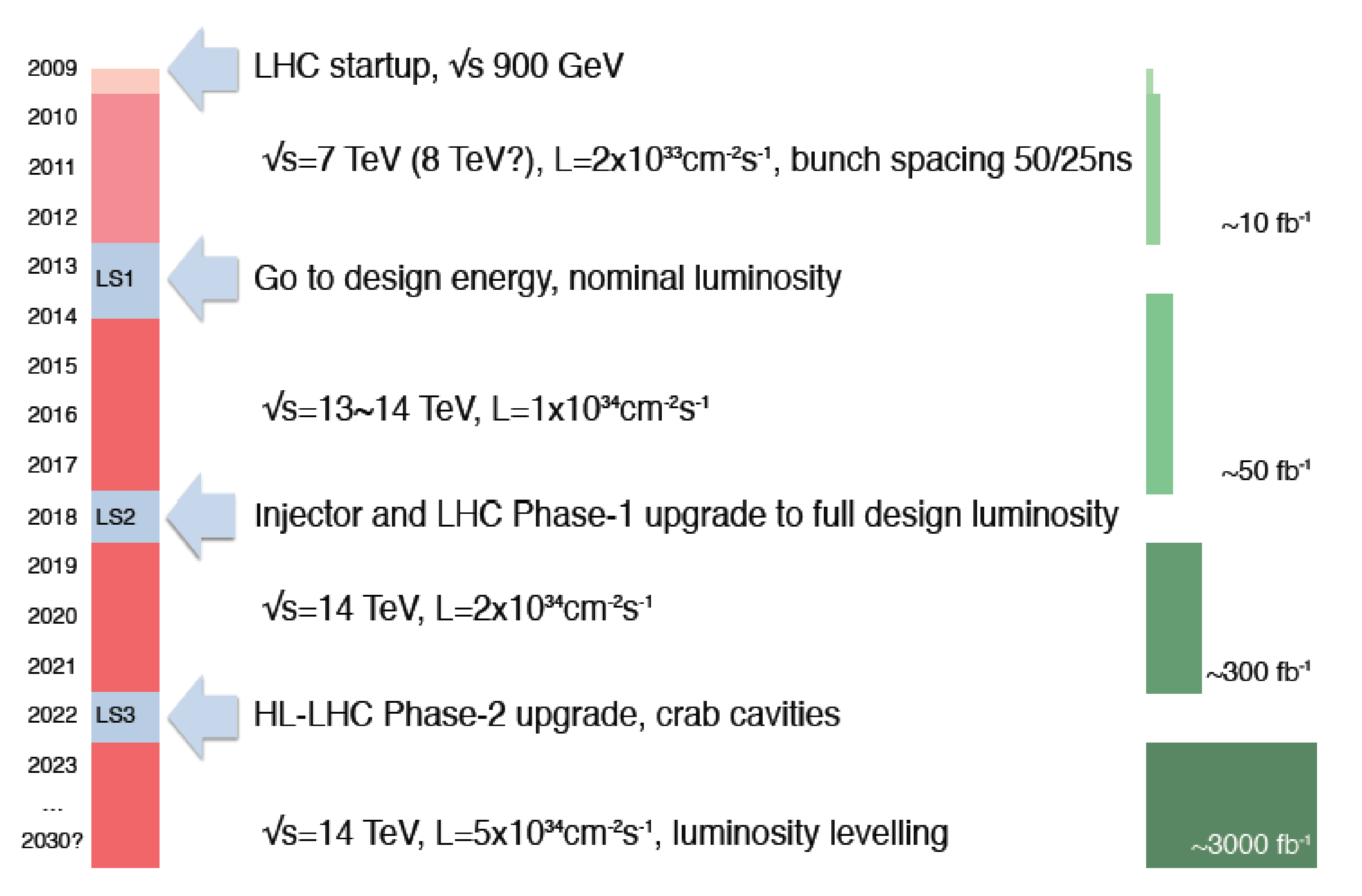
Characterisation of Microstrip and Pixel Silicon Detectors Before and After Hadron Irradiation

9th Position Sensitive Detector Conference (PSD9)
Aberystwyth
15/09/11

Phil Allport, Gianluigi Casse, Valery Chmill, Dean Forshaw, Adrian Pritchard, Ilya Tsurin
University of Liverpool
Kevin Ball, Kevin Hadfield, Peter Pool
e2v Technologies plc

- LHC Long-term Planning
- Required Radiation Tolerance Implications
- Post-irradiation Measurements
- Conclusions

Possible 20 Year LHC Schedule

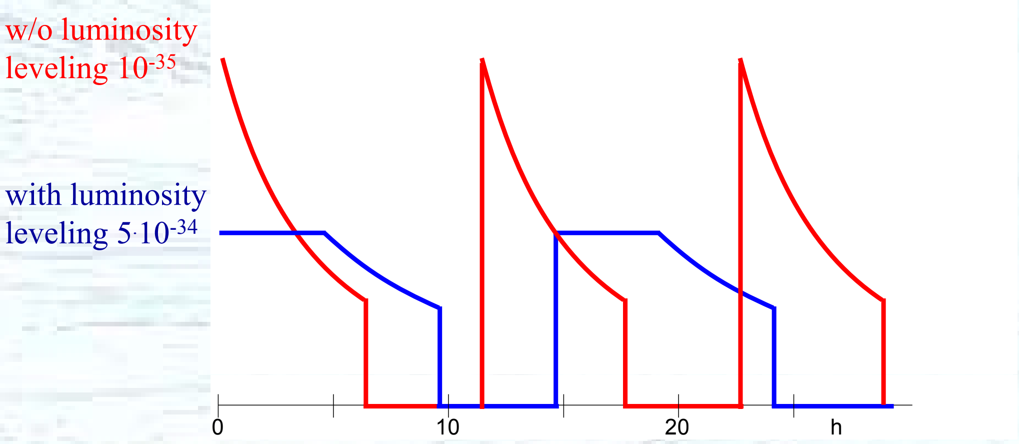


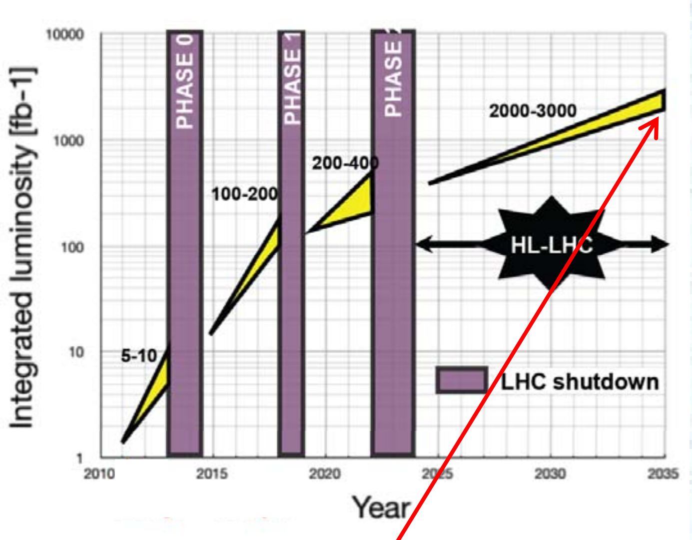
Comments:

- **Remember the Tevatron at Fermilab started operating at 3.5× the SPS (CERN) collider energy in October 1985 and is only finally shutting down this September after 25 years at the energy frontier**
- **The initial design luminosity of the Tevatron was $10^{30}\text{cm}^{-2}\text{s}^{-1}$, however the accelerator has been continually upgraded over the years and is now be able to deliver luminosities up to $4 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$**

HL-LHC Performance Goals

- Leveled peak luminosity: $L = 5 \times 10^{34}\ cm^{-2}\ sec^{-1}$
- Virtual peak luminosity: $L = 10 \times 10^{34}\ cm^{-2}\ sec^{-1}$





- Integrated luminosity: 200 fb^{-1} to 300 fb^{-1} per year
- Total integrated luminosity: ca. 3000 fb^{-1}

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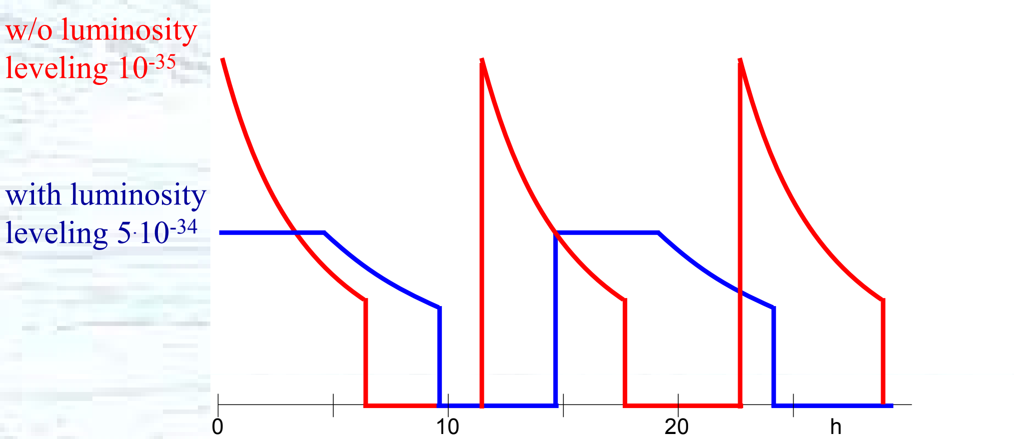
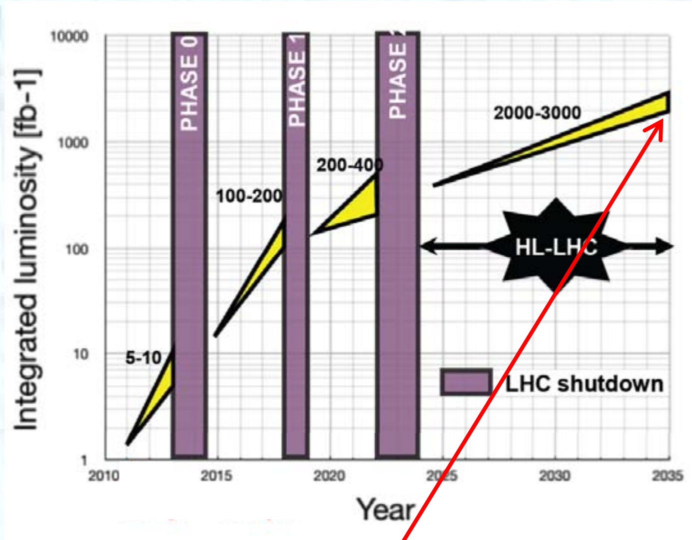


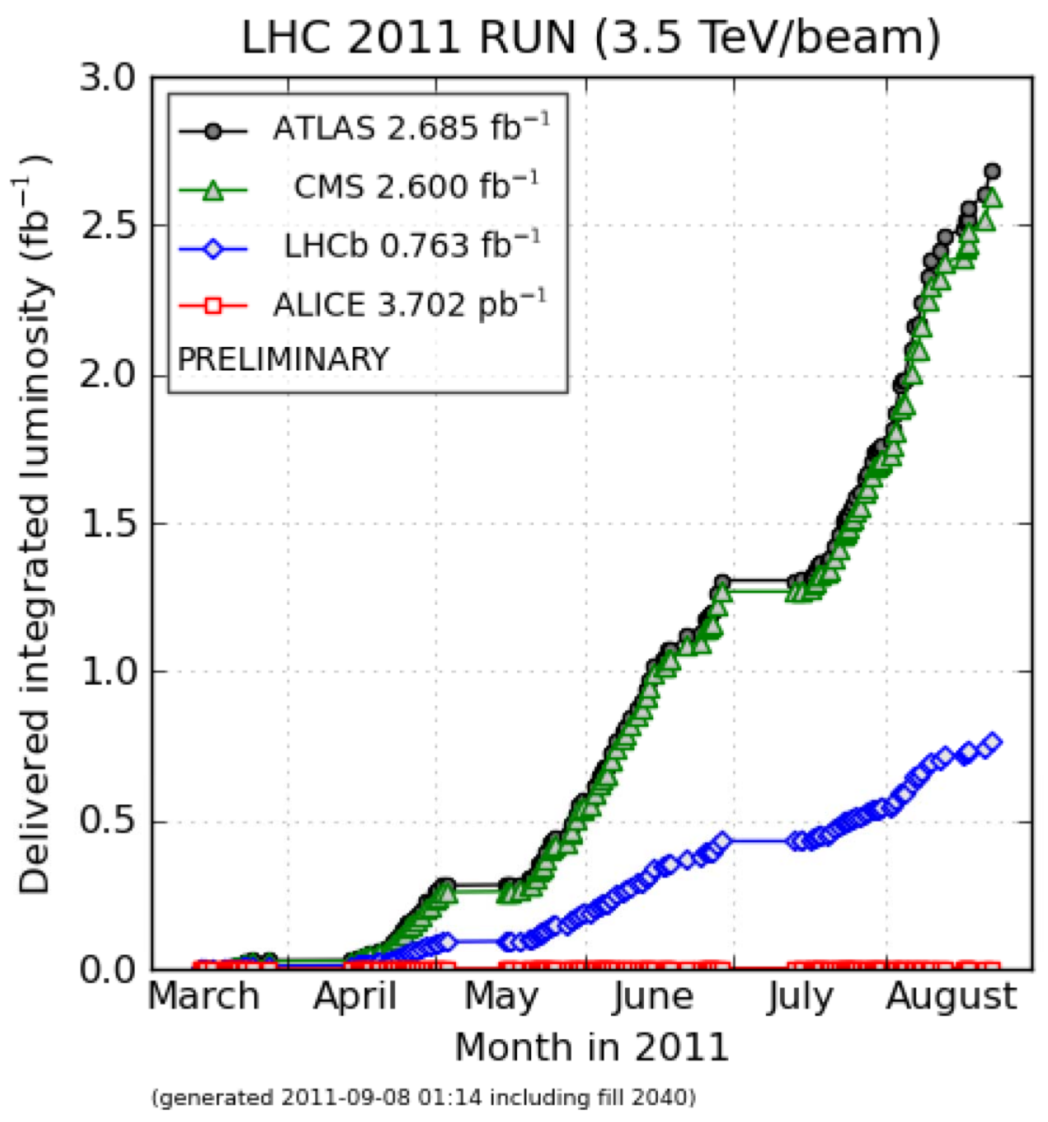


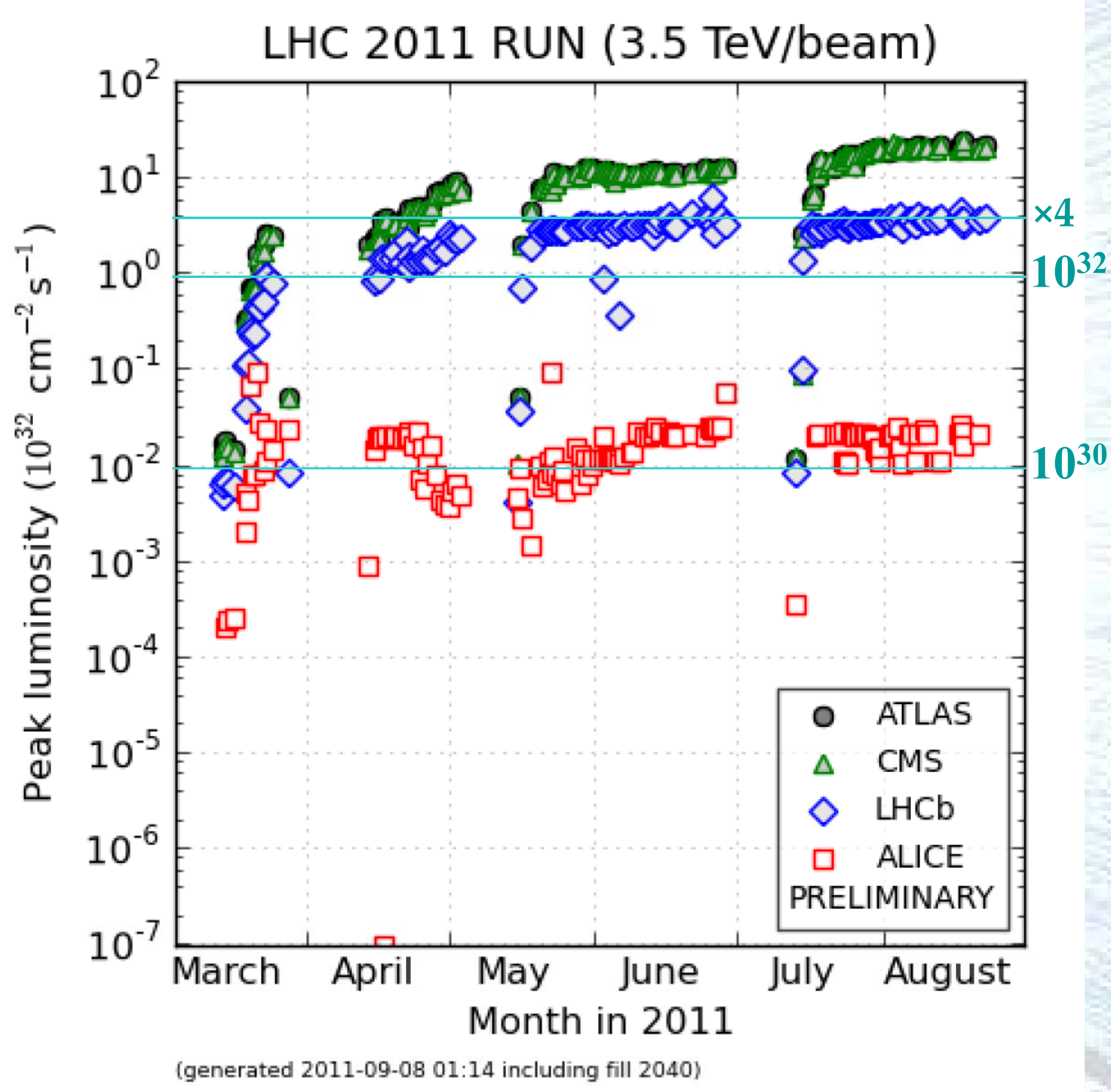
- Integrated luminosity: 200 fb^{-1} to 300 fb^{-1} per year
- Total integrated luminosity: ca. 3000 fb^{-1}

