The Mu2e electromagnetic calorimeter and Mu2e-II upgrade

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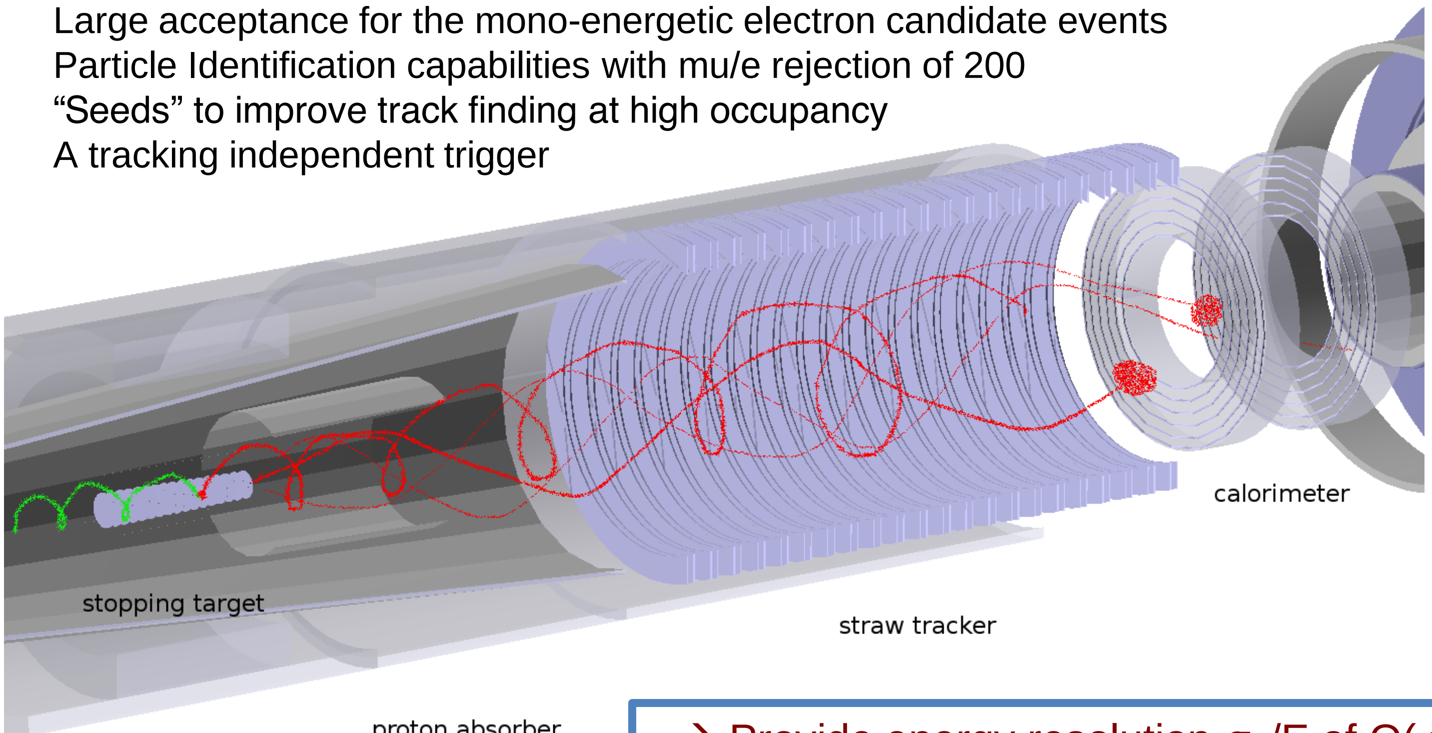
Calorimeter Requirements

For the μ → e conversion search, the calorimeter adds redundancy and complementary qualities with respect to the high precision tracking system

- Large acceptance for the mono-energetic electron candidate events
- Particle Identification capabilities with mu/e rejection of 200
- "Seeds" to improve track finding at high occupancy
- A tracking independent trigger



For 100 MeV electrons @ 50 degrees impact angle

→ Provide energy resolution σ_E/E of O(< 10 %)

