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Charge Collection of the ATLAS ITk Prototype Silicon Strip Sensors ATLAS17LS for the HL-LHC

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ATLAS ITk

Fluence in ATLAS ITk @ HL-LHC

The Phase II ATLAS inner tracker (ITk) will be composed of

- PIXEL (5 layers in barrel) and
- STRIP
  - 4 layers of barrel
  - 6 rings each in the endcaps

The strip pitch:

75.5um in barrel

69.9~80.7um in endcap

The strip length:

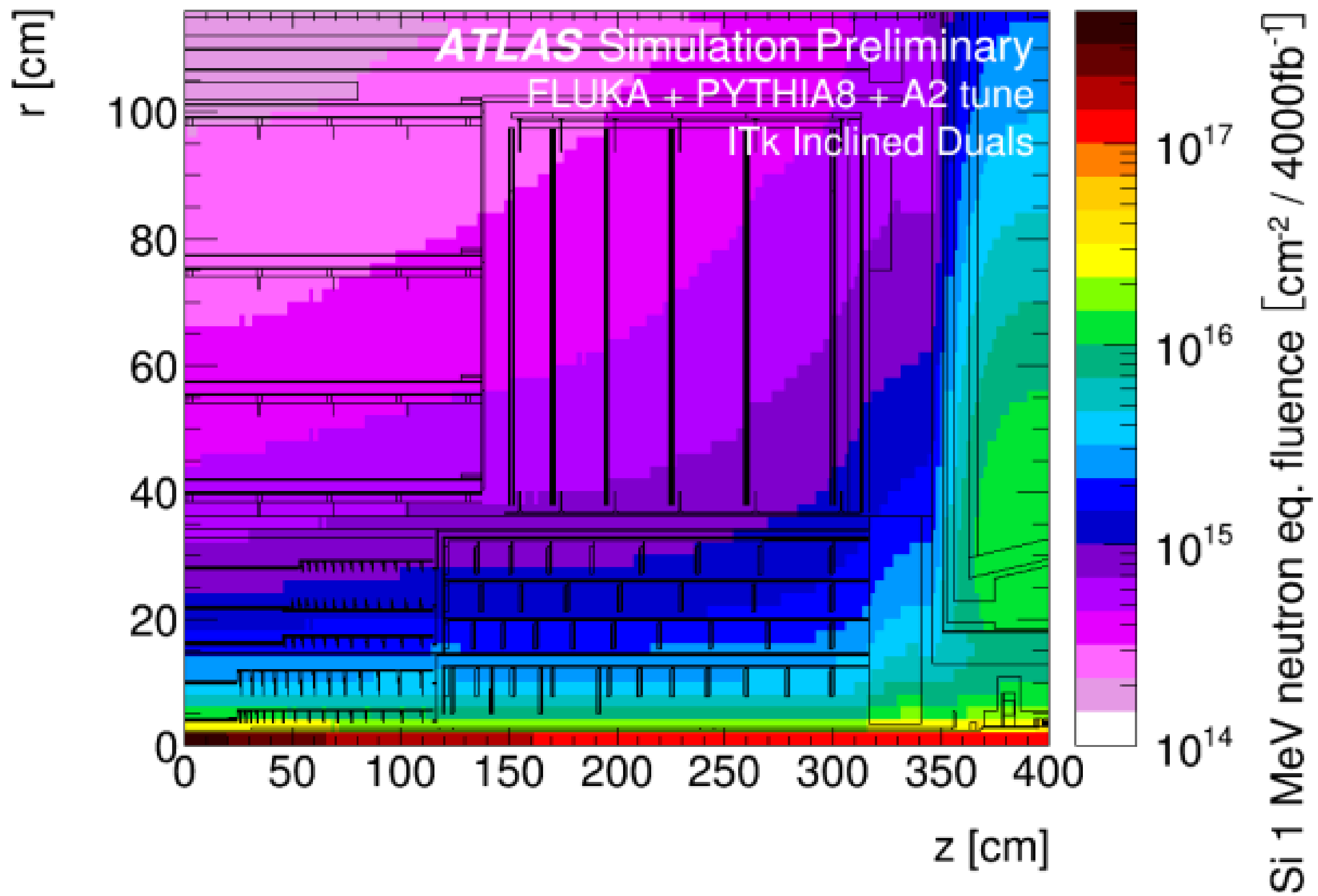
24.1 mm in barrel L0-L1

48.2 mm in barrel L2-L3

18.1~54.6 mm in endcap

to maintain hit occupancy below 1%

ITk **Fluence after 4000/fb**



Maximal fluences: 3.4×10^{14} at barrel L2

6.4×10^{14} at barrel L0

10.6×10^{14} at endcap

We design to keep S/N>10 as precision tracker

N: the detector noise depends on the strip length,

S: charge collection after irradiation

CCE Objectives

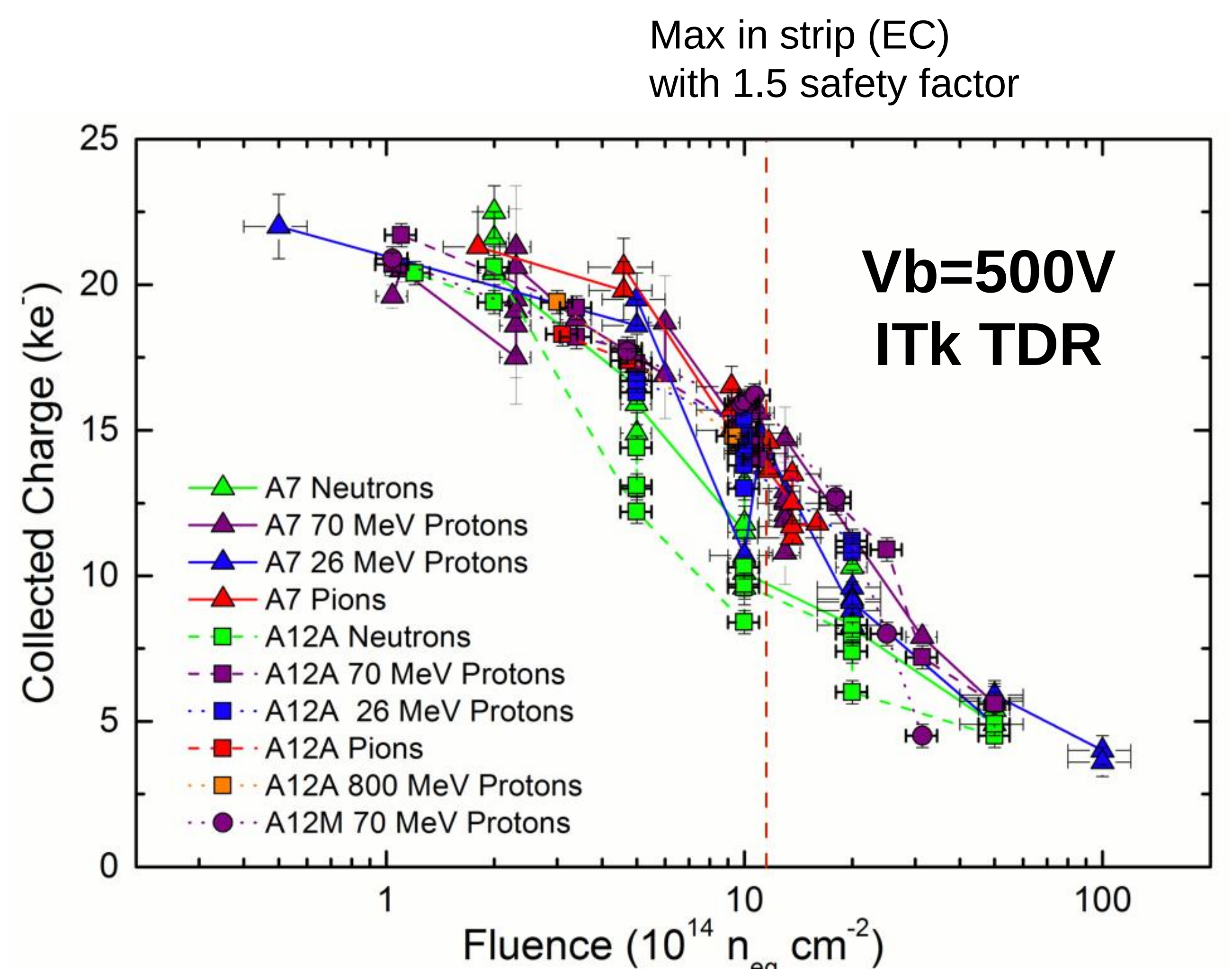
Estimate the Charge Collection of irradiated sensors
- depletion
- degradation due to charge trapping

We tested (irradiated) 1cmx1cm mini samples using penetrating β-rays

Signal read out with LHC compatible fast electronics => Alibava system

Cluster size distribution also provides signal isolation properties

Evaluate if the latest prototype (ATLAS17LS) agrees with the previous study results



ATLAS has evaluated CCE in two major batches (ATLAS07 and ATLAS12, both by HPK)

- **Small difference between protons with 26-800 MeV and pions**
- **Larger damage (by ~30%) by neutrons**

We take neutron damage conservatively to estimate the post irradiation performance

Contents

- Irradiations (fluence, facility)
- CCE measurement with Alibava system
- Proton damage comparison
  - CCE - post annealing comparison PS vs CYRIC-B'ham
  - Active thickness (std and thin)
- CCE (p,n) comparison with previous A12
- Cluster size comparison (p,n)
- CCE of gamma irradiated samples
- Conclusions

Irradiation Campaign

nominal fluence points n_{eq}/cm^2

1×10^{14}	5×10^{14}	1×10^{15}	2×10^{15}	1×10^{16}

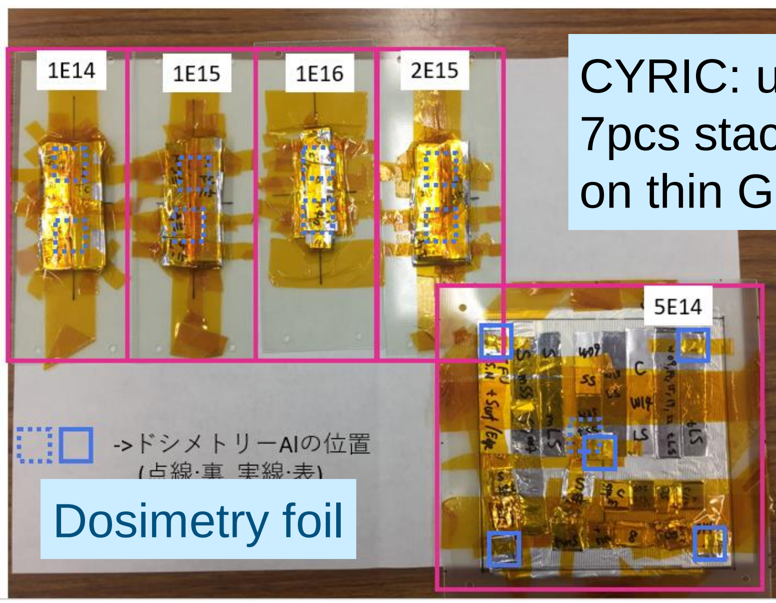
LS($5x10^{14}$) SS ($0.96x10^{15}$) EC($1.6x10^{15}$)
max expected including x1.5 safety factor

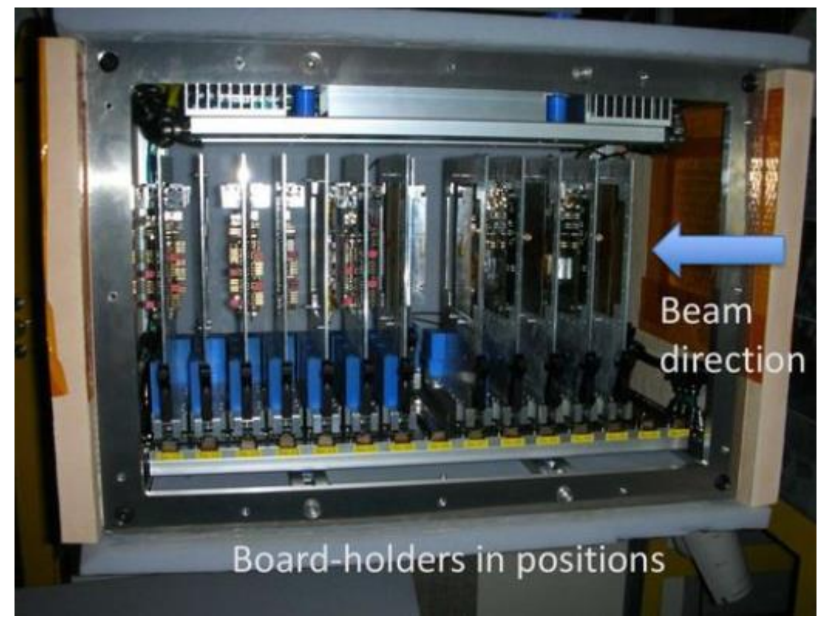
✓ **Proton irradiation***

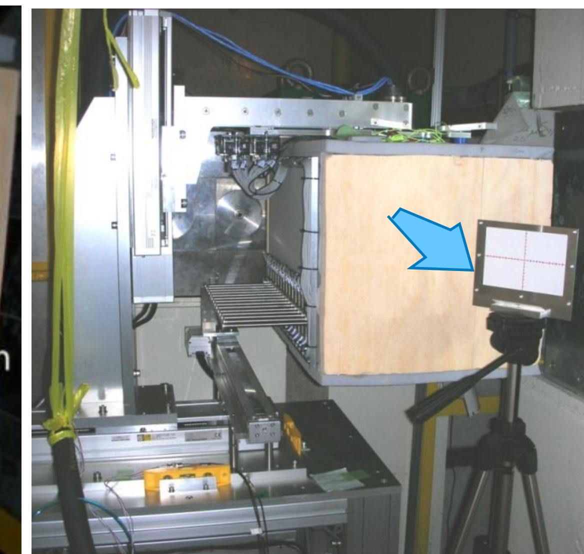
CERN-PS (24GeV, σ～5mm) -20C

CYRIC Tohoku U (70MeV cyclotron, σ～3mm) -15C

Samples were scanned to irradiate uniformly: actual fluences are from Al dosimetry







Thermal box scanned laterally

Birmingham cyclotron: 28 MeV protons (23 MeV at sample), cold box at -30C

Ni foil for dosimetry or Faraday cup current for point-to-point irradiations (more details later)

✓ **Neutron irradiation**

TRIGA reactor in Ljubljana

✓ **Gamma irradiation**

Terabalt, UJP Praha (^{60}Co:Temp<40C, ~14kGy/h)

QST Takasaki (<20kGy/h)

Max dose: 0.29 MGy in barrel
0.44 MGy in endcap

*ionizing dose in proton irradiation is equivalent to or more

much less in neutron irradiation: 10^{15} n/cm^2 ~100Gy

β-ray test with Alibava

ALIBAVA (**A LI**verpool, **BA**rcelona and **VA**lencia) System, development supported by RD50