- Finally look to double the energy (HE-LHC)
  16.5+16.5 TeV proton collider in the LHC tunnel

LHC Performance this Year

3 fb^{-1} Down, 2997 fb^{-1} To Go

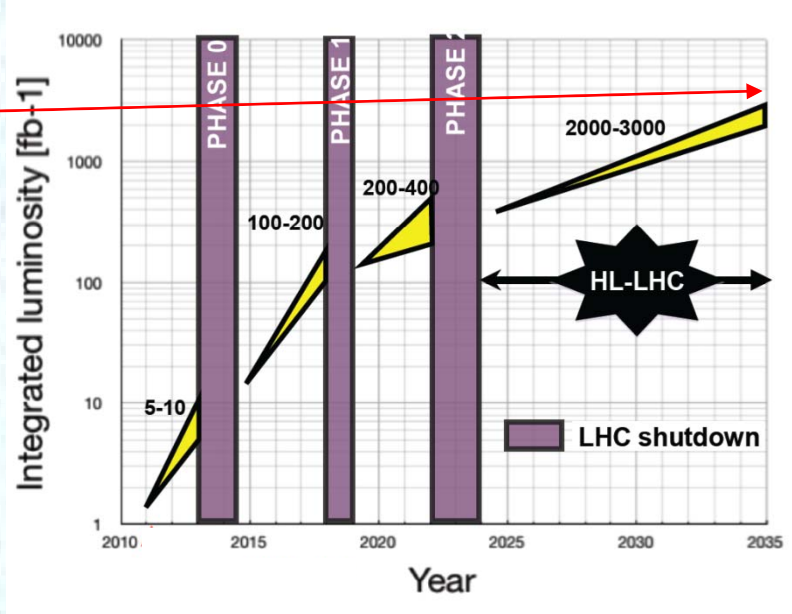




Upgrading the General Purpose Detectors

To keep ATLAS and CMS running beyond ~10 years requires tracker replacement
Current trackers designed to survive up to 10Mrad in strip detectors ($\leq$ 700 fb^{-1})
For the luminosity-upgrade the new trackers will have to cope with:

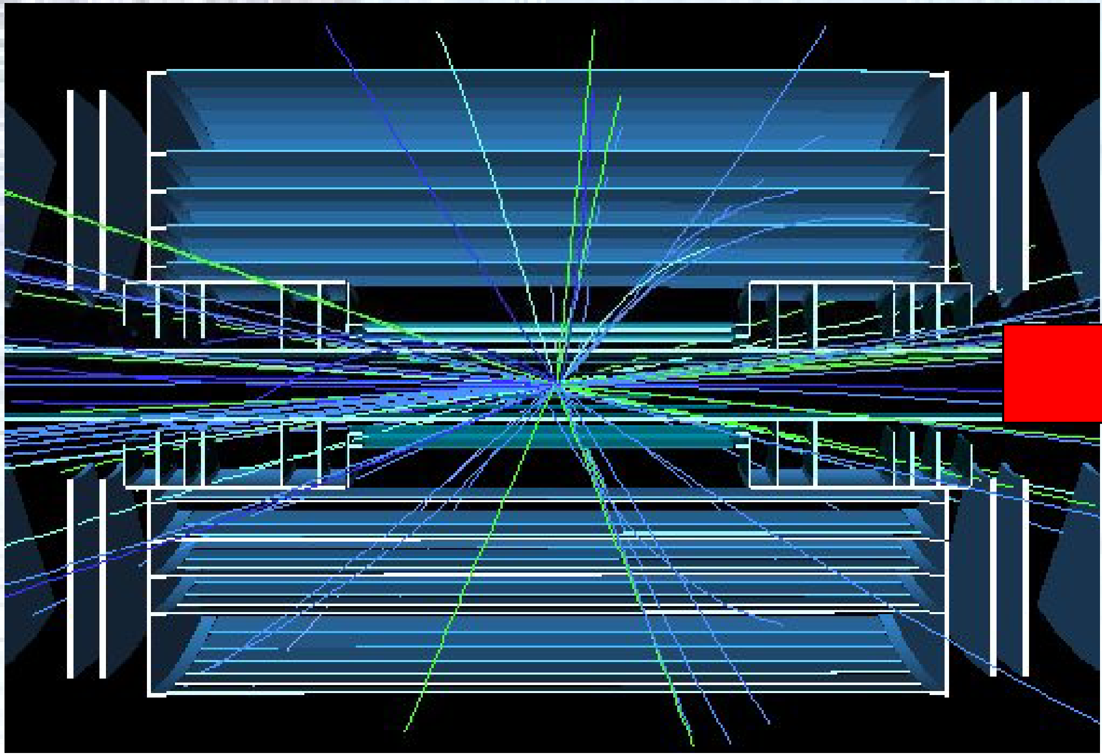
- **much higher integrated doses** (need to plan for 3000 fb^{-1})
- much higher occupancy levels (up to 200 collisions per beam crossing)
- Installation inside an existing 4π coverage experiment

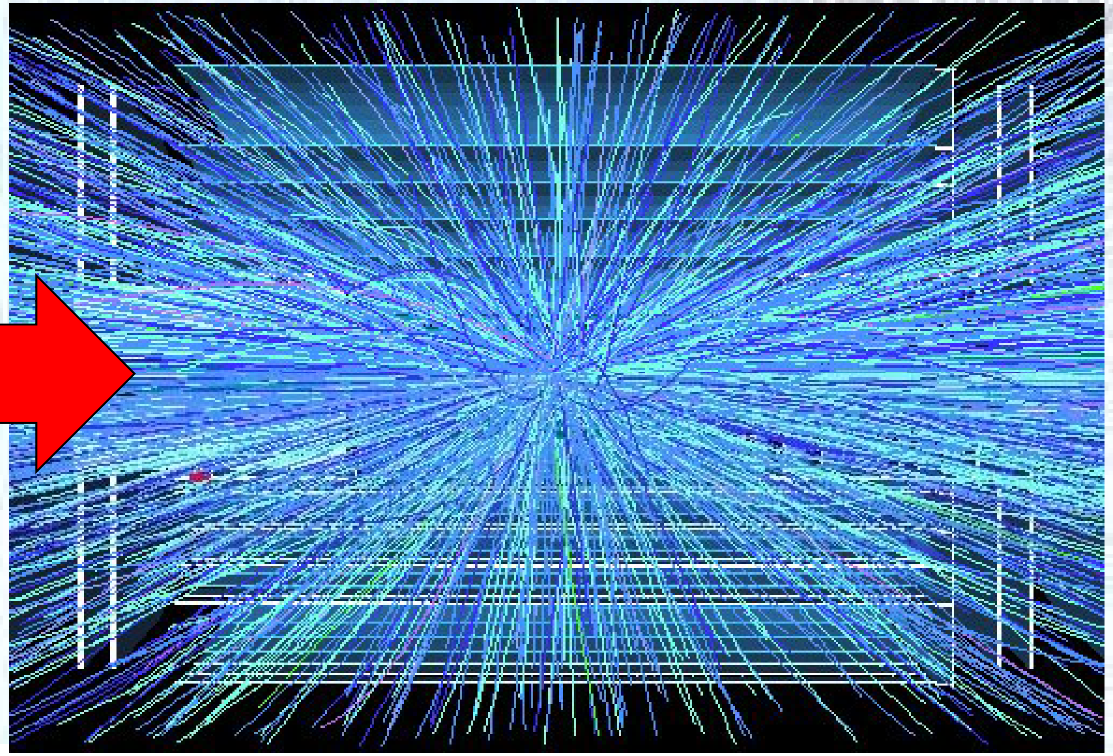


- Budgets are likely to be such that replacement trackers, while needing higher performance to cope with the extreme environment, cannot cost more than the ones they replace

To complete a new tracker for ~2020, require Technical Design Reports by 2014/15
(Note the ATLAS Tracker TDR: April 1997; CMS Tracker TDR: April 1998)

Radiation Background Simulation





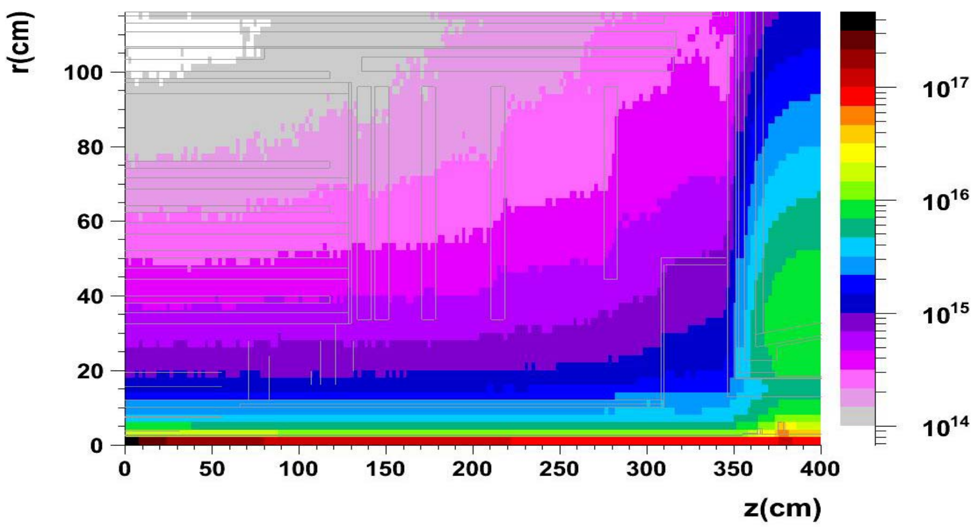
1 MeV neutron eq fluence

At inner pixel radii - target survival to 1-2×10^{16} n_{eq}/cm^2

Numbers obtained 9/10/09 (corresponding to new layout) assuming 3000fb-1 and 84.5mb

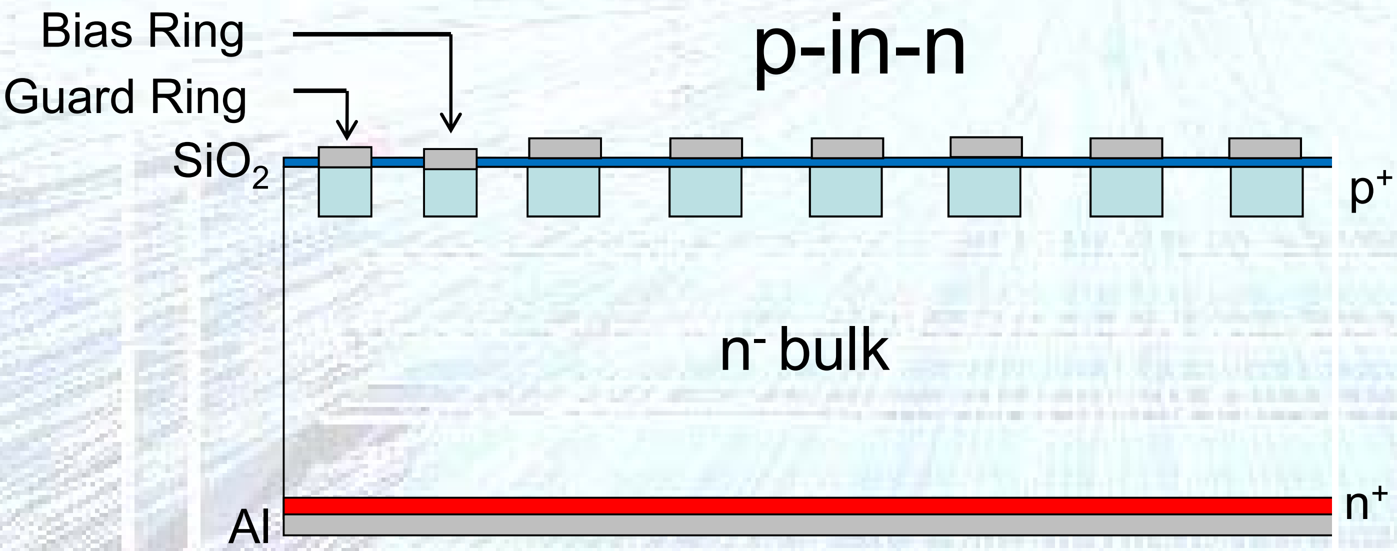
Strip barrel 1 (SS)	(r=38cm; z=0cm)	4.4x10^14
	(r=38cm; z=117cm)	4.9x10^14
Strip barrel 4 (LS)	(r=74.3cm; z=0.0cm)	1.6x10^14
	(r=74.3cm; z=117cm)	1.8x10^14
Strip Disc 1	(z=137.1, Rinner=33.6)	6.0x10^14
Strip Disc 2	(z=147.6, Rinner=33.6)	6.2x10^14
Strip Disc 3	(z=174.4, Rinner=33.6)	5.8x10^14
Strip Disc 4	(z=214.1, Rinner=33.6)	6.1x10^14
Strip Disc 5	(z=279.1, Rinner=44.4)	5.8x10^14
Strip Disc 5	(z=279.1, Rinner=54.1)	4.4x10^14
Strip Disc 5	(z=279.1, Rinner=61.7)	3.9x10^14
new		
Strip Disc 5	(z=279.1, Rinner=73.6)	3.0x10^14
Strip Disc 5	(z=279.1, Rinner=84.9)	2.7x10^14

For strips 3000fb^{-1} ×2 implies survival required up to ~1.3×10^{15} n_{eq}/cm^2



Geometry Choices

- p-in-n
  - Least expensive
  - Single-sided processing
  - Available from all foundries
  - Most experience in production
    - All strips at CMS/ATLAS/ALICE, Tevatron, b-factories, LEP …



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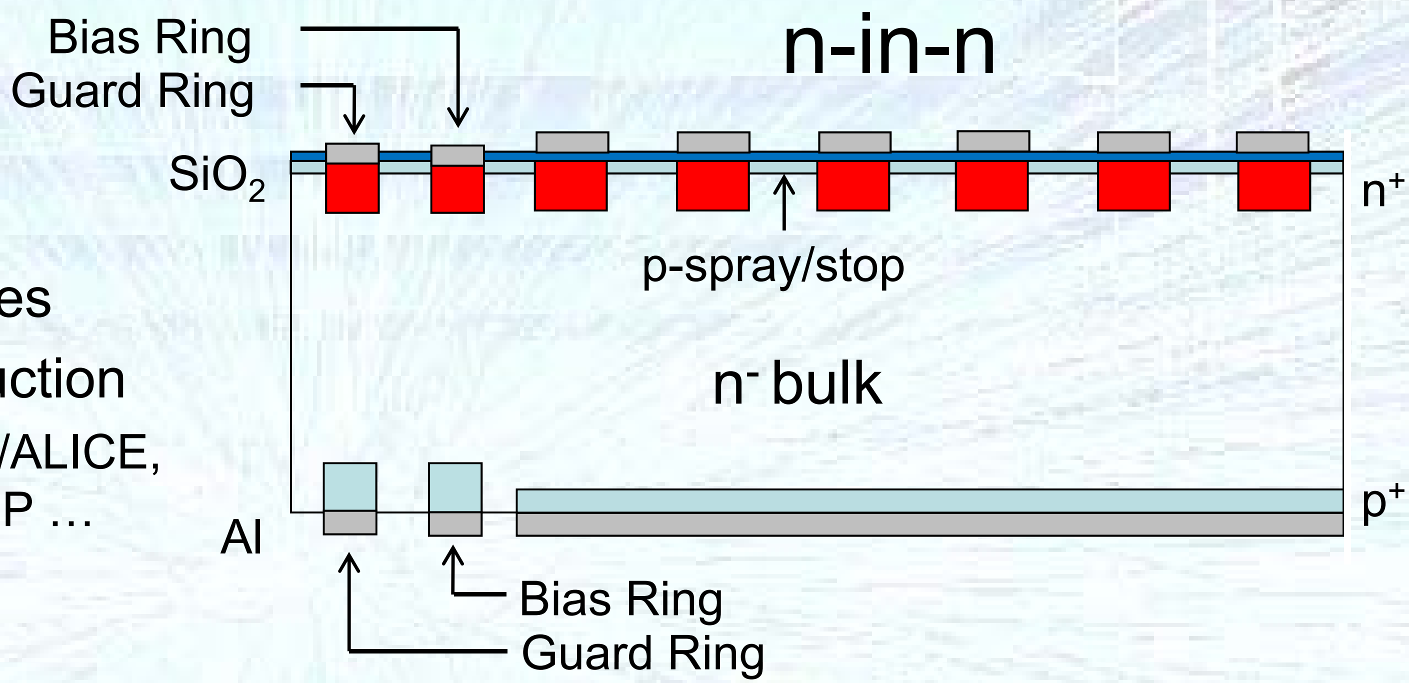
  - Limited suppliers
  - Some experience with "large" scale production
    - CMS/ATLAS pixels, LHCb VELO
  - Guard rings both sides (edge voltage)
  - Much more radiation hard than p-in-n



