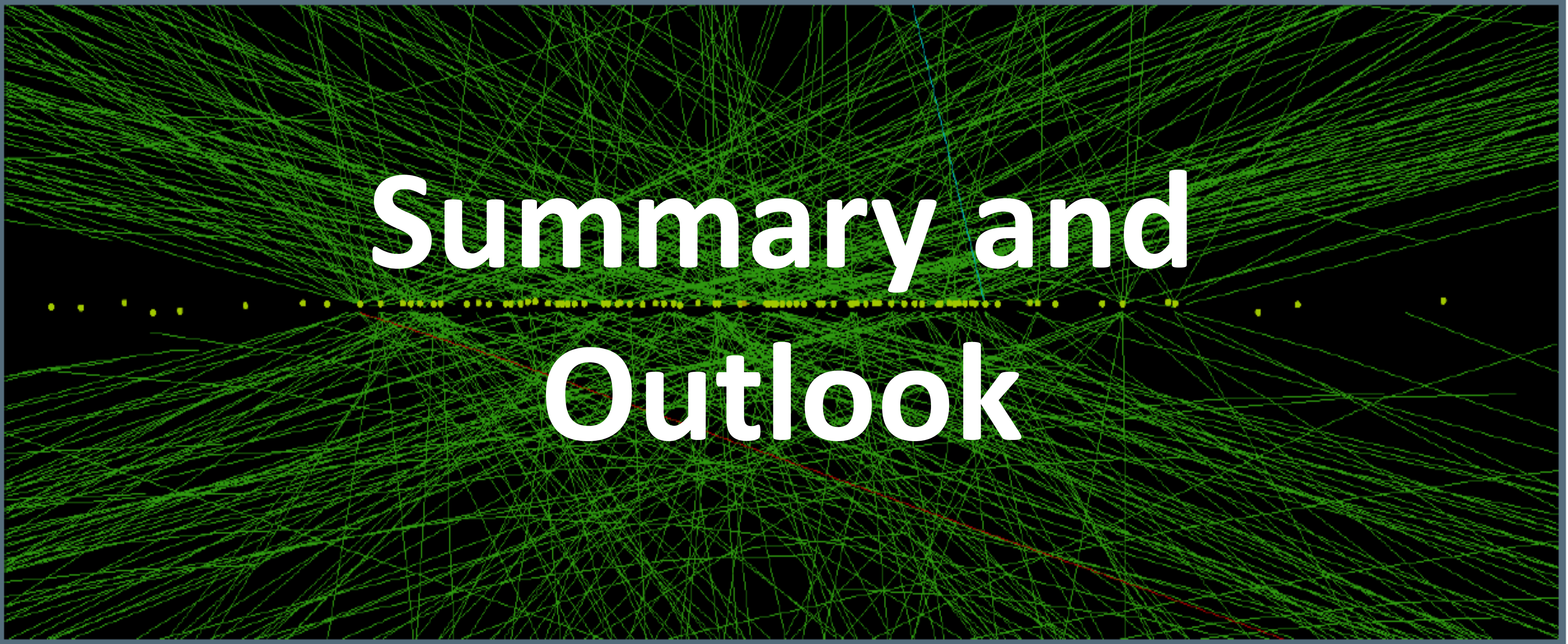


Summary and Outlook

Marko Mikuž

University of Ljubljana & Jožef Stefan Institute

10th Pixel Workshop

Santa Fe, December 16th 2022

Pixel’22 in Brief

- We’ve been through 5 exciting (exhausting) days
  - 17 sessions & poster session
    - 20 + 23 + 7 + 21 + 7 = 70 ± 5 talks
    - 16 posters
  - Dealing with various aspects of pixel detectors
    - Sometimes loooong pixels called strips
  - Focussing on HEP
    - Operational, in construction, future
  - Not forgetting applications
    - Medicine, space, material science…
- Impossible to pay tribute to every single one…
  - Have to adopt a statistical mechanics approach
  - My sincere apologies to those not mentioned explicitly

Structure of the Talk

- Pixels started in the 80's
- 1st Pixel Workshop – Genova 2000
- 10th Pixel – Santa Fe 2022
  - There seems to be a natural time constant of 22 ± 2 y
- We enjoy exciting times at the second tick of this clock, the HL-LHC is about to start
- What do we need to do to make
  - 20th Pixel in 2044 (FCC-ee started ?)
  - 30th Pixel in 2066 (FCC-hh about to start ??)

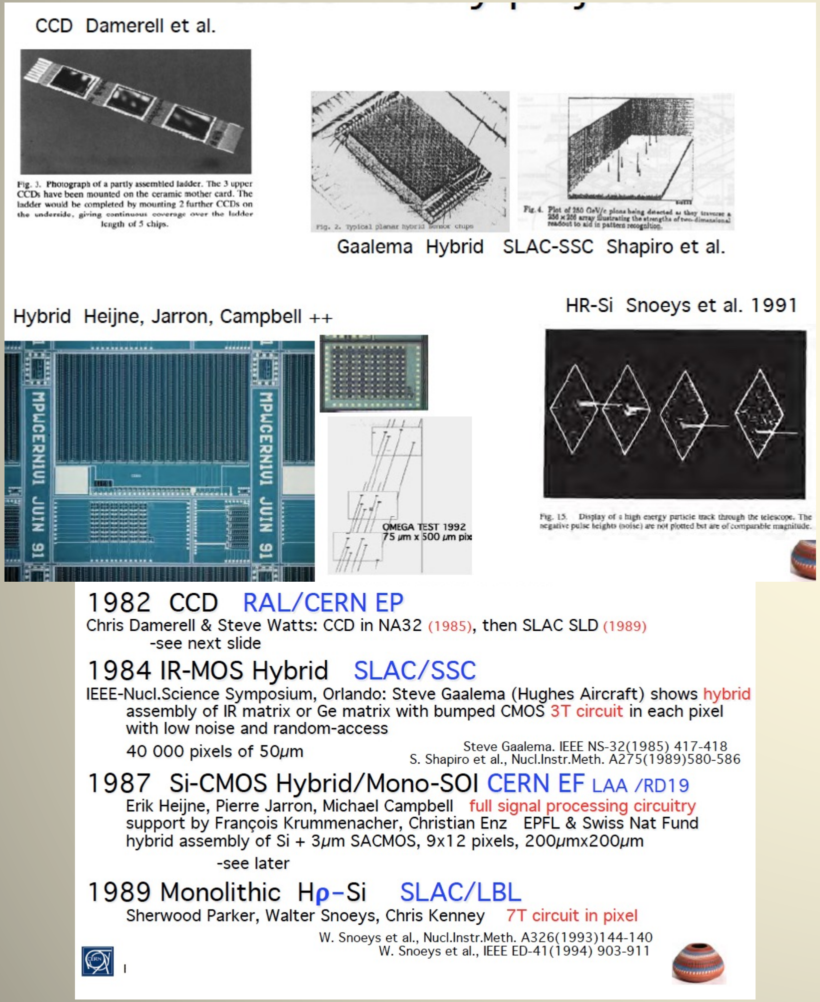
  as exciting as the 10th ?

- I'll (of course) focus on the latter in my Outlook

Part I : Summary

Historical Prelude

- Pixels from the 80's



CCD Damerell et al.

Fig. 3. Photograph of a partly assembled ladder. The 3 upper CCDs have been mounted on the ceramic mother card. The ladder would be completed by mounting 2 further CCDs on the underside, giving continuous coverage over the ladder length of 5 chips.

Fig. 2. Typical planar hybrid sensor chips

Fig. 4. Plot of 250 GeV/c pions being detected as they traverse a 256 × 256 array illustrating the strengths of two-dimensional readout to aid in pattern recognition.

Gaalema Hybrid SLAC-SSC Shapiro et al.

Hybrid Heijne, Jarron, Campbell ++

HR-Si Snoeys et al. 1991

Fig. 15. Display of a high energy particle track through the telescope. The negative pulse heights (noise) are not plotted but are of comparable magnitude.

1982 CCD RAL/CERN EP

Chris Damerell & Steve Watts: CCD in NA32 (1985), then SLAC SLD (1989)
-see next slide

1984 IR-MOS Hybrid SLAC/SSC

IEEE-Nucl.Science Symposium, Orlando: Steve Gaalema (Hughes Aircraft) shows hybrid assembly of IR matrix or Ge matrix with bumped CMOS 3T circuit in each pixel with low noise and random-access

40 000 pixels of 50μm

Steve Gaalema. IEEE NS-32(1985) 417-418
S. Shapiro et al., Nucl.Instr.Meth. A275(1989)580-586

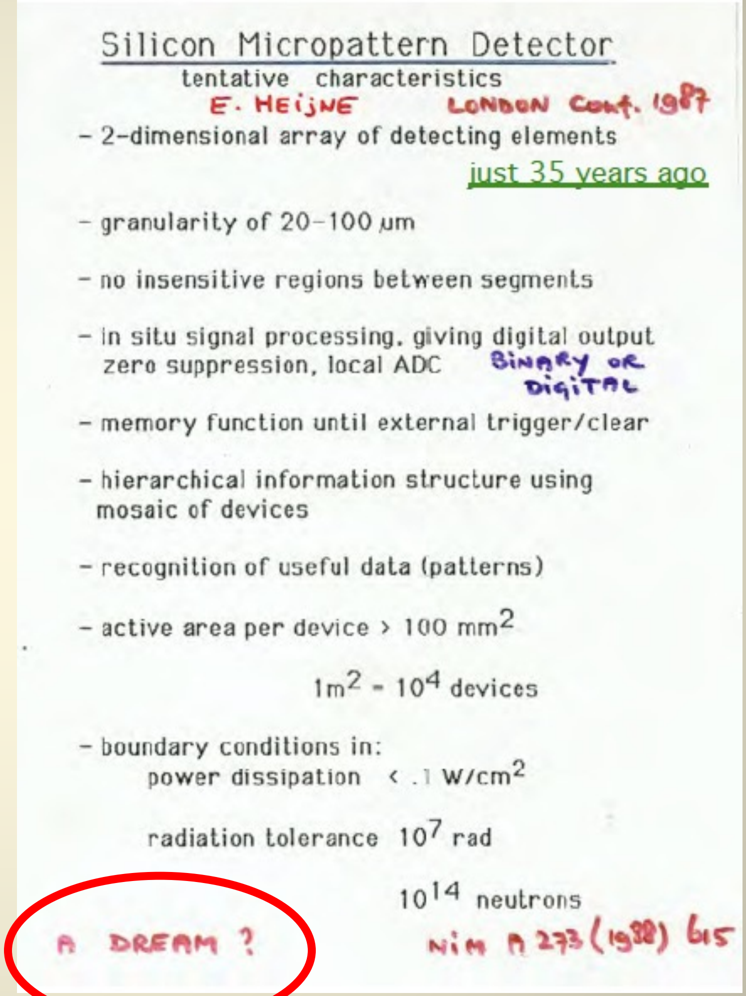
1987 Si-CMOS Hybrid/Mono-SOI CERN EF LAA /RD19

Erik Heijne, Pierre Jarron, Michael Campbell full signal processing circuitry
support by François Krummenacher, Christian Enz EPFL & Swiss Nat Fund
hybrid assembly of Si + 3μm SACMOS, 9x12 pixels, 200μmx200μm
-see later

1989 Monolithic Hρ-Si SLAC/LBL

Sherwood Parker, Walter Snoeys, Chris Kenney 7T circuit in pixel

W. Snoeys et al., Nucl.Instr.Meth. A326(1993)144-140
W. Snoeys et al., IEEE ED-41(1994) 903-911



Silicon Micropattern Detector

tentative characteristics

E. HEiJNE LONDON Conf. 1987

- 2-dimensional array of detecting elements

just 35 years ago

- granularity of 20-100 µm
- no insensitive regions between segments
- in situ signal processing, giving digital output zero suppression, local ADC BINARY OR DIGITAL
- memory function until external trigger/clear
- hierarchical information structure using mosaic of devices
- recognition of useful data (patterns)
- active area per device > 100 mm^2

1m^2 - 10^4 devices

- boundary conditions in:
  power dissipation < .1 W/cm^2
  radiation tolerance 10^7 rad
  10^{14} neutrons

A DREAM ?

NIM A 273 (1988) 615

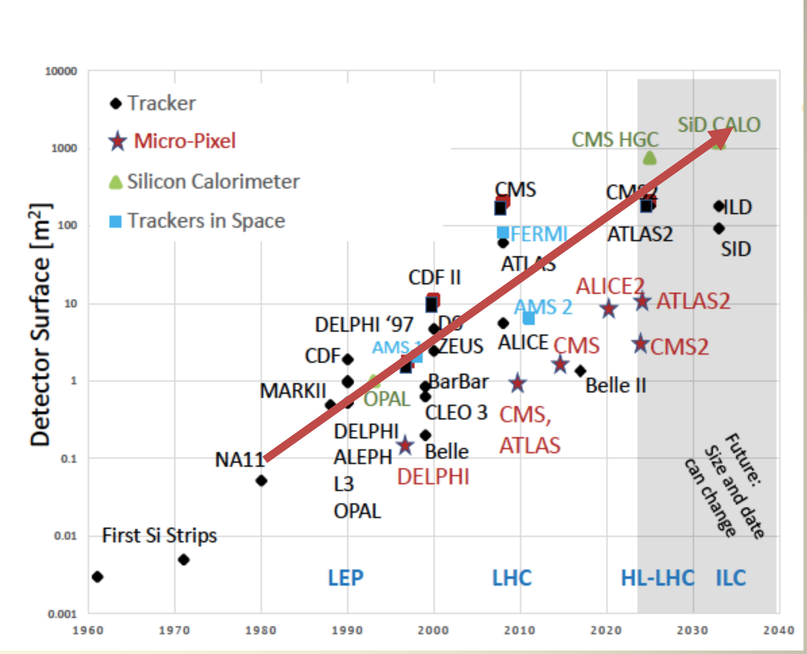
- Wishlist in 1987

E.Heijne

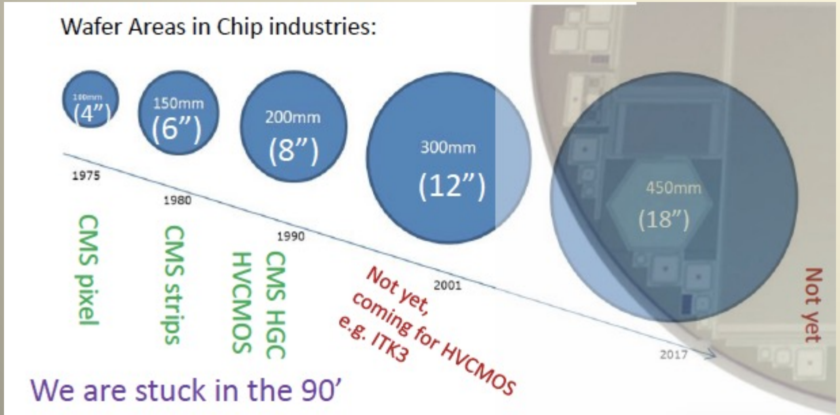
Dreams Come True

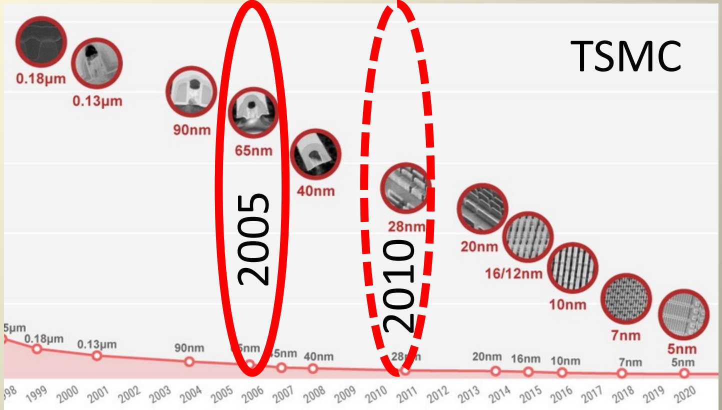
- Position sensitive silicon detectors in HEP
  - Moore’s law
    - Doubling in 4 years
    - For strips and pixels
- Not exactly technology drivers
  - Just made it to the ‘90s in sensor wafers
  - In 2005 for CMOS (->2010)

Log-scale



F. Hartmann

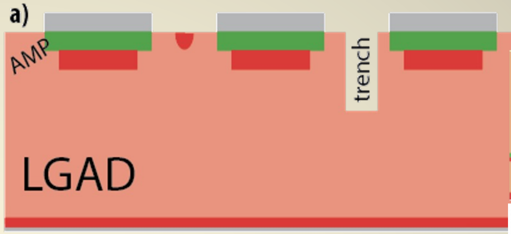




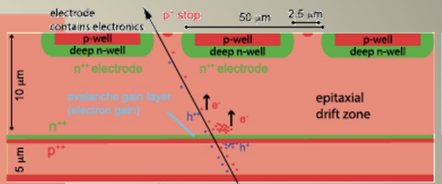
Beyond the Dream

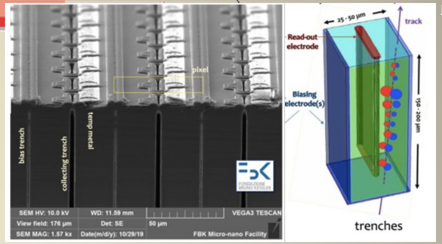
- 4-D tracking
  - 4th D: timing (<50 ps)
  - LGAD's, trench (@column ?) 3-D…
    - In fact 5-D: energy
  - Timing layers (LGAD) in Phase2 (ATLAS, CMS)
- 3-D sensors have made it !
  - From ATLAS IBL to inner pixel layers of Phase2 in ATLAS & CMS
    - Yield under control (done deal ?)
- From hybrid to monolithic
  - The future of tracking
  - (Too?) Many approaches
    - No application in Phase2
  - Reticle stitching allow wafer size detectors
  - Thinning allows bending (ITS3)
    - Run5 upgrades are theirs !

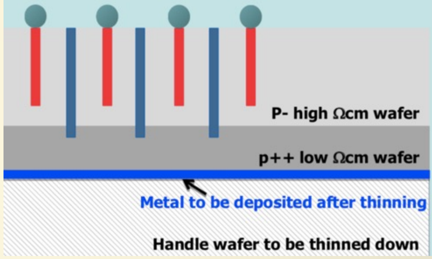
F. Hartmann

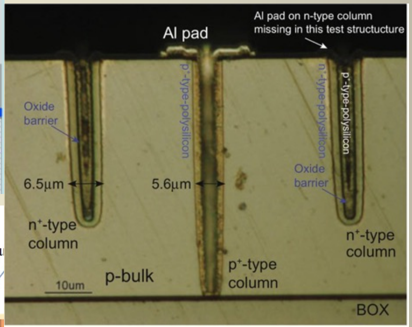


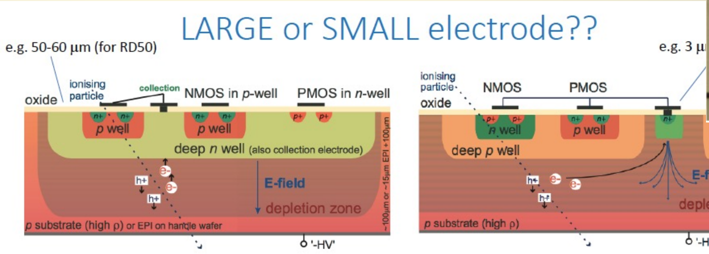
- Monolith

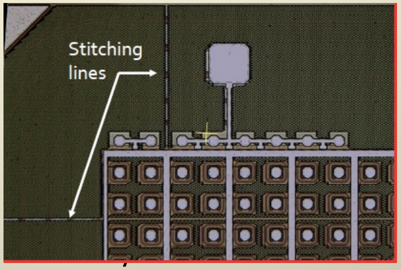


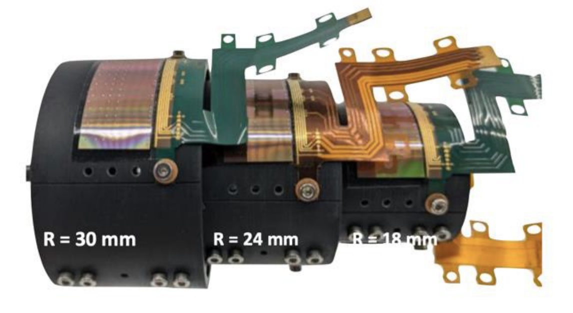






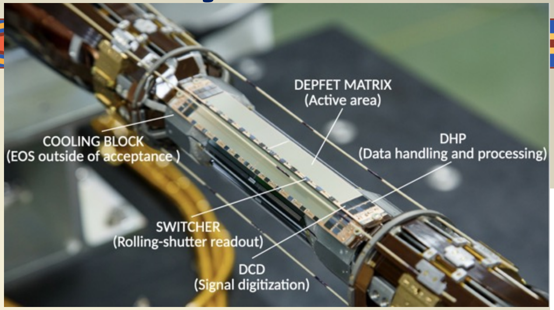


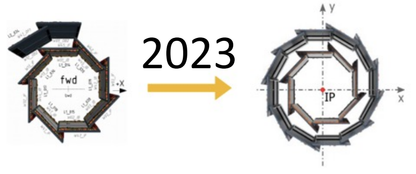


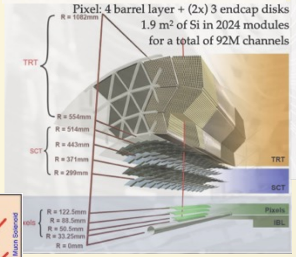


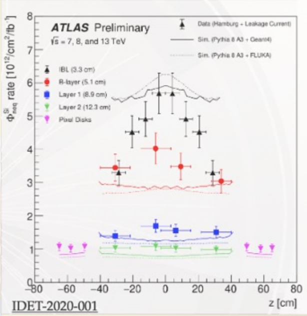
Current Pixel Systems

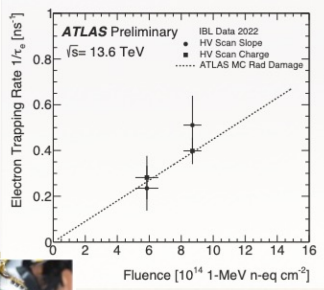
- Belle II, ATLAS, CMS, ALICE
  - Wildly different requirements and realizations
    - DEPFET (incomplete, 2023)
    - 3D, planar hybrid (LS0, LS1)
    - Planar hybrid (LS1, LS2)
    - MAPS (LS2)
  - Common
    - They all perform !

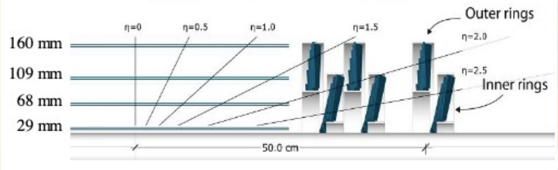


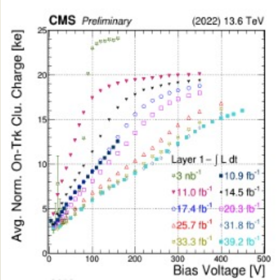


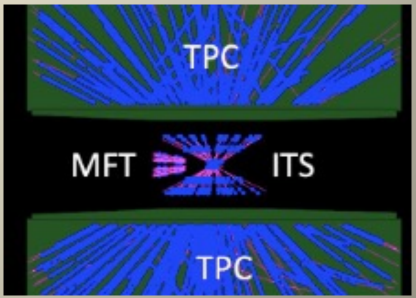






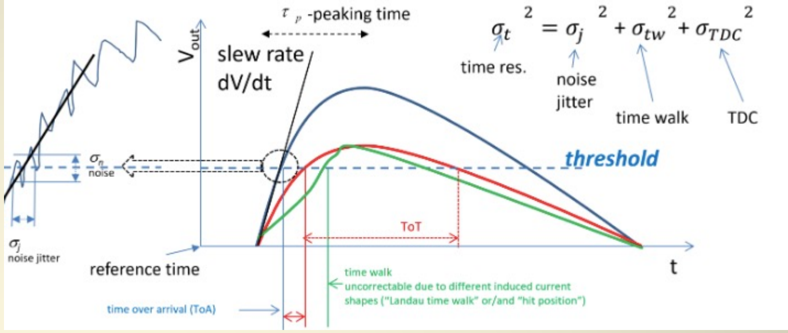


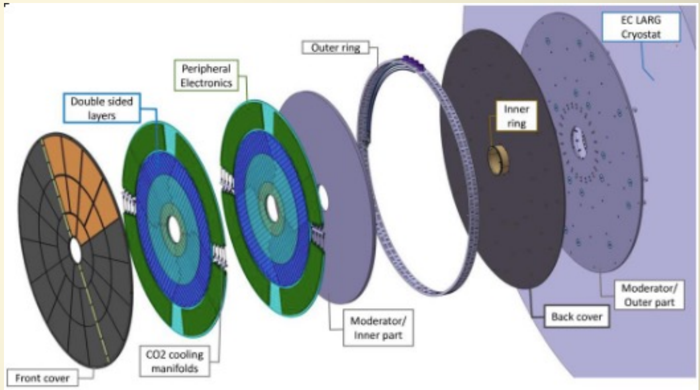


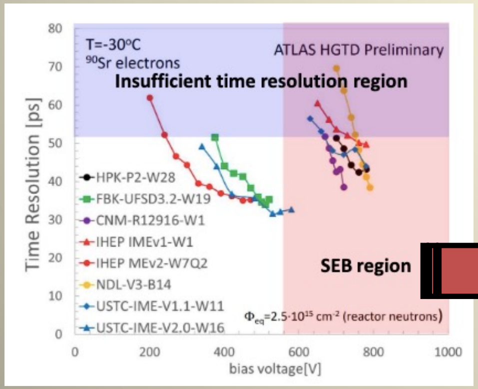


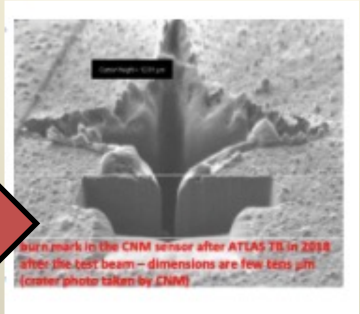
Precision timing

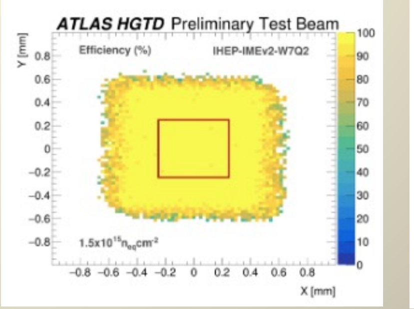
- Goal <50(30)ps
  - Ultimate: 5ps FCC-hh
- Progress on all contributions
  - Sensor and electronics
- 50 ps timing resolution achieved on large scale
  - ATLAS HGTD
  - C-enriched LGAD
  - up to $2.5\times10^{15}\ n_{eq}/cm^2$

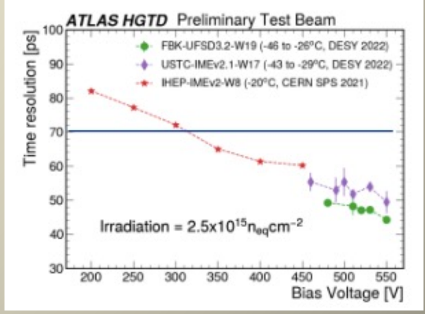






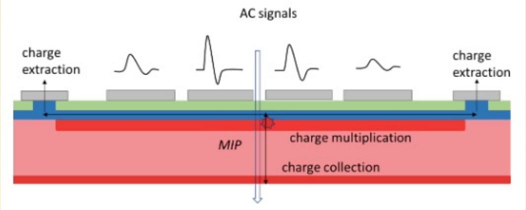


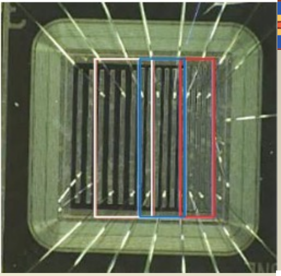




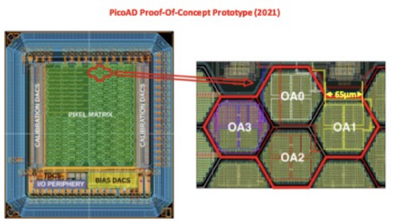
Precision timing (cont.)

