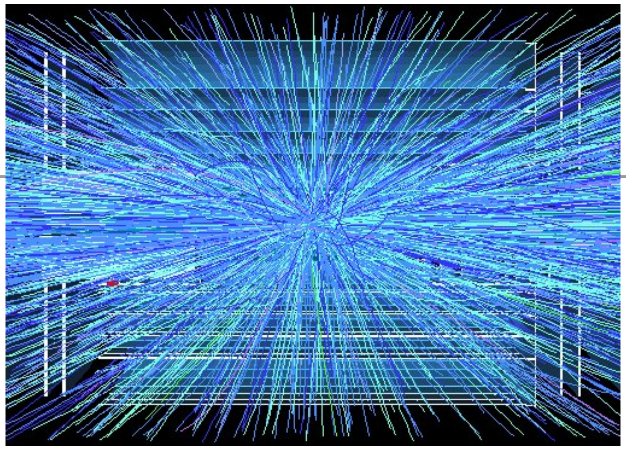
Recent results of the ATLAS Upgrade Planar Pixel Sensor R&D Project

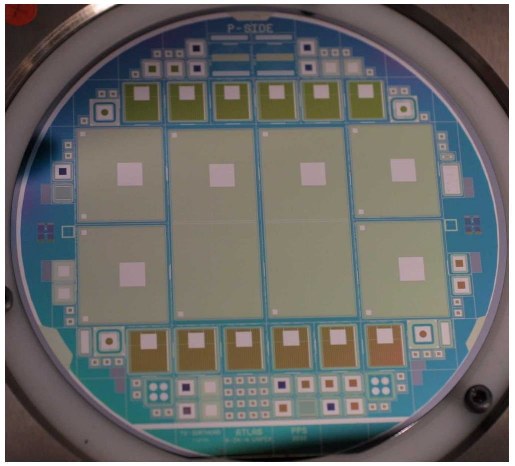
Giovanni Marchiori
LPNHE - Paris (CNRS/IN2P3)

for the ATLAS Upgrade PPS Collaboration

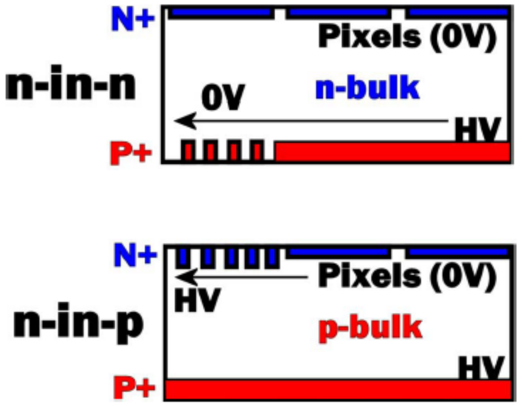
RD11, Firenze, 7/7/2011

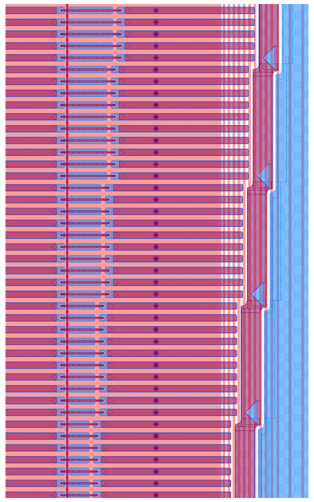
Outline

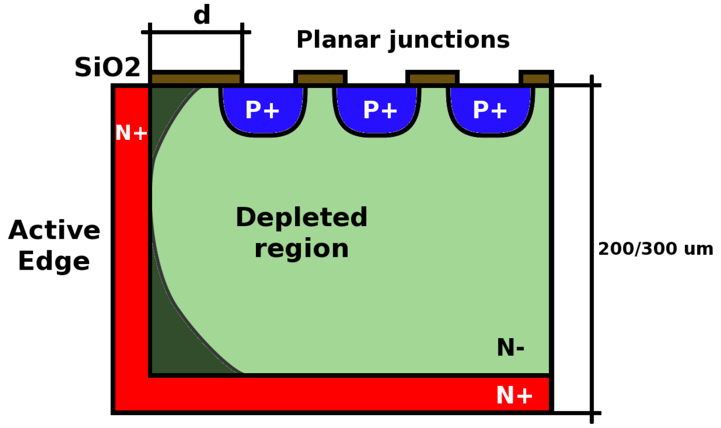


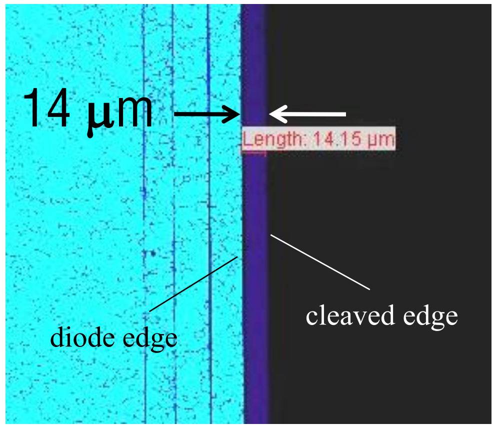


- LHC and ATLAS tracker upgrade paths
- ATLAS Planar Pixel Sensor R&D Project
- Radiation hardness
  - n-in-n and n-in-p sensors
- Sensor thinning
- Slim/active edges
- Other activities
- Conclusions





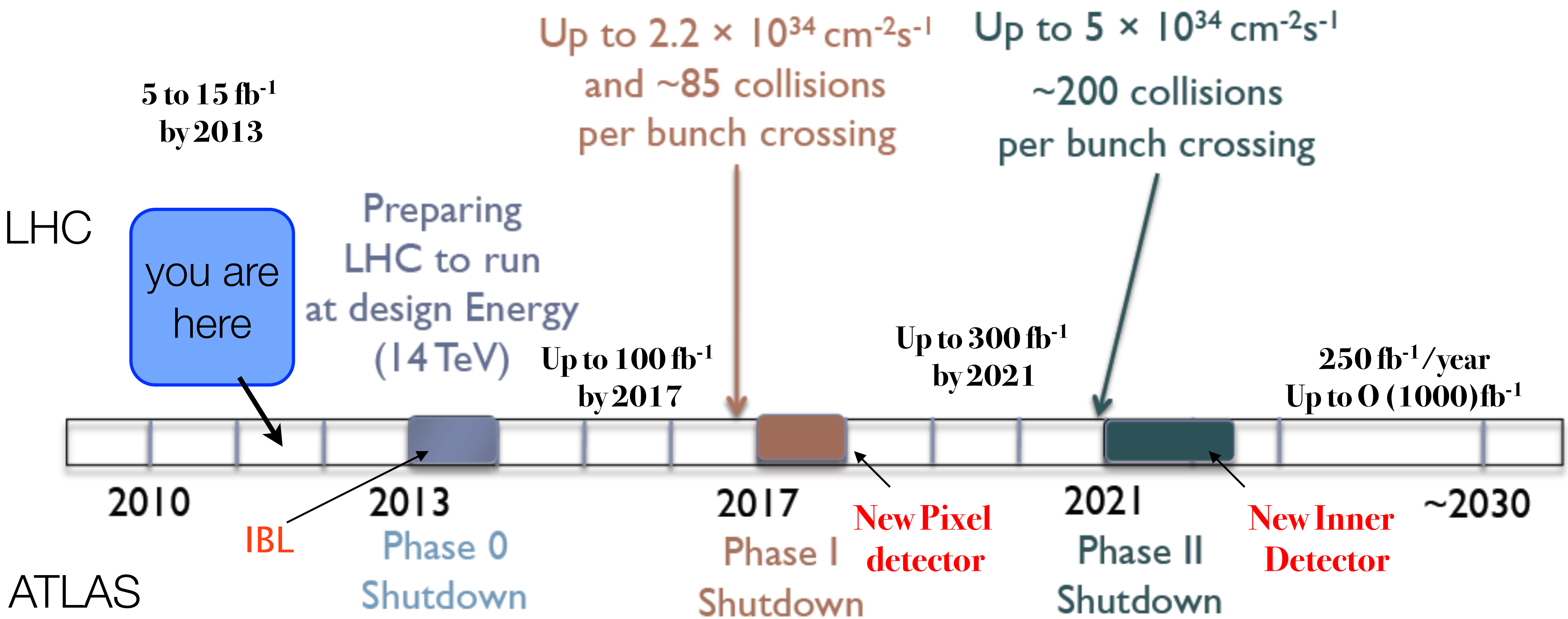




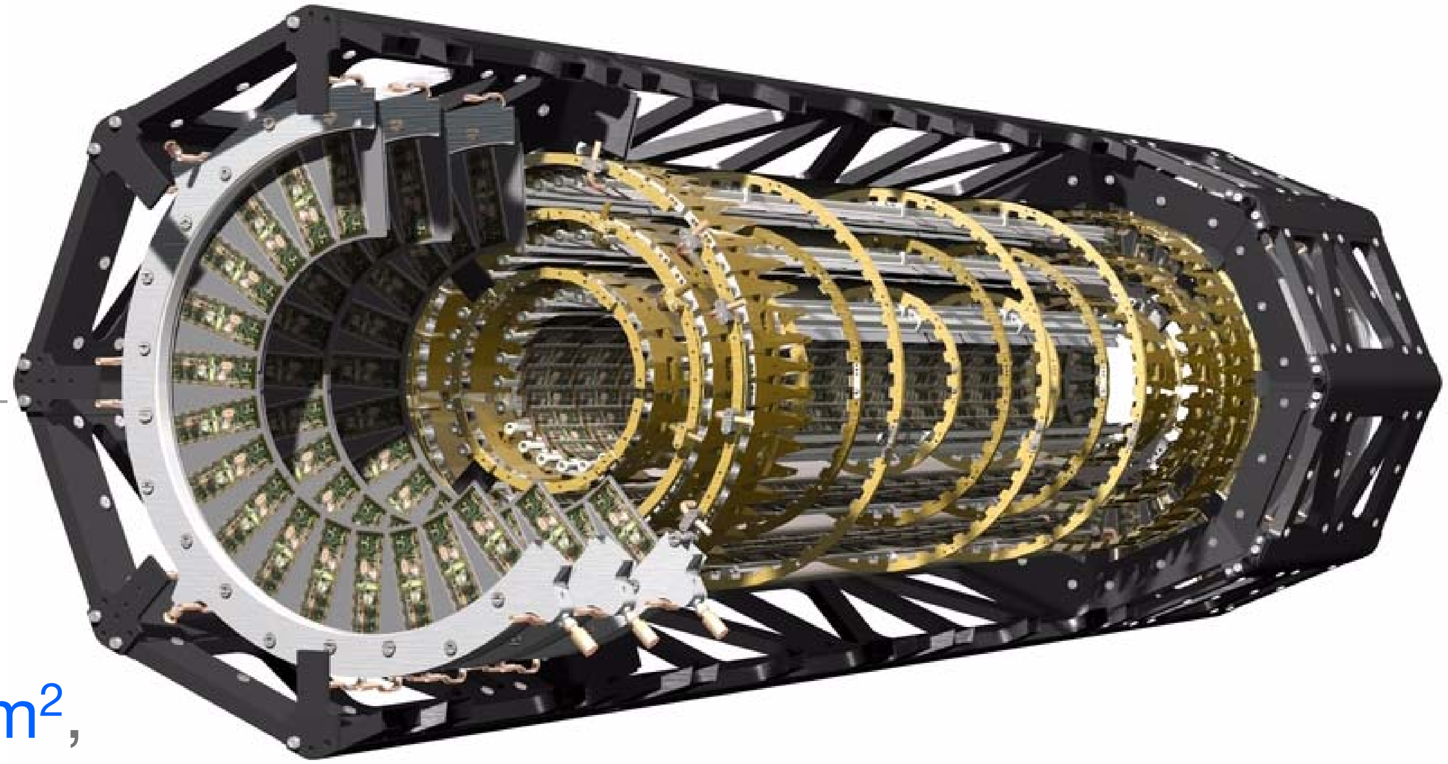
LHC and ATLAS tracker upgrade scenario

- LHC "ultimate" goal: extend physics reach (Higgs/SUSY/extradimensions/new bosons) with x5-10 increased peak luminosity (HL-LHC, or Phase-II)