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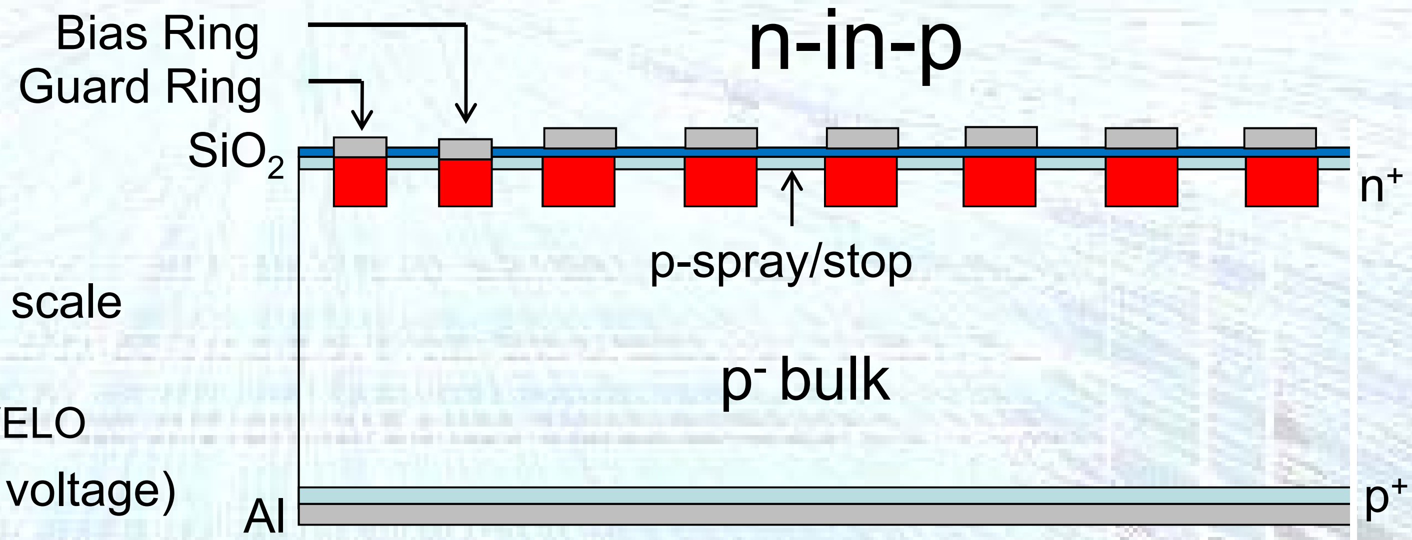
    - CMS/ATLAS pixels, LHCb VELO
  - Guard rings both sides (edge voltage)
  - Much more radiation hard than p-in-n
- n-in-p
  - ~50% less expensive than n-in-n
  - Single-sided processing
  - More suppliers (including Hamamatsu)
  - Limited operation experience
    - 1 VELO module installed, replacement VELO system constructed in p-type
  - Edge expected to be at bias voltage

  As radiation hard as n-in-n



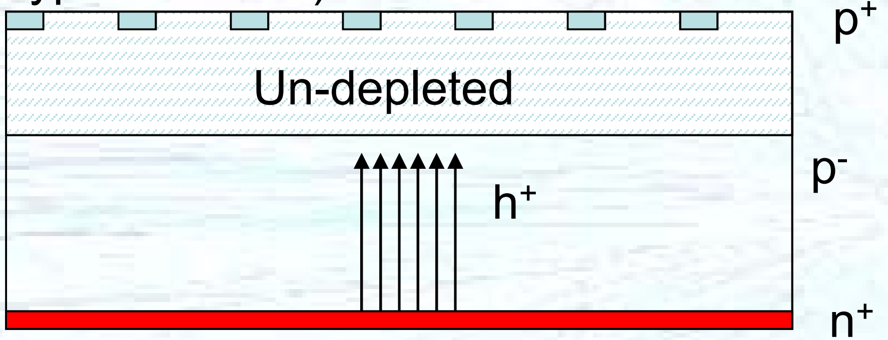
P-strip vs. N-strip Readout

Effect of trapping on the Charge Collection Efficiency (CCE)

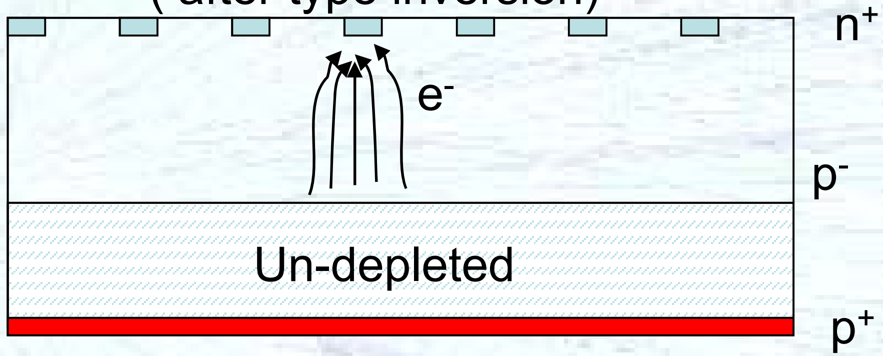
$$Q_{tc} \cong Q_0 \exp(-t_c/\tau_{tr}),\ 1/\tau_{tr} = \beta\Phi.$$

t_C is collection "time", τ_{tr} is effective trapping time

"Standard" p-in-n geometry (after type inversion)



"New" n-in-p geometry
"New" n-in-n geometry (after type inversion)

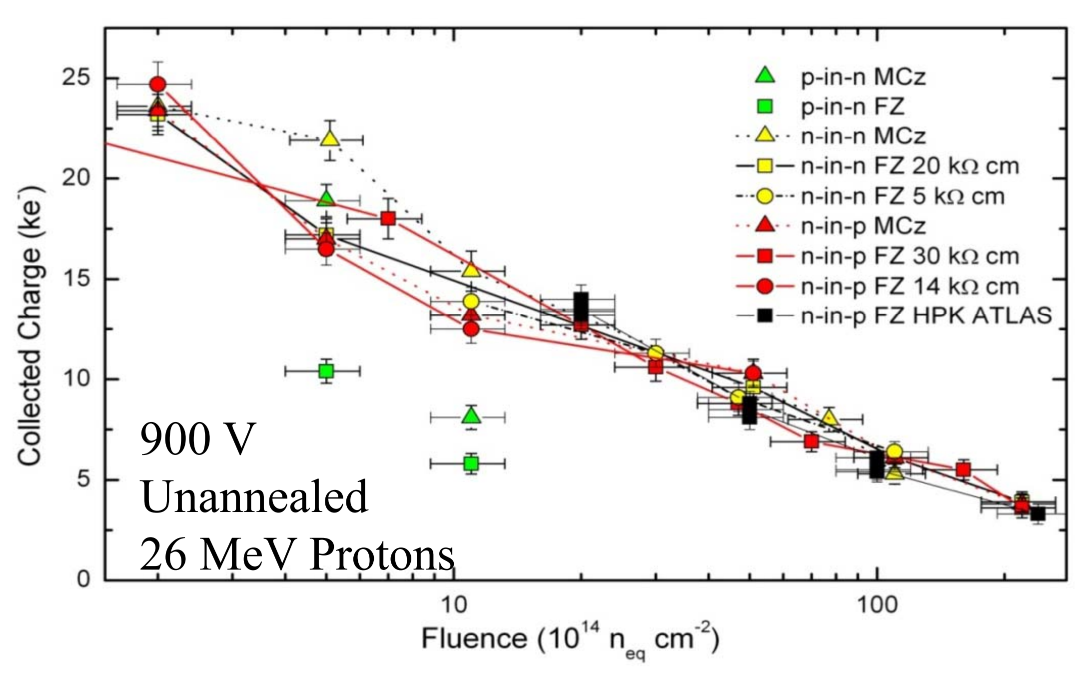


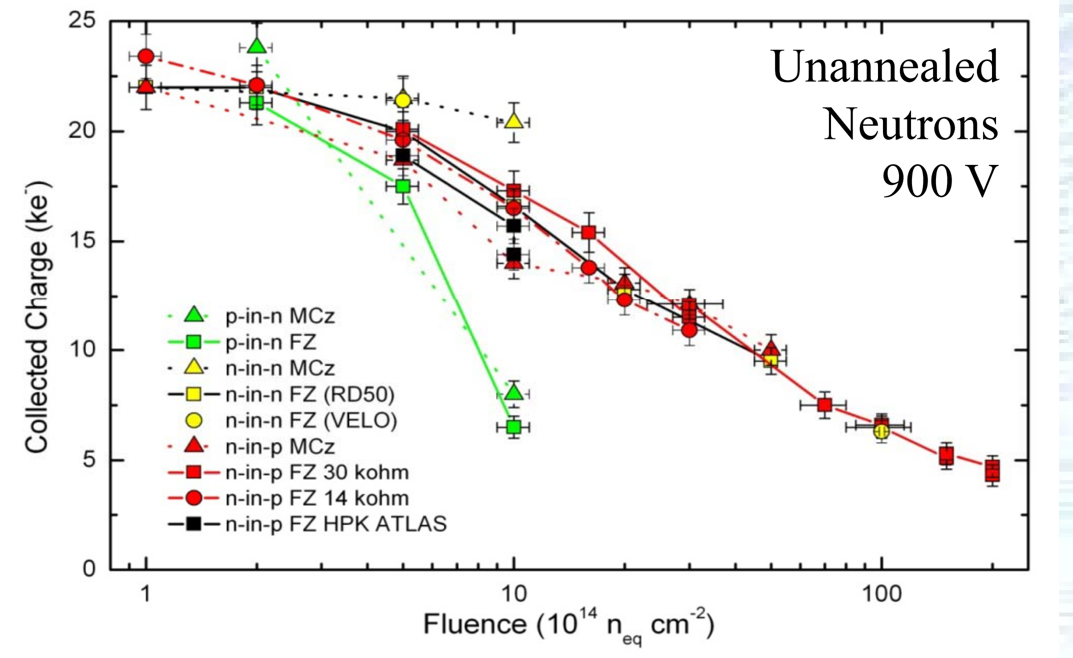
Type inversion turns lightly doped material to "p" type

- Holes collected
- Deposited charge cannot reach electrode
  - Charge spread over many strips
  - Lower signal

- Electron collected
  - Higher mobility and ~33% smaller trapping constant
- Deposited charge can reach electrode

RD50 Charge Collection Studies





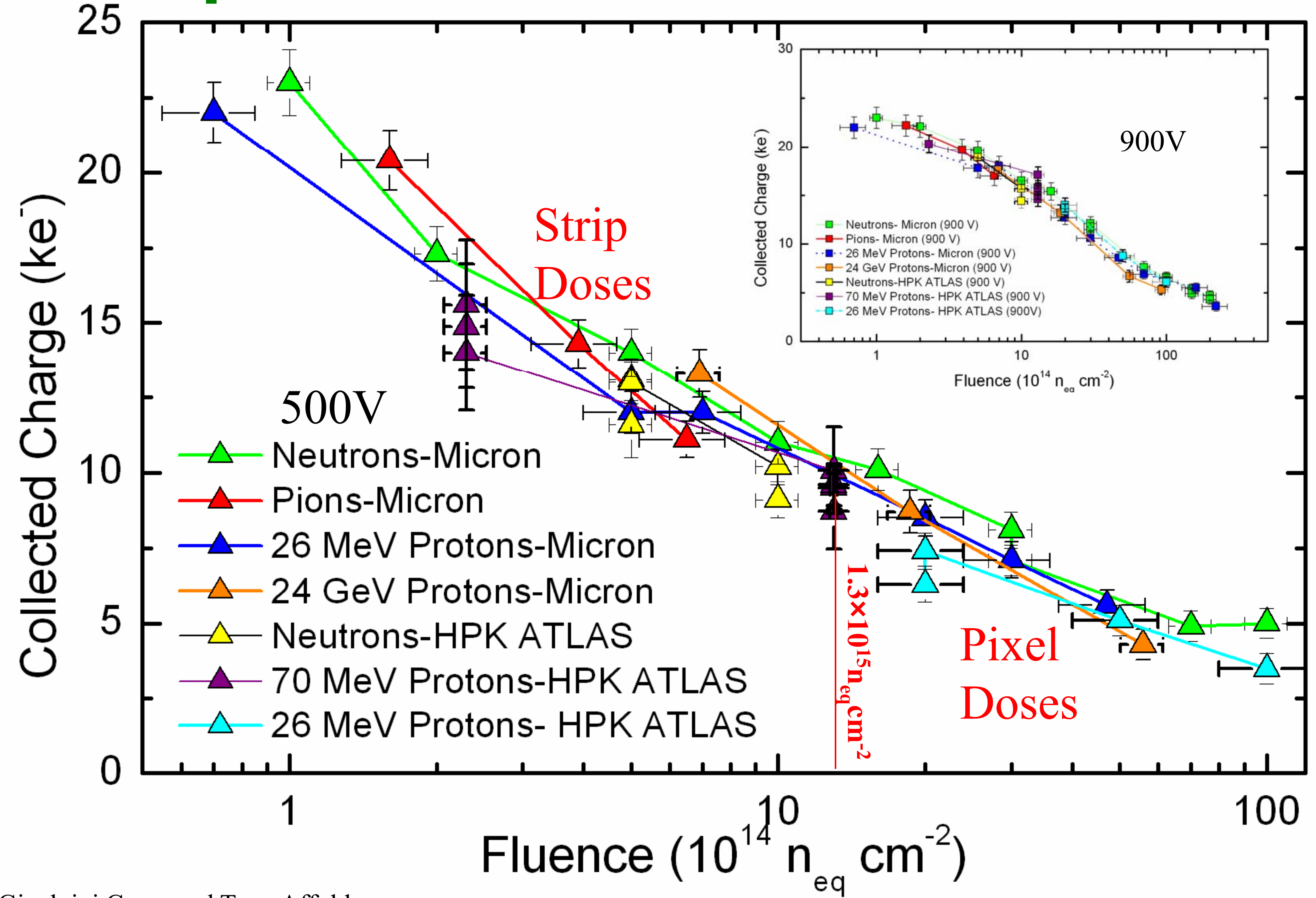
All n-strip readout substrates studied become more and more similar with irradiation. This is true after neutron, proton and pion irradiations and with Hamamatsu and Micron devices.

MICRON SEMICONDUCTOR ltd

HAMAMATSU

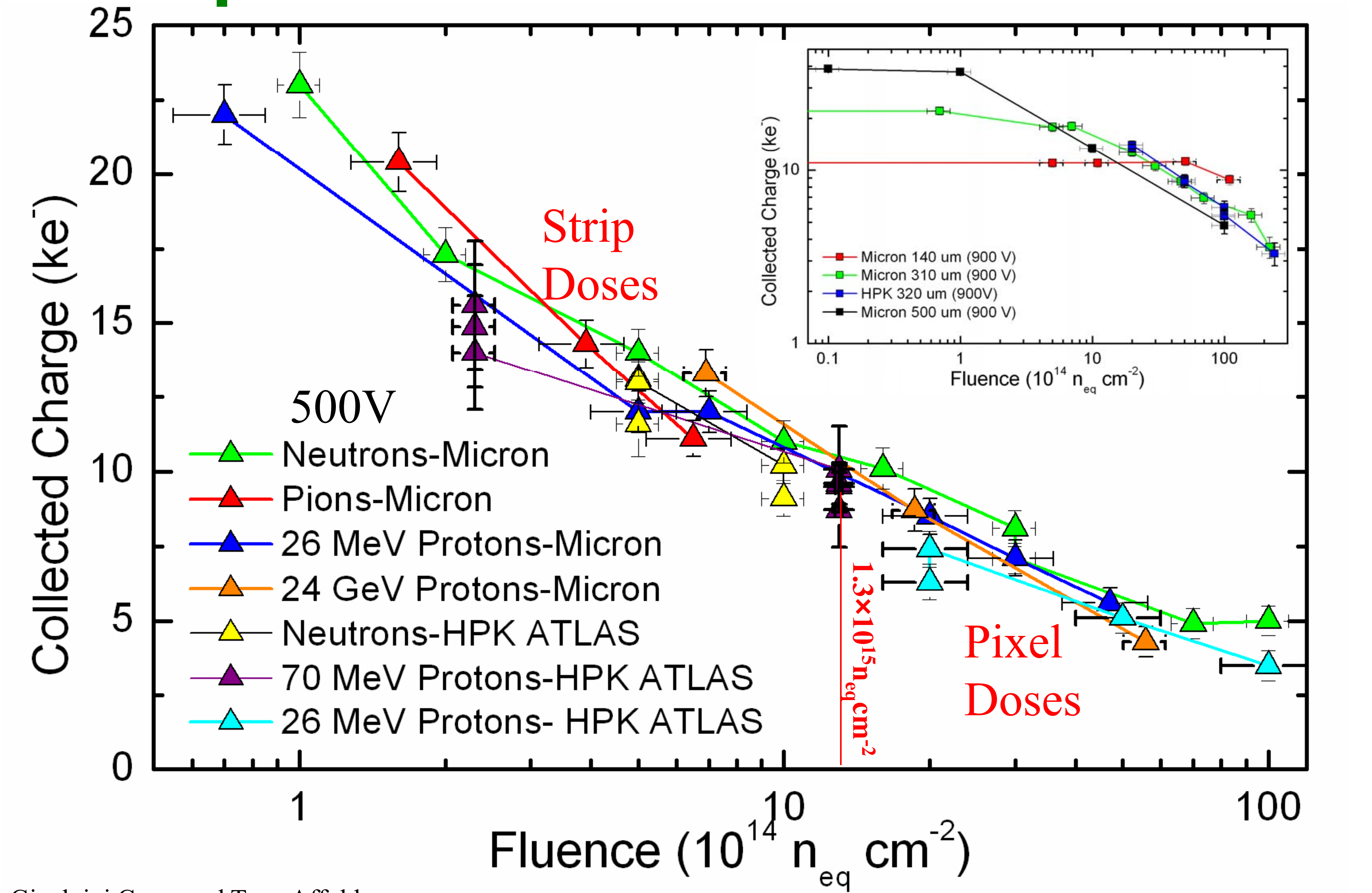
Micron Neutrons: A. Affolder, et. al., Nucl. Instr. Meth. A, Vol. 612 (2010), 470-473.
Micron 26 MeV Protons: A. Affolder, et. al., Nucl. Instr. Meth. A, Vol.623 (2010), 177-179.
HPK Neutrons: K. Hara, et. at., Nucl. Inst. Meth. A, Vol. 636 (2011) S83-S89.
HPK 26 MeV Protons: New and unpublished

