筑波大学
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Charge Collection and Field Profile Studies in Heavily Irradiated Silicon Strip Sensors for the ATLAS Inner Tracker Upgrade

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On behalf of the ATLAS ITk Strip Sensor Collaboration

ATLAS ITk LoI Layout and Fluence at HL-LHC

Fluence evaluations per 3000 fb^{-1}

1 MeV neutron equivalent fluence

BL4-6 : 4.8cmL strips

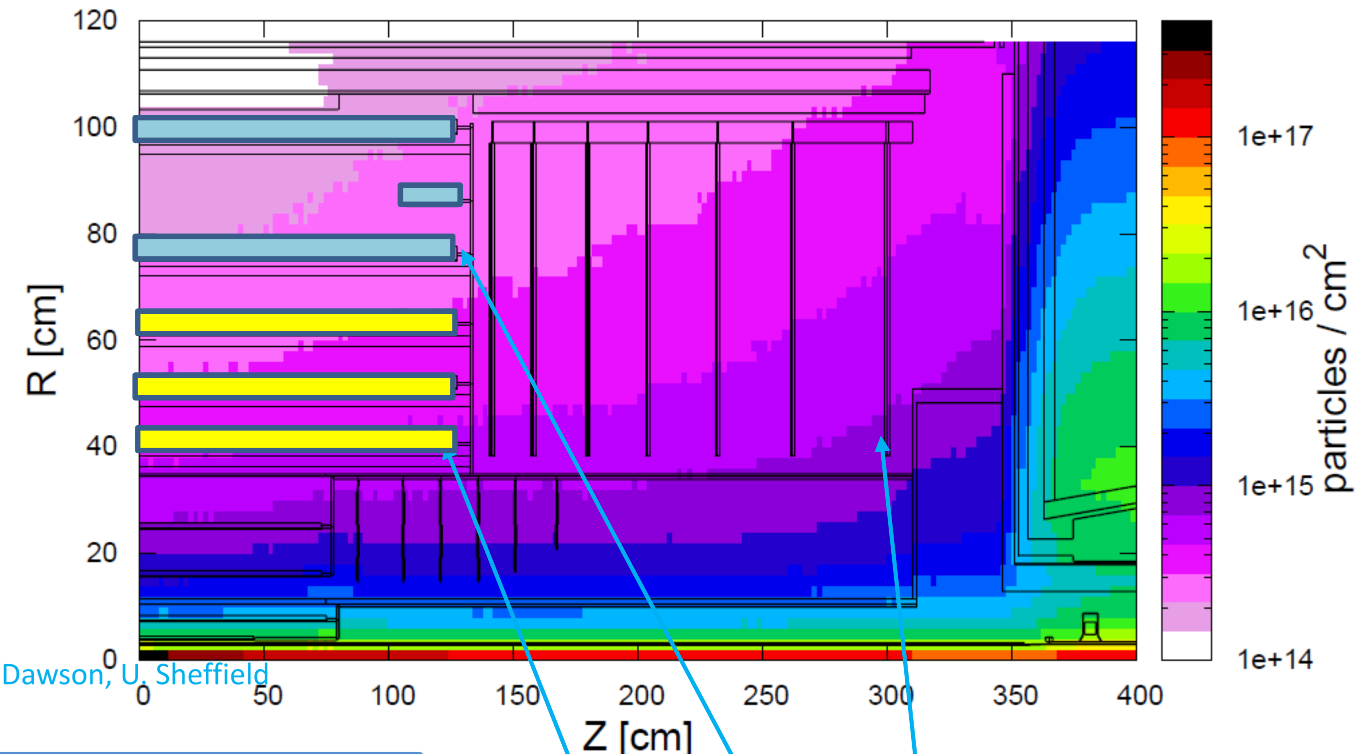
BL4(73%,19%,8%)

BL1-3: 2.4cmL strips

BL1(57%,35%,8%)

NIEL contributions by (n, π/K, p)

private comm with P. Miyagawa &I. Dawson, U. Sheffield



EC7: 8.1 x 10^{14} /cm^2

BL4: 2.9 x 10^{14} /cm^2

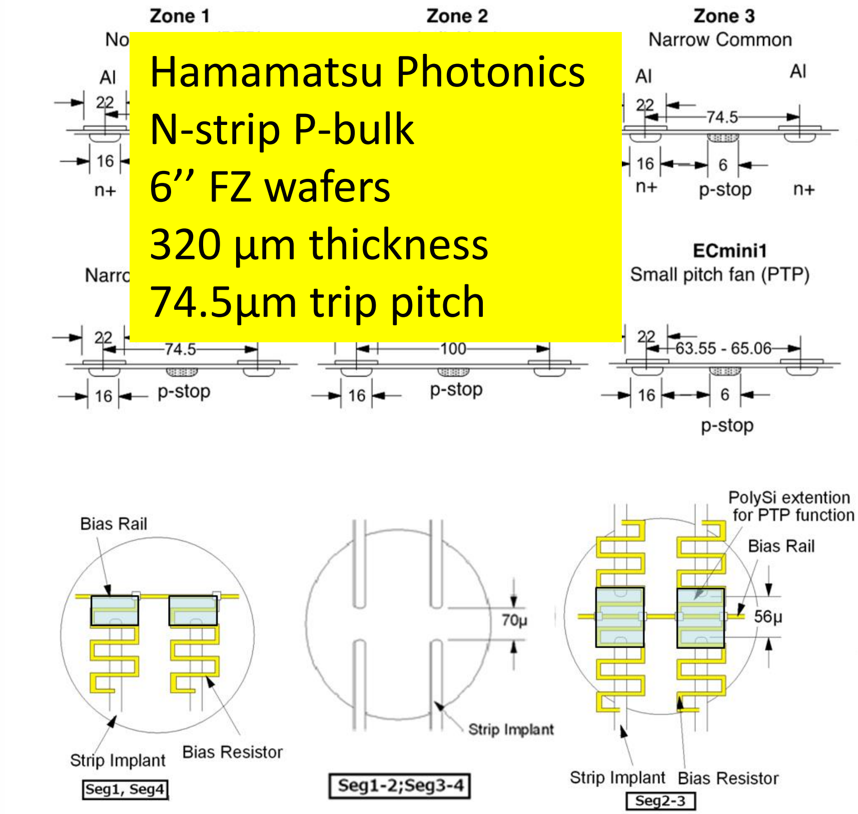
BL1: 5.3 x 10^{14} /cm^2

I.Dawson, PoS (VERTEX2012)015
ATL-GEN-2014-003

Taking a safety factor of 2,
- Barrel short strips up to : 1.1 x 10^{15} /cm^2
- Barrel long strips up to : 0.6 x 10^{15} /cm^2
- Endcap (8-48mm): 1.6 x 10^{15} /cm^2

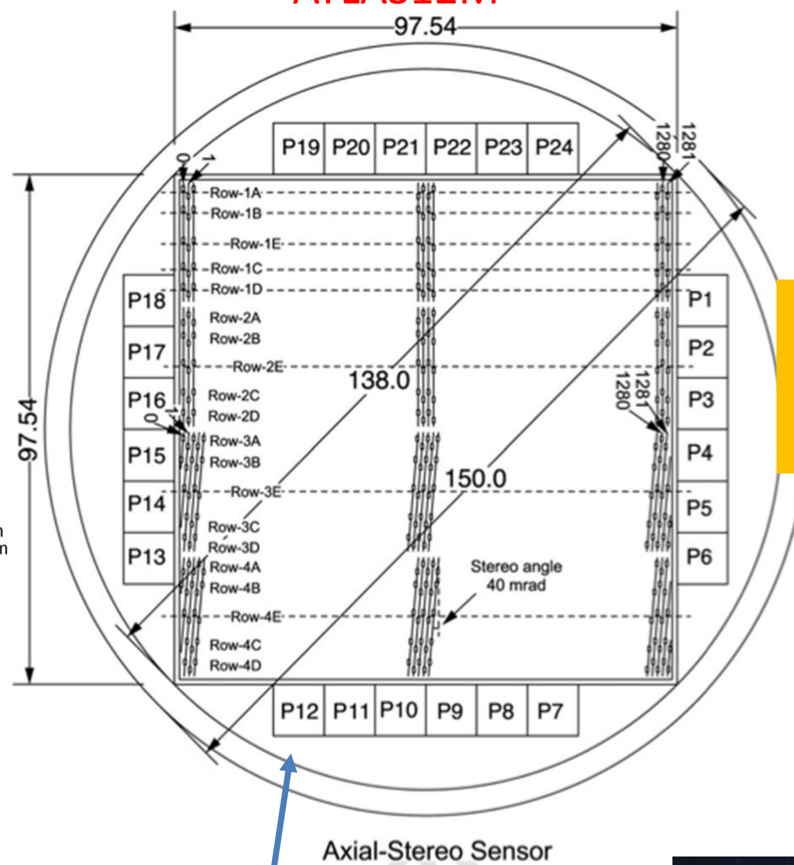
Difference in n/p damages is an issue

ATLAS12 design



Hamamatsu Photonics
N-strip P-bulk
6'' FZ wafers
320 µm thickness
74.5µm trip pitch

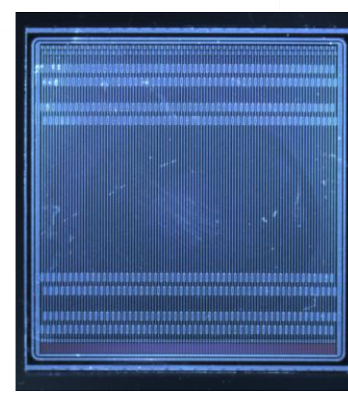
ATLAS12M



4 sections
with 2.4cm
long strips

P1-P24: miniature test sensors
1x1cm, strips 8 mm long

used for rad-hard study



Hamamatsu FZP320 wafers (3-8 kΩcm)

ATLAS12A	ρ~3.5-5 kΩcm
ATLAS12M	ρ~6 kΩcm
ATLAS07	ρ~5-5.5 kΩcm

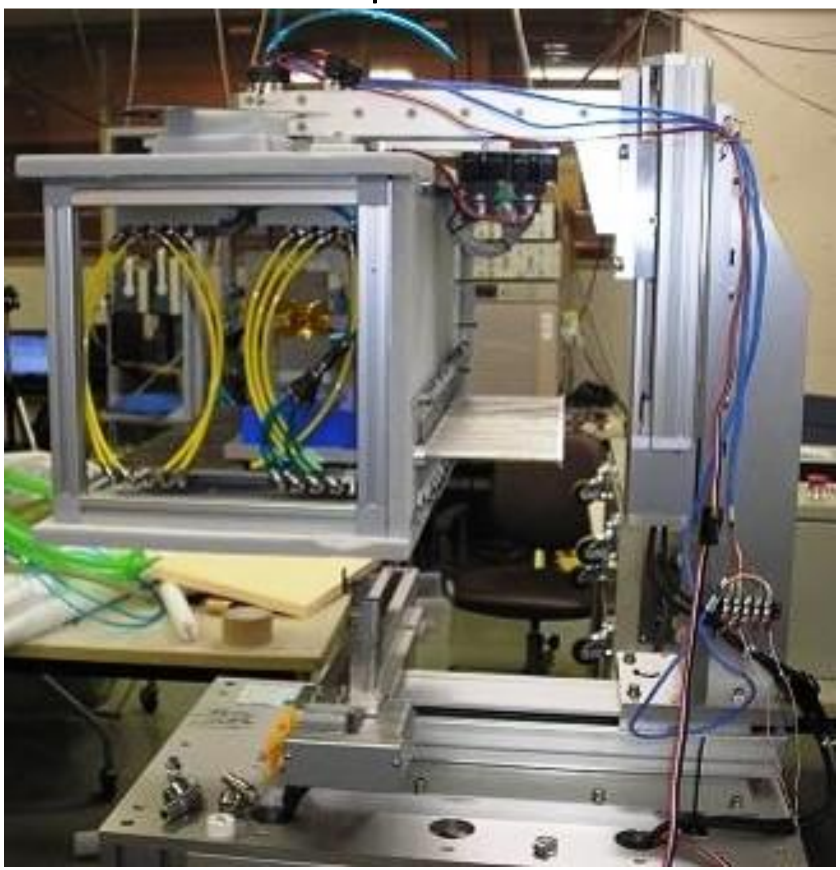
Irradiation

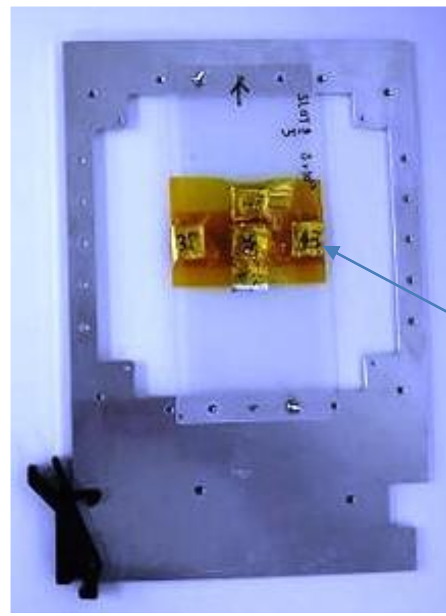
Neutron irradiation: Ljubljana reactor
Pion irradiation: PSI 300 MeV
Proton irradiations: Karlsruhe 23 MeV
Birmingham 27 MeV
CYRIC 70 MeV
Los Alamos 800 MeV

