Thoughts on Mu2e Electromagnetic Calorimeter

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Mu2e Meeting

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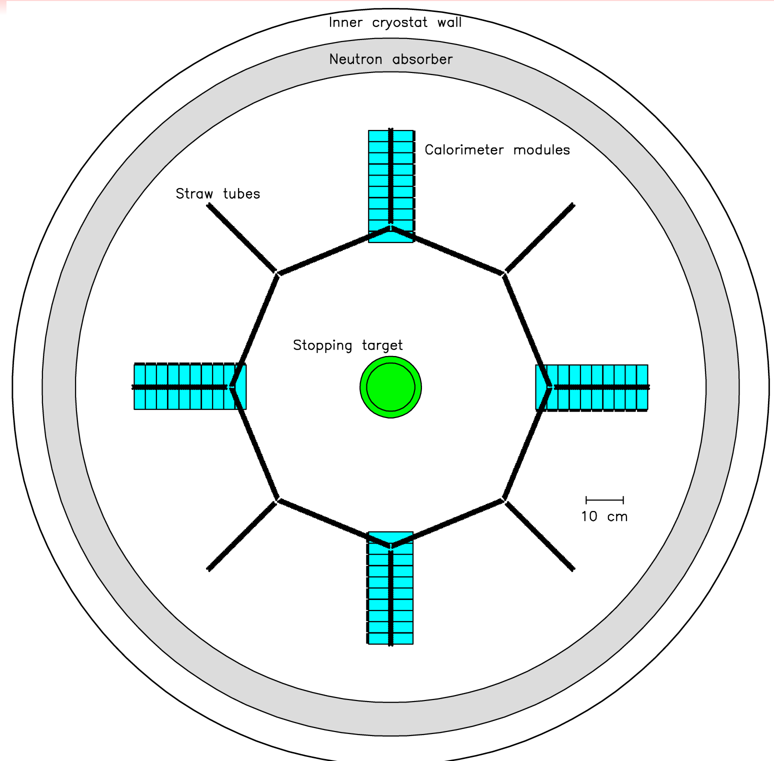
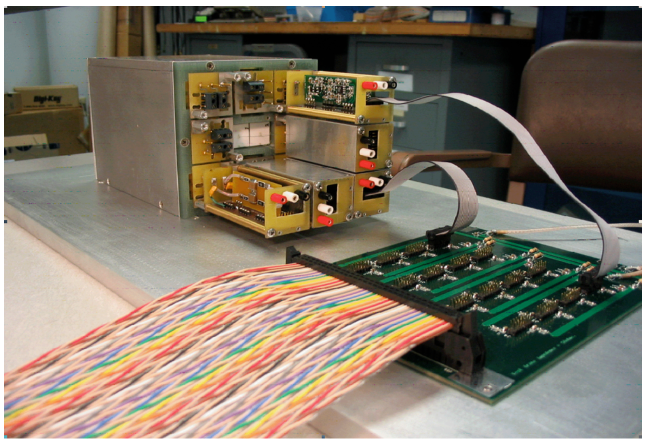
Performance Requirements

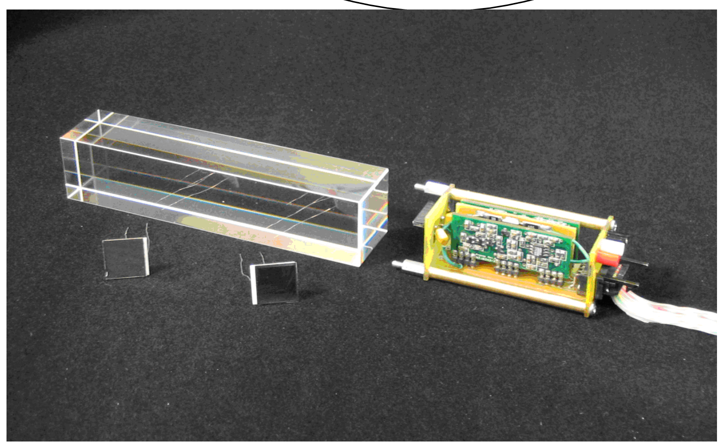
- Calorimeter provides
  - experimental trigger
  - redundant measurement of electron momentum
  - particle ID
- Supposed to produce a trigger rate < 1 KHz
  - 80 MeV threshold, 6-7 MeV resolution @ 100 MeV
- Should have a large acceptance and efficiency for conversion electrons (~90%)
- Should have negligible acceptance for DIO electrons
- Must operate in:
  - 1 T magnetic field
  - Vacuum
- Must be fast
- Must survive beam flash
- Must be tolerably radiation hard

Calorimeter Design

- Done by the NYU group for MECO
- Crystal choice: PWO
  - Fast response, rad hard
  - used by: CMS, Alice, PRIMEX, DVCS, PANDA
- Cooled to -25° C to increase light yield
- Read out by large area (1x1 cm^2) avalanche photodiodes
  - 2 per crystal for light yield and nuclear
- 4 vanes of 256 3.75x3.75x12.0 cm^3 crystals each for a total of 1024
  - down from 2000 in TDR by increasing crystal size from 3.0x3.0 cm^2 and by decreasing length







What are the Radiation Levels?