n-in-p Planar FZ Sensor Irradiations



Gianluigi Casse and Tony Affolder,

n-in-p Planar FZ Sensor Irradiations



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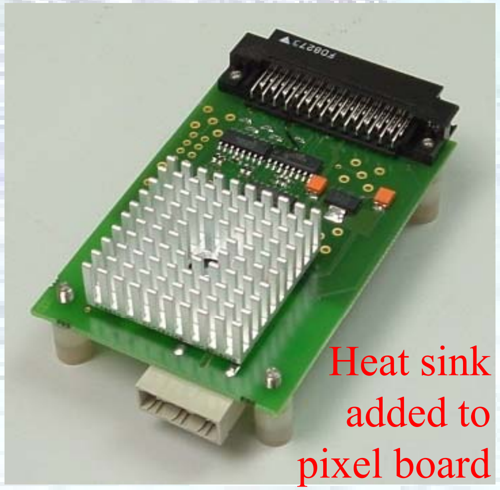
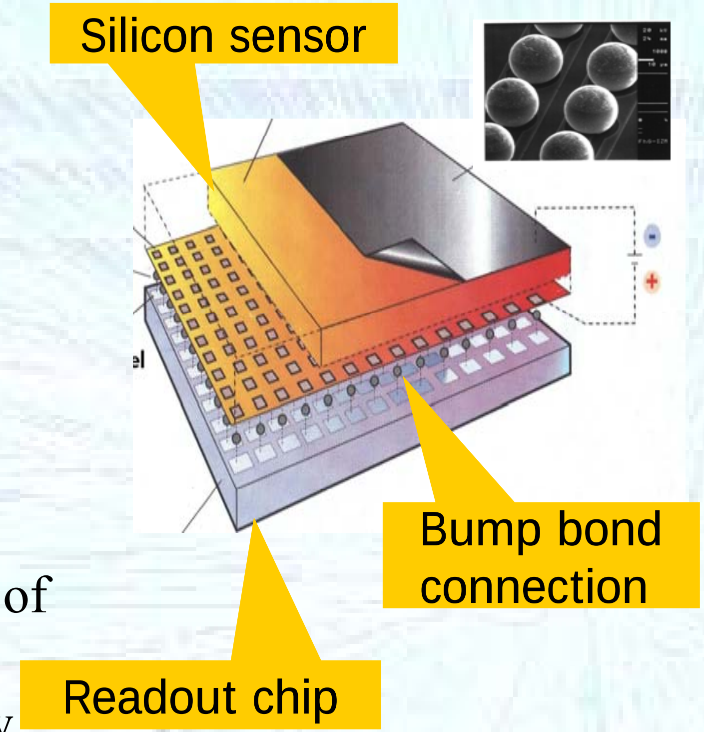
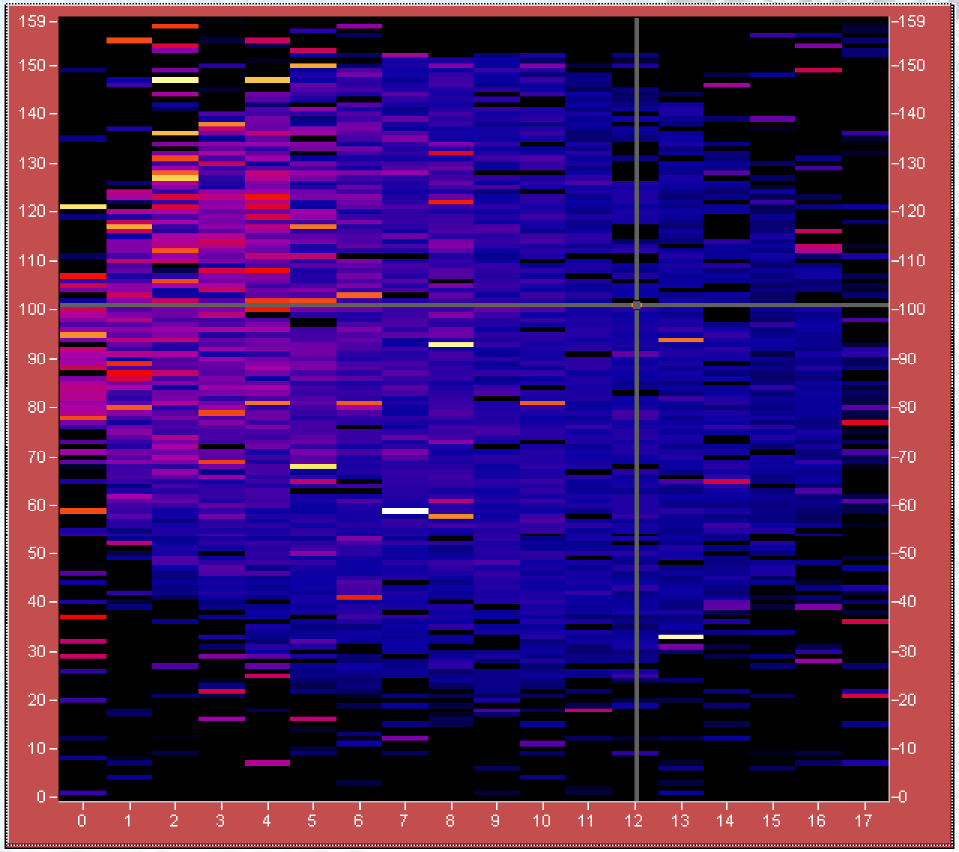
Micron n-in-p Irradiated FE-I3 Pixel Package

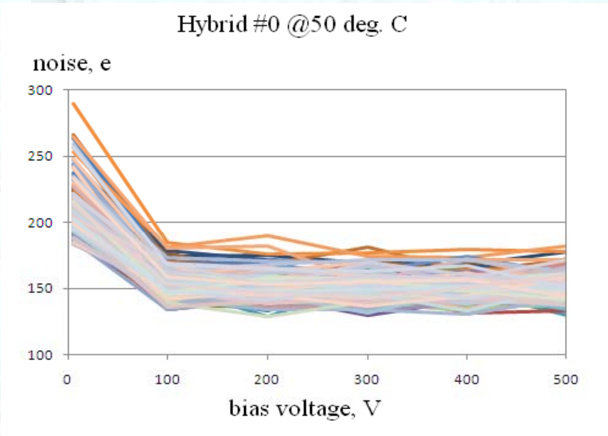




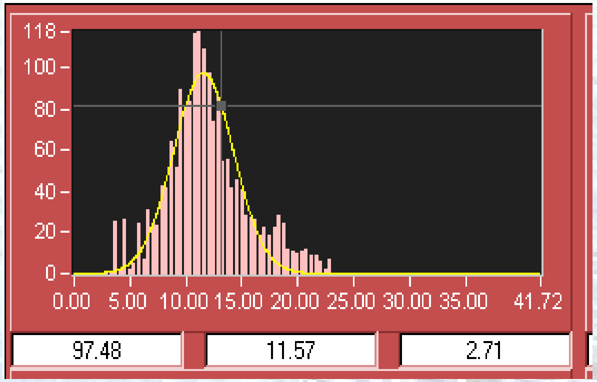


Measurements pre-irradiation and at doses of 4×10^{15} n_{eq} cm^{-2} and 9×10^{15} n_{eq} cm^{-2} all show no evidence of edge breakdown at 500V.

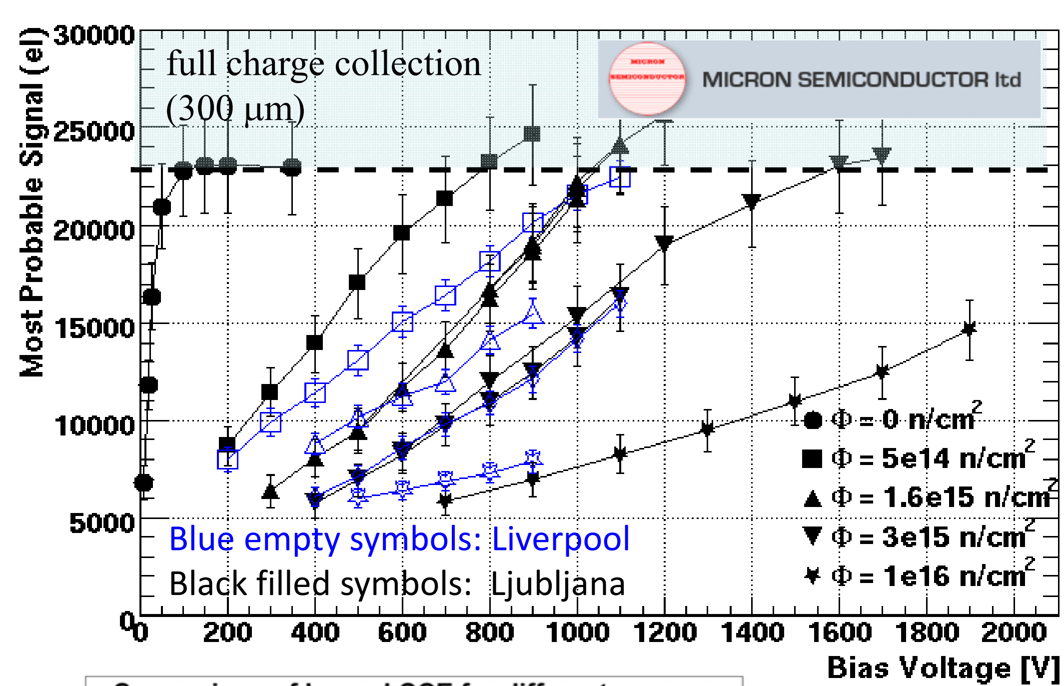
FE-I3 ASIC surprisingly robust but number of dead channels does increase at doses well above design target.

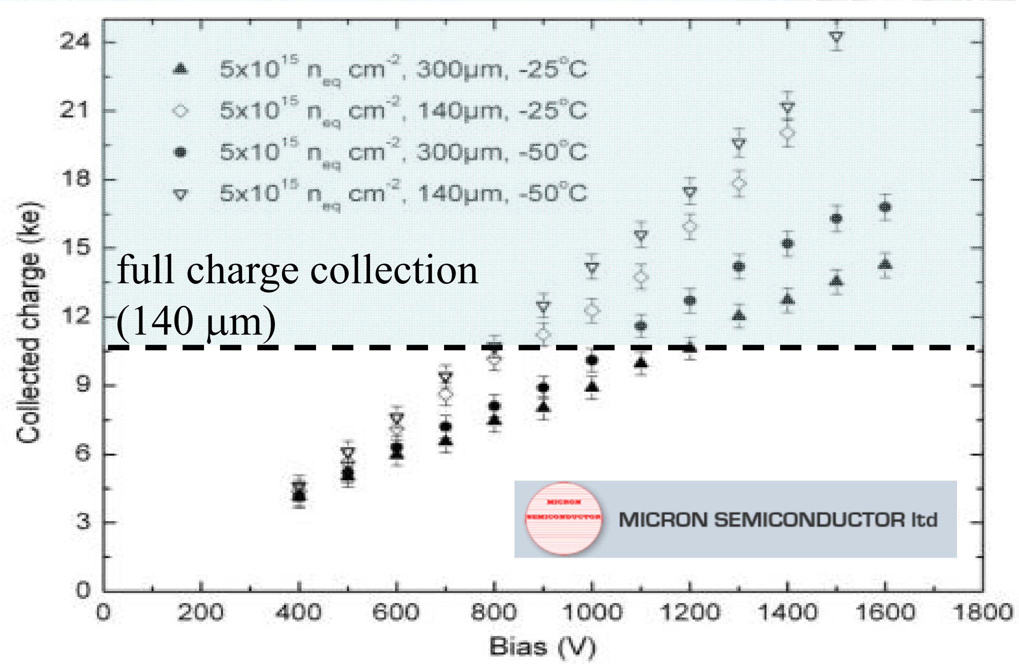


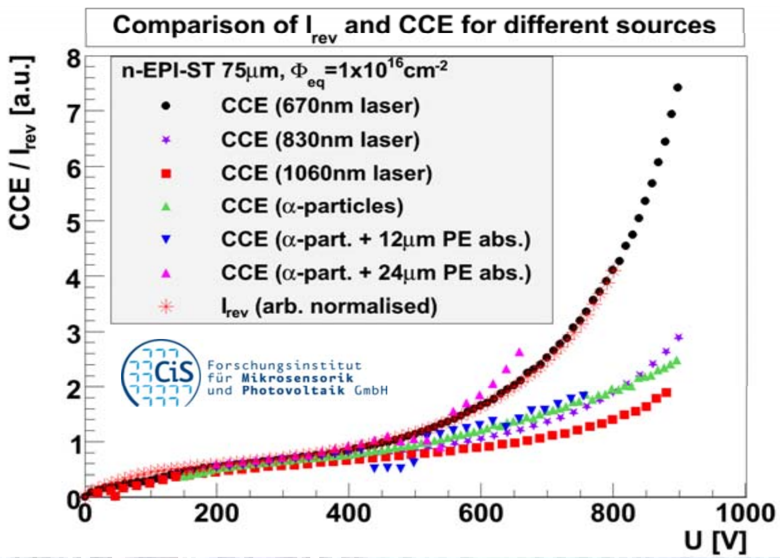
After irradiation to 1.5×10^{16} p/cm^2
At CERN PS
(9×10^{15} n_{eq} cm^{-2})
peak charge at 500V is ~4000e
(Threshold 3500e -26°C, I_b 44uA)



RD50 Charge Multiplication Studies







More than 100% charge collection seen at high bias voltages after irradiation for both n-in-p strips and EPI

- Multiplication is consistent with high fields at implants
  - Multiplication largest at segmented implant
- Current also correlated with charge as expected

See also M. Backhaus, P. Dervan, A. Dierlamm, J. Olzem, A. Rummler, E. Verbitskaya, P. Weigell, J. Weingarten, T. Wittig et al.

