Digital Hadron Calorimetry

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CPAD Workshop 2023

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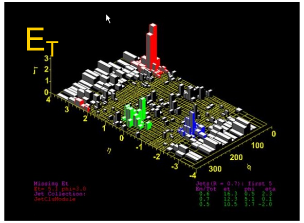
Trend in Calorimetry

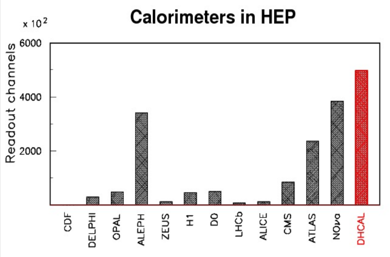
Tower geometry

Energy is integrated over large volumes into single channels

Readout typically with high resolution

Individual particles in a hadronic jet not resolved



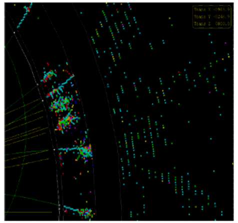


Imaging calorimetry

Large number of calorimeter readout channels ($\sim 10^7$)

Option to minimize resolution on individual channels

Particles in a jet are measured individually



Particle Flow Algorithms (PFAs)

Attempt to measure the energy/momentum of each particle with the detector subsystem providing the best resolution

Maximum exploitation of precise tracking measurement

- Large radius and length to separate the particles
- Large magnetic field for high precision momentum measurement
- "no" material in front of calorimeters (stay inside coil)
- Small Moliere radius of calorimeters to minimize shower overlap
- High granularity of calorimeters to separate overlapping showers

Emphasis on tracking capabilities of calorimeters

Development of the Digital Hadron Calorimeter

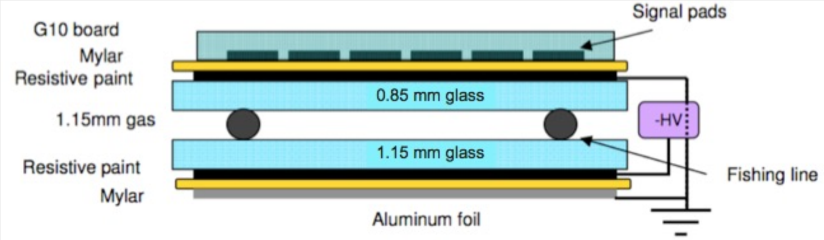
- Develop a tracking Hadron Calorimeter
- Implement digital readout (1-bit) to maximize the number of readout channels
- Place the front-end electronics in the detector

The active medium should:

- Be planar and scalable to large sizes
- Not necessarily be proportional (only yes/no for the traversing particle)
- Be easy to construct, robust, reliable, easy to operate, …

→ Resistive Plate Chambers

Resistive Plate Chambers (RPCs)



Gas: Tetrafluorethane (R134A) : Isobutane : Sulfurhexafluoride (SF_6) with the following ratios 94.5 : 5.0 : 0.5

High Voltage: 6.3 kV (nominal)

Average efficiency: 96 %

Average pad multiplicity: 1.6

The DHCAL Prototype

Description

Hadronic sampling calorimeter

Designed for future electron-positron collider (ILC)

54 active layers (~1 m^2)

Resistive Plate Chambers with 1 x 1 cm^2 pads

→ ~500,000 readout channels

Electronic readout

1 – bit (digital)

