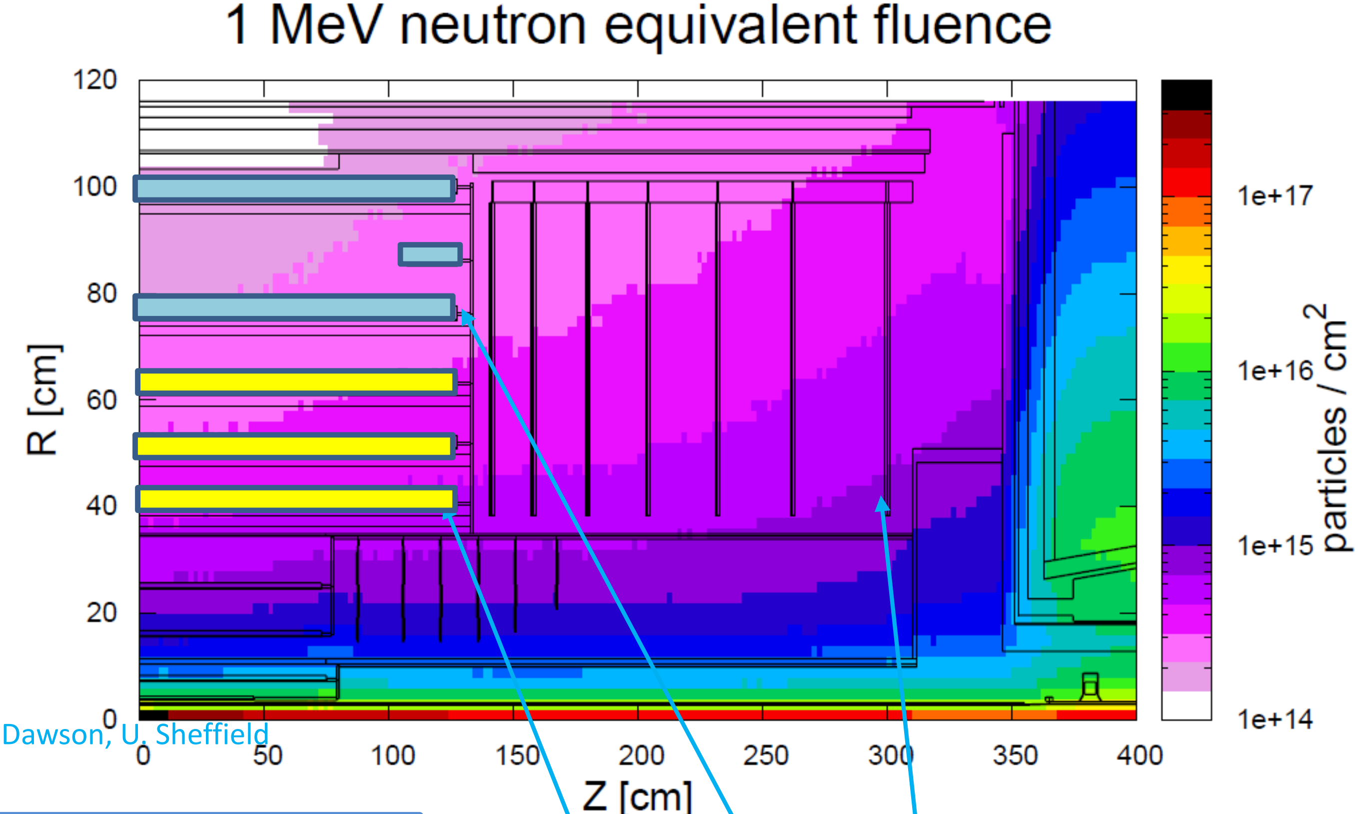
筑波大学
University of Tsukuba

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

K. Hara (University of Tsukuba)
On behalf of the ATLAS ITk Strip Sensor Collaboration

ATLAS ITk LoI Layout and Fluence at HL-LHC

Fluence evaluations per 3000 fb^{-1}



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

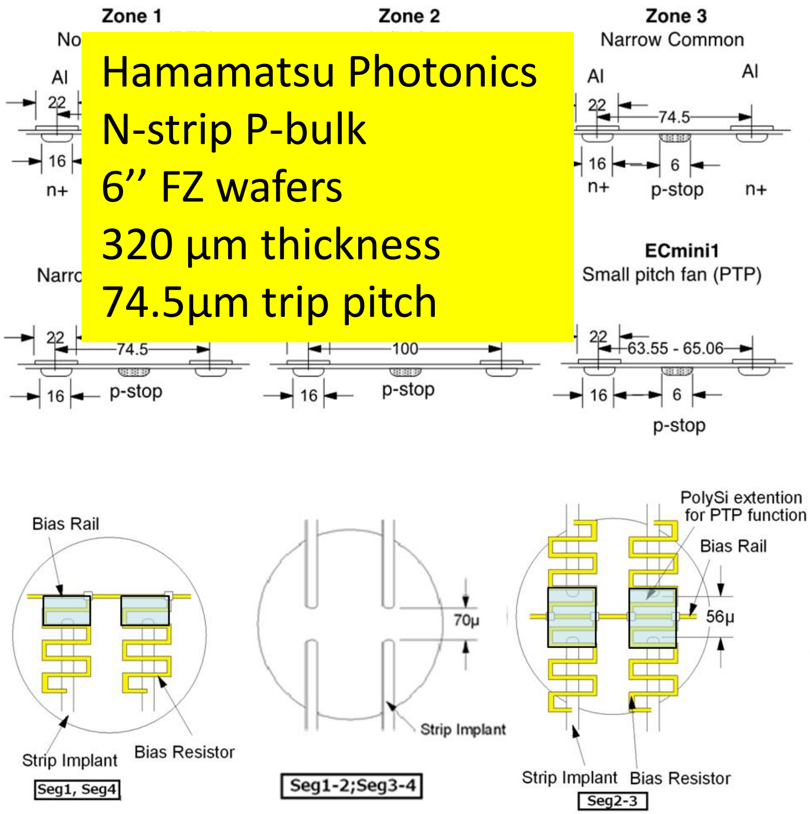
BL1: 5.3 x 10^{14} /cm^2

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

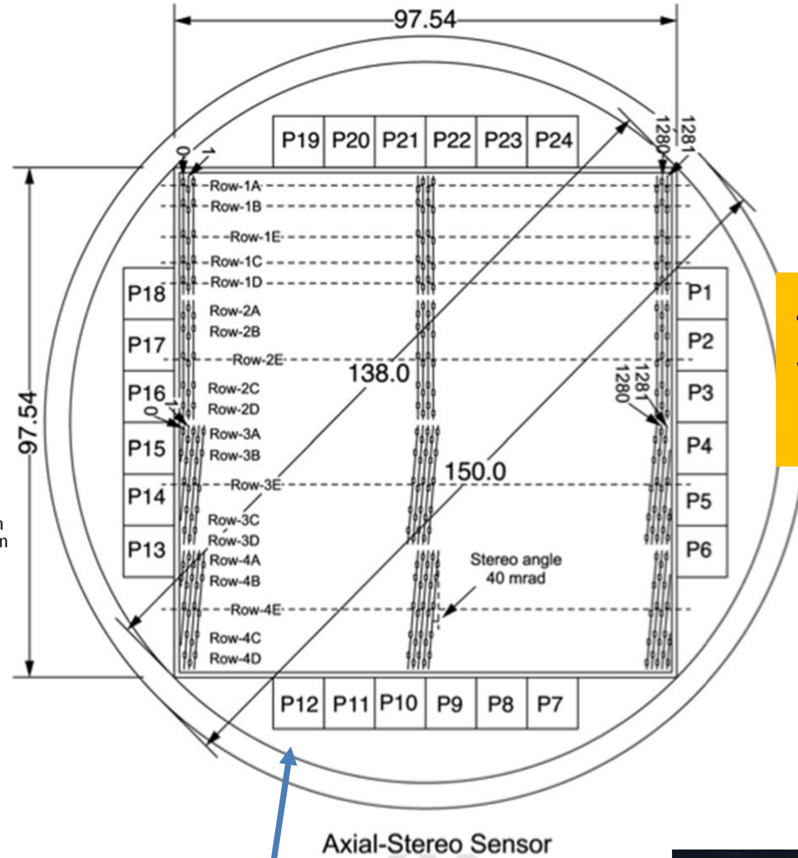
Difference in n/p damages is an issue

ATLAS12 design



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

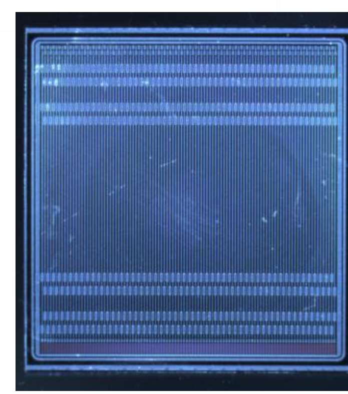
ATLAS12M



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)

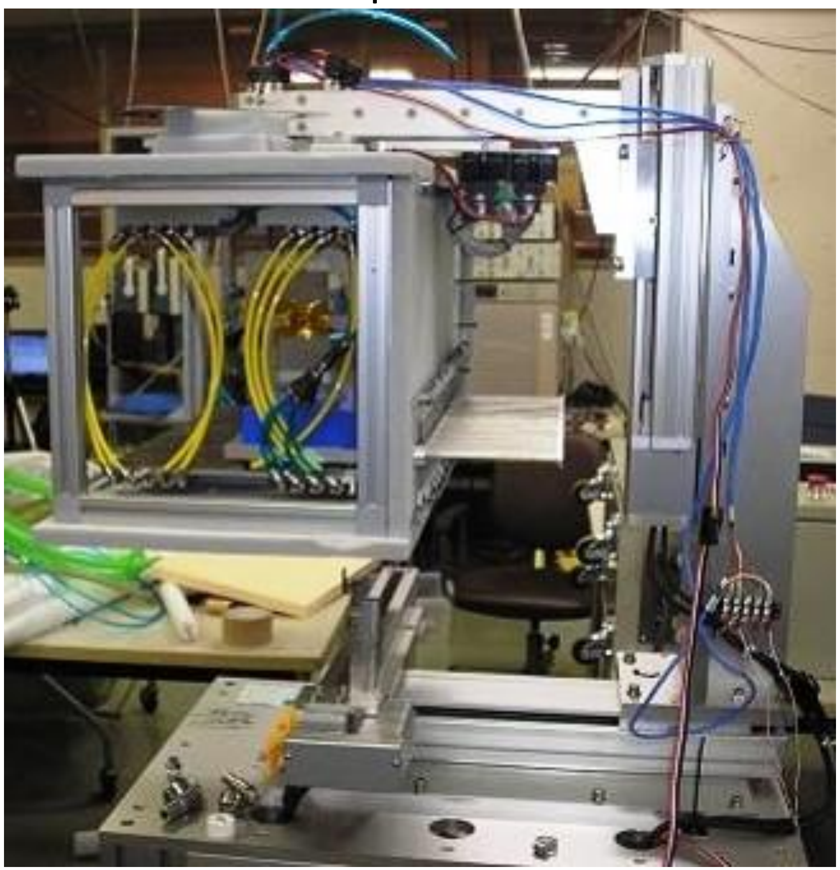
ATLAS12A	ρ~3.5-5 kΩcm
ATLAS12M	ρ~6 kΩcm
ATLAS07	ρ~5-5.5 kΩcm