MECO 2001 TDR:

"The estimated radiation dose to a calorimeter cell is about 270 rad/year, coming from beam electrons (118 rad/yr), neutron interactions (43 rad/yr), photon interactions (59 rad/yr), and muon decay electrons with less than 55 MeV (49 rad/yr)."

Reference Design:

"The resistance to radiation damage, at an estimated dose of 500 Gray is expected to be comfortable for the PWO Crystals, and acceptable for the APD photodetectors."

MECO 2001 TDR

Background Source	Beam e	Neutron n	Photon γ	DIO < 55 MeV	DIO > 55 MeV
ΔE AT MBS (units)	0.1 0.2	0.7 0.9	0.5 0.8	0.5 0.2	14.2 0.6
Energy Dep. AT MBS (Joules/Expt)	1250 16600	464 260	625 720	58 860	83 4.3
Affected Mass AT MBS (kg)	133 133	1788 1788	133 133	133 133	5.5 133
Dose Rate AT MBS (10^{-2} Gy/hr)	0.4 5	0.01 0.007	0.2 0.2	0.02 0.23	0.6 0.001
Dose/Expt AT MBS (Gy)	10 125	0.3 0.2	4.7 5.4	0.5 6.5	15 0.03

Note: dose distribution highly non-uniform!

MECO Test Results

- Collected photo-electrons 38 p.e./MeV with 2 APDs per cooled crystal. Crystal size 3 x 3 x 14 cm^3
- Measured Electronic Noise: 0.7 MeV. This is consistent with calculations
  - APD Gain (M) = 200
  - APD dark current = 10nA
  - APD capacity (C_D) = 130 pF
  - APD serial resistor = 100 ohms
  - FET capacity (C_i) = 10 pF
- Pile up noise estimated to be: 0.9 MeV

Source	Beam μ	Neutron	Photon	DIO
Target	0.2 MeV	0.36 MeV	0.4 MeV	0.28 MeV
Beam Stop		0.2 MeV	0.36 MeV	0.47 MeV

- Energy resolution: σ = 4.1 MeV (@100 MeV)
- Position resolution: σ_r = 1.4 cm, σ_z = 0.9 cm

No test beam results! Only cosmic ray test done.

Estimated Trigger Rates

Triggers after Calorimeter Reconstruction

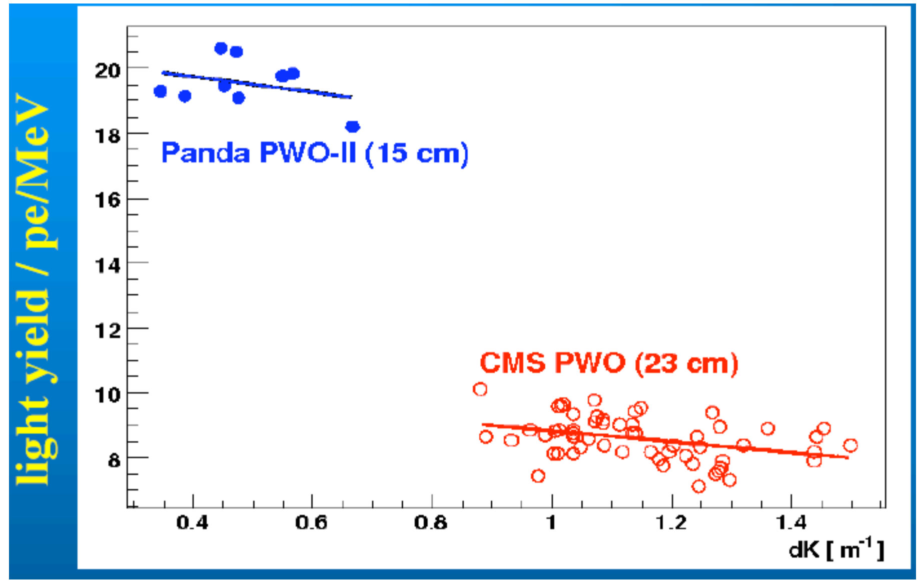
$E_{THRESHOLD}$ (MeV)	Trigger Rate (kHz) σ = 4.1 MeV	Trigger Rate (kHz) σ = 5.6 MeV
75	0.6	0.8
80	0.2	0.3

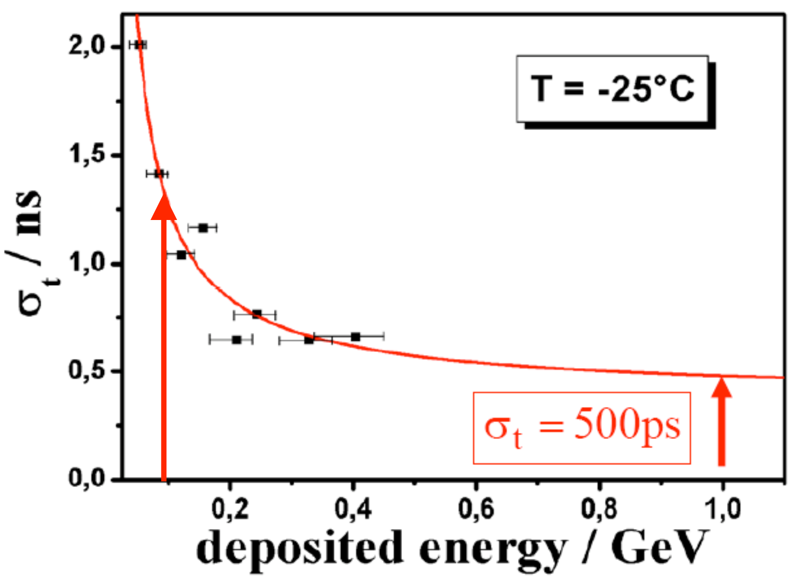
Level 0 Overlapping Trigger Towers (16 cells)

