Development of Mip Timing Detector for the CMS Phase-2 Upgrade and LGAD sensor in Korea

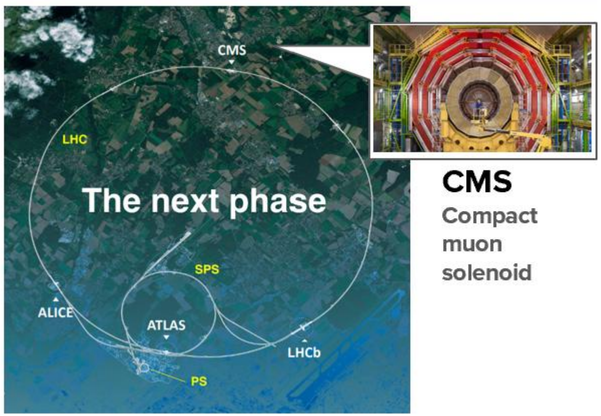
KSHEP workshop

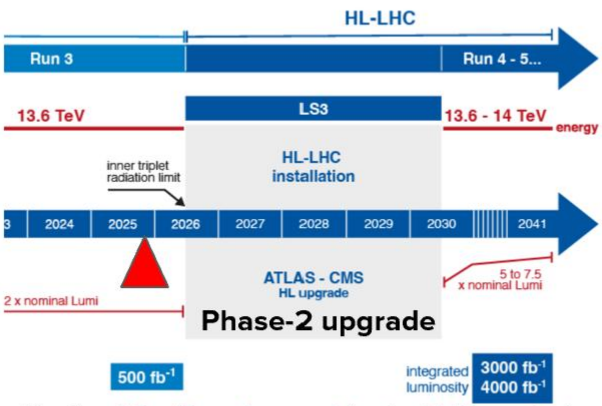
2025/11/19-11/22

Youngdo Oh

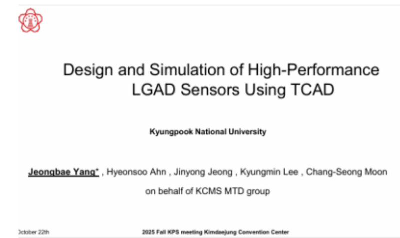
(Kyungpook National University)

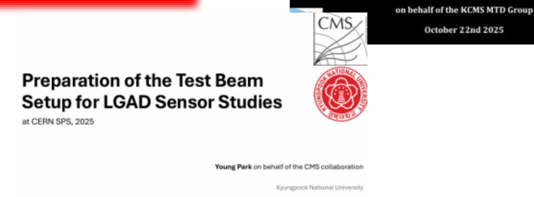
Based on various talks presented at Korean Physical Society meeting(2025/10/22-10/24) (Thanks to KCMS MTD group)

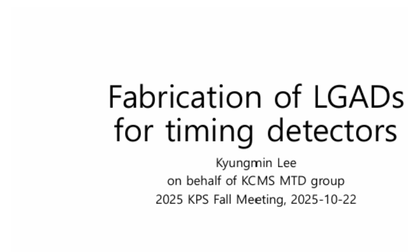


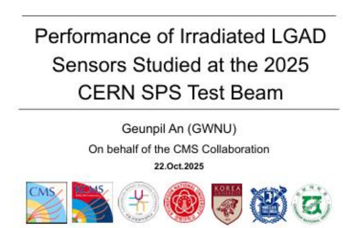


Timeline: hilumilhc.web.cern.ch/content/hl-lhc-project





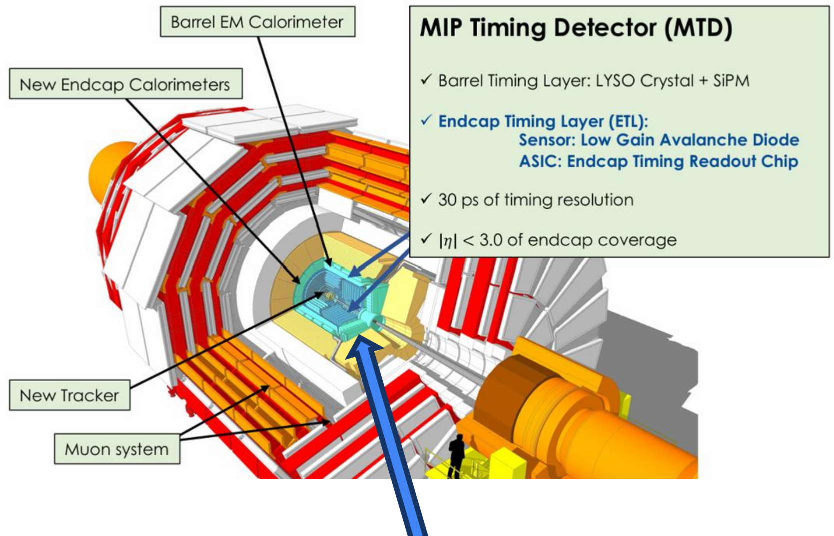




LGAD sensor

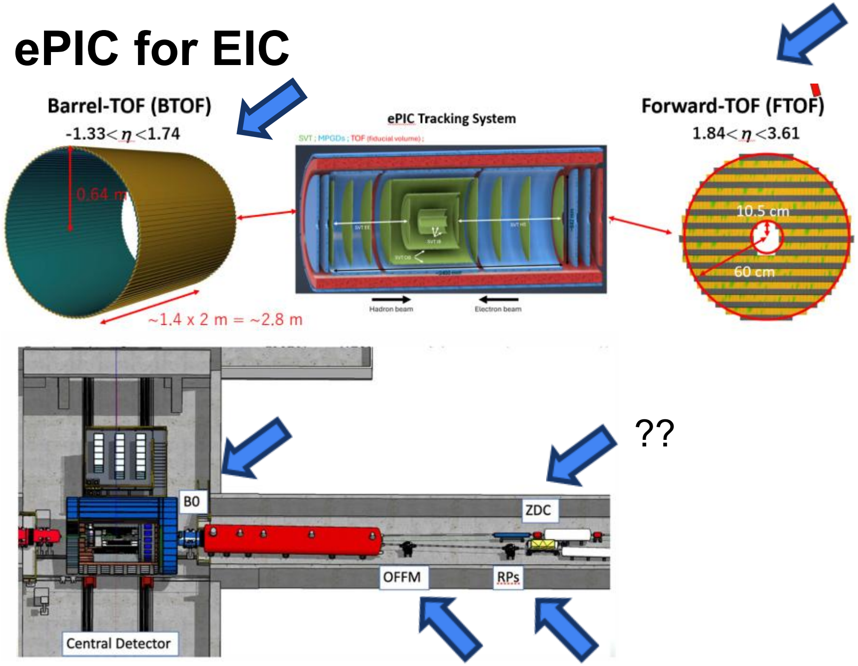
- LGAD(Low Gain Avalanche Detector) , silicon sensor
- Future particle and nuclear physics experiment have adopted LGAD sensor for fast timing detector.

CMS for HL-LHC



DC-LGAD

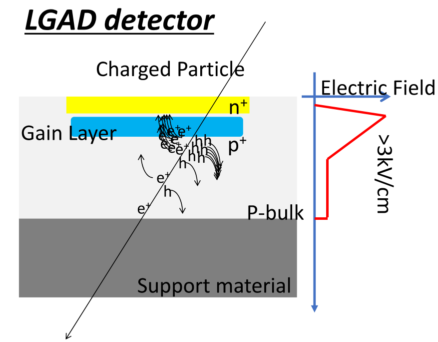
ePIC for EIC

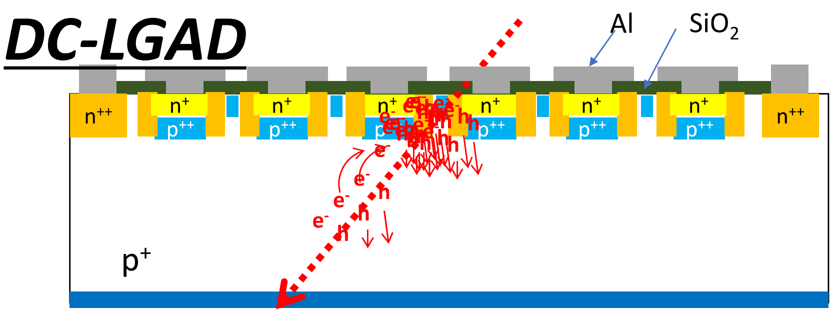


AC-LGAD

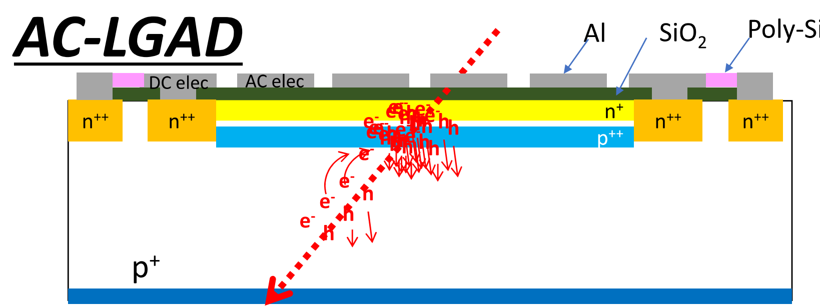
LGAD sensor

- LGAD has a thin gain layer making high electric field
  - High electric field makes high signal rise time and improves time resolution ; ~ 30ps
  - Gain : ~ 20, < 100
  - Fast developing technology





Each pixel has its gain layer
➔ There is inactive area

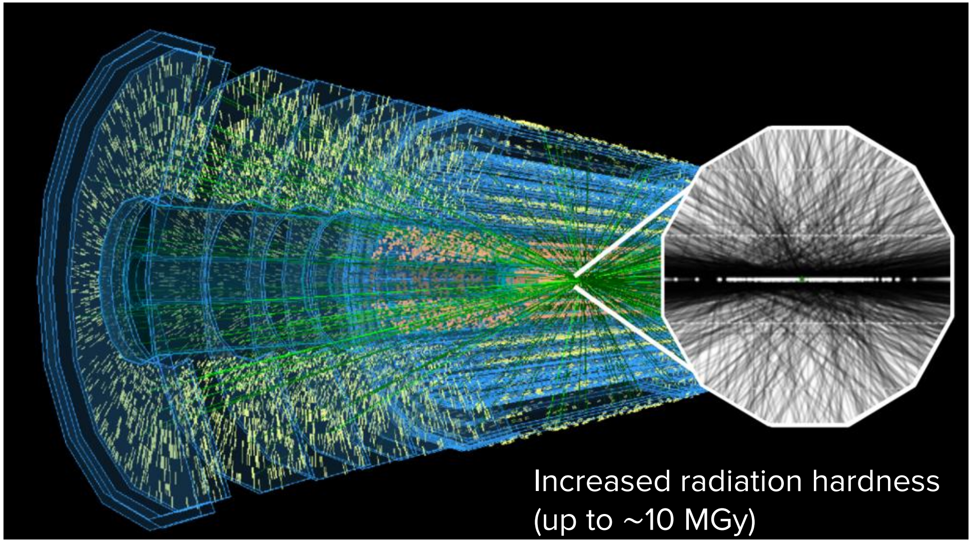


Large gain area
➔ Reducing inactive area
➔ better position resolution by charge sharing