All damages translated to 1-MeV n_{eq} fluence (NIEL factor)

Irradiation example: CYRIC (Tohoku Univ)

Scan box: 15 sample slots



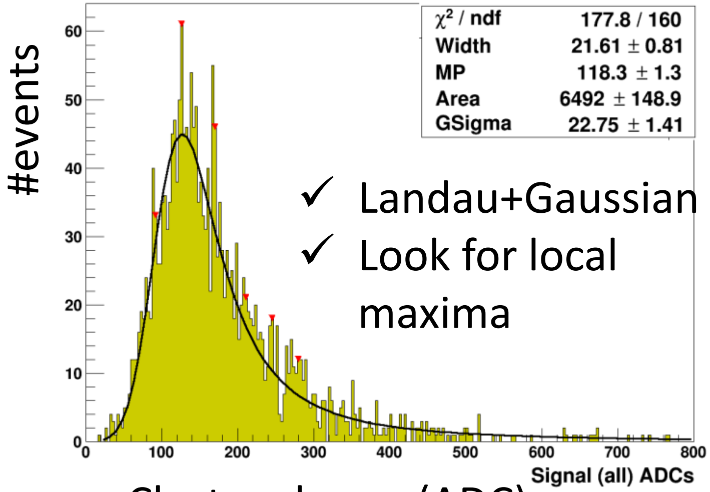


Sample holder/slot (11x11cm opening)

$Al^{27}(p, 3pn)\mathbf{Na^{24}}$
Al foils for dosimetry

CYRIC case:
For 10^{12}~10^{16}/cm^2 range irradiation,
A few min ~6 hrs at beam current 10nA~1μA

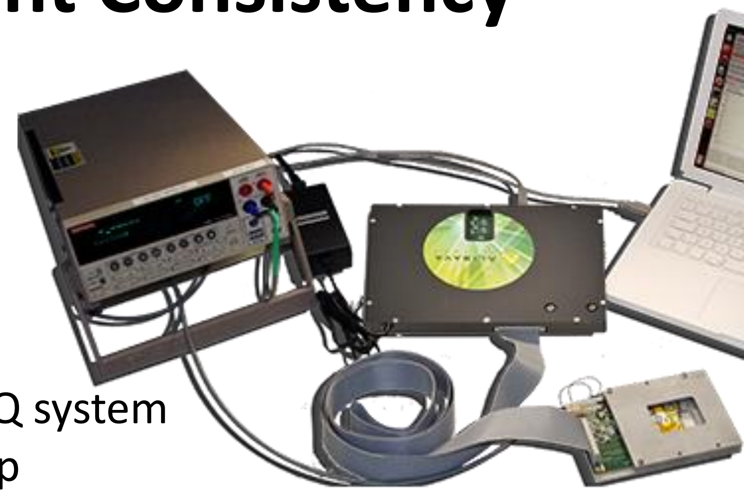
Charge Collection Measurement Consistency



✓ Landau+Gaussian
✓ Look for local maxima

Cluster charge (ADC)

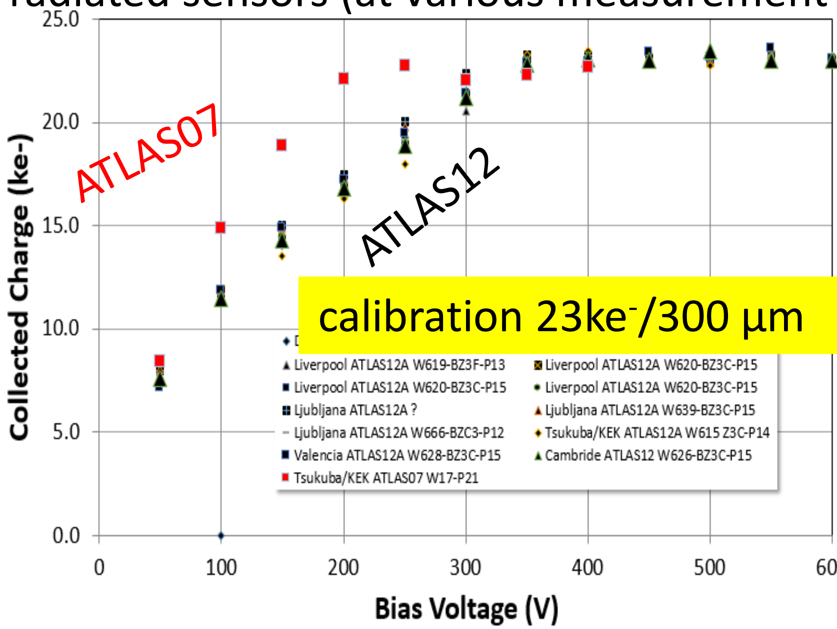
β-source
(electron beam)

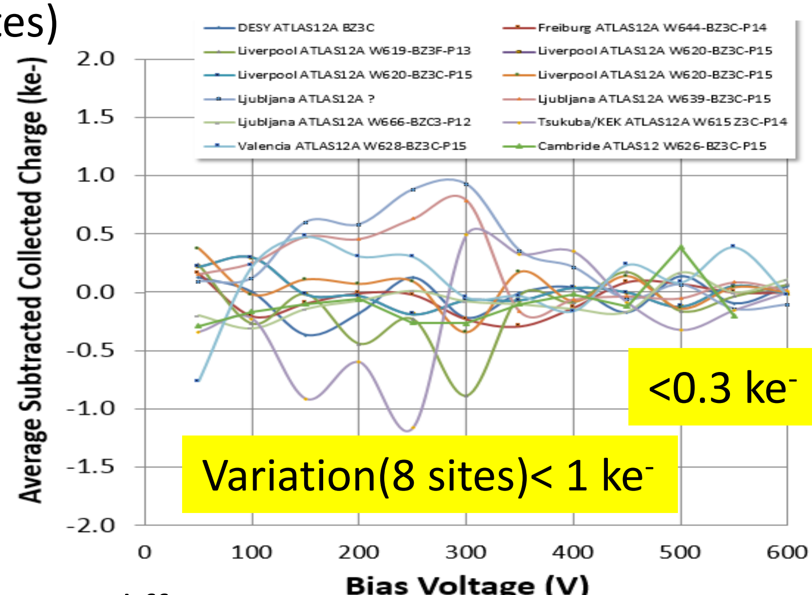


Alivaba:
FPGA based DAQ system
LHCb Beetle chip

http://www.alibavasystems.com/

Non-irradiated sensors (at various measurement sites)

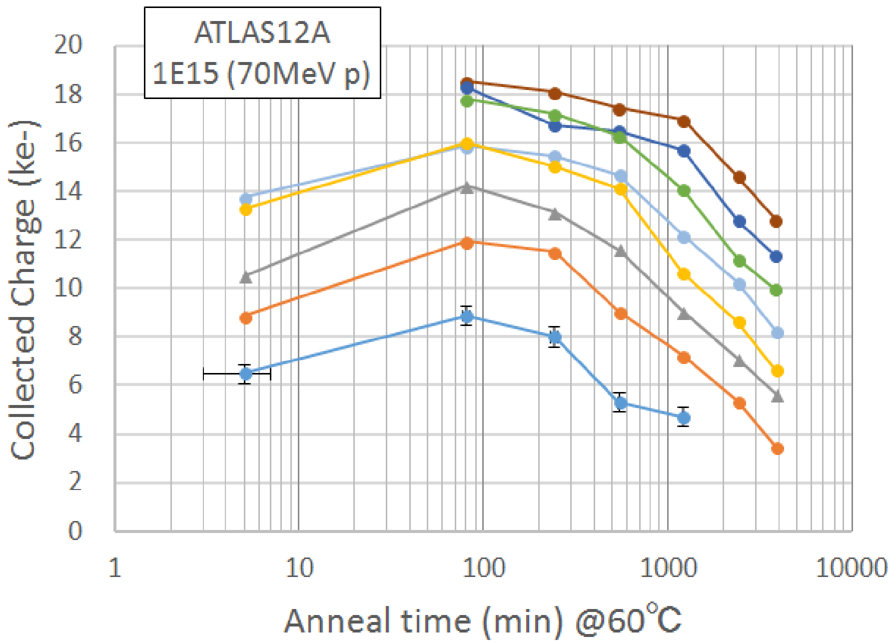


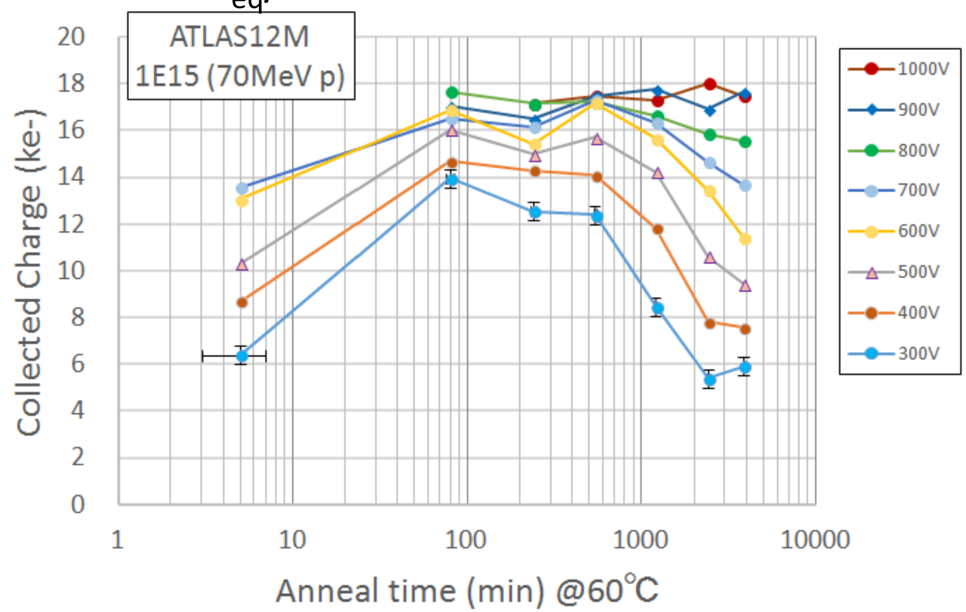


different sensors
(thickness and resistivity variations)

Long term annealing at 60°

Proton irradiation: $1\times10^{15}\ n_{eq}/cm^2$

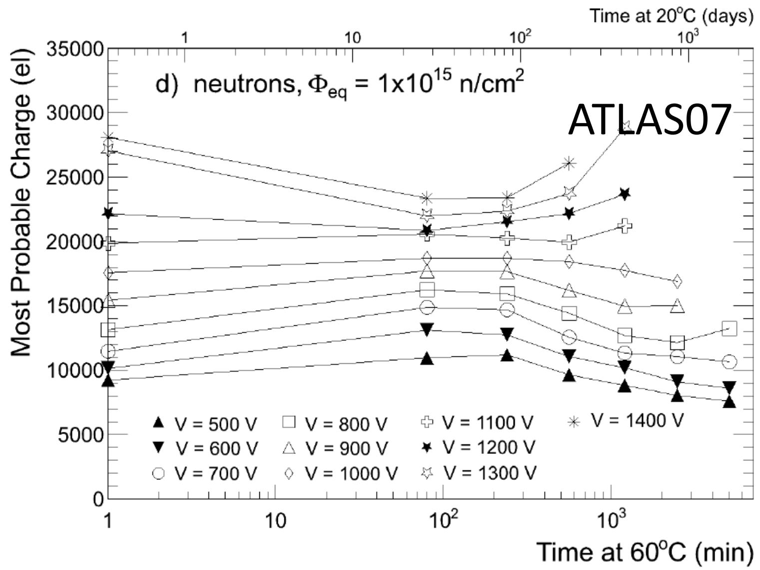




- Annealing is similar for A12A/A12M for bias below 600V (proton 1E15/cm²)