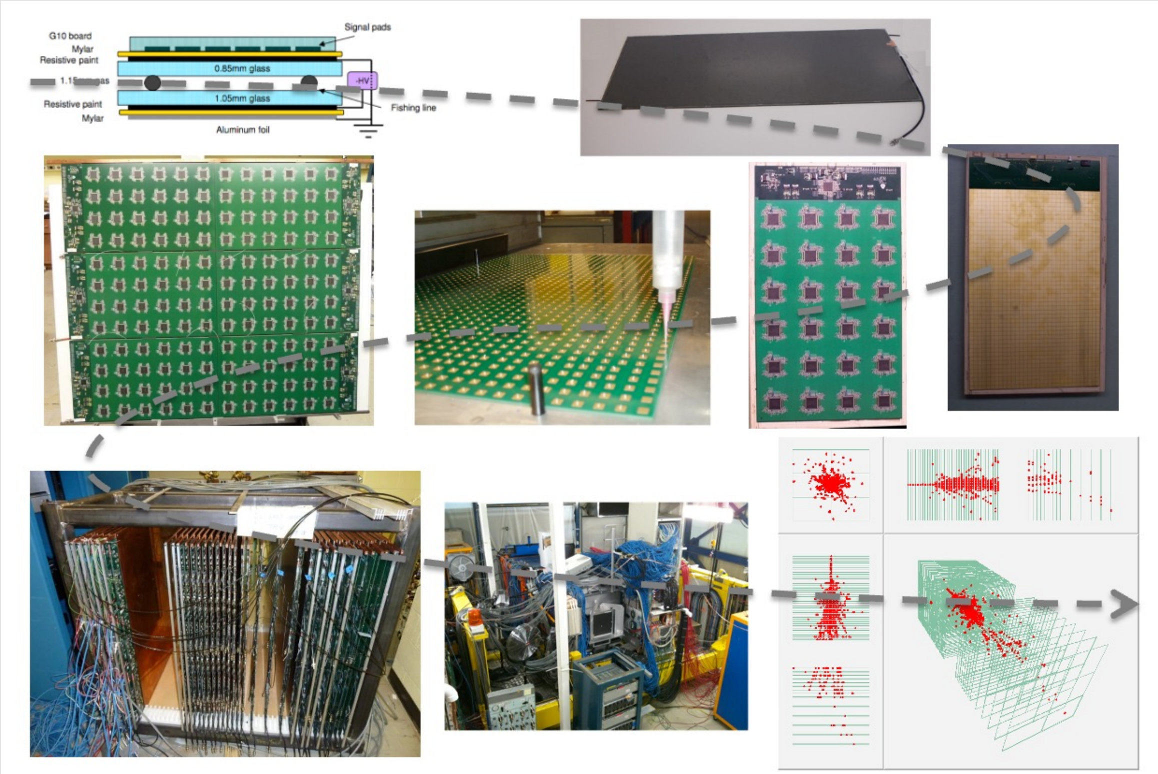
Tests at FNAL

with Iron absorber in 2010 – 2011

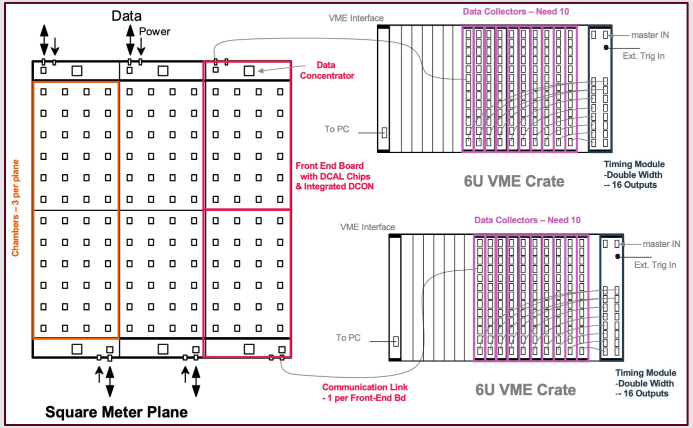
with no absorber in 2011

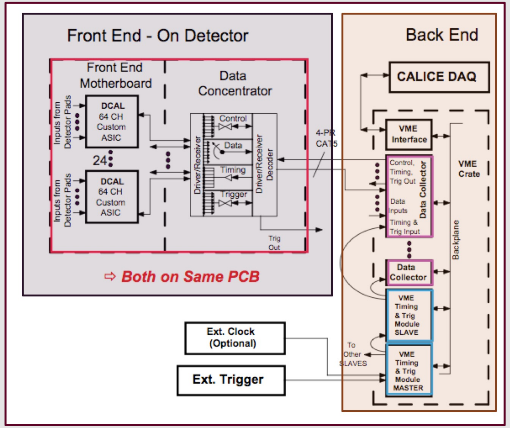
Tests at CERN

with Tungsten absorber in 2012



Readout Electronics Overview





The DCAL Chip

Developed by

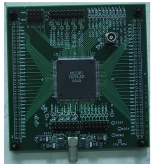
FNAL and Argonne

Input

64 channels
High gain (GEMs, micromegas…) with minimum threshold ~ 5 fC
Low gain (RPCs) with minimum threshold ~ 30 fC

Threshold

Set by 8 – bit DAC (up to ~600 fC)
Common to 64 channels



Readout

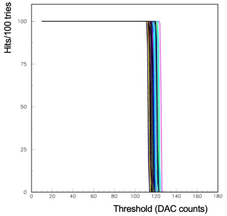
Triggerless (noise measurements)
Triggered (cosmic, test beam)

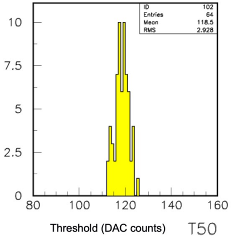
Versions

DCAL I: initial round (analog circuitry not optimized)
DCAL II: some minor problems (used in vertical slice test)
DCAL III: no identified problems (final production)

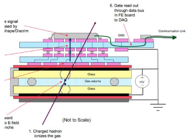
Production of DCAL III

11 wafers, 10,300 chips, fabricated, packaged, tested



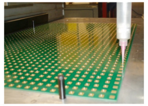


Front-end Electronics and Gluing



Front-end board (FEB) assembly

- Build electronics and pad boards separately to avoid blind and buried vias
- Each FEB contains 1536 channels
- A data concentrator is implemented
- Test electronics (noise rates, threshold curves,…)



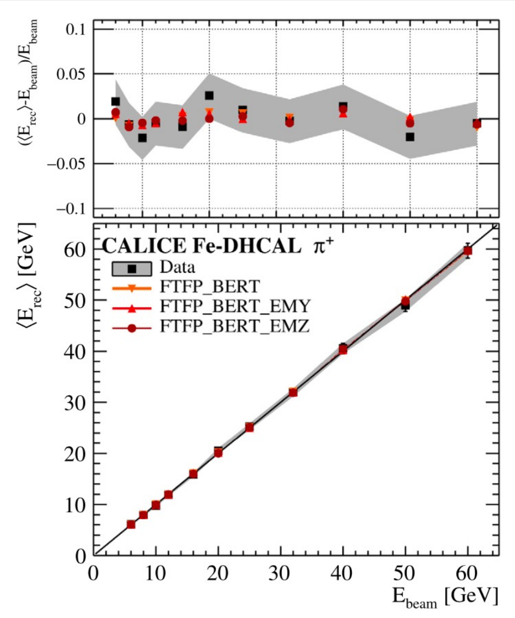
Glue Robot

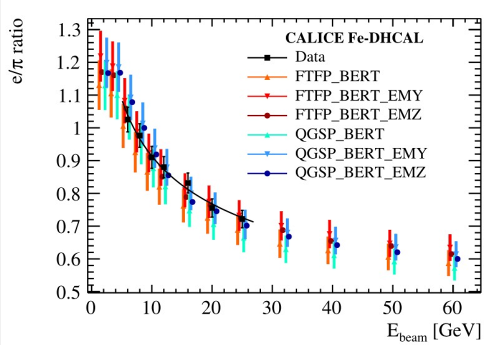
- Glue is a conductive epoxy
- Robot precisely places glue dots
- 0.001” thick plastic film used as spacers
- dried in oven over night
- 10 boards/day
- >300 FEB fabricated

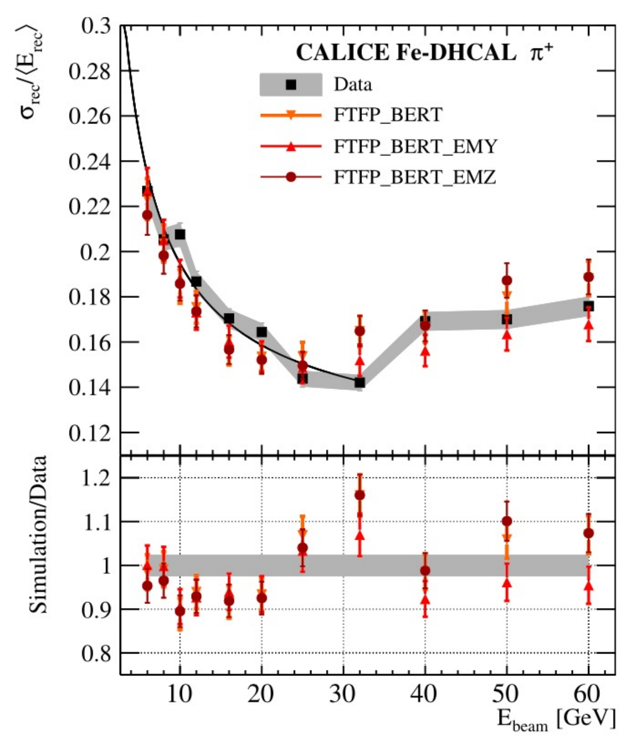
Cassette Assembly

- Cassette is compressed horizontally with a set of 4 (Badminton) strings
  - Strings are tensioned to ~20 lbs each
  - ~45 minutes/cassette