High-Luminosity LHC (aka Phase-II) upgrade

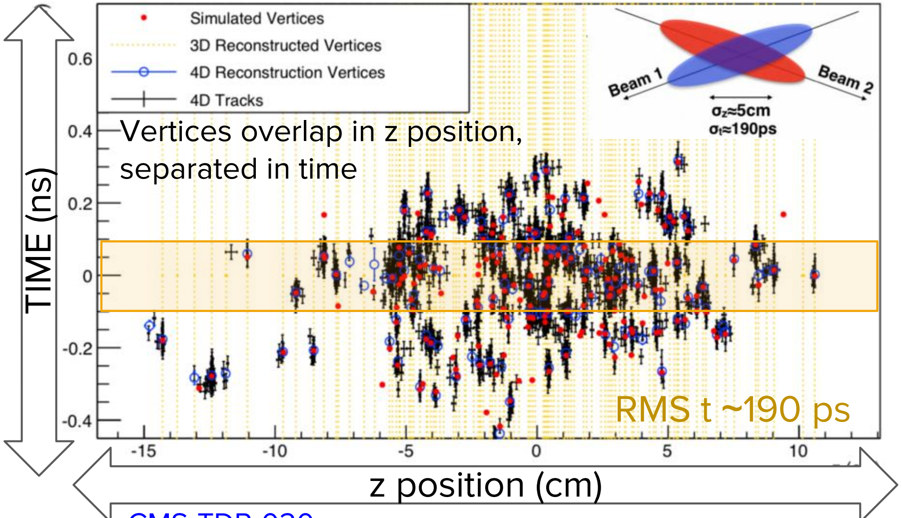
Ambitious goal: $L_{int} > 2500\ fb^{-1}$ in 9 years of operation (for a total delivered luminosity of 3 ab^{-1})

		Bunch intensity [protons / bunch]	β* [cm]	Peak lumi [$cm^{-2}s^{-1}$]	Pileup ⟨μ⟩	Int. lumi / year [fb^{-1}]
LHC design		$1.15 \cdot 10^{11}$	55	$1 \cdot 10^{34}$	23	30
LHC today	**Run3**	$1.6 \cdot 10^{11}$	60/18	$2.2 \cdot 10^{34}$	64	120
HL-LHC	**Run4**	**$2.2 \cdot 10^{11}$**	**15**	**$5\text{–}7 \cdot 10^{34}$**	**140–200**	**up to 300**



Expecting 140 – 200 simultaneous interactions per bunch crossing (pileup)

Why Timing is important at the HL-LHC?



CMS-TDR-020

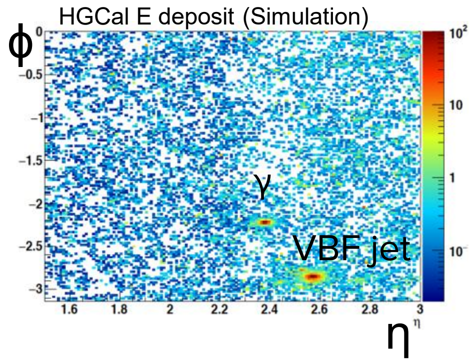
HL-LHC's high pileup requires unprecedented new detectors technologies

Addition of
MIP Timing detectors (MTD) to CMS detector

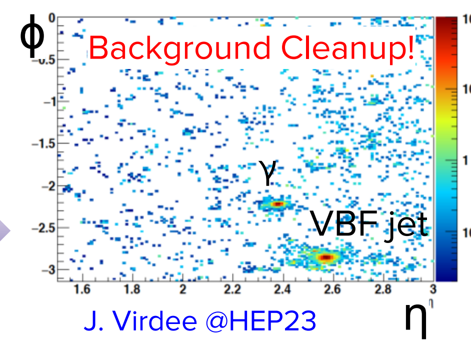
⇒ 4D vertexing/tracking enables new capacity to mitigate pileup, enhanced detection of VBF/LLP signatures, Particle Identification...

1 example is here,
Great pileup mitigation in VBF ($H \to \gamma\gamma$) events with 1 γ + 1 VBF jet in quadrant Calorimeter (η, ϕ)

No timing cut
(Pilup 200 scenario)

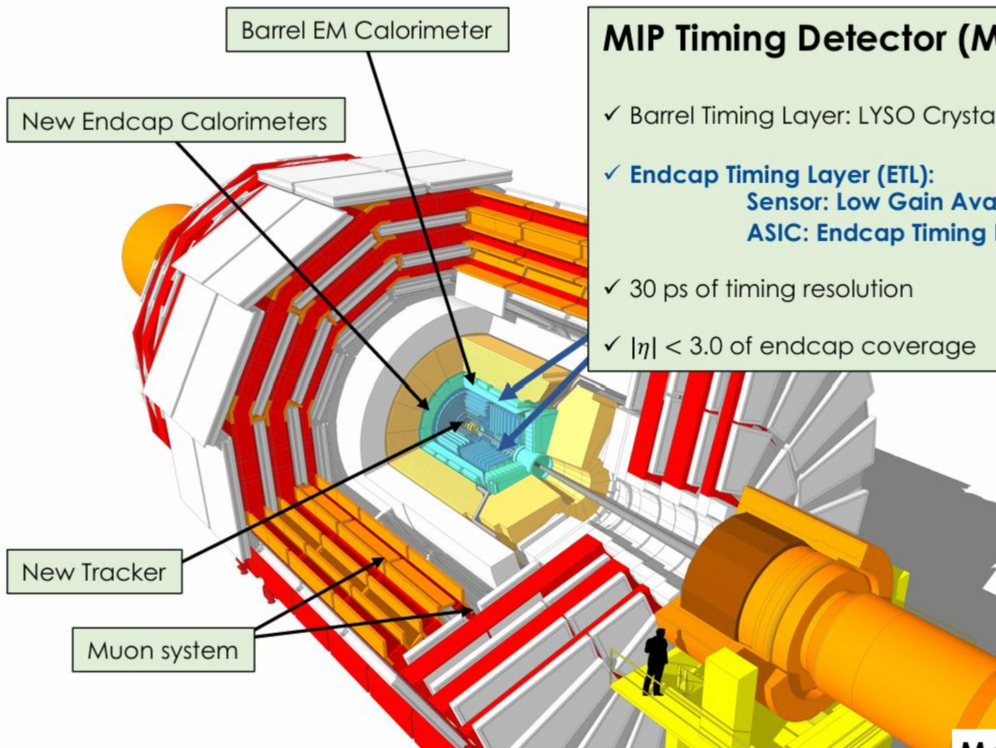


With timing cut
Δt < 90 ps and
Q > 12 fC



J. Virdee @HEP23

CMS Detector and MIP Timing Detector



MIP Timing Detector (MTD)

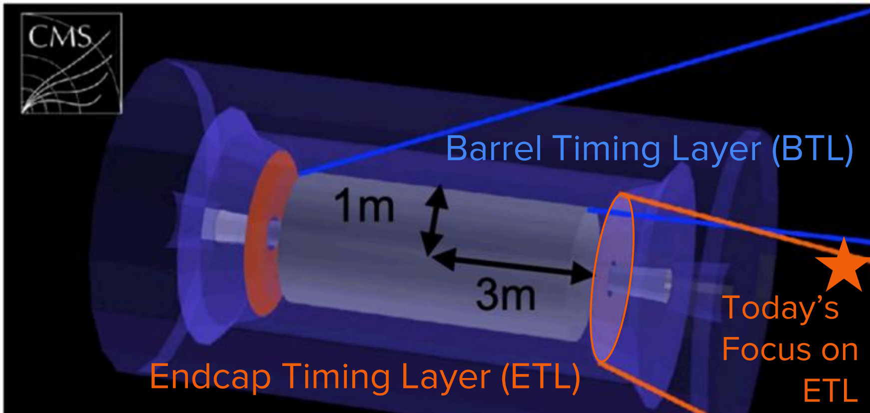
- ✓ Barrel Timing Layer: LYSO Crystal + SiPM
- ✓ **Endcap Timing Layer (ETL):**
  Sensor: Low Gain Avalanche Diode
  ASIC: Endcap Timing Readout Chip
- ✓ 30 ps of timing resolution
- ✓ $|\eta| < 3.0$ of endcap coverage

Maintaining "Run-2 performance"

See Jeongeun's presentation **D1.02**

CMS MIP Timing Detector at a Glance

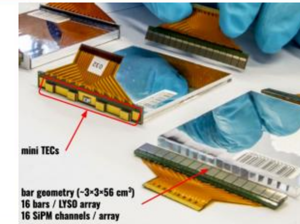
A NEW **MIP Timing Detector will be installed** for **precision timing** of minimum ionizing particles



Thin layer between tracker and calorimeter
MIP sensitivity with time resolution of ~30ps

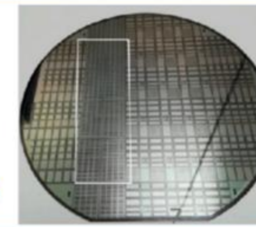
BTL: LYSO bars + SiPM read-out

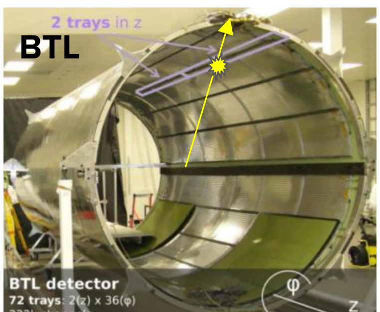
- TK/ECAL interface ~ 45 mm thick
- $|\eta| < 1.45$ and $p_T > 0.7$ GeV
- Active area ~ 38 m^2 ; 332k channels
- Fluence at 3 ab^{-1}: 2×10^{14} n_{eq}/cm^2

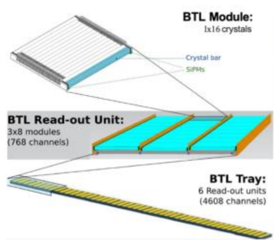


ETL: Si with internal gain (LGAD)

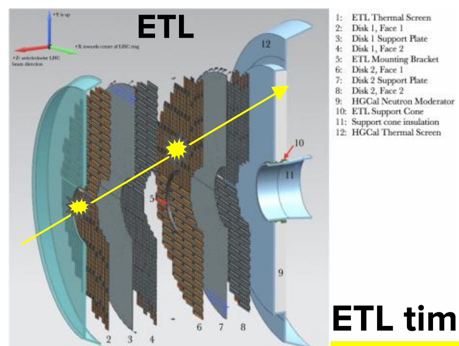
- On the HGC nose ~ 99 mm thick
- $1.6 < |\eta| < 3.0$
- Active area ~ 14 m^2; ~ 8.5M channels
- Fluence at 3 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2

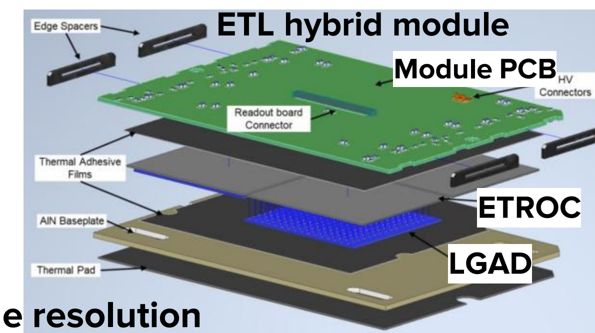






BTL time resolution
< 40 (60) ps/track (at EoL)





ETL time resolution
< 50 ps/hit = 35 ps/track (until EoL)

How better can we do with MIP timing detector?

Table 1.1: Expected scientific impact of the MIP Timing Detector, taken from Ref. [8].