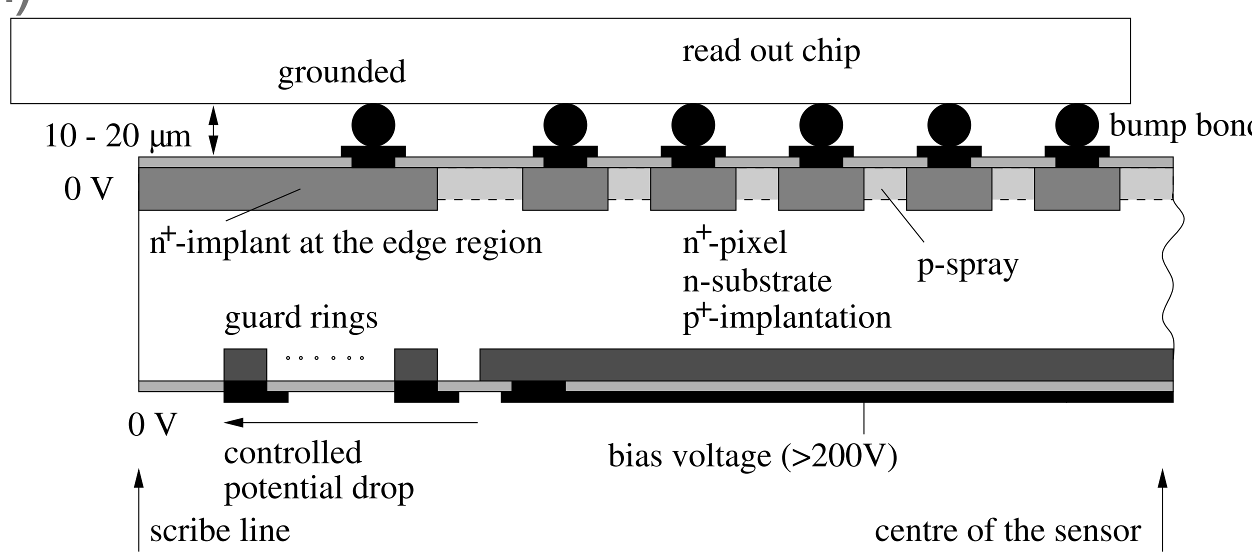
- ATLAS tracker upgrade: several steps to cope with increasing peak luminosity and total dose



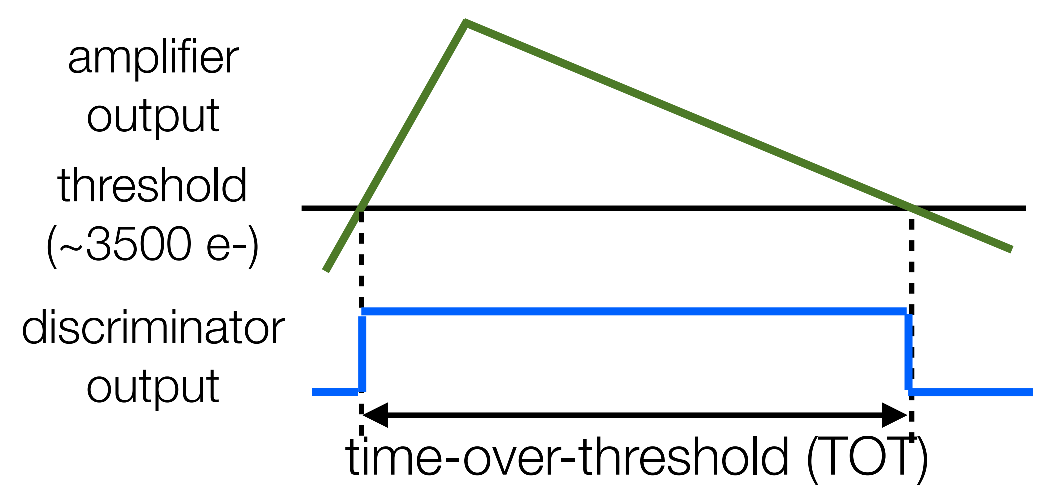
ATLAS pixel detector



- sensors:
  - planar n-in-n pixels, 400 x 50 μm^2, DOFZ Si, 250 μm thick. 1.1 mm inactive edge (16 GRs + safety margin)
  - ϕ_{max} = 1-2e15 n_{eq}/cm^2
  - 80M channels

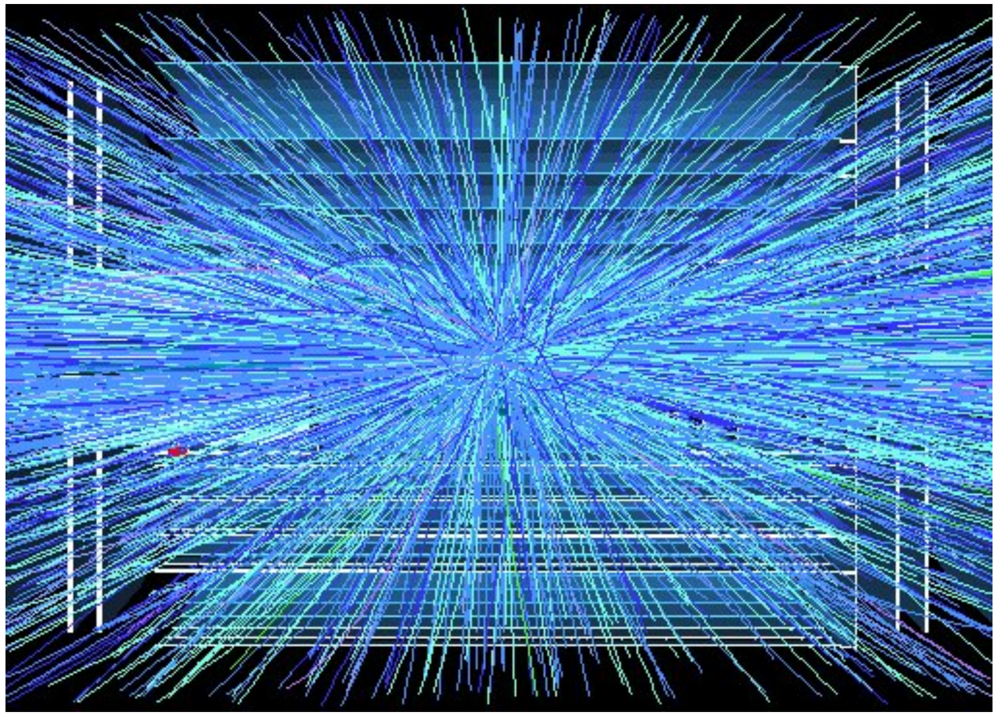


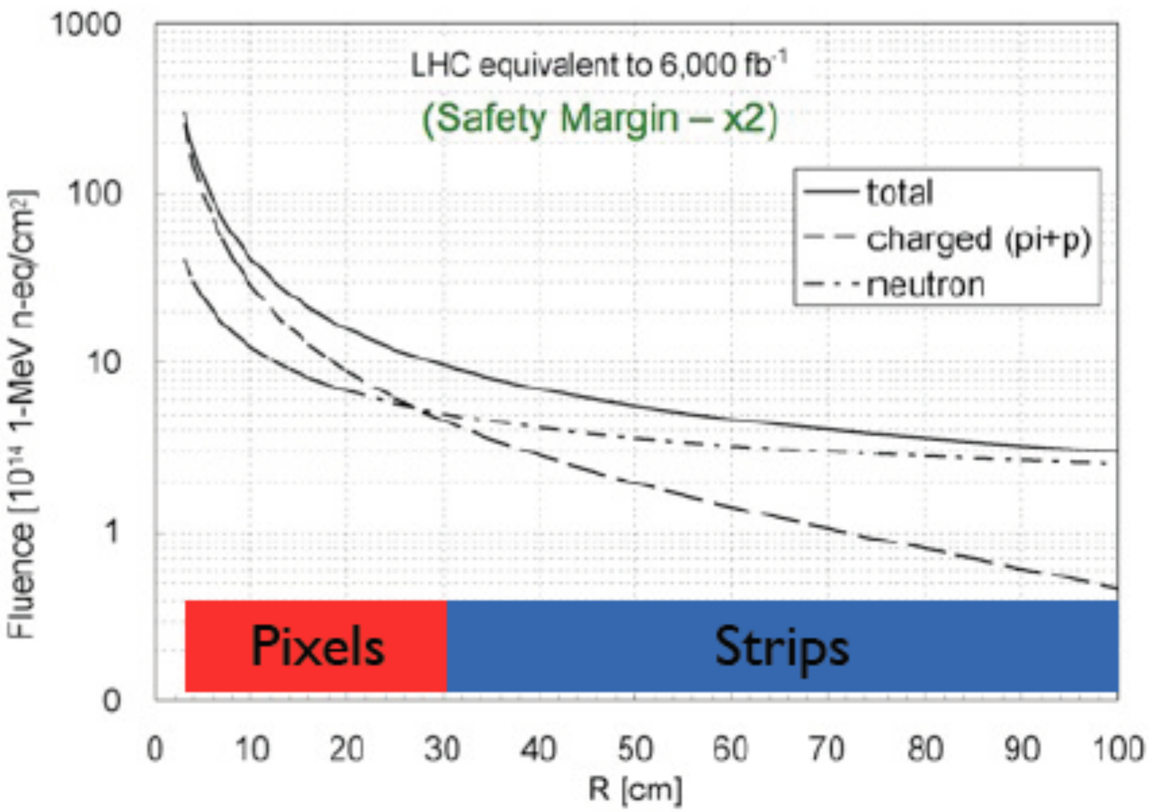
- readout (FEI3 chip):
  - DC coupled (bump-bonding)
  - shaper + amplifier + discriminator ⇒ TOT ⇒ Q



Challenges at high luminosity

- increased occupancy & event rate
  - O(10^2) events/BC
  - higher sensor granularity (400 ⇒ 250 µm on long pixel side)
- radiation damage (CCE, depletion)
  - ϕ_{max} = 2e16 n_{eq}/cm^2 in inner layer
  - rad. hard material / lower threshold / higher V_{bias} / thinner sensors / ...





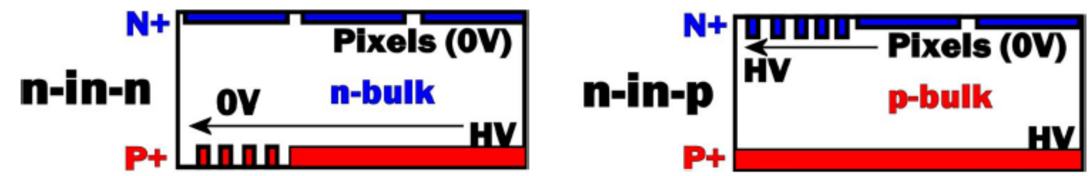
Planar pixel sensor R&D for the ATLAS upgrade

- 17 institutes, >80 scientists (full list in appendix), official ATLAS R&D project

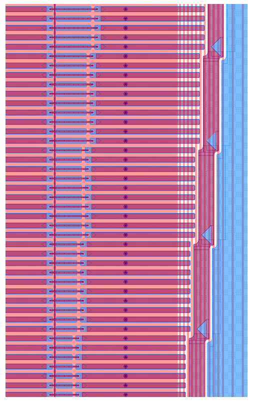
- goals:
  - evaluate/improve performance of PPS at high(est) fluences
    - rad. hardness, operation at low threshold, ..
  - cost reduction & instrumentation of large areas (strips ⇒ pixels?)
    - n-in-p devices, cheaper bump-bonding ..
  - active area optimization (slim/active edges)
- timeline: new pixel (2018), new tracker (2022)

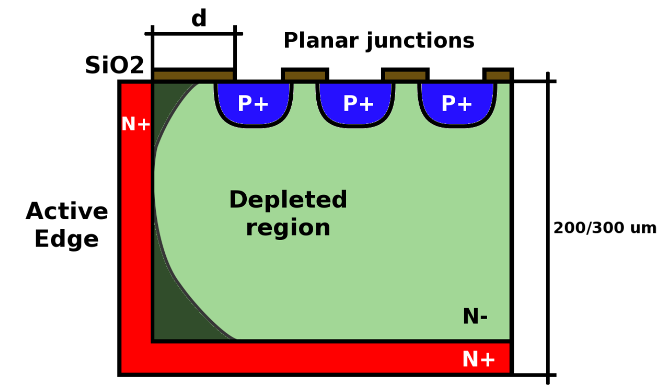
PPS program

- Directions of research:

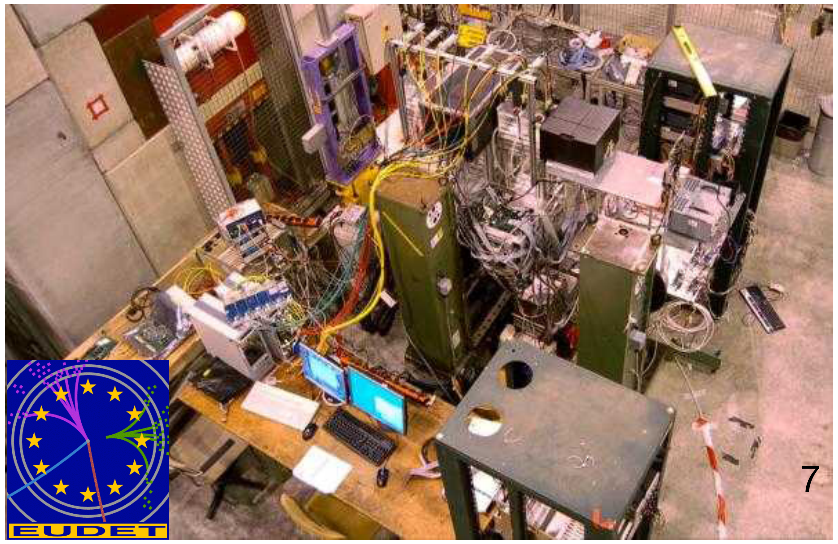


  - explore rad-hardness and cost effectiveness of different bulk options
  - sensor thickness optimization
  - slim/active edges: reduce inefficiency at edge





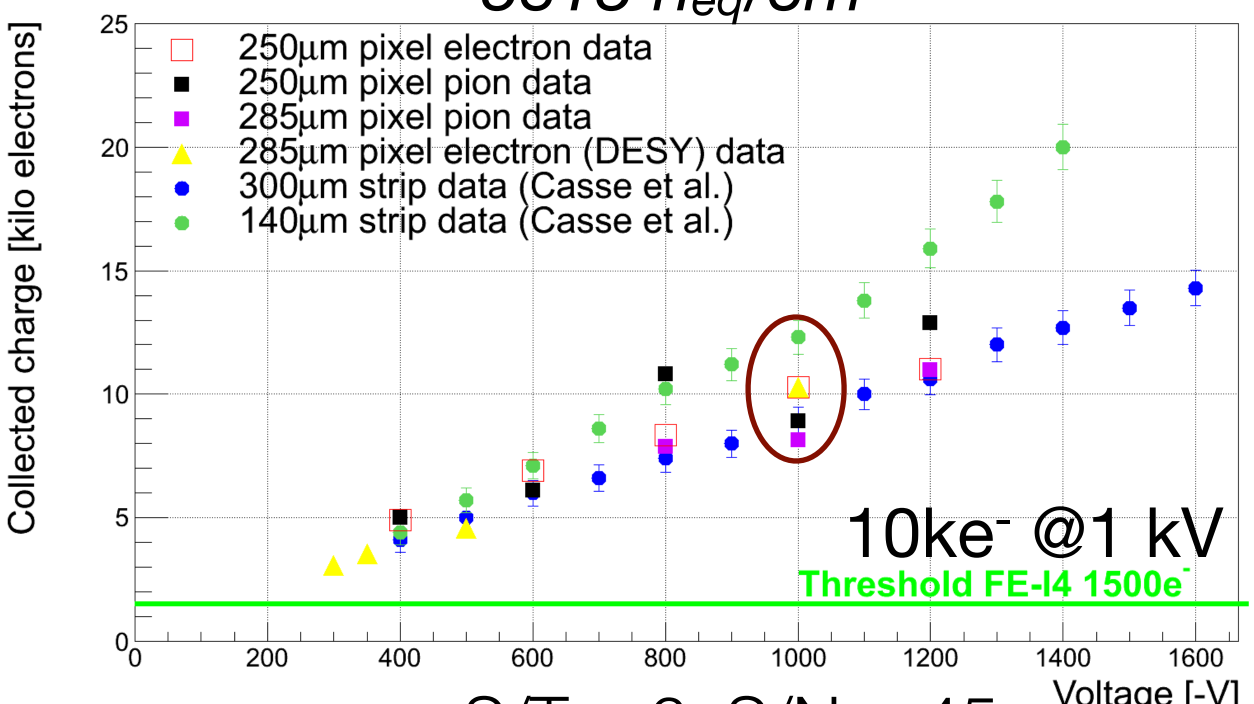
- Tools:
  - neutron / proton irradiations (Ljubljana/CERN/Karlsruhe) up to 2e16 n_{eq}/cm^2
    - annealing: 25-30 days at 20C or 120’ at 60C
  - characterization in lab / testbeams (CERN/DESY)
    - leakage current, efficiency, collected charge
  - TCAD simulations to help optimization



n-in-n pixels: radiation hardness

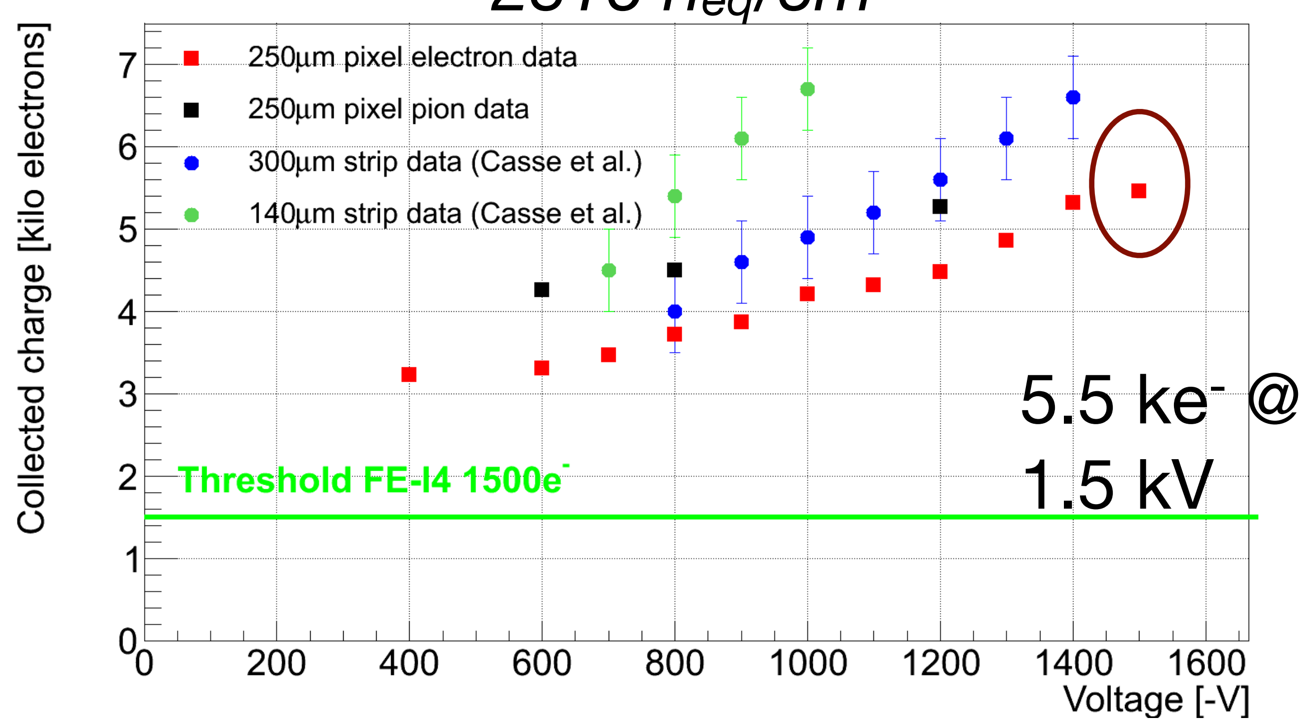
- used in current ATLAS pixel detector (rad. hard beyond 1e15 n_{eq}/cm^2)
- the "natural" candidate for the upgrade **IF** rad. hard up to 2e16 n_{eq}/cm^2
- encouraging results from neutron irradiation (Ljubljana) at 2e16 n_{eq}/cm^2 + lab/testbeam measurements at -30C (to-do: investigate thinner pixels)