Fe-DHCAL at Fermilab

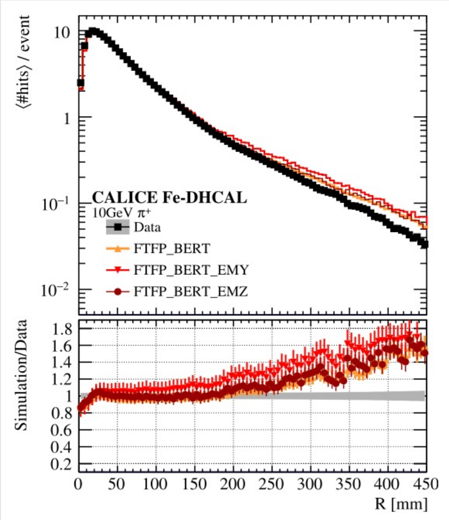


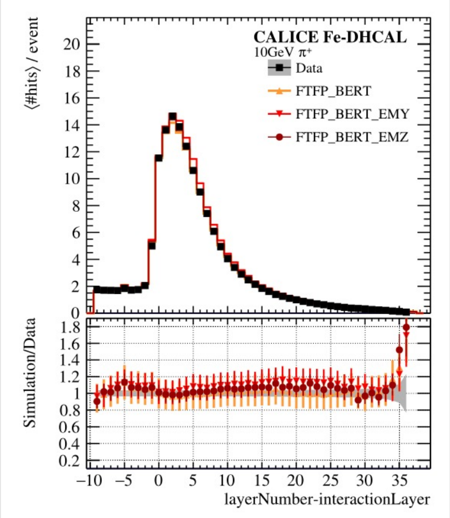




$$\frac{\sigma}{E} = \frac{(51.5 \pm 1.5)\%}{\sqrt{E}} \oplus (10.6 \pm 0.5)\%$$

M. Chefdeville, et.al., Nucl. Instr. And Meth. A 939, 89, 2019



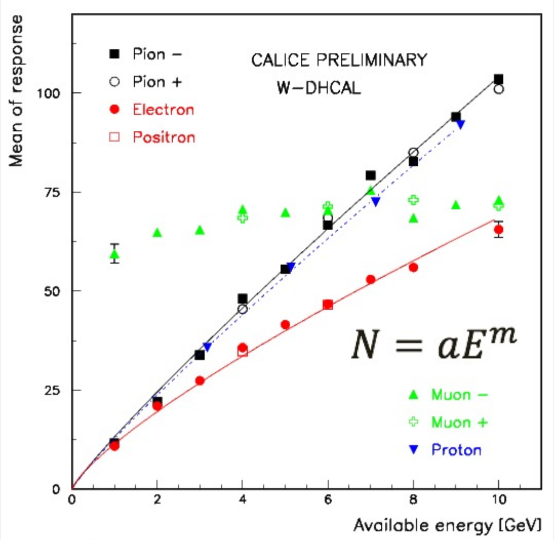


W-DHCAL at CERN

PS

Covers 1 – 10 GeV/c
Mixture of pions, electrons, protons, (Kaons)
Two Cerenkov counters for particle ID
1-3 400-ms-spills every 45 second
Data taking with ~500 triggers/spill

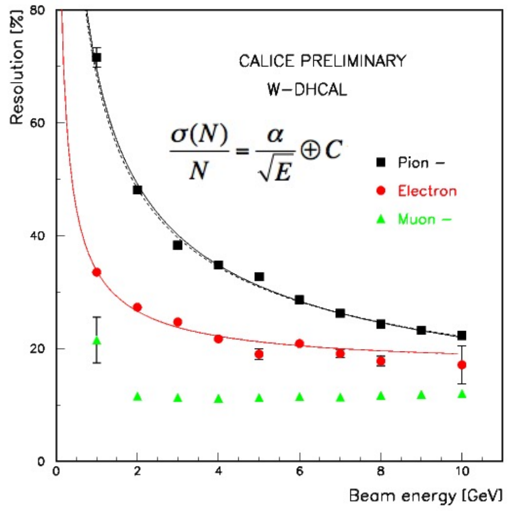
m= 0.90 (**hadrons**), 0.78 (**electrons**)

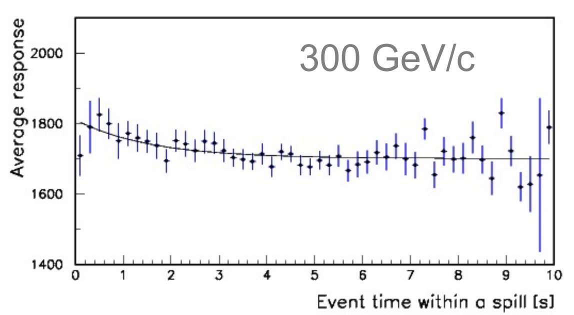


SPS

Covers 12 – 300 GeV/c
Mostly set-up to either have electrons or pions (18 Pb foil)
Two Cerenkov counters for particle ID
9.7-s-spills every 45 – 60 seconds
RPC rate capability a problem