Signal	Physics measurement	MTD impact
$H \rightarrow \gamma\gamma$ and $H \rightarrow 4$ leptons	+15–25% (statistical) precision on the cross section → Improve coupling measurements	Isolation and Vertex identification
VBF→H→ $\tau\tau$	+30% (statistical) precision on cross section → Improve coupling measurements	Isolation VBF tagging, p_T^{miss}
HH	+20% gain in signal yield → Consolidate searches	Isolation b-tagging
EWK SUSY	+40% background reduction → 150 GeV increase in mass reach	MET b-tagging
Long-lived particles (LLP)	Peaking mass reconstruction → Unique discovery potential	β_{LLP} from timing of displaced vertices

so as to achieve a level of performance comparable to the Phase-1 CMS detector at pileup of about 200. The integrated luminosity × efficiency is increased and this gain is equivalent to collecting data for three additional years beyond the ten year run planned for the HL-LHC.

CMS-TDR-020

Korea CMS(KCMS) MTD upgrade Group

~ 30 professors, Phd researchers, engineers and students

5 institutes

- Kyungpook National University
- Korea University
- Seoul National University
- Chonnam National University
- Gangneung-Wonju National University

What Korea CMS MTD group is doing

CMS ETL development
- LGAD test
- Module assemble
- Beam test

General LGAD R&D for future experiment
- TCAD simulation
- Co-work with Korean foundry (ETRI)

Roadmap of Sensor QA/QC

QA/QC procedure and Korea contributions

Wafer production → **Sensor on-wafer testing:**
- Optical inspection
- Sensor Quality check

Wafer post-processing:
- UBM
- Thinning (if > 300μm)
- Back metallization
- Dicing

(1x1, 1x2, 2x2, 5x5, 16x16)

★ Korea-CMS contribution in the red box

⇒ Dedicated Market Survey is ongoing

Korea is responsible for
- Wafer post-processing (25 % of total, 8K)
- Hybridization (50 % of total, 16K)

Test structure testing (< 10 %):
- Optical inspection
- Sensor Quality check
- Gain, single-pad IV/CV

High-level testing (< 1 %)
- Time resolution
- Collected charge
- Interpad resistance
- irradiation test (pre vs. post)

Full size sensor testing:
- Optical inspection
- Sensor Quality check
- total IV, VGL
- Pad IV uniformity,
- Interpad resistance,
- Leakage current stability

Hybridization
LGAD + ETROC
(bump bonding)

Hybrid module assembly sites
(BU, **FNAL**, Torino, ICFA)

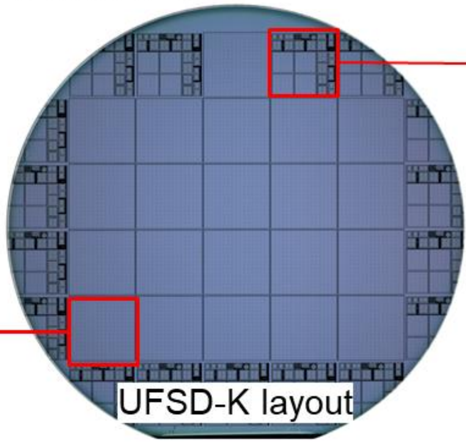
Test beam(CERN,DESY KOMAC)

⇒ ETL QA/QC testing sites
- **KNU, KU, CNU Korea**
- INFN Torino, Italy
- Fermilab, USA
- USTC, China
- U. Helsinki, Finland

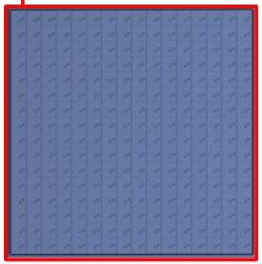
- A fraction of the diced sensors will be re-tested in Lab
- the remaining part will go directly to hybrid/assembly

FBK UFSD Sensor Design and Specification

UFSD-K1 and UFSD-K2



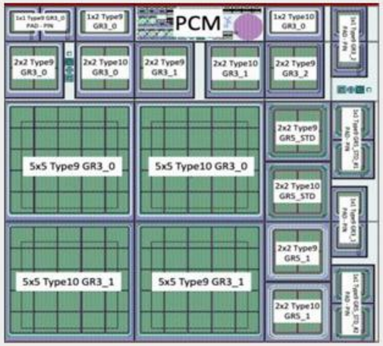
6 inch (15.23 cm)

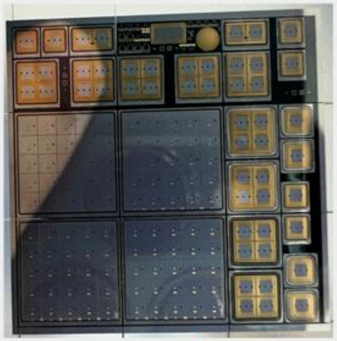


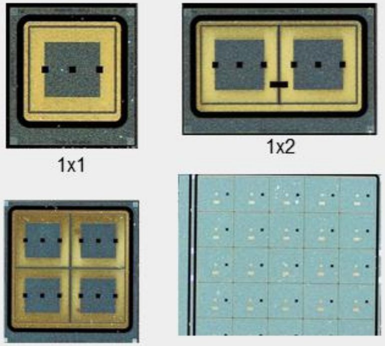
x 21 full-size sensor per wafer

16x16 Type9 GR3_0 (21 x 21 mm^2)

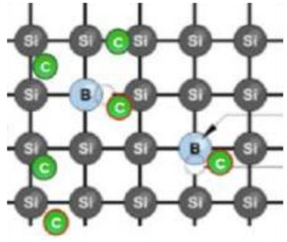
1.3 mm^2 pixel pitch



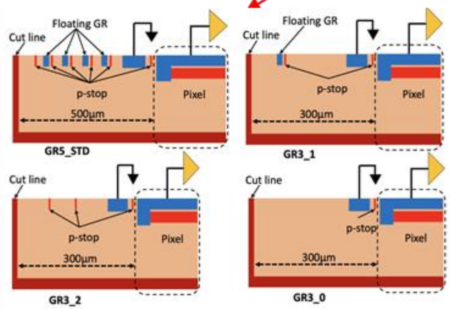




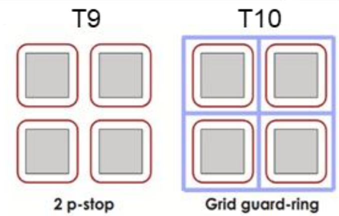
- Test structure are classified by mutlipad size, guardring and interpad design



Carbon-Boron co-implantation in the gain layer



Type	Nominal inter-pad width [µm]	*Region A/B design*
9	38	*2 p-stops*
10	49	*Grid guard-ring*



J.Y. Kim (KNU)'s talk KPS 2025 Spring

Proton Irradiation Campaign in KOMAC

KOMAC (Korea Multi-purpose Accelerator Complex)

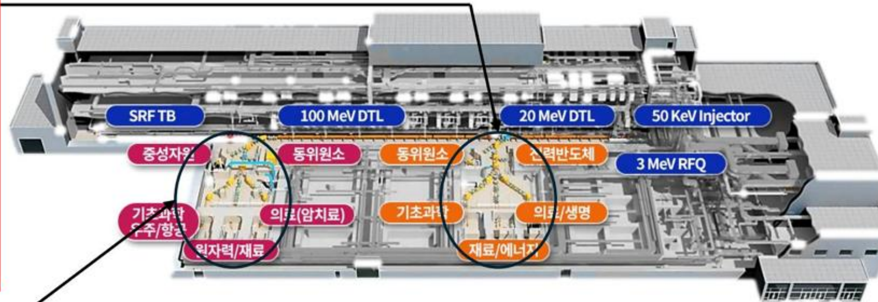
TR23 (20 MeV versatile beamline)

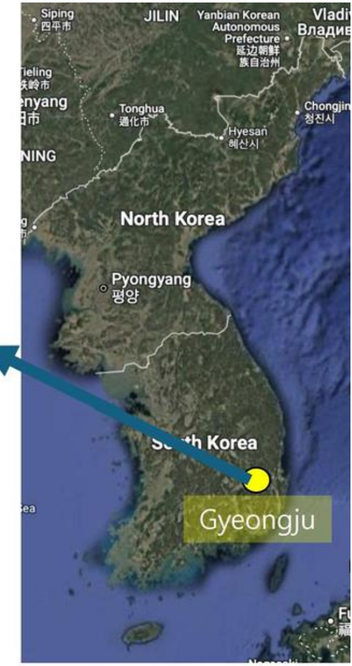
A research facility where materials or products are irradiated with a proton beam accelerated up to 20 MeV under various conditions.

High-dose proton beam research facility

Specifications of the TR23

Engergy	15 - 20 MeV
Beam Current	1 - 10 mA
Beam Flux	1E10 - 1E11 #/cm²/pulse
Irradiation Area	30 mm-ø
Quality standards (ISO 9001)	Fluence: ± 10% Uniformity: ± 10% Energy: ± 5%
Application fields	Materials, Nuclear Physics, Semiconductors, etc.





TR103 (100 MeV versatile target room)

A research facility for irradiating materials or products with a proton beam accelerated to 100 MeV under various conditions.

High-dose proton beam research facility

Specifications of the TR103

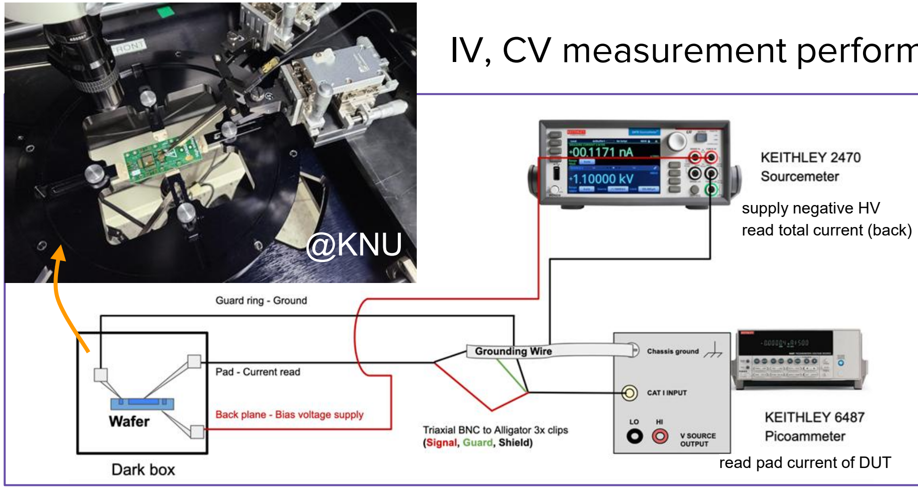
Engergy	30~100 MeV
Beam Current	1~10 mA
Beam Flux	1E10 - 1E11 #/cm²/pulse
Irradiation Area	30 mm-ø
Quality standards (ISO 9001)	Fluence: ± 10% Uniformity: ± 10% Energy: ± 5%
Application fields	Biotechnology, materials, nuclear physics, semiconductor