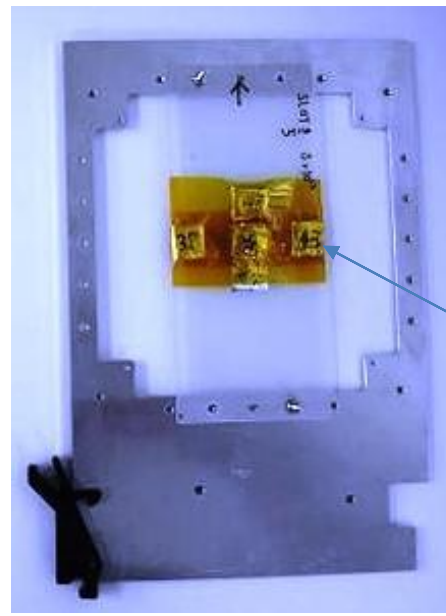
Irradiation

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



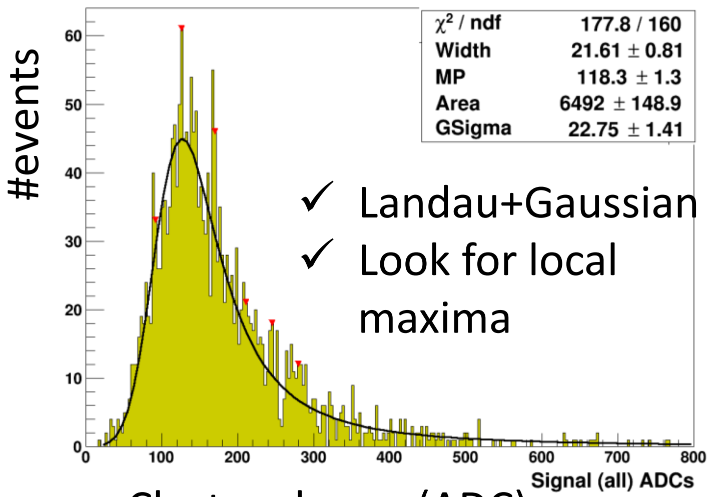


Sample holder/slot
(11x11cm opening)

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

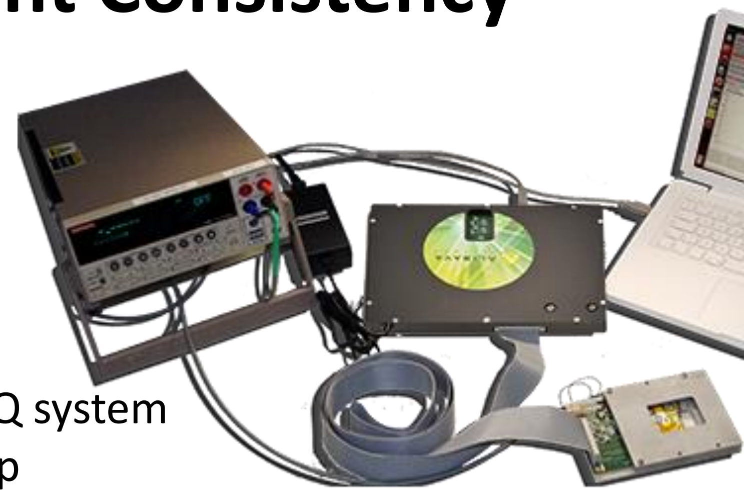
Charge Collection Measurement Consistency



✓ Landau+Gaussian
✓ Look for local maxima

Cluster charge (ADC)

β-source (electron beam)



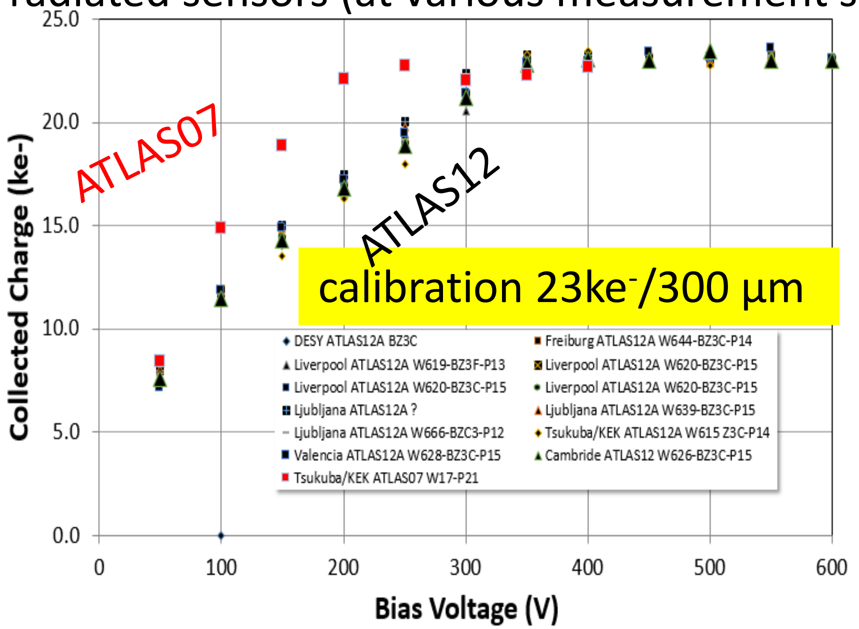
Alivaba:

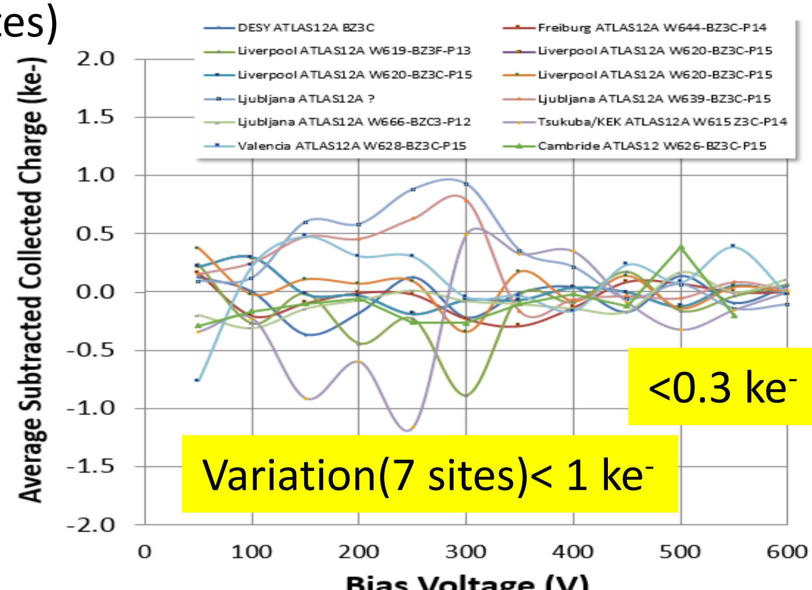
FPGA based DAQ system

LHCb Beetle chip

http://www.alibavasystems.com/

Non-irradiated sensors (at various measurement sites)

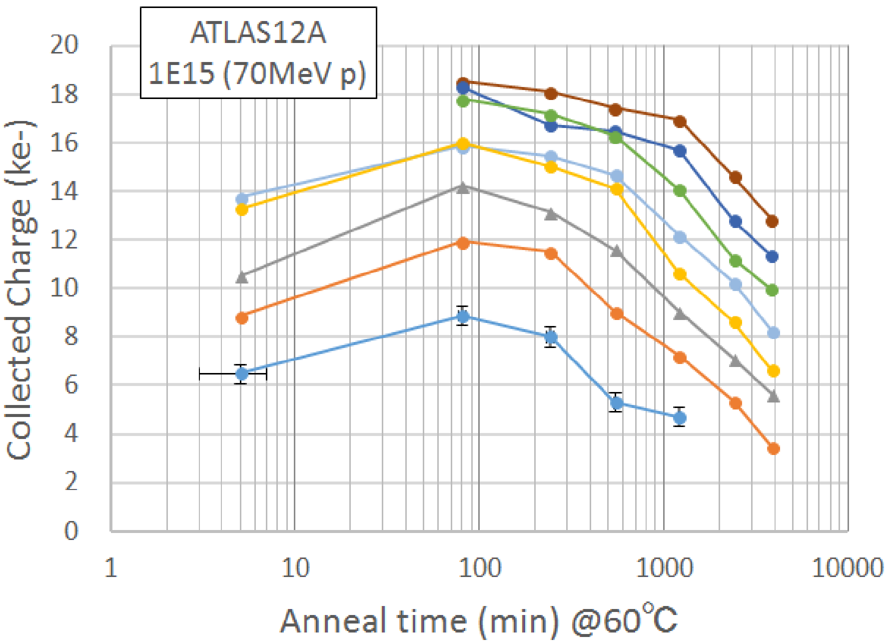


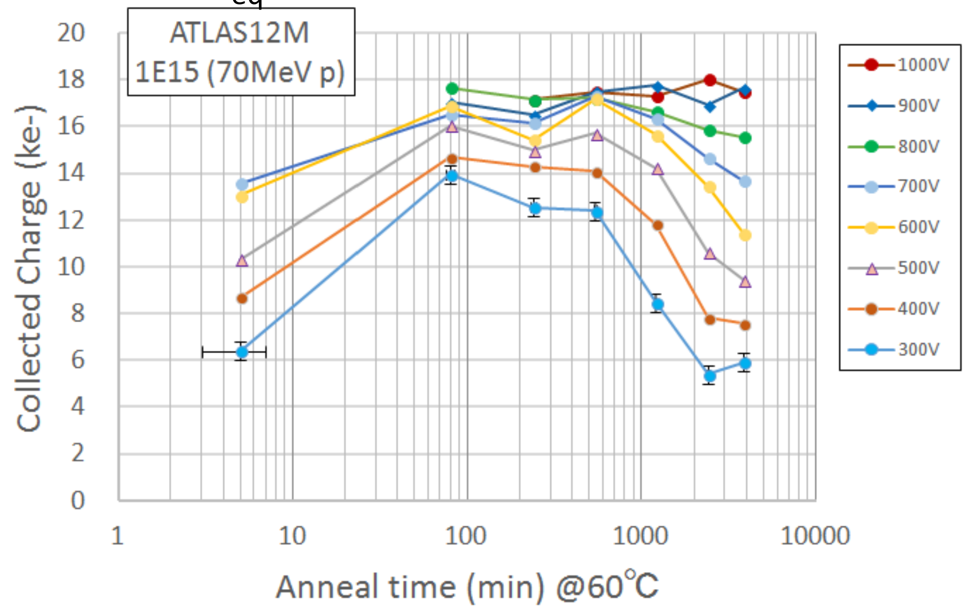


different sensors
(thickness and resistivity variations)

Long term annealing at 60°

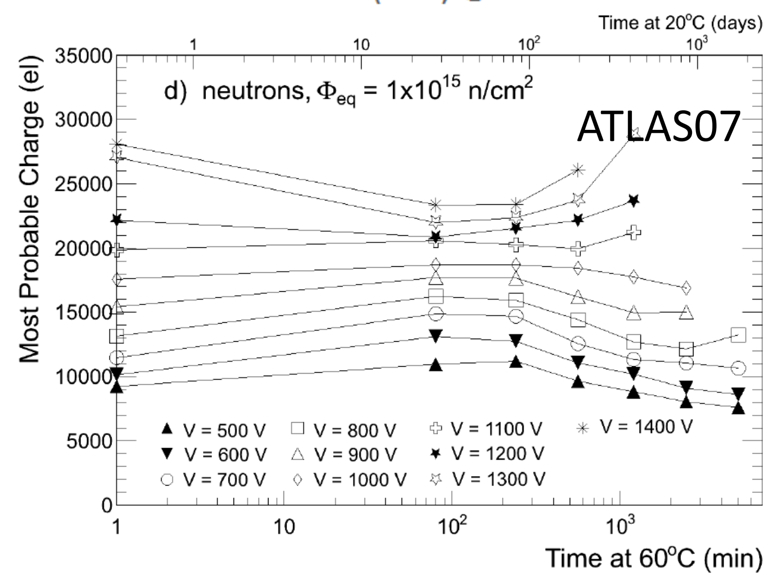
Proton irradiation: $1\times10^{15}\ n_{eq}/cm^2$