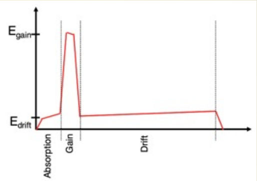
- LGAD flavours
  - AC-LGAD
    - true 4-D -> ATAR, EPIC

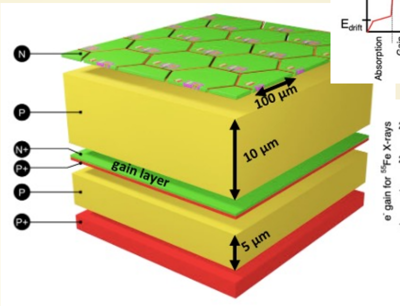


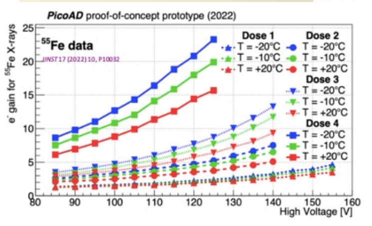


  - MONOLITH

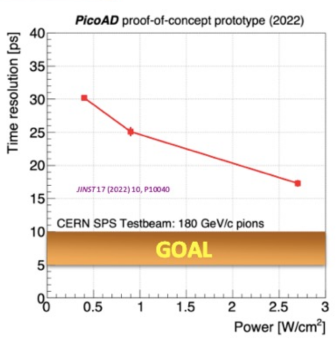






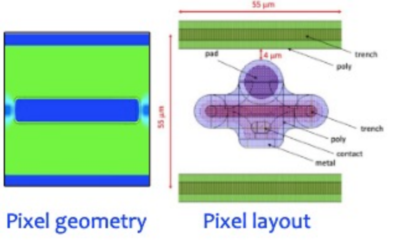


A **gain up to ≈ 20 for ^{55}Fe X-rays**



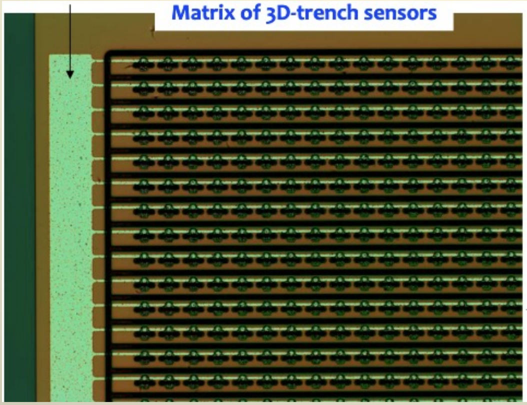
- 3D trench

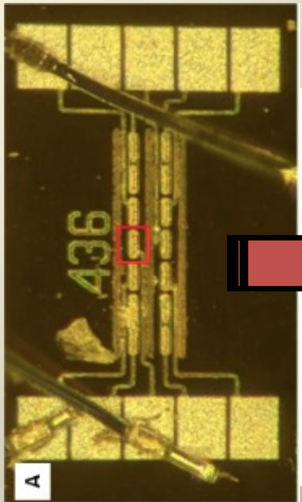
TimeSPOT
TIME and SPace real-time Operating Tracker

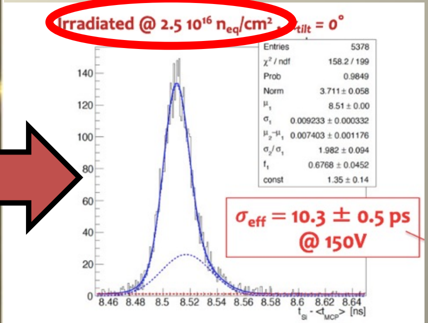


Pixel geometry Pixel layout

Matrix of 3D-trench sensors



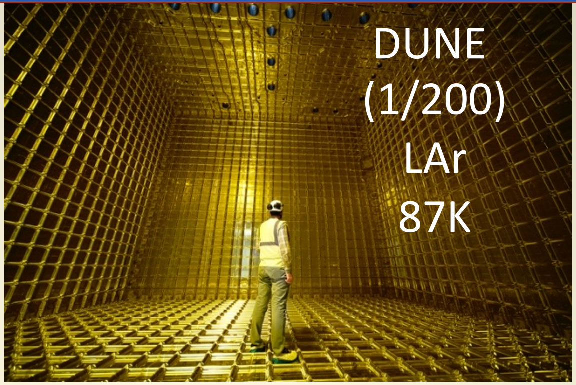


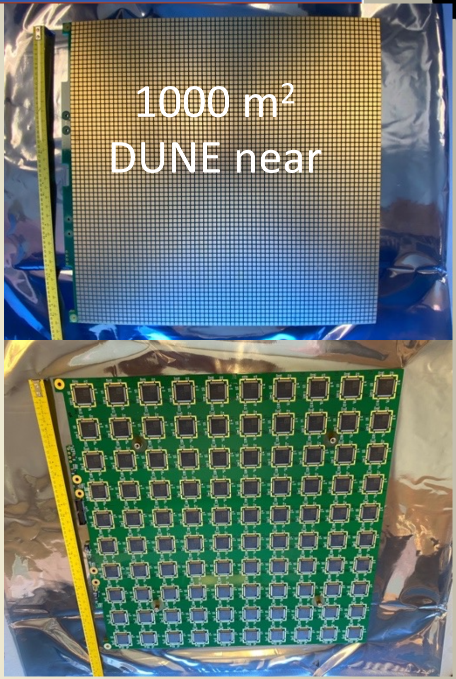


To be compared with 11 ps @ 100 V of the not-irradiated case

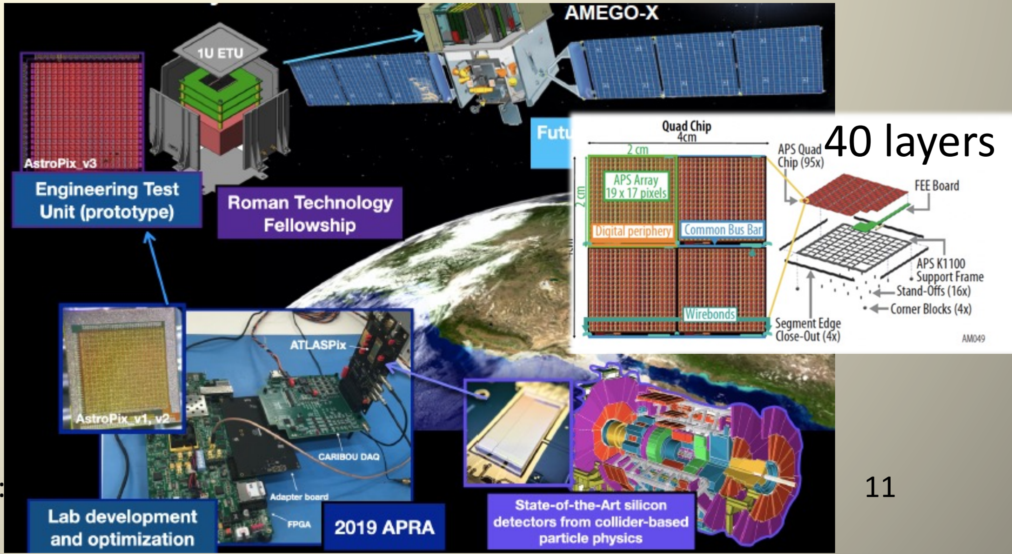
Space, Astronomy, Dark Matter

- Neutrinos - LArPix
  - LAr TPC
  - Cryo, huge



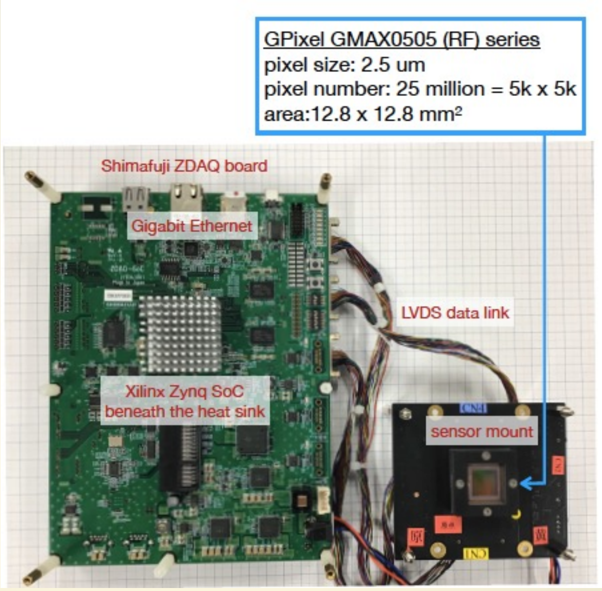


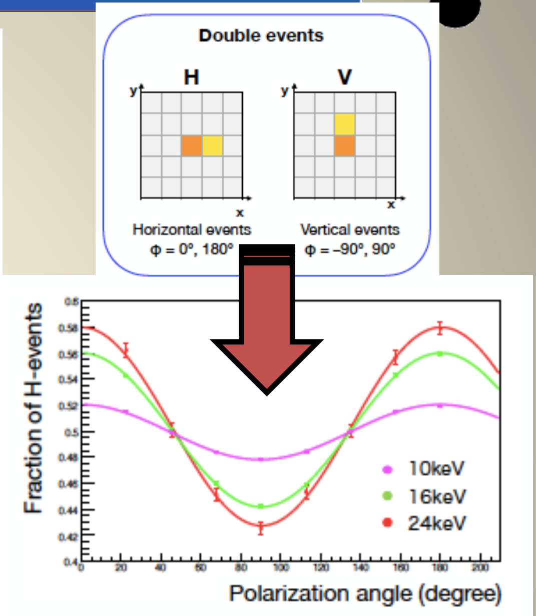
- Gamma rays
  - Adaptation of ATLASPix for space
    - HEP→ astronomy
    - AstroPix v1, 2, 3
  - AMEGO-X mission



Space, Astronomy (cont.)

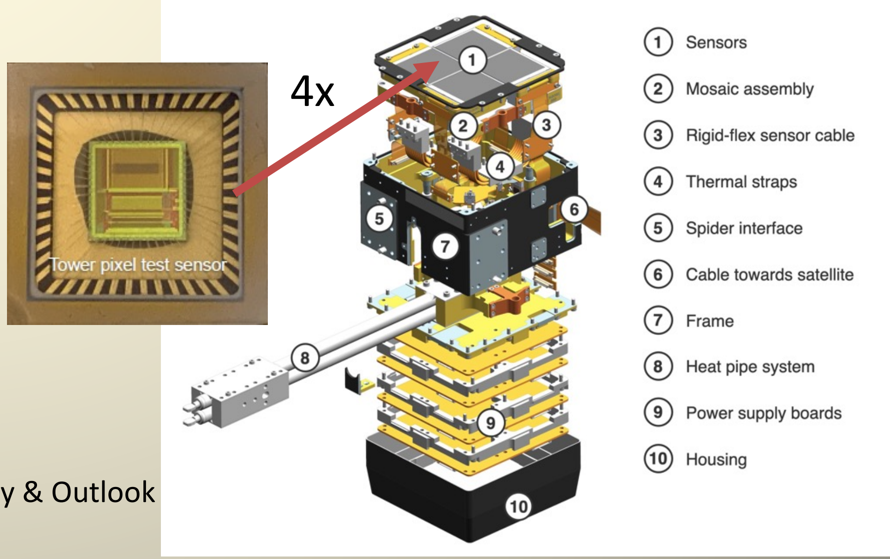
- X-ray polarimeter
  - GigaPixel
  - 5k x 5k pixels
  - Up to 15 % modulation





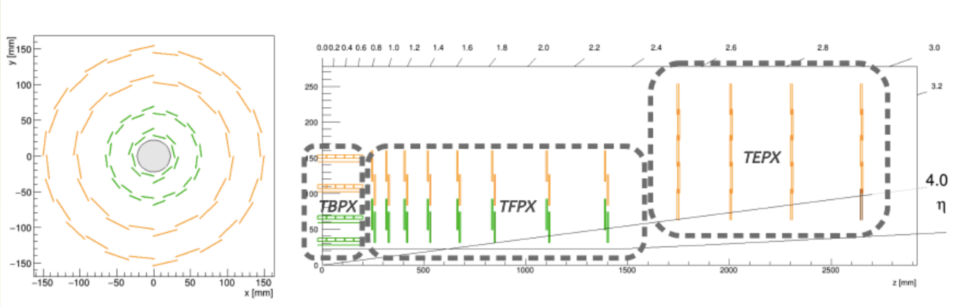
- UV-astronomy
  - Tower 180nm MAPS stiched to 4.5x4.5 cm^2 active area
  - 4 MAPS -> 90Mpixel camera
  - Ready for launch in 2025

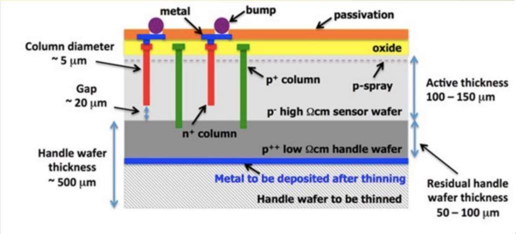
ULTRASAT
SKYLIGHT TO SPACE

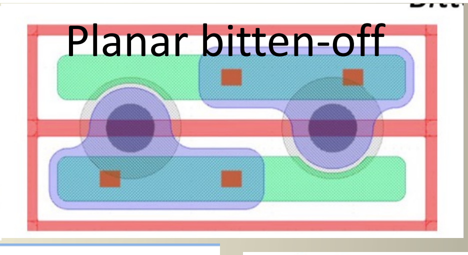


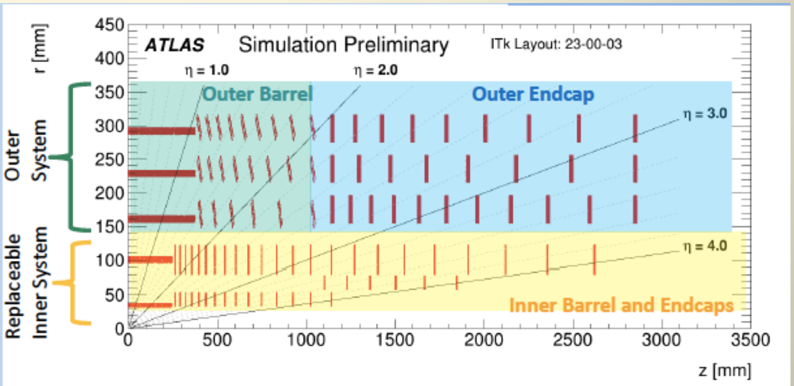
Pixel System Upgrades – Run4

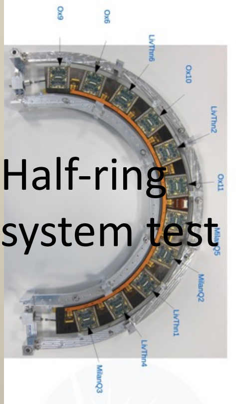
- CMS Phase II
  - 4.9 m^2, 3900 modules
  - 3D inner layer, 150 μm
    - thermal constraint
  - The rest 150 μm planar
  - All cells 25x100 μm^2
- ATLAS ITk Phase II
  - 13 m^2, 9400 modules
  - 3D layer L0, 150 μm
  - The rest 150 μm planar
    - 100 μm in L1
  - Cells 50x50 μm^2
    - Except 3D L0 25x100 μm^2

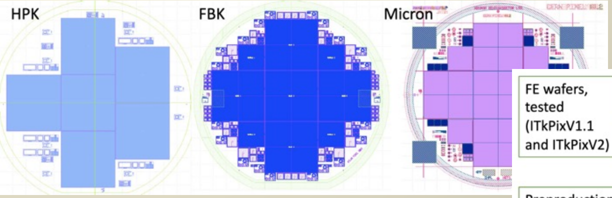


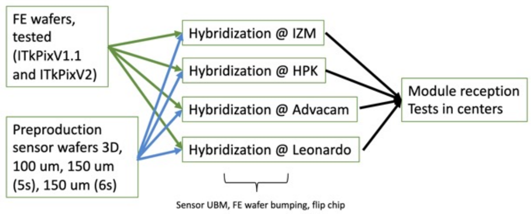



Planar bitten-off




Half-ring system test




FE wafers, tested (ITkPixV1.1 and ITkPixV2)

Preproduction sensor wafers 3D, 100 um, 150 um (5s), 150 um (6s)

Hybridization @ IZM

Hybridization @ HPK

Hybridization @ Advacam

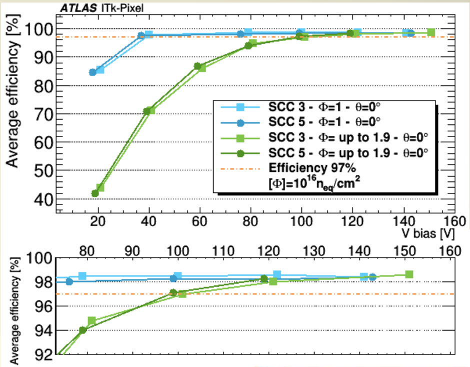
Hybridization @ Leonardo

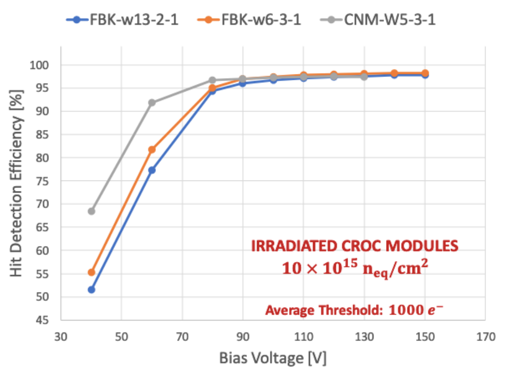
Sensor UBM, FE wafer bumping, flip chip

Module reception Tests in centers

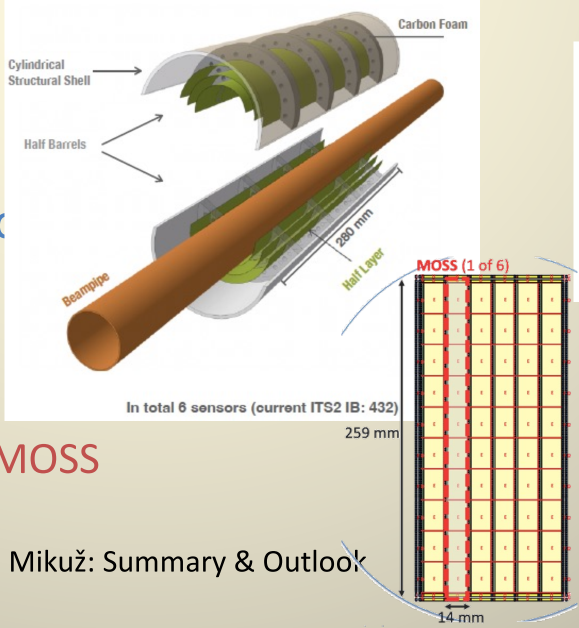
Pixel System Upgrades (cont.)

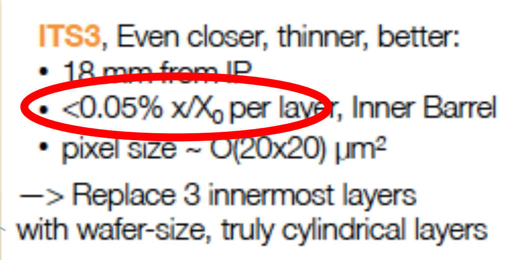
- ATLAS & CMS 3D modules
  - FBK 3D sensors
  - ITkPixV1.1 or CROC
    - Irradiated to 1-2x10^{16} n_{eq}/cm^2
    - Need 90-120 V for ~full efficiency
  - Comfortable operation window before (soft) breakdown





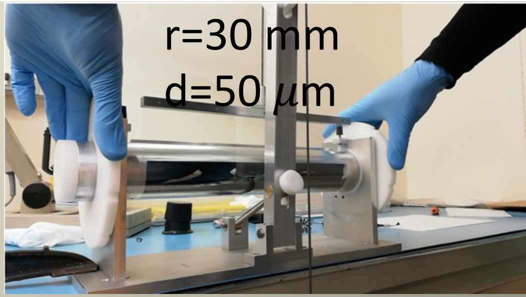
- ALICE ITS3
  - 3-layer cylindrical
  - 50 μm thick Si
  - self-supporting, air co 0.05% X_0
  - MAPS in 65 nm
  - Wafer-scale stitching
    - MOnolithic Stitched Sensor - MOSS




ITS3, Even closer, thinner, better:

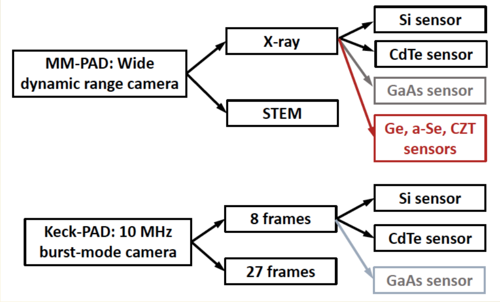
- 18 mm from IP
- <0.05% x/X_0 per layer, Inner Barrel
- pixel size ~ O(20x20) μm^2

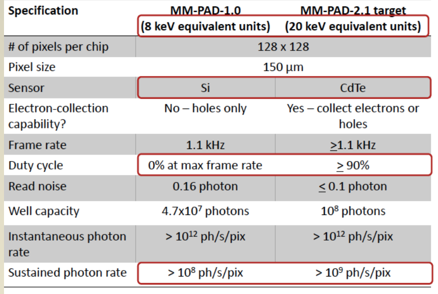
—> Replace 3 innermost layers with wafer-size, truly cylindrical layers


r=30 mm
d=50 μm

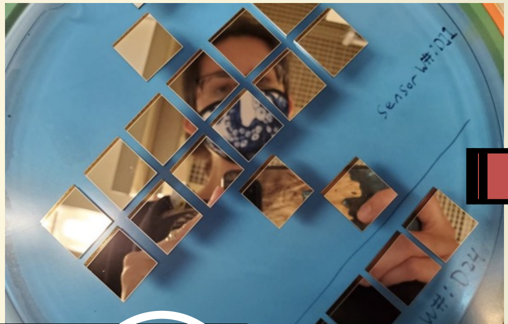
X-ray Detectors

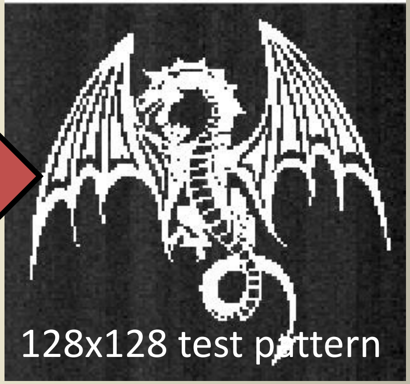
- Cornell
  - MM-PAD 1.0 and 2.1
    - Integrating
    - Dynamic range extension by overflow counting
    - Hybrid: Si, CdTe


MM-PAD: Wide dynamic range camera
X-ray
STEM
Si sensor
CdTe sensor
GaAs sensor
Ge, a-Se, CZT sensors
Keck-PAD: 10 MHz burst-mode camera
8 frames
27 frames
Si sensor
CdTe sensor
GaAs sensor

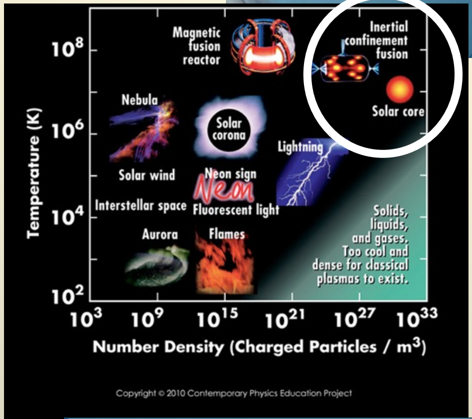


Specification	MM-PAD-1.0 (8 keV equivalent units)	MM-PAD-2.1 target (20 keV equivalent units)
# of pixels per chip	128 x 128	
Pixel size	150 μm	
Sensor	Si	CdTe
Electron-collection capability?	No – holes only	Yes – collect electrons or holes
Frame rate	1.1 kHz	$\geq$1.1 kHz
Duty cycle	0% at max frame rate	$\geq$ 90%
Read noise	0.16 photon	$\leq$ 0.1 photon
Well capacity	4.7x10^7 photons	10^8 photons
Instantaneous photon rate	> 10^{12} ph/s/pix	> 10^{12} ph/s/pix
Sustained photon rate	> 10^8 ph/s/pix	> 10^9 ph/s/pix



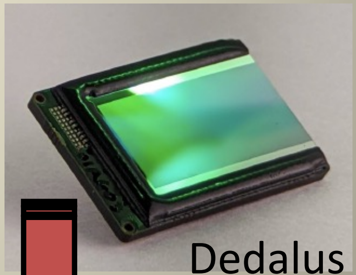

128x128 test pattern

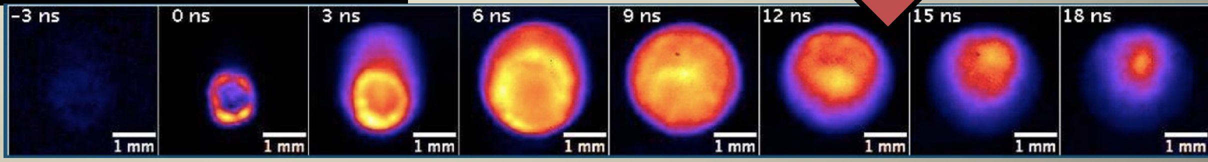
- Ultra-fast
  - X-ray “movies”
  - HDEP e.g. ICF
  - Icarus, Dedalus
    - Hybrid
    - ns shutters