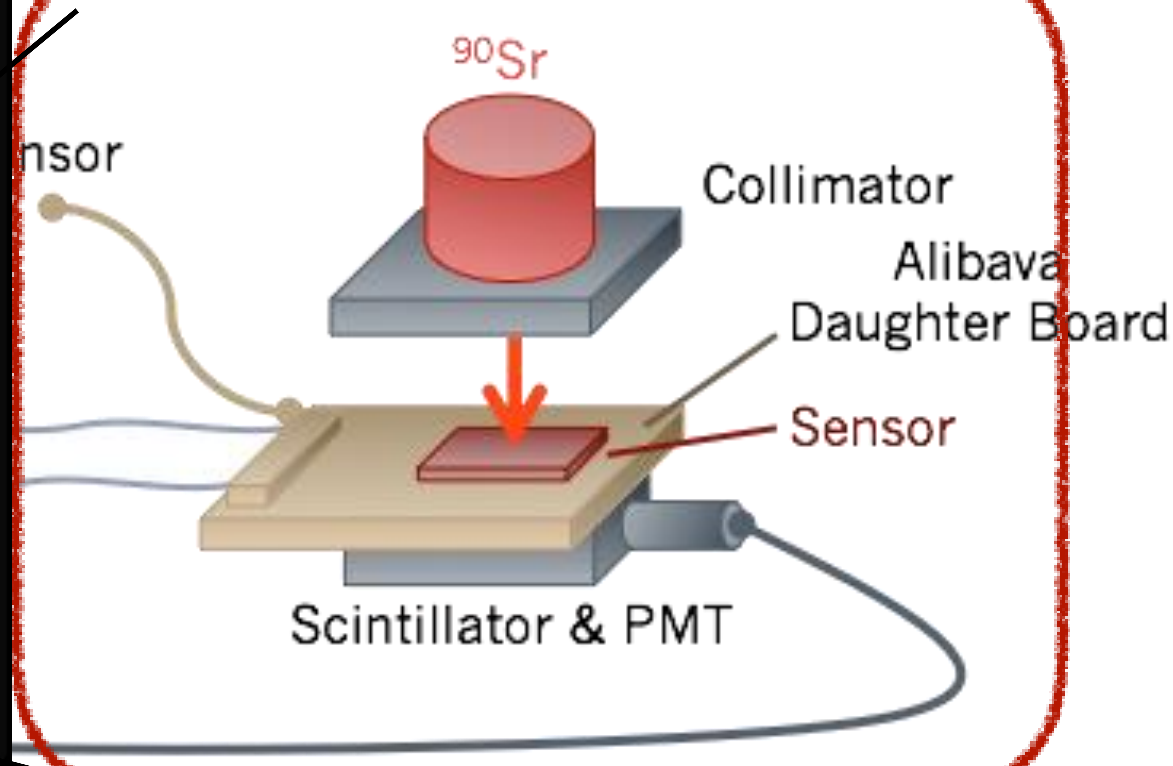
- **Portable evaluation board based on LHC compatible 40MHz analog electronics built around the LHCb Beetle chip.**
- **Signal shaping adjusted to 20ns (see next page)**
- **Signal triggered by penetrating β-rays off ^{90}Sr**
- **Time cut on the asynchronous β-signal using Alibava TDC info (see next page)**

- **MPV (300um active thickness, non-irrad) assumed to be 23ke* for CC calibration**

*H. Bichsel,Rev.Mod.Phys.60–3 (1988)663.

from Alibava homepage

Environm. chamber



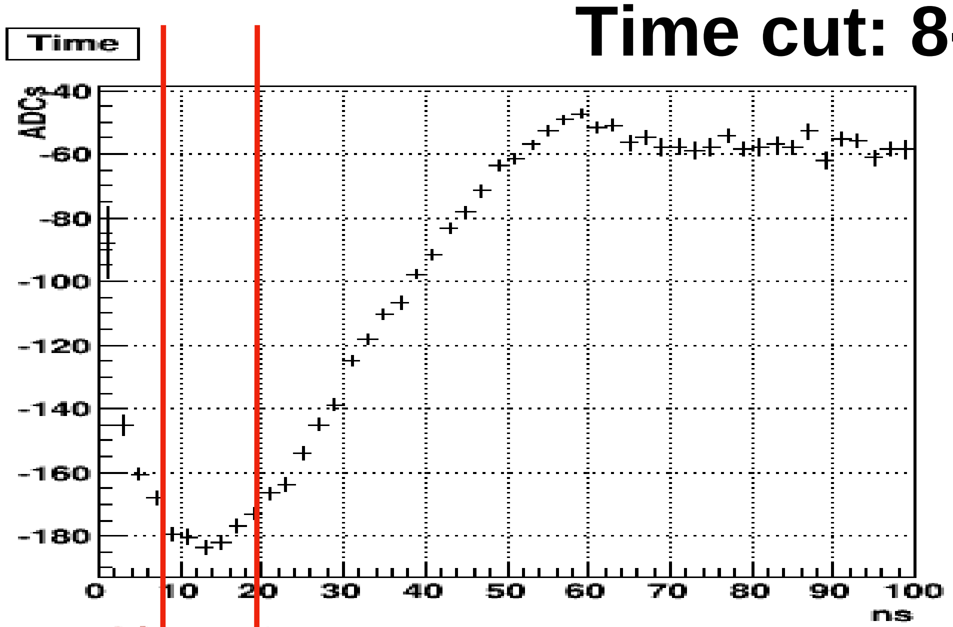
Alibava Raw Data examples

Time profile btw trigger and Alibava clock

Non-irrad. Sample −400V

or peak±5ns

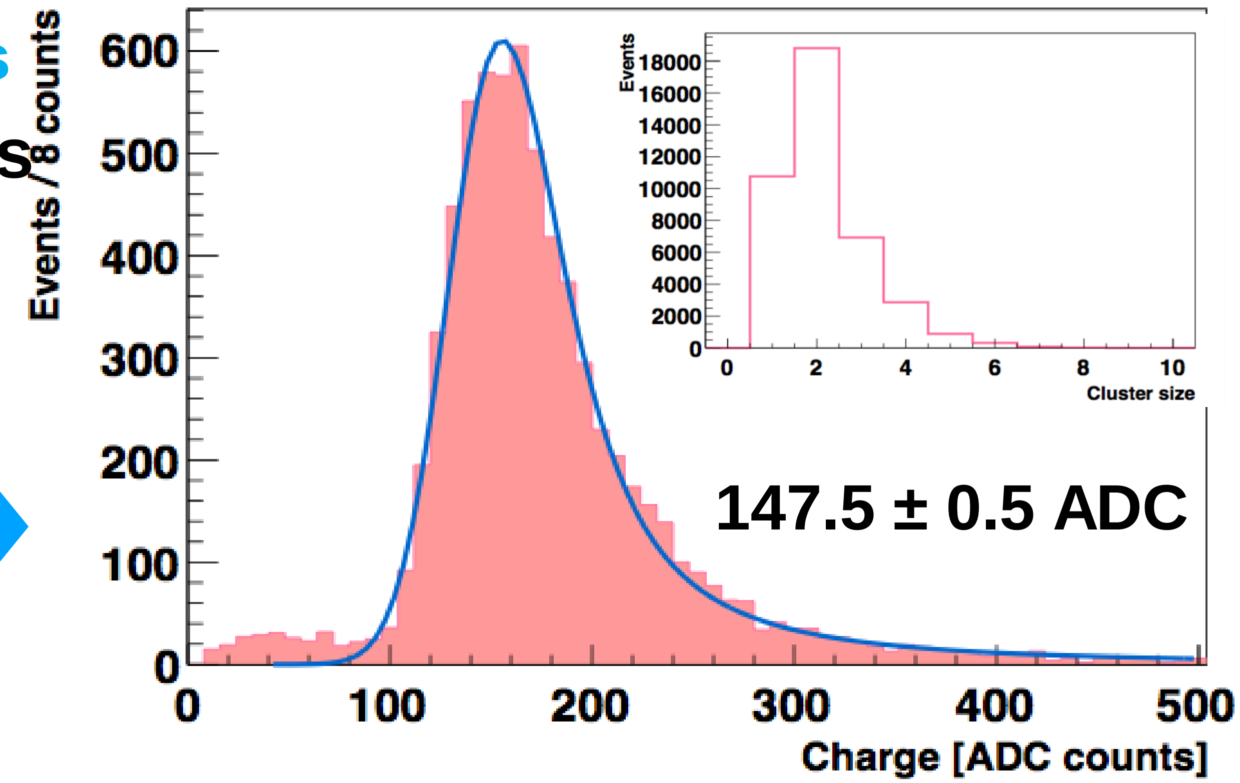
Time cut: 8-20 ns



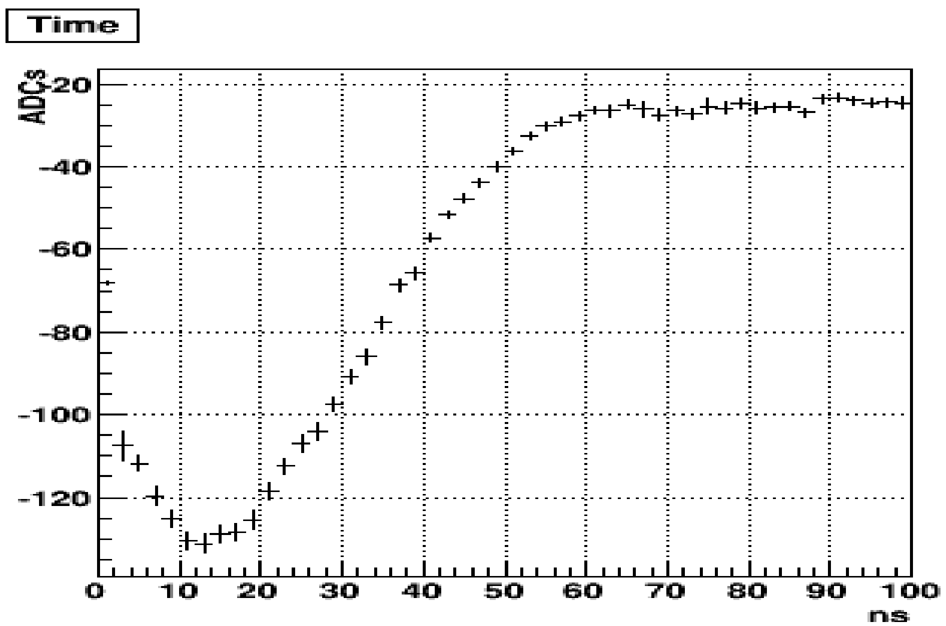
8-20 ns

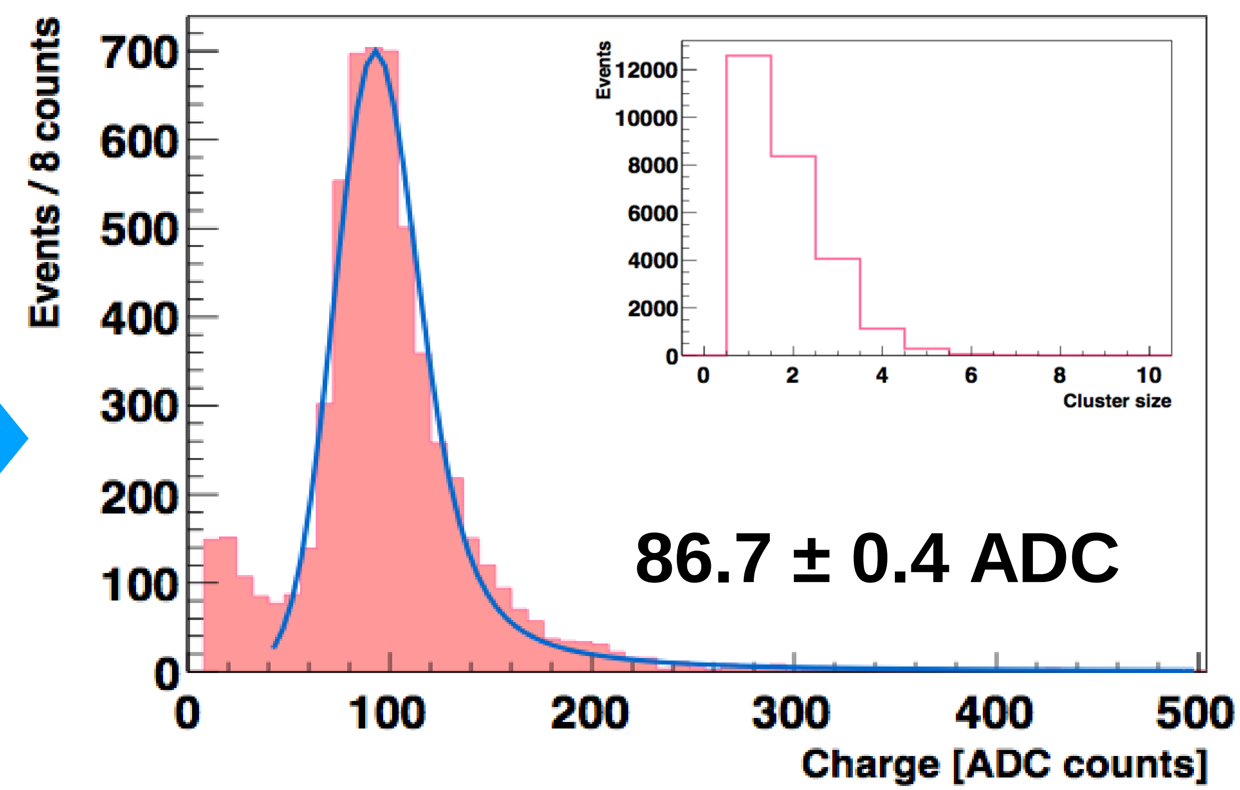
Cluster charge:

Seed > 3.5σ, Neighbor > 1.5σ

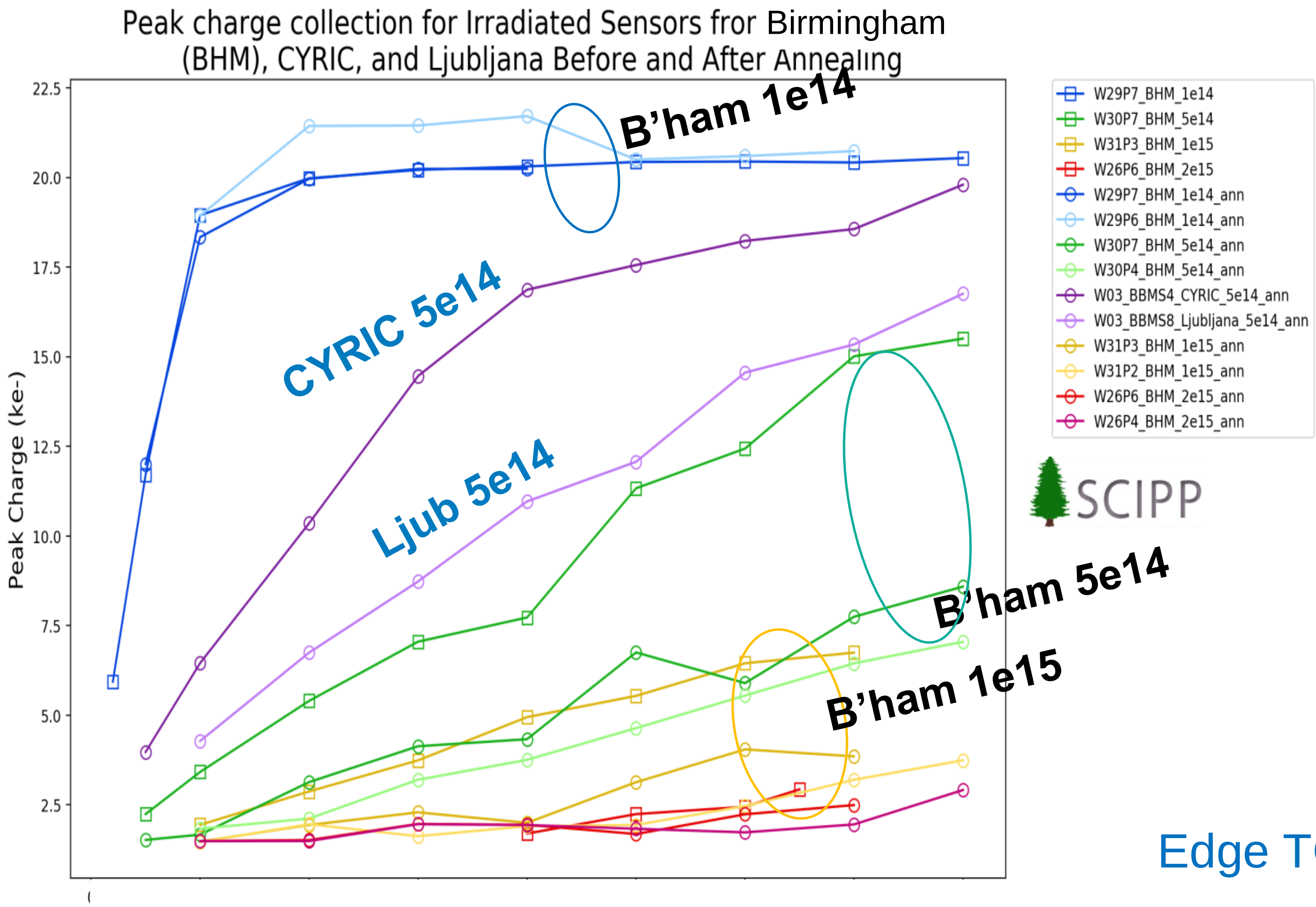


1E15-irrad. Sample −400V





CCE of B'ham campaign data

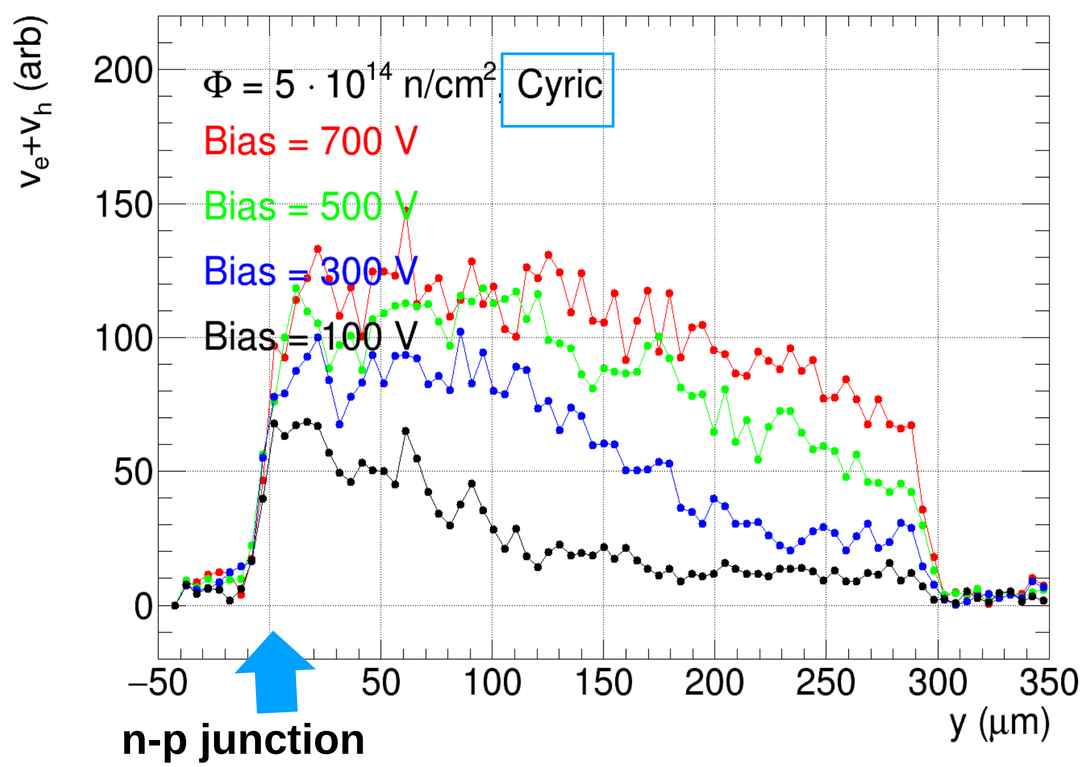


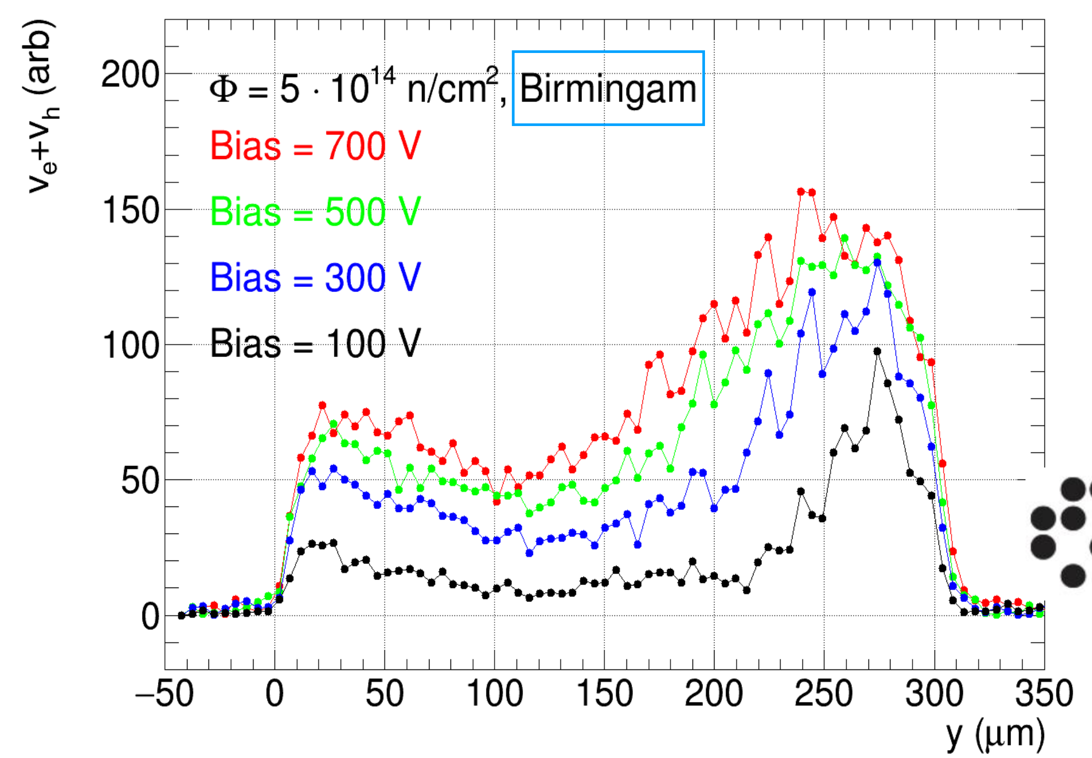
Wide variation of B'ham 5e14 <green> samples
Almost no signal out of B'ham 1e15 <orange>.

Ljubljana (n) and CYRIC (p) show higher CCE compared to those of the same fluence at B'ham. (The n/CYRIC-p difference is consistent with TDR observation)

Suspect some strange component in the B'ham beam (>5e14) as also confirmed by other groups (JSI and Freiburg)

Edge TCT suggests unusual E-field in B'ham sample





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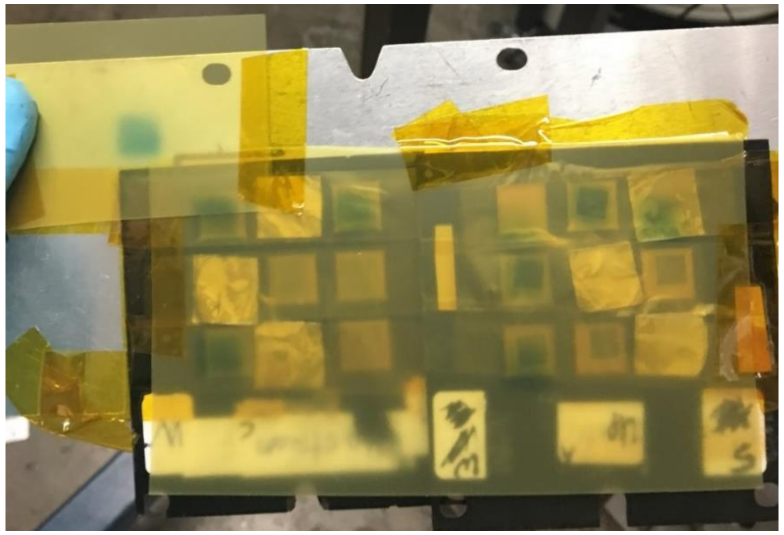
Birmingham Irradiation

Birmingham cyclotron: 28 MeV protons, cold box at -30C

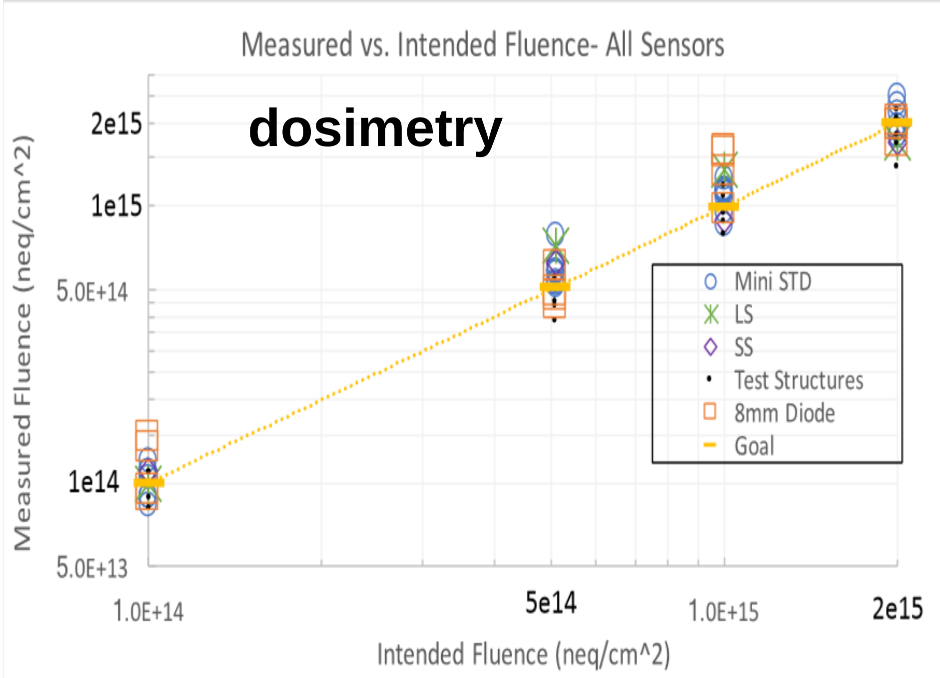
- Nickel foils for dosimetry
- Dosimetry calculated from counts in Faraday cup if no nickel foil (point-to-point irradiations)

at campaign



samples

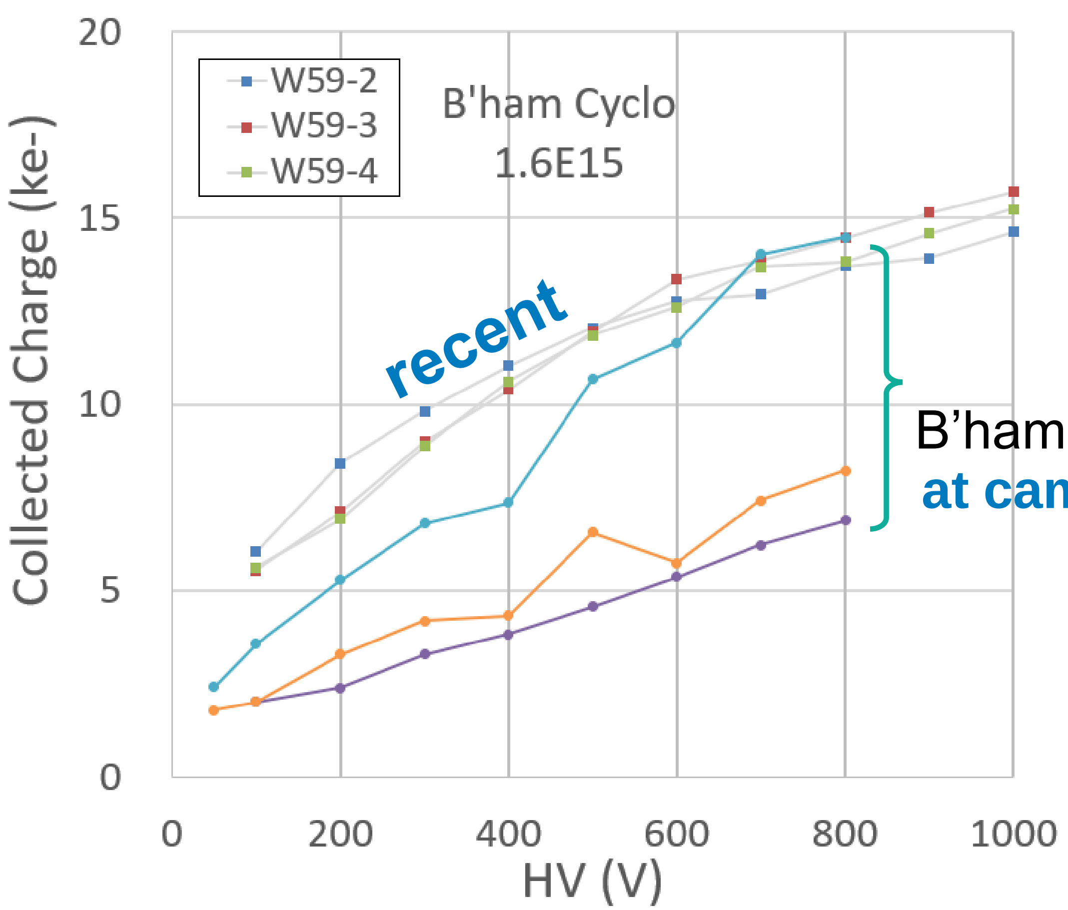
beam masked to 1cmx1cm area



I=100nA

Suspects:

- Heating effect due to point-to-point irradiation
- Change in low-energy contamination due to higher beam energy/steering



recently

Three ATLAS17 mini sensors irradiated to **1.6E15 n_{eq}/cm^2**

– **27 MeV** protons, **400 nA** beam current, **scanning mode**

– Different Al shielding thickness on each sensor: **300, 400, 500 µm**

Consistent CC is obtained

300 µm Al shielding seems enough

Data Compiled

Data compiled for p/n irradiations are:

Put the Birmingham irradiation campaign data aside but include recent data only

UCSC (Birmg'm, Ljubljana, CYRIC-p)

Uni. Freiburg (Birmingham-Cyclo)

University of Tsukuba (CYRIC-p)

IFIC (CERN-PS)

University of Toronto (CERN-PS)

U of Birmingham (B'ham-Cyclo, recent B'ham-Cyclo-p)

JSI-Ljubljana (TRIGA-n)

CCE proton irrad (PS)

CERN-PS (24 GeV protons)