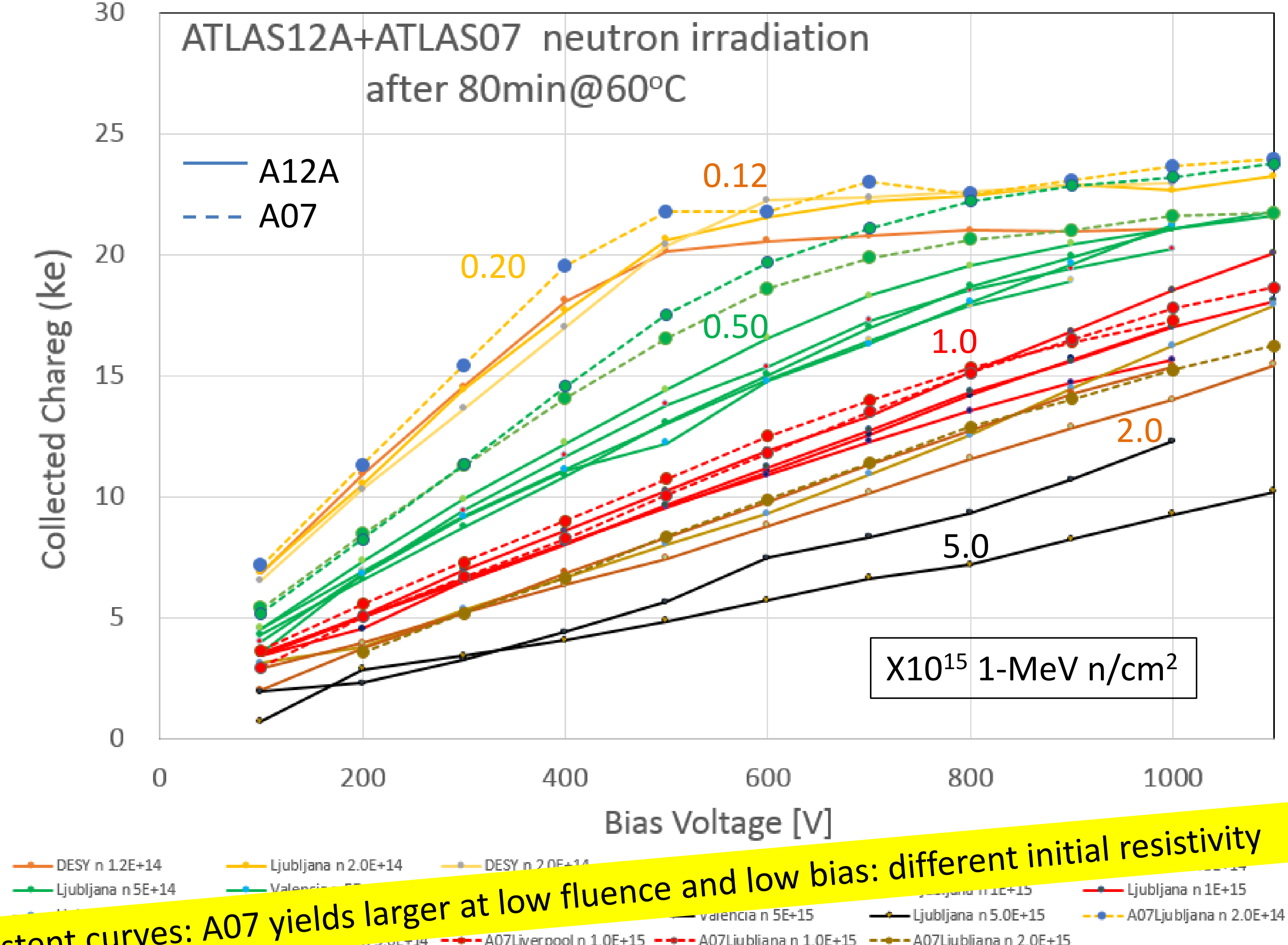
- Annealing is similar for A12A/A12M for bias below 600V (proton 1E15/cm^2)

- A07 (neutron) studied previously
  => behavior similar to A12M
  I. Mandic et al., NIMA 629 (2011) 101



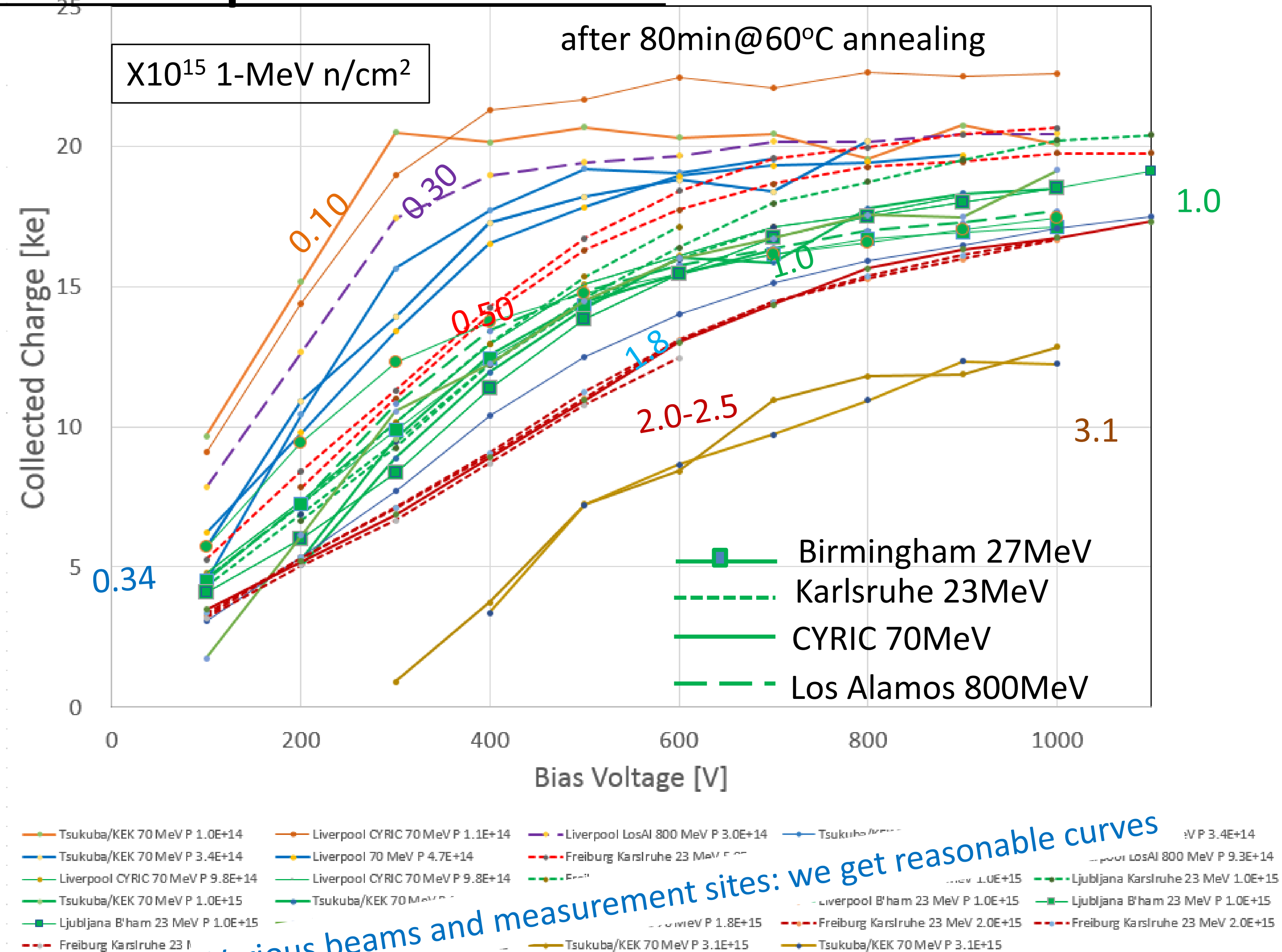
All data shown below are after controlled annealing of 80min @ 60°C

ATLAS12A+ATLAS07 Neutron irradiation



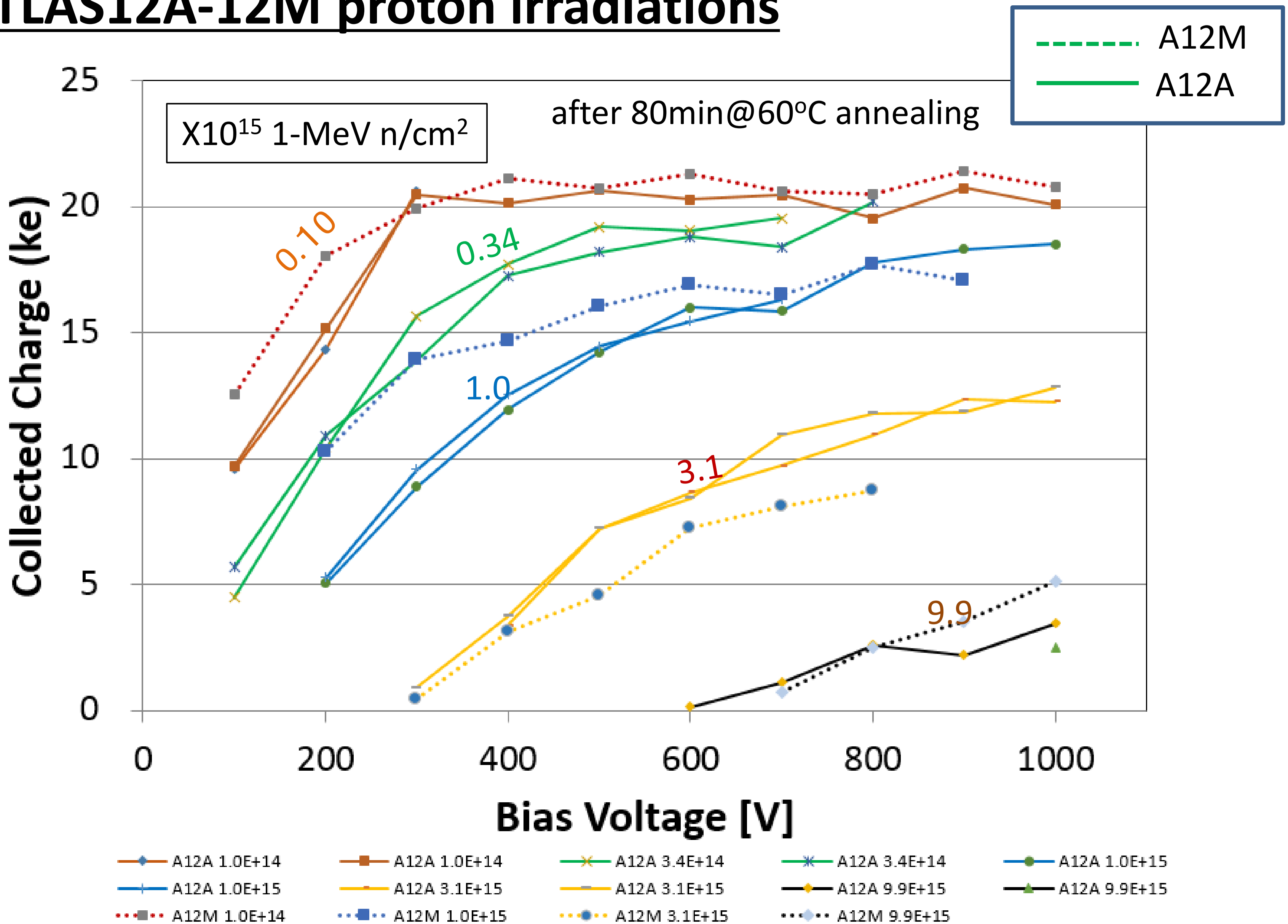
Consistent curves: A07 yields larger at low fluence and low bias: different initial resistivity

