Digital Hadron Calorimeter with Resistive Plate Chambers

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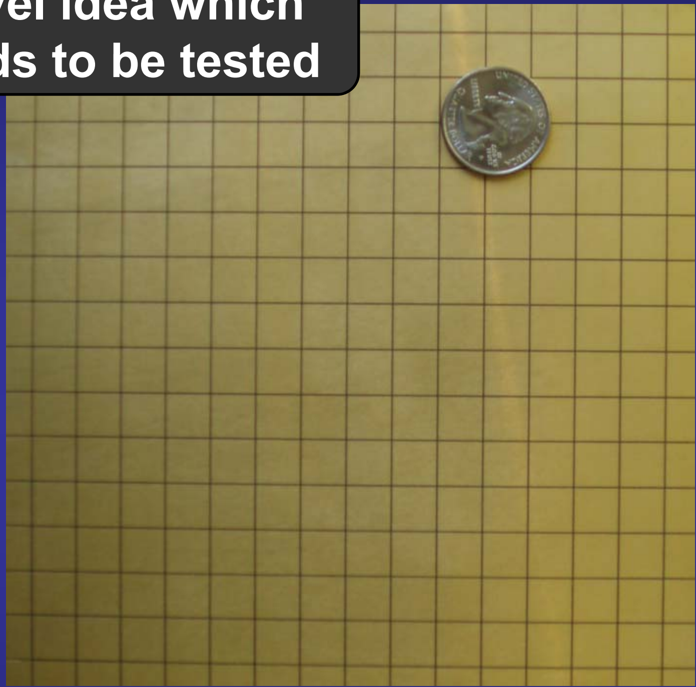
CALICE Meeting, Kobe University, May 10 – 12, 2007

Concept of a Digital Hadron Calorimeter

Novel idea which needs to be tested



Absorber

40 Steel plates of 20mm (~1 X_0)
Corresponds to ~4 λ_I

Active medium

Resistive Plate Chambers with 1 single gap
Glass as resistive plates
Operated in avalanche mode
} **No aging!**

Readout

1 x 1 cm^2 pads → $5 \cdot 10^7$ channels for the entire HCAL
1-bit resolution per pad (digital readout) ⟵ preserves single particle resolutions

Trading high resolution of the readout of calorimeter towers with the low resolution of a large number of channels

Staged approach

I — R&D on RPCs
Concept of electronic readout system

RPC tests with cosmic rays and in particle beams — **Done**

II — Prototyping of RPCs for prototype section (PS)
Prototyping of all components of electronic readout for PS

Vertical slice test in particle beam — **Planned for 6/2007**

III — Construction of 1 m^3 Prototype section with RPCs

Detailed test program in Fermilab test beam — **Planned for 2008**

IV — Further R&D on RPCs and electronic readout system — **Earliest in 2009**

V — Scalable prototype

Detailed test program in test beam — **Earliest in 2010**

I R&D with RPCs

A) Extensive tests with analog readout

Build O(10) RPCs → Explored various designs

Tested thoroughly with RABBIT system
Results to appear in N.I.M. (paper accepted)

Resistive Plate Chambers for Hadron Calorimetry: Tests with Analog Readout

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Abstract. Resistive Plate Chambers (RPCs) are being developed for use in a hadron calorimeter with very fine segmentation of the readout. The design of the chambers and various tests with cosmic rays are described. This paper reports on the measurements with multi-bit (or analog) readout of either a single larger or multiple smaller readout pads.

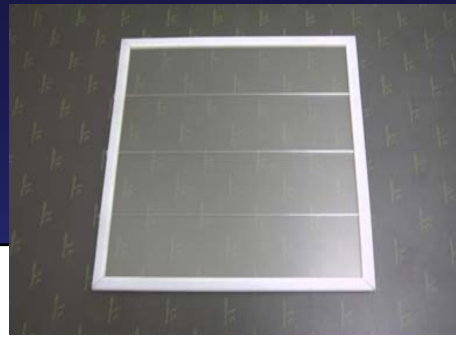
Keywords: Calorimetry, Linear Collider, Particle Flow Algorithms, Resistive Plate Chambers.
PACS: 29.40.Vj, 29.40.Cs, 29.40.Mc, 29.40.Wk

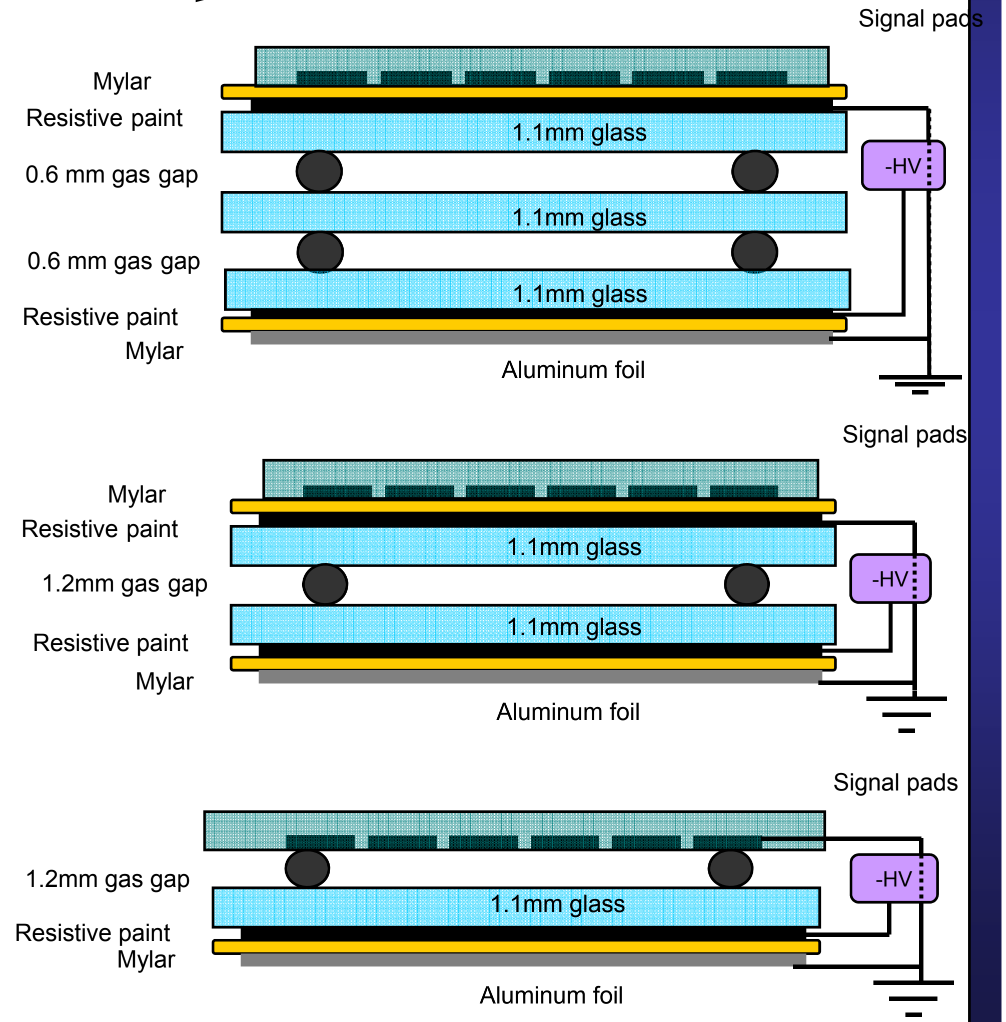
INTRODUCTION

Particle Flow Algorithms (PFAs) have been applied to existing detectors, such as ZEUS and CDF, to improve the energy resolution of hadronic jets. The algorithms attempt to measure all particles in a jet (originating from the interaction point) individually, using the detector component providing the best momentum/energy resolution. Charged particles are measured with the tracking system (except for high momenta, where the calorimeter provides a better measurement), photons are measured with the electromagnetic calorimeter (ECAL), and neutral hadrons, i.e. neutrons and K_L^0's, are measured with both the ECAL and the hadronic calorimeter (HCAL). The energy of a jet is reconstructed by adding up the energy of the individual particles identified as belonging to the jet. Additional details on PFAs can be found in reference [1].

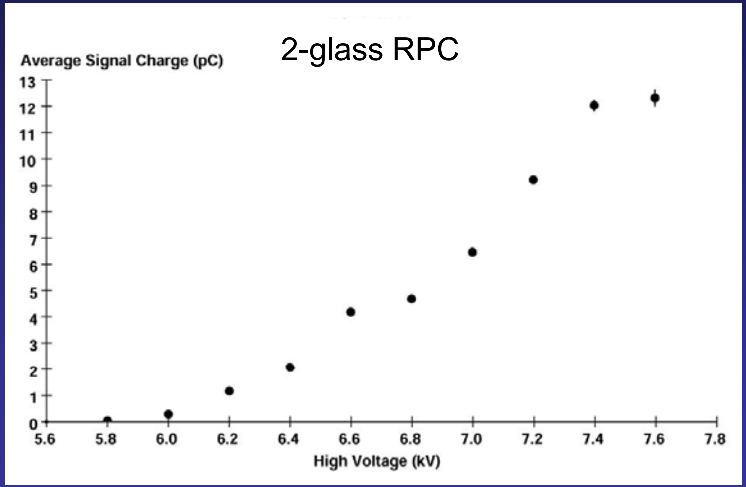
The application of PFAs at HERA and the Tevatron is limited by the relatively coarse segmentation of the existing detectors. By contrast, detectors for the International Linear Collider (ILC) are being designed [2] explicitly with adequate segmentation to optimize the performance of PFAs. In particular, this optimization imposes the following constraints on the design of the HCAL:

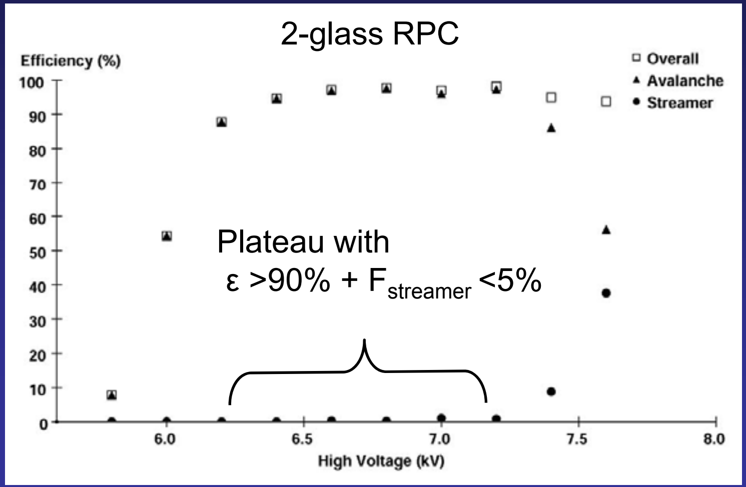
- In order to effectively identify energy deposits in the calorimeter belonging to charged or neutral particles, the readout needs to be very finely segmented, of

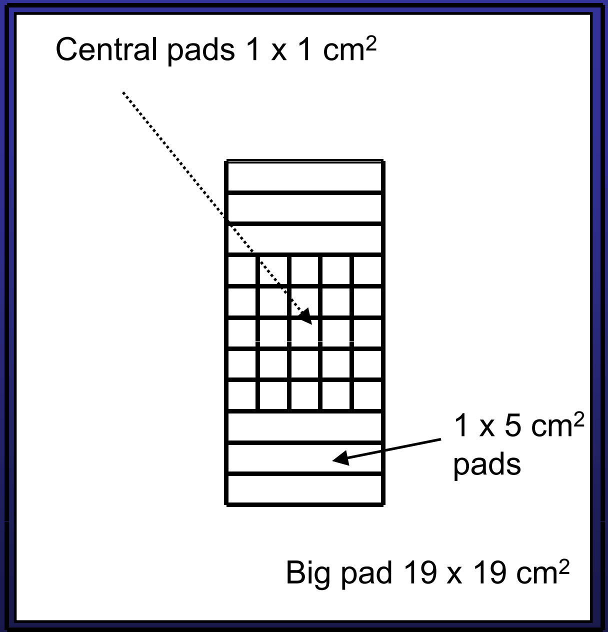




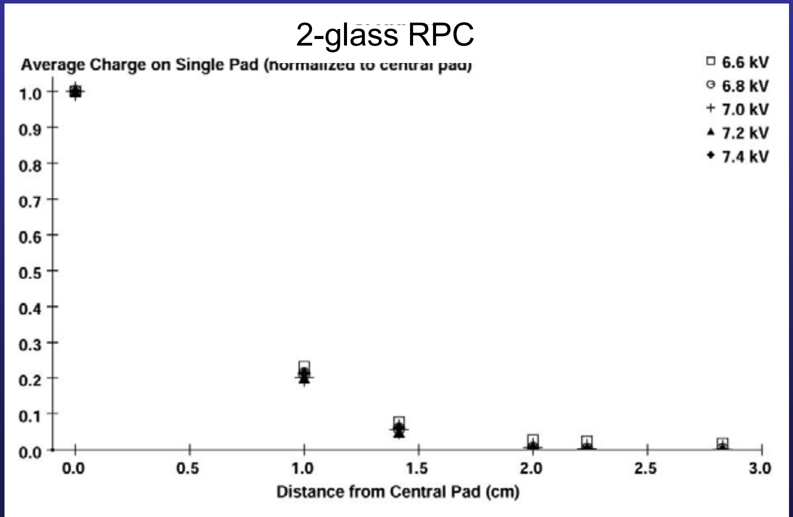
Some results with single readout pad of 16 x 16 cm²…

