



U.S. DEPARTMENT OF
ENERGY

Office of
Science

Mu2e Director CD-2 Review: Calorimeter 475.07.02 Crystals

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Cost and Schedule: DOE/INFN sharing

The Calorimeter is the only Mu2e system where we have a strong sharing of resources between DOE and INFN.

Costs are shared between INFN and DOE

Crystal cost INFN 1/3 : DOE 2/3

QA stations INFN 1/2 : DOE 1/2

Labor costs shared in same percentage (INFN+JINR 0.5)

Similar distributions for WBS photosensors:

Photosensor cost INFN ½ : DOE ½

Labor cost shared in same percentage (INFN+JINR 0.5)

For the WBS calibration

Source system DOE, Laser system INFN

For the WBS Digitizers: Development and design 0.5 INFN, 0.5 Illinois

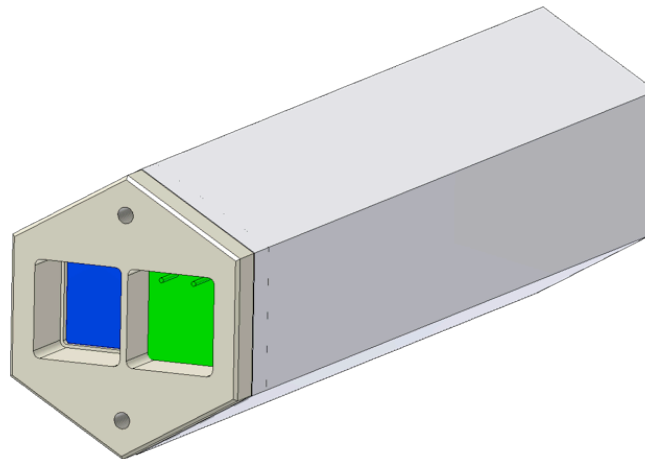
For the other WBS → INFN has the responsibility of construction and gets assigned the cost part.

→ INFN is going through a similar process review. OK for HeP committee,

→ Next autumn: CTS technical review for Cost and Schedule

Calorimeter Crystals Requirements

- Fast in response → aiming at < 500 ps @ 100 MeV
- With reasonable high light yield (> 15 pe/MeV/APD)
 - aiming at 5 % @ 100 MeV
 - stochastic term < 2 %
 - Electronic noise $O(300 \text{ keV}) < 1.5\%$
- Have a reduced temperature and gain variation
- Dense → small space + two disks and FEE in between
- Radiation hard. It should sustain up to 12 krad/year



A
scintillating
crystal can
do this.

Crystal possible choices ..

Crystal	BaF ₂	LYSO	CsI	PbWO ₄
Density (g/cm ³)	4.89	7.28	4.51	8.28
Radiation length (cm) X_0	2.03	1.14	1.86	0.9
Molière radius (cm) R_m	3.10	2.07	3.57	2.0
Interaction length (cm)	30.7	20.9	39.3	20.7
dE/dx (MeV/cm)	6.5	10.0	5.56	13.0
Refractive Index at λ_{\max}	1.50	1.82	1.95	2.20
Peak luminescence (nm)	220, 300	402	310	420
Decay time τ (ns)	0.9, 650	40	26	30, 10
Light yield (compared to NaI(Tl)) (%)	4.1, 36	85	3.6	0.3, 0.1
Light yield variation with temperature (% / °C)	0.1, -1.9	-0.2	-1.4	-2.5
Hygroscopicity	None	None	Slight	None

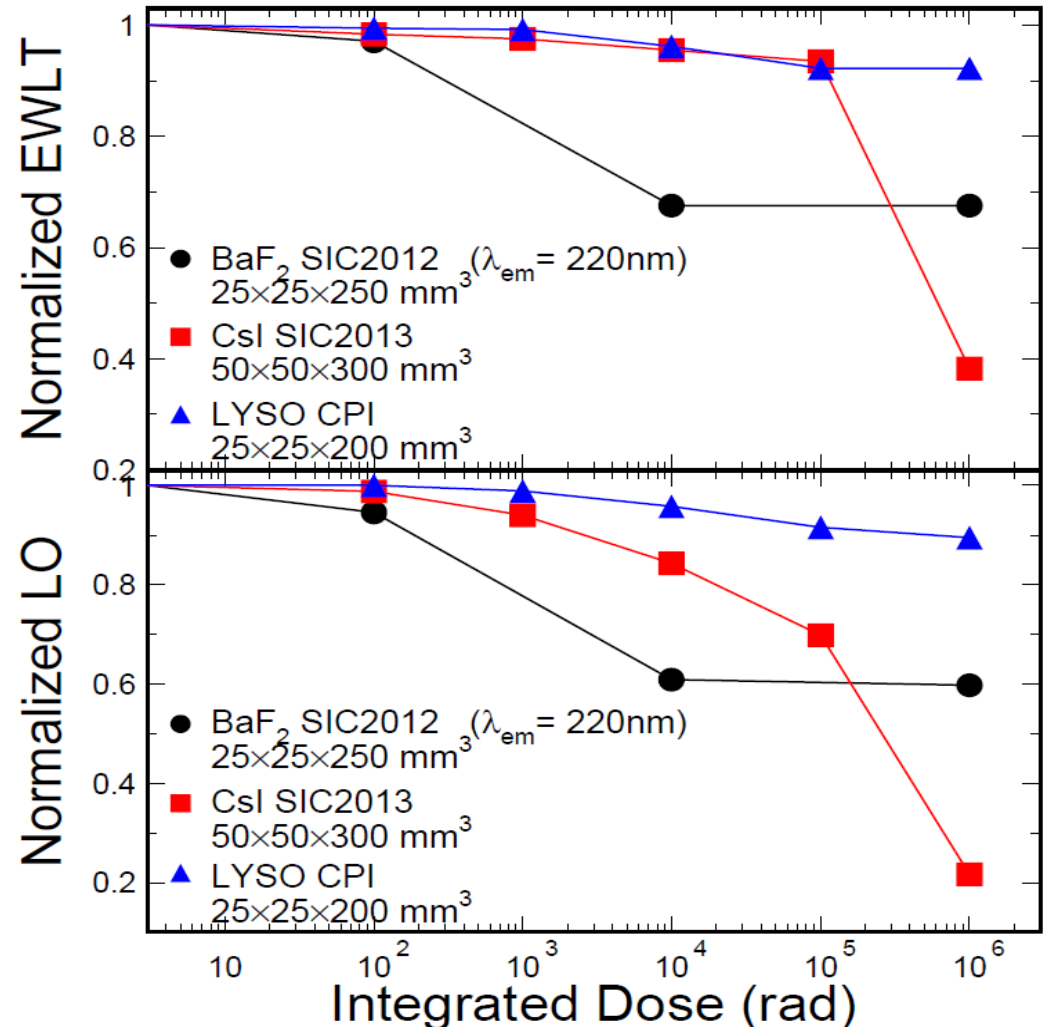
Our favorite CD-1 choice was the LYSO.