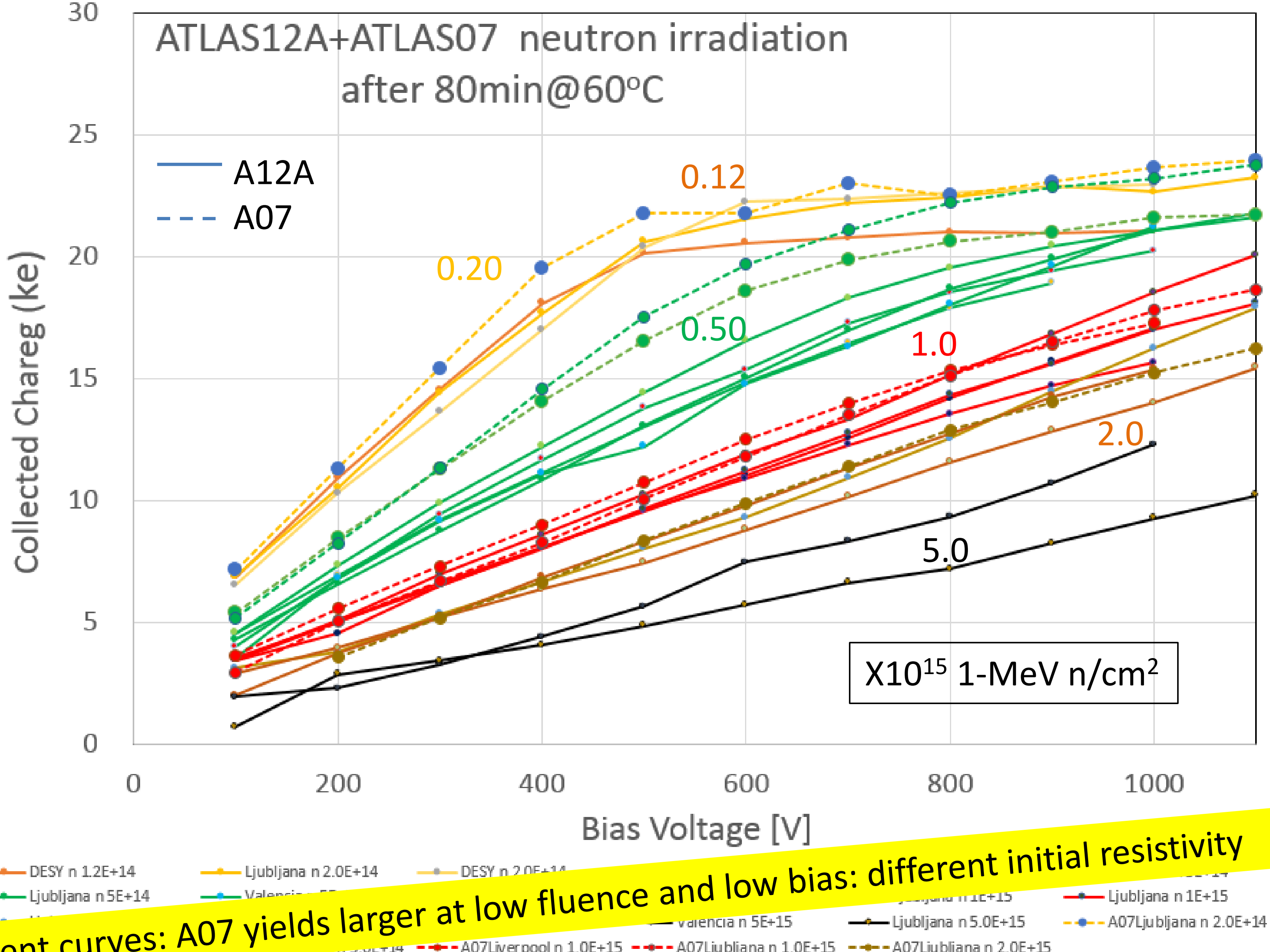
- A07 (neutron) studied previously
  => behavior similar to A12M

I. Mandic et al., NIMA 629 (2011) 101



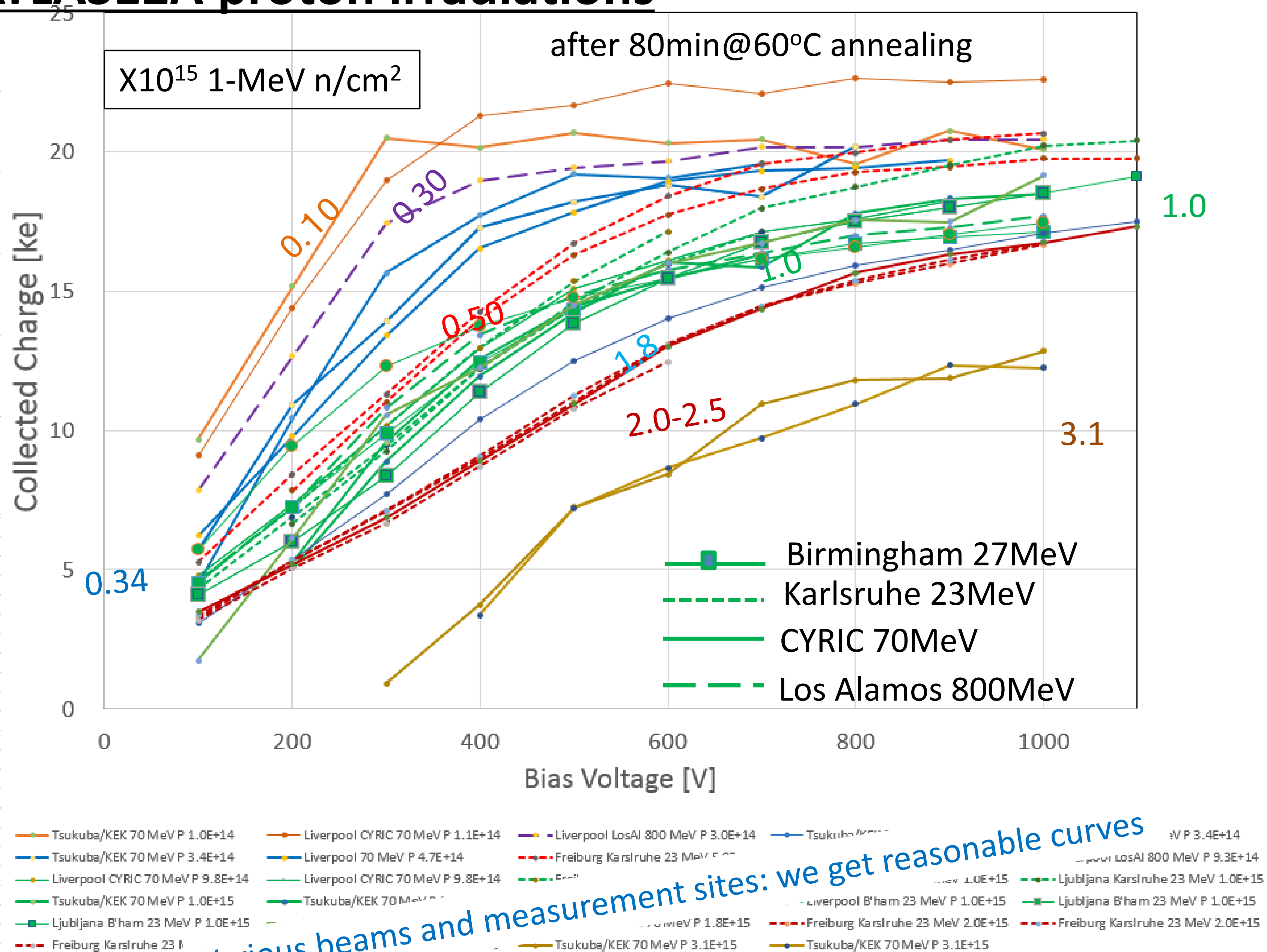
All data shown below are after controlled annealing of 80min @ 60°C

ATLAS12A+ATLAS07 Neutron irradiation



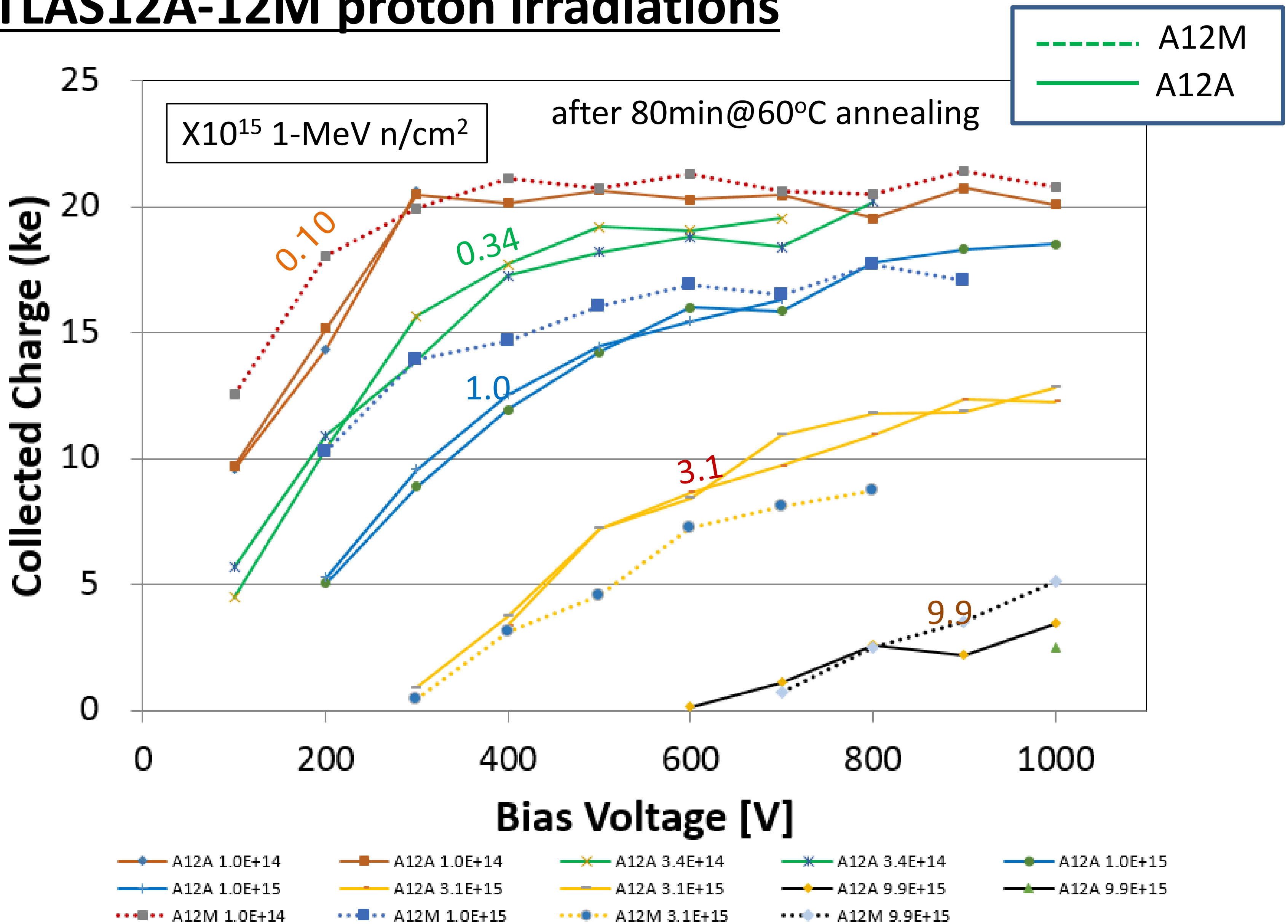
Consistent curves: A07 yields larger at low fluence and low bias: different initial resistivity