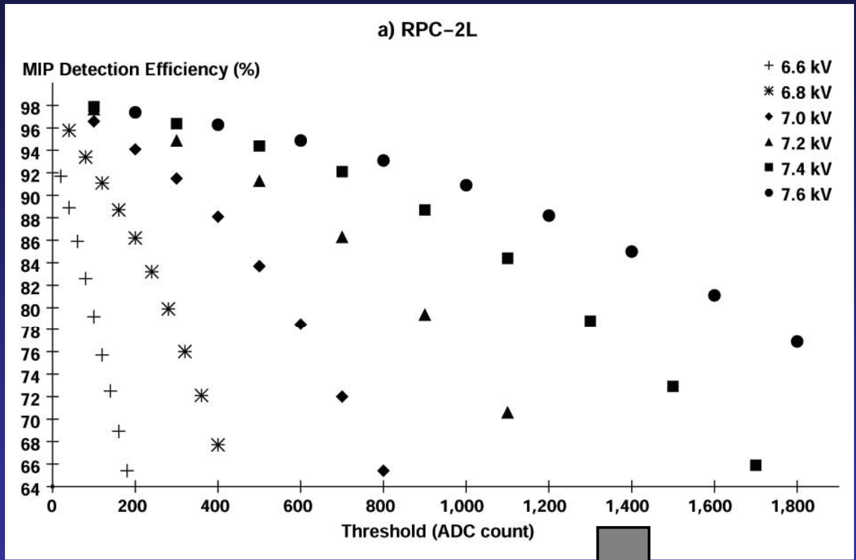


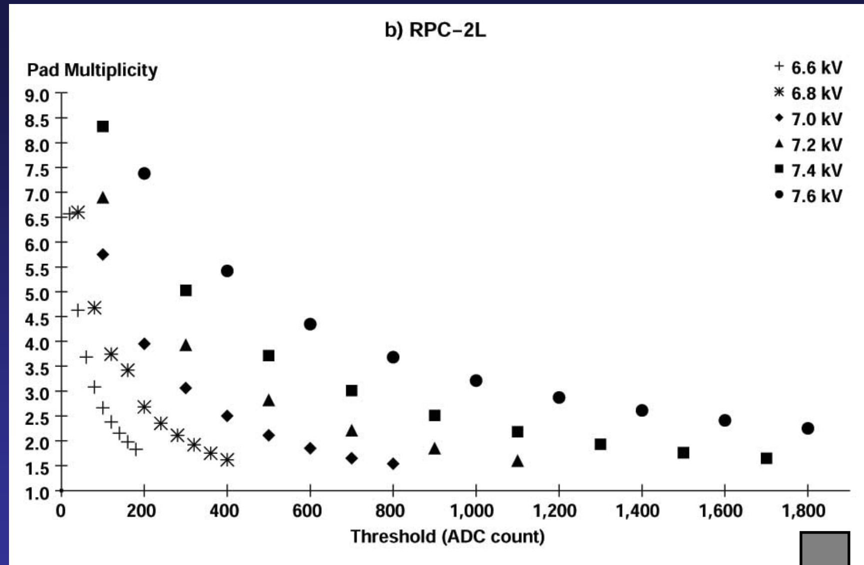




…some results with multiple readout pads of 1 x 1 cm²

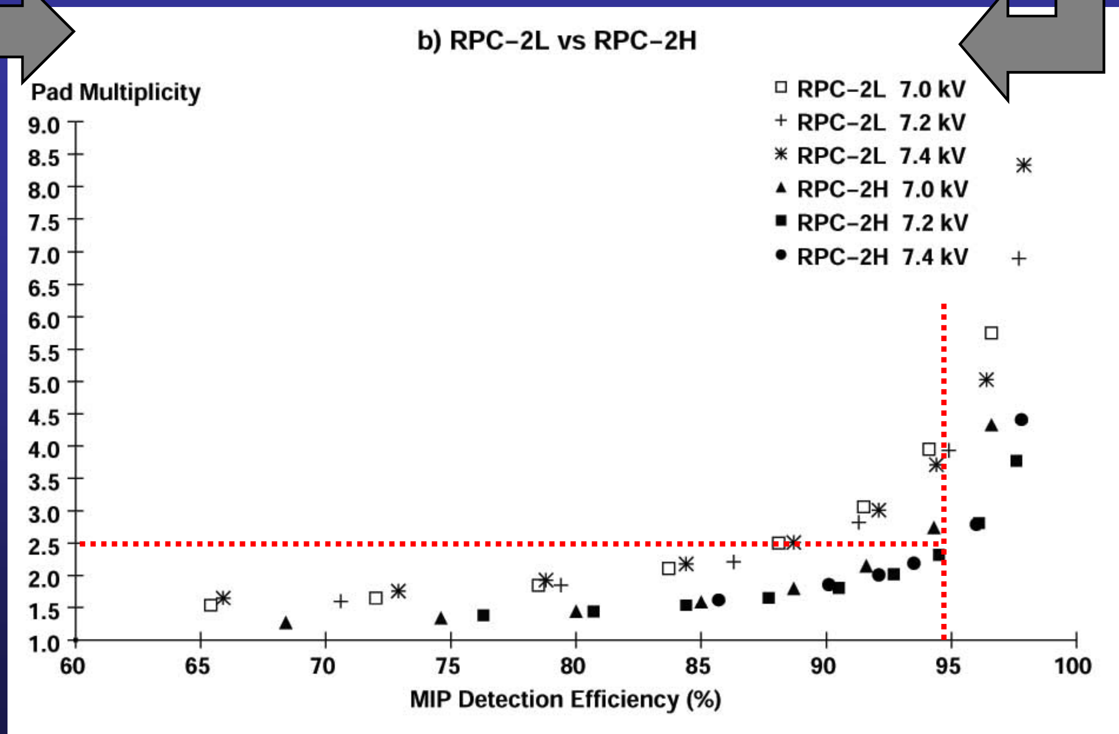


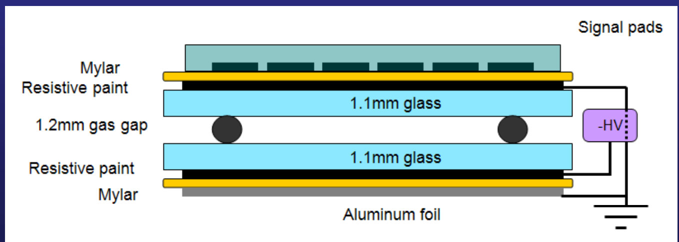




The importance of the surface resistivity of the conductive paint

RPC-2L → R□ ~ 0.1 MΩ
RPC-2H → R□ ~ 50 MΩ

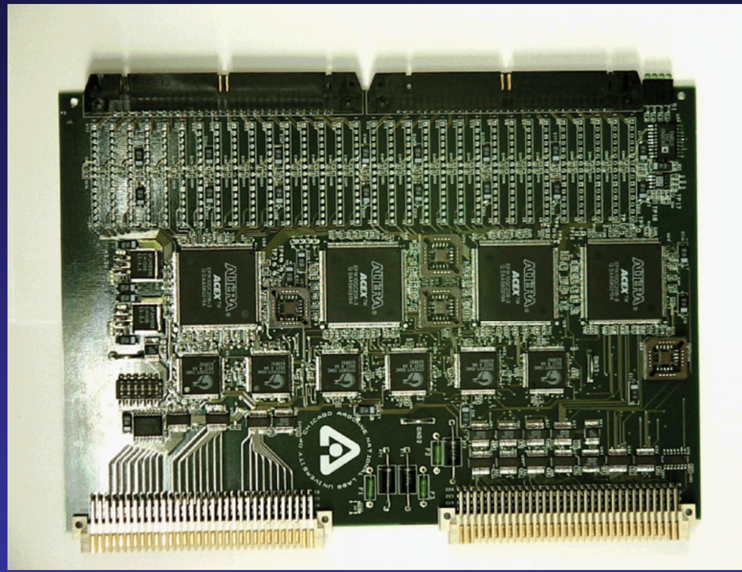


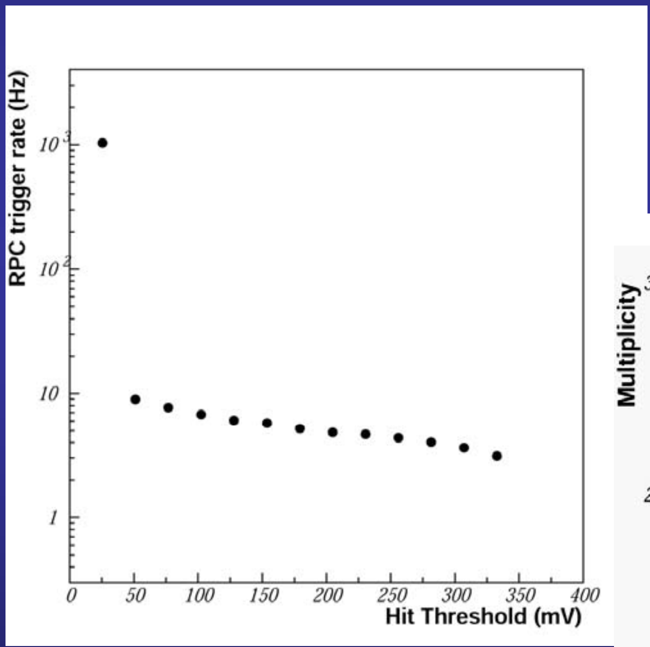


B) Tests with Digital Readout

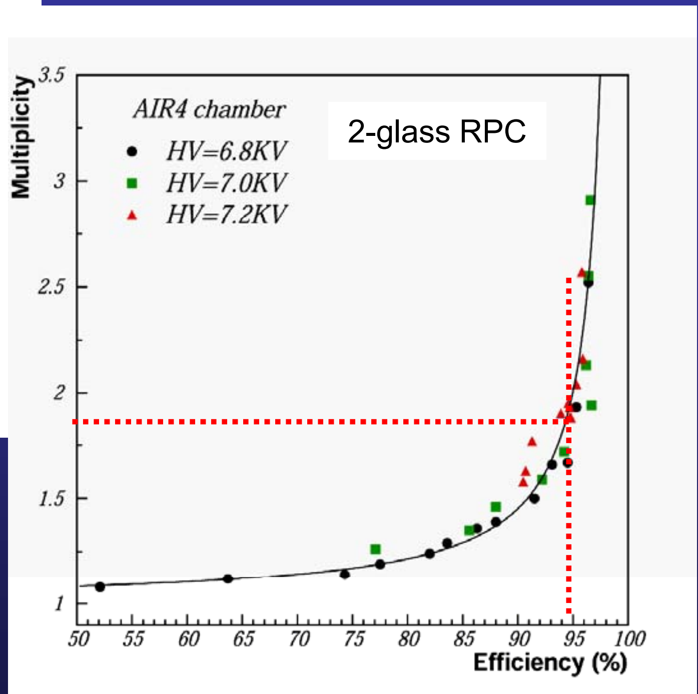
Built VME-based readout system
→ readout for 64 pads

Needed additional amplifiers on pads
Preliminary results only
(results with 'final' system expected to be better)





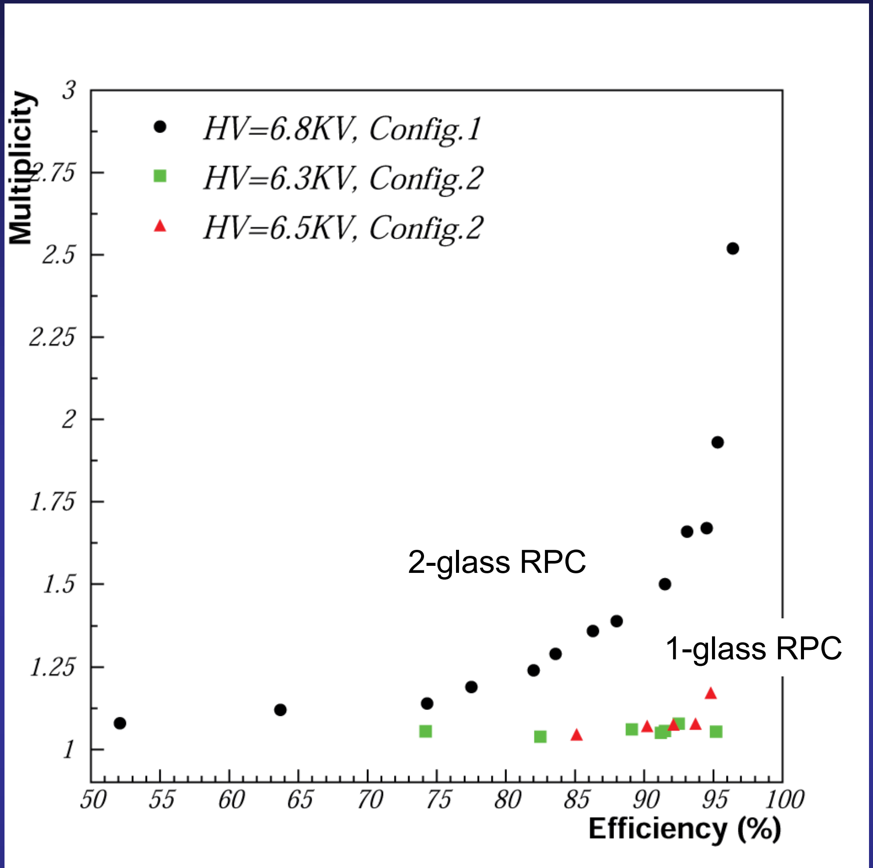
Noise ~ 0.1 Hz/pad



Pad multiplicity much reduced compared to analog case

For ε ~ 95%

→ M ~ 1.7 – 1.8

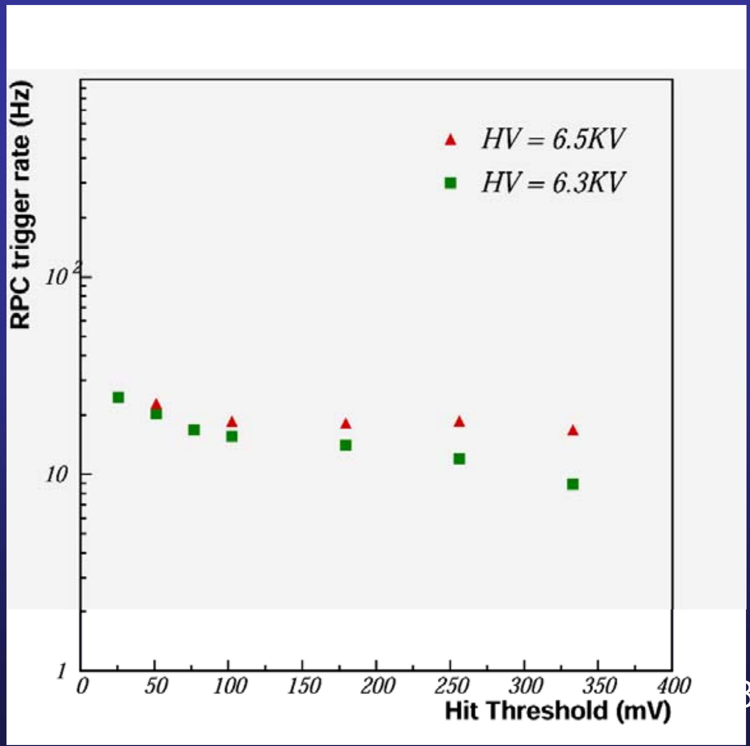


Pad multiplicity much reduced with 1-glass RPC

For ε ~ 70 ÷ 95%

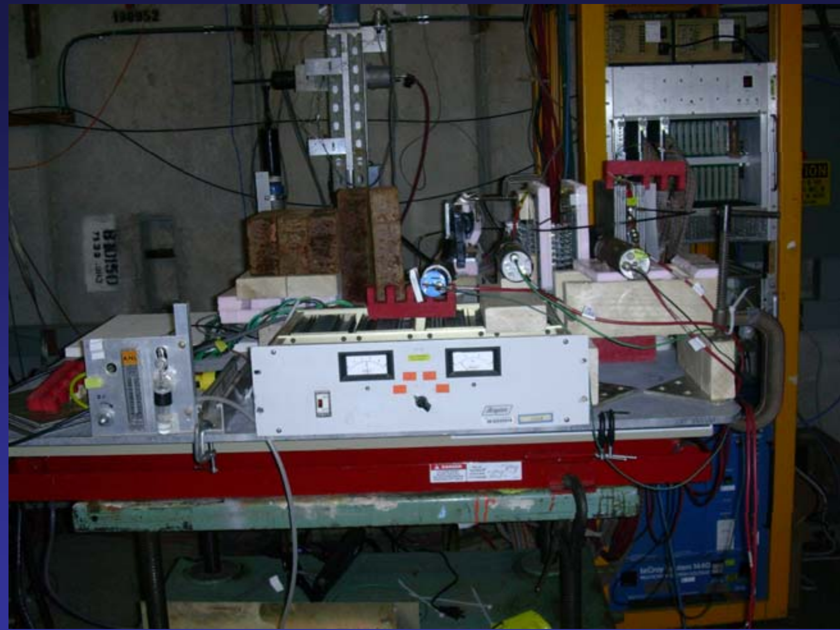
→ M ~ 1.1

(this result recently confirmed by Russian group)



Major issue: long-term stability?