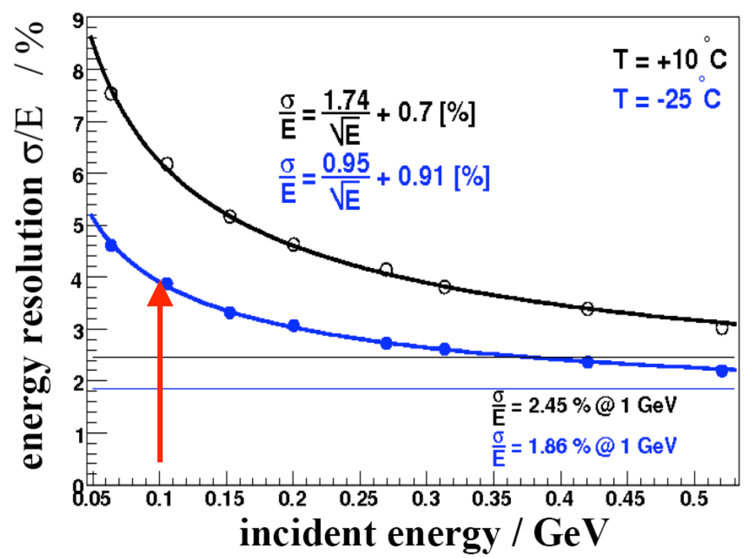
$E_{THRESHOLD}$ (MeV)	Trigger Rate (kHz) σ = 5.4 MeV	Trigger Rate (kHz) σ = 7.9 MeV
75	0.8	1.4
80	0.3	0.5

Options for Improving Calorimeter: PWO-II

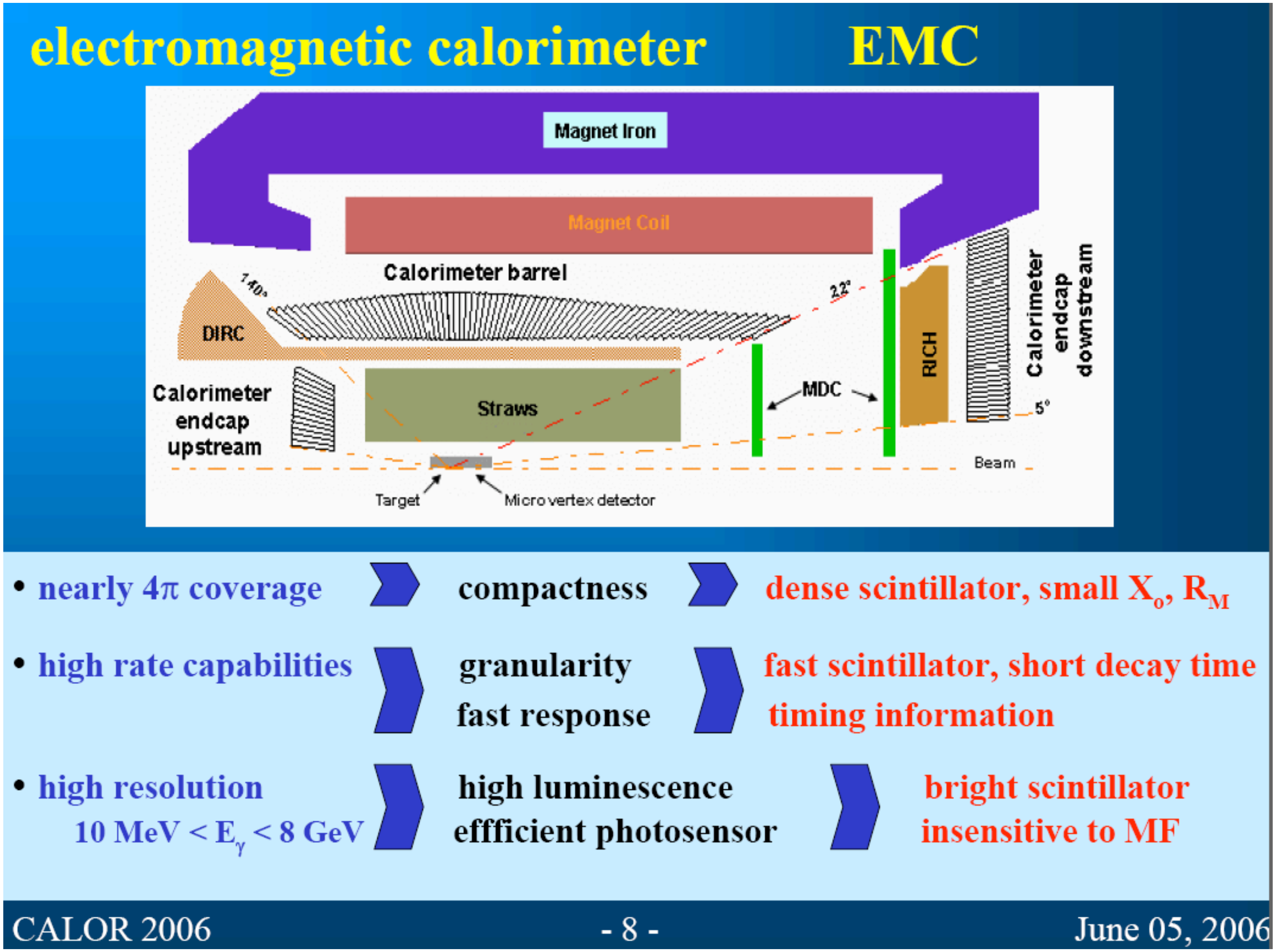
- Reduced defects
- Less La and Y doping ⇨ less quenching of primary luminescence yield
- Fast: τ_1 = 6.5 ns (97%)
  τ_2 = 30.4 ns (3%)
- Double CMS PWO light yield!
- σ/E = 4% @ 100 MeV @ -25C
- σ = 1.5 ns @100 MeV @ -25C





