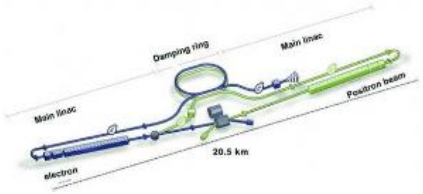
Instrumentation development for particle physics experiment

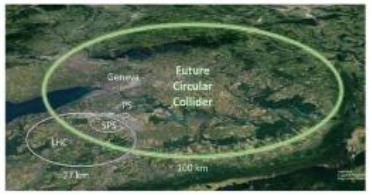
KEK IPNS-ITDC
Yuji Enari

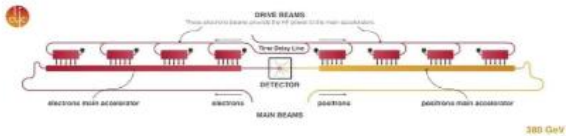
LCWS 2026 pre-school
2026 Nov 8

Detector concepts for Higgs factories

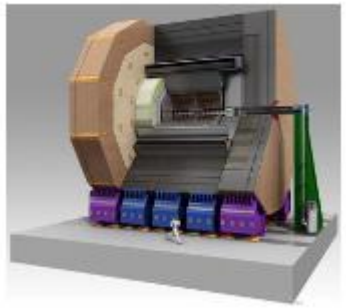




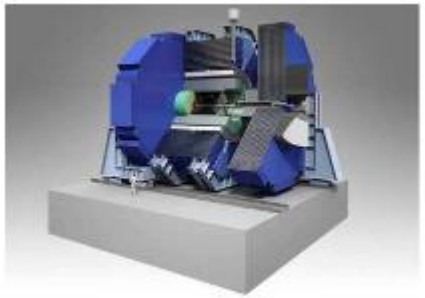




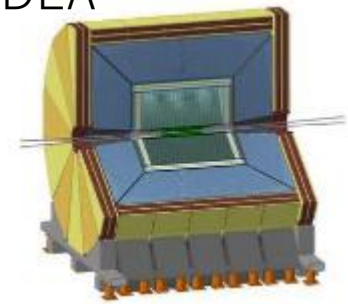
ILD



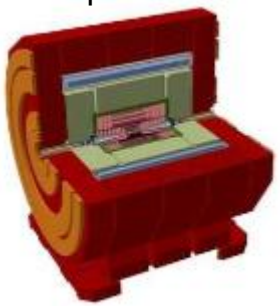
SiD



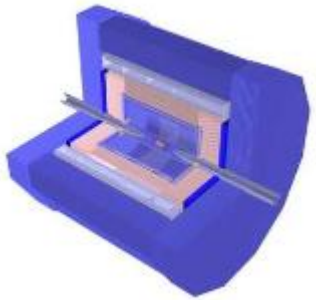
IDEA



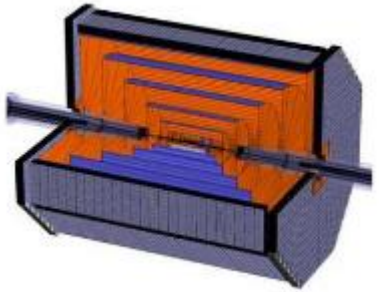
CLICdp



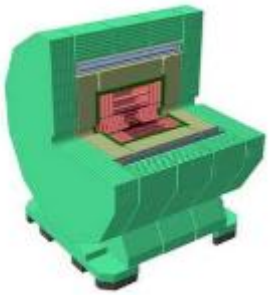
CEPC baseline



FST



CLD



We are going to build at least one of accelerator with multiple detectors!

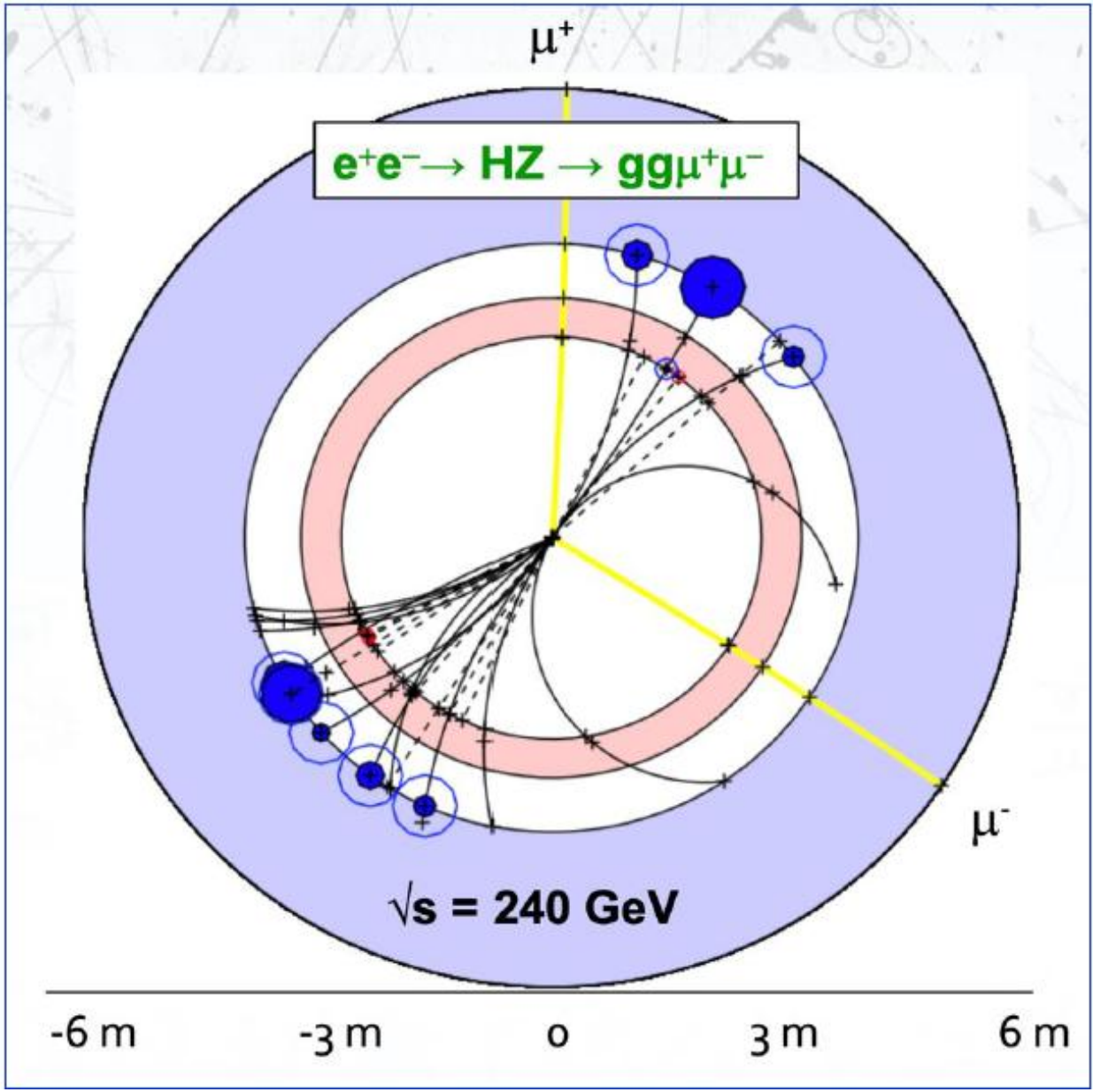
Requirement from Physics

Higgs Factory Programme

- At √s=240 and √s=365 GeV collect 2.6M HZ and 150k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (~4 σ) via loop diagrams
- Unique possibility: s-channel e^+e^- → H at 125 GeV

- **Momentum resolution $\sigma(p_T)/p_T \simeq 10^{-3}$ @ $p_T \sim 50$ GeV**
  - σ(p)/p limited by multiple scattering → minimise material
- **Jet σ(E)/E ≃ 3-4% in multijet events for Z/W/H separation**
- **Superior impact parameter resolution for b, c tagging**
- **Hadron PID for s tagging**

  - Consider other aspects
    - Electroweak precision measurement
    - Flavor physics
    - Dark Matter searches (i.e. long lived particle)



What kind of detector component we need?

- Vertex
  - Precise position resolution
  - Low material, Low power
  - (Timing resolution)

  → Pixel detector (strip detector)
- Tracking
  - Position resolution
  - Large volume coverage
  - (Particle Identification → dE/dx, TOF)

  → Strip detector

  → Gas detector (small cell / TPC)
- Magnet
  - Bend charged particles (2~3 Tesla)
  - Low material

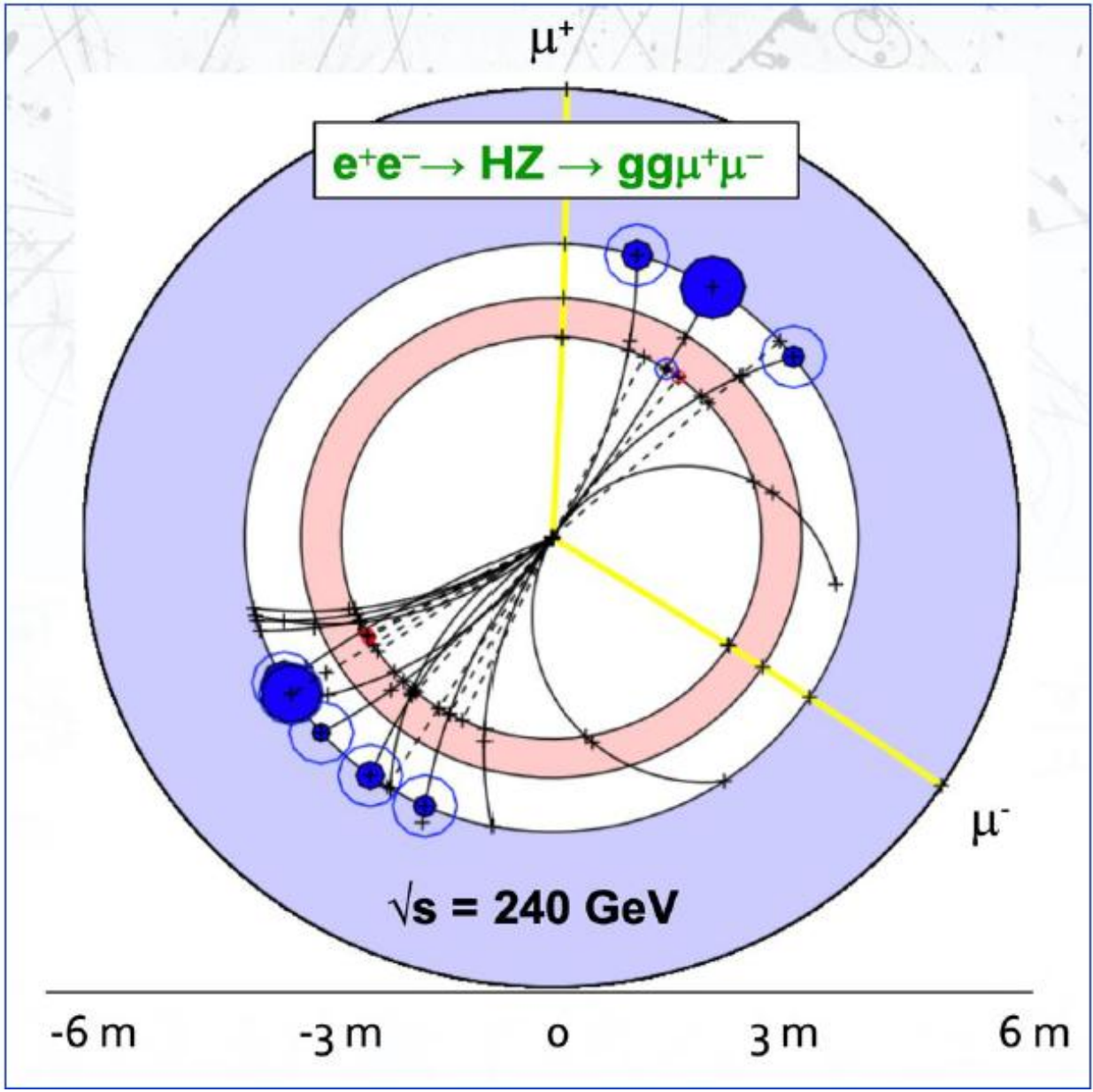
  → Solenoid

  → Toroid
- Calorimeter
  - Measure energy for EM and Hadron particles
    - Particle by particle / Jet energy
  - Fine segment for particle flow

  → Crystal / novel liquid

  → fine segment sampling calorimeter

  → dual readout
- Muon detector



What kind of technology we need?

