Innovative Technologies for Detectors
- for Future Colliders -

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- I will NOT cover
  - Detector systems
    - They are mostly covered in other talks
  - Front-end electronics, Trigger, DAQ
    - Even though they are crucial and involves innovative technologies
  - Alignment and calibration systems
    - Some involves innovative technologies

- This talk is organized by detector elements :
  - Gas amplifiers
  - Photon detectors
  - Silicon pixel detectors

  Some highlights only!

Apology in advance that many important works are not mentioned!

Gas Amplifiers

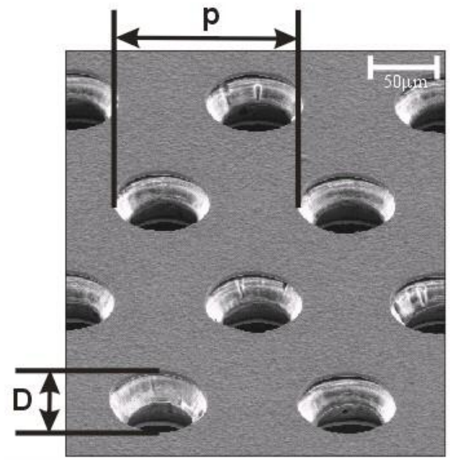
Amplify electrons (photoelectrons, ionization…) in gas
by avalanche multiplication.

Traditionally by MWPC
→ MPGDs (Micro-Pattern Gas Detectors)
e.g. GEM, MicroMEGAS . . .

Features of MPGDs (very roughly):
Large area (~mm^2) for low cost
Large gain (~10^4) with stable operation at high rate (~MHz/mm^2)
Good position resolutions (<100μm) and time resolutions

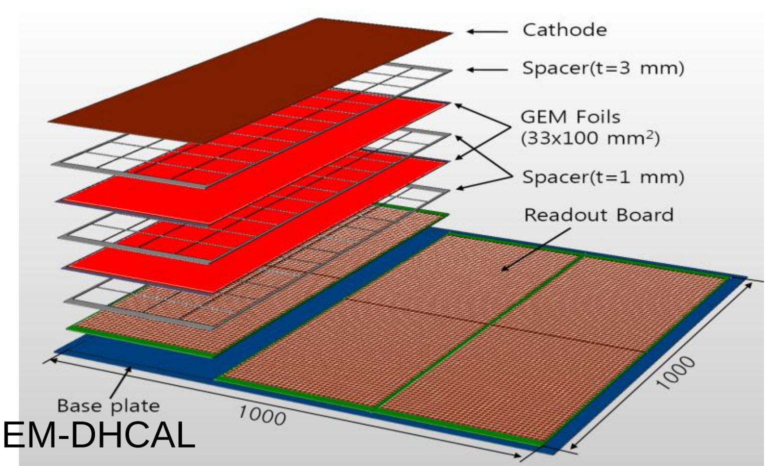
GEM (Gas Electron Multiplier)

- Two copper foils on both sides of Kapton layer of ~50μm thick
- Amplification at the holes
- Gain~10^4 for 500V
- Readout by anode pads, or silicon pixels (Timepix, Medipix, etc.)
- Can be used multi-staged
  - reduces ion feed back & discharges
- ‘Thick GEM’
  - X10 feature size (w/ PCB tech.)
  - Low cost