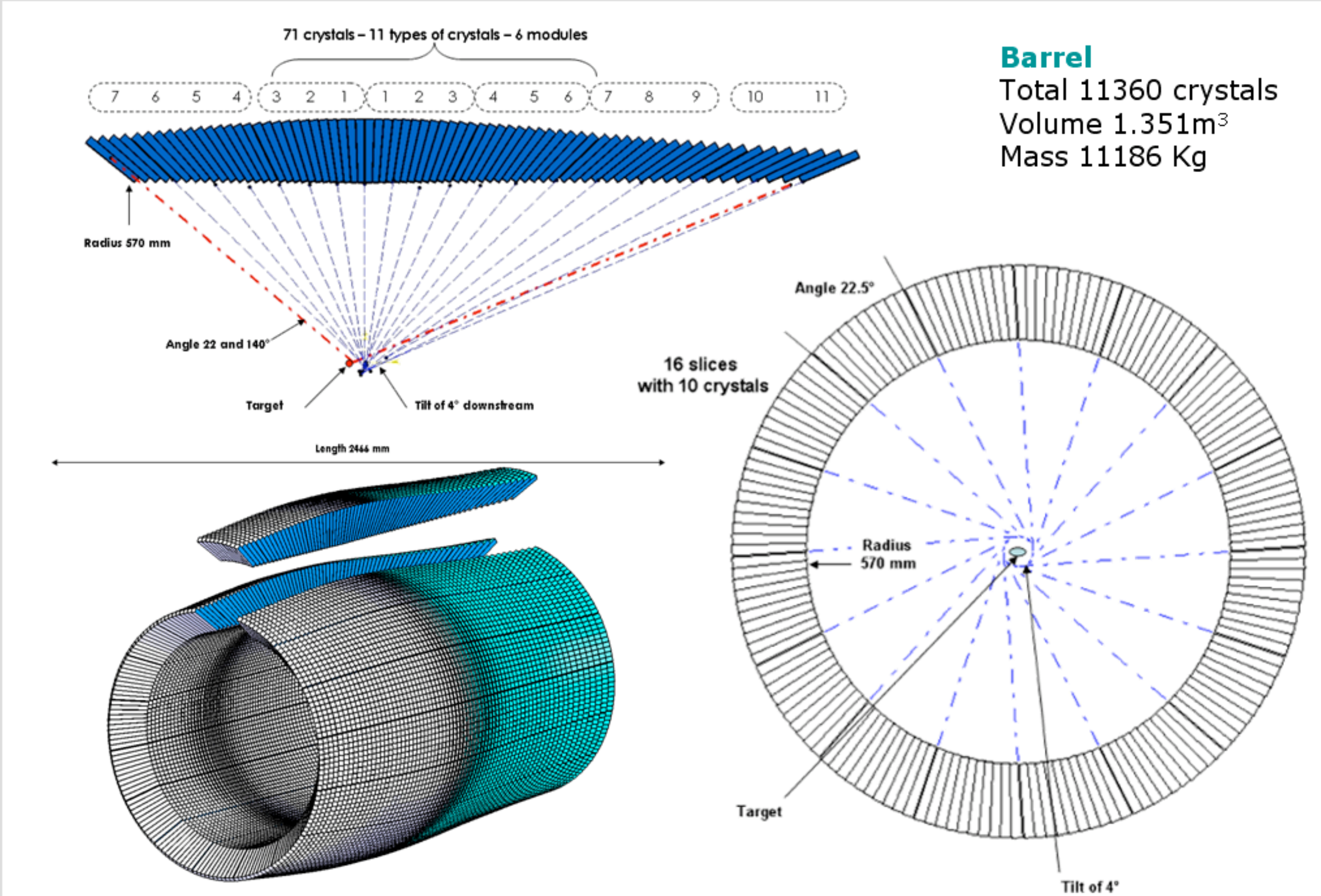


PWO-II Being Used for PANDA

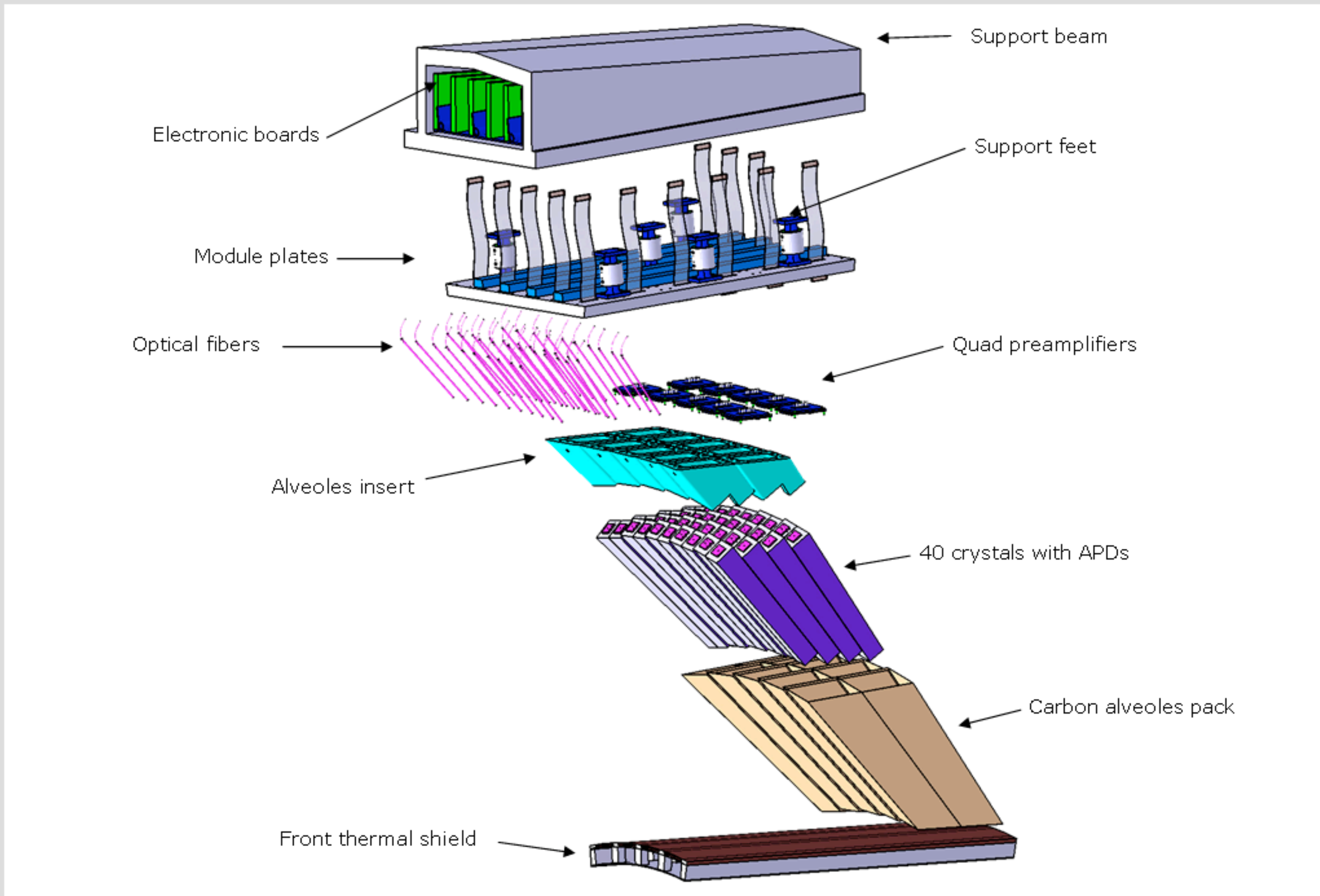


PANDA Calorimeter

EMC barrel design – geometry