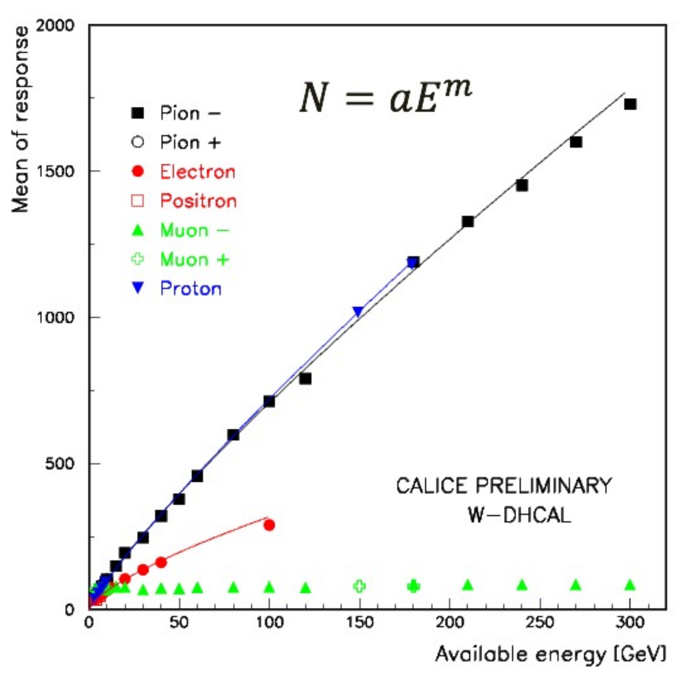
Particle	α	c
Pions	(68.0±0.4)%	(5.4±0.7)%
Electrons	(29.4±0.3)%	(16.6±0.3)%





~6 % loss of hits
(in the following not yet corrected)
Time constant ~ 1 second

W-DHCAL at CERN – Combined PS and SPS Measurements

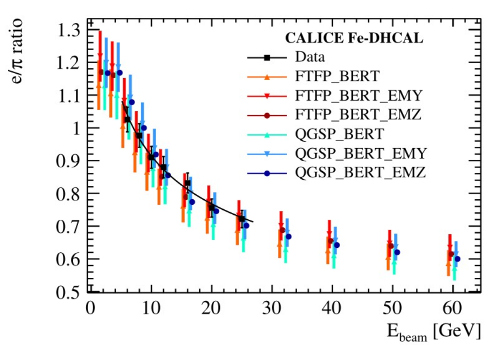


Particle	a	m
Pions	14.7	0.84
Protons	13.6	0.86
Electrons	12.7	0.70

W-DHCAL with 1 x 1 cm^2

Highly over-compensating for the entire energy range (compare to the Fe-DHCAL compensation curve below).

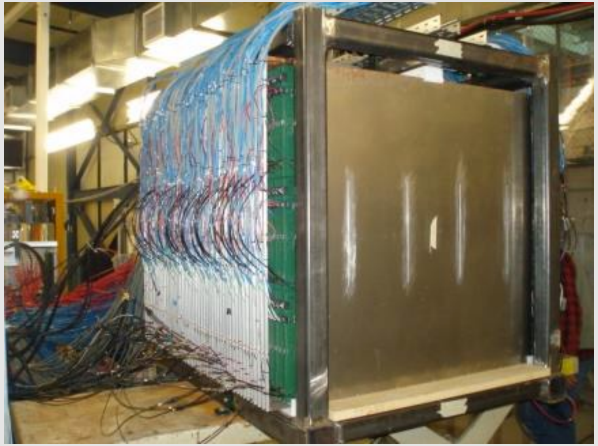
Smaller pads would increase the electron response more than the hadron response, therefore would alter the compensation characteristics.

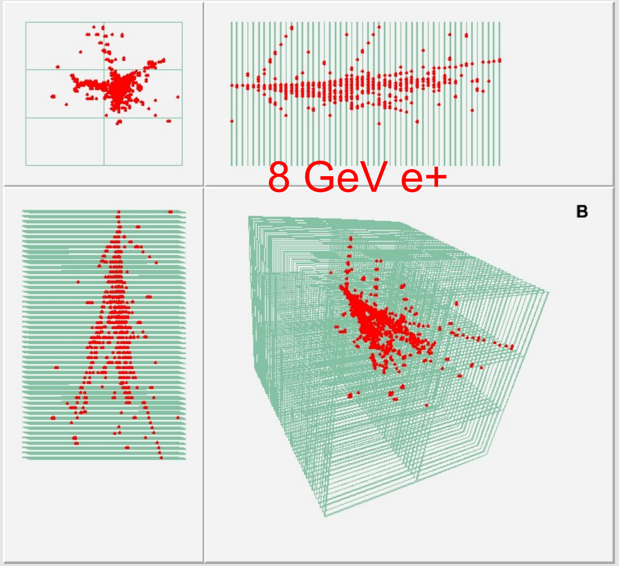


Min-DHCAL, DHCAL with Minimal Absorber, at Fermilab

- Special testbeam taken at Fermilab in November 2011 in minimal absorber configuration without absorber plates
- 2.54 cm spacing between each layer which feature a front-plate (2 mm copper) and rear plate (2 mm steel)
- Each cassette has a thickness of 12.5 mm corresponding to
  - 0.29 radiation lengths (X_0)
  - 0.034 Interaction lengths (λ_I)

