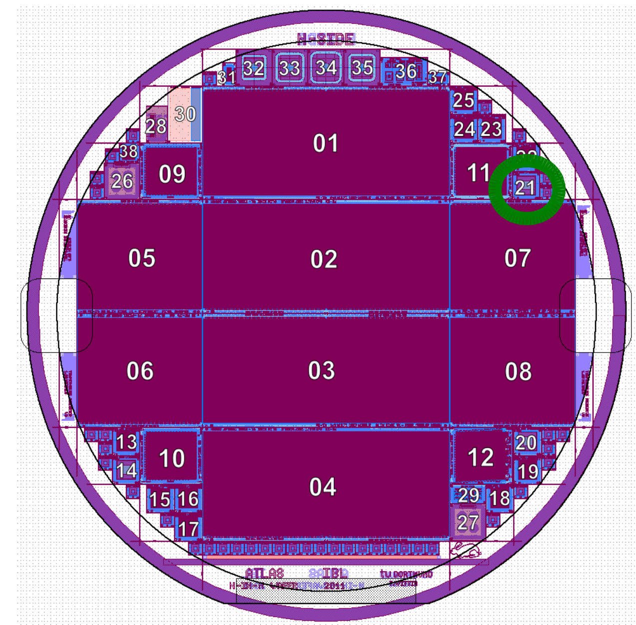
- 3 orders for 50 + 25 + 75 = 150 sensor wafers, where each wafer carries four FEI4 double chip sensors (DCS)
- wafers with two, three or four working FEI4 DCS will be counted
- current status: 119 accepted planar sensor wafers from in total 6 production batches



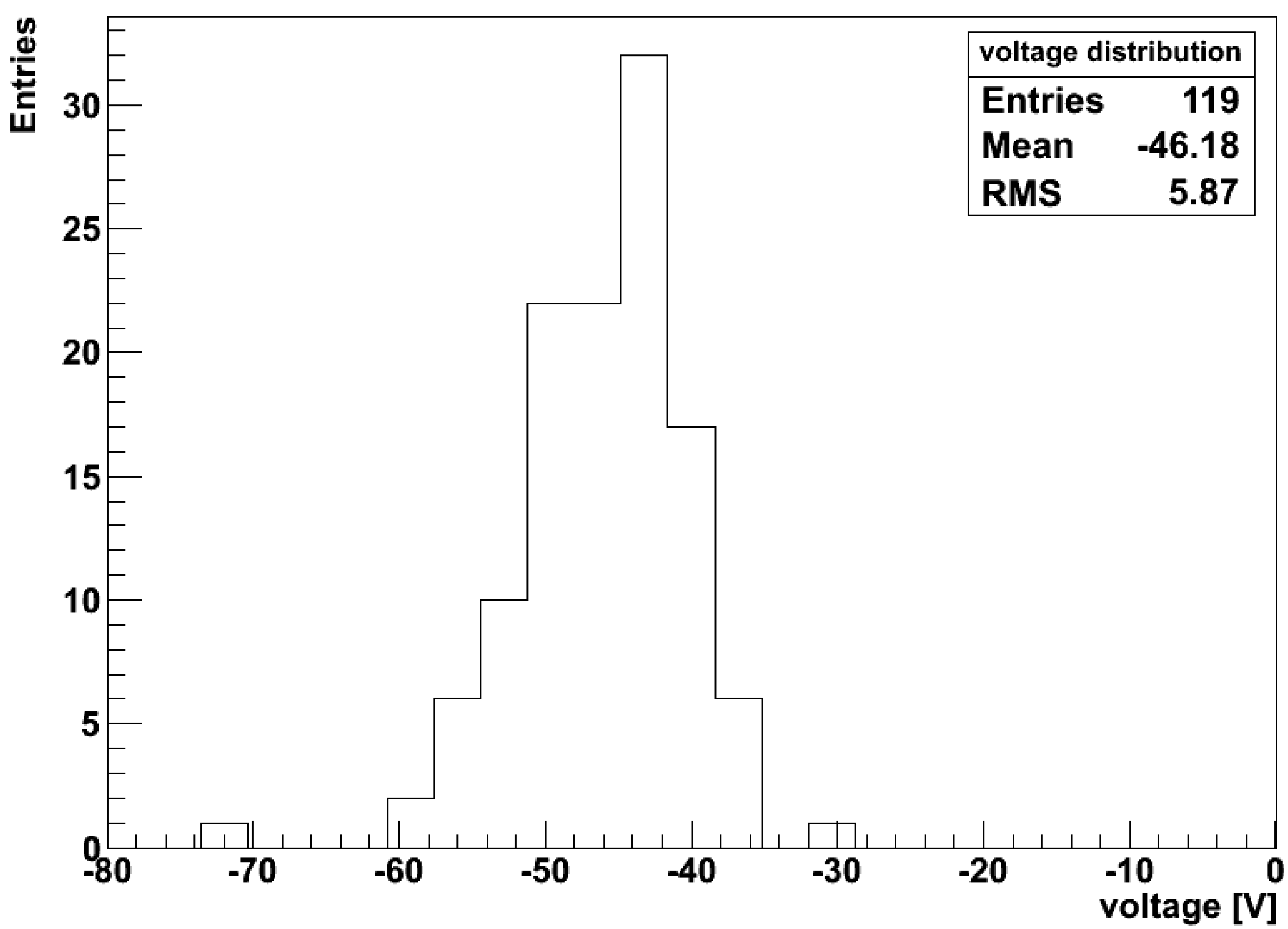


Quality and yield of received wafers

- measurement results performed at CiS
- these include IV measurements and depletion voltage distribution of 119 depletion voltages