PANDA Calorimeter



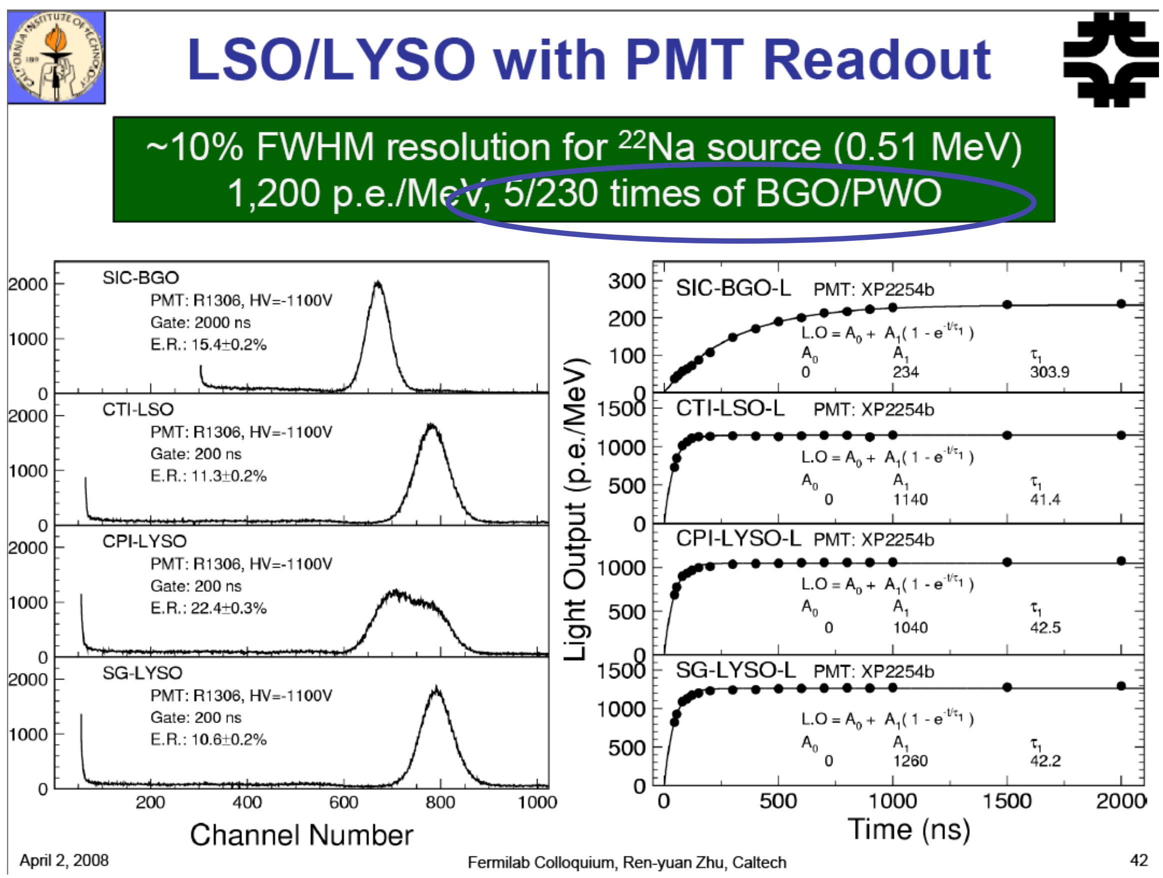
Options for Improving Calorimeter: LSO/LYSO

See talk by R. Zhu, Fermilab, April 2, 2008.