→ Total thickness: 15 X_0
Or 1.7λ_I

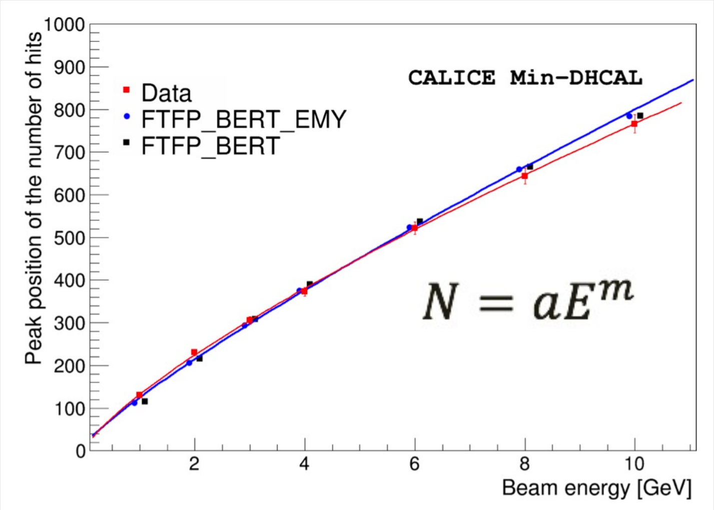


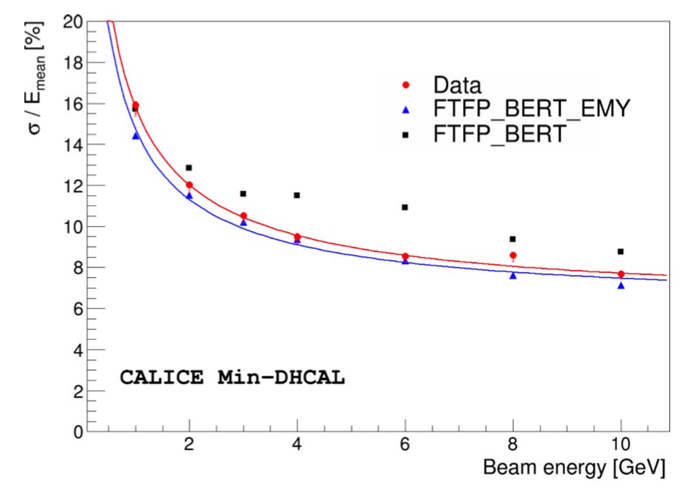


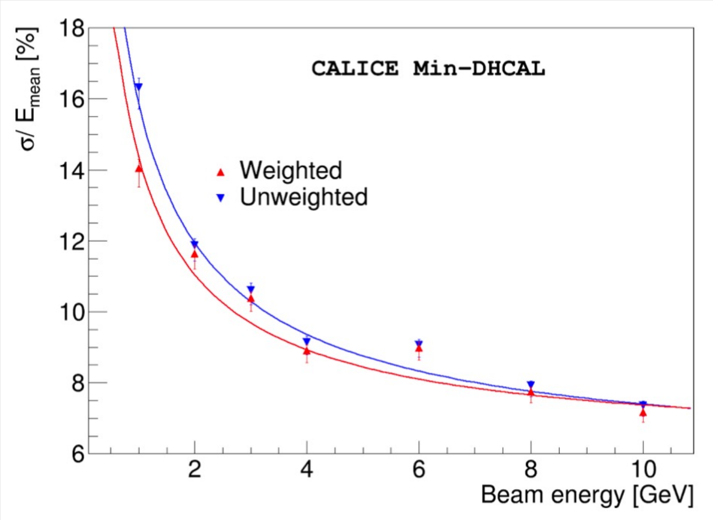
Unprecedented details of low energy electromagnetic showers!

Excellent device to study the effects of energetic particles on matter at the microscopic scale!

Min-DHCAL Positrons







Data	a [GeV^{-1}]	m
Before corrections	132±3	0.76±0.02
After leakage corrections	133±3	0.78±0.02
After linearization	99±2	0.94±0.01

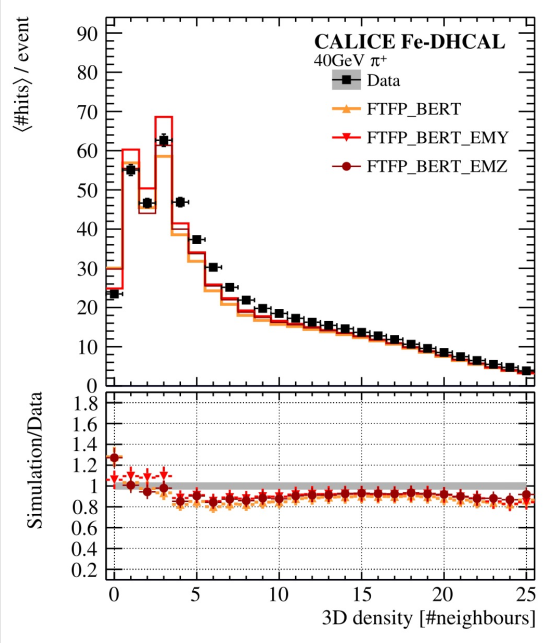
Fit	c[%]	α [%]
Unweighted	5.7 ± 0.2	14.8 ± 0.4
Weighted (linearized)	6.2 ± 0.2	13.0 ± 0.4

B. Freund et.al., JINST 11 P05008, 2016

Simulation of the DHCAL Response

- is particularly challenging
- shows significant improvements in newer versions of Geant4 and EM physics packages
- Involves several interconnected steps:

1. The primary ionization locations in the gas gaps of the RPCs are obtained from Geant4.
2. The ionization charges are sampled from the distribution obtained with the analog readout of a DHCAL RPC.
3. A dedicated software called RPCSim was developed to distribute the generated charge over the pads, apply the threshold and reconstruct the hits.



3D density of hits for 40 GeV π^+ showers in the DHCAL with iron absorbers (Fe-DHCAL)

The disagreements are at the very fine level of detail which is not available in conventional calorimeters. ➔ Work ongoing.

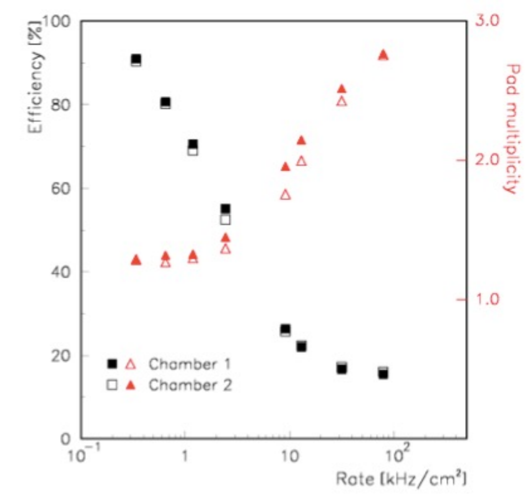
Recent Hardware Development:

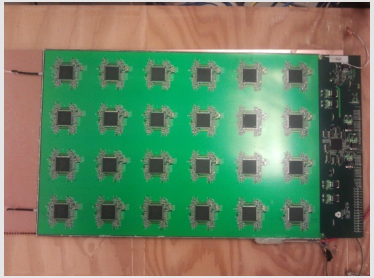
1-glass and semi-conductive glass RPCs

1-glass RPCs

Offers many advantages

Pad multiplicity close to one
→ easier to calibrate
Better position resolution
→ if smaller pads are desired
Thinner
→ $t = t_{chamber} + t_{readout}$ = 2.4 + ~1.5 mm
→ saves on cost
Higher rate capability
→ roughly a factor of 2

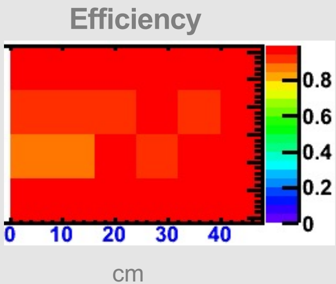


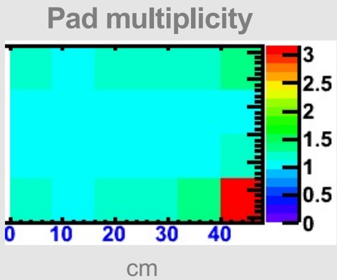


Status

Built several large chambers
Tests with cosmic rays very successful
→ chambers ran for months without problems
Both efficiency and pad multiplicity look good
Good performance in the test beam