ATLAS12A proton irradiations



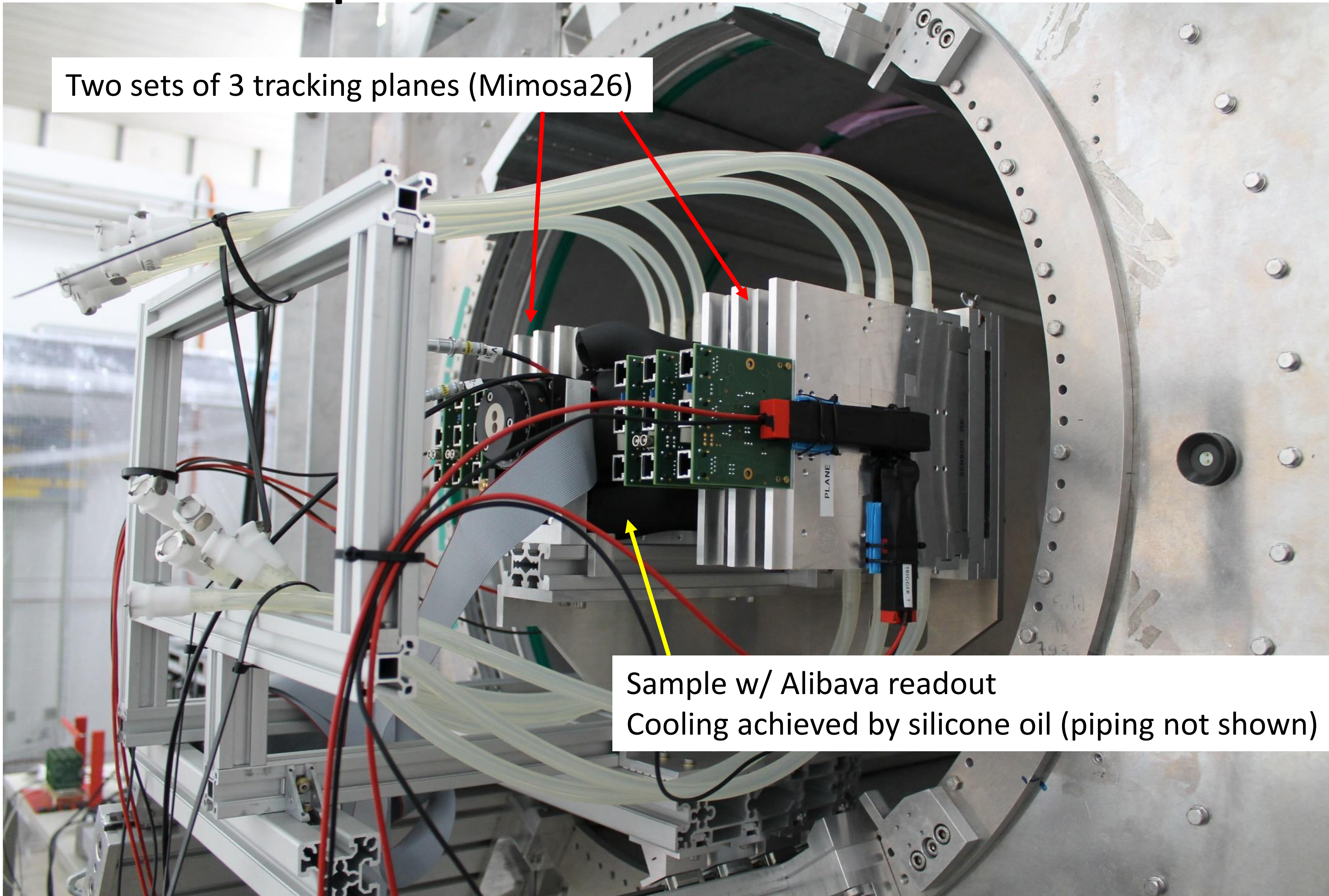
Various beams and measurement sites: we get reasonable curves

ATLAS12A-12M proton irradiations

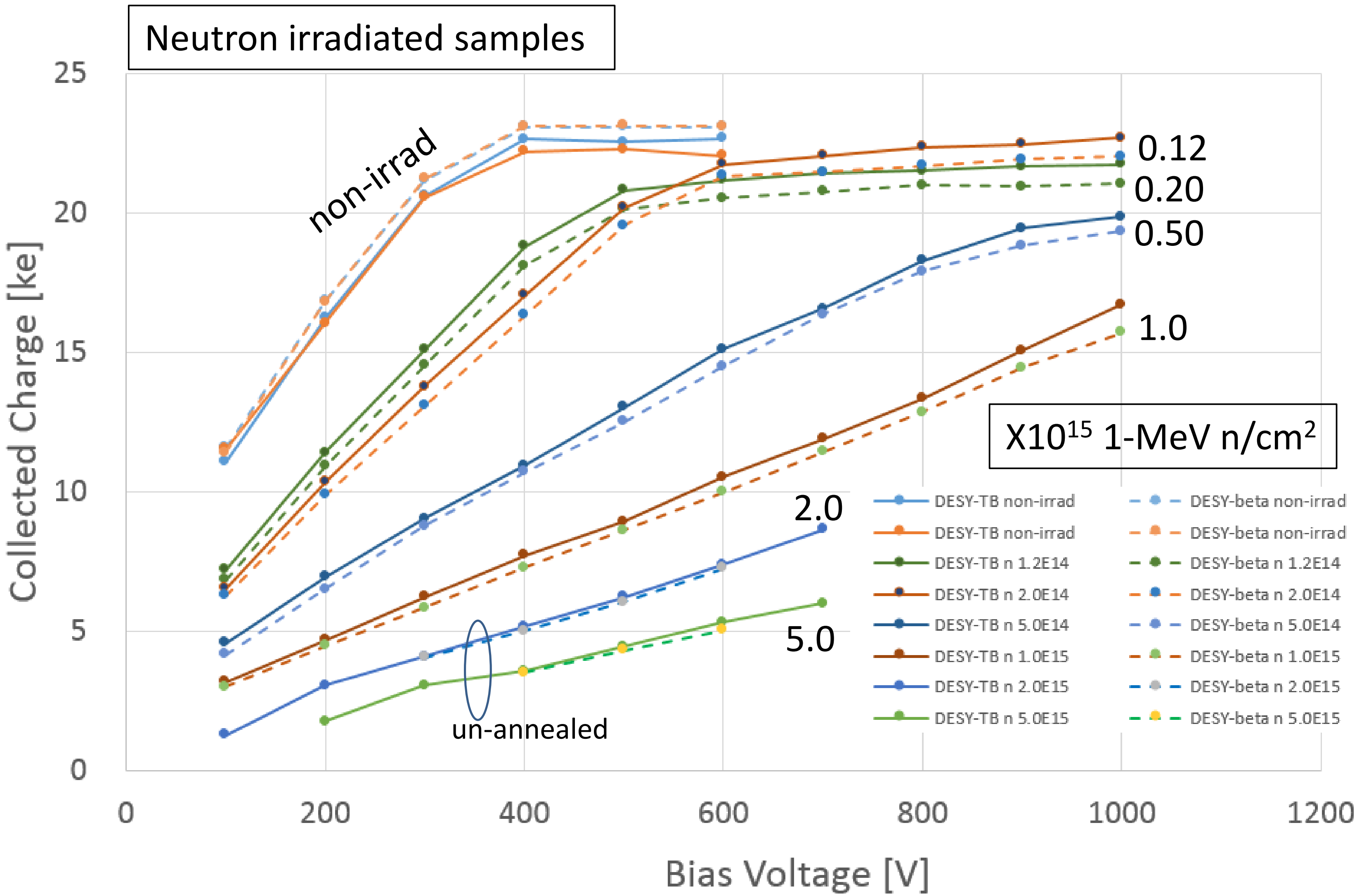


12M yields larger signal at low fluence and at low bias: different initial resistivity

Testbeam setup at DESY 4.4 GeV electrons



Source vs testbeam (DESY 4.4-GeV electrons)

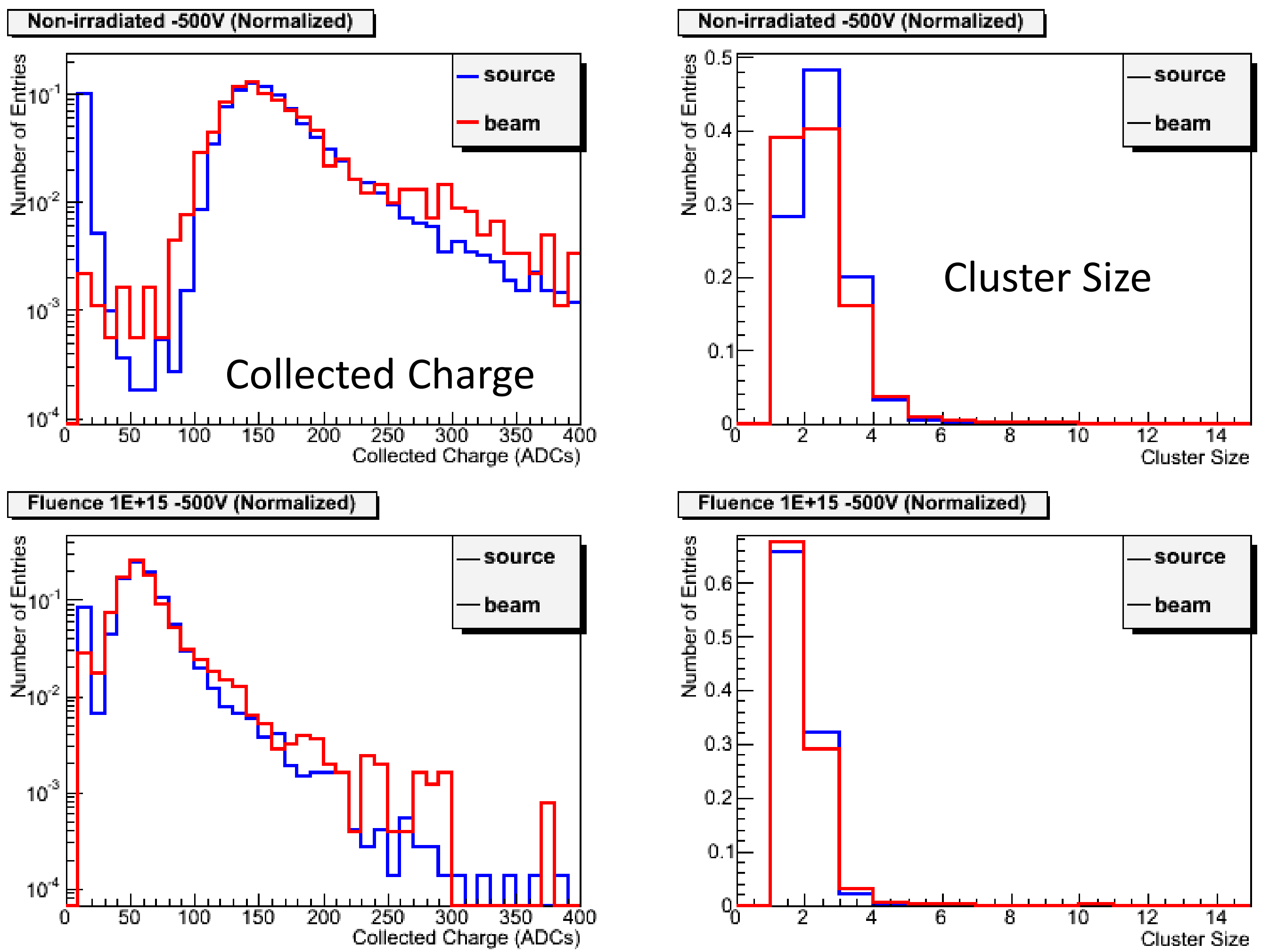


Very consistent results obtained!

Source vs testbeam (DESY 4.4-GeV electrons)