- Vertex
  - Precise position resolution
  - Low material, **Low power**
  - (Timing resolution)

  → **Pixel detector** (strip detector)
- Tracking
  - Position resolution
  - Large volume coverage
  - (Particle Identification → dE/dx, TOF)

  → Strip detector

  → Gas detector (small cell / TPC)
- Magnet
  - Bend charged particles (2~3 Tesla)
  - **Low material**

  → Solenoid

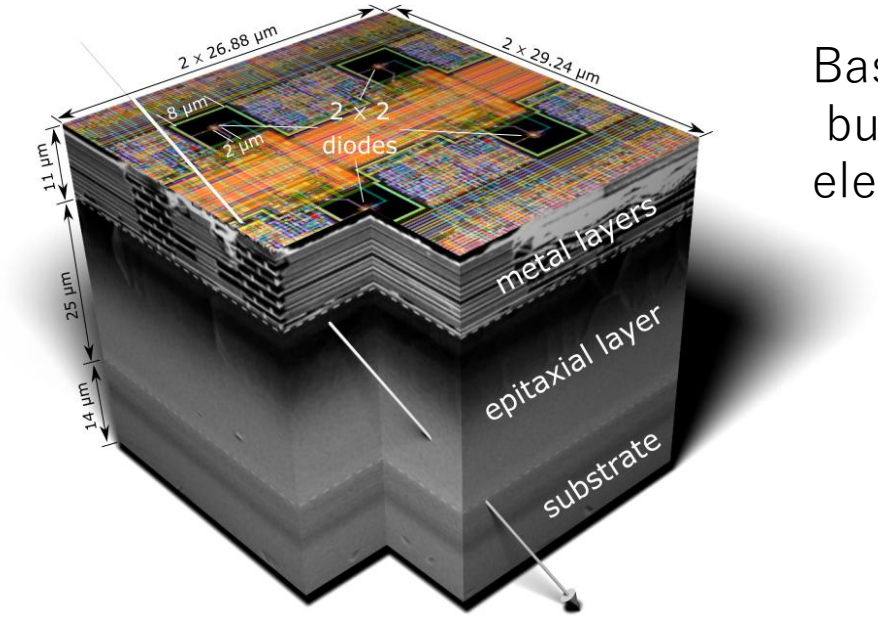
  → Toroid
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  - Measure energy for EM and Hadron particles
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  - Fine segment for particle flow

  → Crystal / novel liquid

  → fine segment sampling calorimeter

  → dual readout
- Muon detector

Monolithic Active Pixel Sensor



Based on CMOS process, building up readout electronics on the sensor

Application:
Vertex, Tracking, Calorimeter, Muon detector

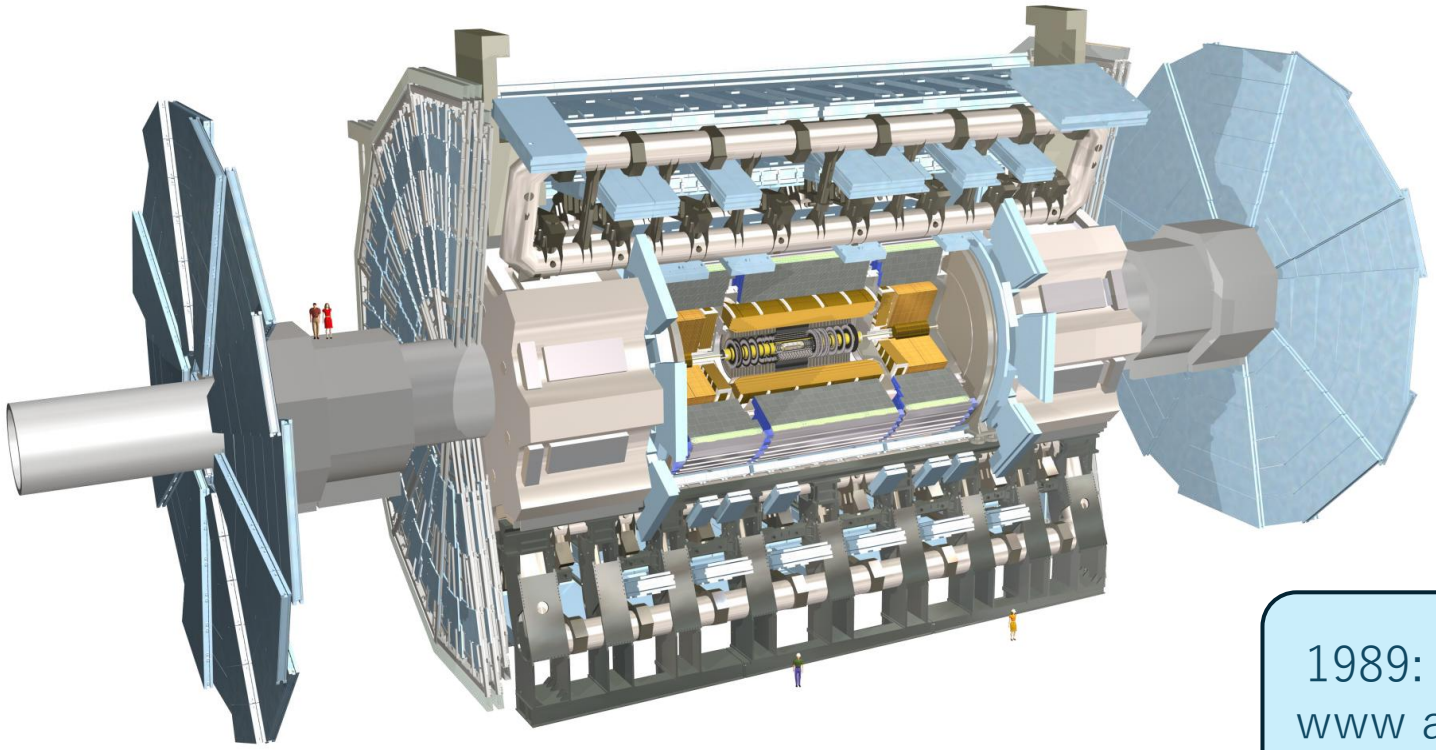
Super conducting wire for detector solenoid



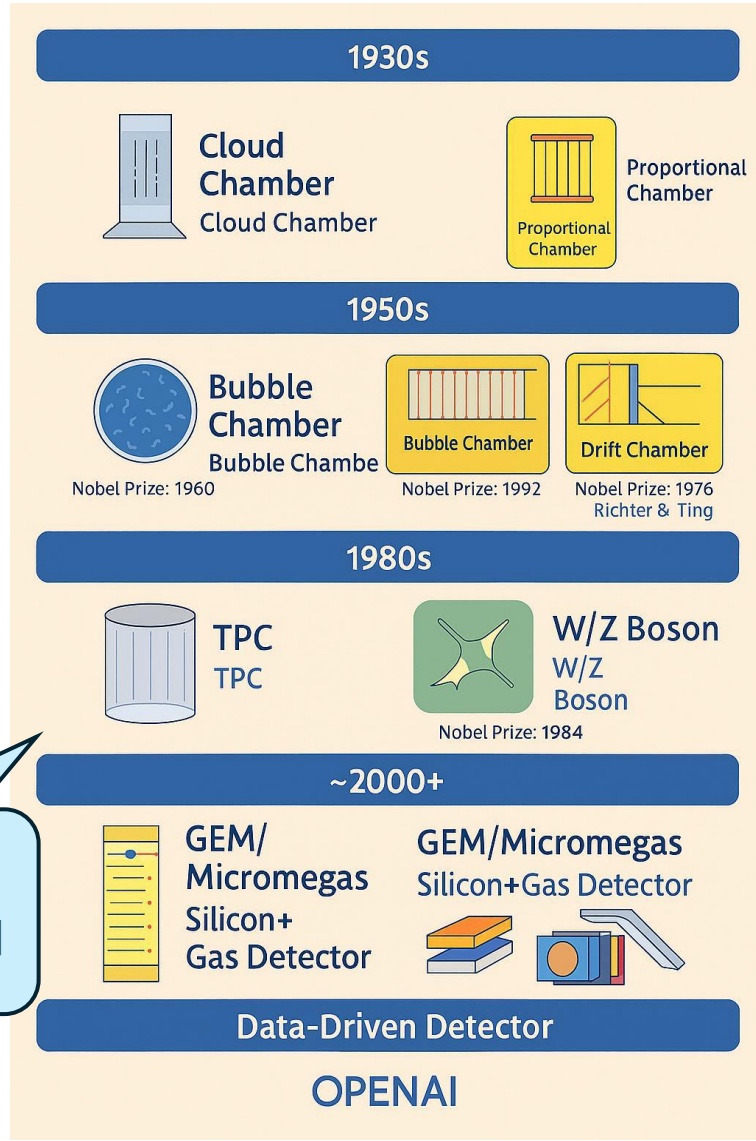
We need low material magnet.
- Lost engineering technology.
  Re-develop for future collider

No solution? Build it.

ATLAS Detector: 25 m x 45 m, 7000 tons.



1989: birth of www at CERN

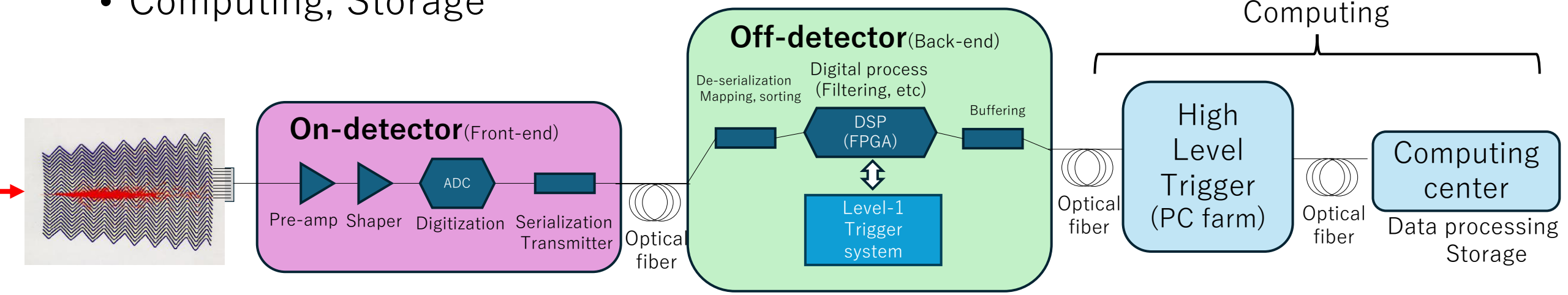


New technology, new idea explore physics and open new era!

All detector need electronics!

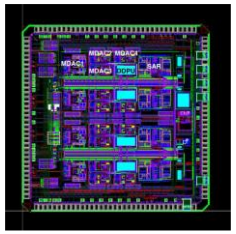
- Basics: Any detector needs electronics to readout!
  - Simplest: probe with oscilloscope?
    - > 20 M yen… multi-channel, upto 25 GHz bandwidth. etc…
    - Various analysis can be done on several channels.
- Nominal collider experiment has >10M channels
  - Custom made, specialized electronics are necessary.
  - Analog: Amplification, Transformation, Digitization
  - Digital: Processing, Triggering, Data transfer
  - Computing, Storage



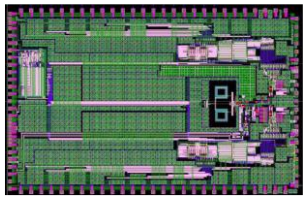


Electronics: recent trend

- ASIC development
  - Application Specific Integrated Circuit
    - Design by ourselves for specific use.
      - Analog amplifier
      - ADC
      - Constant Fraction discriminator
      - Serializer
      - Transmitter
      - Trigger specific



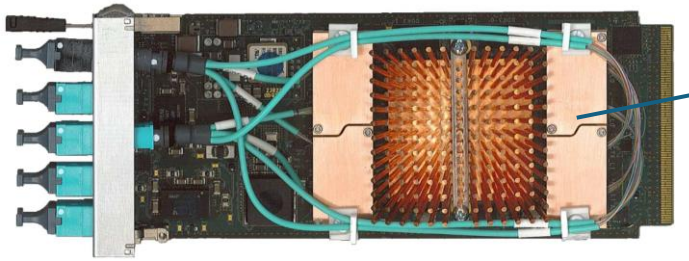
Navis-15 ADC :3.6 x 3.6 mm, 72 pins QFN
130 nm CMOS



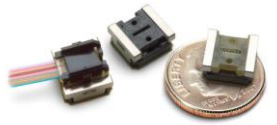
LOCx2: 6.036x3.68mm, 100 pins QFN
250 nm Si-on- Saphire

→ 65 nm CMOS
→ 28 nm CMOS

- High speed data transmission and Digital processing



Mezzanine card carry 96 fibers
High spec FPGA



Broadcom μPOD
11.2 Gpbs x 12 lane

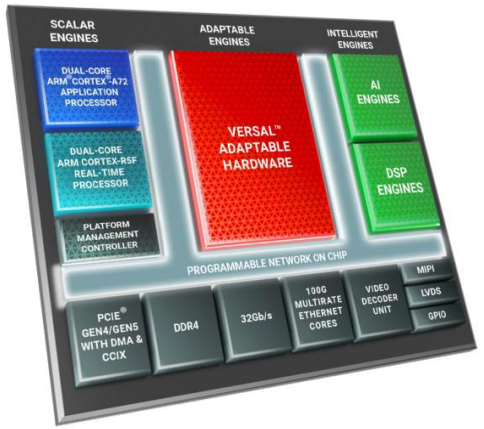


samtec

28 Gpbs
x 12 lane

Versal project

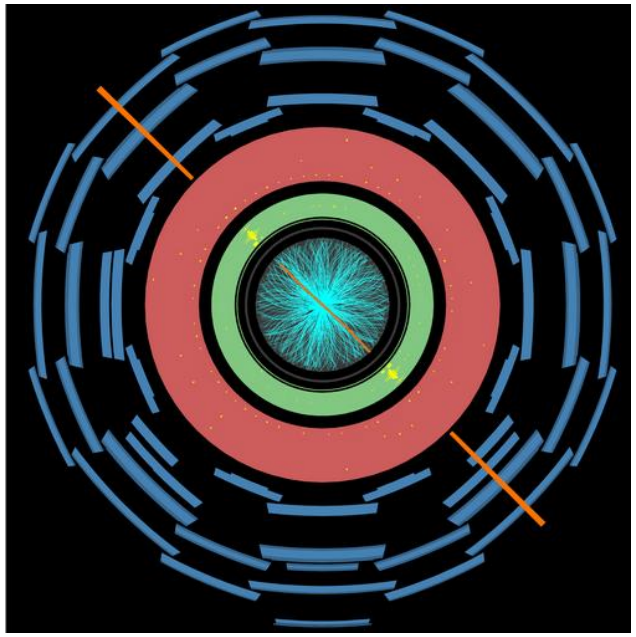
Xilinx Versal series FPGA

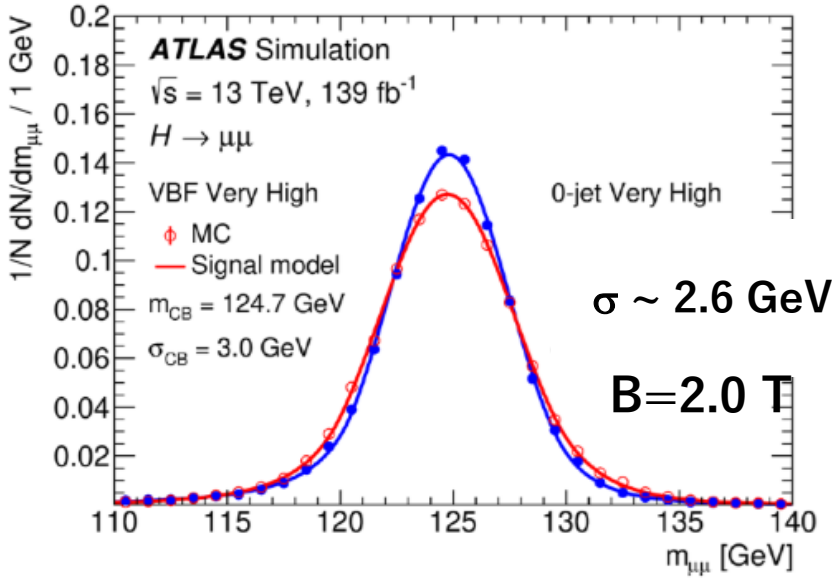


- ACAP SoC
- Computation acceleration engines
- High Bandwidth Memory (HBM)
- Larger number of cells
  + High transmission bandwidth
  (56 Gbps with PAM-4)