C) Exposure to Fermilab Test beam



Tests included 3 chambers

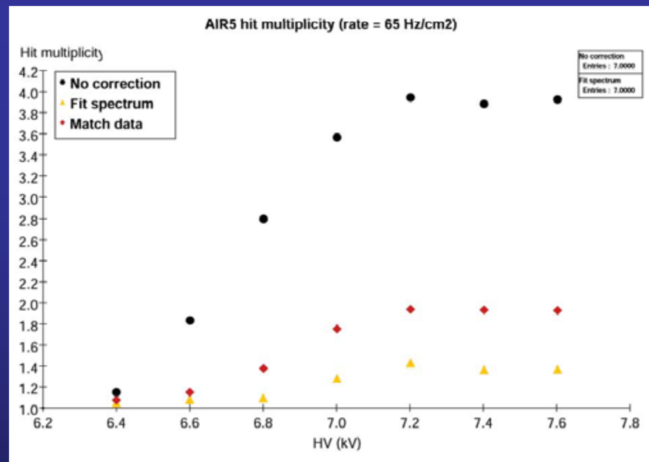
2-glass RPC with digital readout
1-glass RPC with digital readout
(2-glass RPC with independent digital readout)

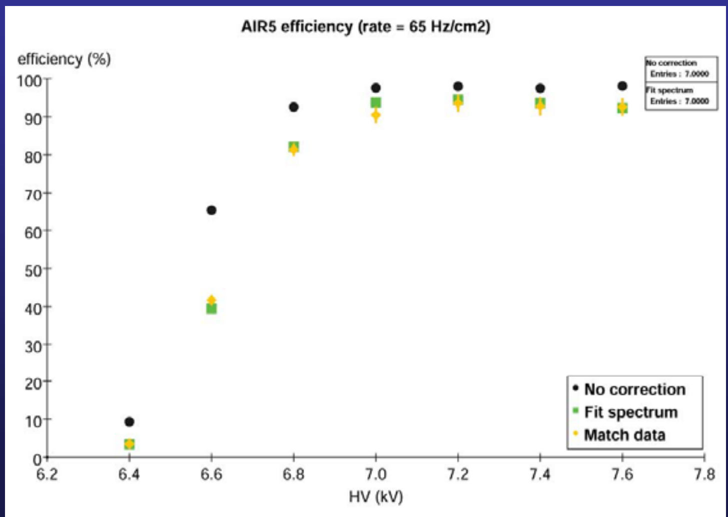
Tests took place in February 2006

Mostly ran with 120 GeV protons

Problem

Only realized later that trigger counter off beam axis
Triggered mostly on events which showered upstream
→ High multiplicity in the chambers





Great learning experience !!!!
Results (after corrections) confirmed previous measurements with cosmic rays

D) RPC construction and testing (Russia)

Measurements with 1-glass plate chambers

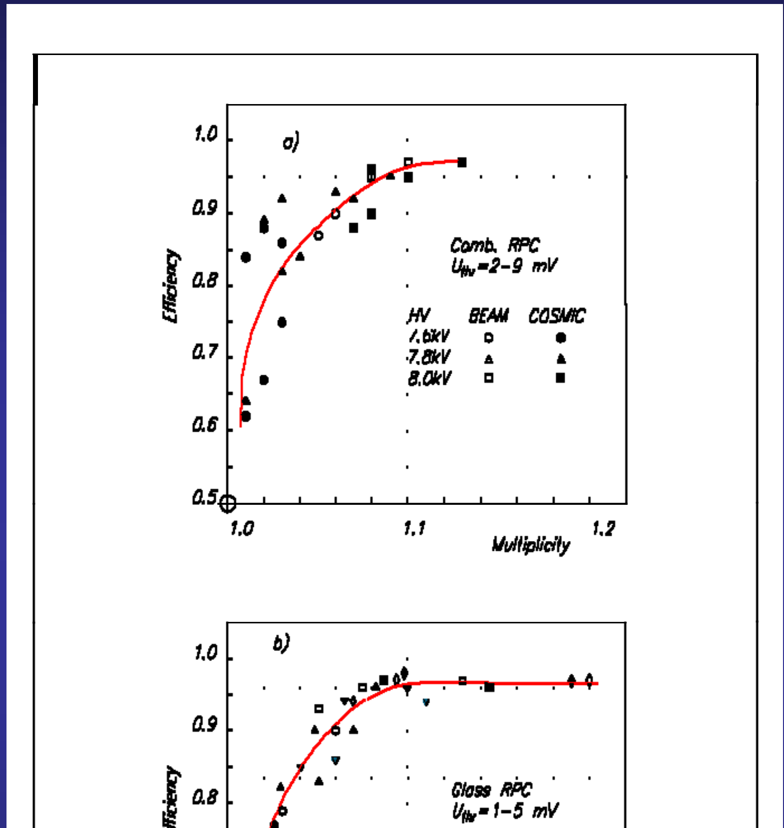
Pad multiplicity ~1.1 for an efficiency of 95%
Confirms results obtained at ANL
Long term tests ongoing

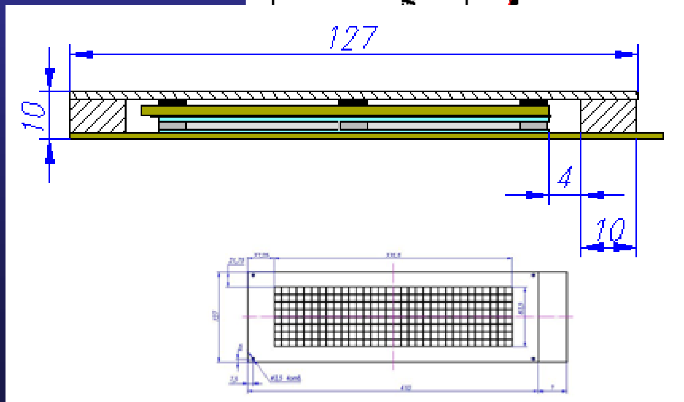
Constructed 4 chambers with 8x32 pads

One sent to Lyon for testing
Others waiting for MAROC chip + FE-board
Successfully tested with strip readout

Preparation for 1 m^2 chamber construction

Preparation of facility
Cosmic ray test stand being assembled
Design being finalized



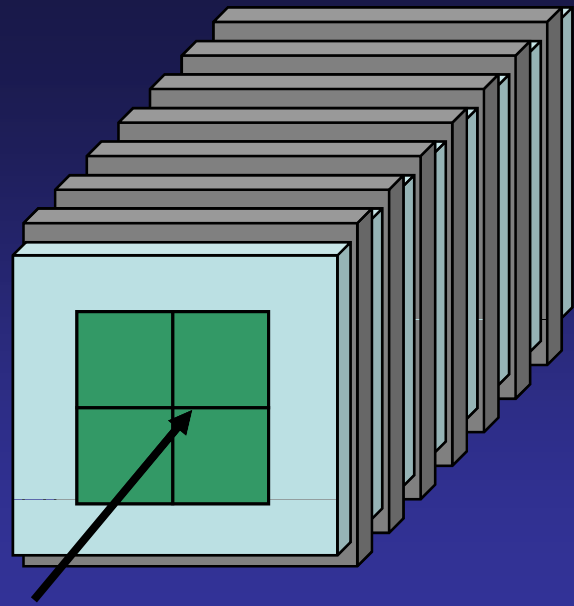


Summary of R&D with RPCs

Measurement	RPC Russia	RPC US
Signal characterization	yes	yes
HV dependence	yes	yes
Single pad efficiencies	yes	yes
Geometrical efficiency	yes	yes
Tests with different gases	yes	yes
Mechanical properties	?	yes
Multi-pad efficiencies	yes	yes
Hit multiplicities	yes	yes
Noise rates	yes	yes
Rate capability	yes	yes
Tests in 5 T field	yes	no
Tests in particle beams	yes	yes
Long term tests	ongoing	ongoing
Design of larger chamber	ongoing	ongoing

R&D virtually complete

II Vertical Slice Test



Uses the 40 front-end ASICs from the 2nd prototype run

Equip ~10 chambers with 4 chips each

256 channels/chamber
~2500 channels total

Chambers interleaved with 20 mm copper - steel absorber plates

Electronic readout system (almost) identical to the one of the prototype section

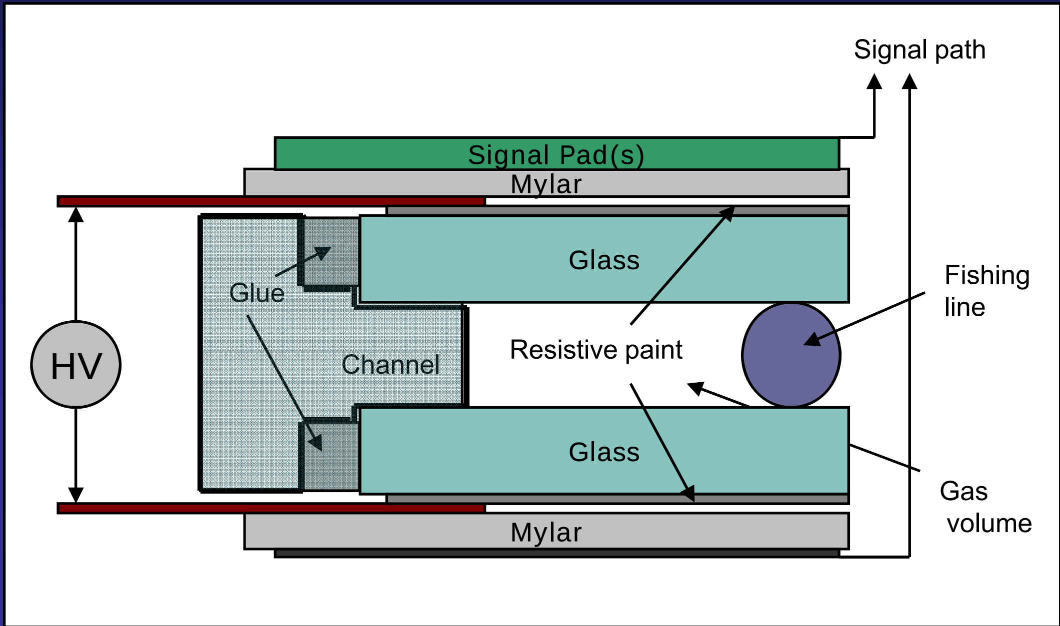
Tests in FNAL test beam planned for June 2007

→ Measure efficiency, pad multiplicity, rate capability of individual chambers
→ Measure hadronic showers and compare to simulation

Validate RPC/GEM approach to finely segmented calorimetry
Validate concept of electronic readout

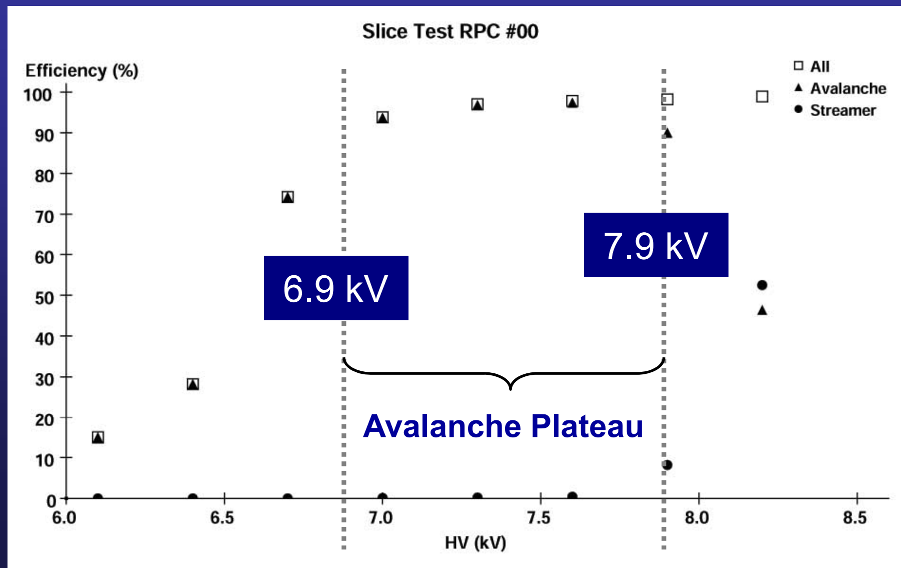
CALICE Calorimeter for ILC

RPC construction and testing for the VST



New design with simplified channels

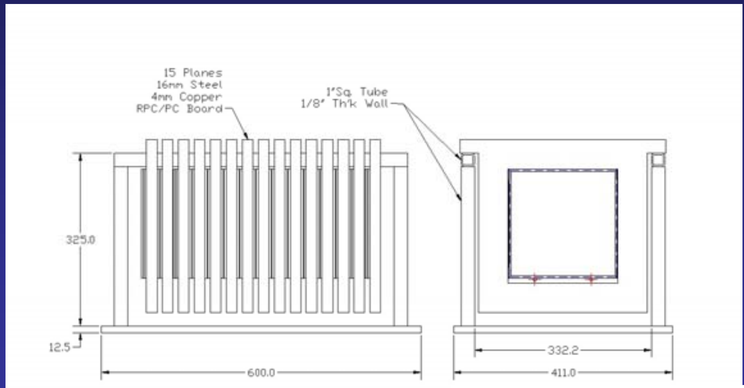
1st chamber assembled and tested
→ Excellent performance
2nd chamber assembled and tested
→ Excellent performance
3rd – 6th chamber being assembled



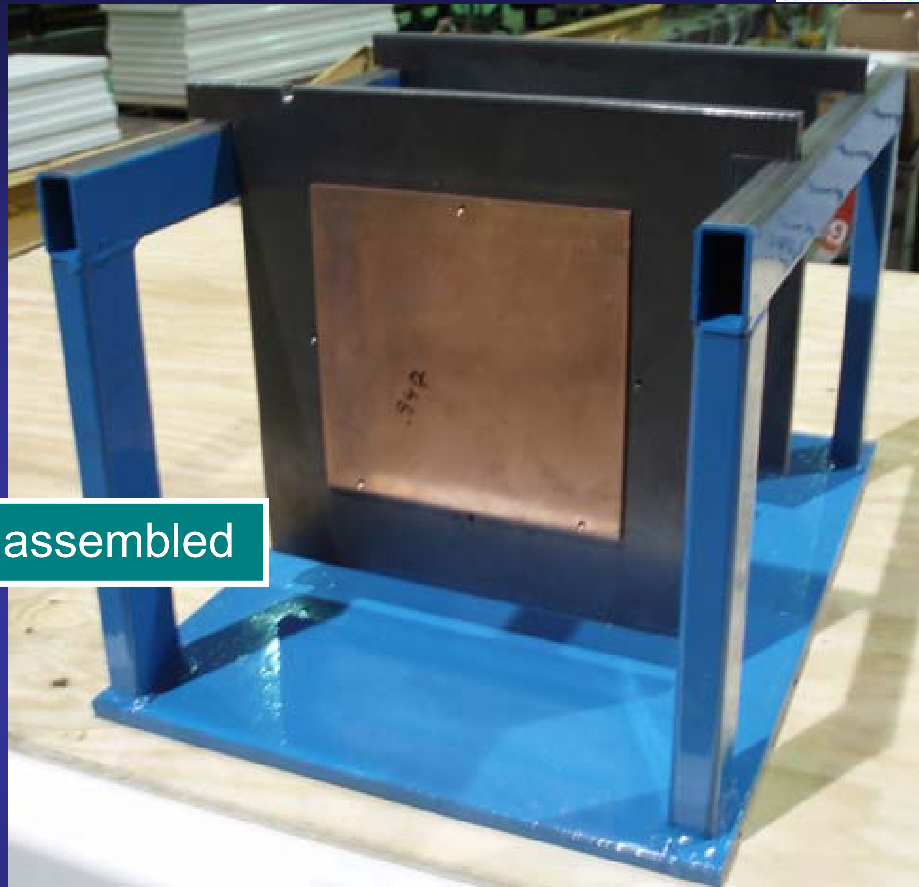
Material in hand for all remaining chambers