→ Provide timing resolution σ(t) < 500 ps

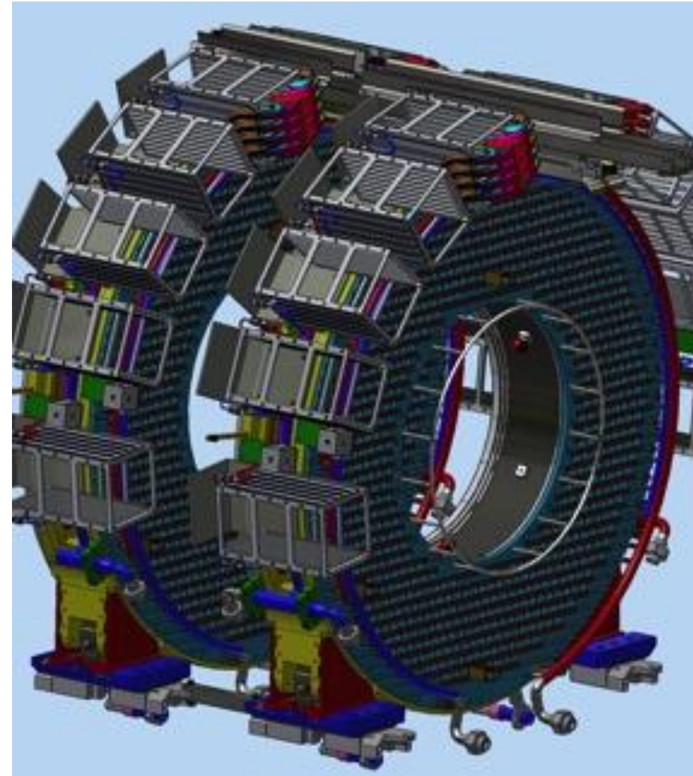
→ Provide position resolution < 1 cm

→ **Work in vacuum @ 10^{-4} Torr and 1 T B-Field**

→ **Survive the harsh radiation environment**

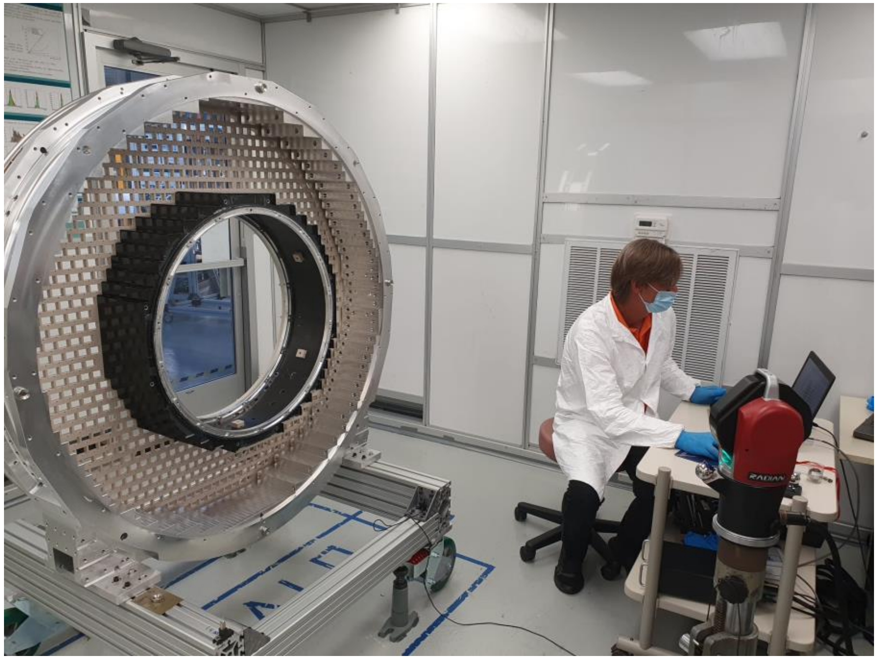
Mu2e calorimeter design

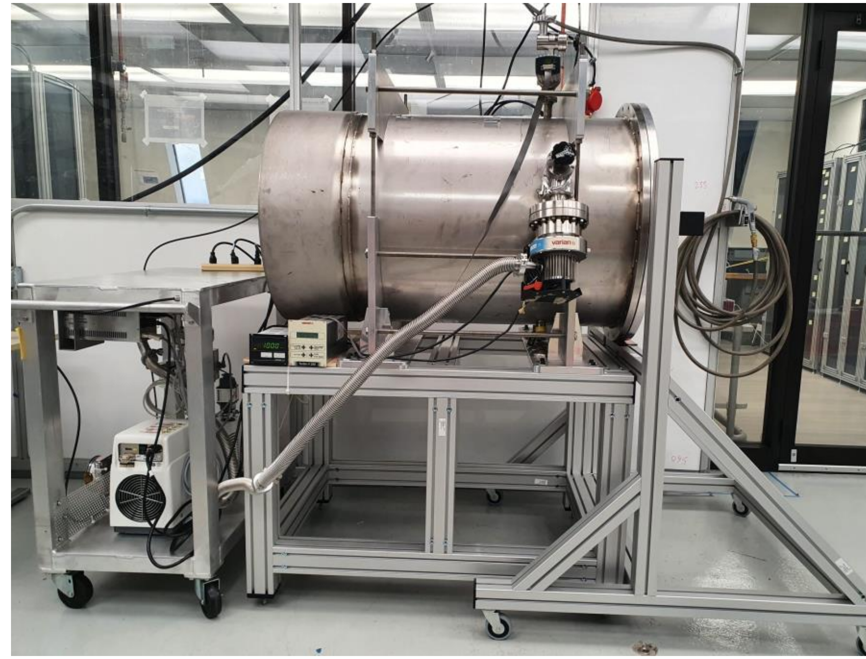
- ✓ Two annular disks, each one with 674 un-doped CsI parallelepiped crystals with square faces:
  - ➔ Crystal dimensions (34 x 34 x 200 mm^3) ~ 10 X_0
  - ➔ Inner/Outer Radius = 374/660 mm
- ✓ Each crystal is read out by two large area UV extended Mu2e SiPM's (14x20 mm^2) through a 2mm air gap
