Development and application of precision timing silicon detectors (LGAD)

Koji Nakamura (KEK)

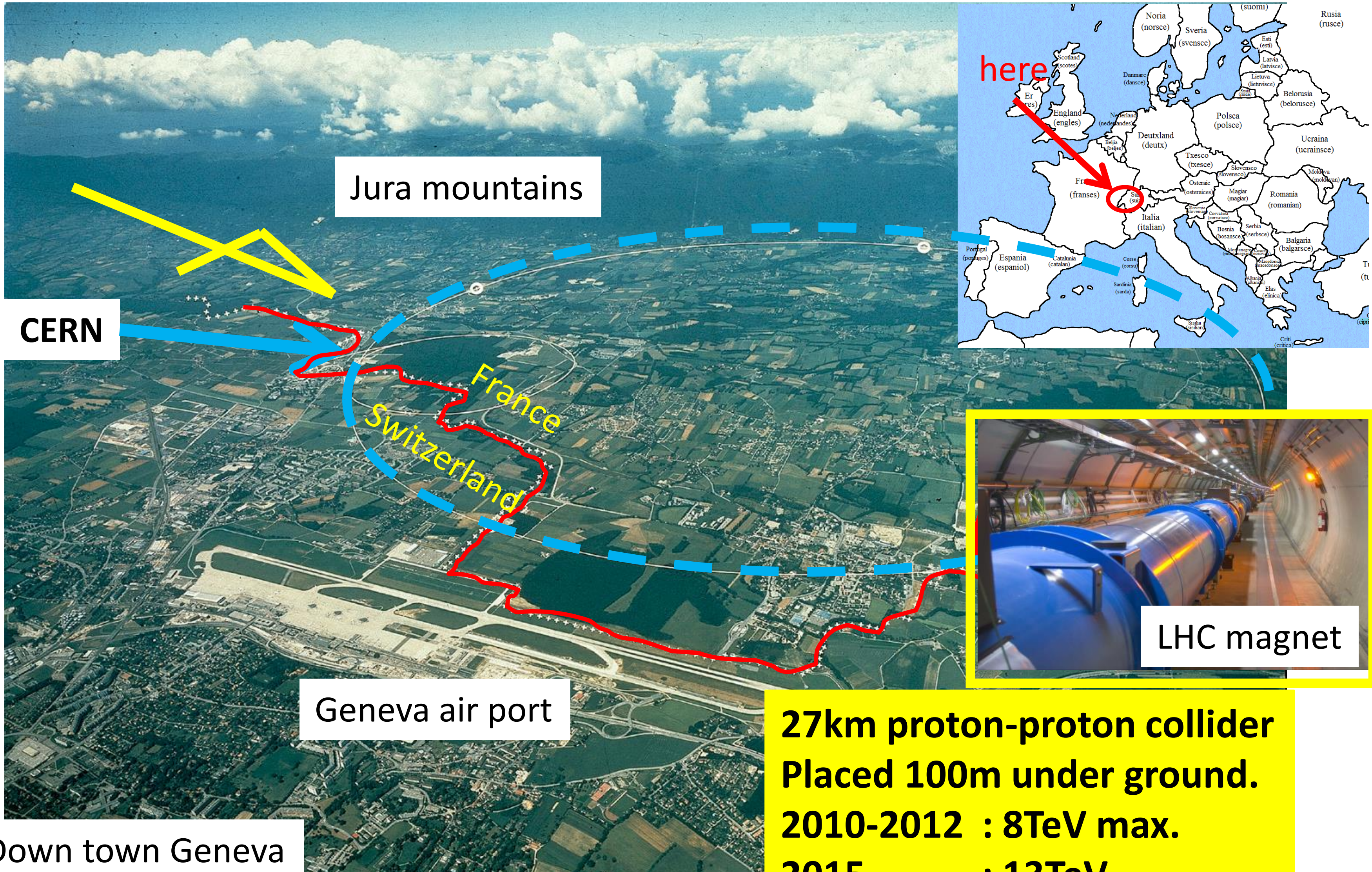
Contents

- ***Tracking detector for High energy hadron collider.***
  - Current situation
  - What is necessary for the future collider?
- ***Low gain avalanche detector (LGAD)***
  - What is LGAD?
  - History and recent R&D devices.
  - Next plan
- **Possible application of LGAD based device?**

Motivations for the R&D

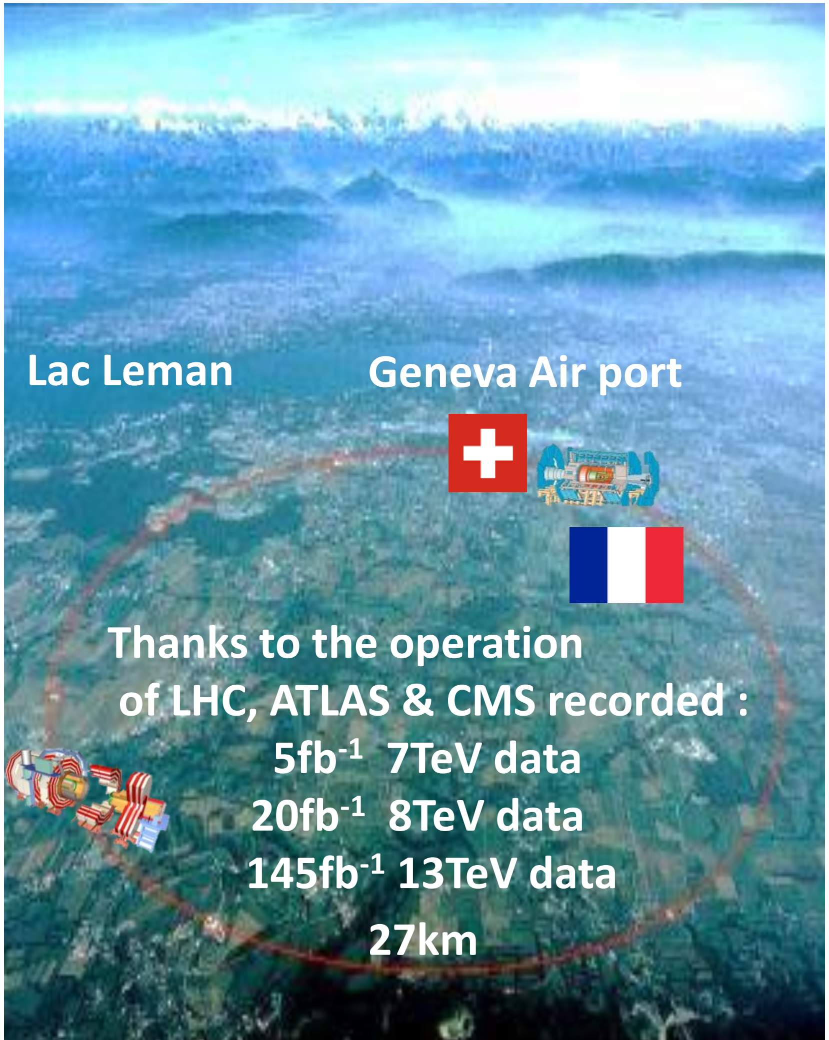
also to introduce myself…

Large Hadron Collider (LHC)



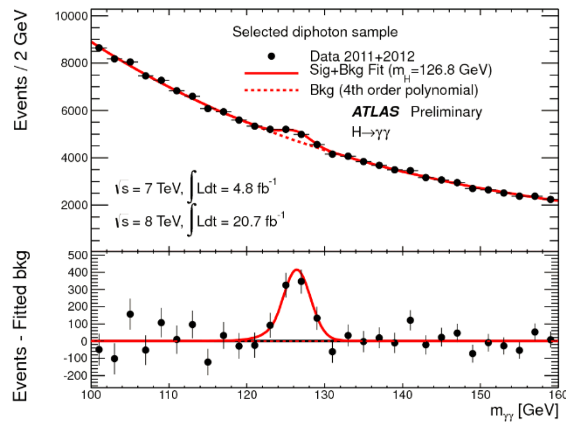
27km proton-proton collider
Placed 100m under ground.
2010-2012 : 8TeV max.
2015- : 13TeV

LHC and ATLAS/CMS experiment



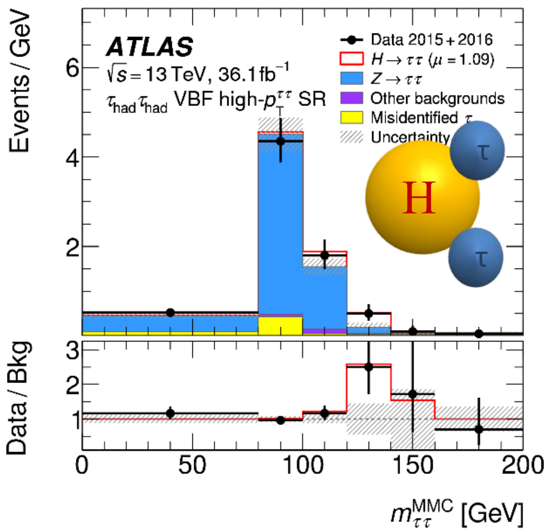
Great achievement in 4th July:

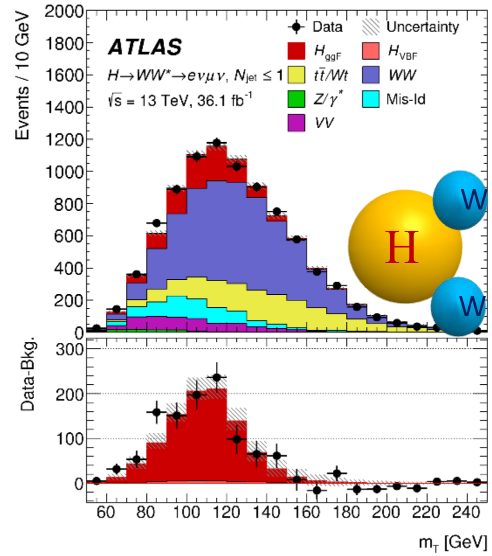
Higgs observation

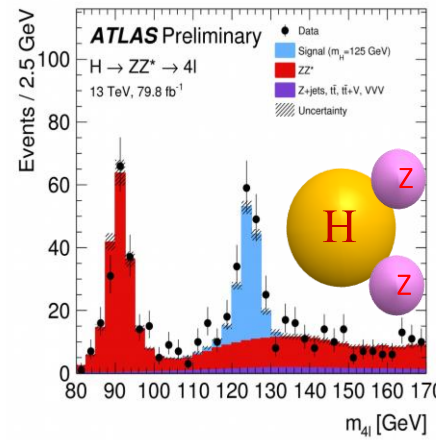


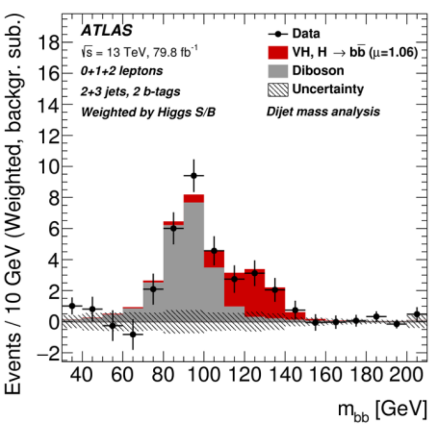
ATLAS Celebration 4th July @ CERN B40

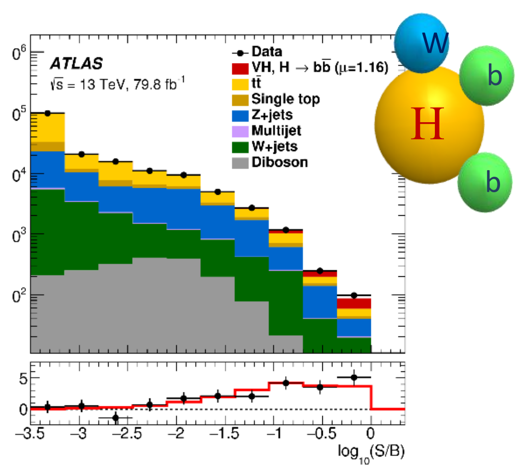
Observation of Higgs couplings

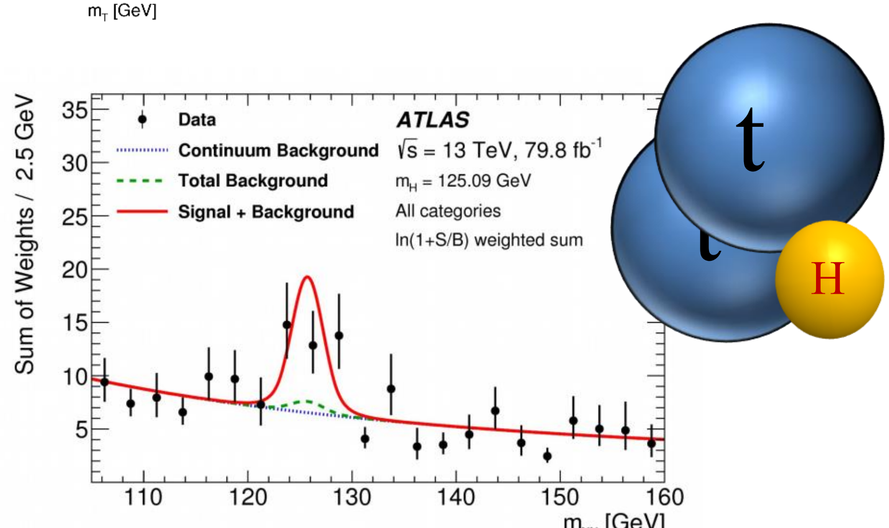




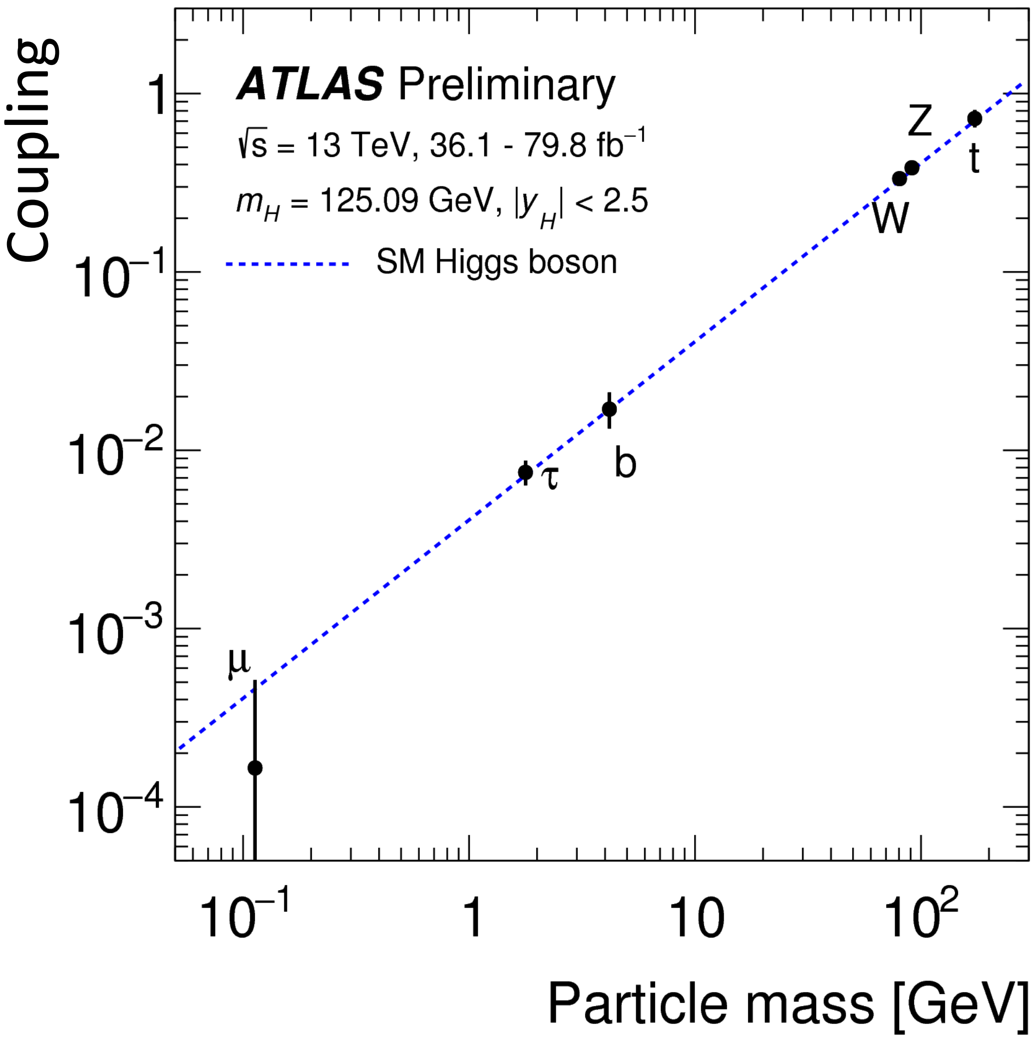








What we are now?



Coupling proportional to the particle mass

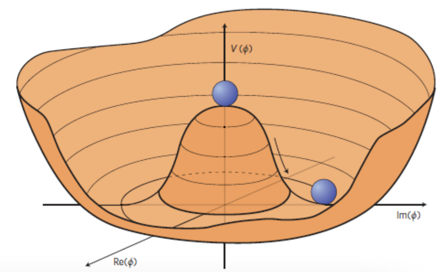
→This is the evidence of

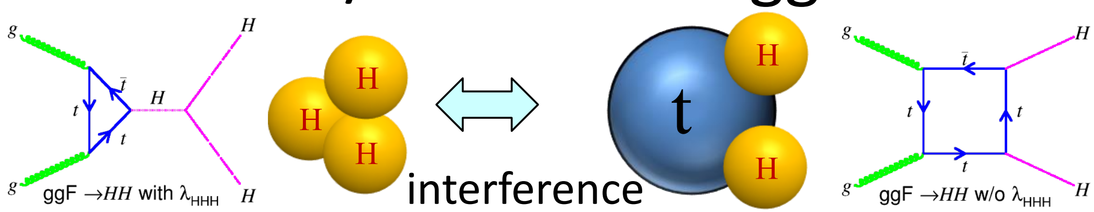
"Higgs give the mass of elementally particles"

What we want to know next?

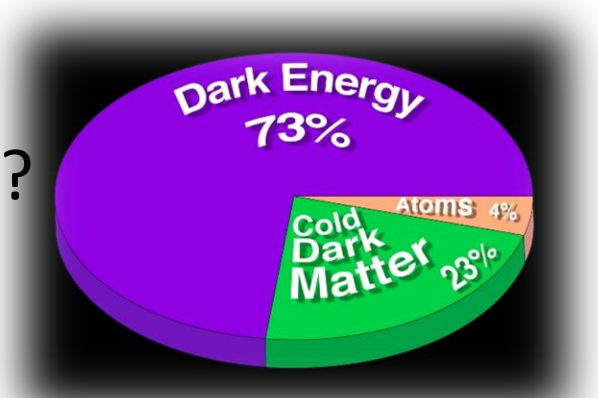
- ***"Vacuum"***
  - "Vacuum" is nothing? Filled by Higgs boson?
  - How Higgs boson/field condensed to the "Vacuum"?
  - Need to determine/observe the shape of Higgs Potential.

  → Observe/measure "Higgs self coupling".





- ***"Dark Matter/Energy"***
  - We only know 4%. What's the others?
  - Beyond the Standard Model?
    - Super Symmetry?



Future High Energy Colliders

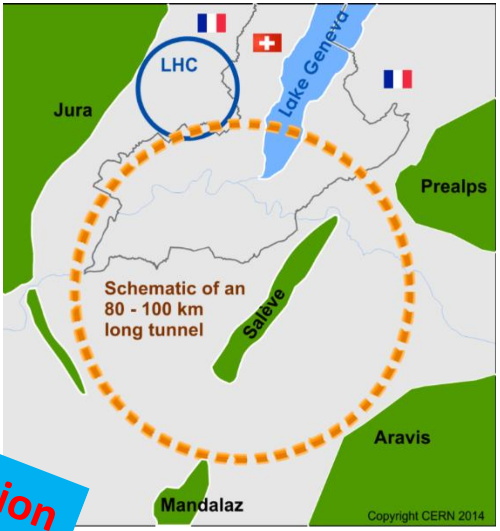
- Need "Higher Luminosity" and/or "Higher Energy"
  - High Luminosity LHC (HL-LHC)
    - 20 times more data (~3000-4000fb^{-1})
    - Plan : Start at 2026
  - High Energy LHC (HE-LHC)
    - Use Super Conducting Magnet with Higher Magnetic field(16T)
    - 28TeV collider in the same tunnel as LHC.
  - Future Circular Collider (FCC)
    - Use Super Conducting Magnet with Higher Magnetic field(16T)
    - 100TeV collider with 100km tunnel at CERN.
  - International Linear Collider (ILC)
    - 250GeV e+ e- collider in Japan

Approved!

Discussion Started

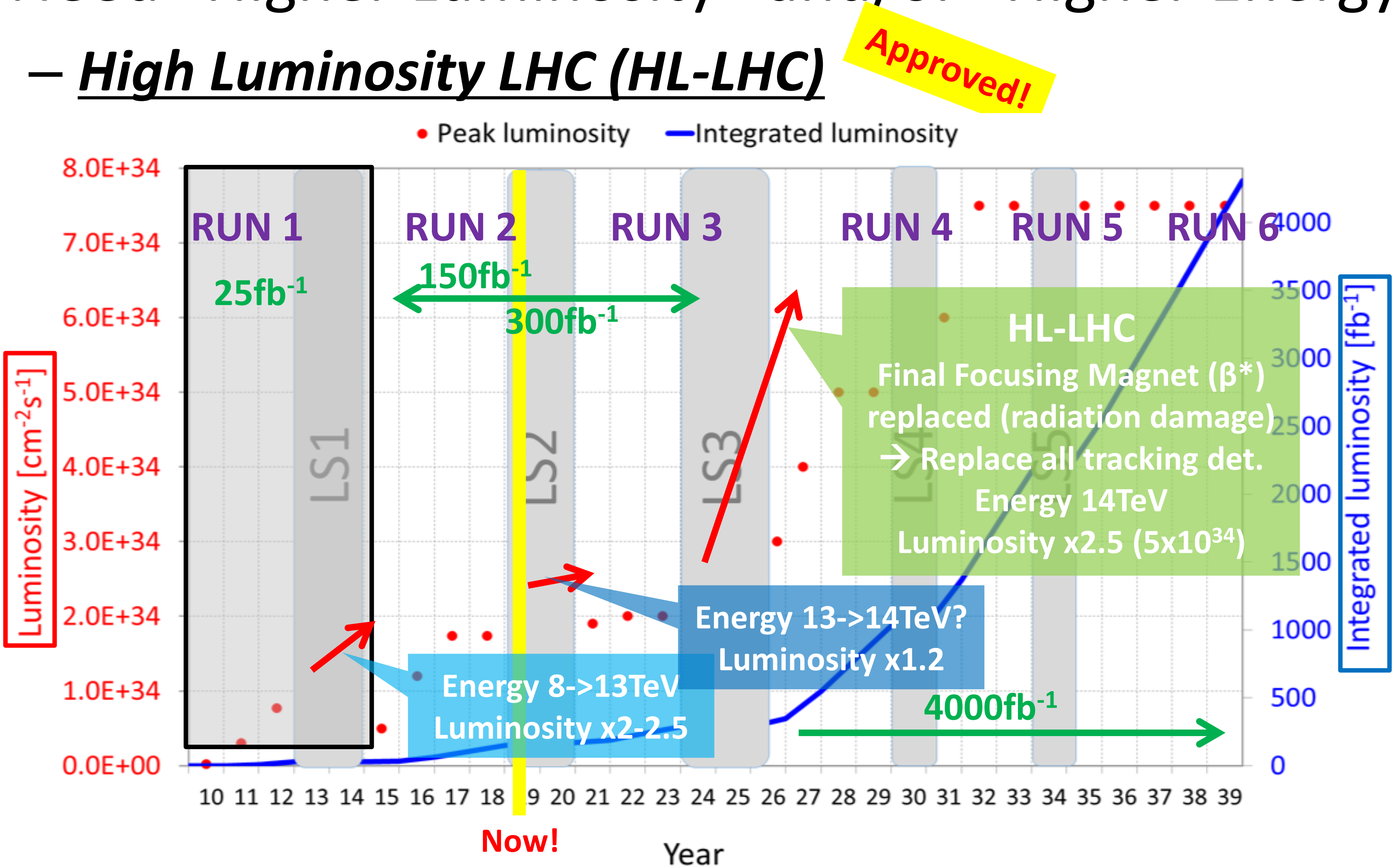
Discussion Started

Final decision soon



Future High Energy Colliders

- Need "Higher Luminosity" and/or "Higher Energy"
  - ***High Luminosity LHC (HL-LHC)***