G. Kramberger – 5th Trento Workshop, 24 - 26 February 2010, Manchester, UK

Active p-type Foundries for HEP

Producers	Wafer Size	Thicknesses	Productions
MICRON SEMICONDUCTOR ltd	4”/6”	150/300/500	ATLAS pixels, LHCb pixels, RD50
HAMAMATSU	6”	320/150	ATLAS pixels/strips, CMS pixels/strips
CNM – Centre Nacional de Microelectrònica, IMB	4”	300	ATLAS endcap strips, RD50
e2v	6”	300	ATLAS barrel strips
CiS Forschungsinstitut für Mikrosensorik und Photovoltaik GmbH	4”	285/200/150	ATLAS pixels, CMS pixels, RD50
FBK – Fondazione Bruno Kessler	4”	≥ 200	ATLAS pixels
VTT	6”	100/200/300/500	ATLAS pixels, RD50
MPI HLL	6”	150/75	ATLAS strips/pixels

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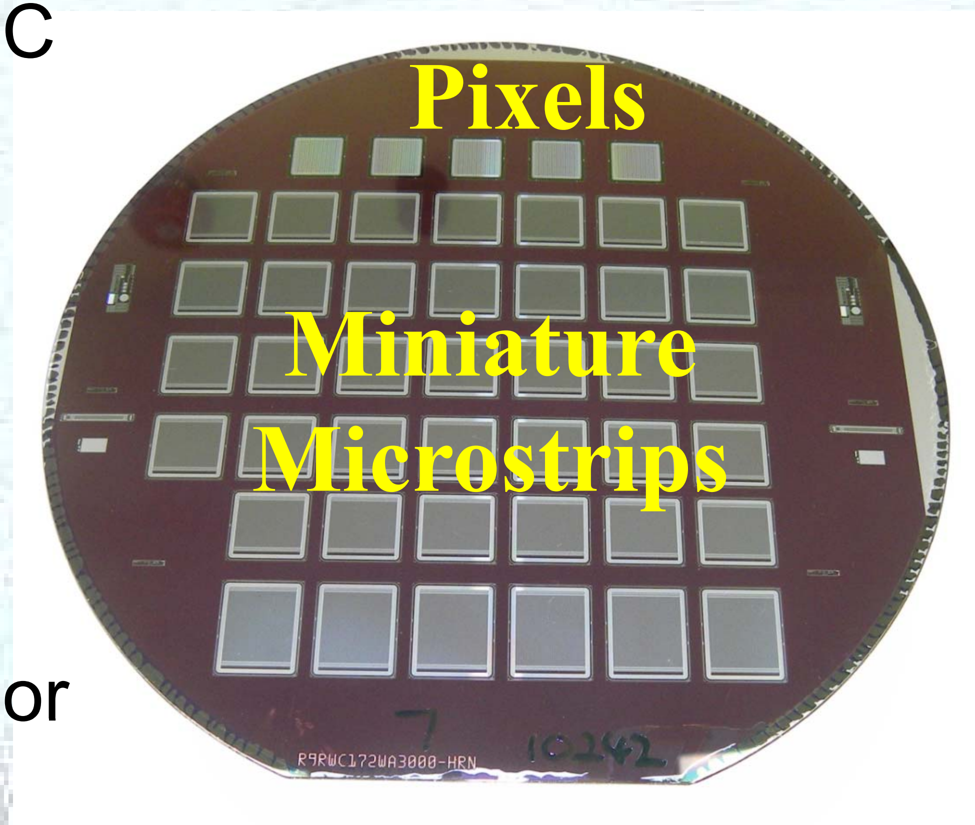
FONDAZIONE BRUNO KESSLER	4"	≥ 200	ATLAS pixels
VTT	6"	100/200/300/500	ATLAS pixels, RD50
MPI HLL	6"	150/75	ATLAS strips/pixels

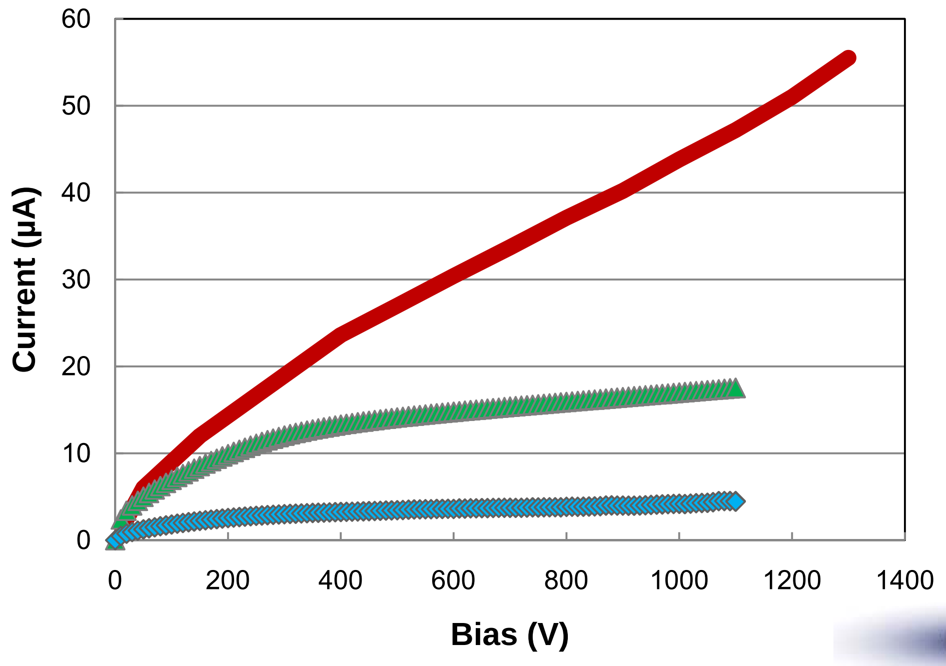
e2v: New to Deep Depletion HEP Devices

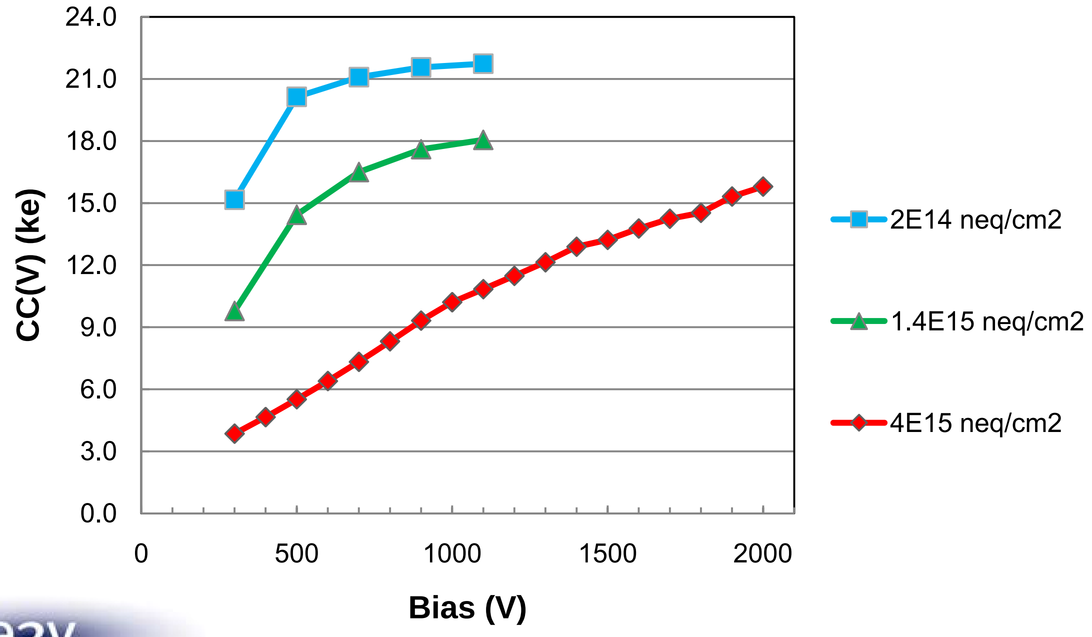
- STFC funded joint proposal between e2v Technologies plc and Liverpool Particle Physics to adapt high yield CCD processing technologies to HEP applications
- e2v offer production capability better suited than many other European suppliers to the (>20,000 6” wafer) requirements for full tracker replacement at HL-LHC
- Both RD50 capacitively-coupled, polysilicon biased miniature micro-strip detectors and FE-I3 ATLAS pixel ASIC compatible arrays manufactured and tested
- Full-size (10cm×10cm) ATLAS HL-LHC module compatible sensor designed and in production



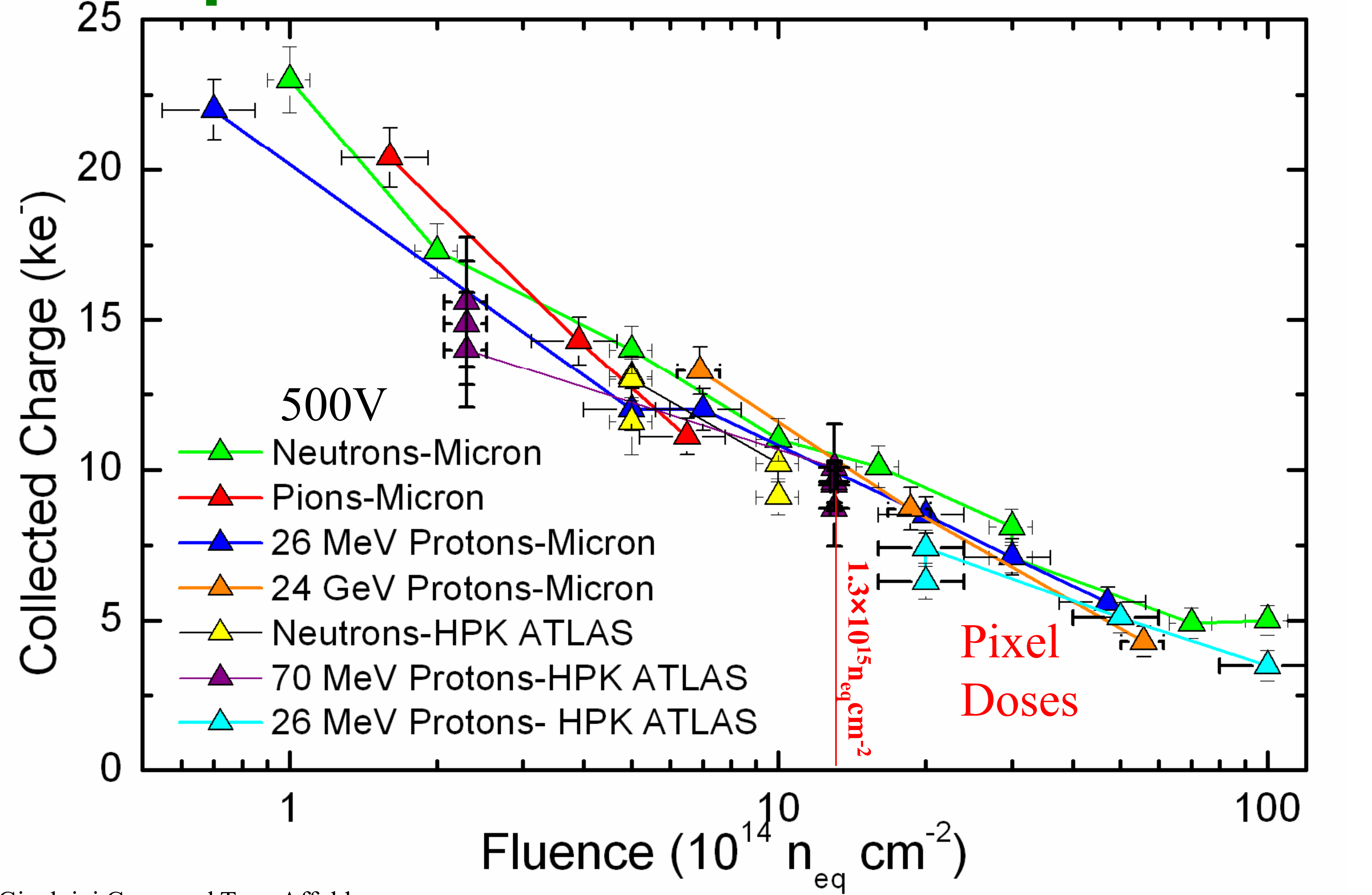
e2v: Miniature Microstrip Prototyping

- A number of processing and design variations have been explored (SiO_2 Si_3N_4 insulation, implant energy and high temperature diffusion, isolation doses and technology,...)
- Good results from the start, with main emphasis to improve pre-irradiation high-voltage leakage currents
- Post-irradiation results compatible with other suppliers



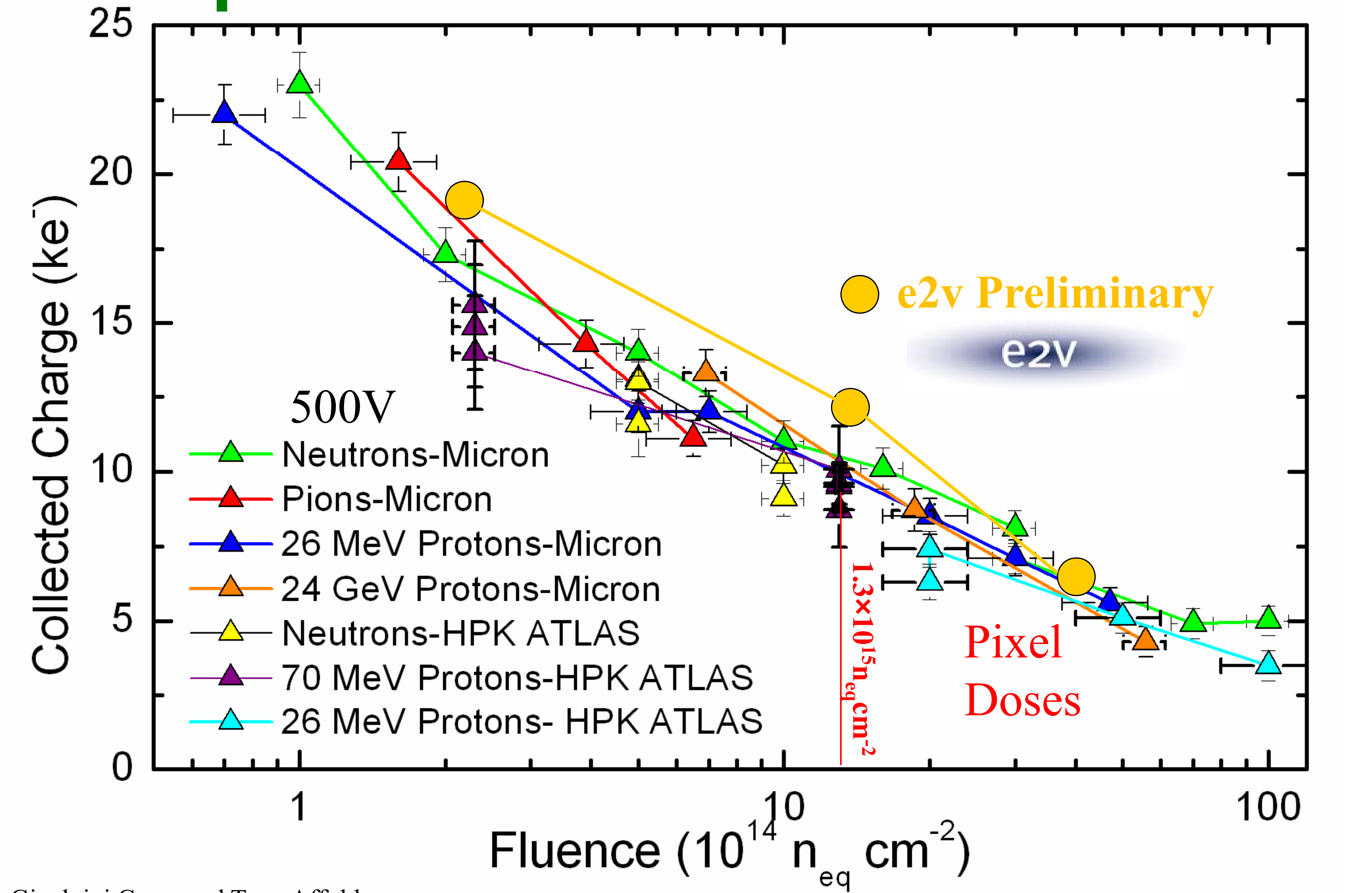


n-in-p Planar FZ Sensor Irradiations



Gianluigi Casse and Tony Affolder,

n-in-p Planar FZ Sensor Irradiations



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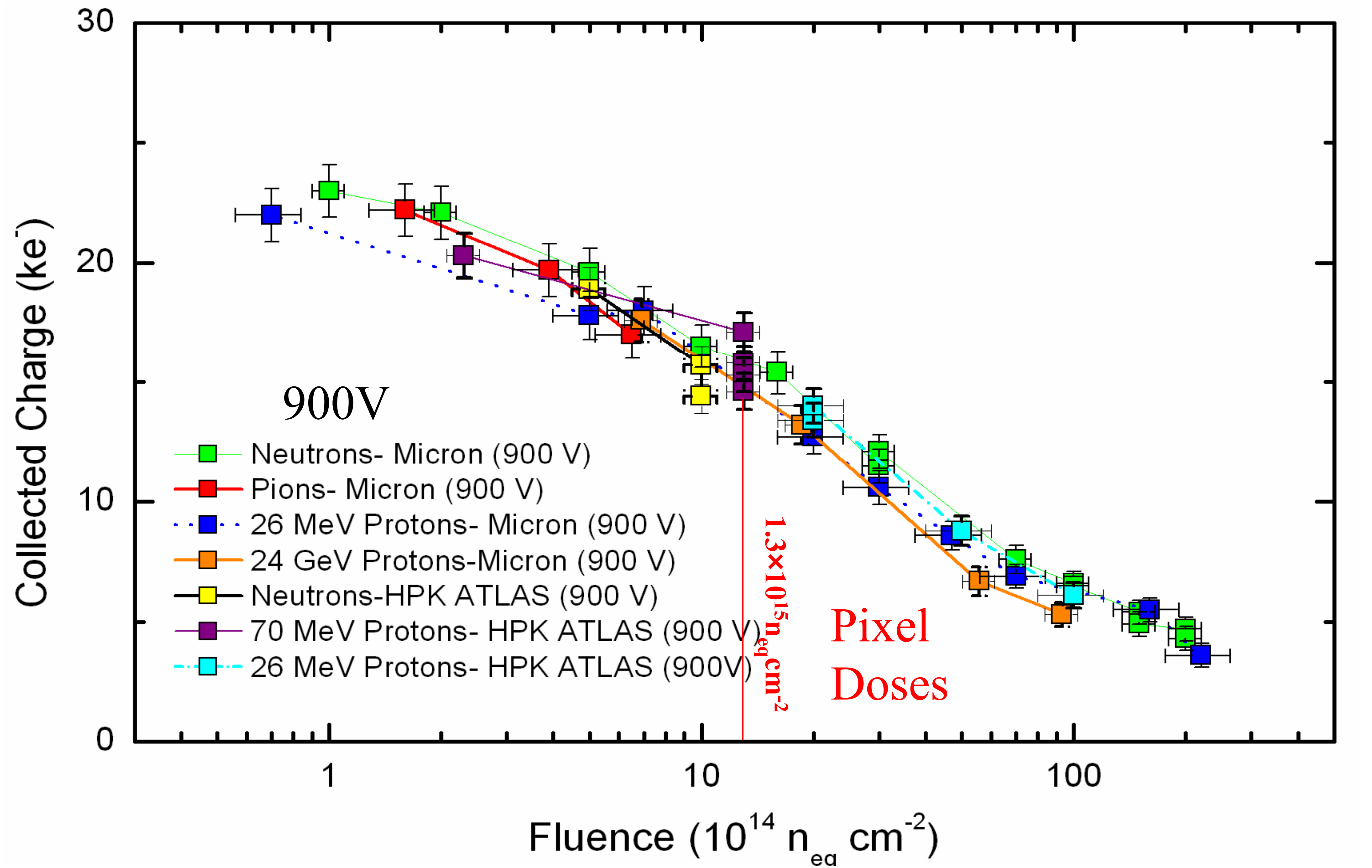
n-in-p Planar FZ Sensor Irradiations



