Scintillating-Fiber Trackers for PRAD Experiment at JLab

Zhihong Ye
Argonne National Lab
01/05/2018

About Me:

- Bachelor Degree in Theoretical Physics, Lanzhou Univ., July 2005
- Doctor of Philosophy in Experimental Nuclear Physics, Univ. of Virginia, Dec. 2013
- Postdoc Research Associate, Duke Univ., Nov. 2013- Sep. 2015
- Postdoc Research Associate, Argonne National Lab, Sep. 2015-current

Selected Skills:

- Particle physics detectors design, prototyping, construction and calibration
- Large scale data analysis, e.g. events reconstruction, efficiencies evaluation, error analysis, etc.
- Monte-Carlo Simulation using Geant4, ROOT and other packages
- Programming: Fortran, C/C++, Python, Linux Shell Languages
- Design, propose and execute nuclear physics experiments
- Conference Presentations, Seminar talks and publication on journals

Selected Experience:

- **Hardware Experience:**
  - ✓ Built and installed Lucite Cherenkov Detectors; refurbished Aerogel Cherenkov Detectors
  - ✓ Refurbished and installed Drift-Chambers
  - ✓ Maintained and calibrated Scintillator Detectors, Gas Cherenkov Detectors, Electromagnetic Calorimeters, Drift-Chambers etc.
  - ✓ Proposed and developed a Scintillating Fiber Tracker with SiPM read-out (2014 JSA Postdoc Award)

(this talk)

- **Software Experience:**
  - ✓ Geant4 Simulation to design, evaluate and optimize new detector systems for new SoLID project
  - ✓ Monte-Carlo Simulation to study physics programs at Jefferson Lab and on future Electron-Ion Colliders.
  - ✓ Developed and maintained 10+ software tools for nuclear physics which are all shared on GitHub

https://github.com/yezhihong?tab=repositories

- **Professional Experience in Experimental Particle Physics:**
  - ✓ Carried out more than 10 experiments in Hall A, B, C at Jlab and at Fermi-Lab
  - ✓ Spokesperson of two experiments at JLab (one is running now)
  - ✓ Supervised more than 15 PhD students from different universities
  - ✓ Proposed new experiments in Hall-A and Hall-B at Jlab

- **20 + Invited Talks & 14+ Contributed Talks**
- **40 Publications on top journals (3+ first authors); 1300+ Citations;**

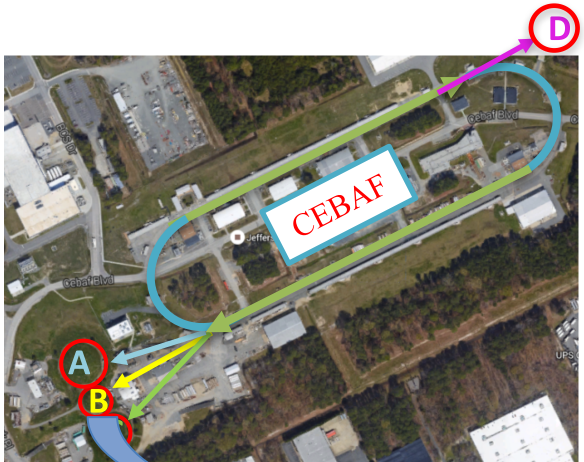
Outline of This Talk

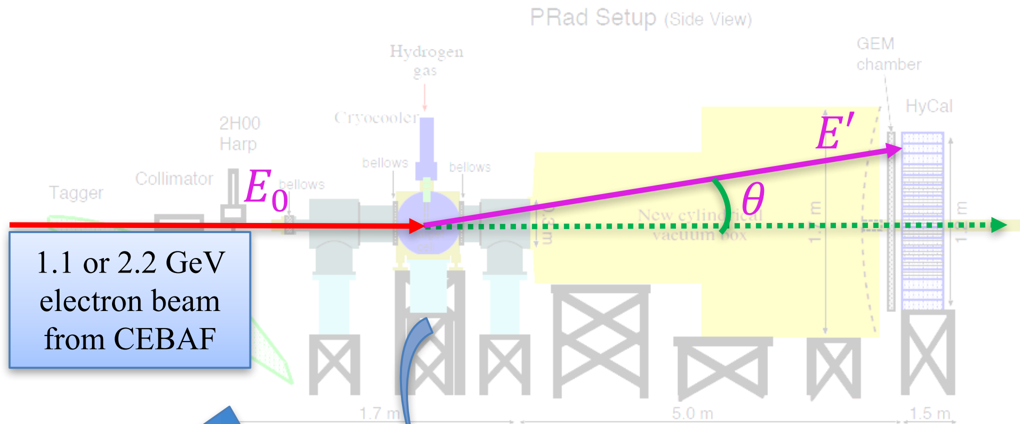
Main Topic: Scintillating Fiber Trackers (SFT)

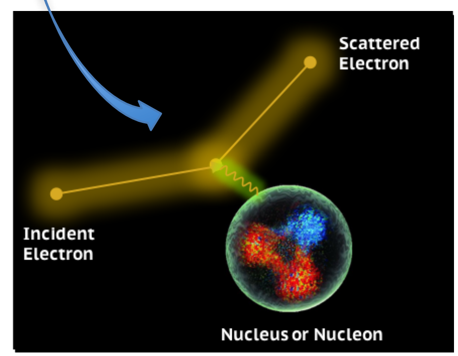
- Physics Motivation – Proton Charge Radius Measurement at Jefferson Lab
- Selections of Tracking Devices for PRAD
- SFT Design and The Prototyping Project
- Summary

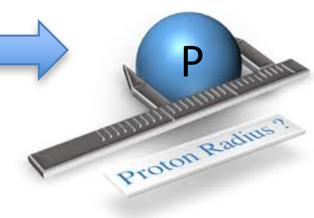
Physics Motivation

❑ The Proton Charged Radius Experiment (PRad) in Hall-B JLab:









Experimental Requirements:

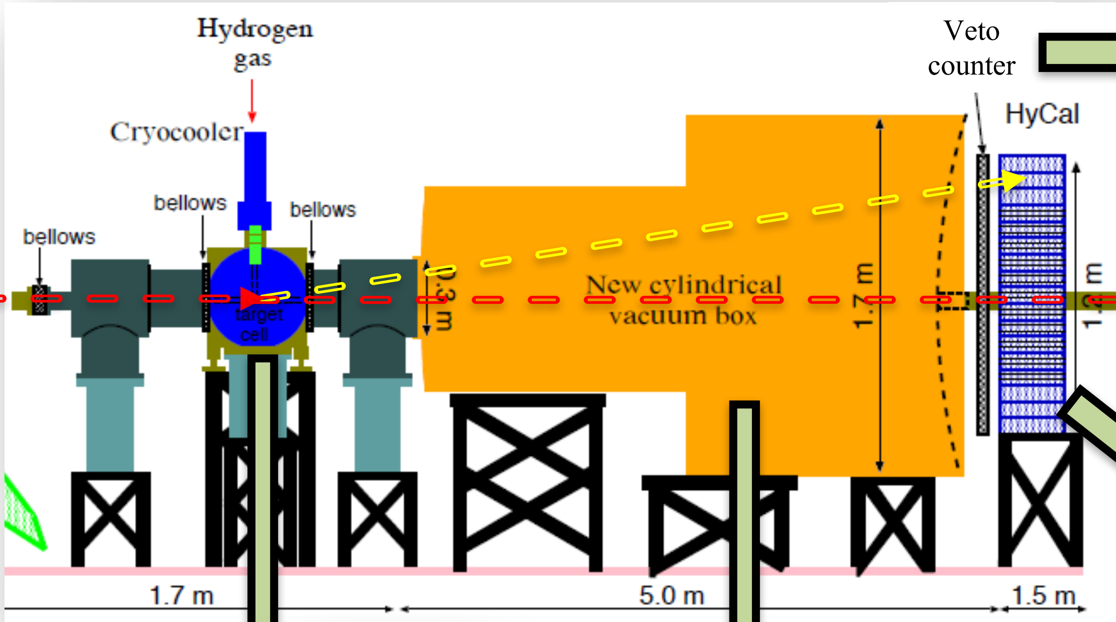
- ➢ Measured the cross sections (probabilities) of electron-proton elastic scattering, as functions: $Q^2 = 4E_0E'sin^2\left(\frac{\theta}{2}\right)$
- ➢ Need to measure very low Q^2 values (i.e., ~10^{-4} GeV^2);
  → very low angles (0.6^o~7.5^o)
- ➢ Total relative uncertainty <1%
  → Need high precisions on E' and θ

Cross-Sections:

For a given total numbers of incoming electrons w/ known energy, the numbers of electrons scattered by the target (proton here) per unit energy per solid-angle

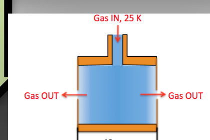
PRAD Experiment

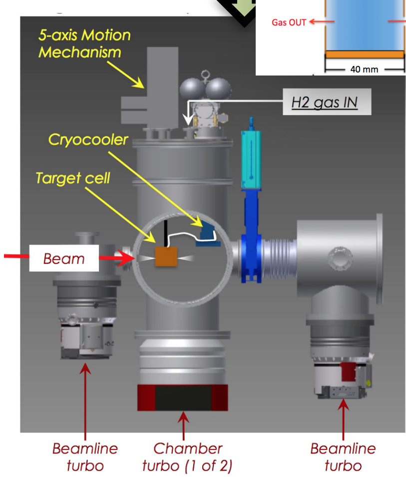
- Proposed Experimental Designs:

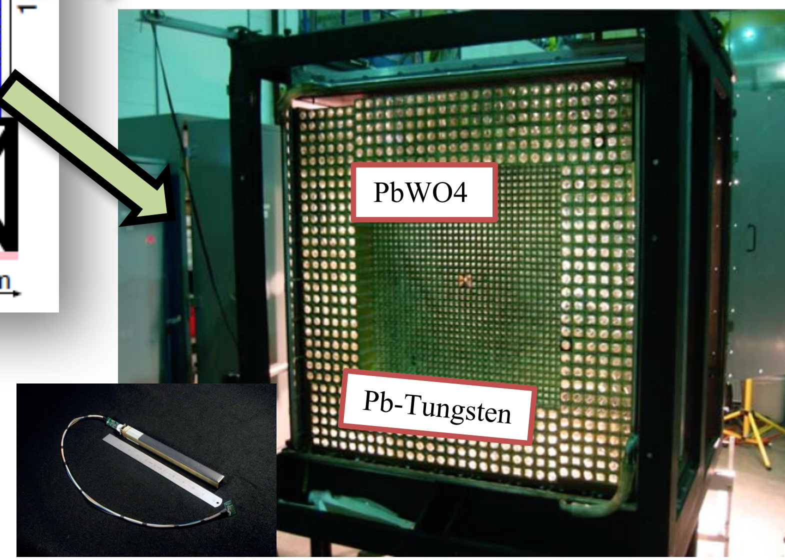


Plastic Scintillating Bars (2cm thick) as a veto counter

Note: Most of electrons won't hit on the protons but travel though freely







Hybrid Electromagnetic Calorimeters (**HyCal**)

Window-less Target System and Vacuum-Box to minimize materials

PRAD Experiment

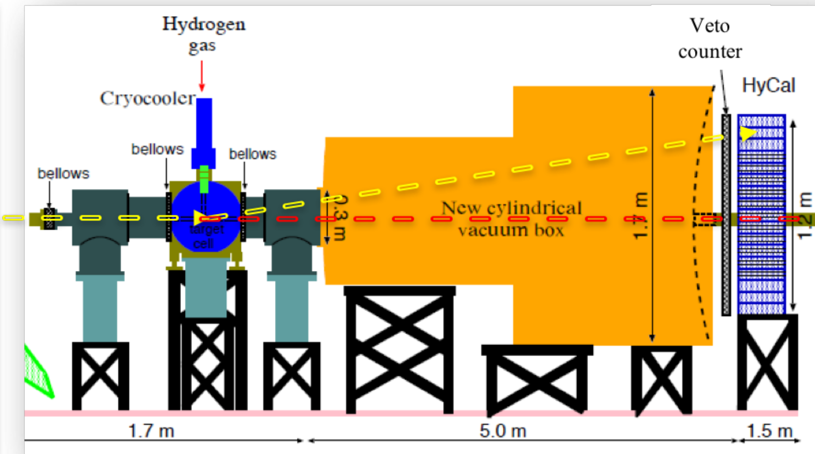
- ❑ Proposed Experimental Designs:

Challenges to get a <1% Measurements:

- ✓ CEBAF electron energy resolution ~0.1%
- ✓ Unique feature of the Elastic-Scattering: w/ known E_0, just need to measure E' or θ:

$$Q^2 = 2M_p(E_0 - E'), or\ Q^2 = \frac{2M_p E_0^2(1-cos\theta)}{M_p + E_0(1-cos\theta)}$$

- ❖ **HyCal**: ~2.5~5.5 mm Spatial Resolution
  ~2.6%/$\sqrt{E}$ Energy Resolution (too poor!)
- ❖ To reach the goal, we have to get precise angles

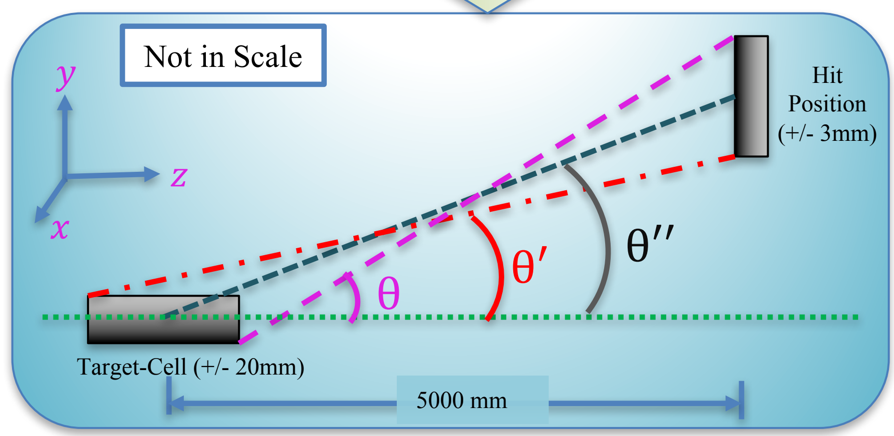


Determination of the scattering angles:

- ✓ The angle is given by the positions of the reaction point (0,0,0) inside the target-cell and the hit-point (x_1, y_1, z_1) on the HyCal (after cluster reconstruction)

$$\theta = arctan\frac{y_1}{z_1} \qquad \sigma_\theta \approx \frac{1}{y_1^2 + z_1^2}\sqrt{y_1^2\sigma_{z_0}^2 + z_1^2\sigma_{y_1}^2}$$

$$\sigma_{Q^2}/Q^2 \approx \frac{sin\theta}{1 - cos\theta}\sigma_\theta$$



PRAD Experiment

- Proposed Experimental Designs:

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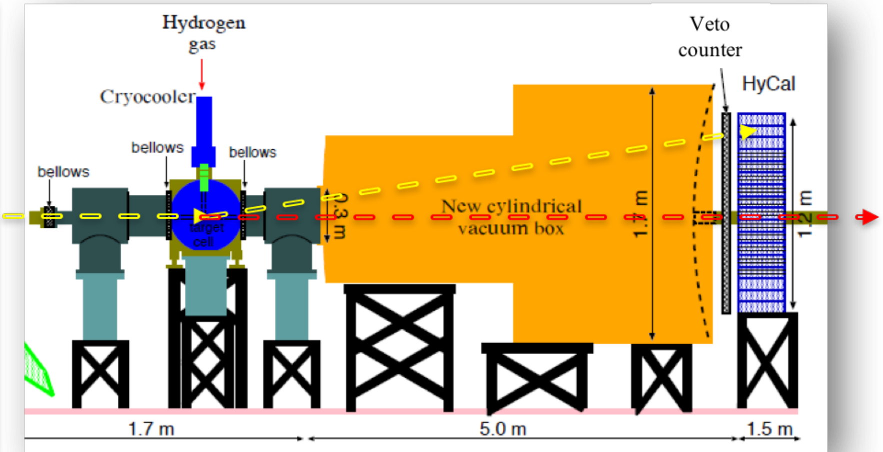

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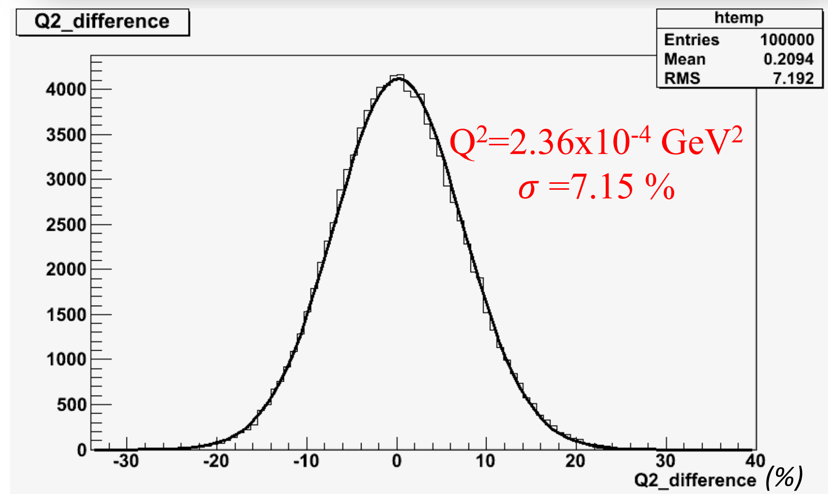
$$\sigma_{Q^2}/Q^2 \approx \frac{sin\theta}{1 - cos\theta}\sigma_\theta$$

✓ At (0,0,0), $(\sigma_x, \sigma_y, \sigma_z) = (0.2\ mm, 0.2\ mm, 20.0\ mm)$,
At (x_1, y_1, z_1), $(\sigma_x, \sigma_y, \sigma_z) = (3\ mm, 3\ mm, 0.0\ mm)$,

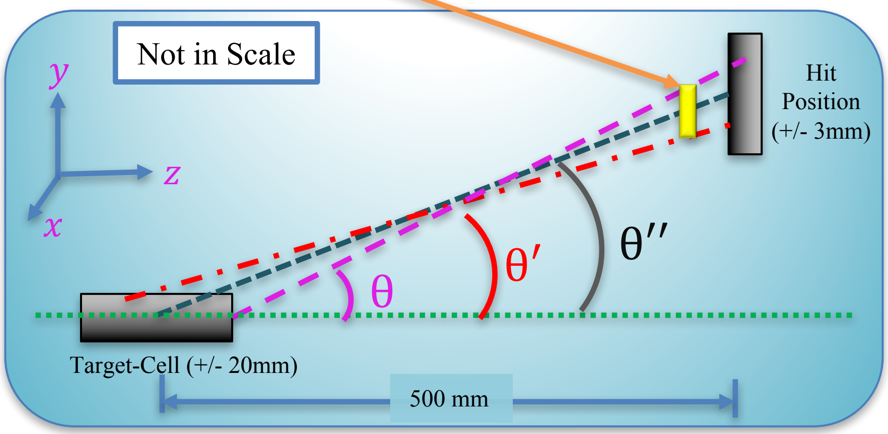


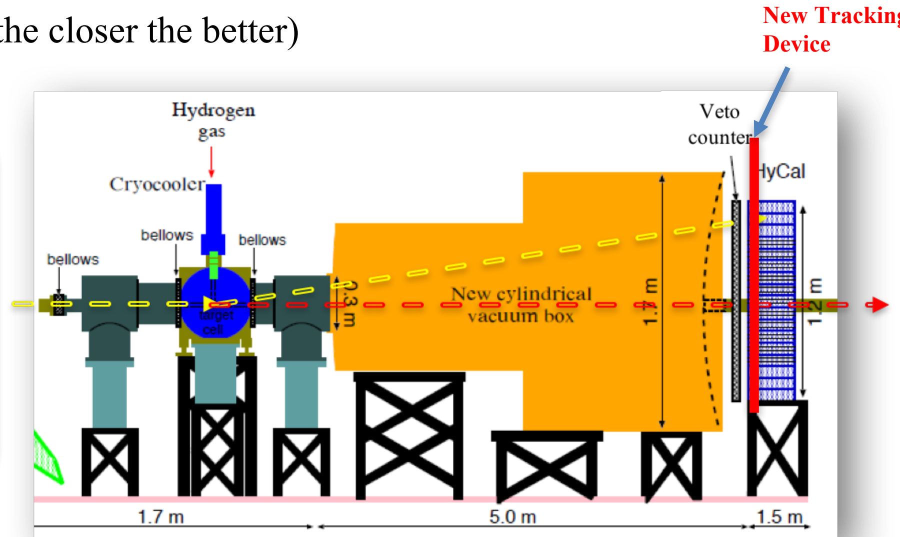
✘ The uncertainties propagated to Q^2 is huge!

Adding tracking (positioning) detectors is required to improve angular resolution; It can also help the HyCal reconstruction (background suppression)

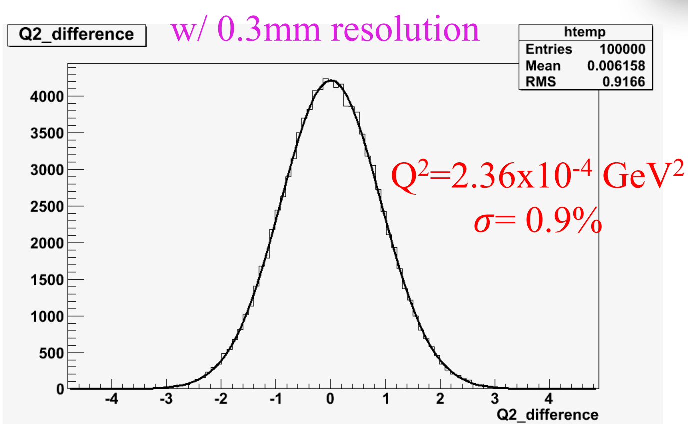
PRAD Experiment

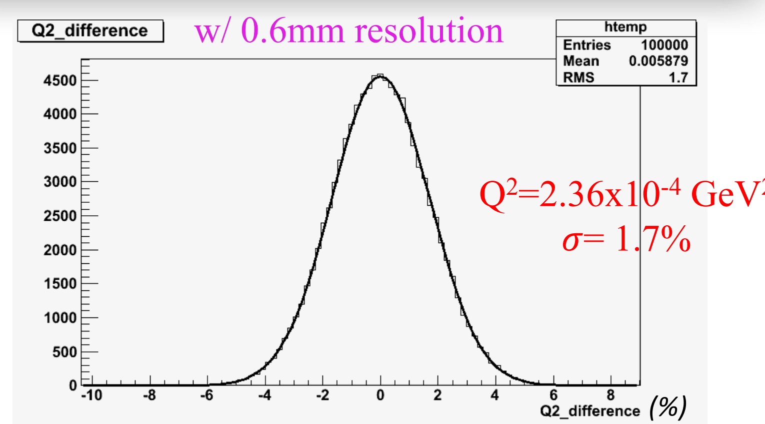
- Updated Designs – Add Tracking Detectors
  - Option: Add **one** tracking plane right in front of HyCal (the closer the better)





e.g., one at 499 cm,



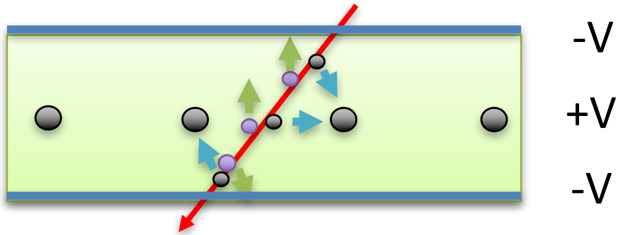


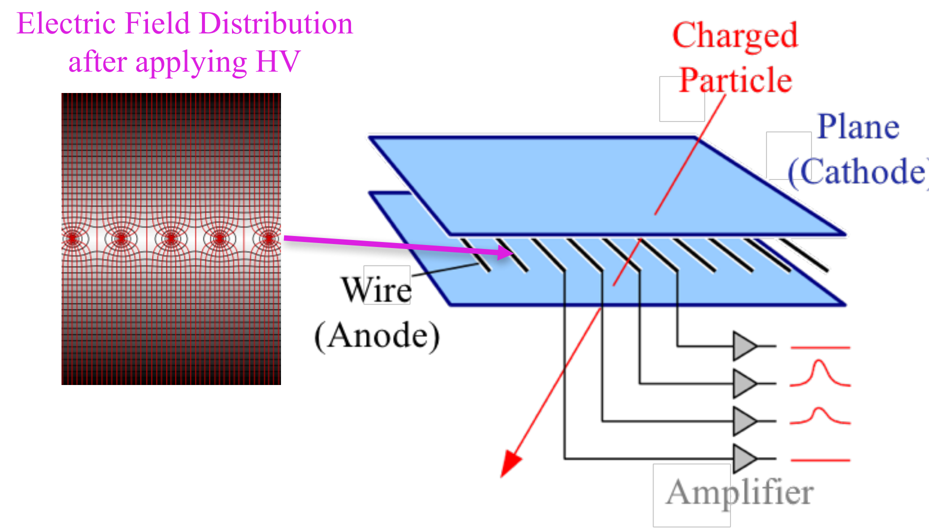
- ✓ When the tracking device is next to the HyCal, a 0.3 resolution can meet our goal (0.6mm is acceptable)
- ✓ A hole at the center of the tracker is needed to allow the beam-pine going through
- ✗ Due to space limitation, we can not put both the Veto-Counter and the Tracker.
  (Removing Veto-Counter and hence lost high-precision timing info)