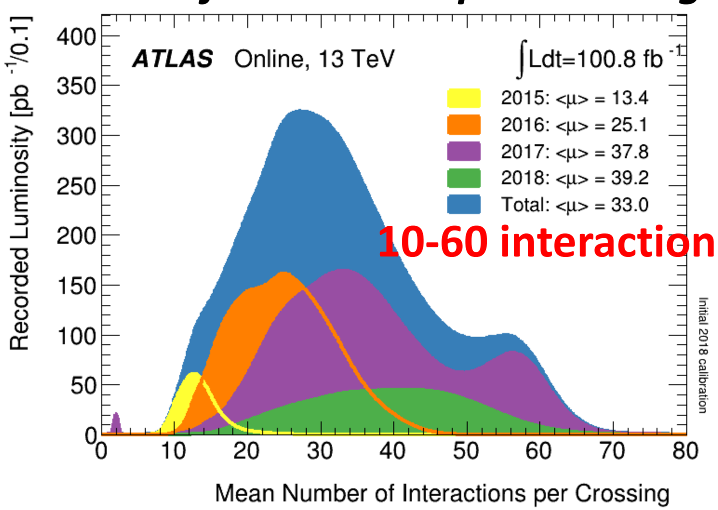


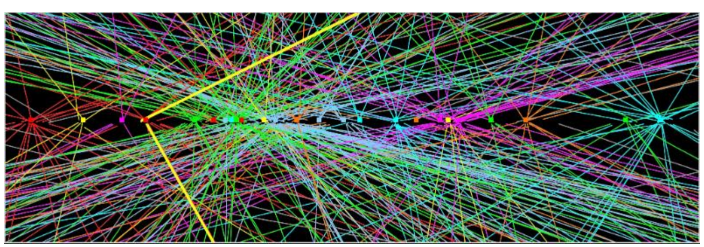
Challenge for Detector building

- Design Luminosity of HL-LHC
  - Current LHC: $L=2x10^{34}cm^{-2}s^{-1}$
  - HL-LHC : **$L=7x10^{34}cm^{-2}s^{-1}$**

3-4 times higher

Number of Interaction per Crossing





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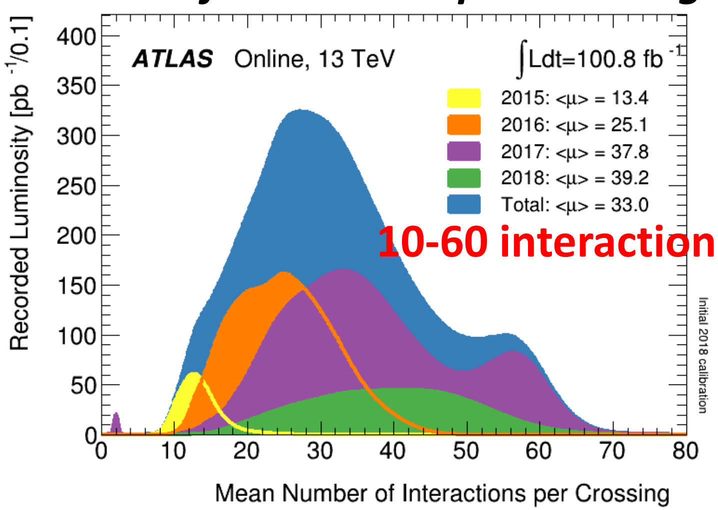
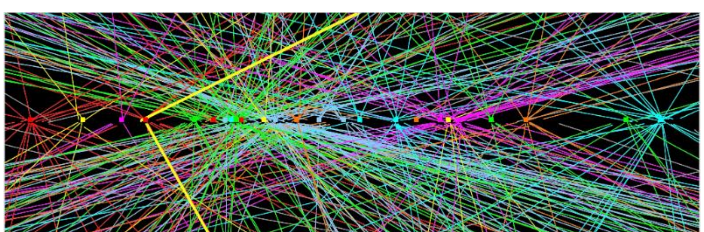
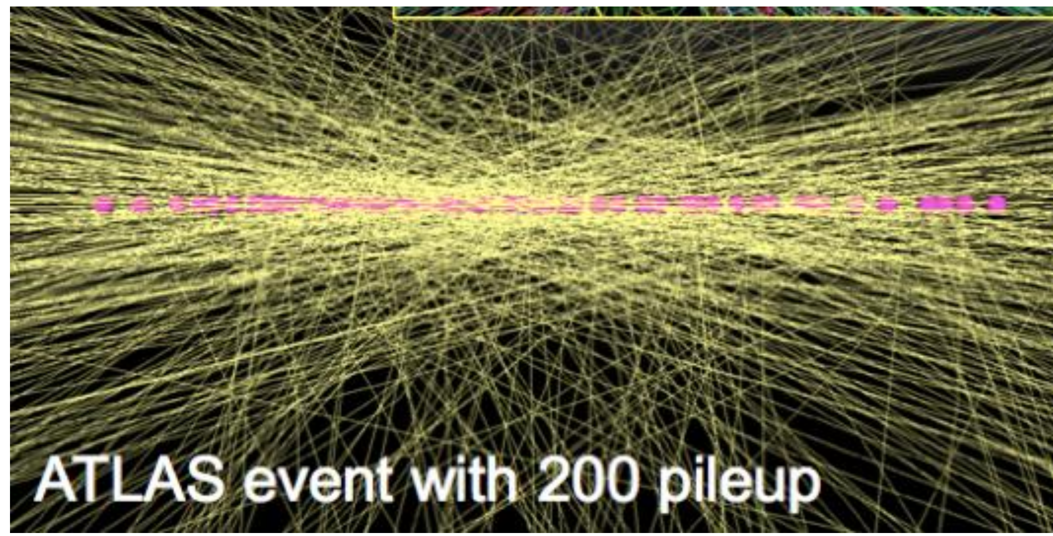




HL-LHC : 140 interaction per bunch crossing



Need to identify the primary vertices to reduce Pileup oriented background

Challenge for Detector building

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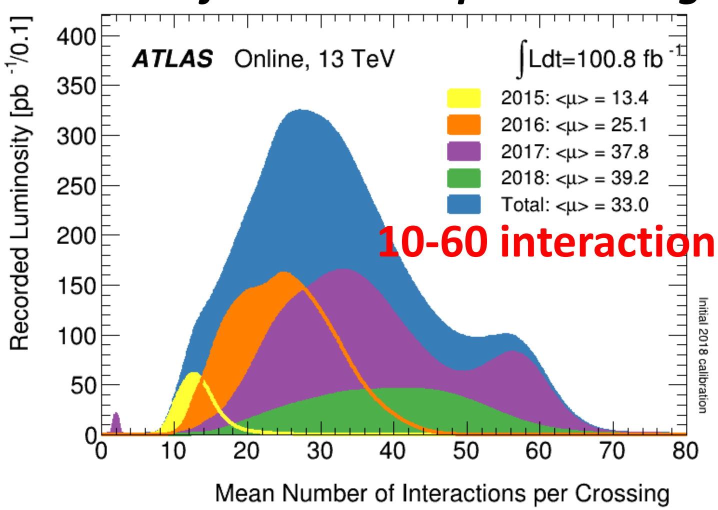
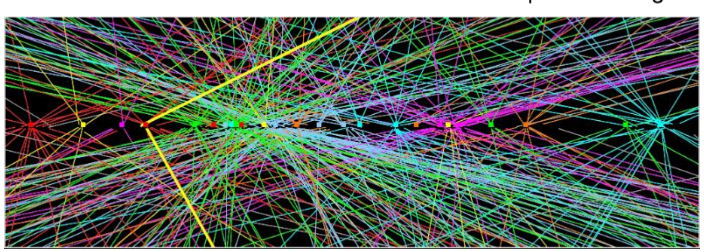
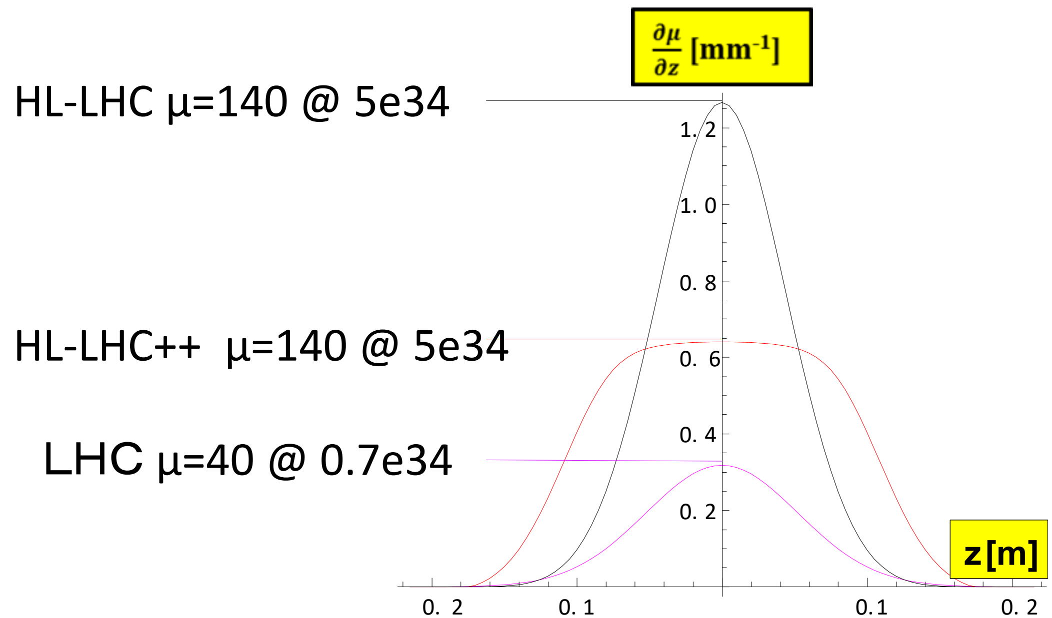


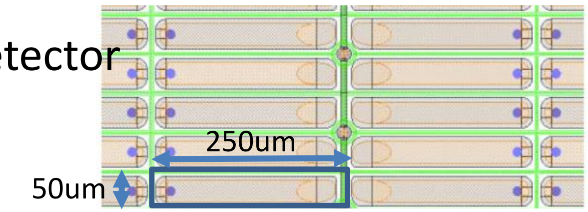


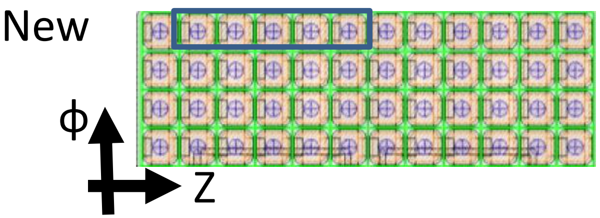
HL-LHC : 140 interaction per bunch crossing

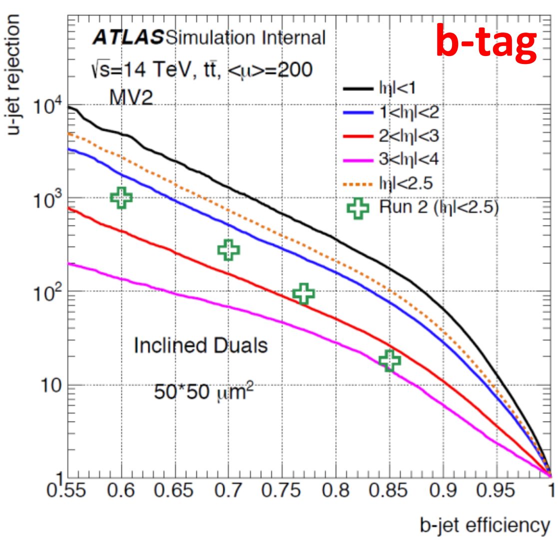


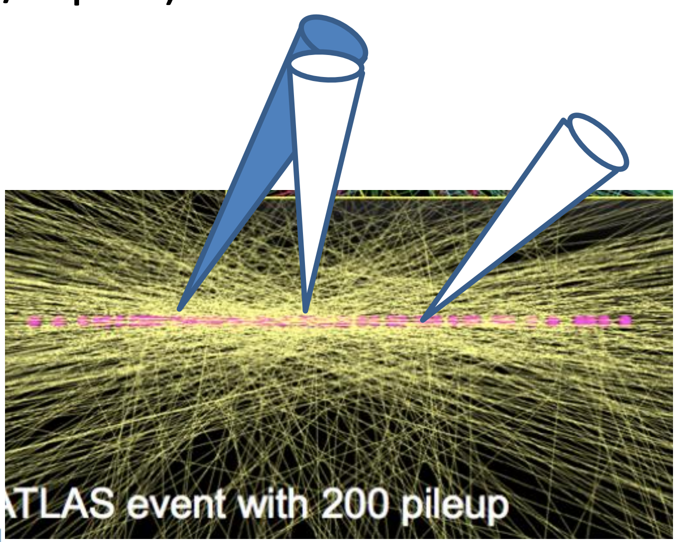
Specification for Upgrade detector

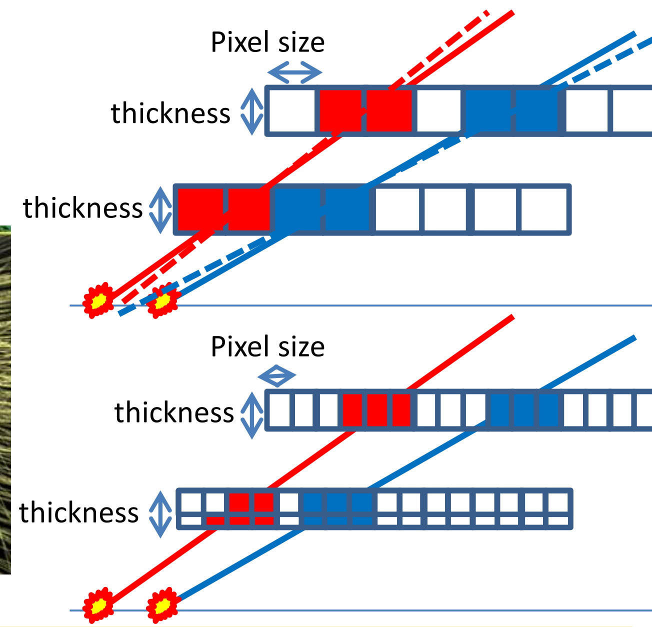
- Pixel size for charged particle detection
  - 5 times finer pixel size
  - **50um x 50um or 25um x 100um**
- Sensor thickness
  - Thinner sensor could reduce occupancy.
  - **1st and 2nd layer 100um, the others 150um**
  - Need 100um thickness to have enough charge (~7000 e-/h pair)







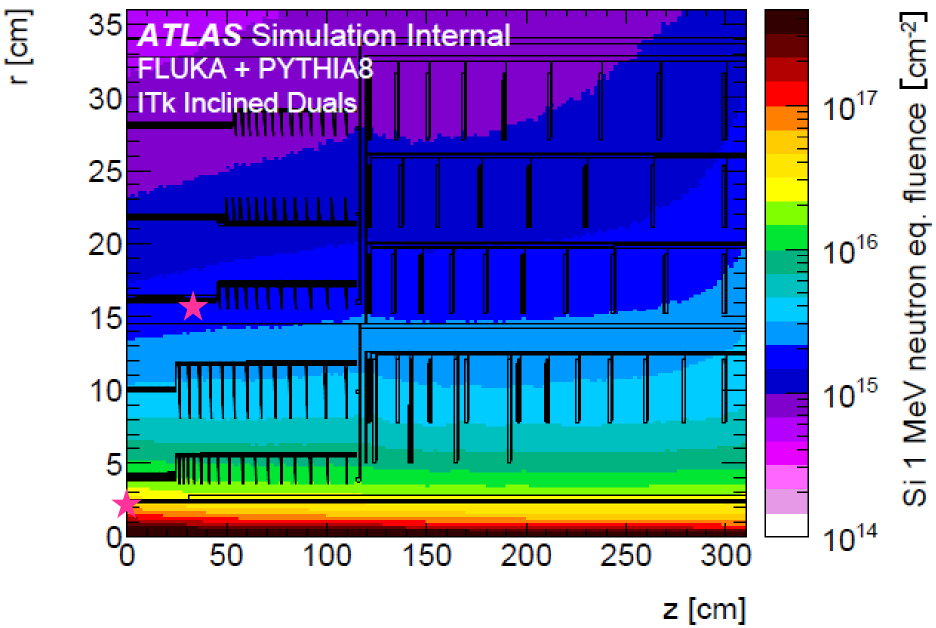


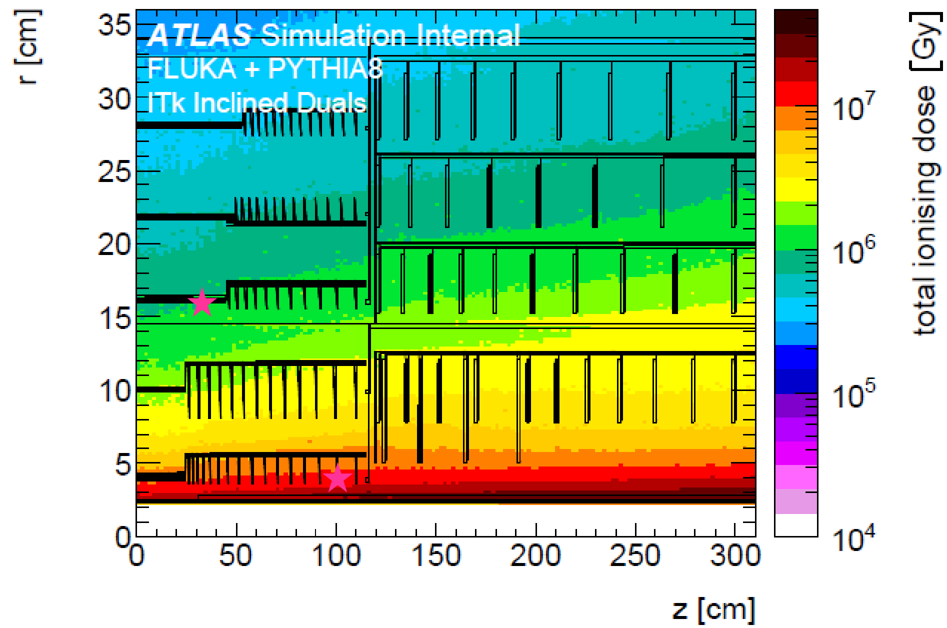


Radiation environment

- Expected radiation level for $4000 fb^{-1}$
  - Non Ionizing Energy Loss (NIEL):
    - 3^{rd} layer: 2.8×10^{15} n_{eq} $/cm^2$ 1^{st} layer : $2.6 \times 10^{16} neq/cm^2$
  - Total Ionizing Dose (TID) :
    - 3^{rd} layer : 1.6MGy 1^{st} layer : 19.8MGy

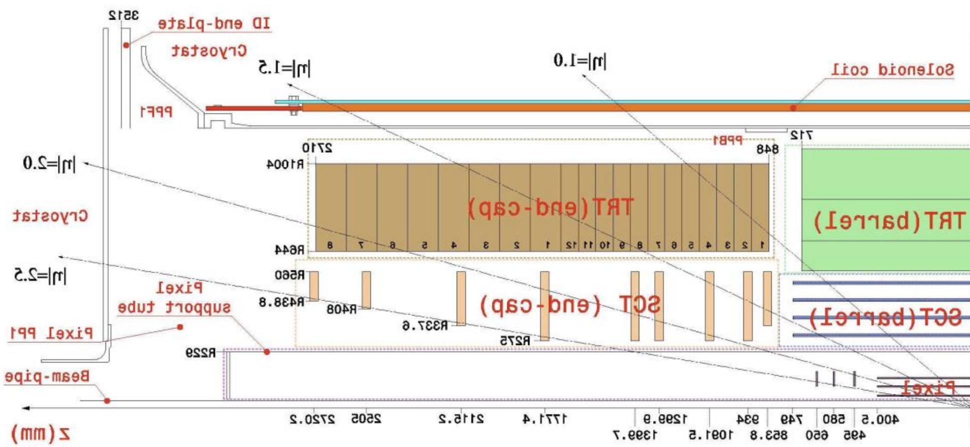
Could replace detector at the middle of runs.



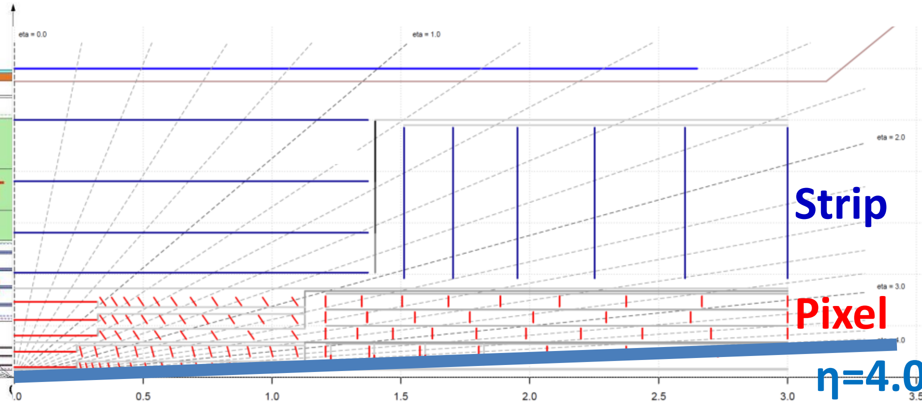


ATLAS inner tracker(ITK) project for HL-LHC

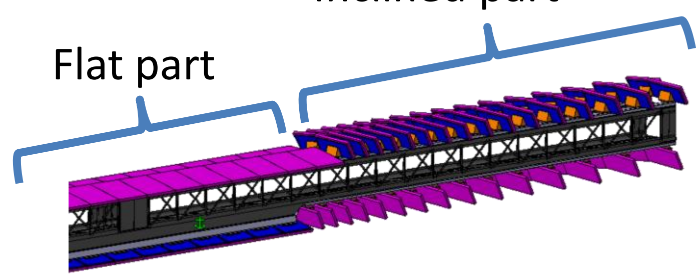
Current ATLAS Detector

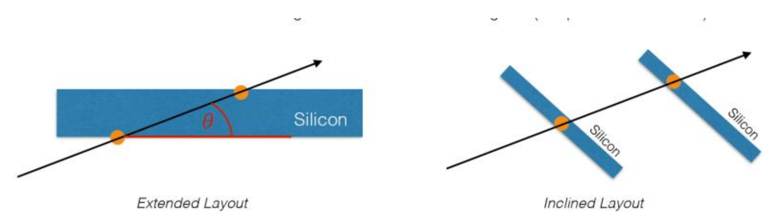


ITK upgrade detector



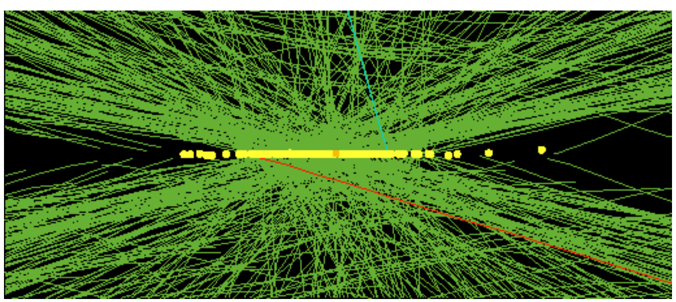
- Larger coverage area
  - Pixel : current 2.7m^2 ➔**upgrade 8.2m^2**
  - Strip : current 34m^2 ➔upgrade 165m^2
- Higher Forward coverage
  - Current η<2.5 ➔ **upgrade η<4.0**
  - **Better Pileup removal**
- Mechanics : inclined
  - Reduce material
  - Higher tracking resolution.

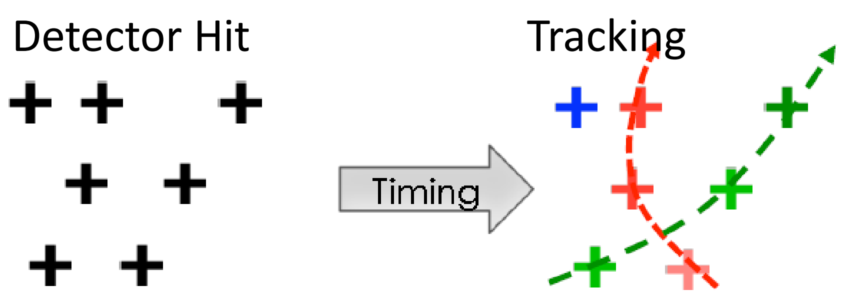




What's the issue in tracker for future?

- Most serious issue in the future hadron collider should be a number of **multiple interaction** per bunch crossing.
  - About 140-200 at the HL-LHC and 1400 in future colliders.
  - Idea to solve the issue?
    1. ***Pixel size*** : Construct smaller pixel size detector and make better vertices separation →**May be hard to improve 10 times…**
    2. ***Time resolution*** : If we could use timing information for the hit in the track, may have better track finding using the information. →If the timing resolution is less than 1cm/*c* = **50ps** it should help a lot.