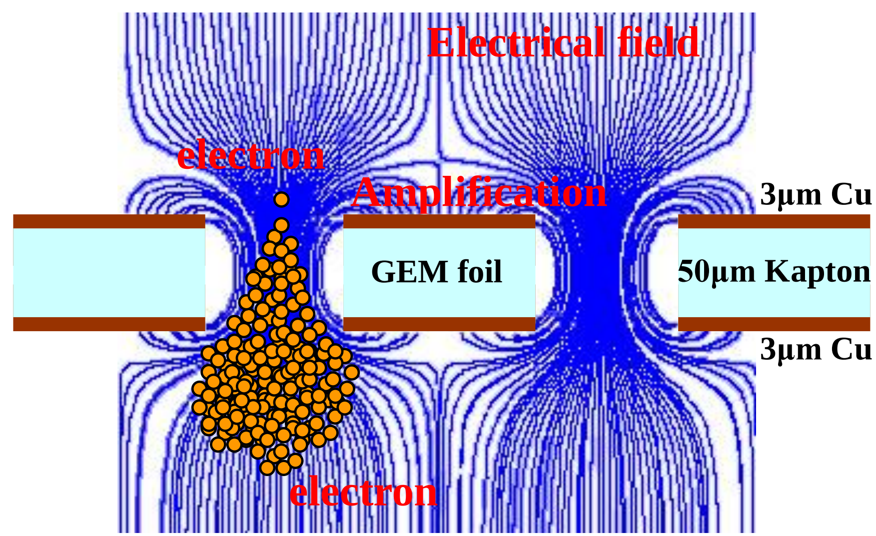


p~140μm

D~60μm



GEM-DHCAL



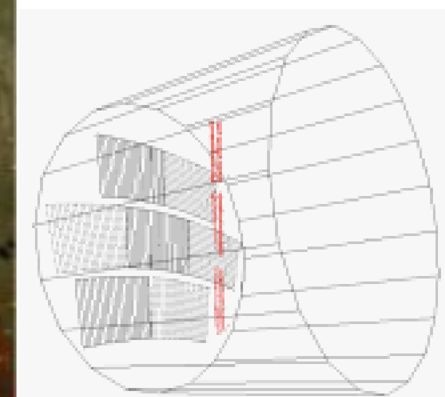
GEM at Work

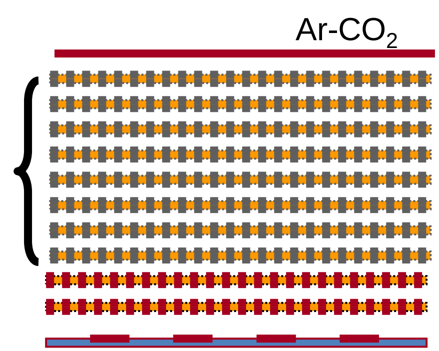
- Tracking layer
  - ATLAS/CMS muon upgrades
  - KLOE2 cylindrical GEM, etc.
- TPC endplate
  - Linear Collider (LCTPC collab.)
  - ALICE TPC
  - PANDA TPC, etc.
- Calorimeter
  - DHCAL (digital hadron cal.)
- Neutron detector
  - 3He (short supply) in gas
  - Boron10 coating
- Photon detector (Cerenkov etc.)

  → next section

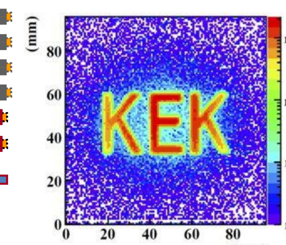
KLOE2 cylindrical GEM

LCTPC large prototype





Neutron image w/ TOF cut



MicroMEGAS
(MicroMEsh GAseous Structure)

- Micromesh with pitch~50µm
- Gap height ~ 50-100µm
  - Must be uniform
- Amplification in the gap between mesh and pads/strips
- New manufacturing techniques: large, stable, low-cost, all-in-one

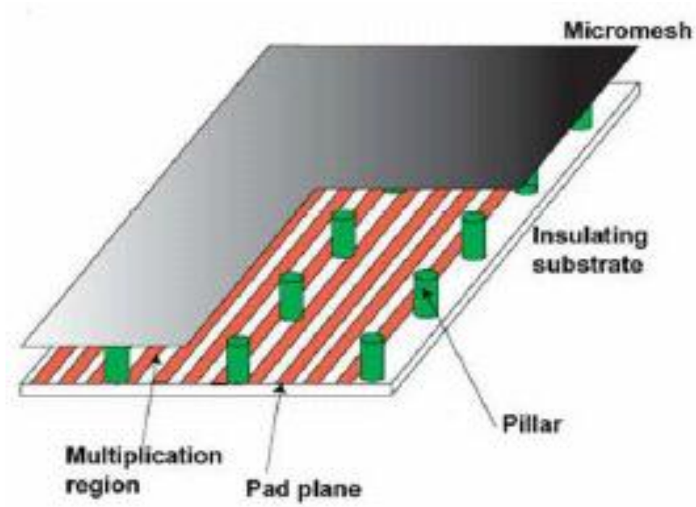
  ‘bulk’ MicroMEGAS

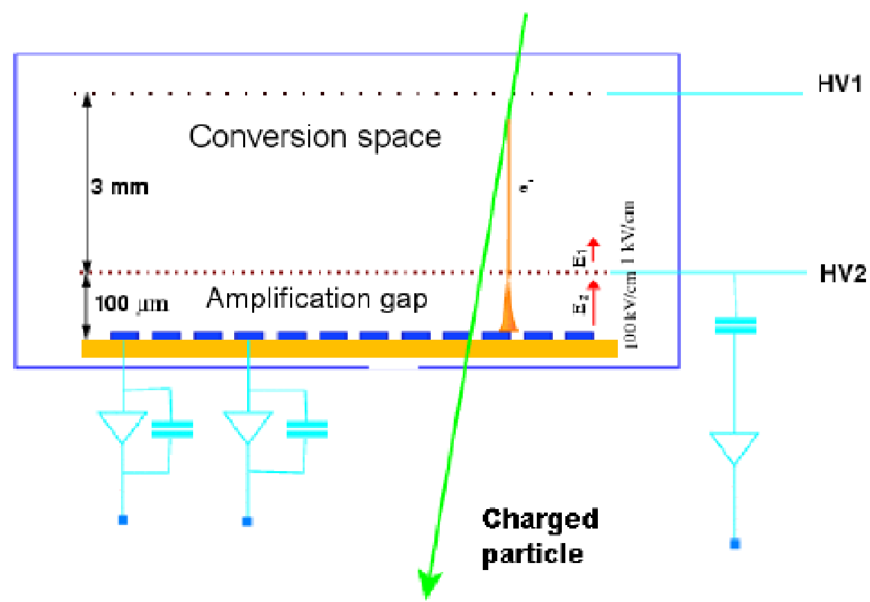
  Metal woven mesh laminated on PC board – pillars by photochemical technique