Now we have opted for BaF₂: motivated by the LYSO cost increase and by the BaF₂ faster signal → **It can be a good option also for Mu2e-2**

In the next slides I first summarize the work done so far with the LYSO and then show the R&D in progress for the BaF₂

Radiation Hardness

- ❑ Radiation dose driven by the beam-flash arriving in the first 300 ns from interaction on production target.
- ❑ Dose related to muon capture much smaller
- ❑ Strongly limited to the innermost radius (up to 400 mm)
- ❑ **Highest dose <12 krad/year**
- ❑ **LYSO is very Hard**
- ❑ **BaF₂ is OK in our range**

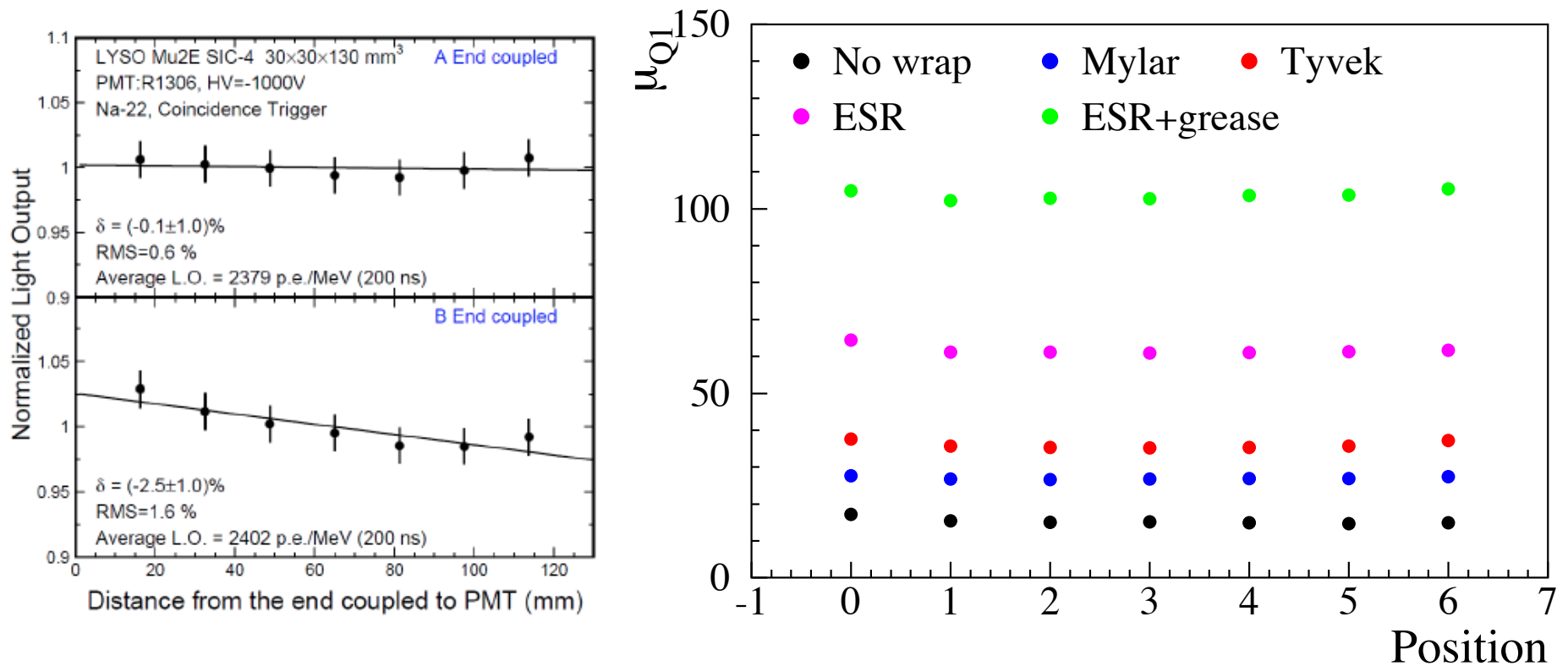


CD-1 choice → LYSO

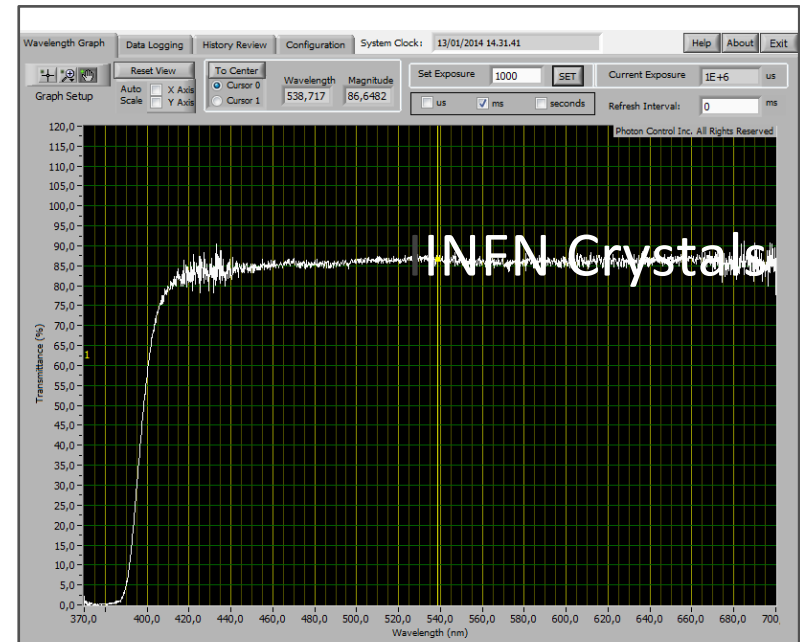
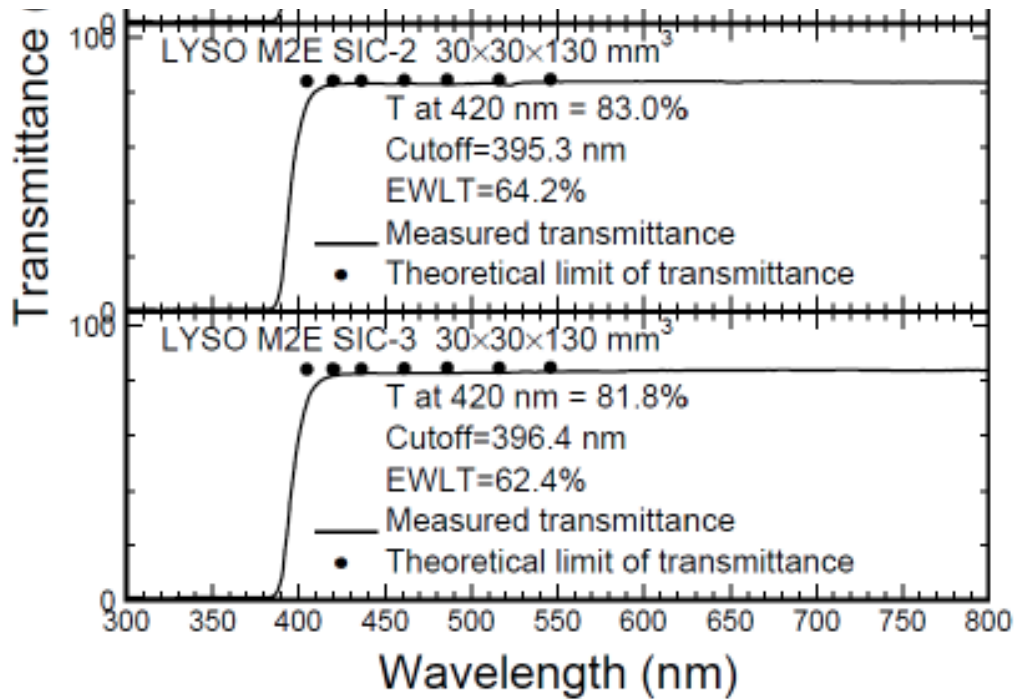
- **LYSO (lutetium-yttrium oxyorthosilicate) properties**
 - Small radiation length - 1.14 cm, Small Molière radius - 2.07 cm
 - High light output – 85% of NaI(Tl), Fast decay time - 40ns, Radiation resistance > 1 MRad
 - Excellent mechanical properties (UTS and Young's modulus highest of any scint. Crystal)
- **LYSO developments/tests have been underway at Caltech and LNF for several years**
 - Both groups have been engaged for several years in a development program in concert with Chinese producers (SIPAT and SICCAS), with the aim of preparing for HEP-scale production of HEP-sized crystals, at less than the current commercial price (*c.f.* St. Gobain (SG))
 - A lot of R&D carried out to bring this choice as a final design for Mu2e
 - QA stations were built both at LNF and Caltech.
 - Measurement of Light Yield with Na22 source
 - Measurement of LRU (Longitudinal response uniformity) along the crystal axis
 - Measurement of Longitudinal transmission
 - Tuned from 300 to 600 nm (peak LYSO emission 420 nm)