Copyright © 2010 Contemporary Physics Education Project

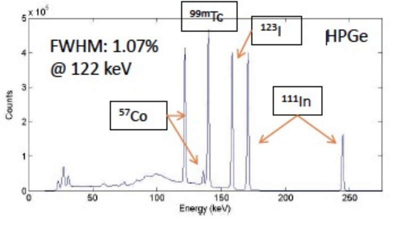

Icarus

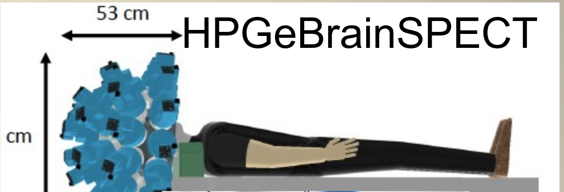

Dedalus

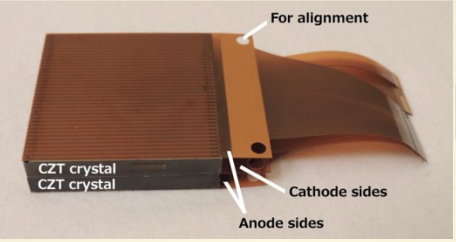


Imaging (Medical, IR, DE)

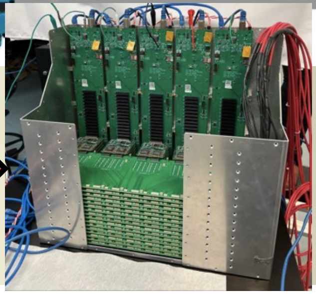
- Ge and CZT hybrid for SPECT/PET
  - DSSD
  - Scaled up assemblies







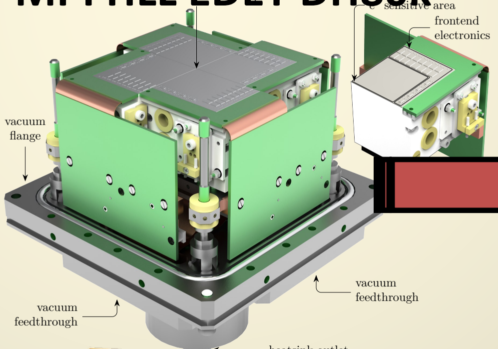
x 110

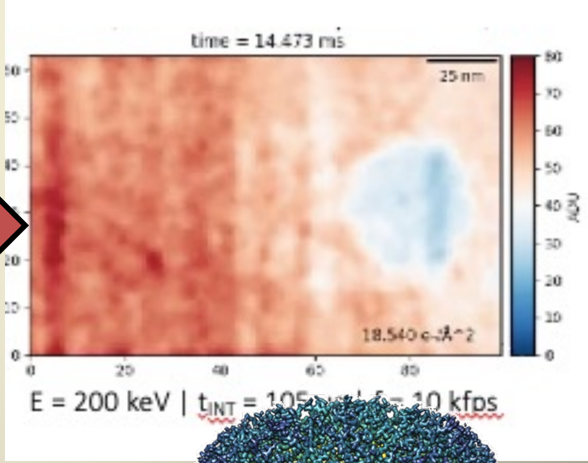


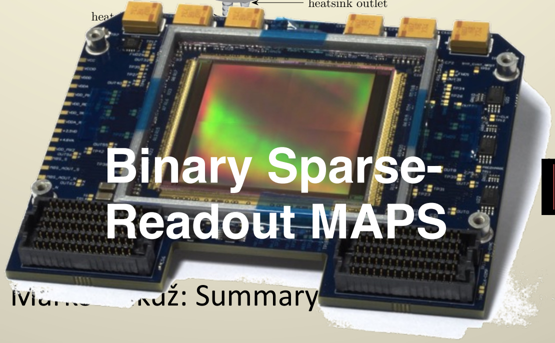
CZT PET array

- DEPFET/MAPS monolithic for direct electron at SEM
  - Fast, precize and large
    - TEM movies (DEPFET)
    - sparsification and electron counting (MAPS)

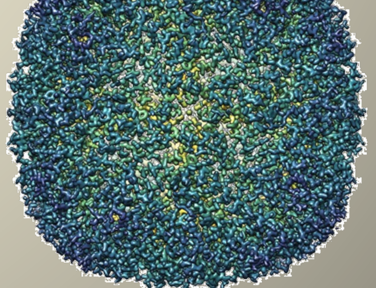
MPI HLL EDET DH80k





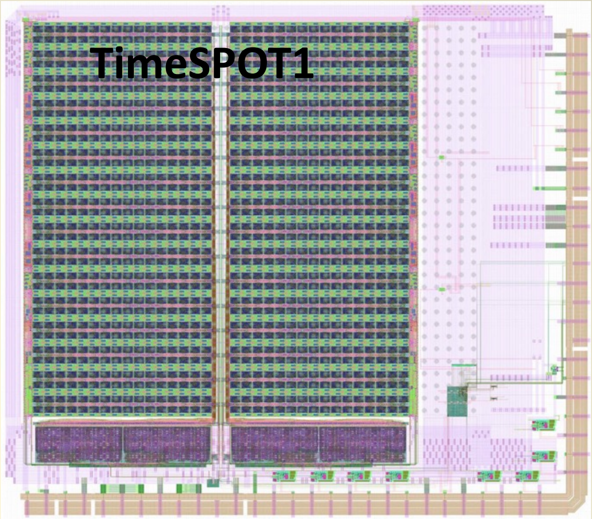


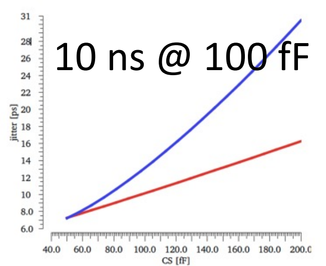
Binary Sparse-Readout MAPS



Pixel Electronics

- **TimeSPOT**
  TIME and SPace real-time Operating Tracker
  INFN
  - 1st HEP ASIC in 28 nm
  - 4D tracking



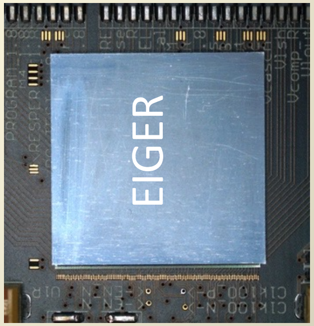


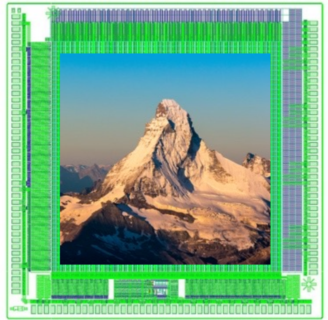
IGNITE INFN Istituto Nazionale di Fisica Nucleare
INFN Ground-up iNITiative for μElectronics developments

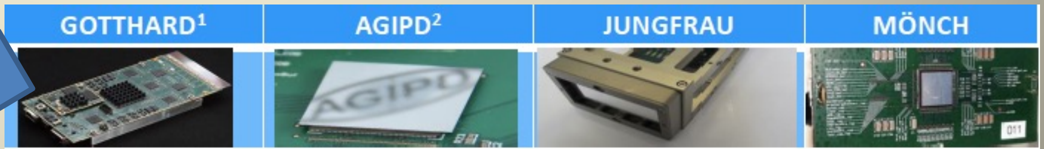
- The Alpine Landscape
  - From HEP to Swiss peaks

SPC

Integrating



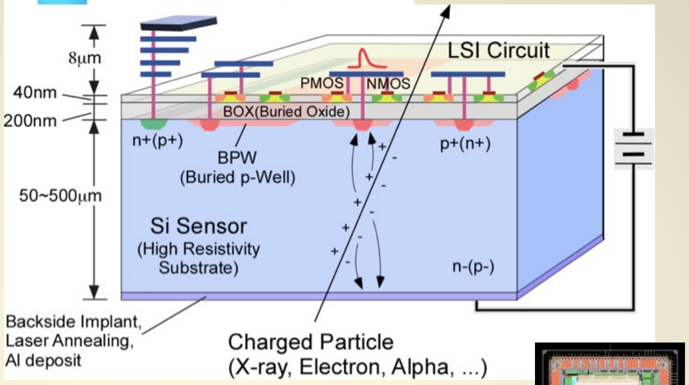


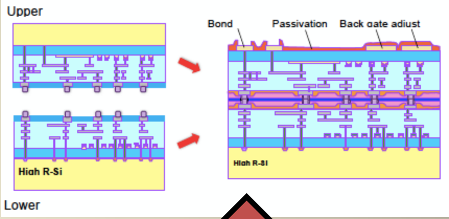


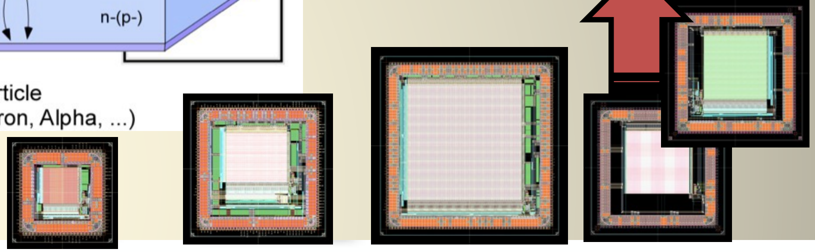
SOI

- Strong Japanese community
  - ILC - SOFIST
  - X-ray Astronomy
  - Compton Camera

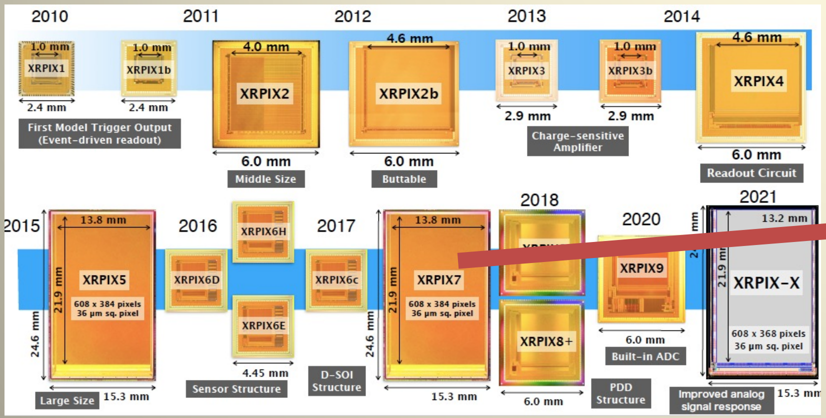
SOIPIX
Silicon-On-Insulator Pixel Detector Project

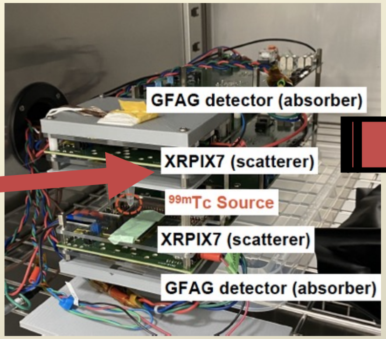


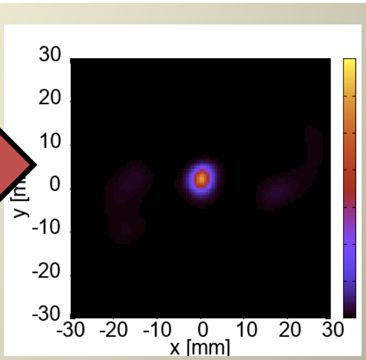




SOFIST1	SOFIST2	SOFIST3	SOFIST4
Position resolution	Time resolution	Full function	Full function
σ~1.4 µm	σ~1.55 µs	(30x30 µm² pixel)	(20x20 µm² pixel)

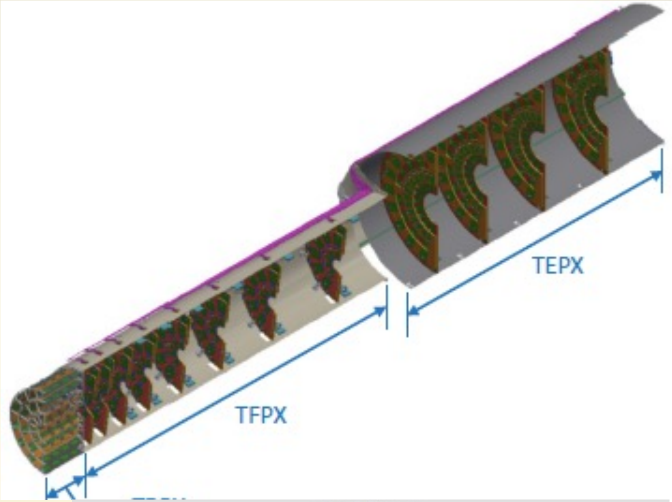


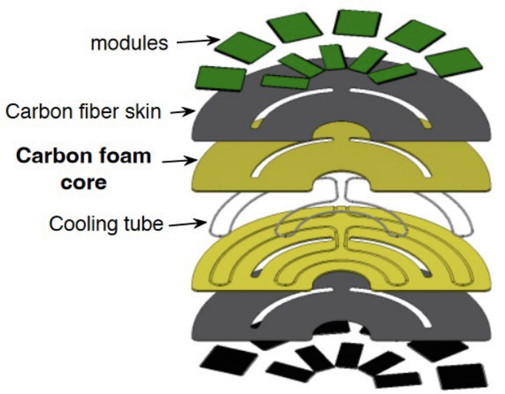


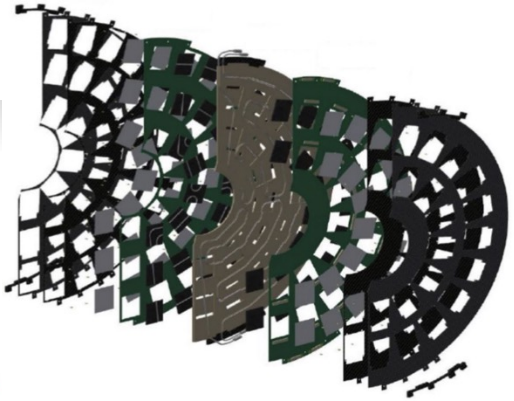


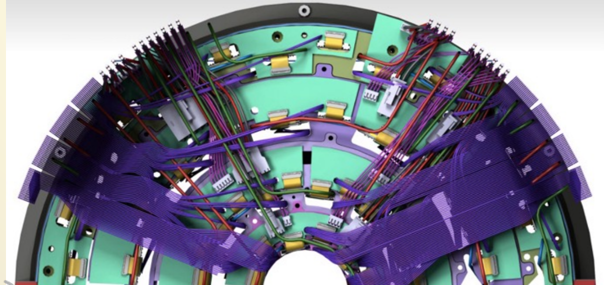
Mechanics and Integration

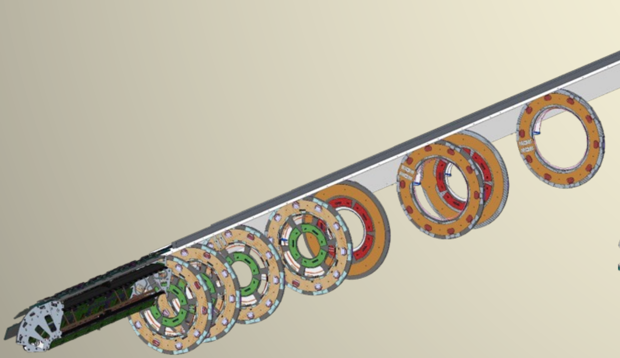
- Vital part of HEP experiment
- Contradicting requirements
  - Power-Cooling
  - Precision-Mass

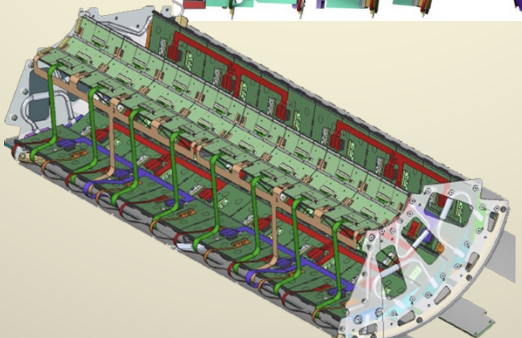


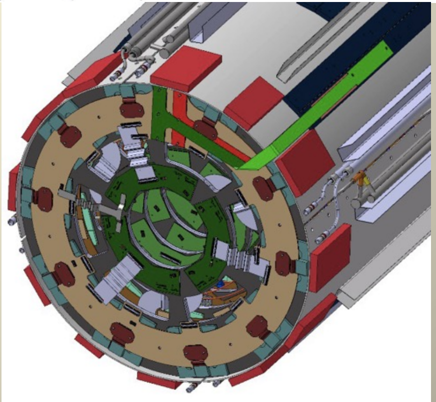






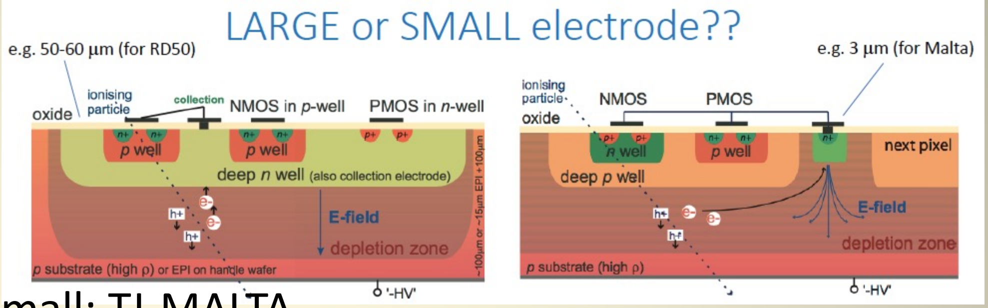






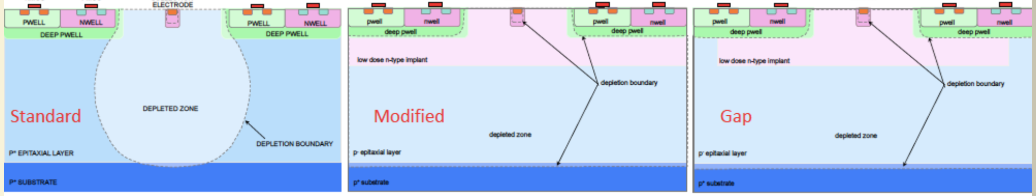
CMOS Detectors

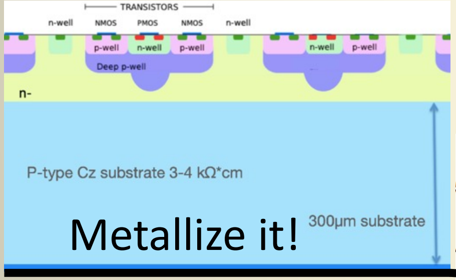
- The future is theirs !
  - Small vs. large electrode
    - Can small be radhard enough?



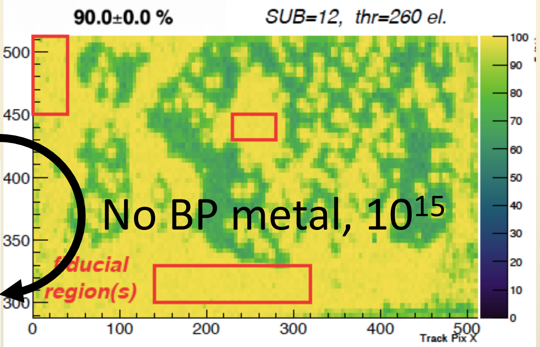
LARGE or SMALL electrode??

Small: TJ-MALTA

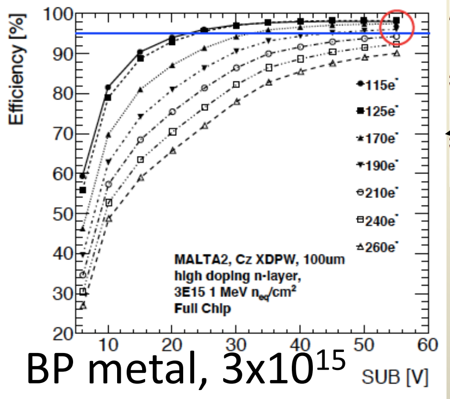




Metallize it!

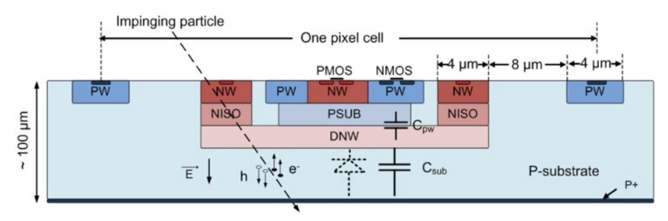


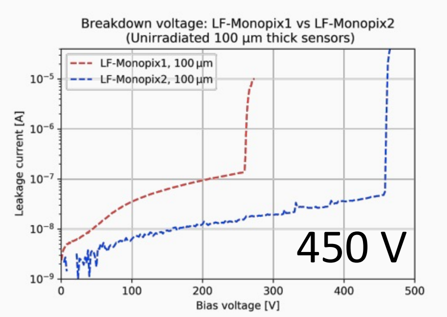
No BP metal, 10^{15}



BP metal, $3x10^{15}$

Large: LF-Monopix

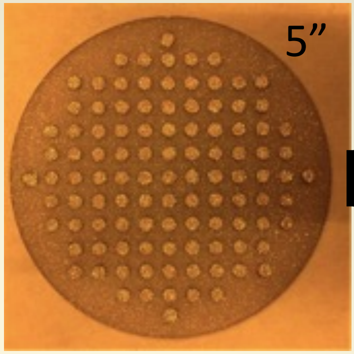


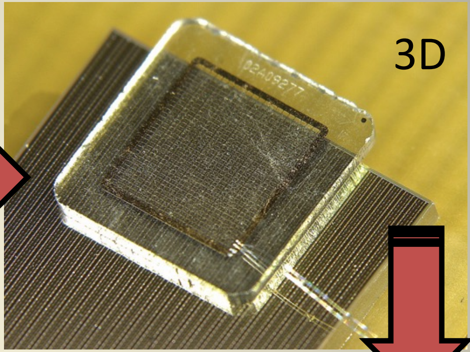


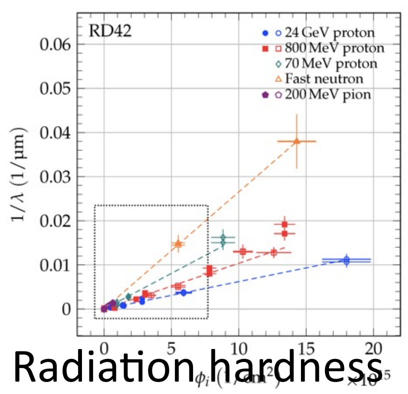
450 V

Beyond Silicon - Diamond

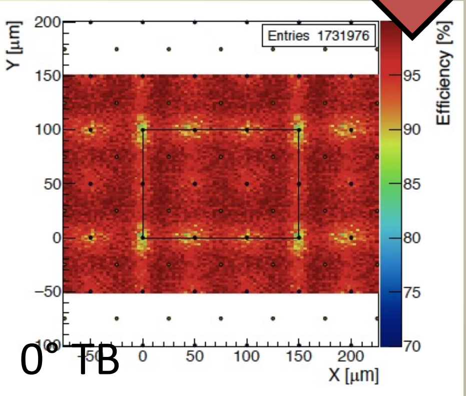
- 3D pixel (RD42)
  - Laser drilling of pCVD
  - 100x150, 50x50 μm^2
  - PSI46dig2 chip
  - 99.7% efficiency @70% CCE (@0° !)
  - Production up-scaling ??
  - Radiation hardness summary published
- BCM' (ATLAS ITk)
  - Planar pads 1-50 mm2 on 10x10 pCVD
  - Protection and lumi
  - Calypso asynchronous R/O
  - To be installed in inner pixel in 2025



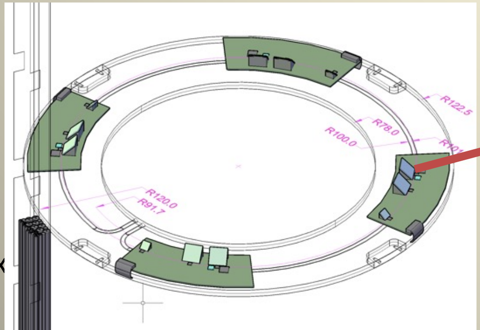


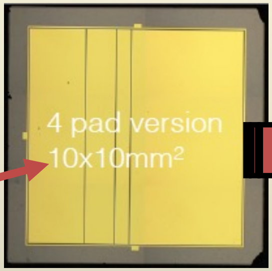


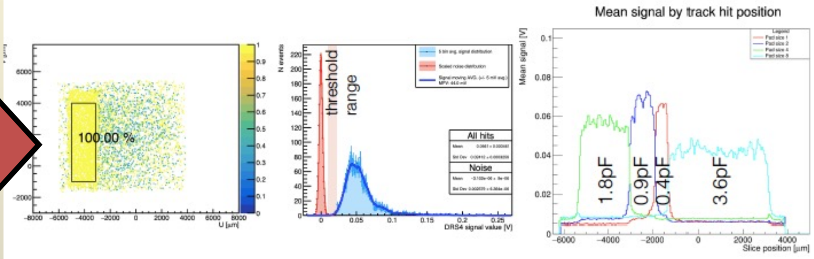
Radiation hardness



0° TB



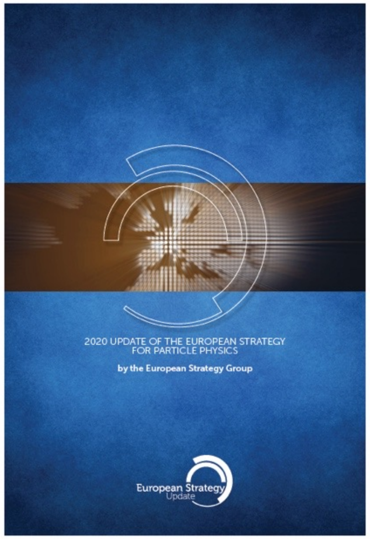




Part II : Outlook

Future (Global) HEP Projects

- The 2020 *European Strategy for Particle Physics* establishes two project initiatives as high-priority
  - *"the highest-priority next collider"*: "*an electron-positron Higgs factory*"
  - for the longer term: *"a proton-proton collider at the highest achievable energy"*, dubbed as the *FCC-hh* project.
- End of 2021 the *ECFA Detector R&D Roadmap* was approved by the CERN Council
  - Long term HEP Detector R&D goals defined
  - Implementation strategy in terms of Detector R&D Collaborations (DRDC) worked out, starting in 2024
- Development cycle towards the use of a new technology in detectors spans over 10 to 20 years.
  - *prospective* detector R&D ("Blue Sky" research) – TRL 1
  - *guided* detector R&D, according to known needs of future projects – TRL 2-5
  - *focussed* detector R&D of approved experiments – TRL 5-7



2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

European Strategy Update

SYNOPSIS OF THE 2021 ECFA DETECTOR RESEARCH AND DEVELOPMENT ROADMAP

by the European Committee for Future Accelerators Detector R&D Roadmap Process Group

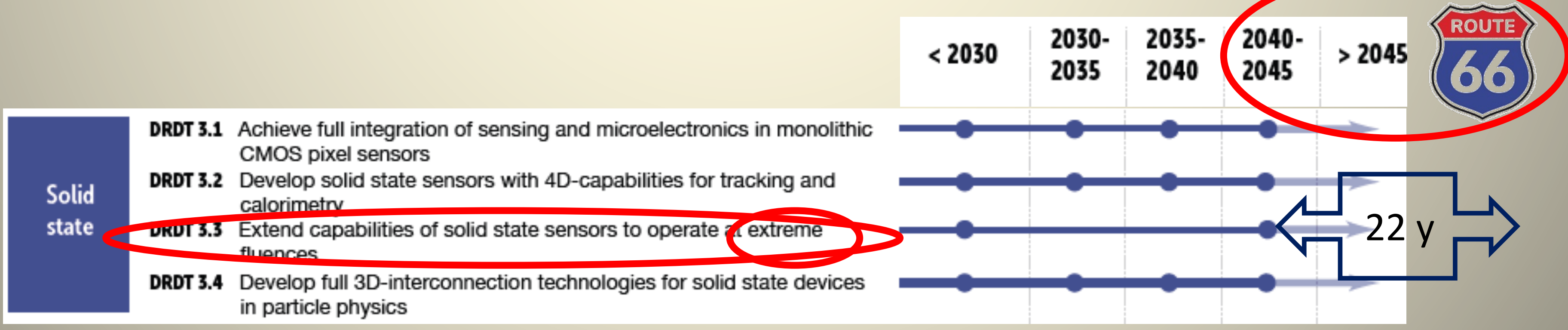
European Strategy Update

ECFA European Committee for Future Accelerators

What’s in for Pixels ?