- ✓ SiPM glued on copper holders with FEE mounted on SiPM pins
- ✓ Digital electronics at 200 Msps located in near-by electronics crates
- ✓ Radioactive source (ala Babar) and laser system provide absolute calibration and monitoring capability



Operate with very high reliability in vacuum and radiation hard environment → -10 ℃ for SiPMs

Assembling Disk-0 in SiDet





→ Clean Room ISO-7, services

→ Outgassing vessel mounted + ORC for the Outgassing vessel

→ final adjustments in progress: N2 lines, bottles, ORC + calorimeter tent

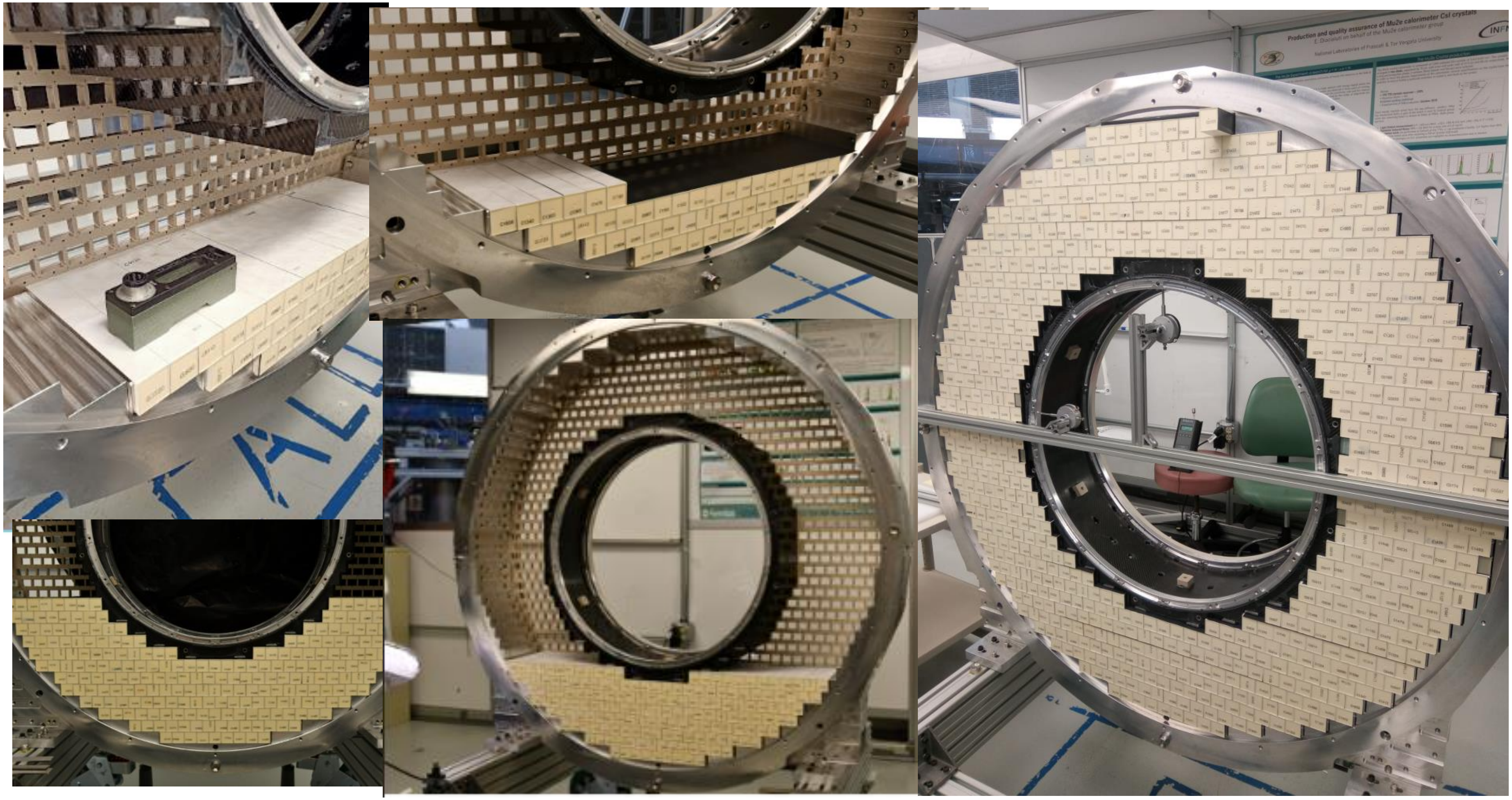
→ Very dry athmosphere (RH ~ 30-35%)