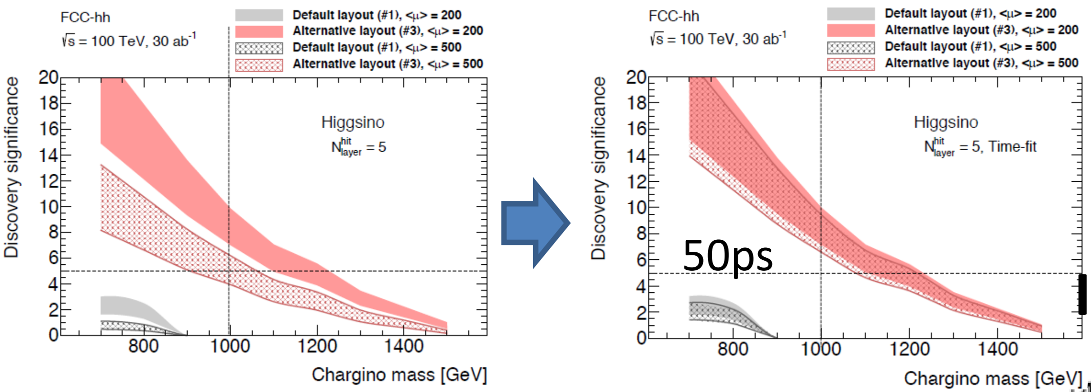




4D Detector??

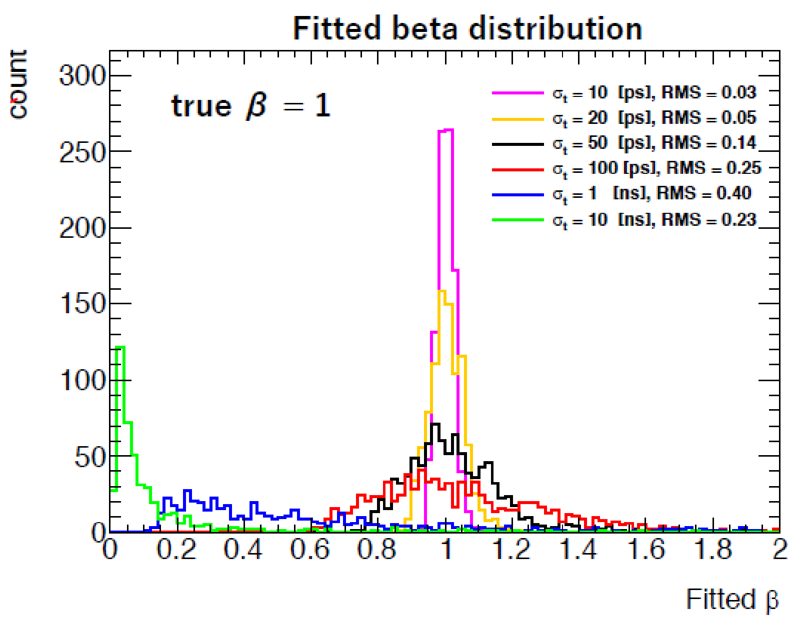
Impact to the Physics

Higgsino production by using disappearing track

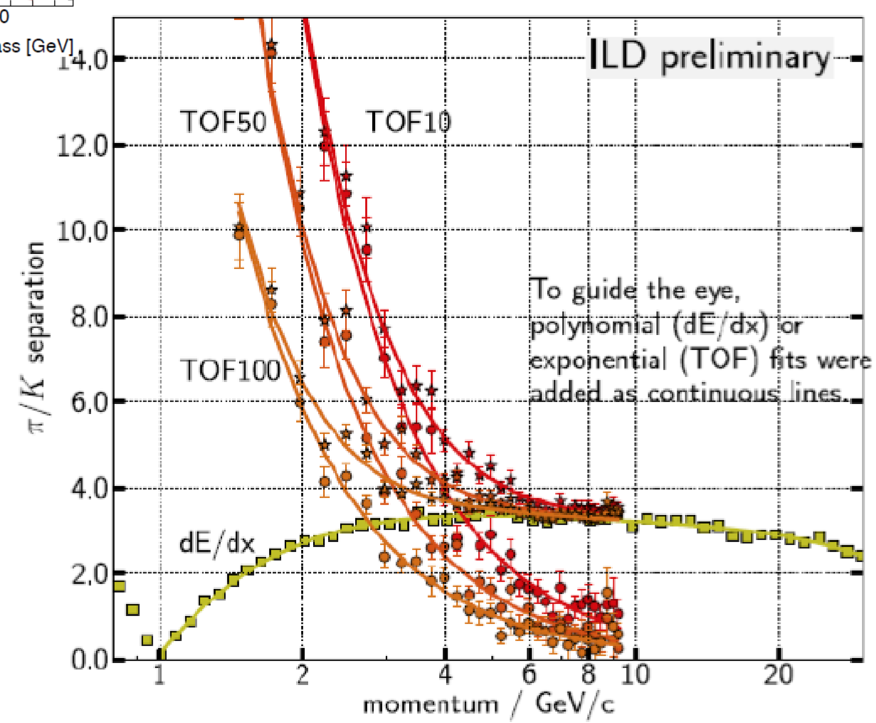


- See more information in timing detector workshop last year : https://indico.cern.ch/event/747424/timetable/#20181208

β measurement in FCC detector



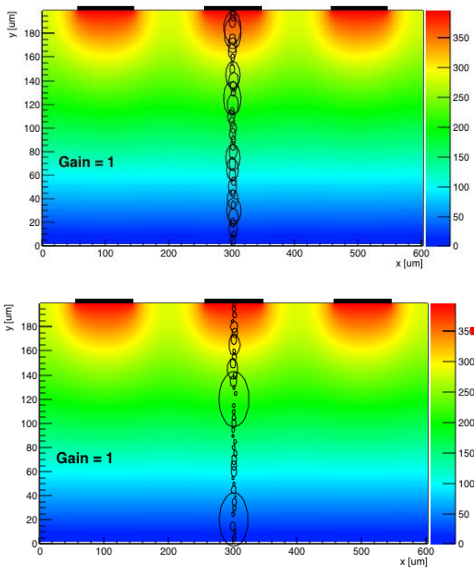
ILC K/π separation



Timing sensitive semi-conductor tracking detector

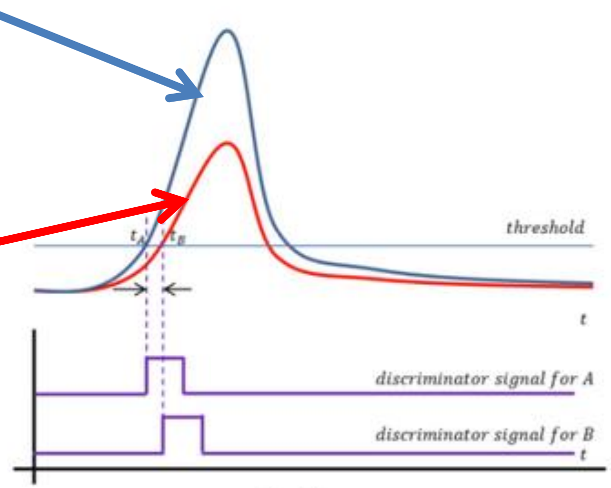
Timing resolution

- What is driving the timing resolution of detector?
  - Time walk and time jitter



Time Walk

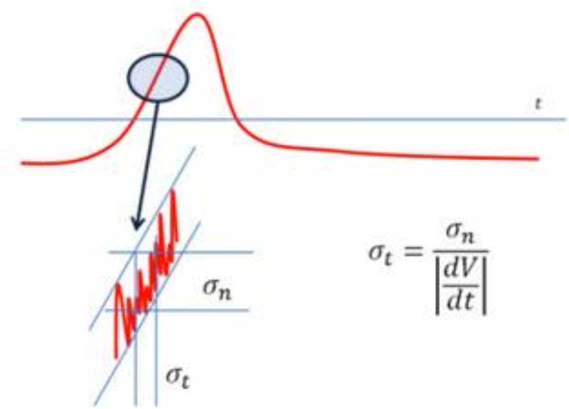
Over-threshold Timing difference due to the size of the signal



Time walk effect

Time Jitter

Due to various noise souces



Jitter effect

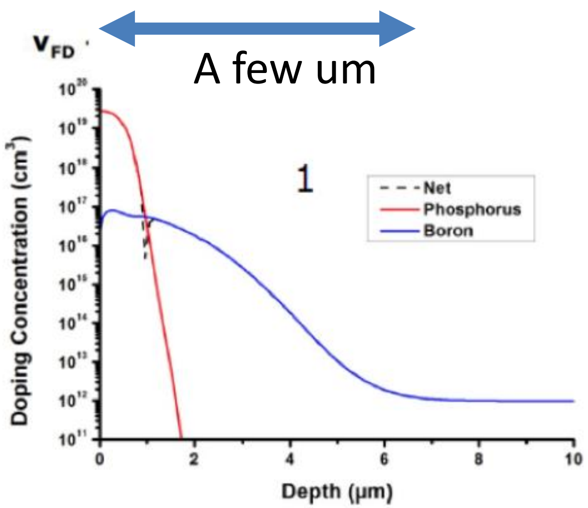
Fast turn on (i.e high dV/dt) should have better timing resolution.

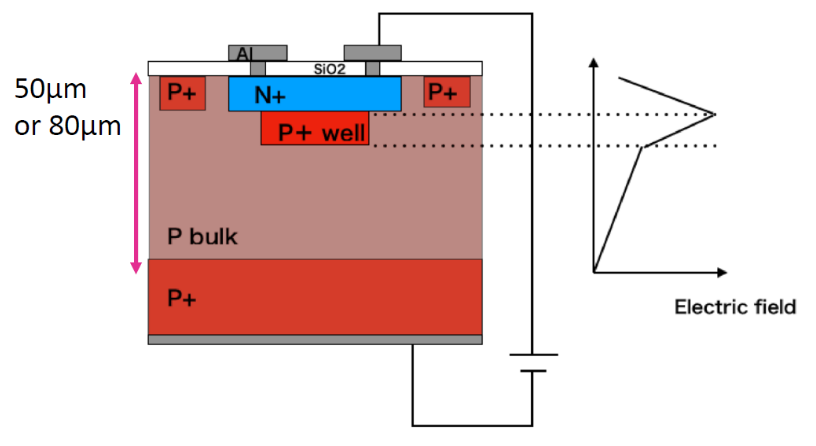
Need lower noise level.

Low gain avalanche detector (LGAD)

- To make faster turn-on
  - Need faster drift velocity of the electron-hole pair.

    $v_{e/h}=\mu_{e/h}$ x **E** (where μ_e is mobility, E is electric field.)
  - How to realize 100kV/cm field?
    - ***<u>Higher bias voltage?</u>***
      - If need 100 times velocity we need 100 times bias voltage → **a few 10kV bias is necessary → impossible due to break down.**
    - ***<u>Is it possible to make localized higher field?</u>***
      - **Doping p+ under the n+ implant electrode makes around 300kV/cm field locally →Low Gain Avalanche Detector (LGAD)**

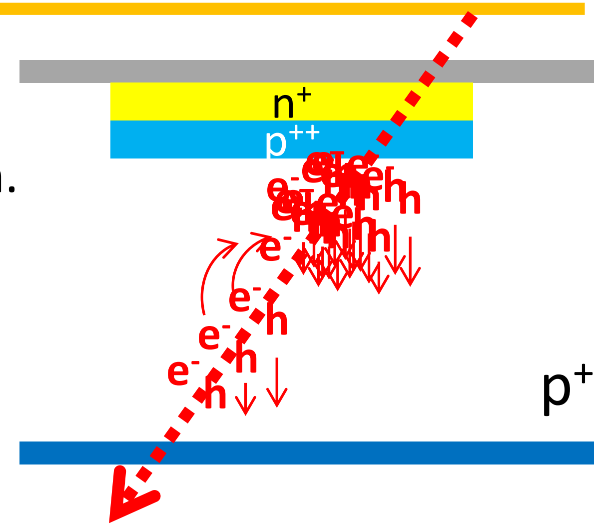


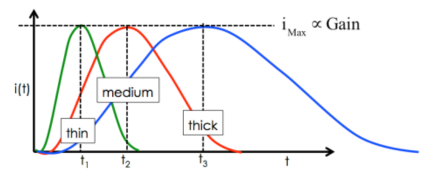


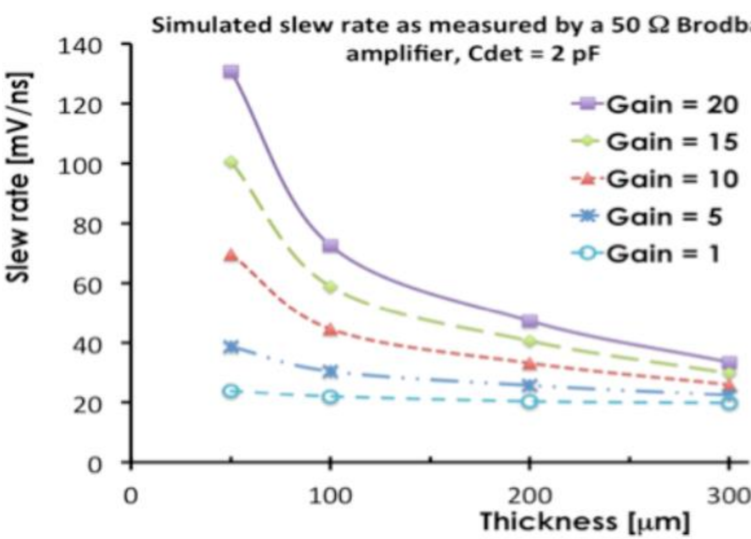
LGAD structure

Low gain avalanche detector (LGAD)

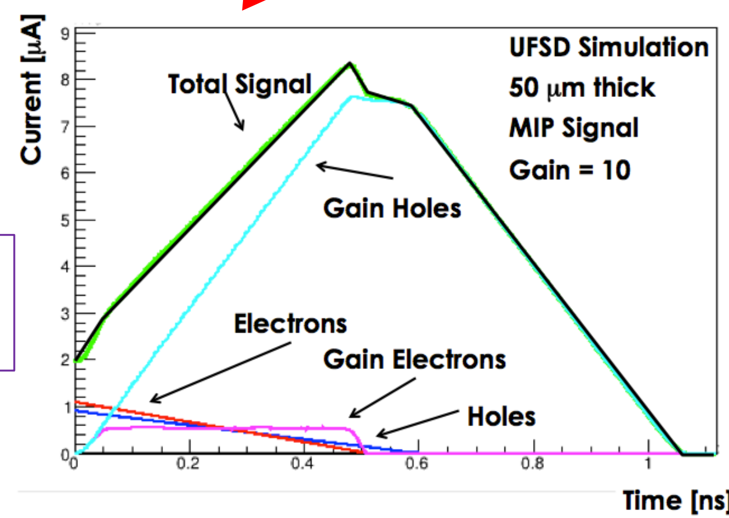
- Sources of signal on the electrode.
  - Initial e/h is not contributing much.
  - e/h pair produced by avalanche is high contribution.
    - e have short driving length (not dominant)
    - **h have longer drift length (Dominant)← Ramo's theorem**
  - Thinner detector is better slew rate.







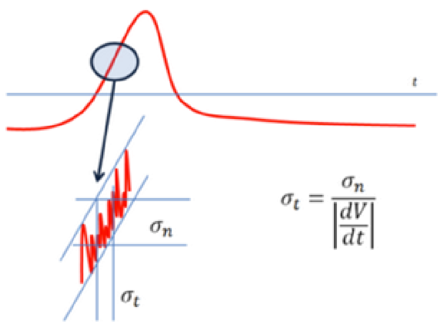
Slew rate ∝ Gain
∝ 1/d



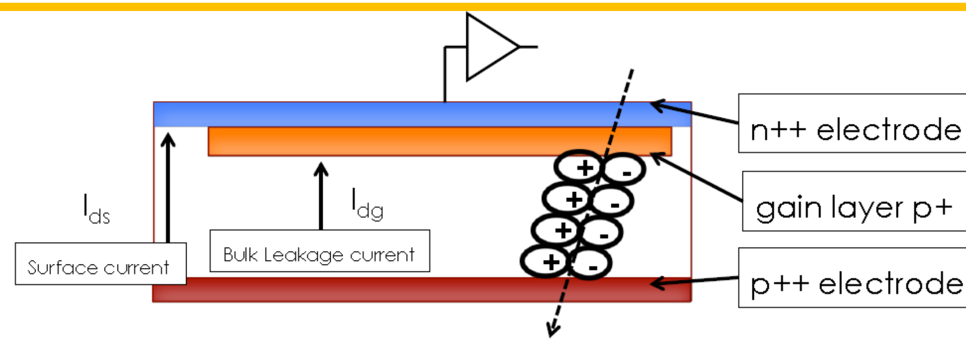
Detector with higher gain and thinner bulk is better.

Why "Low" Gain?

- It is important to reduce noise even faster turn-on with higher gain



Jitter effect



$$i^2_{Shot} = 2eI_{Det} = 2e\left[I_{Surface} + (I_{Bulk})M^2F\right]$$

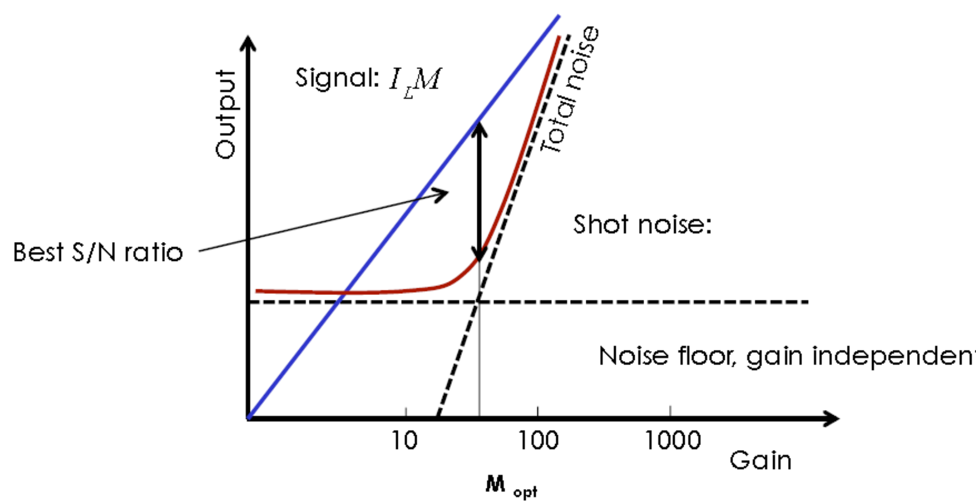
$$F = Mk + \left(2 - \frac{1}{M}\right)(1-k)$$

$$F \sim M^x$$

k = e/h ionization rate
x = excess noise index
M = gain

- **Shot-noise increase by power of Gain**

- Noise will be increased faster by increasing gain ➔Best S/N ratio can be optimized : G=10-20?



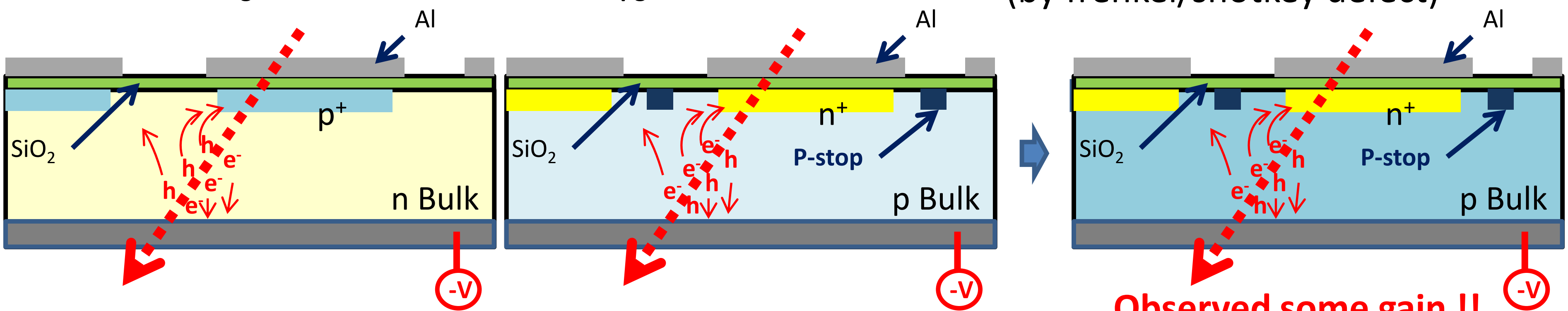
History of LGAD

Silicon detector with High resistivity bulk

~2005 **All existing ATLAS detector**

2005- **Upgrade ATLAS detector**

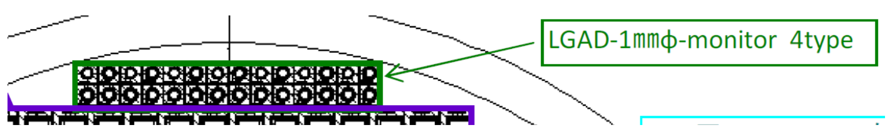
After proton/neutron irradiation :
higher p+ like doping potential
(by frenkel/shotkey defect)

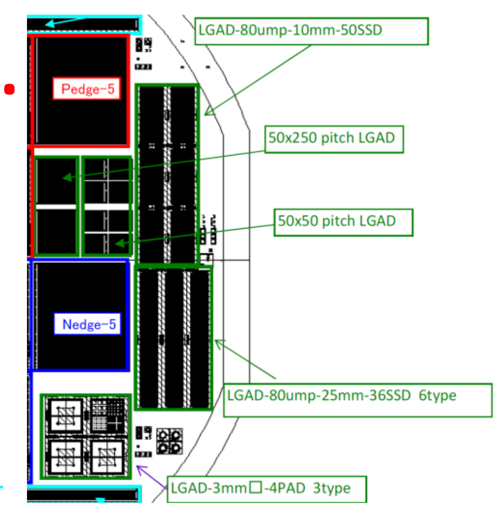


Observed some gain !!

2015-

- In 2015, **first LGAD detector build with HPK.**
  - Although this is the same technology to the Avalanche photo diode(APD) since 1970s…
- First detector is 1mm monitor diode.

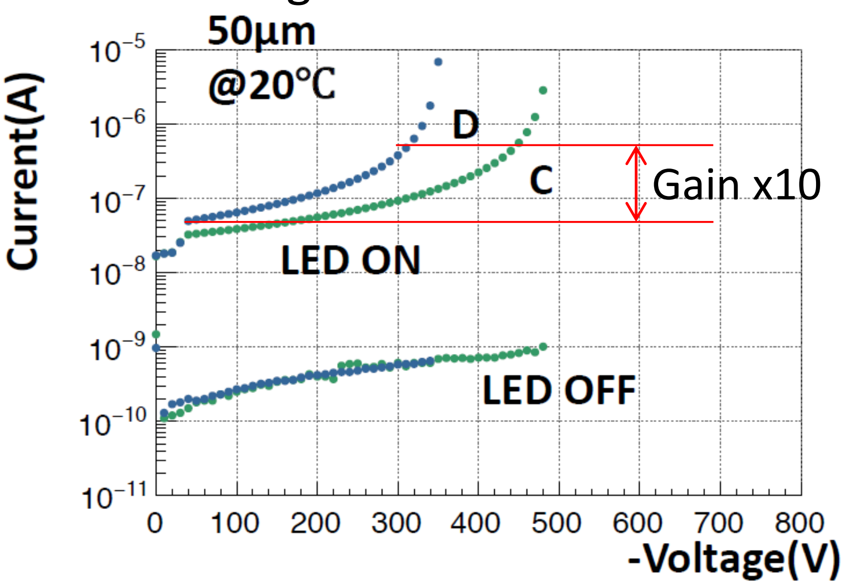


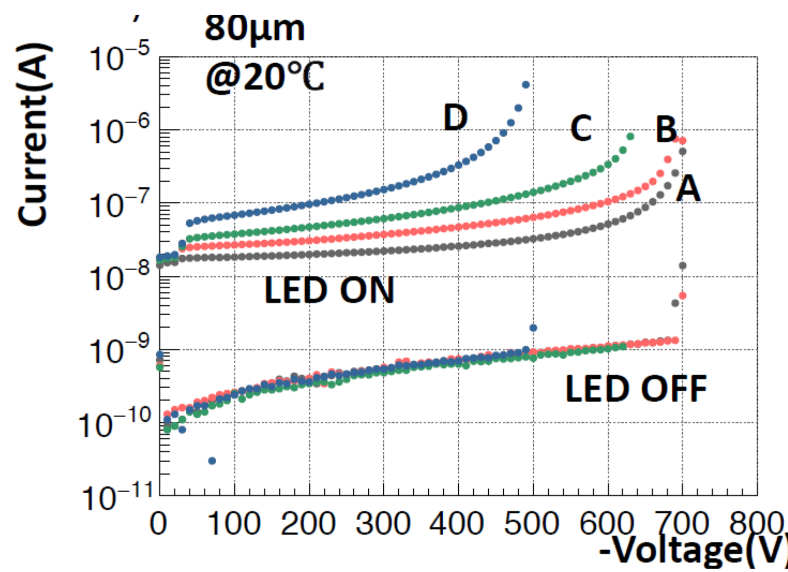


First pad detector – IV measurement

- ***Pad detector***
  - Size 2.5mm x 2.5mm
  - Opening windows 1mmϕ
  - ***Leakage current***
    - measured w/ and w/o LED light on.