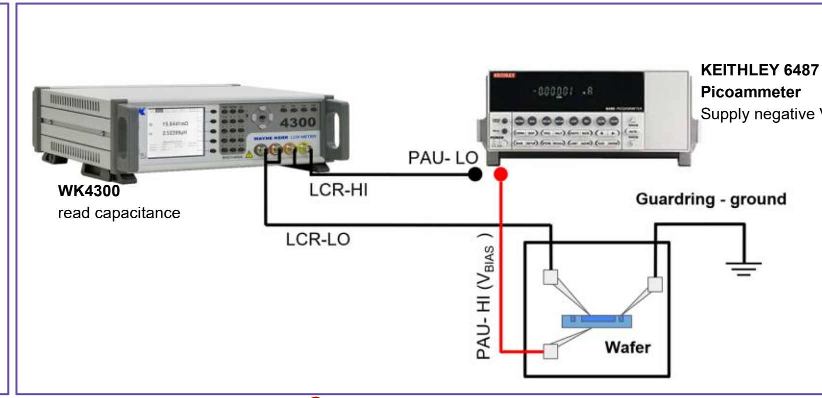
- For both room, beam flux would be 1E10-1E11/pulse
  - ➔ Depend on the beam status
  - ➔ Beam size: 30 mm ϕ
    - insure the fluence within 10% uncertainty
    - Outside the area beam is still active
  - ➔ only use single sample per each irradiation
- With 100 MeV beam, deposited dose is so small and expect larger irradiation time
  - ➔ Decide to use 20 MeV beamline (TR23)

2025 KPS Spring meeting; Daejeon, Seonghak Lee

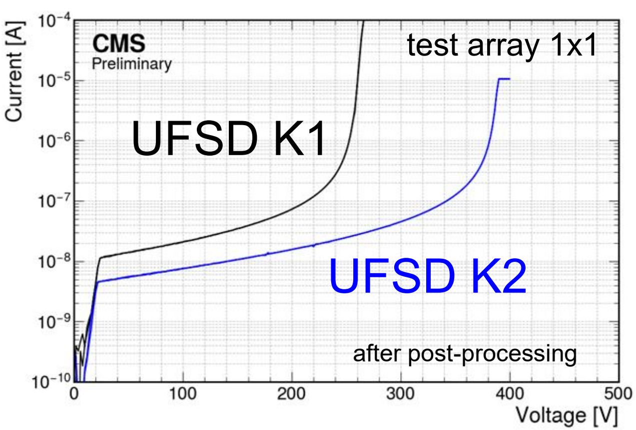
IV, CV Characterizations of LGAD (test array)

IV, CV measurement performed with post-processed LGADs using Probe station

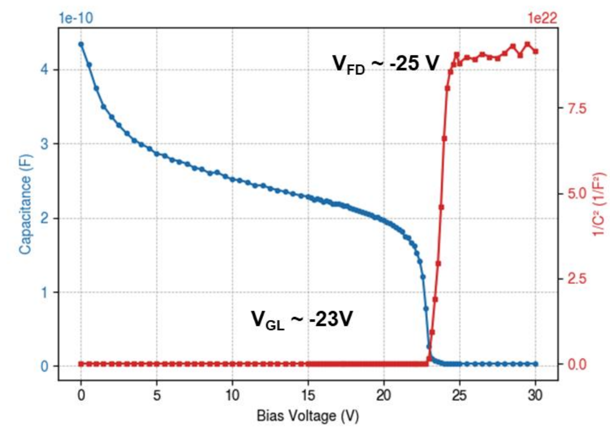




I-V measurement

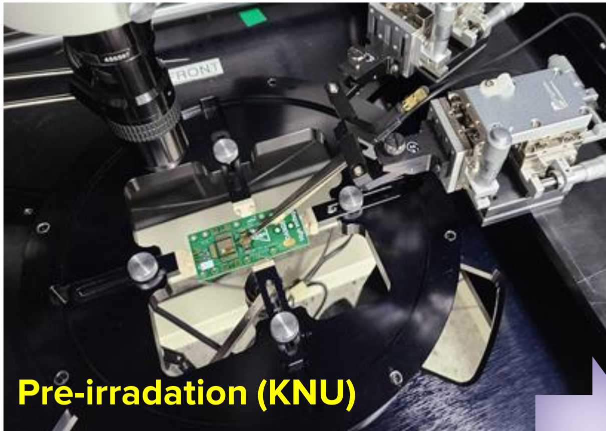


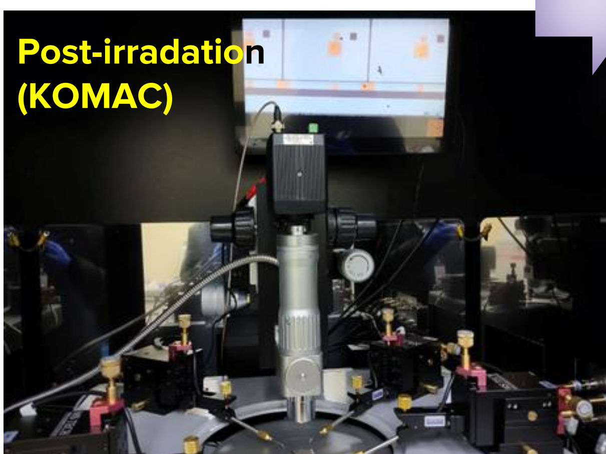
C-V, $1/C^2$-V measurement



Static Test – IV/CV characteristic of LGAD

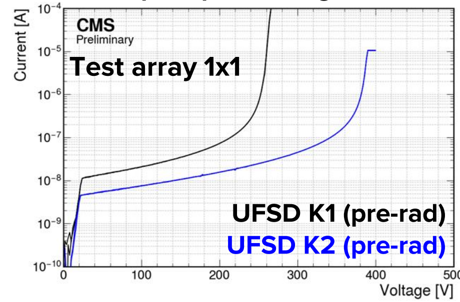
Static Test with Probe Station

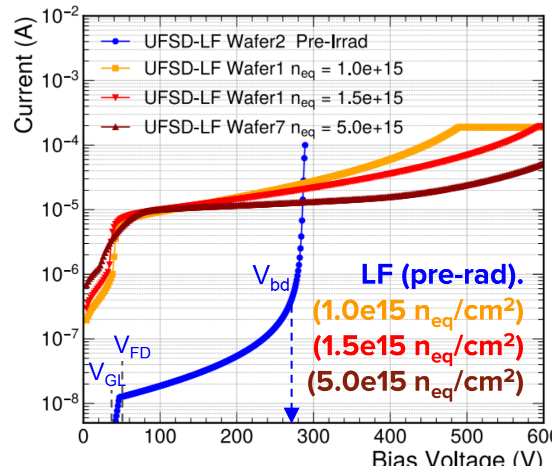




I-V measurement

After post-processing

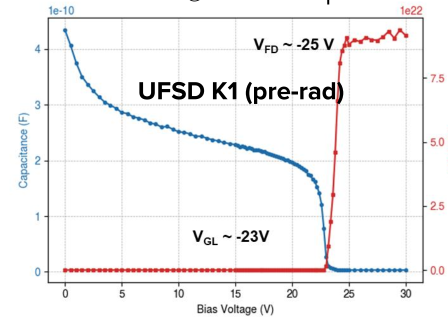


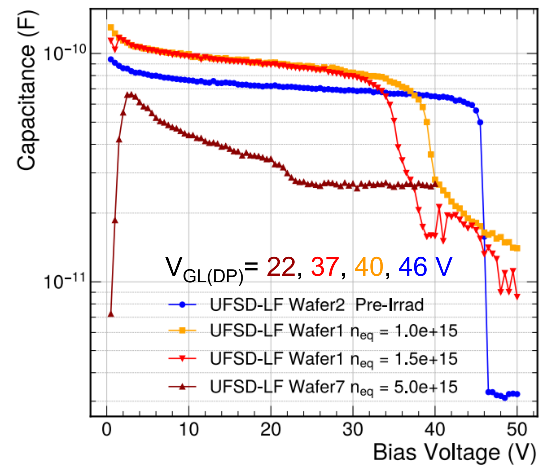


$k(I,V) = (\Delta I/\Delta V)\times(V/I) > 20$

C-V, $1/C^2$-V measurement

All results @ room temperature

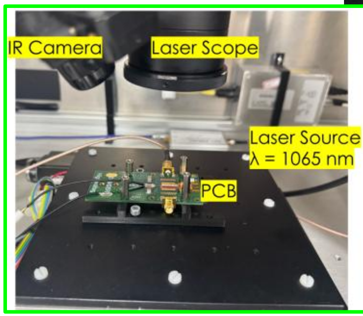


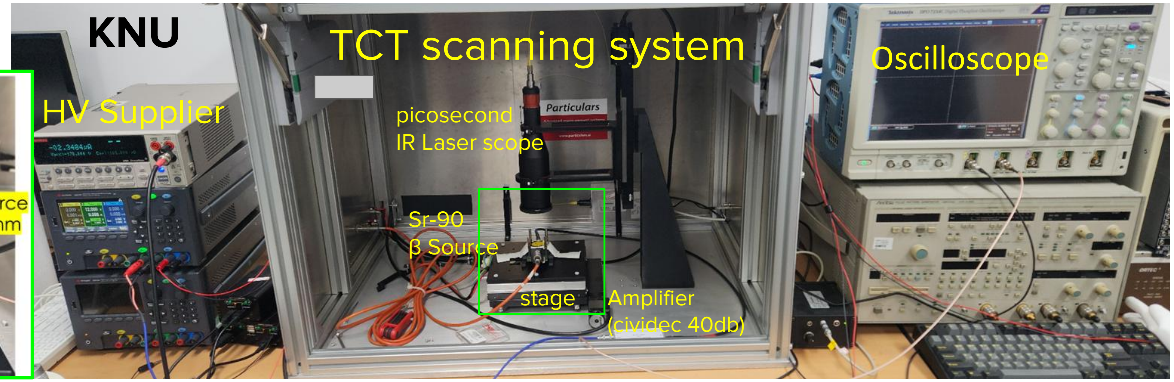


T.W Kim and J.Y. Kim (KNU)'s talks (B1.04, P2-pa.012) KPS 2025 Fall

High-level Test – Gain/Collected Charge/Time Resolution

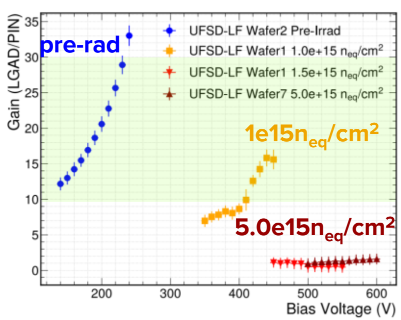
Test Bench with Laser / β-source



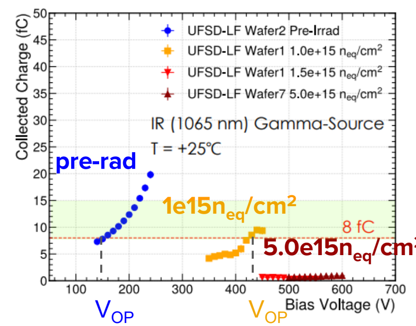


Transient Current Technique (TCT) system from *Particulars*

KNU Test Bench with Laser (Room Temp)