5e15 n_{eq}/cm^2



$\Rightarrow$ S/T > 6, S/N > 45

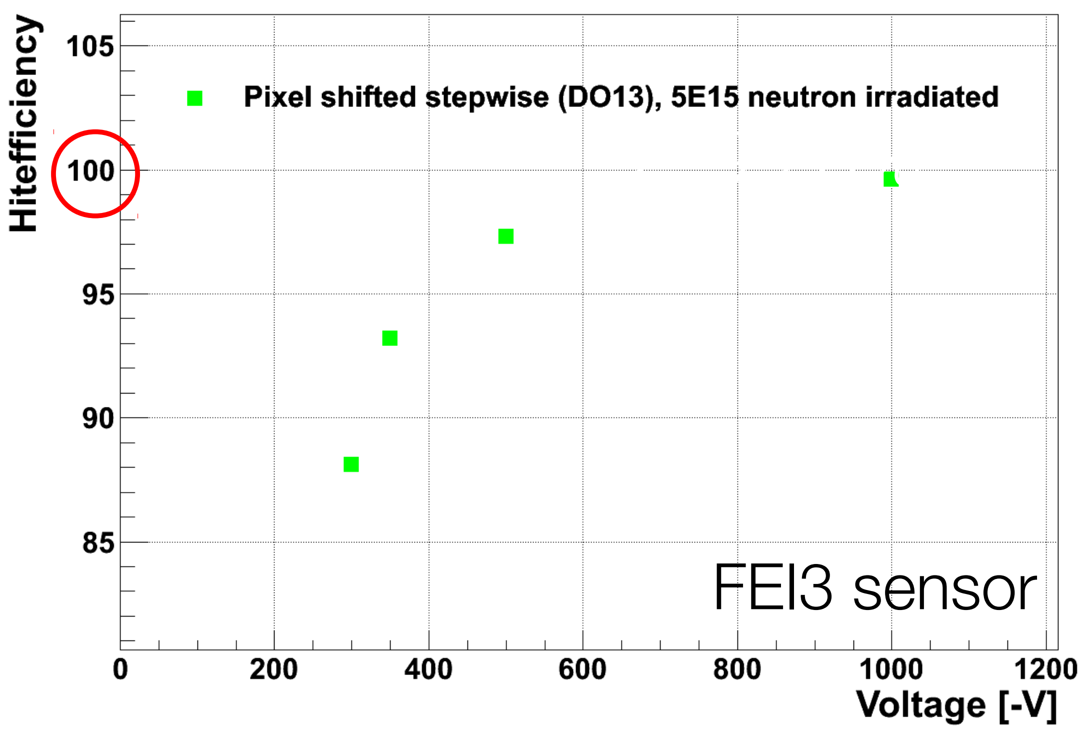
2e16 n_{eq}/cm^2



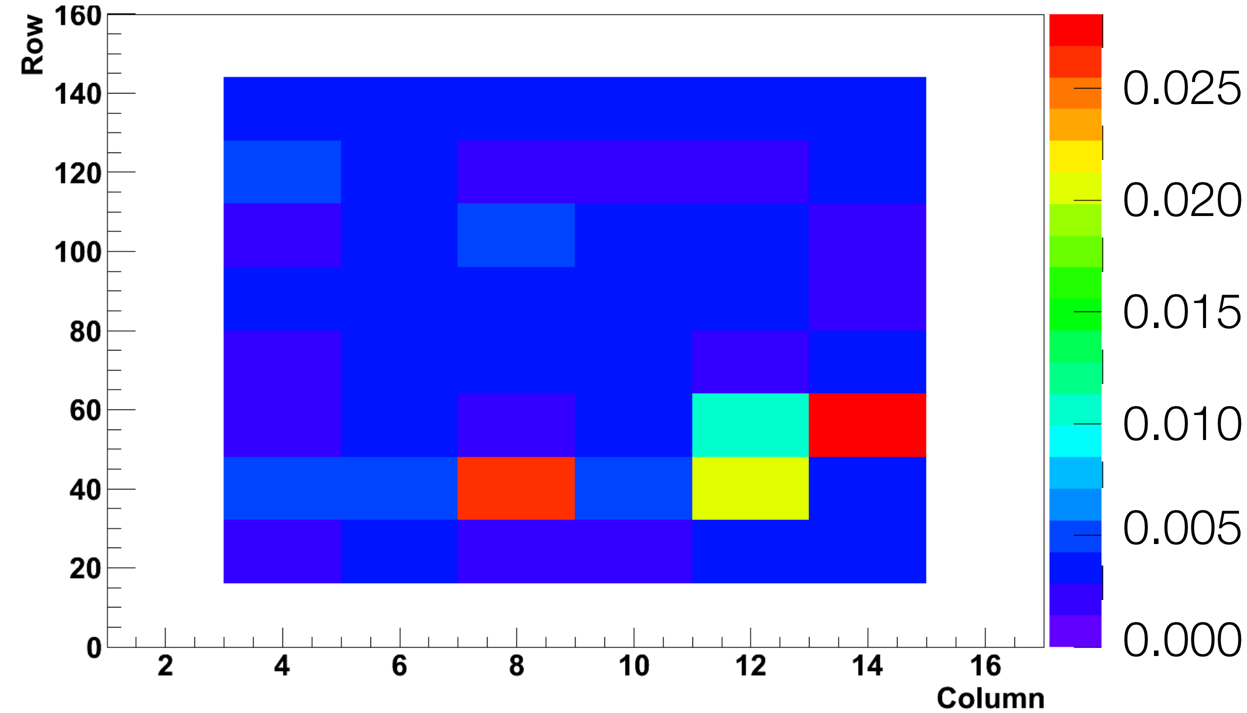
Hit efficiency at high fluences

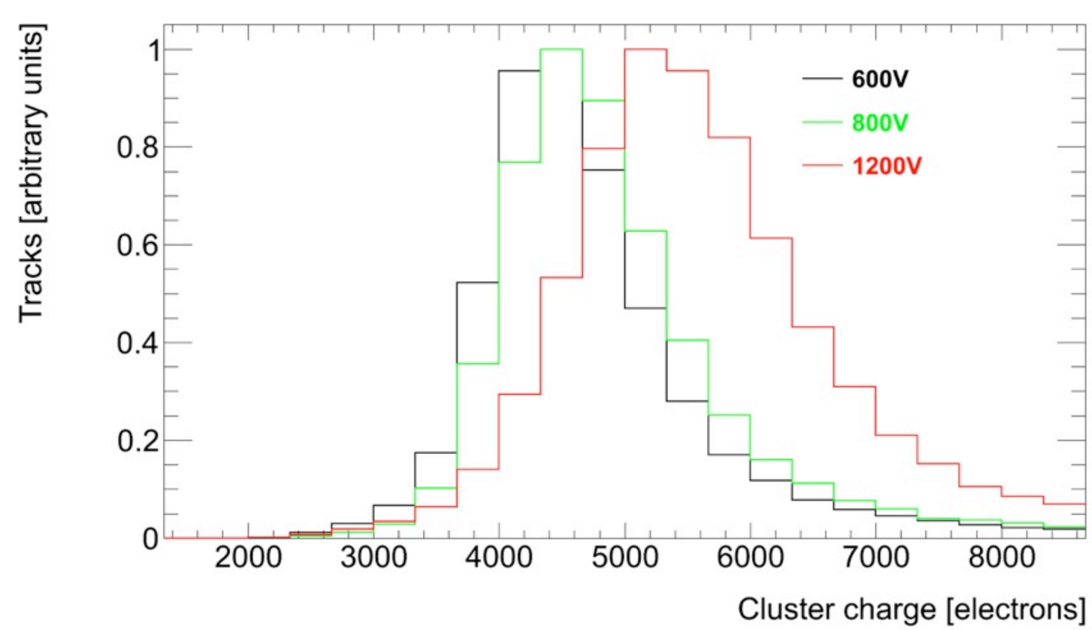
- Hit efficiency can be fully recovered by increasing Vbias

Efficiency vs V_{bias}



Inefficiency @ 5e15 n_{eq}/cm^2, 1000 V

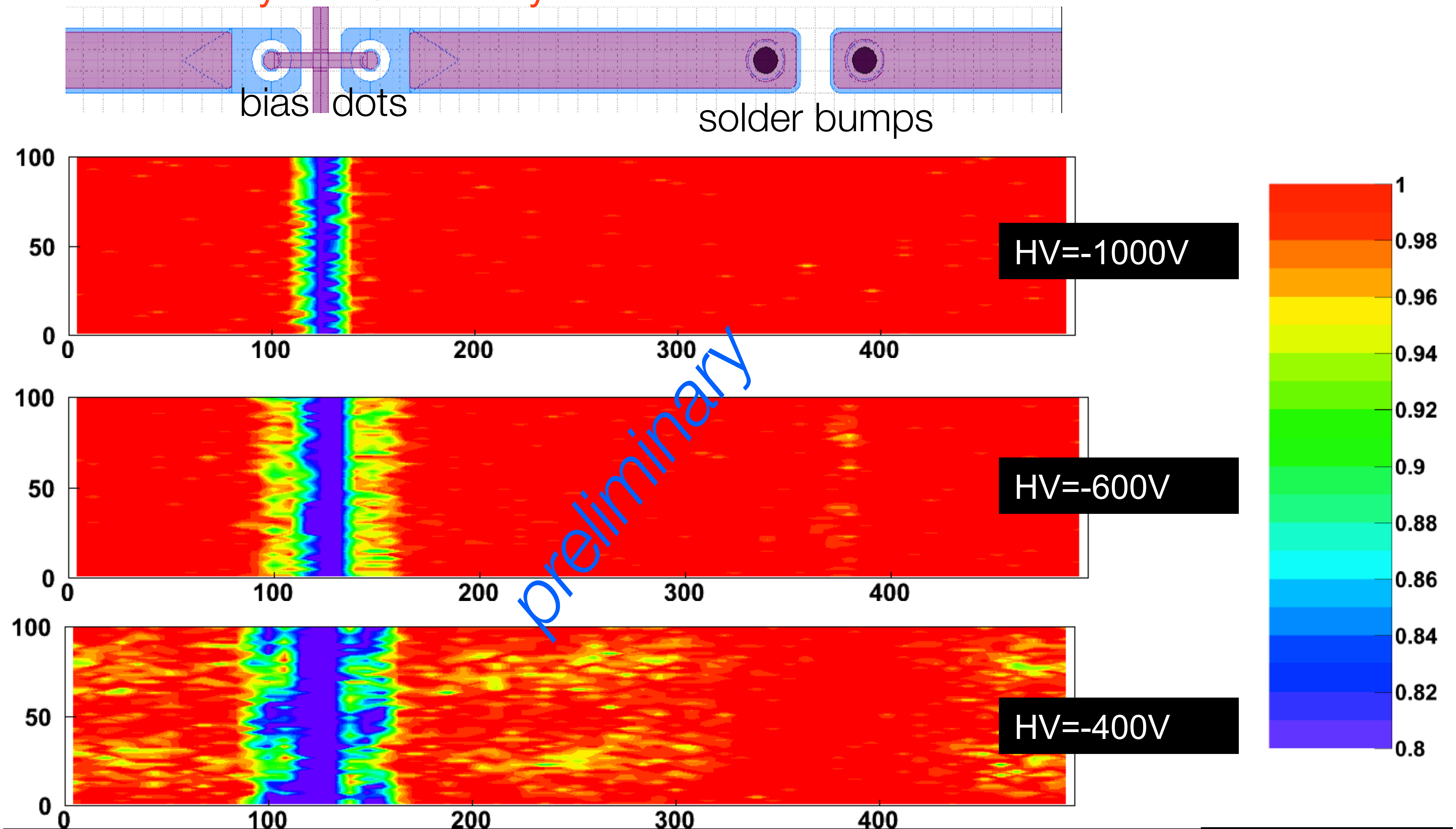




- Some charge seen @2e16 n_{eq}/cm^2 (efficiency still to be estimated)

Hit efficiency (FEI4 sensors)

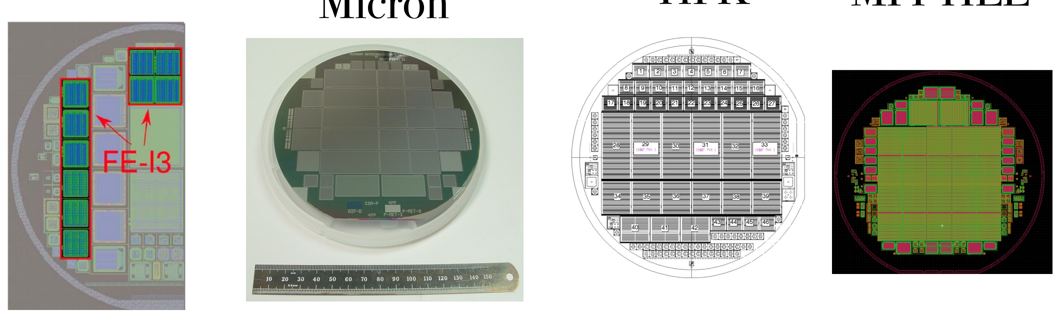
- Data from CERN June 2011 TB, 250 μm sensor n-irradiated @ 4e15 n_{eq}/cm^2
- Efficiency > 97% already at 600 V

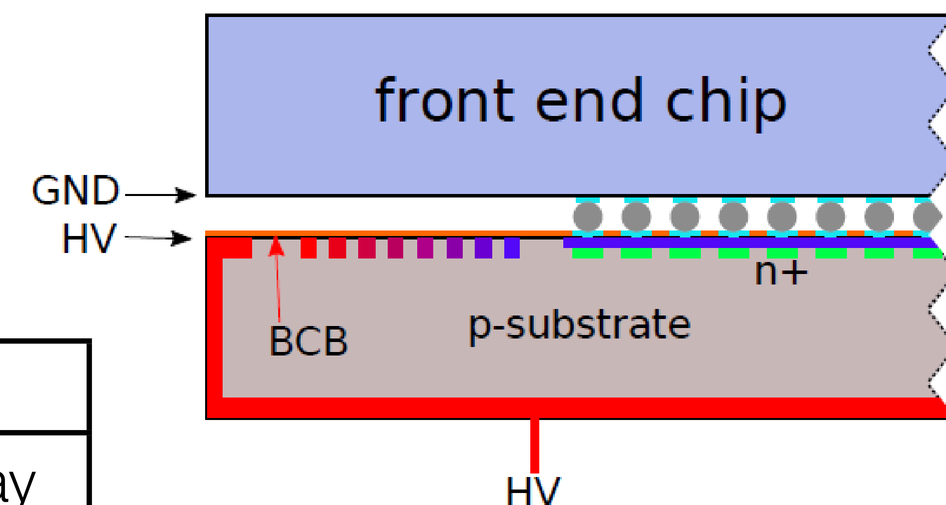


n-in-p pixels: radiation hardness

- Good alternative to n-in-n for future ATLAS pixel upgrades
  - radiation hardness (no type inversion, partial depletion OK)
  - higher yield/lower cost (GRs on front ⇒ single side processing)
- Problems with HV facing chip (0V) overcome with additional insulation
  - 3 μm benzocyclobutene/parylene (isolation >> SiO_2) ⇒ no sparks @1000V

CiS Micron HPK MPI-HLL



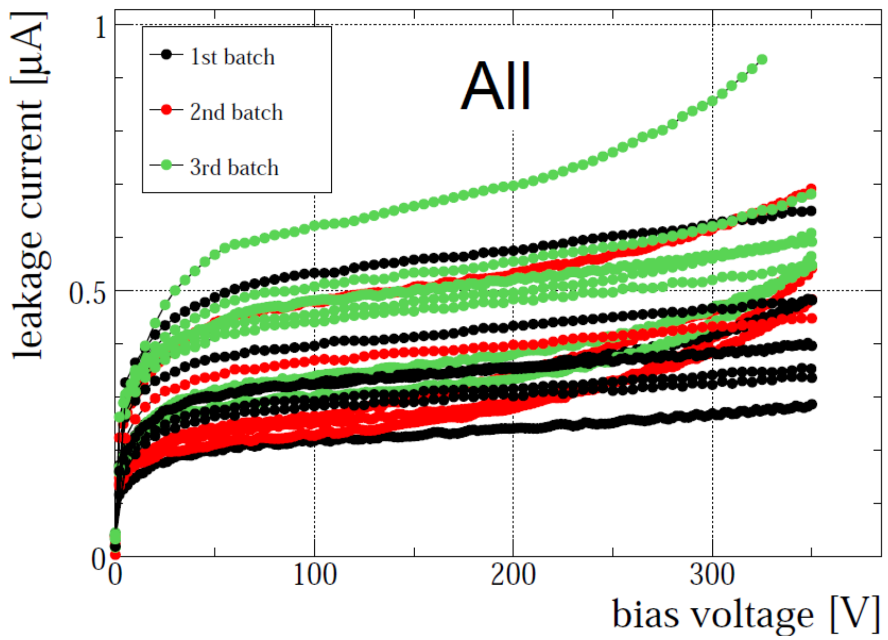


Production	Thickness (μm)	Material	PIX isolation
CiS	285/200/150	FZ	hom./mod. p-spray
Micron	300/150	FZ	p-spray
HPK	320/150	FZ	p-stop/spray
MPI/HLL	150/75	FZ	p-stop/spray