ATLAS12A proton irradiations



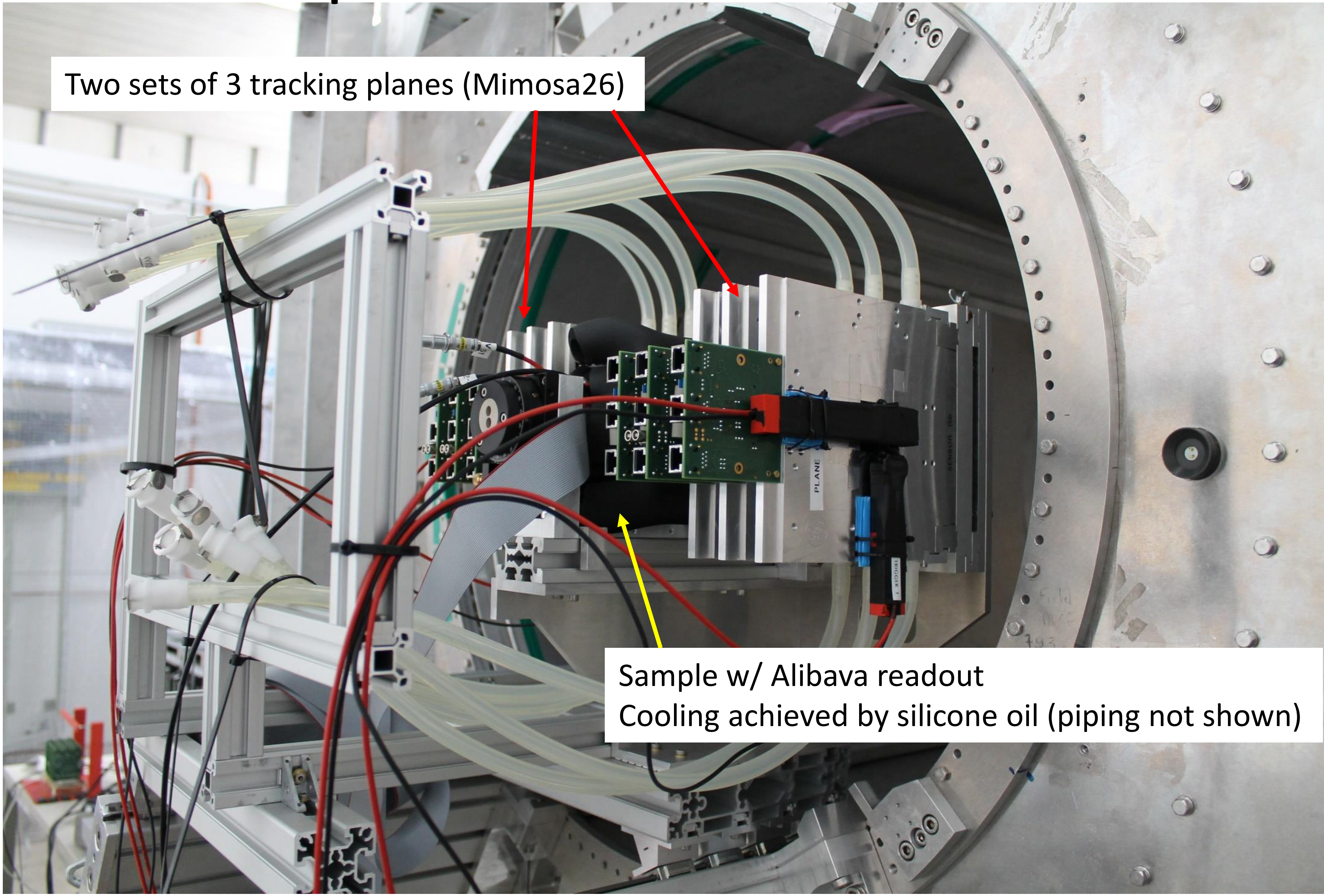
Various beams and measurement sites: we get reasonable curves

ATLAS12A-12M proton irradiations

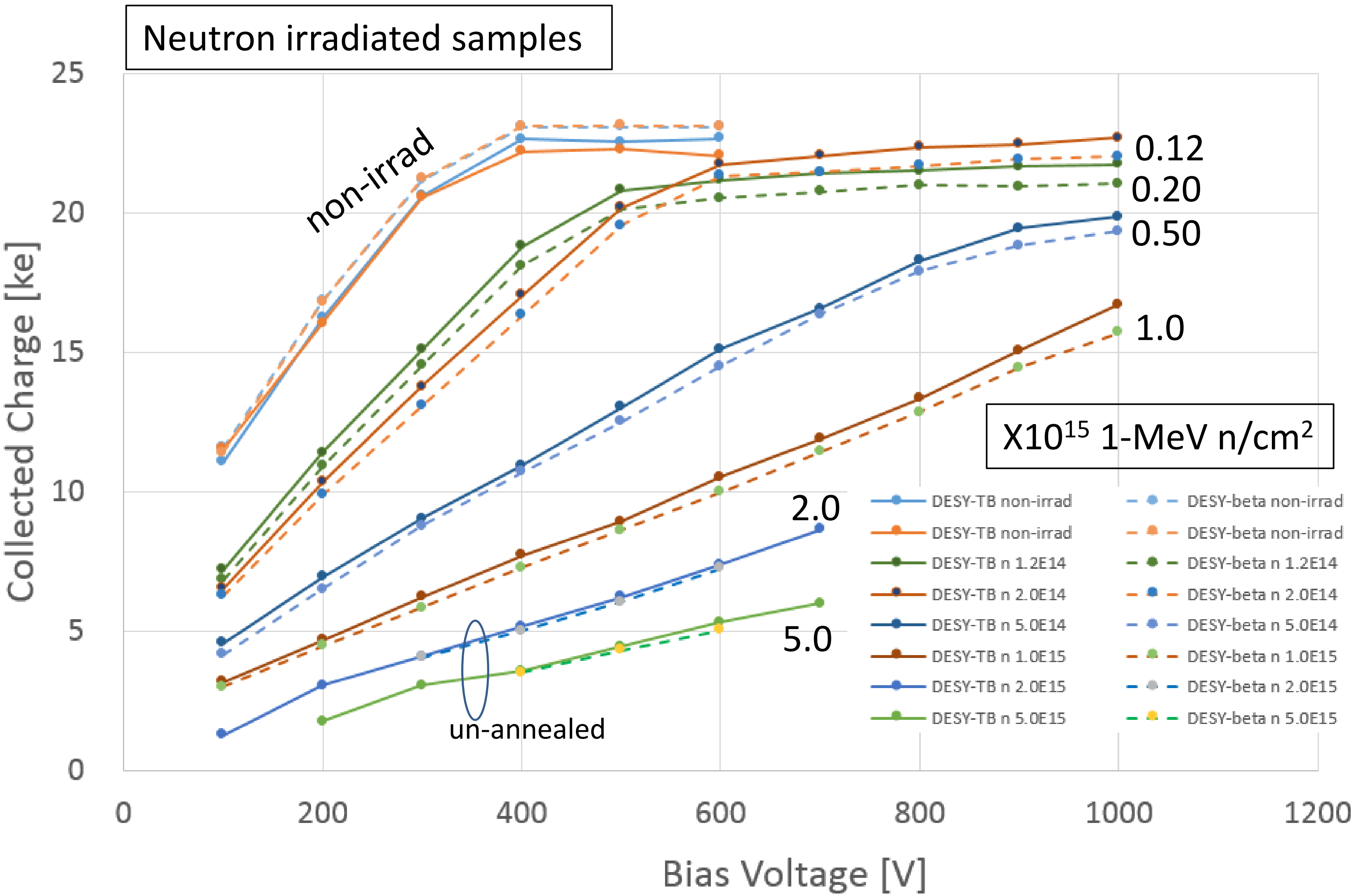


12M yields larger signal at low fluence and at low bias: different initial resistivity

Testbeam setup at DESY 4.4 GeV electrons



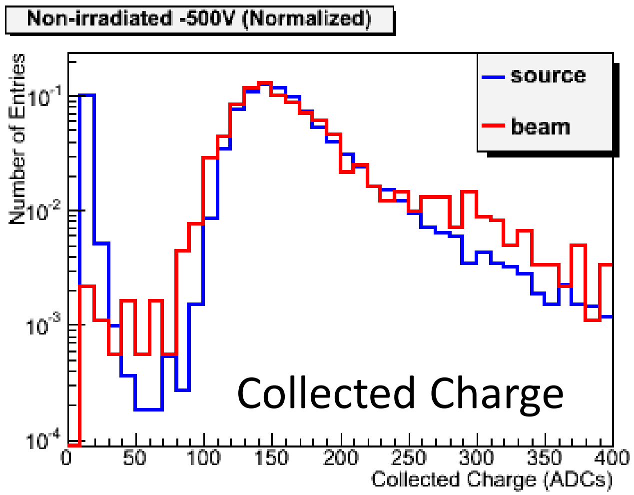
Source vs testbeam (DESY 4.4-GeV electrons)

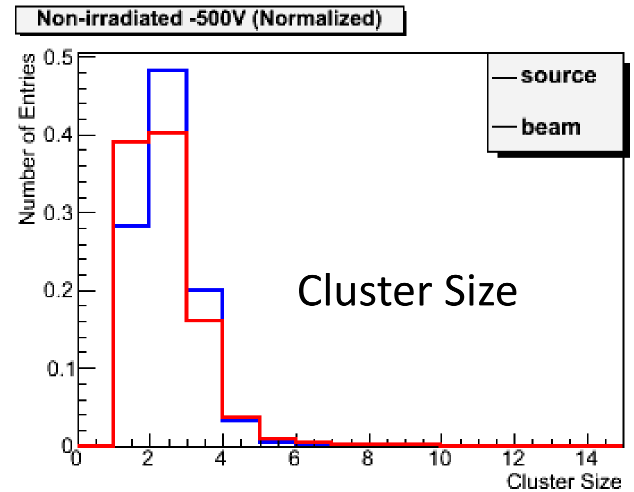


Very consistent results obtained!

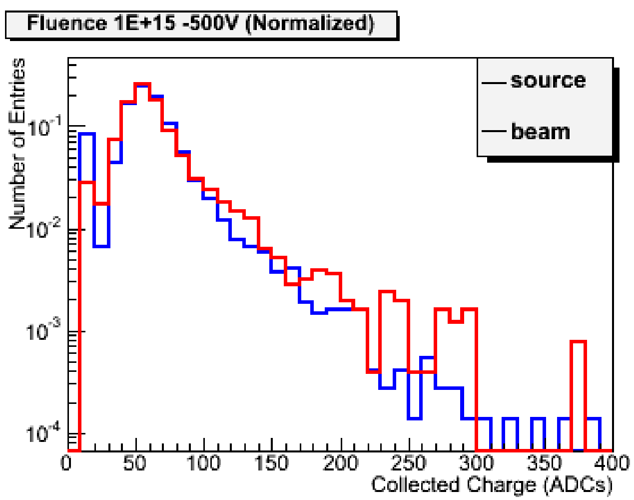
Source vs testbeam (DESY 4.4-GeV electrons)

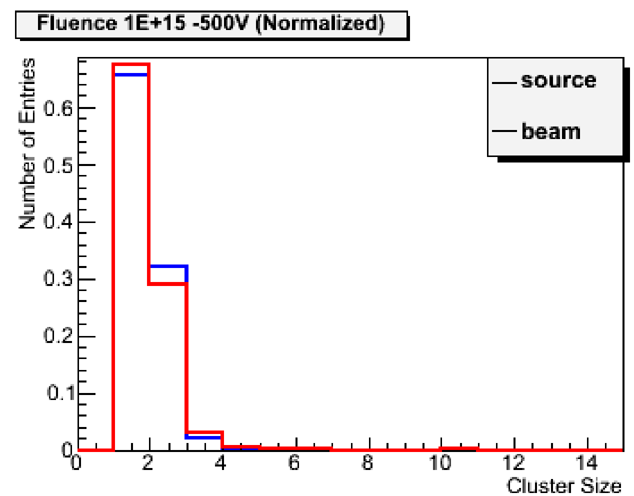
Non-irrad@





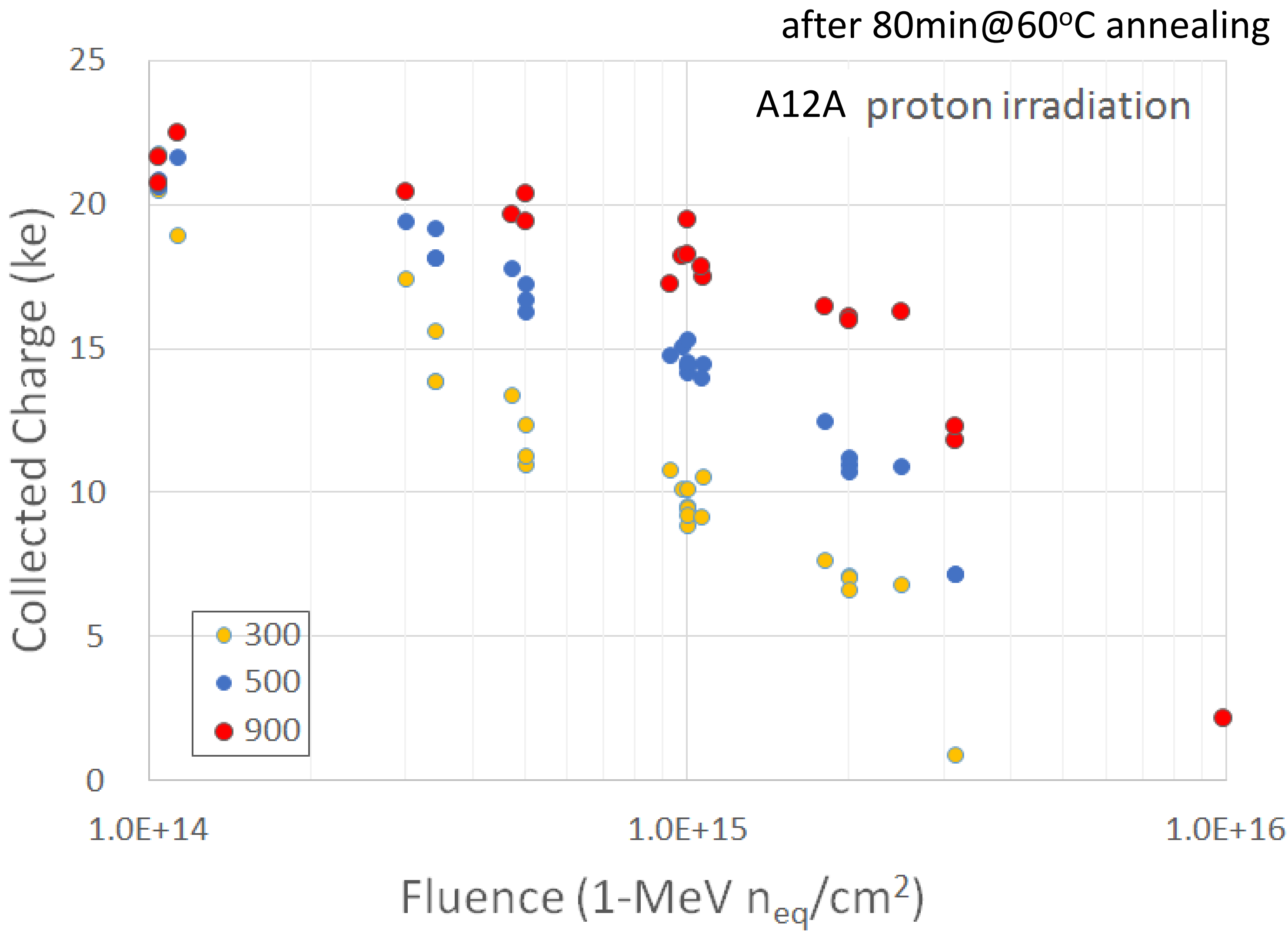
1E15 neutron irradiated





Source vs beam:
- Charge distributions in reasonable agreement
- Cluster Size slightly wider for source as expected