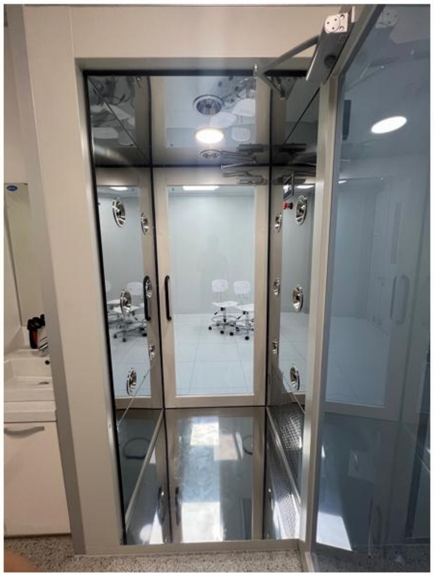
Gain (LGAD/PIN) vs. Bias V



Collected Charge vs. Bias V

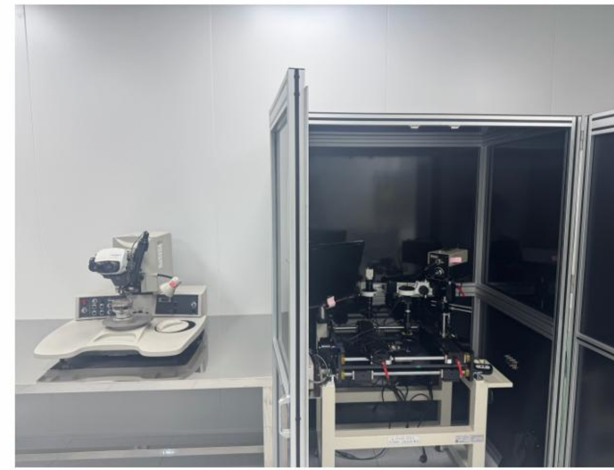
T.W Kim and J.Y. Kim (KNU)'s talks (B1.04, P2-pa.012) KPS 2025 Fall

ETL Testing Site: KNU Clean Room



Air shower

Main Chamber



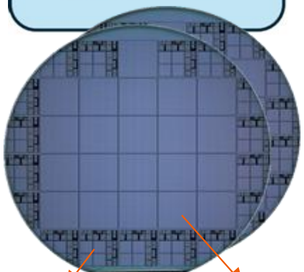
Wire Bonding Machine / Probe Station

- ❖ We built dedicated clean room (class 1000) as an ETL tesing site.
- ❖ This room will serve a QA / QC site during entire ETL production period.

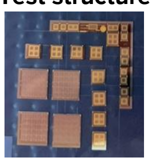
Wafer post-processing and Hybridization

Courtesy J.H. Lee (KNU)

LGAD wafer from FBK

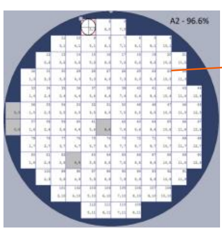


Test structure

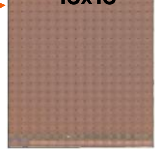


Full size sensor 16x16

+ ETROC wafer (TSMC)

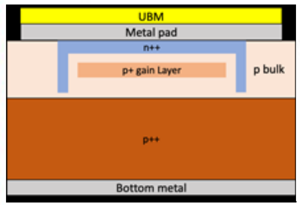


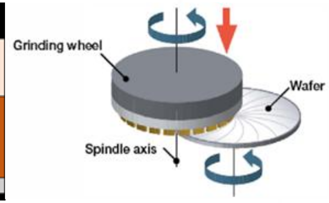
Full size ASIC chip 16x16

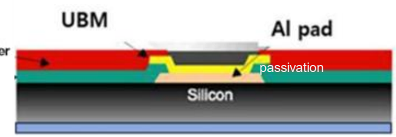


1) LGAD wafer post-processing

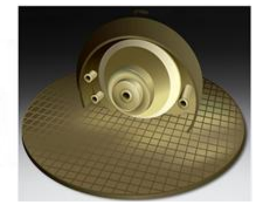
UBM (Under Bump Metallization) → **Wafer Back-grinding (550um → 300um)** → **Backside Metal deposition** → **Wafer dicing** →





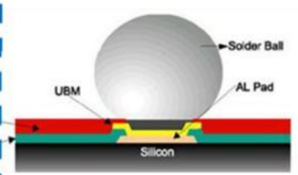


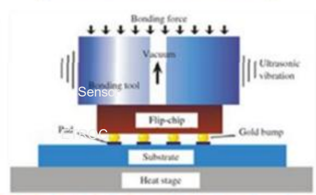
Al Metal deposition

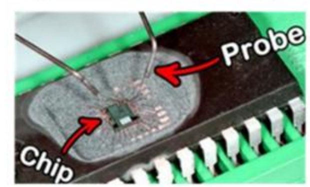


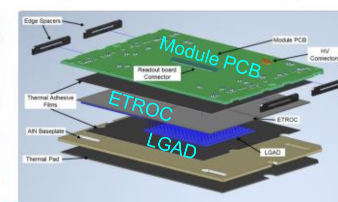
2) Bump bonding and module assembly

Solder ball attachment → **Flip chip bonding** → **Electrical measurement** → **Module assembly**



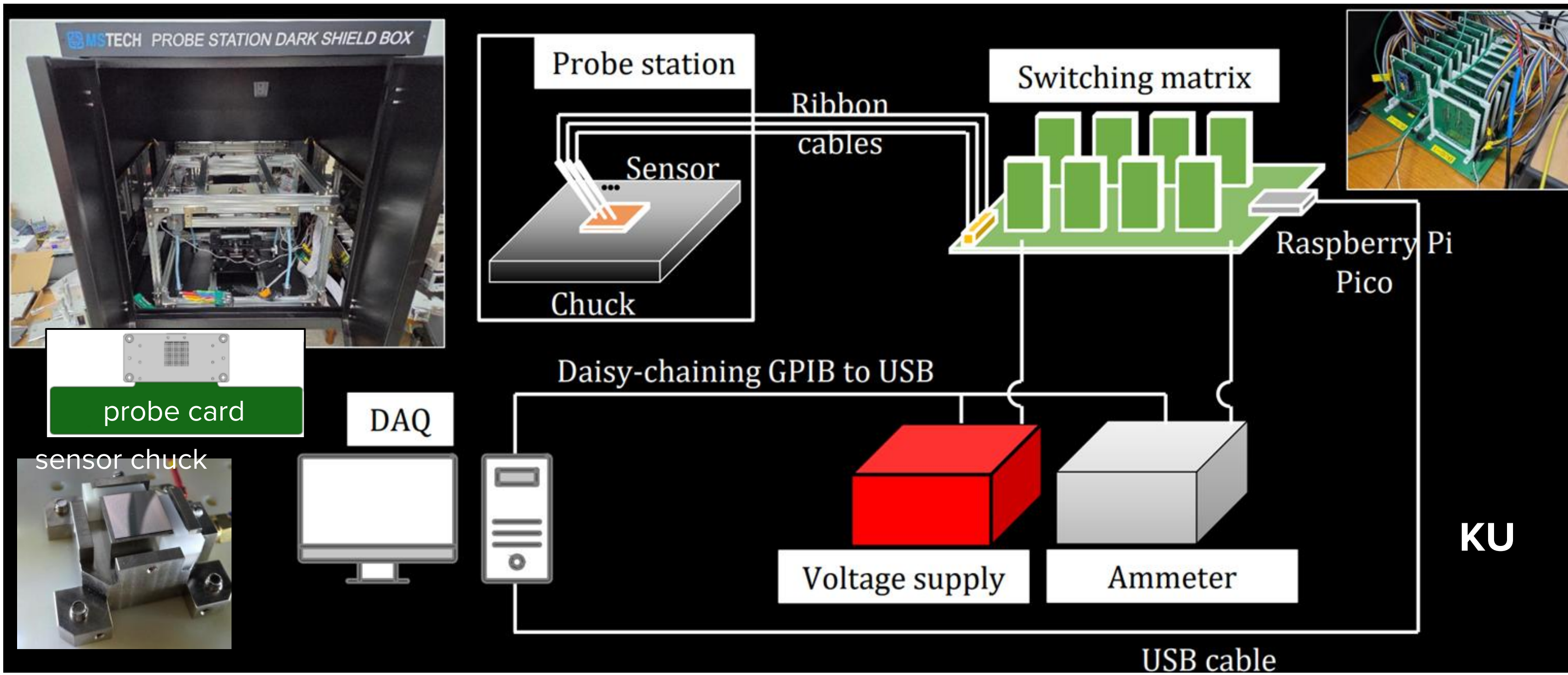






Test for full size LGAD (16x16)

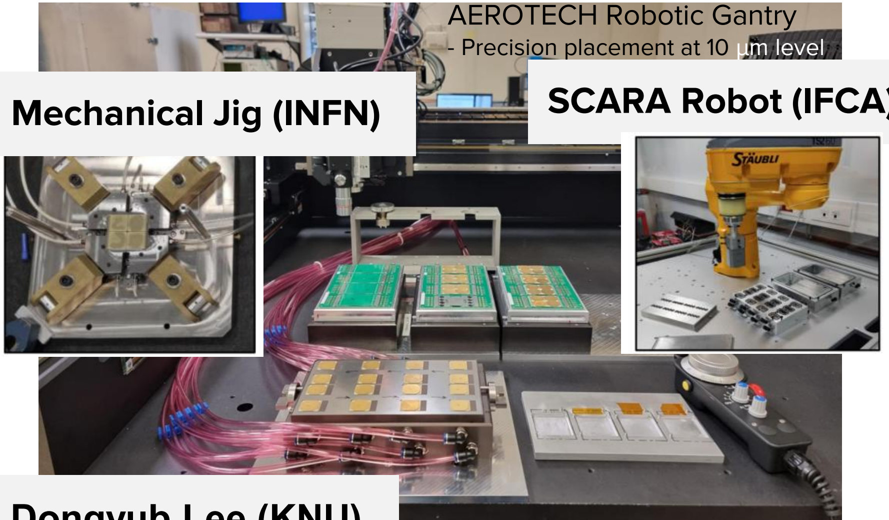
- New setup with probe card, switching matrix, Jig system, and DAQ system in development at KU.
- To efficient QA/QC testing for full size LGAD 16x16 (256) channel:
- SW update is ongoing : automated, scalable, and remotely controlled daq testing system



Custom-built switching matrix enables selective readout of any pixel w/o manual reconnection H.Y Jeong (KU)'s Talk (B1.07) KPS 2025 Fall

ETL hybrid Module assembly(FNAL) Mechanics(CERN)

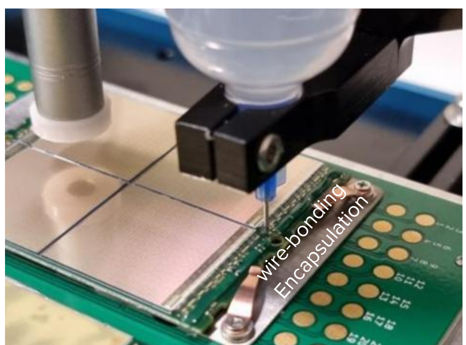
Gantry (Fermilab Sidet)



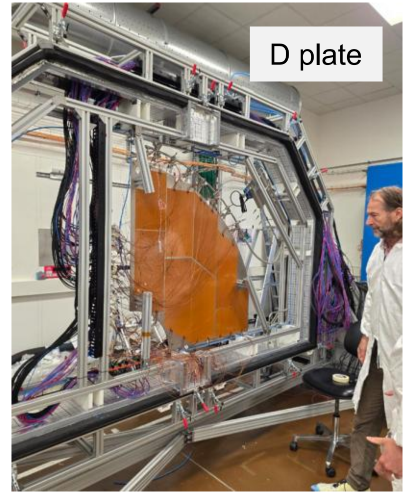
Mechanical Jig (INFN)

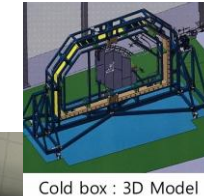
SCARA Robot (IFCA)