LSO : Lu_2SiO_5 : lutetium oxyorthosilicate

LYSO : $Lu_{2(1-x)}Y_{2x}SiO_5$: lutetuim-yttrium oxyorthosilicate

$\sigma(E)$ ~ 1% possible



Crystal Scintillator Comparison

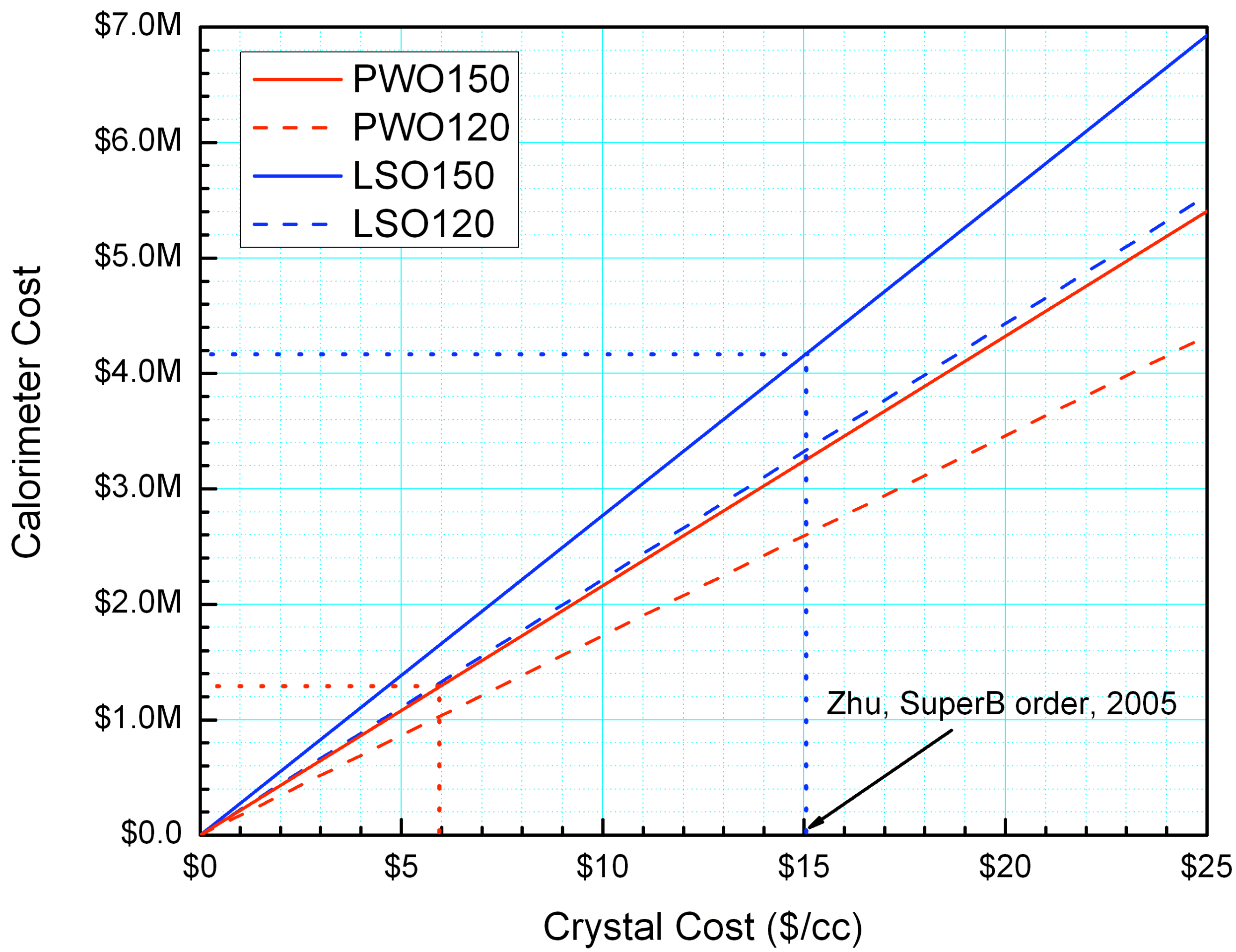
TABLE I
PROPERTIES OF SOME HEAVY CRYSTAL SCINTILLATORS

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	PWO	LSO(Ce)	GSO(Ce)
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	8.3	7.40	6.71
Melting Point (°C)	651	621	621	1280	1050	1123	2050	1950
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	0.89	1.14	1.38
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.00	2.07	2.23
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.7	20.9	22.2
Refractive Index[a]	1.85	1.79	1.95	1.50	2.15	2.2	1.82	1.85
Hygroscopicity	Yes	slight	slight	No	No	No	No	No
Luminescence[b] (nm) (at Peak)	410	560	420 310	300 220	480	560 420	420	440
Decay Time[b] (ns)	230	1250	35 6	630 0.9	300	30 10	40	60
Light Yield[b,c]	100	45	5.6 2.3	21 2.7	14	0.4 0.1	75	30
d(LY)/dT[b,d] (%/°C)	~0	0.3	-0.6	-2 ~0	-1.6	-1.9	-0.3	-0.1

a At the wavelength of the emission maximum.