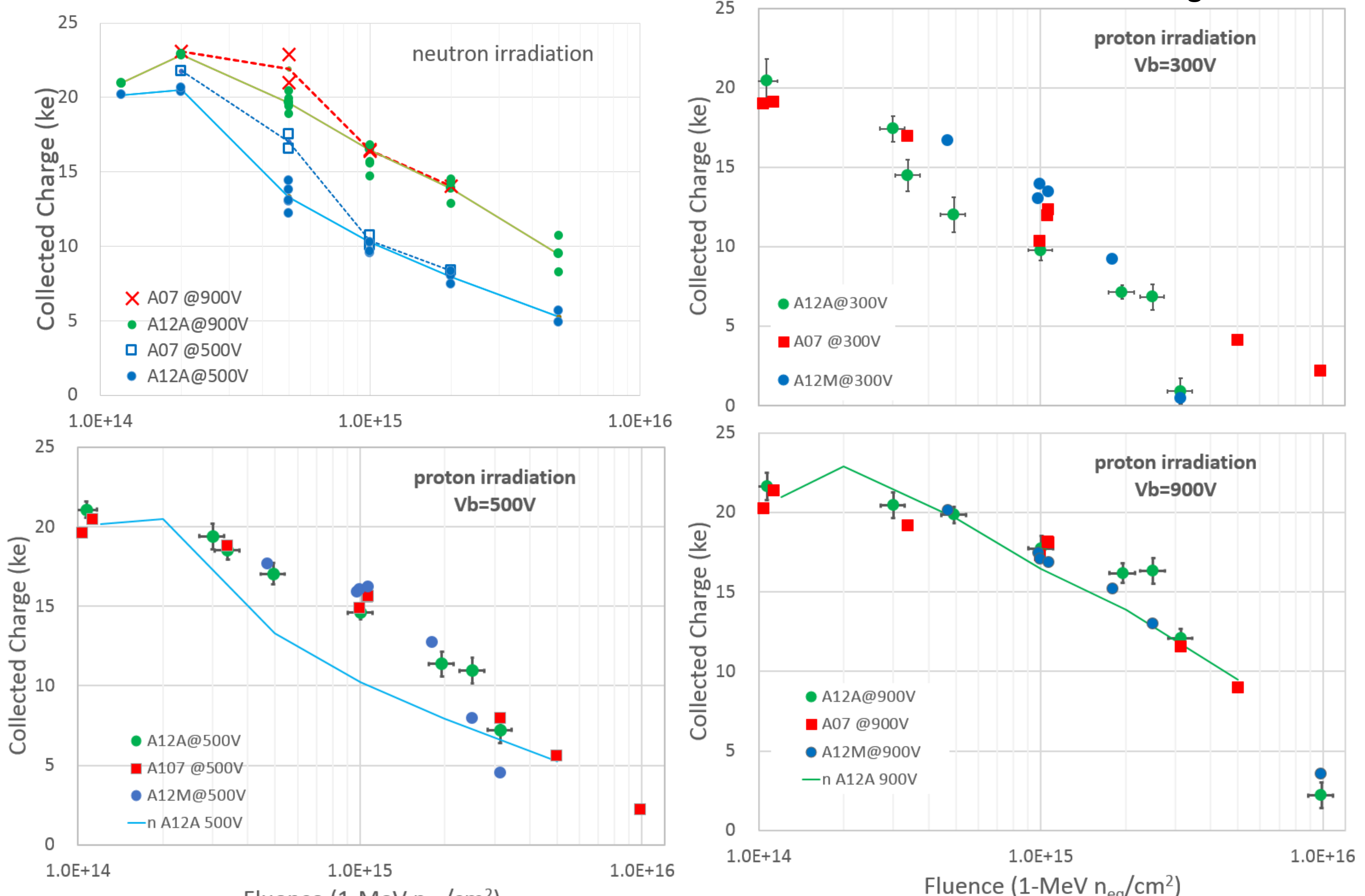
Fluence dependence (all A12A data points)



Fluence dependence

after 80min@60^{o}C annealing

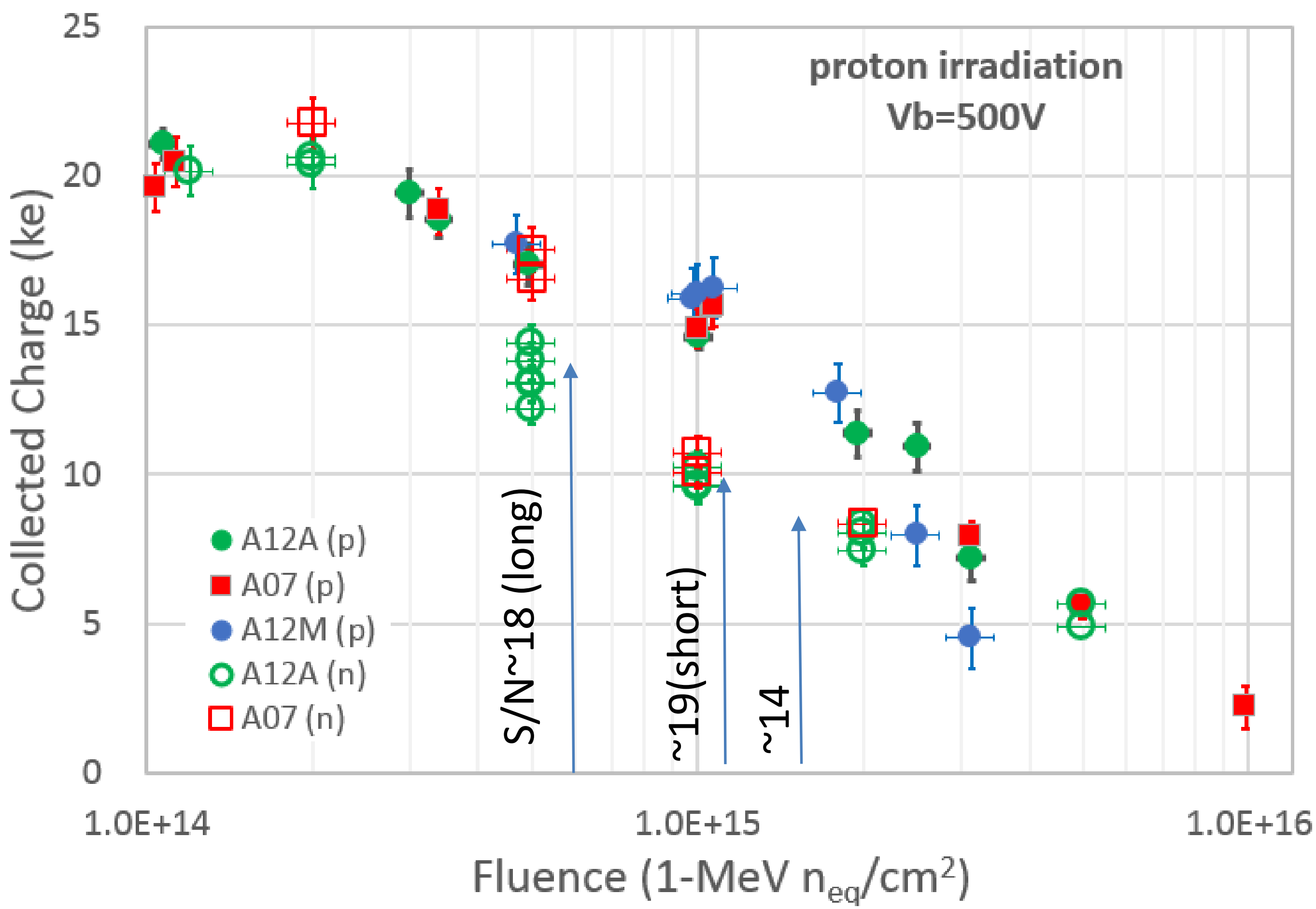
A12A yield slightly smaller & n-damage is larger at low fluence and low bias => becomes similar at large fluence



S/N at HL-LHC

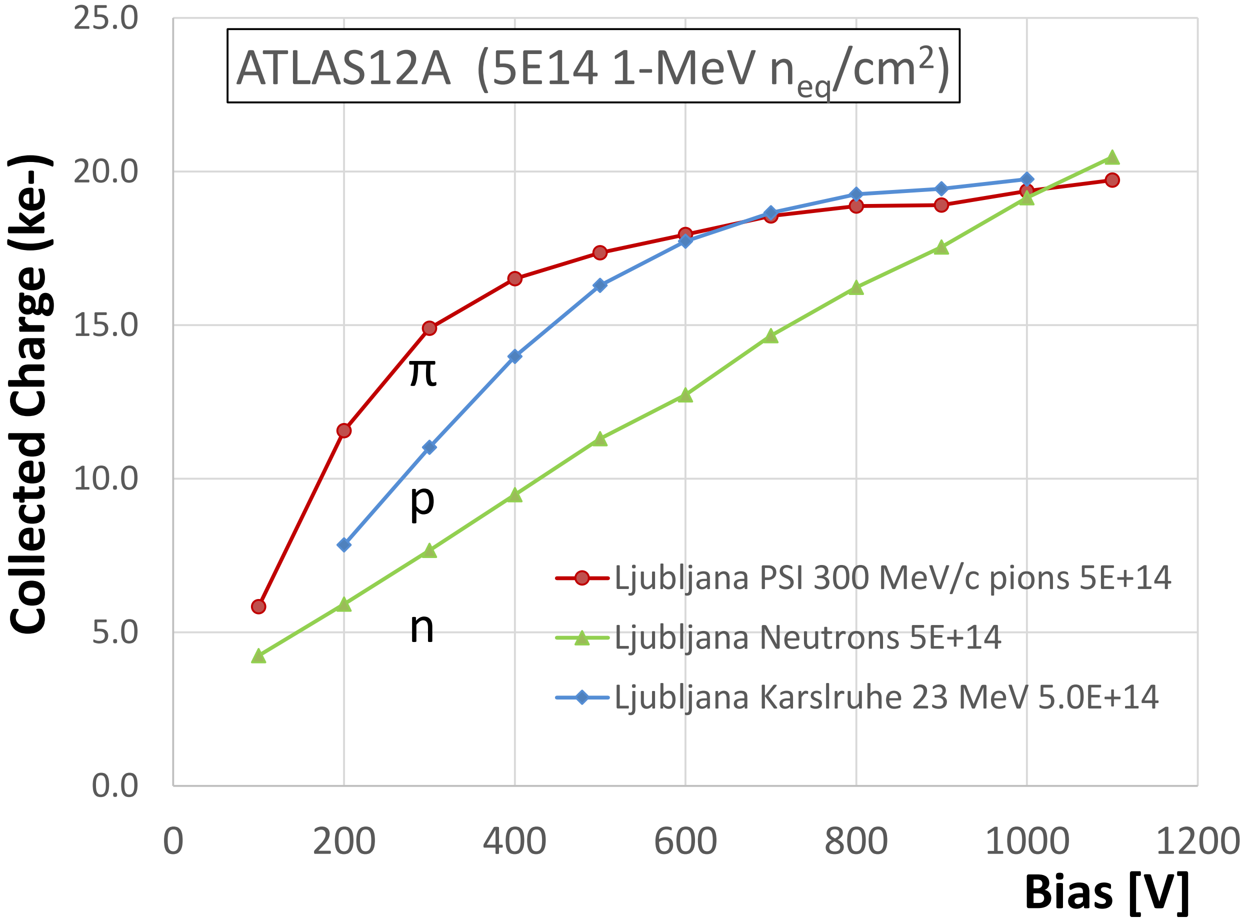
Barrel short (24mm)strips up to : 1.1 x 10^{15} /cm^2
Barrel long (48mm) strips up to : 0.6 x 10^{15} /cm^2
Endcap (8-48mm) strips: max 1.6 x 10^{15} /cm^2