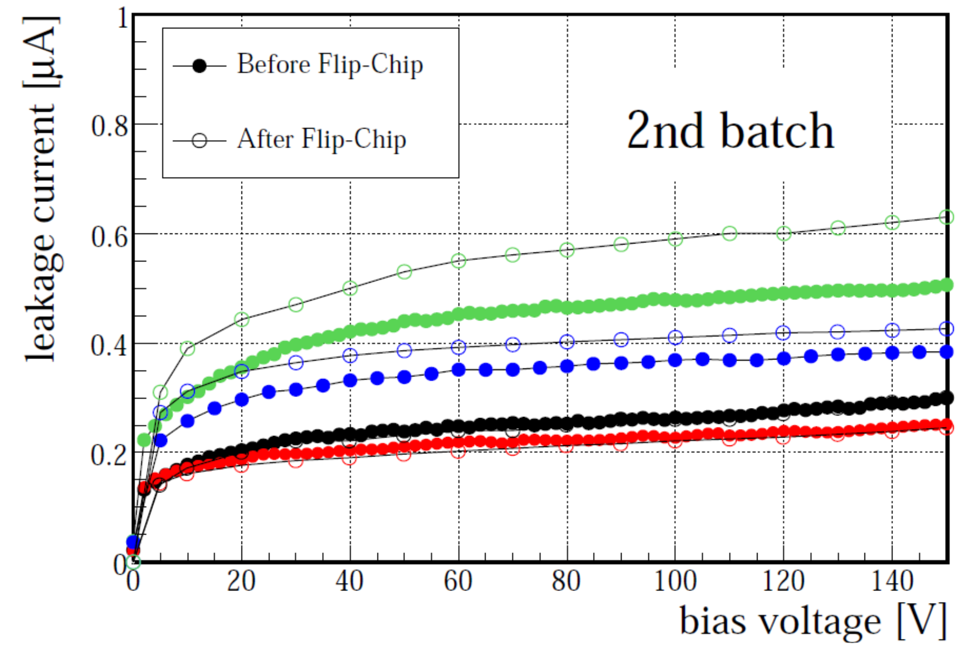
CiS sensors before irradiation

(285 μm thick sensors only)

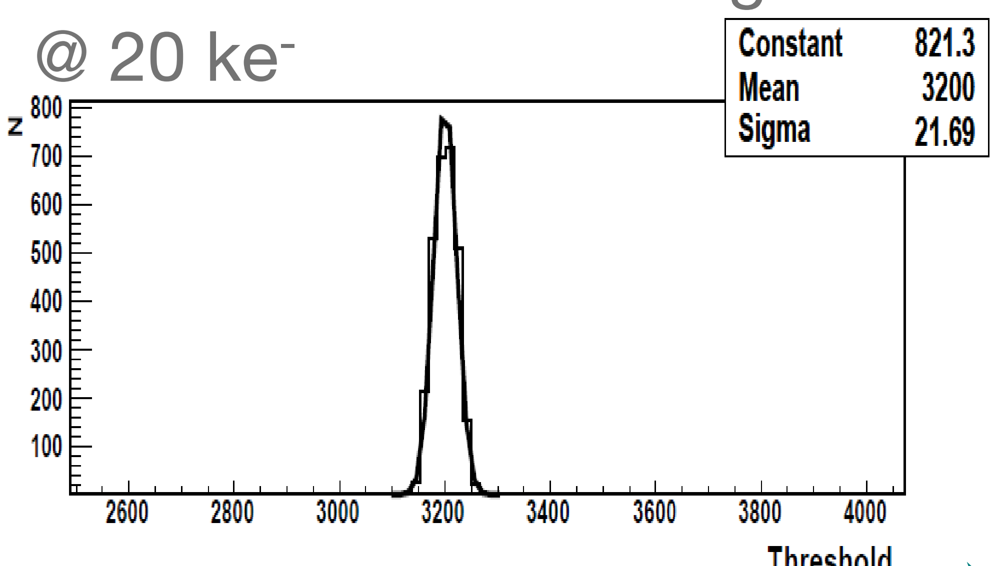
- V_{BD} (breakdown) >> V_{depl}=60V



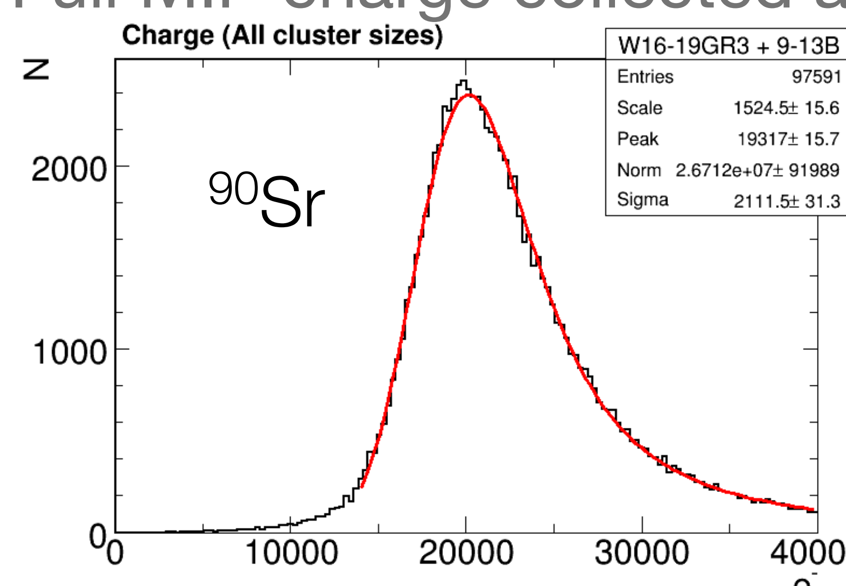
- Bump-bonding (@ IZM-Berlin) not affecting I_{leak} and V_{BD}



- narrow threshold tuning achieved @ 20 ke$^-$



- Full MIP charge collected above V_{depl}

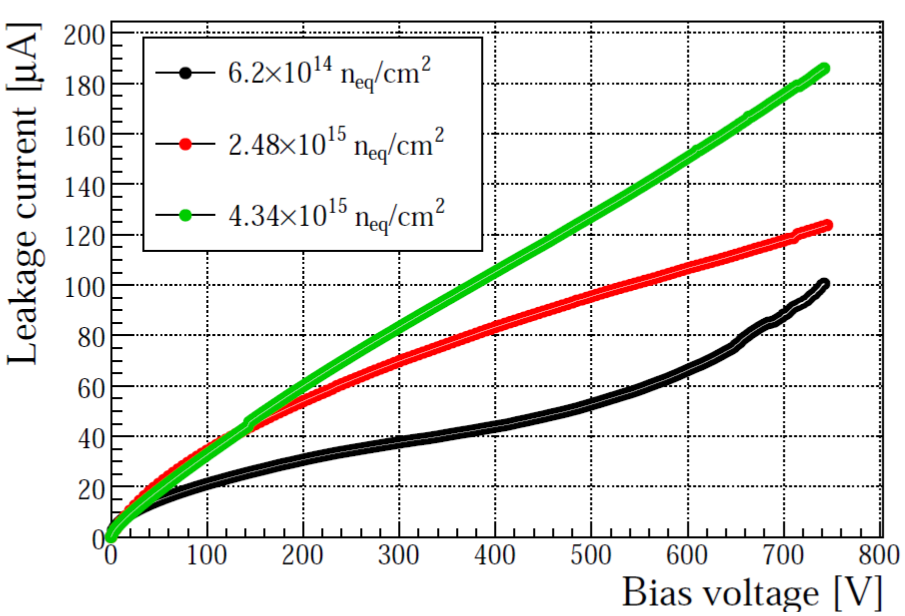


- Threshold dispersion (24e$^-$) and noise (171e$^-$) comparable to n-in-n pixels
- Tracking efficiency measured in testbeam > 99% (also for HPK and Micron)

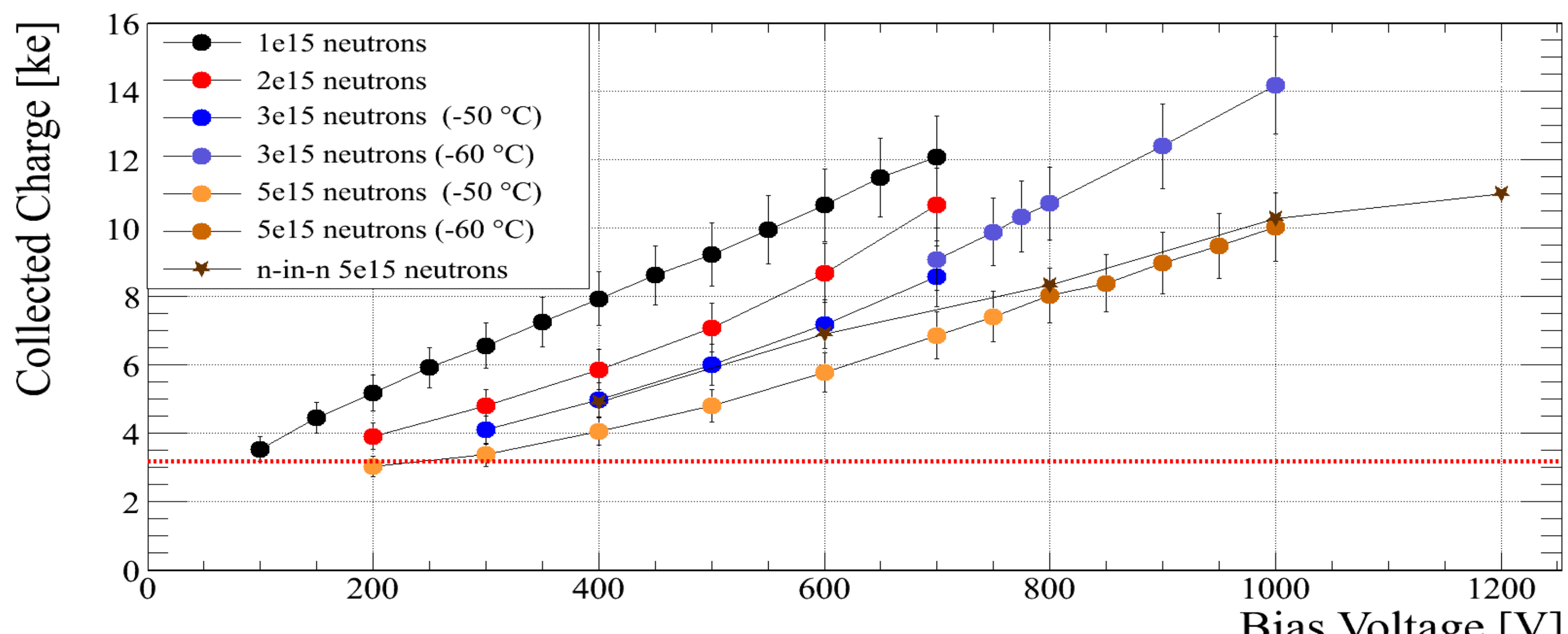
CiS sensors after irradiations

Facility location	particle type	momentum	ϕ_{max} (n_{eq}/cm^2)	responsible
CERN	p	24 GeV/c	5.0E+15	M. Glaser
Karlsruhe	p	25 MeV/c	5.0E+15	A. Dierlamm
Ljublijana	n	continuous, from reactor	1.0E+15	V. Cindro

