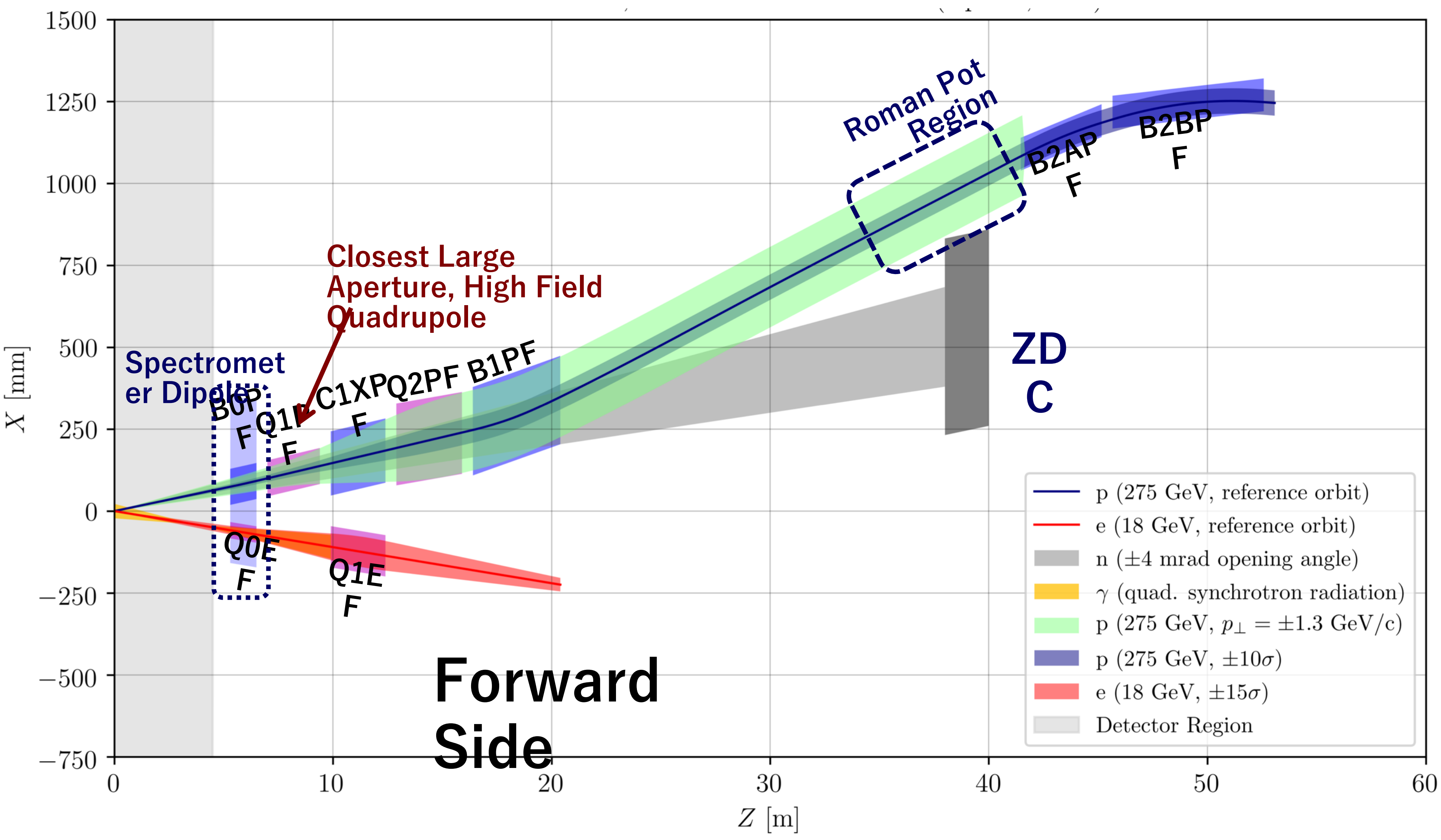
ZDC Detector Technology Choice

RIKEN

Itaru Nakagawa

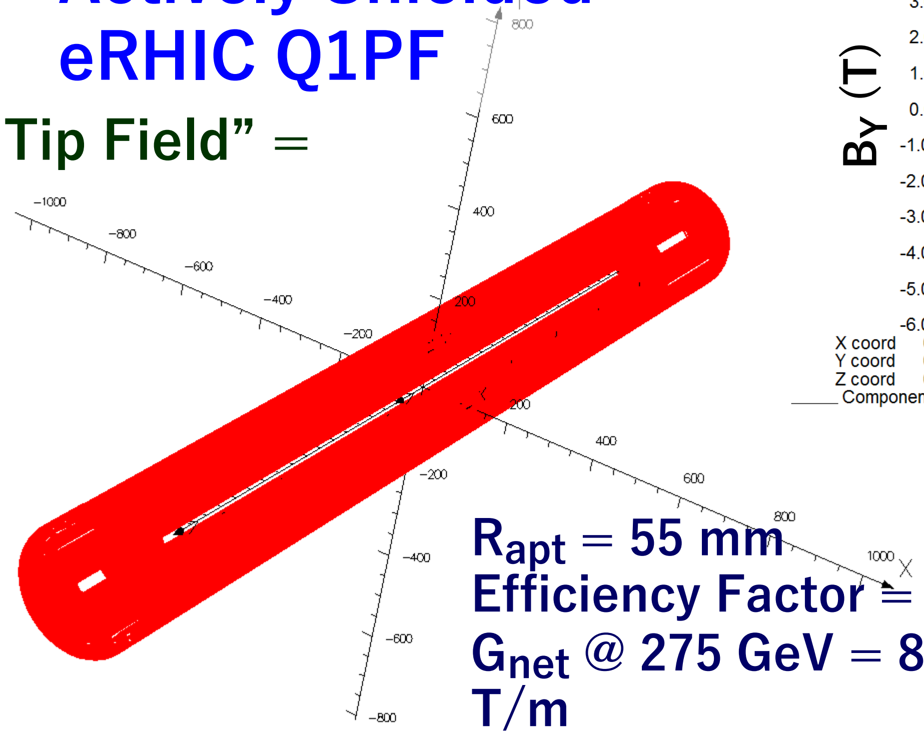
eRHIC Forward Magnet Apertures



Compact Forward Magnet Example

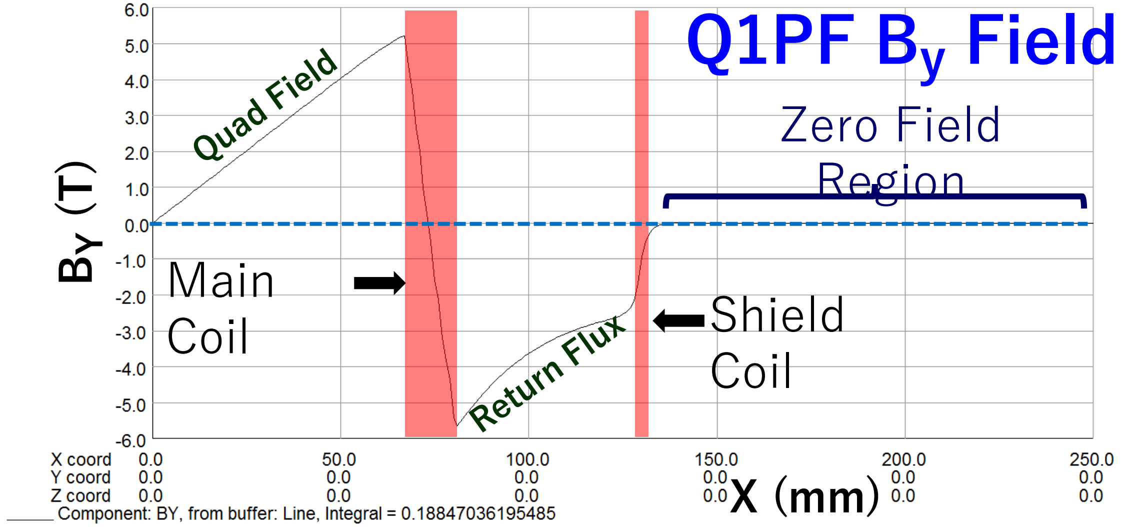
Direct Wind, NbTi, Actively Shielded eRHIC Q1PF

“Pole Tip Field” = 4.4 T



R_{apt} = 55 mm
Efficiency Factor = 90%
G_{net} @ 275 GeV = 80.8 T/m

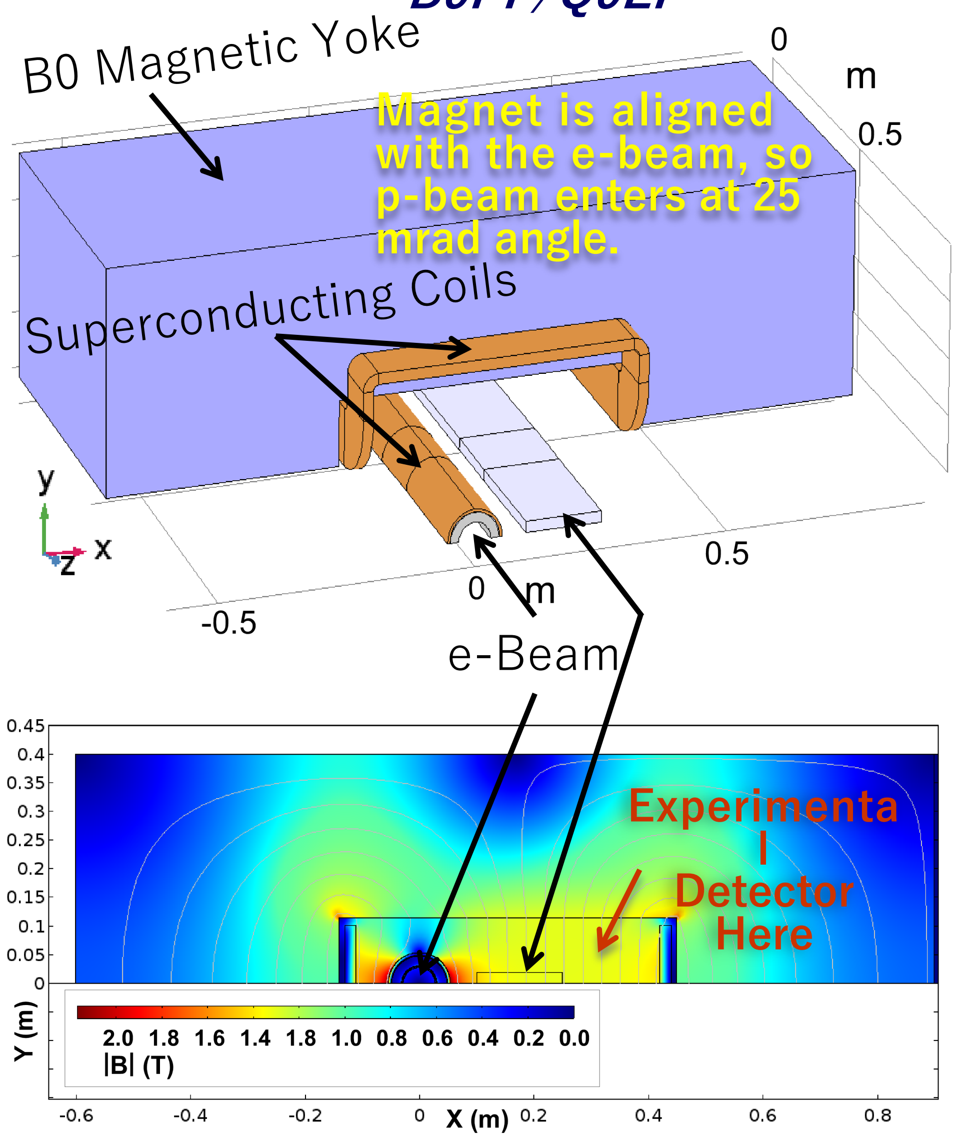
Budget for outer structure was set to accommodate the electron beam pipe.



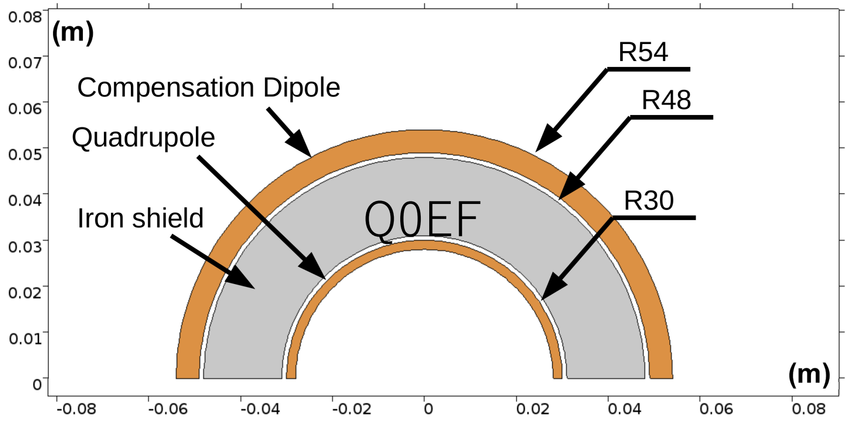
- Forward magnets must have large apertures to accommodate neutrons and forward charged particles.
- But combination of large aperture and large gradient mean a large B-field at the coil….
- However, the electron beam must be shielded from any large external fields.