IFIC

- Time cut 10ns
- Seed cut 3.5
- Neighbour 1.8
- Freezer at -25ºC

- Annealing: 60ºC / 80min
- Alibava system
- Beta source: ^{90}Sr

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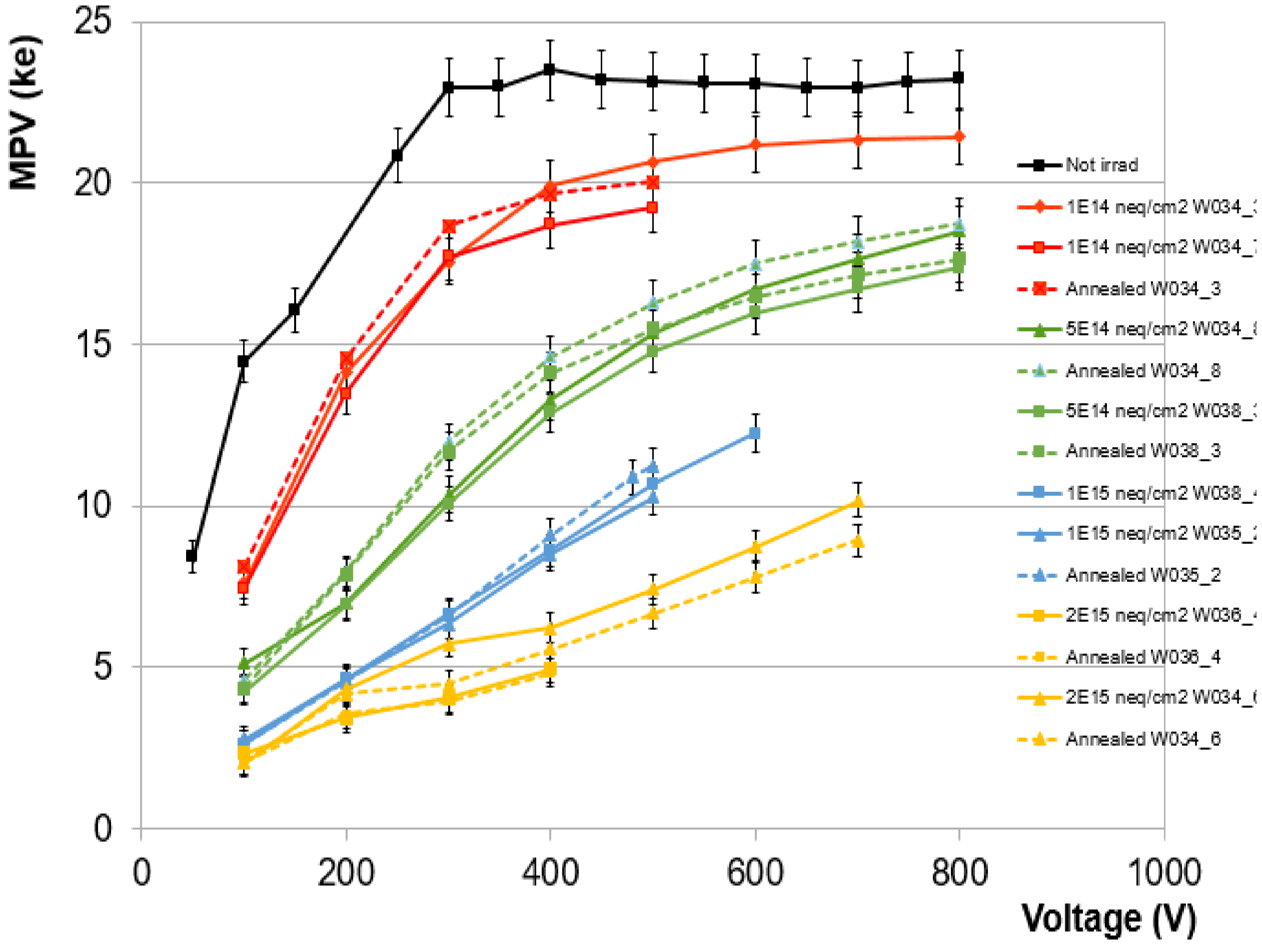
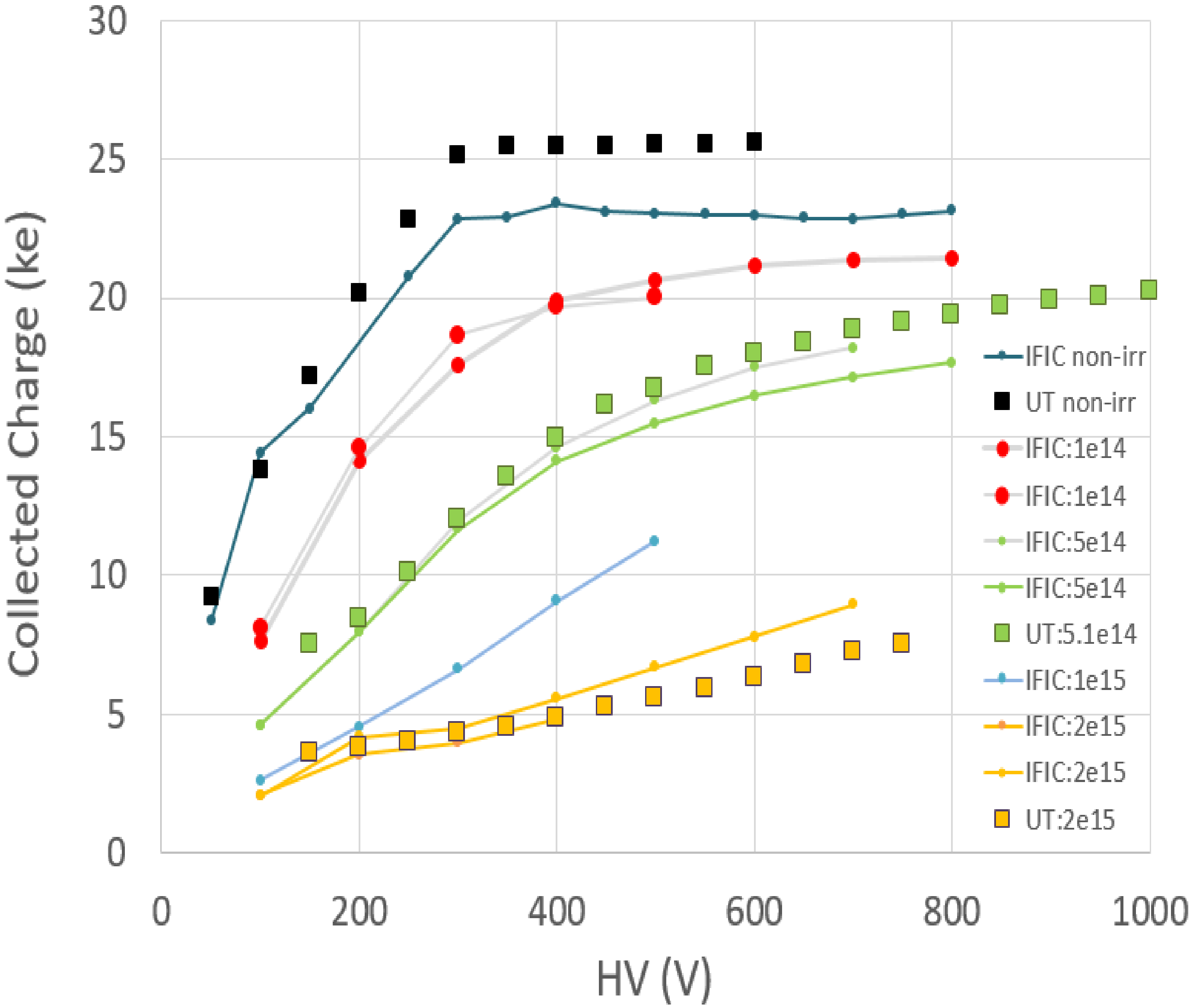
- Time cut 10ns
- Seed cut 3.5
- Neighbour 1.5
- Freezer at -20ºC





Two groups measured CCE of PS samples: good agreement within 10%

CCE proton irrad (PS/CYRIC-B'ham)

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- Annealing: 60ºC / 80min
- Alibava system
- Beta source: ^{90}Sr

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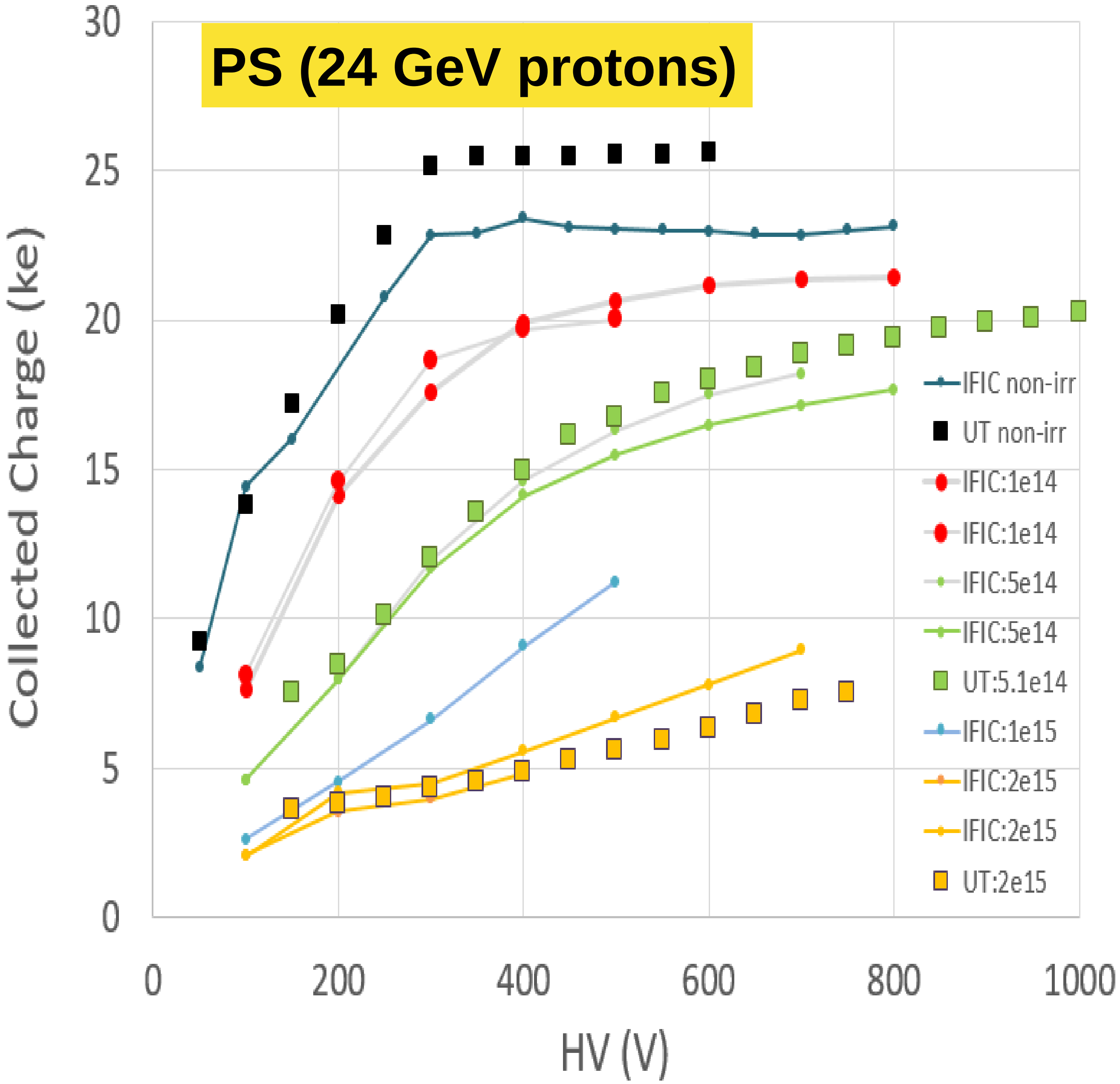
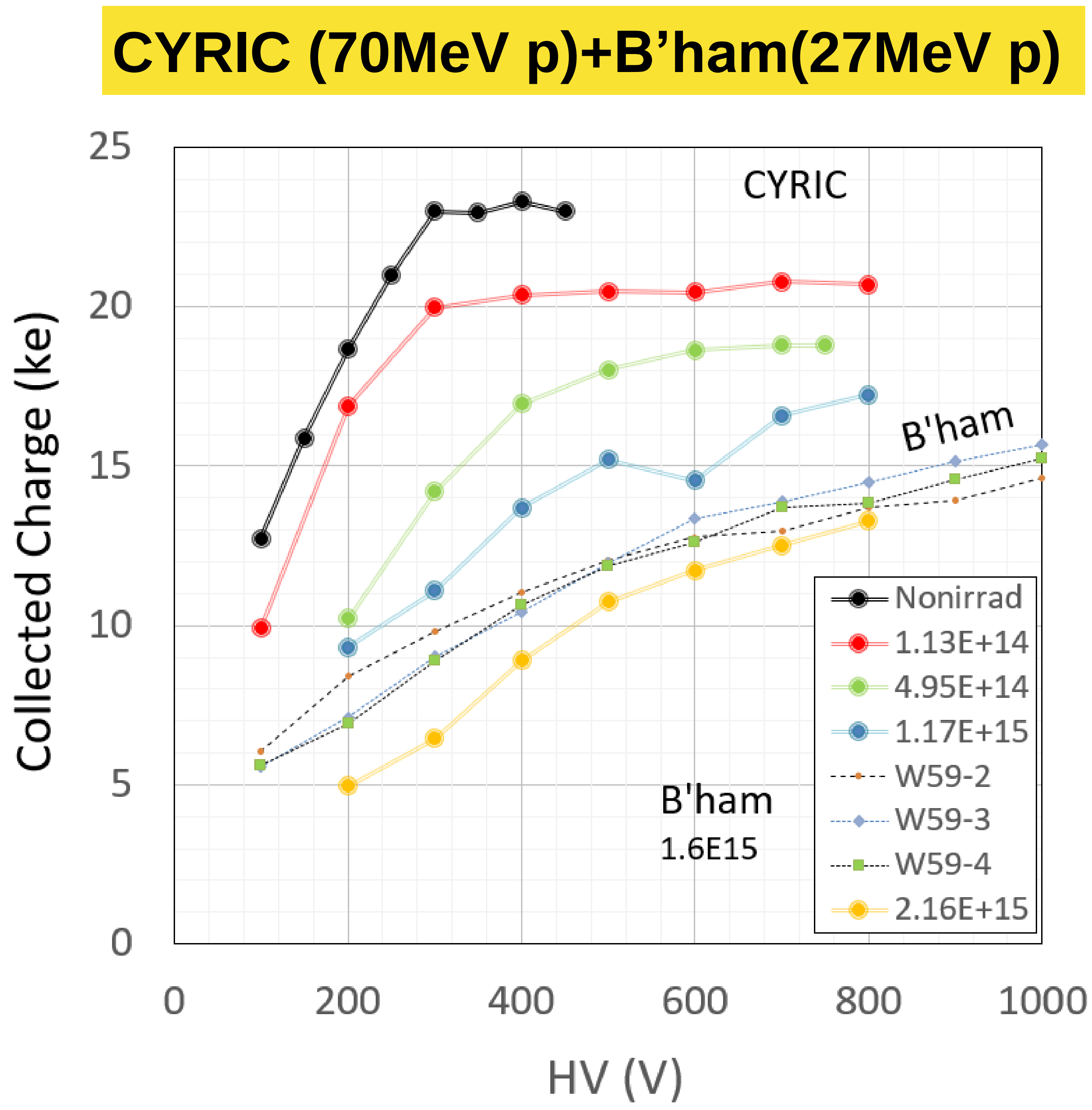
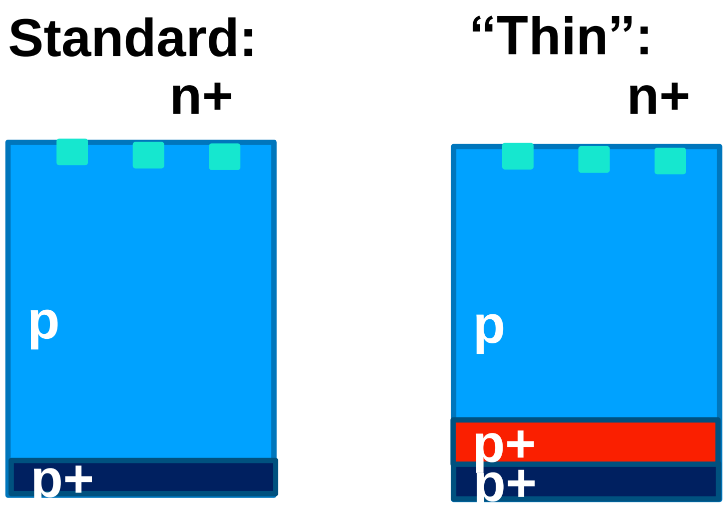
- Time cut 12ns
- Seed cut 3.5
- Neighbour 1.8
- Freezer at -20ºC





PS and CYRIC-B'ham are in agreement in overall – detail comparison comes later

Active thickness (Ljub-neutron)



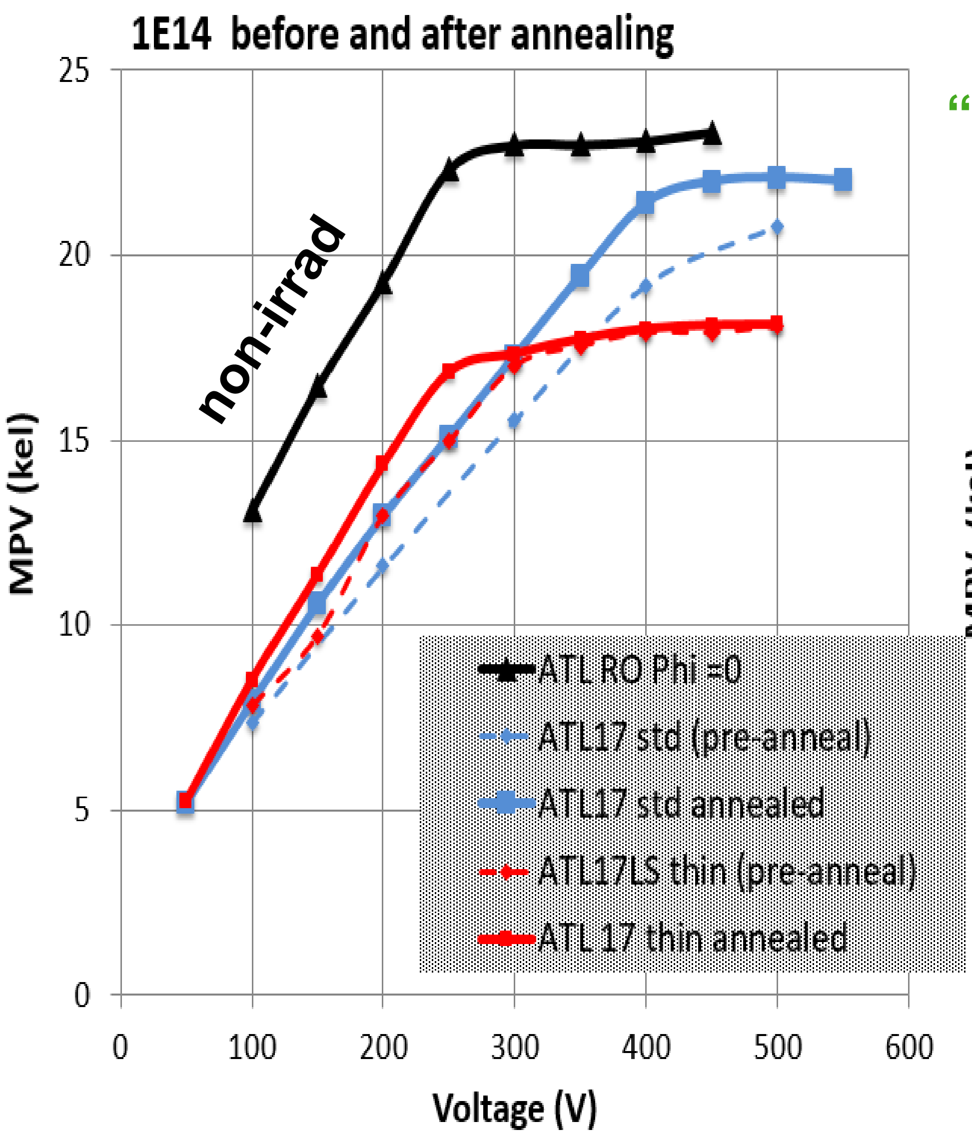
The active thickness variation (>270um in specification) should not deteriorate the performance significantly after irradiation