ENC noise ~550/720/650 ENC for barrel short/barrel long/EC innermost strips



At Vb=500V, strip detectors remain as precision tracker after HL-LHC fluence

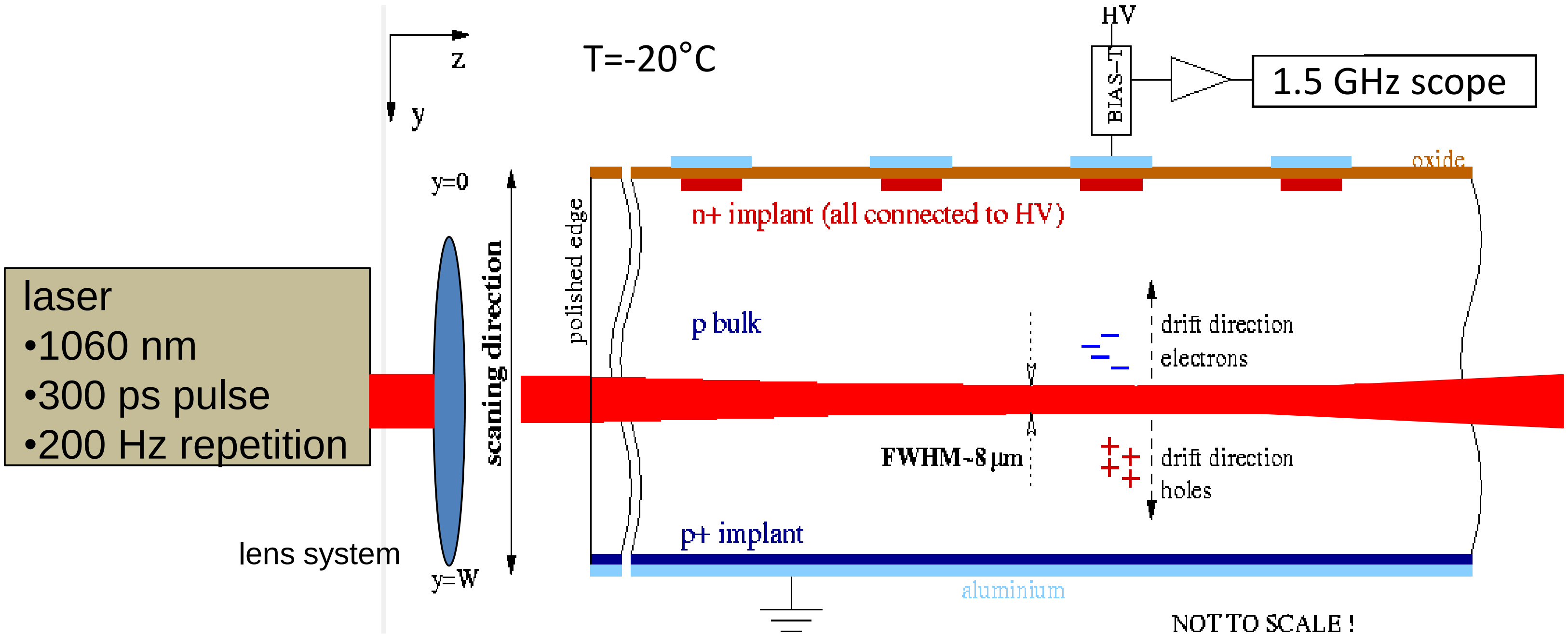
Charge collection of samples irradiated with p/n/π



Different CCE curves measured for the same NIEL fluence
Investigated E-field profile using e-TCT technique

edge TCT (transient current technique)

G. Kramberger et al., PoS (VERTEX2012) 022



IR laser injected from polished side scanning depthwise to investigate the charge collection dependence in depth
=> E-field distribution in depth

Polished edge

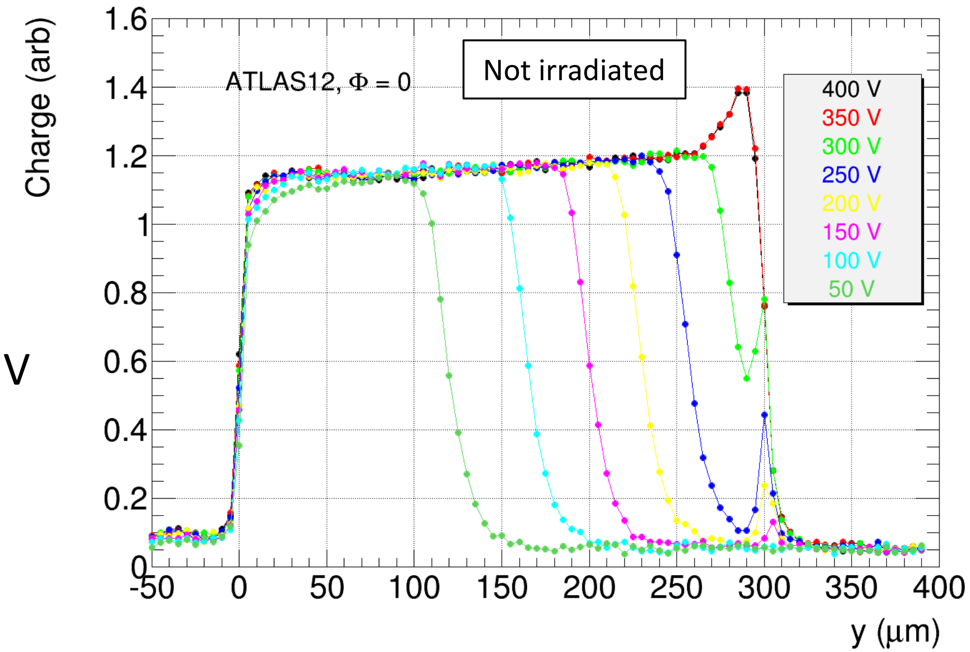
detectors on a Peltier cooled support in dry air atmosphere (down to -20°C)

e-TCT

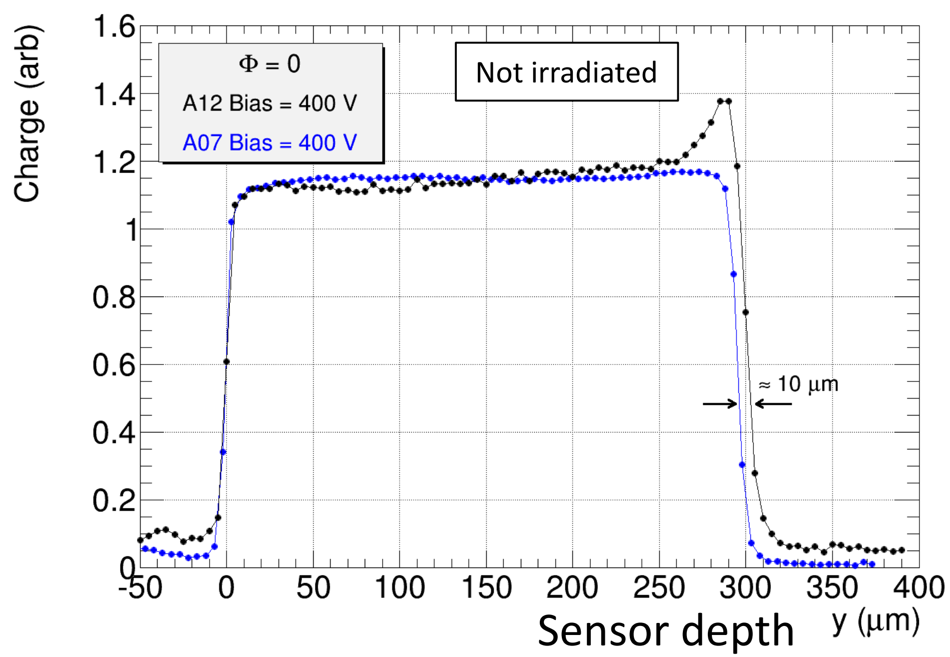
non-irradiated samples

Charge vs. depth

- A12A detector depleted at 350 V
  (A07 deplete at 200V)



- active depth ~ 305/295 μm
- A12A about 10 μm more than A07 → as expected from physical thicknesses
  (320/310 μm for A12A/A07)

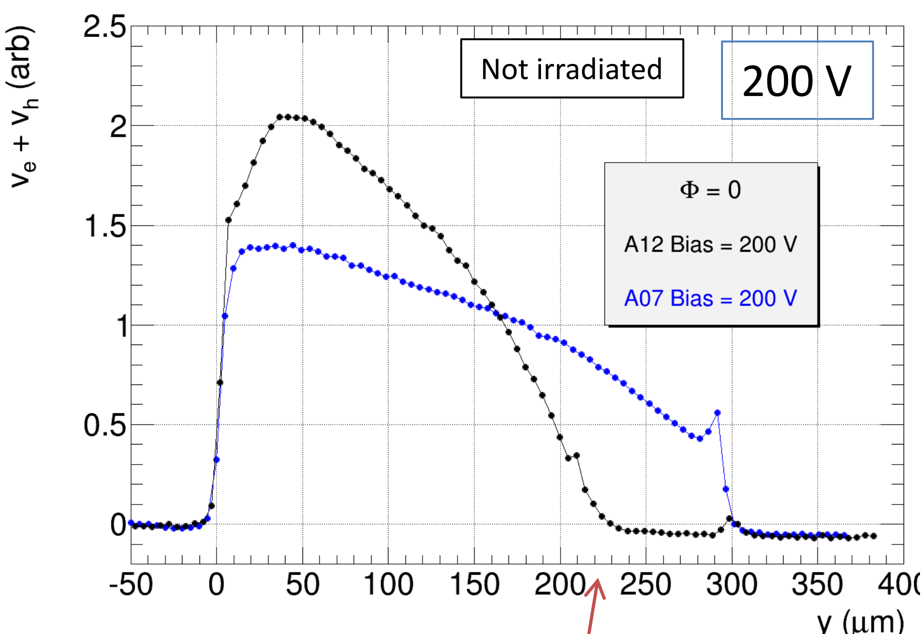


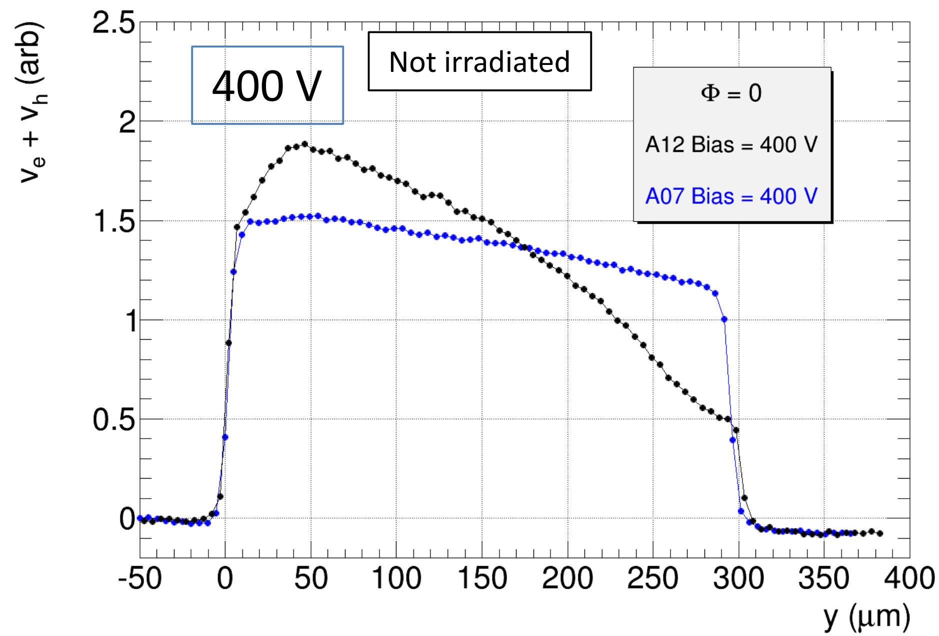
Velocity profile

$$I(y,t \sim 0) \approx qE_w(y)\left[\bar{v}_e(y)+\bar{v}_h(y)\right] \propto E; \quad \bar{v}_e(y)+\bar{v}_h(y) \propto E$$