Shielding e-Beam Inside Spectrometer Dipole

B0PF/Q0EF



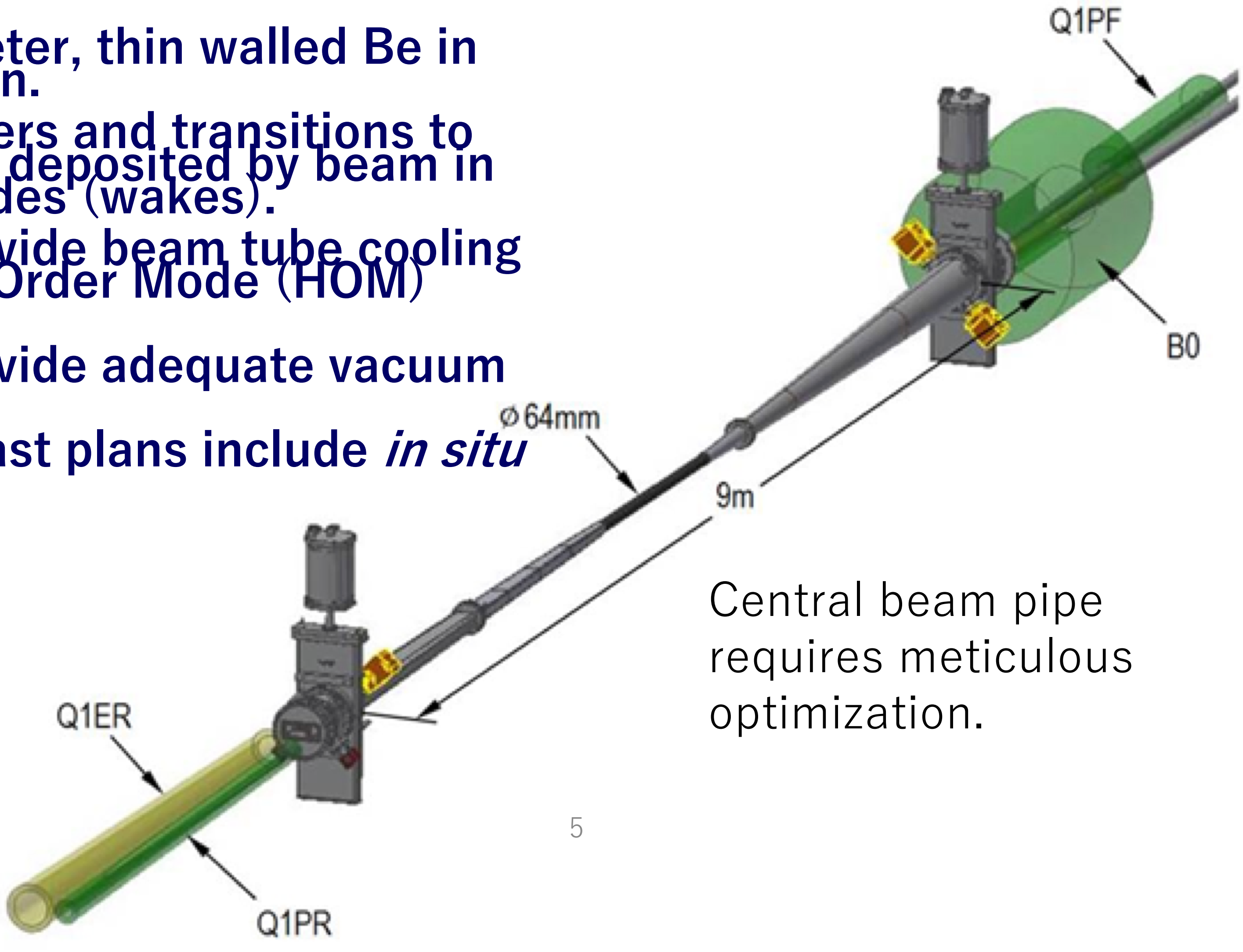
1.3 T Cancel Coil Detail



- eRHIC IR needs to pass an e-beam through main aperture of first hadron spectrometer dipole (B0PF).
- First electron quad (Q0EF) inside B0PF.
- With a combination of a bucking dipole and passive shielding, this can be accomplished.

Detector Beam Pipe

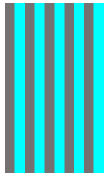
- **Small diameter, thin walled Be in center region.**
- **Smooth tapers and transitions to limit energy deposited by beam in trapped modes (wakes).**
- **Need to provide beam tube cooling and Higher Order Mode (HOM) absorbers.**
- **Need to provide adequate vacuum pumping.**
- **eRHIC / Beast plans include *in situ* bakeout.**



Central beam pipe requires meticulous optimization.

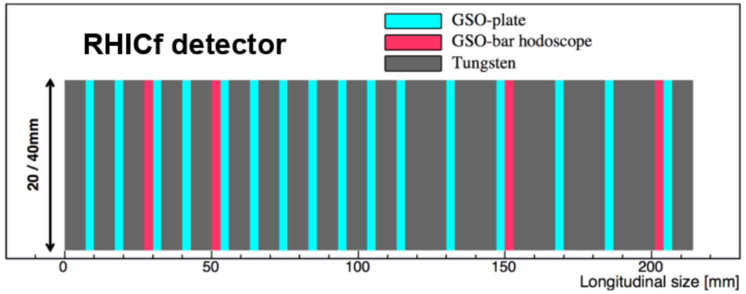
Detector Idea?

Low Energy Section?



$2\sim3X_{rad}$

Sampling Type EM Section



Hcal Extension

Shower Max Choices	Radiation Hardness	Cost	Position Resolution	Experiments
Quartz Fiber	good	Inexpensive	Poor	ALICE, JZCaP
Scintillator Fiber	poor	inexpensive	OK	RHICf
Silicon Sensors	OK	Expensive	Best	RHICf, FoCAL, TOPSiDE

JZCAP

Joint **Z**ero degree **Ca**lorimeter **P**roject (**JZCaP**)

- ATLAS + CMS joint R&D effort
- In contact with LHCb and sPHENIX to expand the collaboration
- New collaborators are welcome! j.zdcrd@cern.ch

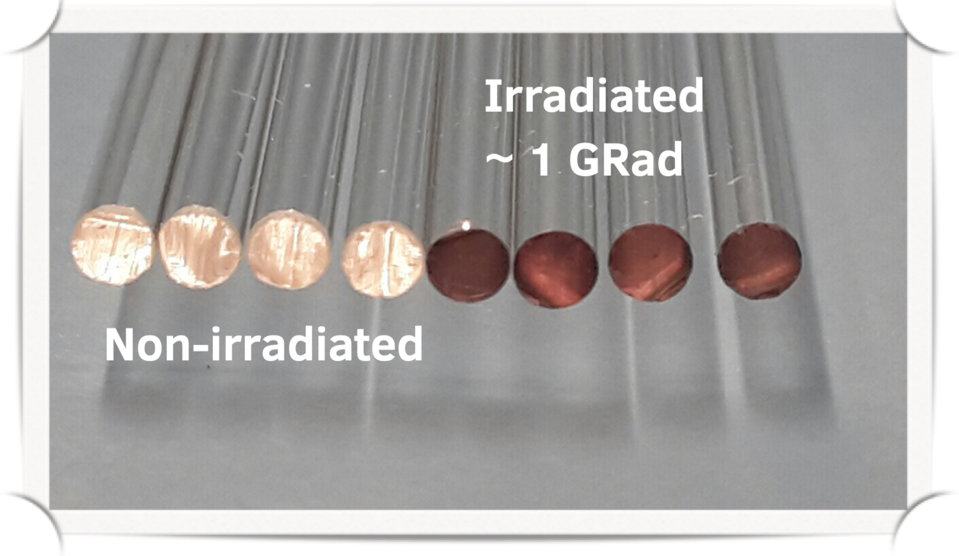
- University of Kansas
- University of Maryland

- Ben Gurion University
- BNL
- Columbia University
- University of Illinois

MOTIVATION - RADIATION DAMAGE

- The LHC upgrade during LS3 requires a rearrangement of the beam line.
- Less space left for the ZDC (from TAN - 10 cm, to TAXN, 5 cm) —> **Narrower ZDC** modules for Run4.
- TAXN ~ 15 m closer to the interaction point compared to TAN.
- Radiation levels will further increase.

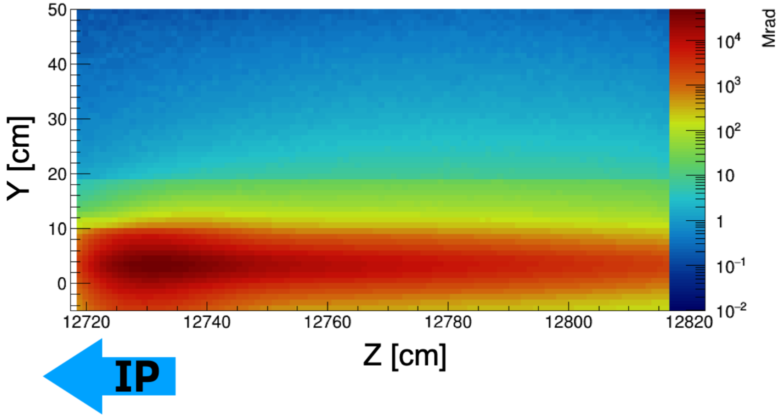
Current ZDC rods (GE 214 fused quartz)



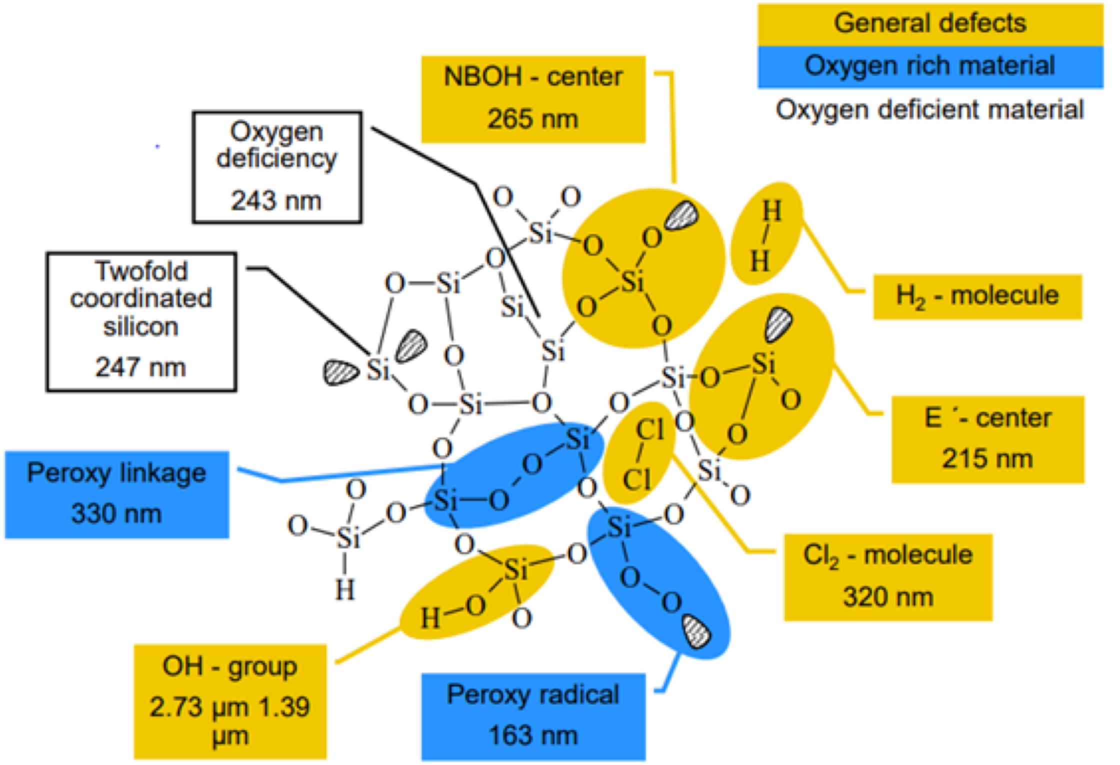
- Fused quartz with high level of impurities inadequate for any pp running and damaged during PbPb running.

- Hardening the detector for pp running allows flexibility in installation to accomodate special LHC runs (e.g. O+O, p+O in Run3) that take place in the middle of pp running

HL-LHC *pp* dose map (TAXN region - 1year)



RADIATION DAMAGE IN FUSED SILICA



Dr. Frank Nürnberg | HQS Photonics SO | 20.10.2015

Schematics showing known defects to SiO4 tetrahedral characteristics (courtesy of Frank Nuernberg [Heraeus])

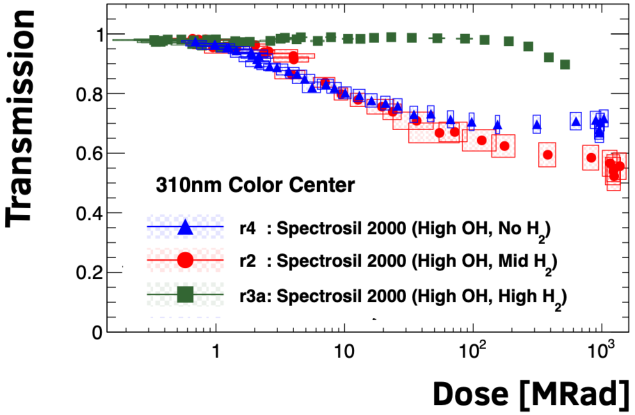
- Increasing number of defects and color centers induced by radiation damage decreases the transmission
- Materials with a high purity level show a lower absorption and a better radiation hardness.
- In the UV region:
  - Saturation of absorbing defects by H_2
  - Decrease in transmittance more pronounced/rapid
- Our results represent the first study of radiation hardness of fused silica exposed to **high energy hadron cocktail**

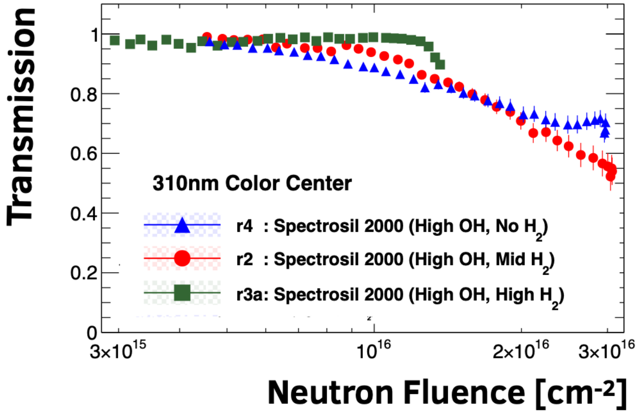
λ = 310 nm – DIFFERENT H_2 LEVEL

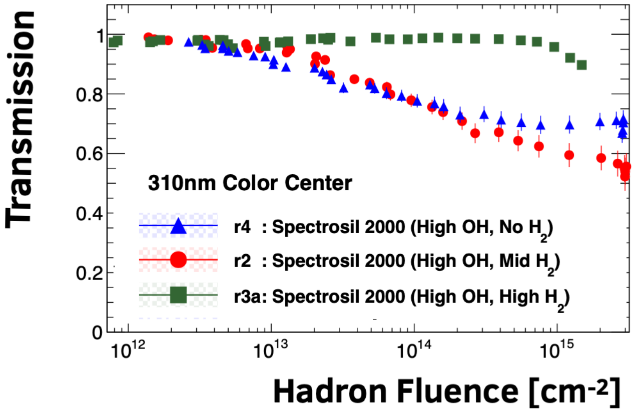
Increasing level of H_2

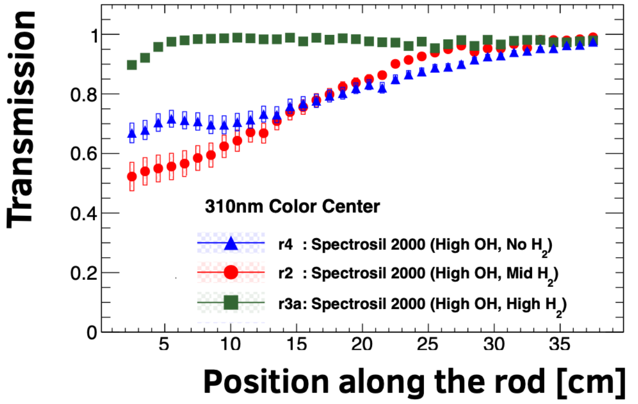
Rod	Irr. Period	Peak exp.	Material	H_2 [mol/cm³]	OH [ppm]
4	04/2016 - 12/2017	1 Grad	Spectrosil 2000 (High OH, H2 free)	0	1011
2	04/2016 - 12/2017	1.5 Grad	Spectrosil 2000 (High OH, Mid H2)	7.20e17	1120
3a	04/2016 - 12/2016	0.5 Grad	Spectrosil 2000 (High OH, High H2)	2.80e18	1000