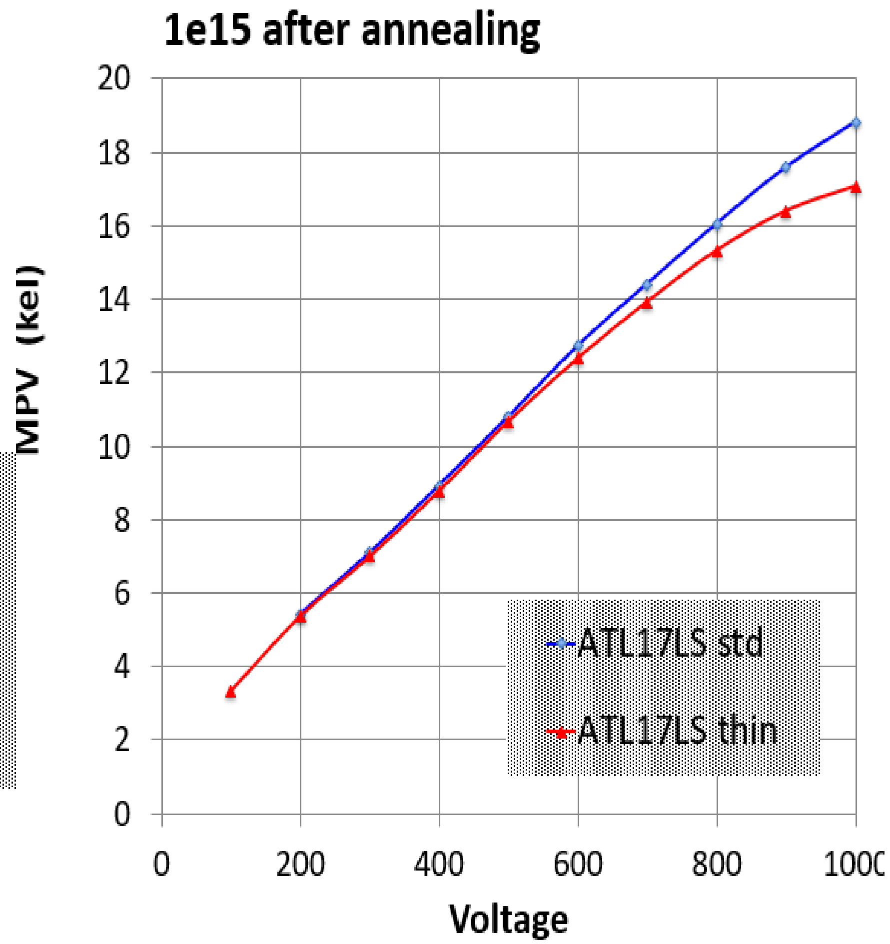
To demonstrate it, we tested sensors with two active thicknesses

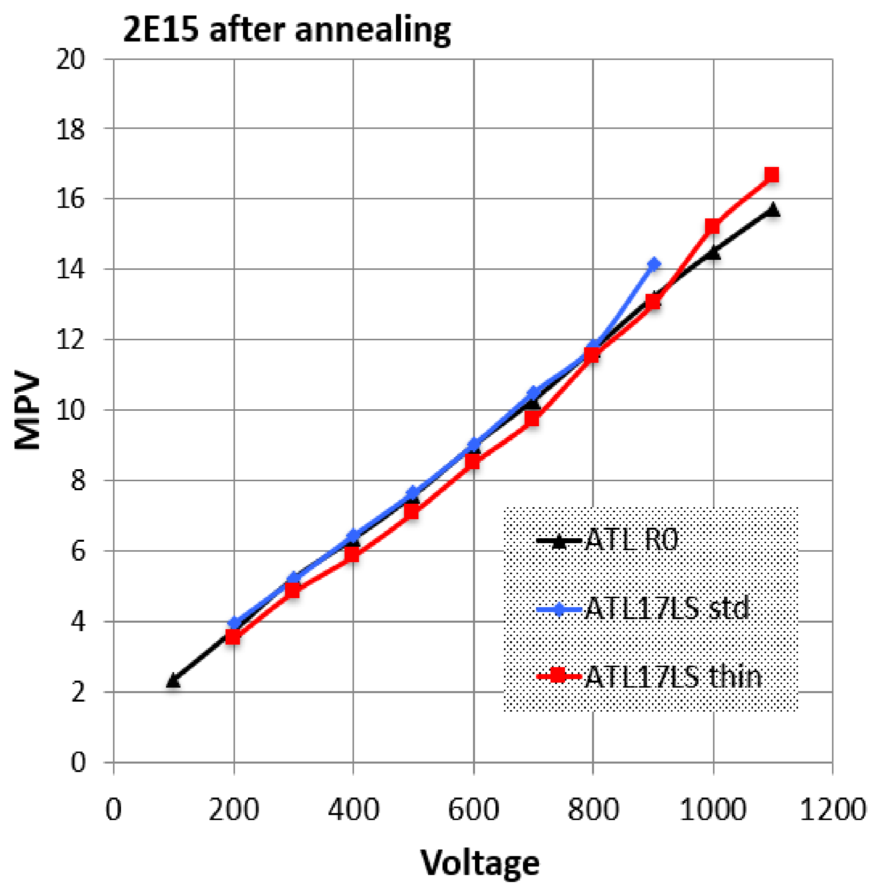
HPK ATLAS17LS:
300 um (std) and 240 um ("thin")

Jožef Stefan Institute Ljubljana, Slovenia

"thin" and standard sensors have very similar signal at high fluence







Active thickness (Edge-TCT n)

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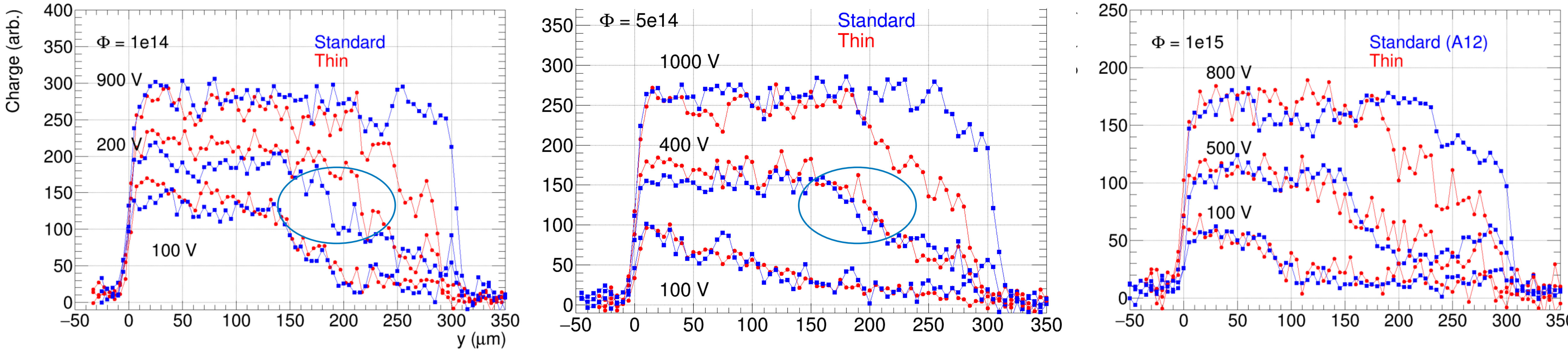
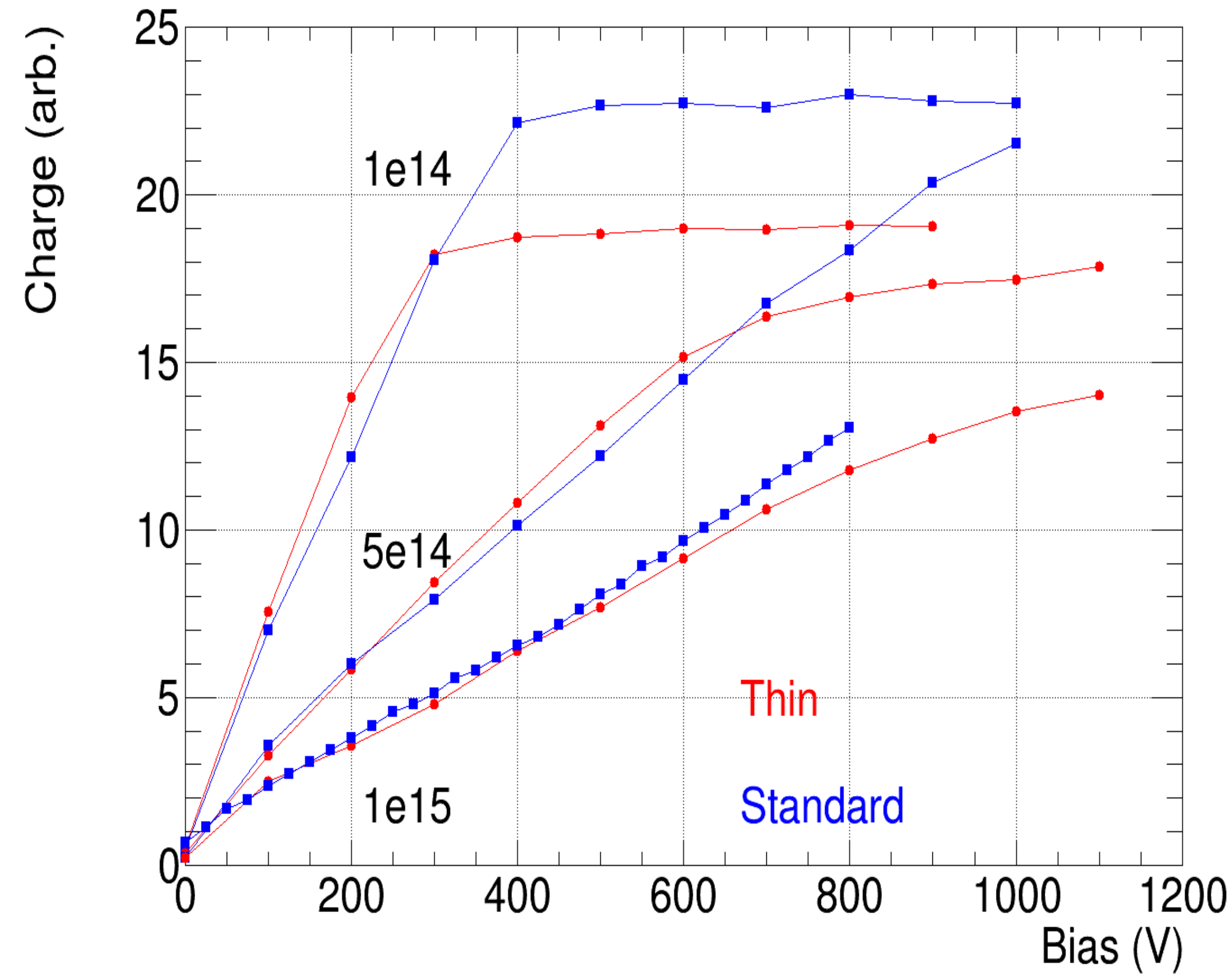
Neutron irradiation



Charge collection as function of depth



Some difference seen at low fluence (1E14) disappears at 5E14 and higher (circled)

although more charge collection possible at higher bias voltages (>800V for 5E14)

"thin" and standard sensors have very similar signal at high fluence

Active thickness (PS proton)

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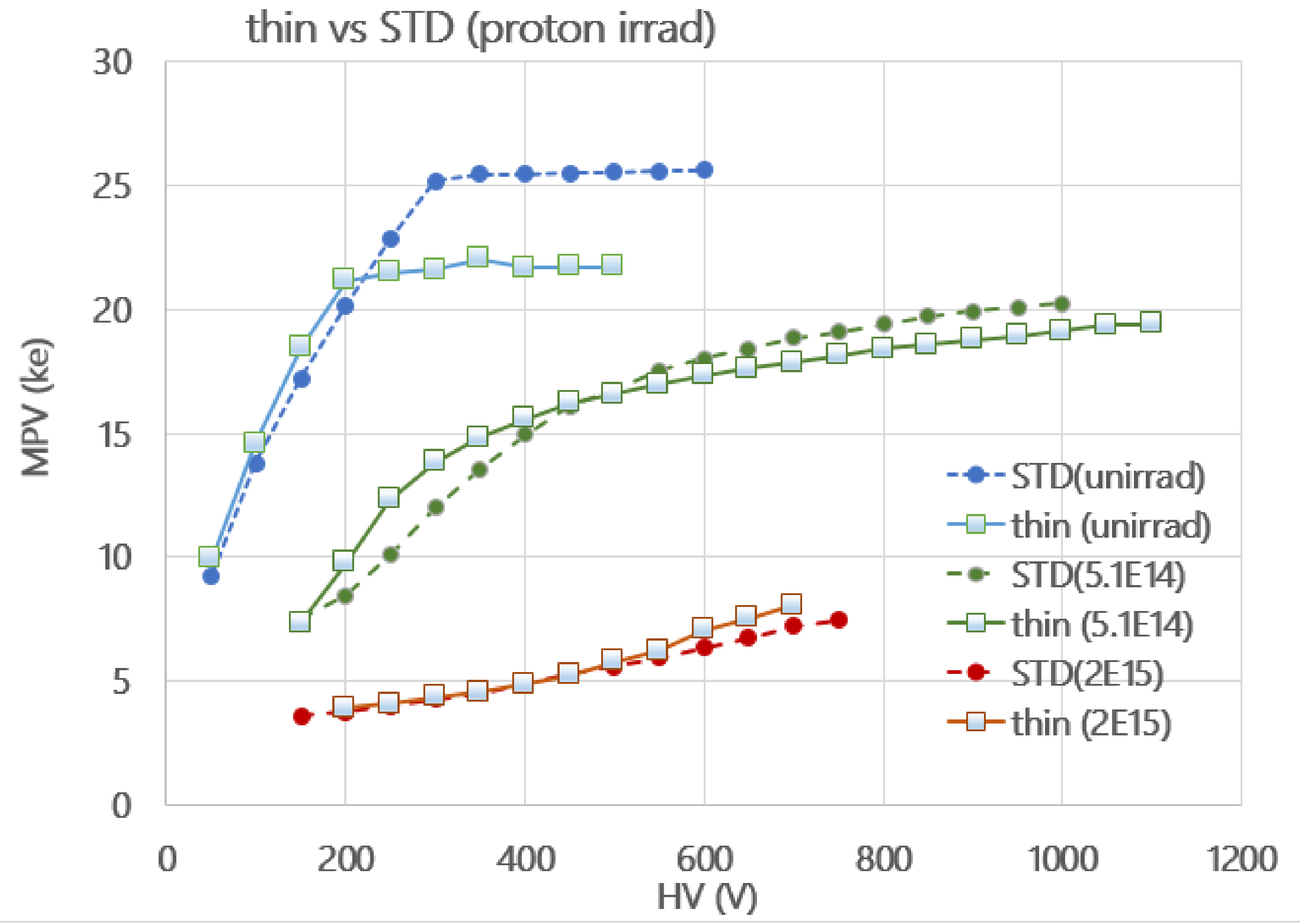
Proton irradiation