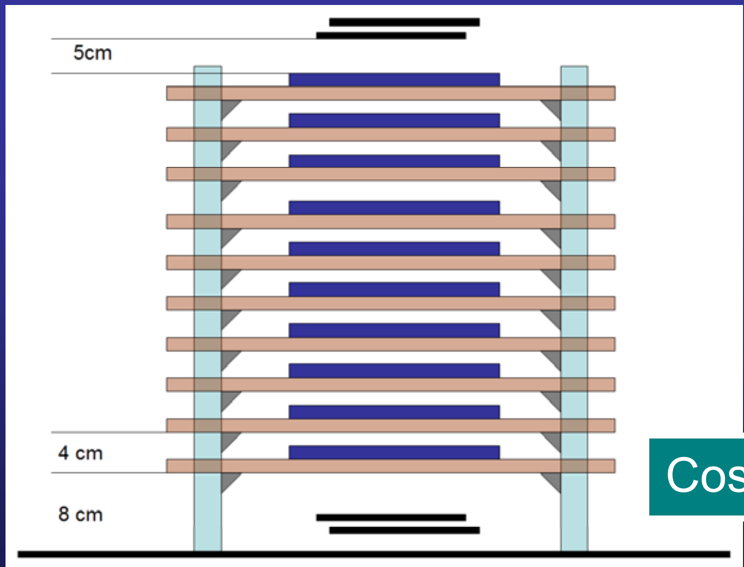
Mechanical: Stack for VST

for cosmic rays and test beam



Test beam stack is assembled





Cosmic ray stack will be assembled this week

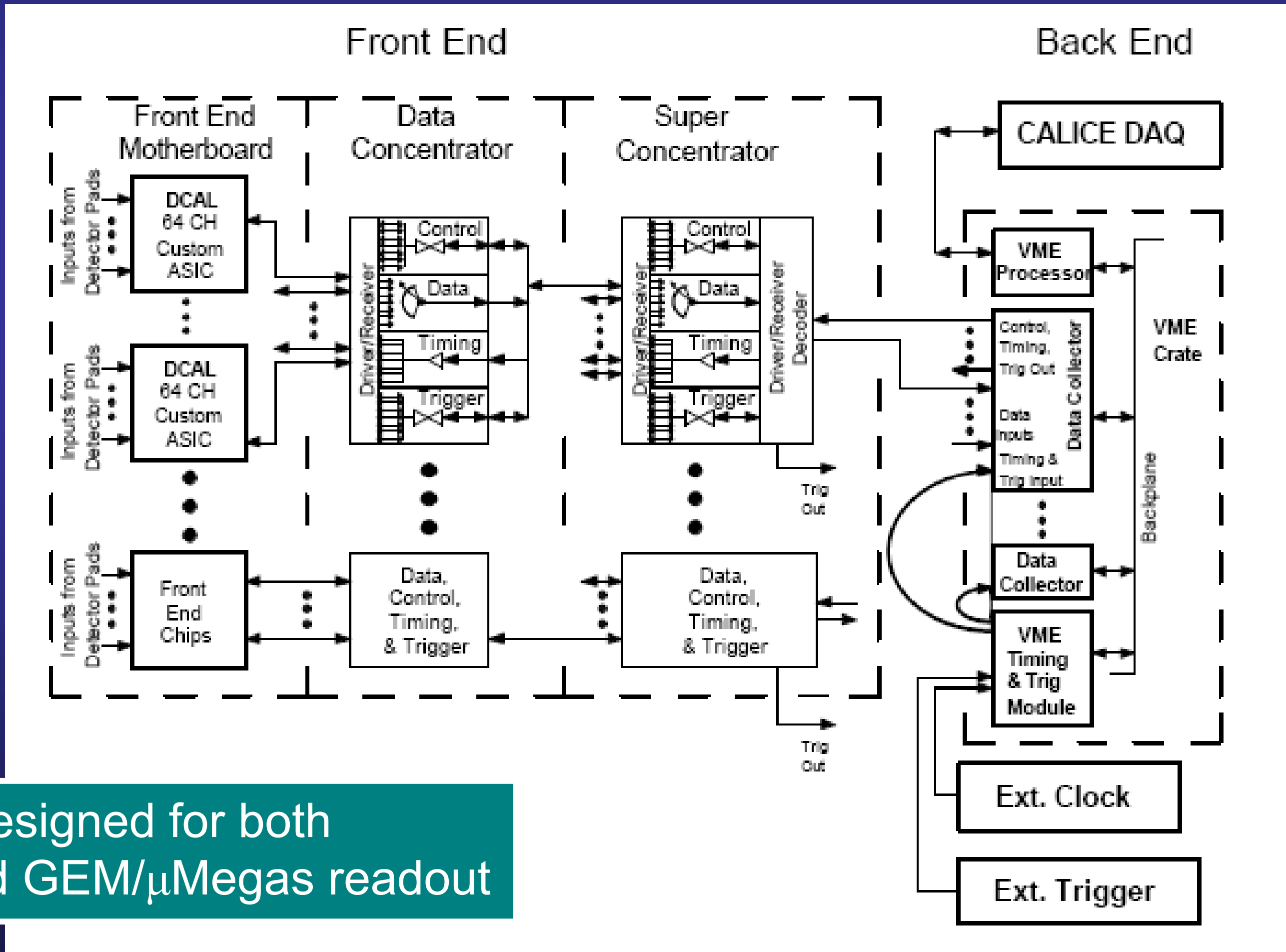
Design accommodates 20 x 20 cm^2 RPCs as well as 30 x 30 cm^2 GEMs

Electronic Readout System

Prototype section: 40 layers à 1 m^2 $\rightarrow$ 400,000 readout channels

More than all of DØ in Run I
Half of CDF channel count

- A Front-end ASIC
- B Pad and FE-board
- C Data concentrator
- D Super Concentrator
- E VME data collection
- F Trigger and timing system



System designed for both
RPC and GEM/μMegas readout

A The front-end DCAL chip

Design

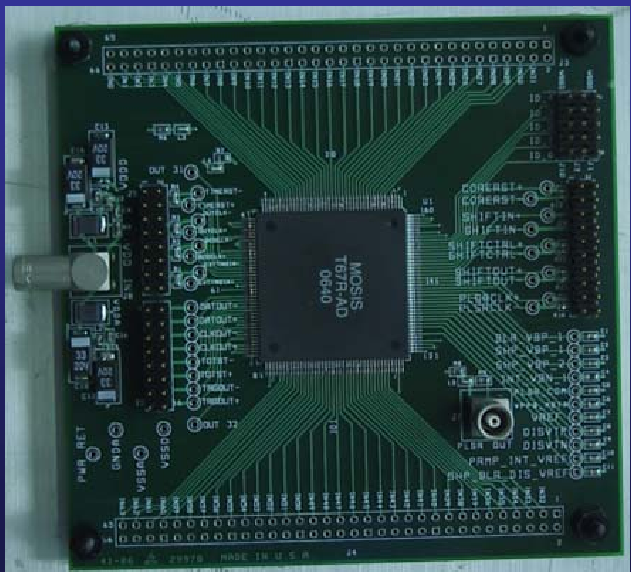
→ chip specified by Argonne
→ designed by FNAL

2nd version

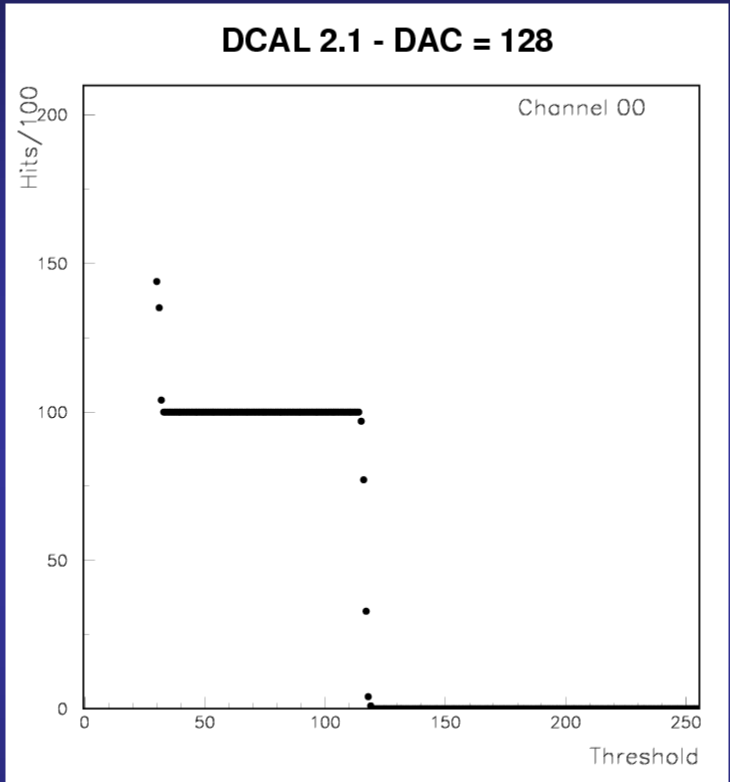
→ prototyped (40 chips in hand)
→ extensively tested at Argonne
→ tests complete
→ ordered 25 + 40 additional chips

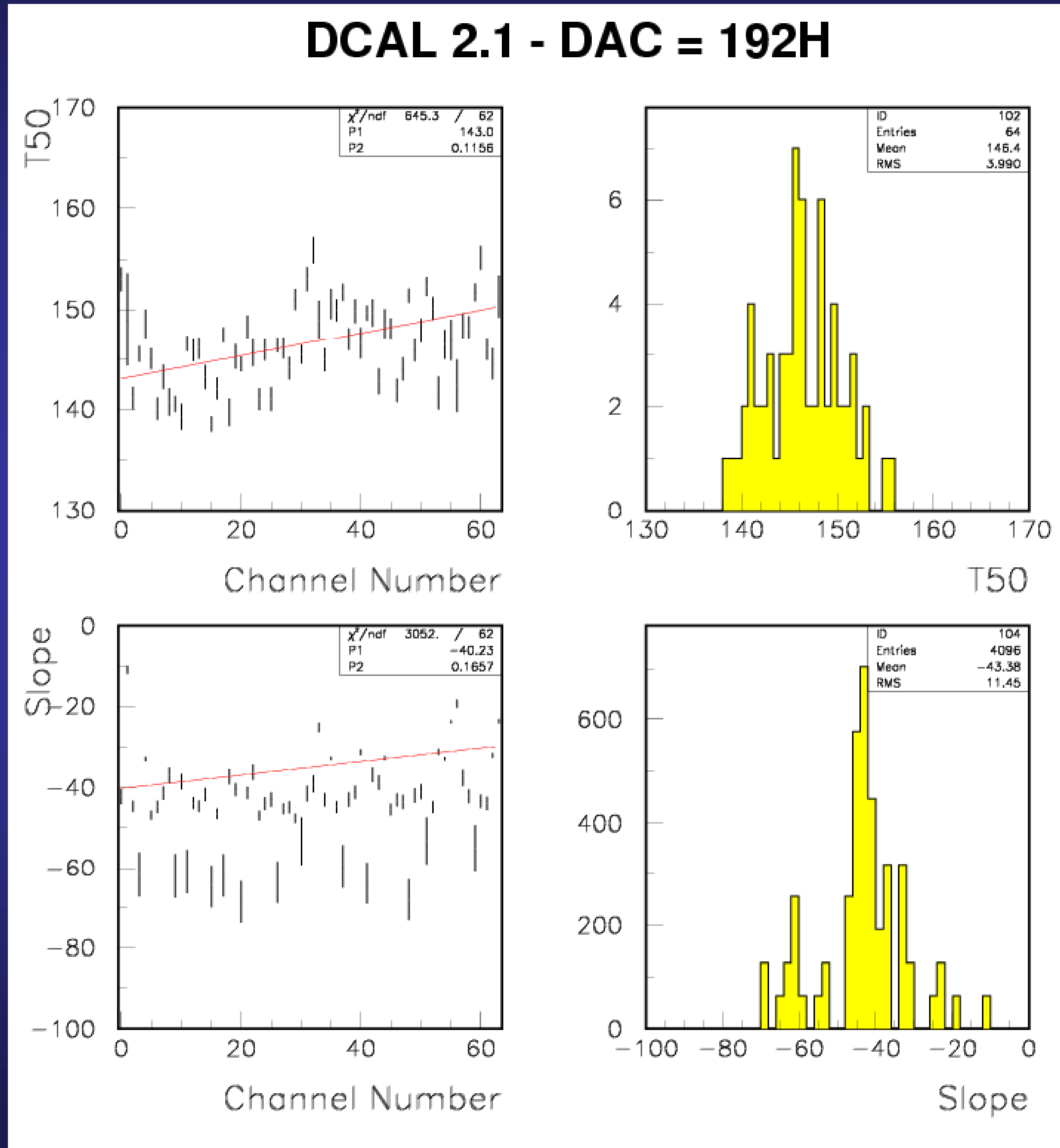
Reads 64 pads
Has 1 adjustable threshold
Provides
- Hit pattern
- Time stamp (100 ns)

Operates in
- External trigger or
- Triggerless mode



DCAL2 Testing I: Internal pulser

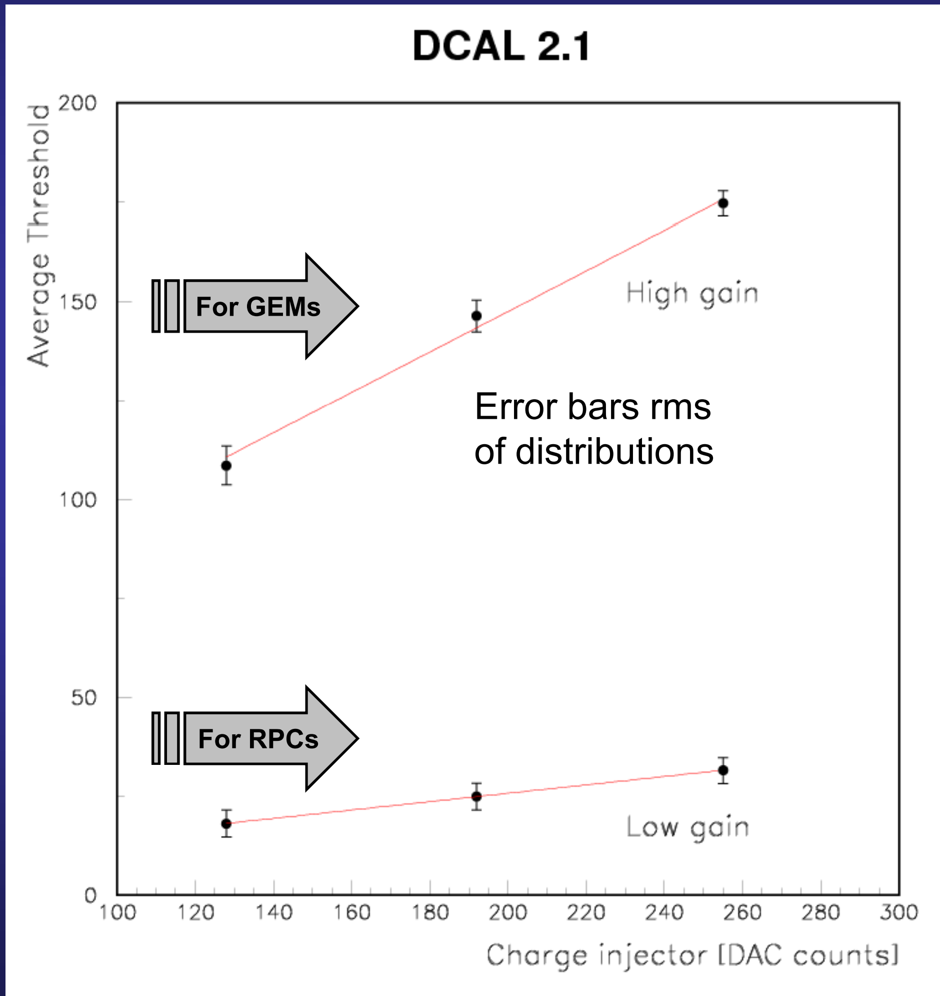




Threshold scans…

All channels OK, except
Channels #31/32 show some anomalies
(understood, no problem)