- Self-repairing effect observed with increasing H_2 concentration
- Hints for a cut-off of this effects (lack of H_2?)
- H_2 free rod shows initial loss but stable plateau above 100 MRad
- More irradiation needed to extend analysis to higher doses and confirm observed features





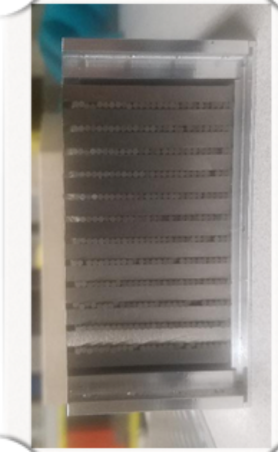




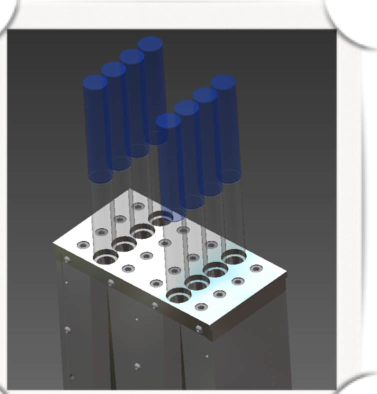
RUN3 UPGRADED ZDC: EM MODULE

- **Segmented design**: 4 segments in x, 2 in z.
- Small (Run4 like size) prototype tested during July test-beam @ Fermilab.
- Different sampling ratio were tested. Data analysis ongoing @ KU.

EM module
2 mm sampling



EM module
4 mm sampling



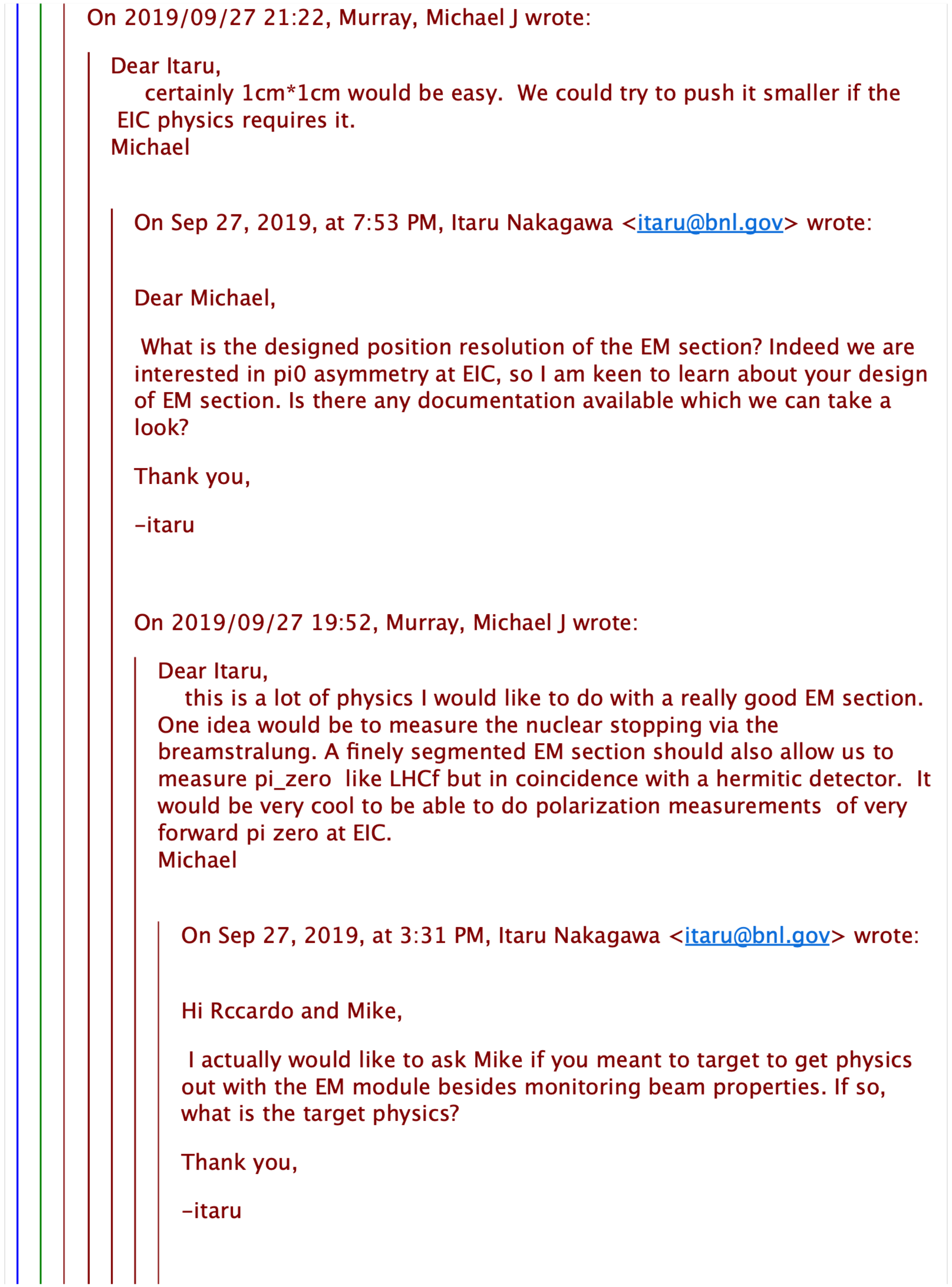
Segmented PMT
readout

Light-guides of two z-segments

- The detector will be equipped **Radiation-hard fused silica rods**
- **Winston Cone light-guides** will be tested in 2020 test beam
- Final design for Run3 under discussion

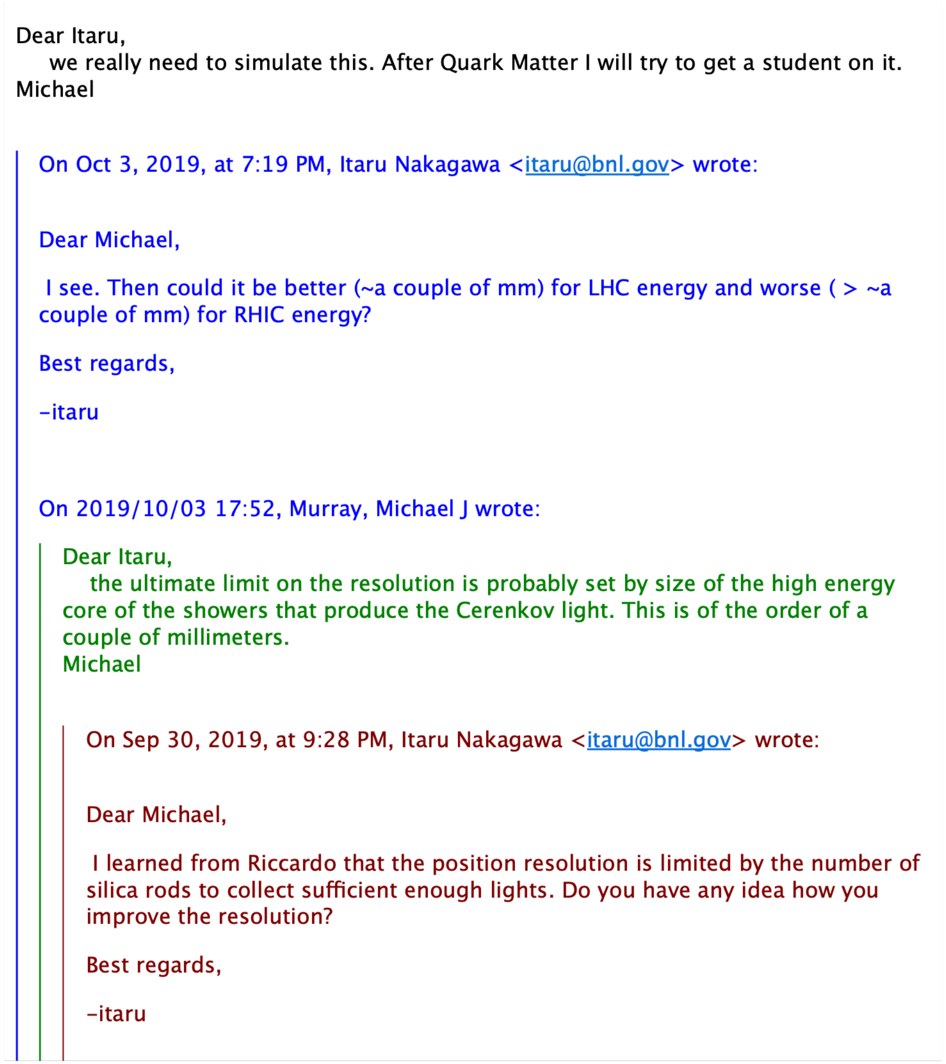
Discussion with Mike Murray

About EM Section of ZDC Upgrade



On 2019/09/27 21:22, Murray, Michael J wrote:

> Dear Itaru,
> certainly 1cm*1cm would be easy. We could try to push it smaller if the EIC physics requires it.
> Michael
>
>> On Sep 27, 2019, at 7:53 PM, Itaru Nakagawa <itaru@bnl.gov> wrote:
>>
>> Dear Michael,
>>
>> What is the designed position resolution of the EM section? Indeed we are interested in pi0 asymmetry at EIC, so I am keen to learn about your design of EM section. Is there any documentation available which we can take a look?
>>
>> Thank you,
>>
>> -itaru
>>
>> On 2019/09/27 19:52, Murray, Michael J wrote:
>>
>>> Dear Itaru,
>>> this is a lot of physics I would like to do with a really good EM section. One idea would be to measure the nuclear stopping via the breamstralung. A finely segmented EM section should also allow us to measure pi_zero like LHCf but in coincidence with a hermitic detector. It would be very cool to be able to do polarization measurements of very forward pi zero at EIC.
>>> Michael
>>>
>>>> On Sep 27, 2019, at 3:31 PM, Itaru Nakagawa <itaru@bnl.gov> wrote:
>>>>
>>>> Hi Rccardo and Mike,
>>>>
>>>> I actually would like to ask Mike if you meant to target to get physics out with the EM module besides monitoring beam properties. If so, what is the target physics?
>>>>
>>>> Thank you,
>>>>
>>>> -itaru



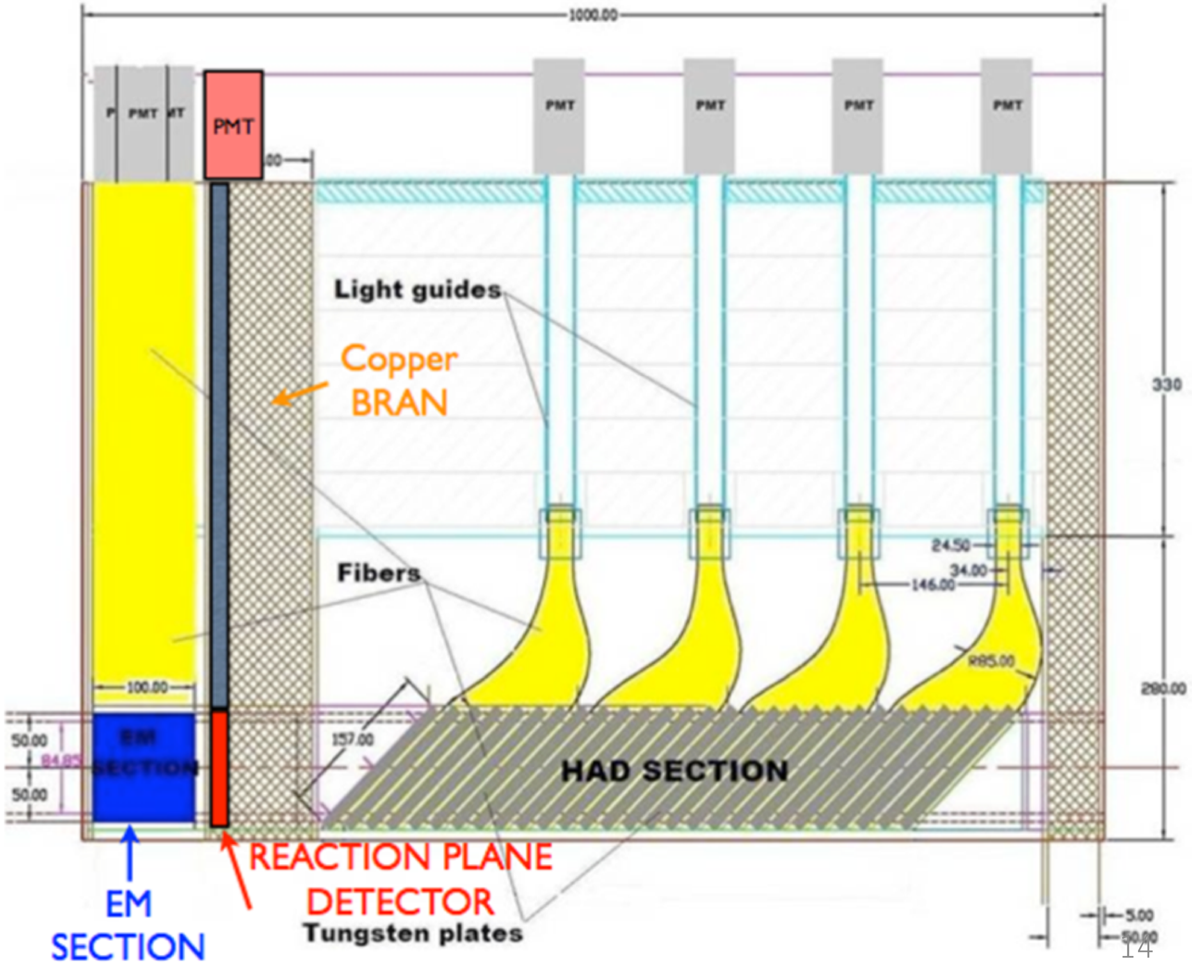
Dear Itaru,
we really need to simulate this. After Quark Matter I will try to get a student on it.
Michael