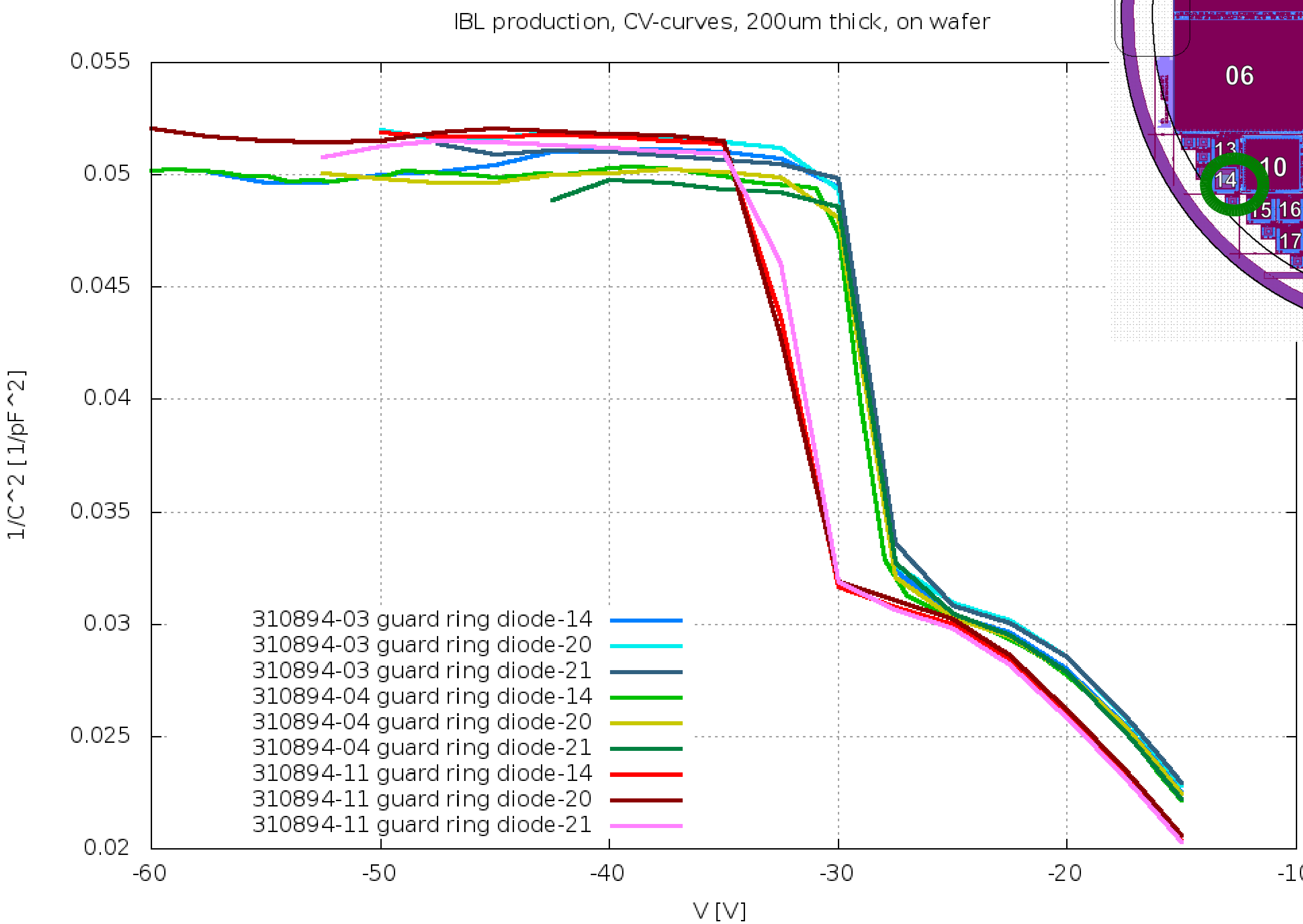


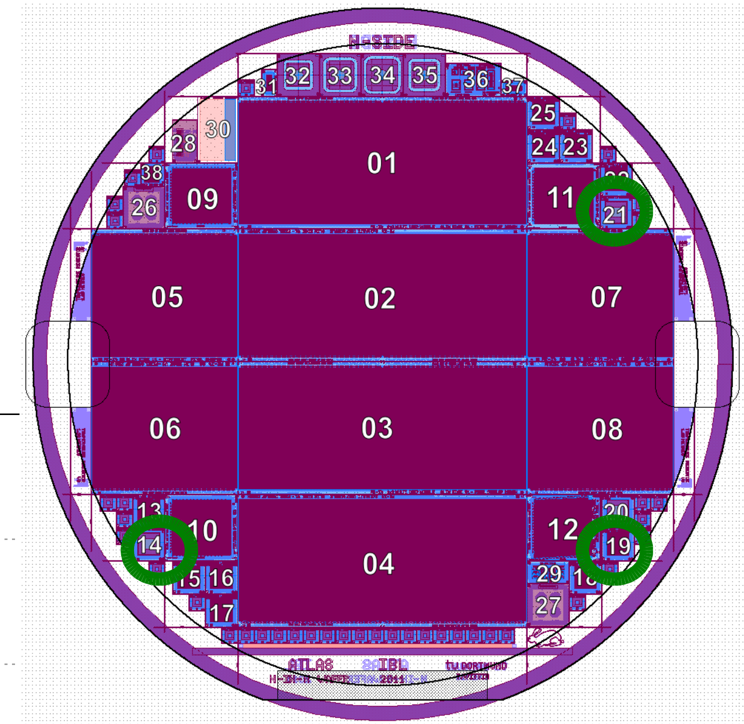
Depletion voltage 46±6 V



Quality of received wafers (CV, depletion voltage)