- V_{BD}>750V, I_{leak} < 200µA at -10C



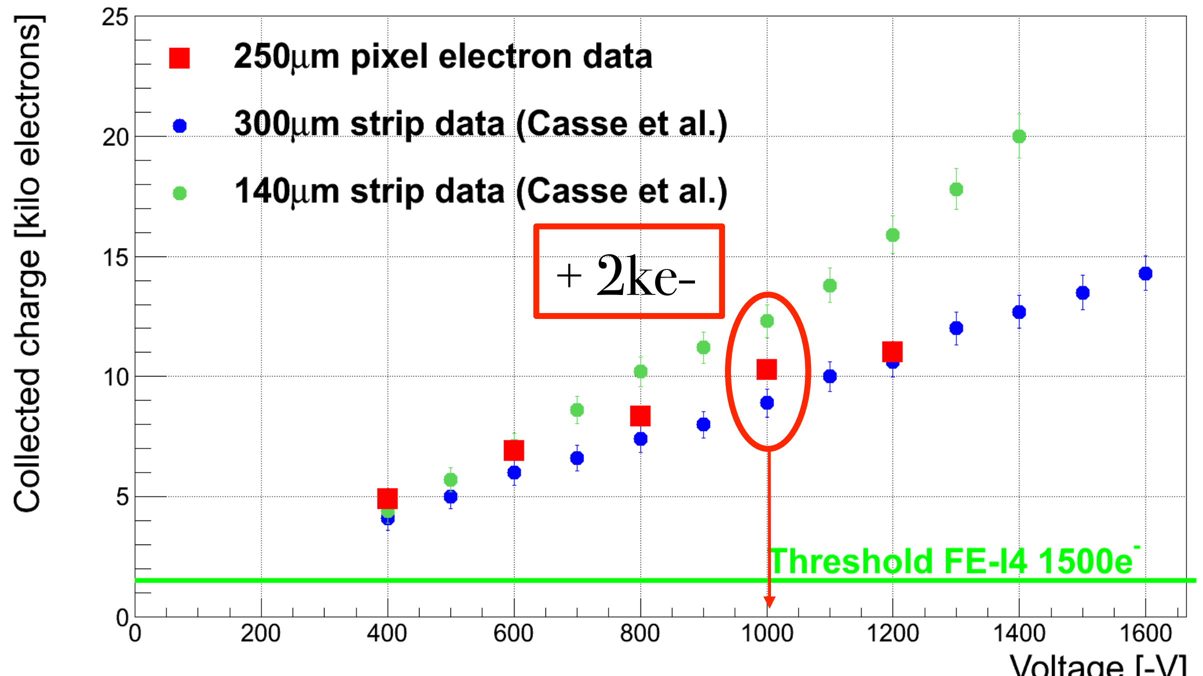
- CCE: significant fraction of charge (above threshold) collected at high V_{bias} (>600 V) after annealing



Vbias not high enough to see charge-multiplication as observed in Micron devices for V_{bias}>1600V, >1e15 n_{eq}/cm^2

Thinning

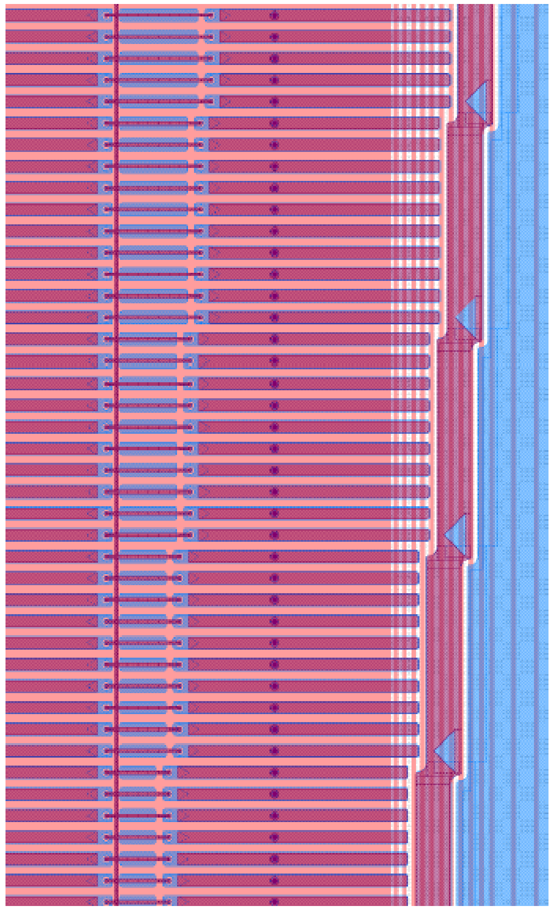
- Strip-sensors data: thinner bulk yields more charge after 5e15 n_{eq}/cm^2 at 1kV
  - higher E with same V; charge amplification?
- Less radiation length
- n-in-n pixel production with 5 different thicknesses (150-250 µm, steps of 25 µm) started at CiS; studies of CCE will follow (promising results for 250 µm):

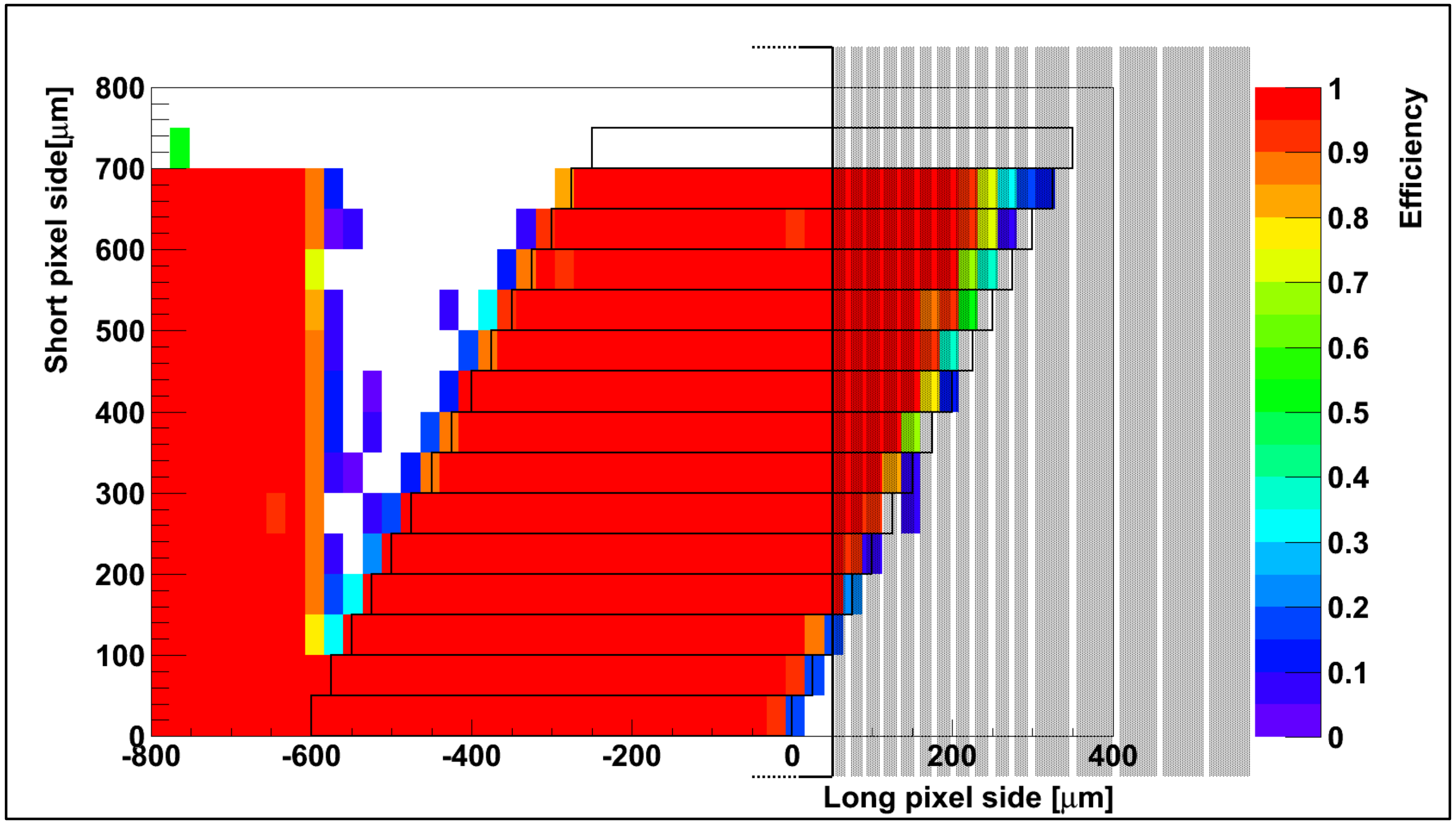


- reasonable wafer yield (90%) (sensor yield on good wafer ~100%)
- similar studies to be done for n-in-p

Slim edges (n-in-n)

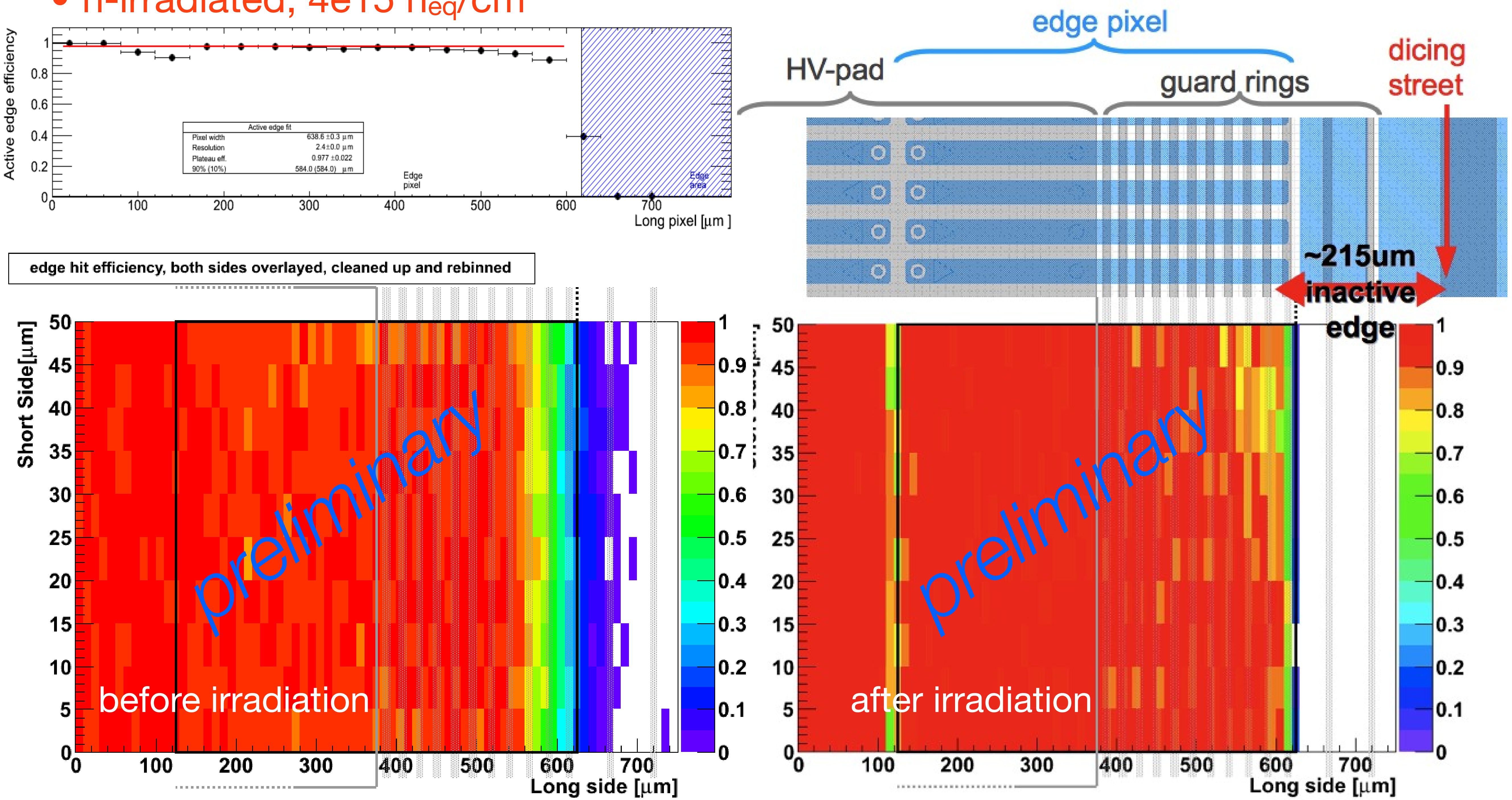
- minimize inactive area (inner layers: no shingling in z from geometry constraints)
- increase active area by shifting pixels inside region opposite to GRs
- dicing trials: same yield as standard GR design
- testbeam results (FEI3 sensors) high efficiency up to ~250 µm from edge (consistent with TCAD simulation) in non-irradiated and irradiated devices