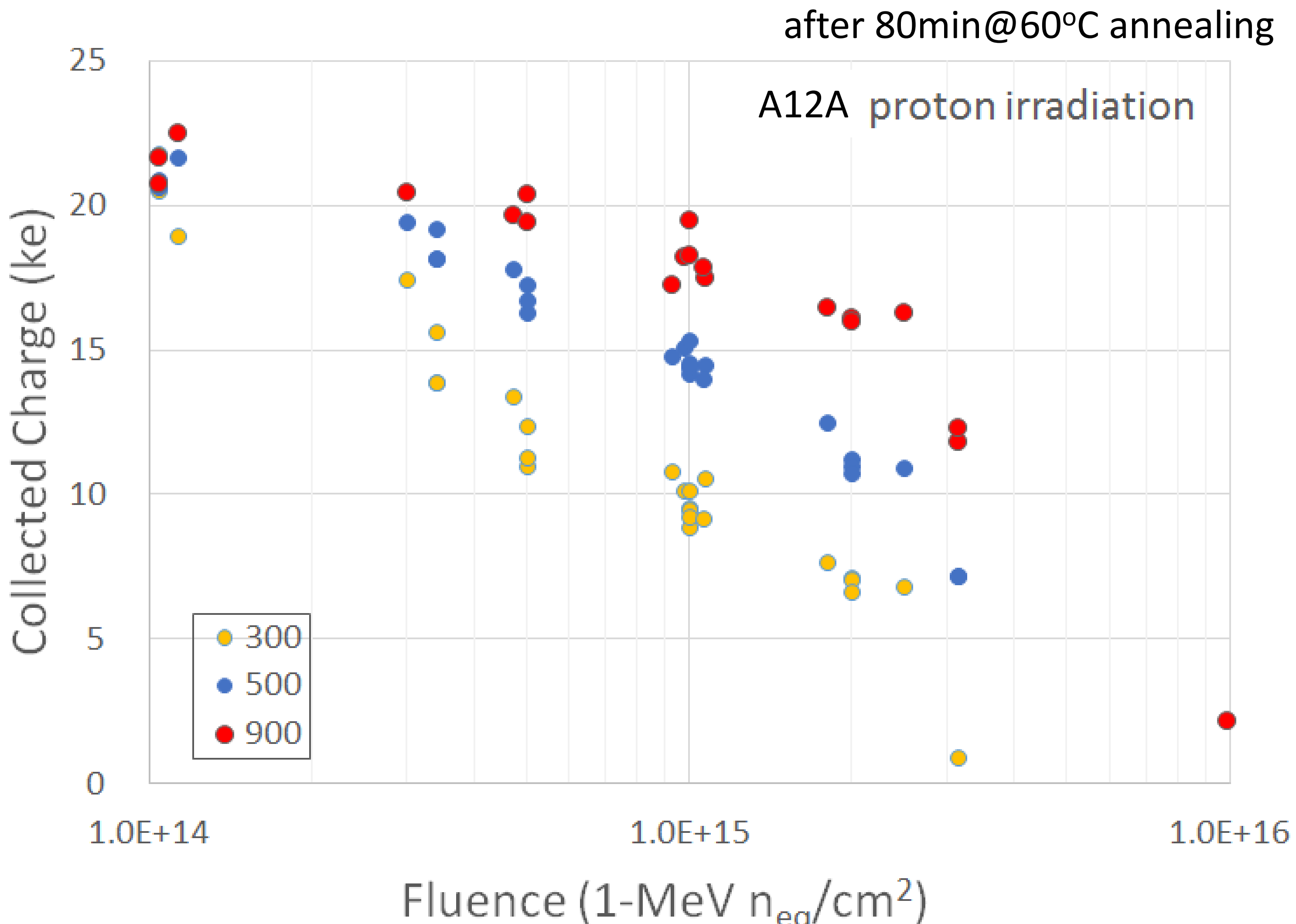
Non-irrad@

1E15 neutron irradiated



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

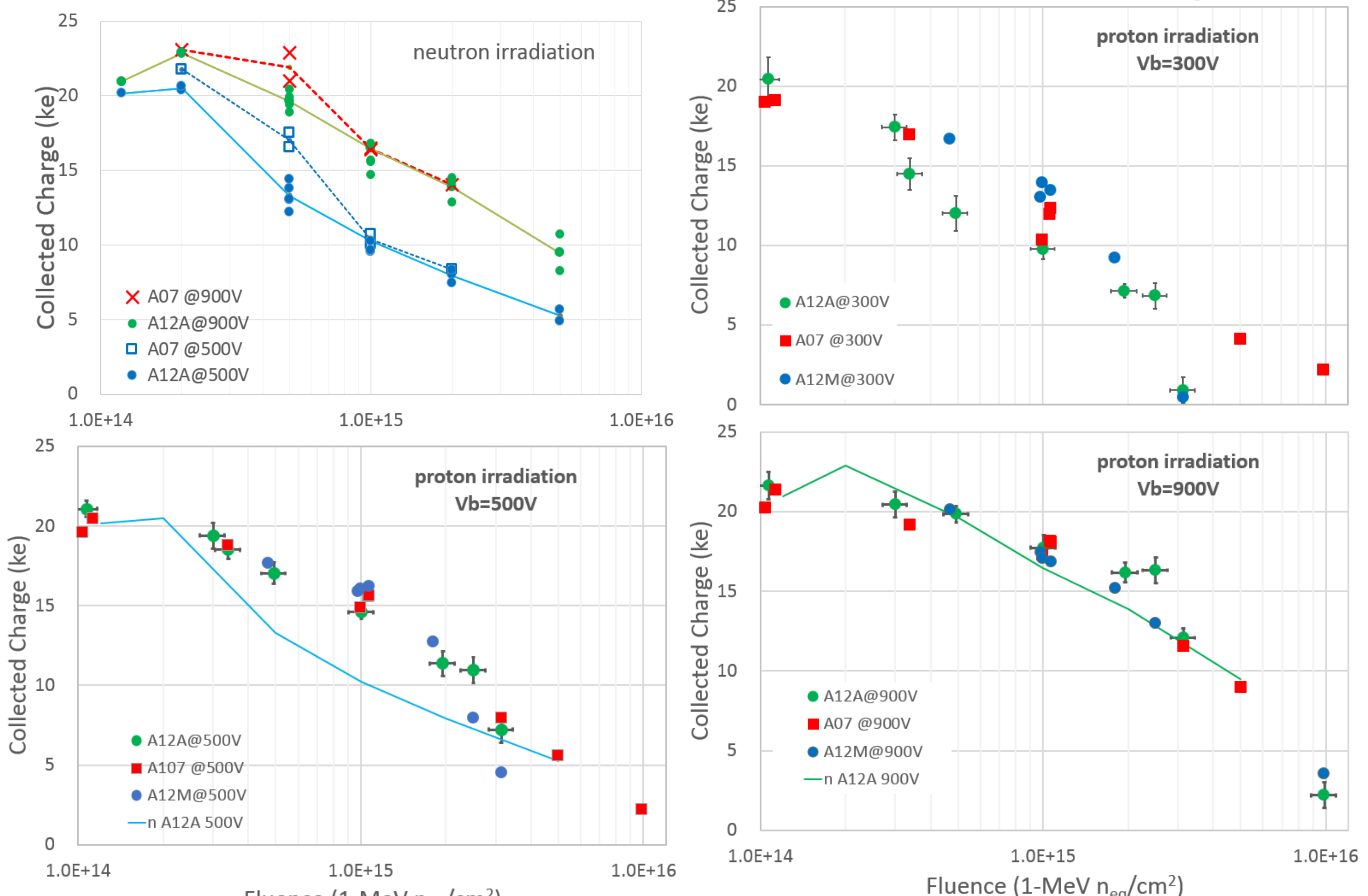
Fluence dependence (all A12A data points)



Fluence dependence

after 80min@60°C annealing

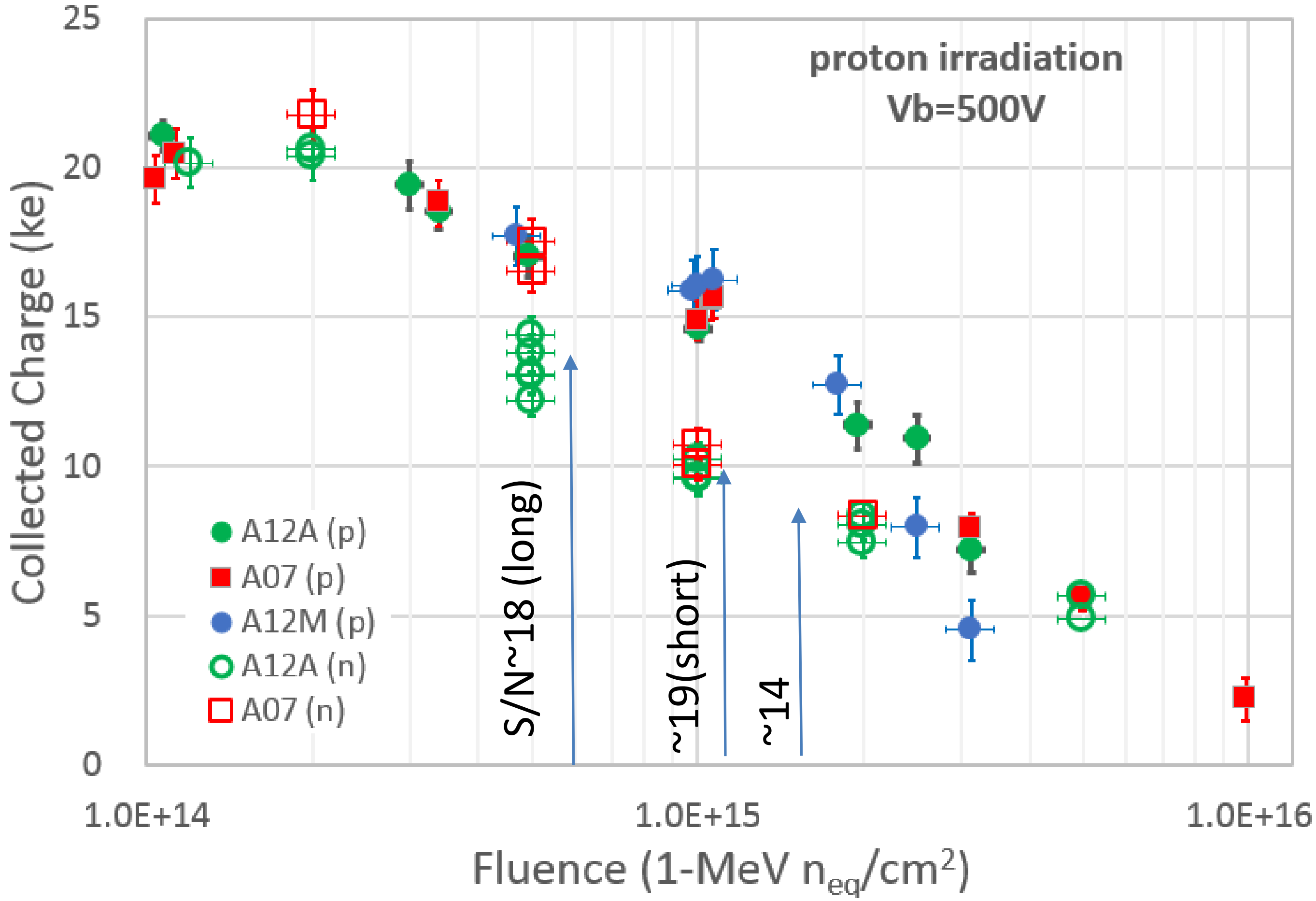
A12A yield slightly smaller & n-damage is larger at low fluence and low bias => becomes similar at large fluence



S/N at HL-LHC

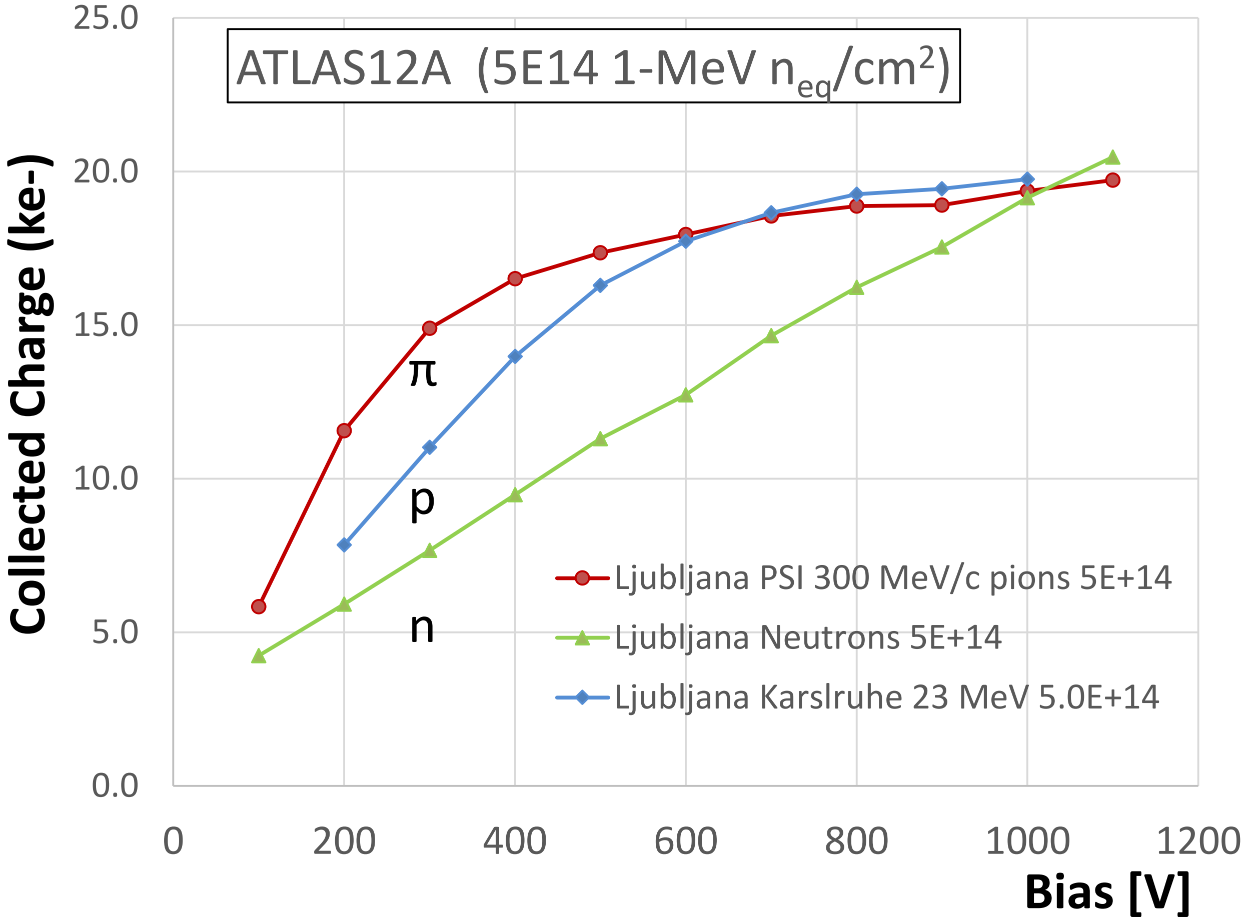
Barrel short (24mm)strips up to : 1.1 x 10^{15} /cm^2
Barrel long (48mm) strips up to : 0.6 x 10^{15} /cm^2
Endcap (8-48mm) strips: max 1.6 x 10^{15} /cm^2