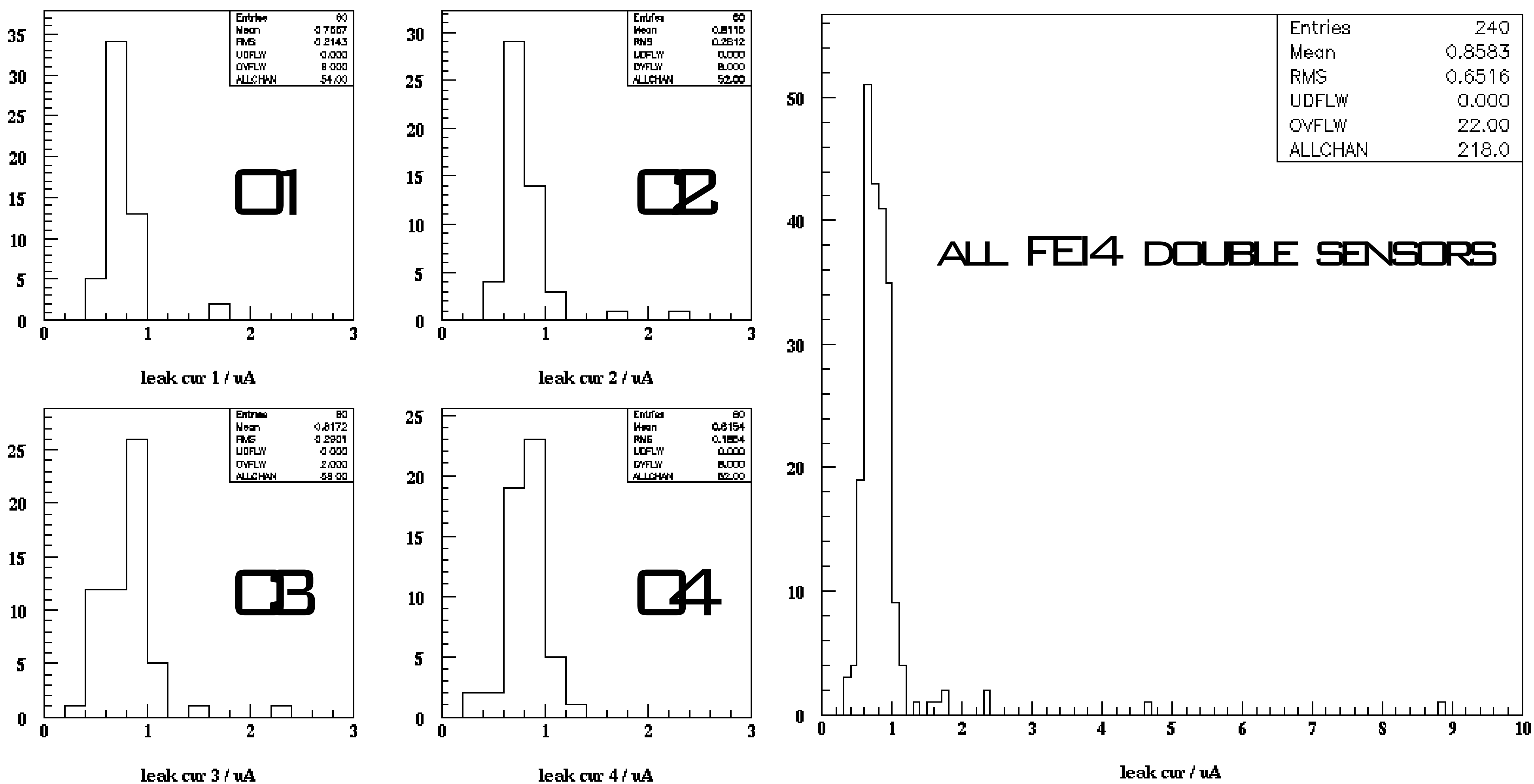
- on a few wafers, the homogenity of the CV characteristics for different pad diodes 14, 20 and 21was checked





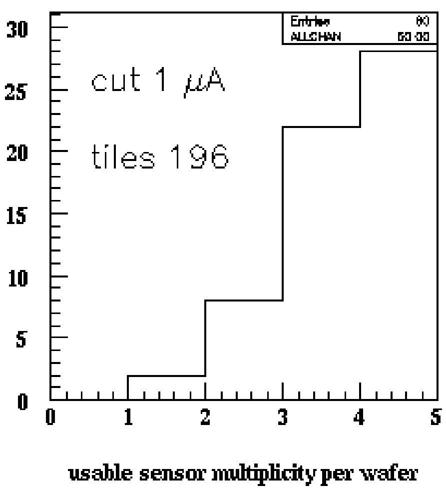
Quality and yield of received wafers (IV, leak.curr.)