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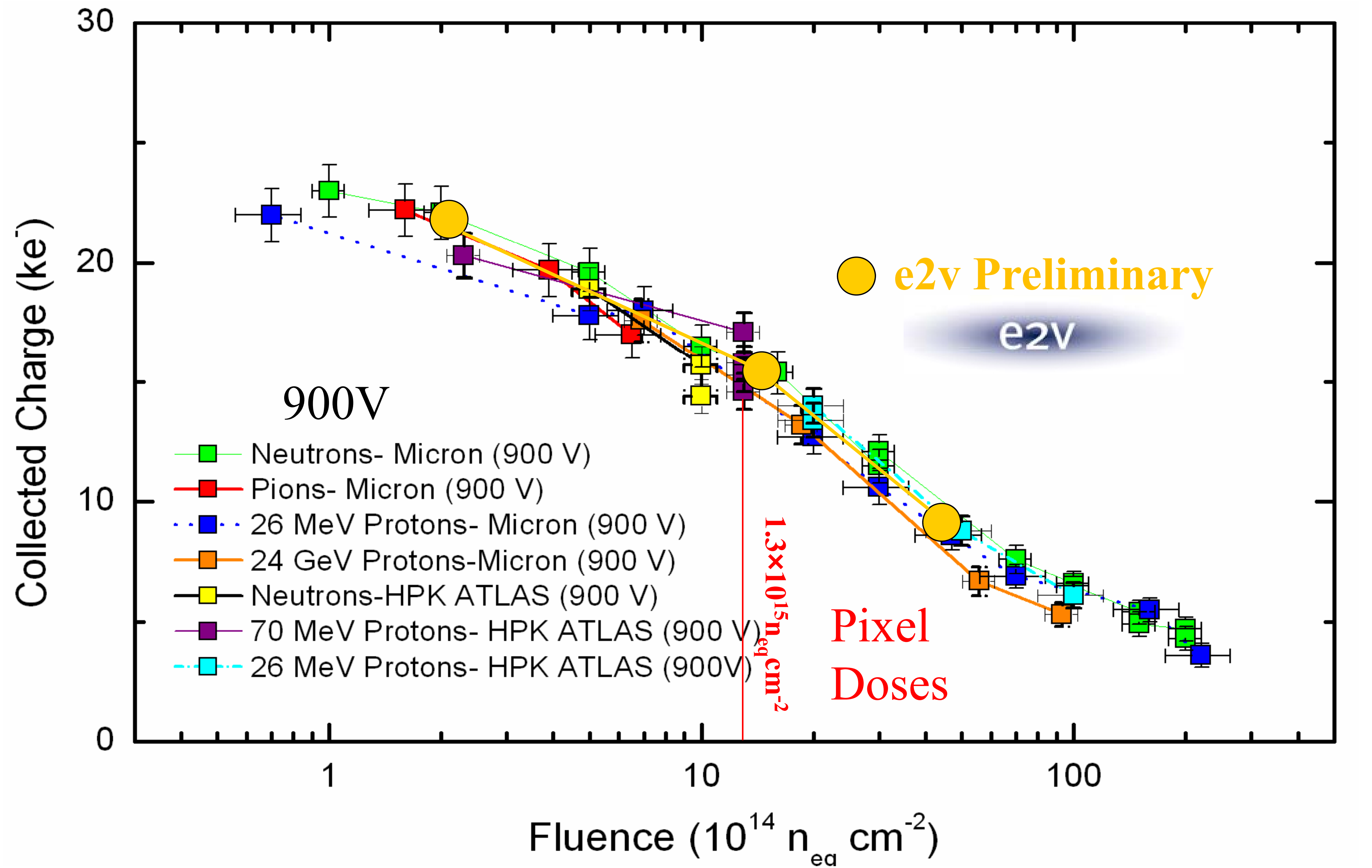


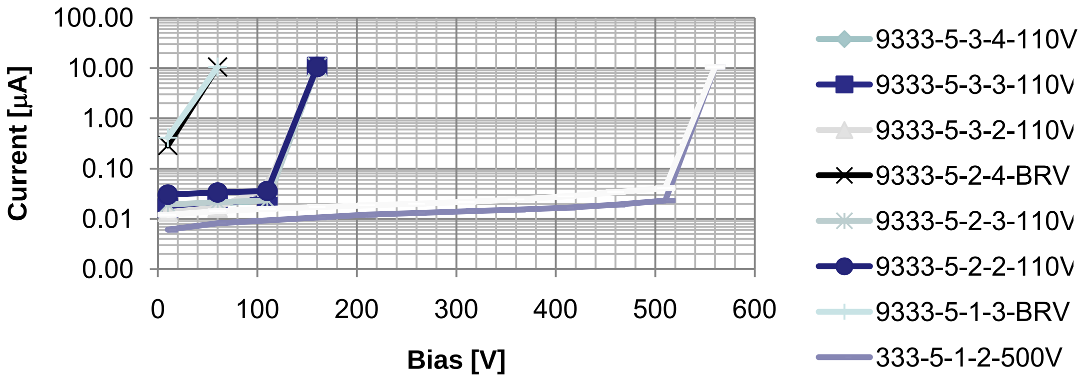
Gianluigi Casse and Tony Affolder,

e2v: Device Design and Processing

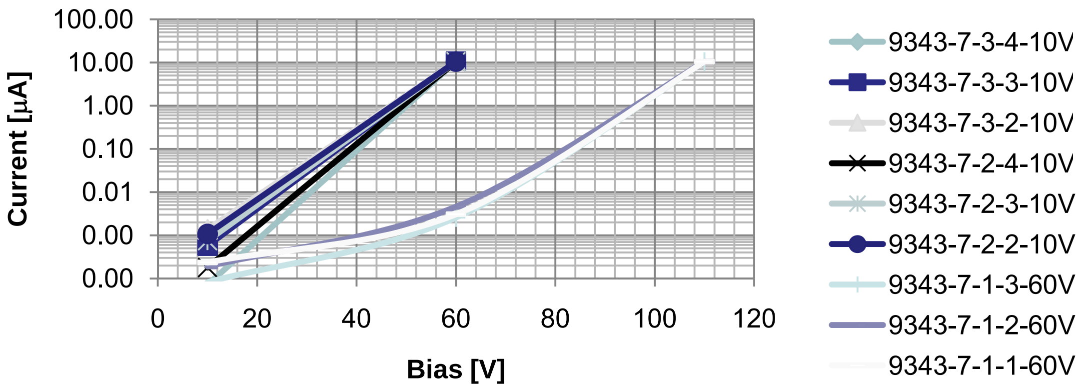
An example of studies looking at the impact of the capacitive dielectric is varying from a "standard" 300nm SiO_2 and150nm Si_3N_4 to either all oxide or 125nm SiO_2 and150nm Si_3N_4 ("thin film"). These results for first iteration of devices.

Pre-irradiation 1cm^2 miniature microstrip detectors and FE-I3 compatible single chip pixel sensors

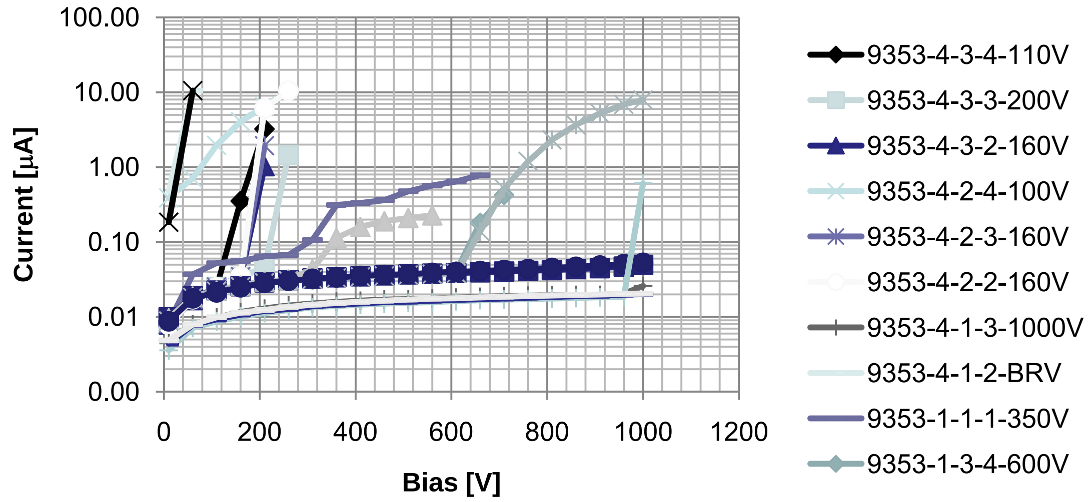
Standard processing



Thin film



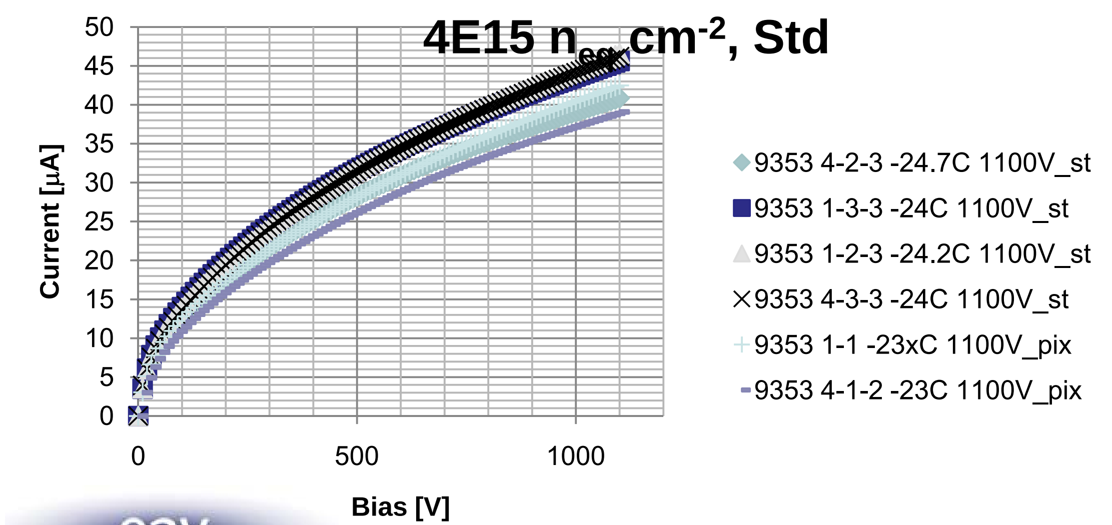
All oxide

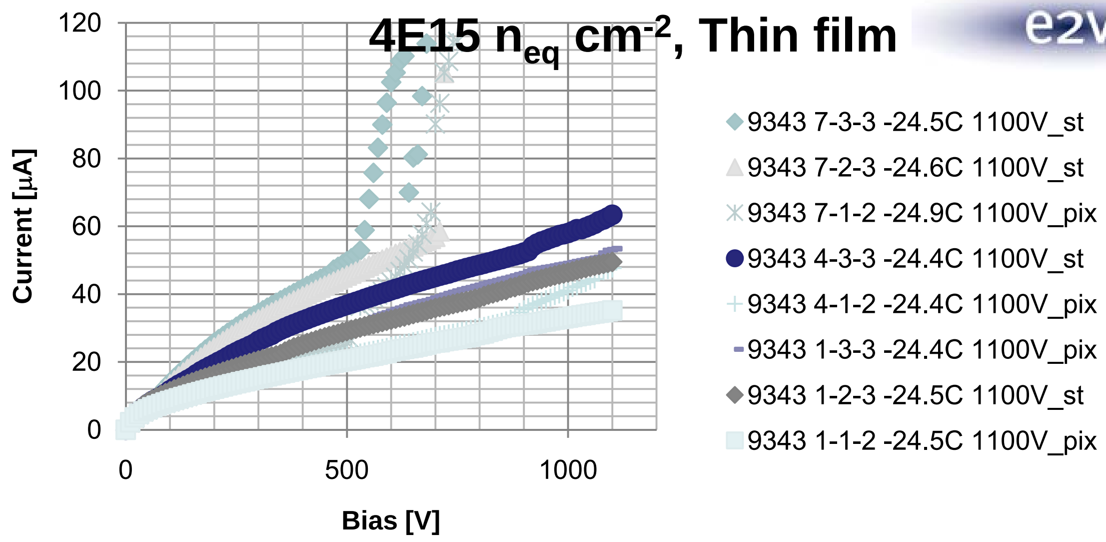


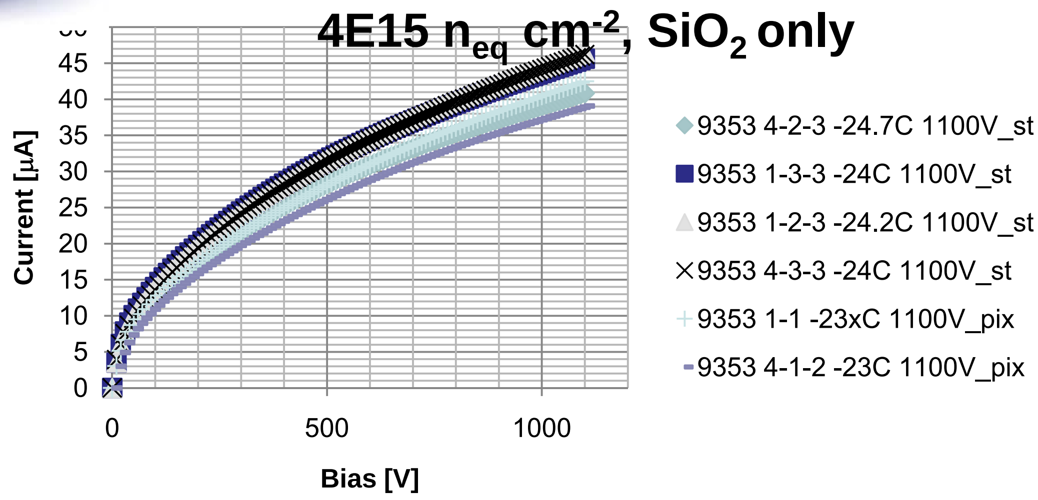
e2v: Device Design and Processing

"Std" (300nm SiO_2 and150nm Si_3N_4) or "SiO_2 only" (300nm) or "thin film" (125nm SiO_2 and150nm Si_3N_4). I(V) after highest dose ($4\times 10^{15} n_{eq} cm^{-2}$):

Oxide only gives best results before and after irradiation







Conclusions

- The future programme at the energy frontier requires a further factor of 10 in radiation tolerance compared with the already extreme requirements of the LHC
- Detectors have been fabricated and tested after irradiation to doses compatible with HL-LHC operation and sufficient signal for efficient operation is found for detectors with n-implant read-out
  - Noise for strips after irradiation ~650e^- (ABCN250 measured)

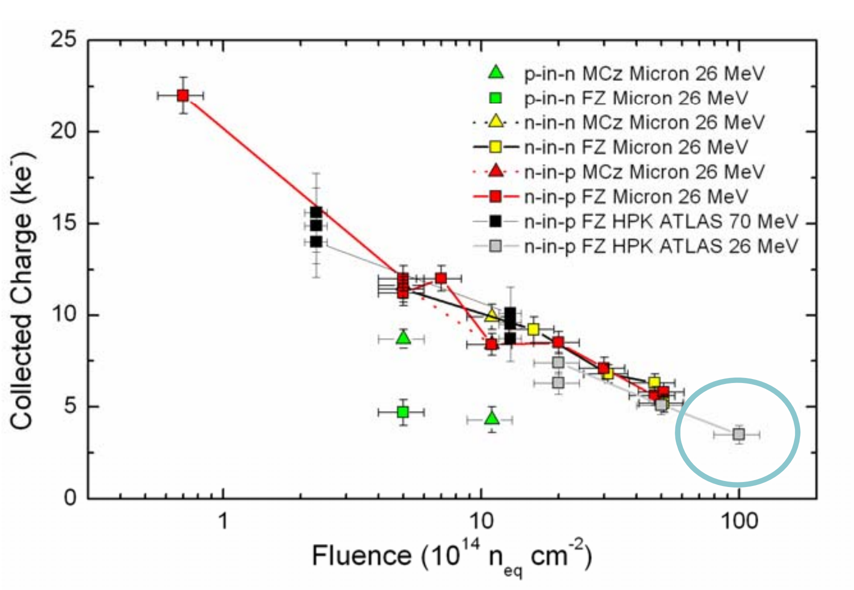
    See presentation by Paul Dervan (this conference)
  - FE-I4 ASIC operated with irradiated sensors at thresholds ~1600e^-