- No doubt we’re Solid State…
- We’ve heard a lot of the 3 out of 4 DRDT’s
  - Monolithic CMOS
  - Precision timing –> 4D tracking
  - 3D interconnects
- Nothing on extreme fluences (DRDT 3.3)

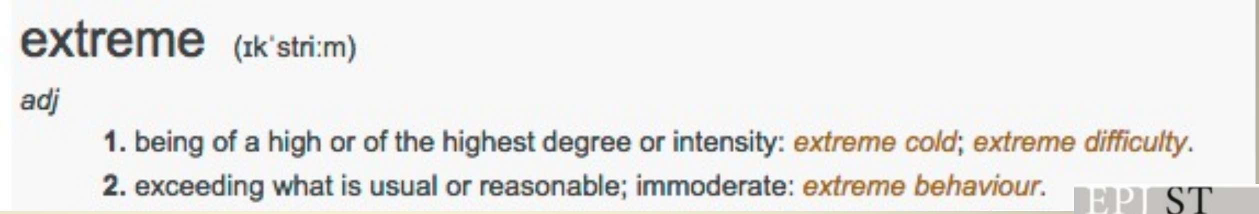
… so let me try to make up for this !



			< 2030	2030-2035	2035-2040	2040-2045	> 2045
Solid state	**DRDT 3.1**	Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors	●	●	●	●	→
	DRDT 3.2	Develop solid state sensors with 4D-capabilities for tracking and calorimetry	●	●	●	●	→
	DRDT 3.3	Extend capabilities of solid state sensors to operate at extreme fluences	●			●	→
	DRDT 3.4	Develop full 3D-interconnection technologies for solid state devices in particle physics	●	●	●	●	→

Extreme ?

- What is extreme ?

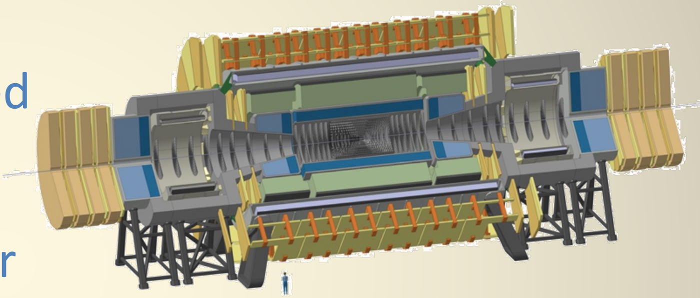


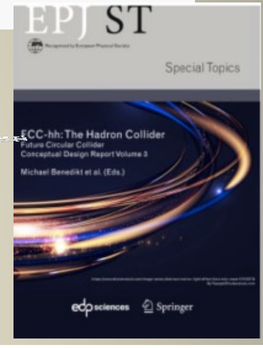
extreme (ɪkˈstriːm)

adj

1. being of a high or of the highest degree or intensity: *extreme cold*; *extreme difficulty*.
2. exceeding what is usual or reasonable; immoderate: *extreme behaviour*.

- A rather subjective measure
  - for LHC 10^{15} n_{eq}/cm^2 was considered extreme
    - design was 730/fb @14TeV...
  - HL-LHC takes it to nx10^{16} (vertex) or even 10^{17} (FW calo)
    - 4000/fb @14TeV
  - FCC-hh is *specifying* towards 10^{18} for the tracker (*FCC-hh CDR*)
    - 30/ab @100TeV
    - 300 MGy TID in addition (not addressed)
  - Ratio 1:20:600 !
    - well, you *need* ~7^2≈50 in HL/FCC lumi...
- What is the limit of tracking sensors ?
  - TRIGA, NPP and ITER are 10^{21} ⟷10^{24}





EPJ ST

Special Topics

FCC-hh: The Hadron Collider

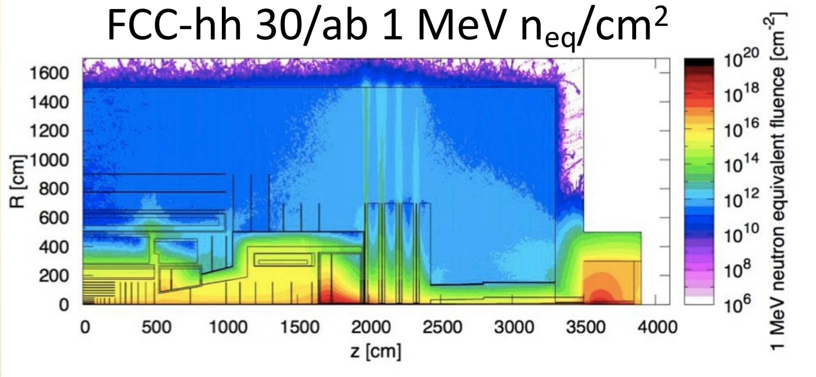
Future Circular Collider

Conceptual Design Report Volume 3

Michael Benedikt et al. (Eds.)

edp sciences Springer

FCC-hh 30/ab 1 MeV n_{eq}/cm^2



First tracking layer:

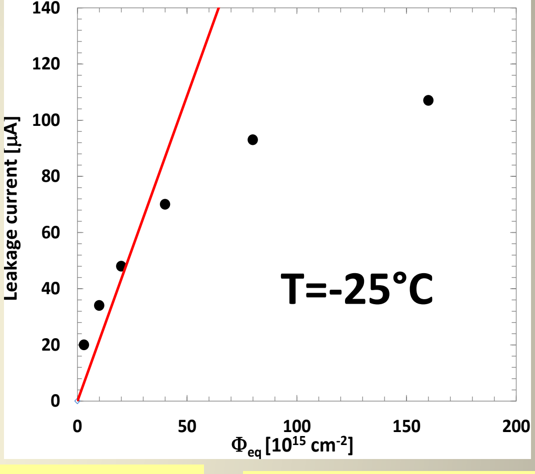
- 10 GHz/cm^2 charged particles
- 10^{18} hadrons/cm^2 for 30/ab

Expectations for 10^{17} n_{eq}/cm^2

- For a ~yearly replacement of FCC-hh inner tracker !
  - Or a 2-stage operation 5->30/ab
- Linear extrapolation from low fluence data
  - Current: I_{leak} = 4 A/cm^3 @20°C
    - 2 mA/cm^2 (2W @ 1 kV) for 300 μm thick detector @ -20°C
  - Depletion: $N_{eff} \approx 1.5\times10^{15}$ cm^{-3}
    - $FDV \approx$ 100 kV
  - Trapping $\tau_{eff} \approx$ 1/40 ns = 25 ps
    - $Q \approx Q_0/d\, v_{sat}\tau_{eff} \approx$ 80 e/μm 200 μm/ns 1/40 ns = 400 e in very high electric field (>>1 V/μm)
- Looks much like *Mission Impossible* (part n...)

CCE measurements up to $1.6\times10^{17}\ \mathrm{n_{eq}/cm^2}$

- *n^+p* ”spaghetti” strips, 300 µm
- Observed signal not at all compatible with expectations
  - Above 3×10^{15} linear *$CCE(V_{bias})$*
  - Power law scaling with fluence, *b* ≈ -⅔
  - Leakage current “saturating”

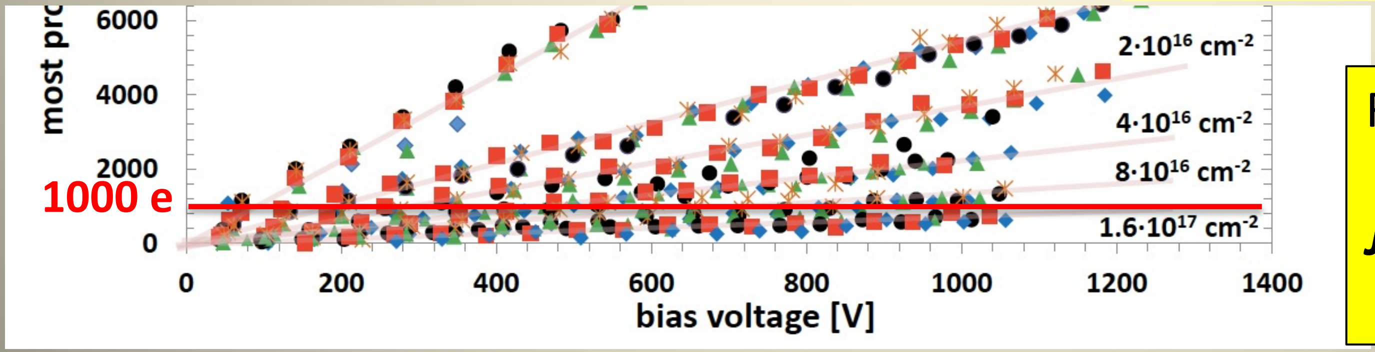


$$Q_{MPV}(V,\Phi) = k\cdot\left(\Phi/10^{15}\ \mathrm{n_{eq}/cm^2}\right)^{b}\cdot V$$

$$k = 26.4\ \mathrm{e_0/V}$$

$$b = -0.683$$

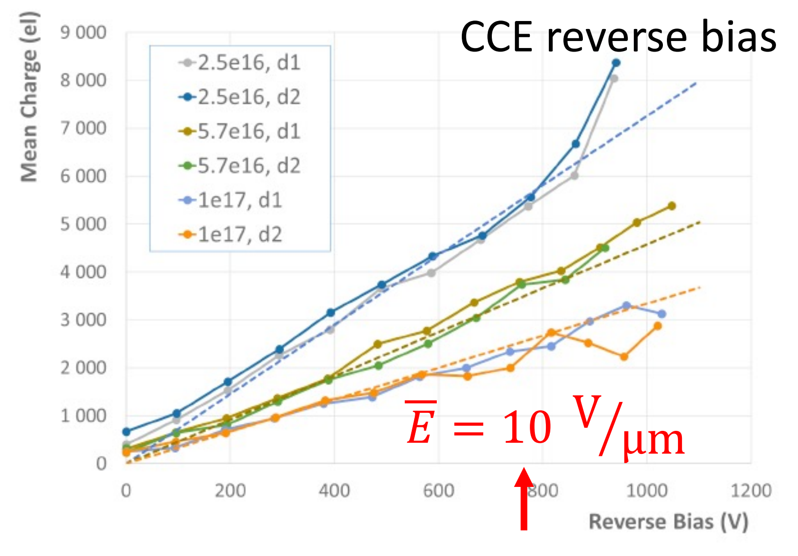
“Magic formula”

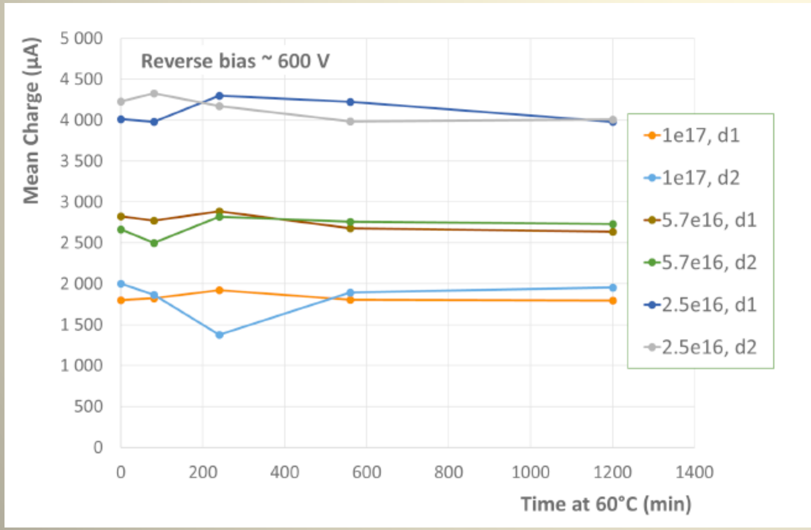


From:
G. Kramberger et al., *JINST 8 P08004 (2013).*

More measurements on thin detectors

- 75 µm epi detectors from CNM on low-resistivity substrate
- Irradiated to 0.25, 0.57 and 1.0x10^{17} n$_{eq}$/cm^2
- *CCE* in reverse and FW
- Annealing 1200 min @ 60°C





$$Q_{mean} = k \cdot \phi^{b} \cdot V$$

$$k_{75} = 44\ \mathrm{e_0/V}$$

$$b_{75} = -0.56$$

Thinner is better!

From:
I.Mandić et al.,
JINST 15 P11018 (2020).

Linear *CCE(V)* ??

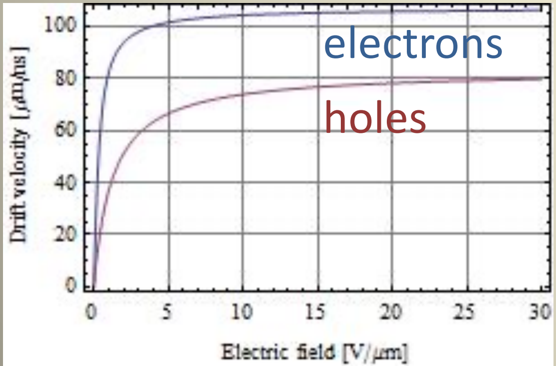
- What could be linear
  - SCR governed *CCE(V)* after irradiation (√*V*), highly resistive ENB (√*V*), without trapping
  - Trapping dominated with non-saturated drift velocity
- What is *not* linear
  - velocity saturation
  - charge multiplication
  - double junction
  - field in ENB
  - …
- Just a nice coincidence or some physics behind ?
  - look *into* silicon to search for an answer

➢ Using edge-TCT to probe silicon

Electric Field Measurement

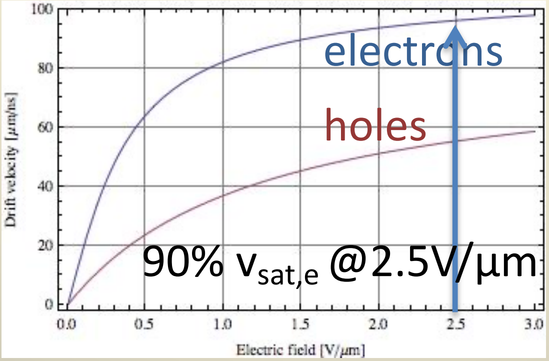
- Initial signal proportional to velocity sum at given detector depth
- Caveats for field extraction
  - Transfer function of electronics smears out signal, snapshot taken at ~600 ps
    - Problematic with heavy trapping
    - Electrons with v_{sat} hit electrode in 500 ps
  - Mobility depends on *E*
    - *v* saturates for *E* >> 1V/µm

$$I(t=0) = q\vec{v}\cdot\vec{E}_w =$$
$$= N_{e-h}e_0\cdot(v_e+v_h)/d =$$
$$= N_{e-h}e_0\cdot(\mu_e+\mu_h)\cdot E(x)/d$$



electrons

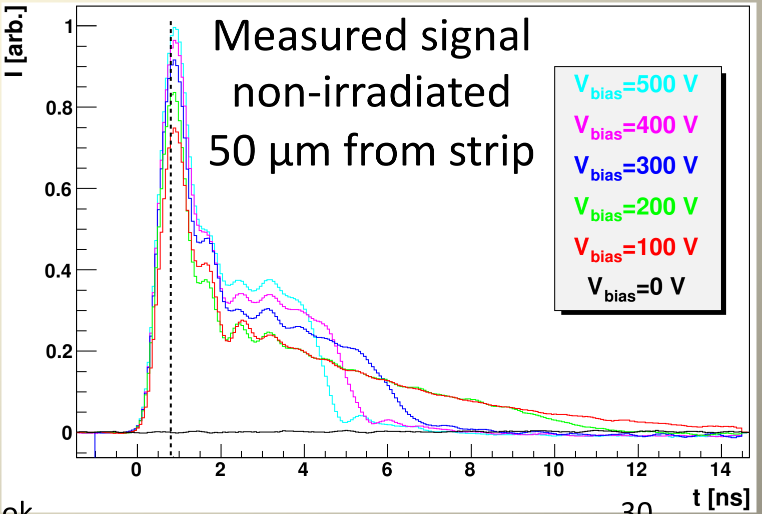
holes



electrons

holes

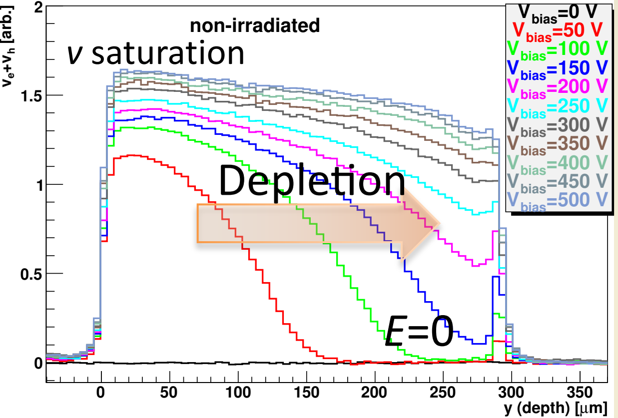
90% $v_{sat,e}$ @2.5V/µm

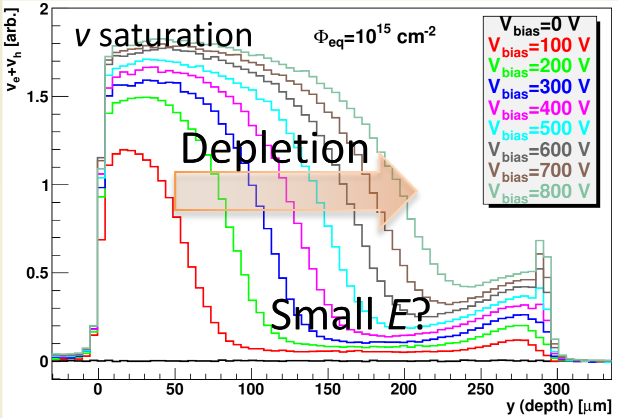


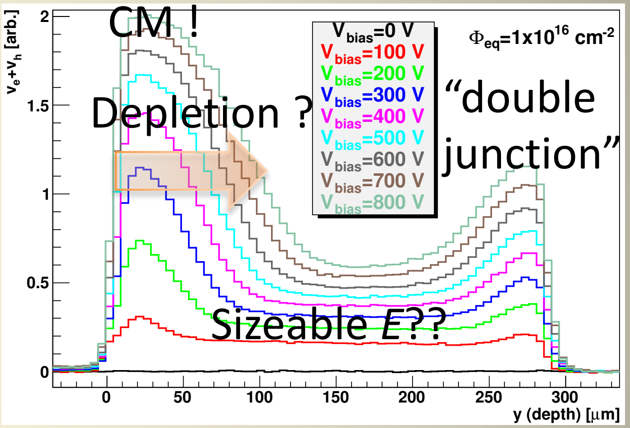
Measured signal
non-irradiated
50 µm from strip

Selected Results from Neutrons

- Hamamatsu ATL07 n^+ mini-strip, FZ p-type, neutron irradiated at JSI TRIGA reactor
  - In steps up to 10^{16} n_{eq}/cm^2





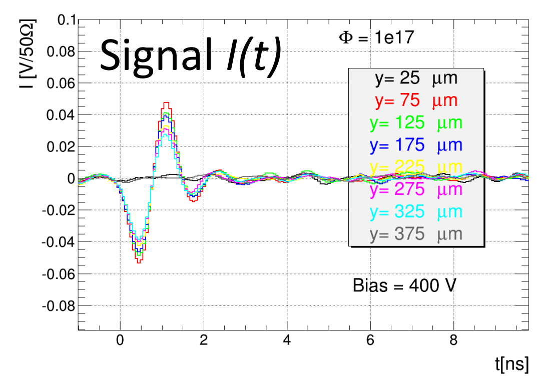


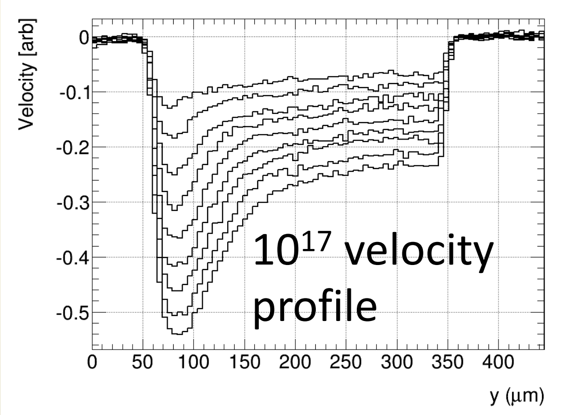
- Very instructive regarding qualitative electric field shape
  - Non-irradiated "by the book" for abrupt junction n^+p diode
    - SCR and ENB nicely separated, small double junction near backplane
  - Medium fluence ($\Phi=10^{15}$ neutrons): some surprise
    - Smaller space charge than expected in SCR, some field in "ENB"
  - Large fluence ($\Phi=10^{16}$): full of surprises
    - Still lower space charge, sizeable field in "ENB"
    - Charge multiplication (CM) additional trouble for interpretation at large *V*
- Nice, but let's try to get *quantitative* !

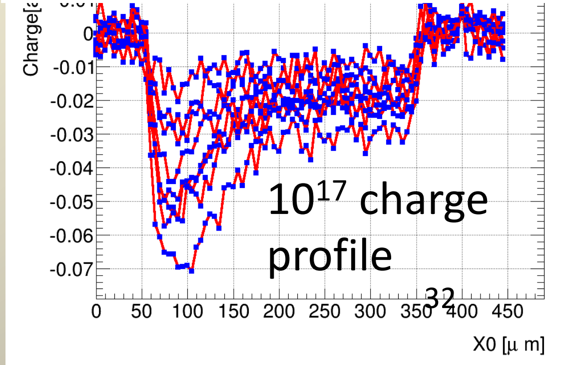
Published in :
G. Kramberger et al.,
JINST 9 P10016(2014).