> On Oct 3, 2019, at 7:19 PM, Itaru Nakagawa <itaru@bnl.gov> wrote:
>
> Dear Michael,
>
> I see. Then could it be better (~a couple of mm) for LHC energy and worse (> ~a couple of mm) for RHIC energy?
>
> Best regards,
>
> -itaru
>
> On 2019/10/03 17:52, Murray, Michael J wrote:
>
>> Dear Itaru,
>> the ultimate limit on the resolution is probably set by size of the high energy core of the showers that produce the Cerenkov light. This is of the order of a couple of millimeters.
>> Michael
>>
>>> On Sep 30, 2019, at 9:28 PM, Itaru Nakagawa <itaru@bnl.gov> wrote:
>>>
>>> Dear Michael,
>>>
>>> I learned from Riccardo that the position resolution is limited by the number of silica rods to collect sufficient enough lights. Do you have any idea how you improve the resolution?
>>>
>>> Best regards,
>>>
>>> -itaru

ALICE ZDC

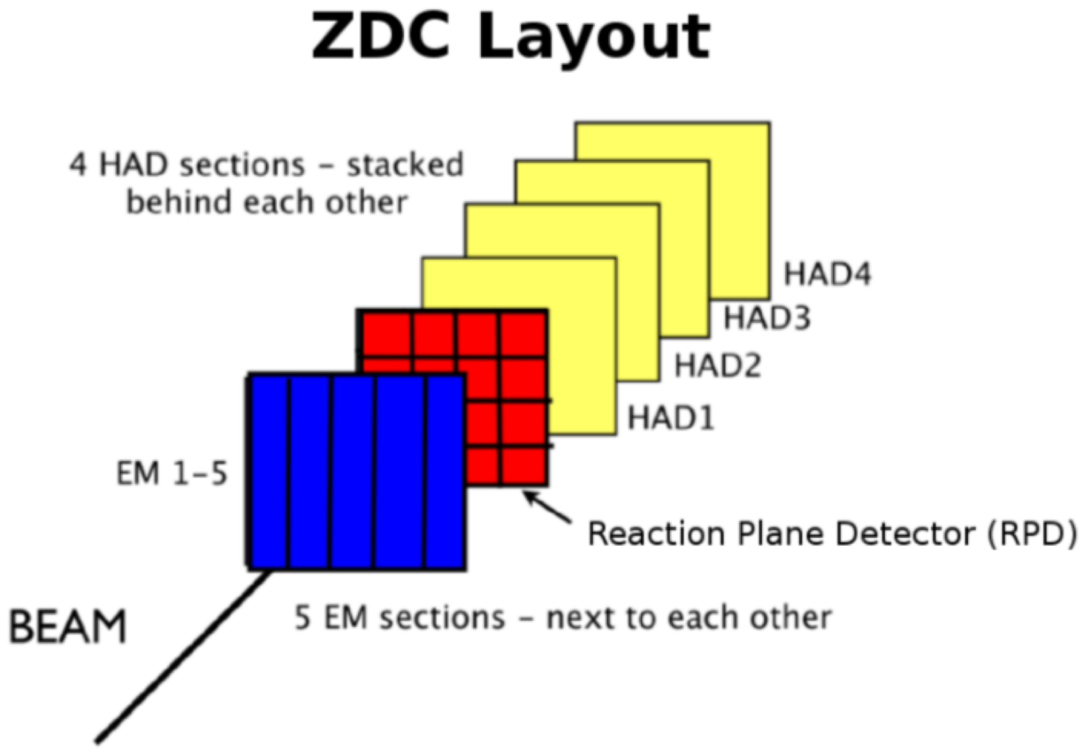
ZDC detector

- Electromagnetic section (EM):
  - 33 vertical tungsten plates
  - 19 radiation lengths or one nuclear interaction length.
  - 5 divisions in the x direction
    - (Not enough room for read-out of y-segmentation)
- Reaction Plane Detector (RPD):
  - 4x4 quartz block array
- Hadron section (HAD):
  - 24 tungsten plates
  - 5.6 hadronic interaction lengths
  - Plates are tilted by 45 ◦ → maximizes the light that a fiber can pick up.
  - Divided into 4 segments in z direction

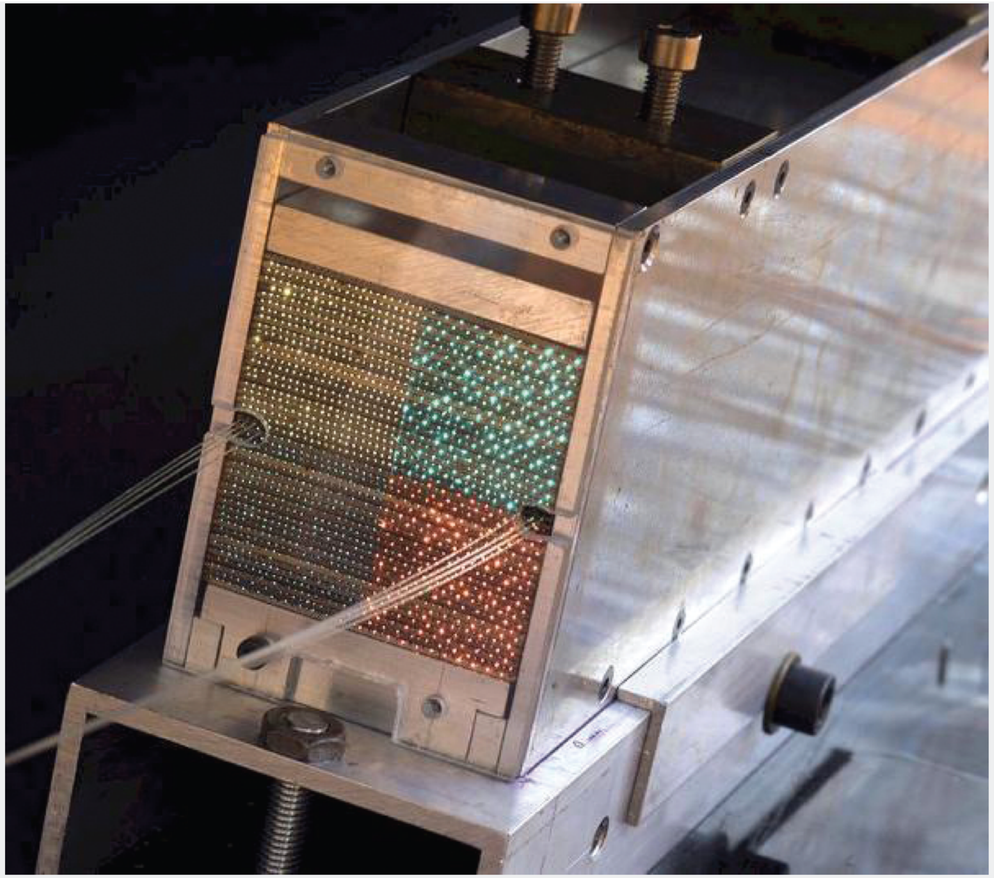


Segmentation of ZDC detector

- Segmentation:
  - EM: x-axis – 5 channels
  - HAD: longitudinally – 4 channels
  - RPD: 4 x 4 quartz array – 16 channels
- Physics capabilities:
  - Centrality in pA, AA
  - Tagging UPC events
  - Event plane (with RPD)



Quartz Fibers



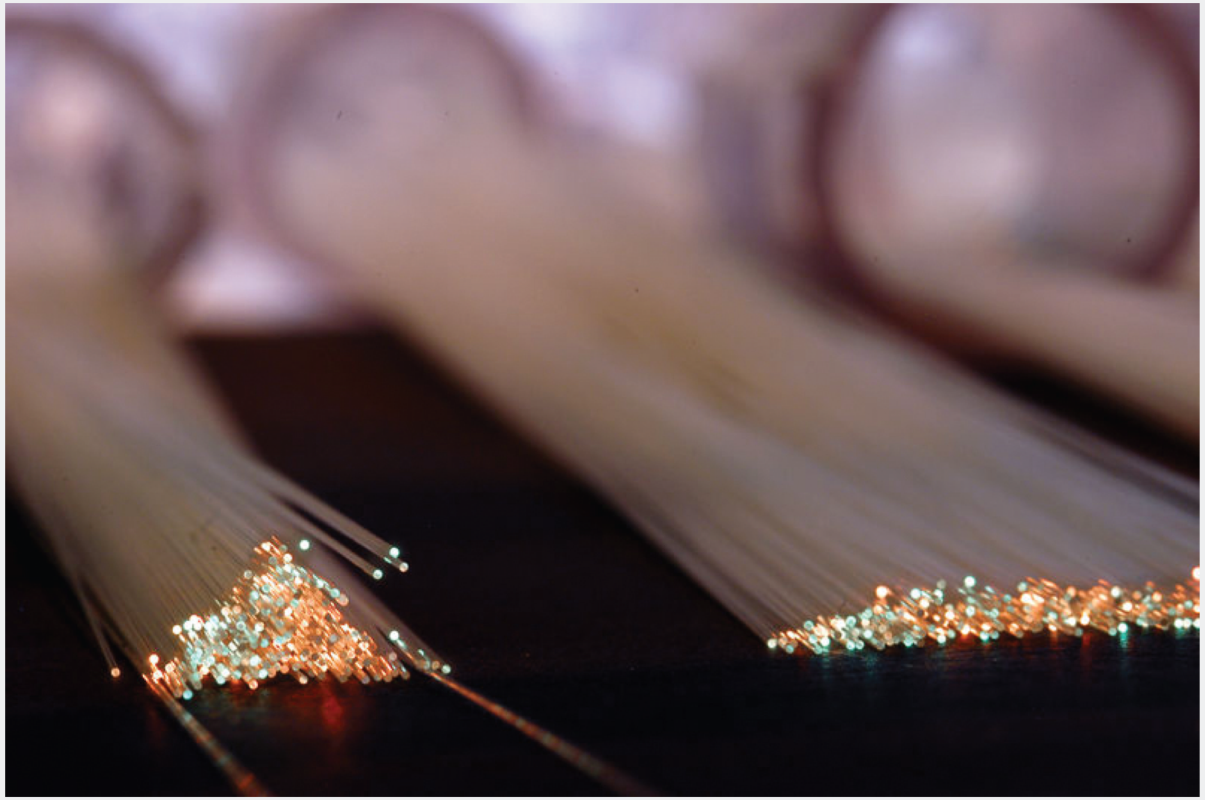
Front face of the ZN calorimeter

Each set of ZDCs is positioned on a movable platform controlled remotely from the ALICE DCS. The ZN and ZP calorimeters can be moved independently in the vertical direction in order to follow the beam crossing angle. The movable support structures are lowered during injection to protect the detectors from possible beam losses and when the ZDCs are not included in data acquisition in order to minimize the absorbed dose.

Technical Details | Performance | Collaboration

The ZDCs are quartz-fiber spaghetti calorimeters, with silica optical fibers as active material embedded in a dense absorber. Their principle of operation is based on the detection of Cherenkov light produced by the charged particles of the shower in the fibers.

The quartz fibers are hosted in the grooves of the absorber slab, W-alloy for ZN and brass for ZP. In the hadronic calorimeters the fibers are placed at zero degrees with respect to the LHC axis and come out from the rear face of the calorimeter, directly bringing the light to the photomultipliers.

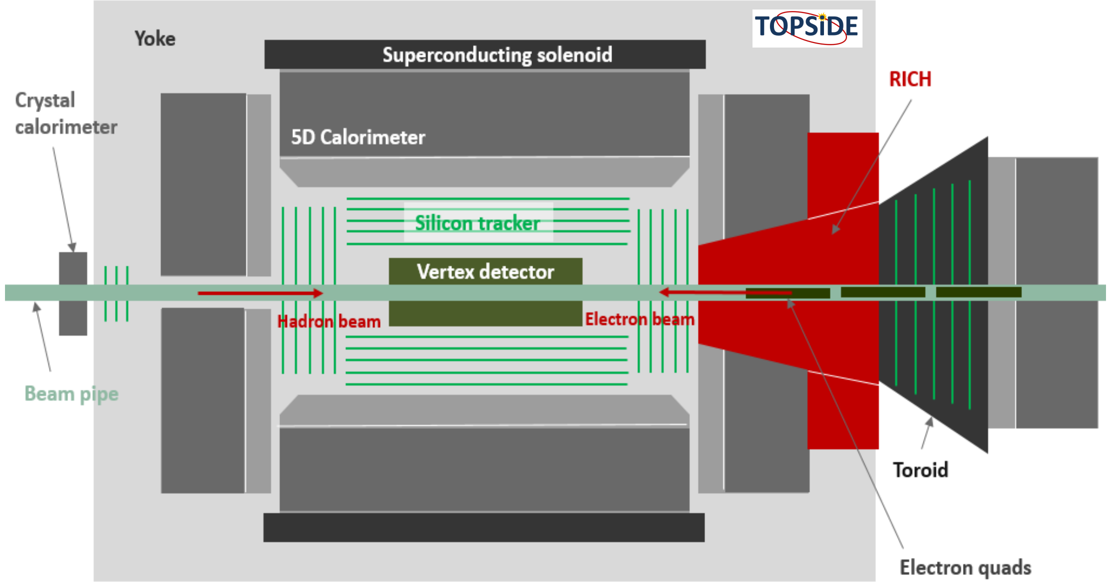


Each of the ZN calorimeters has dimensions: 7 x 7 x 100 cm^3 and the quartz fibers are hosted in the 1936 grooves of the W-alloy slabs. The ZP calorimeters have dimensions of 22.8 x 12 x 150 cm^3 and the quartz fibers are hosted in the 1690 grooves of the brass slabs.