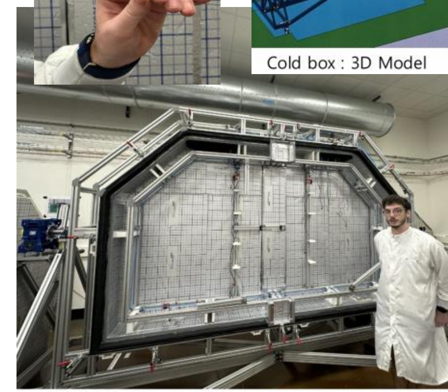
Dongyub Lee (KNU)



CERN

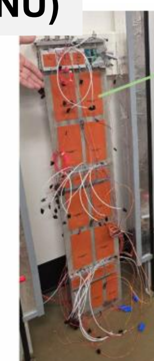


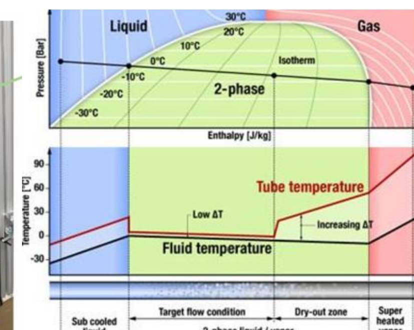




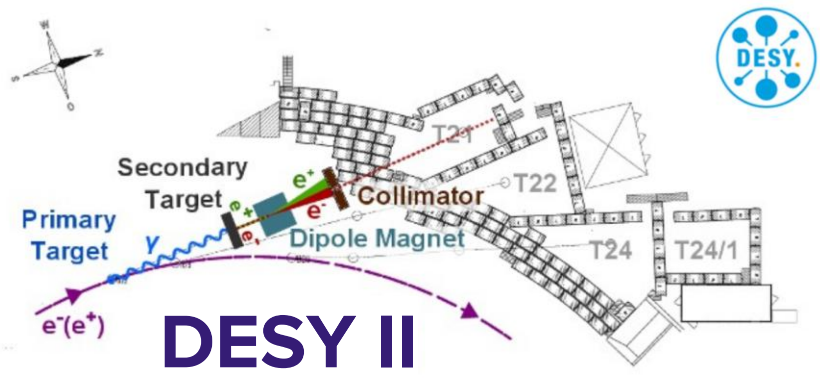
Cold box

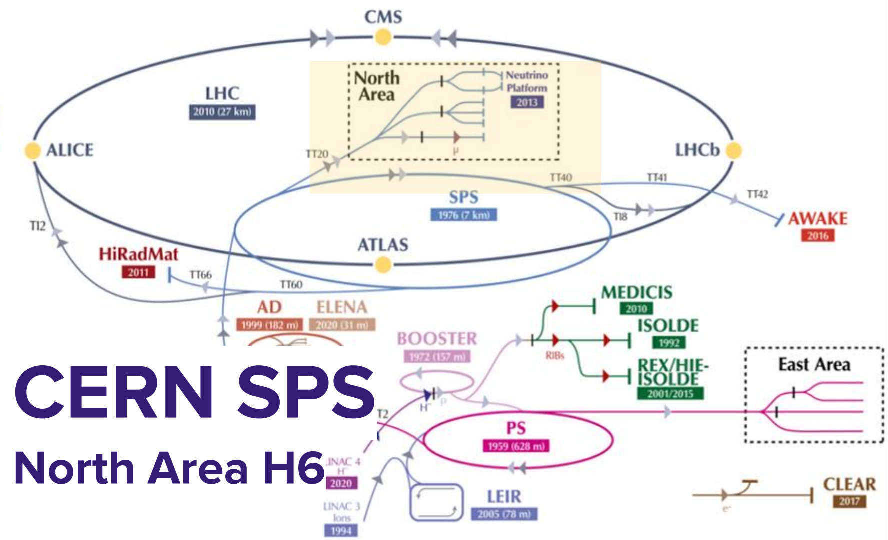
Hanseul Lee(CNU)





Test Beam Facilities





- Particle type: electron beam
- Energy 1 – 6 GeV

\- Used parameters:

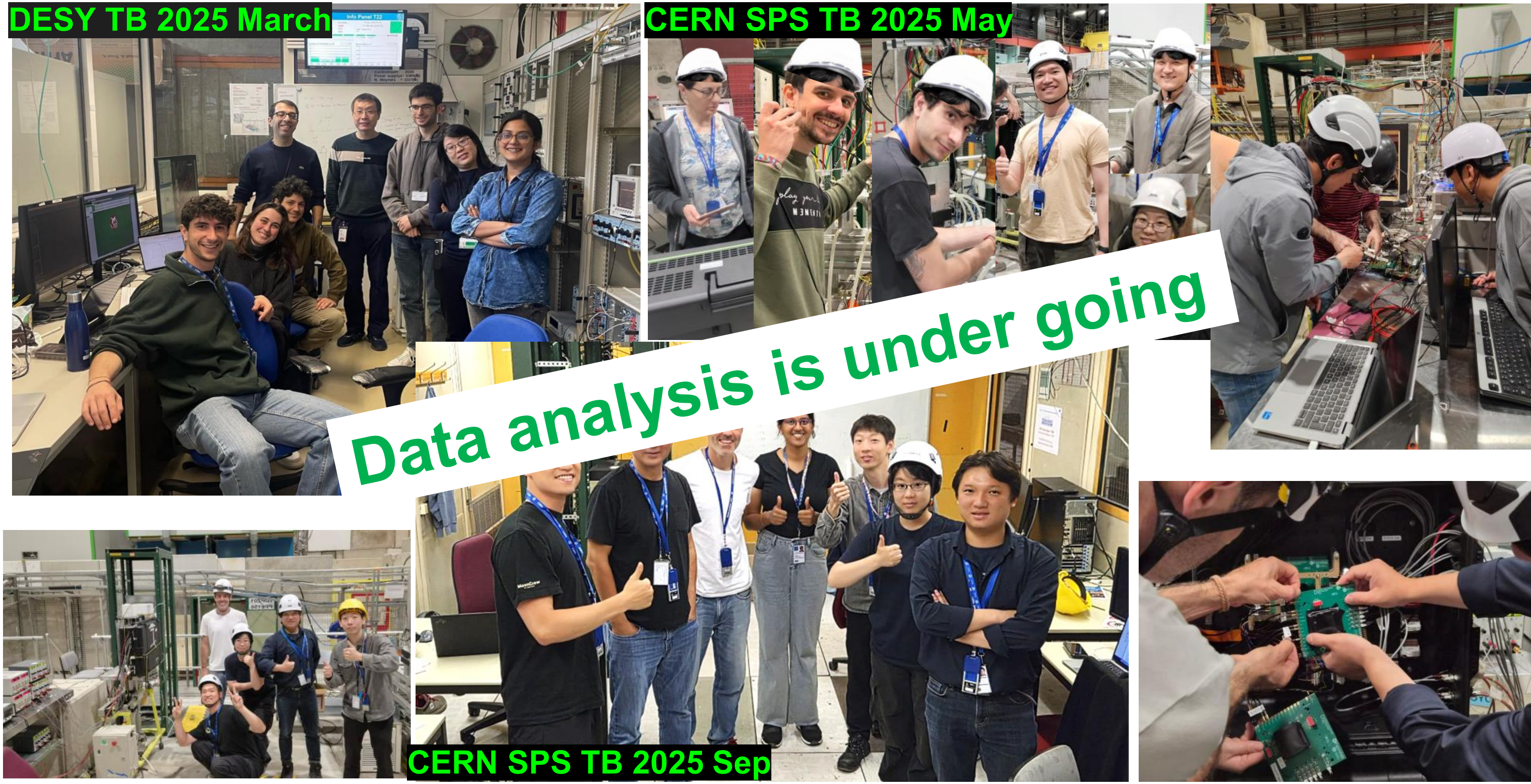
- Energy = between 3 GeV and 5 GeV
- Rate = ~1k particles/s·cm^3
- Beam Size = ~12x12 mm^2

- Particle type: hadron beam (pions, protons)
- Energy 10 – 205 GeV

\- Used parameters:

- Energy = between 100 and 120 GeV
- Intensity= ~10^8 particles per spill (4.8s)
- Beam Size = ~20x20 mm^2

Wonderful team – Never develop alone!

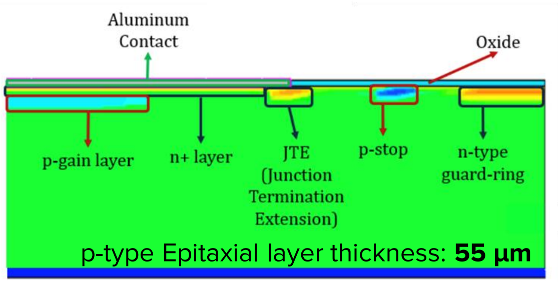


LGAD R&D

LGAD Design and Fabrication in Korea

Design and fabrication of the LGAD by KCMS group (Photomasking ongoing)

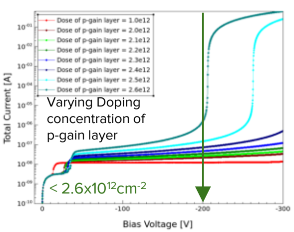
Design & Simulation



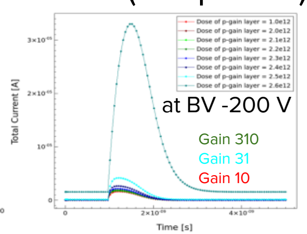
Synopsys Sentaurus

TCAD Simulation

I-V curve

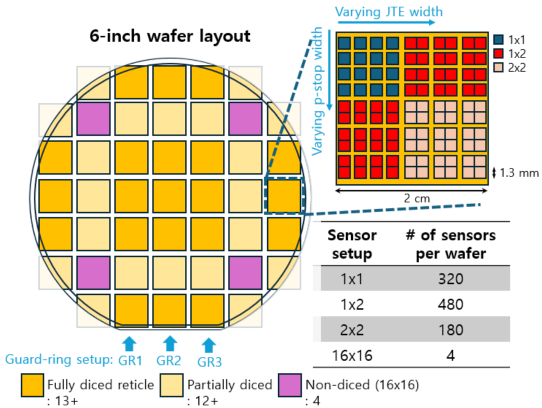


I-time (Response)

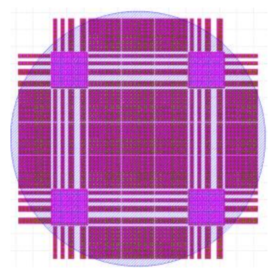


* TCAD: Technology Computer-Aided Design

Photomask design



Sensor setup	# of sensors per wafer
1x1	320
1x2	480
2x2	180
16x16	4



Photomask design

6 layers

by H.S. Ahn (KNU)

Fabrication

ETRI

National Semiconductor R&D Policy Center

KCMS is collaboration with ETRI (한국전자통신연구소) for the fabrication of LGAD using photomasks & wafers

Full depletion voltage	~ 25 V
Breakdown voltage	~ 250 V
Gain	~ 10
Timing resolution	< 50 ps

K.M. Lee (KU) and J.B. Yang (KNU) talks (B1.05, B1.06) in KPS 2025 Fall

Plan of LGAD R&D

- LGAD design
  Based on the UFSD design
  TCAD simulation for optimization of the design