Firmware is designed based on HLS
High Level Synthesis → Deep Neural Net on FPGA

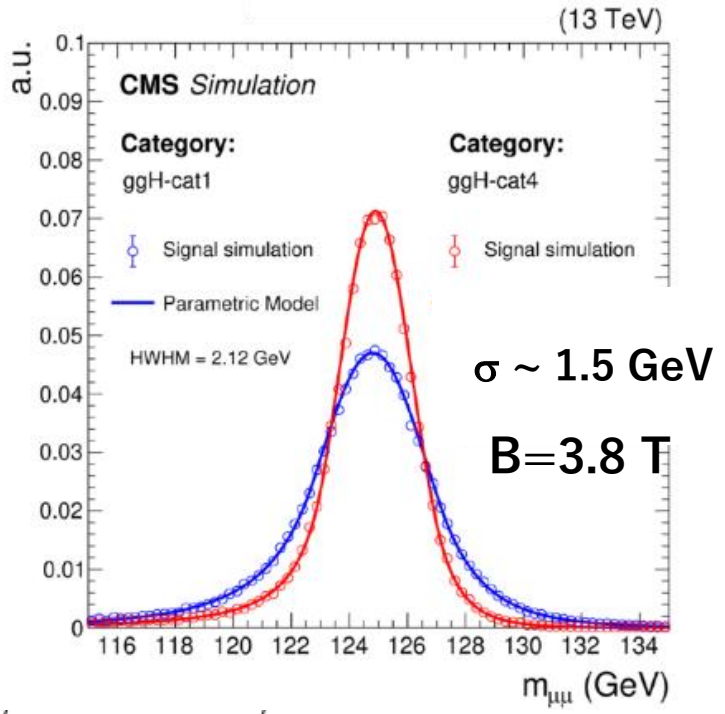
Solenoid magnet: Lesson learned on H→μμ





σ ~ 2.6 GeV

B=2.0 T



σ ~ 1.5 GeV

B=3.8 T

- Performance of objects reconstruction are almost same between ATLAS and CMS, except muon.
- Due to magnetic field.

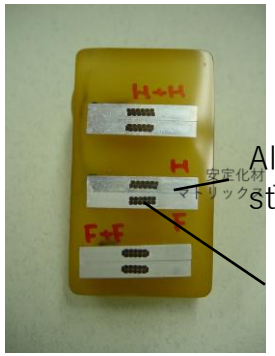
$$\left(\frac{\sigma(p_T)}{p_T}\right)^{meas} = \frac{\sigma(s)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x)\cdot 8p_T}{0.3BL^2}$$

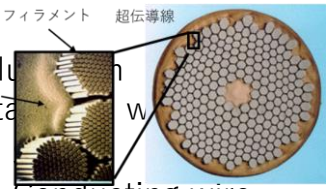
L ~ 1 m for both ATLAS and CMS

ITDC's top down R&D project

Al stabilized super-conducting wire

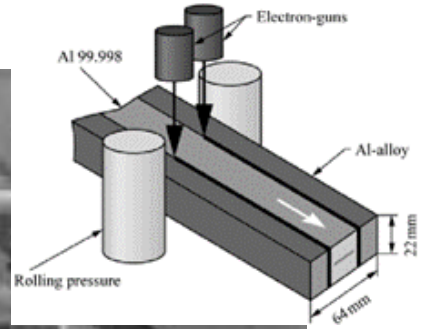




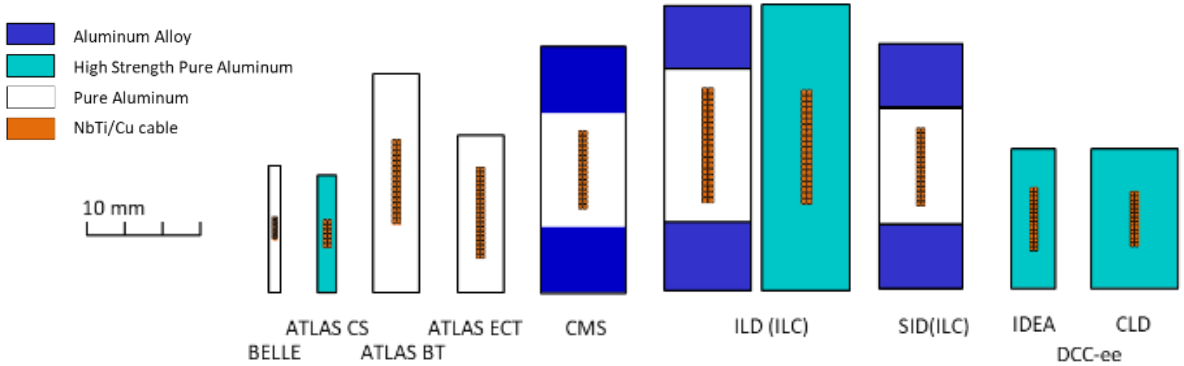


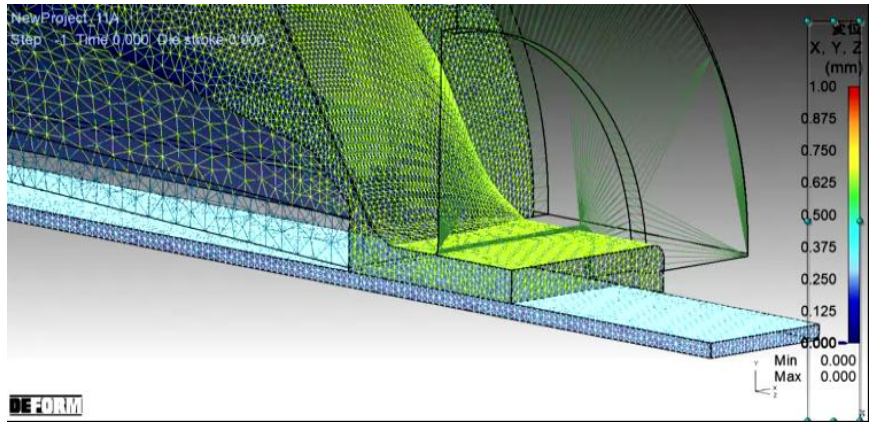






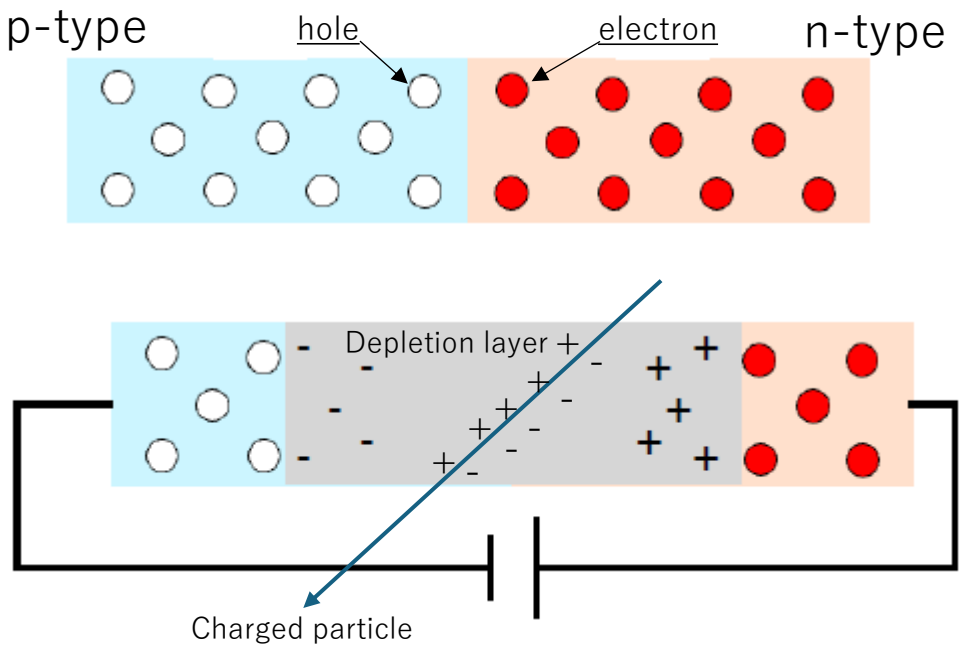
- We can not make low-material solenoid magnet.
- Technology on Al stabilized super conducting wire is almost lost.
  - Technology revival effort has started (CERN, KEK with company)
  - A company in China also started
- New wire material for solenoid
  - HTS for solenoid would be applicable
  - Low material wire, MgB_2(2.2 g/cm^3) in stead of NbTi(6.6 g/cm^3)



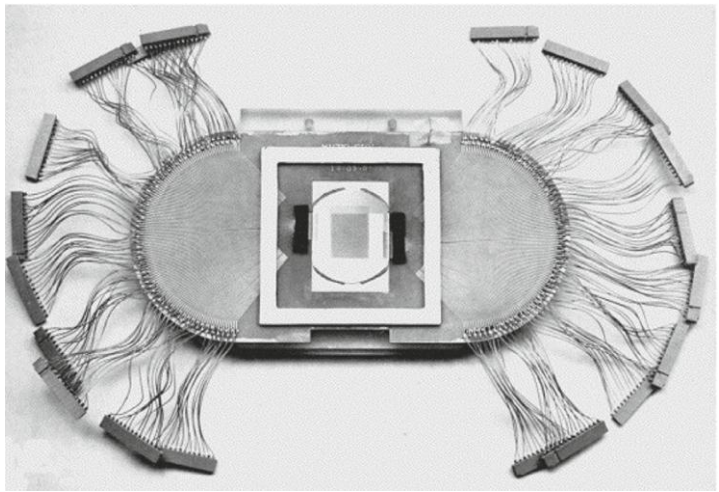


Semiconductor sensor

- Basics: Collect charges of electron-hole pair from ionization
  - Apply bias voltage on p-n junction, collect charge of electron-hole pair.
    - Strip sensor: strip readout. (strip pitch 75 μm)



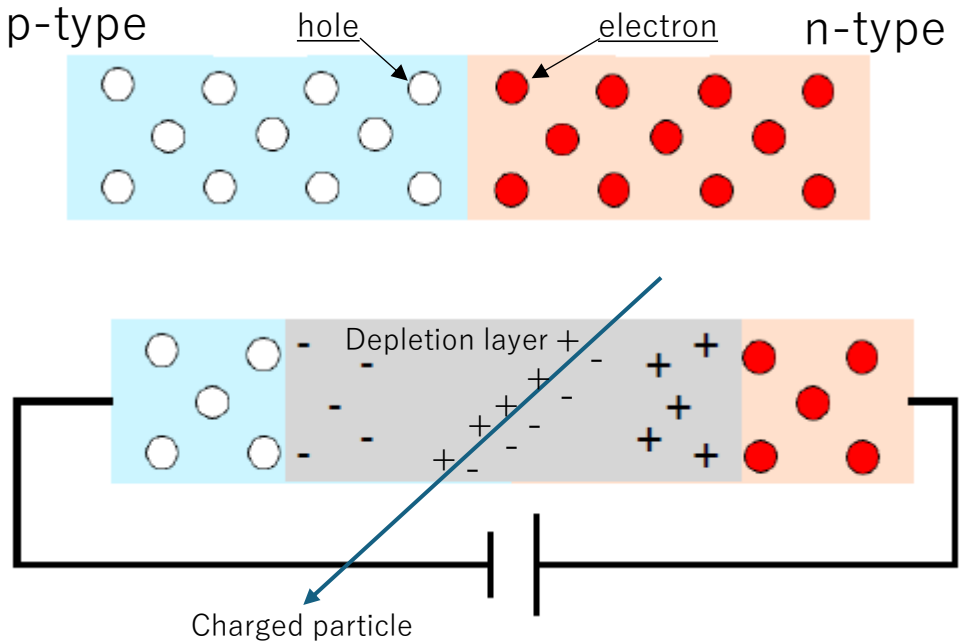
Energy deposited according to Bethe-Bloch formula.
Expected signal:
1600 electrons
noise: 70 electrons.
→ large S/N.