  ‘micro-bulk’ MicroMEGAS

  Cu on both sides of Kapton film

  - Holes and pillars by micro-etching technique

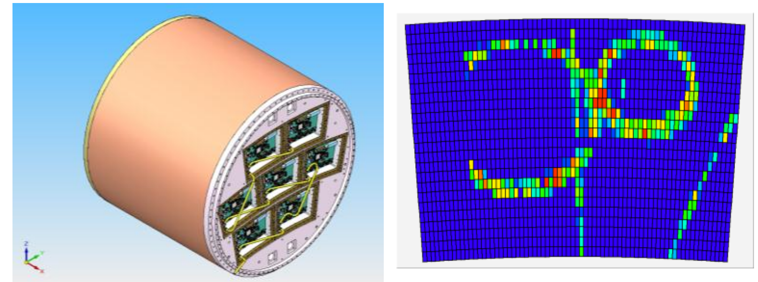




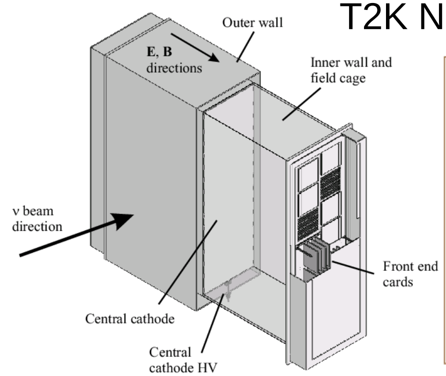
MicroMEGAS at Work

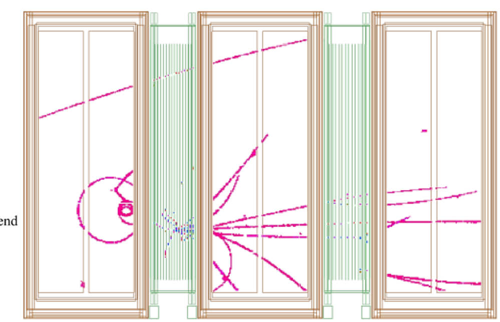
- TPC endplate
  - Linear Collider (LCTPC collab.)
    Resistive layer on anodes
  - T2K : ND280 TPC
  - NEXT : gas Xe TPC
- X-ray detector
  - CAST: Axion search
    ~3 keV X-ray scattered by axion
- Neutron detector
  - nTOF: 10B and 235U coatings
    Neutron flux and profile

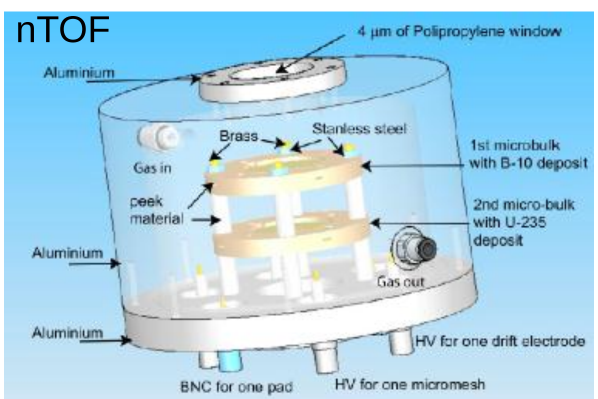
LCTPC MicrMEGAS



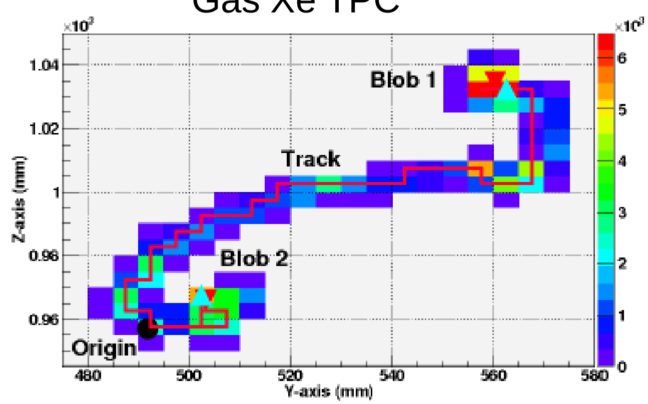
T2K ND280 TPC

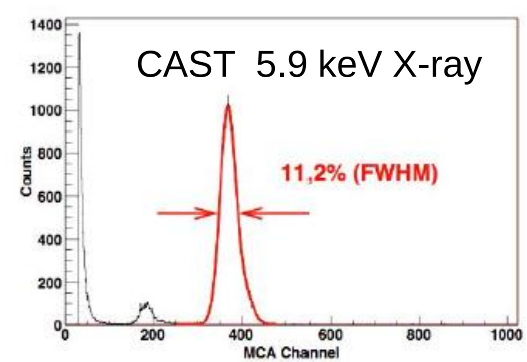






Gas Xe TPC





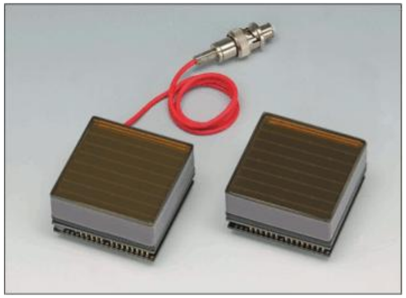
Photon Detectors

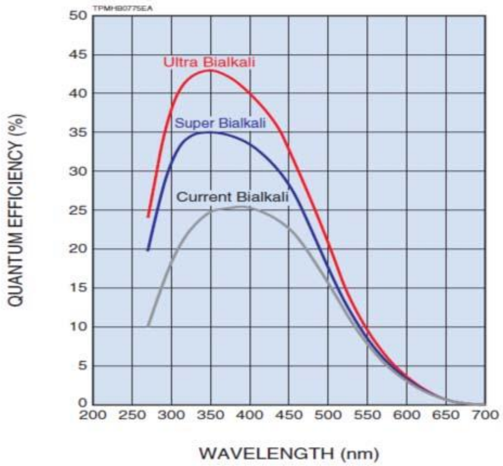
PMT (PhotoMultiplier Tube)
MCP (Micro Channel Plate)
HAPD (Hybrid Avalanche PhotoDiode)
SiPM (Giger-mode APD array)
Photon detectors by MPGD

PMTs (Photomultilier Tubes)