R&D on LYSO → L.Y. measurement

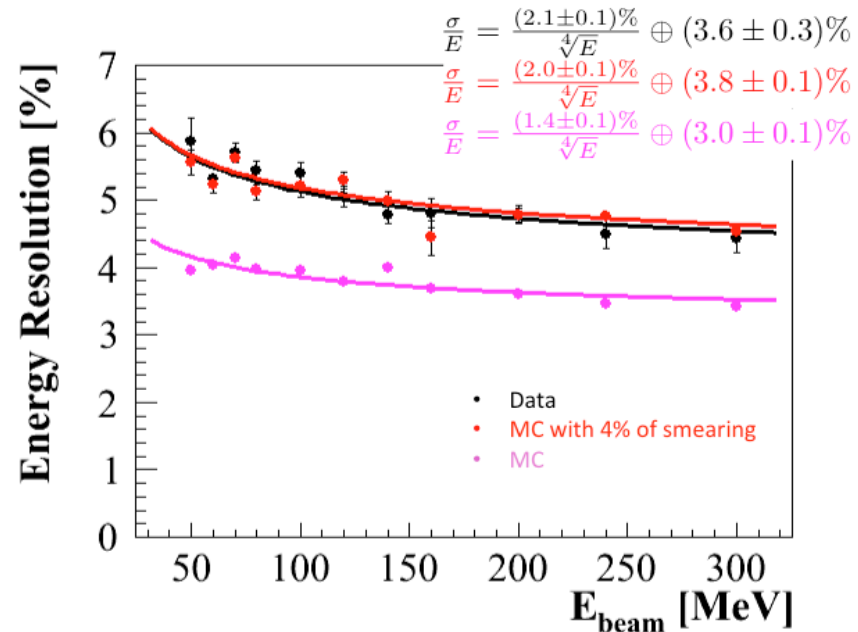
- Great longitudinal uniformity found in the 25 measured crystals, RMS < 2%
- Dependence of pulse-height and uniformity studied also as a function of wrapping and optical contact.



R&D on LYSO →LRU Measurement

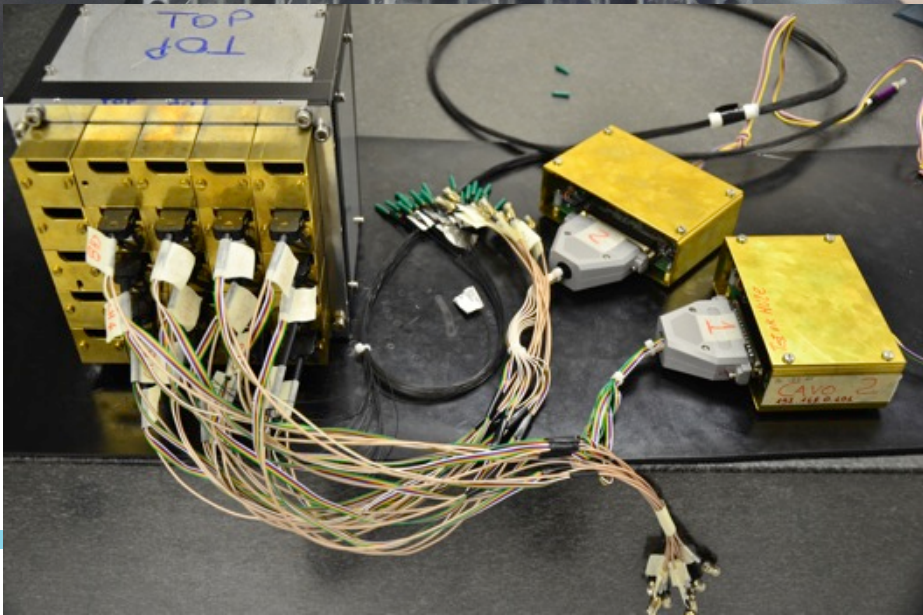
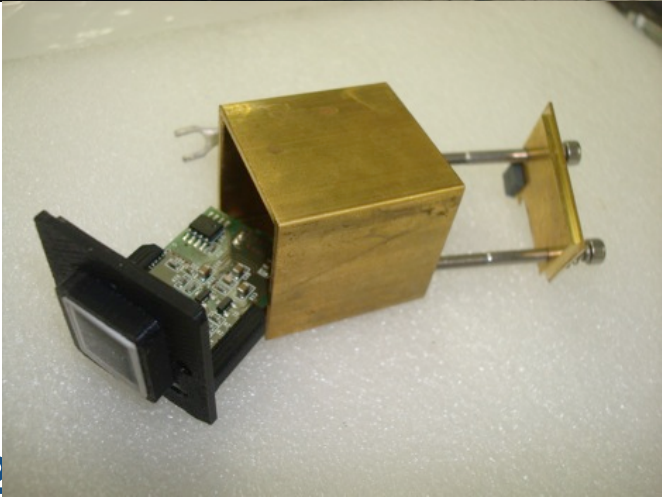
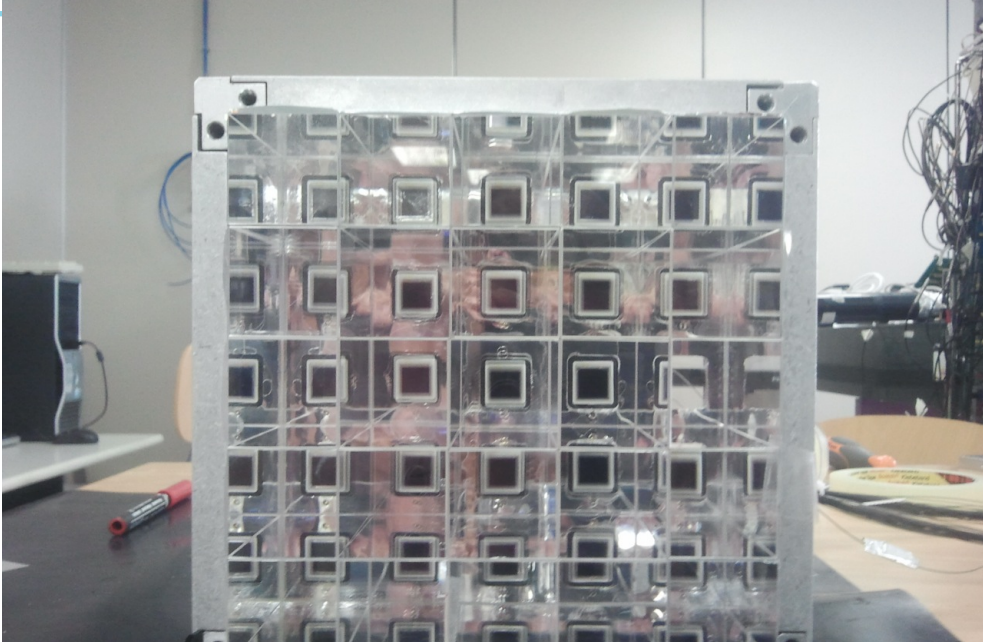
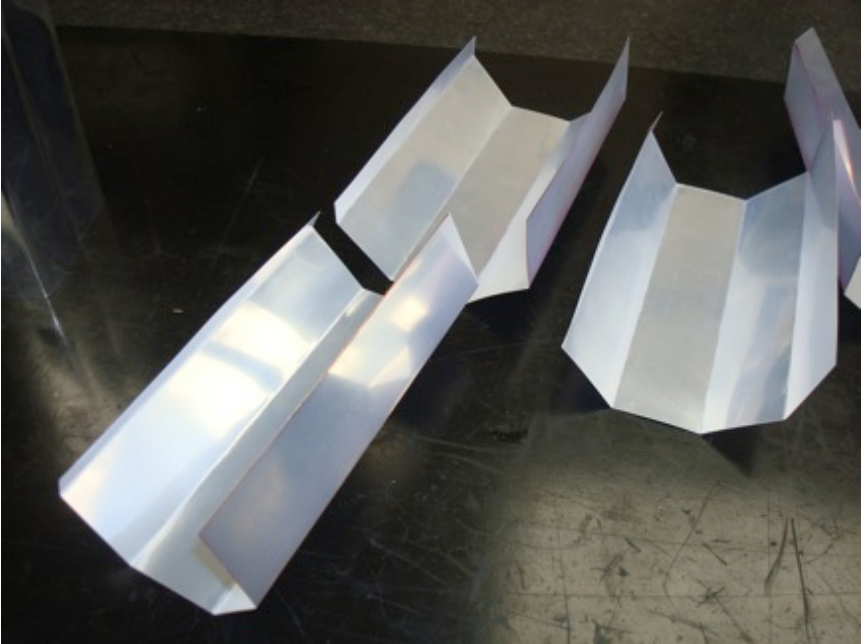