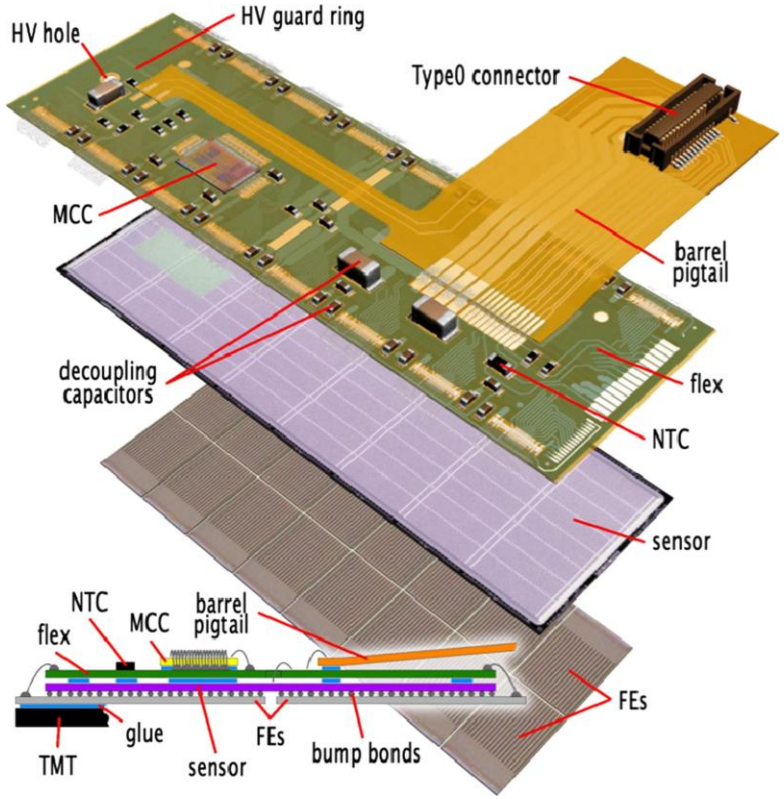
First use of Silicon Strip sensor:
NA11 (1981)

Semiconductor sensor

- Basics: Collect charges of electron-hole pair from ionization
  - Apply bias voltage on p-n junction, collect charge of electron-hole pair.
    - Strip sensor: strip readout. (strip pitch 75 μm)
    - Pixel sensor: pixel readout. (50 μm x 50 μm)
      needs bump-bonding to readout with FE electronics



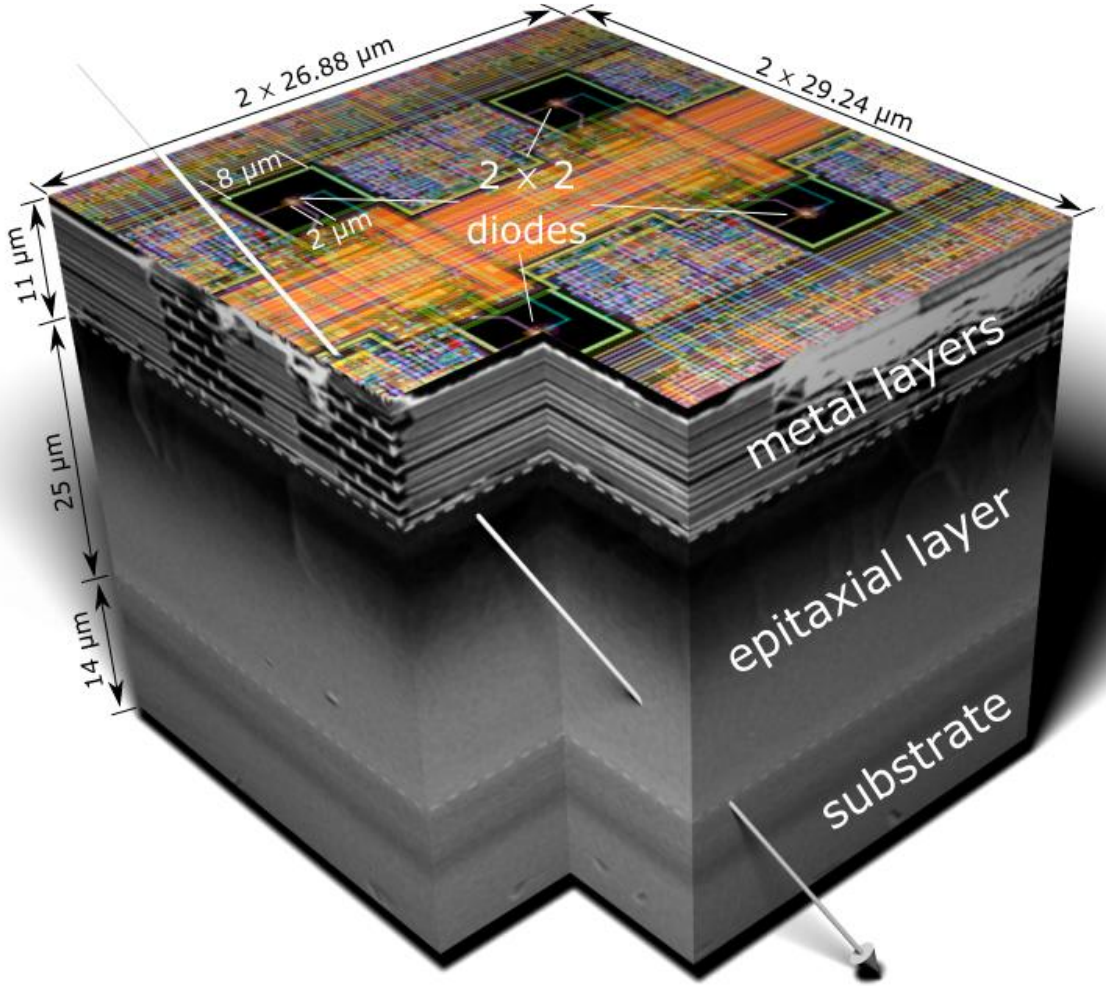
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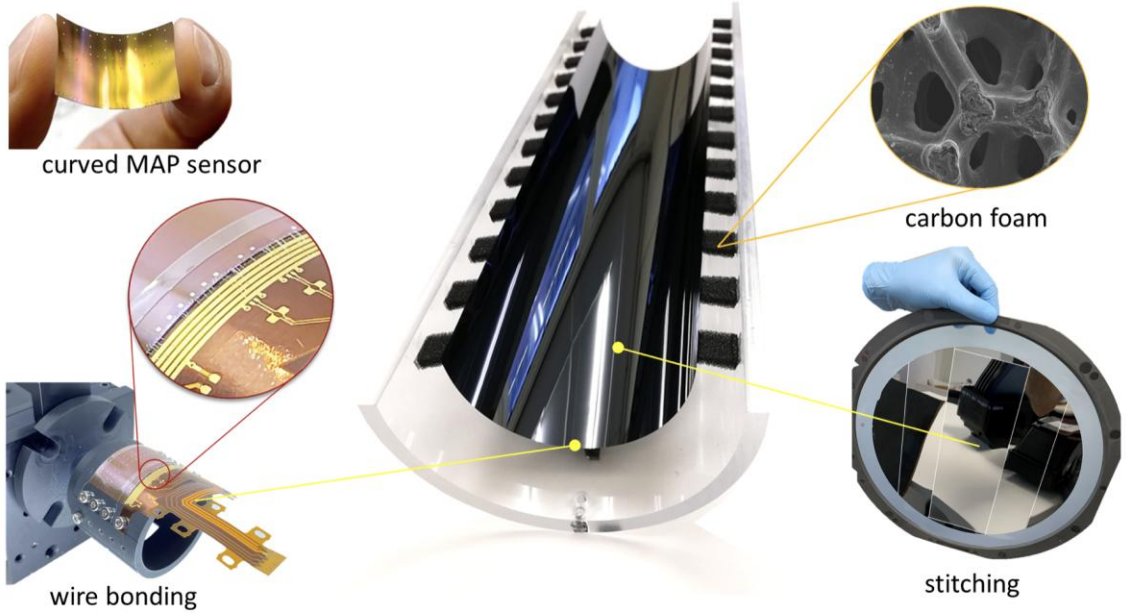


ATLAS pixel module
50 x 400 μm^2 n-in-n planar pixel
16 FE chips.

Monolithic Active Pixel Sensor Development

Core of the ultimate detector





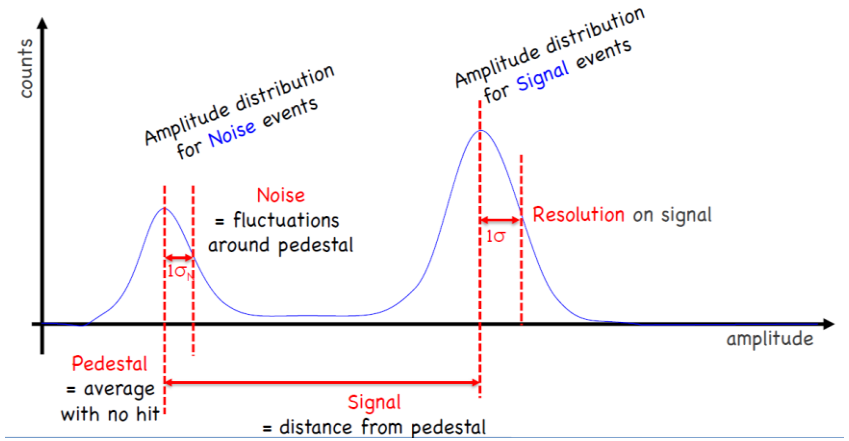
ultralight-air-cooled-mechanics-alice-its3

- Ultra thin : low material
- Air-cooled : low power consumption

Think about thickness for Vertex detector

Signal noise ratio

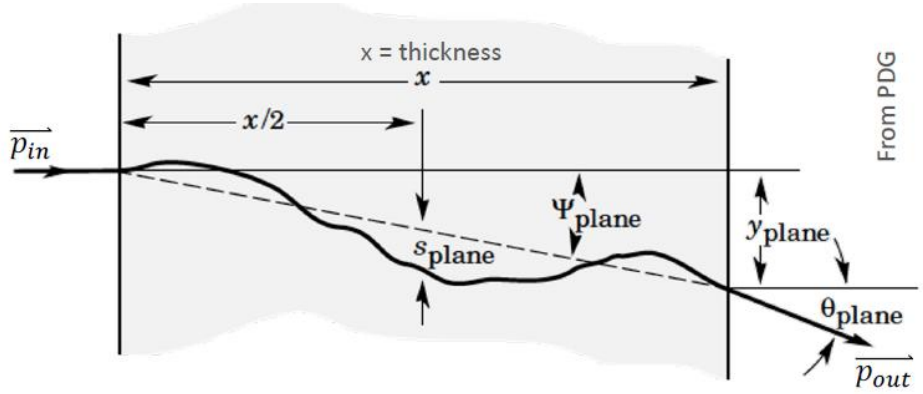
$$SNR = \frac{Signal}{Noise\ (=\sigma_N)}$$



Signal: # of electron-hole pair
→ ~ thickness of depleted region
thicker sensor has large signal
Noise: proportional to the capacitance
→ if Capacitance (noise) is small,
sensor can be thin.

Multiple scattering

$$\sigma_\theta = \frac{13.6\ (\mathrm{MeV/c})}{\beta p} \cdot z \cdot \sqrt{\frac{\mathrm{thickness}}{X_0}} \cdot \left[1 + 0.038\ \ln\left(\frac{\mathrm{thickness}}{X_0}\right)\right]$$

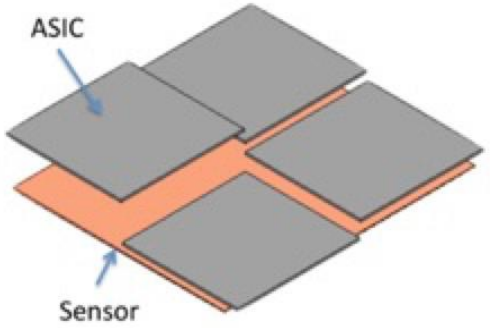


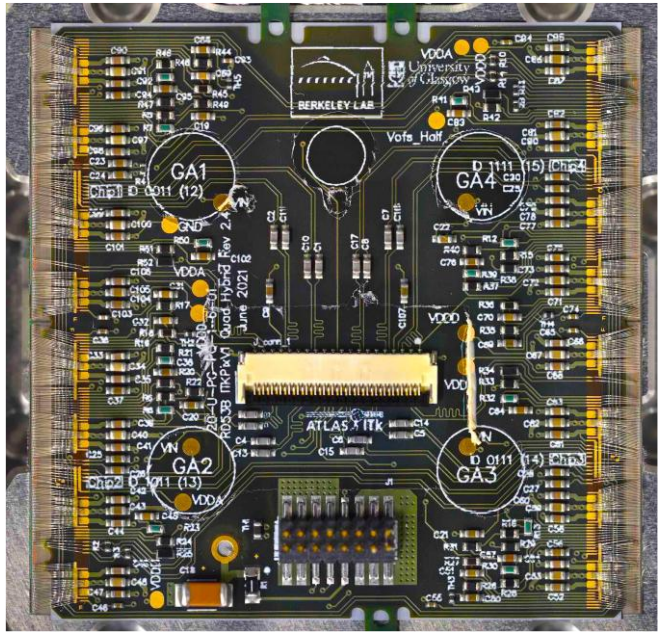
→ Thinner is better!