→ Alignment of mechanical structure with Al Disk + Inner Ring + Peek Front plate

Our goal for assemby and operation in vacuum:

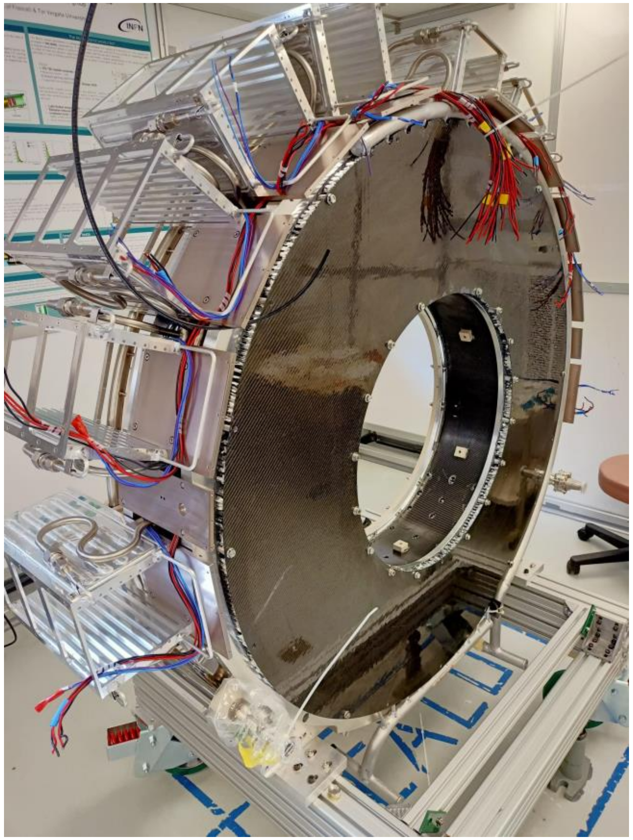
➔ Keep all components cleaned and outgassed to reach a total **OR < 8 E-3 Torr*l/s**