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

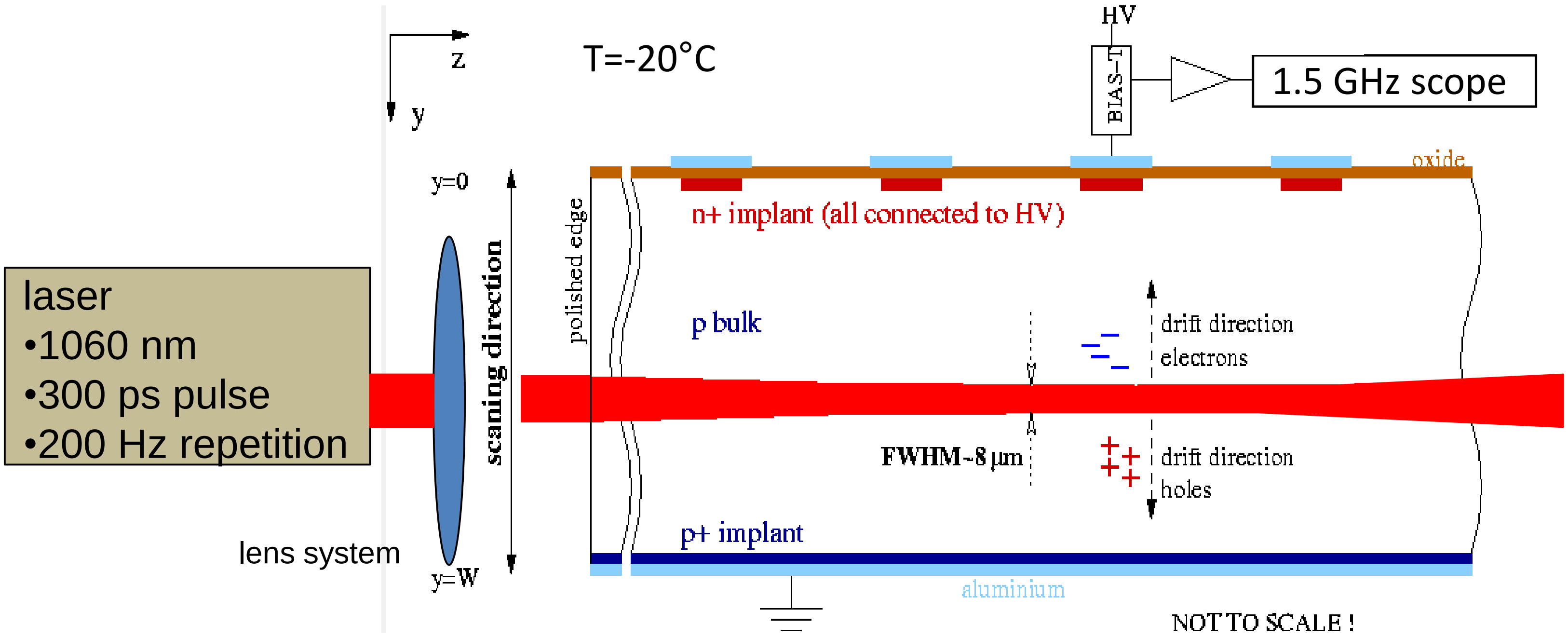
Charge collection of samples irradiated with p/n/π



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

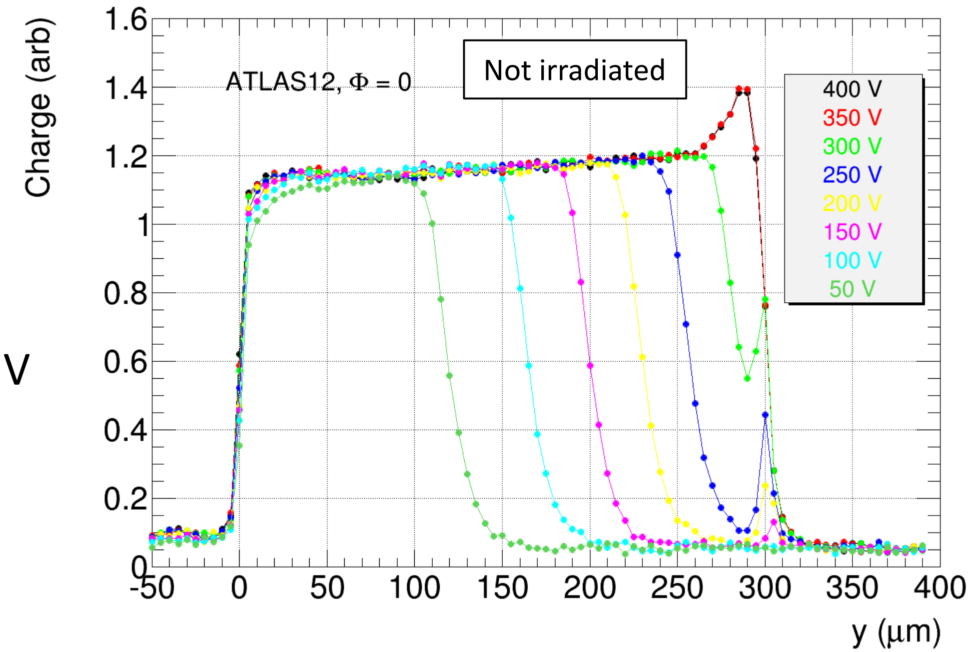
detectors on a Peltier cooled support in dry air atmosphere (down to -20°C)

e-TCT

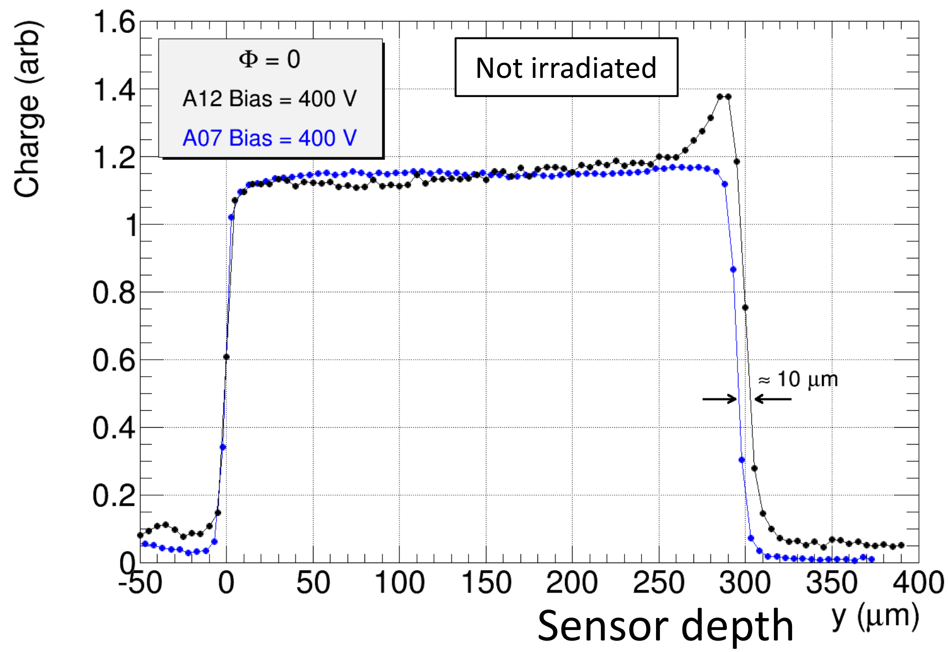
non-irradiated samples

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)