- How thin sensor can be established?
  - Not only sensor
  - Need to think about readout
    - Need to think about cooling
      → power consumption

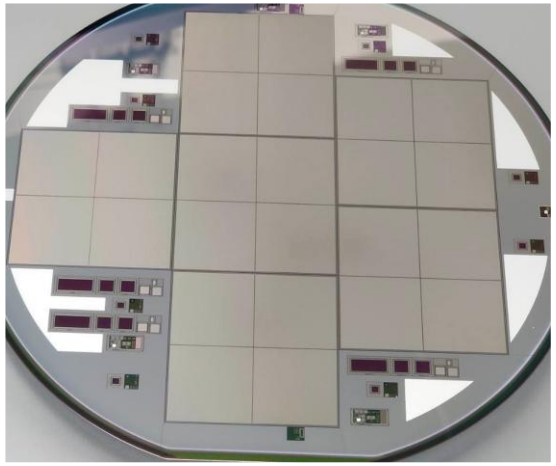
Comparison with the hybrid pixel sensor

- ATLAS ITK Planar n-in-p sensor
  - 40 mm x 40 mm sensor
  - Pixel size: 50 μm x 50 μm
  - 4 ASICs are bump bonded per sensor
- This design was established for high radiation tolerance at HL-LHC
  - Operatable under 10^16 neq /cm^2





	ATLAS ITK Planar n-in-p sensor	ALICE ITS3 MOSAIX (MAPS)
Sensor thickness	150 μm	50 μm
signal per MIP	1500 e-	600 e-
Noise level	100 e-	15~18 e-
Threshold	600 e-	140~200 e-
Material budget	0.89% X_0	0.05% X_0
Power consumption	100 mW / cm^2	<40 mW / cm^2
Pixel capacitance	~ 50 fC	< 5 fC



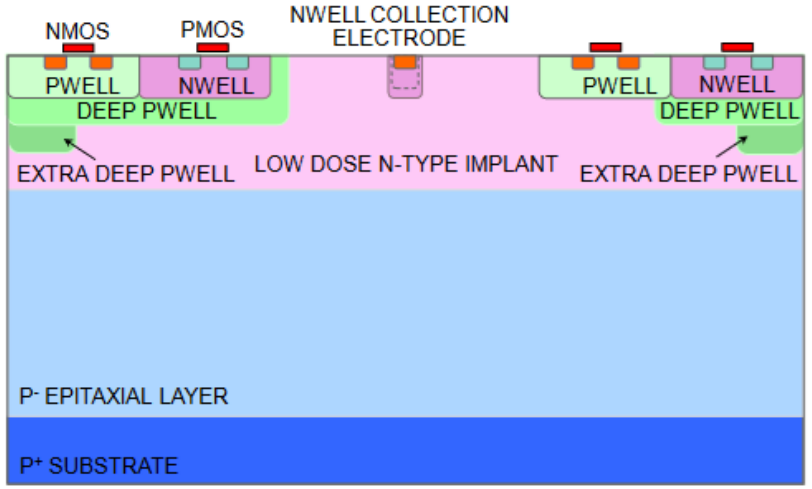
Monolithic Active Pixel Sensor Development

Core of the ultimate detector

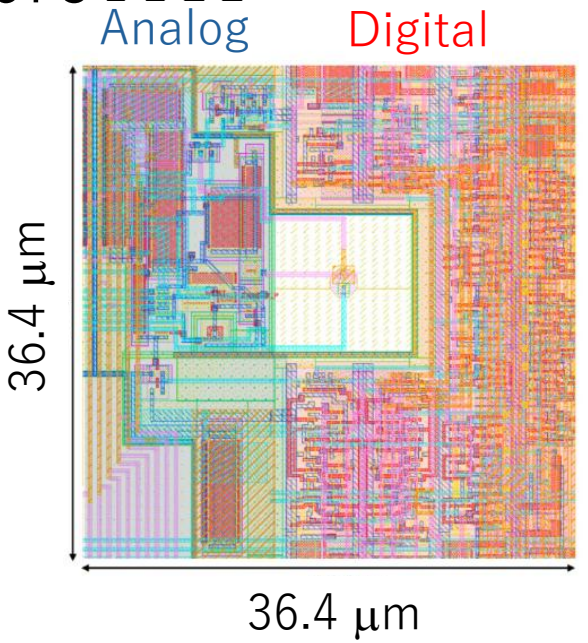
ITDC's top down R&D project

Analog and digital circuit on a thin sensor by CMOS process

- Mono-structure
  - No bump-bond
  - Fine pitch
  - Low material
  - Easy mass production
  - Digital data processing
    - Data compression
    - Track reconstruction



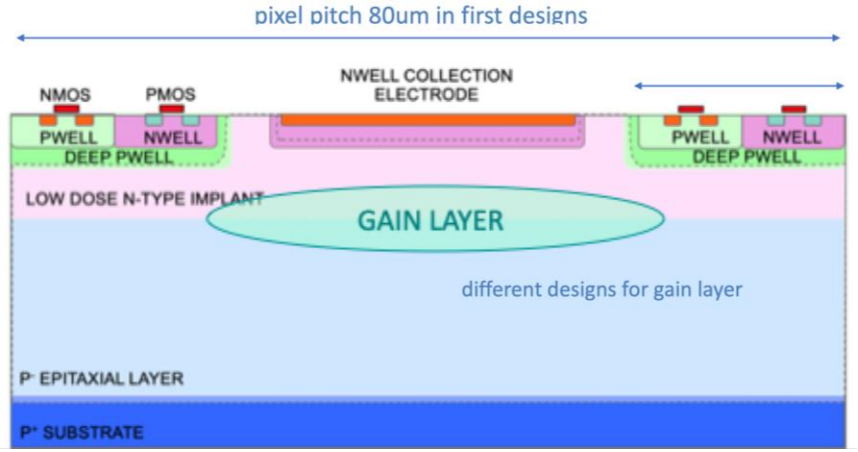
MALTA2, TJ180 nm, 512x512 pixels



- Development
  - Thinner(~ 50 μm), finer pixel (a few μm) and precision timing (a few ps)
    - Currently 180 nm to 65 nm for MAPS.
- This technology will be used everywhere.
  - Build R&D basement at KEK for next generation collider experiments.

Why MAPS is the sensor for the future exp?

- To achieve 3 μm hit position resolution
  - pixel size : 10~15 μm.
    Could we realize with strip? No.
    Could we realize with hybrid pixel sensor? No.
- MAPS can build up circuit on top of sensor.
  → capacitance with a few fC.
    → minimal amplifier with good S/N.
- What is ongoing development?
  - 65 nm process
  - Introduce amplification layer
    → Save analog circuit space, make pixel size smaller.
    also reduce power consumption

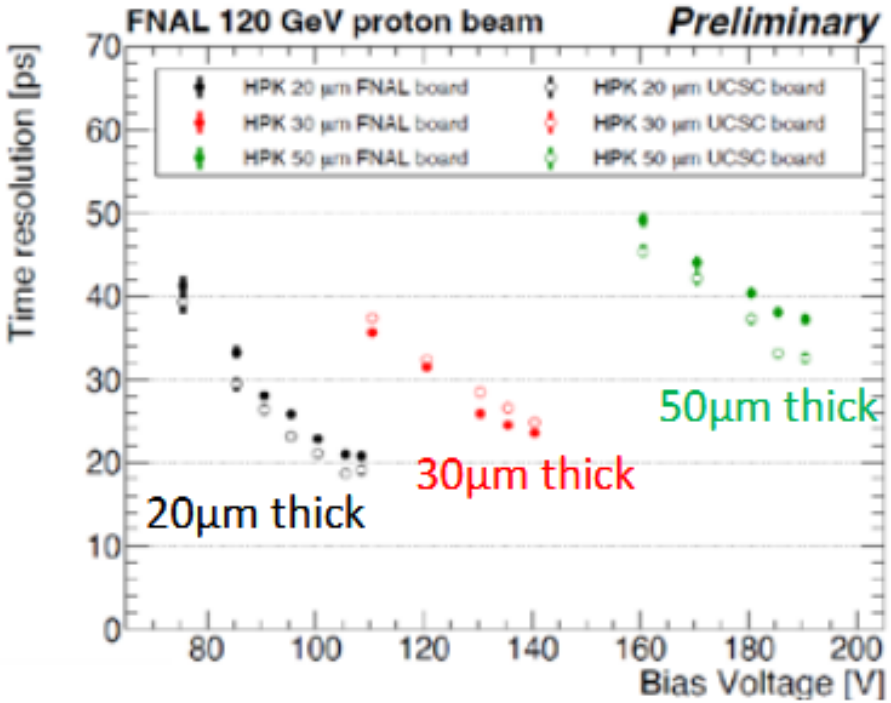


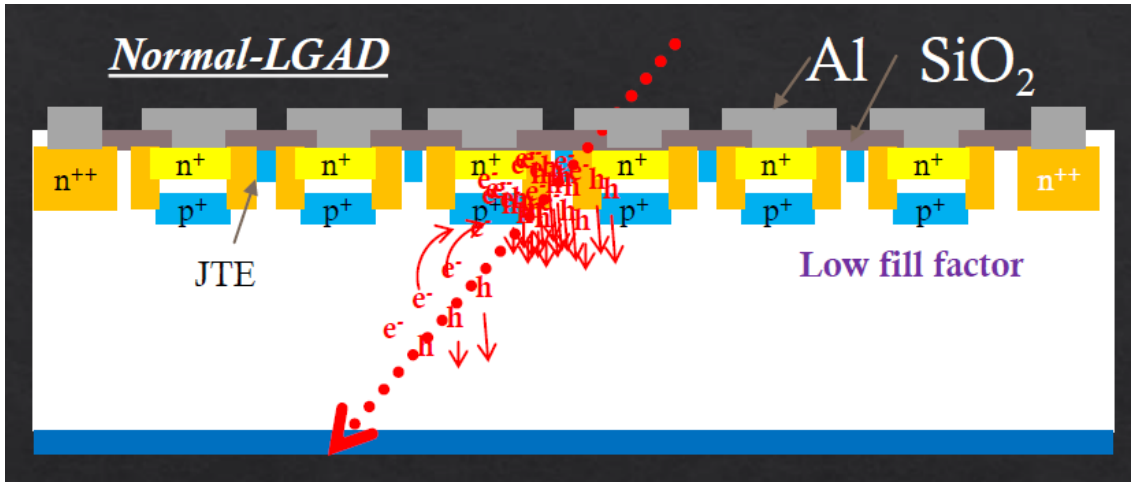
Semiconductor: Recent trend

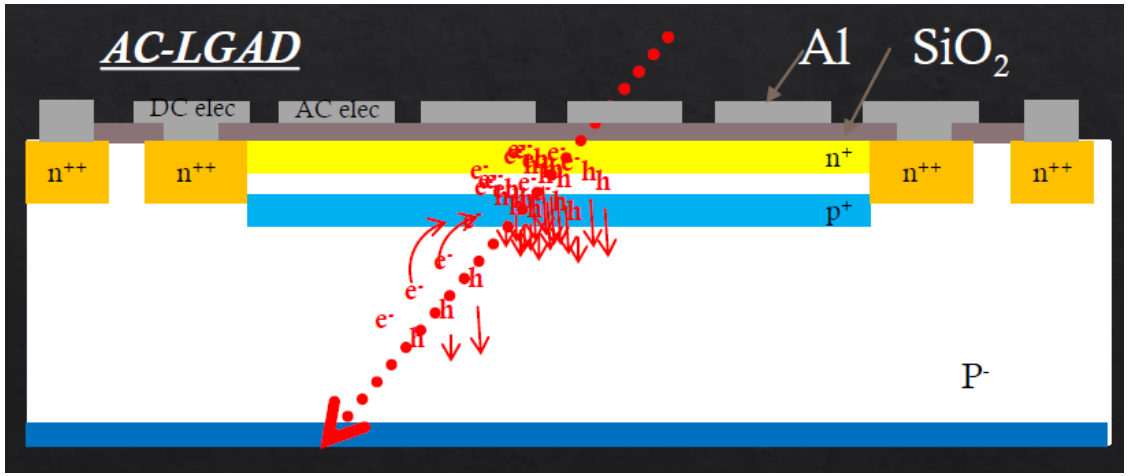
- LGAD: Low Gain Avalanche Diode
  - Grid of Avalanche diode
    - Gain factor: 10-20
  - Normal LGAD and AC-LGAD

K.Nakamura

Can be obtain 20~50 ps timing resolution.
The best performance is obtained AC-LGAD.



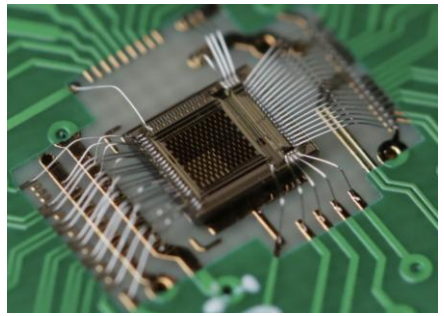




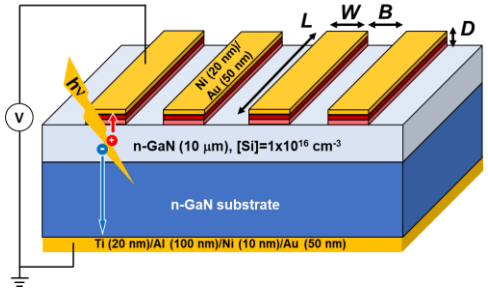
Semi-conductor sensors : Recent trend

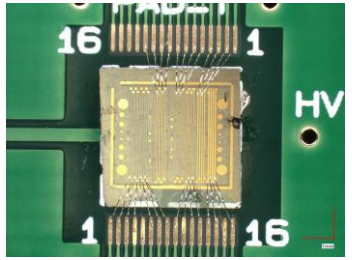
Si (Band Gap: 1.1 eV, Break Down field:~0.3 MV/cm)

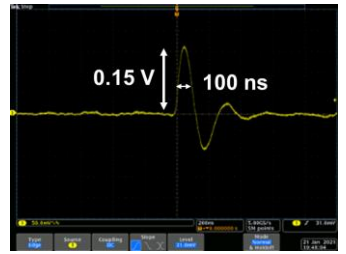
- SiGe (Band Gap: < 1 eV, Break Down field:~0.2 MV/cm)
  - Narrow band gap. Fast time resolution of 36 ps.
- SiC/GaN (BG~3.2 eV, BD ~ 3 MV/cm)
  - High breakdown electric field ~ x10 than Si.
    → high radiation tolerance
- New material
  - CIGS (BG: 1.0~1.7 eV, ~ 1 MV/cm)
  - Solar cell
  - Large annealing effect?