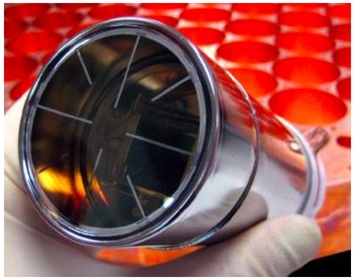
- Still a choice for photon detection in many applications
  - Large diameters (10in, 12in . . .)
    - Neutrino experiments (SK, LBNE . . .)
  - Multi-anode PMT (MAPMT) : position
    - RICH (CLAS12, PANDA . . .)
- Some new developments (Hamamatsu)
  - High QE photo cathodes
    - UBA (Ultra Bialkali) QE = 43% typ.
    - SBA (Super Bialkali) QE = 35 % typ.
      - (Usual Bialkali QE = 25% typ.)
    - Better energy resolution, more #pe in Cerenkov ring, etc.
  - Low temperature operation
    - Operation in Liq. Xe (-110 deg C) etc.
      - Developed for XMASS DM experiment
    - Avoid photocathode current saturation
    - Now PMT can be directly immersed in Liq Ar, Liq Xe (XMASS, LZ . . .)
    - Very low radioactivity

MAPMT (8 by 8)
Hamamatsu H8500C

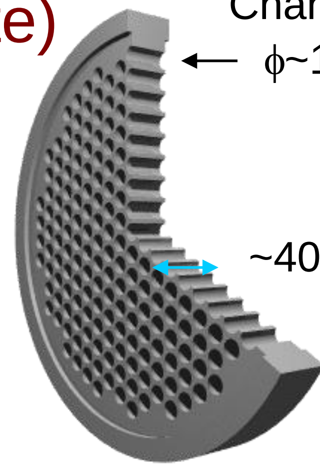


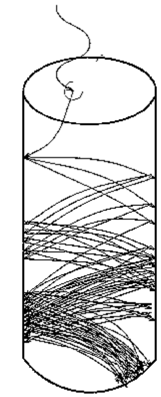


Hamamatsu R8778

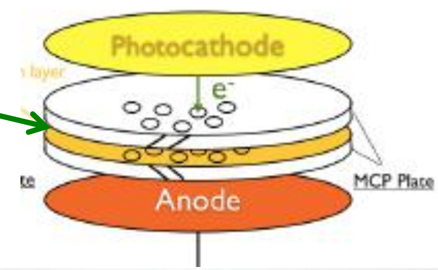


MCP-PMT (Microchannel Plate)

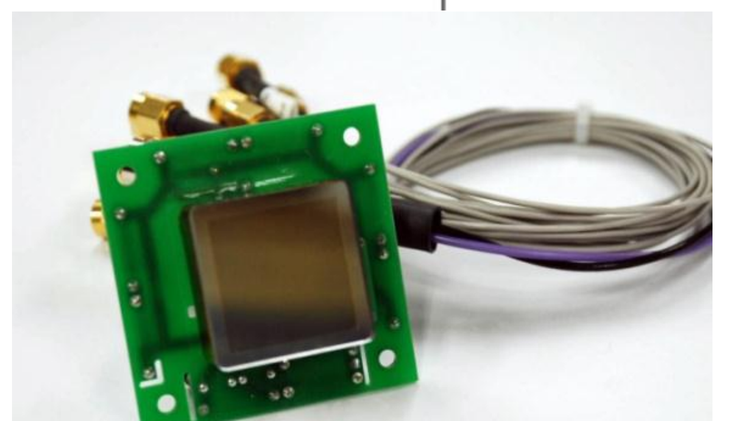




- Amplification in micro capillary
  - 1photon counting
  - QE ~ 28 % (w/ super bialkali)
  - Gain ~ 10^6
  - B field OK (~1.5 T)
  - Position resolution ~5mm typ (multi-anode)
  - Fast !
    - tts (transit time spread) ~ 50 ps or less
  - Al foil to increase lifetime (~1C/cm^2)
    - Blocks ion feedback to photocathode



- Applications
  - X-ray cameras, image intensifiers, etc.
  - Cerenkov photon detections
    - TOP (time of propagation) for Belle-II
    - Focusing DIRC (and FTOF) for SuperB
    - PANDA, CLAS12?

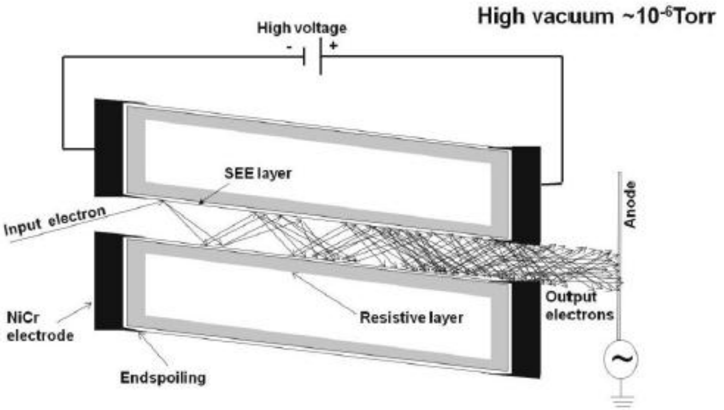


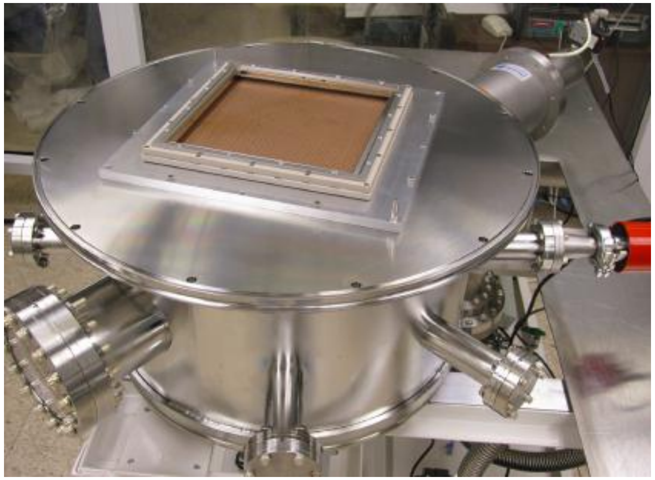
16-ch square MAPMT (2.5cm)