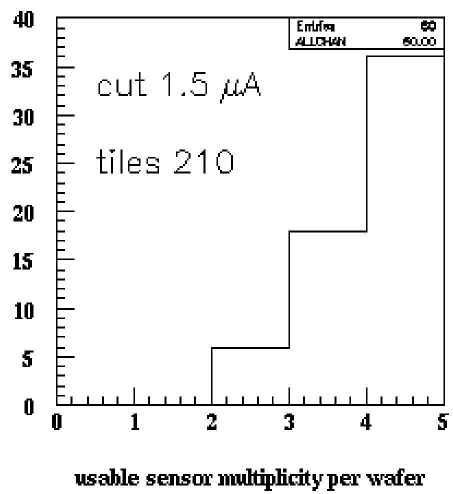
- leakage current at operation voltage (Vdep + 30V) at ambient temperature
- acceptance limit is 2 µA for a double sensor

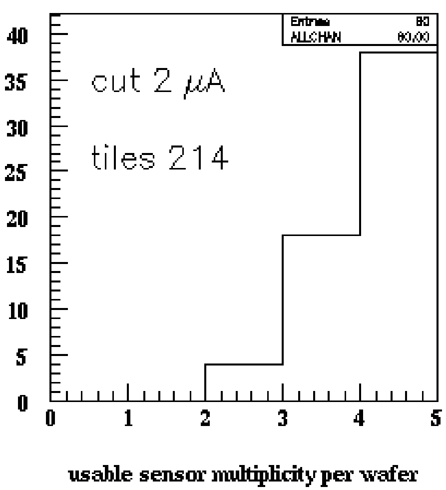


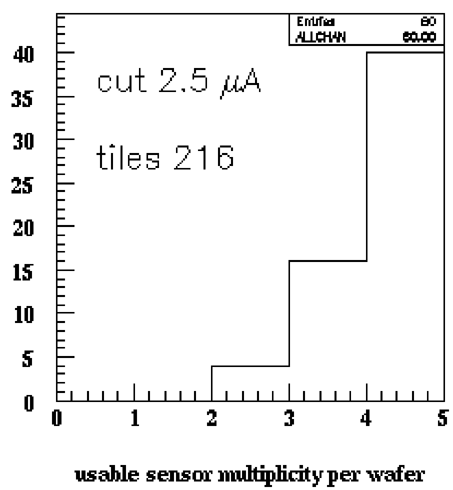
Yield of FEI4 Double Chip Sensors

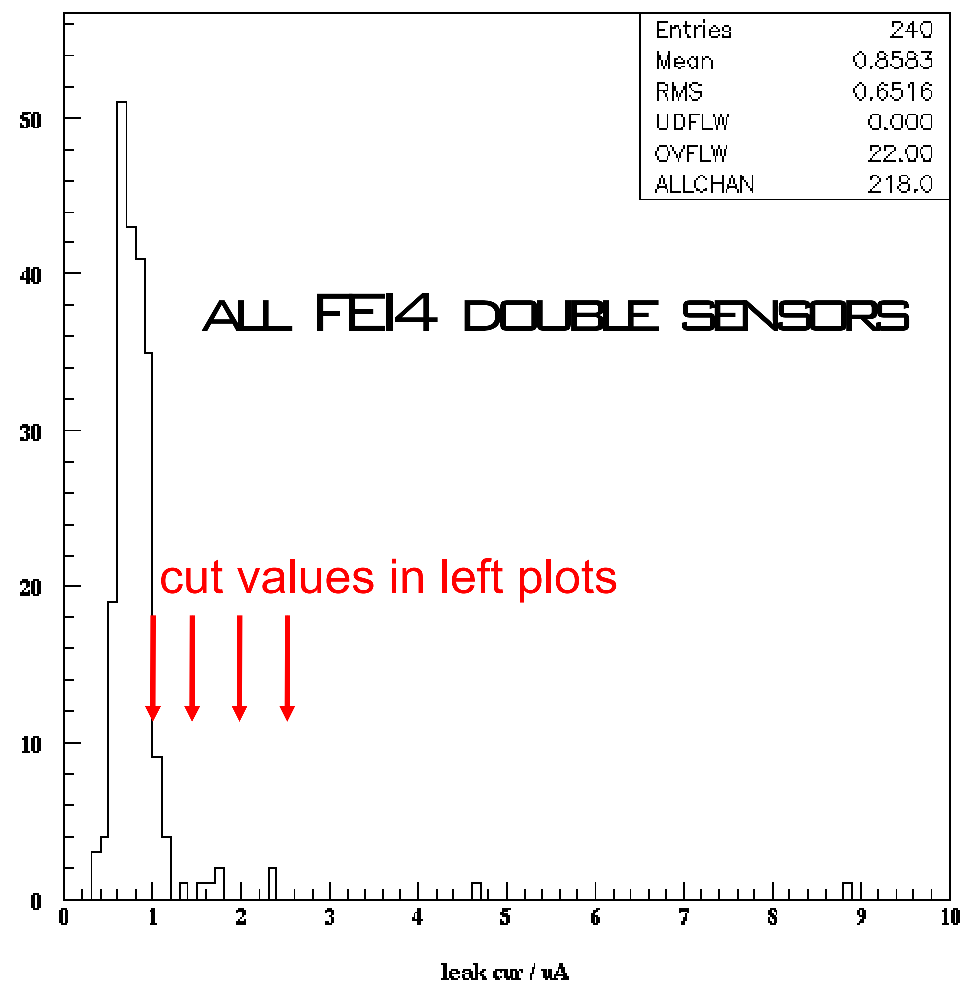
- based on IV measurements carried out @ CiS
- histograms of acceptable tiles per wafer depending on leakage current cut
- mostly 4-tile wafers, some 3-tile wafers – 2-tile rather exception