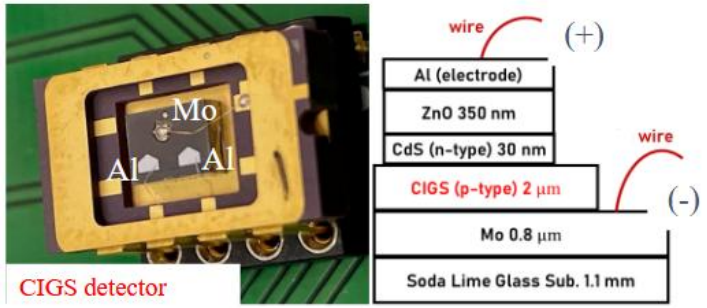


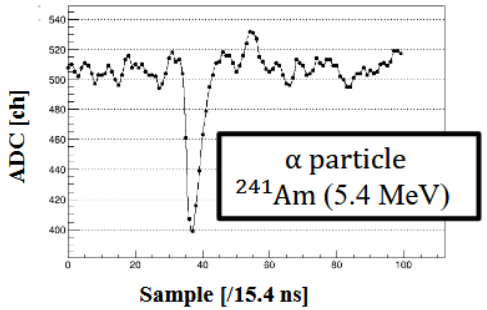
SiGe-BICMOS
JINST P02019

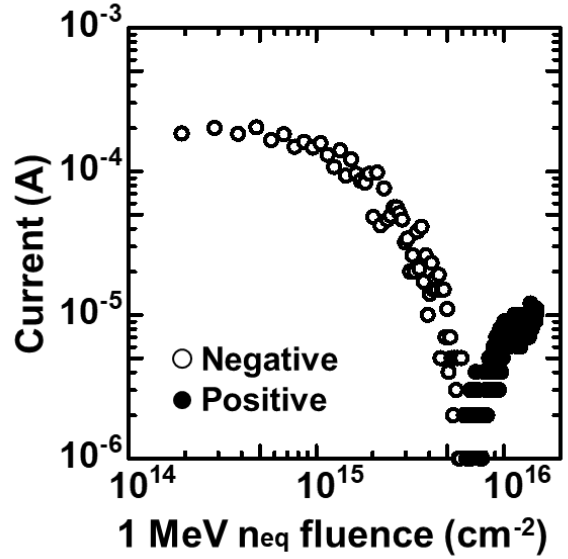












ITDC

測定器開発センター

Instrumentation Technology Development Center

https://itdc.kek.jp/

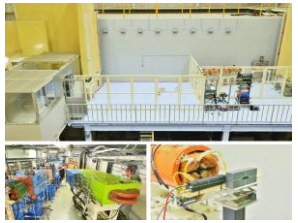
KEK IPNS ITDC (Instrumentation Technology Development Center)

ITDC

Inter-University research

Enhancing inter-Univ research function

- ITDC test beamline
- Efficient and fast development
  - Large scale clean room
  - Helium re-collection system

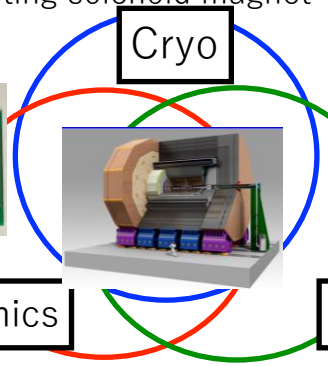


Cutting Edge Technology Development

Promotion of next-gen cutting edge tech Development

- Common / Core technology for next-gen experiment
  Bottom-up Detector R&D platforms
  Top-down R&D by ITDC initiative
  - Monolithic Active Pixel Sensor
  - Cryogenics related technology,
    super conducting solenoid magnet







ITDC Platform

- Photon sensor + Scintillator



- Semi-conductor sensor



- Gas & Active medium



- **Collider Electronics forum**



- Low tem/ Q-sensor
- .....

J-HEP community

In IPNS

- Tsukuba campus
- Tokai campus

In KEK

- Accelerator div.
- Applied Reach div.
- Inst. Material Science
- QUP

Researcher

- University
- Hecforum
- Nuclear Phys. Forum
- Cosmic ray Physics

Industry-academia

- Condensed matter
- Medical and life
- Engineering
- Cryo, new material
- Accelerator phys

Sensor R&D platform

https://itdc.kek.jp/ITDCplatform

Joint R&D

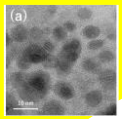
Facility use
Workshop, Training
Exchange know-how
Seminar

PI. A: Photon sensor, Scintillator

Koshimizu (Shizuoka), Nishida (KEK) Nanjo(阪大)

Photon sensor, Scintillator, Quantum dot

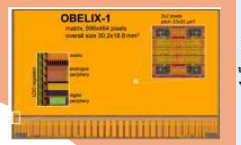


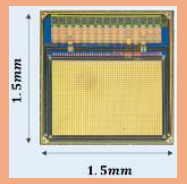



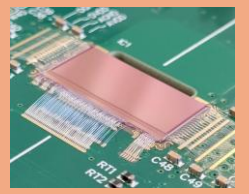
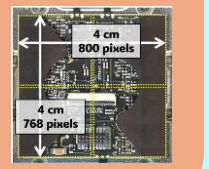
PI. B: Semi-conductor sensor

Hirose(Waseda), Togawa(KEK)

Sensor R&D, Assembling, test



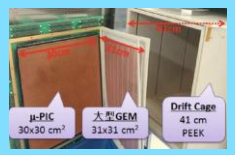


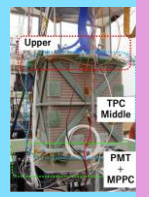



Platform C: Gas, active TPC

Kazama (Nagoya), Sakashita (KEK/Ts

Micro Pattern Sensor, Ar/Xe T

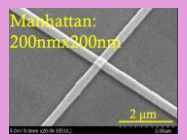


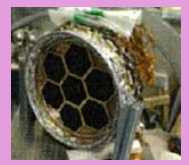
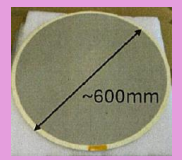



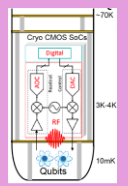
Platform D: Cryo Q-sensing

Ishidoshiro(Tohoku), Hasegawa (KEK)

TES, KID, Qubit, Cryo technology



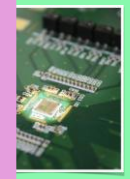





Collider Electronics Forum

Nagano(KEK), Horii(Nagoya),
Yamada(KEK), Honda(KEK)

/GPU/CPU, Versal AI, Fast link



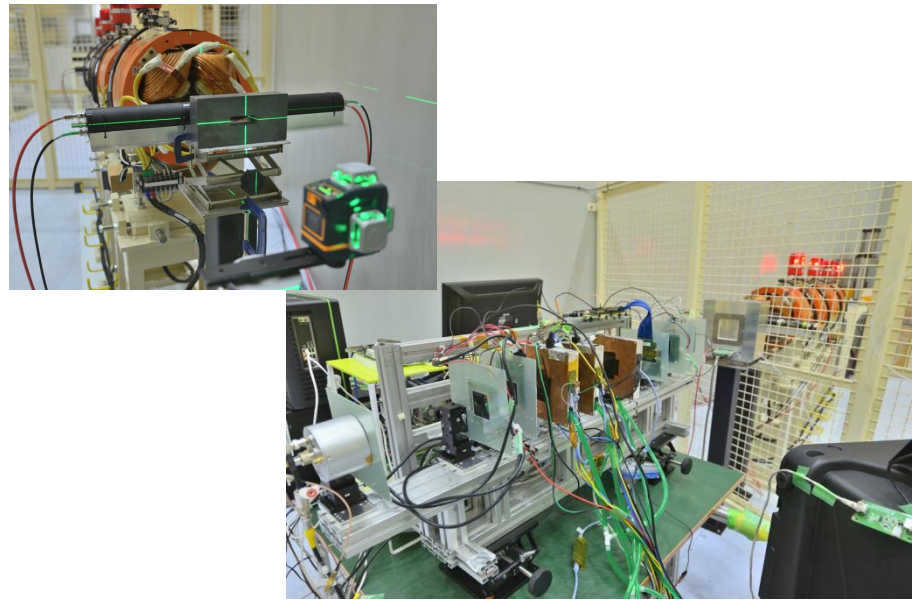


Test beam at KEK

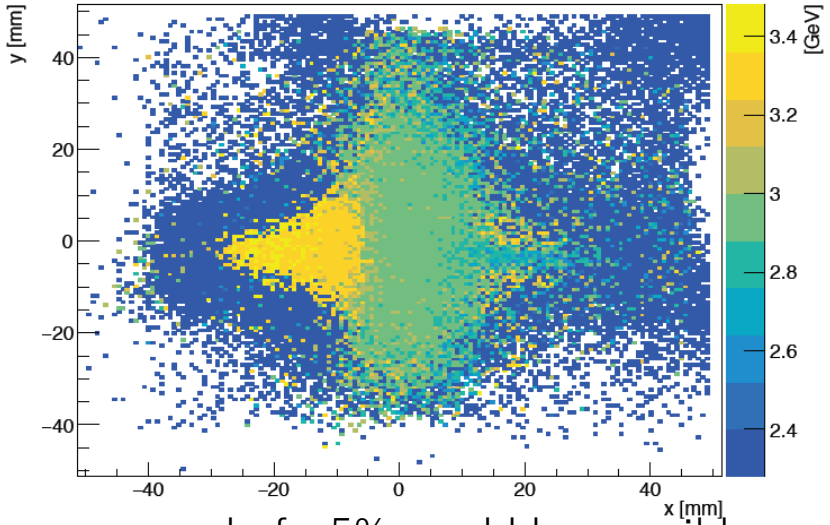
https://itdc.kek.jp/en/testBeamLine/index.html
https://www2.kek.jp/uskek/eng/apply/ar_tbl_eng.html

ITDC project

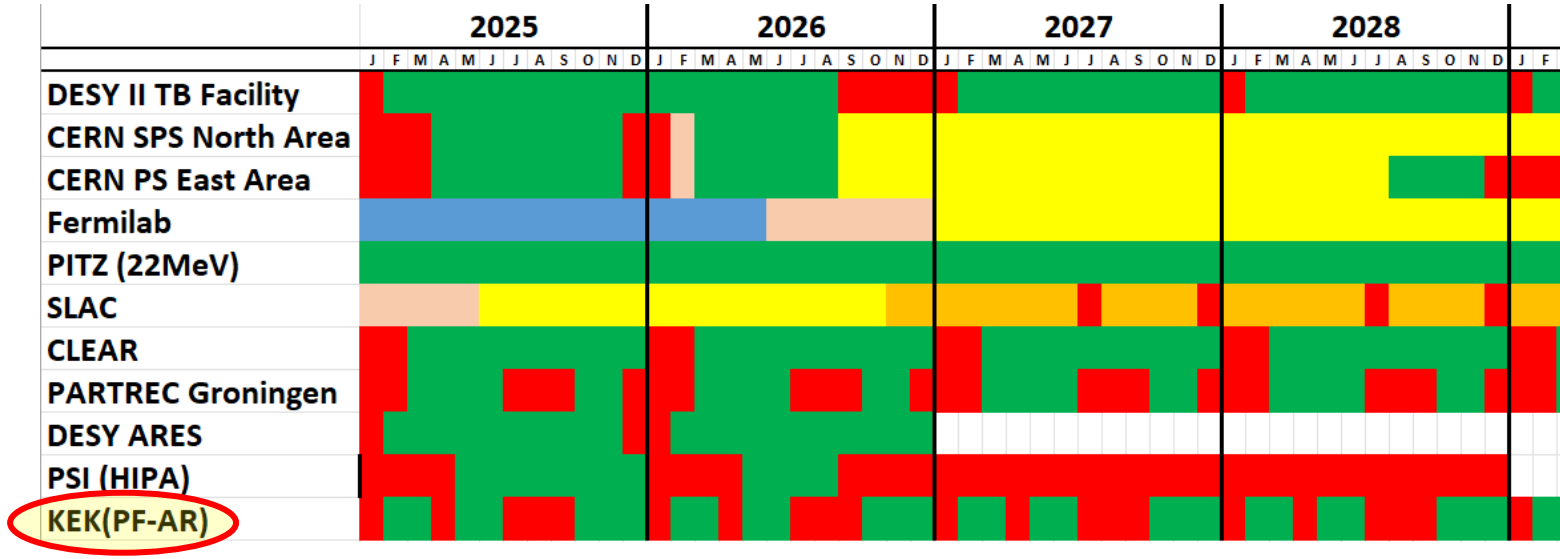
- Electron beam for instrumentation evaluation.
  - 5.5 months / year: May-June, Oct-Dec, Feb-Mar
- Momentum: 0.1 GeV to 5.8 GeV
- 3 ~5 kHz in 2 cm^2 . ~500 Hz in 8 mm x 8 mm
- Investigate a hadron test beam line at J-PARC.