Slim-edge: test-beam results on FEI4 sensors

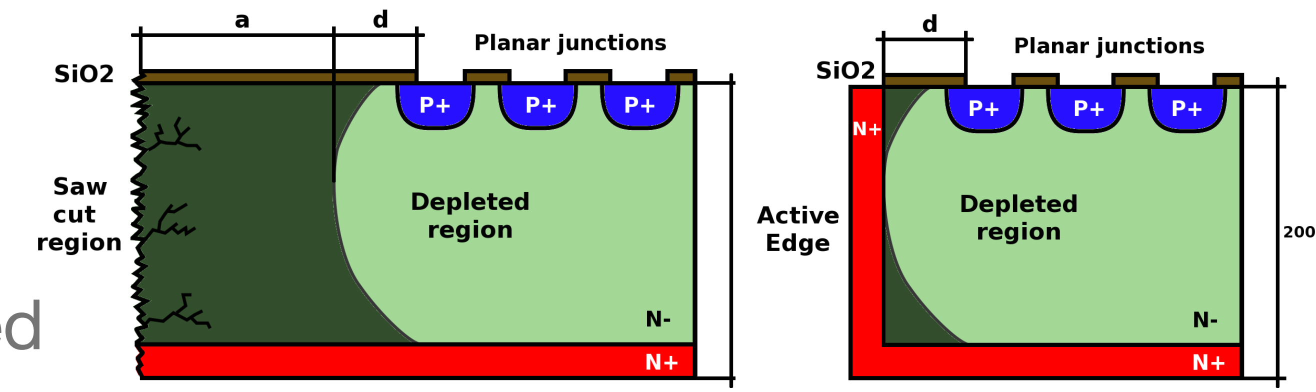
- n-irradiated, 4e15 n_{eq}/cm^2

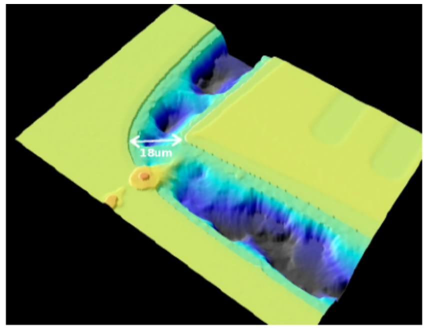


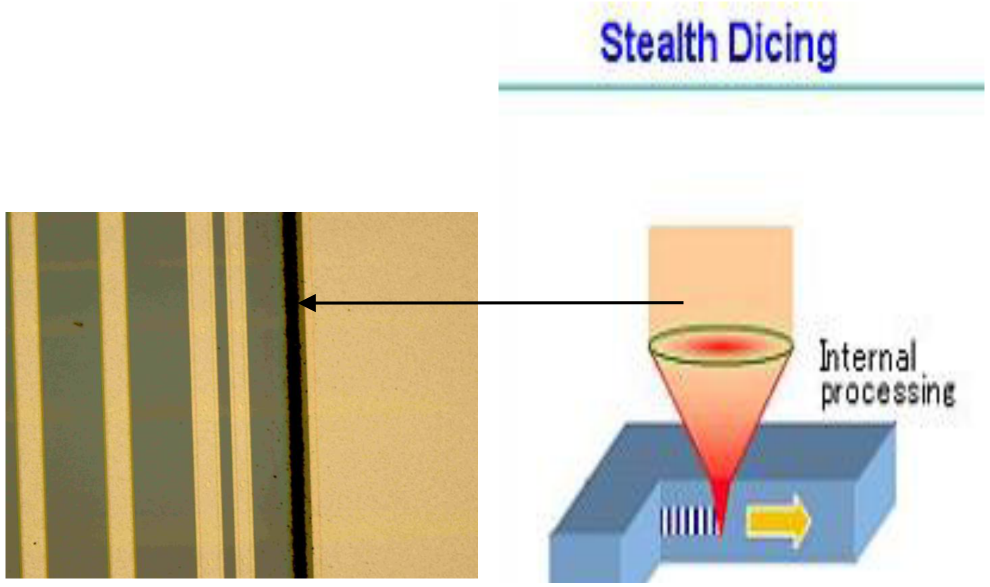
⇒ slim edge design (~98.4% geometric efficiency) chosen as IBL candidate

Active edges

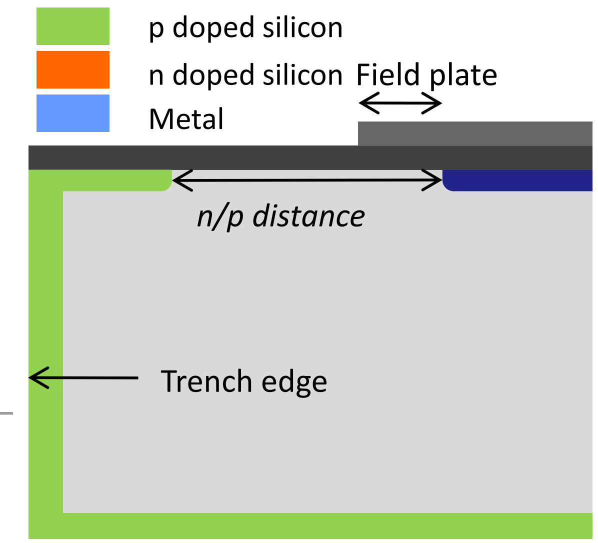
- DRIE-etching (CNM/IFAE, FBK/LPNHE, VTT/Munich):
    - trench etched (DRIE), doped and filled with polysilicon
- “scribe+cleave+edge-passivation” (Santa Cruz/Dortmund):
    - laser scribing & cleaving ⇒ no damage
    - potential drop @ edge partially controlled with SiO_2/Si_3N_4 or Al_2O_3 passivation
    - post-processing, can be applied to virtually any existing detector





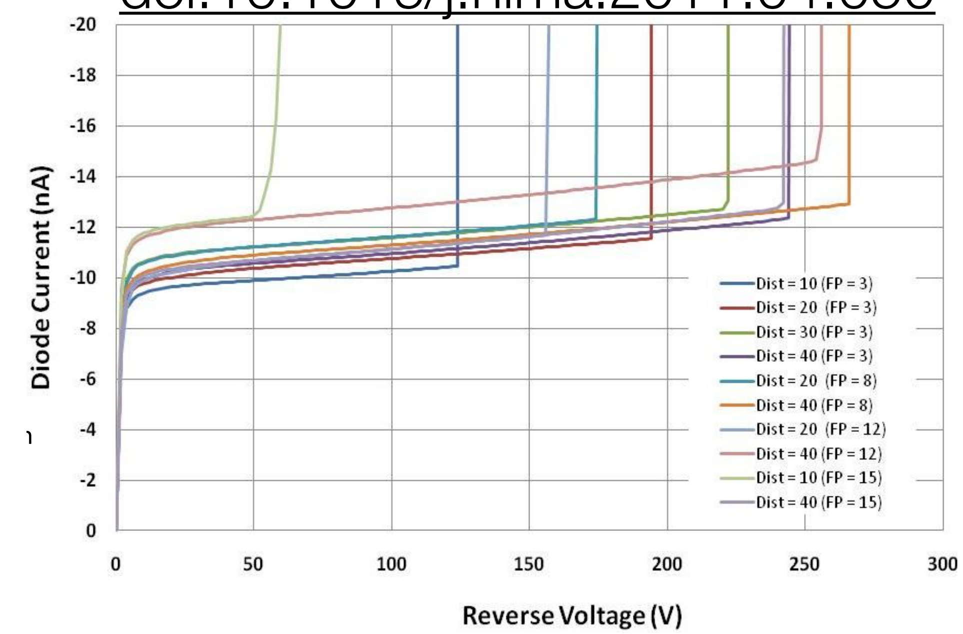


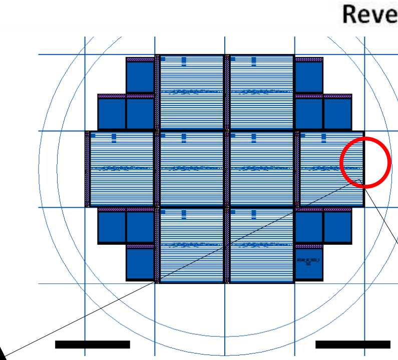
FBK/LPNHE active (doped) edge



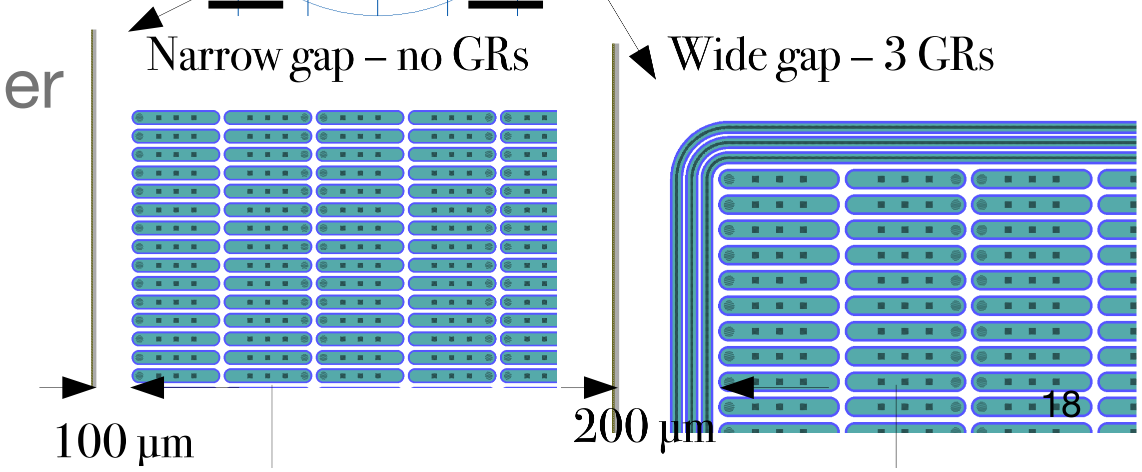
- Challenges:
  - etching: deep (200-230 µm), aspect ratio ~1/20
  - filling: width 8-12 µm
- Good IV and breakdown on test diodes
- Next activities:
  - further leakage current reduction (reduce wafer residual stress)
  - trench optimization (width ~5 µm ⇒ easier filling and photolithography)
  - production of FEI3 and FEI4 sensors

doi:10.1016/j.nima.2011.04.050

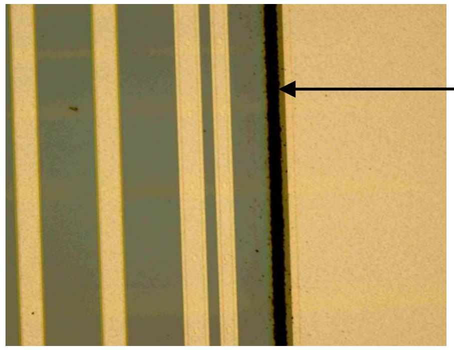


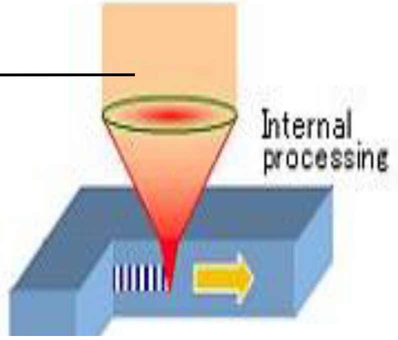


On 4 inch wafer:
- 8 FEI4
- 12 FEI3
- Test structures (diodes, ...)