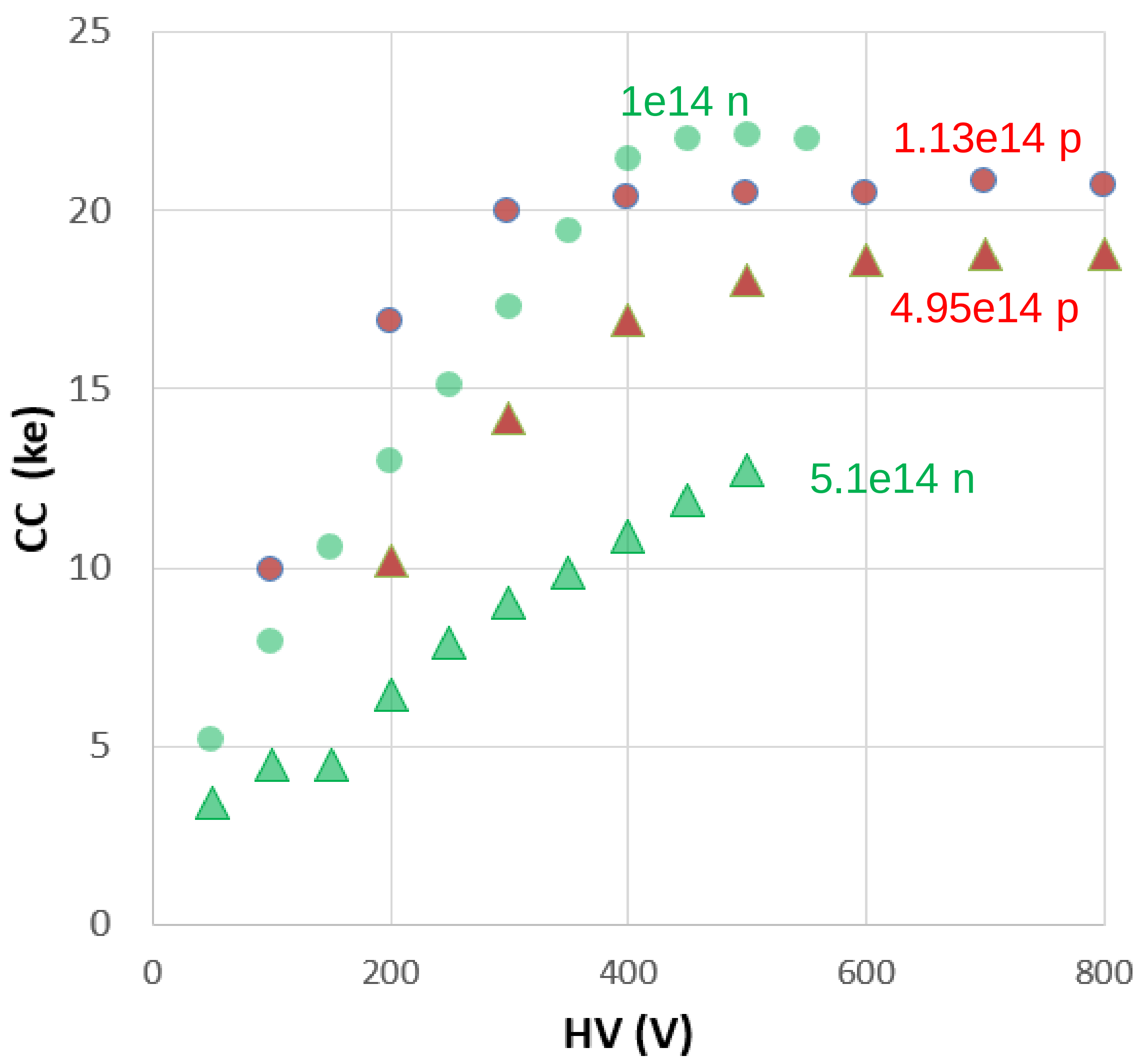
After annealing



"thin" and standard sensors have very similar signal at high fluence

Active thickness specification(>270um) is not crucial
We may prefer physically thin sensors for reducing material and dark current, but further thinning is not practical for time and cost required for large scale sensor production

Proton vs Neutron damage



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Ljubljana neutron

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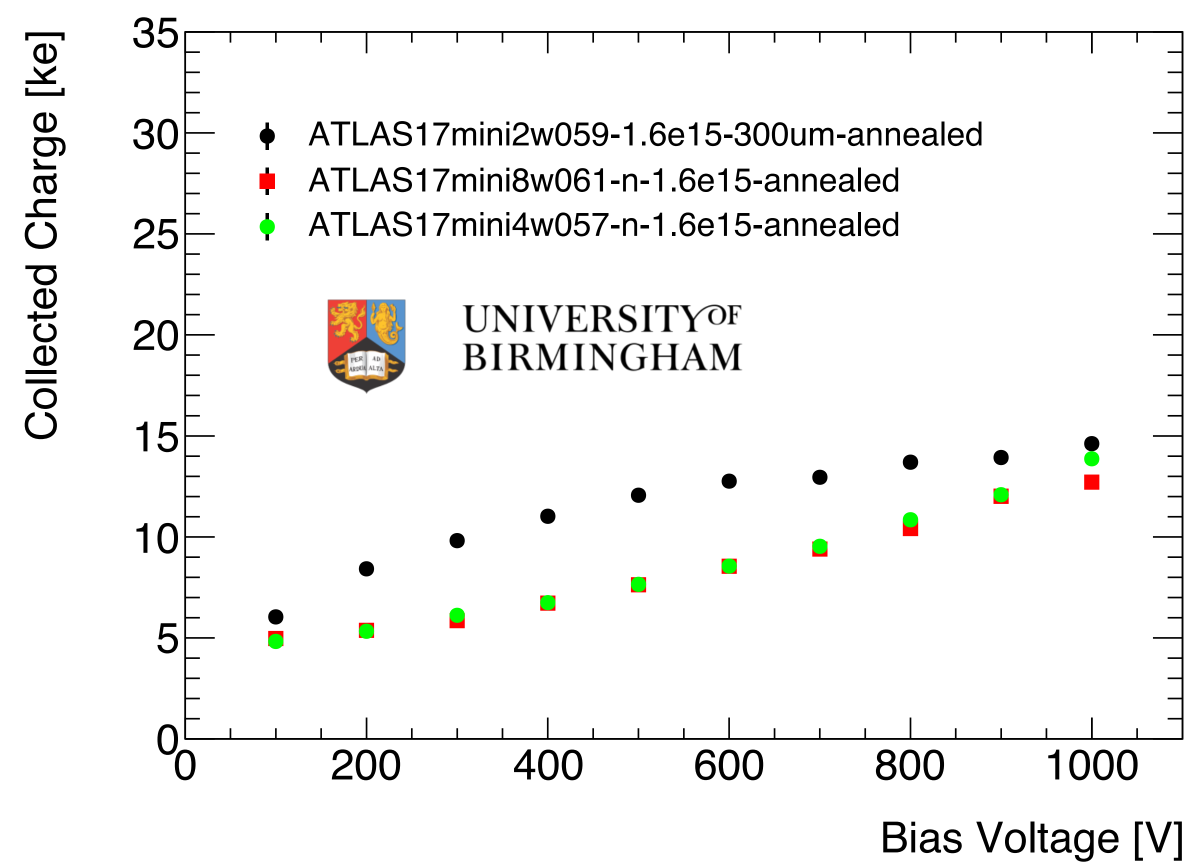
CYRIC proton

CCs of proton and neutron irradiations are not identical. More reduction in neutron samples especially for the fluence >5e14 1-MeV n_{eq}/cm^2.
However, CCE evaluation sites were not same …

Recently @Fluence = 1.6e15 1 MeV n_{eq}/cm^2, CC was measured at UoB for the two irradiations

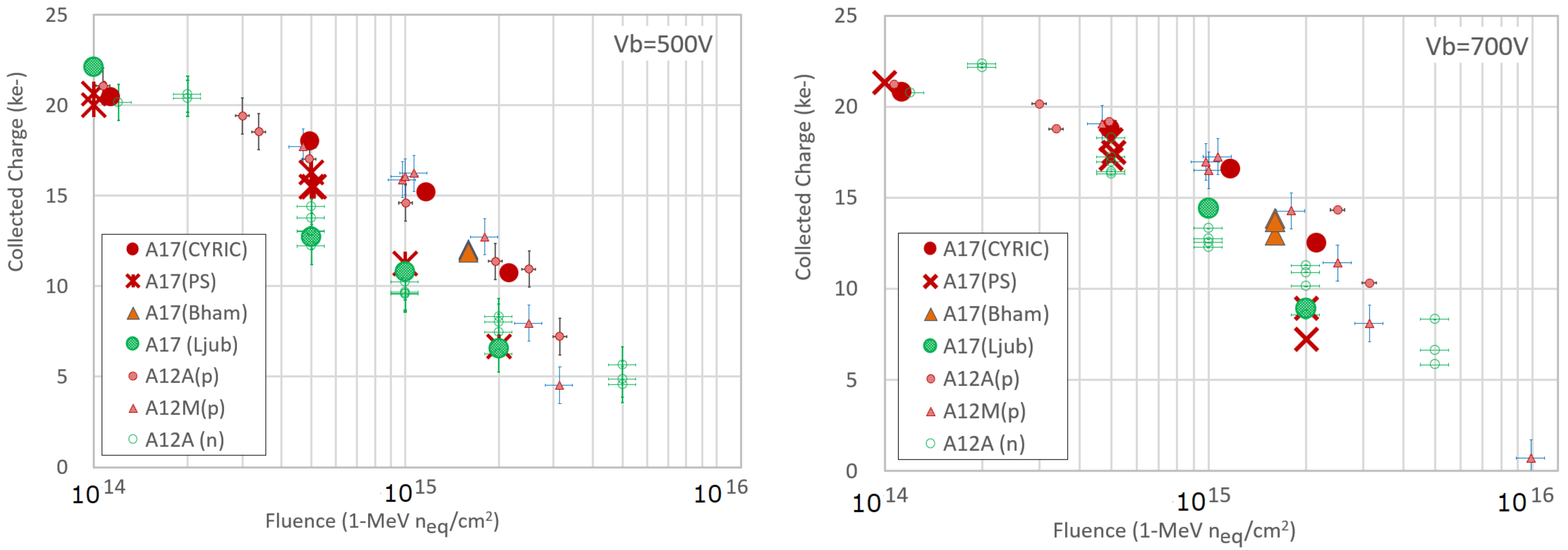


More damage by neutrons as observed for ATL12 => next page

CCE comparison with A12

ATLAS carried out irradiation campaign for previous prototypes ATL12A and ATL12M, reported at HSTD10

CCE at 500V and 700V



A12A/M proton data points are averages of all TDR data with variations represented as uncertainties

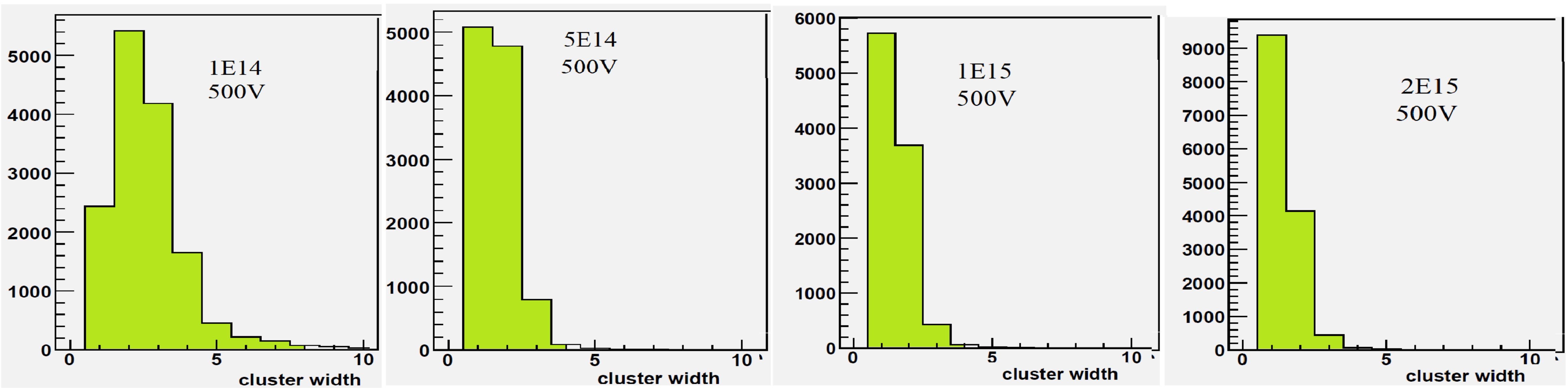
Neutron damages are in good agreement
Proton damages are also in fair agreement (possible deviation for PS(x) >1e15 irradiation)

TDR Post irradiation performance evaluated conservatively from neutron damage is still valid.

ClusterSize n/p irradiation (A17)

Jožef Stefan Institute
Ljubljana, Slovenia

Ljubljana-n **A17LS sensors** ▸ **neighbor/seed=1.5/3.5**



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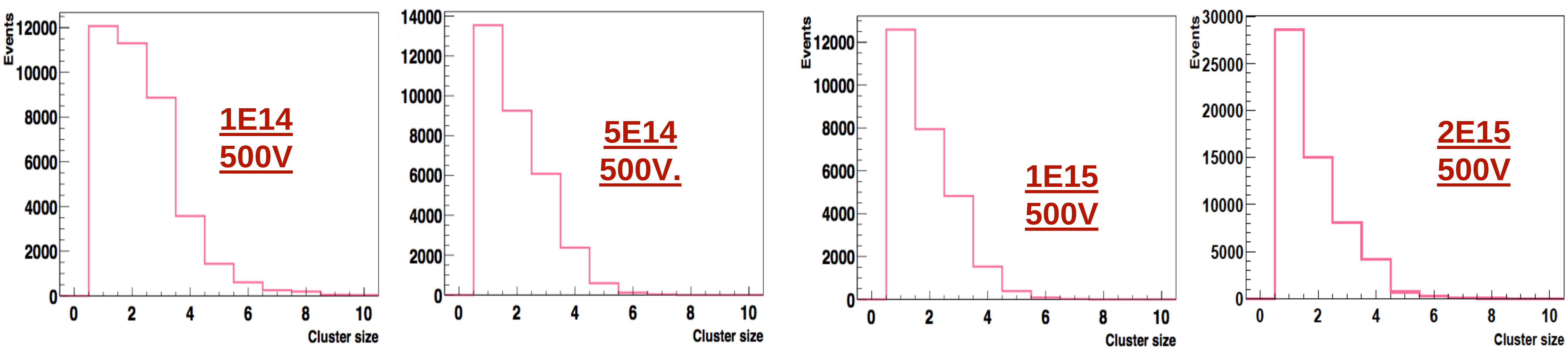
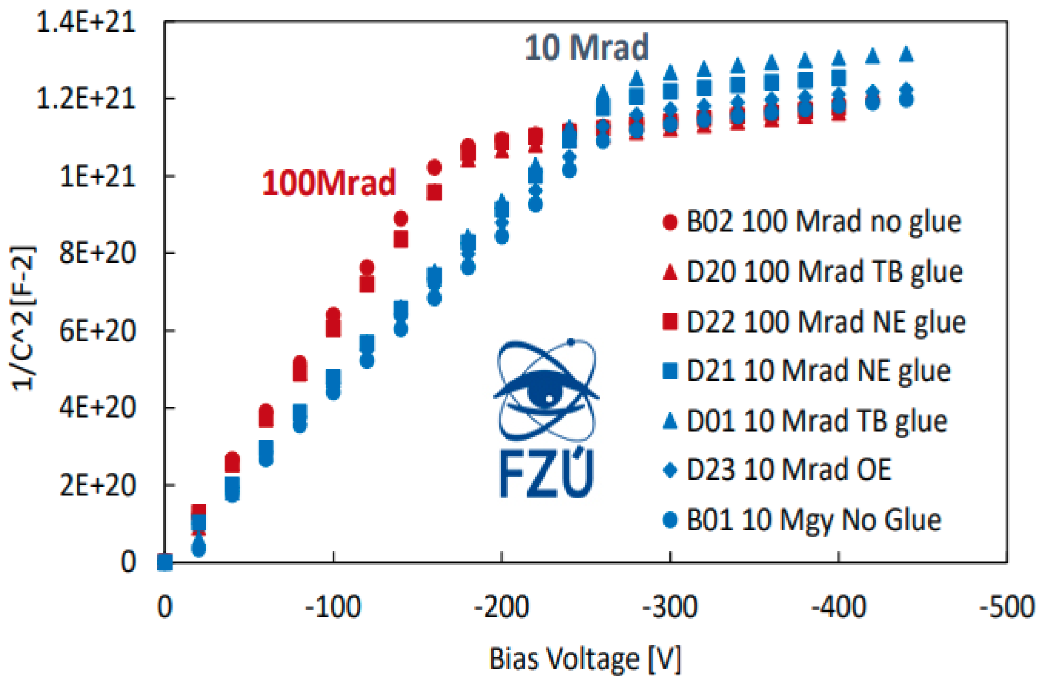
CYRIC-p ▸ **neighbor/seed=1.5/3.5**