Selection of Tracking Detectors

❑ Multi-Wire Drift Chambers:

- Applying high-voltage (HV, ~1000V) between metal plane (cathode) and wires (anode);
- Charged particles ionize gas atoms and create electron+ion pairs along the path;

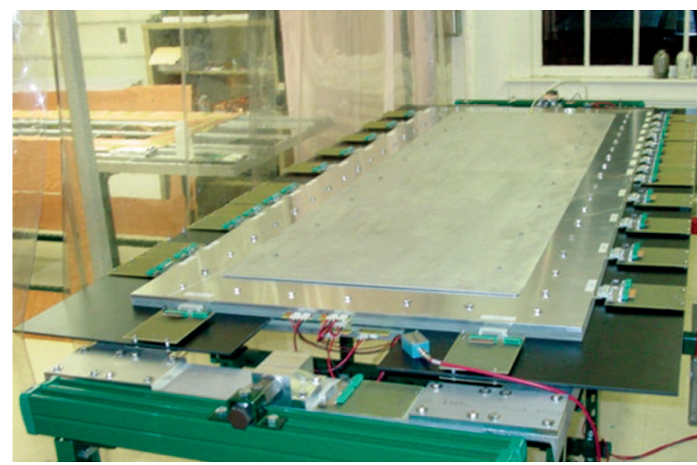




- Electrons drift to sense wires; Ions drift to metal plane;
- Electron signals amplify (10^5~10^6) when drifting to wires
- Read out current signals from wires → Pre-amplified → Discriminated → TDC

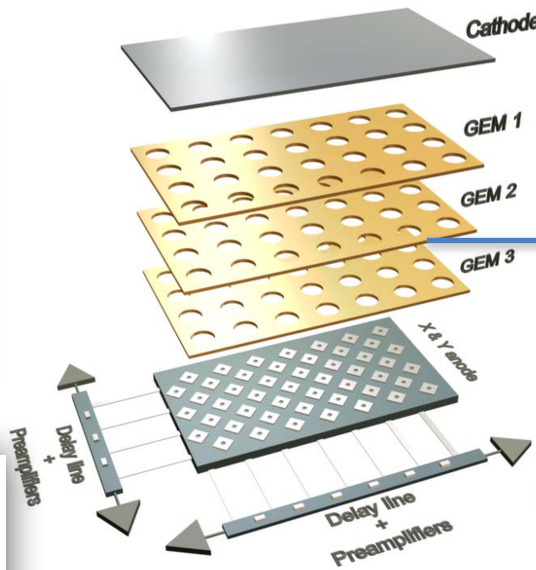
✓ High spatial resolution (~100um)
✓ Very thin materials (gas + aluminum foils)
✓ Well-known techniques; low cost; widely used

✘ Slow timing response (100ns – few µs); Not good at high rate;
✘ Sensitive to magnetic field (not an issue for PRAD)
- For PRAD:
  - ✘ A huge project to build a single 1.2m^2 plane,
  - ✘ almost impossible to put a hole at the center
  - ✘ Huge dead area if using existing two 0.5mx1.2m DC planes (many are available at Jlab)

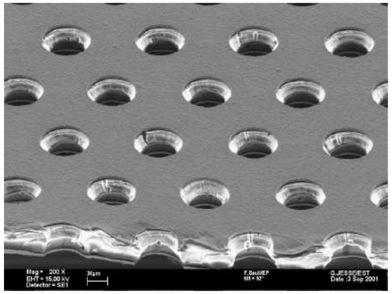


Selection of Tracking Detectors

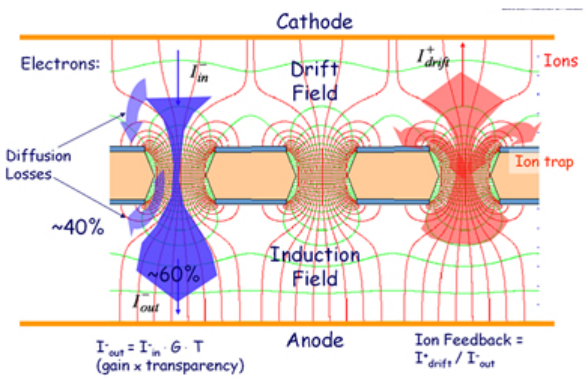
❑ Gas Electric Multipliers (GE]

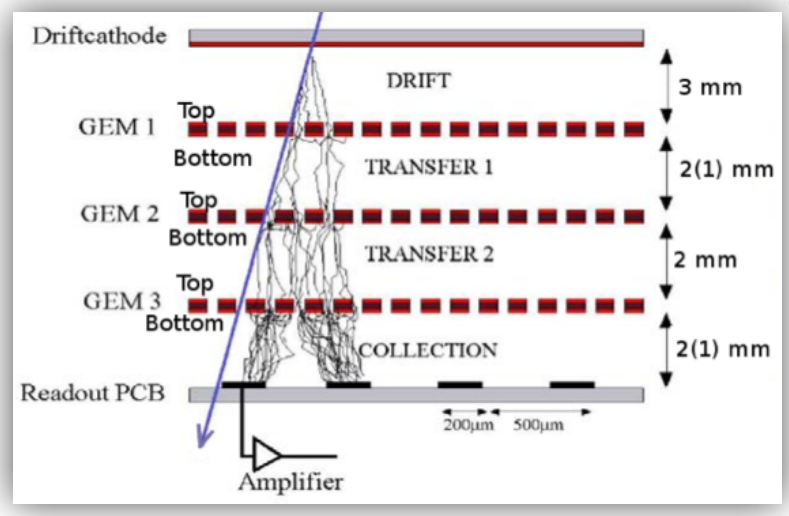


GEM Foil

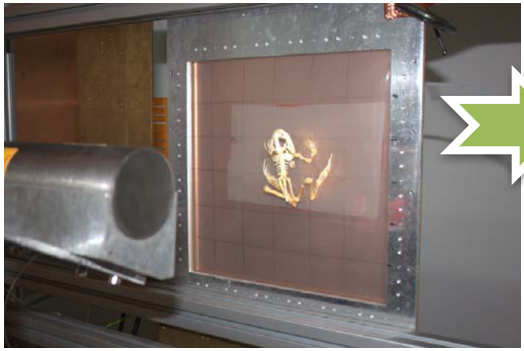


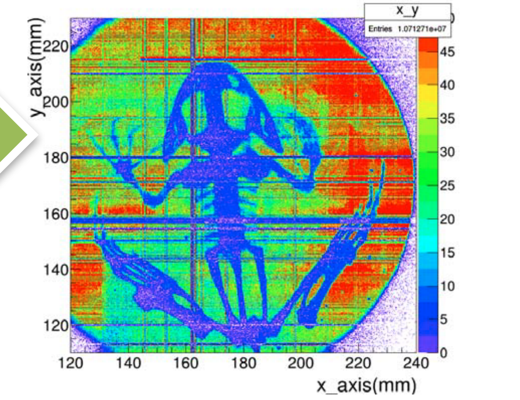
- ➢ Apply HV (~1000V) between cathode plane and GEM foils
- ➢ Strong electric field in holes
- ➢ Ionized electrons in the gas are amplified when passing through holes
- ➢ 2D read-out strips at the back plane





- ✓ High precision (<75um)
- ✓ Very thin materials
- ✓ Work in strong magnetic field
- ✓ Handel high rate
- ✘ slow time response (100ns – few µs);





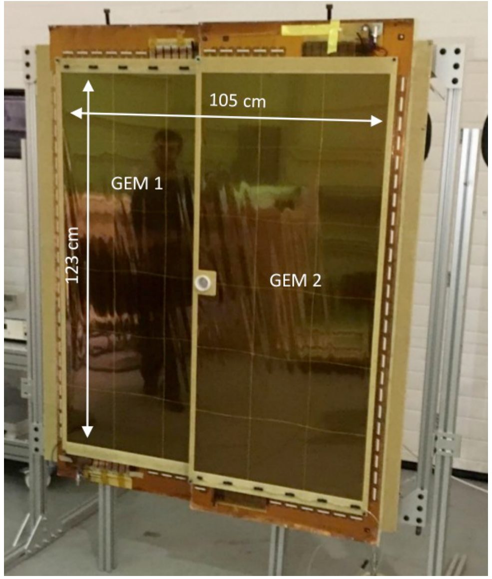
Selection of Tracking Detectors

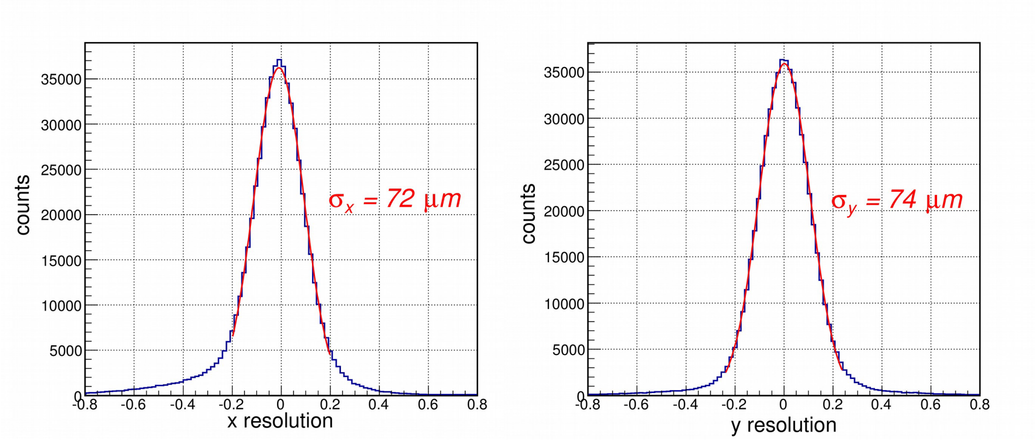
- Gas Electric Multipliers (GEM)

<u>GEM was chose to use in PRAD:</u>

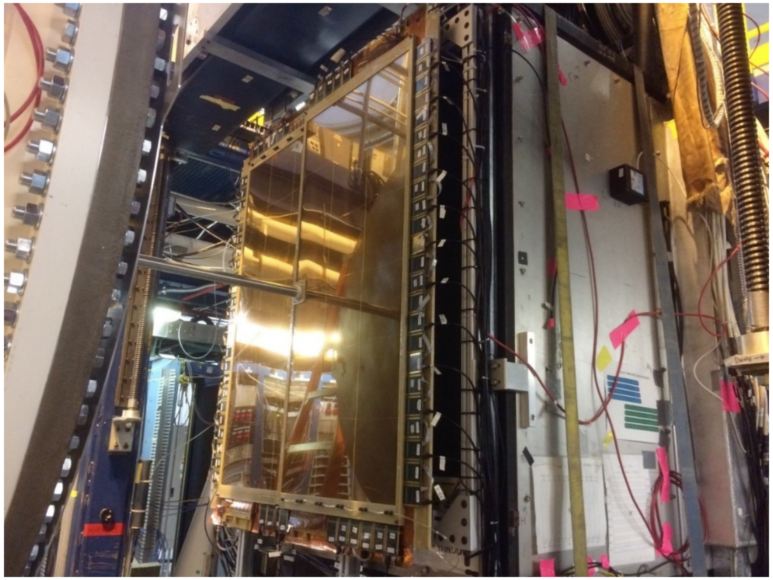
- An active production line at University of Virginia
  built the detector in 2months (PRAD was running soon!)
- APV25 based Scalable Readout System (SRS)
- Two 5 cm x 123 cm GEM detectors with 100 μm spatial resolution
- Tiny overlap between the 2 planes (7.4 x 7.4 cm^2)
- A central hole for the beam line to go through

✗ Solely rely on HyCal to provide trigger timing (large background)





Real PRAD data show very good position resolution!