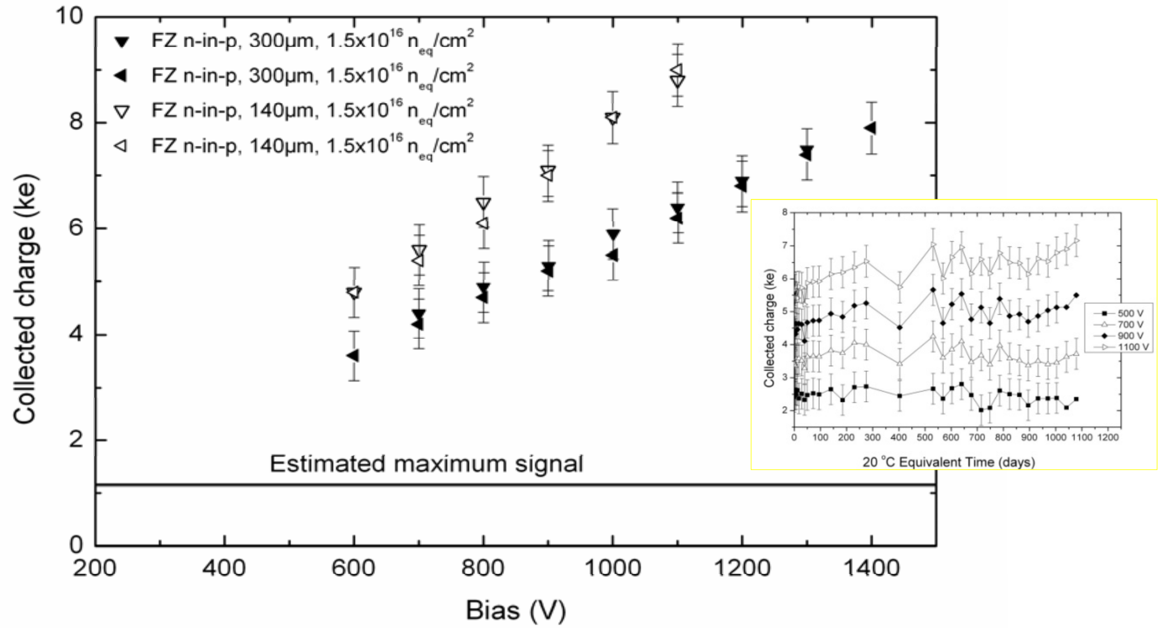
    See presentation by Malte Backhaus (this conference)
- A further potential supplier for large area arrays has been identified and first results look very promising

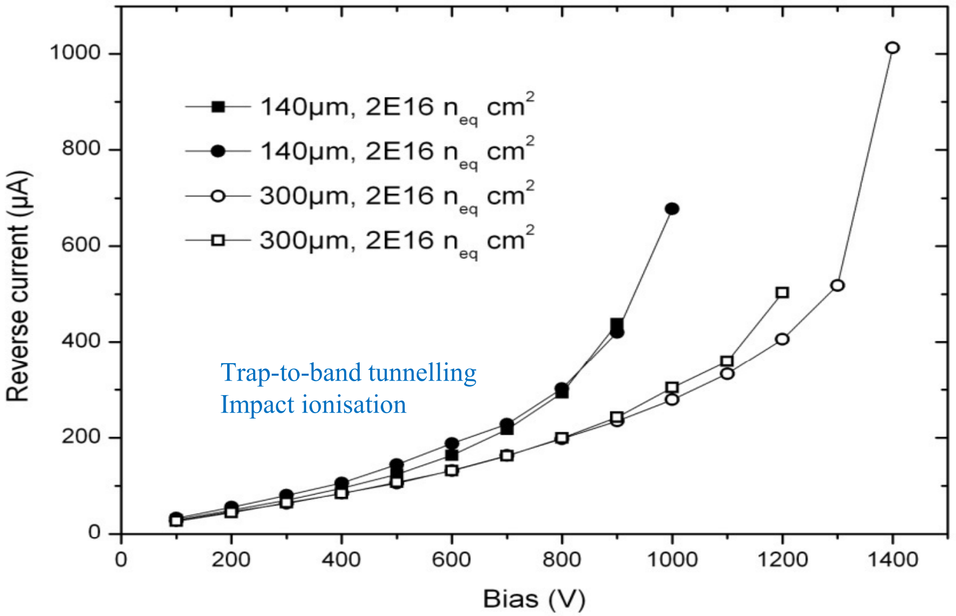
Back-up Material

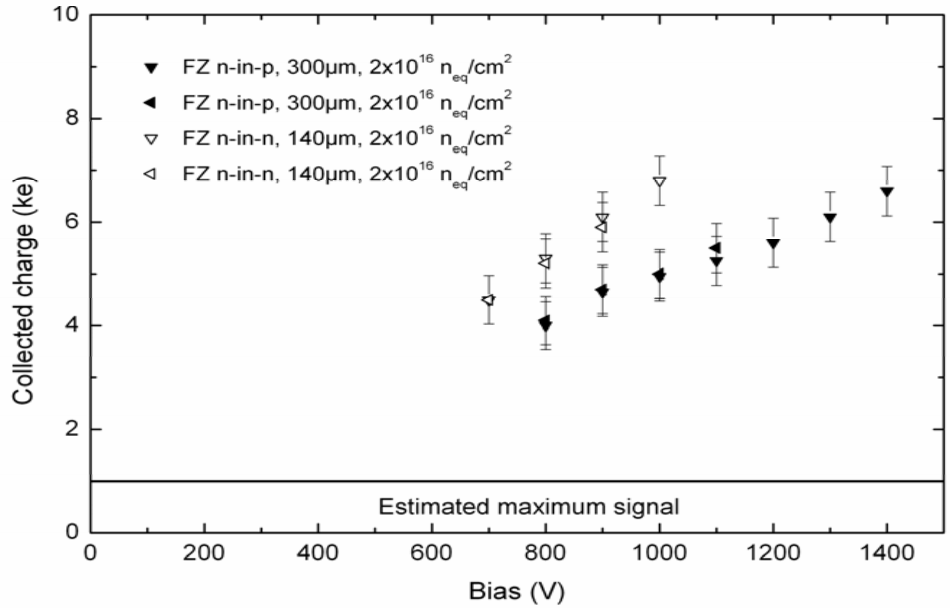
n-in-p Planar Sensors at Extreme Doses

1 and 2×10^{16} n_{eq} (innermost pixel layers at HL-LHC)

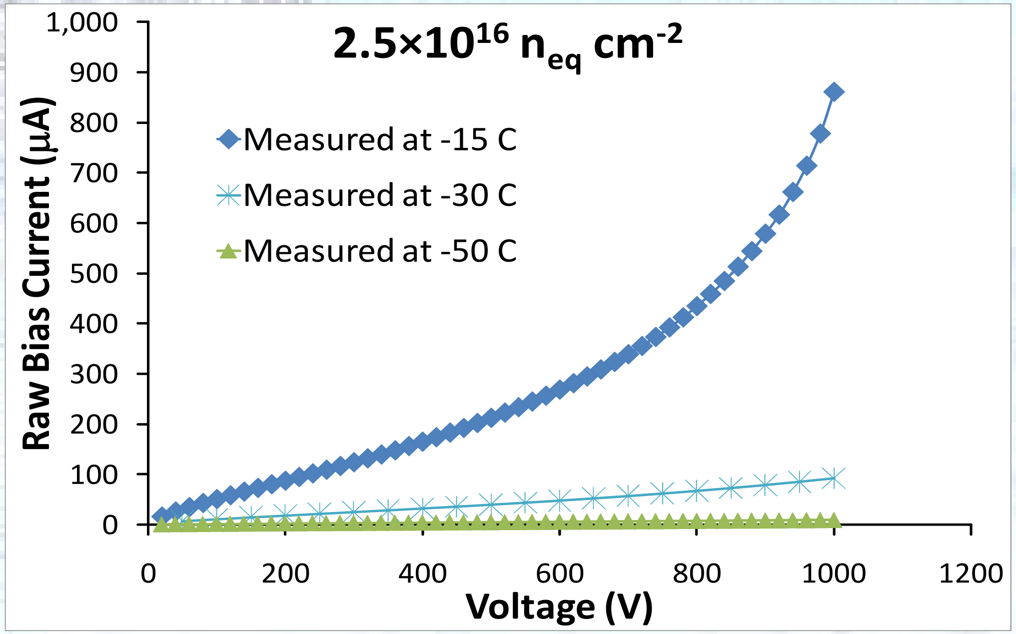


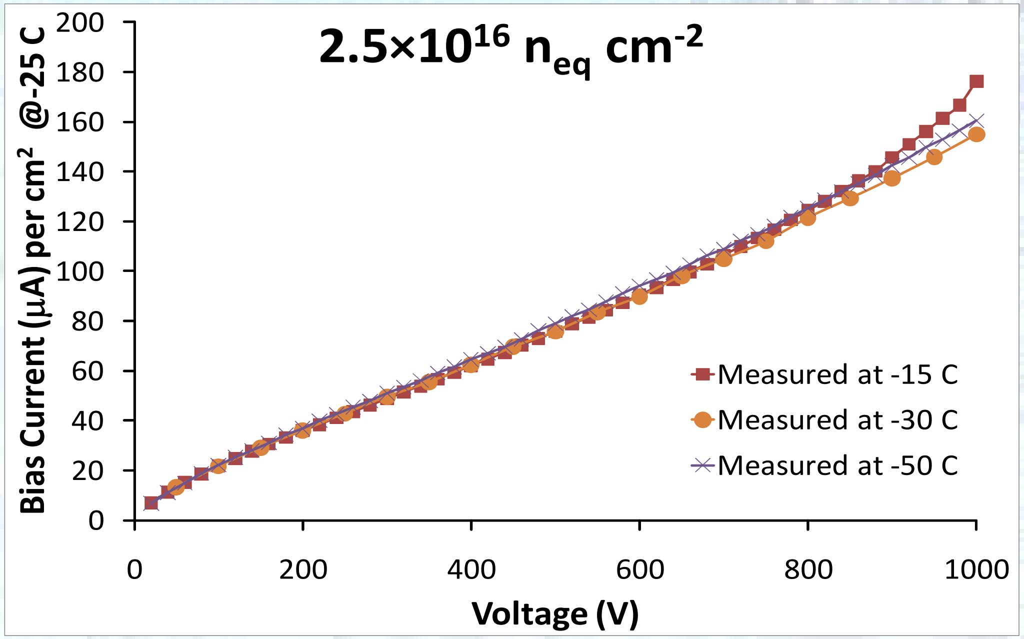






Heavily Irradiated Micron n-in-p Pixel Sensor IV



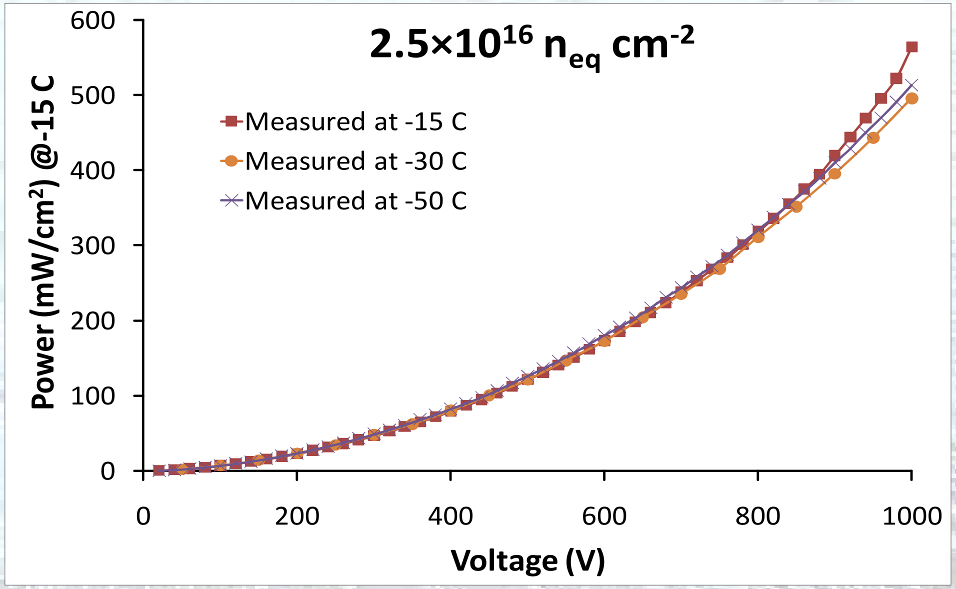


Thermistor glued to surface of detector and covered to reduce the coupling to air

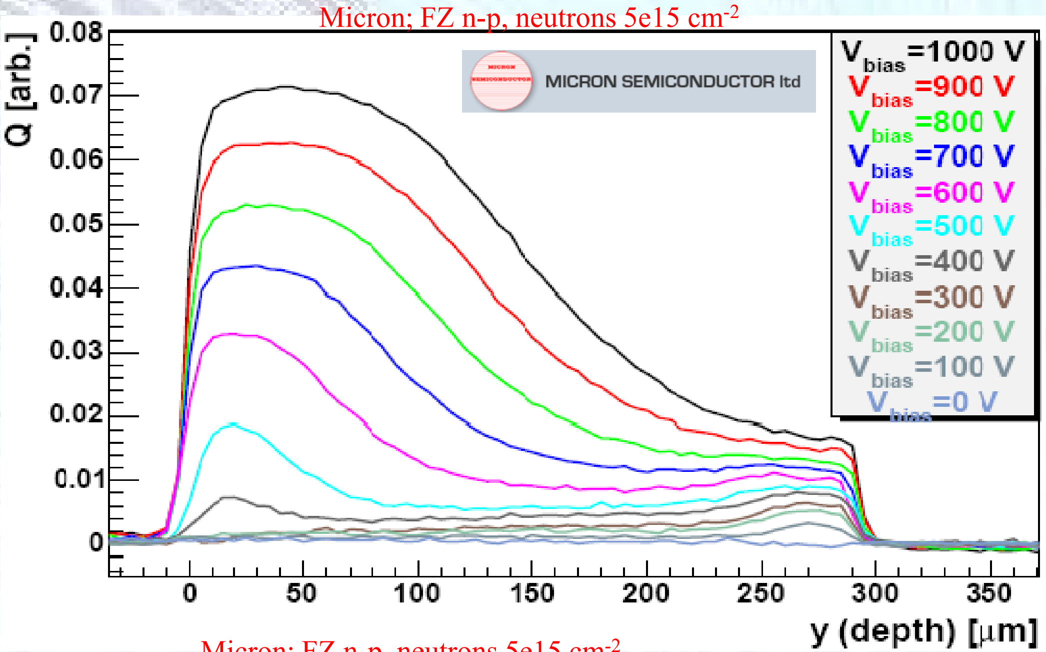
Found a 7 degree increase in sensor temperature during run at -15 C

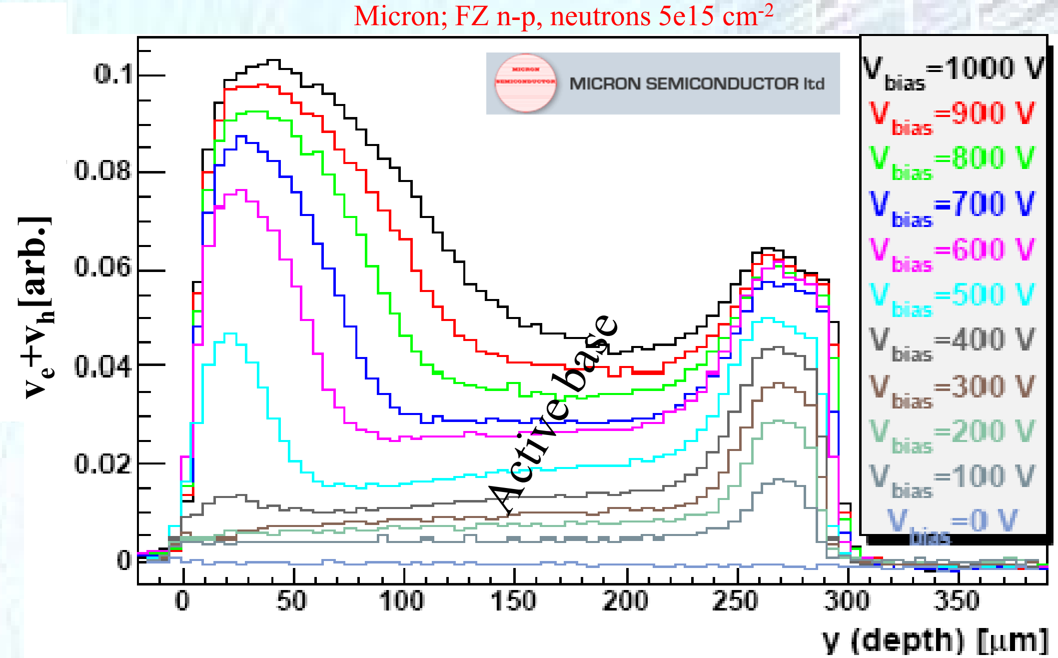
After correcting the current point-by-point with standard temperature correction, all curves are consistent and straight