b Top line: slow component, bottom line: fast component.
c Relative and measured with a PMT with a Bi-alkali cathode.
d At room temperature.

Calorimeter Cost

- LSO cost not prohibitive!
- Don't yet have good estimate for PWO-II



Photodetectors

- Large area APDs (>1.0x1.0 cm^2) now available from Hamamatsu as well as Radiation Monitoring Devices (RMD)
- Silicon photomultipliers show promise, although still too small

	APD	HPD	PMT	SiPM
bias voltage (V_b)	400 V	10 kV	2 kV	40 V
timing (10 PE)	3 ns	100 ps	100 ps	30 ps
sensitivity	10 PE	1 PE	1 PE	1 PE
quantum efficiency	80%	20%	20%	30%
excess noise factor	2.5	1.05	1.1	1.2
dynamic range	10^7	10^7	10^6	10^3
gain (M)	100	2×10^3	10^6	8×10^5
$\delta V_b/V_b$ for $\delta M/M$=1%	5×10^{-4}	5×10^{-3}	5×10^{-4}	10^{-3}
δT for $\delta M/M$=1%	0.3°	3.5°	3°	1°

Readout: Waveform Digitization?

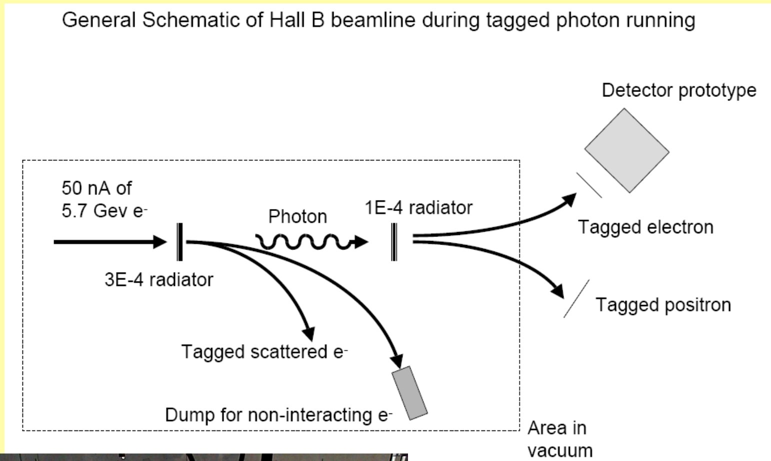
•See: Stefan Ritt, "Tackling the search for Lepton Flavor Violation with GHz waveform digitizing using the DRS chip," Fermilab seminar, Feb. 28, 2008.