TOPSiDE

TOPSiDE : The 5D Concept

Measure (E,x,y,z,t) for (every) hit in tracker + calorimeter



licon pixel vertex + **strip tracker**
Imaging em calorimeter
Imaging hadron calorimeter
Superconducting solenoid (3T)
Forward gaseous RICH
Forward dipole + cloak or
toroid w/out cloak
Forward silicon disks
Forward calorimetry
Zero degree calorimeter
Backward silicon disks
Backward crystal calorimeter

Particle identifying imaging calorimeter

Particle identification (pion – kaon – proton separation)

Particle momenta < 10 GeV/c for most of the solid angle f
Utilizes tracker + calorimeter
Requires **silicon sensors with time resolution of about 10 ps***

Eliminates

The need for preshower counters, TRDs, TOF or Čerenkov (in front of the calorimeter),
muon chambers (in back of calorimeter)

*3 timing layers are sufficient: early in the ECAL, rear of ECAL, rear of HCAL:
A resolution of 20 ps is then adequate. (TBC by simulation)

The Zero-degree Calorimeter

Role

Measure energy and angle of straight going neutrons
Identify (measure) the occasional photon in the calorimeter

Requirements

Dimensions: Laterally ~ 1 x 1 m^2 (to contain hadronic showers)
Longitudinally at least 5 interaction lengths
Event rate (not exorbitant?)
Timing resolution (not particularly challenging?)
Radiation hardness (not a concern?)
Energy range 100 – 200 GeV (EIC) and 7 TeV (LHeC)

Choice of technology

Electromagnetic Calorimeter ECAL

A) Silicon wafers → **Si-W** technology

Hadron Calorimeter HCAL

B) Scintillator pads → **AHCAL** technology

C) Resistive Plate Chambers → **DHCAL** technology

All explored by CALICE

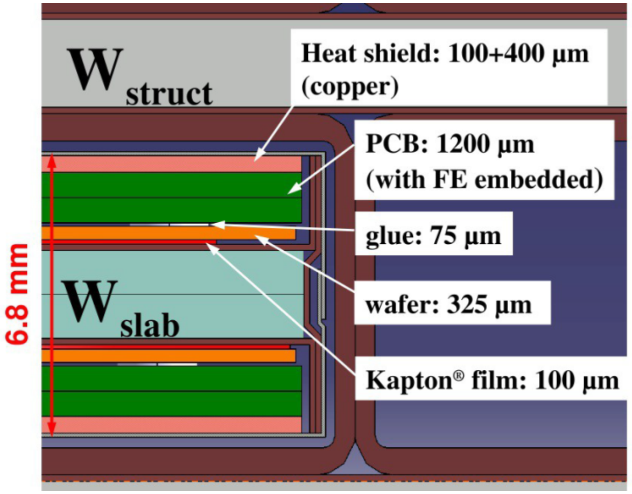
A) The Silicon – Tungsten Electromagnetic Calorimeter – Si-W E

Concept

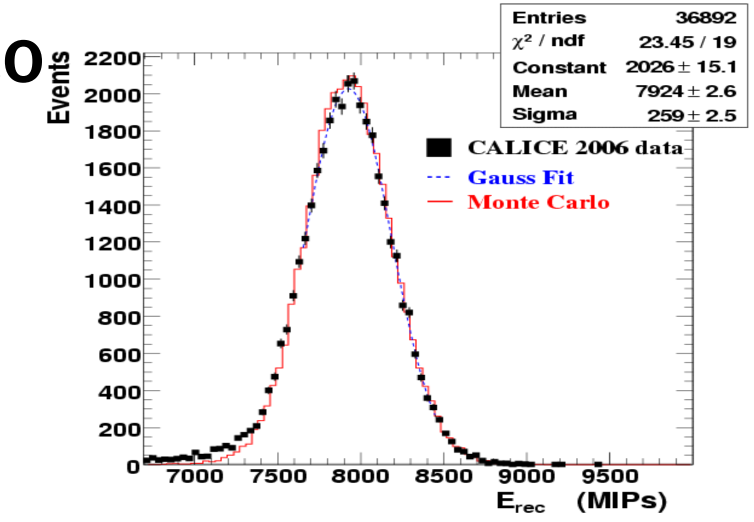
0.5 x 0.5 cm^2 Silicon pixels on 325 μm thick wafer
Tungsten absorber plates (< 1 X_0 each)

Readout

Digitization implemented in each layer
64 channel SKIROC ASIC with 12 – bits
Low noise (1/10 of a MIP)
Option to power pulse (25 μW/channel)



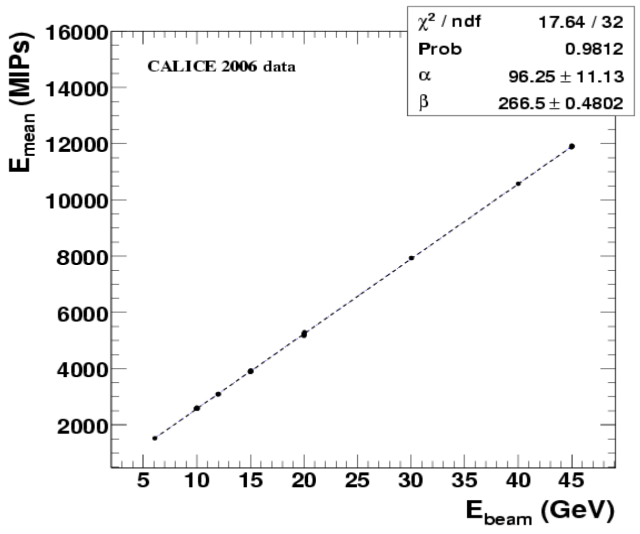
Si-W ECAL Results from Physics Proto

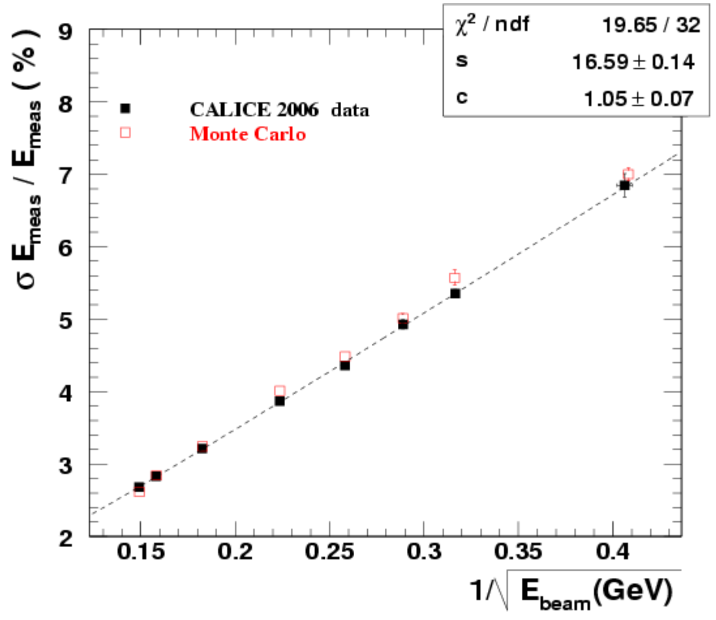


Linear within ±1% up to 45 GeV
Resolution adequate

$$\frac{\sigma_E}{E} = \left(\frac{16.6 \pm 0.1}{\sqrt{E(GeV)}} \oplus (1.1 \pm 0.1) \right) \%$$

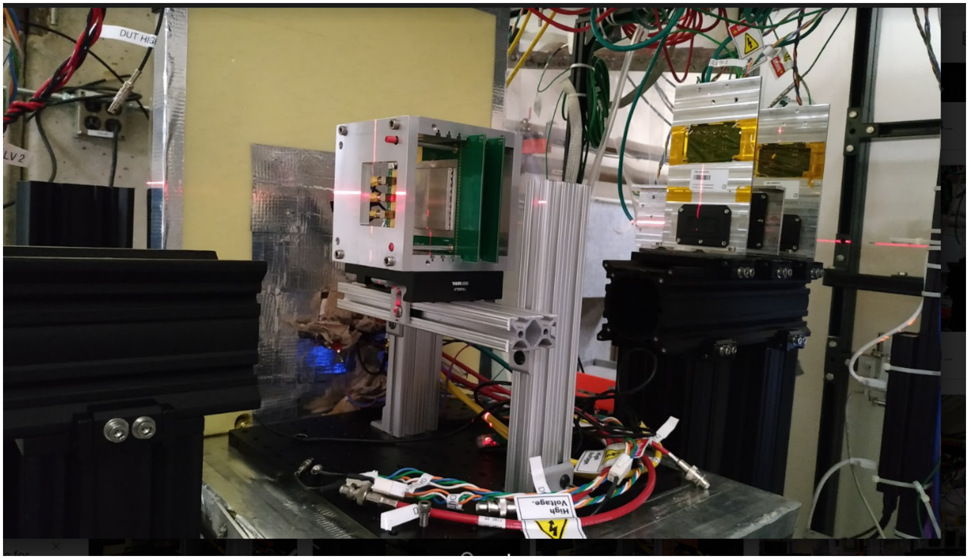
-> Negligible contribution to $\sigma(E_{jet})$
Excellent agreement with GEANT4 simulation





Both concept and technical implementation validated

A step further: the 5D concept



Precision timing information

- Of order 10 picosecond
- In addition to imaging capability

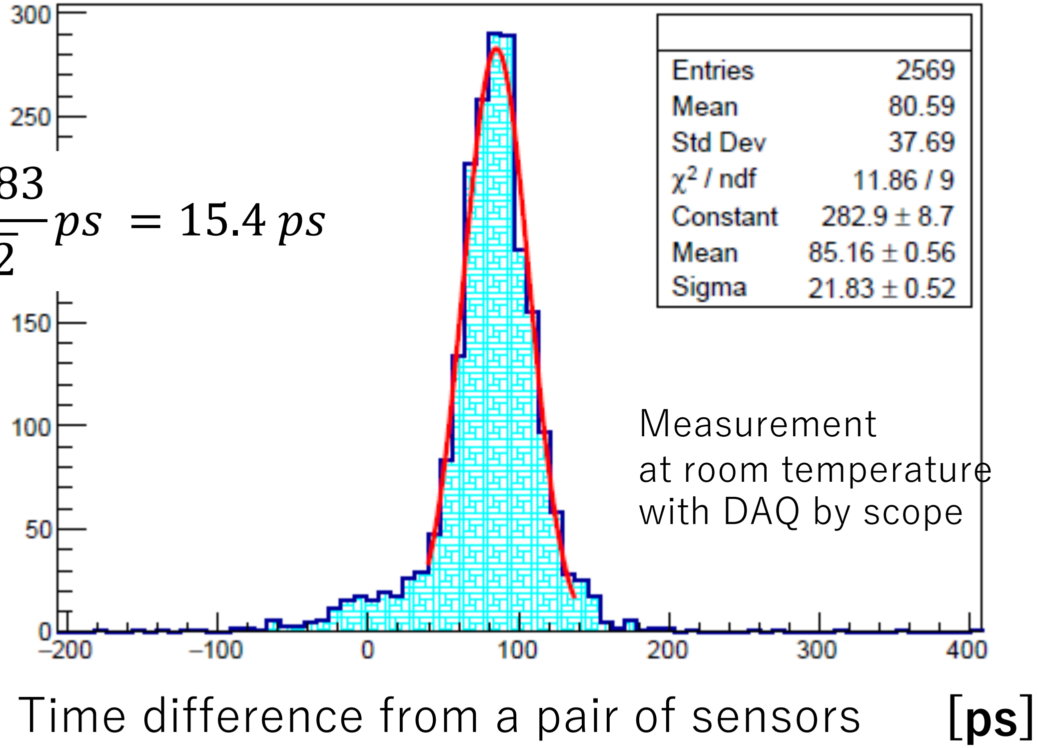
Advantages

- Provides particle identification (pion-kaon-proton separatio
- Identifies vertex in pile-up events
- Suppress noise

Requires

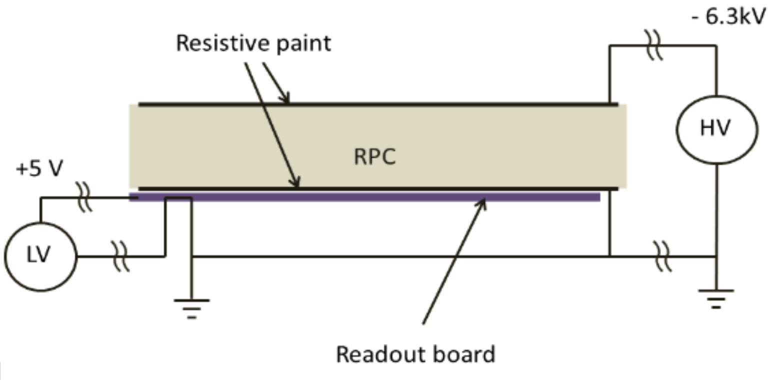
- Ultra-fast silicon detectors (UFSDs)
  - Sensors with 16 ps resolution available
  - Argonne: implementation of readout electronics onto sen
    - → reduce cost and further improve resolutio