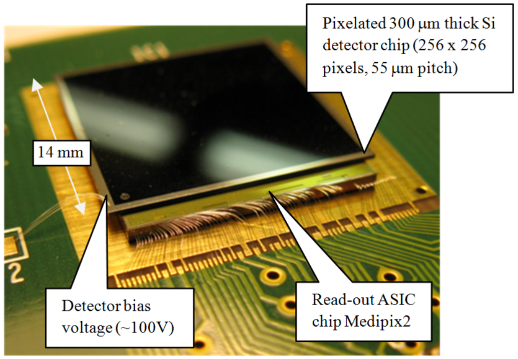
2 GEM detectors installed in Hall B beam line, May 2016

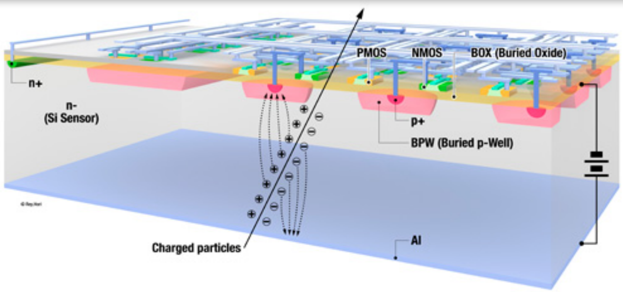
Selection of Tracking Detectors

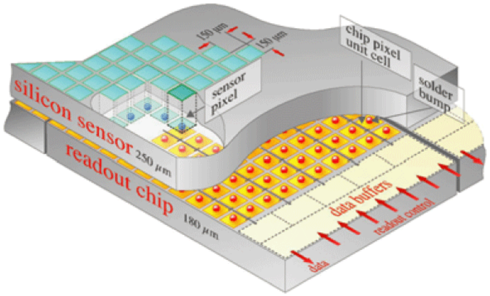
- Other Tracking Devices: *(before talking about Scintillating fiber trackers)*
  - Silicon Trackers

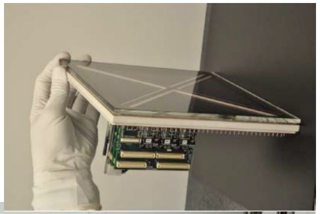
▪ Bias voltage (<80V) applied on a pn-junctions
▪ Ionization energy of charged particles creates electron+hole pairs
▪ Electrons are amplified when drifting to the sensors

✓ Well developed; High precision; Fast timing; Insensitive to magnetic field
✘ High cost; relatively thick compared with DC and GEM





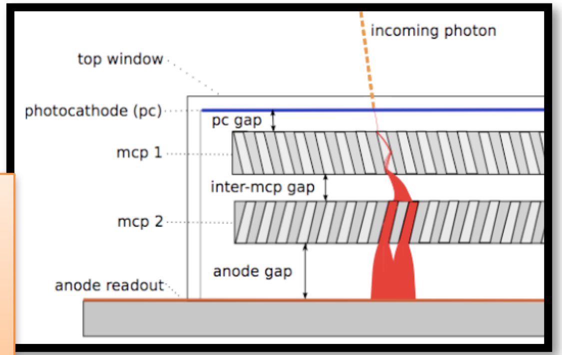




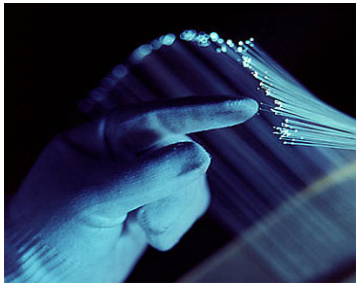
- MCP and LAPPD: *(R&D leaded by Argonne and UChicago)*

MCP→ Micro-Channel Plate
LAPPD→ Large-Area Picosecond Photodetector (MCP based)

▪ Small MCPs have been commercialized
▪ Large MCPs are been developing at UChicago
▪ High spatial resolution and precise timing
▪ Great future applications
✘ In the early R&D stage; High cost;

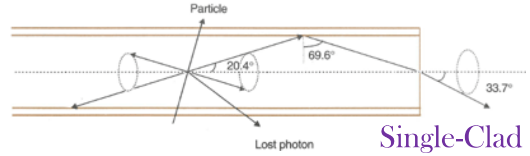


Scintillating Fiber Tracker

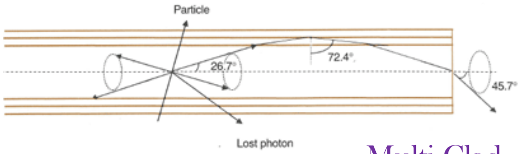


❑ Scintillating Fibers (SciFi)

- **Scintillating Material:** emits visible lights via de-excitation when a charged particle deposits its energy through ionization process;
- **Scintillating Fiber (SciFi)**: A core of plastic scintillating materials with one or several layers of thin cladding with lower index of refraction;



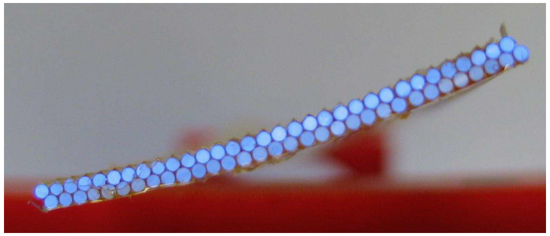
Single-Clad



Multi-Clad

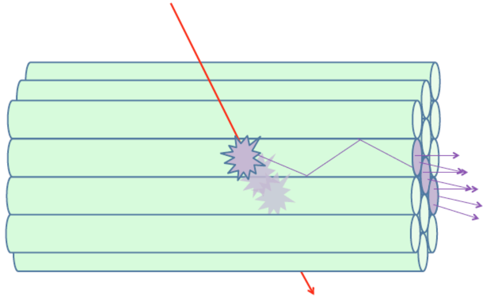
Some Characteristics of SciFi (e.g., Kuraray SCSF-78MH):

- ~1600 photons/MeV for each MIP within a 1mm fiber;
- ~ 3.1% Trap-Efficiency for Single-Clad (~5.4% for Multi-Clad);
- ~ 3 ns Decay Time;
- ~ 4 m Attenuation Length (for blue light);
- Position Resolution: $\sigma = D/\sqrt{12}$, $\boldsymbol{D}$ is the diameter of the fiber



❑ SciFi Tracker (SFT): *an old concept since 1960!*

An active detection plane with arrays of thin SciFi and read out optical light from individual fibers:



Advantages:

✓ **Good Time Response:** Provide better timing than DC and GEM;
✓ **Without Gas Systems:** Unlike GEM and DC;
✓ **Easy Handling**: Easily installed, stored and transported; can be used in vacuum or high EM field;
✓ **Easy Analysis:** Just determine which SciFi is fired ("YES/NO" algorithm).

Scintillating Fiber Tracker

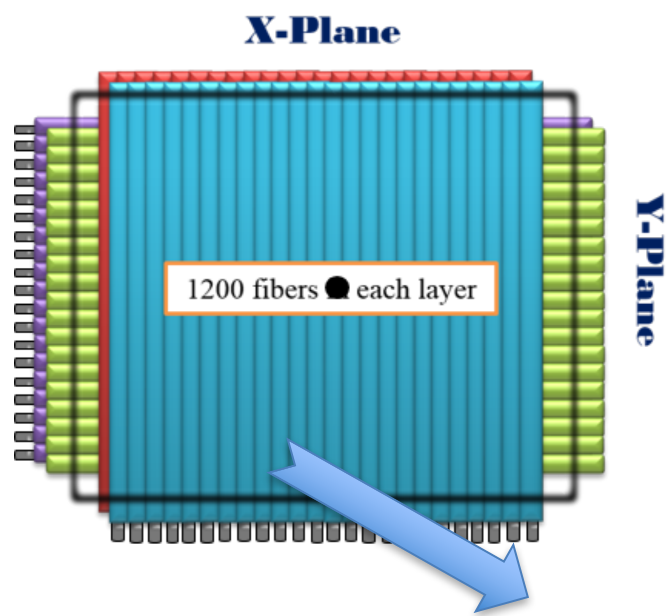
❑ SFT designed for PRAD:

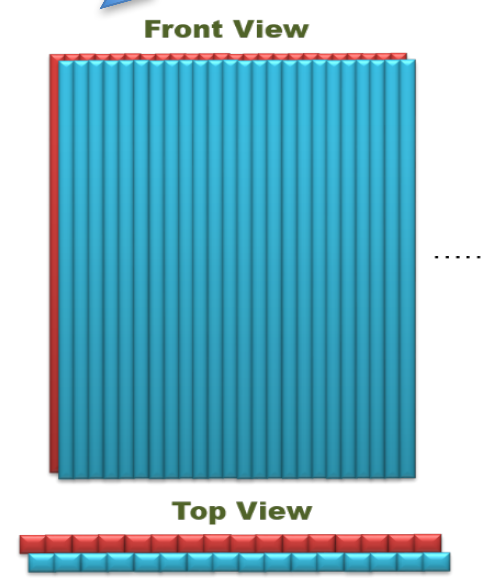
- 120cm x 120cm active area

  SciFi would be about 1.5m long
- X&Y position tracking on electrons

  Two perpendicular planes, two layers for each
- Time measurement on electrons

  Replacing veto-counter to reject photons
- A center hole allowing the beam pipe to go through

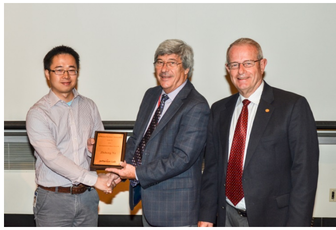




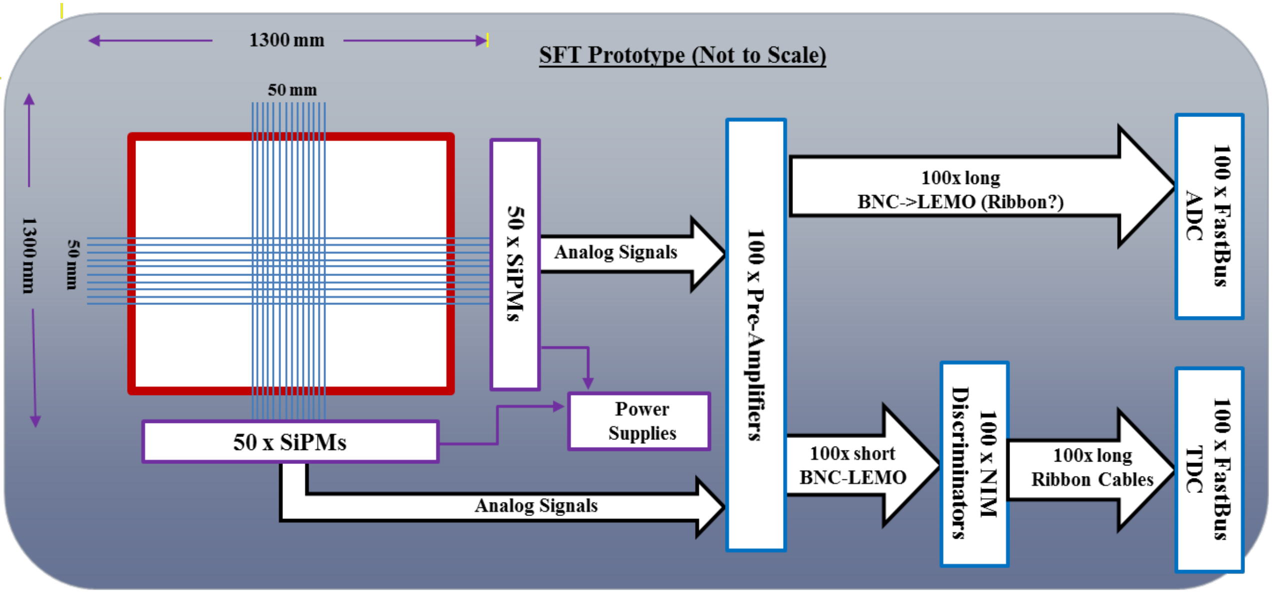
<u>Some key questions required Prototyping R&D:</u>

- What type of SciFi and how many layers?
- How to assemble the SciFi and how to support them?
- What type of photon-detector? SiPM or Multi-Anode PMT?
- What Read-Out system? FastBus, pipeline or ASCII?