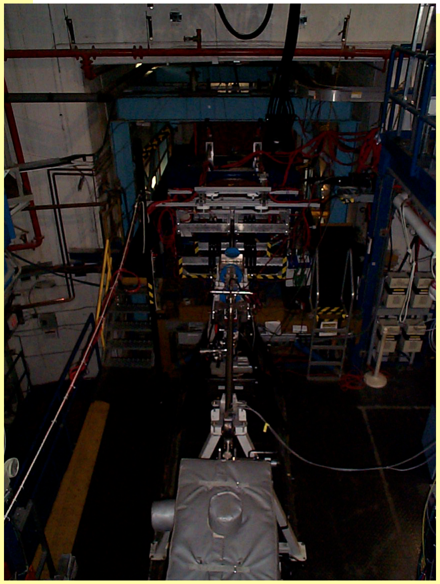
	MATACQ D. Breton	LABRADOR G. Varner	DRS3
Bandwidth (-3db)	300 MHz	> 1000 MHz	450 MHz
Sampling frequency	1 or 2 GHz	10 MHz ... 3.5 GHz	10 MHz ... 5 GHz
Full scale range	±0.5 V	+0.4 ...2.1 V	+0.1 ... 1.1V
Effective #bits	12 bit	10 bit	12 bit
Sample points	1 x 2520	9 x 256	12 x 1024
Channel per board	4	N/A	32
Digitization	5 MHz	N/A	33 MHz
Readout dead time	650 μs	150 μs	3 μs – 370 μs
Integral nonlinearity	± 0.1 %	± 0.1 %	± 0.05%
Radiation hard	No	No	Yes (chip)
Board	V1729 (CAEN)	-	planned (CAEN)

Test Beams

MECO never had any plans to put calorimeter into test beam!

JLab Tagged Photo Facility





Used to test CKM veto counters in 2002

Fermilab Test beam

- Presently: 500 MeV is lowest energy
- @1 GeV, 90% electrons
- Low energy tests beam being built for MINERVA (using UVa built HyperCP chambers)
- Hope to get to 200-300 MeV

Prototyping Important

M&S Contingency Rules

NOvA-doc-616

1) 0% on items that have been completed
2) 10-15% on items that have already been purchased at least once (perhaps in small quantities) or items for which there is a very firm quote and for which there is more than one potential vendor.
3) 15-25% on items that have already been purchased at least once (perhaps in small quantities) or items for which there is a very firm quote but for which there is likely to be only one vendor.
4) 25-50% on items that can be readily estimated from a reasonably detailed design or for which there exists a very close "analogous system", with well understood costs.
5) 50-70% on items for which only a conceptual design exists.
6) 50-70% for items that have unproven yields or for which there are uniqu[e] issues (e.g. an uncertain cost and a single vendor).
7) 70-100% for items that do not yet have a detailed conceptual design.

- You need to know if it works!
- It reduces contingency

Labor Contingency Rules

1) 0% on items that have been completed.
2) 15-25% for a project that has been done before and has a reasonably good estimate based on actual time durations.
3) 15-25% for a project that is conventional and well defined and supported by time and motion studies.
4) 25-50% for a project that is conventional and well defined.
5) 25-50% for a project that is not completely defined but the primary activities are supported by time and motion studies.
6) 50-70% for a project that is not well defined but is supported by a time and motion type study derived from a limited-scale test.
7) 70-120% for a project with uncertain labor requirements. In such cases, the schedule must allow for additional effort to be added so that the cost contingency covers the schedule risk along with other uncertainties that may exist. For example, a contingency of 100% or greater pays for the addition of a second shift so that the base schedule remains intact.

R&D Work

- Crystals
  - need to open up line of communication with manufacturers in Russia - Technical-Chemical Plant (BTCP) - and China- Shanghai Institute of Ceramics, Chinese Academy of Sciences (SICCAS) and Sichuan Institute of Piezoelectric and Acousto-optic Technology (SIPAT)
  - need to acquire PWO-II and LSO crystals and test their intrinsic characteristics and performance with desired APDs
  - need to find low energy, high intensity test beam facility, Fermilab, JLab, PSI?
  - are existing radiation damage studies sufficient?
- Simulation
  - need to establish hard numbers for acceptance: geometrical and trigger energy
  - radiation dose
  - rates from different sources
- Mechanical
  - support structure needs to be designed
  - investigate tilting modules at pitch angle to increase acceptance
  - plausible cooling scheme needs to be worked out
  - cabling scheme
- Photodetectors
  - need to acquire and test large area (> 10x10 mm^2) Hamamatsu and RMD APDs
  - exotic photodetectors: silicon PMTs?
- Calibration
- Electronics
  - any reason to go to waveform digitization?

Conclusions

- Proposal: stick with MECO baseline design, however
  - revisit downsizing volume
  - use the PWO-II crystals, if indeed price is competitive (PWO ~$6/cc)
  - include option of LSO crystals
  - revisit separation of preamp and shaper
  - consider tilting calorimeter to minimize acceptance loss from grazing impacts
- We do not have simulations of calorimeter trigger that can be defended at the proposal level ⇨ important numbers such as calorimeter acceptance have to be understood
- We do not have a design that can be defended at the TDR/CD-2 level ⇨ need to build and test real prototype
- Vital to establish a well thought out, comprehensive R&D program
- Bottom line: unlike the straws, and particularly the L-tracker, there is nothing particularly technically challenging about the calorimeter