Relation of position and energy



Energy spread of ~5% would be possible.



Summary

- New technology, new idea explore new physics and world.
- Identify needs and requirements, and build up detector design
- Towards future collider project:
  - Monolithic Active Pixel Sensor
    - Applicable not only vertex detector. Can be used everywhere.
    - Applicable also non-collider experiment.
  - Super conducting wire for detector solenoid magnet
- ITDC is open for all of you.
  - Joining MAPS development is very welcome.
  - Evaluate your detector with test beam at KEK.
  - Detector R&D platform

    Shared equipment for detector R&D platform

Reference

- MAPS Academy: Summer school for MAPS

  Very nice lectures related to MAPS.

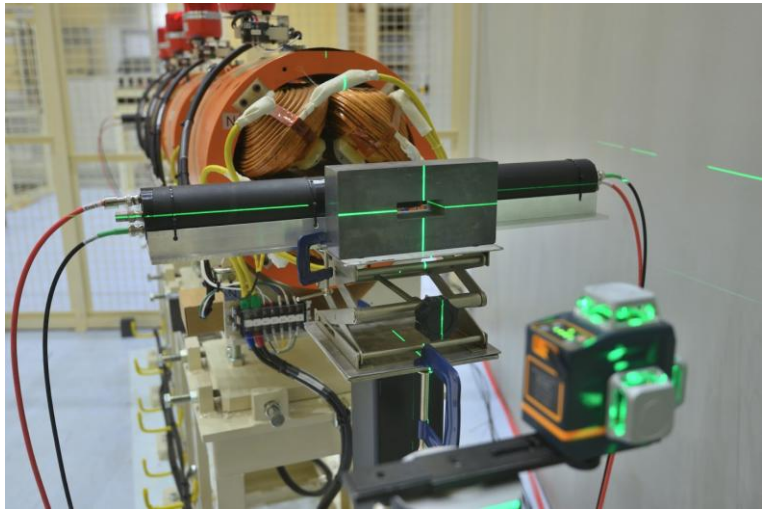
  - 2025: KEK : https://kds.kek.jp/event/56480/
  - 2026: SLAC : https://indico.slac.stanford.edu/event/10416/timetable/

Extra Materials

Electron test beam at KEK

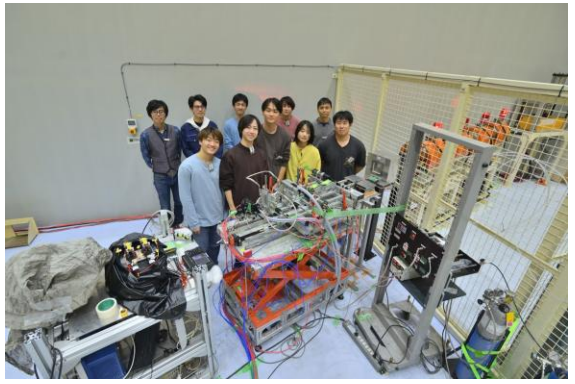
https://itdc.kek.jp/en/testBeamLine/index.html
https://www2.kek.jp/uskek/eng/apply/ar_tbl_eng.html

- ITDC testbeam line
  - Electron beam for instrumentation evaluation.
  - 0.1 GeV to 5.8 GeV
  - Up to 5 kHz in 2 cm^2
    - 5.5 months / year
      - May-June, Oct-Dec, Feb-Mar

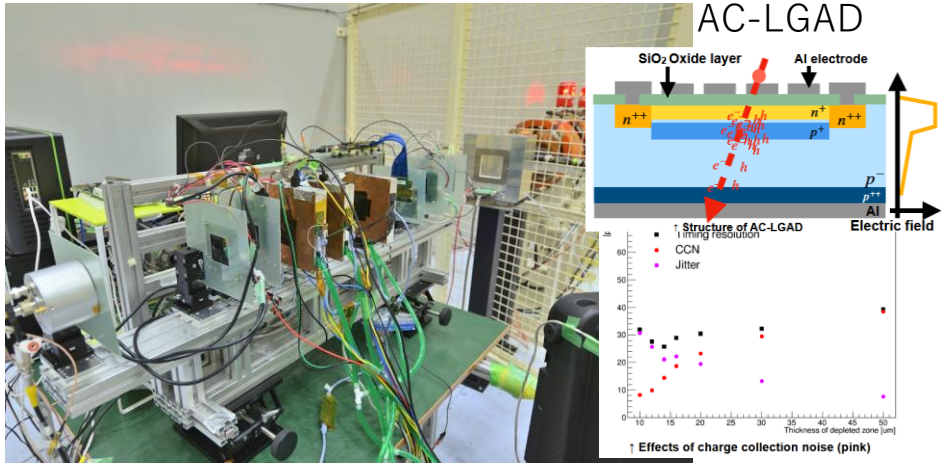


Why do they use test beam??

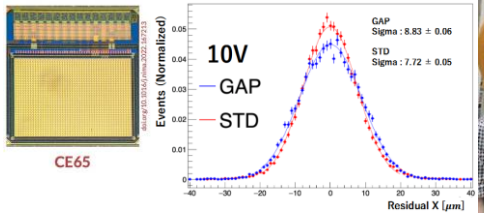




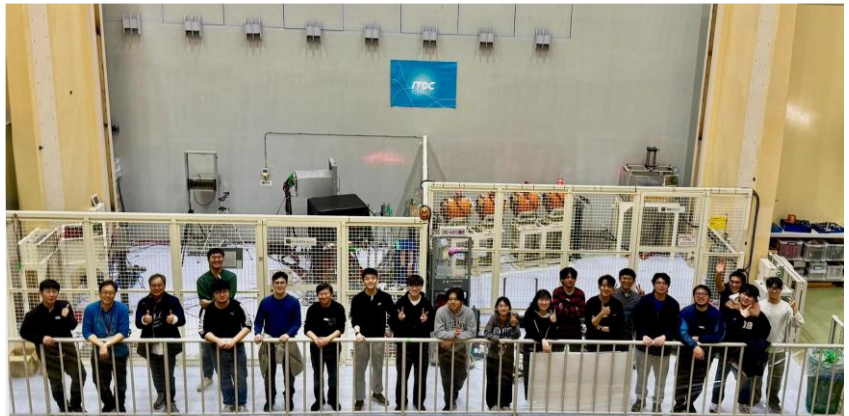
AC-LGAD



MAPS CE65







PI-D Low temp

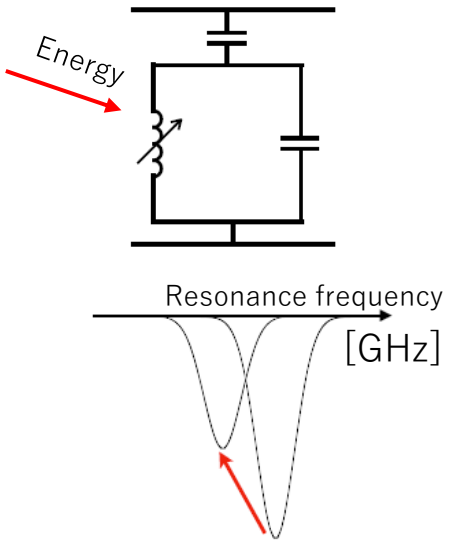
Axion search: DarQ T. Nitta (KEK-QUP)

Quantum sensor in a cavity

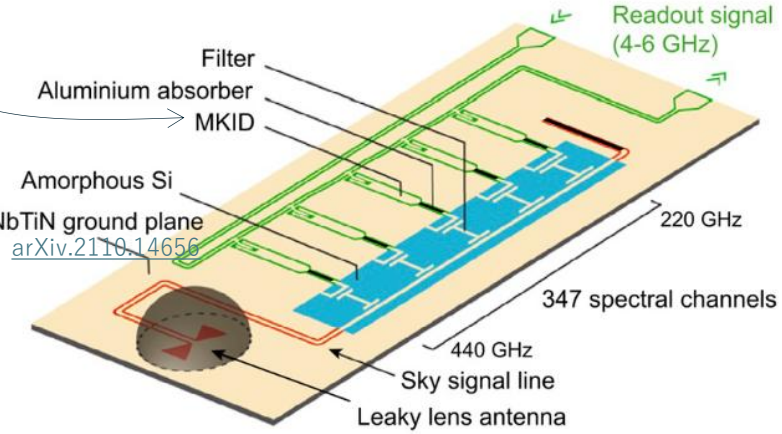
- Wave detection with resonance
  - Noise needs to be low as much as possible
  - T=~mK.

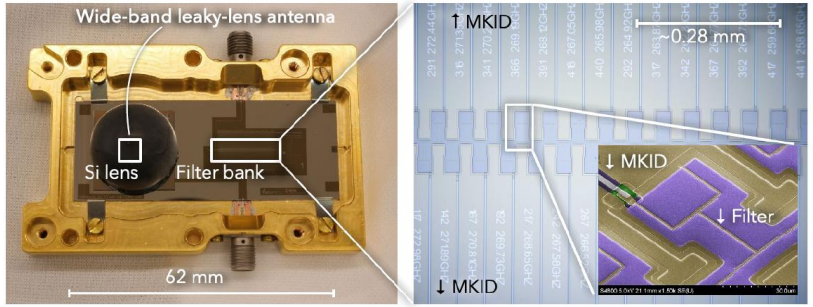
MKID: Microwave Kinetic Inductance Detector

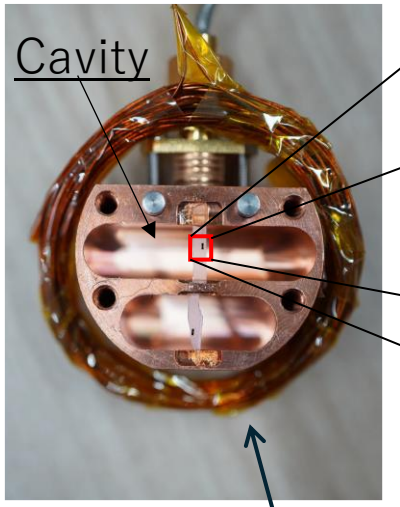
Injected energy can be measured as resonance frequency shift.

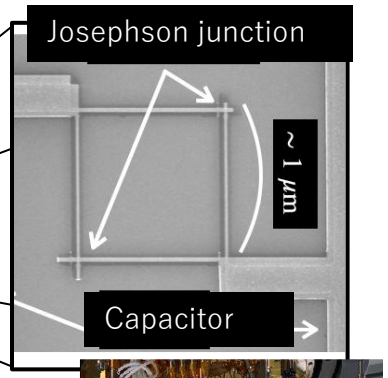


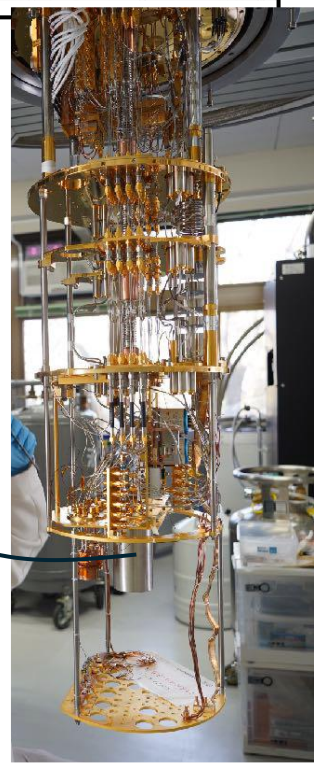
DESHIMA 2.0
the Ultra-wideband spectrometer
arXiv.2110.14656











Operate at 10-300 mK
→ Cryostat with dilution refrigerator

PI-A Photon and scintillator: Recent trend

From Slides from Prof. Koshimizu

Scintillator

- Build any shape w/ 3D printer

UV-curable resin

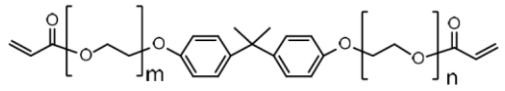
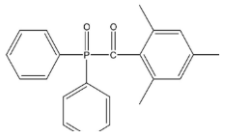
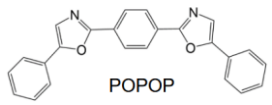
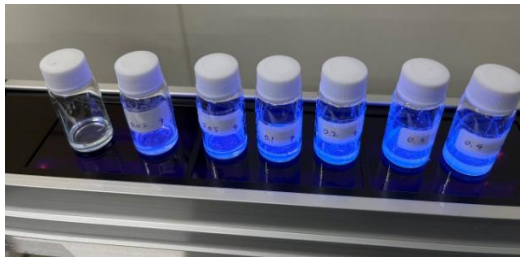


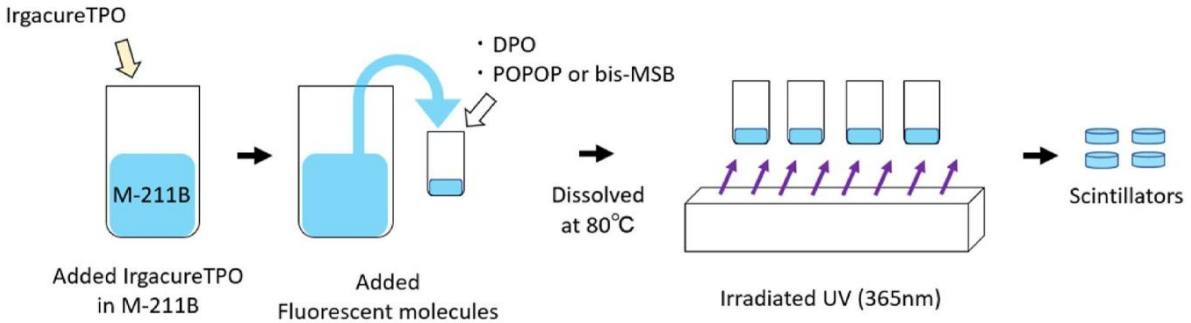
photo-initiator



fluorophore

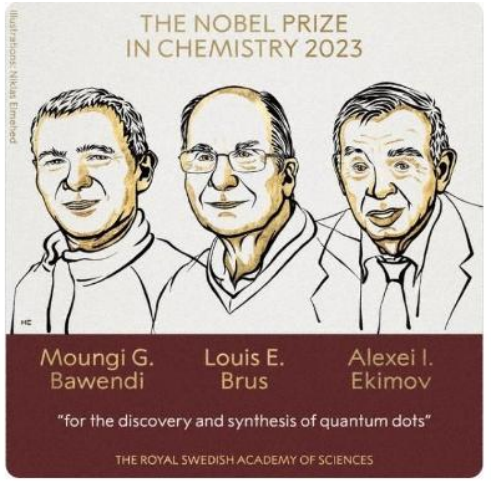






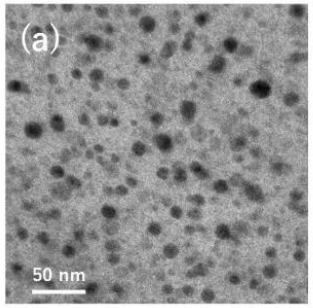
9100 photons / MeV has been achieved.