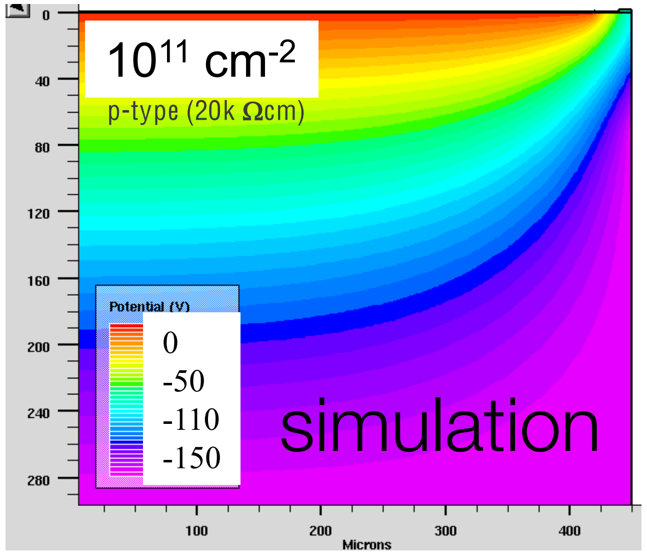


SCIPP/Dortmund scribe + cleave + edge passivation



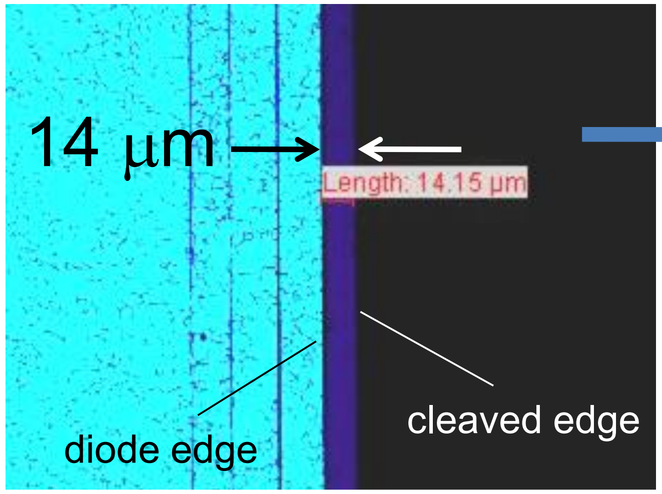


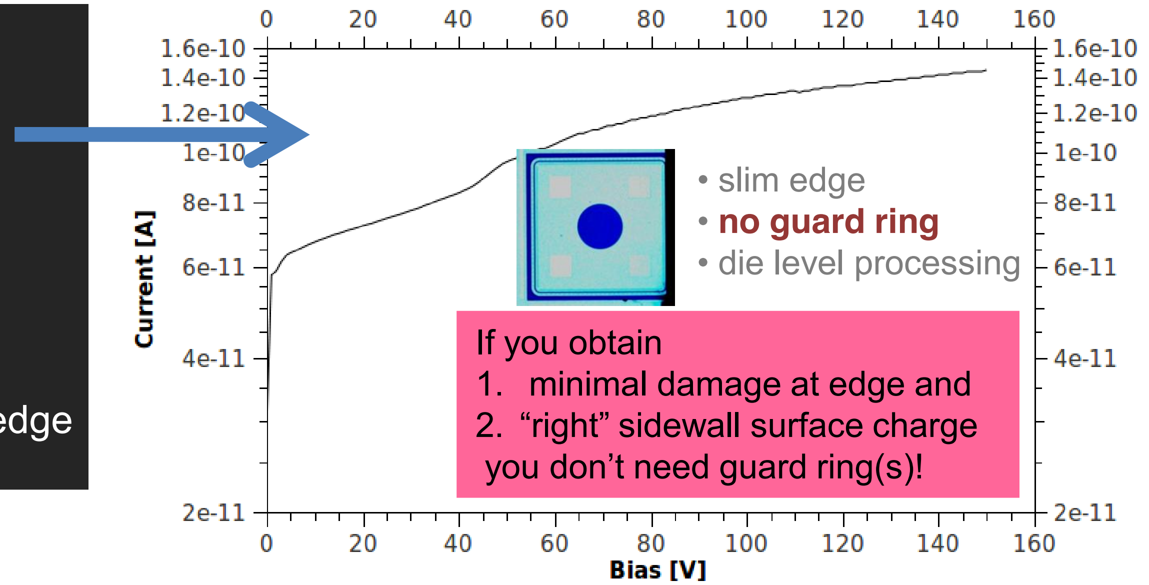
- laser scribe + cleaving of sensors ⇒ less surface damage
- edge passivation with natural oxide growth (for n-type bulk) or atomic layer deposition (ALD) of Al (for p-type bulk) to control potential drop at edge



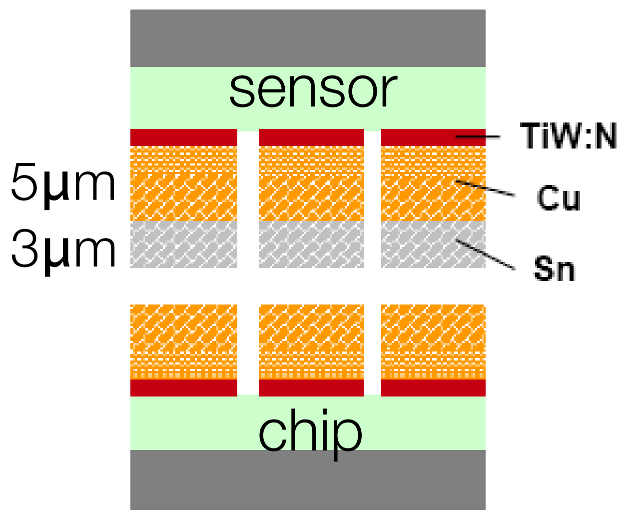
p-type + Al_2O_3

- can be done on finished die
  - no need for GR (14 µm distance to active area achieved)
  - I_{leak} OK up to 1000 V
  - 100% CCE near edge
  - *rad. hardness to be investigated*

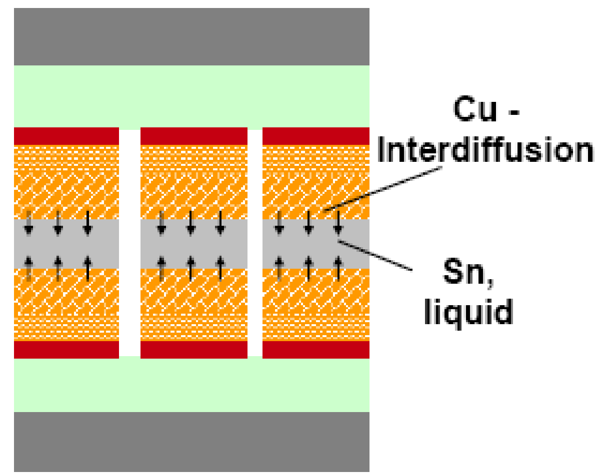




SLID interconnections (MPP/Fraunhofer)

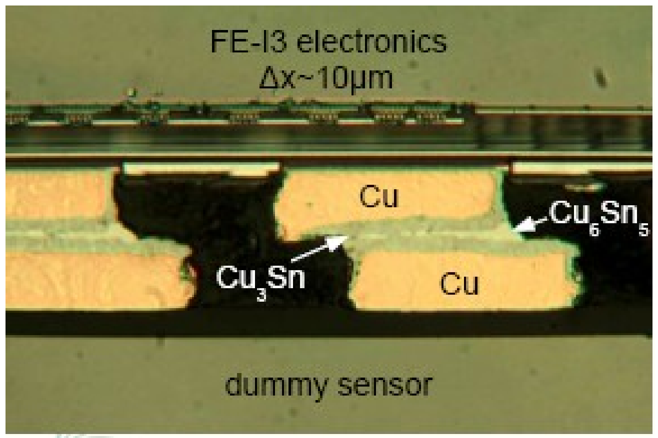


Through Mask Electroplating



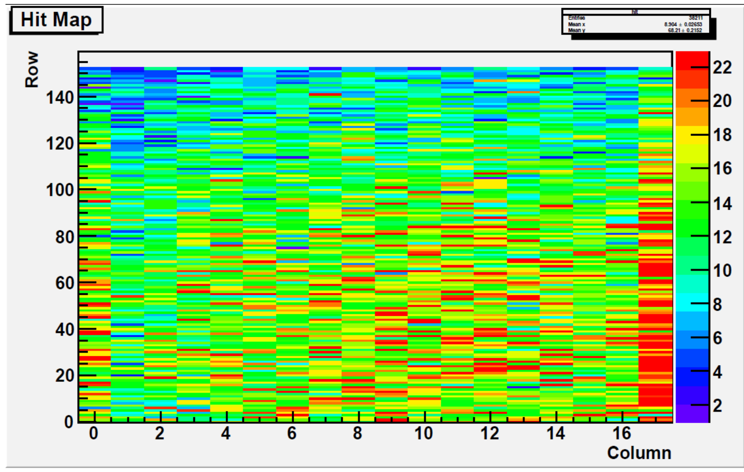
Contact under Pressure and Heat
~ 5 bar, 260 – 300 °C (Sn-melt)

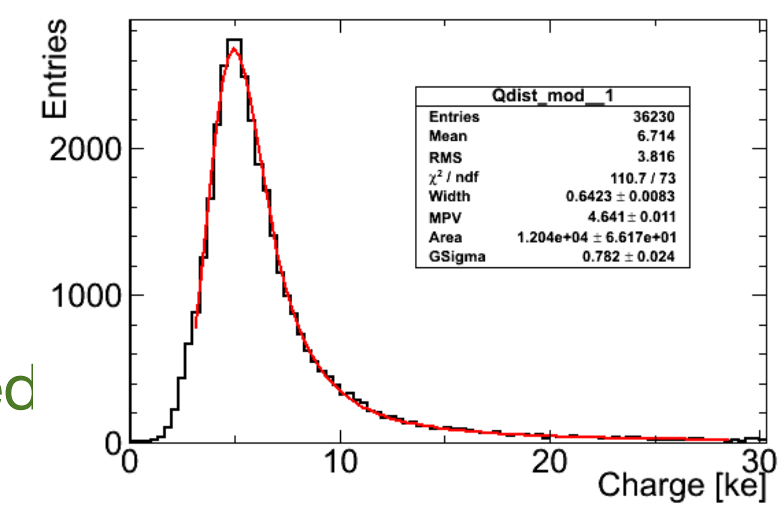
SLID cross-section



Formation of Eutectic Alloy; T_{melt} > 600 °C

- Solid-Liquid InterDiffusion: metallization alternative to bump-bonding
  - cheaper (less process steps)
  - small pitch and stacking possible, BUT no rework
- First results w/ thin (75µm) n-in-p pixels connected to FEI3:
  - a few problems with chip misalignment
  - disconnected channels: chip aplanarity? BCB openings?
  - threshold dispersion/noise/CCE comparable to bump bonded sensors





Conclusion

- planar pixels = the "natural" choice for the ATLAS pixel detector upgrade
- encouraging results for n-in-n sensors at 5e15 n_{eq}/cm^2 (full efficiency) and 2e16 n_{eq}/cm^2 (some charge collected)
- several efforts on n-in-p pixels promise cheaper sensors, similar performances
- several efforts on geometry optimization to improve performances (thickness) and reduce inactive area (edges):
  - slim edge: proof-of-principle established in testbeam, reduced to 250 um
  - active edge: new ideas being developed and tested, no need for GR...
- other activities (e.g. cost reduction of bonding) ongoing
- future activities: assess radiation hardness up to 2e16 n_{eq}/cm^2 for devices under development; full evaluation of thin and edgeless sensor performances

ATLAS PPS R&D project collaborators

CERN
D. Dobos, B. Di Girolamo, D. Muenstermann, H. Pernegger, S. Roe, A. La Rosa
AS CR, Prague (Czech Rep.)
V. Vrba, P. Sicho, J. Popule, M. Tomasek, L. Tomasek, J. Stastny, M. Marcisovsky, M. Havranek, J. Bohm, Z. Janoska, M. Hejtmanek
LAL Orsay (France)
M. Benoit, N. Dinu, D. Fournier, J. Idarraga, A. Lounis
LPNHE / Paris VI (France)
M. Bomben, G. Calderini, Eve Chareyre, J. Chauveau, C. La Licata, G. Marchiori, P. Schwemling
University of Bonn (Germany)
M. Barbero, F. Hügging, H. Krüger, N. Wermes
HU Berlin (Germany)
H. Lacker
DESY (Germany)
C. Hengler, I. M. Gregor, U. Husemann, V. Libov, I. Rubinsky
TU Dortmund (Germany)
S. Altenheiner, C. Gößling, J. Jentzsch, T. Lapsien, R. Klingenberg, A. Rummler, G. Troska, T. Wittig, R. Wunstorf
University of Goettingen (Germany)
J. Grosse-Knetter, M. George, A. Quadt, J. Weingarten
MPP und HLL Munich (Germany)
L. Andricek , M. Beimforde, A. Macchiolo, H.-G. Moser, R. Nisius, R. Richter, P. Weigell
Università degli Studi di Udine – INFN (Italy)
D. Cauz, M. Cobal, C. del Papa, D. Esseni, M. P. Giordani, P. Palestri, G. Pauletta, L. Selmi
KEK (Japan)
Y. Unno, S. Terada, Y. Ikegami, Y. Takubo
IFAE-CNM, Barcelona (Spain)
M. Cavalli, S. Grinstein, Korolkov, M. Lozano, C. Padilla, G. Pellegrini, S. Tsiskaridze
University of Liverpool (UK)
T. Affolder, P. Allport, G. Casse, T. Greenshaw, I. Tsurin
UC Berkeley/LBNL (USA)
M. Battaglia, T. Kim, S. Zalusky
UNM, Albuquerque (USA)
I. Gorelov, M. Hoeferkamp, S. Seidel,K. Toms
UCSC, Santa Cruz (USA)
V. Fadeyev, A. Grillo, J. Nielsen, H. Sadrozinski, B. Schumm, A. Seiden