B. Bilki, et.al., JINST 5, P05003, 2015





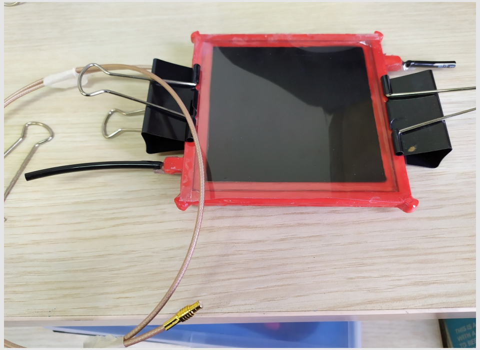
Further Development of 1-glass RPCs

Probing a hybrid readout where part of the electron multiplication is transferred to a thin film of high secondary emission yield material coated on the readout pad with the purpose of reducing/removing gas flow and enabling the utilization of alternative gases.

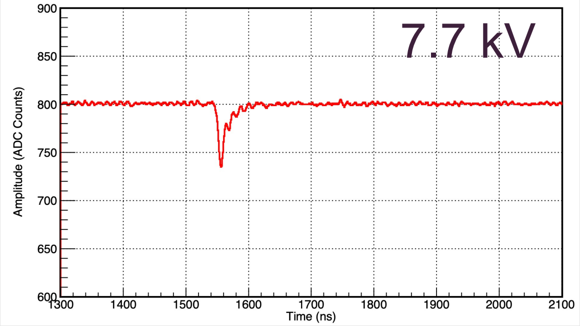
Built several 10 cm x 10 cm chambers with single pad readout.

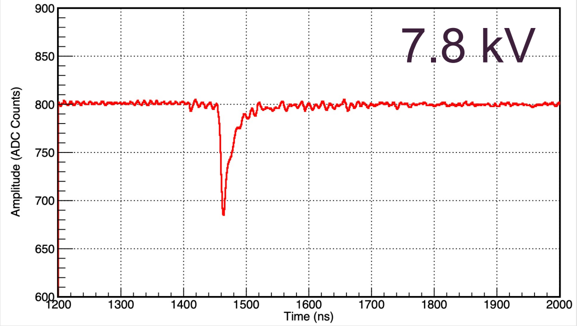
Coating of Al_2O_3 made with magnetron sputtering.

Coating of TiO_2 made with airbrushing after dissolving TiO_2 in ethanol.



Cosmic muon response



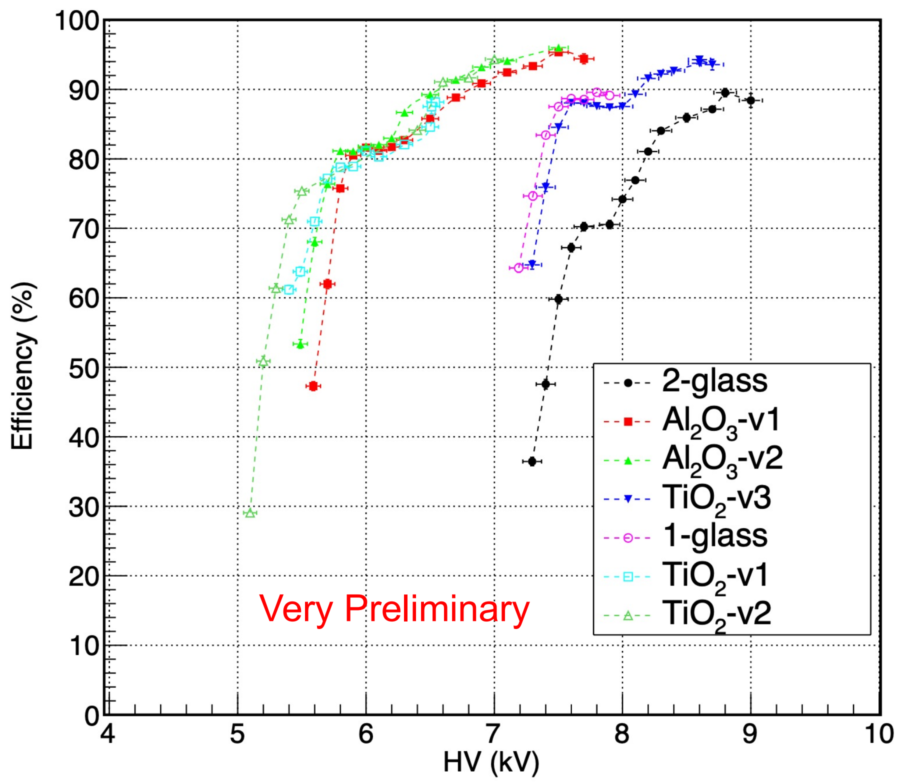


First-Generation Hybrid RPCs

We tested the first-generation hybrid RPCs as well as the standard 1-glass and 2-glass RPCs at Fermilab test beam. The lateral size of the chambers was 10 cm x 10 cm, the gas gap was 1.3 mm and the gas mixture was the DHCAL RPC gas mixture R134A : Isobutane : SF_6 ; 94.5 : 5.0 : 0.5 at 2-3 cc/min flow rate (lower than the nominal 5 cc/min).

Chambers tested and their 90% efficiency crossing HV:

1. 2-glass RPC (8.5 kV)
2. 1-glass RPC (7.5 kV)
3. 500 nm Al_2O_3 (v1) (6.5 kV)
4. 350 nm Al_2O_3 (v2) (6.5 kV)
5. 1 mg/cm^2 TiO_2 (v1) (6.5 kV)
6. 0.5 mg/cm^2 TiO_2 (v2) (6.5 kV)
7. 0.15 mg/cm^2 TiO_2 (v3) (7.5 kV)



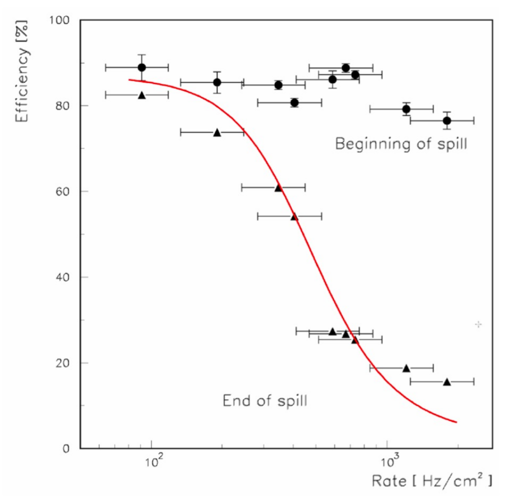
The charge multiplication in the secondary emission layer is qualitatively validated.