Extending the Reach

- In 2014 added 5×10^{16} and 10^{17} n_{eq}/cm^2 measurements of the same detector
  - 10^{16} of this fluence fully annealed, the rest 80 min @ 60°C
- Intrinsic feature – signal oscillations
  - period ~5/4 ns
  - LRC (C~2pf => L~20 nH ~ 1cm of wire)
- Velocity (slope) and charge (integral) yield consistent results
- should be, as $Q \approx Q_0 v_{sum} \tau_{eff} / d$

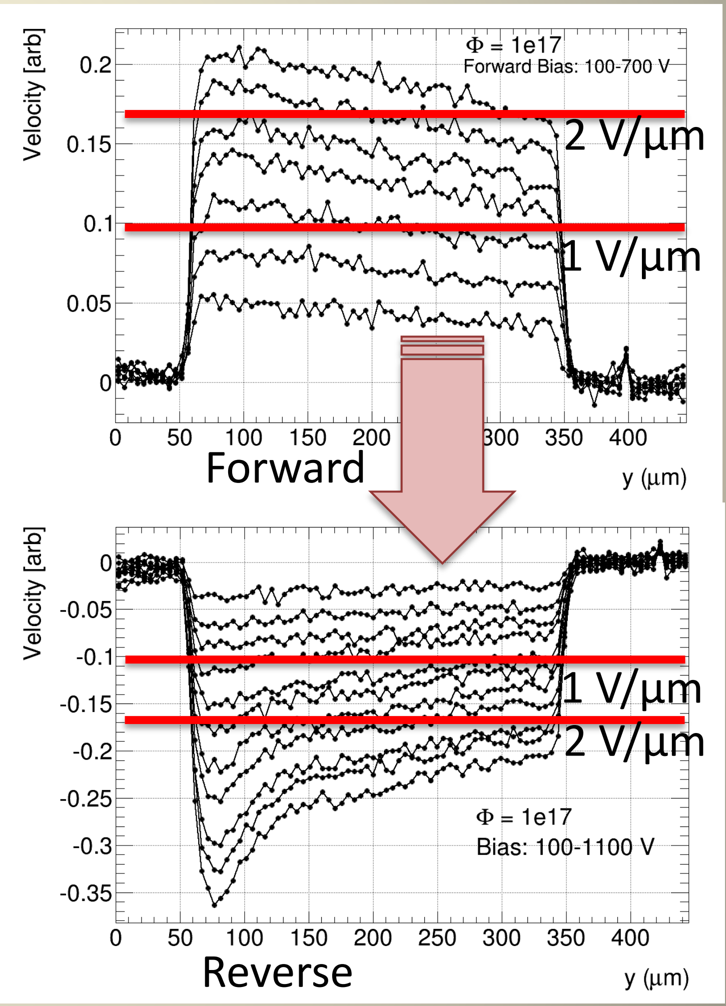






Absolute Field Measurement

- Solution: *concurrent* forward bias v_{sum} measurements
  - Ohmic behaviour with some linear (field) dependence
    - constant (positive) space charge
  - can use $\int E(y)dy = \bar{E}d = V$ to pin down field scale
    - corrections from *v(E)* non-linearity small
- Use same scale for reverse bias!
- FW measurements up to 700 V
  - know *E* scale up to 2.33 V/µm
  - can reveal *v(E)* dependence

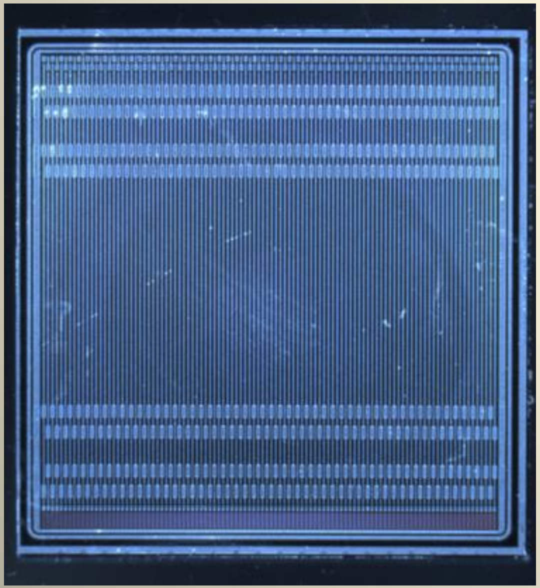


Proton Irradiations

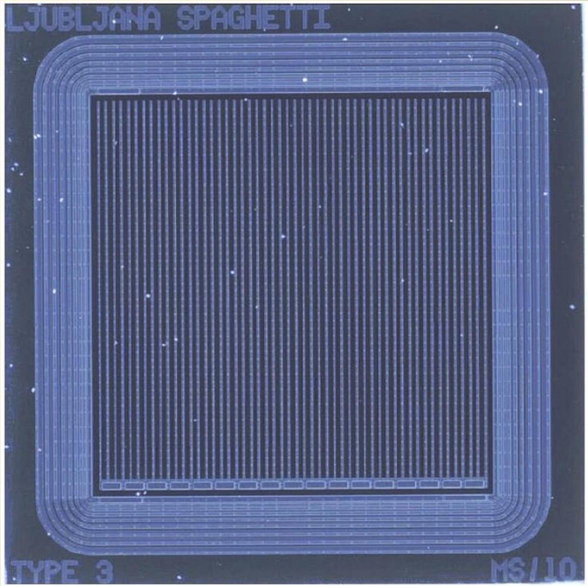
- 5 sample pairs of ATL12 mini-strips irradiated at CERN PS during summer 2015
  - got 0.5, 1.0, 2.9, 11, 28e15 protons/cm^2, no scanning
  - NIEL hardness factor 0.62
  - thanks to CERN IRRAD team
    - took **41 PS days** to reach the highest fluence
- Covers HL-LHC tracker range well
  - does really not look practical for 10^{17}++
- 2 samples per fluence investigated by E-TCT for all fluences
  - concurrent forward and reverse bias measurements

Additional Irradiations

- 3e17 n_{eq}/cm^2, JSI reactor neutrons
  - A12 mini, 7x8 mm^2, 75 µm pitch, 300 µm thick
    - Also to 3e16, 1e17
  - Spaghetti: 4x4 mm2, n-on-p, strip pitch 80 um, 300 um thick, strips connected together at side
    - 1.6e17 received previously, 4.6e17 total



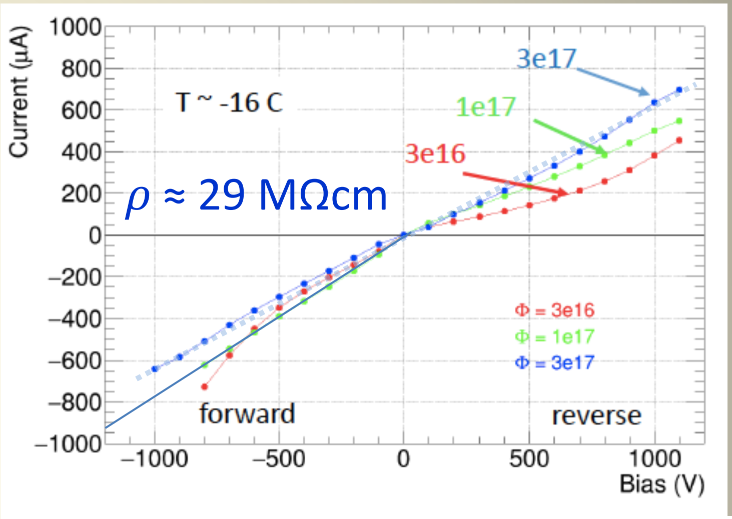
A12



Spaghetti

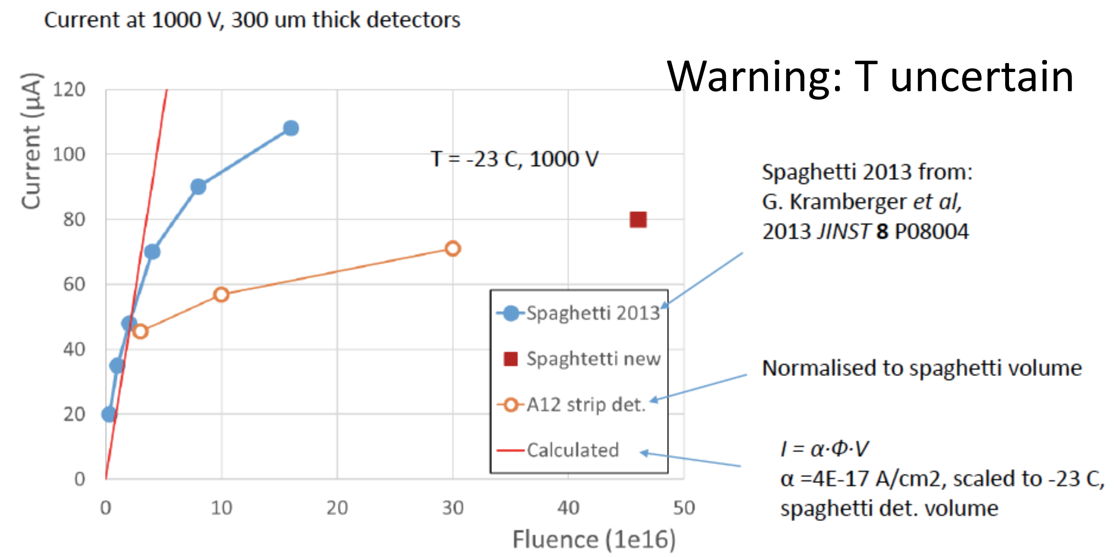
Basic Measurements

- *I-V* for 3&4.6e17 looks very linear with little difference between reverse/FW bias
  - No breakdown, as observed in LGAD's
- *I* @1000 V does not scale linearly with fluence !
  - Not governed by generation current ?
- Tried to measure 4.6e17 spaghetti *CCE* with ^{90}Sr
  - No signal above background observed up to 320 V
  - Magic formula predicts 120e for 4.6e17 @320 V



$\rho \approx 29$ MΩcm

Current at 1000 V, 300 um thick detectors

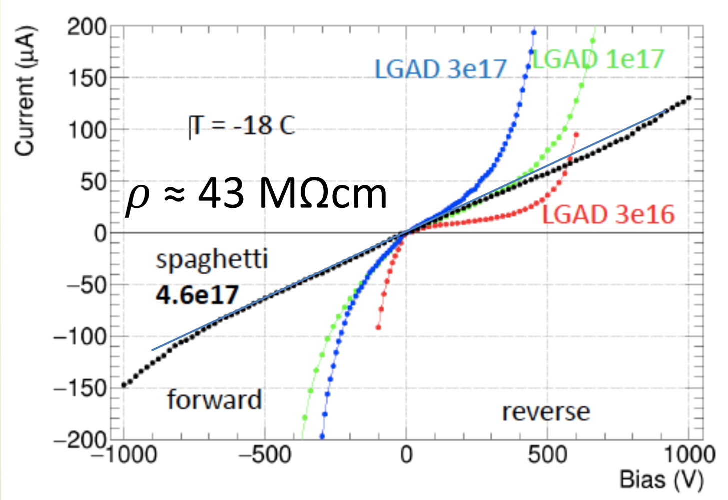


Warning: T uncertain

Spaghetti 2013 from:
G. Kramberger *et al*,
2013 *JINST* **8** P08004

Normalised to spaghetti volume

$I = \alpha \cdot \Phi \cdot V$
α =4E-17 A/cm2, scaled to -23 C, spaghetti det. volume



$\rho \approx 43$ MΩcm

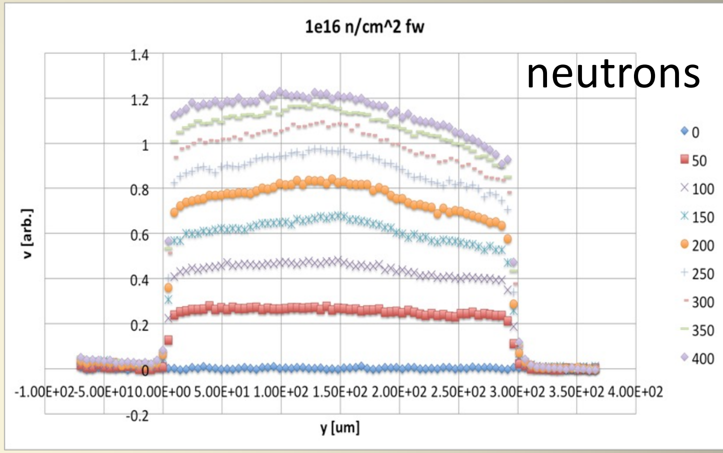
Mobility Considerations FW bias

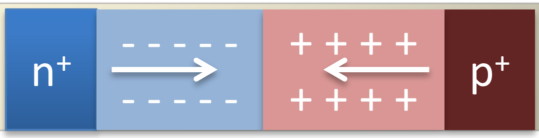
- For forward bias can extract *v(E)* up to a scale factor
- Observe less saturation than predicted
- Model with

$$v_{sum}(E)=\frac{\mu_{0,e}E}{1+\mu_{0,e}E\Big/v_{e,sat}}+\frac{\mu_{0,h}E}{1+\mu_{0,h}E\Big/v_{h,sat}}$$

  - keep saturation velocities at nominal values @-20°C ($v_{e,sat}$ = 107 µm/ns; $v_{h,sat}$ = 83 µm/ns)
  - float (common) zero field mobility degradation
  - fit *v(E)* for $\phi_n \geq 5\times10^{15}$ and $\phi_p \geq 3\times10^{15}$

n.b. FW profiles less uniform for lower fluences & protons; departures from average field still small, corrections *O(%)*




n^+

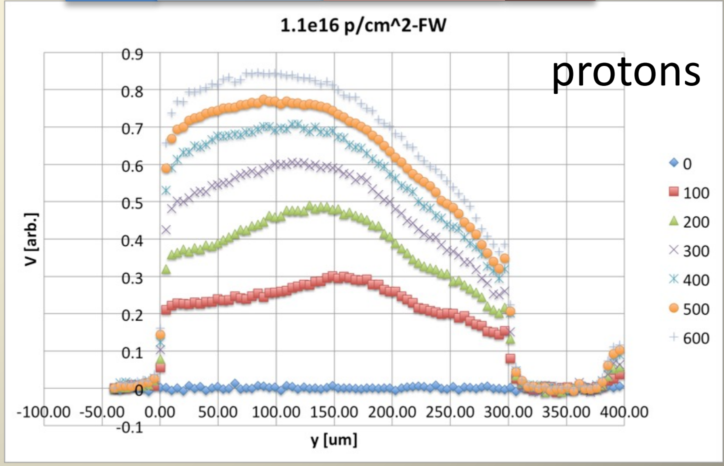
\- - - - -

\- - - - -

\+ + + +

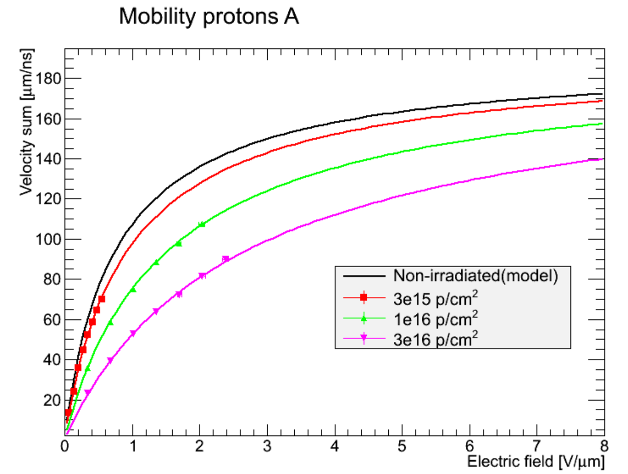
\+ + + +

p^+

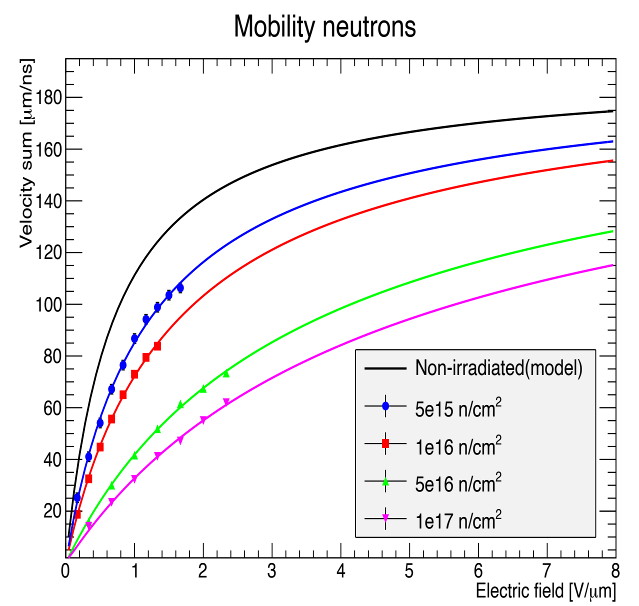


Mobility Fits

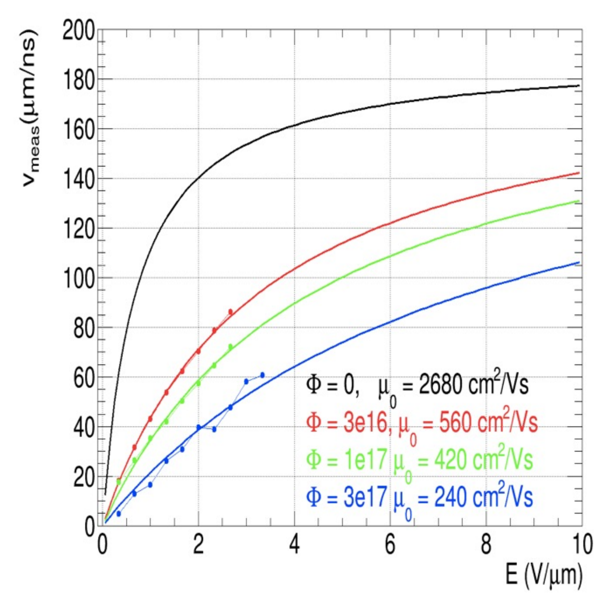
- Data fits model almost perfectly
  - μ_0 degradation the only free parameter, scale fixed by $v_{sum,sat}$
  - At 3e17 *E* range too limited (*v(E)* linear), regard result as upper limit

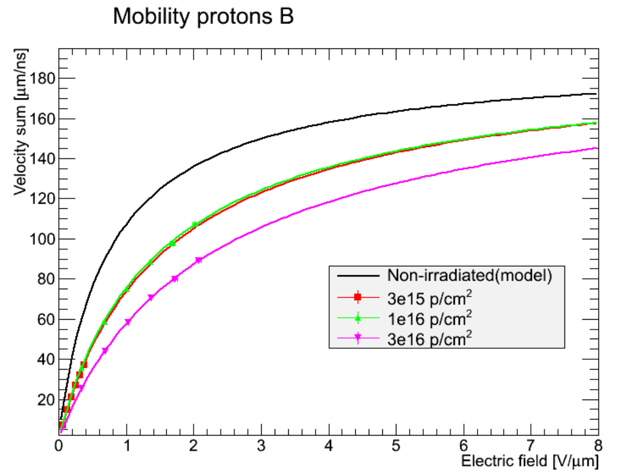


Mobility protons A



Mobility neutrons





Mobility protons B

Mobility Results

- Fit to $v_e + v_h$ with common mobility degradation factor
  - factor of 2 at 10^{16} n_{eq}/cm^2, 6 at 10^{17} n_{eq}/cm^2, >10 at $3x10^{17}$ n_{eq}/cm^2
  - need 2x/6x/>10 higher *E* to saturate *v* !
  - ☠ correspondingly higher *E* for charge multiplication !

Φn	$\mu_{0,sum}$	Φp	$\mu_{0,sum}$
[10^{15} n_{eq}/cm^2]	[cm^2/Vs]	[10^{15} n_{eq}/cm^2]	[cm^2/Vs]
non-irr (model)	2680		
5	1661 ± 134	1.6	2063± 188
10	1238 ± 131	6.1	1337± 47
30	560	15.4	817± 42
50	555 ± 32		
100	407 ± 40		
100	420	**T=-20°C**	
300	<240		

Mobility Analysis

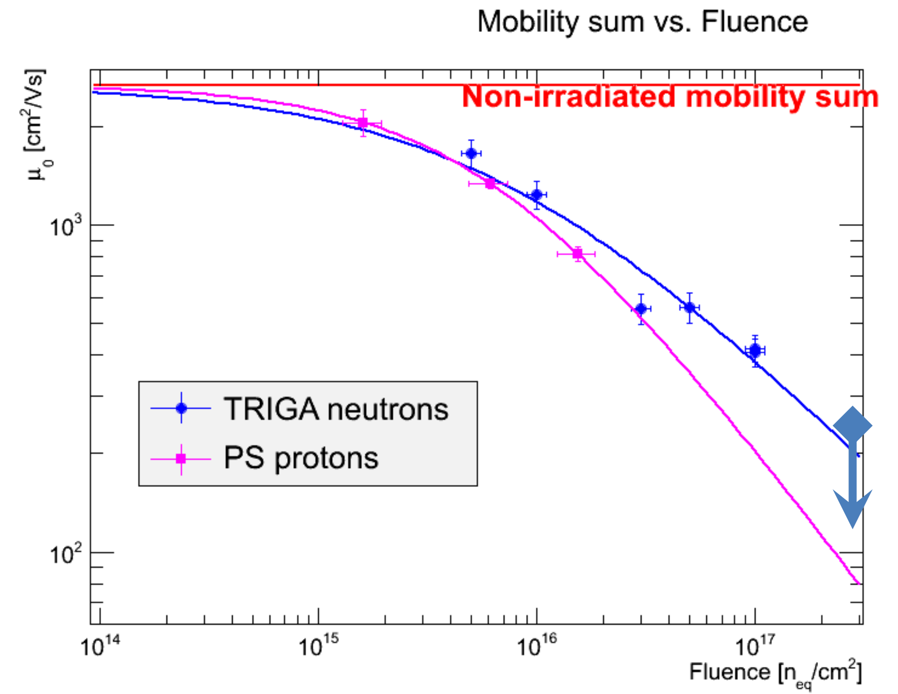
- Mobility governed by hard scattering on acoustic phonons and traps

$$1/\tau = 1/\tau_{ph} + 1/\tau_{trap}$$

- Fit mobility dependence on fluence with a power law

$$\mu_{0,sum}(\Phi) = \frac{\mu_{0,sum,phonon}}{1+\left(\frac{\Phi}{\Phi_{1/2}}\right)^{a}}$$

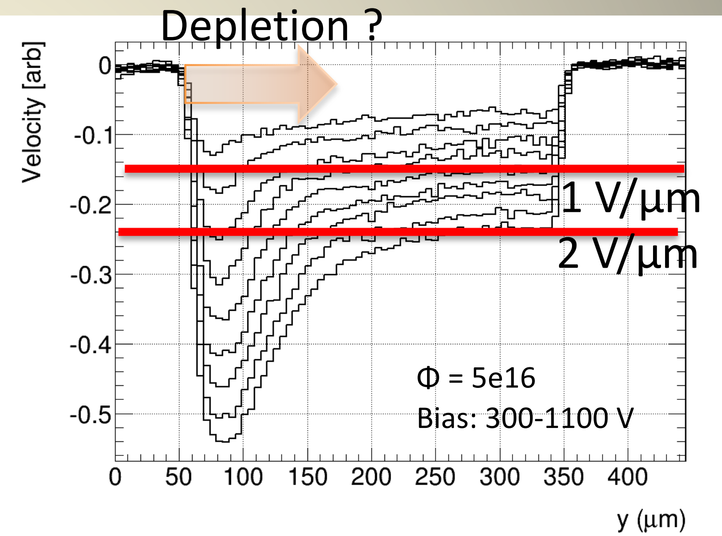
- Fits perfectly, value of *a* close to linear
  - 10% error assumed for all neutron data
- At same NIEL, mobility decrease worse for protons
  - NIEL violation ? Large errors ?

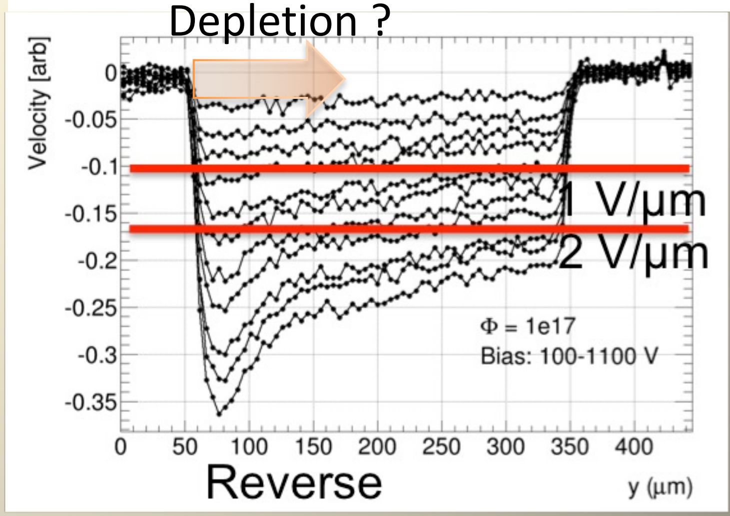


Irradiation particle	*a*	σ_a	$\Phi_{1/2}$ /10^{15}	$\sigma_{\Phi 1/2}$ /10^{15}
Reactor neutrons	-0.68	0.08	6.9	1.7
PS protons	-0.90	0.19	6.1	1.0

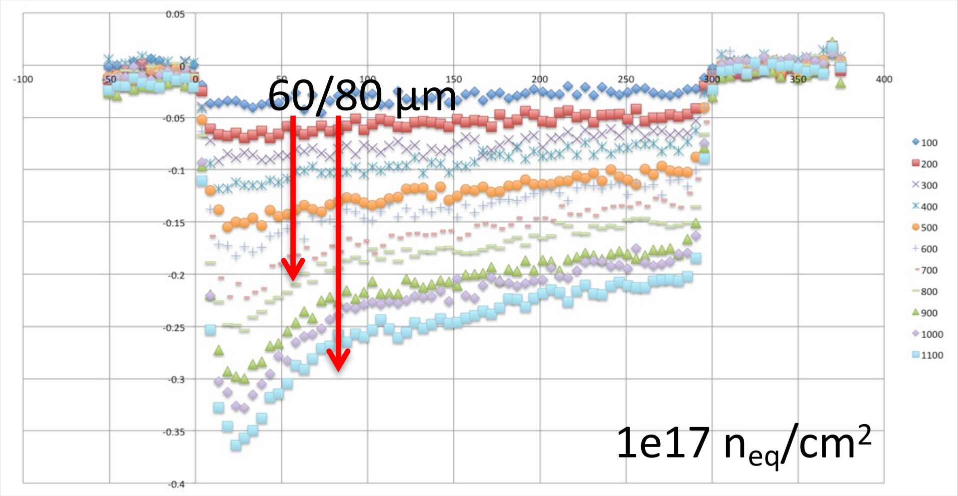
Reverse Bias Field Profile

- Two distinct regions at high biases
  - Large region from backplane with (small) slope in the field
    - constant (small, negative) space-charge
    - *E = j.ρ* at junction ? like “ENB” ?
    - indication of thermal (quasi)equilibrium: $np = n_i^2$?
    - thus no current generation ?
  - Small region at junction building up with bias
    - depleted space-charge region ?
    - source of generation current ?