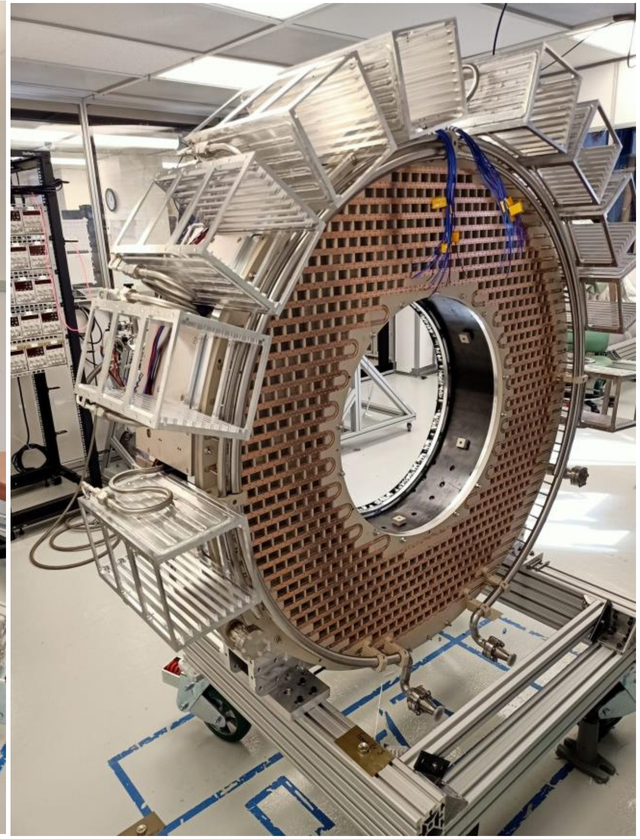
Crystals Stacking



Successful outgassing of all 674 crystals selected for optimized positioning on the disk + great stacking of all crystals on mechanical support

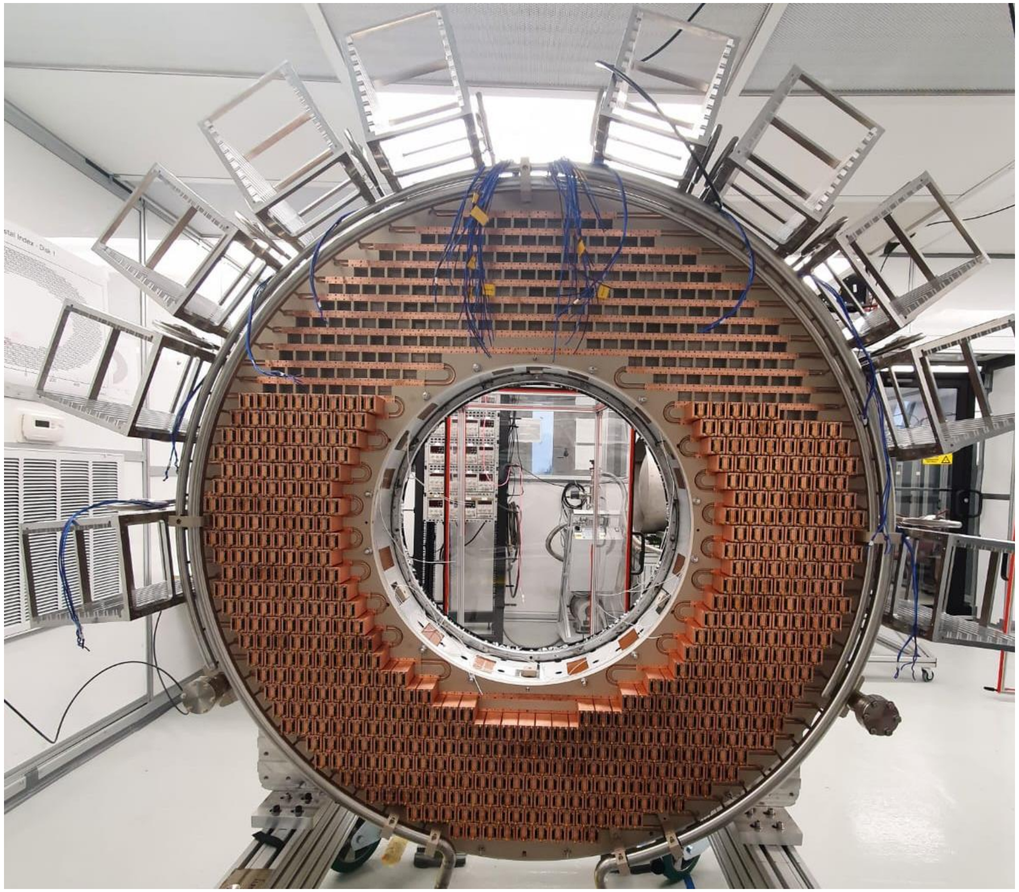
Crates and Cooling Installation





- After installation of the ten crates , their connection to the cooling circuits have been carefully tested. Leaks below 10^{-11} mbar*l/sec
- Calorimeter protected by dust with a BOX where dry air is kept circulating