DCAL2 Testing II: Internal pulser

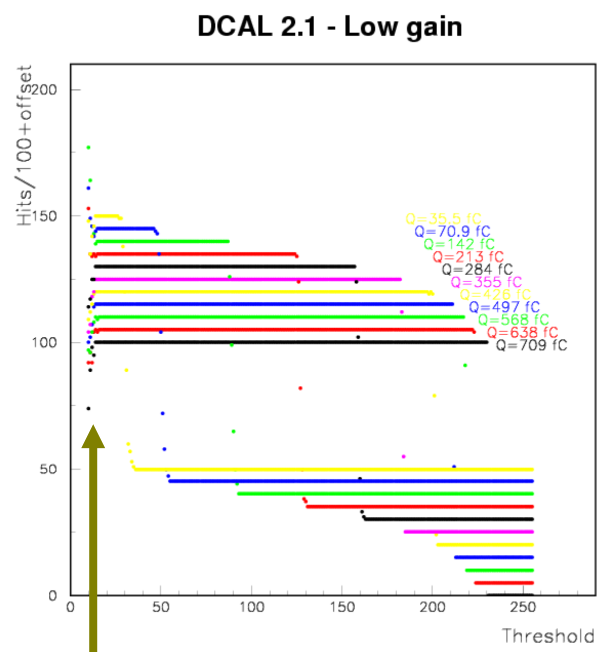


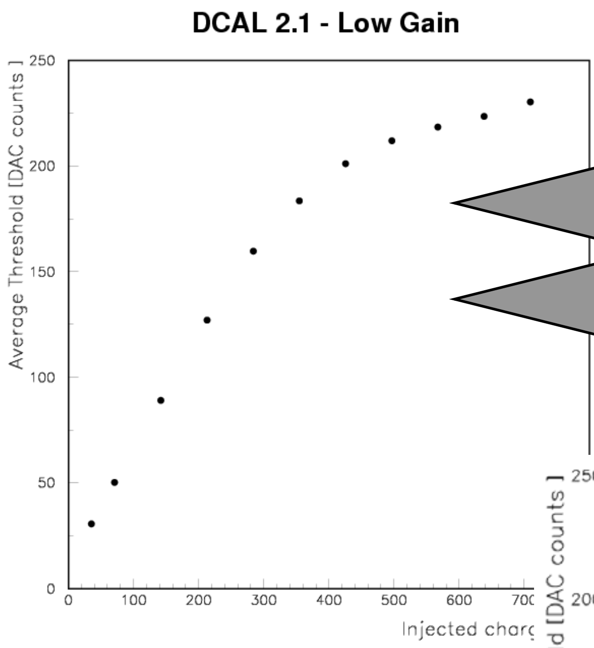
Ratio of high to low gain

R = 4.6 ± 0.2

(roughly as expected)

DCAL2 Testing III: External pulser



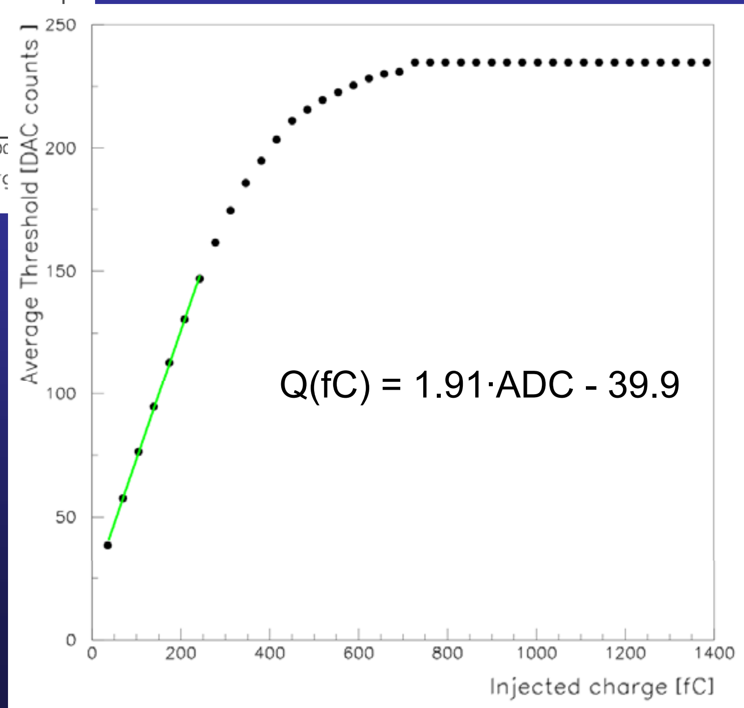


Linear up to ~300 fC

Range up to ~700 fC

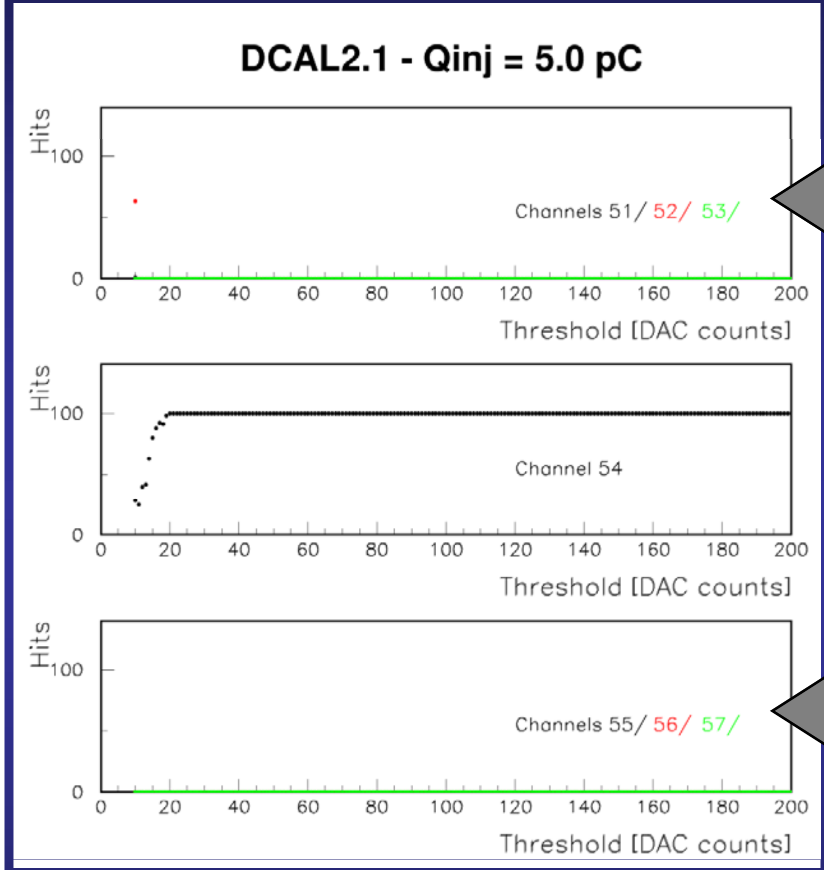
(RPC: Q = 100 fC ÷ 10 pC)

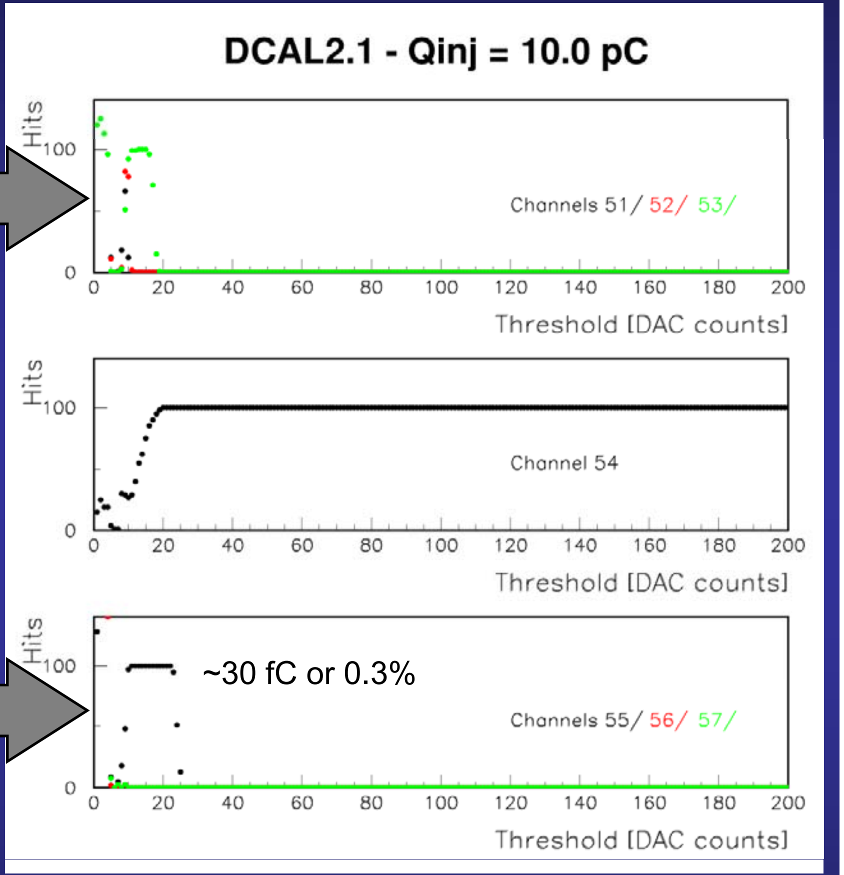
Corresponds to zero charge
(Offset in charge)



100 hits per point
Average threshold defined as ε=50% point

DCAL2 Testing IV: external pulser





Crosstalk

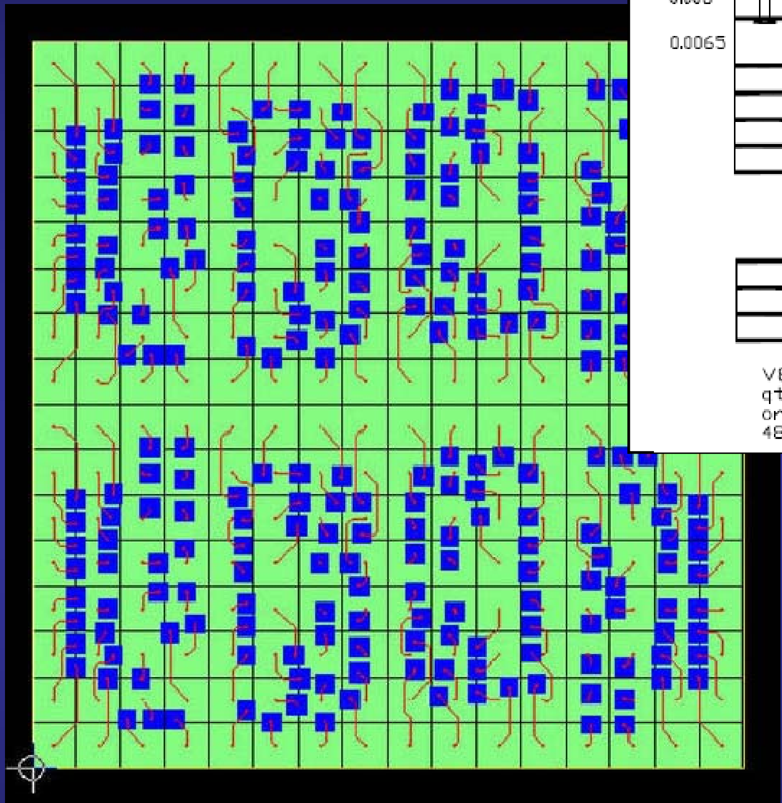
Crosstalk

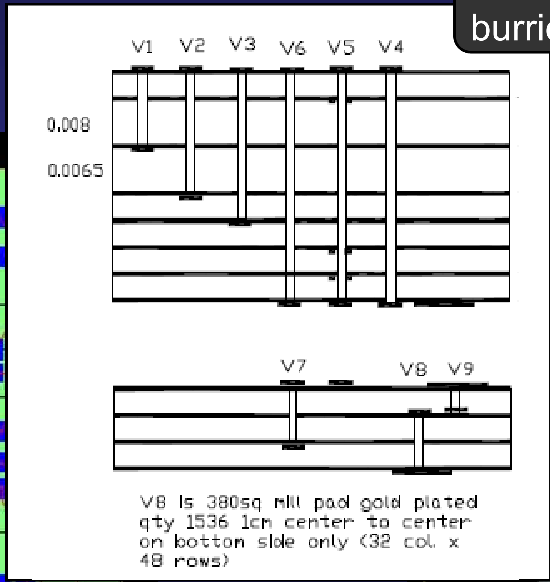
Chips can be used for VST
Small modifications still necessary for production