SCR Consistency



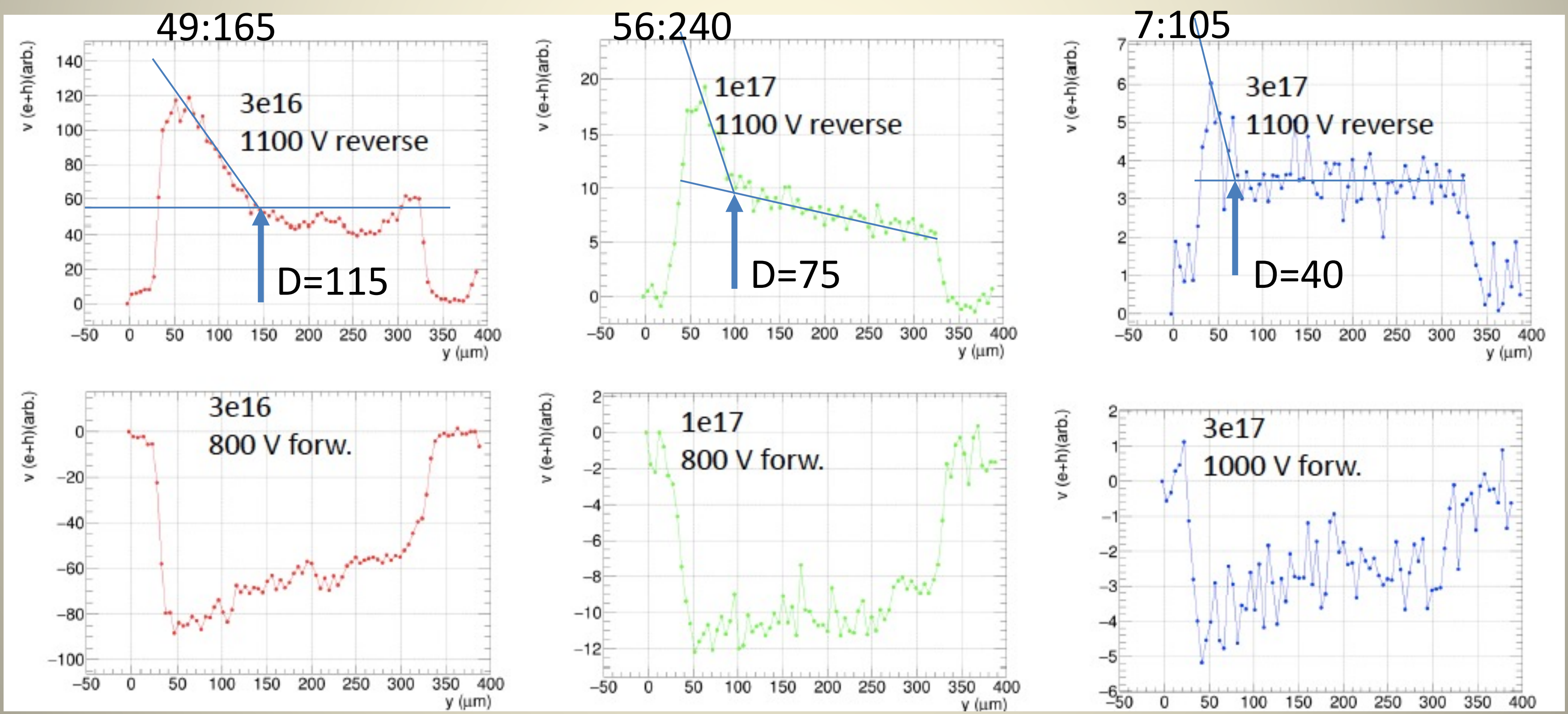
- Hard to estimate SCR extent, especially at lower bias and highest fluence
- A crude estimate
  - 5×10^{16} n_{eq}/cm^2 :

    ~80 µm @ 600 V; ~120 µm @ 1000 V
  - 10^{17} n_{eq}/cm^2 :

    ~60 µm @ 600 V; ~80 µm @ 1000 V
- Predicted/measured currents
  - 5×10^{16} n_{eq}/cm^2: 300/300 µA @ 600 V; 400/500 µA @ 1000 V
  - 10^{17} n_{eq}/cm^2: 400/300 µA @ 600 V; 500/600 µA @ 1000 V
  - Not compatible with linear *I-V* at 3 & 4.6e17 – pure resistor ?
- Reasonable agreement with current generated exclusively in SCR
  - n.b. - current "saturation" observed @1000V in *JINST 8 P08004 (2013)*
- Acceptor introduction rates: $g_c \approx 6/4 \times 10^{-4}$ cm^{-1}
  - substantial part (up to 80 %) of voltage drop "spent" in "ENB"
  - matches well data in ***JINST 9 P10016(2014)*** (up to 10^{16})

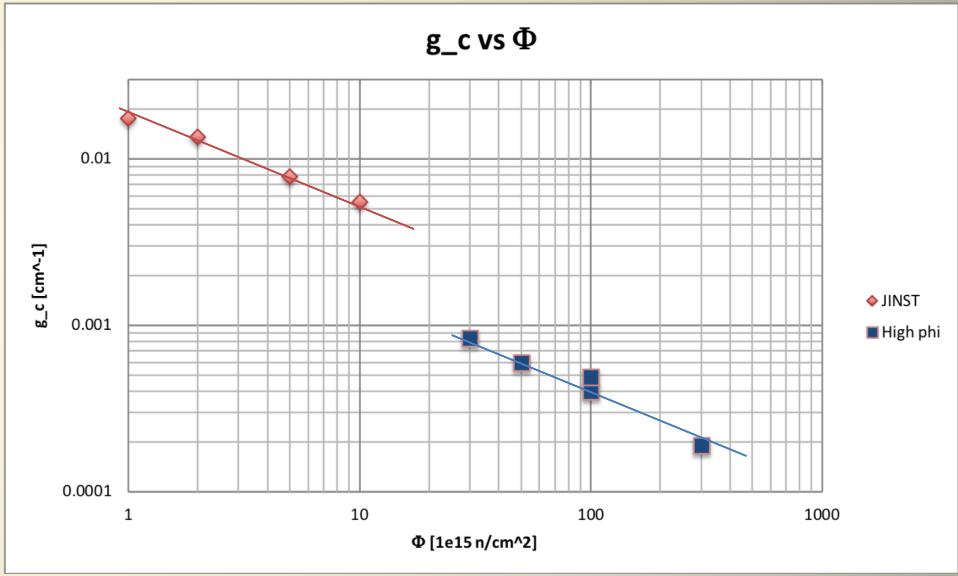
ATL12 up to 3e17

- Estimate of SCR width 115 -> 75 -> 40 µm
- V_{drop} in SCR only 23 -> 19 -> 6 % of 1100 V



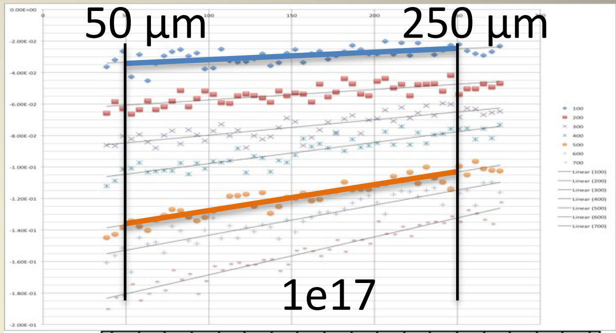
Acceptor introduction in SCR

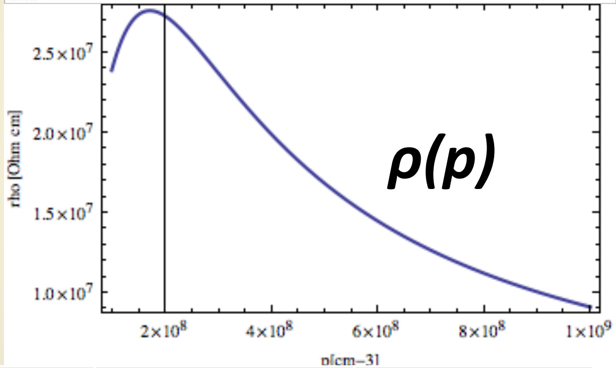
- Stable acceptor introduction rate g_c drops by nearly two orders of magnitude from low fluences to $3\text{x}10^{17}$
  - – Observed up to 10^{16} in ***JINST 9 P10016(2014)***
  - – Looks like a power law
    - g_c in JINST not taking into account voltage drop out of SCR – higher values of g_c



“ENB” Consistency

- Space charge in “ENB” rising with bias, e.g. for 10^{17} n_{eq}/cm^2
  - $1.6\text{x}10^{11}$@ 100 V, $9.2\text{x}10^{11}\text{cm}^{-3}$ @ 500V
  - c.f. ~$4\text{x}10^{13}\text{cm}^{-3}$ in SCR
  - negative space charge, like in SCR
- Resistivity from *ρ = j/E* @ 100 V
  - maximum *ρ(p)* ≈ $2.8\text{x}10^7$ Ωcm using nominal mobilities @ *p* ~ $2\text{x}10^8$ cm^{-3}
    - all measured values exceed this limit
  - compatible with measured mobility sum and $p \sim \mathcal{O}(10^9)$ cm^{-3}
  - Compatible also with *ρ* from *I-V* for 3 & 4.6e17



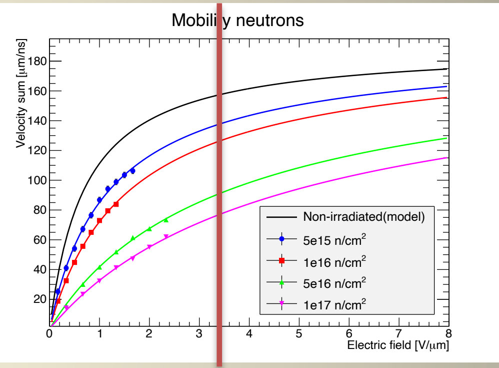


Φ	*ρ*	*p*
$[n_{eq}/\text{cm}^2]$	$[10^7\ \Omega\text{cm}]$	$[10^9\ \text{cm}^{-3}]$
1e16	3.3	0.5
5e16	3.0	1.5
1e17	2.8	2.1

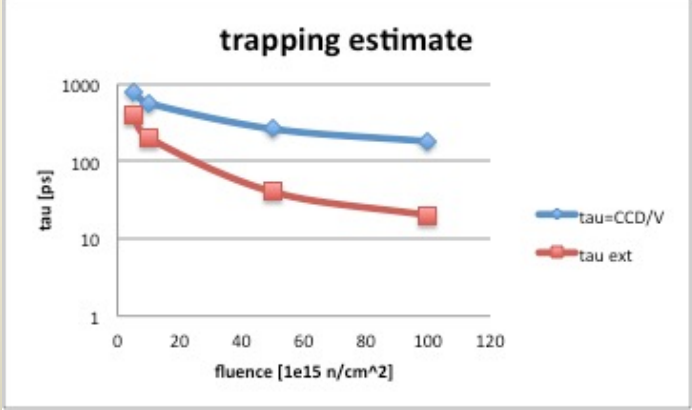
Trapping analysis

- Take v_{sum} at average E = 3.3 V/µm
- Calculate *CCD* from “magic formula”

Φ [1e15]	5	10	50	100
v_{sum}(3.3 V/µm)	137	126	90	77
$CCD_{1000\ \mathrm{V}}$ [µm]	110	70	23	14
$\tau \approx CCD/v$ [ps]	800	560	260	180
τ_{ext} [ps]	400	200	40	20

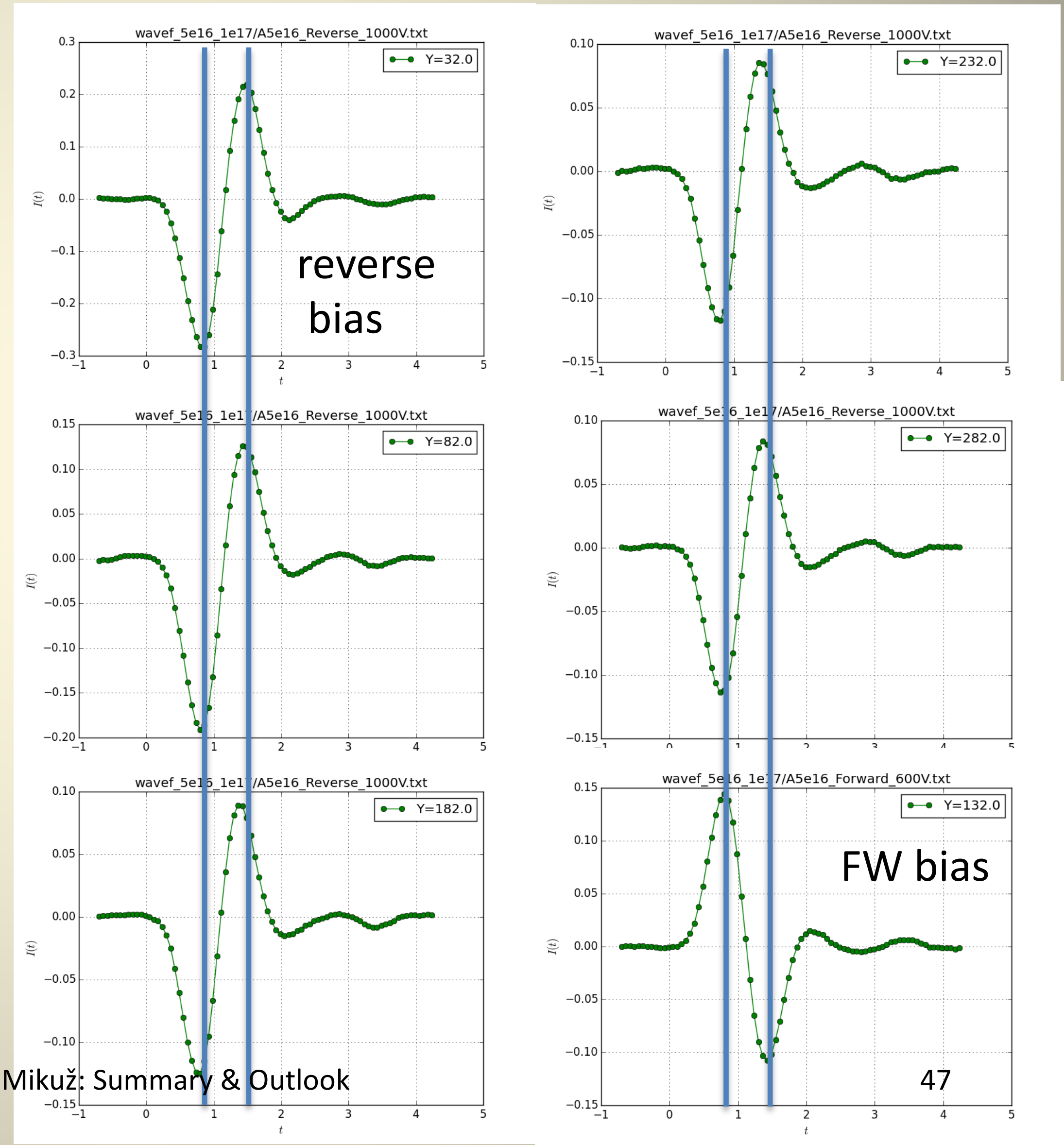


- Implies factor of 6-9 less trapping at highest fluences
  - lowest fluence still x2 from extrapolation
  - weak dependence on fluence as anticipated
  - CM would effectively shorten trapping times
  - not good when large *E* variations (*v(E)* saturates)
  - not good when *CCD* ≈ thickness (less signal at same *τ*)



Trapping – position dependence ?

- Waveforms plotted every 50 um in detector depth for reverse bias at 1000 V
- Forward bias in middle of detector added at 600 V
- Very little, if any, wf dependence on position observed
- Trapping not position (even not bias) dependent !?



Trapping revisited

- From *I.Mandić et al., JINST 15 P11018 (2020)*
  - FW bias CCE estimated by

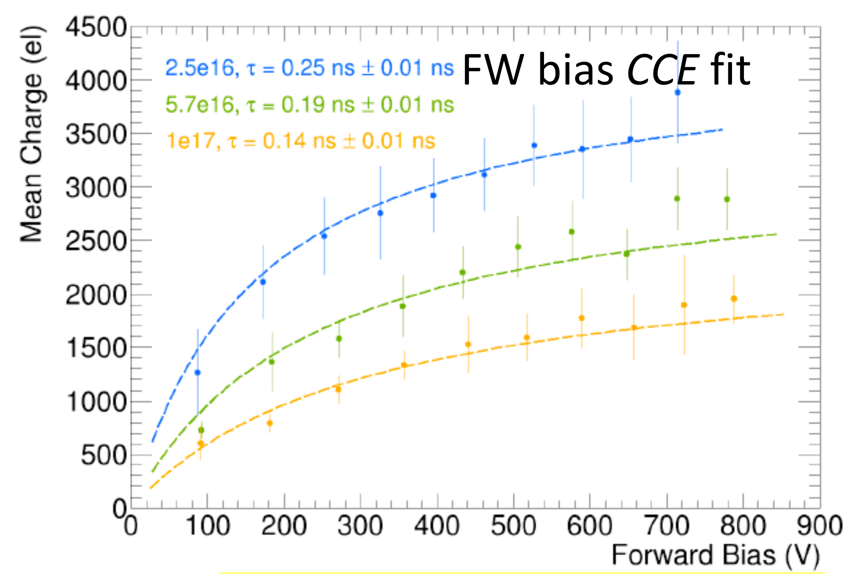
$$Q = \frac{\Delta Q}{\Delta x} \cdot v \cdot \tau$$

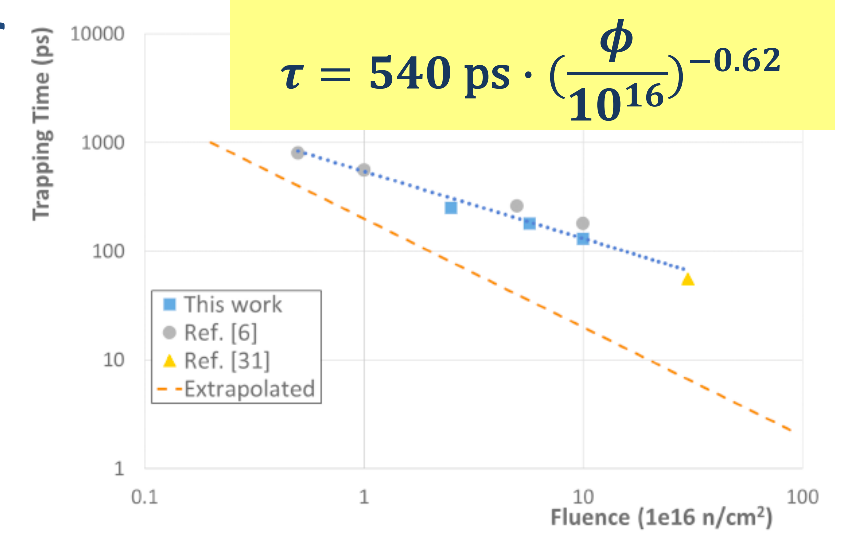
    - *v(E)* with fluence dependent *μ*
    - constant *E=V/D* (FW)

😀 Order of magnitude smaller than extrapolated !

😀 Agrees with estimates from reverse bias CCE

- Trapping independent of bias, seen in wave-forms





$$\boldsymbol{\tau = 540\ \mathrm{ps} \cdot \left(\frac{\phi}{10^{16}}\right)^{-0.62}}$$

Summary

- Measurements performed on Si detectors irradiated to extreme fluences
  - Neutrons from 10^{15} to 4.6×10^{17} n_{eq}/cm^2, PS protons from 5×10^{14} to 3×10^{16} p/cm^2
  - Velocity vs. electric field impact observed and interpreted as reduction of zero field mobility
    - Zero field mobility follows power law with $|a| \leq 1$, $\Phi_{½} \approx 10^{16}$ n/cm²
    - Protons degrade mobility more than neutrons
    - Induces resistivity increase in-line with measured *I-V*
    - Exhibits adverse effect on charge multiplication !
  - Simple field profile for very high neutron fluences
    - Diminishing SCR and highly resistive ENB
    - Effective acceptor introduction rates reduced by factor ~100 wrt low fluences
    - Current much lower than anticipated. Generated in SCR only ? Ohmic at highest fluences…
  - Trapping estimates for very high neutron fluences
      - from charge collection in FW and reverse bias
      - from waveforms
    - All estimates point to severe non-linearity of trapping with fluence, 10x lower at 10^{17}
    - Trapping appears independent of electric field
- Conclusion: ***Low fluence extrapolations do not work at all !***

… go out and ***measure*** to get anything working at ***extreme*** fluences !!!

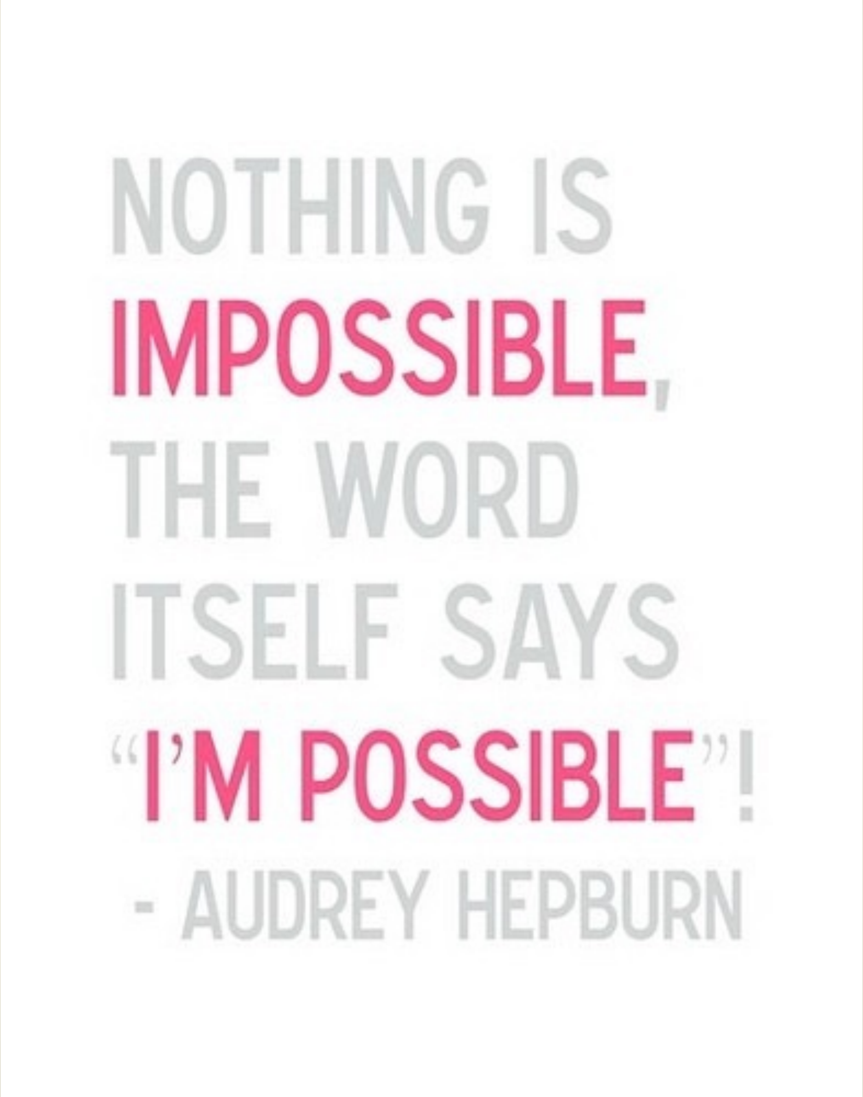
Implications for DRDT 3.3

- Basic bulk silicon properties in the fluence range to master are the prerequisite to any inner tracking detector design for *FCC-hh*
- They need to be ***measured***
  - Only pioneering consistency checks done so far
- Need resources far beyond current ones
  - Facilities
  - Measurement techniques
  - People

at least for the first ~5 of the 20 years

- New DRD Collaboration based on the RD50 research line essential for achieving the goal
  - EU funding should help to rise funds at national level

Conclusion



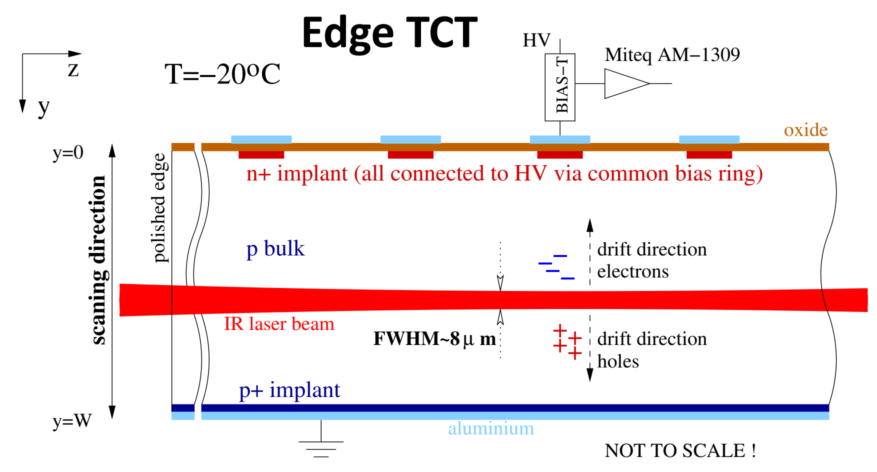
NOTHING IS IMPOSSIBLE, THE WORD ITSELF SAYS "I'M POSSIBLE"!