Sample name	P+ dose A<B<C<D	Physical thickness	Active thickness
50A	A	150	50
50B	B		
50C	C		
50D	D		
80A	A		80
80B	B		
80C	C		
80D	D		

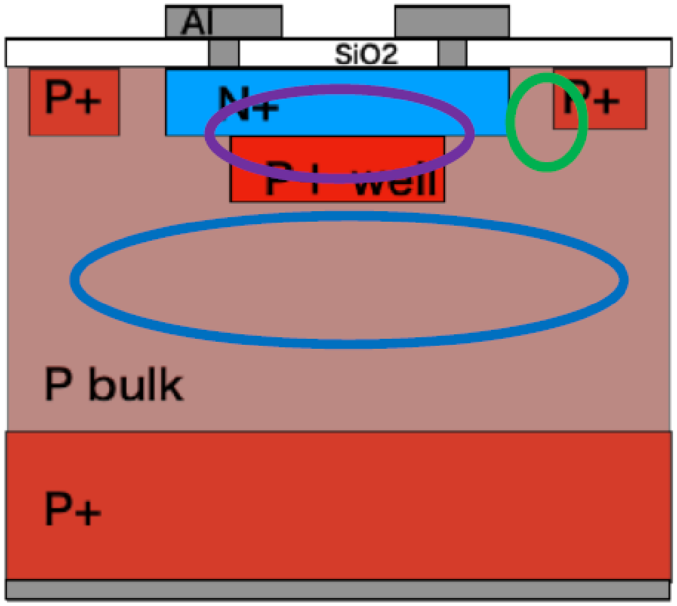


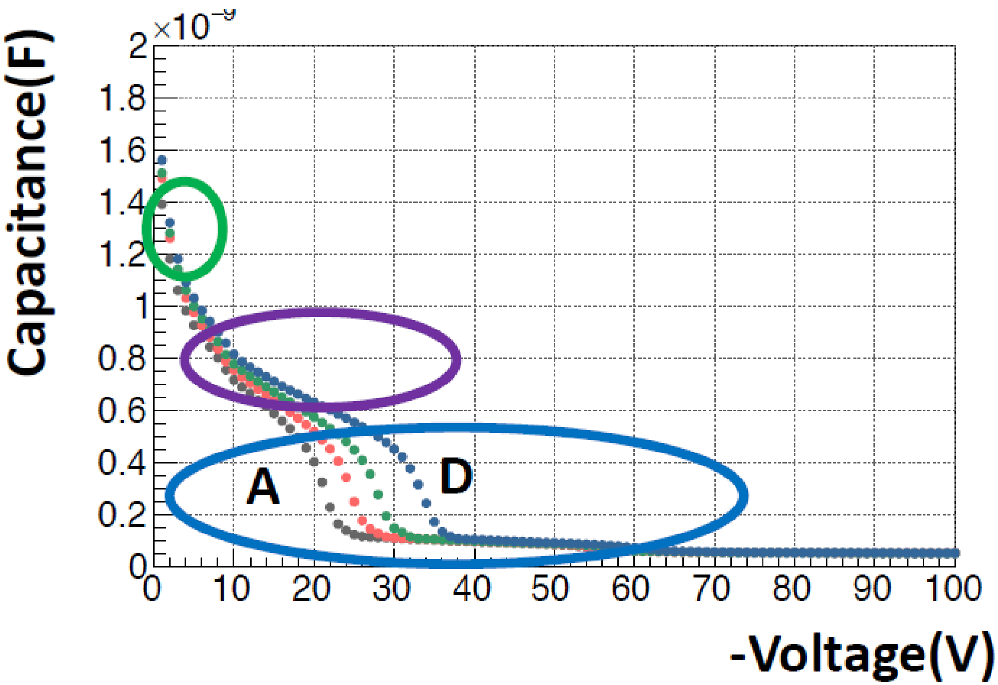


Thinner detector is just better (could operate with lower voltage.)

First pad detector – CV measurement

- Bulk capacitance measurement
  - Two (or three?) step function.
    - **Side region**
    - **Multiplication region →higher p+ doping need higher depletion voltage**
    - **bulk**





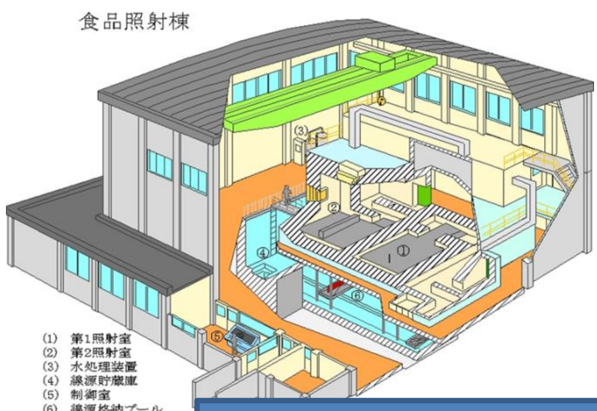
Irradiation Facilities

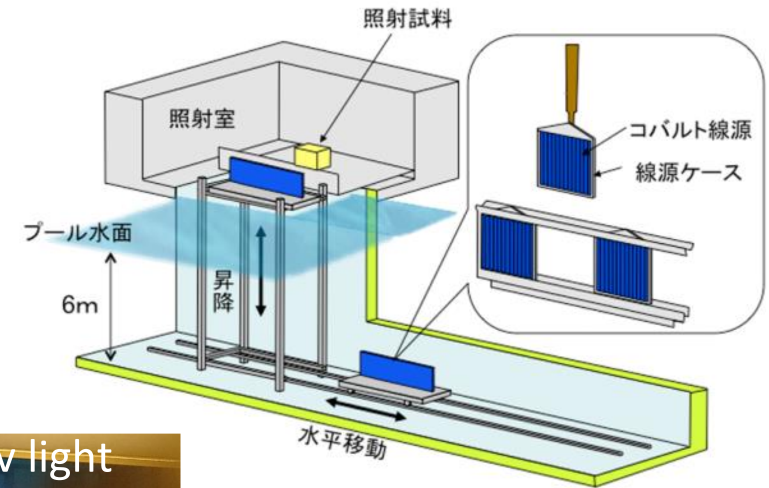
- Gamma irradiation (surface damage by TID)
  - ^{60}Co irradiation at QST, Takasaki, Japan
- Proton irradiation (bulk damage by NIEL)
  - Proton irradiation by CYRIC Tohoku University

Gamma Irradiation Facility in Japan

- QST, Takasaki is gamma irradiation facility with ^{60}Co source

Food Irradiation Room





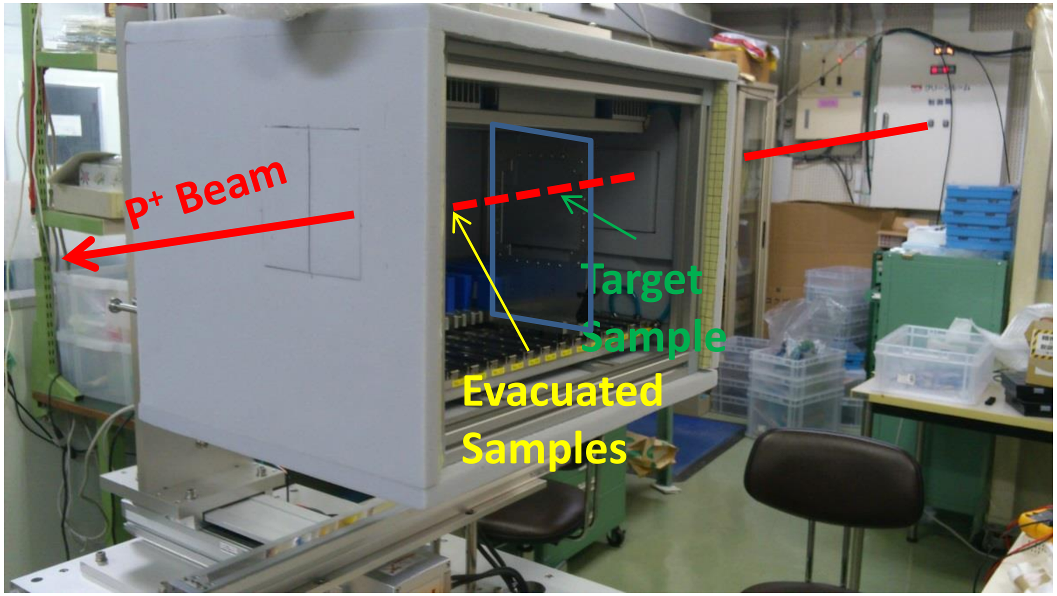
Height : 22.5cm
Distance : 5cm (2014.10)
1.14e6 R/h~11.4kGy/h

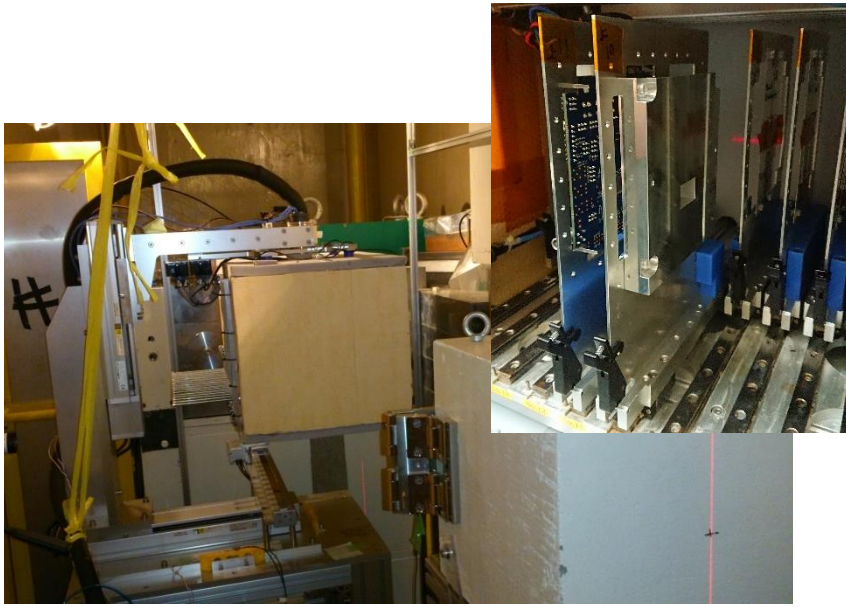
線源中心からの距離（Xcm）　　測定点の高さ（22. 5cm）

	0	20	40	60	80	100		
5	1.14E+06	1.08E+06	9.45E+05	5.69E+05	2.67E+05	1.34E+05		
10	9.01E+05	8.59E+05	7.41E+05	4.84E+05	2.55E+05	1.34E+05		
20	6.04E+05	5.77E+05	4.98E+05	3.68E+05	2.26E+05	1.34E+05		
30	4.32E+05	4.14E+05	3.61E+05	2.84E+05	1.93E+05	1.27E+05		
50	2.51E+05	2.42E+05	2.17E+05	1.82E+05	1.43E+05	1.10E+05		
90	1.14E+05	1.11E+05	1.04E+05	9.42E+04	8.22E+04	7.01E+04		
130	6.44E+04	6.35E+04	6.09E+04	5.71E+04	5.23E+04	4.71E+04		
170	4.13E+04	4.09E+04	3.97E+04	3.80E+04	3.58E+04	3.33E+04		
210	2.90E+04	2.91E+04	2.82E+04	2.72E+04	2.58E+04	2.44E+04		
250	2.12E+04	2.11E+04	2.09E+04	2.03E+04	1.97E+04	1.90E+04		
270	1.89E+04	1.86E+04	1.84E+04	1.80E+04	1.73E+04	1.66E+04		

Proton Irradiation Facility in Japan

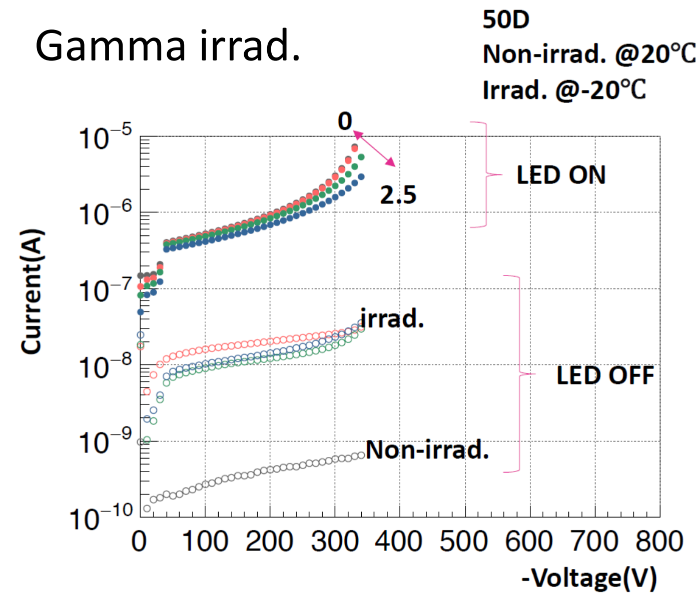
- CYRIC@Tohoku Univ. is an irradiation facility with 70MeV proton beam (~1μA).
  - This allows 5-6 pixel modules with backing Al plate at the same time(3% E loss/pixel).
  - Operated at -15℃ temperature with dry N_2 gas.
- Programmable X-Y stage and "push-pull" mechanism are implemented to the machine.
  - Choose to irradiate one or more target samples in max 15 pre-installed samples.
- Scanning over full pixel range during irradiation.
- **Actual Fluence difference relative to the target fluence is within ~10%.**



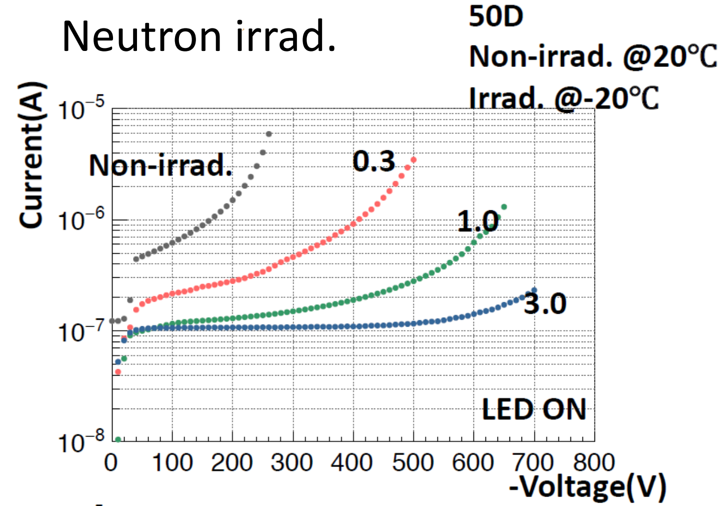


I-V performance after irradiation

- Gamma irradiation
  - Irradiated 0.1/1.0/2.5MGy
  - Leakage current w/o LED on
    - Increases but no dose dependence.
      - Probably due to only surface damage.
  - Gain w/ LED on
    - **Slight degraded but can be recovered by 20% higher voltage.**

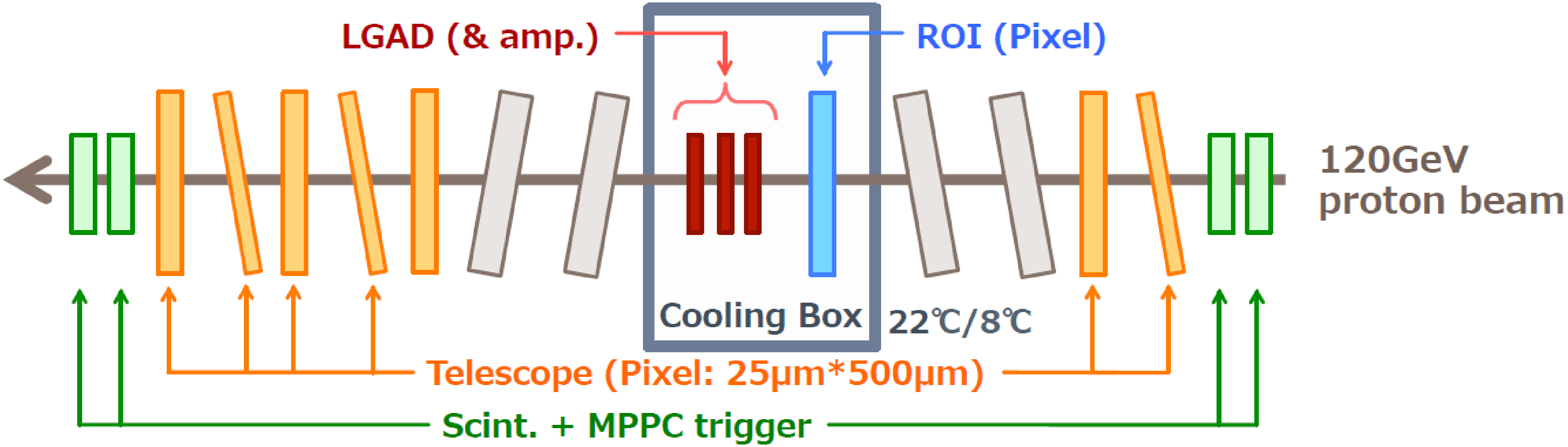


- Proton/Neutron irradiation
  - 0.3/1.0/3.0 x 1015 n_{eq}/cm^2
  - After 60°C 80min Annealing.
  - Gain degraded a lot.
    - **May not possible to have Gain=10 after 3×10^{15} n_{eq}/cm^2 irradiation.**
    - Effect is smaller in case of higher p+ dope.



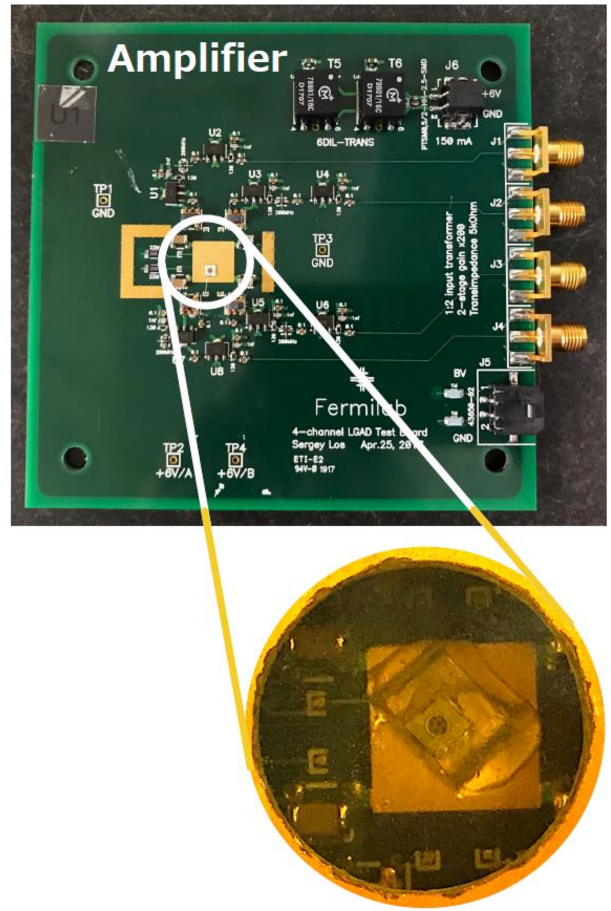
Timing resolution measurement

- Testbeam @ Fermilab
  - 120GeV proton beam
  - Telescope by pixel detector
  - Stacked 3 LGAD sensor
  - Signal readout by Flash ADC(V1742, 5GS/s)



Discrete Amplifire & Flash ADC

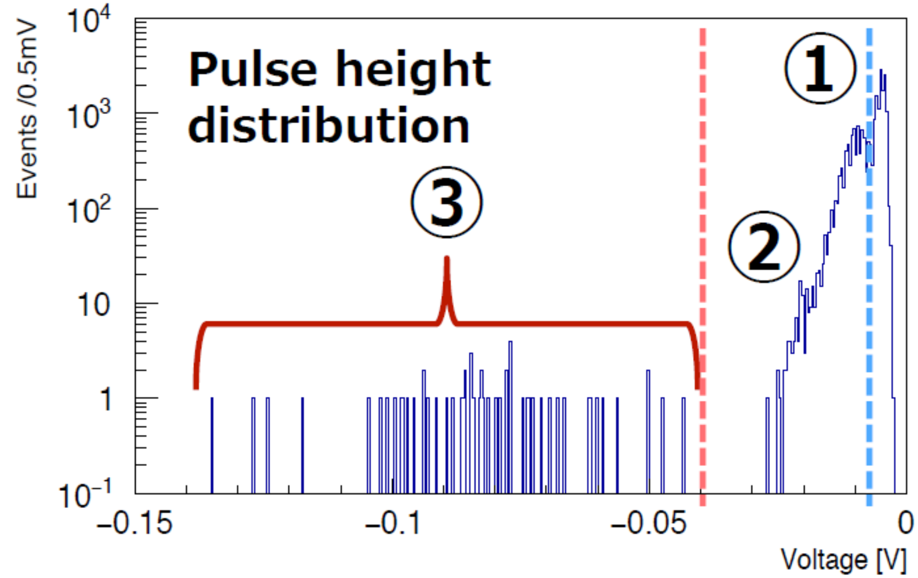
- Bi-polar high-speed transistor
  - Frequency Band :<75GHz
  - Gain : 100
- Flash ADC (VME)
  - CAEN : V1742 (DRS4)
  - Pulse Height
    - 12bit / 1Vpp
    - 1V/4096~0.25mV
  - Time
    - 10bit / 5GS/s
    - 200ps * 1024 ~ 200ns

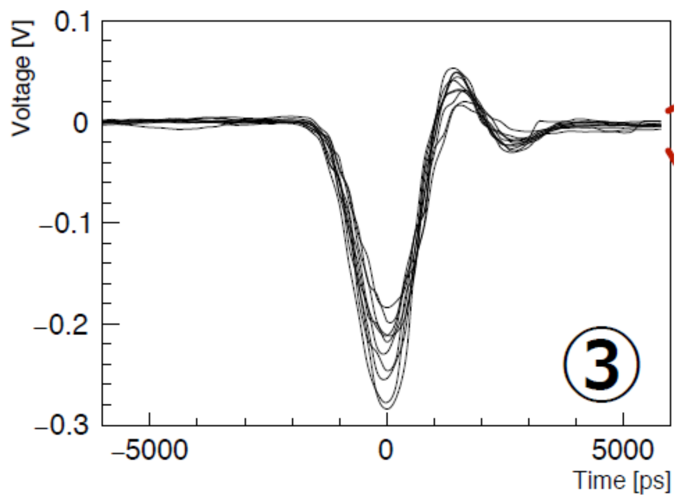


V1742

Pulse shape

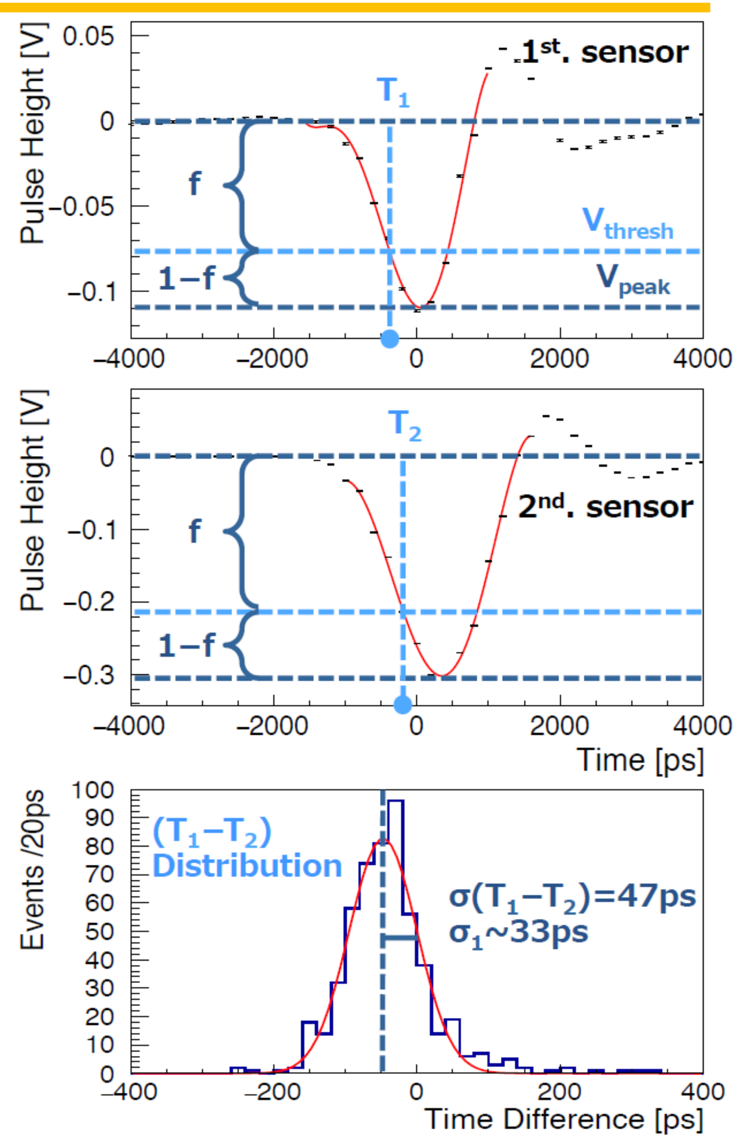
- Pulse height distributions shows 3 components.
  - ① Noise
  - ② Region w/o p+ implant (G=1)
  - ③ Region w/ p+ (Gain~10)
- Evaluated time resolution by the hits with gain.