B Pad- and Front-end Boards

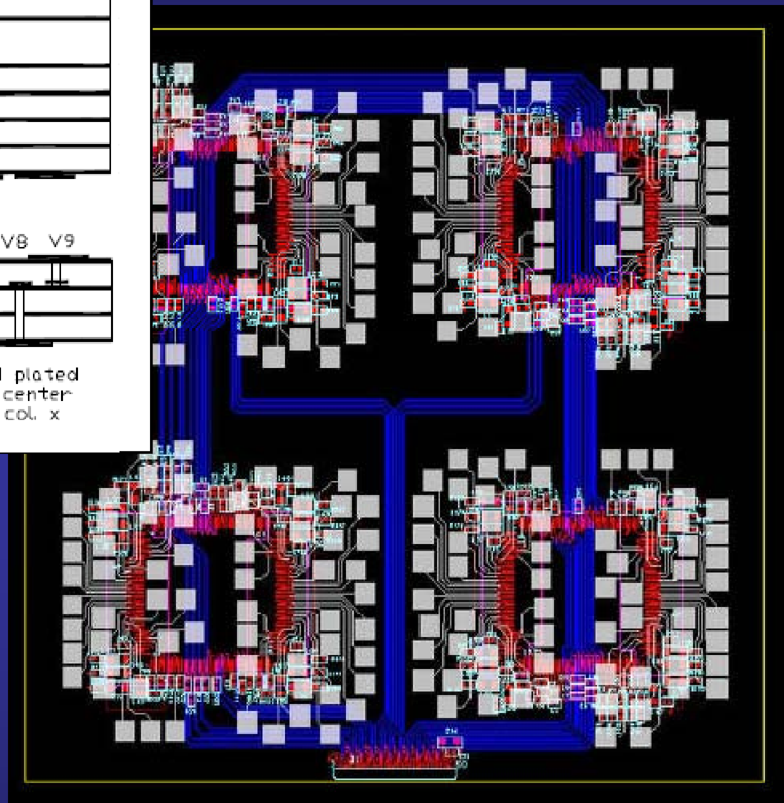
Blind, but no burried vias

4-layer Pad-board





8-layer FE-board



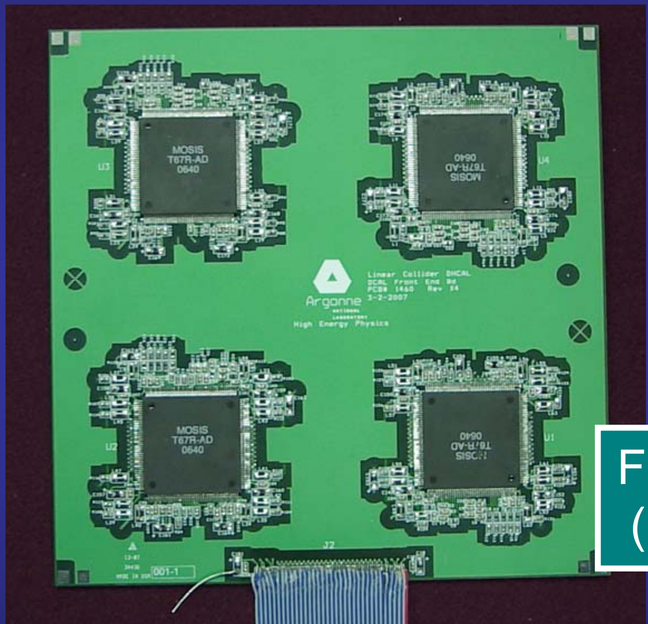
VST – 20 x 20 cm^2 16 x 16 cm^2

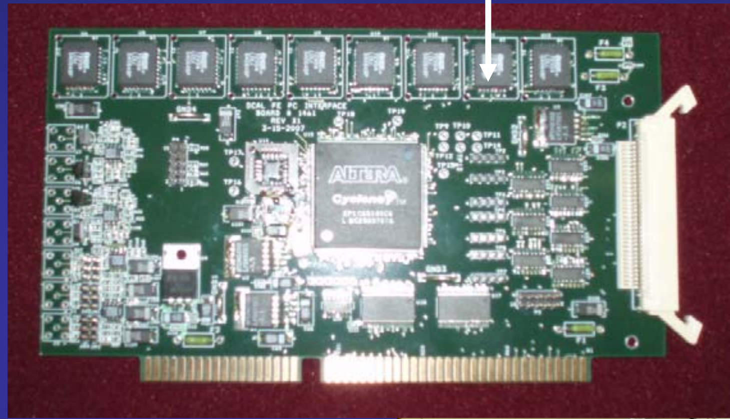
PS – 32 x 48 cm^2 16 x 16 cm^2

Very intricate design. Difficult to manufacture.
→ several iterations with vendors

Pad- and Front-end Boards – Tests

Front-end boards: fabricated and 1.5 assembled
Test-board (computer interface): fabricated and assembled
Testing software written





FE-board functional
(passed all basic tests last week)

Pad-board: design completed
Fabrication: received *reasonable* quotes

Ordered …

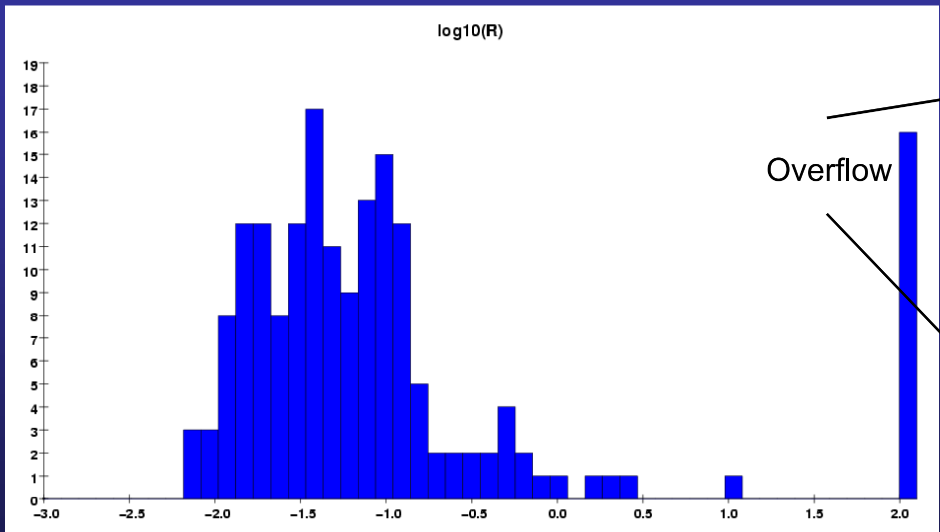
Gluing Tests

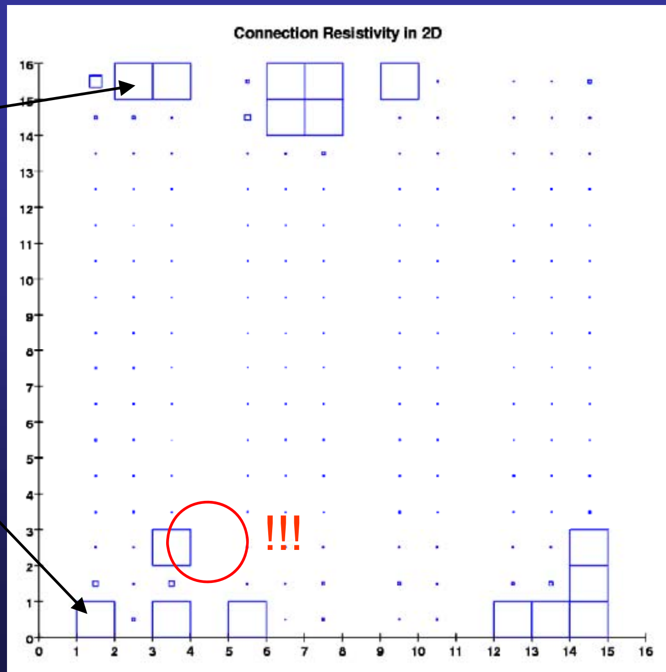
Test boards

Glued two boards to each other
→ strips of mylar for constant gap size

Results

Resistance < 0.1 Ω
Glue dots small (<3 mm Ø) and regular
Edges lift off → additional non-conductive epoxy

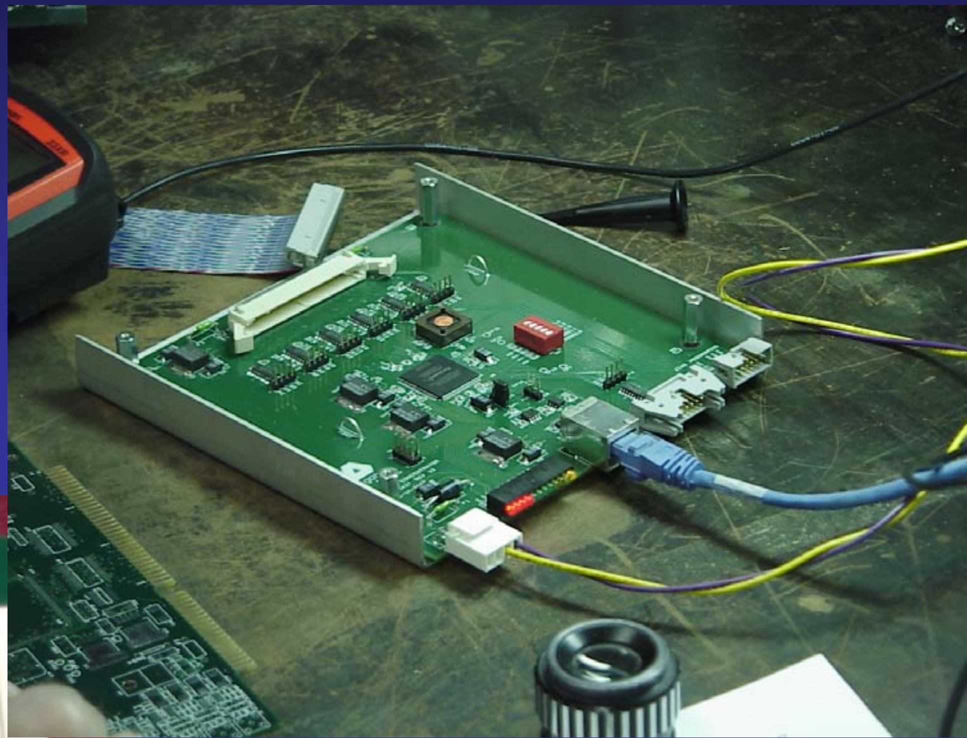




Further tests with 'realistic' test boards this week

C Data concentrator boards

Design completed
Boards fabricated
1/10 board assembled



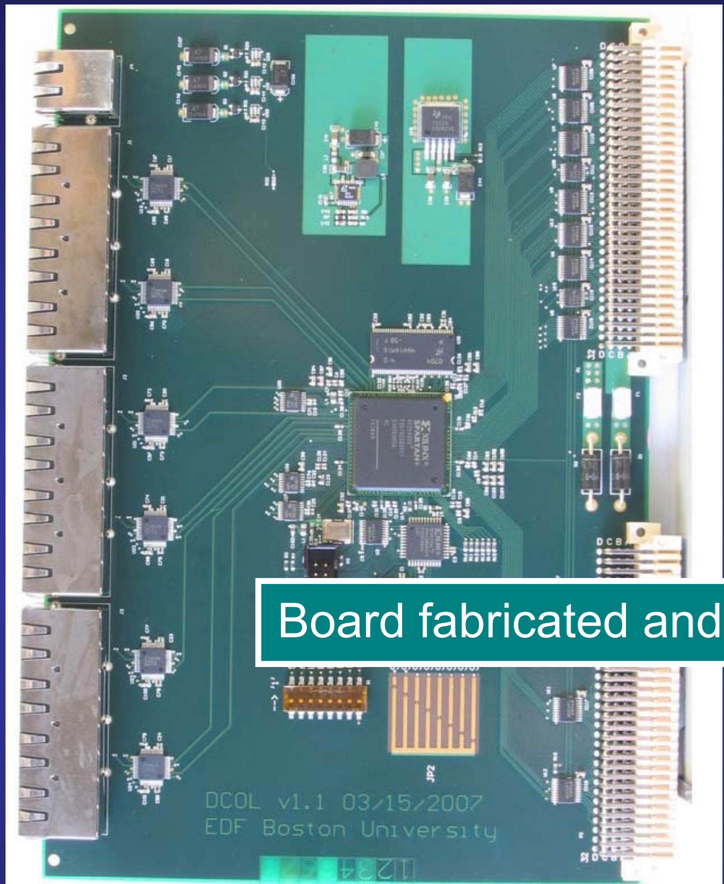
Test board fabricated and assembled
Tests began last week…
(board showing signs of life)

Reads
- 4 DCAL chips in the VST
- 12 DCAL chips in the PS

Sends data to
- DCOL in the VST
- Super-concentrator in the PS

CALICE
Calorimeter for ILC

E Data collector boards

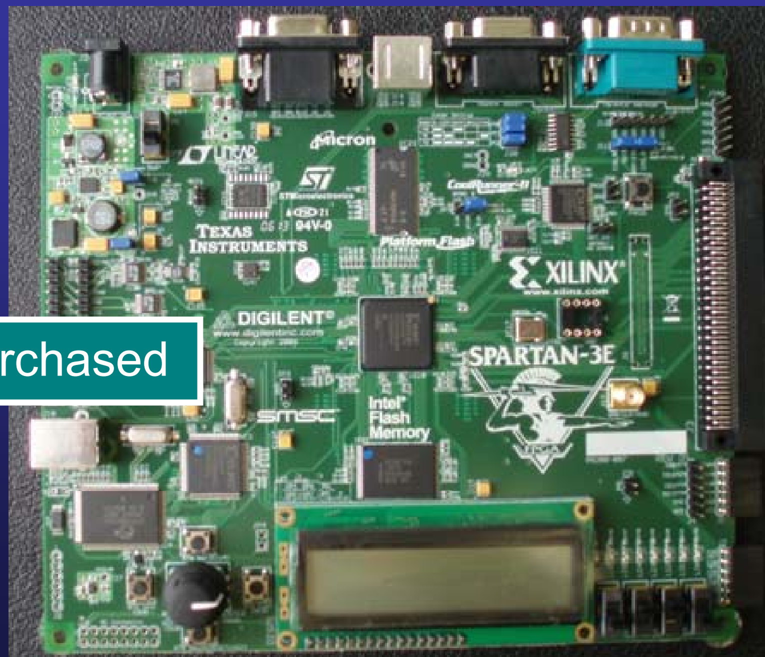


Reads packets
of timestamps, addresses and hit patterns
Groups packets
in buffers with matching timestamps
Makes buffers
available for VME transfer

BOSTON UNIVERSITY

Argonne NATIONAL LABORATORY

Board fabricated and 3 assembled



Test board purchased

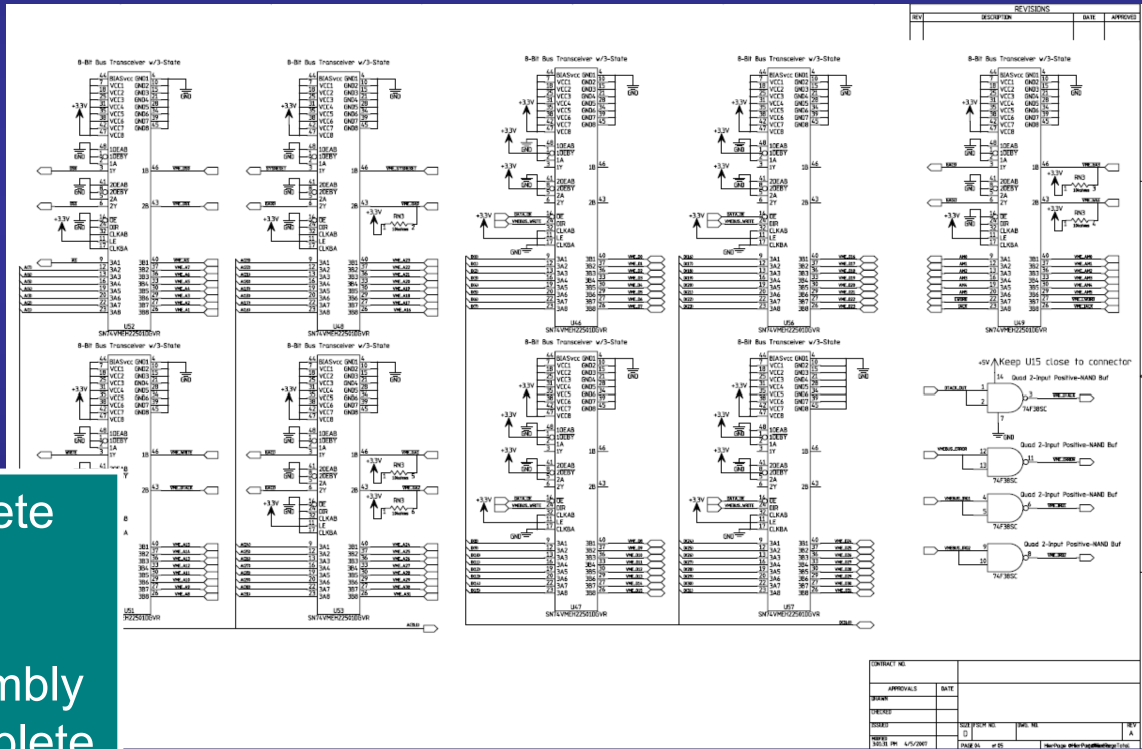
Testing software written
Testing ongoing
Unit received at Argonne on April 30th…