Scintillating Fiber Tracker



- SFT Prototype Project (2014 JSA Postdoc Prize):



Goals:

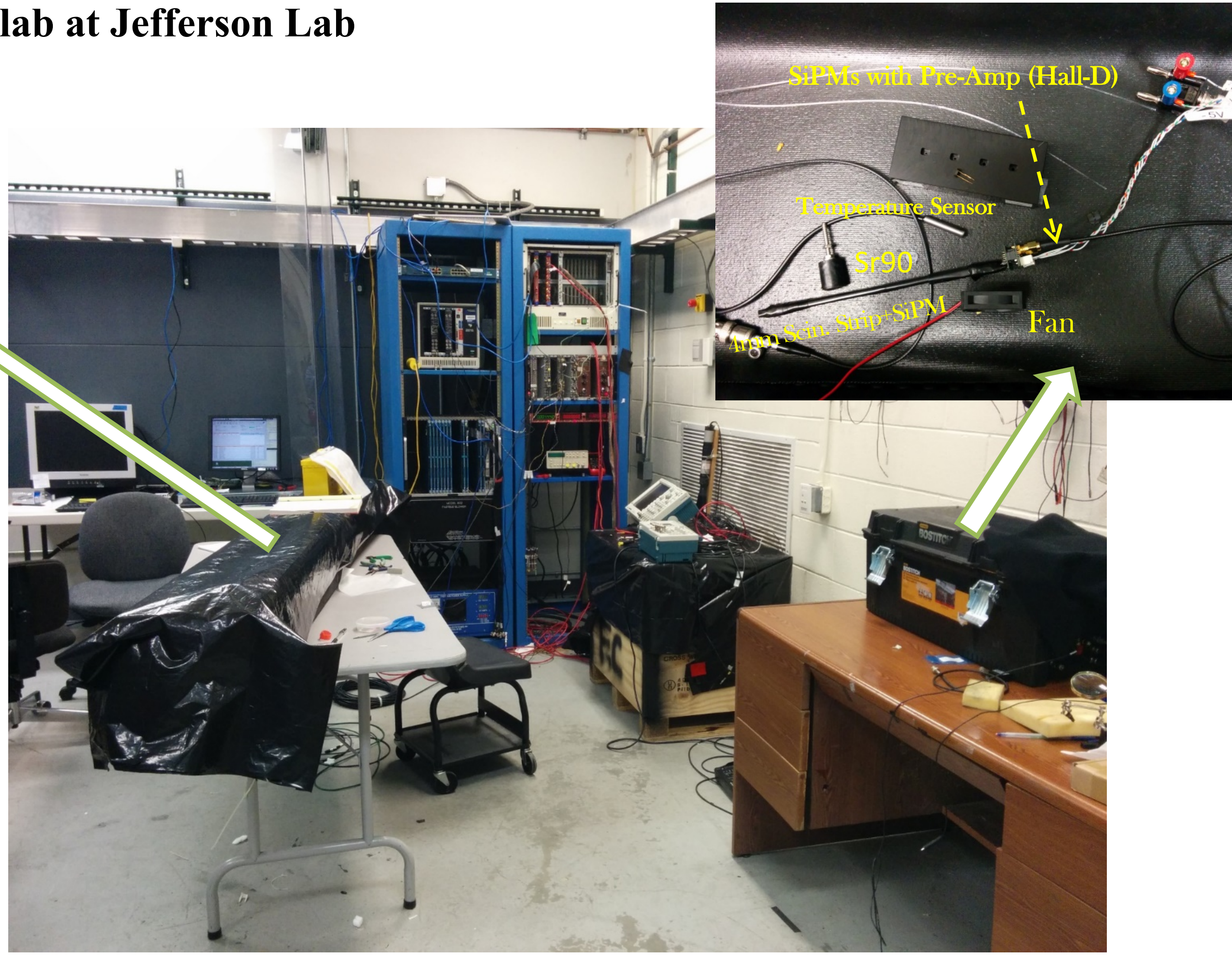
- Build a 5 cm^2 active area:
- Study the construction of a 1.2 m^2 full size detector
- Alternative Read-Out Systems

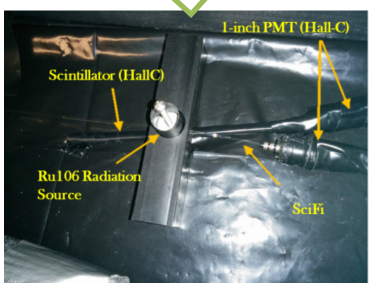
Timeline:

- After demonstrating the need of adding a tracking detector, immediately proposed a small SFT prototype Project to JSA/Jlab Initiative fund (Jan. 2014):
- Started setup the lab in March 2014 (two outstanding graduate students)
- Received award of $12K in June 2014
- *Suspended the project* in July 2014 since PRAD decided to use GEM; Graduate students and myself were pulled out to other projects.
- A Jlab experiment (DarkLight) picked up my design; MIT is building the a 10cm^2 SFT
- Moved to Argonne and setting up a lab locally; Looking for other applications.

Scintillating Fiber Tracker

- Overview of my lab at Jefferson Lab





Scintillating Fiber Tracker

- SciFi Testing Setup:

Goal:
Measuring the Light-Yield and Attenuation Length for different types of SciFi.

The types SciFi being testing:

✓ New Fiber-Samples from Kuraray:

1, x2 SCSF-78MJ , 1mm, **Round**, 3meters, Multi-Clad

2, x2 SCSF-78MSJ , 1mm, **Round**, 3meters,
mechanics stronger, Single-Clad (30% less light yield)

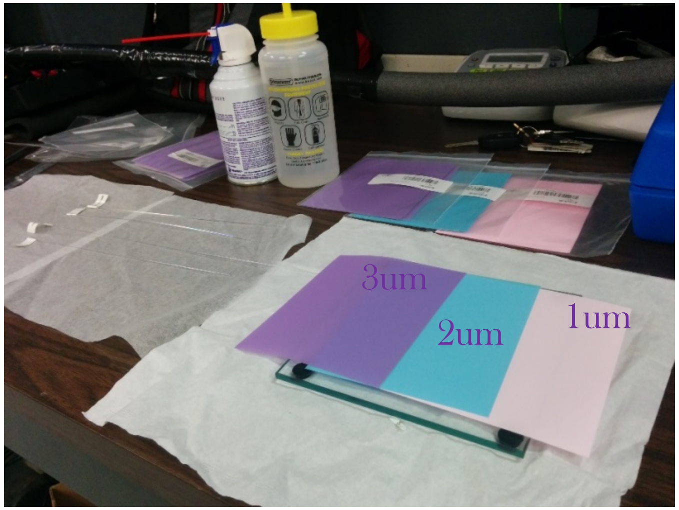
3, x2 SCSF-78J, 1mm, **Square** , 3meters

4, x2 SCSF-78J, 1.5mm, **Square** , 3meters

✓ From Hall-D: x8 SCSF-78MJ 1mm, **Round**, 2 meters

Fiber Polishing:

- Used sand paper to polish the fiber end (very inefficient and poor quality control)
- Borrow a diamond cutter & polisher from Jlab detector group for 1mm round fibers (worked great)
- Still had to polish other fibers by hand



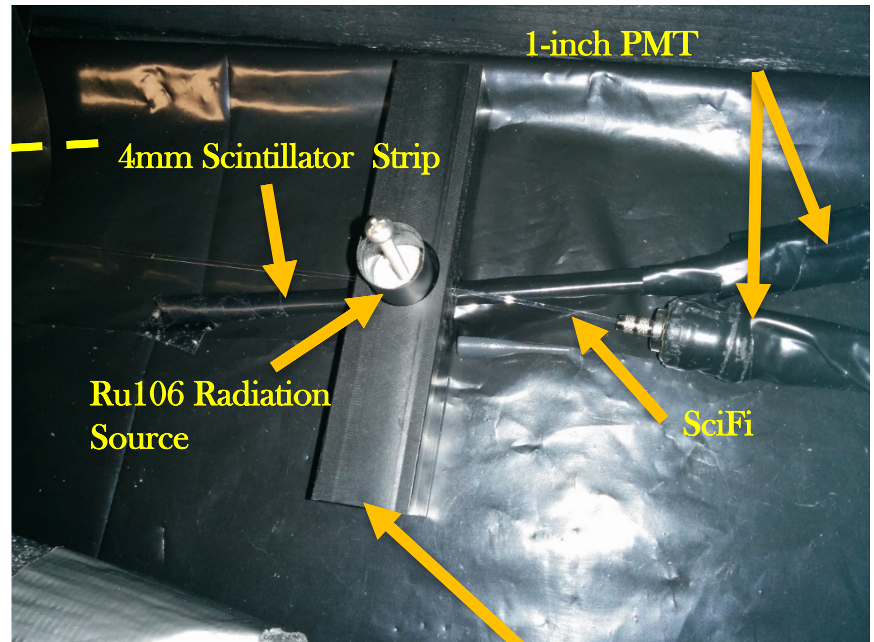
SciFi Polishing Tools

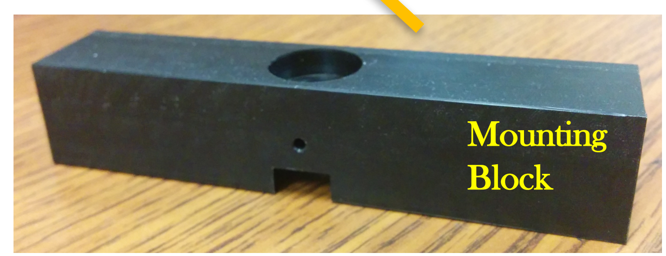
Scintillating Fiber Tracker

- SciFi Testing Setup:

A 200cm x 20cm Black-Box

SciFi Test Setup





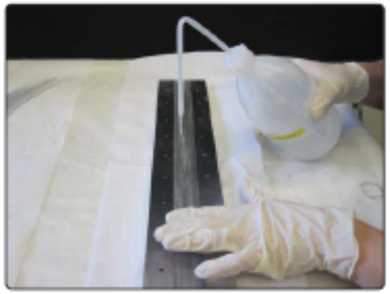
Designed by myself and made by Hall-C Machine Shop (for free)

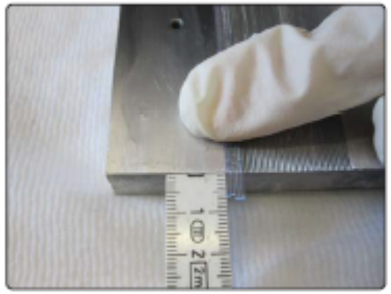
- Used Ru106 Radiation Source to study the light output from different types of SciFis
- Used a 4mm scintillator-strip as a reference
- Use 1-inch regular PMT as photo-detectors
- Tested the reduction of light-yield along the 1.5m-long fiber
- Blue- and green-light LEDs were available (didn’t have chances to implement before I left Jlab)

Scintillating Fiber Tracker

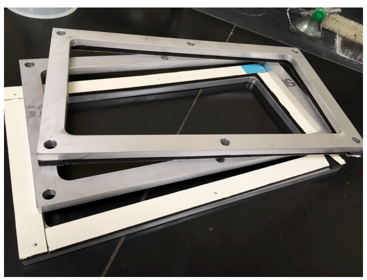
❑ Investigating the Assembling & Mounting

Aluminum Assembly Plate (Mainz Univ.)