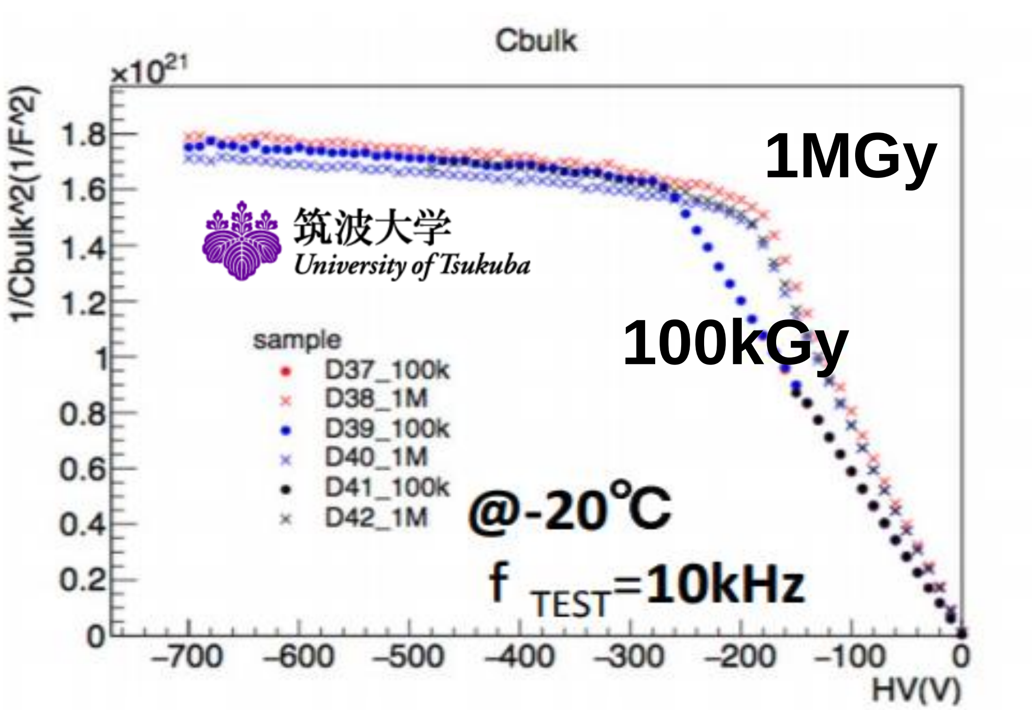
Smaller clustersize for n is as expected from more damage in CCE
Precise comparison requires understanding of collimation: distributions are reasonable

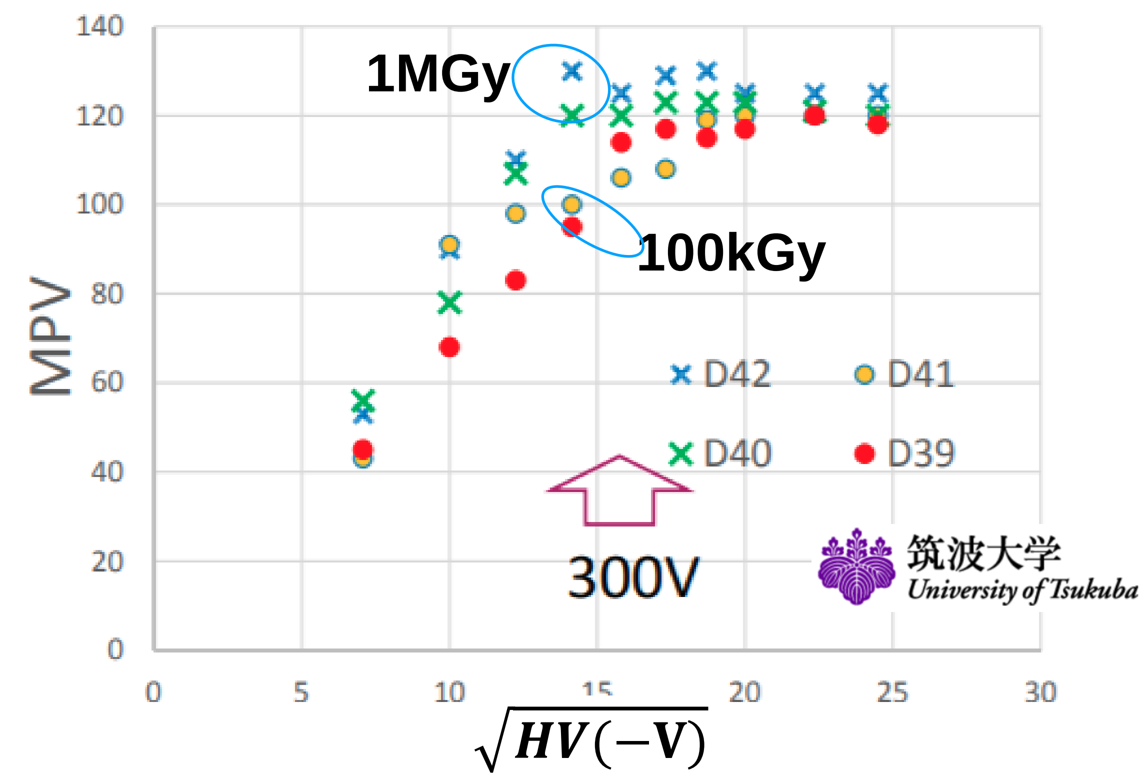
Gamma irradiation

Still a lack of studies of gamma irradiated high resistivity p-type silicon sensors
Decrease in FDV and N_{eff} was observed in n-in-p sensors (ATL12) irradiated by ^{60}Co up to 1 MGy



- Initial FDV ≈ -350 V
- From CV: 100 kGy FDV ≈ -260 V … 26% decr.
  1 MGyr FDV ≈ -170 V … 51% decr.
- From CC: 100 kGy FDV ≈ -250V
  1 MGy FDV ≈ -200V





Displacement damage caused by ^{60}Co gammas is primarily due to Compton electrons having a max energy of 1.2 MeV. Cluster production is not possible – mini.required~8 MeV

Damage mechanism is different from damage caused by hadrons

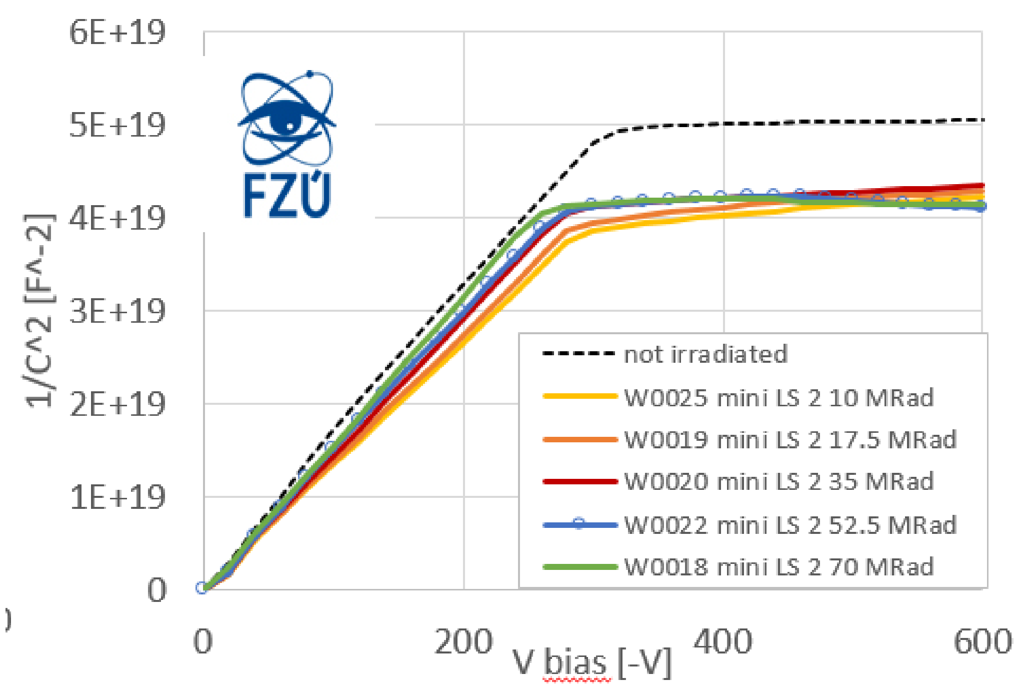
Gamma irradiation (A17LS)

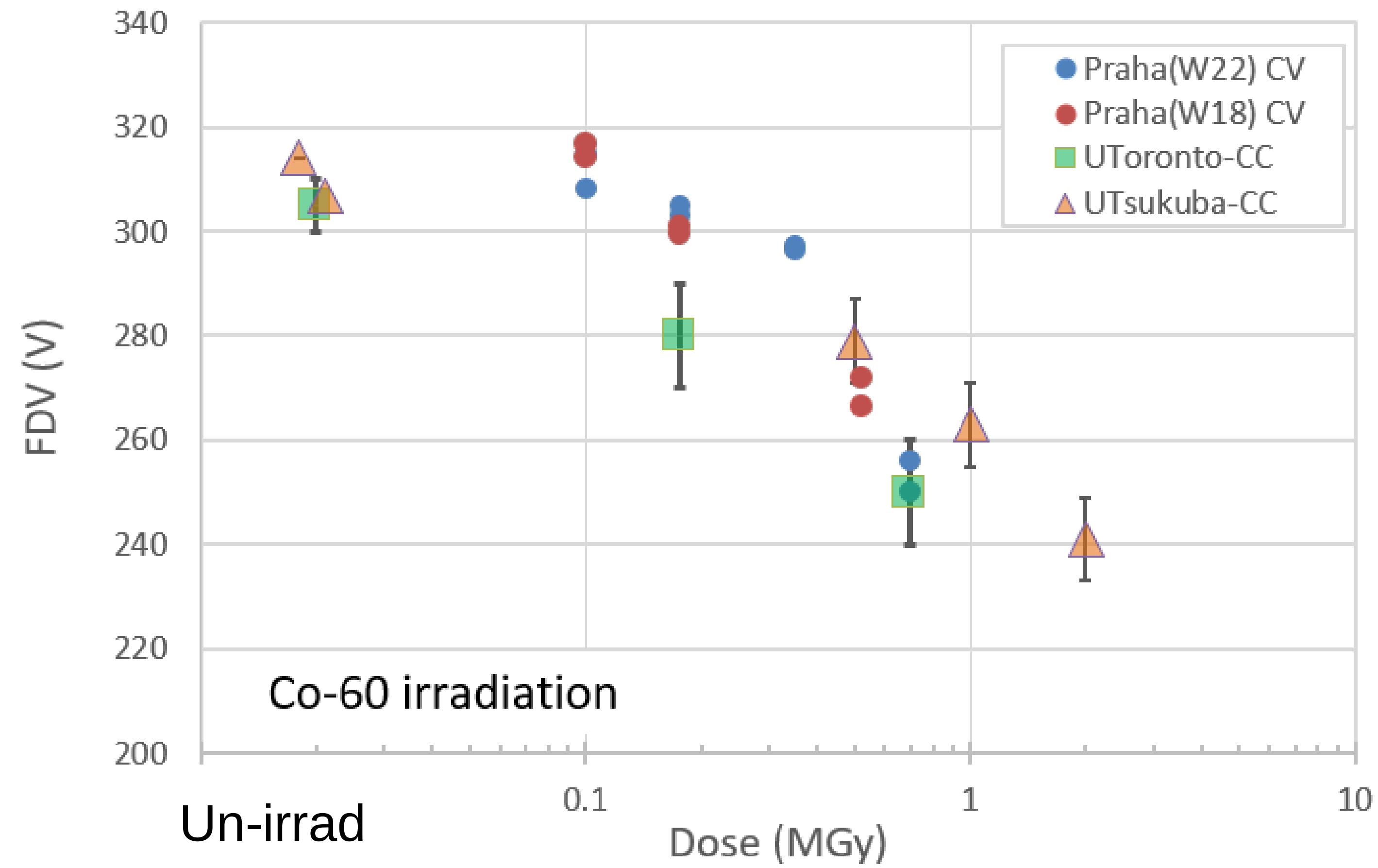
Non-irradiated sensors
- **Same slope of $1/C^2$ => uniform N_{eff}**
- **Full depletion voltage -302 ± 4 V**

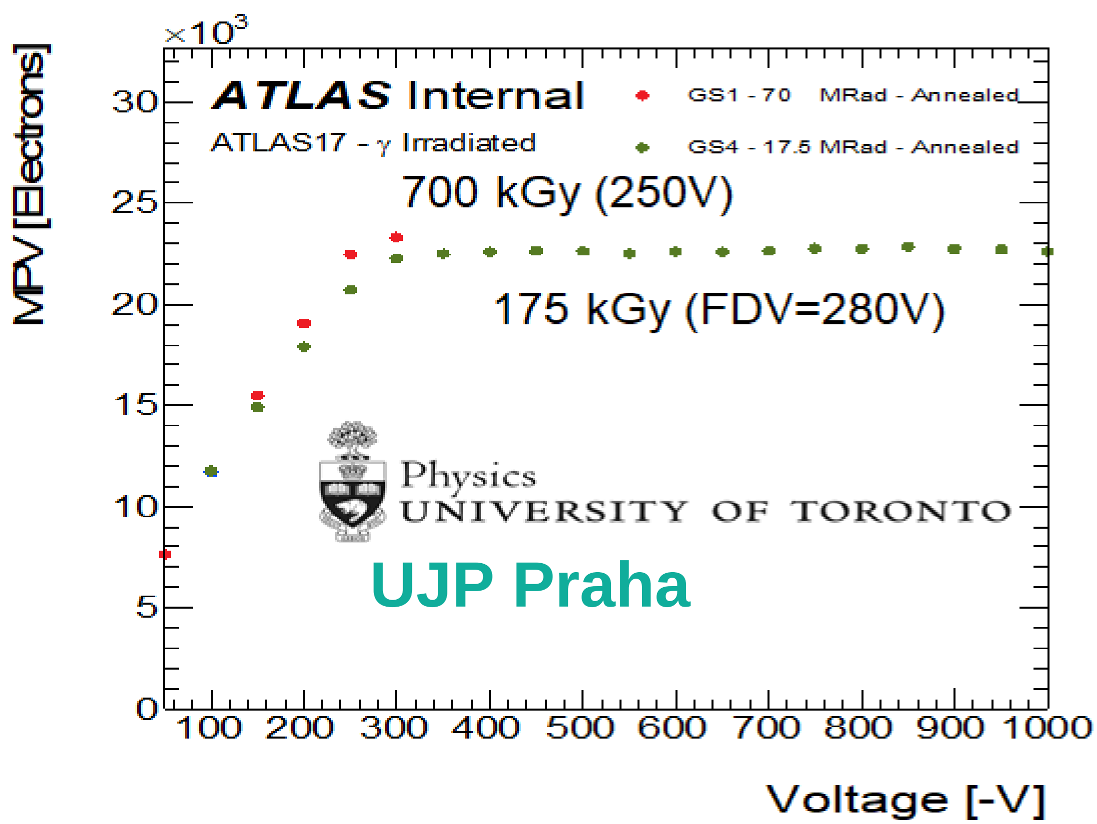
Irradiated sensors show smaller slopes

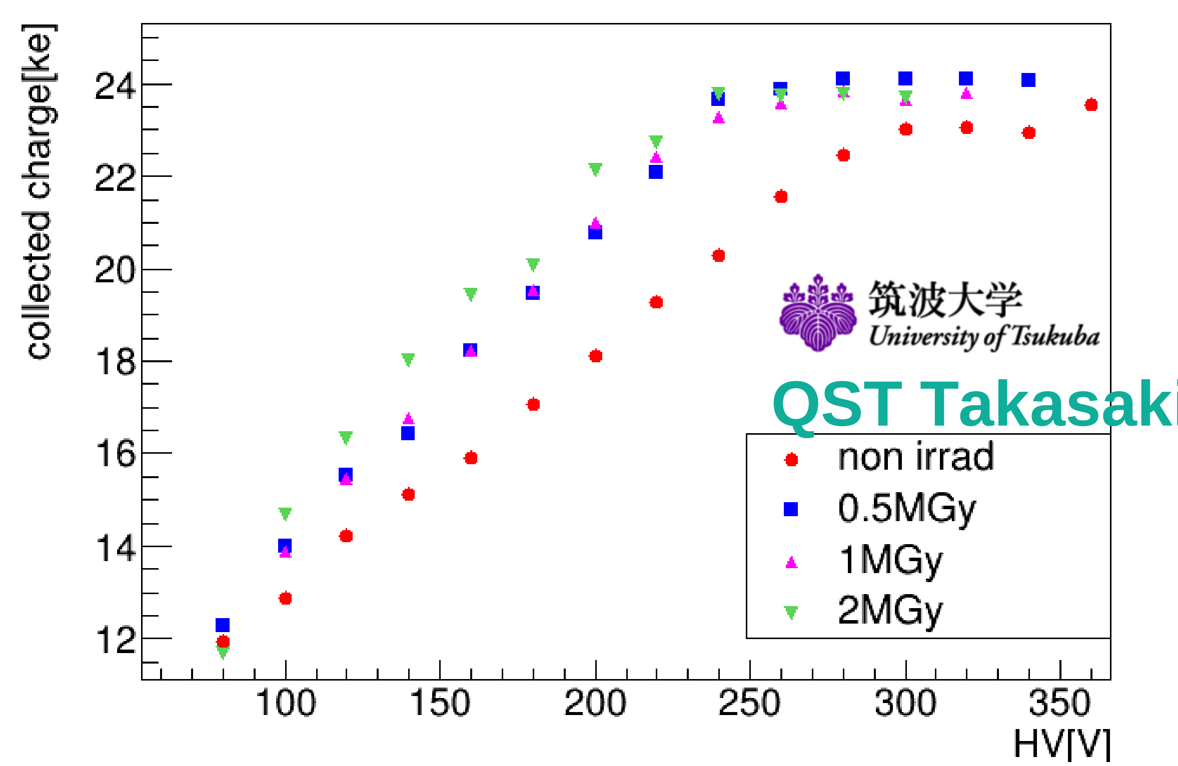
For extended study from CV, see M. Mikeštíková et al., “Preliminary results of bulk damage study in ^{60}Co irradiated n-in-p silicon strip sensors”, presented at RD50 meeting Lancaster 2019

CV









Conclusions

ATLAS17LS mini's have been irradiated with protons, neutrons and gammas. CCE measurement results from various institutes are compiled.