R&D on LYSO → Test Beam measurement



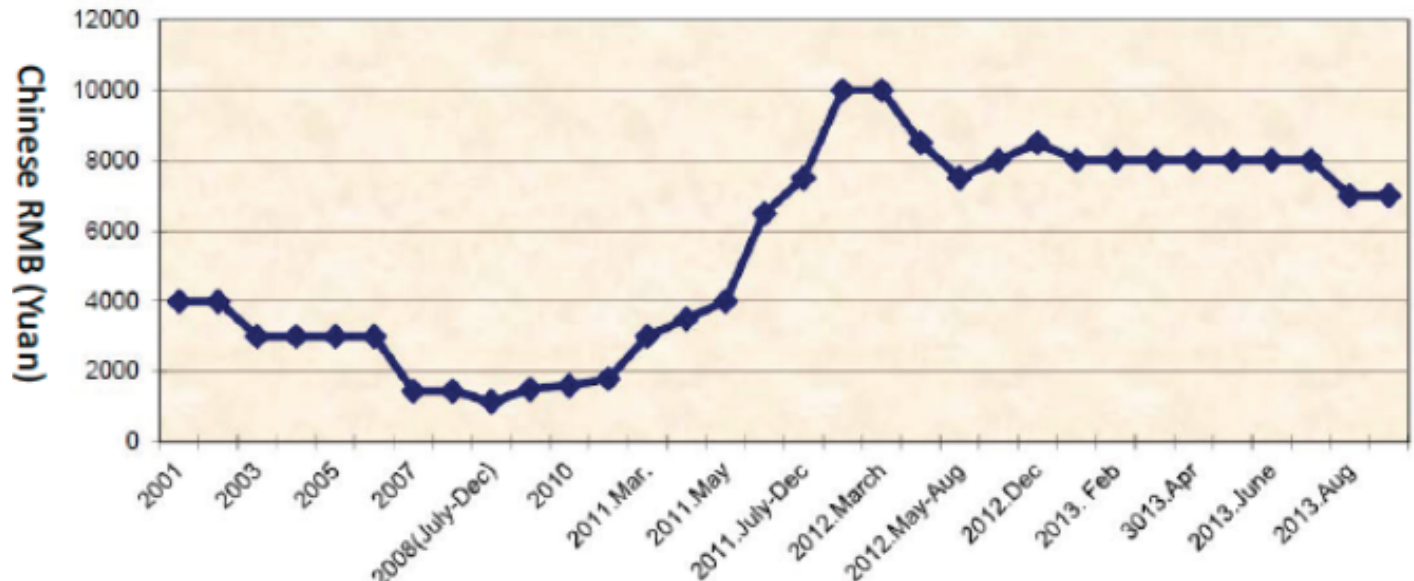
- ❑ Test Beam measurements at MAMI (Mainz) with Tagged photon beams and at BTF (LNF-Frascati) with e- beams with small size prototypes (< 2 Rm) proved that LYSO can make 4% energy resolution and < 200 ps @ 100 MeV.
- ❑ New test beam with larger size prototype (5x5 3x3x15 cm3 crystals) of ~ 4 Rm planned at MAMI in September and at LNF in November to close the R&D Phase for LYSO.
- ❑ It will be used at PSI for measurement of muon capture (AlCap)

R&D on LYSO → Matrix Prototype



Changes since CD-1: LYSO Cost

The Lu_2O_3 price fluctuates up a lot since mid 2011, showing market speculation



Last September when asking for budgetary requests of Large samples we discovered a 2.5 increase on LYSO Cost w.r.t. CD-1

The manipulation of rare earth prices by China has resulted in:
→ The reopening of rare earth mines in the US and Australia
→ A World Trade Organization **ruling** against China (and an appeal which has been denied)

We are closely following this situation, as it may result in a reduction in the price of Lu salt

BaF₂ characteristics and BaF₂ choice

Barium Fluoride (BaF₂)

- very fast (220 nm)
- non-hygroscopic
- Contains a slow component at 300 nm → need to suppress it due to high rates
- APD should be UV extended and “solar”-blind (See Next Talk)

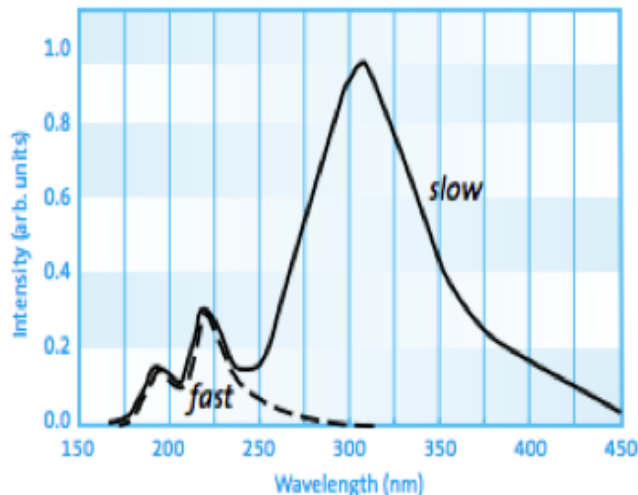


Figure 1. Scintillation emission spectrum of BaF₂

	BaF ₂
Density (g/cm ³)	4.89
Radiation length (cm)	2.03
Moliere Radius (cm)	3.10
Interaction length (cm)	30.7
dE/dX (MeV/cm)	6.52
Refractive index	1.50
Peak luminescence (nm)	220 (300)
Decay time (ns)	1 (650)
Light yield (rel. to NaI)	5% (42%)
Variation with temperature	0.1% (-1.29)% / deg-C

- We expect signal full width ~ 40 ns w.r.t. 200 ns for the LYSO
- Factor 5 improvement in separation

BaF₂ R&D plans

- Complete the characterizations with updated QA crystals stations
- Characterize the single crystal with new APD RMD

Make a new test beam @ BTF LNF (Nov 2014, Feb 2015)

- 20 BaF₂ crystals acquired by DOE from SICCAS
- 5 Ba_{F2} crystals from St.Petersburg University acquired by JINR/INFN that have to be polished in Kharkov

Problematic procurement due to the Ukraine situation

- 1 BaF₂ from SICCAS from INFN
- FEE in development @ LNF-INFN

Compare single crystal properties with backup →

Technical Choice end of 2014

Status of QA stations

- ◆ As shown in the next slides, Caltech has updated its QA stations both for Longitudinal Transmission and for Light Yield and LRU measurements.
- ◆ INFN QA stations:
 - INFN has procured all parts to perform transmission measurement down to 200 nm. Expect to complete the station before end of the ye
 - Manual station for light yield and LRU ok with UV-extended PMT. Now moving this PMT on the automatic station
 - Scan of crystals improved for Longitudinal/transversal transmission. 9 points along z, 9 points in the front face. Both crystal directions. Labview controlled. 3'/crystal.