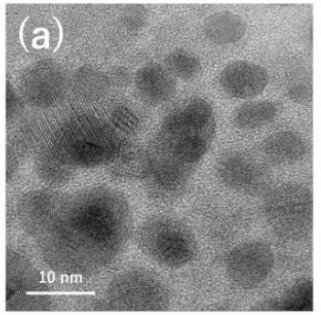
- Use Quantum dot for scintillator



https://filgen.jp/Quantum_Solutions/





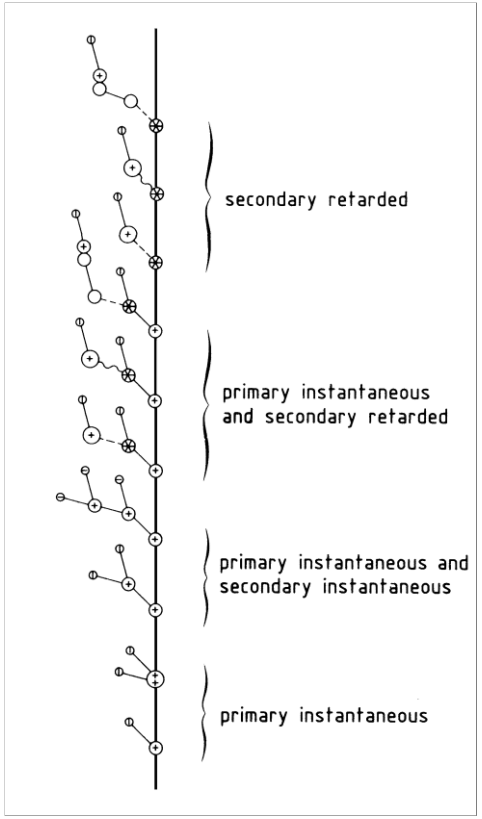


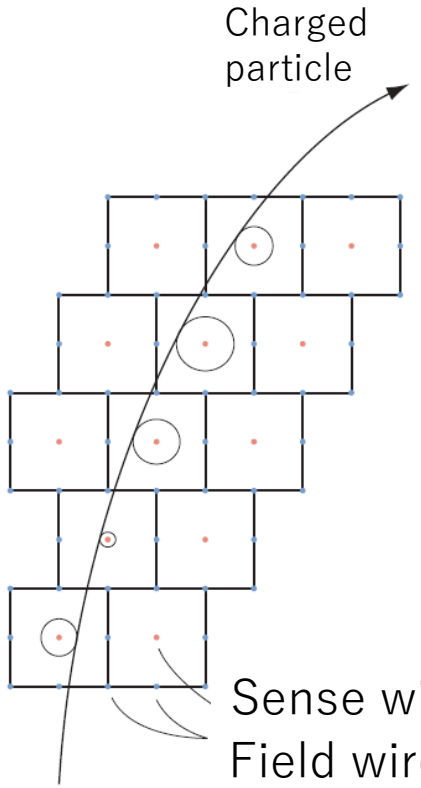


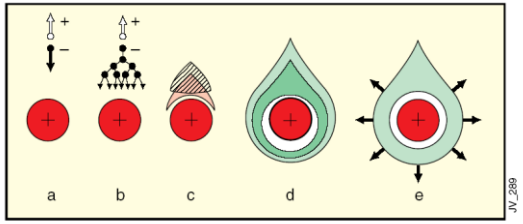
Q-dot: < 10 nm.
Can be made with chemical synthesis.
5000 photons / MeV achieved.
Self-absorption needs to be avoided.

PI-C Gas and novel liquid

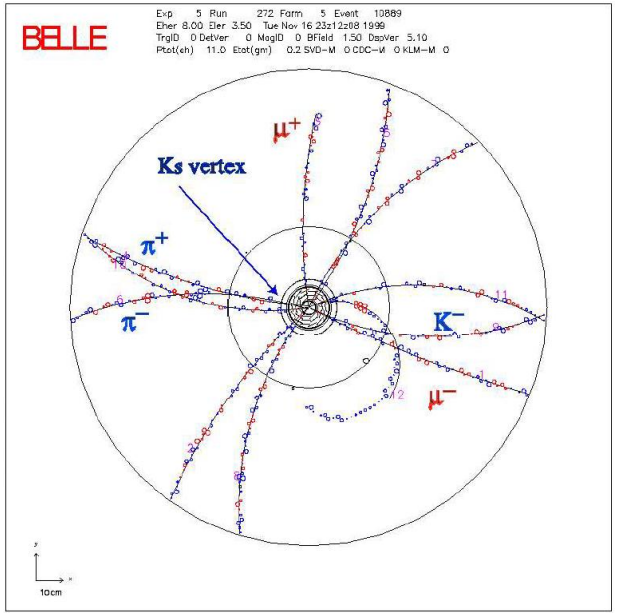
- Basics: Collect charges of electron-ion pair from ionization
  - High gain multiplication can be obtained by gas avalanche due to high electrical field around sense wire (30~50 μm)

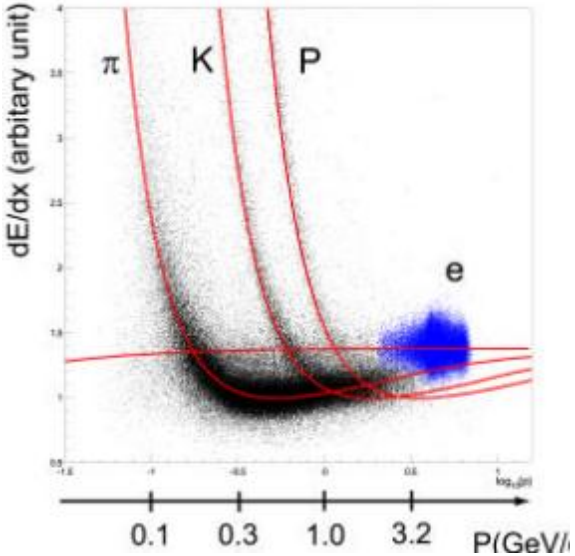






- Very low material budget (< 0.04 X_0) for central region
- Large signal
- dE/dx for particle Identification.



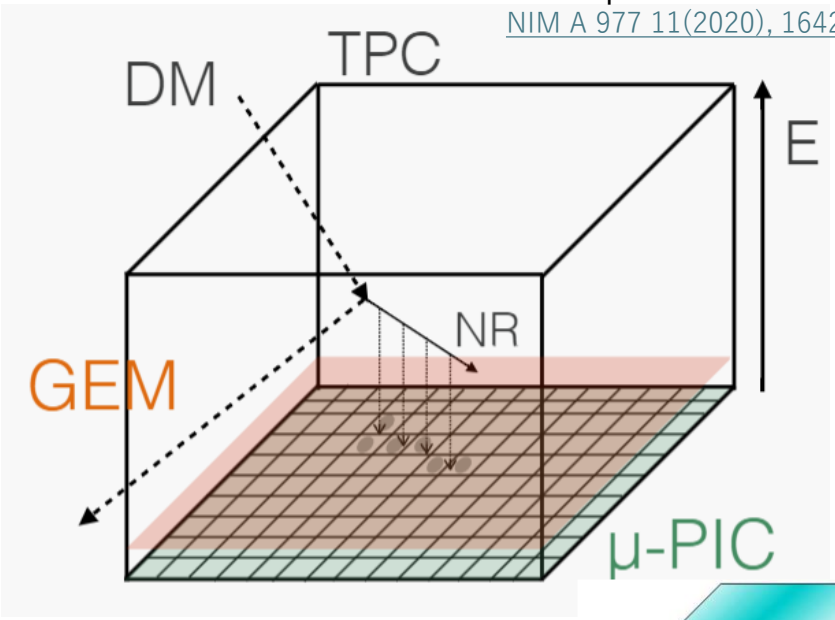


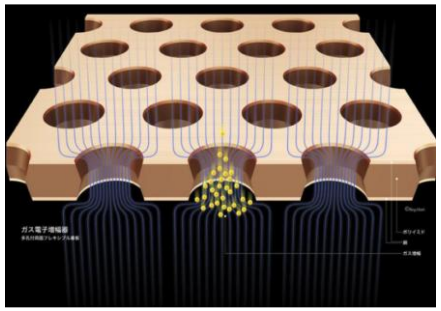
PI-C Gas and novel liquid: recent trend

- Micro pattern gas detector

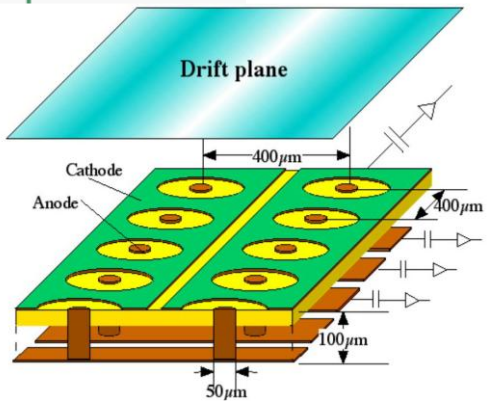
NEWAGE dark matter search experiment

NIM A 977 11(2020), 164285





Amplification by GEM

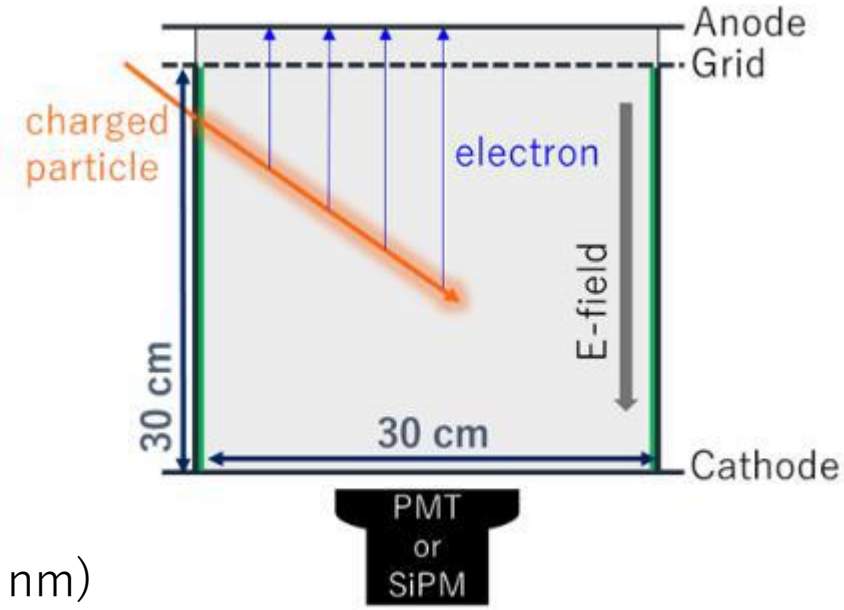


Read out by Micro Pixel Sensor

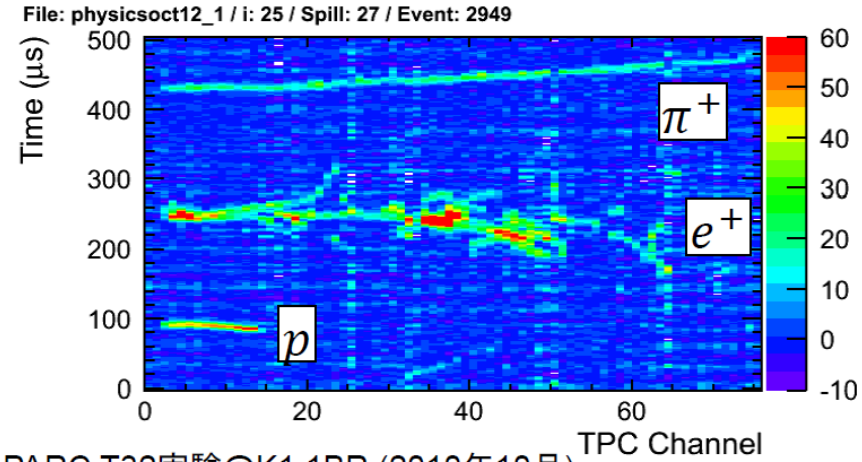
- Dual phase Liq-Ar TPC

M. Tanaka (Waseda)





Two types of signal
- Ionization
- Scintillation (128 nm)



J-PARC T32実験@K1.1BR (2010年10月)