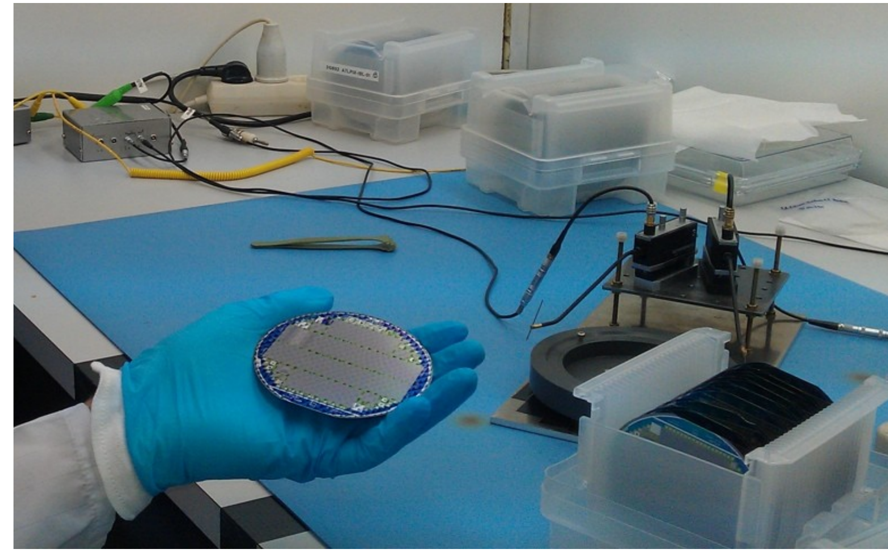


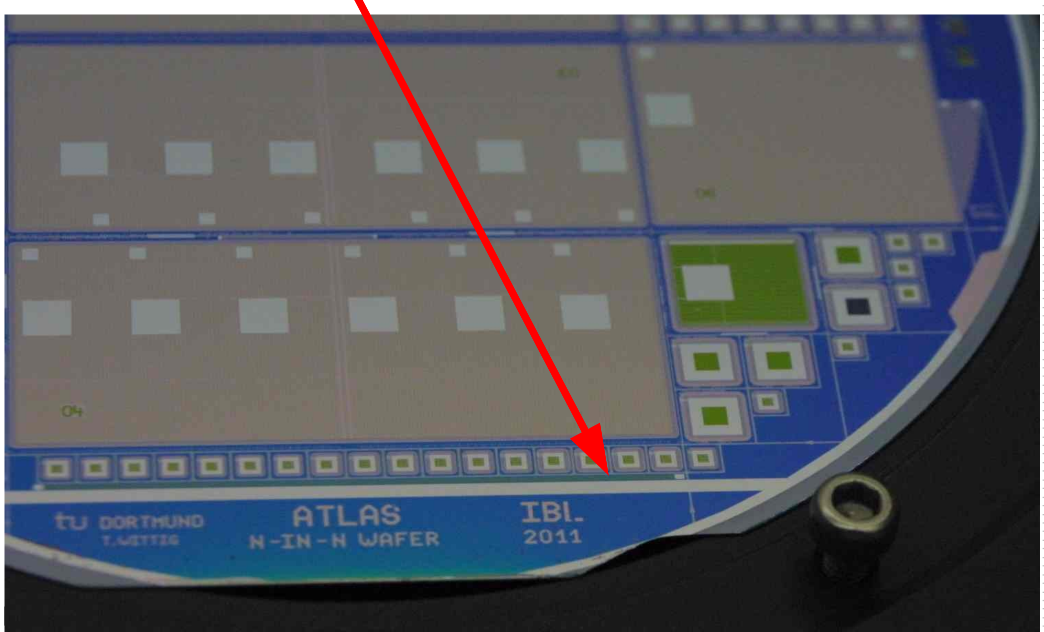


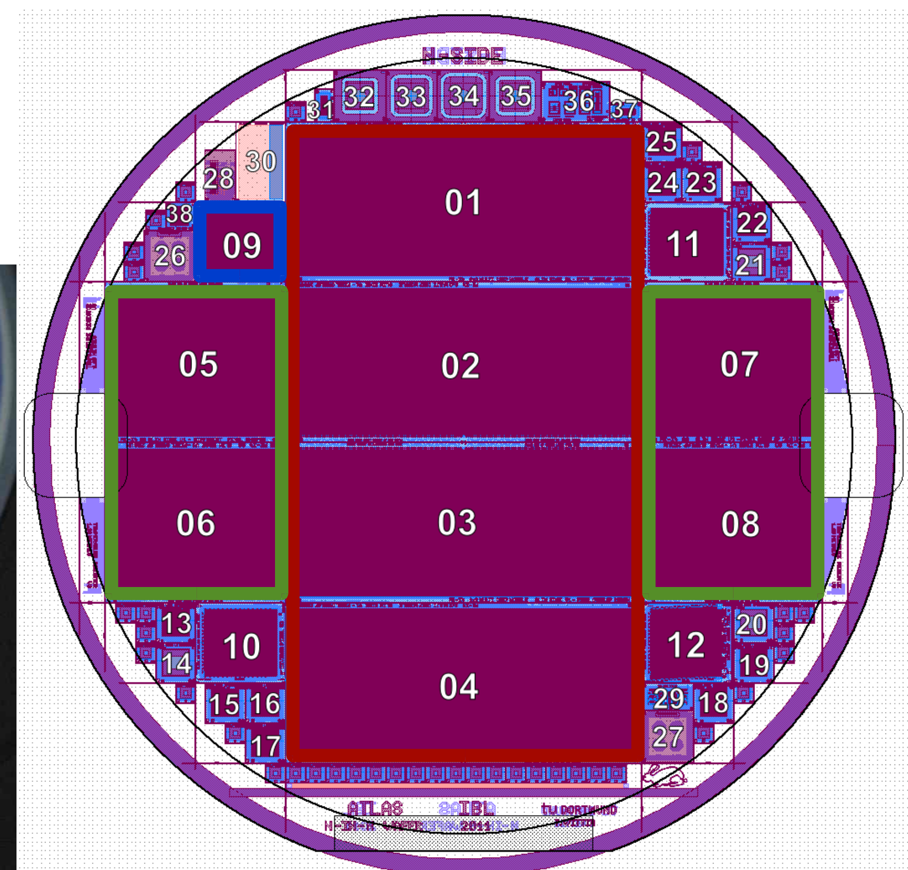
Planar ATLAS IBL Sensors

Cross Checks @ Dortmund

- Visual and optical checks of all wafers, which includes the surfaces and the wafer labeling in terms of batch and wafer number
- IV measurements are done on
  - 4 FE-I4 Double Chip Sensors
  - 4 FE-I4 Single Chip Sensor
  - 1 FE-I3 Single Chip Sensor
- Example: two wafers we received with a slight damage (still performing well)