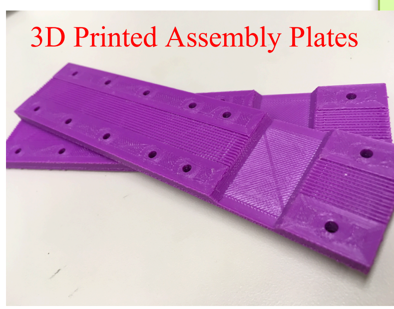


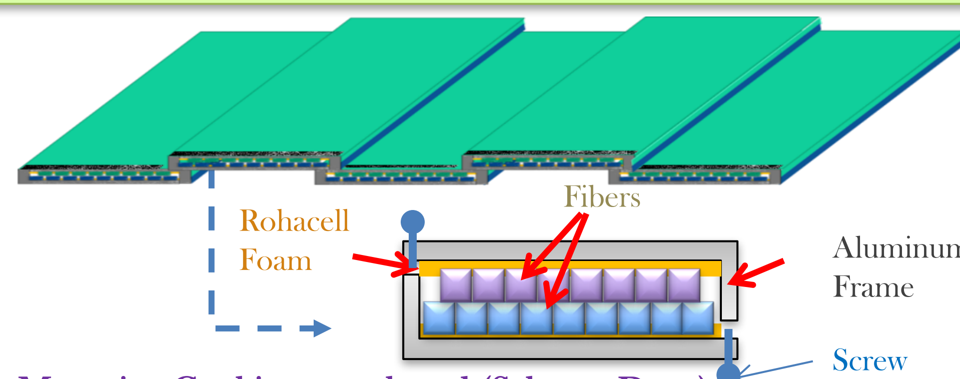


- Use the assembly method developed by another lab
  - Aluminum plate with fine curves to hold fibers into array
    (Currently used 3D printer to make small plates)
  - Used non-Oil-based pains to glue fibers and shield light
- Divided the 1.2 wide plane into multiple groups
- Need Good mounting cookie design



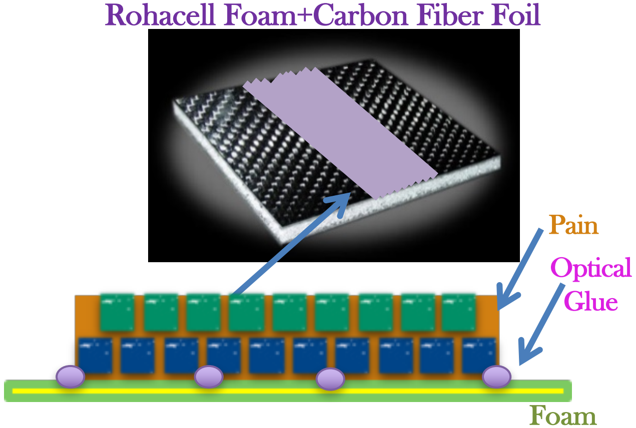
5cm x 10 cm mounting frame





Mounting Cookie on each end (Scheme Draw)

Rohacell Foam+Carbon Fiber Foil



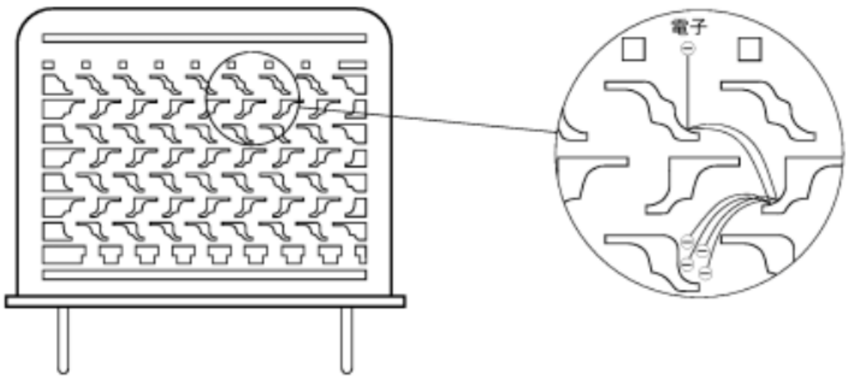
❖ **Challenge**– How to avoid the horizontal SciFis (Y-plane) to be pulled down by their weights?

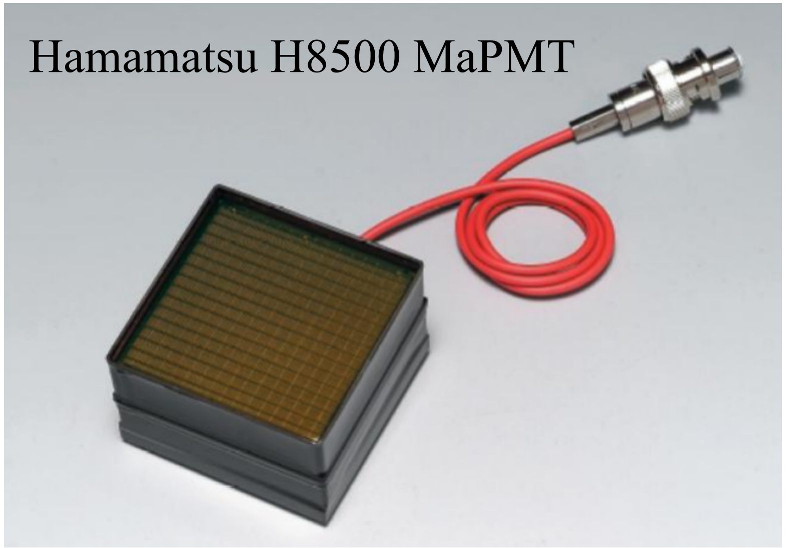
Solution: Glue them on a plane with Rohacell foam+carbon fiber foils
Problem: Adding more dense materials (potential radiation background)

Scintillating Fiber Tracker

- Photon Detectors:

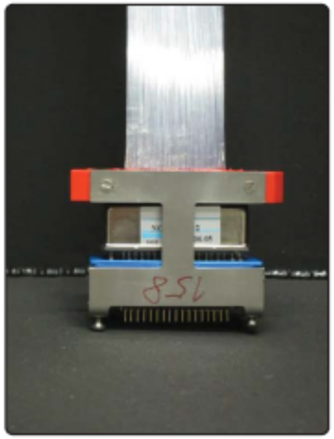
Option#1: Multiple Anode PMT (MaPMT)

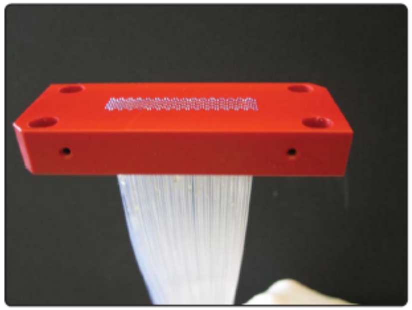




- ✓ More commonly used;
- ✓ Multi-channels outputs (x16, x32 or x64)
- ✓ High radiation tolerance;
- ✓ Can use ASCII Read-Out (e.g., MAROC)

- ✗ Degraded performance in strong magnet field;
- ✗ Cross Talk
- ✗ Expensive ($3K for a 64 Hamamatsu MaPMT+HV power suppliers + TDC/ADC);





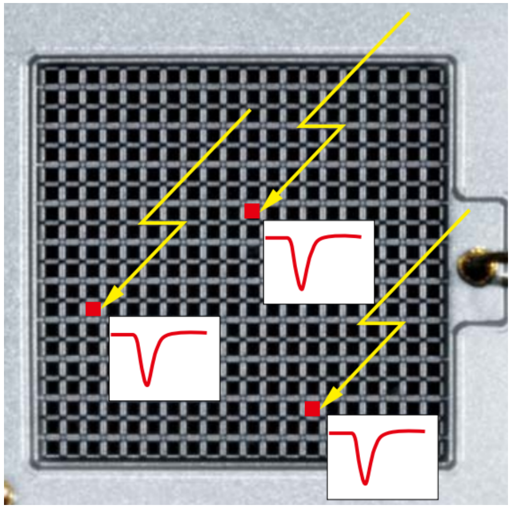
Scintillating Fiber Tracker

❑ Photon Detectors:

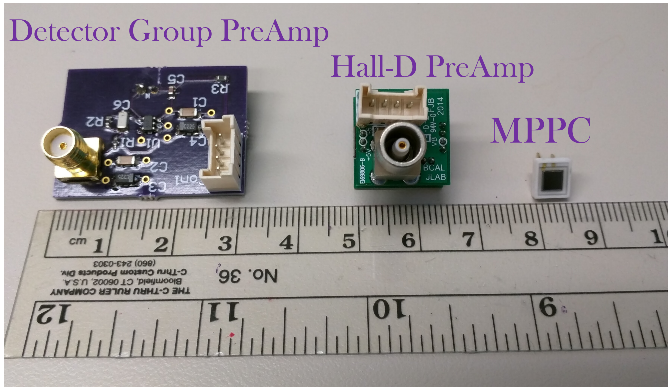
Option#2: Silicon Photon Multiplier (SiPM) Avalanche Photodiode (APD) pixels working in Geiger-mode

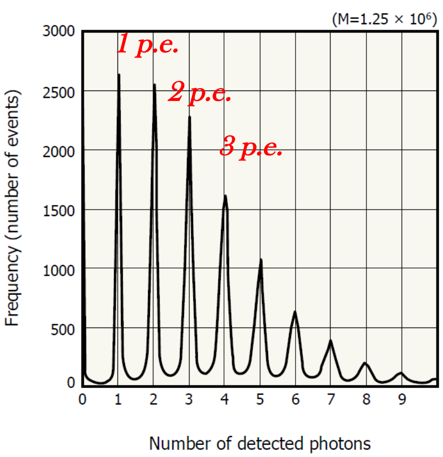
- ✓ Cheap →~$10 per SiPM+~$10 power supply+~$10 Pre-Amp;
- ✓ Large Gain → x10^6 ;
- ✓ Insensitive to magnet field
- ✓ Sensitive to low photon yield; Photon Counting (at low rate)
- ✓ Need a good Pre-Amp Design
- ✓ Can use ASCII Readout

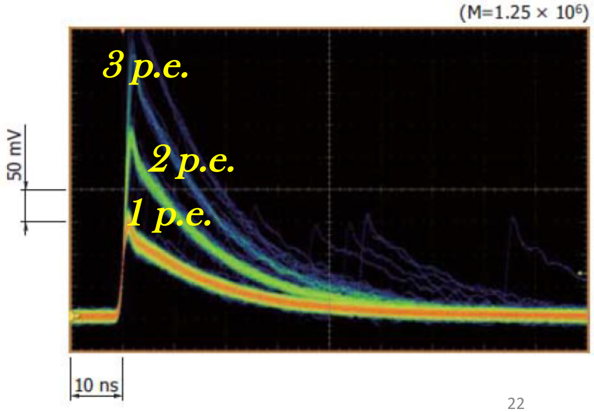
- ✗ Gain is temperature-depended
- ✗ Relatively larger dark current;
- ✗ Radiation damage by the neutron background;
- ✗ Cross-Talk



One photon only fire one pixel (unless cross-talk or dark-current)