- AUDREY HEPBURN

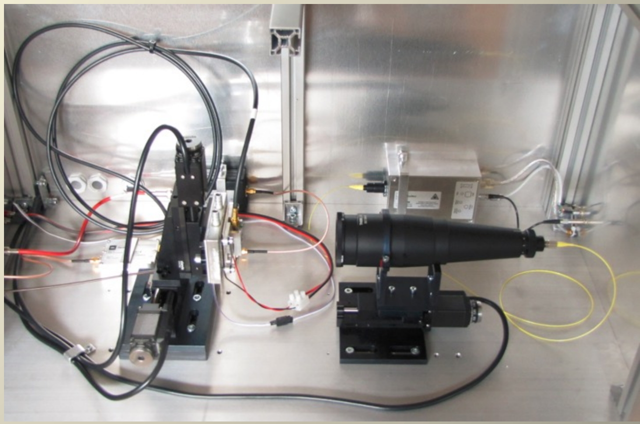
Backup Slides

Edge TCT

- Edge-TCT
  - Generate charges by edge-on IR laser perpendicular to strips, detector edge polished
  - Focus laser under the strip to be measured, move detector to scan
  - Measure induced signal with fast amplifier with sub-ns rise-time (Transient Current Technique)
  - Laser beam width 8 µm FWHM under the chosen strip, fast (40 ps) and powerful laser
    - Caveat – injecting charge under all strips effectively results in constant weighting (albeit not electric !) field



www.particulars.si

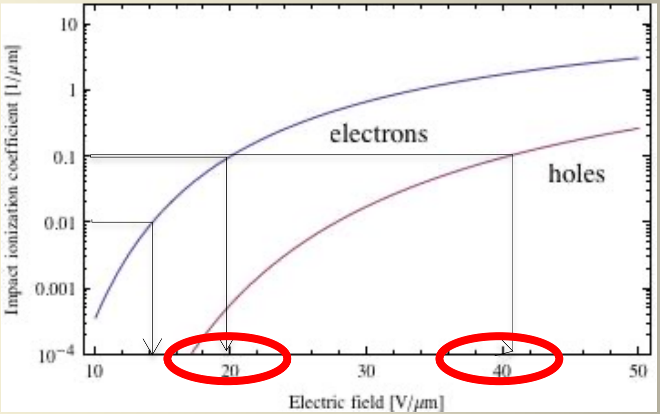


Charge Multiplication

- Multiplication is textbook physics
  - e.g. S.M. Sze, Physics of Semiconductor Devices, Wiley, New York, 1981
    - Ch 1.6.4 High-Field Property
      - Velocity saturation, impact ionization
    - Ch 2.5.3 Avalanche Multiplication
      - Junction break-down
- Measured impact ionization
  - Electrons create 1 pair in 10 µm at *E*~20 V/µm (100 µm at 14 V/µm), holes need *E*~40 V/µm
  - Holes need ~1 mm for pair creation at *E*~20 V/µm
    - Neglect hole multiplication in signal creation altogether
    - Need to invoke hole multiplication for junction breakdown
- $\alpha_e >> \alpha_h$ - Nature gentle to us (in silicon)
  - Large range in *E* where electrons multiply without inducing breakdown
  - But beware of (too) high electric fields !

$$\alpha_{e,h}(E) = \alpha_{e,h}^{\infty} e^{-b_{e,h}/E}$$

A. G. Chynoweth, Phys. Rev. 109, 1537(1958).



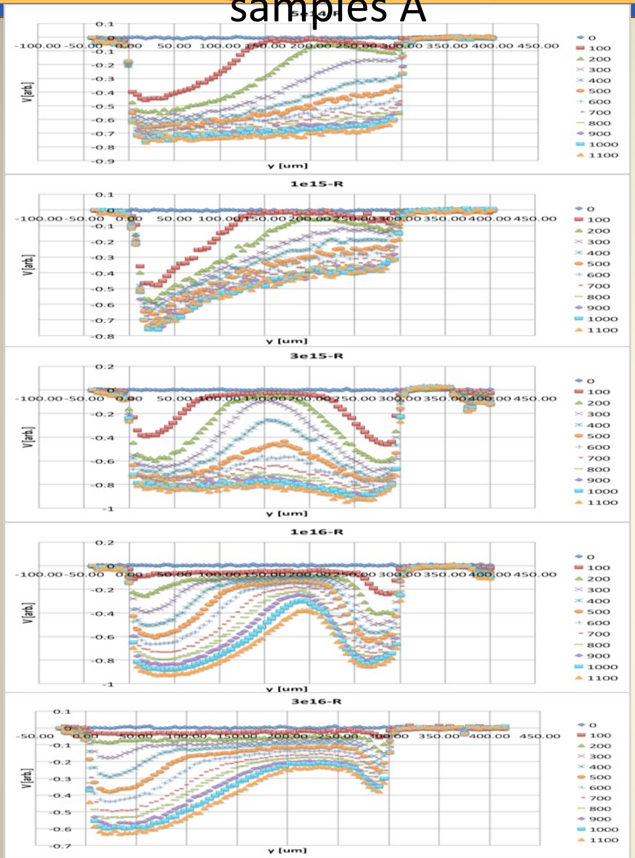
R.VAN OVERSTRAETEN and H.DE MAN, Solid-State Electronics 13(1970),583-608.
W.MAES, K.DE MEYER, R.VAN OVERSTRAETEN, Solid-State Electronics 33(1990),705-718.

$$\int_0^w dx\, \alpha_e(x) e^{-\int_0^x (\alpha_e(x')-\alpha_h(x'))\, dx'} = 1$$

Breakdown condition, can swap α_e with α_h

Reverse velocity profiles

samples A



5e14

1e15

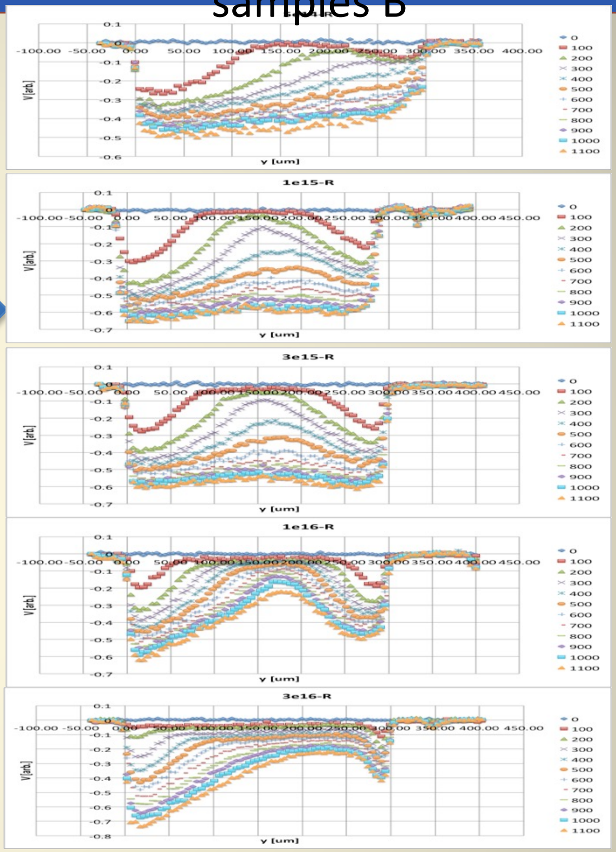
?

3e15

1e16

3e16

samples B

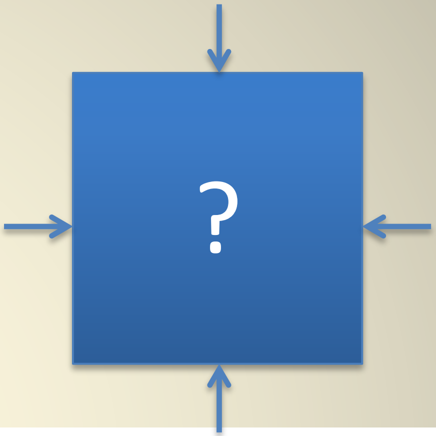


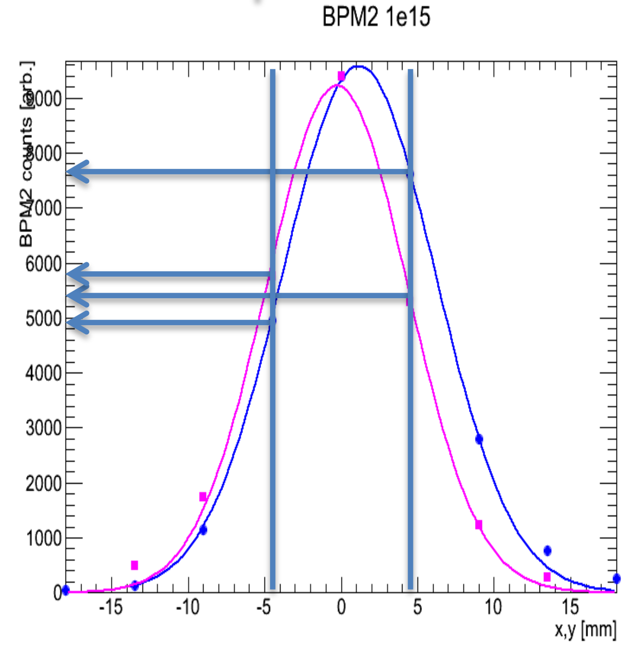
- 🙃 Something’s fishy... never repeat experiments ?!
  - 😀 Explained by PS beam profile variation on sample edges

Proton irradiations - details

- Samples irradiated in PS in pairs
  - in series in same sample holder
- Same leakage current in both samples

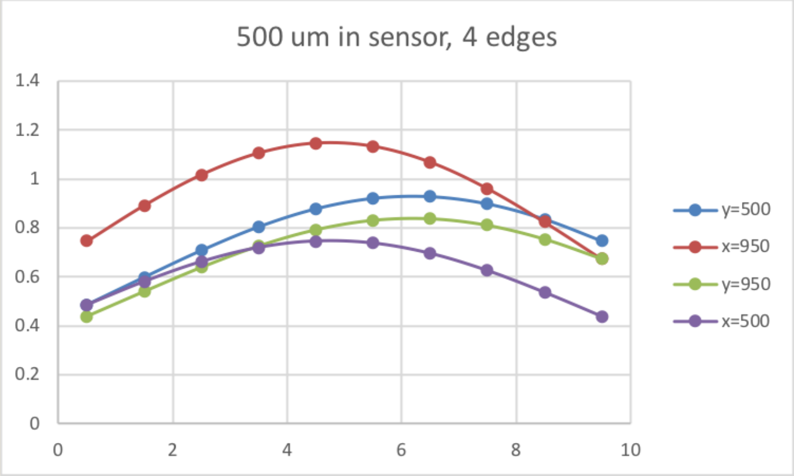
  ⇒same *average* fluence received
- Beam profile asymmetric
  - monitored by BPM2
- Which side did we pick up ?

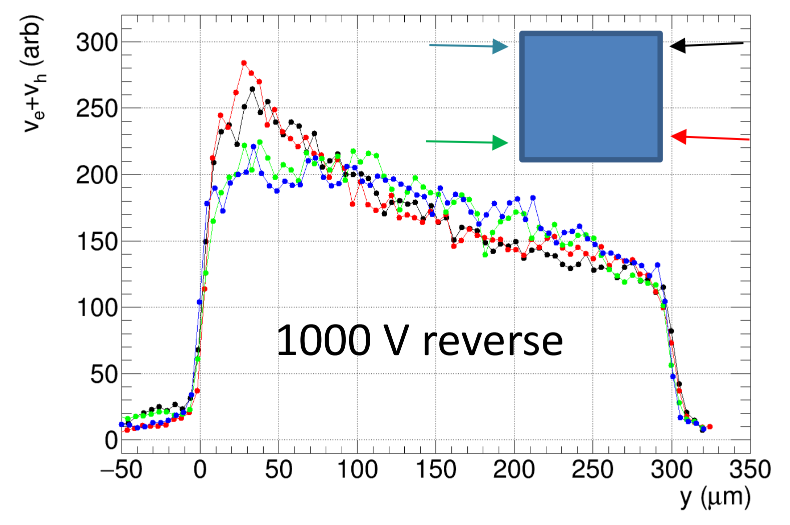




Protons revisited

- BPM2 results for the 1e15 sample, 0.5 mm in sensor
- 10x10 mm^2 average to peak: 0.7
  - Values rescaled
- Mid-side to average:
  - 1.17, 0.88, 0.82, 0.74
    - Must be the larger difference
  - ➢ Correct fluences by -10 %
  - ➢ Assign 20 % error
- ➢ Re-measured one sample from both sides, match with BPM2 data – still in progress
  - ➢ Looks like explaining the issue


500 um in sensor, 4 edges



Mobility Comparison

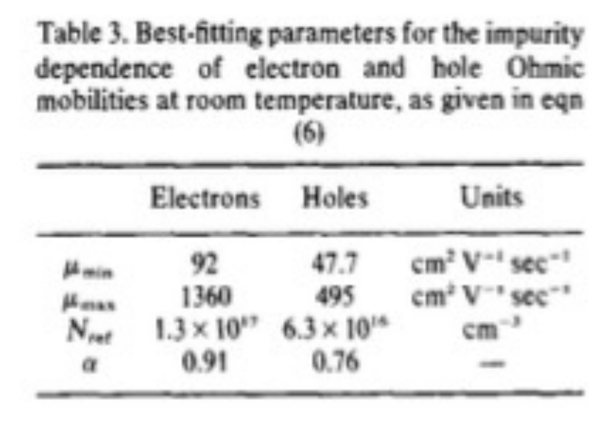


Table 3. Best-fitting parameters for the impurity dependence of electron and hole Ohmic mobilities at room temperature, as given in eqn (6)

	Electrons	Holes	Units
μ_{min}	92	47.7	$cm^2\ V^{-1}\ sec^{-1}$
μ_{max}	1360	495	$cm^2\ V^{-1}\ sec^{-1}$
N_{ref}	1.3×10^{17}	6.3×10^{16}	cm^{-3}
α	0.91	0.76	—

- Dependence on *shallow* dopant concentration
  - Measured in the roaring 60’s
- Characteristic trap concentration N~10^{17} cm^{-3}
  - looks out of reach for typical g=O(10^{-2})
- But g refers to $N_{eff} = |N_a - N_d|$
- While N is more like $N_a + N_d$
  - *x-sections for deep and shallow ?*
- Power law looks compatible: $a \leq 1$

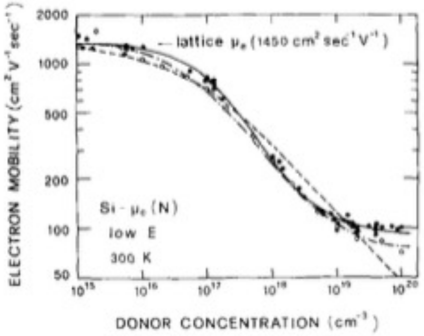


Fig. 5. Electron mobility, μ_e, in silicon at 300 K as a function of impurity concentration. Open and closed circles are the experimental results reported by Irvin[55] and of Mousty *et al.*[56], respectively. The continuous line is the phenomenological best fit (eqn (6)) of Baccarani and Ostoia[53] the broken line the best fit (eqn (7)) of Hilsum[54] the dot-dashed line (eqn (8)) of Scharfetter and Gummel[57] (see Tables 3 and 4).

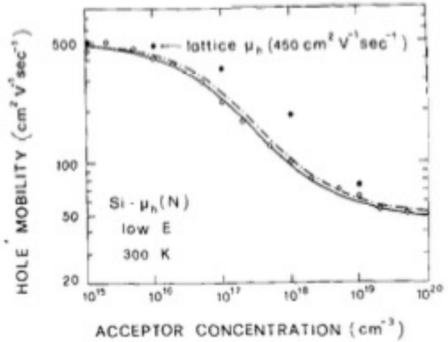
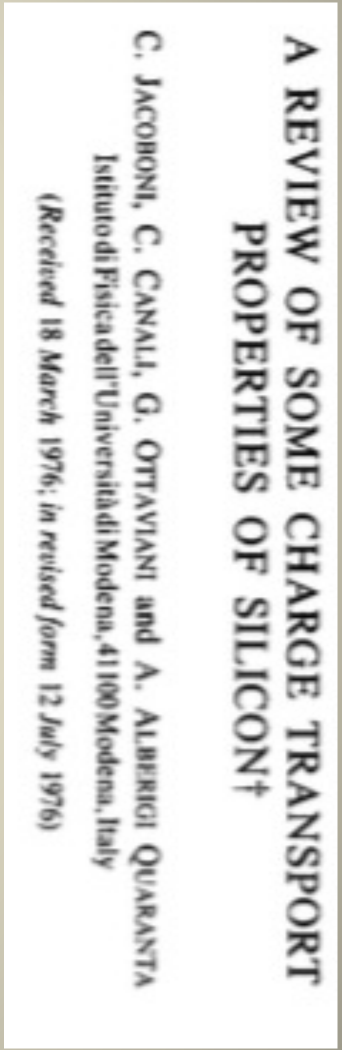


Fig. 6. Hole mobility, μ_h, in silicon at 300 K as a function of impurity concentration. Open circles are experimental results reported by Irvin[55]. Continuous and dot-dashed lines represent the best fitting curves of Caughey and Thomas[58] (eqn (6)) and of Scharfetter and Gummel[57] (eqn (8)), respectively (see Tables 3 and 4).



A REVIEW OF SOME CHARGE TRANSPORT PROPERTIES OF SILICON†

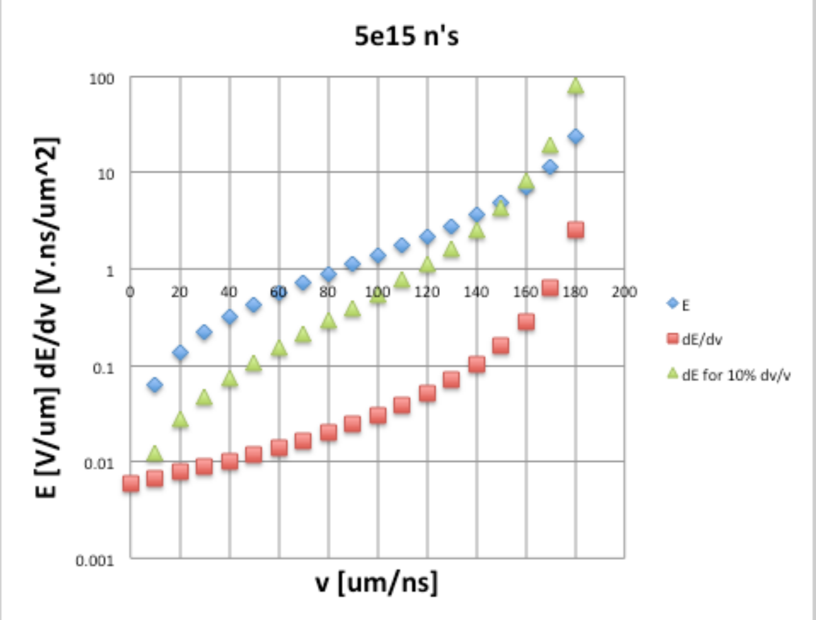
C. JACOBONI, C. CANALI, G. OTTAVIANI and A. ALBERIGI QUARANTA

Istituto di Fisica dell'Università di Modena, 41100 Modena, Italy

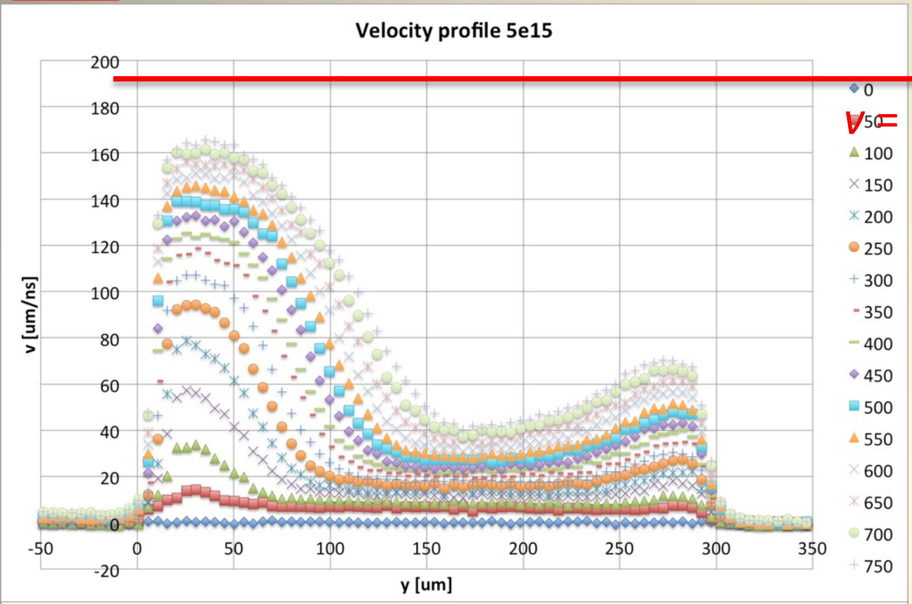
(Received 18 March 1976; in revised form 12 July 1976)

Velocity and Field Profiles

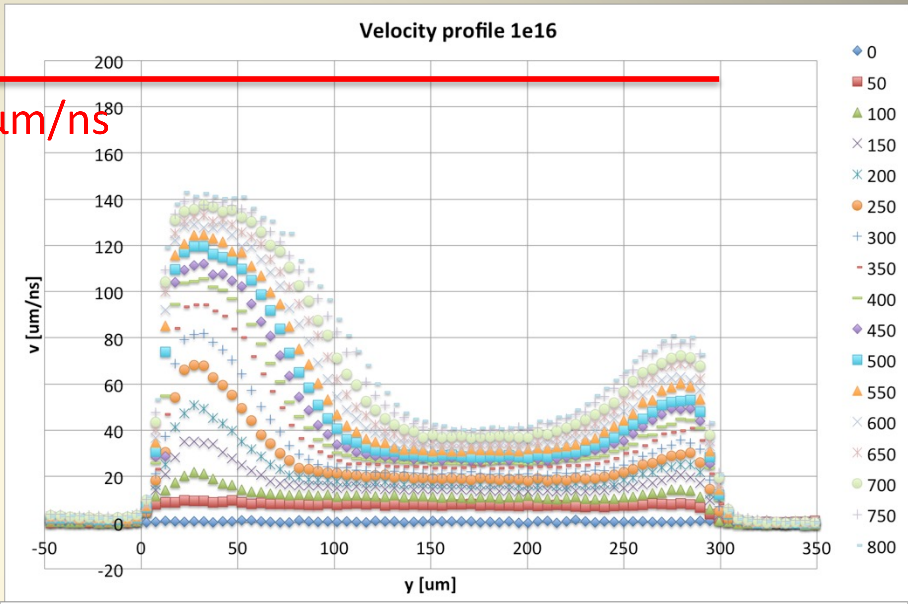
- Knowing *v(E)* can set scale to velocity profiles
  - assumption: same scale on FW and reverse bias
    - protons: for $5\text{x}10^{14}$ and 10^{15} use same scale, fixed by average field for $5\text{x}10^{14}$ at 1100 V (no good FW data)
- Invert *E(v)* to get electric field profiles
  - big errors when approaching v_{sat} i.e. at high *E*
    - exaggerated by CM in high field regions
    - $v > v_{sat}$ not physical, but can be faked by CM