F Timing and trigger module

Provides clocks and trigger signals
to individual DCOL boards

Need 1 module for both the

Vertical Slice Test and the
1 m^3 Prototype Section



Board layout complete
Being fabricated
→ Expected 5/14
2 – 3 days for assembly
Firmware 85% complete

Summary of subcomponents

Subcomponent	Vertical Slice Test		Same?	Prototype Section	
	Inputs → Outputs	Units needed		Inputs → Outputs	Units needed
Pad boards	256 → 256	10	≠	1584 → 1584	240
FE-boards	256 → 256 (analog) → 4 (digital)	10	=	256 → 256 (analog) → 4 (digital)	1440
FE-ASICs	64 → 1	40	=	64 → 1	5760
Data concentrators	4 → 1	10	≠	12→ 1	480
Super concentrators	–	–	≠	6 → 1	80
Data collectors	12 → 1	1	=	12 → 1	7
Trigger and timing module		1	=		1

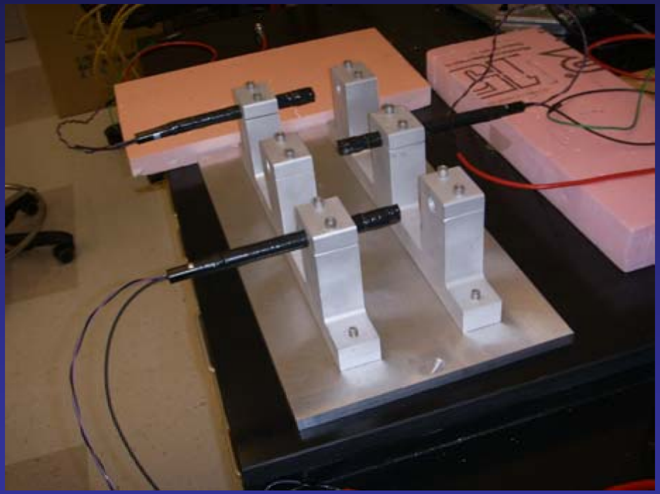
Beam telescope, HV, and gas

Beam telescope

6 counters (3 x (1 x 1 cm^2) + 1 x (4 x 4 cm^2) + 2 x (19 x 19 cm^2)

Mounted on rigid structure

Counters and trigger logic tested → A.White



HV modules

Need separate supplies for each chamber

Modules (from FNAL pool) being tested

With additional RC-filter perform similarly to our Bertan unit in analog tests (RABBIT system)

Digital tests satisfactory too

Gas system

Need manifold for 10 chambers (in hand!)

Will purchase pre-mixed gas (quote in hand)

DAQ Software

Based on

CALICE DAQ framework (→ combined data taking)
CERN HAL library

Two configurations

Vertical Slice Test with 10 x 4 ASICs or 2560 channels
Prototype Section with 40 x 144 ASICs or 400k channels

Data archived for offline analysis

Contains: run metadata, hit patterns &
addresses & timestamps
Configuration data stored in SQL database

DAQ software will be used

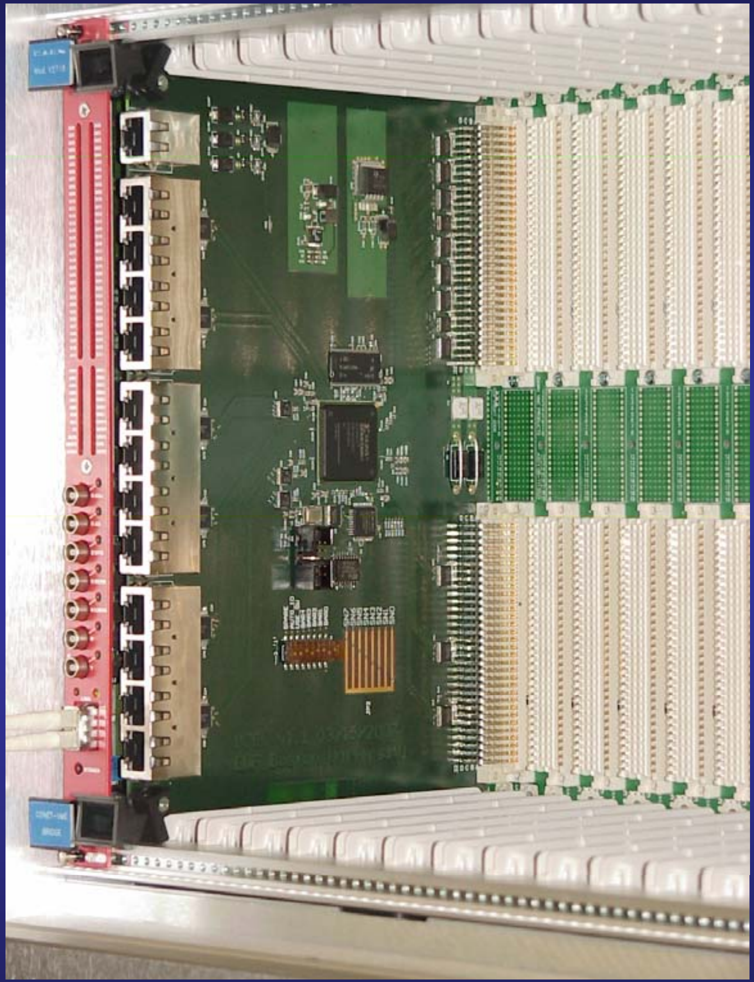
For hardware debugging
In cosmic ray and charge injection tests
In FNAL test beam

Status

HAL based testing and debugging system running
Toy version of CALICE DAQ running with *old* VME hardware
Data structure (binary files) defined

Next steps

Define operations for new hardware



Well advanced…

Argonne NATIONAL LABORATORY

CALICE Calorimeter for ILC

Data Analysis

For Vertical Slice Test only

I Online histograms

DHCAL specific plots to be added

Σ_{all}hit versus time
Σhit versus chamber
2dhisto of chamber hits (all layers)
2dhisto of chambers hits (per layer)
{Chamber efficiency and pad multiplicity}

II Analysis of binary files

Important in debugging phase

III Conversion to LCIO

Standard for LC data bases
Conversion to be done by CALICE expert

a) an event display

b) track segment finder

Programming will start soon…

How to calibrate a DHCAL

Shower energy reconstruction

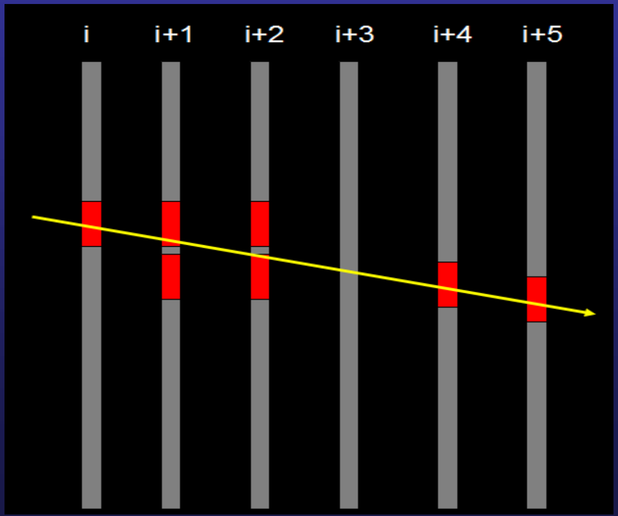
$$E = \alpha N_{hit} = \alpha_{samp}(\Sigma_i H_i) \cdot \Sigma_i(H_i/(\varepsilon_i^{MIP} \cdot \mu_i^{MIP}))$$

$N_{hit} = \Sigma_i H_i$ …number of particles crossing active layers

depends on

i) single particle detection efficiency ε_i^{MIP}
ii) hit multiplicity μ_i^{MIP}

That's all !!



Track Segment Finder

Use any shower

Loops over layers 1 - 8
Loops over hits in layer i
Determines #neighboring hits N_i
Searches for aligned hits in layer i+2,3,4,5
Determines #neighboring hits around aligned hit

$N_{i+2}, N_{i+3}, N_{i+4}, N_{i+5}$
($N_j = 0$ …no aligned hits)

Looks for aligned hits in layer i+1
Determines #neighboring hits N_{i+1}

Efficiency of layer i+1

$$\frac{N_{i+1}>0.and.N_{i+2}>0(.and.N_{i+3}>0)}{N_{i+2}>0(.and.N_{i+3}>0)}$$

Pad multiplicity of layer i+1

N_{i+1}, for $N_i=1.and.N_{i+2}=1(.and.N_{i+3}=1)$

Responsibilities and collaborators

Task	Responsible institutes
RPC construction	Argonne, (IHEP Protvino)
GEM construction	UTA
Mechanical structure (slice test)	Argonne
Mechanical structure (prototype section)	(DESY)
Overall electronic design	Argonne
ASIC design and testing	FNAL, Argonne
Front-end and Pad board design & testing	Argonne
Data concentrator design & testing	Argonne
Data collector design & testing	Boston, Argonne
Timing and trigger module design and testing	FNAL
DAQ Software	Argonne, CALICE
Data analysis software	Argonne, CALICE, FNAL
HV and gas system	Iowa
Beam telescope	UTA

Component	February	March	April	May		June
ASIC	Complete testing Provide new packing scheme Order 40 additional			Test (to start 5/14)	Test with cosmic rays	Move to MT6 Test in test beamongoing
Gluing	Test with regular epoxy	Test with conductive epoxy	Develop gluing procedure Test with real boards Glue all boards			
Pad boards	Specify dimensions Complete design		Fabricate			
Front-end boards	Complete design Order 15	Fabricate Assemble	Test Test			
Interface board **(to test FE-boards + ASIC)**	Complete design	Fabricate Assemble				
Data concentrator		Complete design Fabricate Assemble	Test			
Data concentrator test board		Complete design Fabricate Assemble				
Data collector	Complete design Acquire crates	Fabricate Assemble	Test			
Data collector test board		Acquire Write software				
Timing & trigger module	Discuss with FNAL	Design	Fabricate Assemble Test			
Software	Acquire PC	Complete standalone development (with 'old' VME card)	Complete development with DCOL			
RPCs	Complete #1	Test #1 Test #2	Buil#3-6 Test #3-6	Build #7-10 Test		
Offline	Propose concept	Develop plan	Write software			ongoing

Version from 4/9/2007

III Prototype section

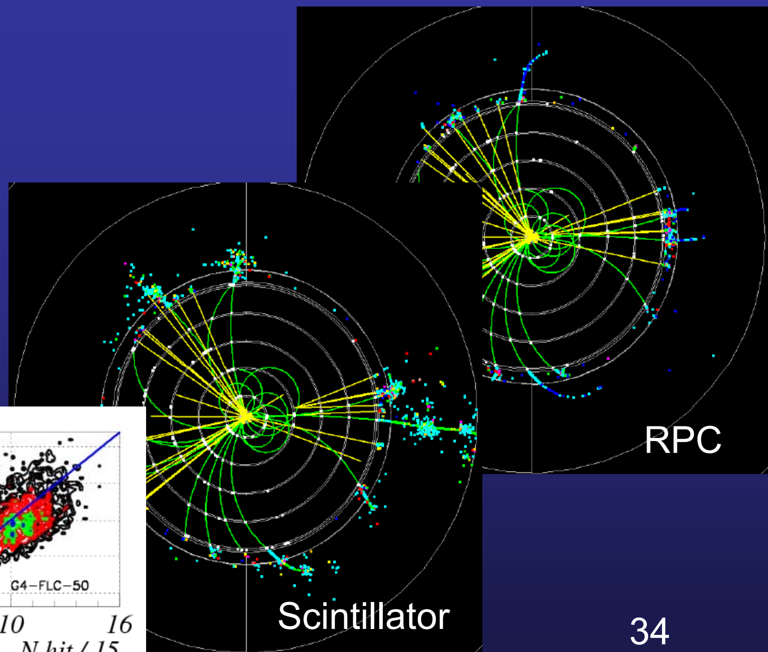
What is it?

40 layers of RPCs interleaved with Fe/Cu plates
Each layer ~ 1 m^2
With 1 x 1 cm^2 → 400,000 readout channels
Reuses stack and movable stage of
CALICE AHCAL (scintillator)

What will we learn technically?

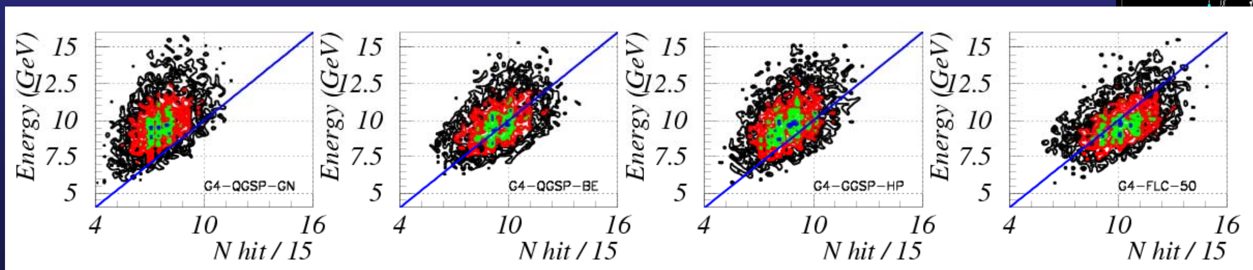
First fine granularity calorimeter with RPCs
(does this work? What's the energy resolution?)
First calorimeter with digital readout of pads
(does this work?)

Test of concept of DHCAL



What will we learn physics – wise?

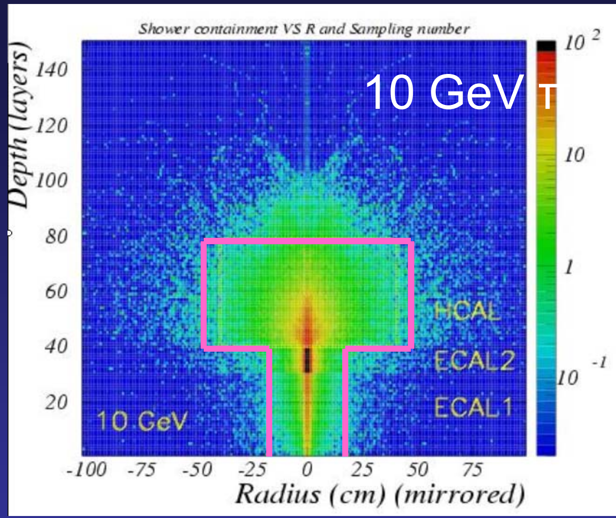
Which GEANT model describes our data (best)?
Comparison with scintillator: sensitivity to low-E neutrons?