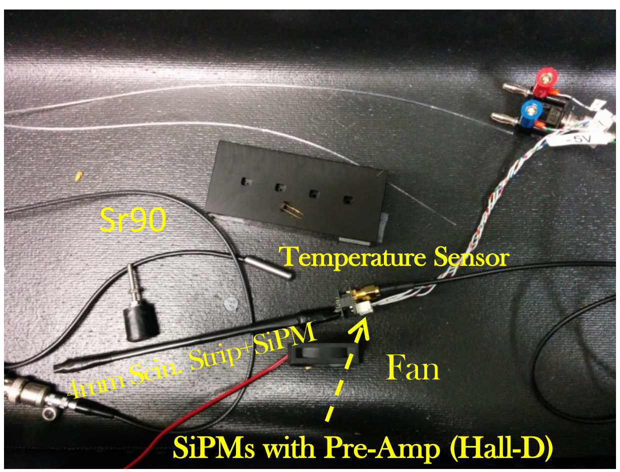
Scintillating Fiber Tracker

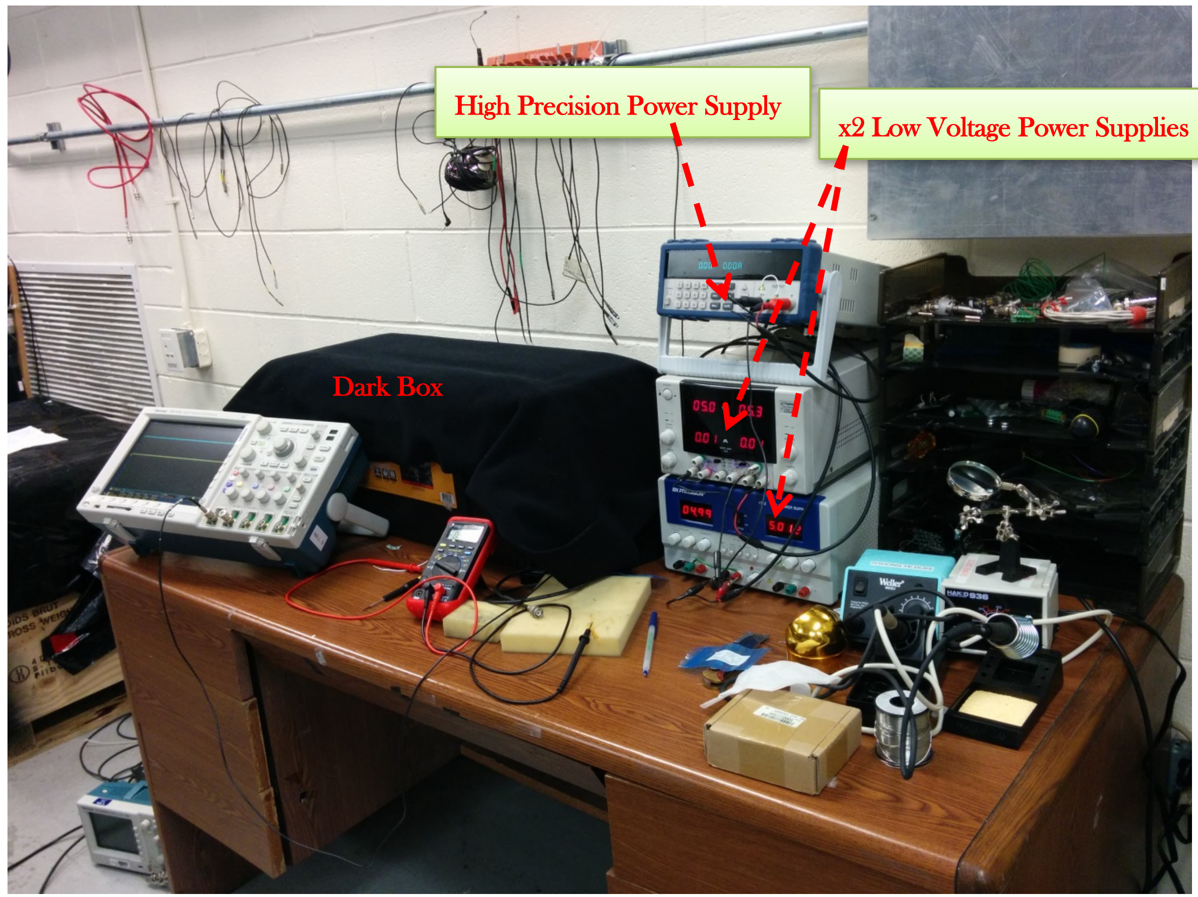
- ❑ SiPM Test Setup:

  Goal:

  Understand the performance of the SiPM --- Gain, Noise Level, Stability with Temperature, ADC & TDC spectra.

Fiber+SiPM Mounting Block designed by myself





Scintillating Fiber Tracker

- ❑ Read-Out System of >2400 Output Channels:

1, SiPM (or MaPMT) + FastBus ADC + TDC

Requires a large amount of NIM modules and long delay cables

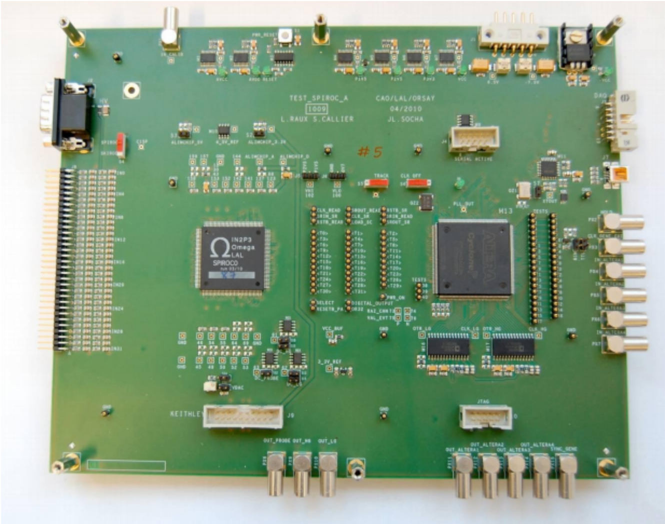
2, SiPM (or MaPMT) + flash ADC (pipeline modules)

Need >20 flash ADC & VME64 which are very expensive

3, A "Cheaper" Solution → ASCII Read-Out Electronics

e.g., EASiROC for SiPM or MaROC for MaPMT

- Pre-Amp integrated with adjustable Low/High Gains;
- ADC outputs and/or TDC outputs;
- Programmable logic output for triggering;
- ADC-SUM analog output ;
- ~$130 for each chip (or <$5 per channel);
- Need an additional readout board ("expensive")



OMEGA Test Board (USB readout)

With SiPM+ASCII Read-Out, the SFT will be "portable"!

Summary

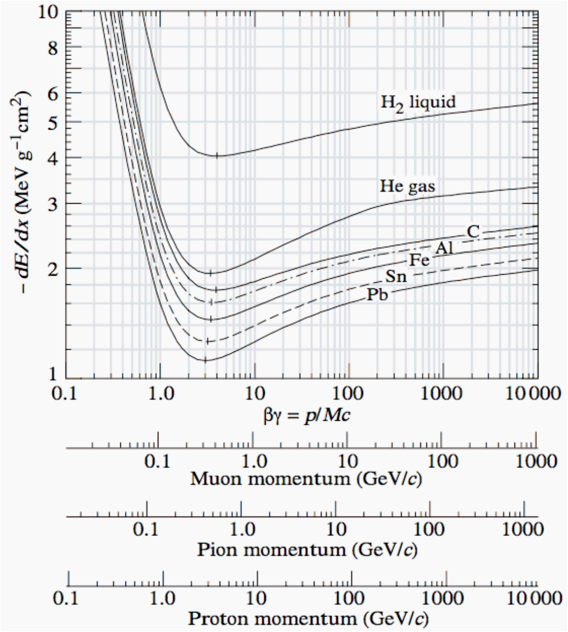
- By examining the precision goal of the PRAD experiment, demonstrated the need of adding a tracking detector with better than 0.3mm spatial resolution
- Among different tracking devices, the Scintillating Fiber Tracker (SFT) can provide both precise position resolution (<0.3mm) and fast timing (<1ns).
- The SFT Prototype Project was proposed to study a 5cm^2 active plane with SiPM read-out, and also investigate the construction of 120cm^2 full size detector for PRAD (2014 JSA postdoc prize)
- Had set up a lab with two graduate students to test the SciFi samples and SiPM samples
- Learned lots of experience about designing a detector, managing a lab and fund, and interacting with different people/groups/companies.
- Due to limited funds man-power and time, PRAD decided not to use SFT but GEM; Project was suspended but the design was picked up by other collaborations;
- The design is in a good shape; Looking for new applications.

Backup Slides

Particle Passing Matters

- Average Energy Loss (Bethe-Block Formula)

$$\frac{dE}{dx} = -Kz^2 \frac{Z}{A} \frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\gamma^2\beta^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$



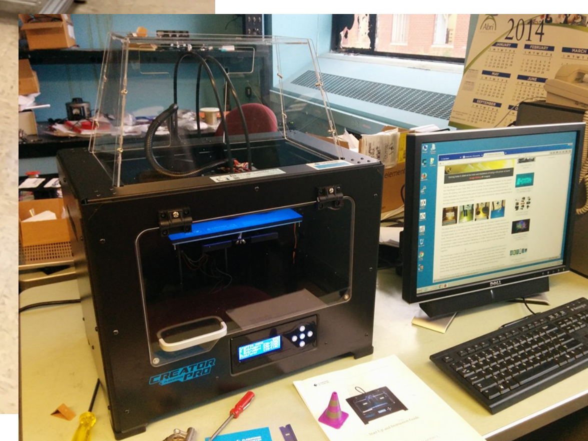
- Multiple Scattering:

$$\theta_0 = \theta_{\text{plane}}^{\text{rms}} = \frac{13.6\,\text{MeV}}{\beta c p} z\sqrt{x/X_0}\left[1 + 0.038\ln(x/X_0)\right]$$

Scintillating Fiber Tracker

- ❑ **Overview of my lab at Argonne National Lab (under development)**

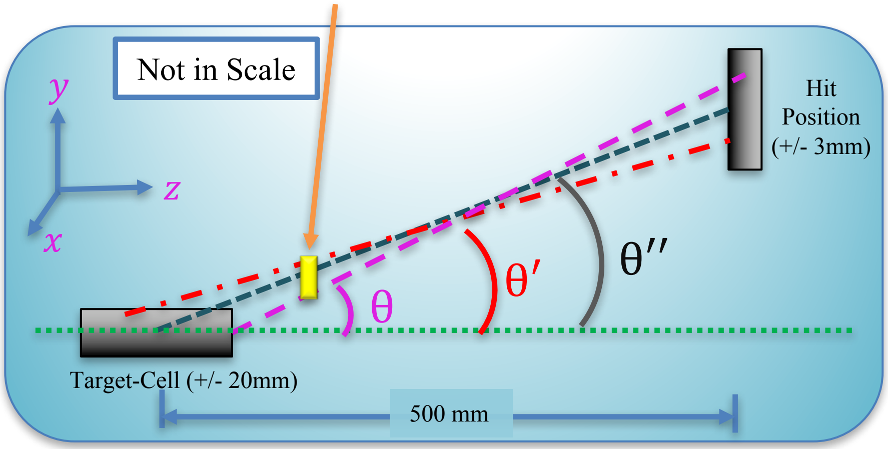
Dark-Box

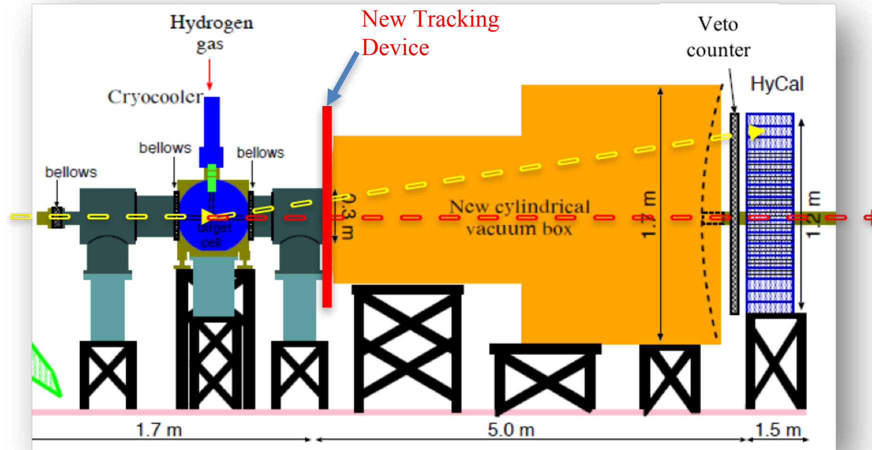


3D Printer

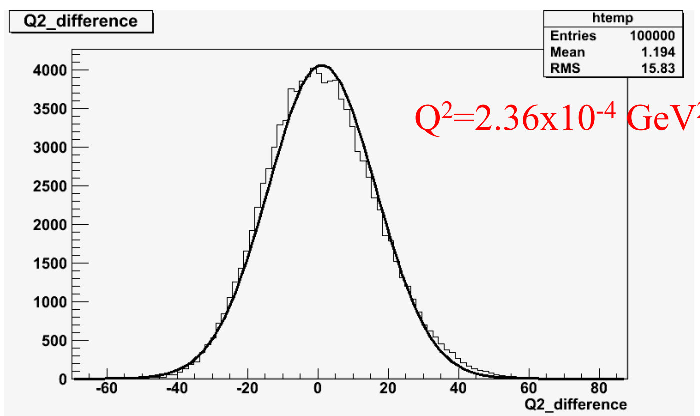
PRAD Experiment

- Updated Designs – Add Tracking Detectors
  - Option#1: Add **one** tracking plane near the target, plus HyCal to determine reaction point+Angle