LAPPD collaboration
(Large Area Picosecond Photon Detector)

- Goal
  - Develop a large, cheap, fast photon detector based on MCP
- MCP by ALD (Atomic Layer Deposition)
  - Start with porous borosilicate glass
  - ALD of resistive layer
  - ALD of secondary electron emission layer
  - Top&bottom electrode coating
  - Good control of the layers
  - Large area possible
  - 8in sq MCP tested
- Photocathode
  - 8in sq photocathode being developed
- 8in sq sealed tube being fabricated

- Large area of applications
  - Cerenkov light, PET, homeland secutiry. . .

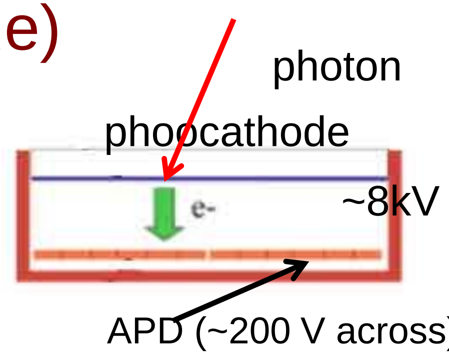




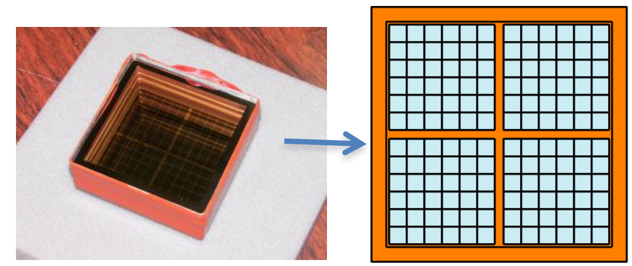
8in sq MCP

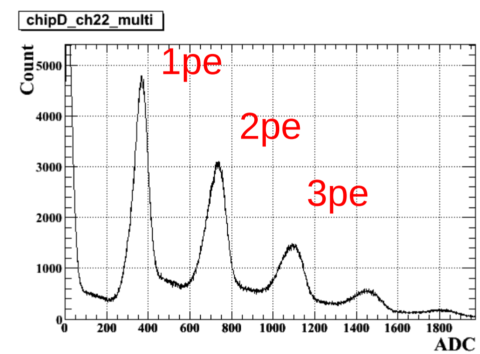
HAPD

(Hybrid Avalanche PhotoDiode)

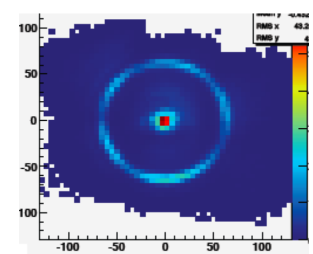


- APD replaces the micro capillary of MCP
  - Amplification by
    - Accelerated e^- hits APD ($\sim 10^3$)
    - APD itself (~40)
  - Typical total gain ~ 4×10^4
- Example
  - 144ch HAPD for Belle-II Forward RICH
    - 72x72 mm^2 , 5x5 mm^2 cell
    - Fill factor 67%
    - QE ~ 25% (→43% by UBA)
    - 1γ counting: good energy resolution
      - Much better than typical PMT
      - Thanks to the large 1^{st} stage gain
    - B ~ 1.5T OK
    - Flat and compact
    - Improved radiation hardness to $10^{12} n/cm^2$

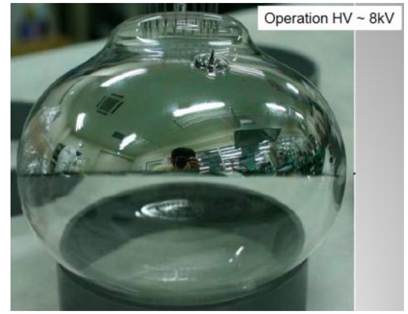


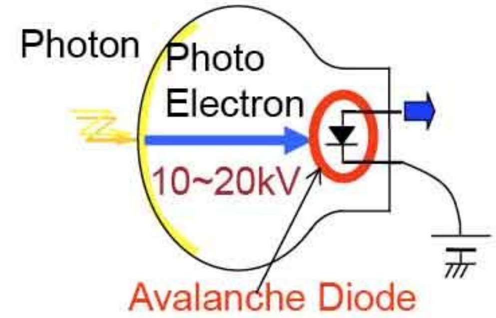


Cerenkov ring by beam test



'Large' HAPDs

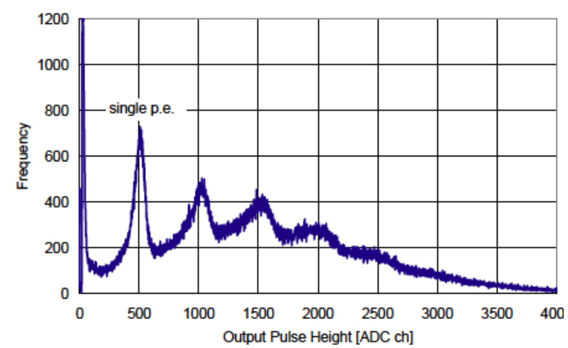


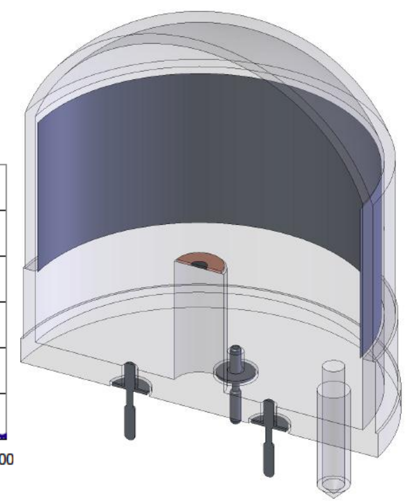


- Replace dynodes of large PMT by APD
- Advantage over PMT
  - Better t-res, E-res, collection eff.