Movie at: https://www.dropbox.com/s/9lszvp6v3c17jbu/MVI_0505_1.MOV

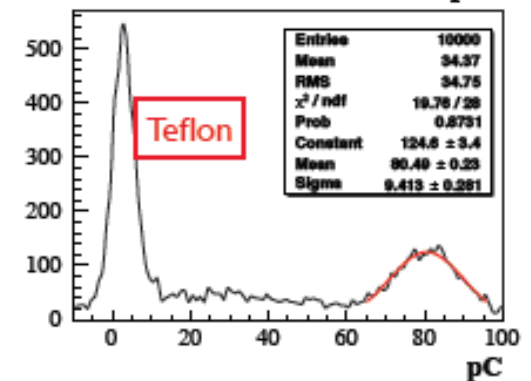
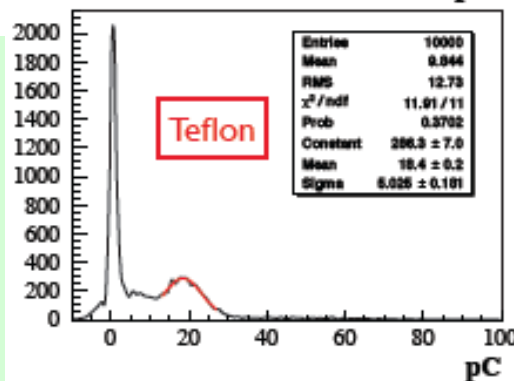
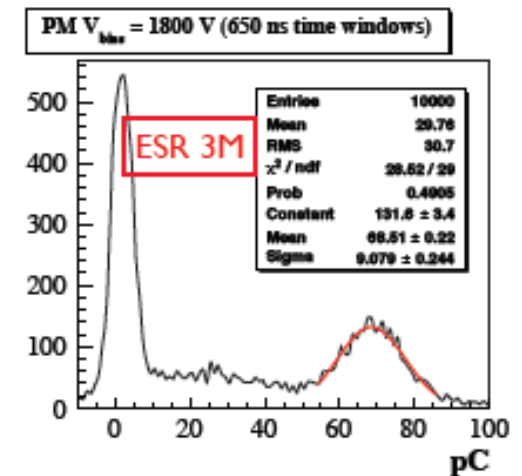
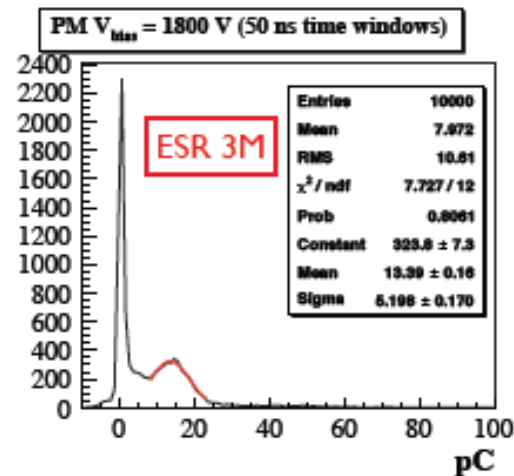
BaF₂ measurement at LNF

First tests with BaF₂ 30x30x230 mm³ crystals by Siccas with:

- **NO GREASE**
- teflon and ESR 3M
- EMI PM @ $V_{\text{bias}} = 1800 \text{ V}$,
gain = 3.8×10^6
QE ~ 30% @ 210 nm
- Na²² source

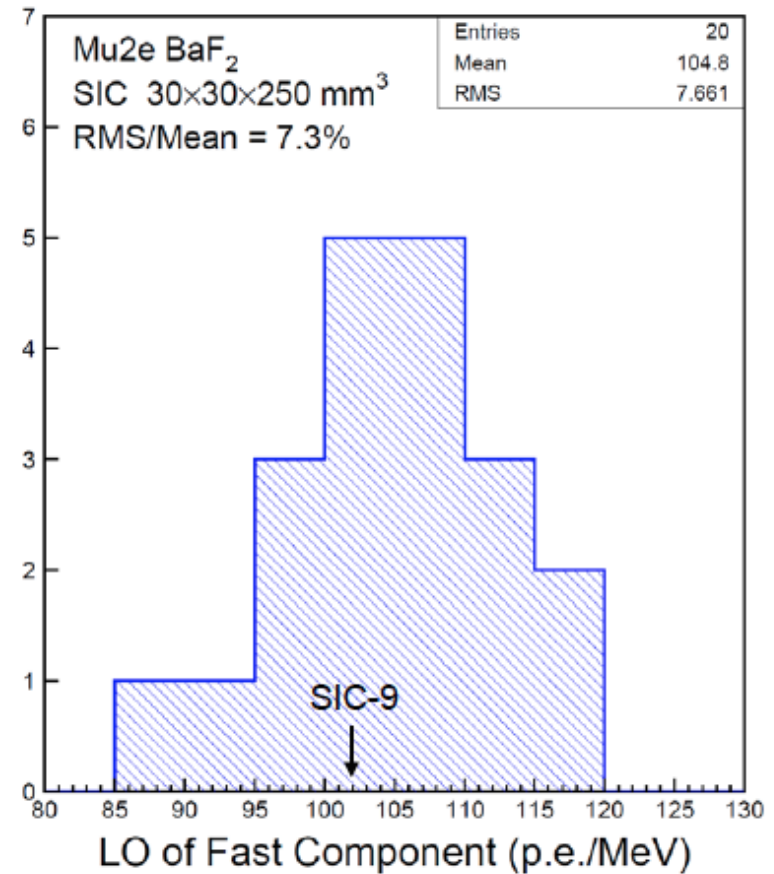
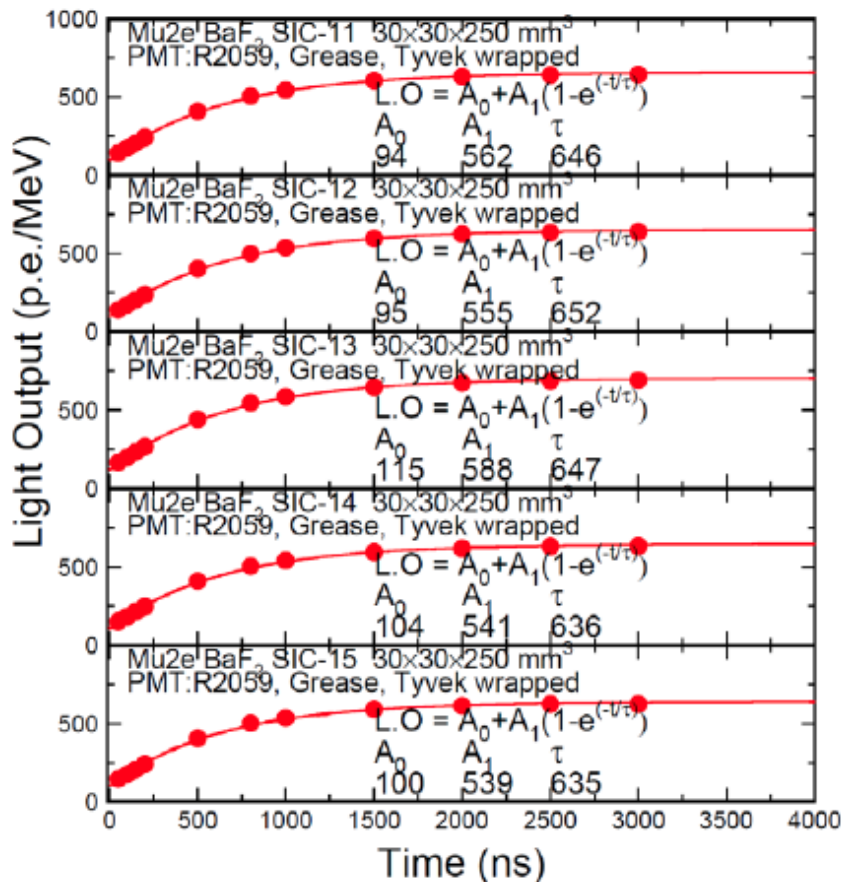
PMT Light Yield:

- Fast Component:
50 pe/MeV, 33% Sigma
- Slow Component:
220 pe/MeV, 12 % Sigma

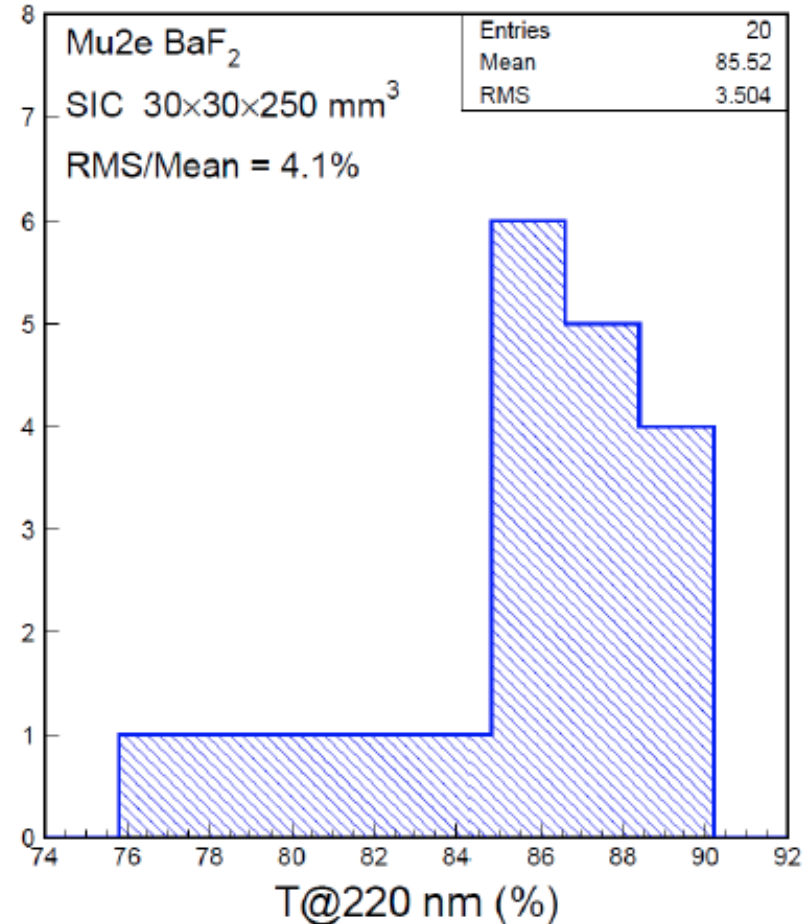
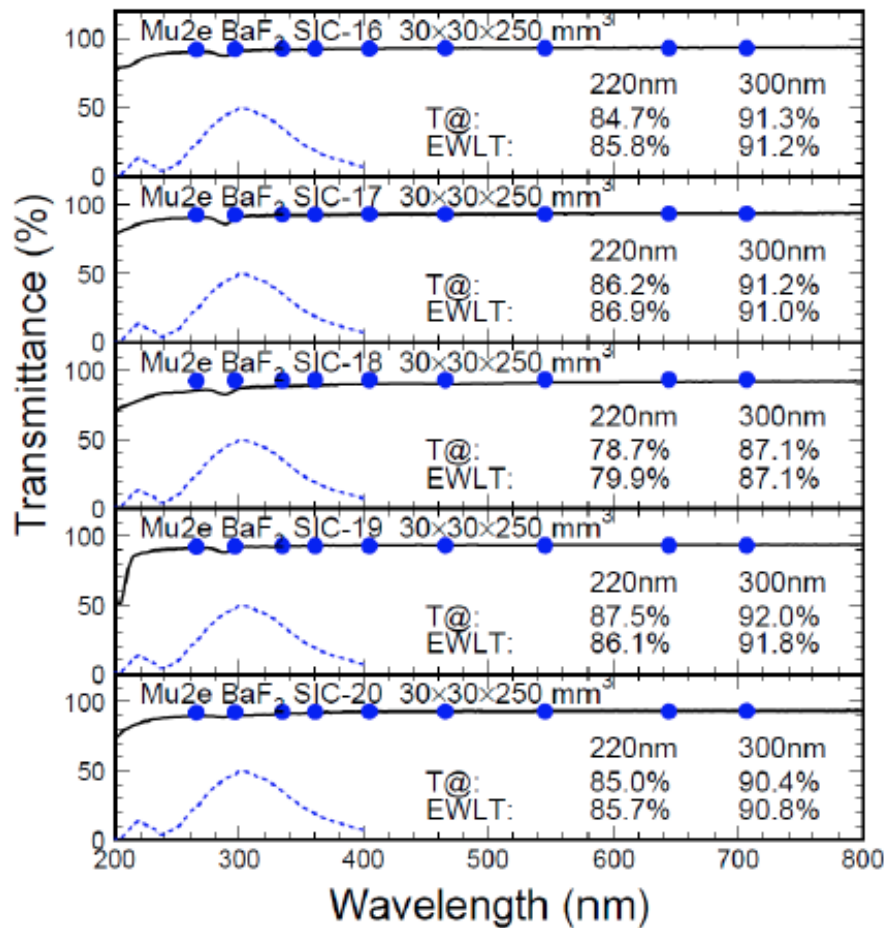


BaF₂ measurements at Caltech: L.Y. with ²²Na

Using Down Corning 2000 optical grease a factor two improvement!
Fast component 100 pe/MeV as expected. Resolution 20%



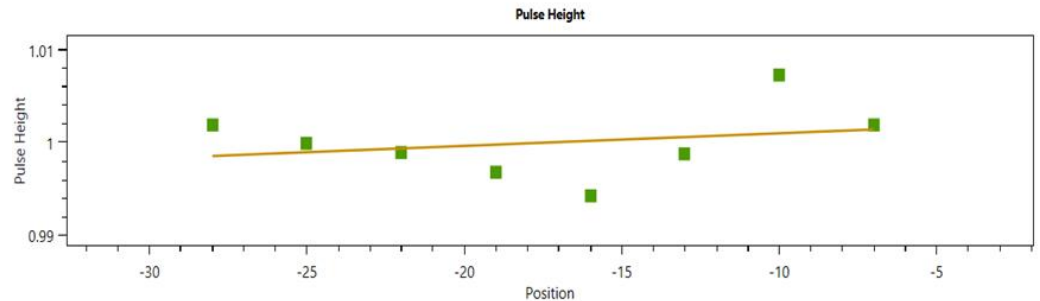
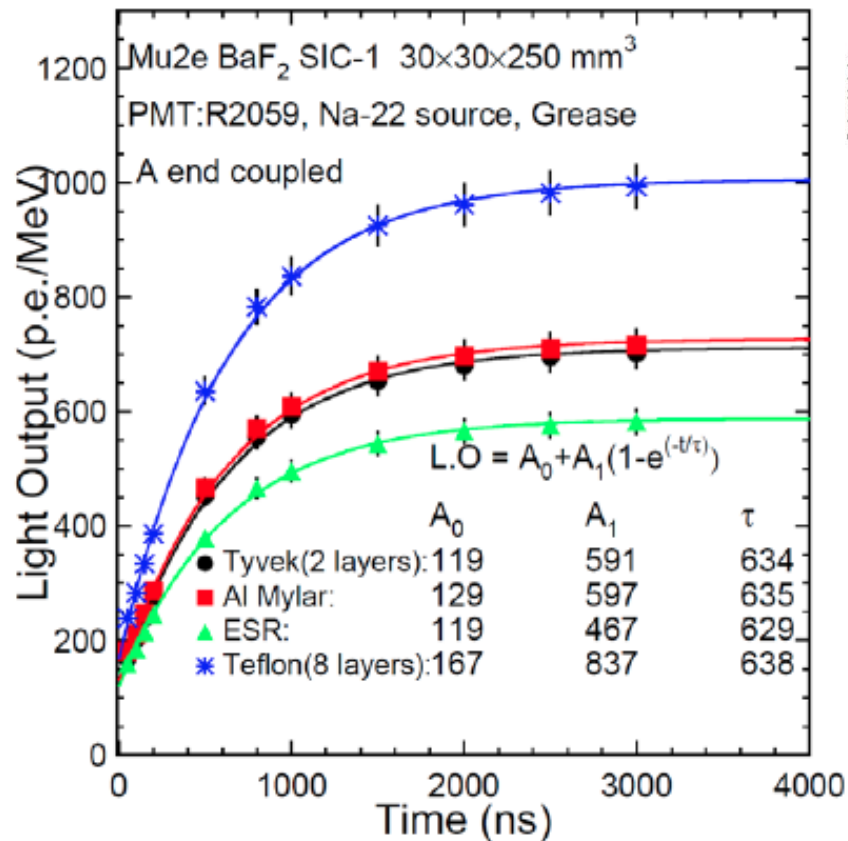
BaF₂ @ Caltech: Longitudinal Transmittance