$$\sigma_t = \frac{21.83}{\sqrt{2}} ps \ = 15.4\ ps$$



Measurement
at room temperature
with DAQ by scope

C) The Digital Hadron Calorimeter - DI

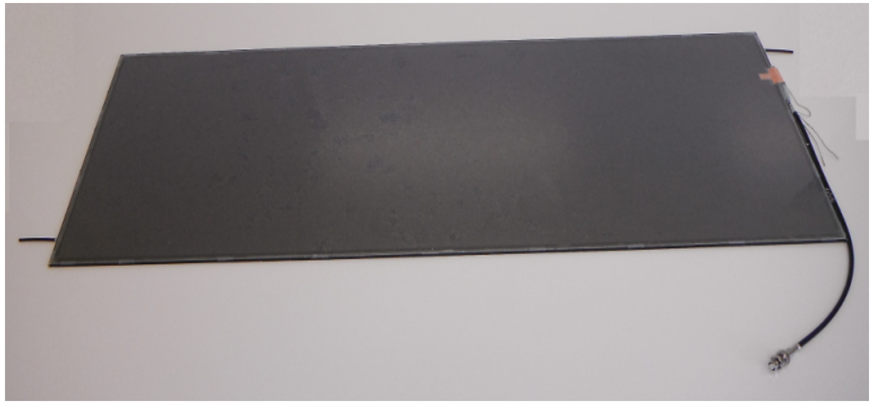


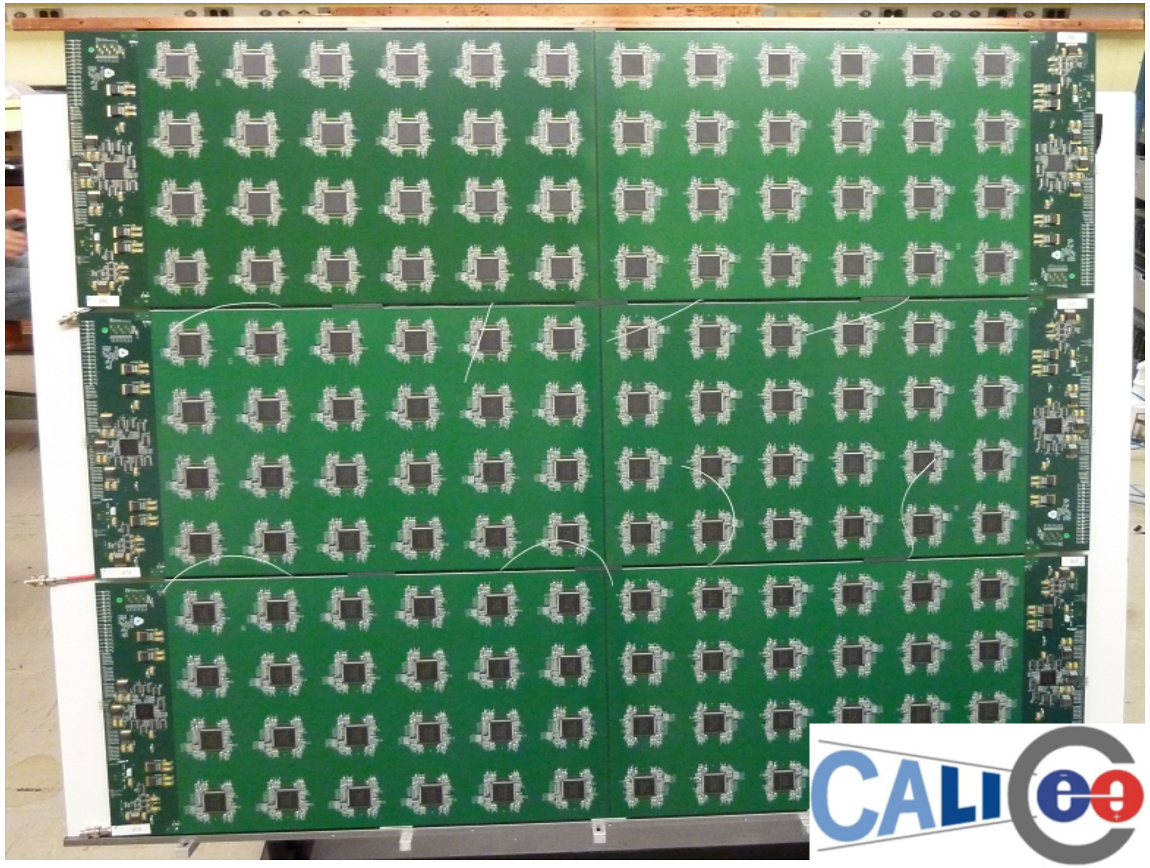
Concept

Resistive Plate Chambers (3 layer to obtain 1 m^2)
Steel absorber plates (~ 1 X_0 each)

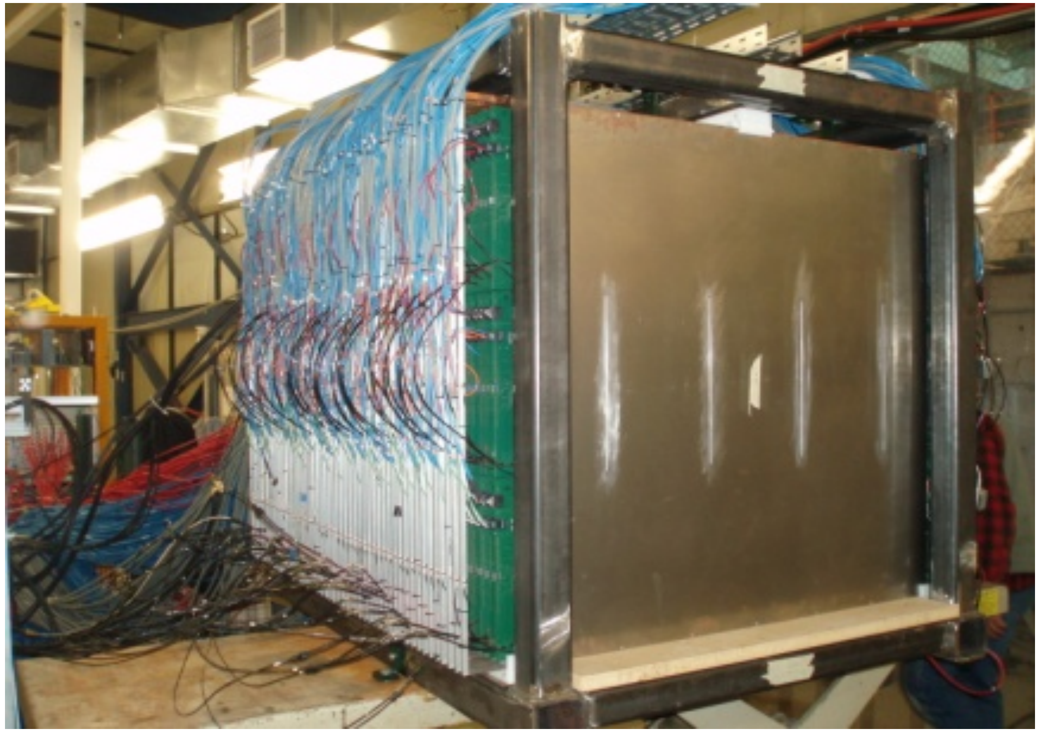
Readout

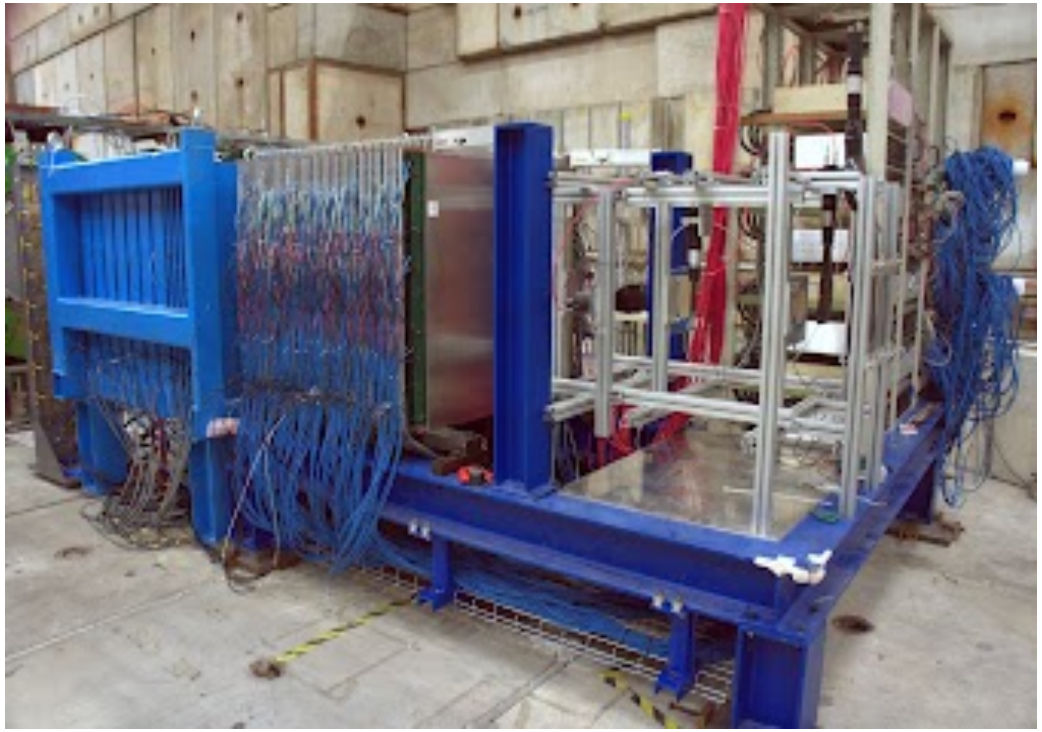
Digitization implemented in each layer
64 channel DCAL ASIC with 1 – bit (digital!)
Timing to ~ 100 ns





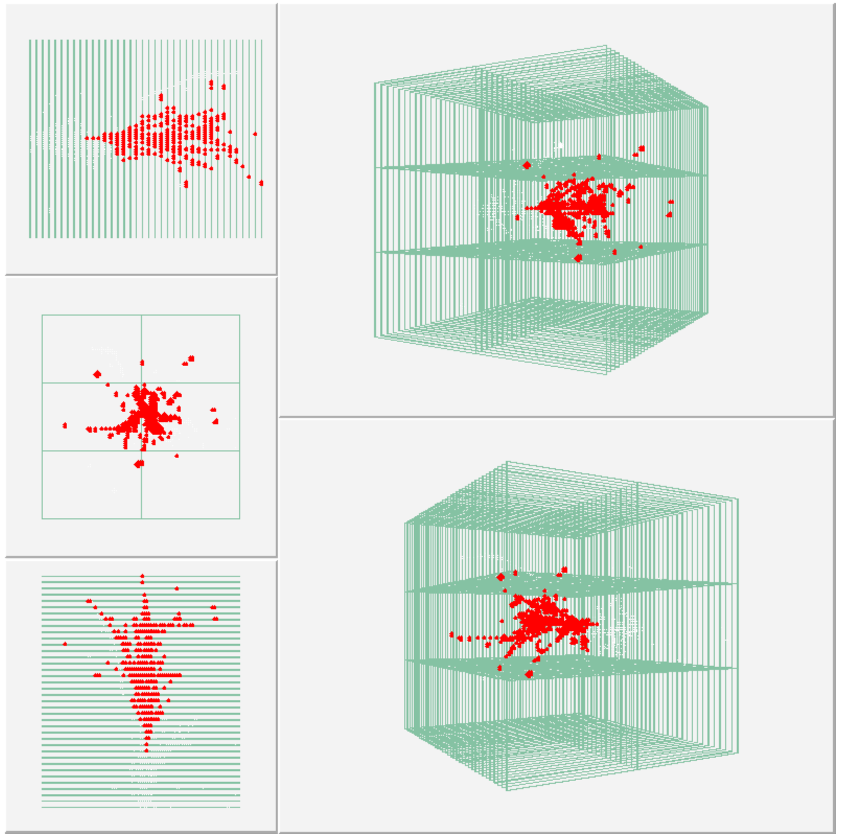
DHCAL Physics/Technological Prototype

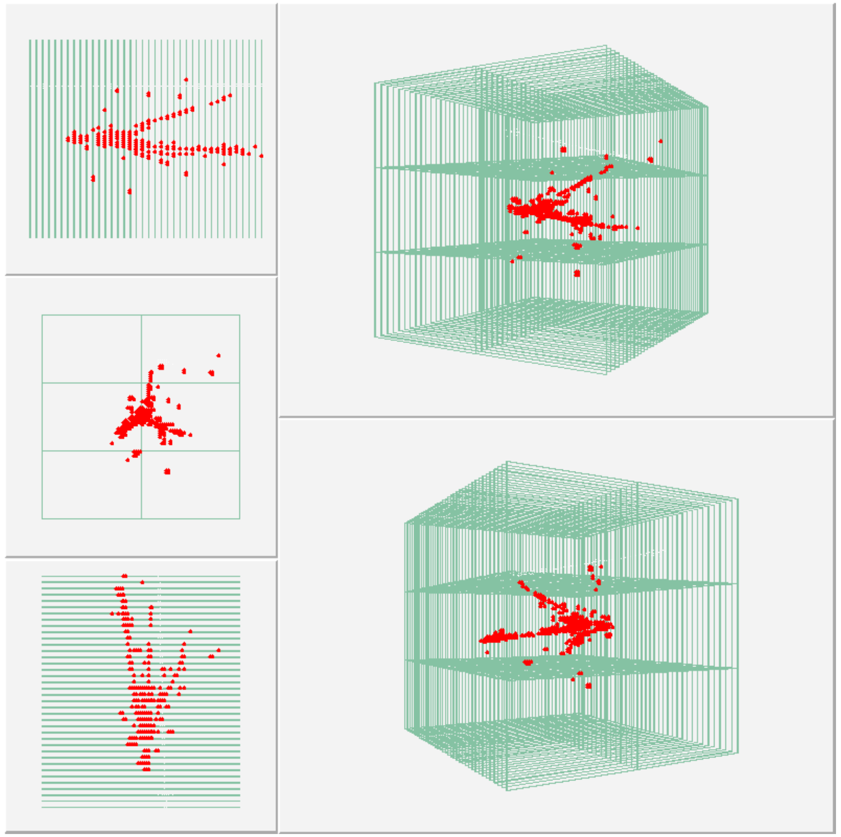




38 layers in main stack – 4 interaction lengths deep
14 layers in tail catcher – additional 4 interaction lengths deep
Tests in Fermilab (Steel) and CERN (Tungsten) test beam

Talking about neutrons…





High energy neutron events

Recorded at Fermilab in self-triggered (streaming) mode
Energy unknown

Summarry of Discussion with Oleg

2019/10/02

Attendee: Oleg, Yuji, Ralf, Itaru

Suggestions from Oleg

- For mini-FoCAL position layers, options can be:
  1. Scintillation fiber
  2. Silicon sensors : existing detector is MPC-EX@PHENIX

- Existing detectors uses scintillation fiber:
  1. LHCb tracker (TDR should be available) the detector can be already built
  2. STAR event plane detector (EBD). Can possibly learn how to connect the scintillation fiber to a **clear fiber** to transfer the photon to the front end electronics. Contact with EBD expert.

Rough Cost Estimate

- Diameter 1.0mm x 2m long round fiber = $3.96/piece

Each shower max layer, we need 1.0mm x 1.0mm square x 100mm long x 100 fibers to cover 10cm wide.
For two layers, 100 x 2 layers = 200 fibers.

The square shape is a bit more expensive than the round one, so assume $20/fiber even it is shorter.

200 fibers x $20/fiber = $4k/xy-layer

Oleg’s estimate for ~$5k (SiPM) + ~$5k (pre-amp). So the total is $4k + $5k + $5k = $14k.

Kuraray

Scintillating Fibers

Formulations 1)

Description	Emission			Decay Time [ns]	Att.Leng.[2] [m]	Characteristics
	Color	Spectra	Peak[nm]			
SCSF-78	blue	See the following figure	450	2.8	>4.0	Long Att. Length and High Light Yield
SCSF-81	blue		437	2.4	>3.5	Long Attenuation Length
SCSF-3HF(1500)	green		530	7	>4.5	3HF formulation for Radiation Hardness

1) Test fibers are Non-S type, 1mmφ.

2) Measured by using bialkali PMT and UV light(254nm).
Quality control is made by another measurement of the transmission loss every batch.