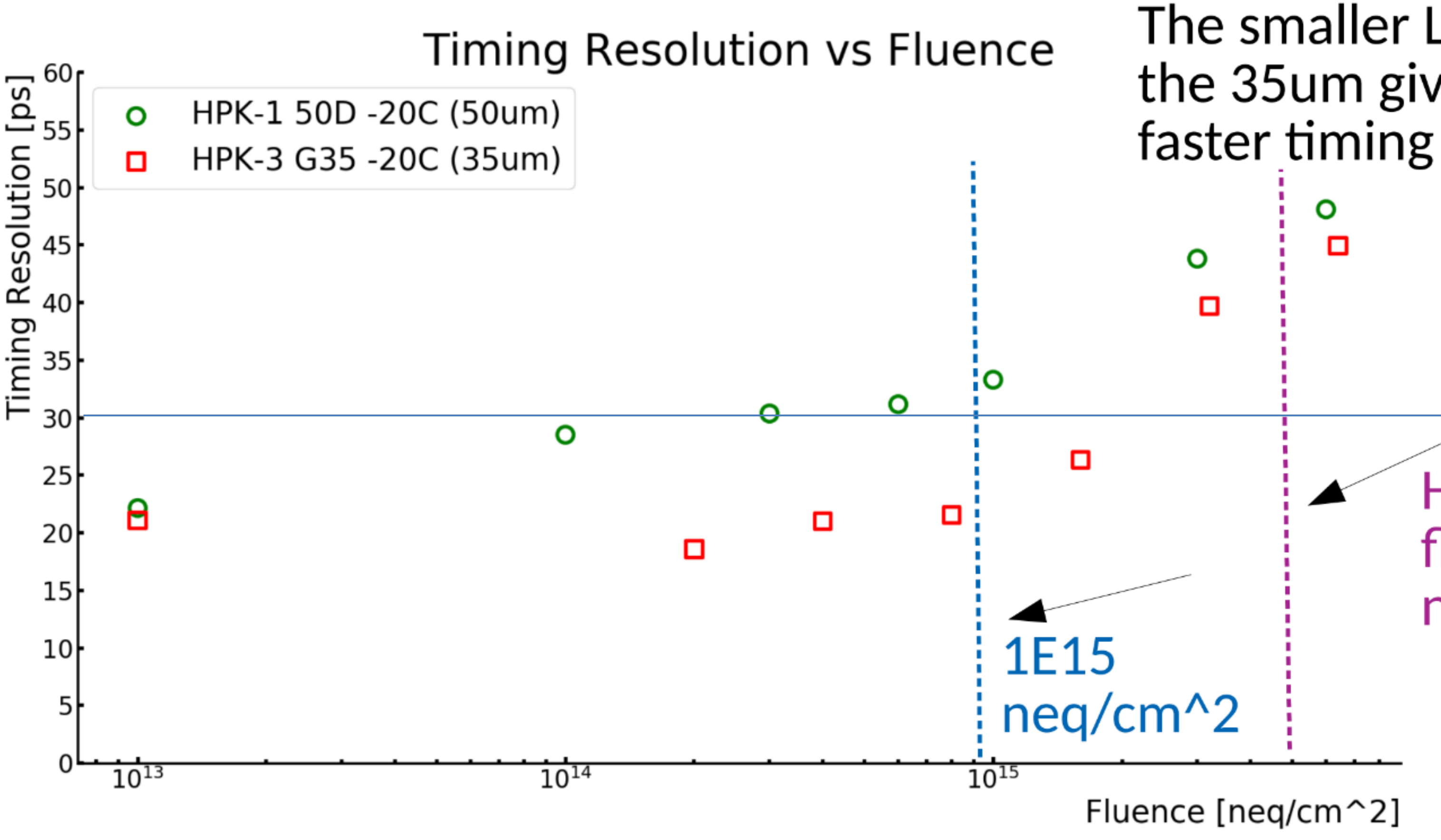
Timing resolutions

- Fit pulse shape by a polynomial function
- Define $V_{theshold}$ depending on peak height
  - $V_{threshold} = f \times V_{peak}$
- Calculated time difference of two different devices. (T_1 - T_2)
  - $\sigma(T_1\text{-}T_2)=\sqrt{(\sigma_1)^2+(\sigma_2)^2}$
- In case the sample 1 and 2 is the same type :
  - resolution should be $\sigma(T_1\text{-}T_2)/\sqrt{2}$
- As a result, single sensor timing resolution is
  - **30ps for 50um thick**
  - **45ps for 80um thick.**



Timing resolution degradation

- After Proton/Neutron irradiation, timing resolution is depredated rapidly @ 1-5x10^{15} n_{eq}/cm^2.

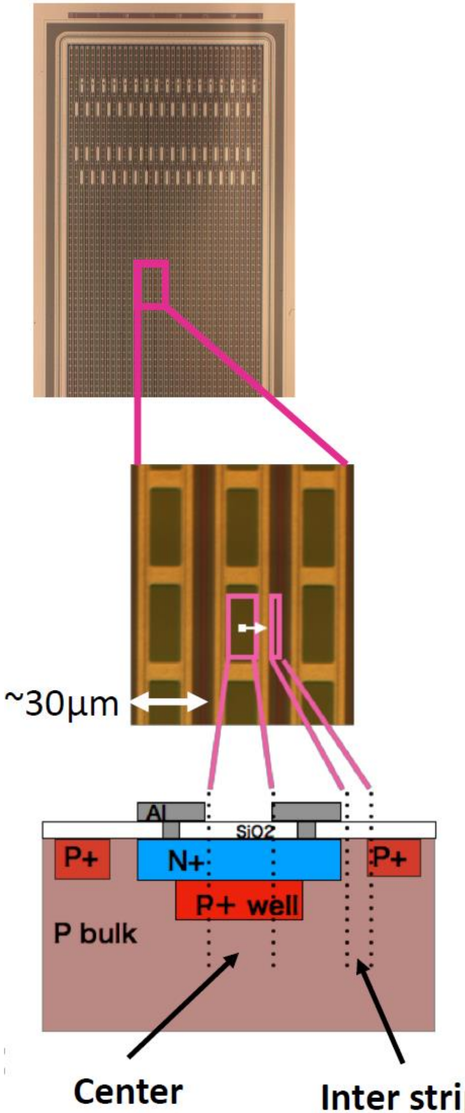


The smaller Landau noise in the 35um gives an overall faster timing resolution.

https://indico.fnal.gov/event/ANLHEP1390/session/8/contribution/68/material/slides/0.pdf

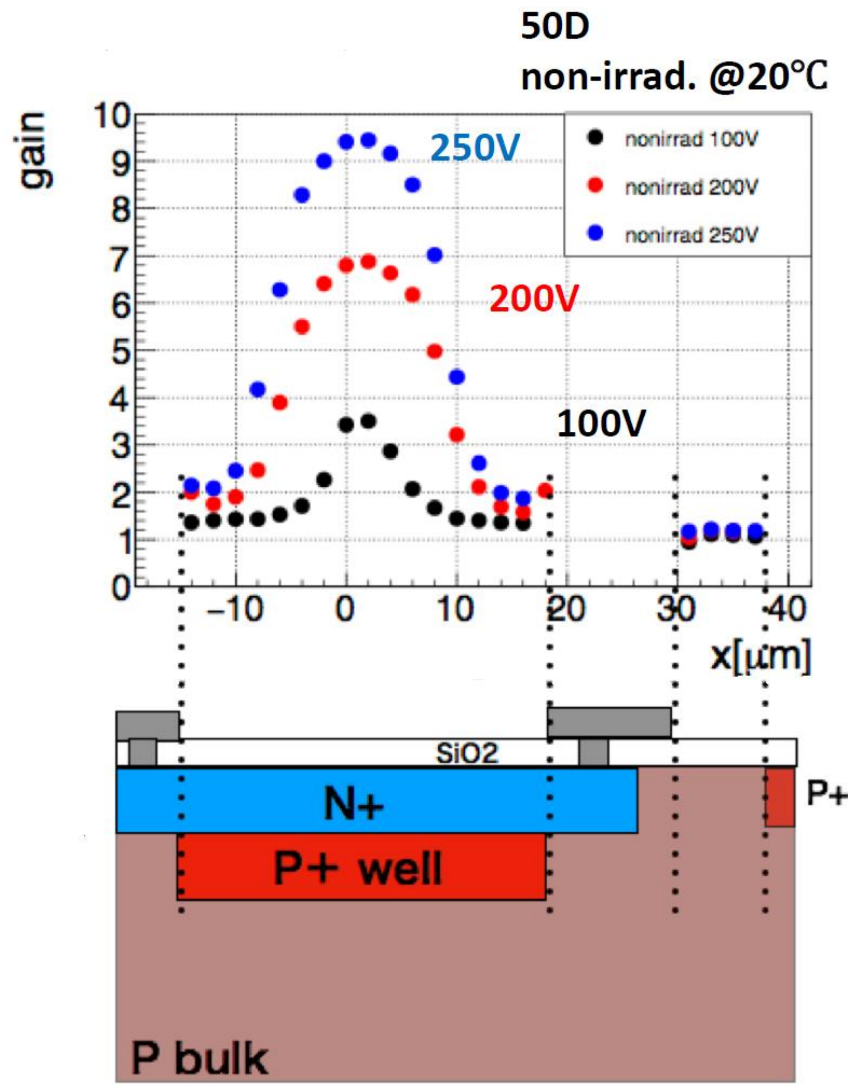
Strip detector

- First strip detector
  - 6mm x 12mm size
  - 80um strip pitch
  - Implemented windows in the top Aluminum to inject Laser.
- Nd:YAG Layser
  - 1.165eV laser which is slight above Si band gap energy and penetrates the Si sensor. (similar signal to MIP signal)
  - 2-3um square spot with 1.5um step stepping motor.
  - *Nuclear Instruments and Methods in Physics Research A 541 (2005) 122– 129*
- Evaluated position dependence Charge collection and Gain



Gain Uniformity

- Position dependence of Gain has been observed.
  - Strip center have close to Gain=10.
  - Only about 20% of the region have gain.
    - Due to the smaller p+ implant.



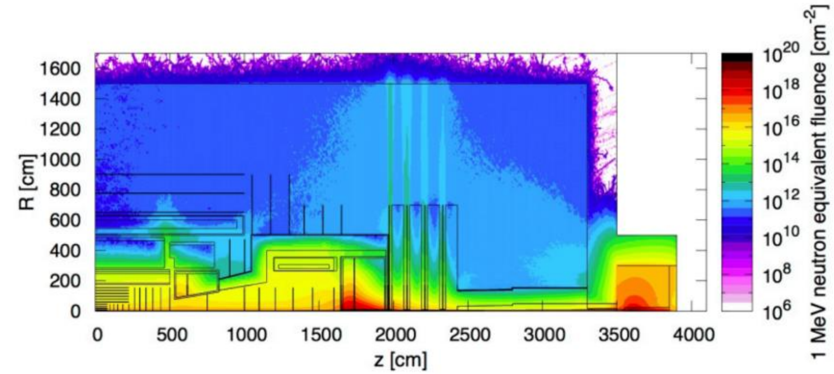
This is critical problem for finer granularity detector.

What we are planning next.

Application for Tracking detector

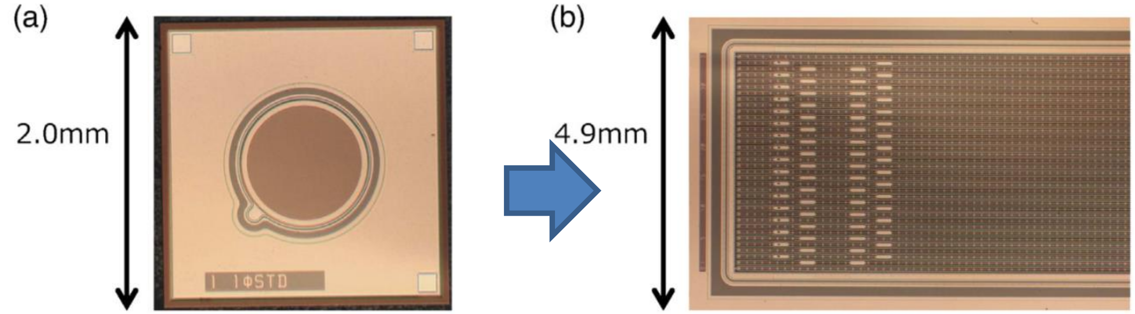
- ***Radiation Torelance***

  Depends on the target collider but 5×10^{15} -$1\times10^{16} n_{eq}/cm^2$ at least.

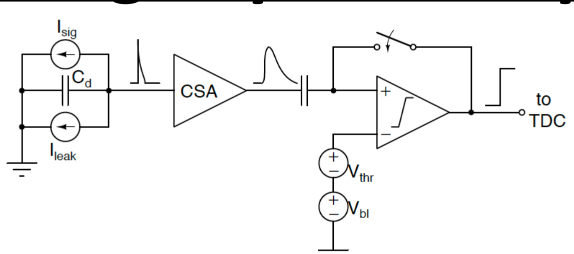


- ***Granularity***

  Need 50um pitch detector (strip or pixel)

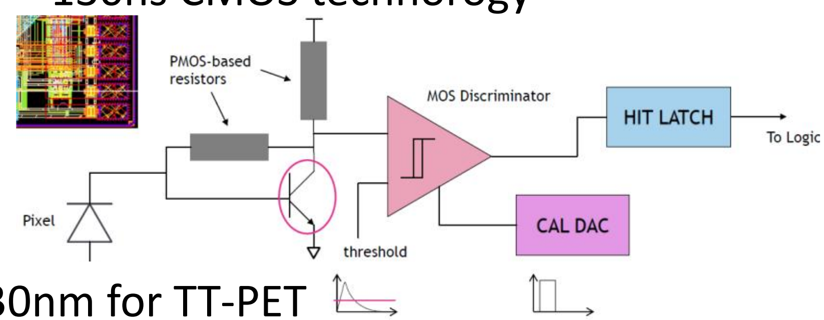


- ***Low noise high speed amp***



CMOS 28-nm F/E scheme

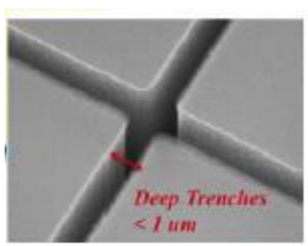
130ns CMOS technorogy



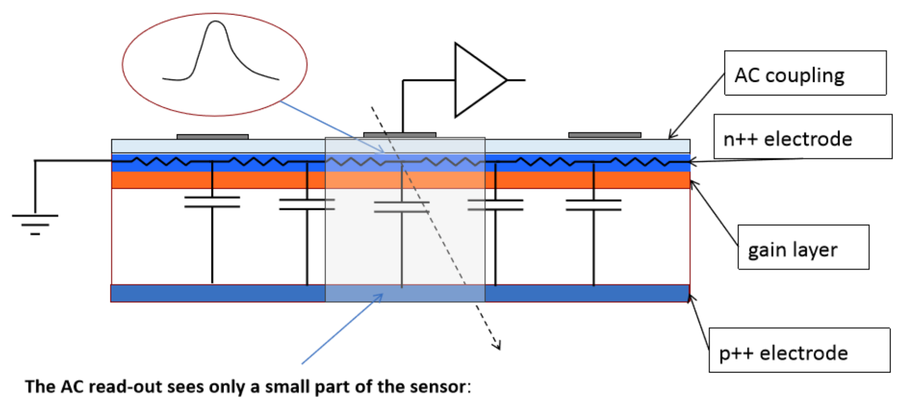
130nm for TT-PET

Fine granularity detector

- Trench protection
  - Physical separation of electrode by trench.
  - Need to study of electric field uniformity
- AC coupled LGAD
  - Uniform n+ and p+ layers
  - Put electrode on the SiO_2 to readout signal with AC.
  - Need to reduce doping concentration of n+ implant.



Deep trench
(2018 CNM)

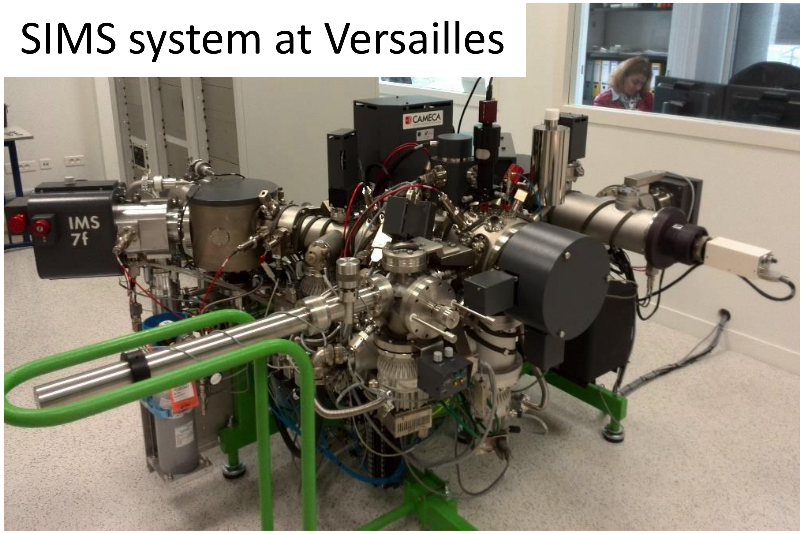


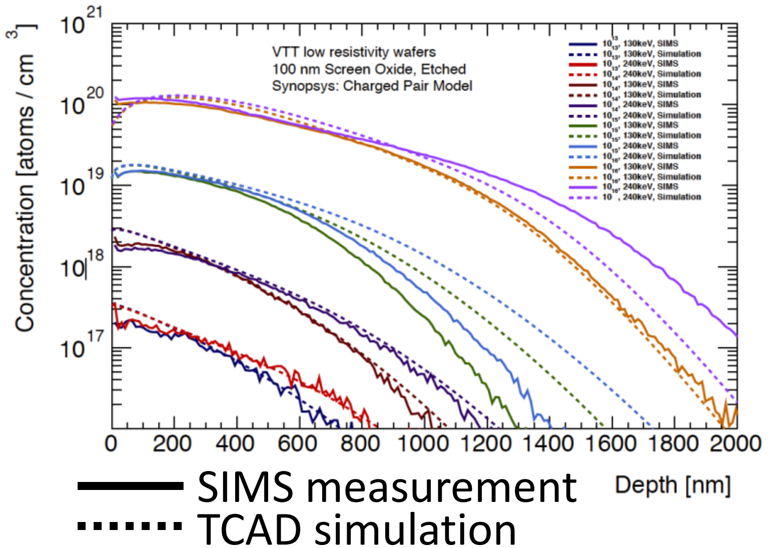
Need carful simulation for these technology.

Secondary Ion Mass Spectrometry and Simulation

- SIMS measurement
  - Analytical technique to characterize the impurities near surface(<30um) by ionized secondary particles.
  - Good detection sensitivity for **B, P, Al, As, Ni, O, Si** etc down to 10^{13} atoms/cm^3 with 1-5nm depth resolution.
- Synopsys TCAD simulation
  - Process simulation:
    - Simulate implantation and resulting concentrations.
    - **Can compare to SIMS result.**
  - Device Simulation :
    - Simulate Electric field to understand the performance of silicon device.
    - Possible to perform simulation of charge correction of MIP signal.

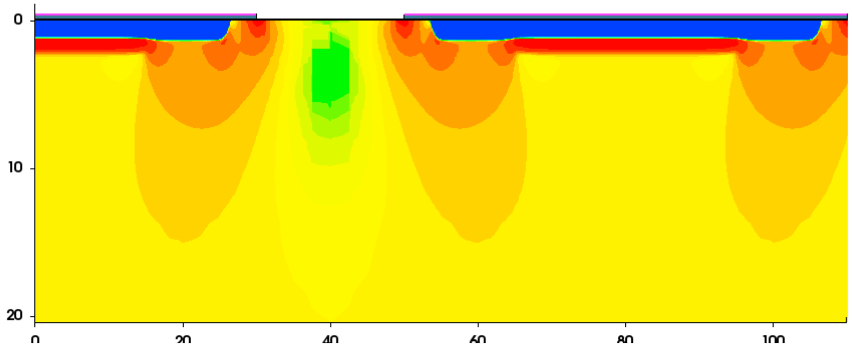
SIMS system at Versailles

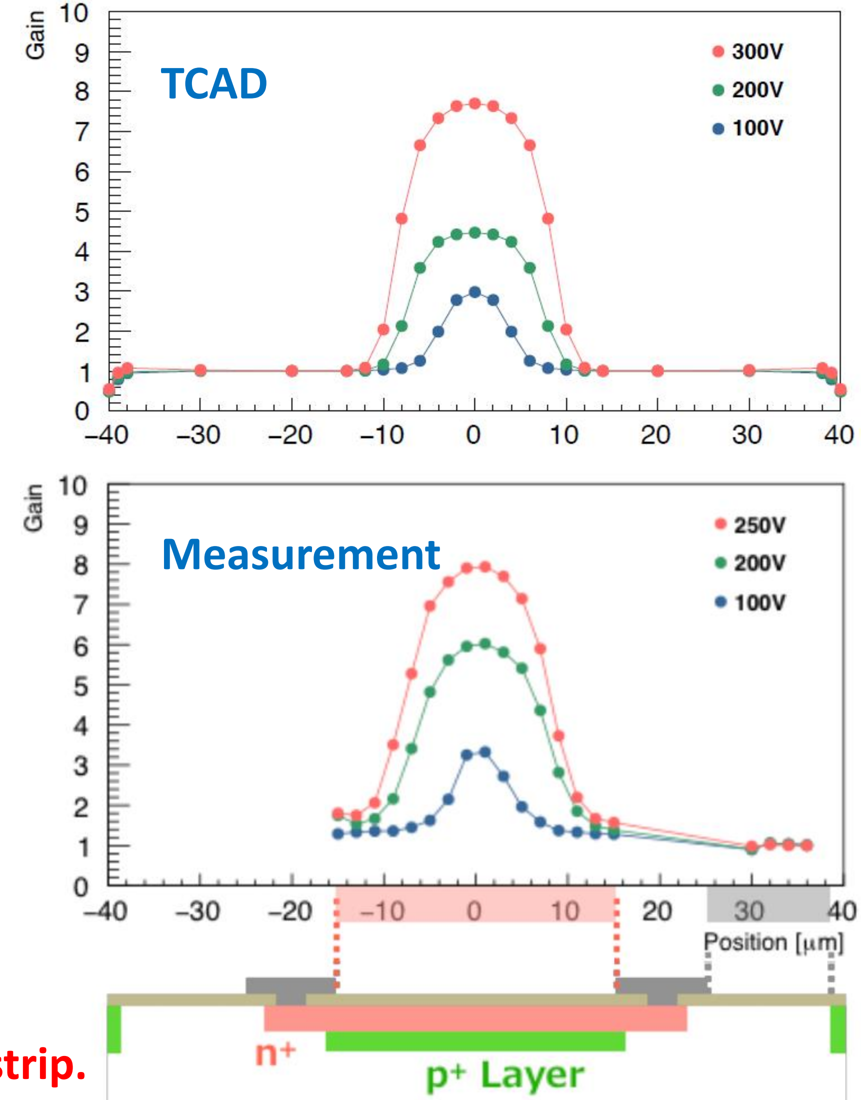




TCAD simulation

- Implement detector structure to simulation.
- Reproduced measurement results by simulation.
- This allows to understand what is the issue more quantitatively.
  - Impact ionization dencity:

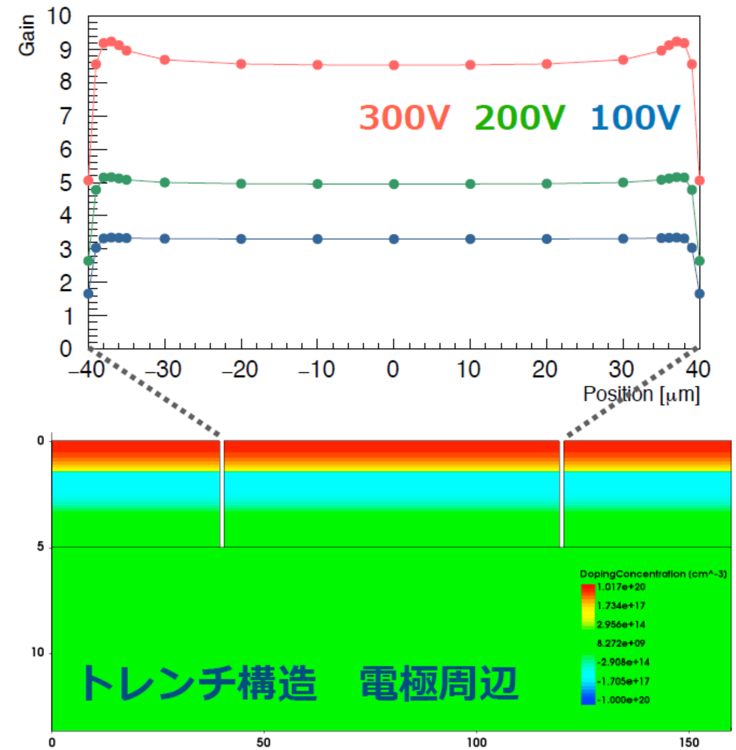


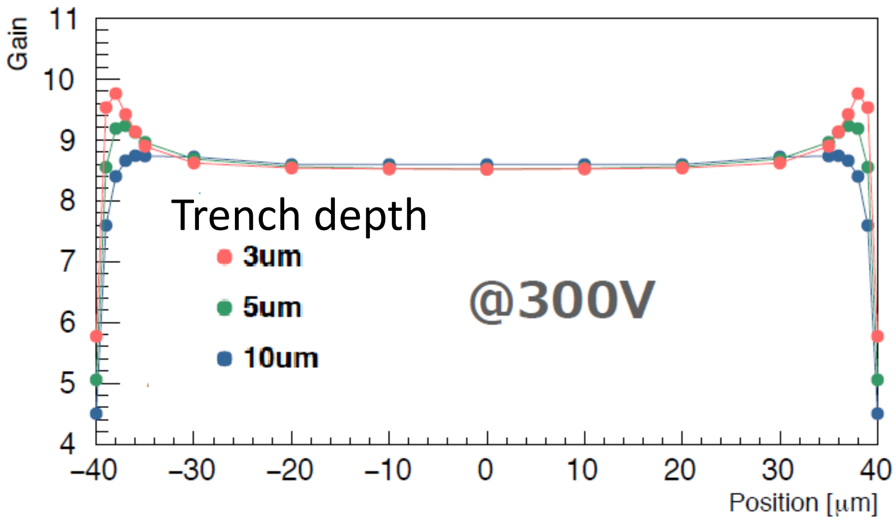


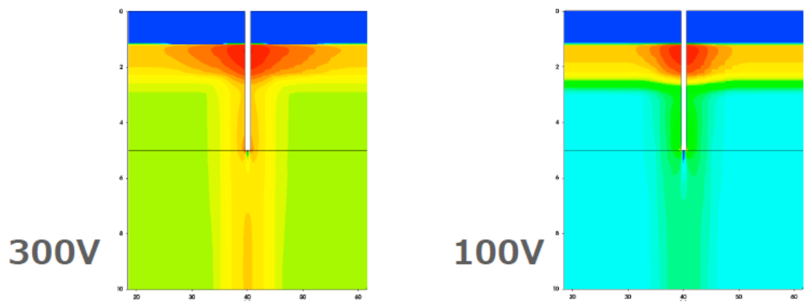
Smaller charge multiplication except the center of strip.