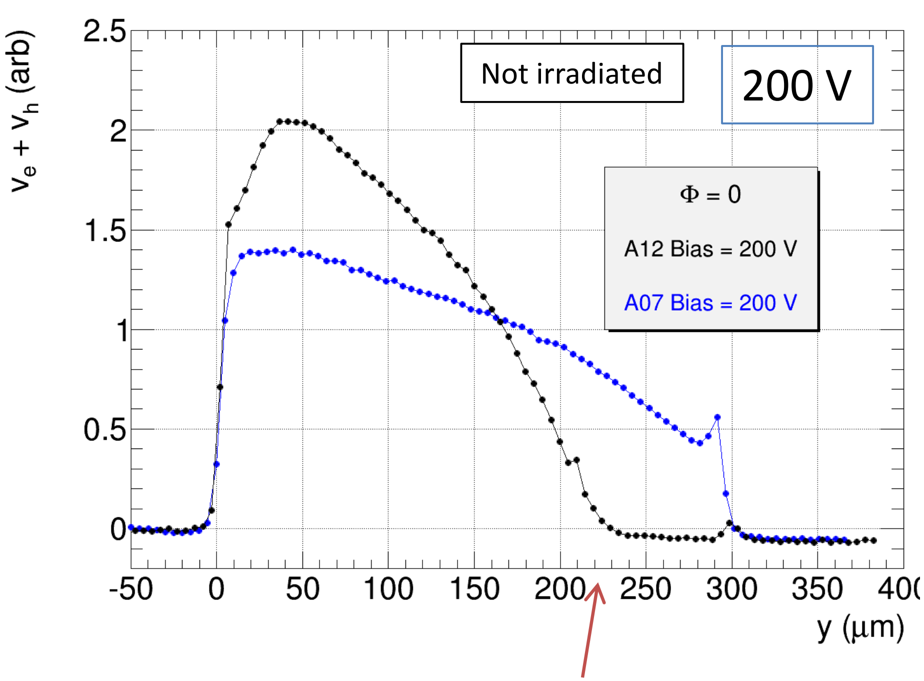


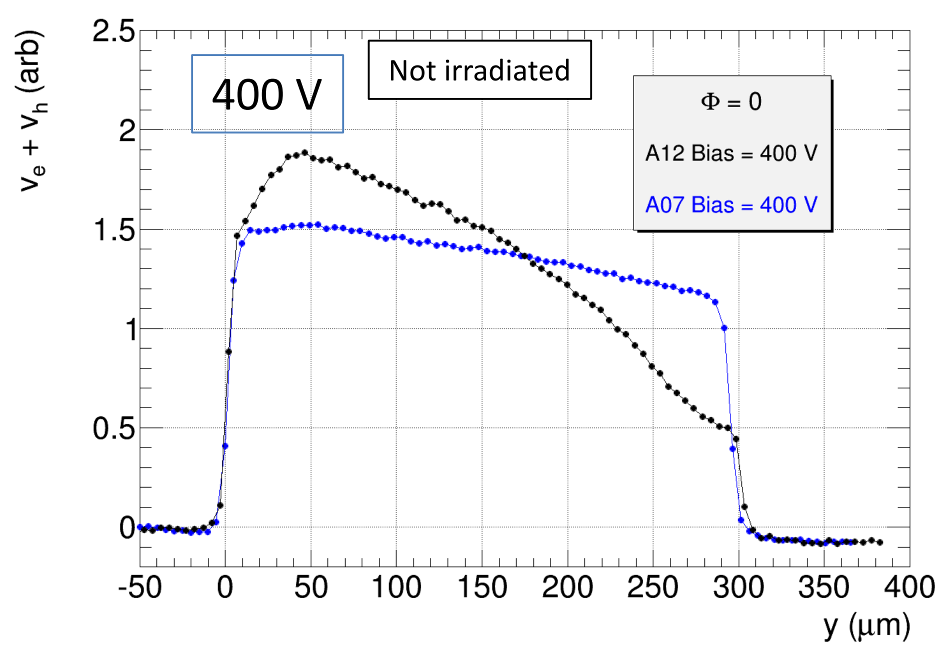
Velocity profile

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

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

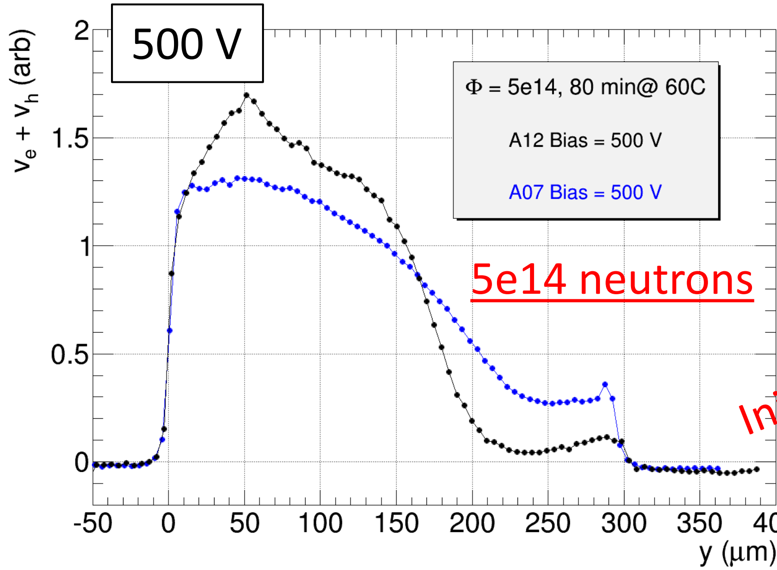
  (E_w ~ constant , see: G. Kramberger, et al.,IEEE TNS NS-57 (2010) 2294.)
- if *E* not too large, *I* proportional to e-filed *E*
- plots normalized to same integral from 0-300 μm (because ∫ Edx = Bias)
  - at 200 V A07 depleted, A12A not depleted
  - at 400 V both depleted

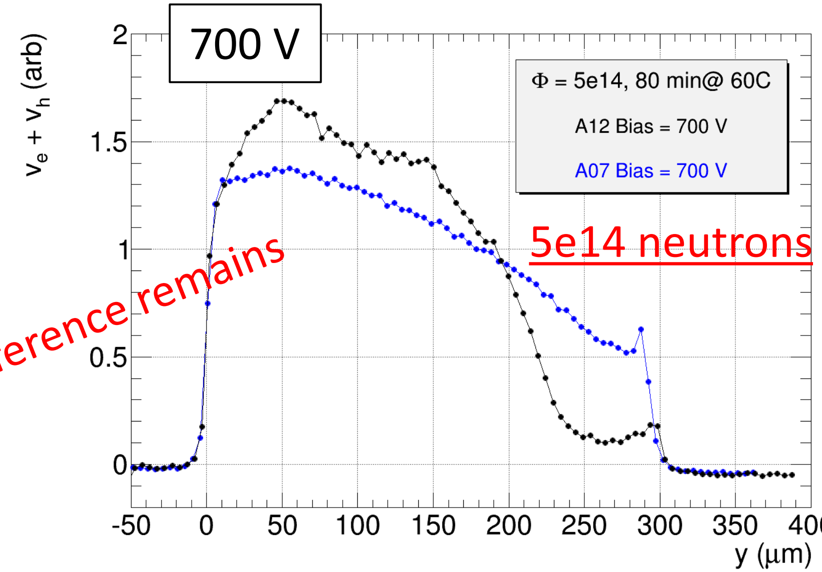




→ expected depletion depth for A12A at 200 V 220 μm!

Edge-TCT with detectors irradiated in Ljubljana (neutron)

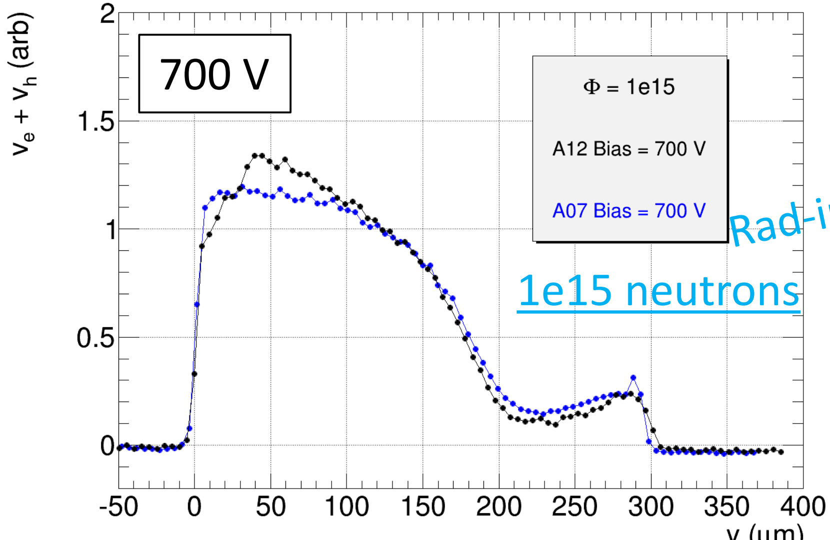


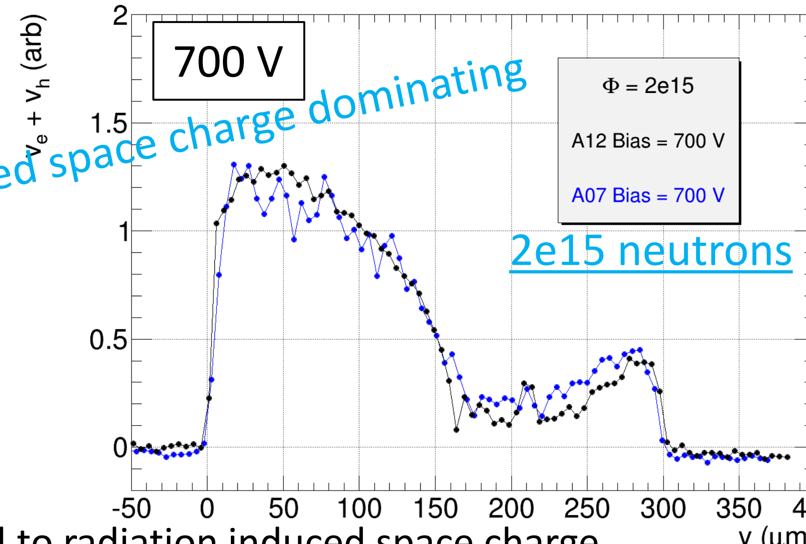


Initial difference remains

- larger field near back plane in A07

→ roughly in agreement with expectation because of different initial resistivities

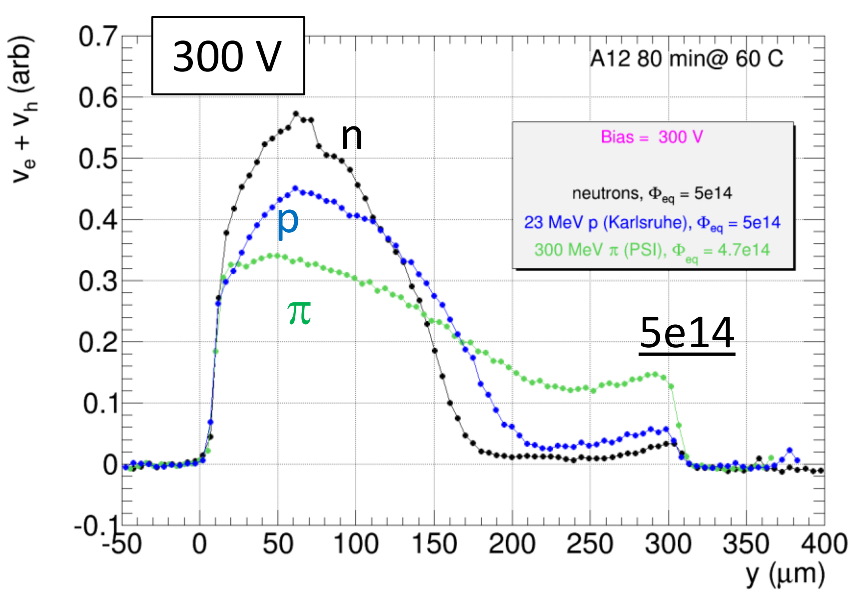


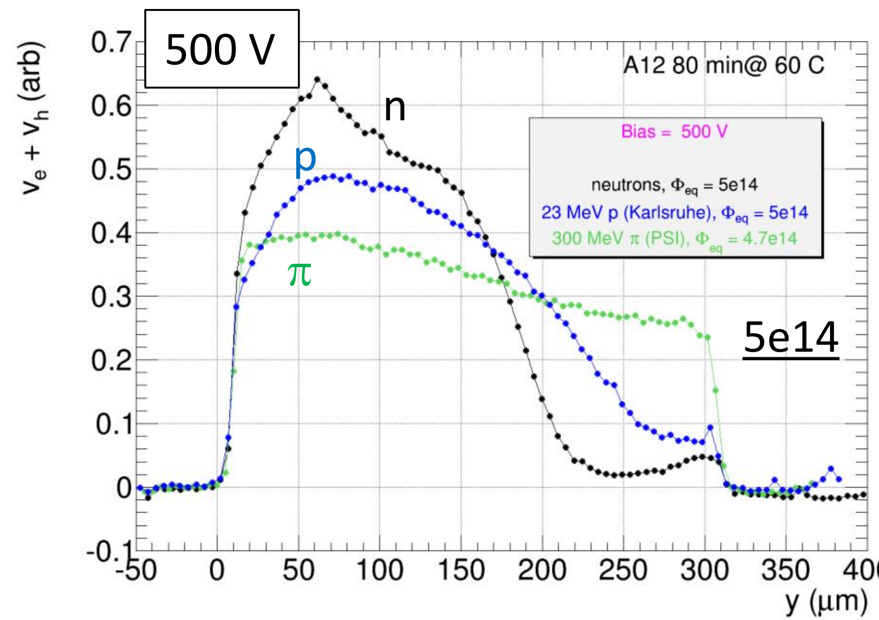


Rad-induced space charge dominating

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

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





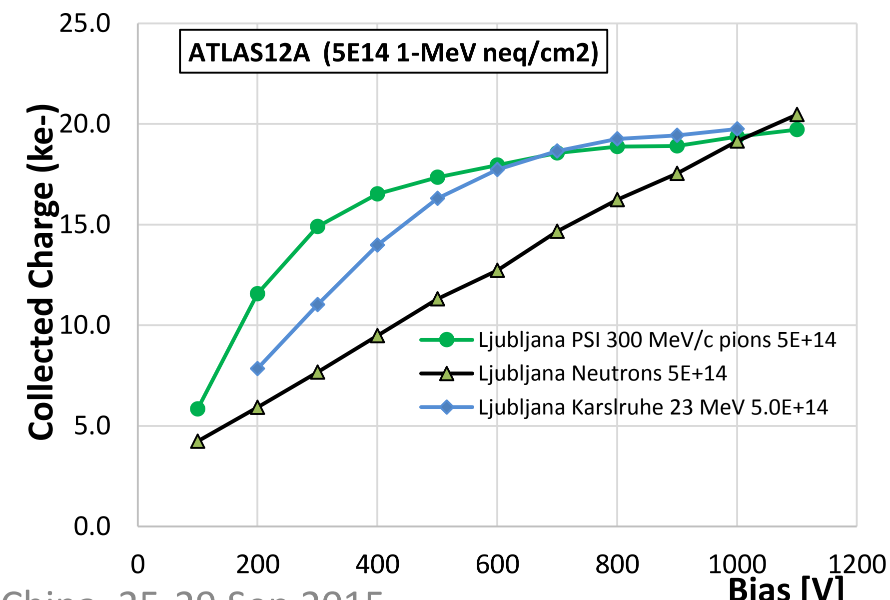
consistent with CCE measurements

→ 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

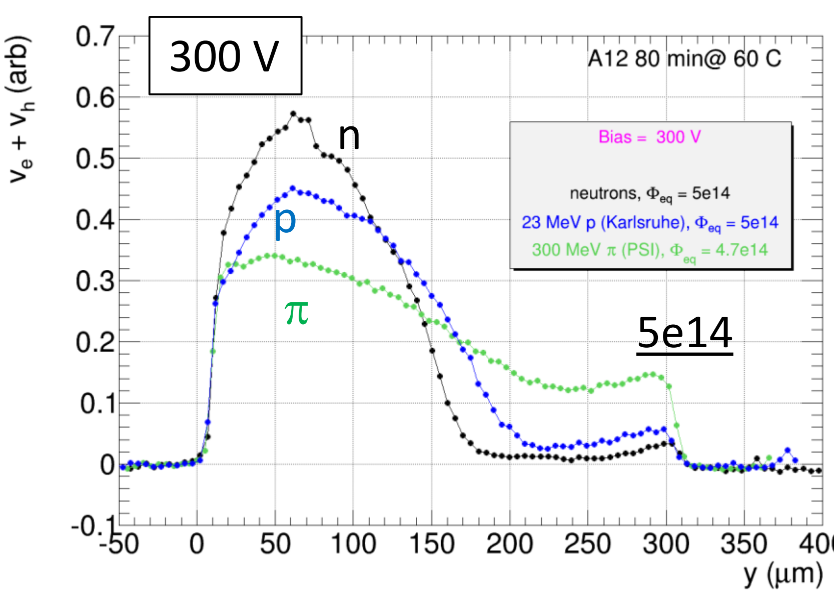
Both dependent on the irradiation particles ($n/p/\pi$)