	13in HAPD	13in PMT (R8055)
1γ time res.	190 ps	1400 ps
1γ energy res.	24%	70%
Collection eff.	97%	70%
QE	~20%	~20%
gain	~10^5	~10^7

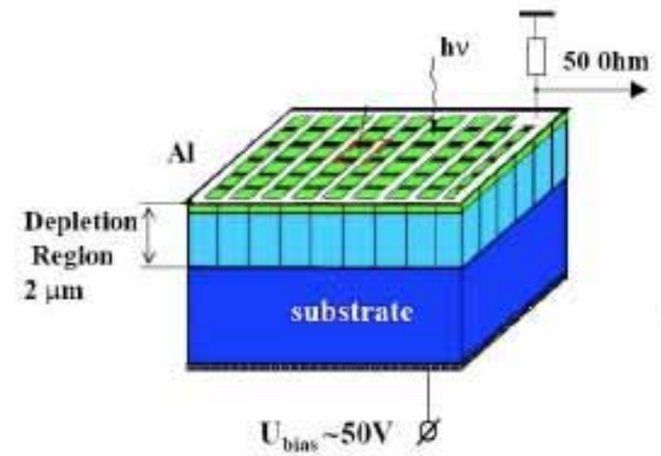
- 'Large HAPD'
  - 13in : for Hyper-K
  - All-grass → dark rate ~2KHz (~PMT)
  - Now w/ digital output
  - Commercially available, March 2012
- QUPID (Quartz Photon Intensifying Detector)
  - 3in, for dark matter experiments
    - Xenon1t, Darkside, etc.
  - Extreme low radioactivity
    - < 0.59 mBq/cm^2

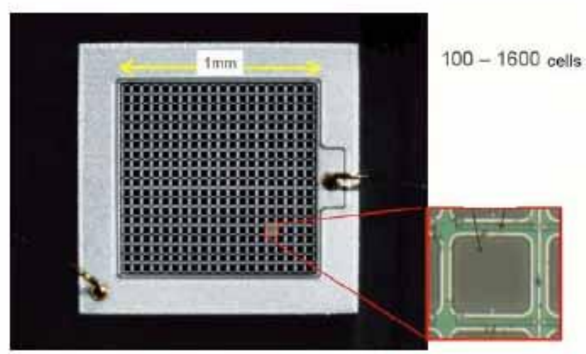




Geiger-mode APD Arrays
(SiPM, MPPC …)

- Operate small APDs w/quench resister in Geiger mode and gang the outputs.
  - Output ∝ number of fired cells
- Invented in Russia
  - Standard MOS process
  - Now produced worldwide
- Many merits
    - High gain ~ 10^6
    - High PDE (phot. det. effic.) 30~60%,
    - Fast : $\sigma_t(1\gamma)$~100 ps
    - Low HV ~ 50 V
    - Insensitive to B field - Up to 7T
    - Low power < 50 μW/mm^2
    - Cheap: ~$1/piece eventually





Hamamatsu MPPC

Geiger-mode APD Arrays

Applications

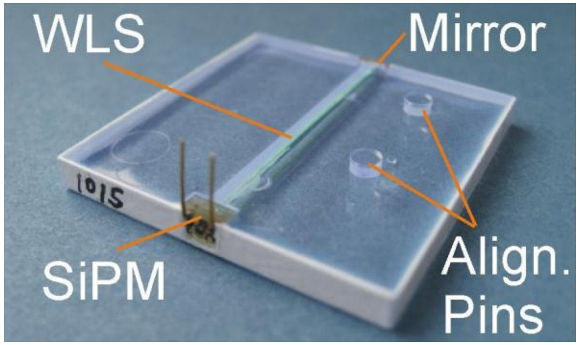
- Scintillating fibre readout
  - Tracking
    - Belle-II muon etc.
  - Calorimeter
    - CALICE AHCAL/ECAL etc.
- Cerenkov photon detection
  - PANDA disk DIRC etc.
- PET (w/ MRI)
  - Gives TOF and DOI (depth of int.)
- etc…

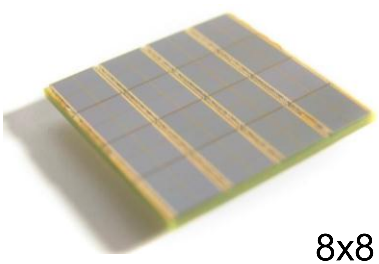
Some disadvantages

- High dark counts
  - ~ 300kHz (a few kHz for PMT)
  - Depends on ΔV (voltage over threshold)
- Radiation hardness
  - Deterioration at a few kRad
- Difficult to cover large area

New development: Digital SiPM

- Binary readout of each cell
- Count hits in ~4mmsq 'pixel'
- Time of 1st hit in 'pixel'
- Scalable!