→ Blue points, theoretical transmission limit. Black curve measurement With spectrophotometer. Great agreement and narrow distribution

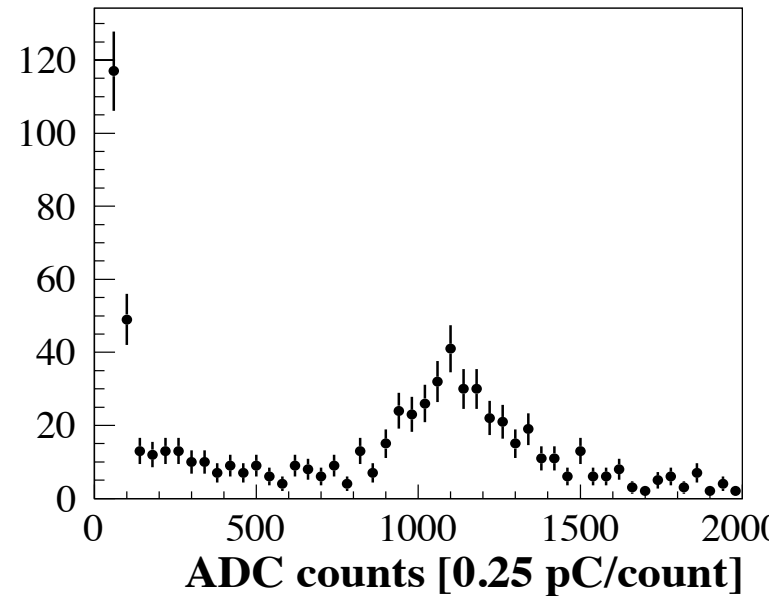
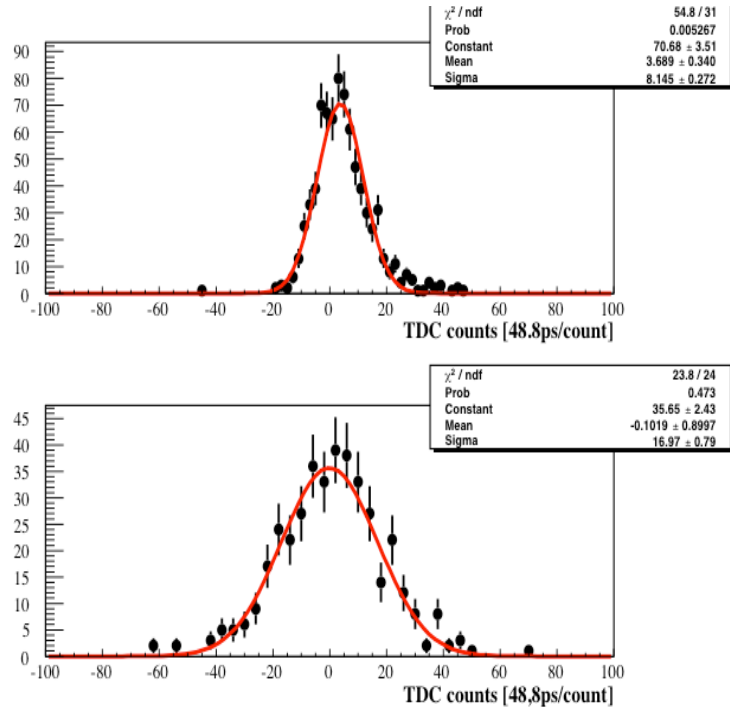
BaF₂ at Caltech: wrapping and LRU with APD

The highest LO observed for crystals wrapped with 8 layer Teflon films



First test of BaF₂ LRU with APD readout, Integrating fast and slow component with Charge integration ... OK

The Backup option: pure CsI + MPPC



- ❖ At INFN we have concluded the study for a single crystal of pure CsI from SICCAS, readout by a 12x12 mm² MPPC from Hamamatsu.
- ❖ Mip signal of 250 pC observed (15% resolution)
- ❖ **Timing resolution of 720 ps / MIP → 15 MeV equivalent with 1 photosensor only.**

Driving cost is the “crystals”

Having already acquired 20 BaF₂ from SICCAS we used their Budgetary request as estimate. 15% contingency

Cheaper proposal from St.Petersburg University (Russia) not yet validated.

INFN and DOE play by different rules

INFN: No escalation, No overhead, VAT, Contingency

Planning to have a single international tender, with INFN contributing its fraction for the crystals procurement as in-kind.

Crystals are going to be delivered 50% at Caltech, 50% at FNAL

→ not to pay custom duties/ travel insurance twice

INFN QA station will be used at FNAL

Typos in the Cost Book and Cost Distribution

- As reported in the BOEs, the best estimate for the **Basic Cost of the DOE part is:**
 - 1965\$/crystal per 1900 x 2/3 = 2.489 k\$,
i.e. 622,5 k\$ for ¼ of production.
- In the cost book we typed 467k\$ for ¼ production
- **The difference to be corrected in the cost book is + 620 k\$**

Rest of the cost is for

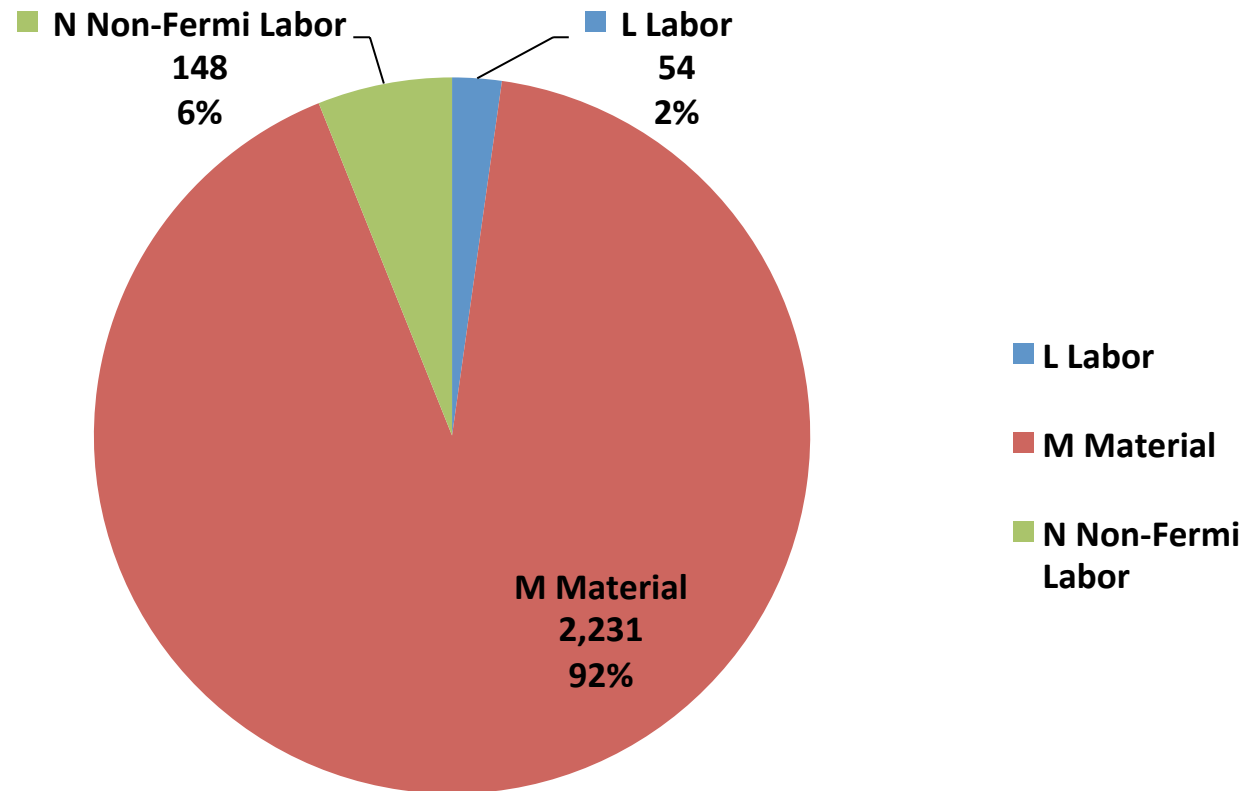
- Preproduction (40+40 crystals)
- Remaining R&D
- Labor Cost for QA of pre-production and production crystals.