- **ATLAS17LS behaves similar to ATLAS12. Performance evaluation presented in TDR is still valid**
- **Std (300um) and thin (240um) thick sensors behave similarly at high fluence and at moderate HV (<800V), therefore no stringent specification on active thickness is required.**
- **ClusterSize distributions are reasonable, consistent between proton and neutron irradiations, although precise comparison requires better understanding of the β collimation.**
- **Vdep decrease with gamma dose, damage probably caused by Compton electrons**

During sensor production periodical irradiation is scheduled as QA

B'ham (p), Lujb (n), Praha (γ) monthly or more frequently, and CYRIC (p) every half year

to monitor any changes in bulk quality

see poster M.Ullan et.al., "Quality Assurance Methodology for the ATLAS ITk Strip Sensor Production"

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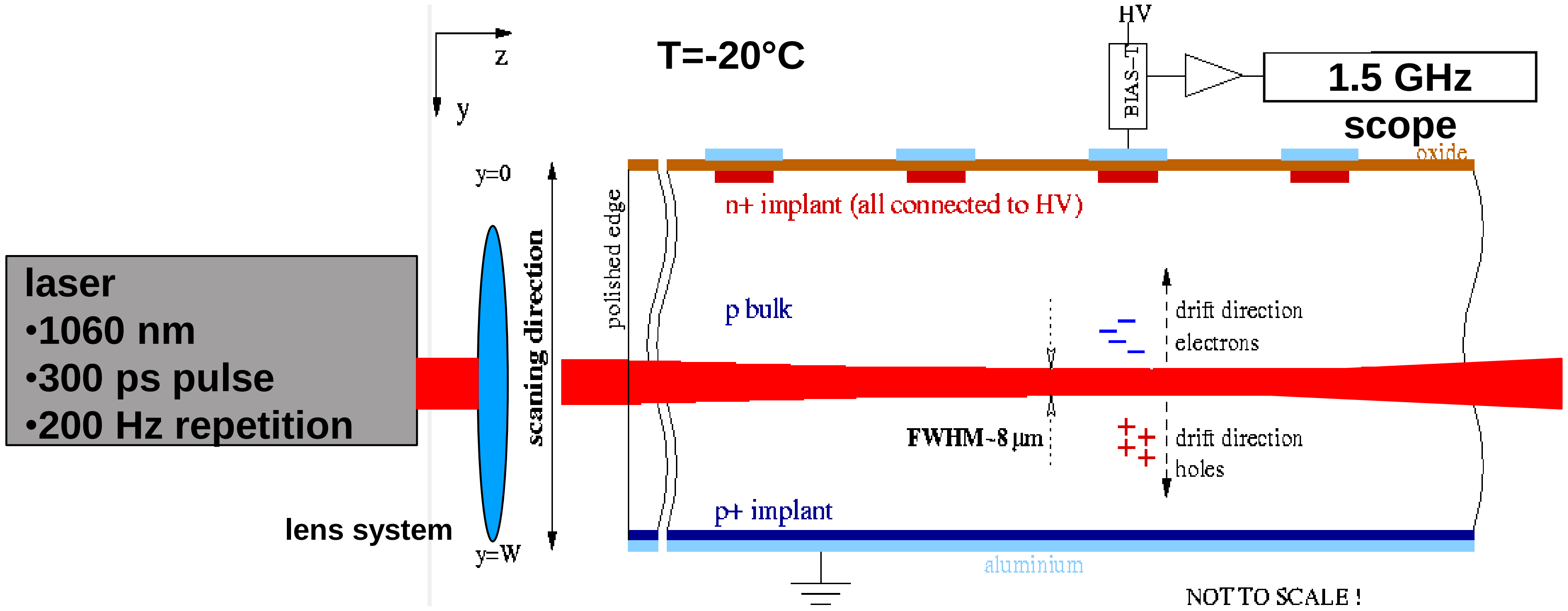
Edge TCT

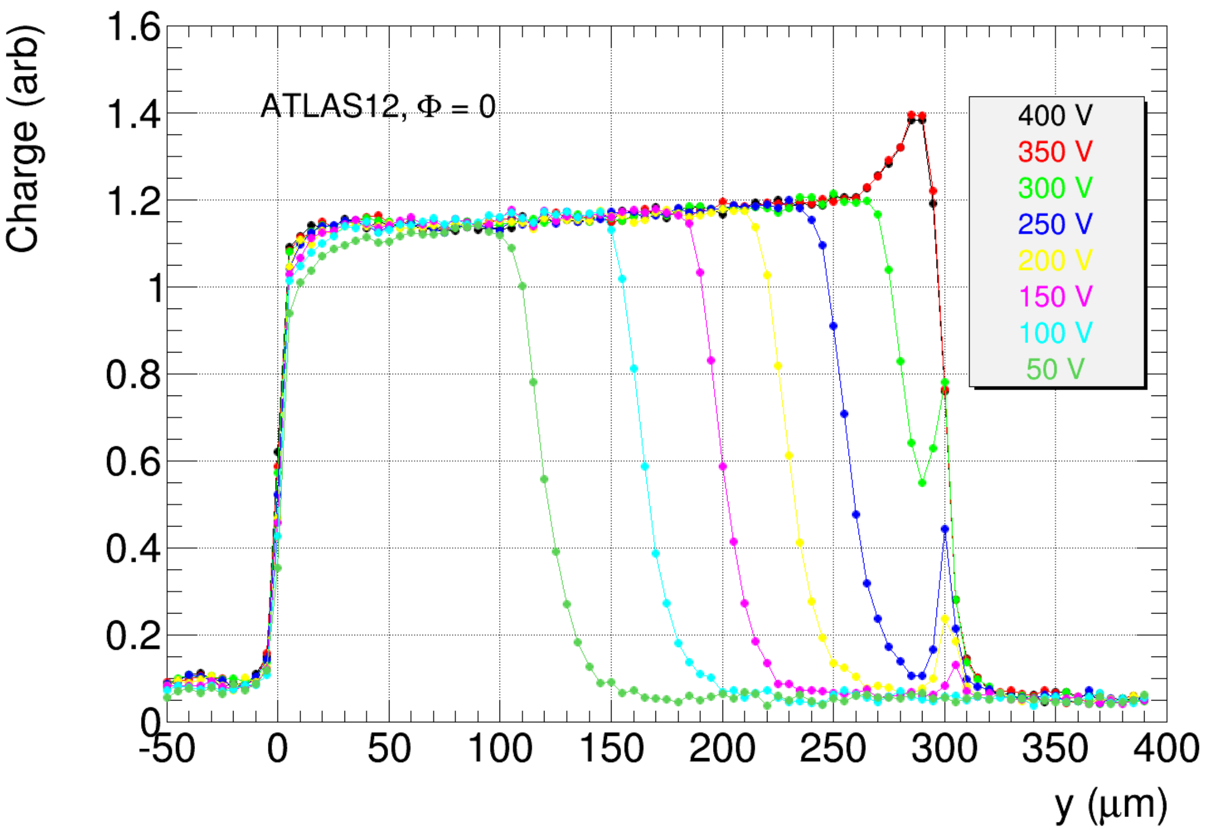
edge TCT (transient current technique)

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



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

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



Charge collection (un-irrad sensor) for various bias voltages

Collection of beta setup drawings

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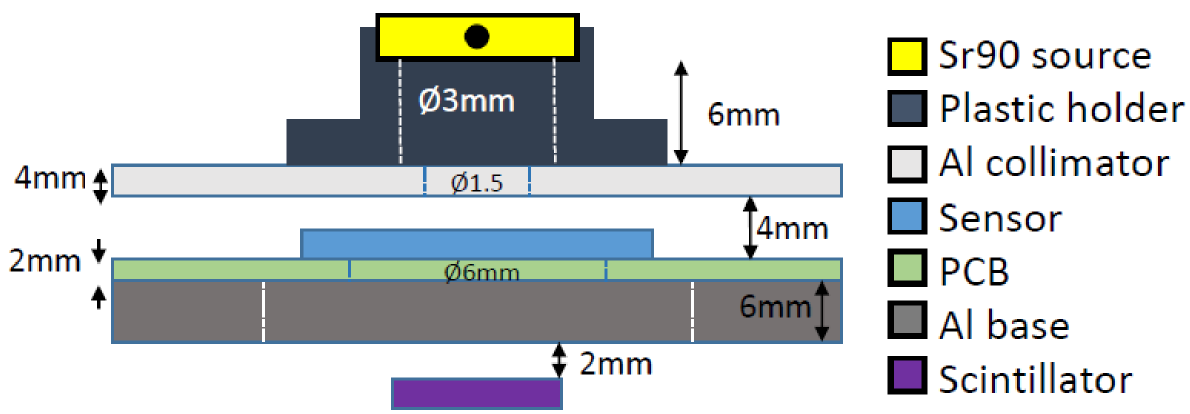
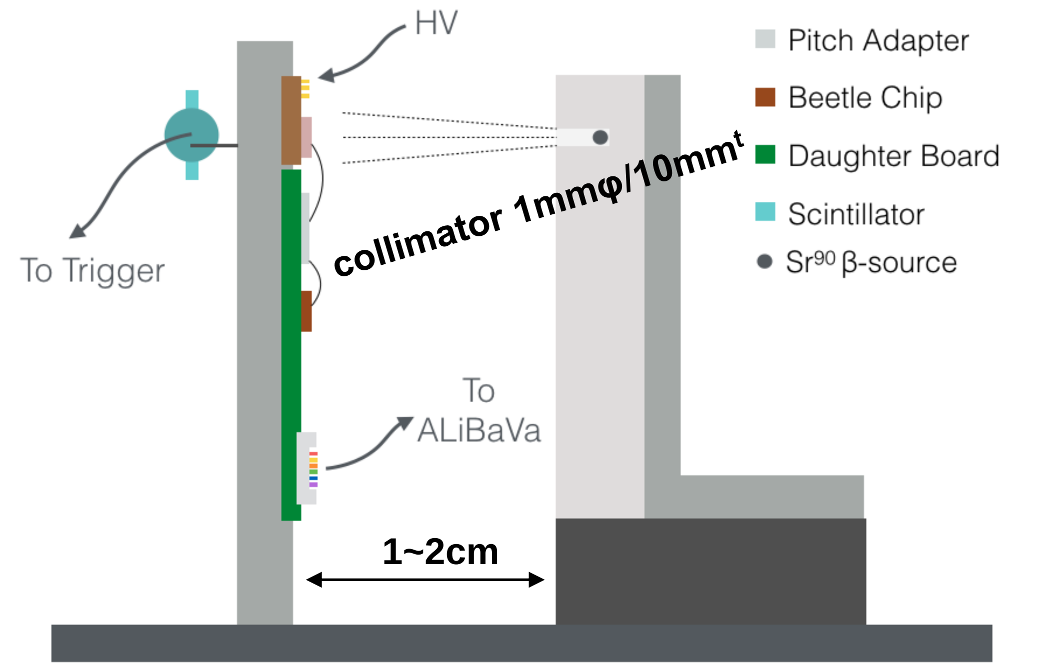
New collimator

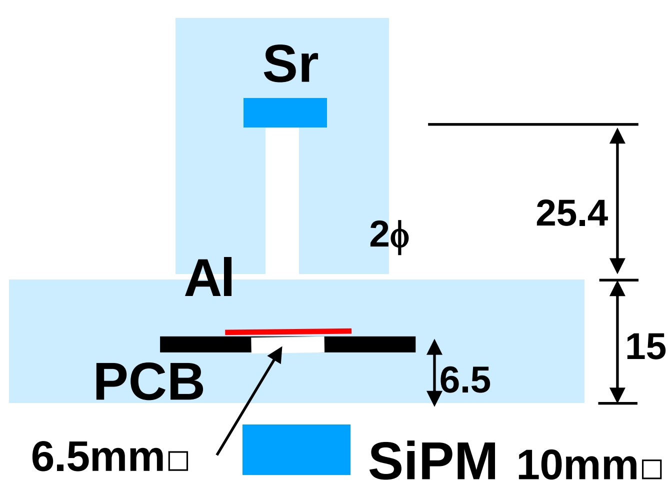


Physics UNIVERSITY OF TORONTO

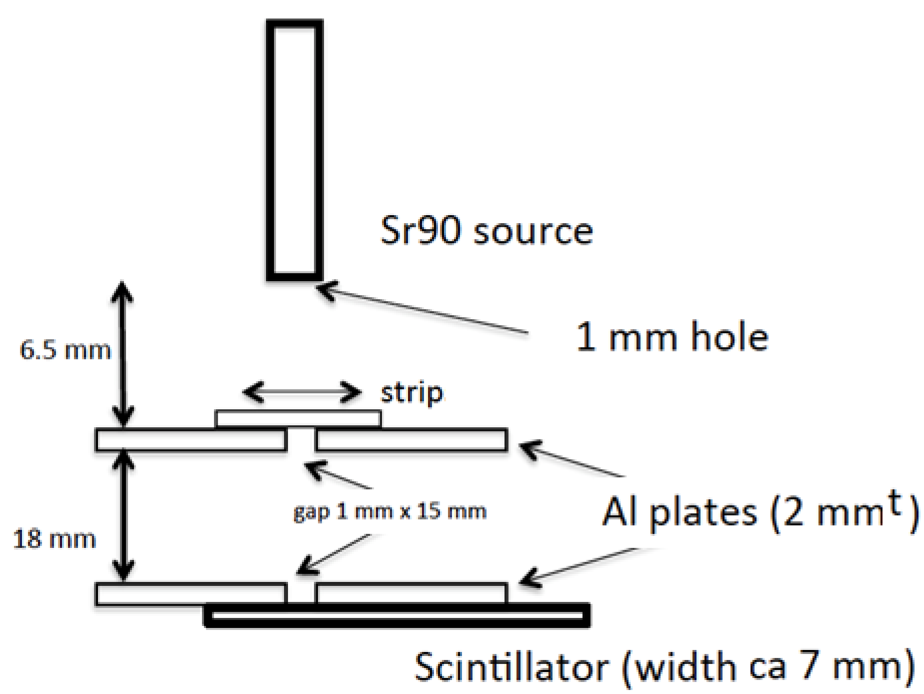


SCIPP

Revised collimator



Jožef Stefan Institute Ljubljana, Slovenia



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