Trench Electrode separation

- Simulated Trench electrode separation.
- Uniform gain except the region close to the trench.
- Impact ionization is higher around trench.
  - Deeper trench helps to reduce the effect.

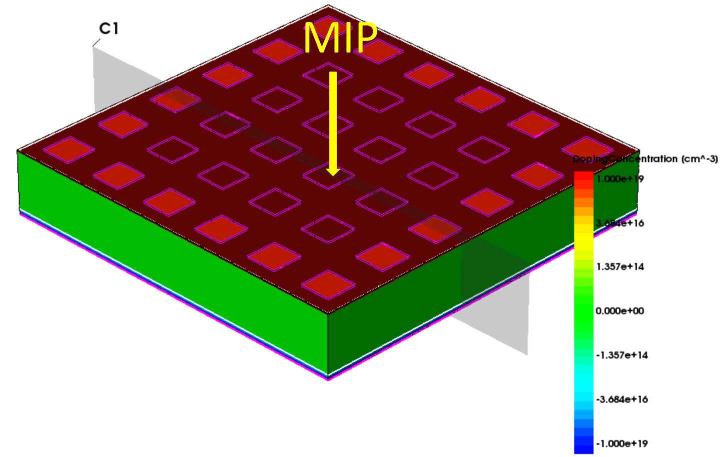




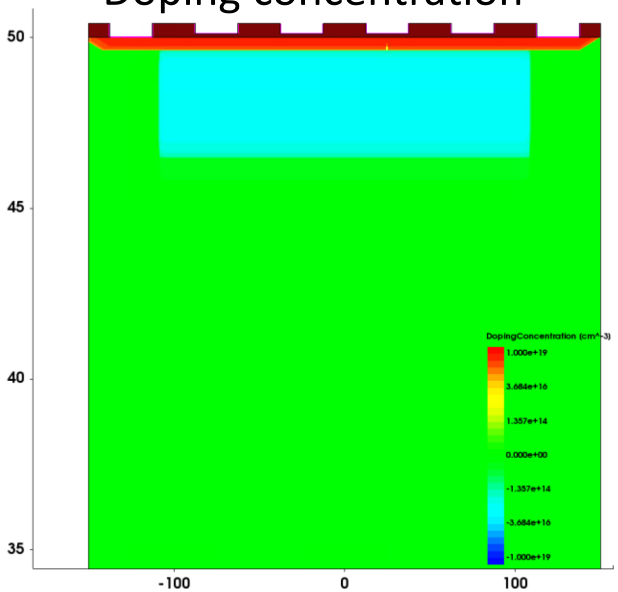


AC coupled LGAD 3D simulation

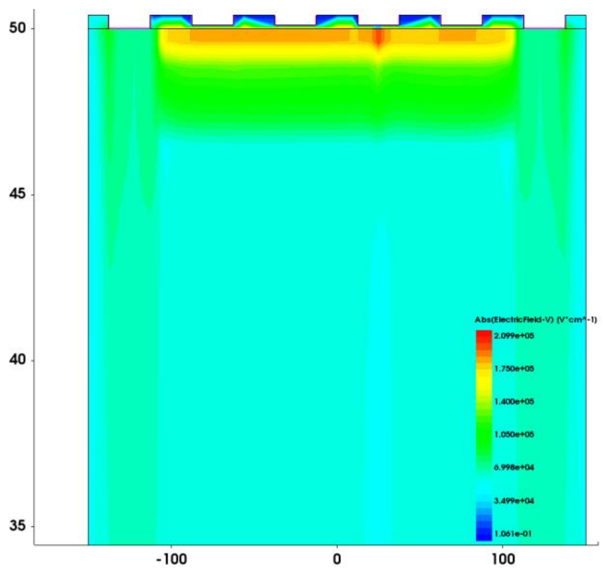
- Simple 6x6 pixel with 50um pitch.
- Red pixel is DC pixels and inner 4x4 pixels are AC coupled.
- Simulation done for MIP signal.
- Impact Ionization density spread ~500ps



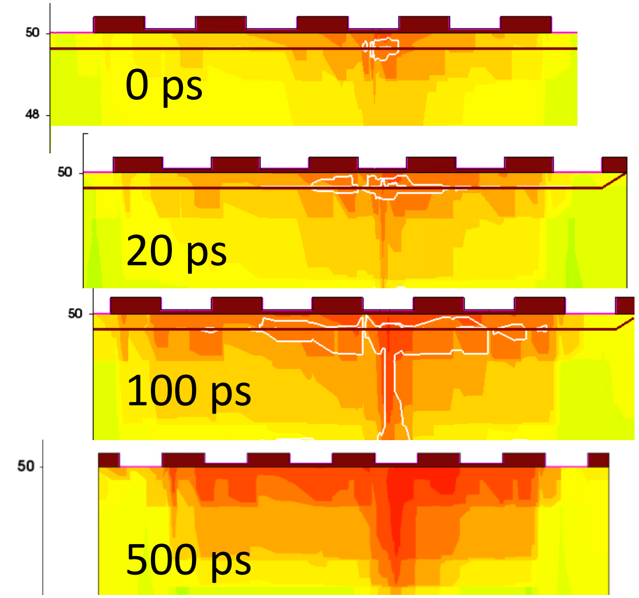
Doping concentration



Electric field

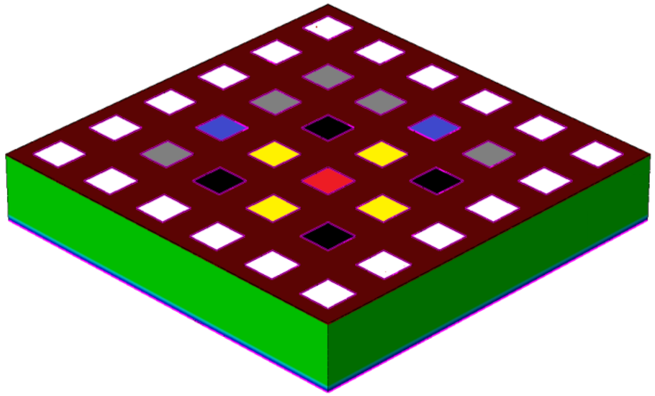


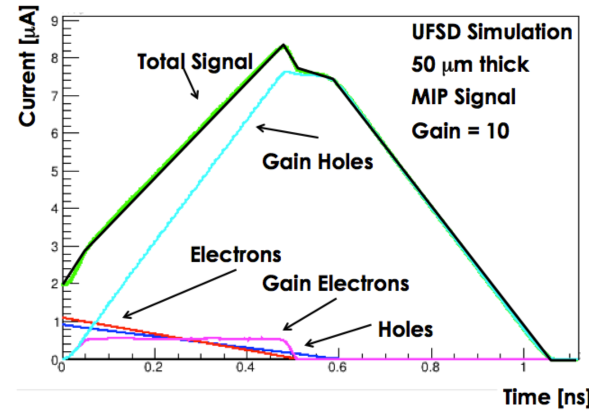
Impact Ionization density

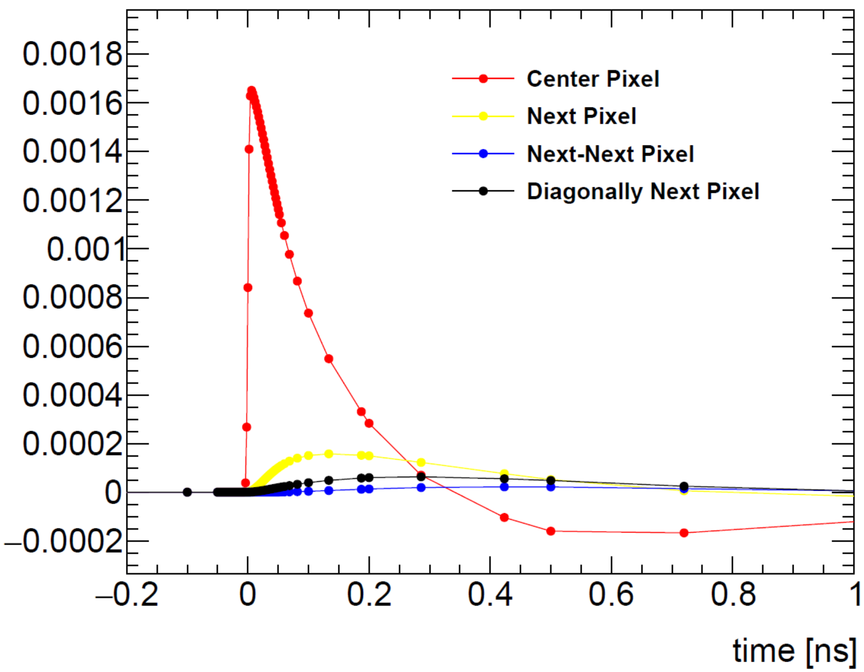


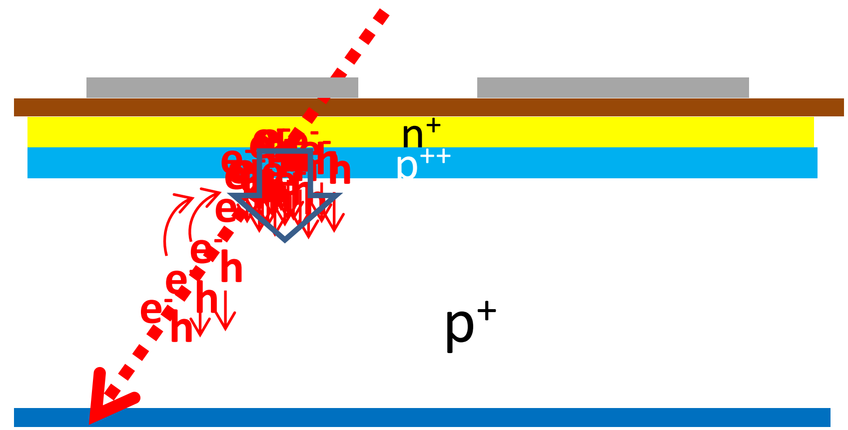
AC coupled LGAD 3D simulation

Pulse height





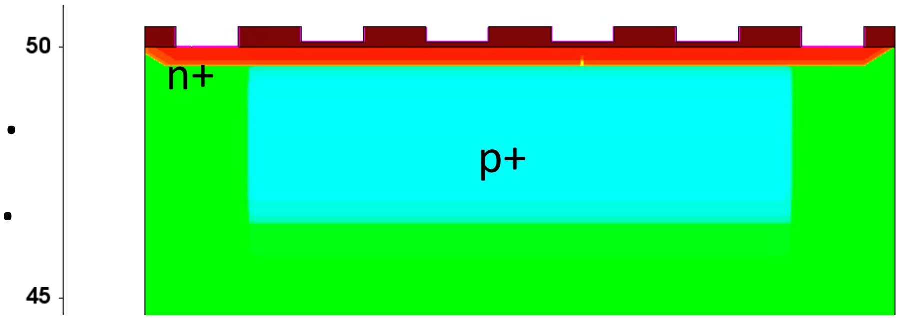




- Gained Holes driving to the signal pulse height.

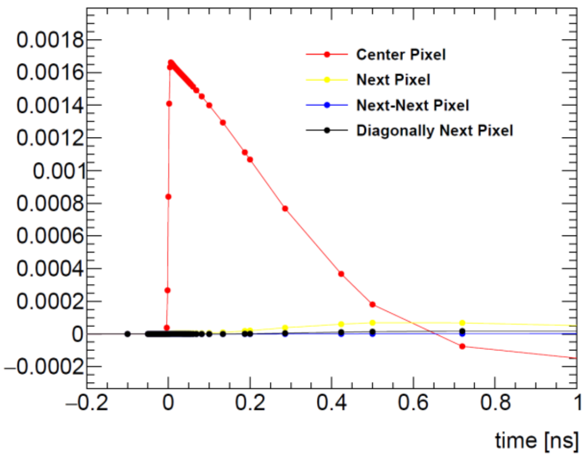
Parameter scan

- **Fixed p+ dope to 3e16.**
- Varied **n+** doping concentration.
- Lower cross talk for lower dope. But all cross talk is slow component.

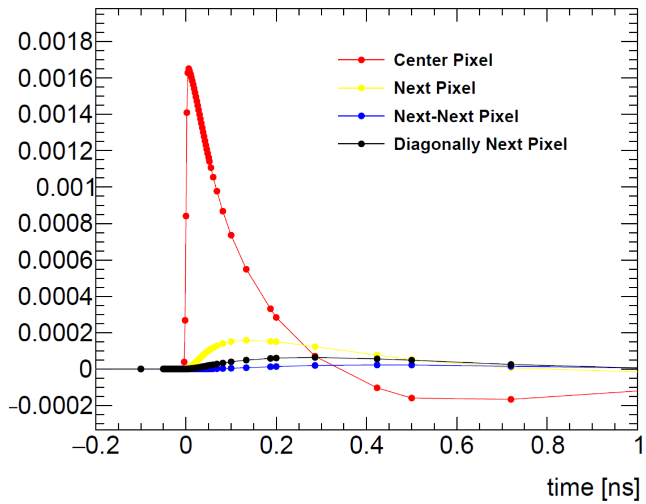


P+ 3e16

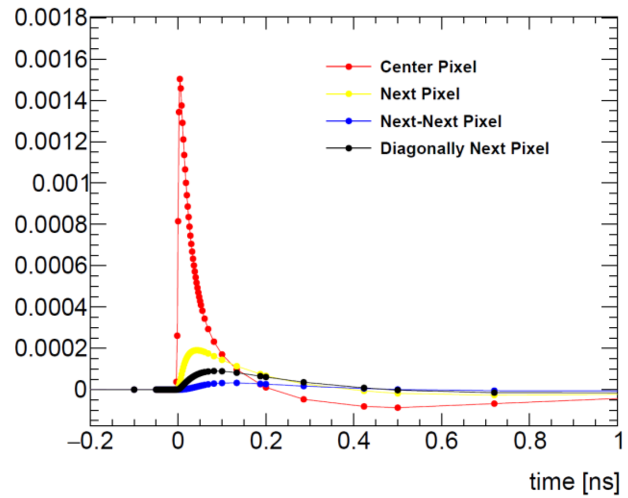
n+ 1e17



n+ 1e18

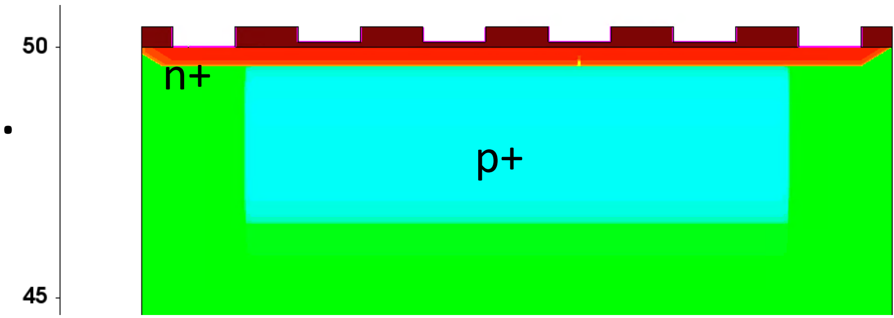


n+ 1e19

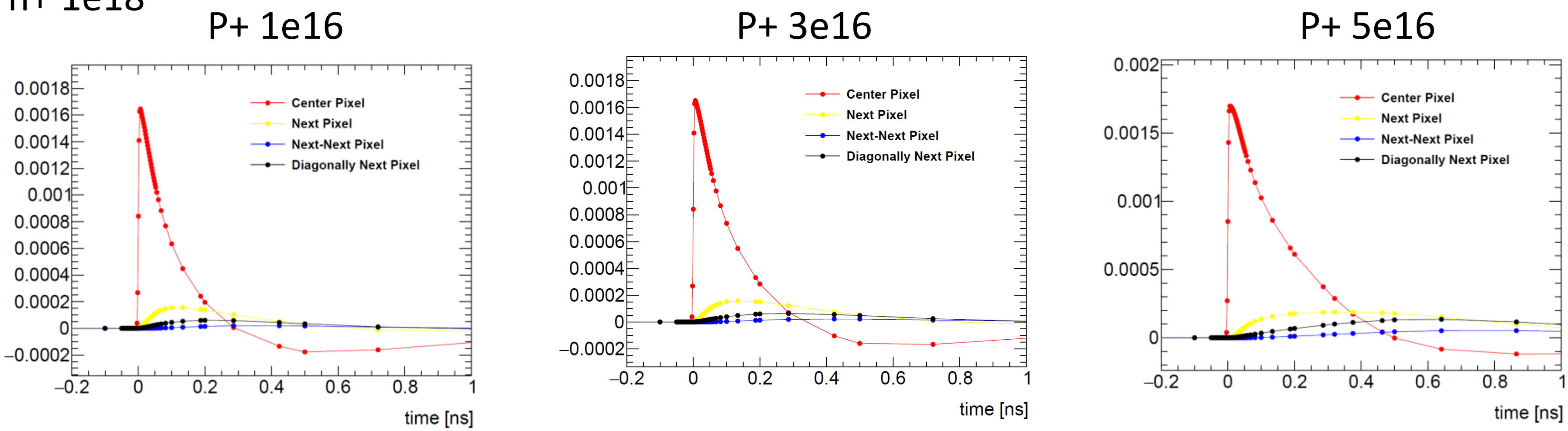


Parameter scan

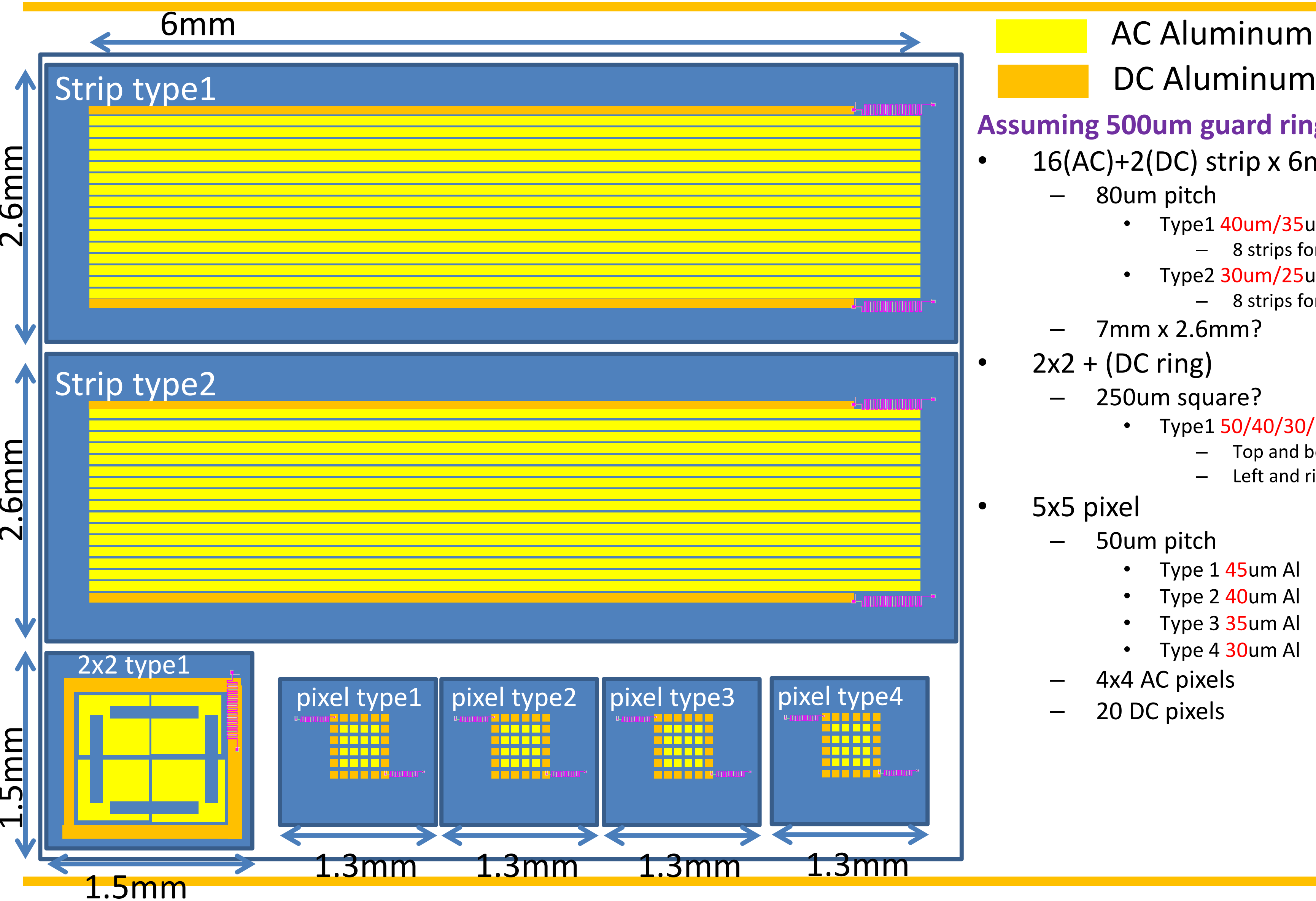
- **Fixed n+ dope to 3e16.**
- Varied **p+** doping concentration.
- Larger(wider) signal in case higher p+ doping
- Turn on shape seems the same.



n+ 1e18



Proposed mask for 2019 run

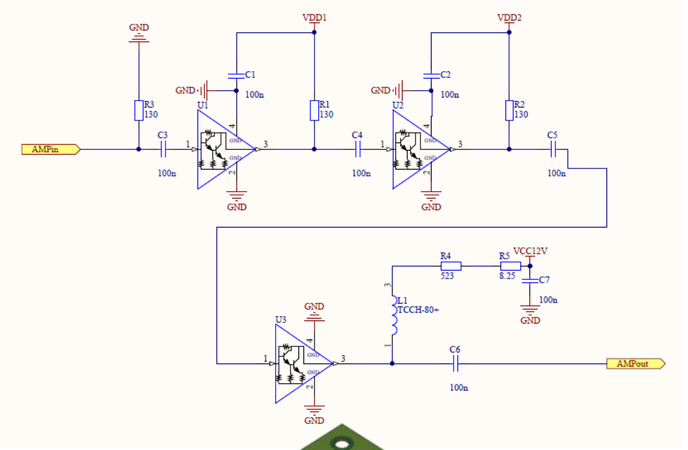


Assuming 500um guard ring

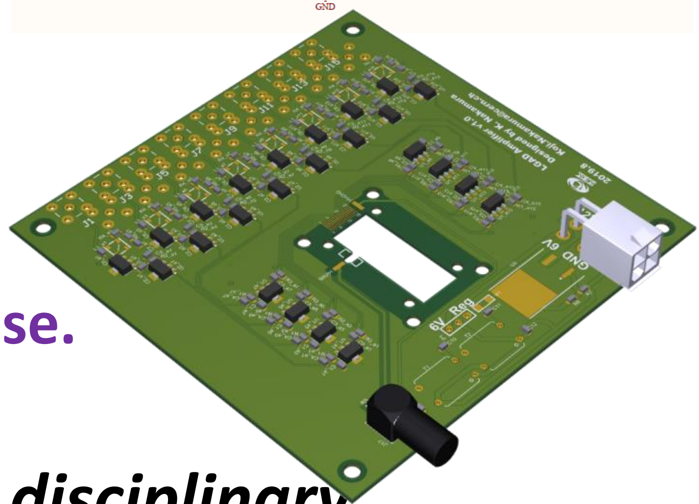
- 16(AC)+2(DC) strip x 6mm
  - 80um pitch
    - Type1 40um/35um Al
      - 8 strips for each width
    - Type2 30um/25um Al
      - 8 strips for each width
  - 7mm x 2.6mm?
- 2x2 + (DC ring)
  - 250um square?
    - Type1 50/40/30/20um gap
      - Top and bottom gap
      - Left and right gap
- 5x5 pixel
  - 50um pitch
    - Type 1 45um Al
    - Type 2 40um Al
    - Type 3 35um Al
    - Type 4 30um Al
  - 4x4 AC pixels
  - 20 DC pixels

Plan for 2020

- ***Processing new LGAD photo mask***
  - Motivation : finer granularity detector
  - Performed TCAD simulations
  - **Design is on-going**
  - Finish processing in this FY.