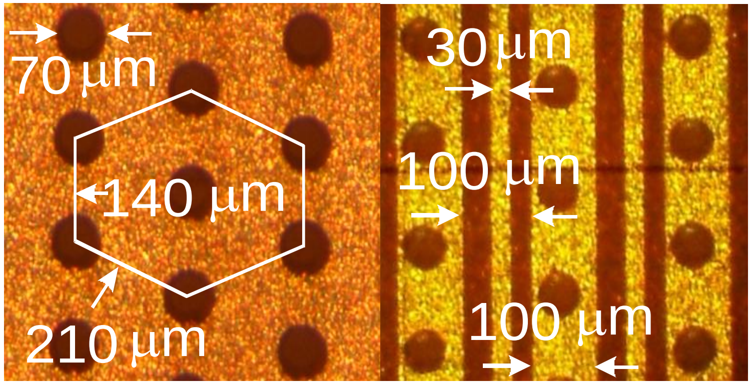


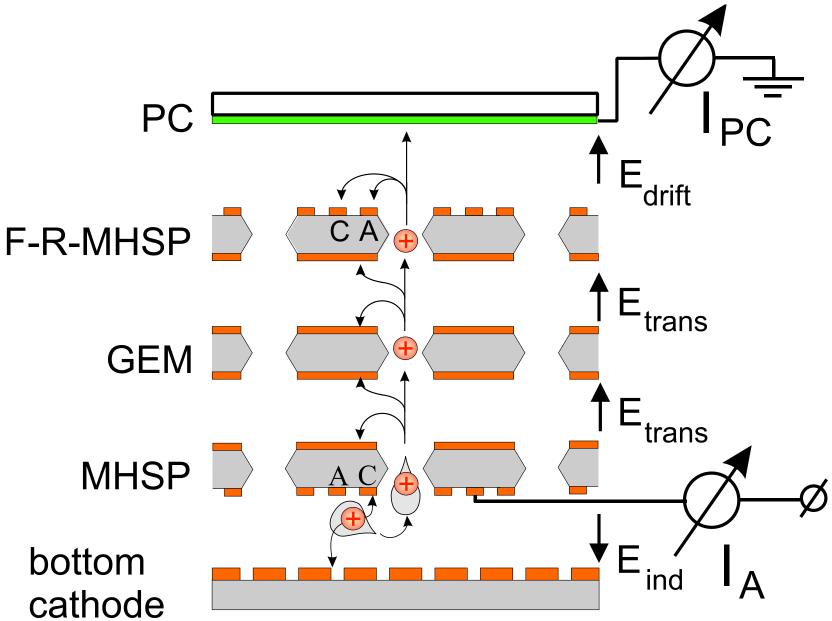
8x8 'pixel' dSiPM

Gas PMT (GPM)

(with MHSP: microhole & strip plate)

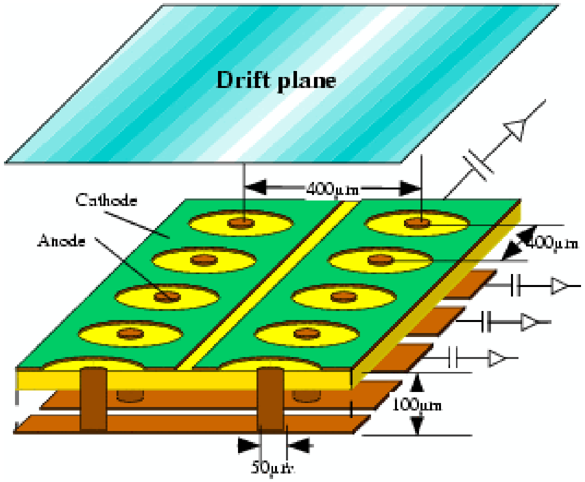
- Replace dynodes or APD by a gas amplification device.
  - ion feedback problem!
- Use strips on GEM plate to guide the field lines so that ions will hit the plates.
- Stable operation at gain~10^5 achieved with electron collection efficiency of ~100%.

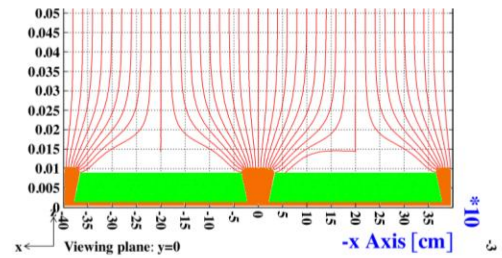




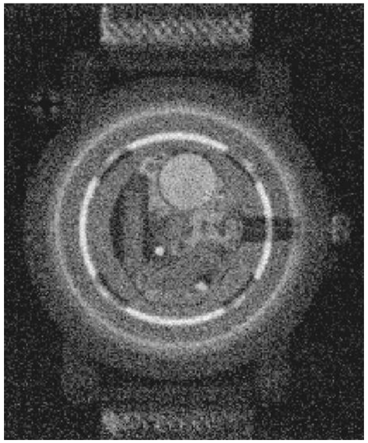
μPIC project

- Micro pixel w/ gas amplification
  - Pitch ~0.4mm, gain ~ 10^4
- By itself (w/ drift plane):
  - Tracking layer (e.g. ATLAS muon)
- With drift space: TPC
  - Compton camera
  - Dark matter wind detector
- With GEM & photocathode:
  - X-ray/photon imaging
- With GEM & 3He
  - Neutron imaging
- All above are moving to practical uses
  - Some: commercialization