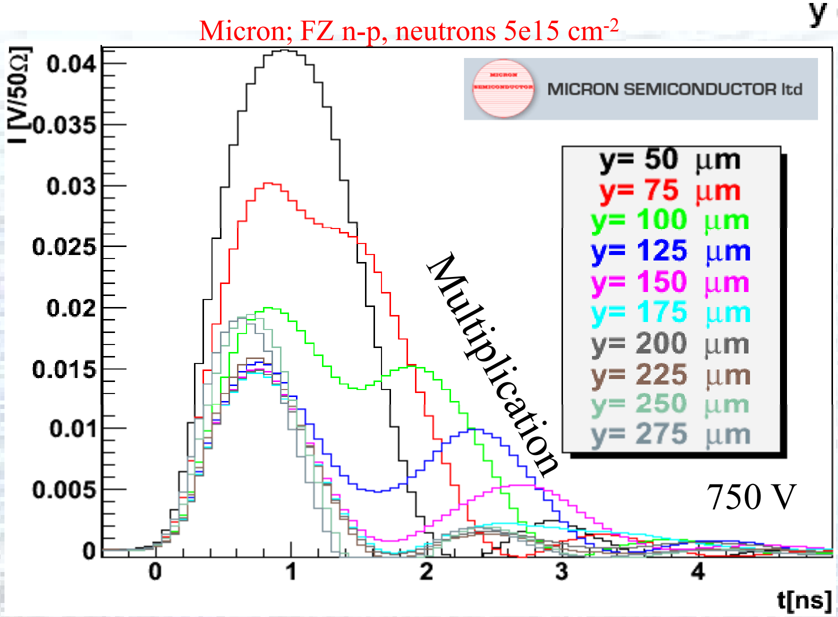
Previous planar p-type power over-estimated at 900 V by a factor of 2



RD50 Edge-TCT Measurements







- Sensor sensitive over entire depth at all bias voltages after high fluences (>5×10^{15} n_{eq} cm^{-2})
  - Fields are larger than expected from assumption of intrinsic carrier concentration in "non-active" region.
  - At 5×10^{15} n_{eq} cm^{-2} can be as high as 1 V/mm at 1000 V.
- At higher fluences and bias voltages charge multiplication seen
  - The relative importance of the active base vs. charge multiplication depends on fluence/bias voltage

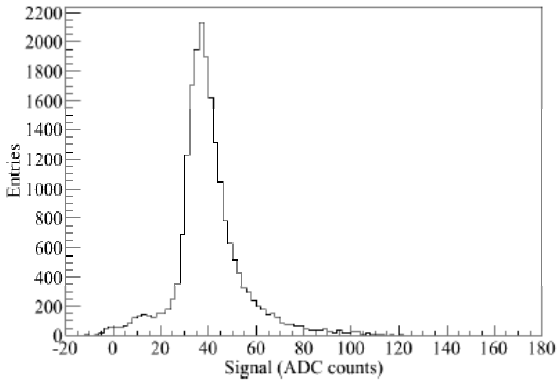
G. Kramberger – 5th Trento Workshop, 24 - 26 February 2010, Manchester, UK
A. Affolder – VERTEX 2011, 19-24 June 2011, Rust, Austria

Alternative Technologies to Planar Silicon

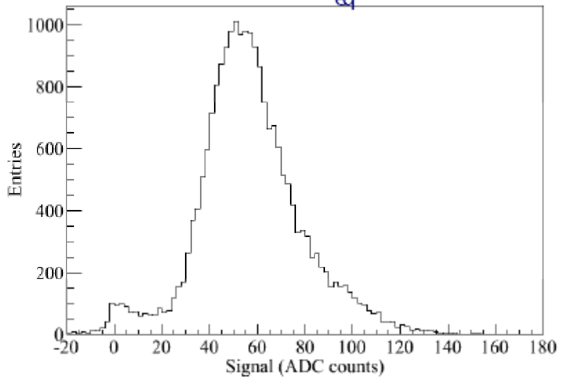
3D Sensors with Doped Through Silicon Columns

- Signal of the channel closest to the track point of impact

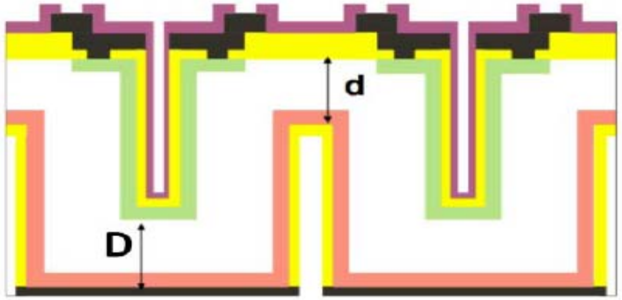
unirradiated, 70 V



irradiated (1×10^{15} n_{eq}/cm^2), 200 V



Double Side Double Type Column



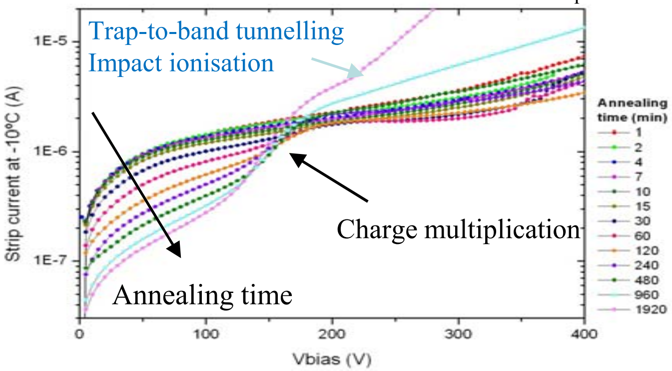
- FBK/IRST:completed a FE-I3 run. Full 3D in the next run.
- CNM: being completed and bump bonded to FE-I3 (March 2010).

- Higher signal after irradiation than before

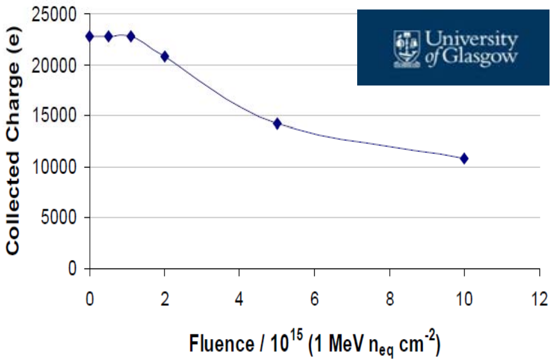
  → Charge multiplication!

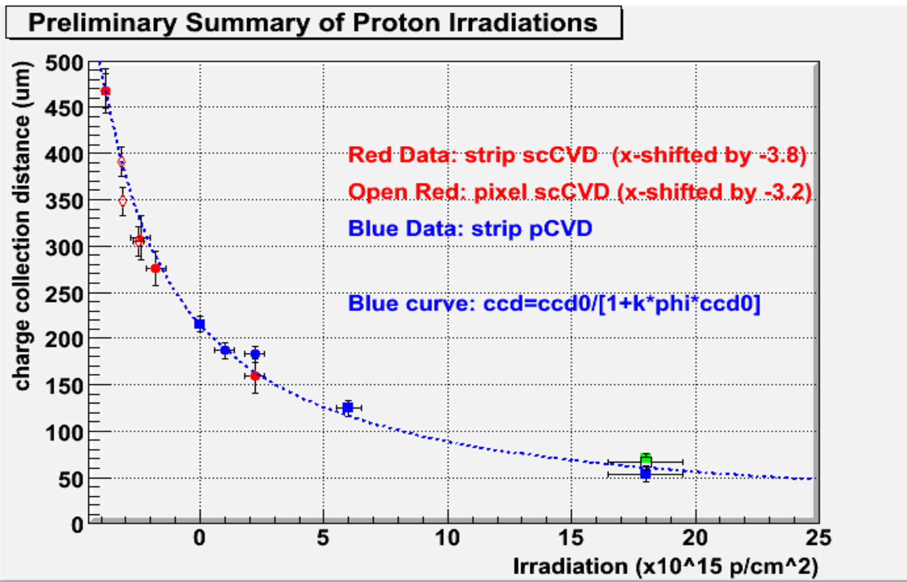
- Entries at low signal values: charge sharing, tracks going straight through columns

Leakage current, -10ºC, 10^{16} n_{eq}/cm^2



V_{bias} fixed at 150V





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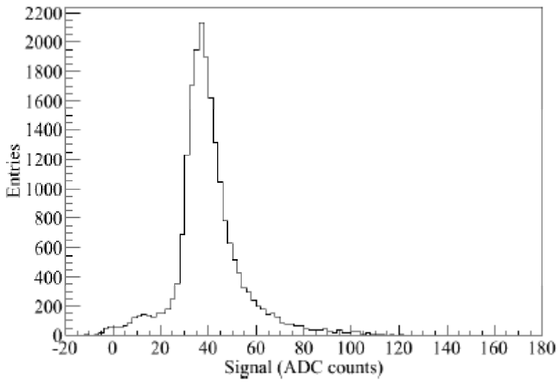
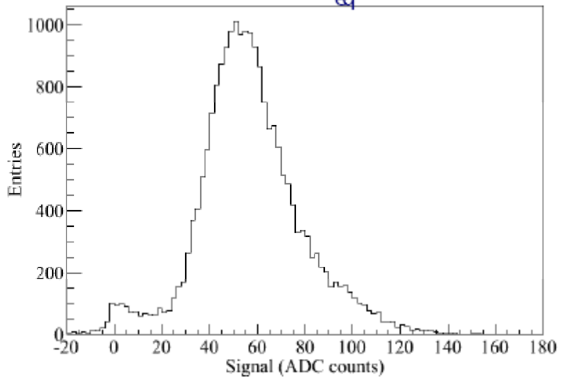


irradiated (1×10^{15} n_{eq}/cm²), 200 V

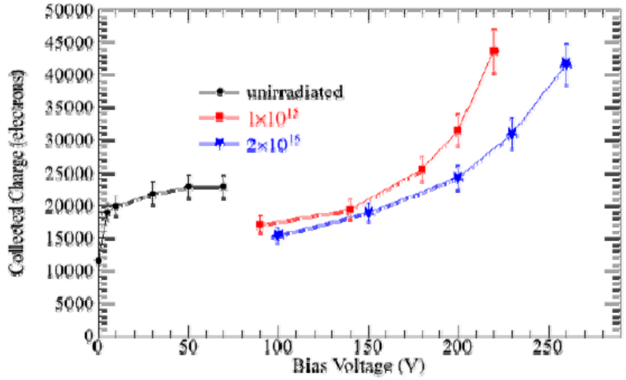


- Higher signal after irradiation than before

  → Charge multiplication!

- Entries at low signal values: charge sharing, tracks going straight through columns

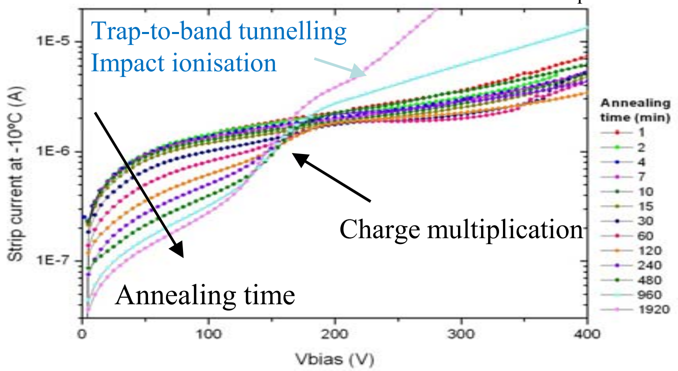
Landau Most Probable Value as a function of bias voltage



Irradiated device: increasing signal above ~150 V

→ Charge Multiplication

Leakage current, -10ºC, 10^{16} n_{eq}/cm^2



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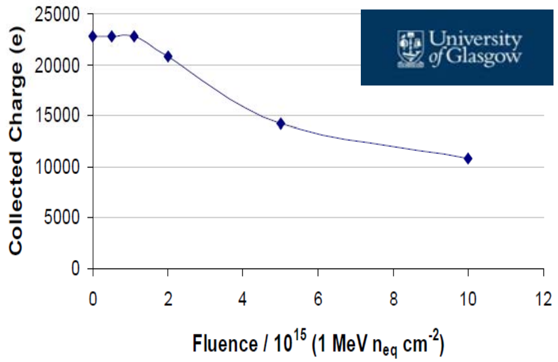

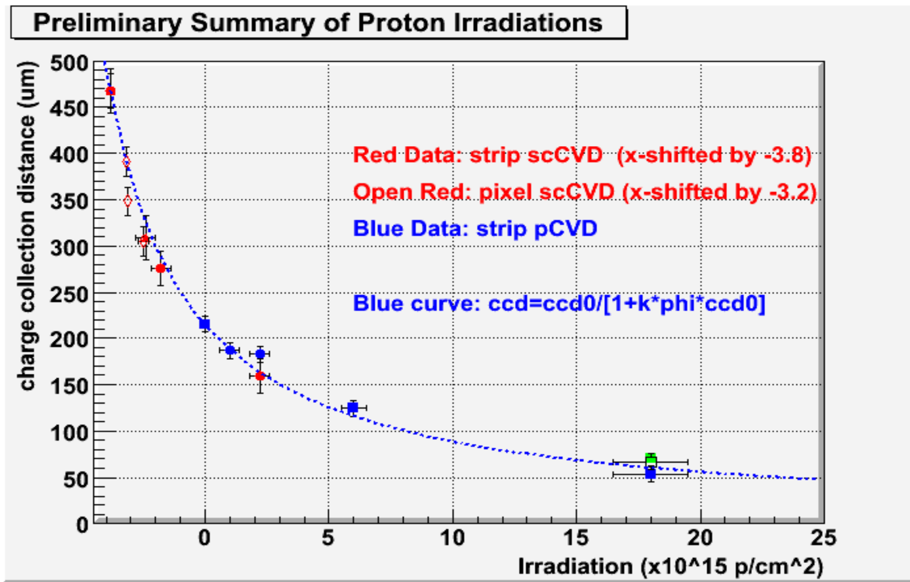

Alternative Technologies to Planar Silicon

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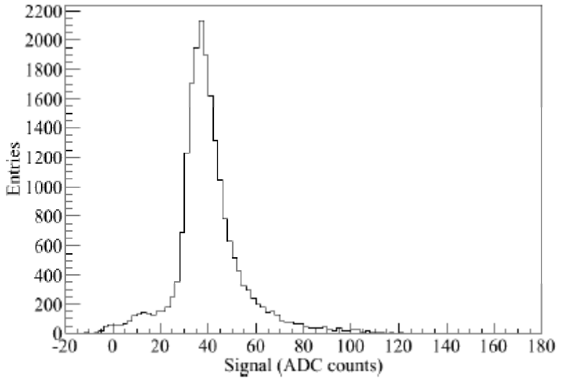
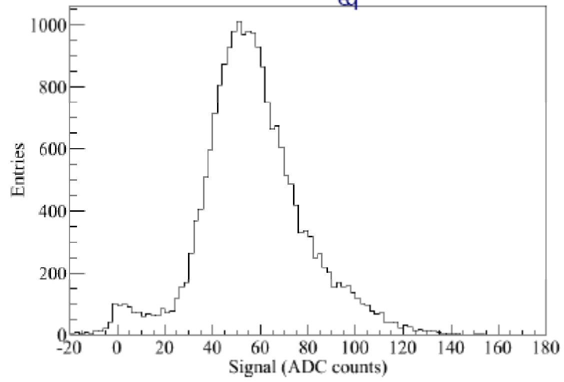


irradiated (1×10^{15} n_{eq}/cm^2), 200 V



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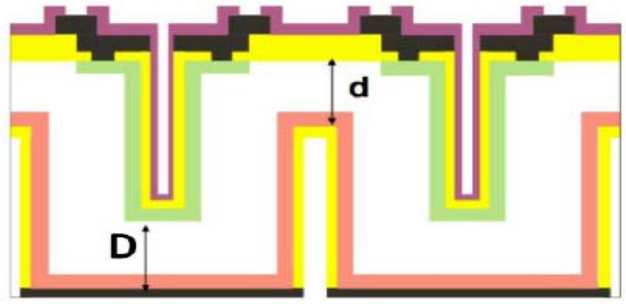

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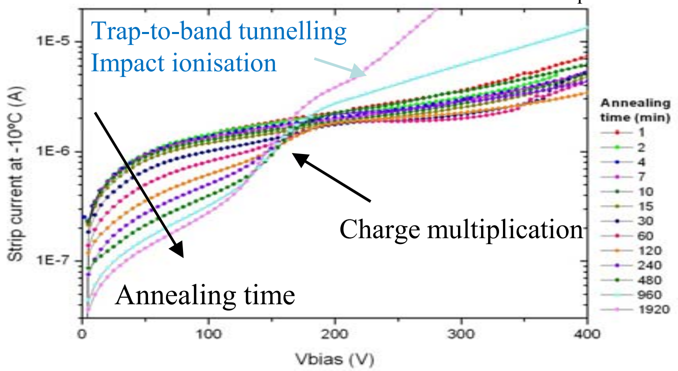
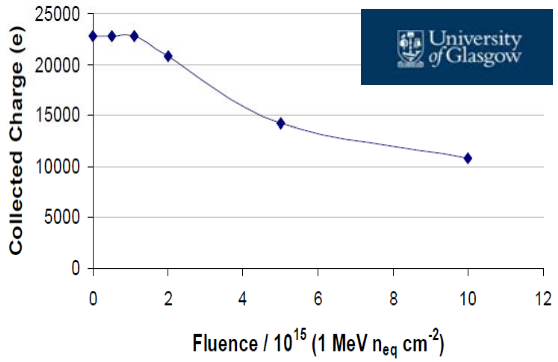
7

Leakage current, -10ºC, 10^{16} n_{eq}/cm^2



V_{bias} fixed at 150V



Planar CVD Diamond: Poly-crystalline or Single Crystal