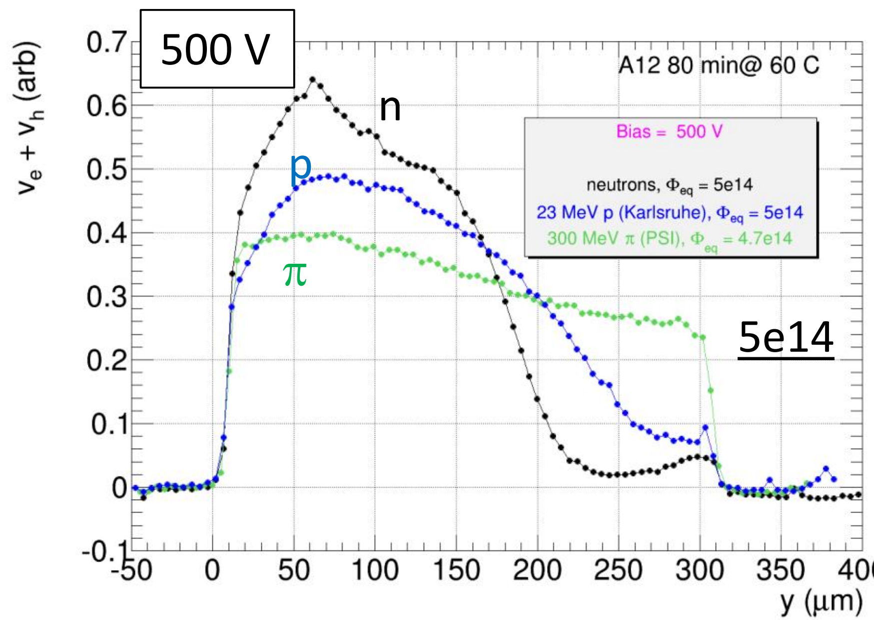
✓Defect introduction rates are more in the order of : $n>p>\pi$

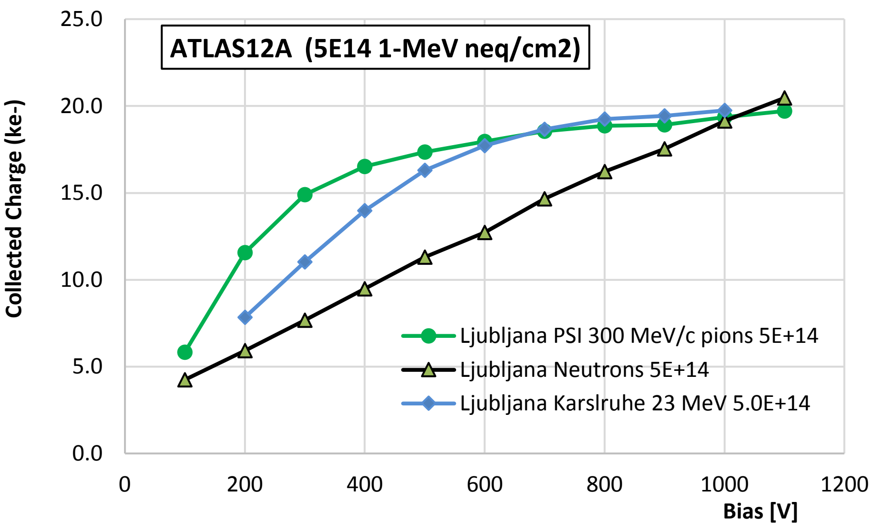
✓Differences in E-filed profile shapes due to double peak E-field:

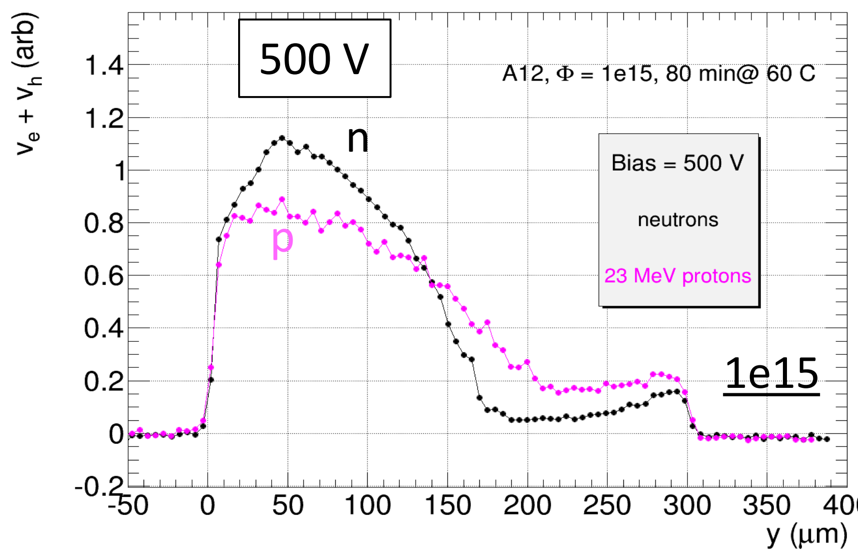
⇒ HPK p-bulk strip sensors are operational at the HL-LHC fluence

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







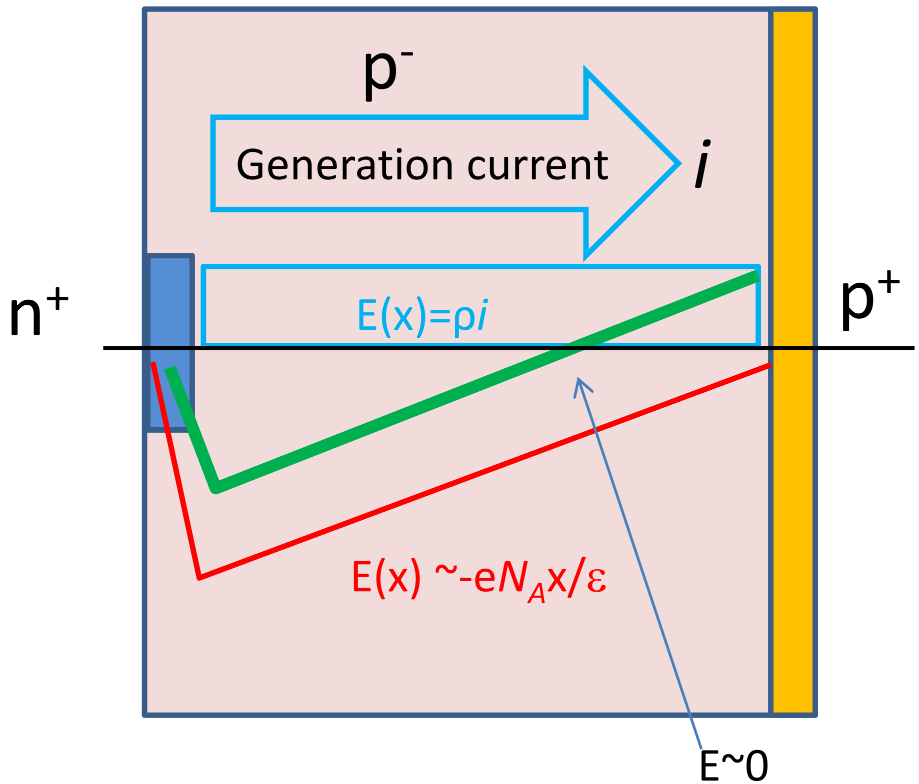


Double Peak E-field   V. Eremin et al. NIMA535 (2004)622.

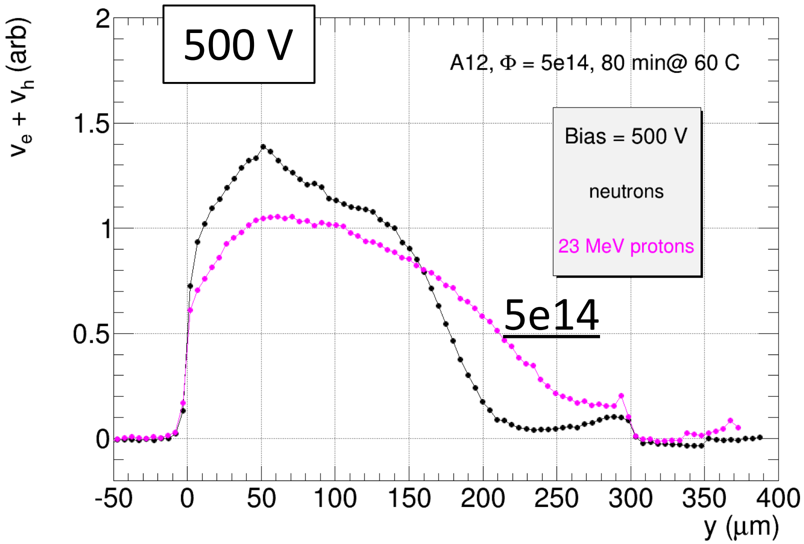
$\rho_{eff} = \rho_{dopants} \sim -eN_A$ … space-charge density

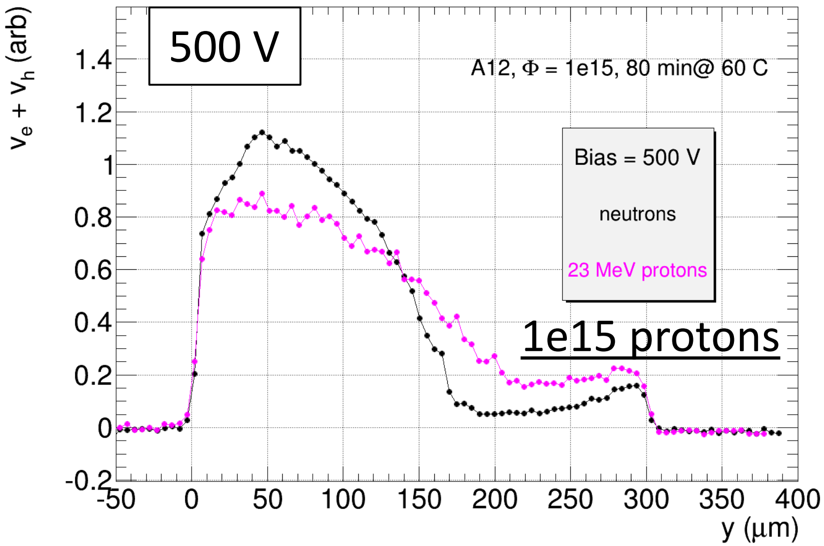
⇨ $\rho_{eff} = e(f_D n_D - f_A n_A) + \rho_{dopants}$

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