Neutron image



Silicon Pixel Detectors

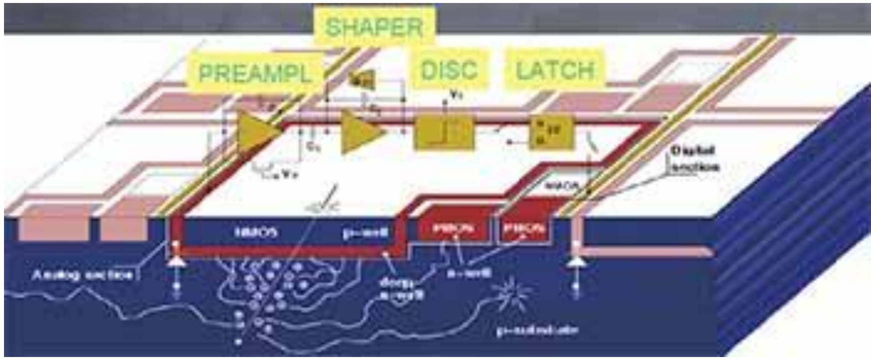
Conventional
Deep n-well
SOI
Vertical Integration (3D)

Pixel Sensors

- CCD
  - CPCCD, FPCCD, ISIS (CCD/MAPS)
- Hybrid
  - Sensors and readout chip are fabricated separately and bump-bonded
    - Allows different processes for sensor and readout chips
    - Fast, rad-hard, flexibility in circuit, but
    - Thick, large pixels, bump-bonding is cumbersome
  - ATLAS pixel, CMS pixel, Alice SPD, Timepix, diamond, etc …
- Monolithic
  - Sensors and readout chip are fabricated on single wafer
    - No bumps, high pixel density, thin, but
    - Type of circuitry is constrained (usually NMOS only)
  - MAPS, DEPFET (Belle-II), etc.

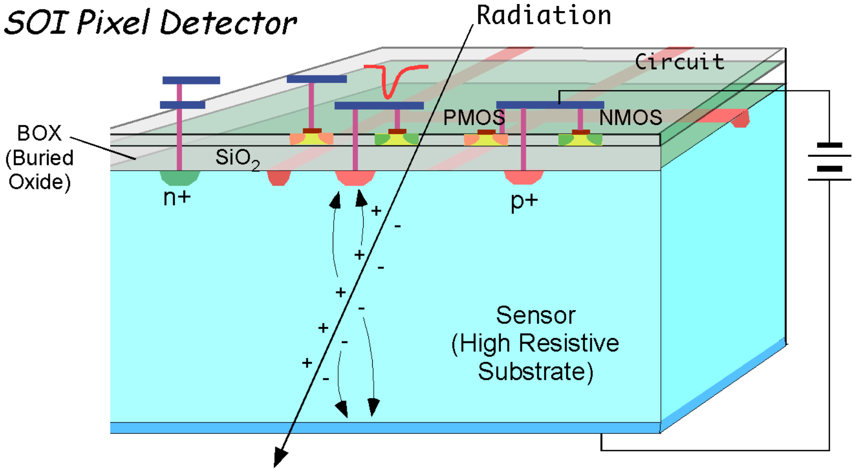
Free from the process bind

- Deep N-Well
  - PMOS can also be used.
    - Sensitivity loss under PMOS.
  - Now trying to use vertical integration to put all readout circuitry to another layer.



- SOI (silicon on insulator)
  - ~semi vertical integration
  - Active area of sensor is very close to the read out circuit (~200nm)
    - Backgate effect now solved by adding BPW (buried p-well)

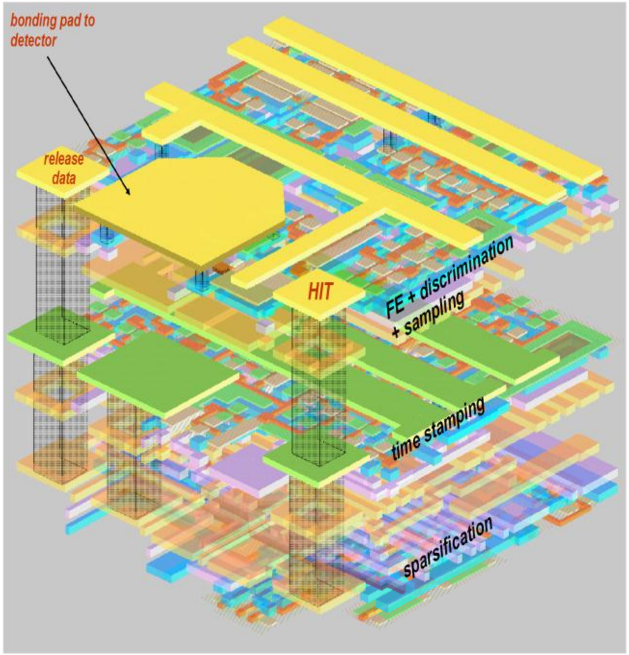
  → Try vertical integration (among others)



Vertical Integration

- Industry-wide trend
  - Not just HEP
  - Technology is industry-driven
- Vertical integration by
  - Via formation
  - Bonding
  - Thinning
- Can use optimal process for each layer
  - E.g. analog, time stamp, sparcification

- Activities in
  - Europe, Japan, US



VIP1: demonstrator chip for ILC Vertex detector

Summary

- Great advances have been made in achieving detection of particles with
  - Better time and position resolutions
  - Tolerance against high rate and radiation dose
  - Large coverage at low cost
  - and that works in strong B field

- Some R&Ds are directly aimed at actual experiments, while some are generic. Both kinds benefit wide uses.

- Individual progress, however, is slow and in general require substantial investment.

- Benefits of technology spread within HEP and outside HEP are enormous. Technologies invented/improved in one fields spread to other field relatively quickly, but can use some help.