V Morgunov: 1 x 1 cm^2 scintillator tiles

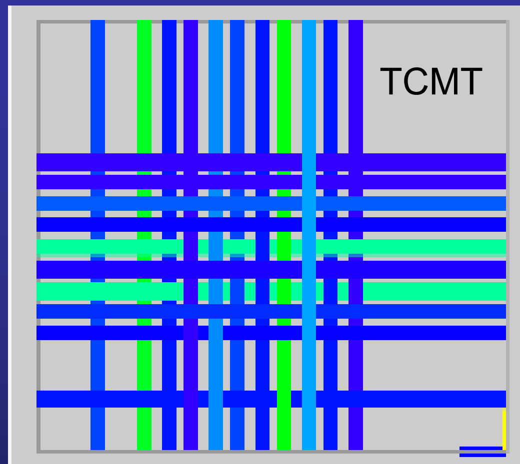
Do you need a full cubic meter?

A cubic meter will contain most of the energy
The scintillator AHCAL is a cubic meter (easier comparison)
Lateral leakage is deadly (see DREAM results)
Need to understand the tails (fragments) of showers



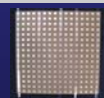
Is gas calorimetry understood?

Other groups tried RPCs with pad readout (and gave up)
No gas calorimeter with our type of fine readout has ever been tested
GEANT4 offers wide range of predictions
Our approach is not 'just' gas calorimetry!



MINOS already measured detailed shower shapes?

Remember: MINOS used scintillator strips: 100 x 4 cm^2
Factor of 400 in granularity!



The test should use the 'final' ILC detector technology?

We have no power pulsing: will it still be needed in 17 years?
We could have more multiplexing: new technologies in 17 years?
(I wouldn't use original ZEUS electronics now)

There is a lot to be done with the non-'final' readout system

Is this data useful for GEANT4?

Yes

Calorimeter data with fine granularity badly needed as a cross check
(see Dennis Wright's talk at the SLAC SiD meeting)

No

This data can't be used for tuning the particle interaction cross sections
(A comprehensive program to measure cross sections to improve hadronic shower models might even take more time to realize than the ILC…)

But

To first order, ILC detectors only need a hadronic shower simulation which describes the features important for PFAs….

↳ Shower radius, number of hits, fragments…

How to test PFAs?

Tests with complete system (tracker+calorimeter) in particle for beam?

Particle beam ≠ hadronic jet (even with a thin target in front)
The major uncertainty is the simulation of hadronic showers from single particles
→ for this, measurements with calorimeters are sufficient (no tracker needed)
(measurements with a calorimeter in a magnetic field might be useful)

There is no way around relying on simulation!

At least until the start of the ILC

Time scale for PS

Provided the VST is successful

→ will need a small amount of R&D and prototyping for PS

- Larger chamber with new design
- Larger pad board (no active components)
- Gluing techniques (automatic)
- Data concentrator board with 12 inputs
- Super-concentrator boards (similar to concentrator)
- HV system for 120 chambers
- Gas system for 120 chambers (???)

} **Can proceed in parallel with construction and testing of other subcomponents**

Supplemental LCDRD funds

Will receive $250k this year to be shared with other institutions
All M&S funding for building the prototype section

Completion date in 2008 is conceivable

IV R&D beyond the PS

Optimized RPCs

Can they be made thinner (currently 3.5 mm/2.5 mm)
Longevity of 1-glass RPC design?
Increased rate capability?

Electronic front-end

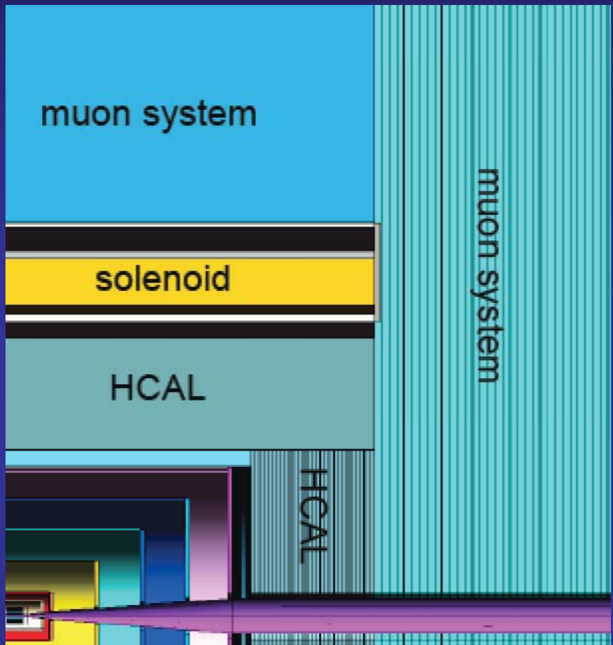
Finer segmentation of readout?
DCAL chip with more inputs (currently 64)
→ Corresponding front-end board ?????
Reduce overall thickness (currently 4.5 mm)
Finer timing (currently 100 ns)?
Cooling: power pulsing?
Higher multiplexing (token rings)

Depends on outcome of tests with PS and further understanding of PFAs

Electronic back-end

Higher multiplexing

V Mechanical Design

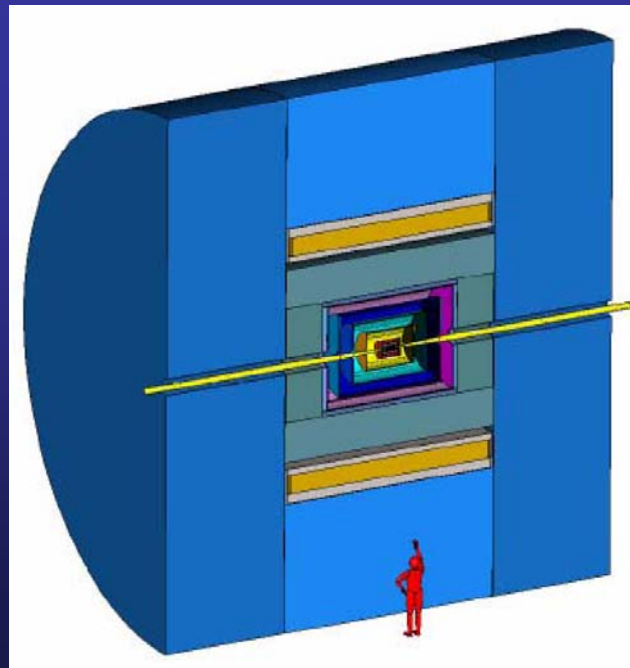


Detector Concept	Optimized for PFA	Compensating Calorimetry
SiD	Yes	No
LDC	Yes	No
GLD	Yes	Yes
4th	No	Yes

Concept (unproven)

Engineers ↓

Mechanical design



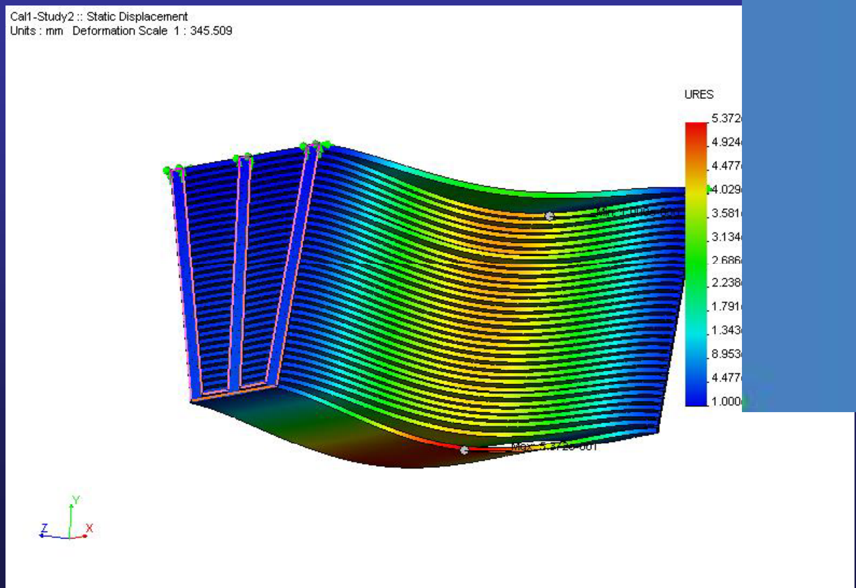
Concept of a BHCAL

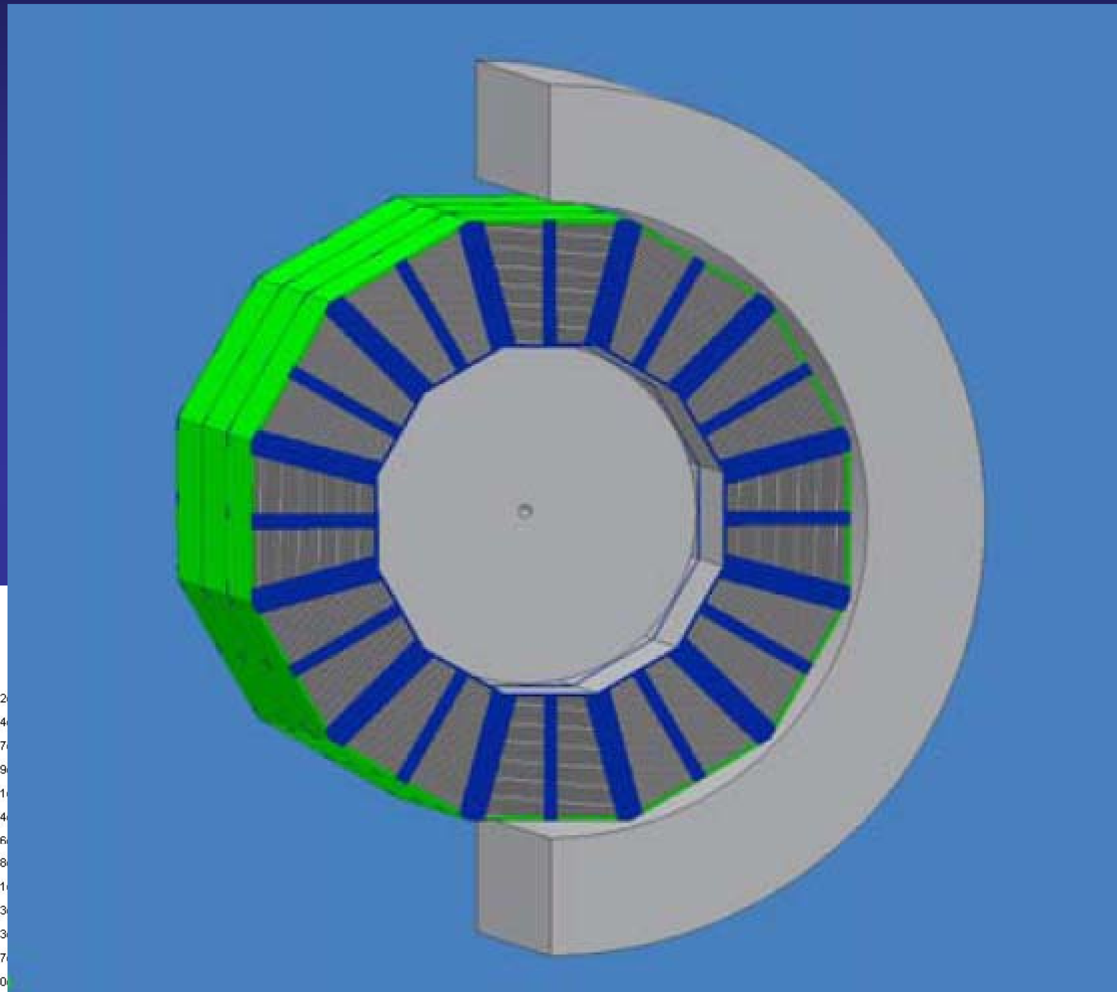
Mechanical design of BHCAL

3 barrels in z
20 mm steel plates

Held in place by
‘picture frames’

→ space for routing cables…





FEA: deflections < 0.53 mm

Prototype of a BHCAL module

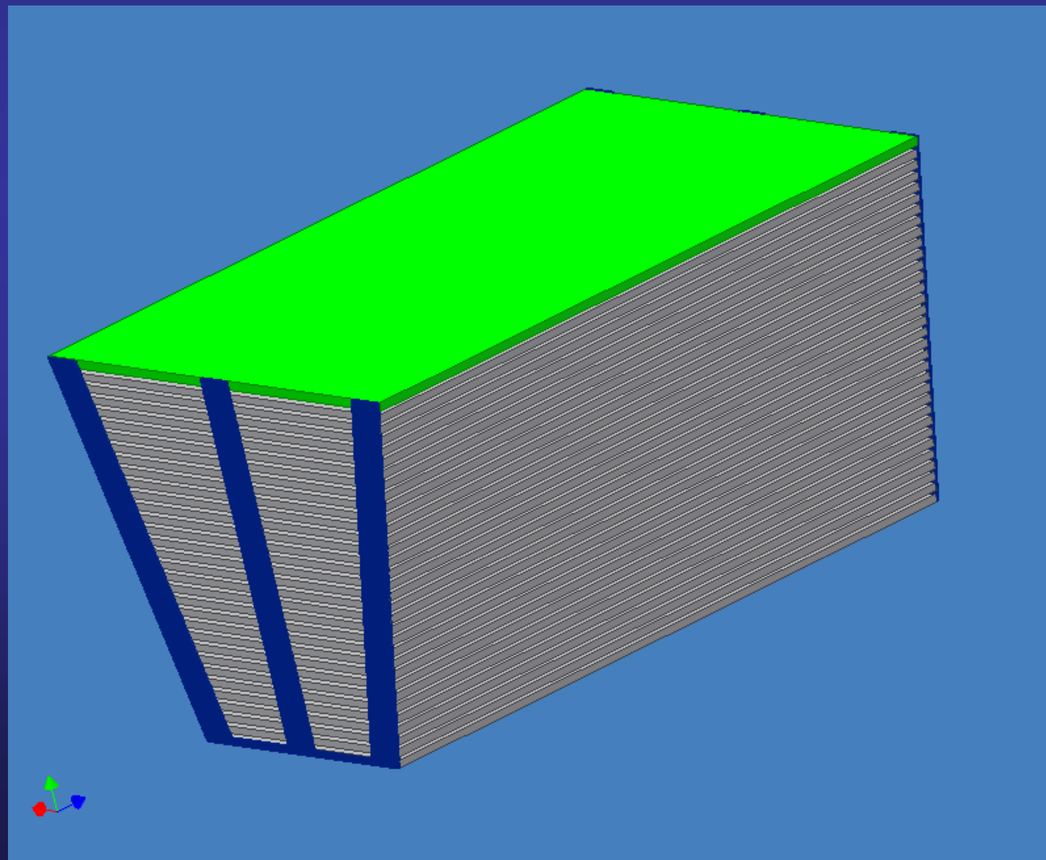
Working on a detailed design

Variable size RPCs (wedge)
Integrated gas distribution system
Integrated HV/LV distribution system
Integrated front-end electronics

Will have to be tested in particle beam

→ Scalable prototype

Still far in the future…



Conclusions

I RPC testing

Virtually complete (first N.I.M. paper)
Still need long-term studies

II Vertical Slice Test

Going full speed ahead
Will be in test beam in June 2007

III Prototype section

Partial funding 'received'
Can be build in 2008
Extensive test program with CALICE ECAL

IV R&D beyond prototype section

Design of both RPCs and electronics can be optimized for ILC

V Scalable prototype

Initial thoughts on barrel hadron calorimeter for SiD