Road to Calorimeter Commissioning



- The mechanical parts, crystals and readout units (photosensors + FEE) installation has been completed
- Mass production and installation of electronics will start in 2023 (see details in E. Pedreschi's talk)
- Integration of the whole system with the rest of the experiment
- Calibration and test of the detector with cosmic rays and radioactive source

In the next two years a huge effort will be necessary in order to successfully commission the calorimeter!

Mu2e-II Calorimeter Requirements

- We exploited the experience gained building the Mu2e calorimeter to start to design the one needed in the Mu2e-II upgrade

- Required performances are the same of Mu2e calorimeter:

  - an energy resolution of **σ_E/E of O(< 10 %)**
  - a timing resolution of **$\sigma(t) < 500$ ps**

- What will change is the **occupancy** of the detector and **the radiation damage**:

  1. Intensity increases by a factor of 3 (Pileup increase)
  2. Duty cycle increases by a factor of 4 (from 25% to 100%)
  3. Overall Dose and Neutron flux increases X 10 (1 Mrad, 10^13 n/cm^2)

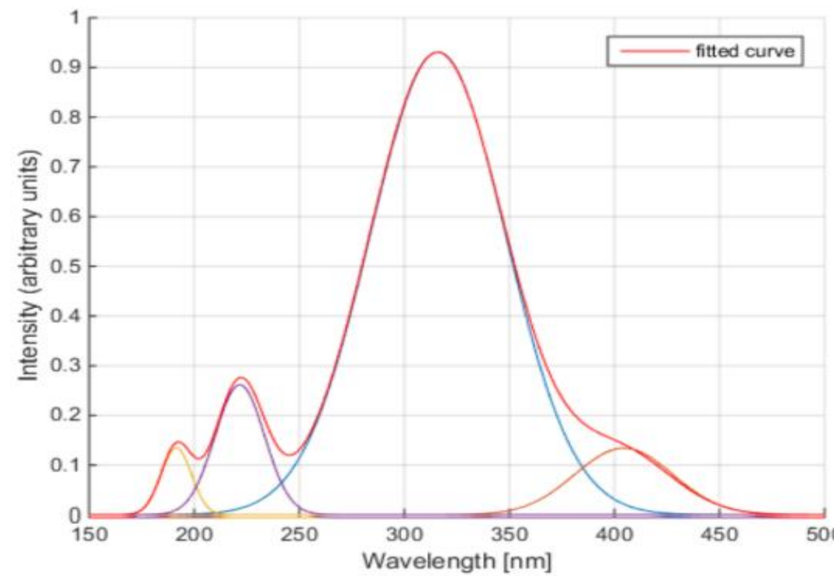
- A **SiPMs + CsI crystals solution is no more viable**.. we need:

  - Fast, high light yield and radiation hard crystal.. (BaF2..)
  - Fast, high PDE and radiation hard photosensor.. (Solar blind SiPMs..)

BaF2 as Baseline Solution

- BaF_2 crystal has a ultrafast scintillation at 220 nm with 0.5 ns decay time and a similar intensity as CsI, and may survive 100 Mrad. Its slow scintillation at 300 nm with 650 ns decay time, however, causes pileup in a high rate environment.