- induced current at *t* ~ 0 proportional to carrier velocity and weighting field at laser spot location

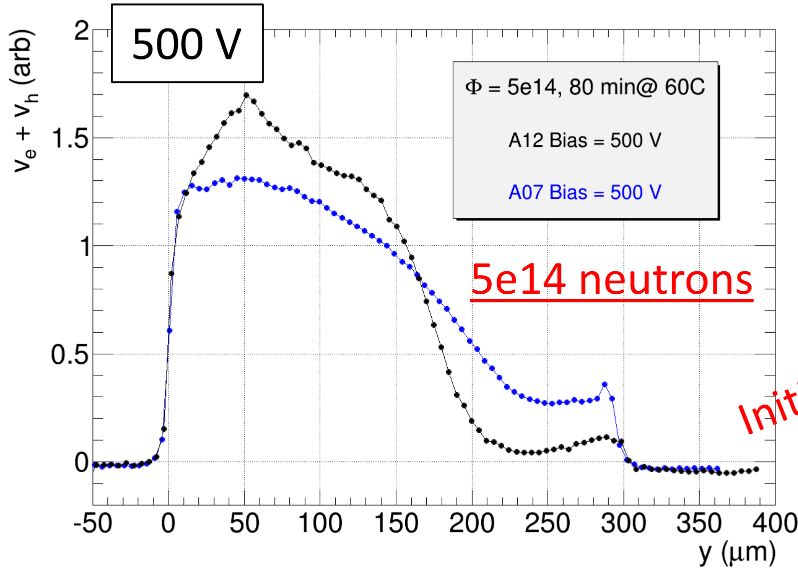
  ($\boldsymbol{E_w}$ ~ constant , see: G. Kramberger, et al.,IEEE TNS NS-57 (2010) 2294.)
- if *E* not too large, *I* proportional to e-filed *E*
- plots normalized to same integral from 0-300 µm (because ∫ Edx = Bias)
  - at 200 V A07 depleted, A12A not depleted
  - at 400 V both depleted



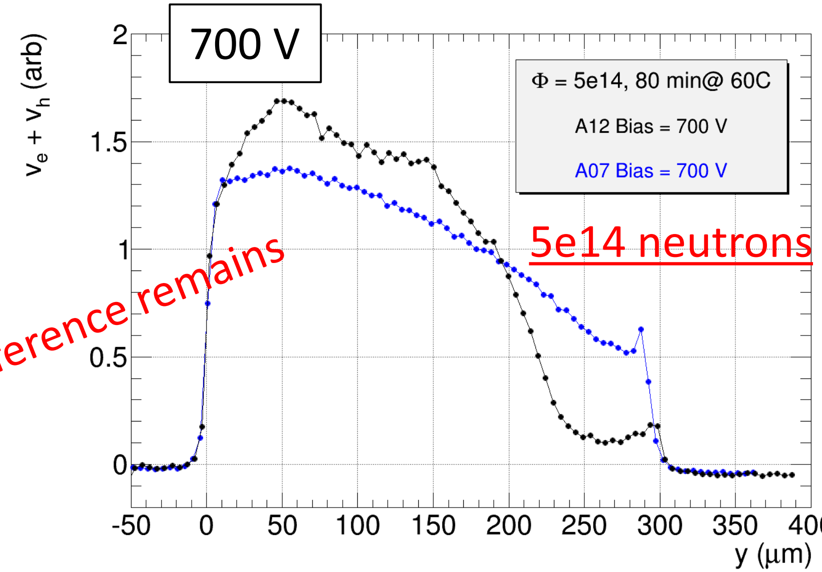


→ expected depletion depth for A12A at 200 V 220 µm!

Edge-TCT with detectors irradiated in Ljubljana (neutron)

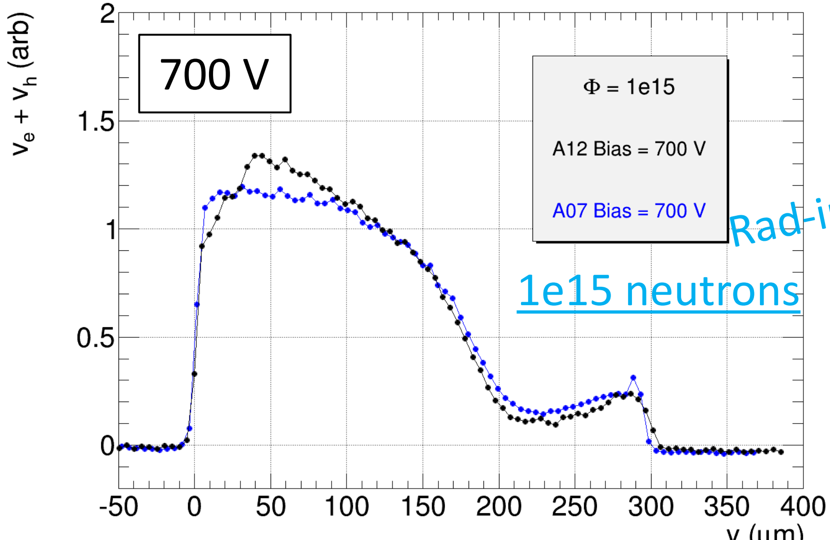


Initial difference remains

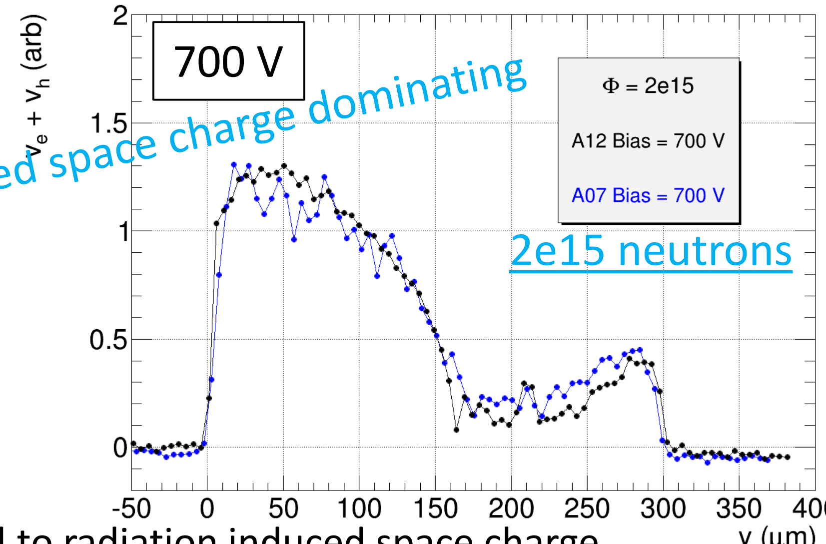


- larger field near back plane in A07

→ roughly in agreement with expectation because of different initial resistivities

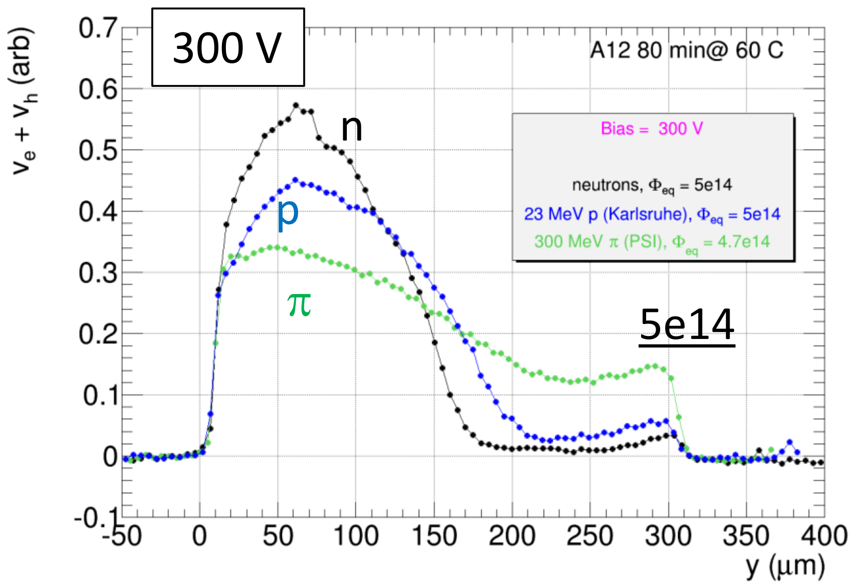


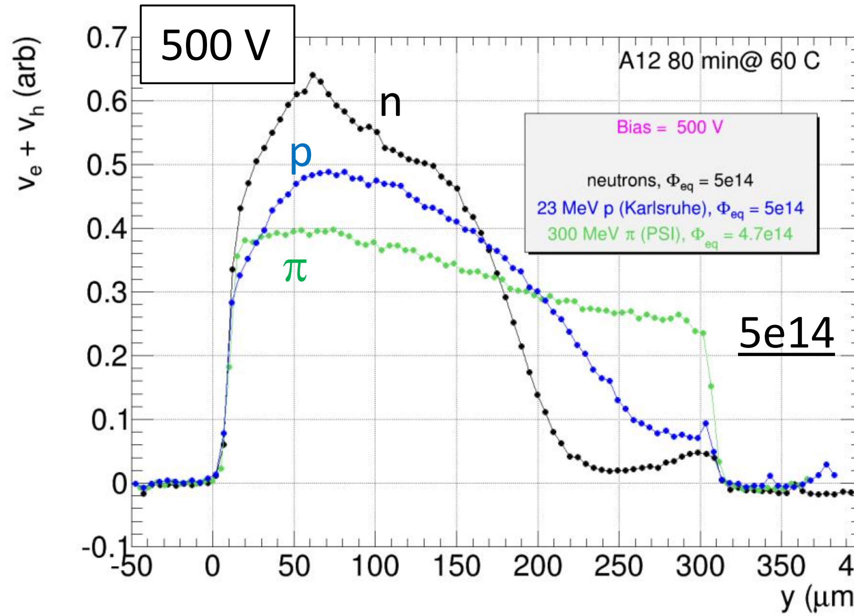
Rad-induced space charge dominating



➔ contribution of initial space charge small compared to radiation induced space charge

Edge-TCT with detectors irradiated by protons/neutrons/pions





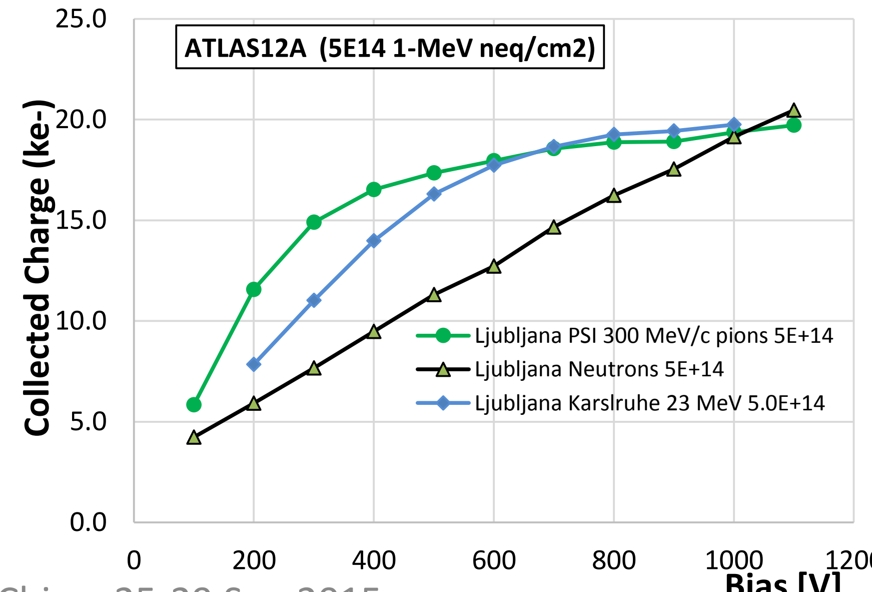
consistent with CCE measurements

→ more CC after charged particle irradiation

→ more CC for pions than for 23 MeV protons:

➔ larger *E* field at back side after pion irrad than after 23 MeV proton irradiation.