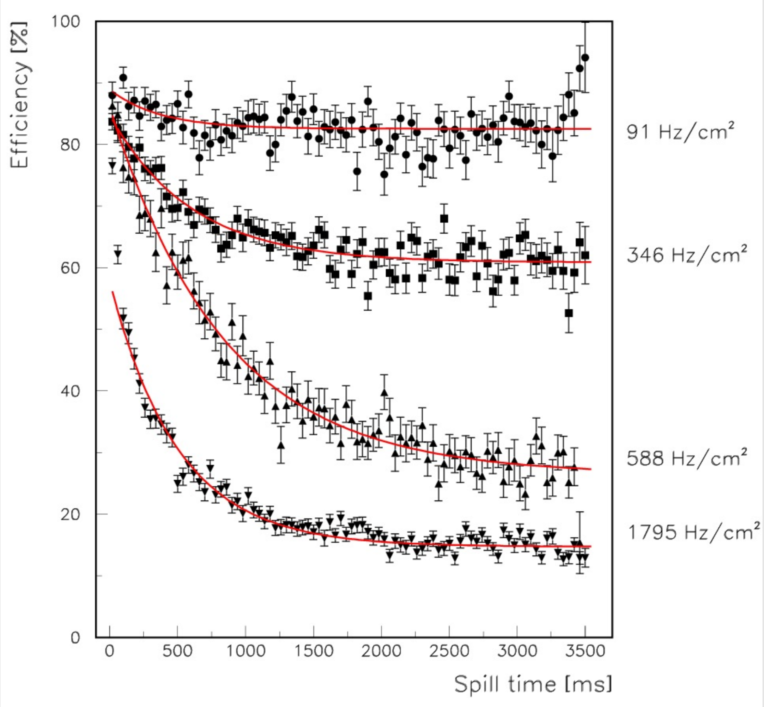
Efficient if charge > 300 fC

Rate capability of RPCs

Measurements of efficiency

With 120 GeV protons
In Fermilab test beam





Rate limitation

NOT a dead time
But a loss of efficiency

Theoretical curves

Excellent description of effect

Rate capability depends on

The bulk resistivity R_{bulk} of the resistive plates

Lower bulk resistivity → higher rate capability

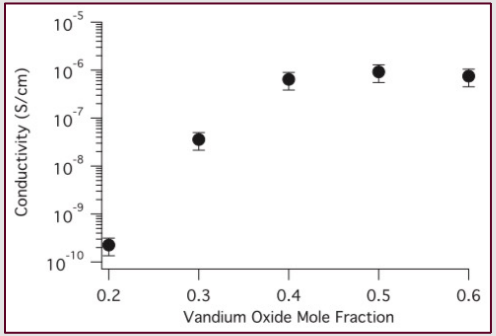
B.Bilki et al., JINST 4 P06003, 2009

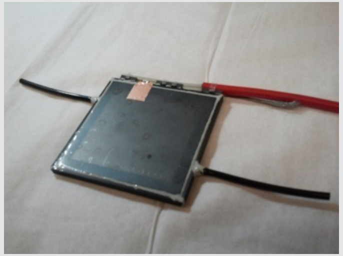
Development of semi-conductive glass

Co-operation with **COE college** (Iowa)

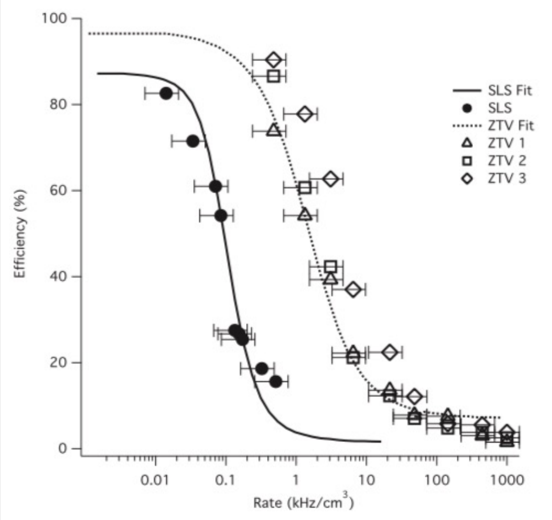
Vanadium based glass

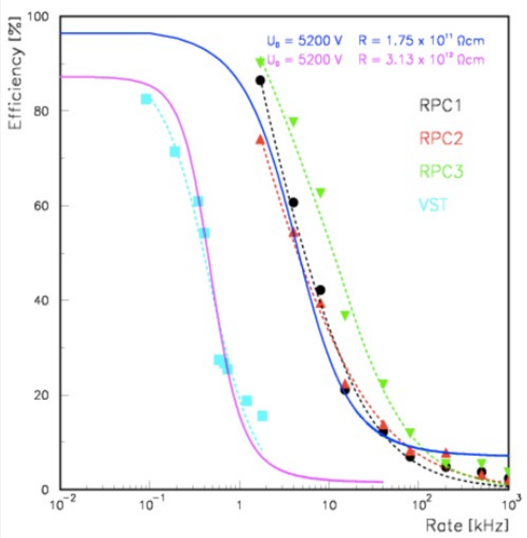
Resistivity tunable

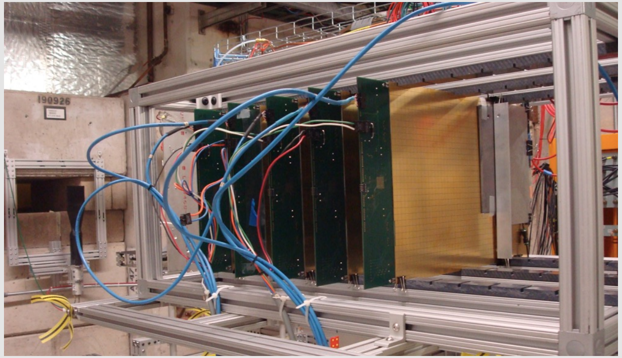




SLS: Soda lime silicate
ZTV: Zinc tellurium vanadate







N. Johnson et al., Int. J. Appl. Glass Sci. 6, 26, 2015

Further Development of High-Rate RPCs

RPC design	Number of glass plates	Area A [cm^2]	Bulk resistivity ρ [Ωcm]	Total thickness t of the glass [cm]	Conductance per area of the glass $G = (\rho \cdot t)^{-1}$ [$\Omega^{-1}cm^{-2}$]	Rate at 50% efficiency [Hz/cm^2]	
1	2	400	4.7×10^{12}	0.22	1.0×10^{-12}	300	Soda-lime
2	1	1536	3.7×10^{12}	0.11	2.4×10^{-12}	1500	Soda-lime
3	2	400	6.3×10^{10}	0.28	5.6×10^{-11}	15,000	Schott