Crystal: Cost distribution by Resource Type

Base Cost (AY \$k)

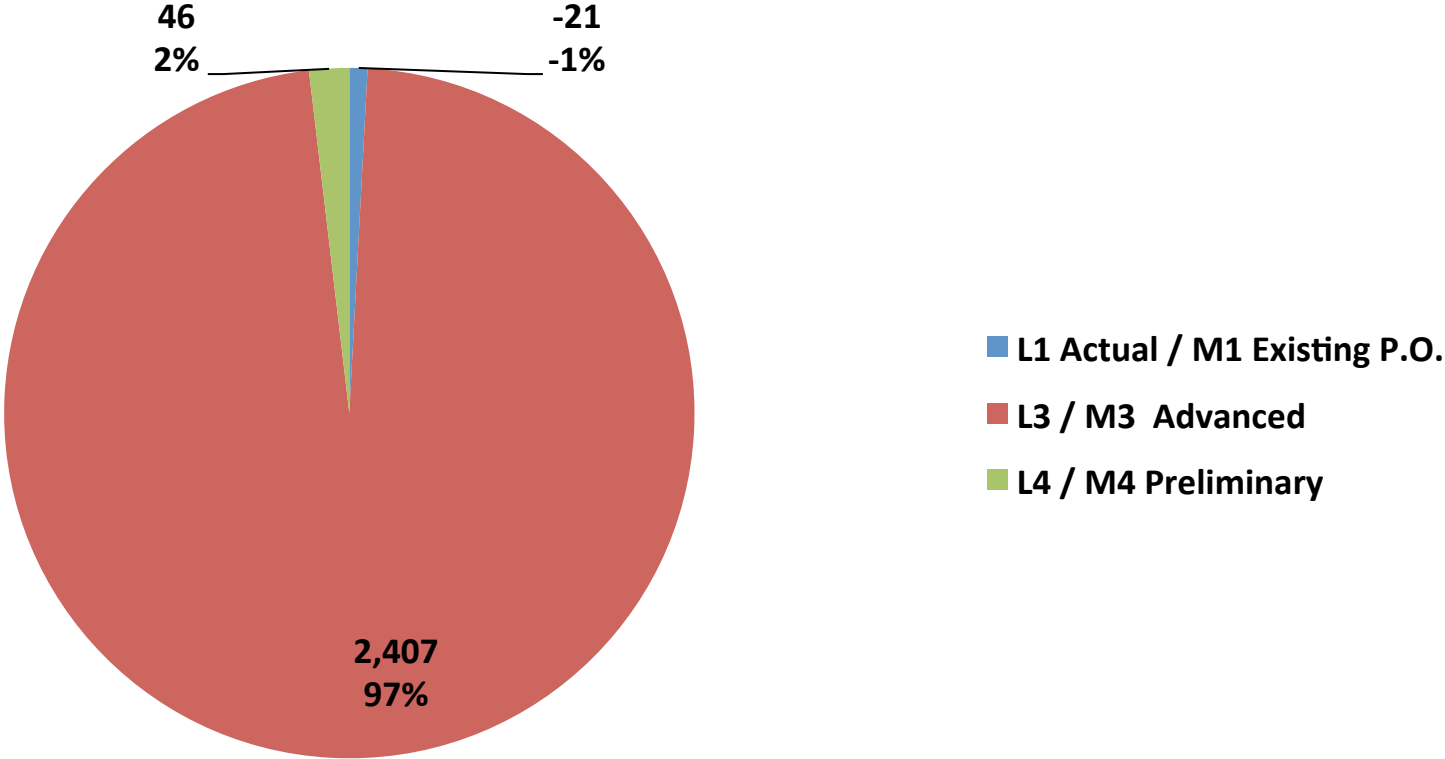
Cost Set	Budget
WBS Level 3	475.07.02 Crystals

Sum of Value	
Resource Type	Total
L Labor	54
M Material	2,231
N Non-Fermi Labor	148
Grand Total	2,433



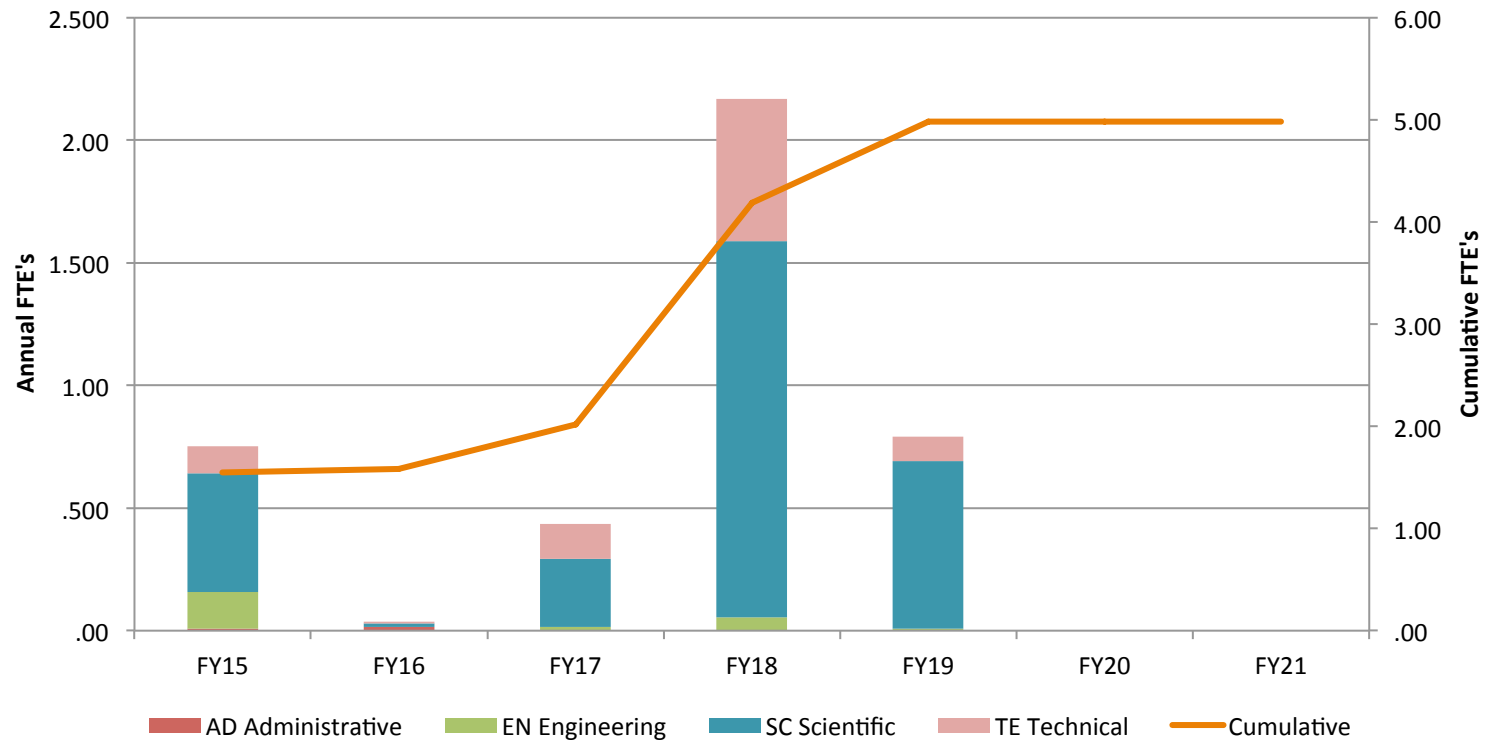
Crystals: Quality of Estimate

Base Cost by Estimate Type (AY\$K)



Crystal: Labor Resources

FTEs by Discipline



Crystal: Labor/Material profile