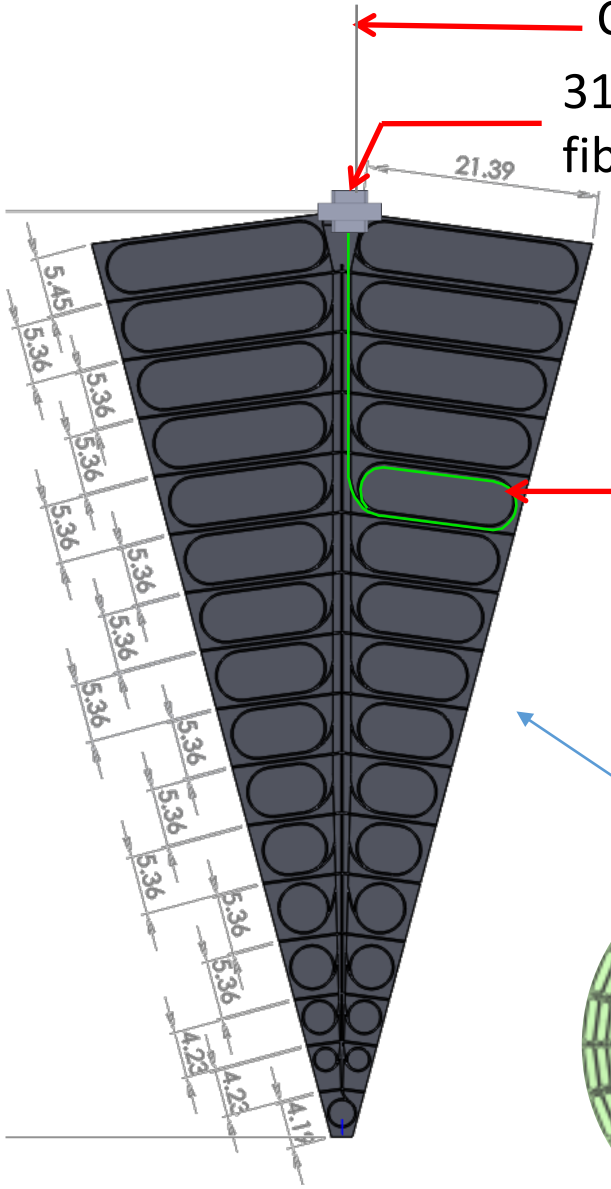
Choice of Fibers

	SCSF-3HF	Blue Fiber
Radiation hardness	good	weak
Light Emission	weaker	stronger
Suitable Use	Shower max	Energy sampling layers

For one year dedicated low luminosity run, the blue fiber may be OK. If we consider about future use, then may be worthy to consider SCSF-3HF.

Design- Scintillator

- 2 Wheels, each composed of 12 ‘super-sectors’
- Super-sectors :Scintillator wedges, milled to form 31 tiles each
  - Optically separated by TiO_2-loaded epoxy
- 3 turns of WLS fiber
  - 3 turns ~doubles light output relative to 1 turn

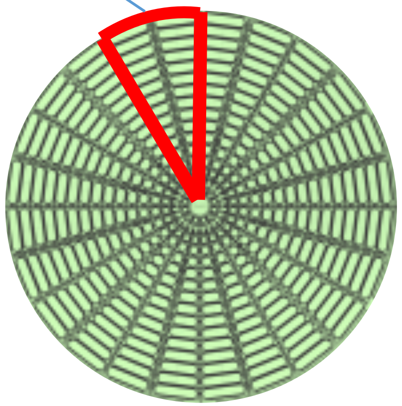


Clear fibers

31-channel fiber-to-fiber connector

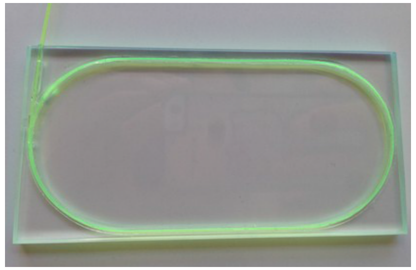
Embedded WLS fibers

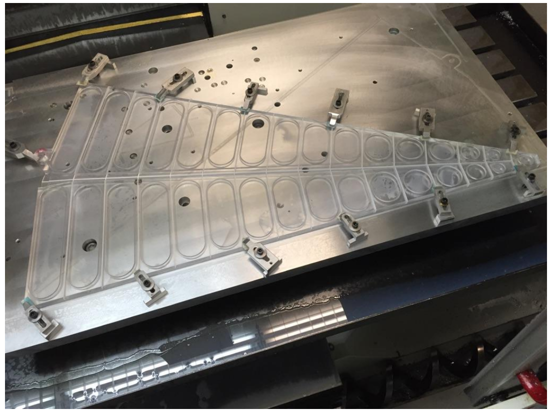
1/12 of a wheel



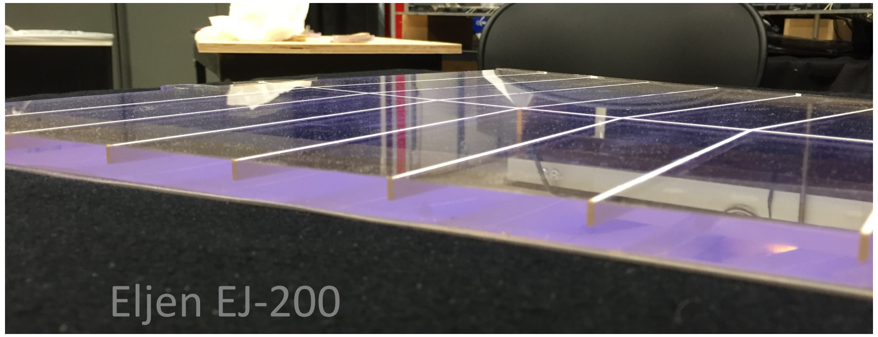
STAR EPD

A test tile





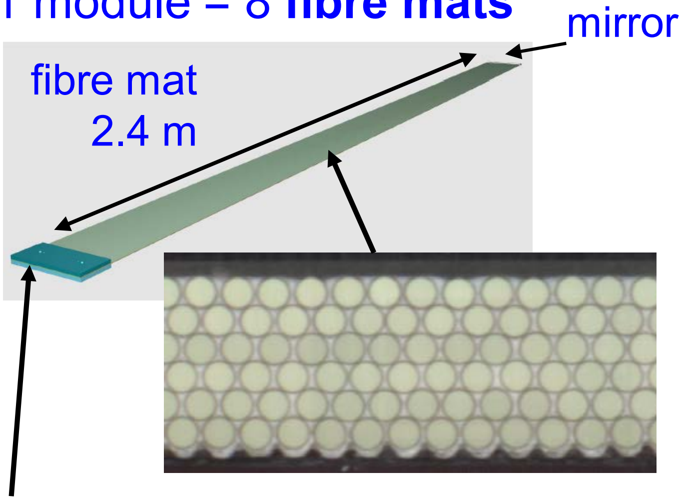
Half milled Super-sector



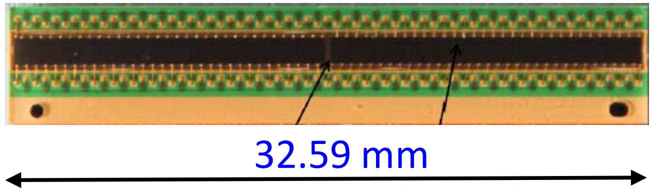
LHCb Fiber Tracker

128 modules (0.5 x 5 m^2)
arranged in 3 stations × 4 layers (XUVX)

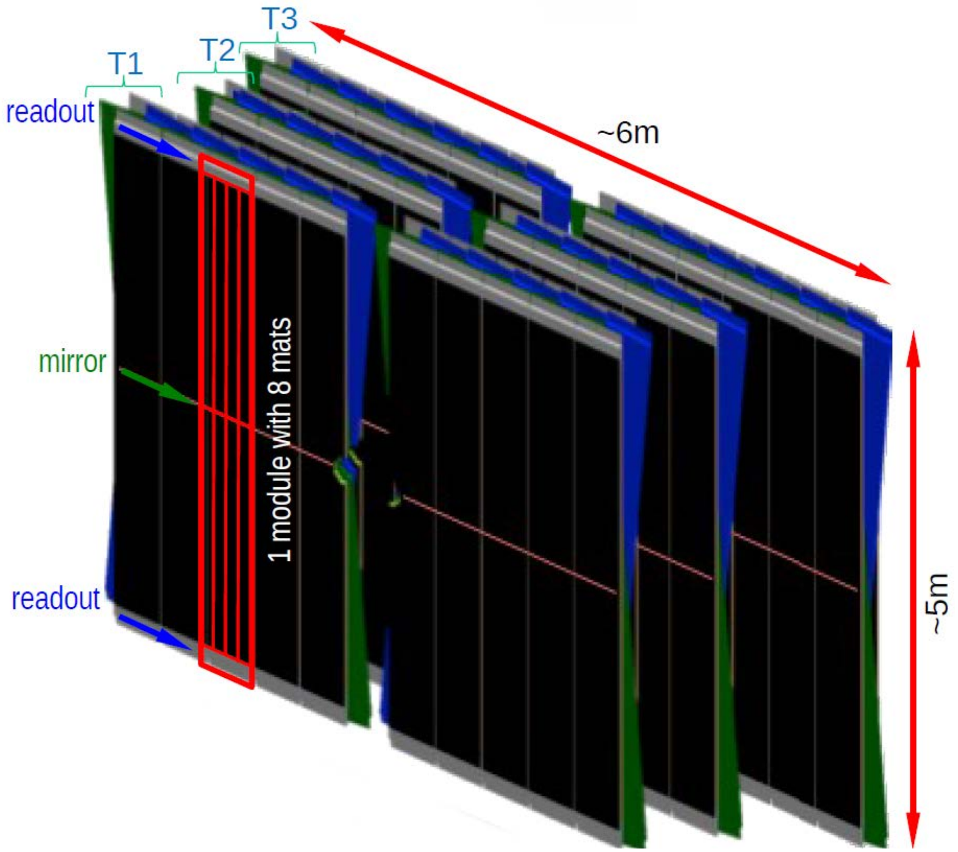
1 module = 8 **fibre mats**



4 silicon photomultipliers (SiPM)



1 SiPM = 128 channels



11,000 km of fibres, 524k channels

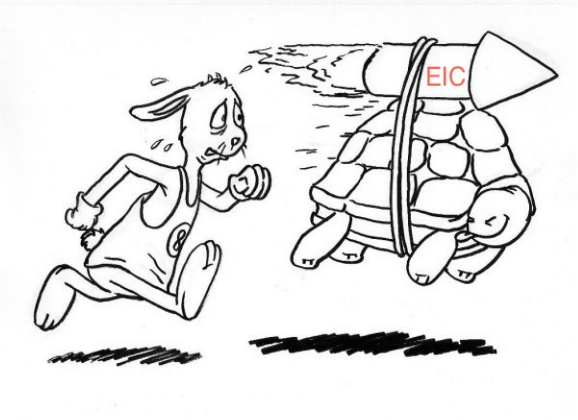
Goal: <100 μm resolution over a total active surface of ~ 340 m^2

LHCb Fiber Tracker

- The modules will have 2.5m long scin- tillating fibres with a diameter of 250 μm. The fibres will be read out by Silicon Photomultipliers (SiPMs) contained in Read-out Boxes at the top and bottom of the detector.

Other Detectors

psTOF for the EIC at 0°



Mickey Chiu

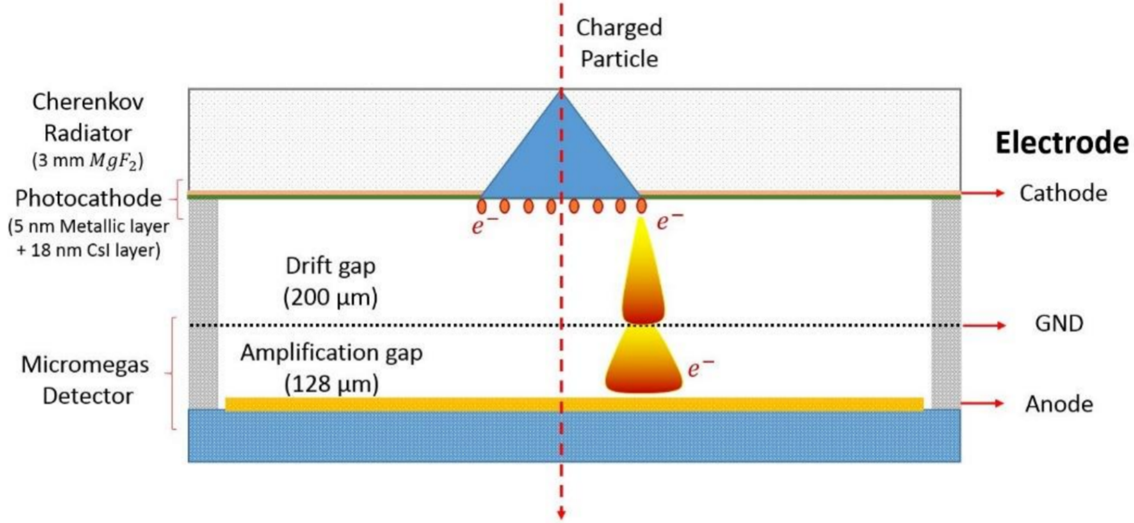
Center for Frontiers in Nuclear Science

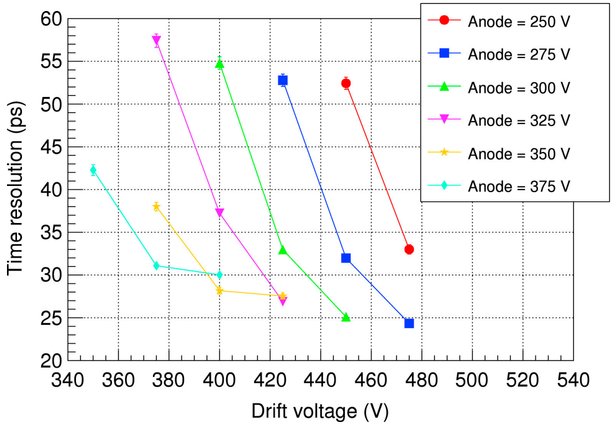
BROOKHAVEN NATIONAL LABORATORY

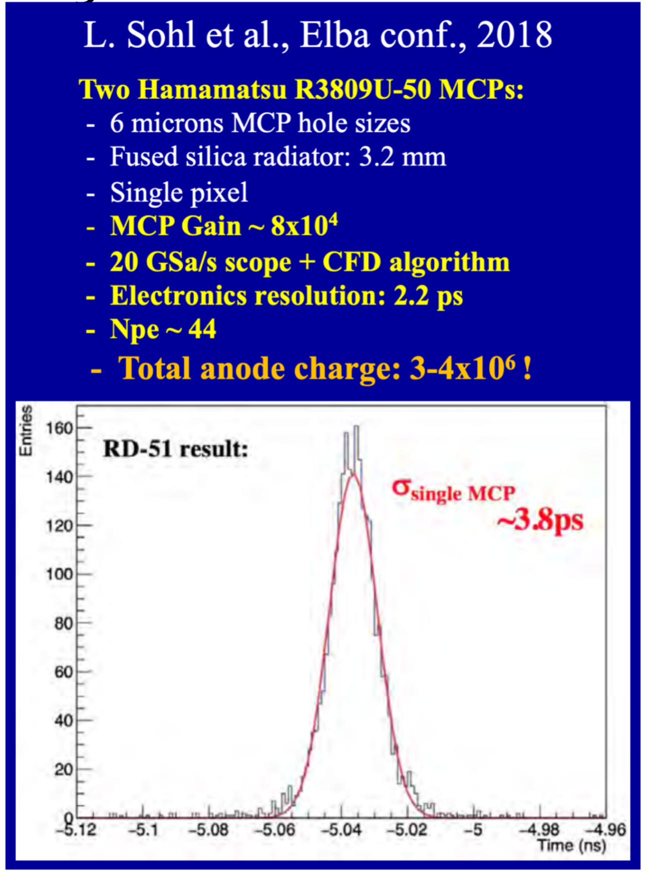
RBRC
RIKEN BNL Research Center

Some Other TOF Technology Today

PICOSEC detector







L. Sohl et al., Elba conf., 2018

Two Hamamatsu R3809U-50 MCPs:

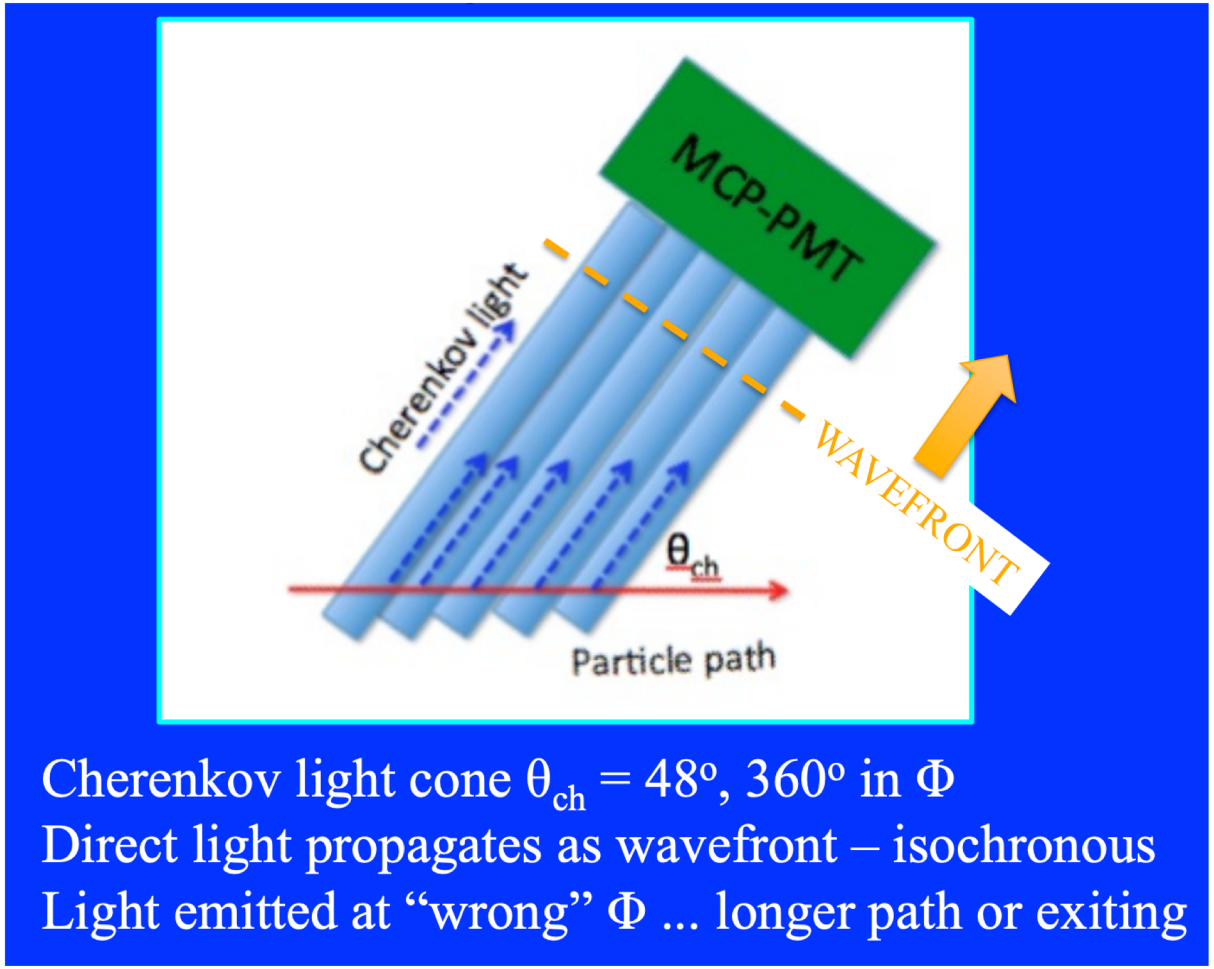
- 6 microns MCP hole sizes
- Fused silica radiator: 3.2 mm
- Single pixel
- **MCP Gain ~ 8x10^4**
- **20 GSa/s scope + CFD algorithm**
- **Electronics resolution: 2.2 ps**
- **Npe ~ 44**
- **Total anode charge: 3-4x10^6 !**

RD-51 result:

$\sigma_{\text{single MCP}}$ ~3.8ps

- RD51 supported PICOSEC has achieved ~25 ps
- MCP-PMTs have been shown to be capable of ~5 ps since 2006 (K. Inami et al), but for very few channels, and at very high cost
  - LAPPDs as a possible solution?

Example d psTOF



Cherenkov light cone $\theta_{ch} = 48^o$, 360^o in Φ
Direct light propagates as wavefront – isochronous
Light emitted at "wrong" Φ ... longer path or exiting

- Similar design to QUARTIC detector proposed for the LHC
- Rad-hard, High Rate Design

How Well Can psTOF Measure A and Z?

1. Mass M (A – BE in the case of Ions)

$$\frac{dM}{M} = \sqrt{\left(\frac{dp}{p}\right)^2 + \gamma^4\left(\frac{dt}{t} + \frac{dL}{L}\right)^2}$$

t ~ 120 ns, γ ~ 100 → dt ~ 0.1 ps for dM/M

2. Charge Z

$$\frac{dN_\gamma}{dx} = 2\pi Z^2 \alpha \sin^2(\theta_C)\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

Num. photoelectrons (1 cm fused silica radiator and LAPPD MCP-PMT Gen1 design):

319K ± 565, Z = 79
311K ± 557, Z = 78

Also means that in principle, the timing resolution one can achieve for the LAPPD (50 ps TTS) is

$$50\ \text{ps}/\sqrt{\text{NPE}} = 0.1\ \text{ps!}$$

3. P_Z
4. P_T

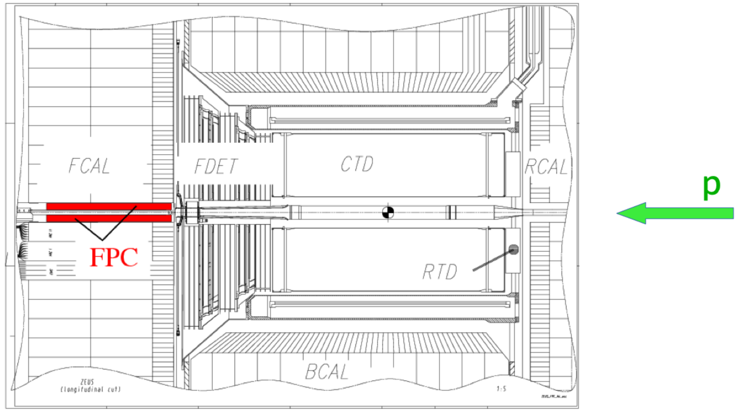
P_Z, P_T } Measured by magnetic spectrometer

HERA zero-degee detectors

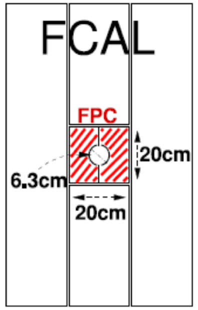
Robert Ciesielski (Rockefeller University)

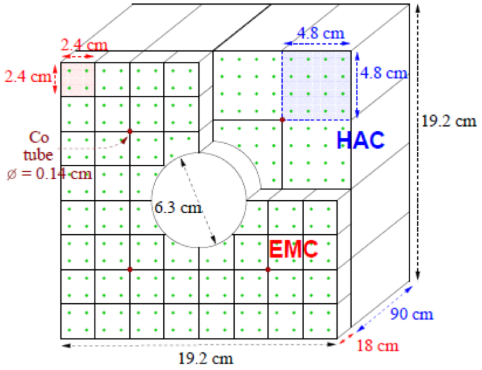
Joint CFNS & RBRC Workshop on Physics and Detector Requirements at Zero-Degree of Colliders,
24-26 September 2019, CFNS, Stony Brook University, NY, USA

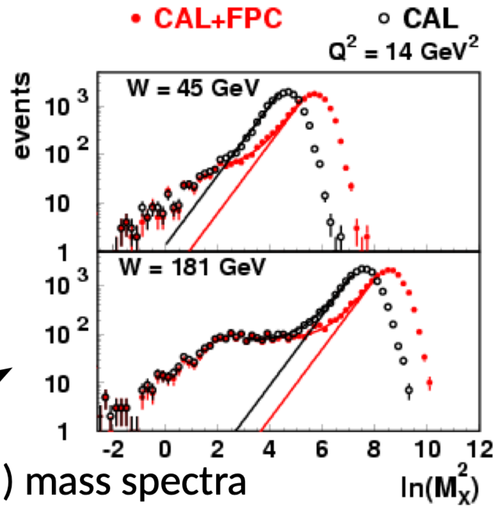
ZEUS Forward Plug Calorimeter (FPC)



- Originally, 20 x 20 cm^2 ZEUS FCAL beam hole
- In 1997 (HERA II), a sampling lead/scintillator calorimeter added limiting the beam hole to 6.3 cm in diameter
- Extends the forward coverage from η>4 to η>5
- Position and energy measurement, EMC/HAD sections





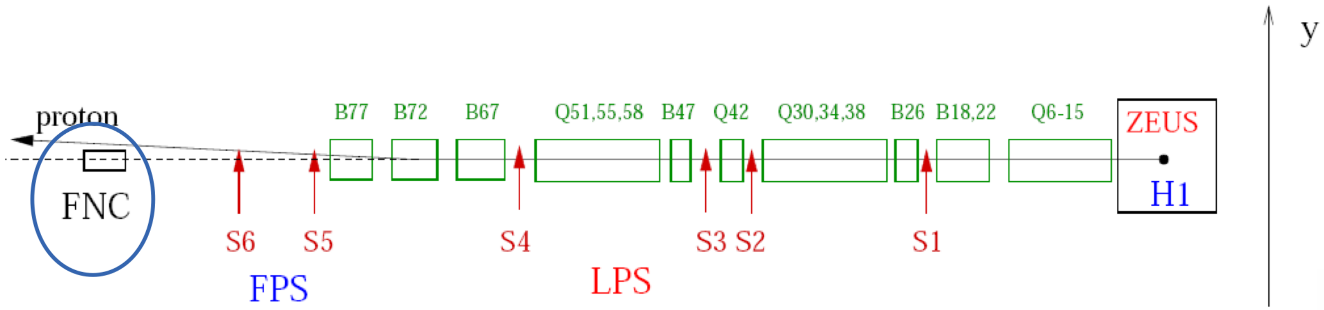


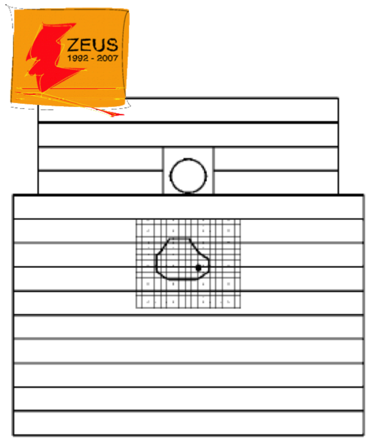
- Improvements in measurement of forward hadronic system, e.g.
- e.g better separation of diffractive (~flat) and non-diffractive (exponentially suppresed) mass spectra
- Used also as a tagger for proton dissociative events.

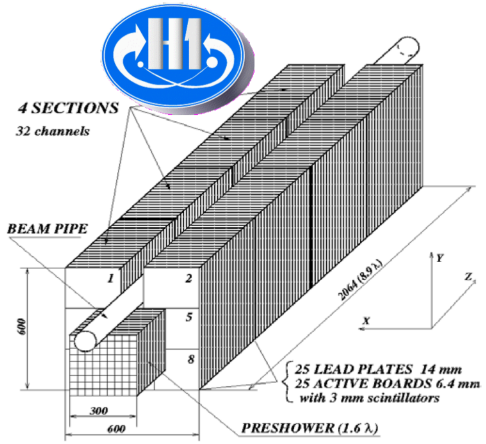
- HERA II: a machine magnet installed in the front of FCAL, hence no instrumentation due to dead material

Similar detector in H1, extending the H1 LAr coverage from η>3.5 to η>5.5

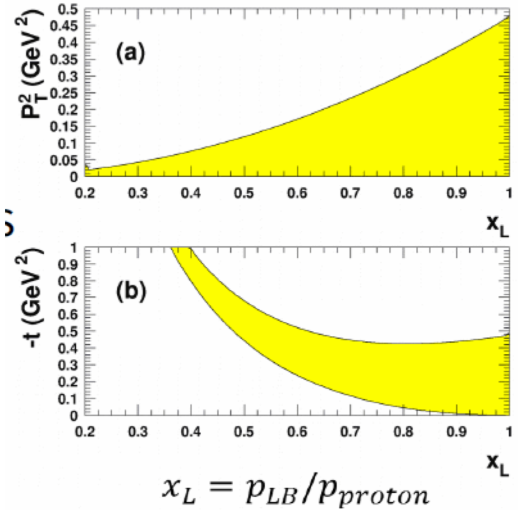
Forward Neutron Calorimeters (FNC)







Geometrical acceptance



$x_L = p_{LB}/p_{proton}$

- Iron/scintillator hadronic calorimeter (with scintilator tracker) at 110 m
- Acceptance limited by beam aperture ($\theta_n < 0.8$ mrad, ~30% of azimuthal coverage)