At moderate bias, CC is least after neutron irradiation



Summary

1. CC of HPK p-bulk sensors irradiated with protons and neutrons are evaluated extensively with β-ray by several institutions in collaboration

- CC of >9 Ke^- can be maintained at Vb=500V after 1.6×10^{15} 1-MeV n_{eq}/cm^2
  - S/N> 19 for short strips (L=2.4cm) after 1.1×10^{15} 1-MeV n_{eq}/cm^2
  - S/N> 18 for long strips (L=4.8cm) after 0.6×10^{15} 1-MeV n_{eq}/cm^2
  - S/N> 14 for innermost EC after 1.6×10^{15} 1-MeV n_{eq}/cm^2

2. β-ray measurements are validated by beam

3. Difference in p/n/pion damages investigated in terms of electric-field profiles using e-TCT

- Reduction in the charge collection due to induced traps
- Change in the field profile across depth due to generated currents

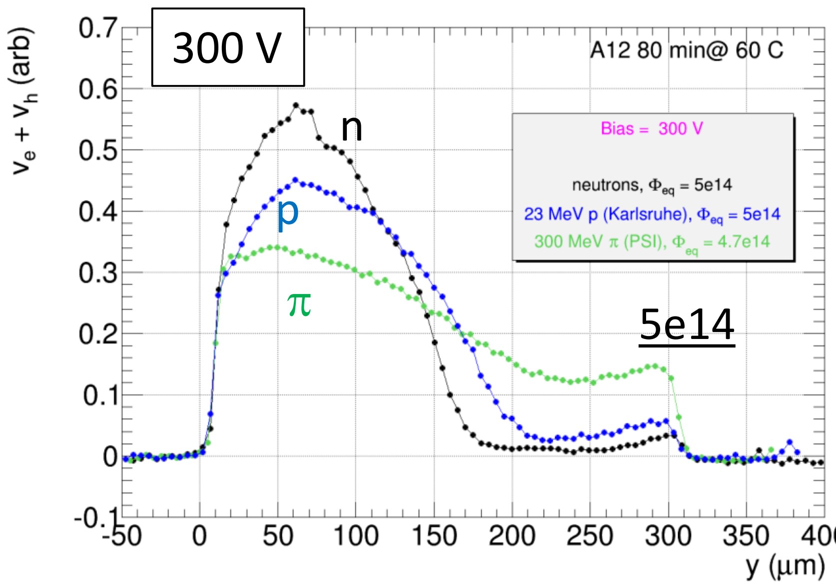
Both dependent on the irradiation particles (n/p/π)

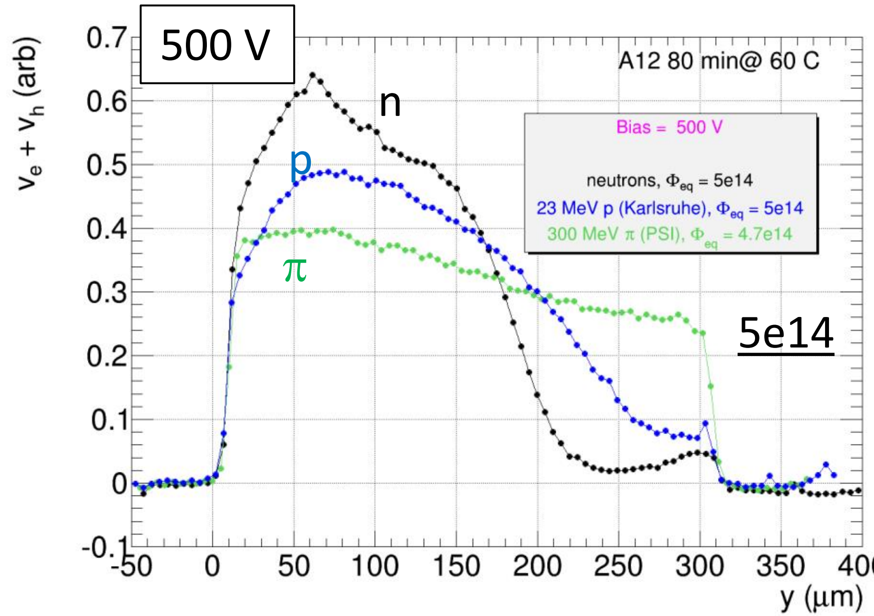
✓Defect introduction rates are more in the order of : n>p>π

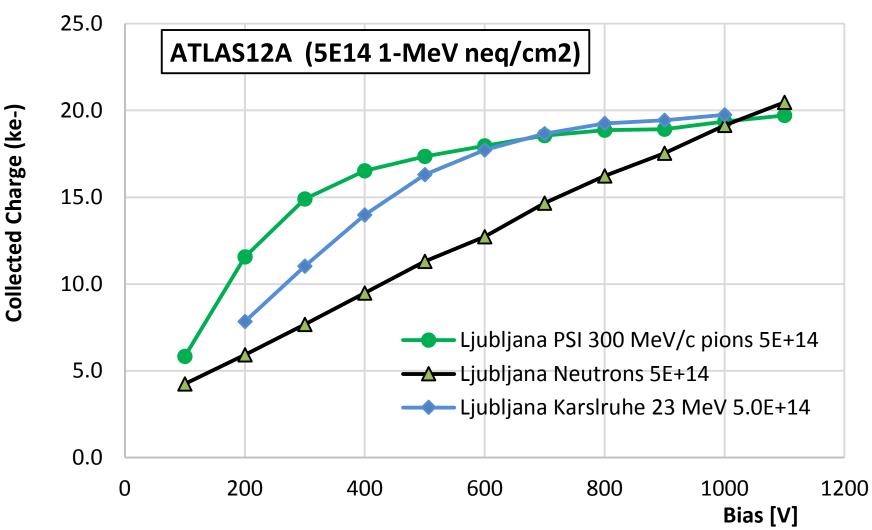
✓Differences in E-filed profile shapes due to double peak E-field:

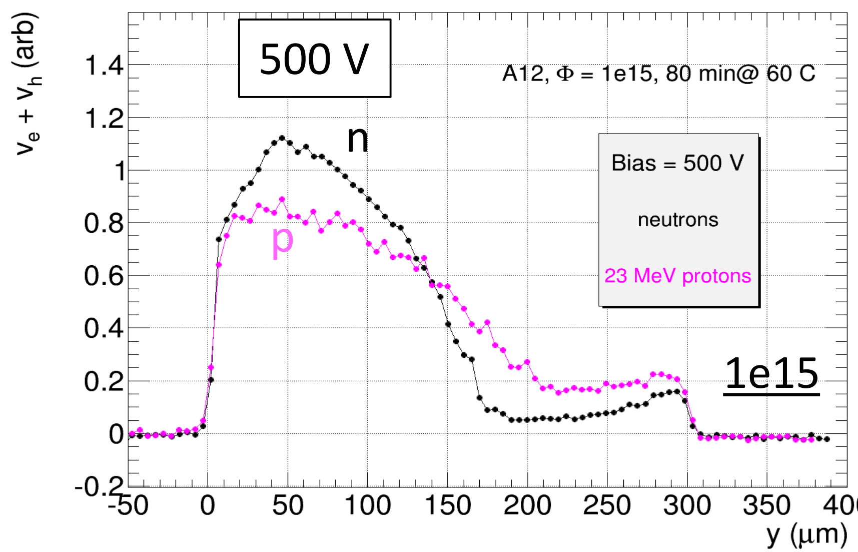
⇒ HPK p-bulk strip sensors are operational at the HL-LHC fluence

Edge-TCT with detectors irradiated by protons/neutrons/pions







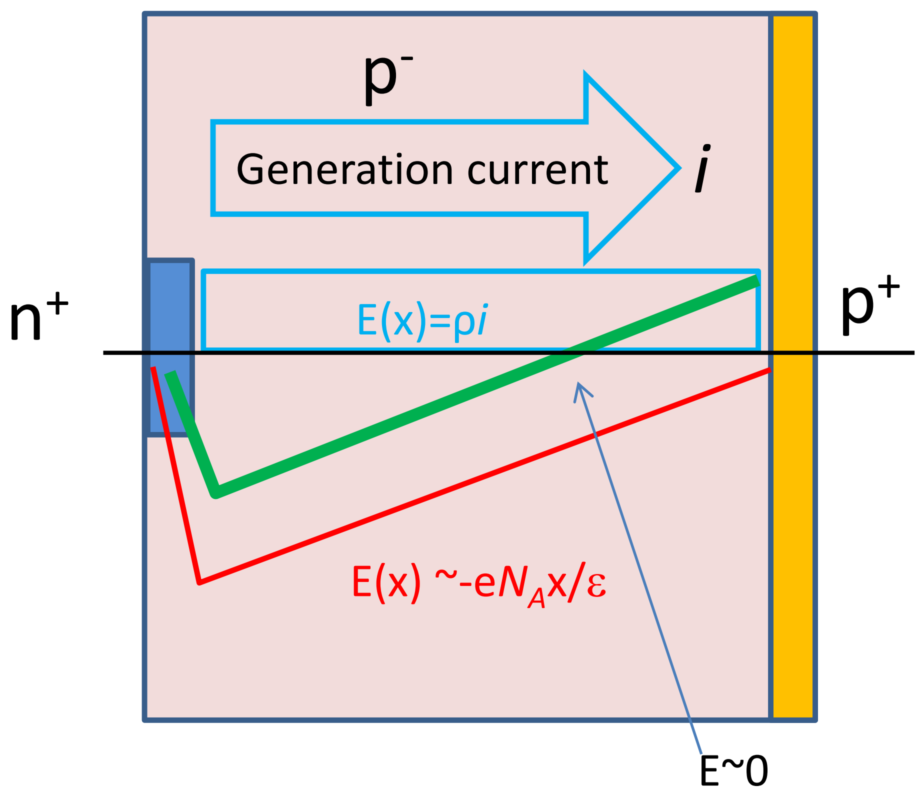


Double Peak E-field V. Eremin et al. NIMA535 (2004)622.

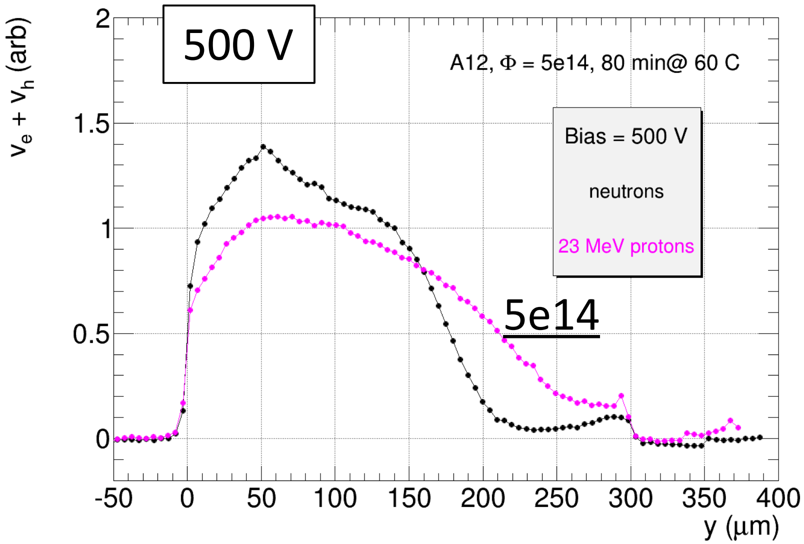
$\rho_{eff} = \rho_{dopants} \sim -eN_A$ … space-charge density

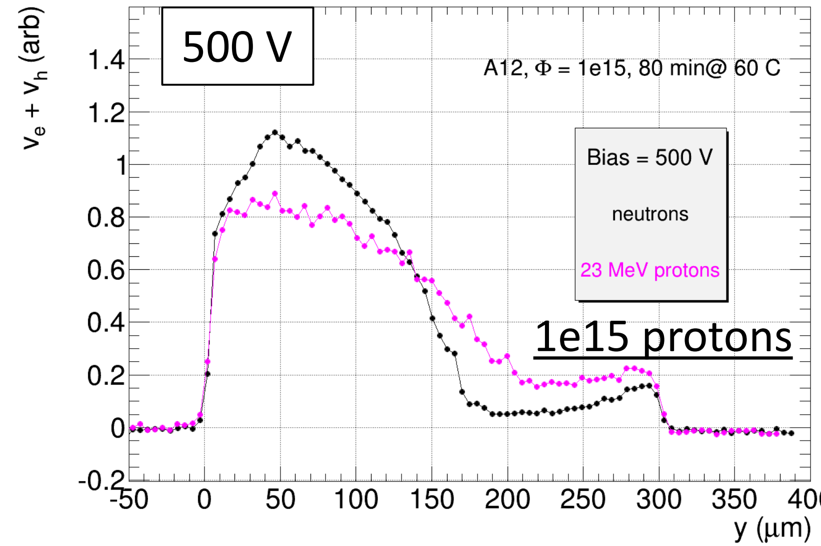
$\Rightarrow$ $\rho_{eff} = e(f_D n_D - f_A n_A) + \rho_{dopants}$

radiation induced trapping levels with occupancies *f*



Edge-TCT with detectors irradiated in Karlsruhe (p 23 MeV)





- larger active volume after irradiation with 23 MeV protons than after neutrons at 500 V
  → consistent with larger charge measured with Alibava