- ***Design for the Fast amplifier board.***
  - Low noise discrete amplifier board.
  - Tested shingle and 16 channel board.
  - **Need fix a couple of point to reduce noise.**
  - By the end of year.

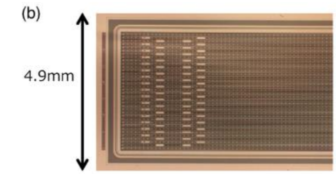


- ***Possibility of application for the other disciplinary.***
  - **Check timing Sensitivity to the γ-ray detection (X ray – IR ray?)**
  - Need Idea for the Biology, Medical and Industry application by this.

Application for the other disciplinary

We have 30ps timing resolution detector in hand

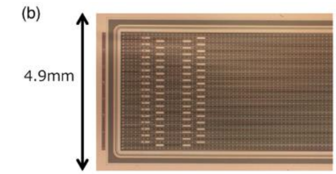
~15um position resolution added(?)

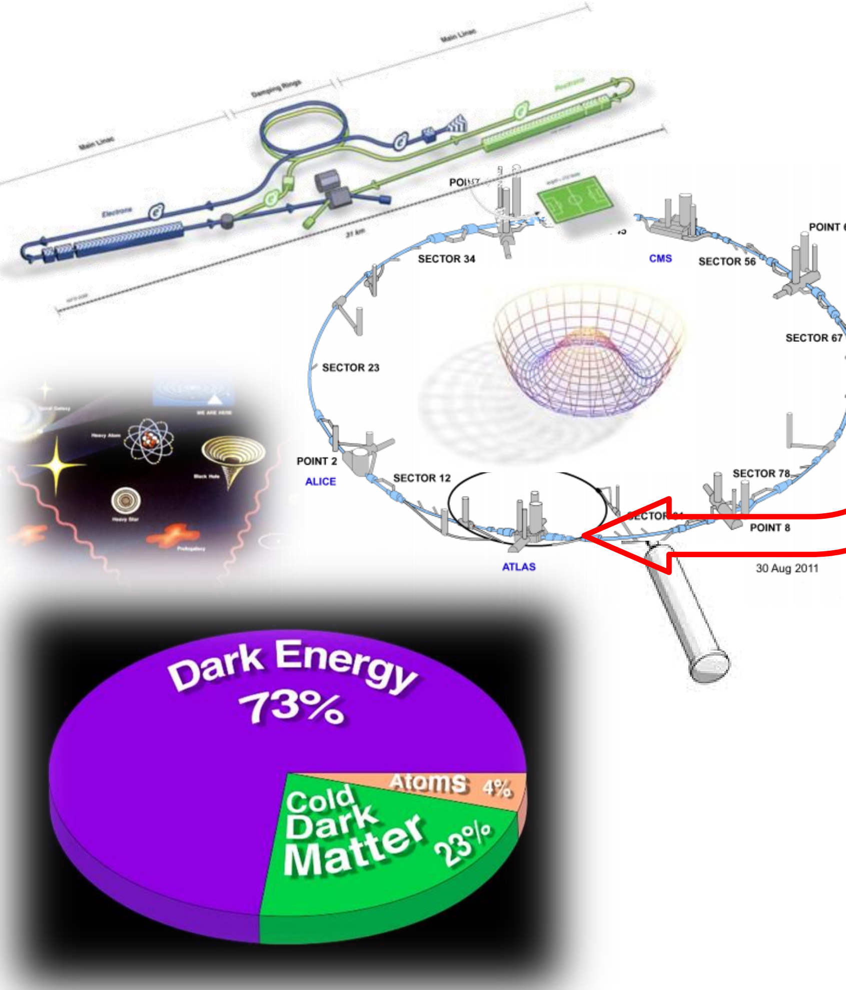


Application for the other disciplinary

We have 30ps timing resolution detector in hand

~15um position resolution added(?)

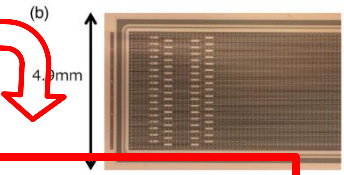




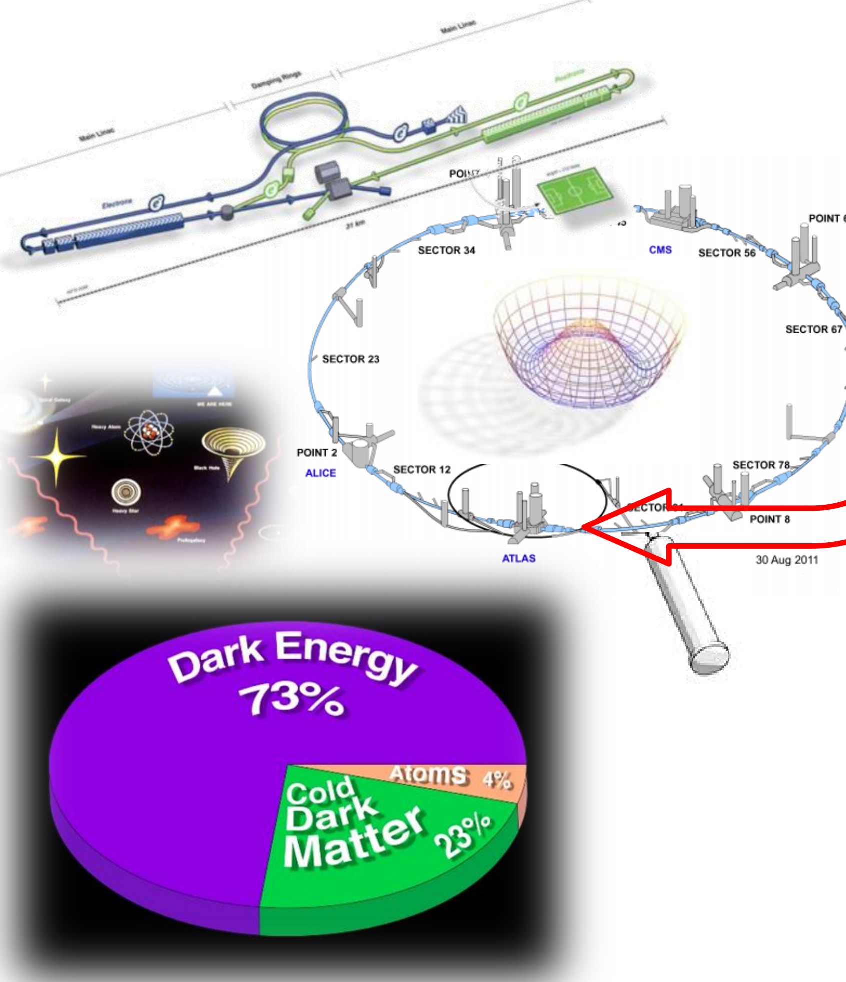
Application for the other disciplinary

We have 30ps timing resolution detector in hand

~15um position resolution added(?)



Need another R&D to check
if the device sensitive to the γ-ray.



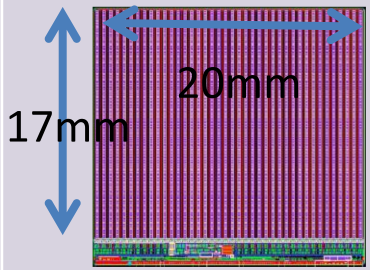
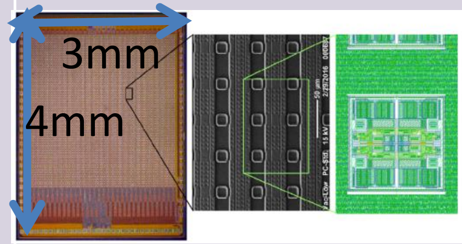
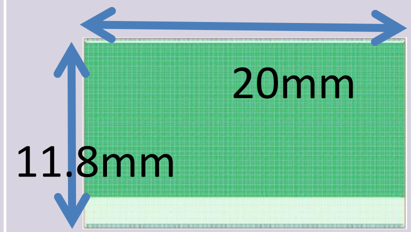
Biology, Medical and Industry

I need ideas...

backup

Available Front End ASICs

- Three FE, FE-I4, FE65p2 and RD53A were produced.
  - Hybridization study was based on FE-I4 the same outer size of production chip.
  - **For Module performance study, RD53A was used the same pixel pitch of production chip.**

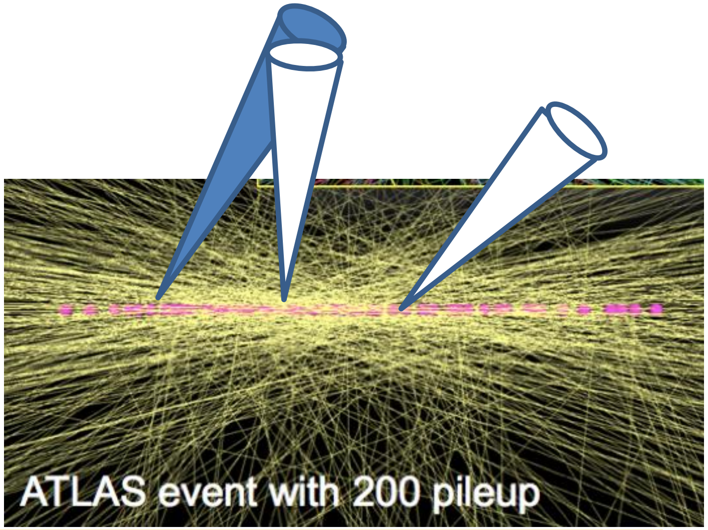
	FE-I4 (2012)	FE65p2 (2016)	RD53A (Nov. 2017)
ASIC demention			
CMOS process	130nm	65nm	65nm
Pixel size	**50um x 250um (25um x 500um)**	**50um x 50um (25um x 100um)**	**50um x 50um (25um x 100um)**
Pixel matrix	336 x 80	**64 x 64**	400 x 192
Max data output rate	160Mbps	160Mbps	**1.28Gbps x 4**
stable threshold (typical threshold)	**~1500 e^- (2000-3000 e^-)**	**500 e^- (700 e^-)**	**500 e^- (1000-1500e^-)**

ATLAS Upgrade for HL-LHC

- **High Luminosity LHC (HL-LHC)**
  - Start around 2026- with new crab cavity in the interaction region.
  - Target : $\sqrt{s}$=14TeV L=5-7x$10^{34}cm^{-2}s^{-1}$ $\int Ldt$=3000-4000fb^{-1}
  - Physics program focus on the precise measurements of the Higgs couplings (e.g. Y_τ, Y_b and λ_{HHH}) and BSM searches.
- **Tracking detector is key element**
  - To keep B/τ-tagging performance up to μ=200 pileup in an event.
  - Need to launch innovative solution for detectors, mechanics, efficient triggering and advanced analysis technics.

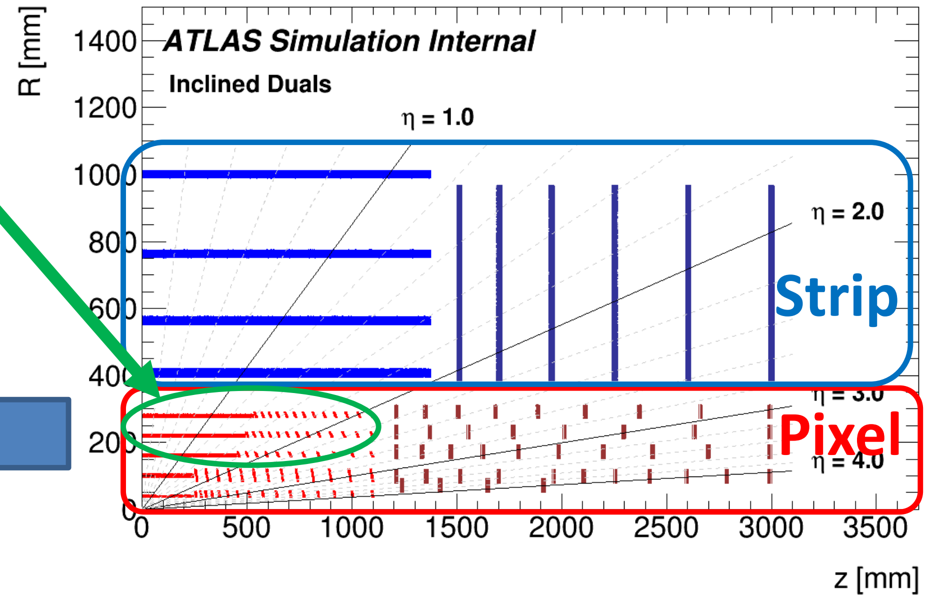
The ATLAS upgrade plans full replacement of Inner Tracker

- All silicon tracker (Pixel & Microstrip)
- ***Requirements for Pixel detector***
  - Pixel Size : 50um x 50um (or 25um x 100um)
  - Radiation @ outer layer : 3x$10^{15}n_{eq}/cm^2$
  - Thickness : 100 or 150um
  - Low noise (<100e) → 600e stable threshold
  - High Readout Rate : 5.2Gbps (or 4x1.28Gbps)



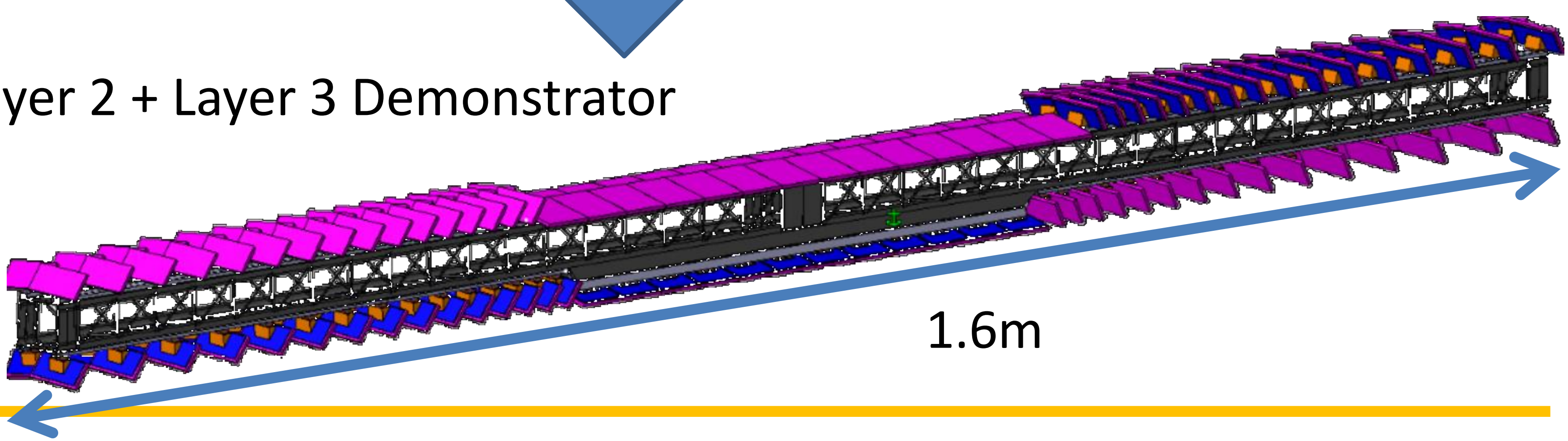
ATLAS Pixel Detector Upgrade

- Japan group : Pixel Detector development
  Target : 3rd – 5th layers
  - High Efficiency Sensor design
  - Readout ASIC and DAQ development
  - Sensor – ASIC attachment
  - Flex PCB design and assembly
  - Module loading to the support



Contributing to all steps
Build detector in Japan

Layer 2 + Layer 3 Demonstrator



ATLAS Pixel Detector Upgrade

- Japan group : Pixel Detector development

  Target : $3^{rd} - 5^{th}$ layers

  - High Efficiency Sensor design
  - Readout ASIC and DAQ development
  - Sensor – ASIC attachment
  - Flex PCB design and assembly
  - Module loading to the support

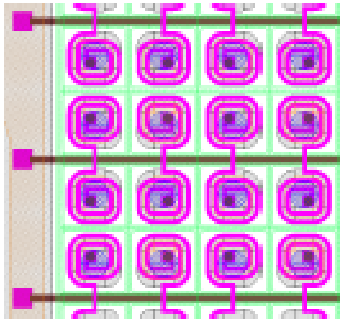
HPK: n+ in p type

Pixel Size : 50umx50um

Requirement :

97% after irradiation

($3x10^{15} n_{eq}/cm^2$)

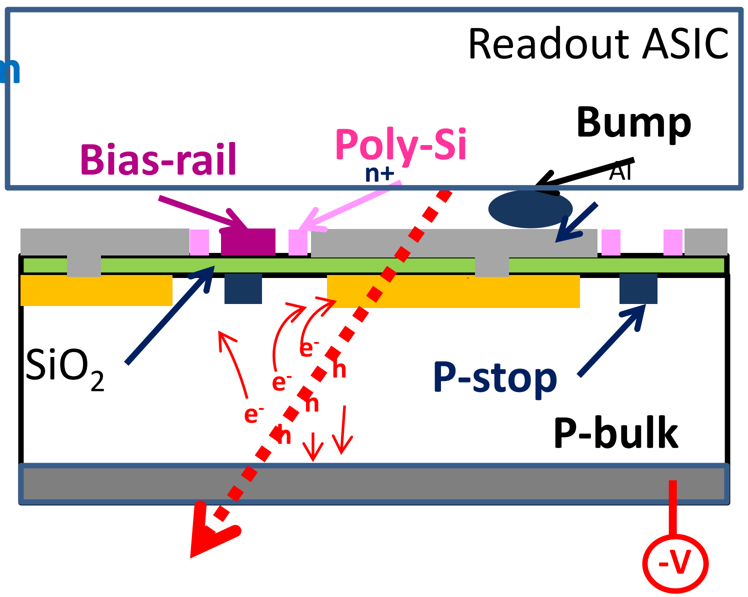


Planar type Pixel module

Efficiency measurement at testbeam

Irradiation test by proton beam

→After irradiation >99% efficiency



ATLAS Pixel Detector Upgrade

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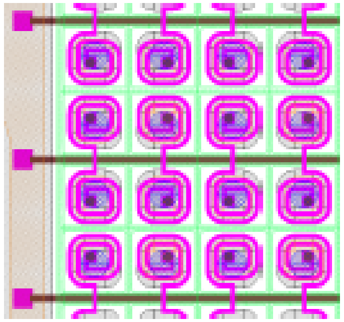
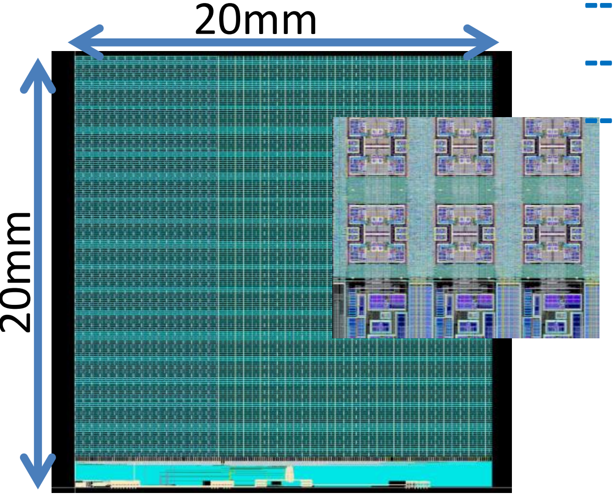
Requirement :
97% after irradiation
($3\times10^{15} n_{eq}/cm^2$)

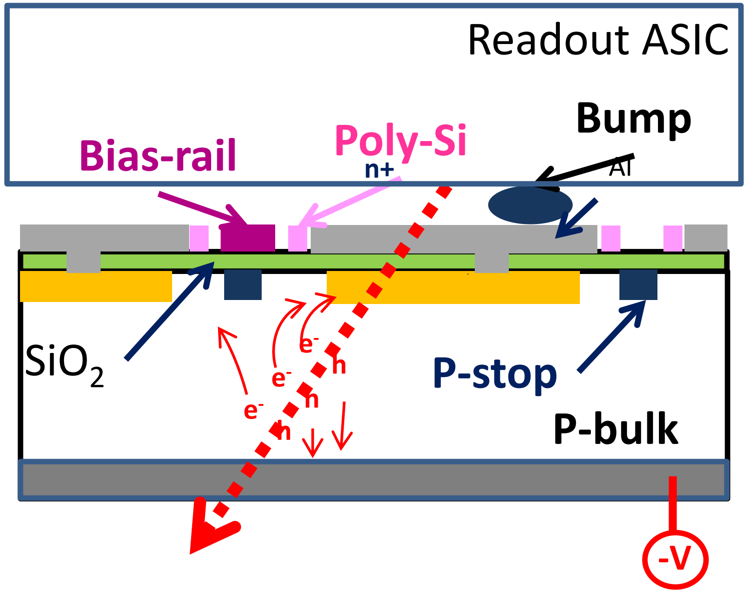


RD53 Collabration
(ATLAS+CMS)
65nm CMOS process



½ size prototype available
DAQ development with US
-- 5.12Gbps / ASIC readout
-- 400x384 pixel matrix
-- Low noise (<100 e)

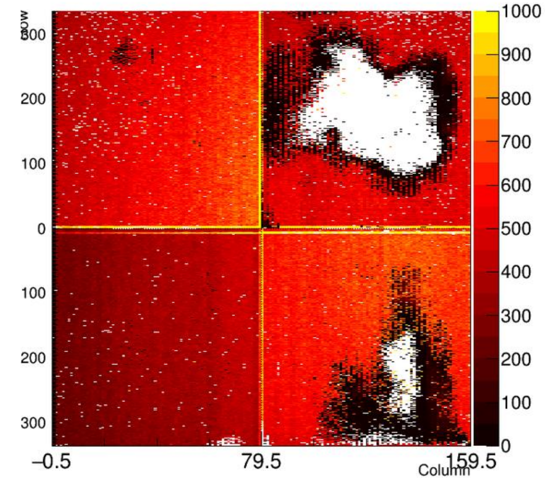
Planar type Pixel module



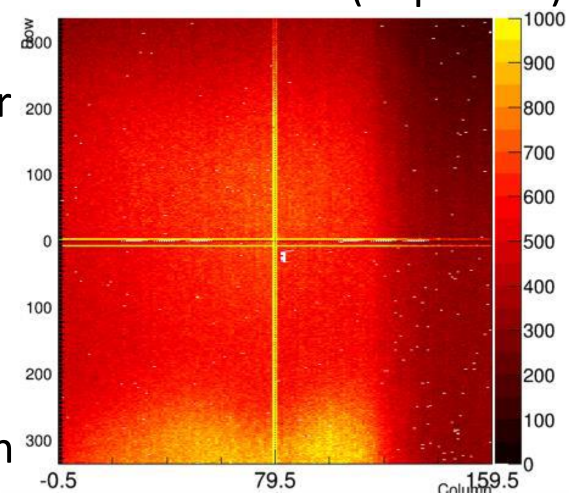
ATLAS Pixel Detector Upgrade

- Japan group : Pixel Detector development
  Target : 3rd – 5th layers
  - High Efficiency Sensor design
  - Readout ASIC and DAQ development
  - **Sensor – ASIC attachment**
  - Flex PCB design and assembly
  - Module loading to the support

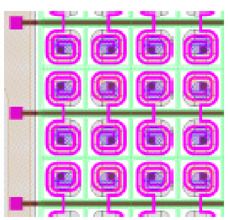
^{90}Sr Source test (beginning)



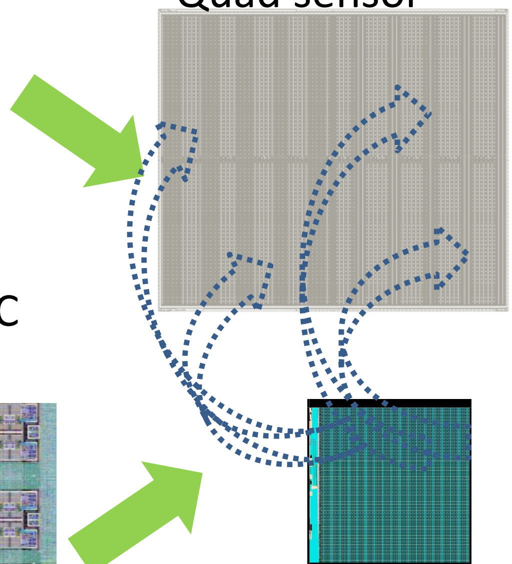
^{90}Sr Source test (improved)