- Photomask
  The draft is almost ready

- Process design
  The draft of run-sheet is almost ready

- Fabrication plan @ ETRI
  Fab-in by the end of November

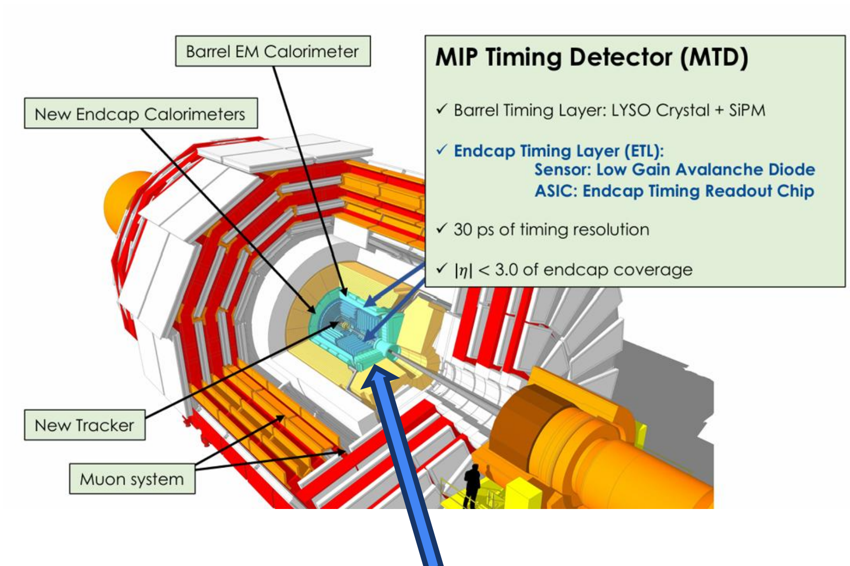
- Goal
  Working LGAD
  AC-LGAD, Large area LGAD . . . . ➔ Future experiments & other applications

Summary

- CMS will deploy new precision timing detector for 4D vertexing reconstruction; K-CMS is leading major pieces of the high-radiation Endcap Timing Layer (ETL) effort.
- K-CMS team spans the almost full R&D chain: Sensor post-processing, UBM/bump-bonding, hybrid/module assembly, QA/QC, irradiation campaigns, and test-beam validation.
- Also, K-CMS wants to design and fabricate LGAD sensor in Korea, which finalizes the full LGAD R&D process.
- The full chain of LGAD R&D process will be used to participate other future experiment.

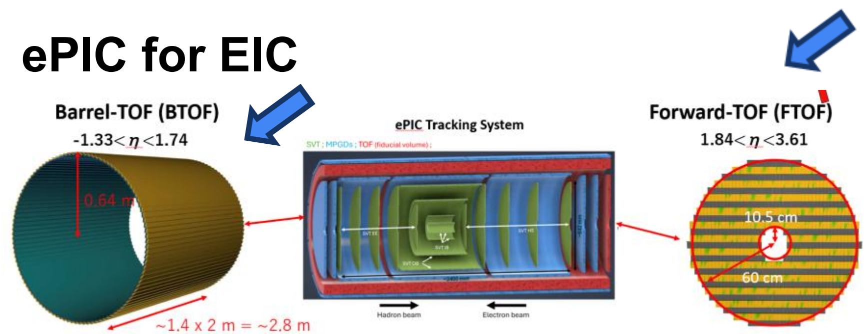
Thank you very much for hearing !

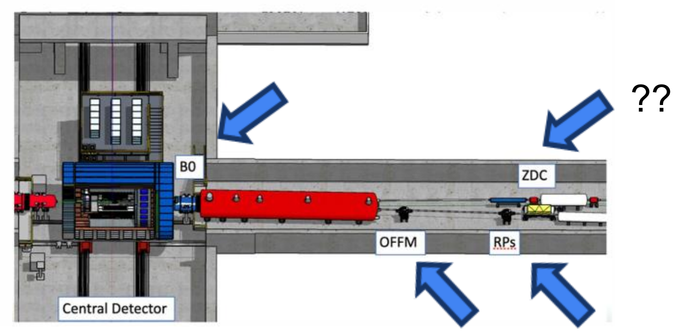
CMS for HL-LHC



DC-LGAD

ePIC for EIC





AC-LGAD

Back up

Radiation damage study of LGAD

- **LGAD must** be qualified up to $\phi \sim 1.5 - 2.5 \times 10^{15}\ n_{eq}/cm^2$ **(innermost ETL)**; Run cold (-25℃) with bias V margin;

- Radiation damage mechanism:
  Acceptor removal deactivates p+ doping in gain layer
  ⇒ Degrading gain, collected charge Q

$$p^+(\Phi) = p_0^+ \cdot e^{-c_A \Phi}$$

c_A = Acceptor removal coefficient

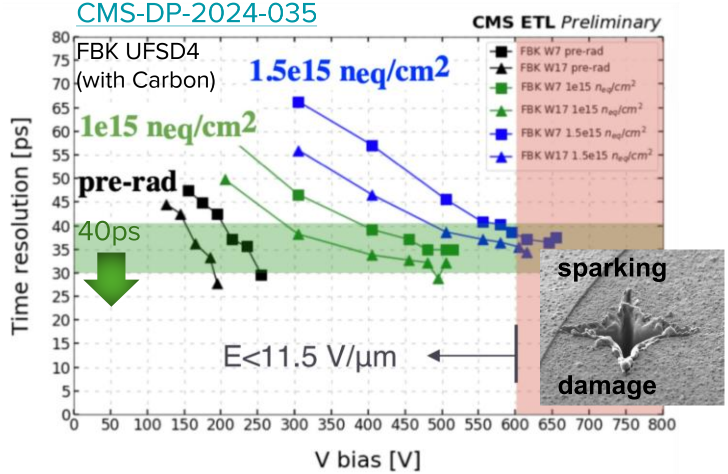
Strategies to recover the gain loss after irradiation

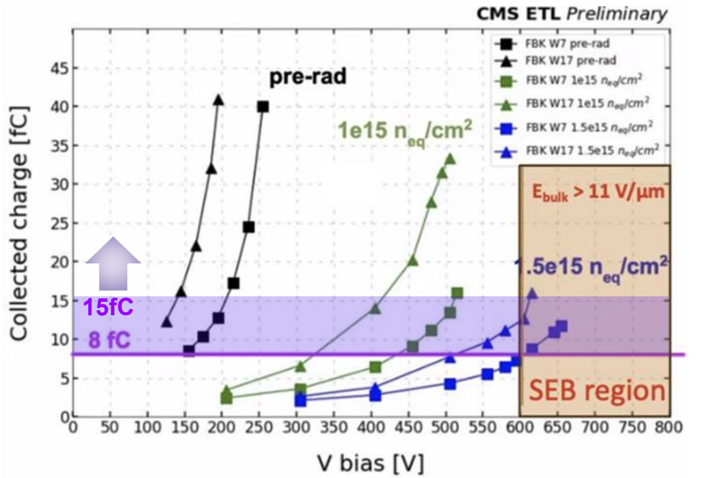
1. Carbon co-implantation (slows removal)
2. Raise bias V (keep E-field ≲ 11.5V/µm to avoid SEB)

- ETL Targets:
- Q ≥ 15 fC, ~40 ps for unirradiated (pre-rad) sensor
  Q ≥ 8 fC, ~40 ps for irradiated sensor up to the EoL
- Uniformity & Safety: maintain Q **≥ 8–10 fC** at EoL, out of SEB region (≲ 605 V for 50µm thickness).

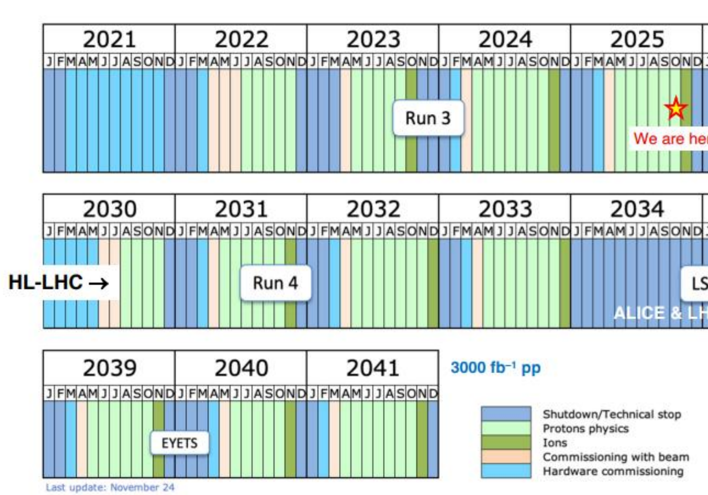
* **Single-event-burnout (SEB)** from rare, large ionizing events where excess charge leads to highly localized conductive path

CMS-DP-2024-035

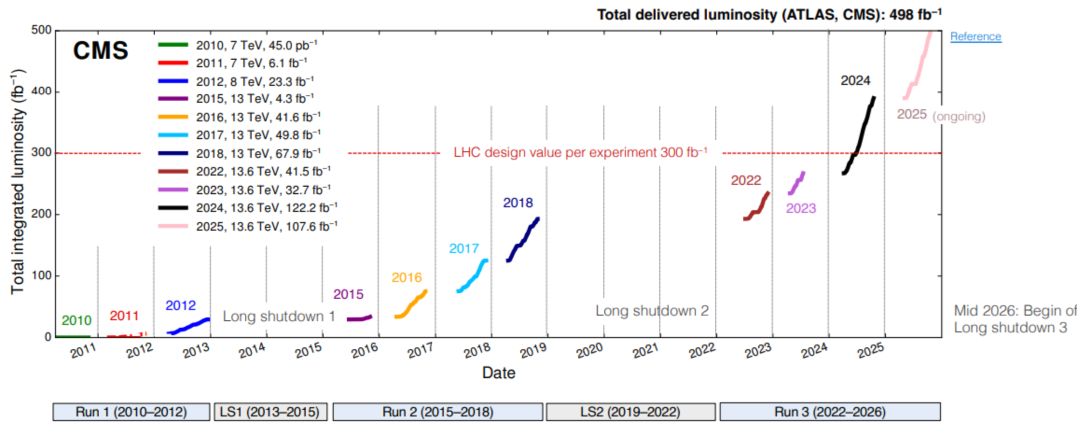




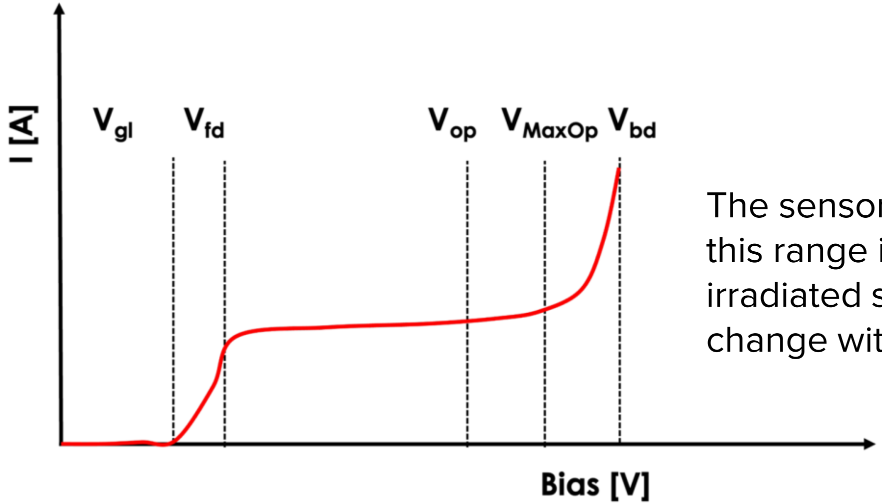
HL-LHC timeline



Power of HL-LHC together with upgraded detectors & ML/AI: huge scientific opportunity for our field — complementary in many ways to a future e⁺e⁻ collider