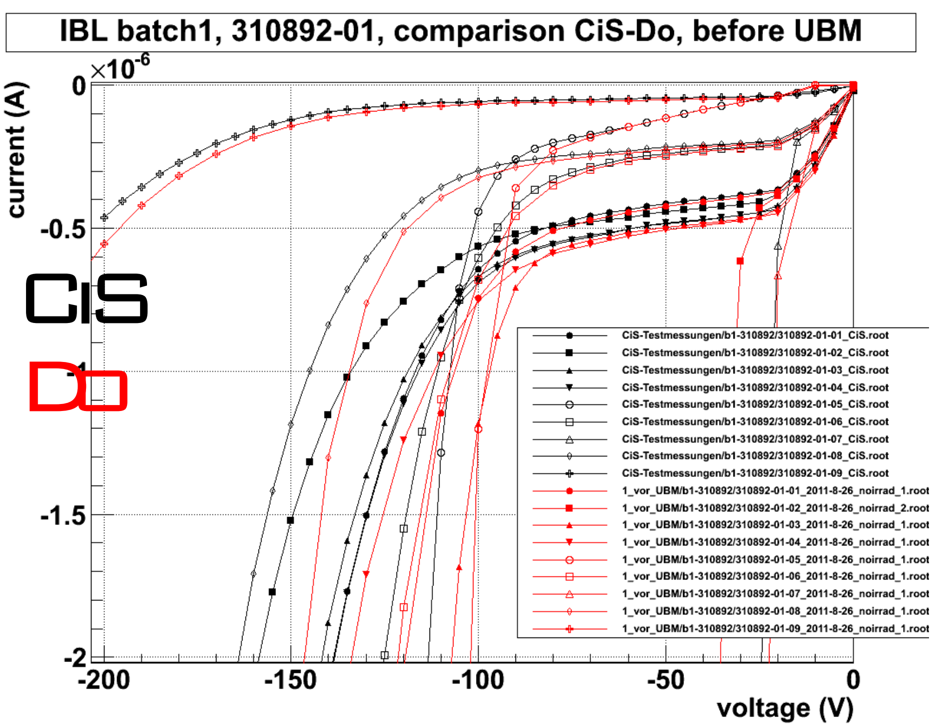




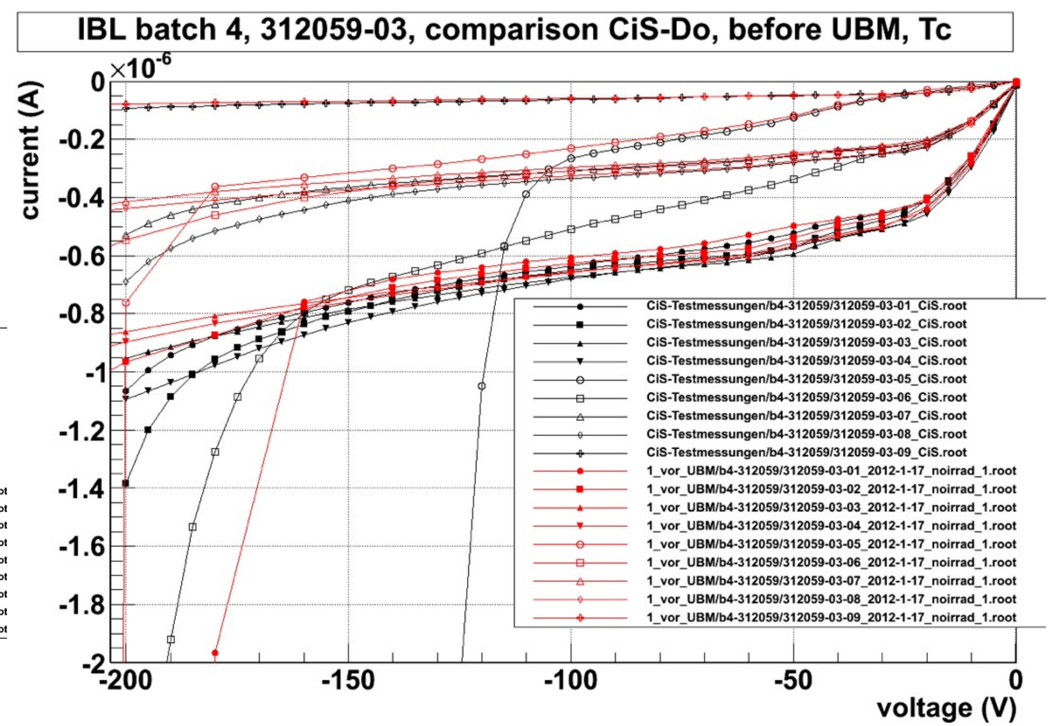
Cross Checks @ TU Dortmund

- For 30 out of 119 wafers, IV curves on FEI3 and FEI4 structures were taken as independent measurement at TU Dortmund
- good agreement between measurements by vendor and TU Dortmund concerning break down voltage and leakage currents

from the first batches 2011



from the latest batches 2012



Cross Checks @ Dortmund

- Acceptance criteria:
  - $I_{leak}(V_{depl}+30V) < 2\mu A$
  - $slope=I_{leak}(V_{depl}+30V)/I_{leak}(Vdepl) < 1.6$
- yield distribution of functional FEI4 double chip sensors:

	batch 1	batch 2	batch 3	batch 4	batch 5	batch 6	sum
received wafers	20	22	18	20	17	22	119
received DCS	80	88	72	80	68	88	476
good DCS	69	76	64	70	62	83	424
yield	86.3%	86.4%	88.9%	87.5%	91.2%	94.3%	89.1%

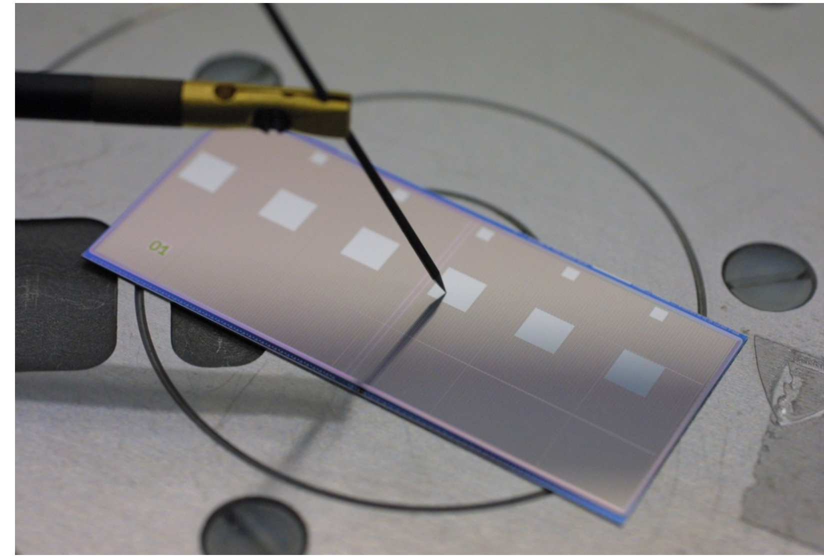
- Bookkeeping: provide sensor data for the IBL data base, e.g.
  - batch, wafer and sensor structure numbers
  - during production steps:
    - characteristic leakage currents, depletion voltages, acceptance
    - raw data of available IV and CV measurements