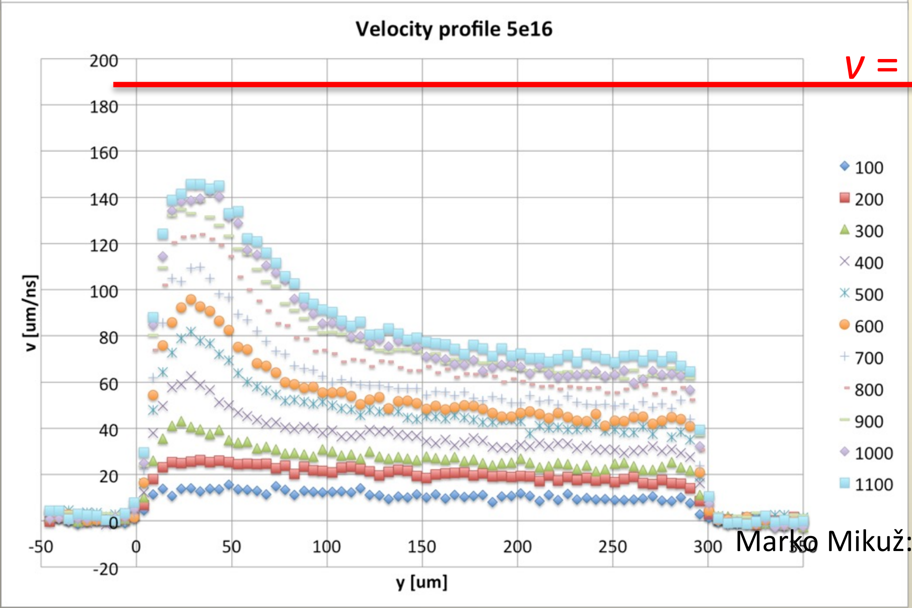


Velocity Profiles Neutrons

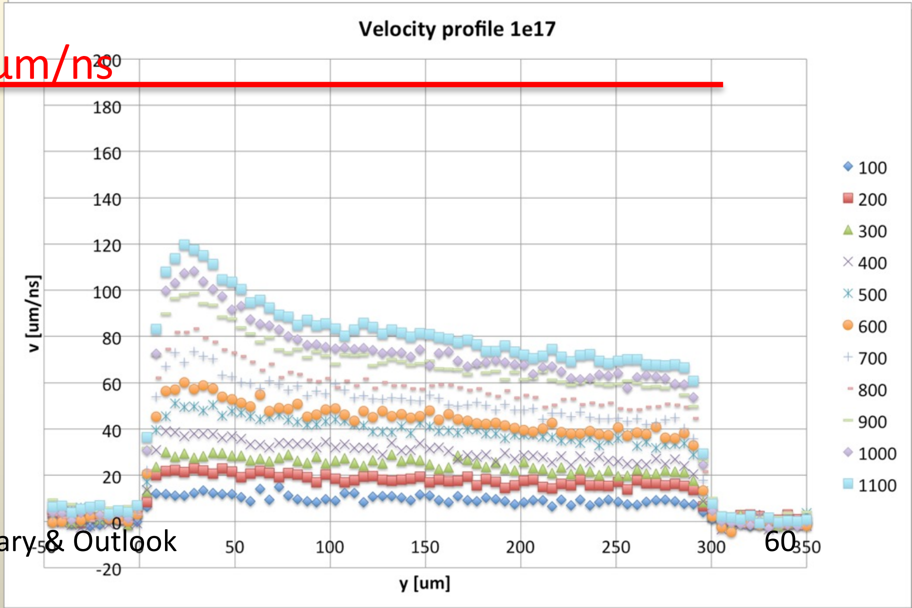

Velocity profile 5e15

v = 190 µm/ns

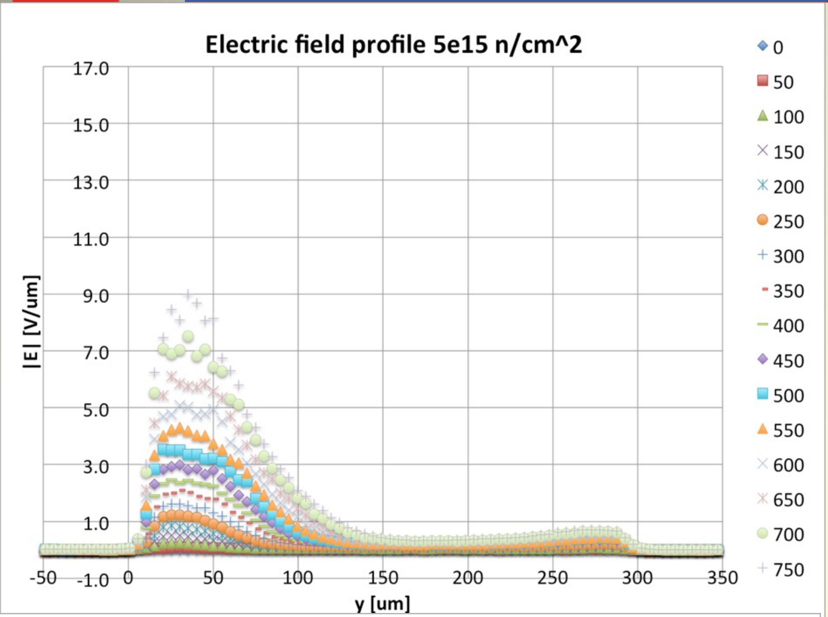

Velocity profile 1e16

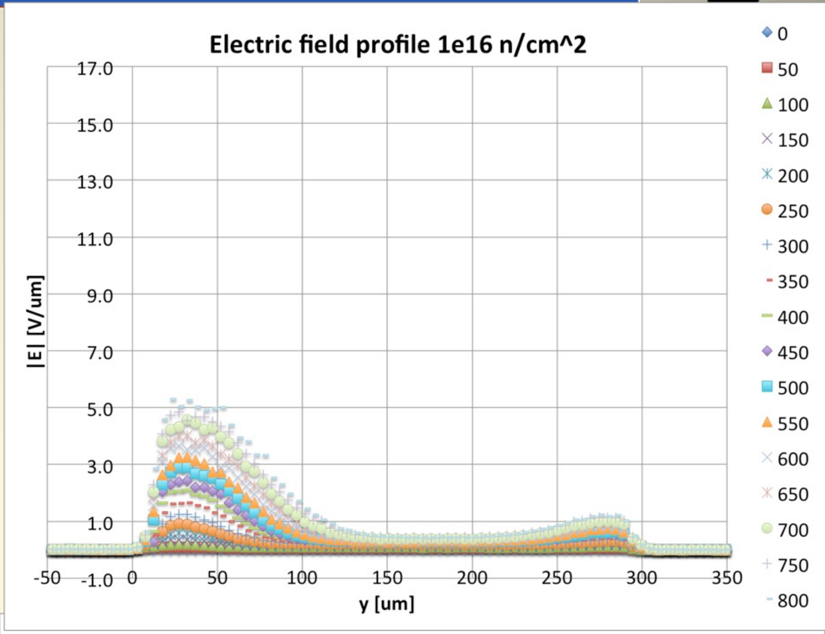

Velocity profile 5e16

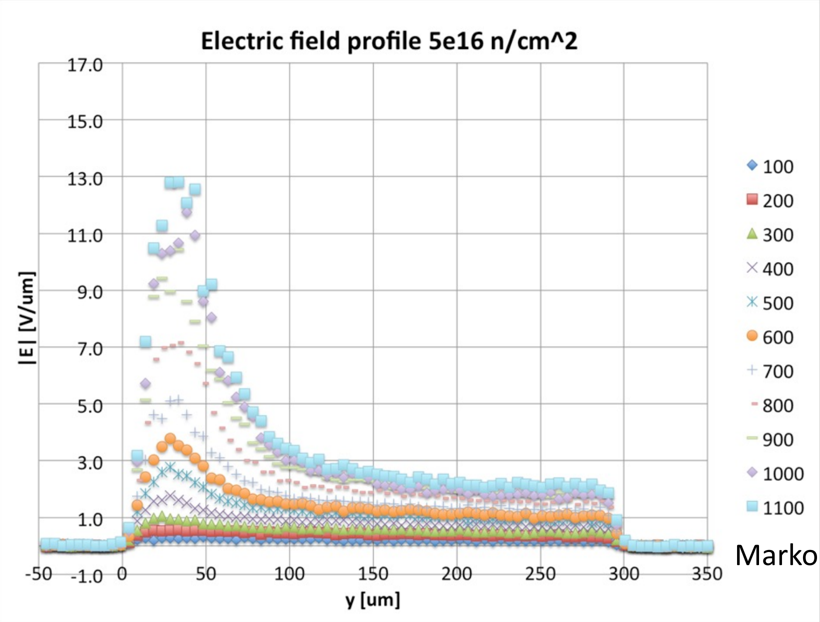
v = 190 µm/ns

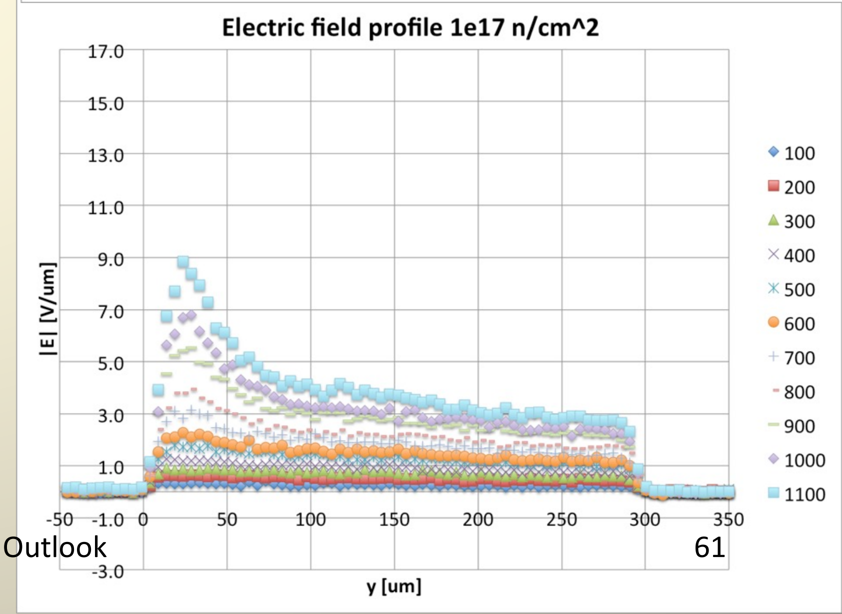

Velocity profile 1e17

Field Profiles Neutrons



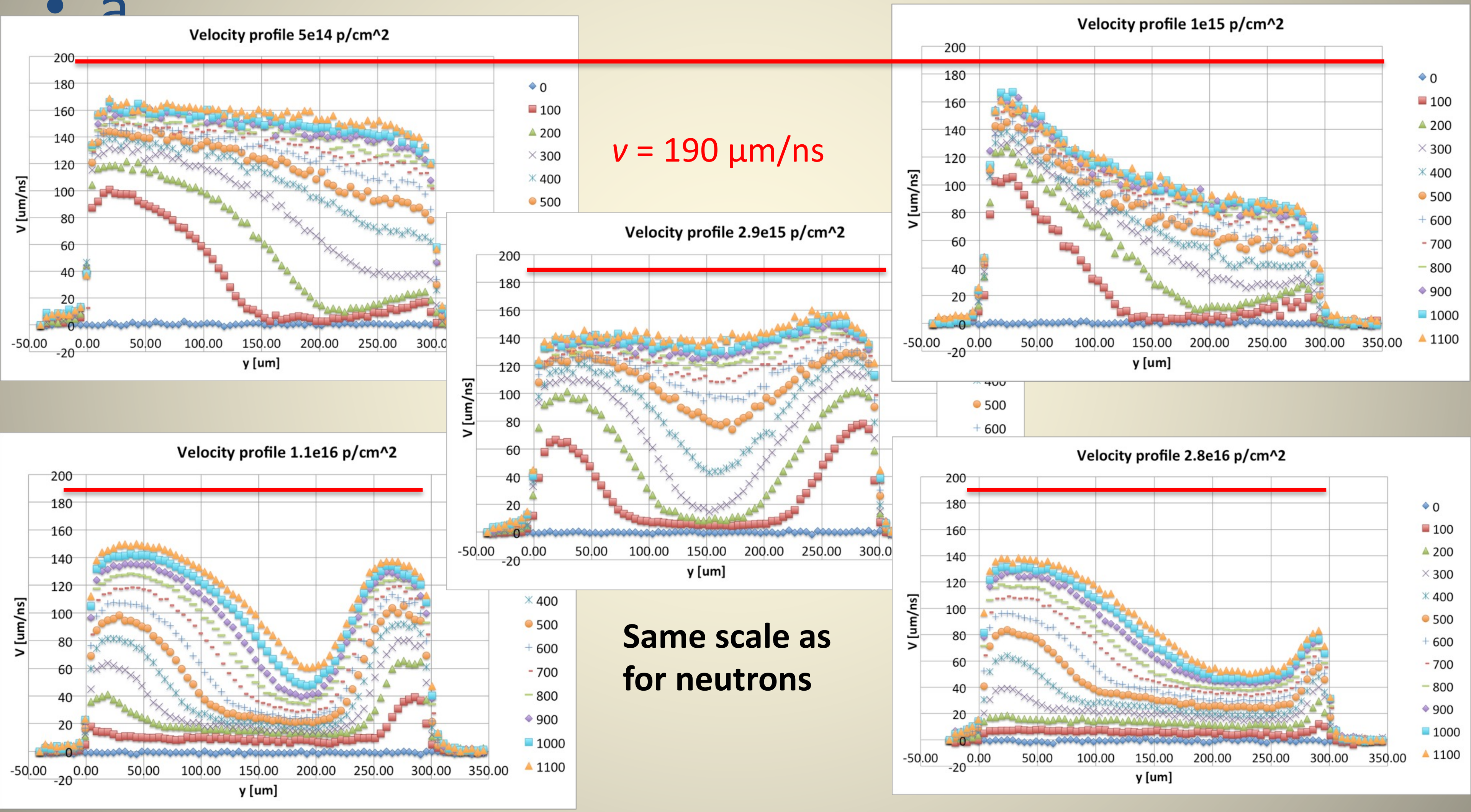






Velocity Profiles Protons

- a


Velocity profile 5e14 p/cm^2

Velocity profile 1e15 p/cm^2

Velocity profile 2.9e15 p/cm^2

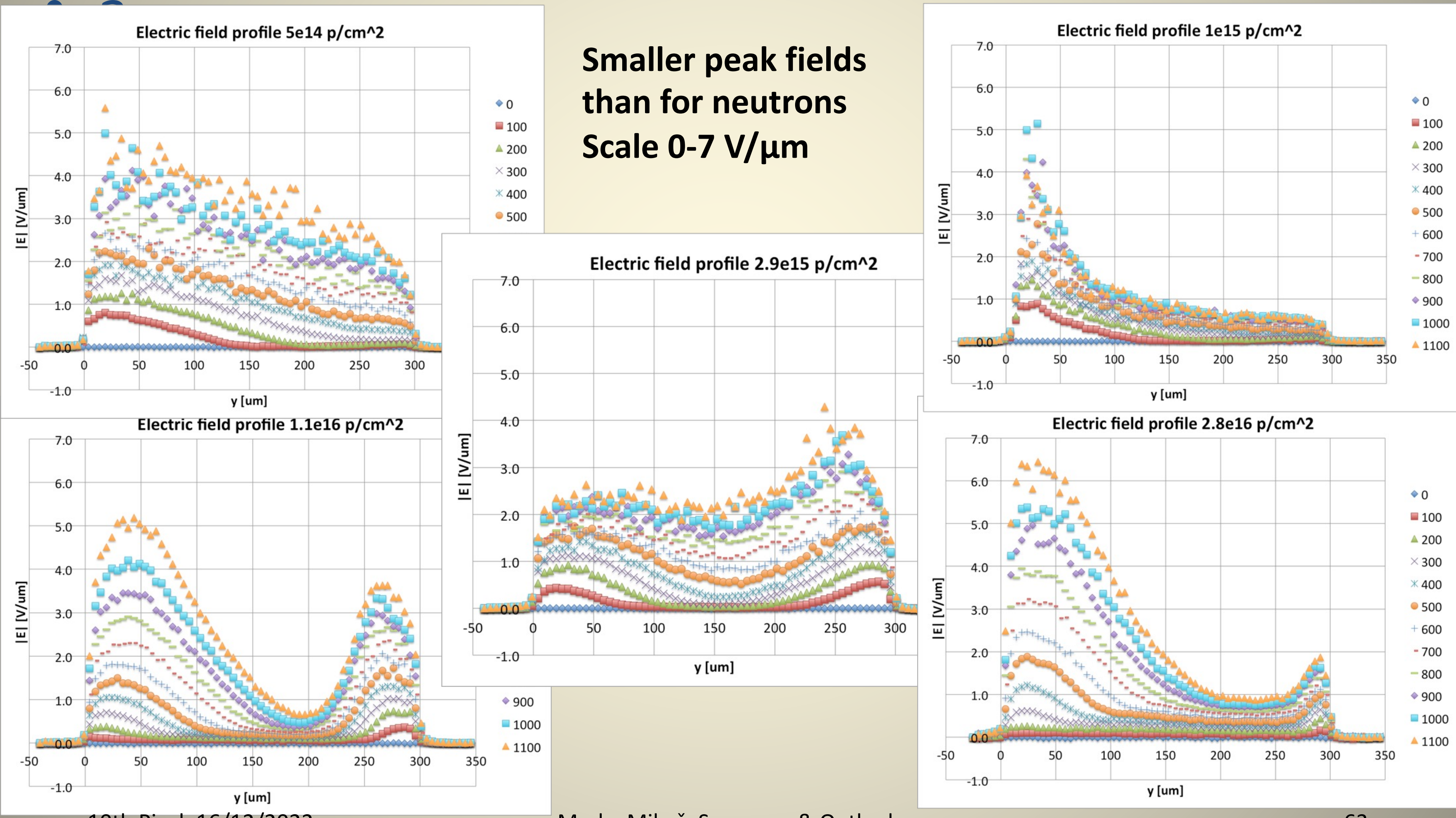
Velocity profile 1.1e16 p/cm^2

Velocity profile 2.8e16 p/cm^2

v = 190 µm/ns

Same scale as for neutrons

Field Profiles Protons

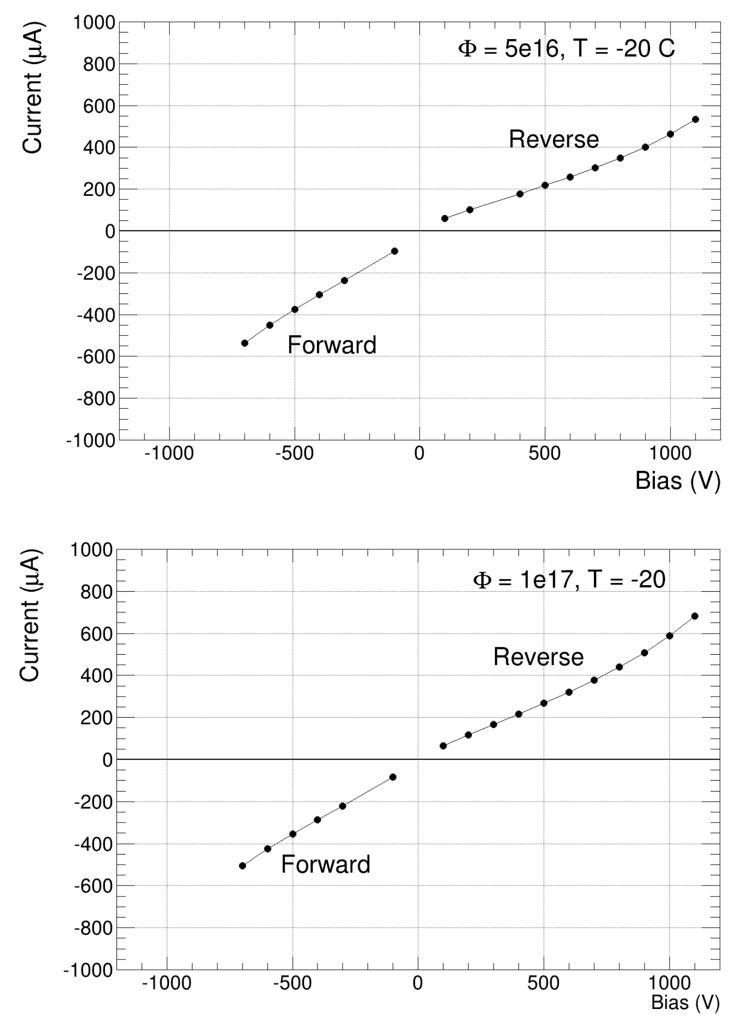


Smaller peak fields than for neutrons

Scale 0-7 V/µm

Current Characteristics

- Smooth behaviour in both directions
  - Highly resistive Si limits FW injection
- Reverse current smaller than predicted by an order of magnitude
- Both currents rising ~linear with bias
  - Slopes FW/reverse more compatible at higher fluences
- Consistent with recent measurements at highest fluences



Trapping Considerations

- Extrapolation from low fluence data with $\beta_{e,h}$(-20°C)=4.4,5.8x10^{-16} cm^2/ns; $1/\tau = \beta\Phi$

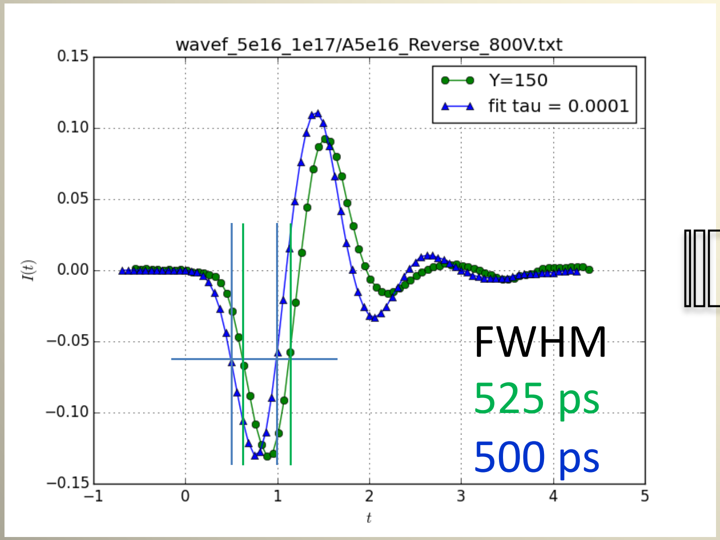
Φ [1e15]	**5**	**10**	**50**	**100**
τ [ps]	400	200	40	20
mfp@v_{sat} [µm]	95	48	9.5	4.8
MPV [e_0]	7600	3800	760	380
MPV@1000 V	8900	5500	1800	1150
CCD$_{1000\ V}$ [µm]	110	70	23	14

From "magic formula"
JINST 9 P10016(2014)

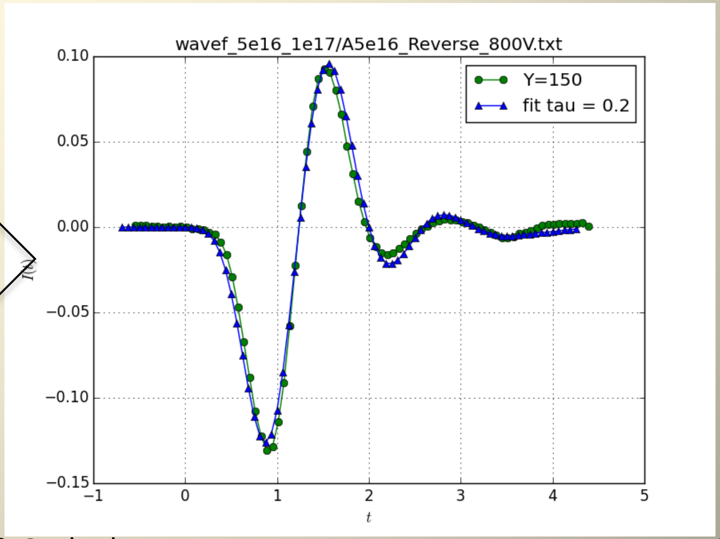
- Measured data exceeds (by far) linear extrapolation of trapping
  - n.b.1: *E*~3 V/µm by far not enough to saturate velocity
  - n.b.2: little sign of CM at highest fluences

Exploiting TCT Waveforms

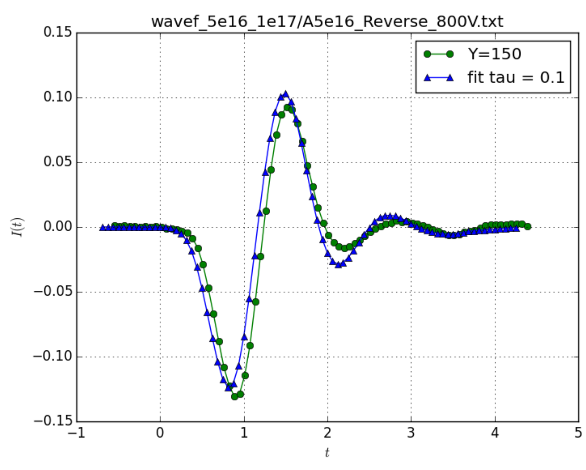
- Waveforms at *y*=100 µm, 800 V, 5x10^{16} and 10^{17}
  - $E \approx 3$ V/µm, *CCD/2* implies signal within ~10 µm or <0.2 ns
    - the rest you see is the transfer function of the system
- Still distinct signals from the two fluences
  - treat 10^{17} waveform as transfer function of the system
    - convolute with $e^{-t/\tau}$ to match 5x10^{16} response
    - $\tau = 0.2$ ns provides a good match
- In fact, measure ~$\Delta\tau$, as "transfer" already convoluted with $e^{-t/\tau(1e17)}$!

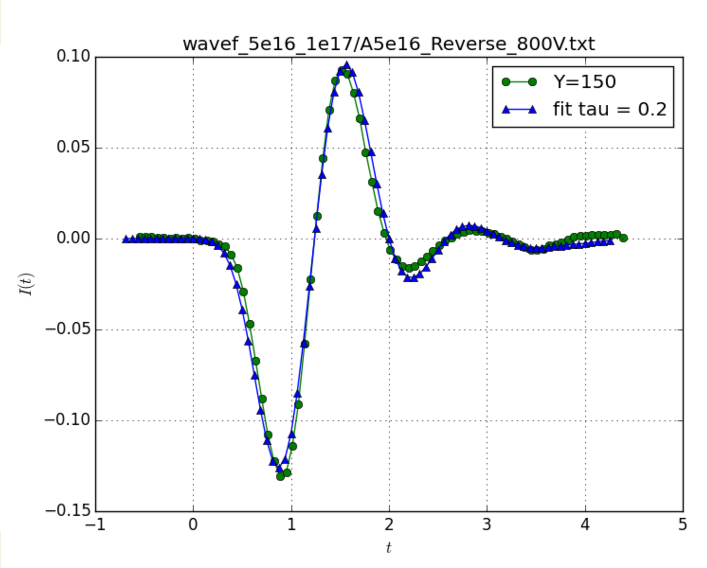


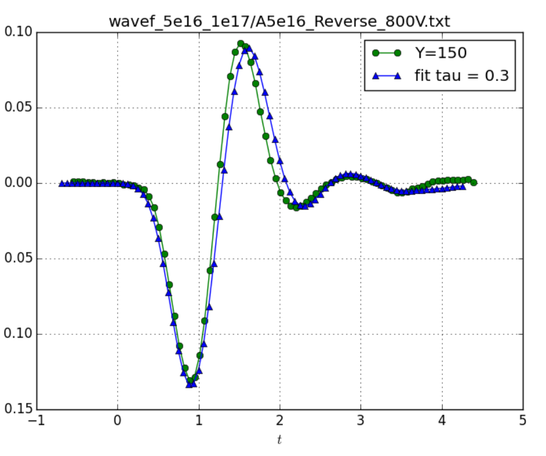
$\tau = 0.2$ ns



Waveforms: How sensitive ?



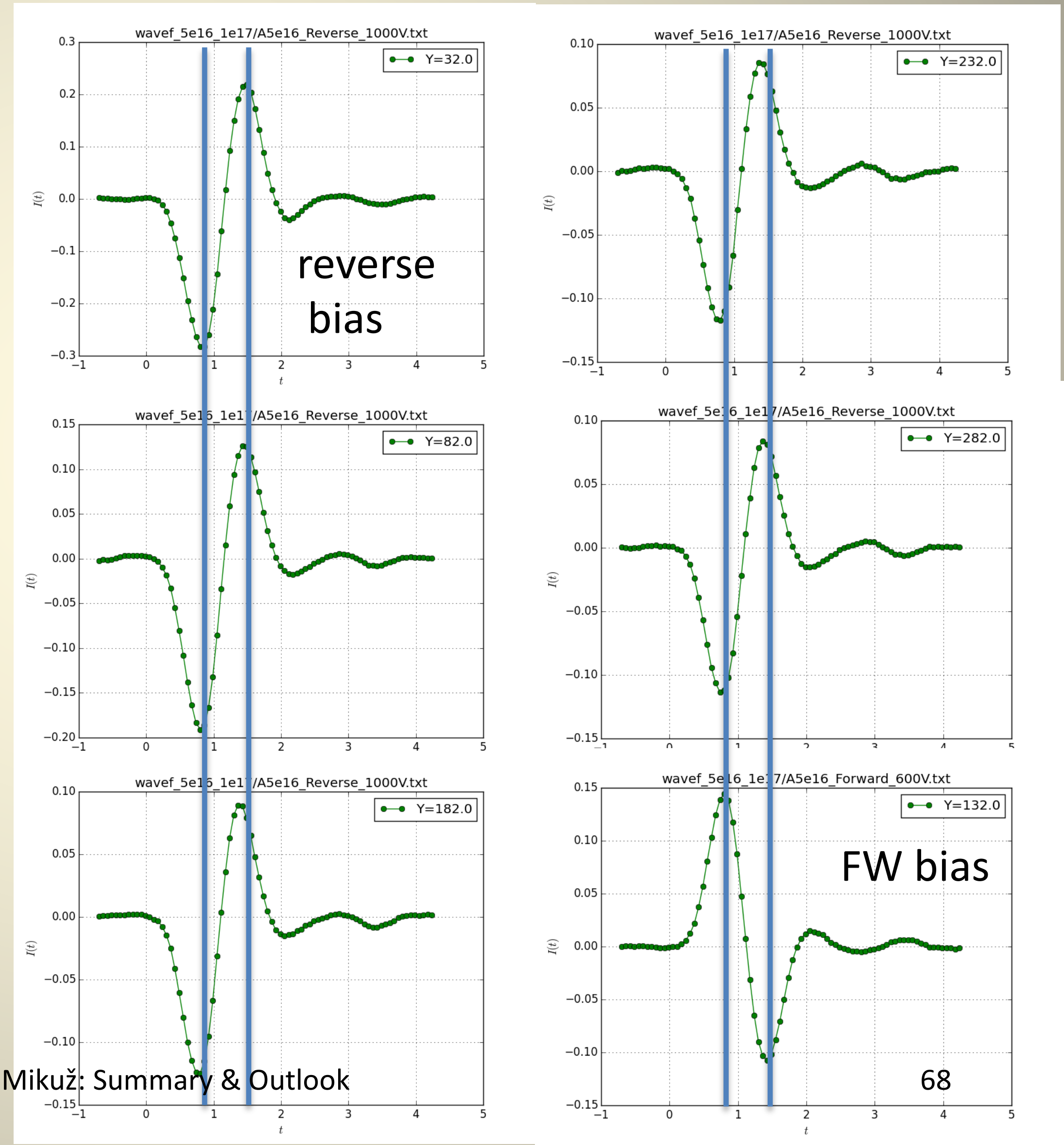




- *Δτ* = 0.2 ns certainly best fit, 0.1 too narrow, 0.3 too broad
- precision ~50 ps

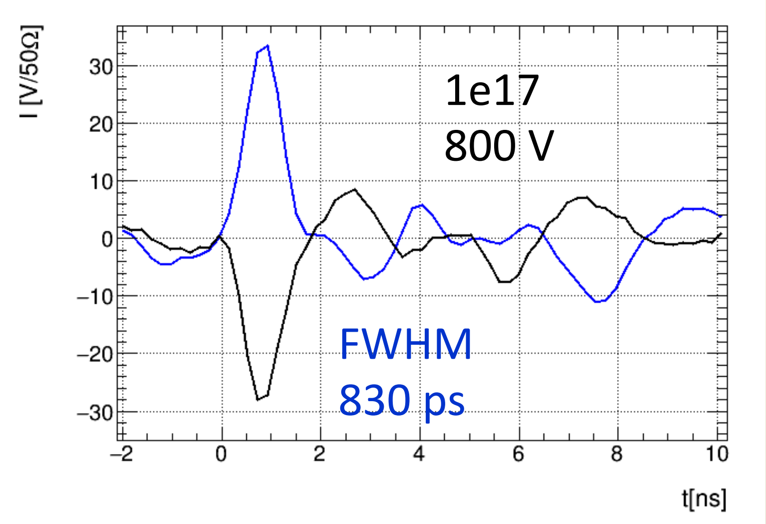
Trapping – position dependence ?

- Waveforms plotted every 50 um in detector depth for reverse bias at 1000 V
- Forward bias in middle of detector added at 600 V
- Very little, if any, wf dependence on position observed
- Trapping not position (even not bias) dependent !?



Trapping @3e17

- Moved to another setup – different waveforms
  - Widths of reverse and FW similar
  - With decreases 1->3e17
  - Irregular waveforms with small signal @3e17
  - Hard to state something more quantitative



Blue
Reverse

Black
FW