e.g., one at 60 cm, w/ 0.3mm resolution

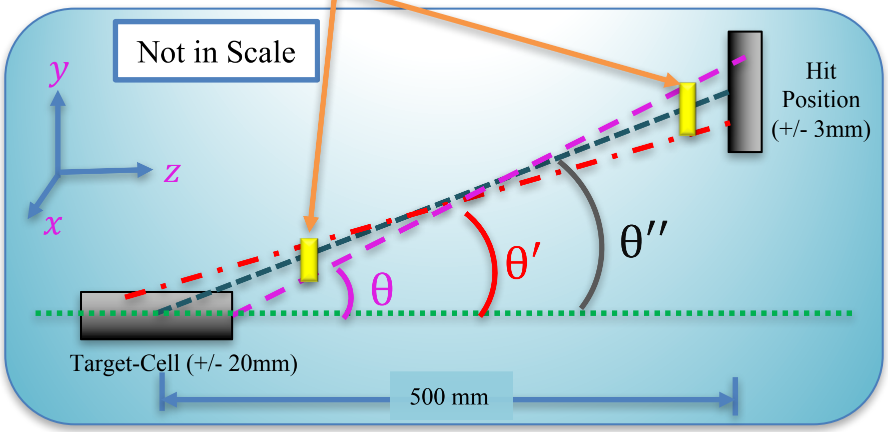


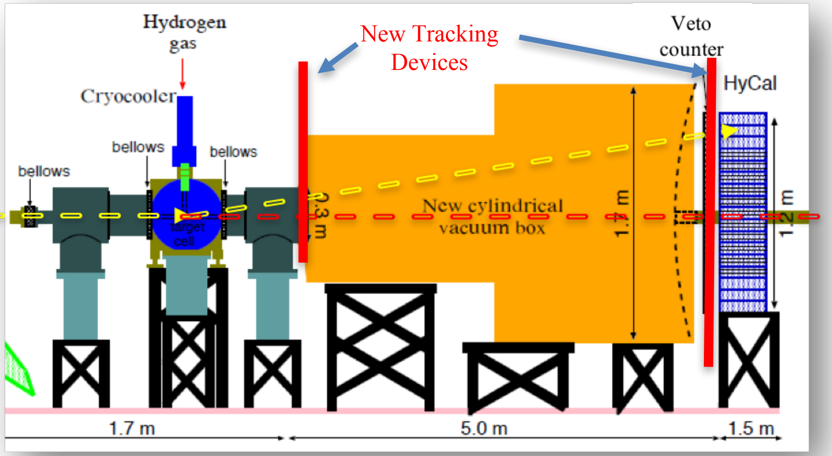
(%)

- ✘ Compared with assuming reactions always happen at the center of the cell (hence assume +/-2mm uncert.), direct reconstruction of the reaction location will totally destroy the resolution of Q2.
- ✘ Putting a detector near the target can introduce "thick" materials which smear the scattering angles due to the multiple scattering effect.
- ✘ It is also extreme difficult to put a tracking detector inside a vacuum chamber

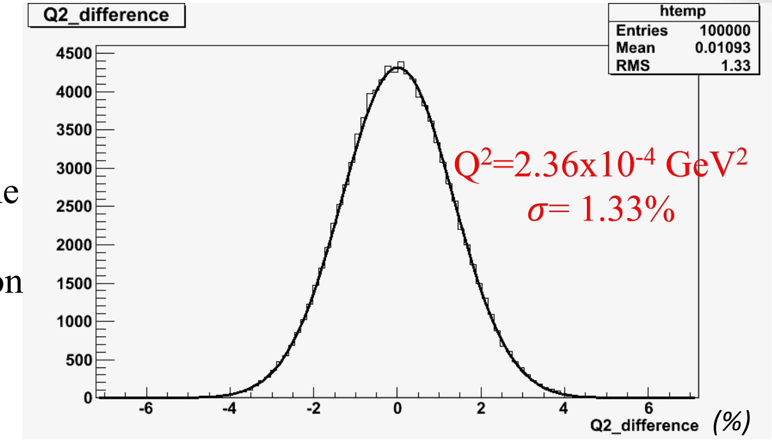
PRAD Experiment

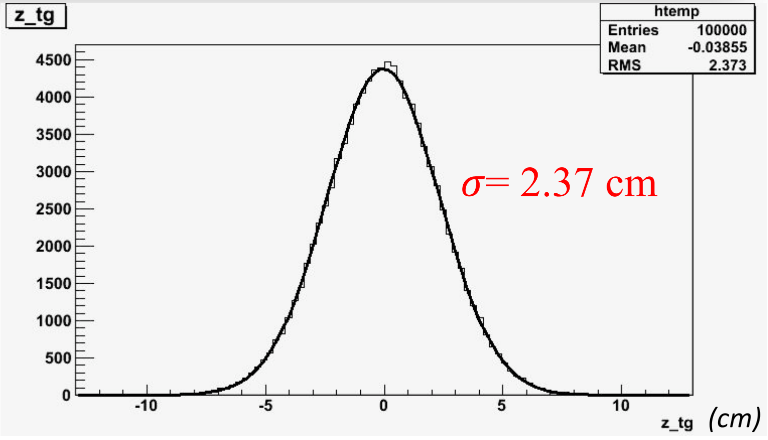
- ❑ Updated Designs – Add Tracking Detectors
  - ➢ ***IF*** we can find a very "thin" tracking detector which can also be installed in a vacuum:
  - ➢ Option#2: Add **two** tracking planes





e.g., one at 60 cm, the other one at 490 cm, w/ 0.3mm resolution





- ✓ The resolution is roughly close to the expectation with two tracking planes
- ✘ The resolution of the reaction point is: 2.37 cm > half of the cell-length (2cm), so not useful totally!
- ✓ It is still a better option to continue assuming the reaction always happens at the center of the target-cell

Scintillating Fiber Tracker

- Existing similar detectors (since 1990s):
  - D0 in Fermi Lab: 0.84 mm SciFi + Visible Light Photon-Counter (VLPC)

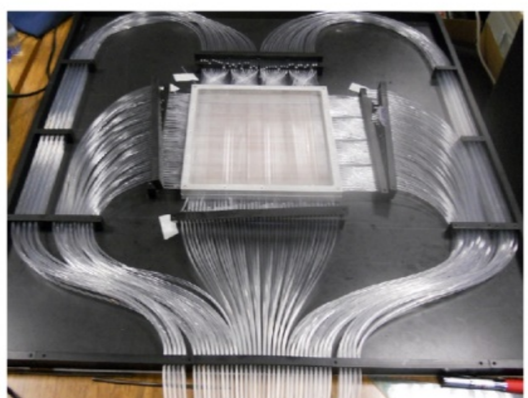
    Four concentric cylinders

  - KAOS in Mainz: 200cm wide 50cm long 0.25mm SciFi + Multi-Anode PMT, 200cm x 50cm, only the vertical plane

  - UA4 (1984), ISPA (1994), CERN-SPS (1994), HERMES, ATLAS, PEBS ...

- New detectors under developing:

LHCb: 300cm long 0.25mm round SciFi+ SiPMs, 250cm x 52 cm, 5 super layers, only the vertical plane

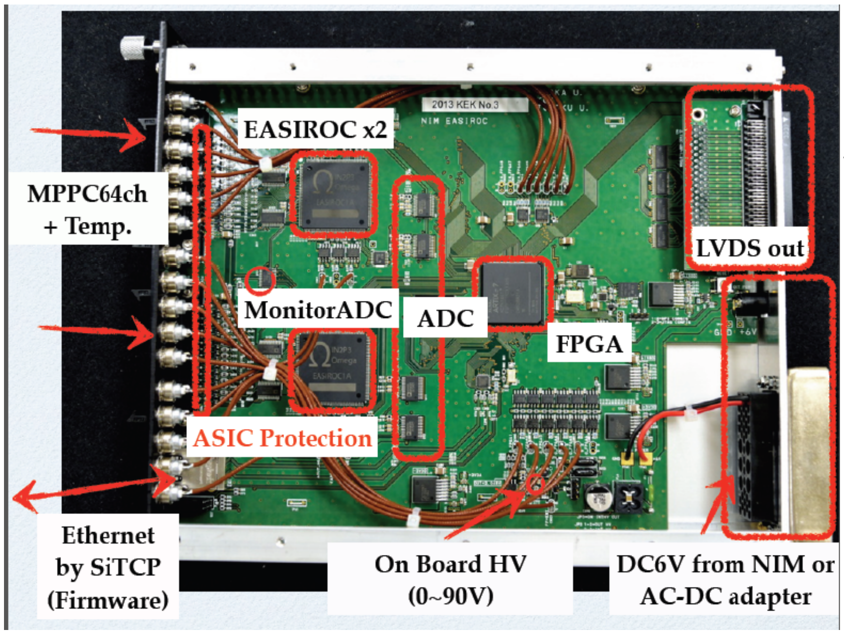


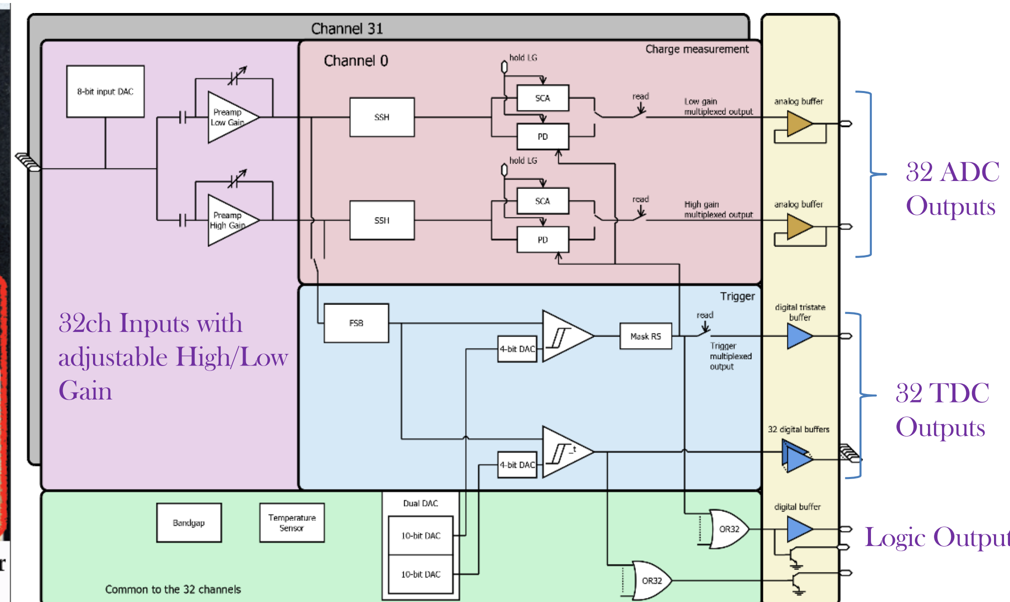
- Mainly applied in Medical Imaging (small size): e.g., Proton Computed Tomography Scanner (FERMILAB-PUB-12-067-E), INFN

Scintillating Fiber Tracker

- Read-Out System of >2400 Output Channels:

EASIROC (or the new version called CITIROC)





SiTCP read-out board designed at KEK (TCP/Ethernet 1Gbps)

NIM-based Read-Out Board designed by I. Nakamura (KEK) for J-PAC

With SiPM+ASCII Read-Out, the SFT will be "portable"!