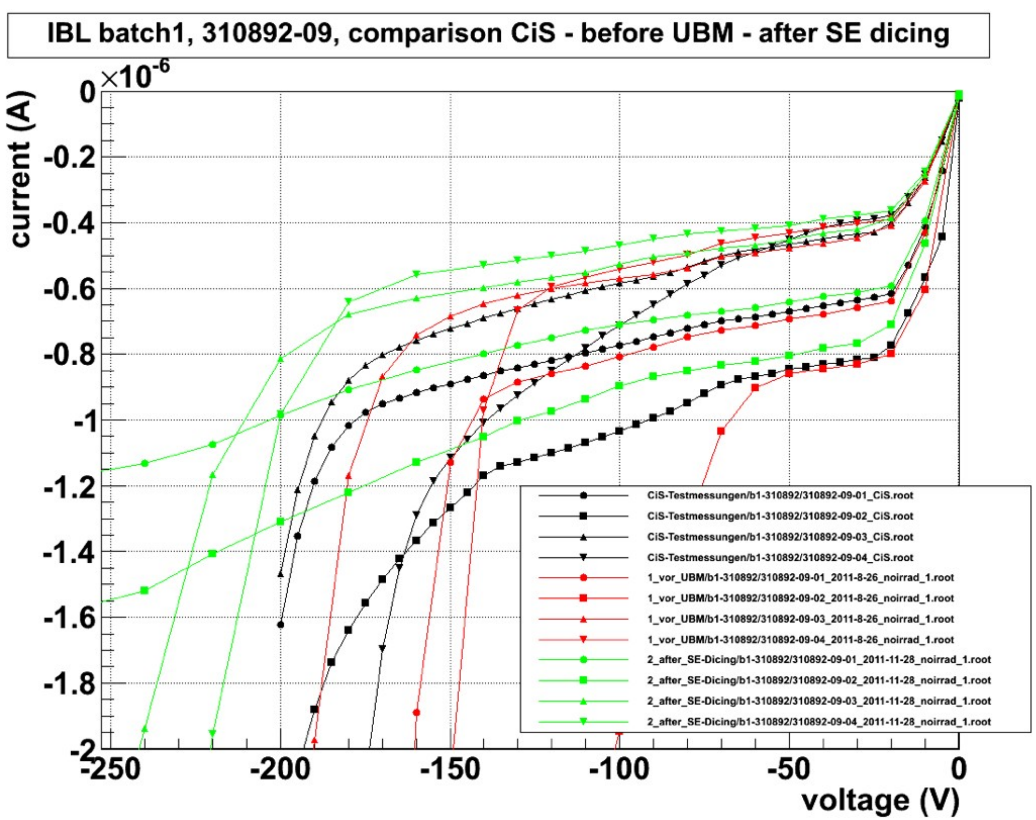
Overview

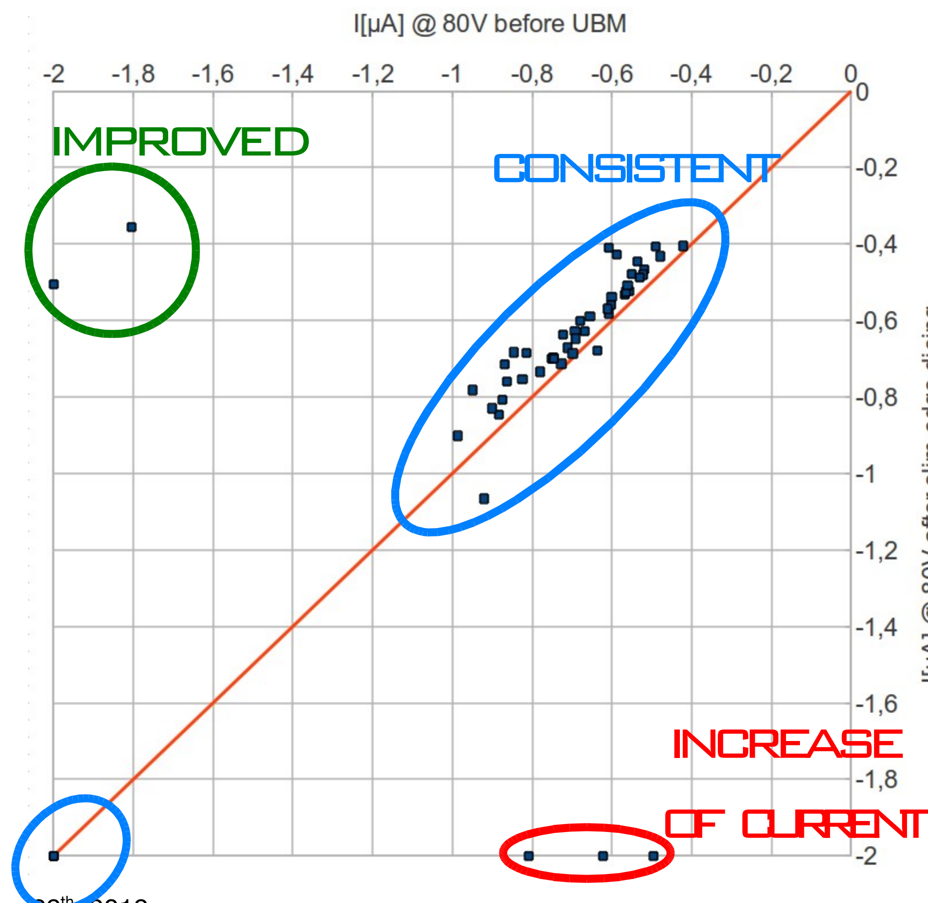
- 119 wafers accepted so far
- expect to have ~ 420 functional FEI4 double chip sensors for the IBL, i.e. already 94% of target number of 448 (which is 2x IBL)
- plus ~ 320 functional FEI4 single chip sensors for further tests, irradiations, test beams, R&D, ...
- all 119 wafers already went to IZM for UBM process and dicing
- diced structures have been sent to Dortmund
  - for labeling on scratch marks
  - to provide IV on diced structures
  - to decide on the usage for flip-chip assemblies
- next and probably last delivery
  - is scheduled for April 2012
  - should fulfill the contracts of in total 150 wafers

Quality Control after dicing

- received at Dortmund structures from 39 wafers
- checked 56 out of 156 FEI4 2x1 DCS
- observe high yield on FE-I4 DCS including dicing step







Summary

- For the ATLAS IBL, planar n-in-n sensors have been chosen which are
  - as similar as reasonable to the current ATLAS Pixel sensor
  - modified to match the new FE-I4 readout chip
  - using a slim-edge design enabling inactive edges of only ~200-250 µm
  - produced on only 200 µm thin wafers
- Test-beam results
  - indicate > 97% efficiency also at 0° incidence angle and after 6e15 neq/cm2 and 1 GRad
  - show that most charge/efficiency is lost in the bias rail/dot region
    - average efficiency *very* close to 100% expected due to r-phi and eta inclination
  - give first hints (preliminary) that at 1kV, the full 200 µm thickness are efficient at high eta angles
- Production status
  - received 420 good 2-chip sensors (224 needed to outfit IBL, 448 ordered)
  - average production yield ~89%, only few wafer losses due to breakage
  - slim-edge dicing working well, ~150 diced sensors in hand

  - IBL production on <111> wafers, but received some <100> wafers to try out scribe/cleave/passivate method for planar AFP sensors with UCSC