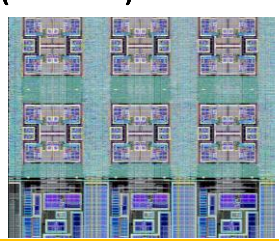
HPK Sensor



Quad sensor



Readout ASIC (TSMC)



Bump bonding @ HPK
SnAg solder bump
no flux / no support wafer
Thickness sensor/ASIC
→150um/150um

Established in 2016
High production Yield
ready for mass production

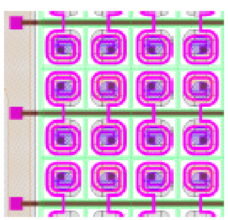
ATLAS Pixel Detector Upgrade

- Japan group : Pixel Detector development

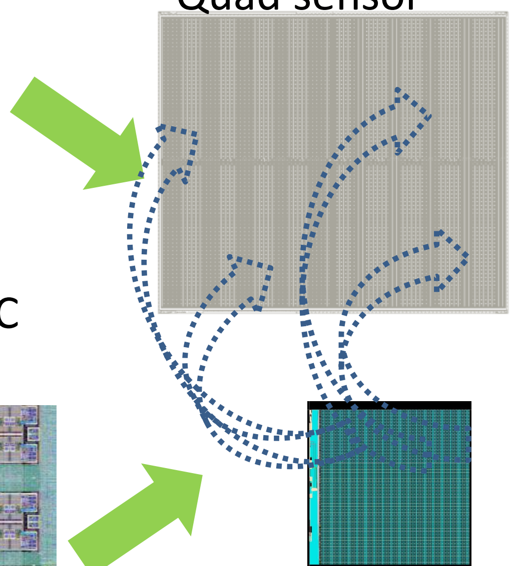
  Target : 3rd – 5th layers
  - High Efficiency Sensor design
  - Readout ASIC and DAQ development
  - Sensor – ASIC attachment
  - **Flex PCB design and assembly**
  - Module loading to the support

Development of Assembly jig
Radiation Tolerance test for Glue
Wire bonding

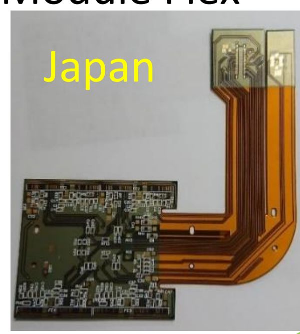
HPK Sensor



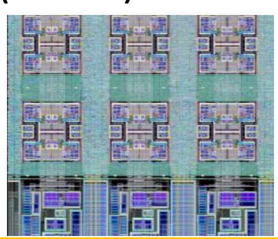
Quad sensor



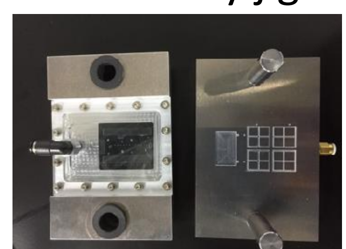
Module Flex

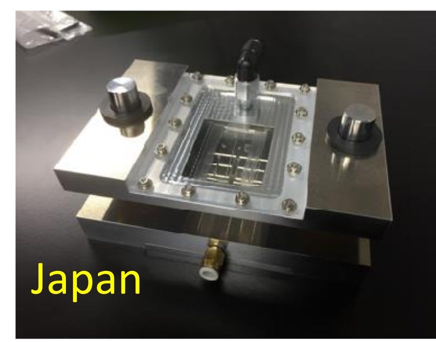


Readout ASIC
(TSMC)



Assembly jig





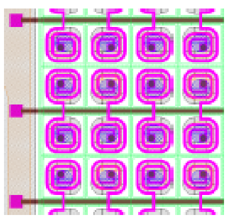
ATLAS Pixel Detector Upgrade

- Japan group : Pixel Dete
  Target : 3rd – 5th layers
  - High Efficiency Sensor
  - Readout ASIC and DA
  - Sensor – ASIC attachm
  - Flex PCB design and a
  - **Module loading to the support**

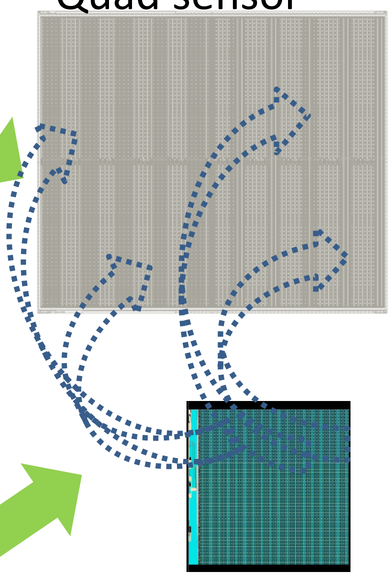
Installation

bending

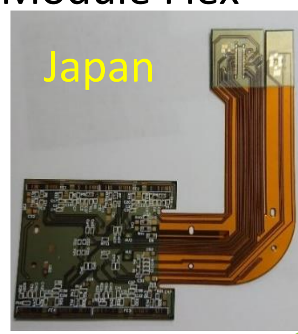
HPK Sensor



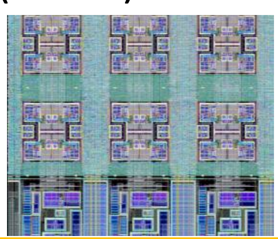
Quad sensor



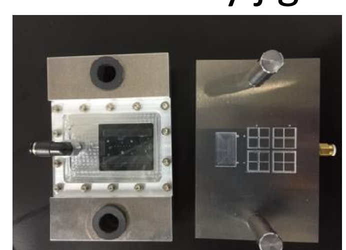
Module Flex

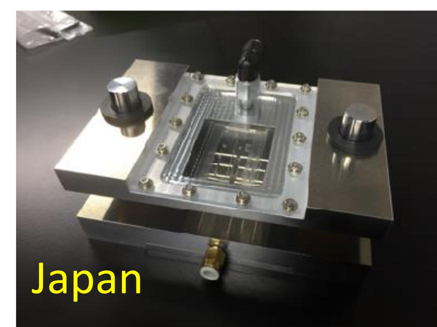


Readout ASIC (TSMC)



Assembly jig

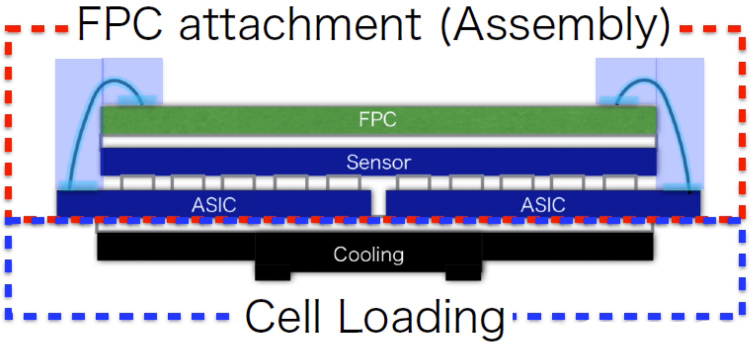


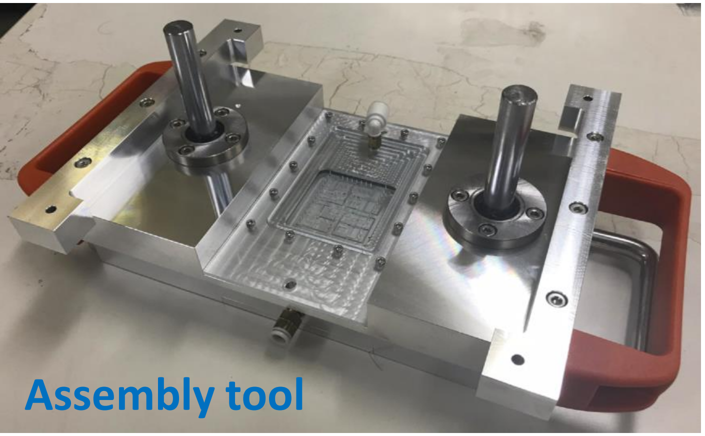


Module Assembly

- Assembly of Quad module to the Flex Printed circuit.
  - Radiation hard glue choice
  - CTE matching to avoid stress for modules.
  - Cooling cell on the back side of modules

Module loading to support





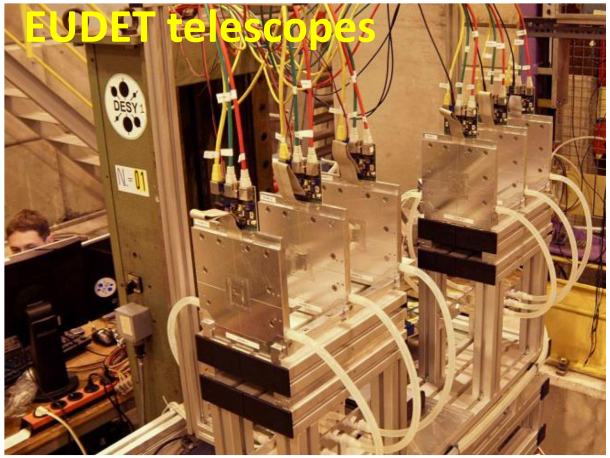
Flex Printed Circuit

Cooling Cell

Irradiation and Testbeam

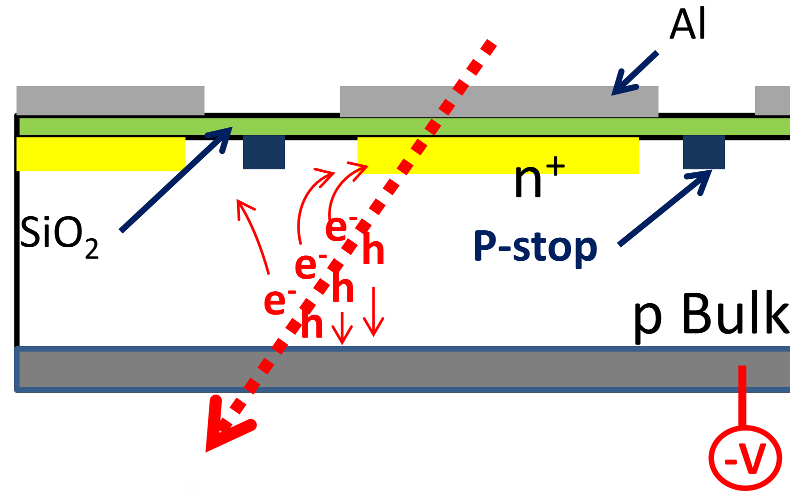
- CYRIC@Tohoku Univ.
  - An irradiation facility with **70MeV proton beam** (~**1μA beam current**).
    - 3-5 hours for $3x10^{15}n_{eq}/cm^2$ irradiation with (600nA beam)
  - This allows 2-3 pixel modules with Al plate at the same time(3% E loss/module).
  - Operated at **-15ºC temprature** with dry N_2 gas.
  - Scanning over full pixel surface at irradiation.

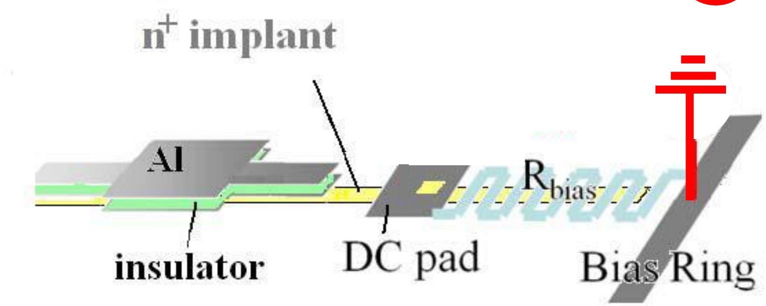
- **Testbeam**
  - **Extremely important to test device performance**
  - Efficiency/Noise monitoring during production
  - Testbeam facility
    - **CERN SPS : 120GeV π+ beam**
    - DESY : 4-5GeV e+ beam
    - FNAL : 120GeV proton beam
  - Telescope planes (Track pointing to device)
    - EUDET based on MIMOSA26 monolithic CMOS detector placed in beamline at CERN/DESY/SLAC (**~3um pointing resolution**).
    - Huge experience of the testbeam operation as having testbeam 3-4 times a year



Semiconductor tracking detector

- Basic principle :
  - Backside is negative bias and n+ is ground.
  - Detect electron-hole pairs created by ionizing energy loss from MIP particle.
- Strip detector
  - **n+ can easily ground at the end of strip.**
  - Readout usually via **“wire bonding”** strips to the readout ASIC.





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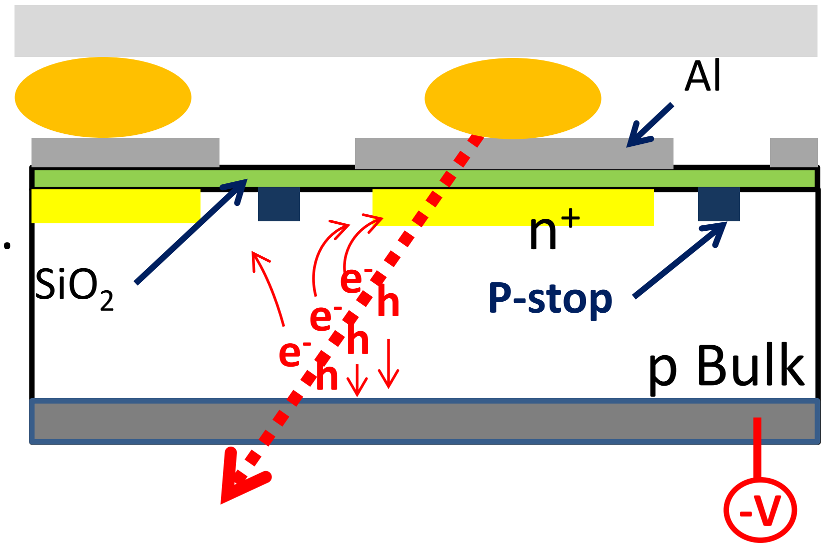
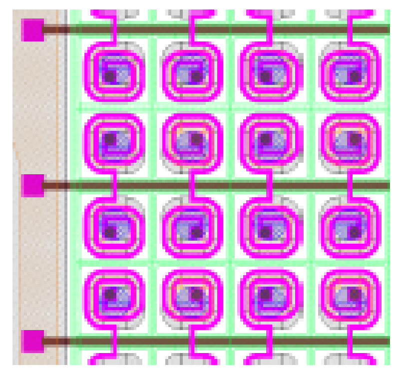
  - Detect electron-hole pairs created by ionizing energy loss from MIP particle.
- Strip detector
  - **n+ can easily ground at the end of strip.**
  - Readout usually via **"wire bonding"** strips to the readout ASIC.
- Pixel detector (new technology)
  - **Electrode placed two dimensionally.**
  - To ground all pixels, high resistivity biasing grid is necessary.
  - Readout ASIC is connected by **"bump-bonding"**.



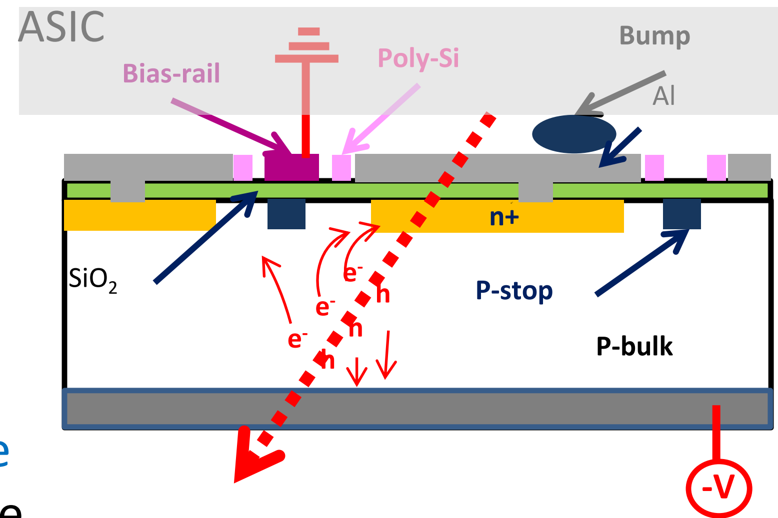


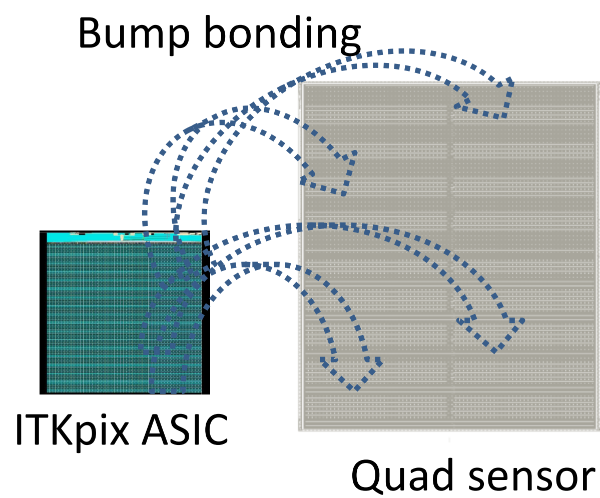
4 chip module

Our development is together with Hamamatsu Photonics K.K (HPK)

Hybrization at HPK

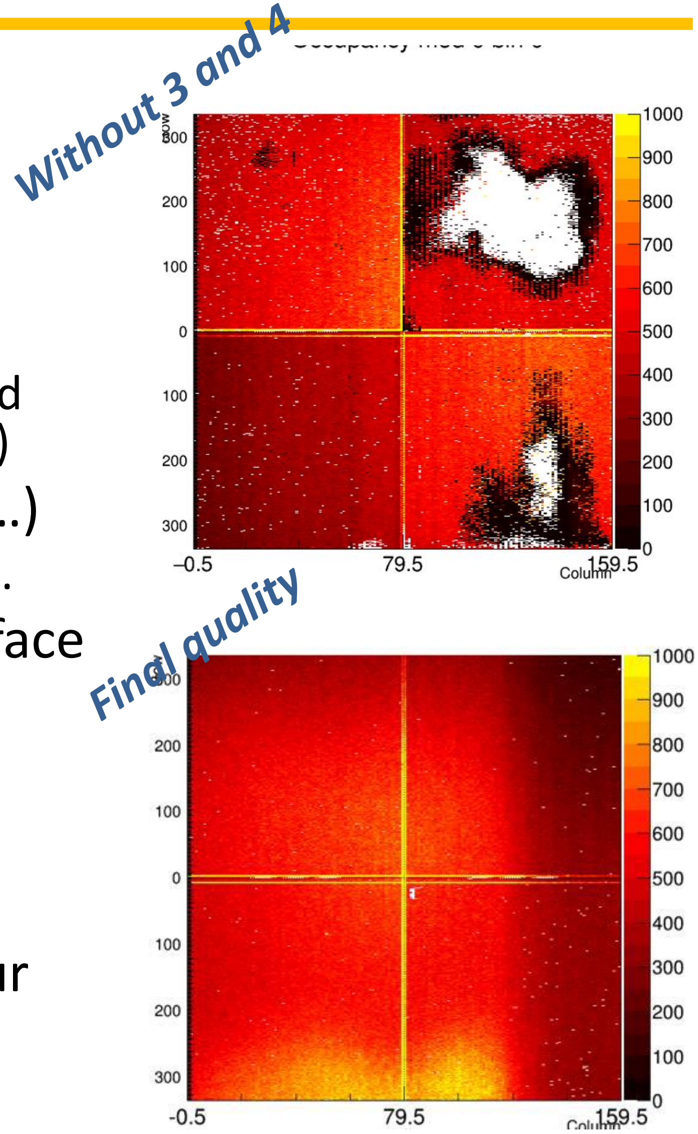
- To readout signals from 2 dimensionally placed electrodes (pixels), readout ASIC needed to be connected.
  - the signal from each channel is read out through a solder bump
  - ***Bump bonding :***
    - Solder bump deposition to the ASIC side
    - Under bump metallization to Sensor side
    - Flip-chipping : 4 chips to one sensor.
- ATLAS Japan group investigated with HPK using bias resistor to each pixel. This allows us to sensor testing before costly bump bonding process





Flip chipping development at HPK

- **Development of Lead-free(SnAg) Bumpbonding (Since 2012)**
  1. ***No Flux used (to avoid corrosion)***
     - confirmed flux improve connection, though
  2. ***No backside compensation***
     - Improvement of Vacuum chuck jig to hold and flatten the ASIC/Sensor…(jig size ~ FE-I4 area)
  3. ***Special UBM*** (key element: confidential…)
     - Simple Ni/Au UBM do not reach 100% yield …
  4. ***Hydrogen plasma reflow*** to remove surface oxide
- Thin sensor/Thin ASIC : 150um/150um
  - **Established Bumpbonding method in the beginning of 2016.**
  - Quite stable quality for both single and four ASICs. 100% yield for last one year (>100 chips are bumpbonded.)



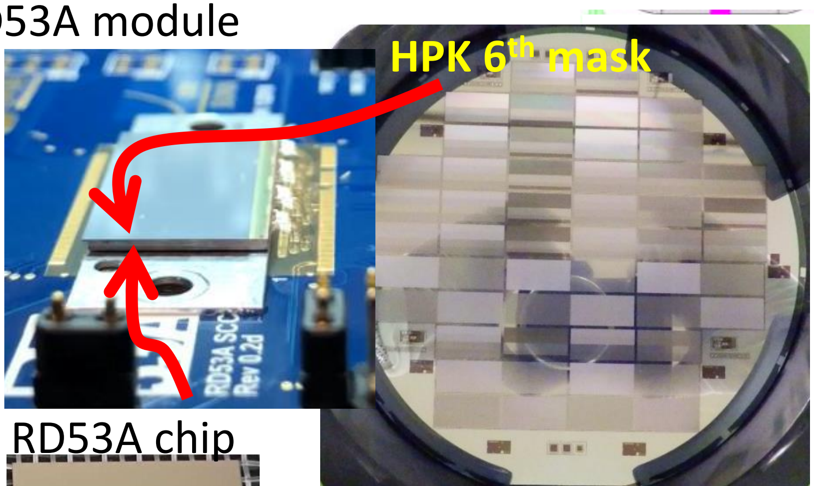
Final Sensor design

- Basic Sensor structure is almost final after years of development.
- Current fine pitch (50umx50um) pixel size sensors are attached to half size prototype ASIC (RD53A).
- Full size sensor and ASIC need to be produced in 2019.
  - RD53B (ITKpix-v1) and 7th HPK mask.

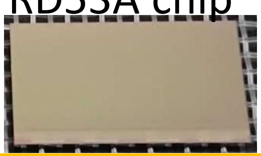
10mm x 20mm half size prototype modules

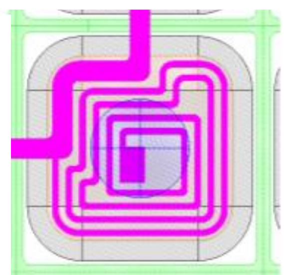
40mm x 40mm production modules (20mm x 20mm ASIC size)

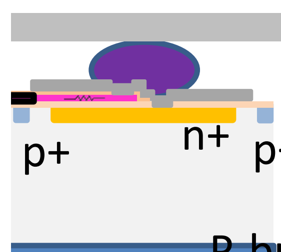
RD53A module



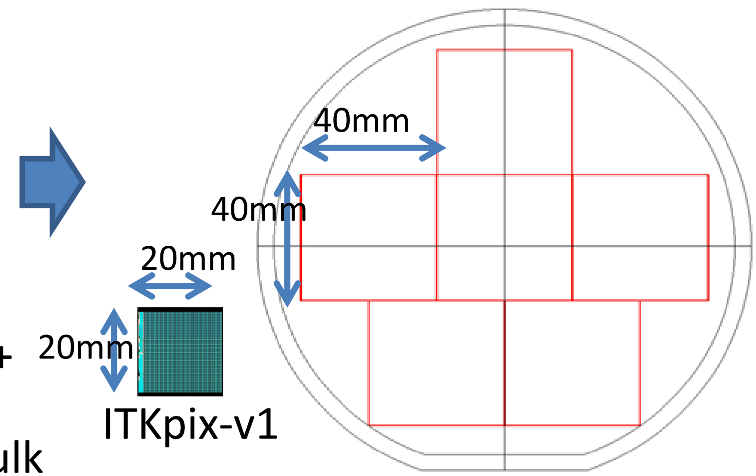
RD53A chip







HPK 7th mask



Efficiency result (irrad $3x10^{15}n_{eq}/cm^2$)

- Efficiencies of HV scan 200-800V have been evaluated.
  - **Analyzed both 1500e and 2400e threshold data for different types.**
  - **All types have over 98% efficiency at 600V.**
    - 1500e threshold results have over 99% efficiency.
    - Small n+ w/ BR have low efficiency at 200V

K. Nakamura Pixel 2018