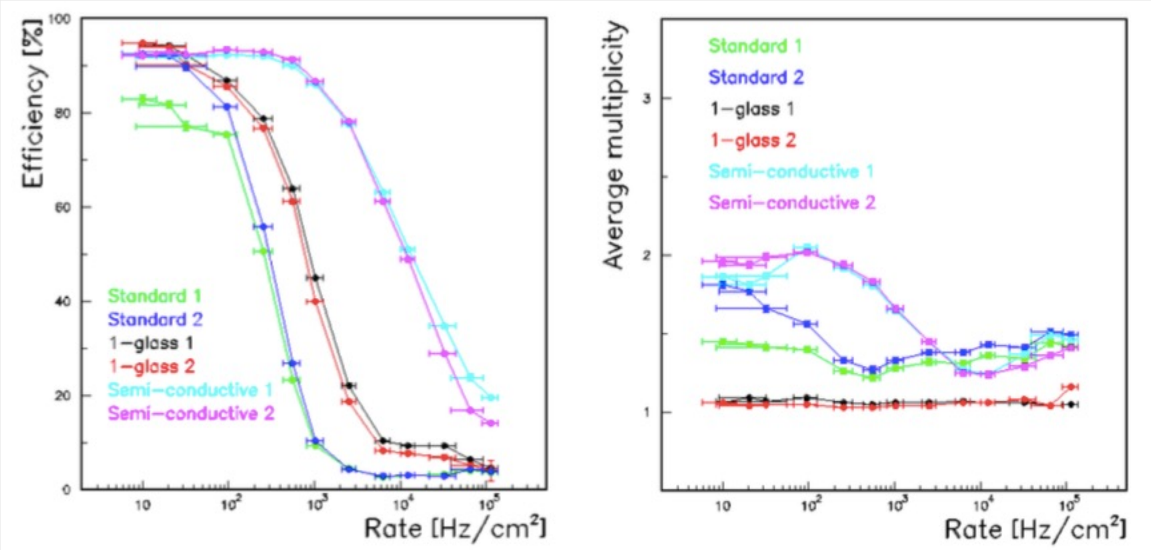
M. Affatigato et al., JINST 10 P10037, 2015

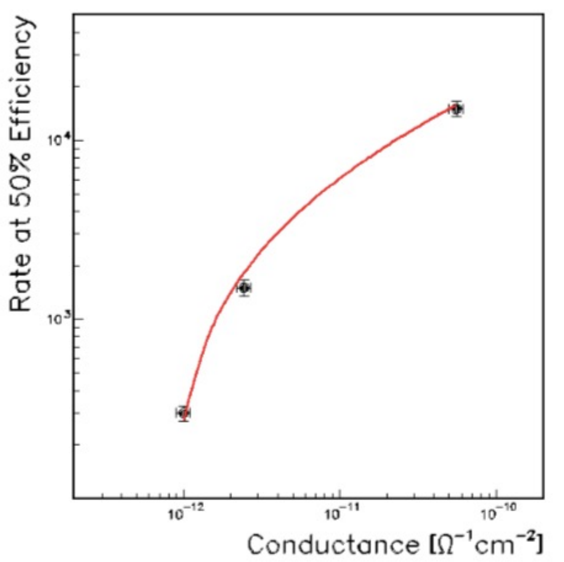
1. *2-glass RPCs with standard glass*
   The chambers were built with two standard soda-lime float glass plates with a thickness of 1.1 mm each. The gas gap was 1.2 mm. The chambers were 20 x 20 cm^2 in size.

2. *1-glass RPCs with standard glass*
   The chambers were built with one standard soda-lime float glass plate with a thickness of 1.15 mm. The gas gap was also 1.15 mm. The size of the chamber was dictated by the size of the readout board, i.e. 32 x 48 cm^2. With only one glass plate the gas volume is defined by the glass plate and the anode board. Thus, the readout pads are located directly in the gas volume.

3. *2-glass RPCs with semi-conductive glass*
   These chambers utilize semi-conductive glass with a bulk resistivity several orders of magnitude smaller than standard soda-lime float glass. The glass, *model S8900*, is available from Schott Glass Technologies Inc. The gas gap of these chambers was also 1.15 mm and the area of the chambers measured 20 x 20 cm^2. With 1.4 mm thickness, the glass plates were somewhat thicker than for the other designs.

Further Development of High-Rate RPCs





$I_{50\%}=a+bH+cH^3$

where H = 1/ $\log_{10}(G)$, where G is the conductance per area of the glass plates; and a, b, and c are free parameters.

a = $1.7\text{x}10^5$, b = $3.2\text{x}10^6$ and c=$-1.7\text{x}10^8$.

Conclusions

- The first Digital Hadron Calorimeter was built and tested successfully. By construction, the DHCAL was the first large-scale calorimeter prototype with embedded front-end electronics, digital readout, pad readout of RPCs and extremely fine segmentation.

- Fine segmentation allows the study of electromagnetic and hadronic interactions with unprecedented level of spatial detail, and the utilization of various techniques not implemented in the community so far (software compensation, leakage correction, …). The level of detail also introduces challenges in the simulation of the response.

- The novel 1-glass chamber design offers a number of advantages over the traditional two-plate design: an average pad multiplicity close to unity, a reduced overall thickness, a simplified construction procedure and an improvement in rate capability by a factor of 2.

- Raising the overall conductance per unit area of the glass plates will enhance the rate capability and increase the range of particle rates for which the chambers retain their full particle detection efficiency.

- By developing the hybrid RPCs, the heavy requirements on gases are planned to be relaxed by shifting part of the electron multiplication in the gas layer to materials with high secondary electron multiplication capability coated on the anode surface of 1-glass RPCs.

- Future plans include high precision tests of hadron interactions with matter and further development of the hybrid RPCs.

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