Key LGAD sensor Operating Voltages definition



The sensors can be operated between V_{op} and V_{MaxOp}. this range is requested to be at least 30 V in un-irradiated sensors (IV not too steep) and will slowly change with time

- V_{gl} : **Gain layer depletion voltage**, proportional to the doping concentration and position of the gain implant
- V_{fd}: **Sensor full depletion voltage**, proportional to the doping concentration of the sensor bulk
- V_{op}: **Operation voltage**, the voltage where new sensors will operate
  - un-irradiated : $Q(V_{op})$ = 15 fC ,
  - irradiated : $Q(V_{op})$ = 8 fC
- V_{MaxOp}: **Maximum voltage of operation** without extra noise
  - At least 10 V from breakdown and Lower than 605 V (SEB limit)
- V_{bd}: **Breakdown voltage**

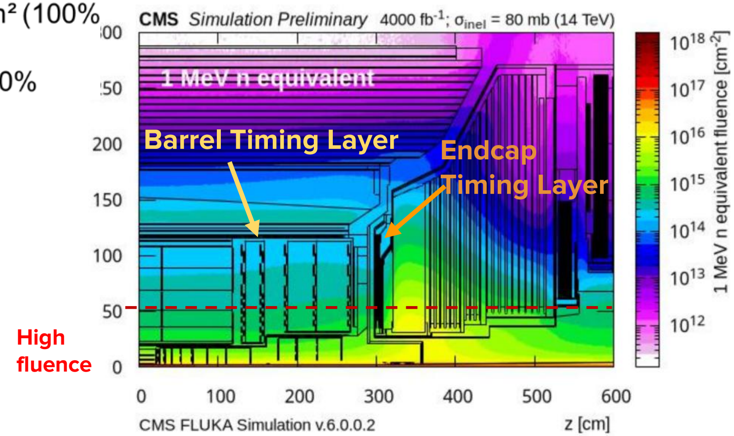
Plan for Irradiation Campaign at KOMAC in Nov

Region	$\|\eta\|$	r (cm)	z (cm)	3000 fb^{-1} n_{eq}/cm^2	3000 fb^{-1} Dose (kGy)	1.5×3000 fb^{-1} n_{eq}/cm^2	1.5×3000 fb^{-1} Dose (kGy)	Ratio to Endcap 3.0 region
Barrel	0.0	116	0	1.65×10^{14}	18	2.48×10^{14}	27	10.3%
Barrel	1.15	116	170	1.80×10^{14}	25	2.70×10^{14}	38	11.3%
Barrel	1.45	116	240	1.90×10^{14}	32	2.85×10^{14}	48	11.9%
Endcap	1.6	127	303	1.5×10^{14}	19	2.3×10^{14}	29	9.5%
Endcap	2.0	84	303	3.0×10^{14}	50	4.5×10^{14}	75	18.8%
Endcap	2.5	50	303	7.5×10^{14}	170	1.1×10^{15}	255	45.8%
Endcap	3.0	31.5	303	1.6×10^{15}	450	2.4×10^{15}	675	100 %

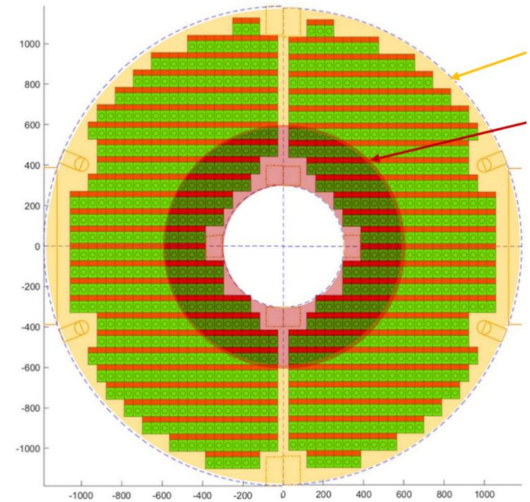
Nominal doses & fluences at various locations of timing layer

HPK(low fluence, r > 52): 4.5E14 n_{eq}/cm^2 (20%)
FBK (high fluence, r < 52): 2.5E15 n_{eq}/cm^2 (100%

Beam session: 10%, 20%, 50%, 75%, 100%



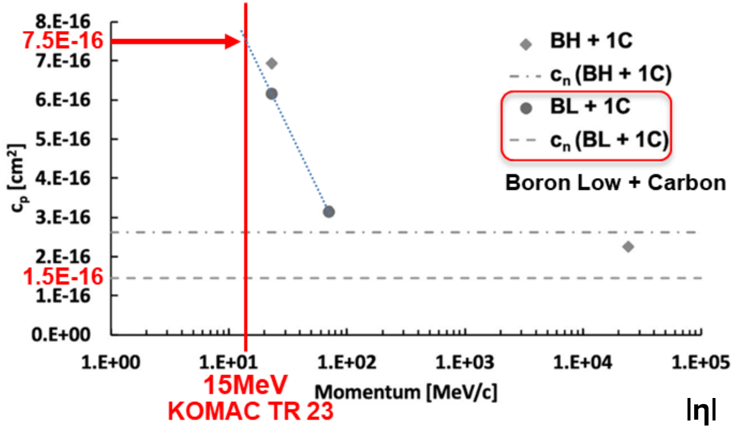
CMS-DP-2023_087



Proton Fluence calculation (NIEL factor)

- **Updated Fluence**

  : $2.5 \times 10^{15}\ n_{eq}/cm^2$ @ EOL



$$\frac{V_{GL}(\Phi)}{V_{GL}(0)} = \frac{N_A(\Phi)}{N_A(0)} = e^{-c(N_A(0))\Phi},$$

V_{GL} : depletion voltage of the gain layer

N_A : active acceptor concentration

c_n : acceptor removal coefficient of neutron

c_p : acceptor removal coefficient of proton

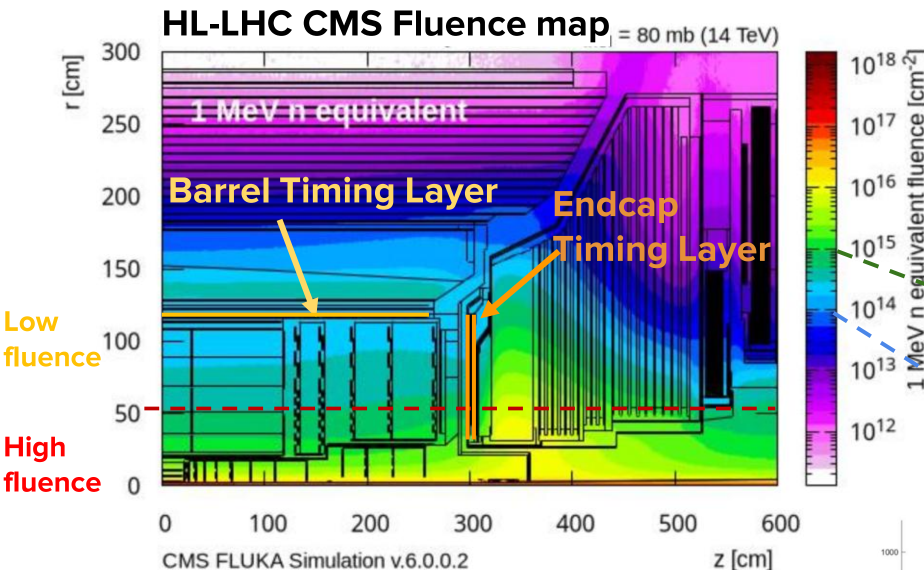
$$\phi_{n_{eq}} = \frac{c_p}{c_n}\phi_p = k\phi_p$$

Hardness factor (NIEL factor) $k = 5$

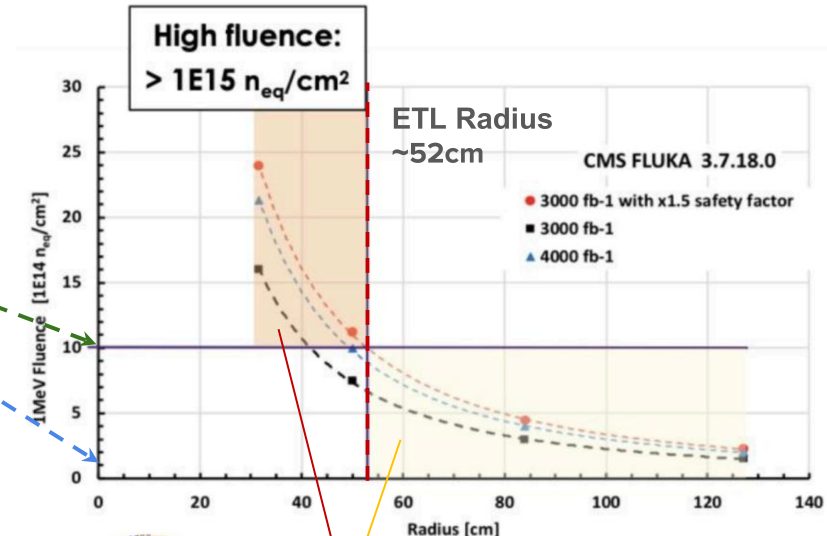
|η|	(%)	1MeV Neutron Fluence	Proton Fluence
1.6	(10%)	$2.5\text{x}10^{14}\ n_{eq}/cm^2$	$5\times10^{13}\ n_p/cm^2$
2.0	(20%)	$2.0\text{x}10^{14}\ n_{eq}/cm^2$	$1\times10^{14}\ n_p/cm^2$
2.5	(50%)	$1.25\text{x}10^{15}\ n_{eq}/cm^2$	$2.5\times10^{14}\ n_p/cm^2$
2.7	(75%)	$1.875\text{x}10^{15}\ n_{eq}/cm^2$	$3.75\times10^{14}\ n_p/cm^2$
3.0	(100%)	$2.5\text{x}10^{15}\ n_{eq}/cm^2$	$5\times10^{14}\ n_p/cm^2$

x 1/5

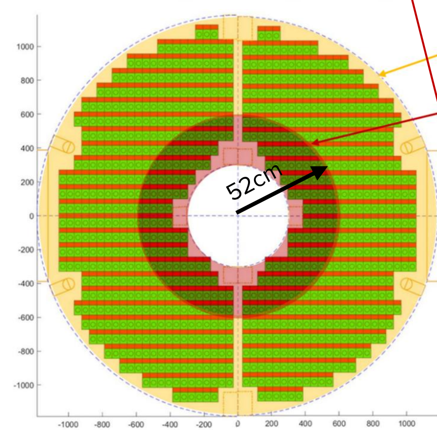
Radiation Hardness: Fluence gradient



[CMS-DP-2023_087](CMS-DP-2023_087)



- At L_{int}= 3 ab^{-1} (x 1.5) the expected fluence spans 1.5 (2.5) × 10^{15} n_{eq}/cm^2 (highest at small r)
- Phase-2 radiation levels substantially exceed Phase-1; Detector must operate reliably over ~10 years of HL-LHC to end-of-life (EoL)



Endcap Timing Layer (ETL) Geometry:

- 31.5 < R < 120 cm
- z = ±3.0 m
- ~85 % Low fluence area
- ~15 % High fluence area