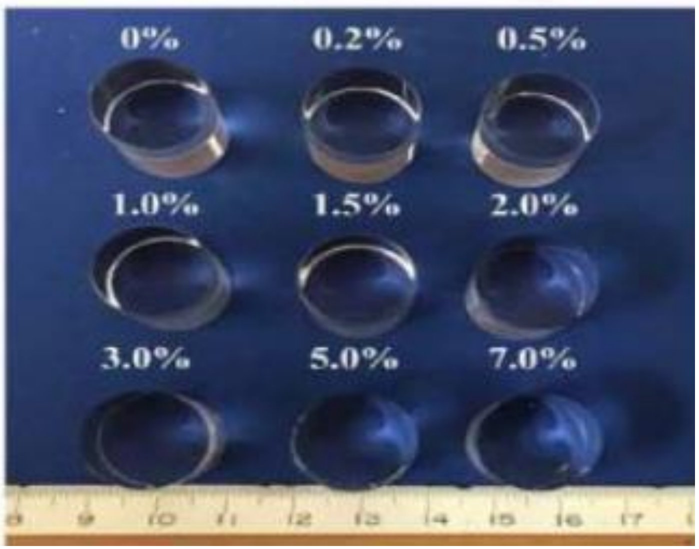
	LSO/LYSO	CsI	BaF_2
Density (g/cm^3)	7.4	4.51	4.89
Melting point (°C)	2050	621	1280
Radiation Length (cm)	1.14	1.86	2.03
Molière Radius (cm)	2.07	3.57	3.1
Interaction Length (cm)	20.9	39.3	30.7
Z value	64.8	54	51.6
dE/dX (MeV/cm)	9.55	5.56	6.52
Emission Peak[a] (nm)	420	310	300 220
Refractive Index[b]	1.82	1.95	1.5
Relative Light Yield[a,c]	100	3.6 1.1	42 4.1
Decay Time[a] (ns)	40	30 6	650 0.5
d(LY)/dT[d] (%/°C)	-0.2	-1.4	-1.9 0.1

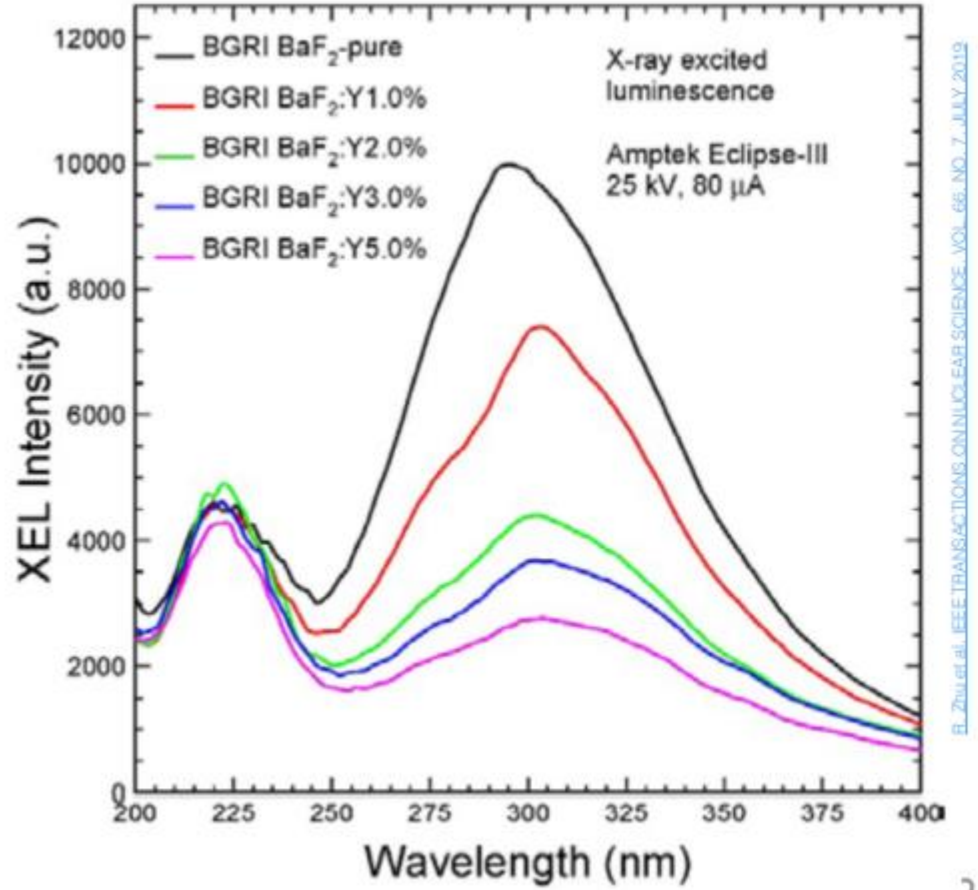


- Slow suppression may be achieved by rare earth (Y, La and Ce) doping, and/or solar-blind photo-detectors, e.g. Cs-Te , K-Cs-Te and Rb-Te cathode

BaF2 Yttrium Doping R&D

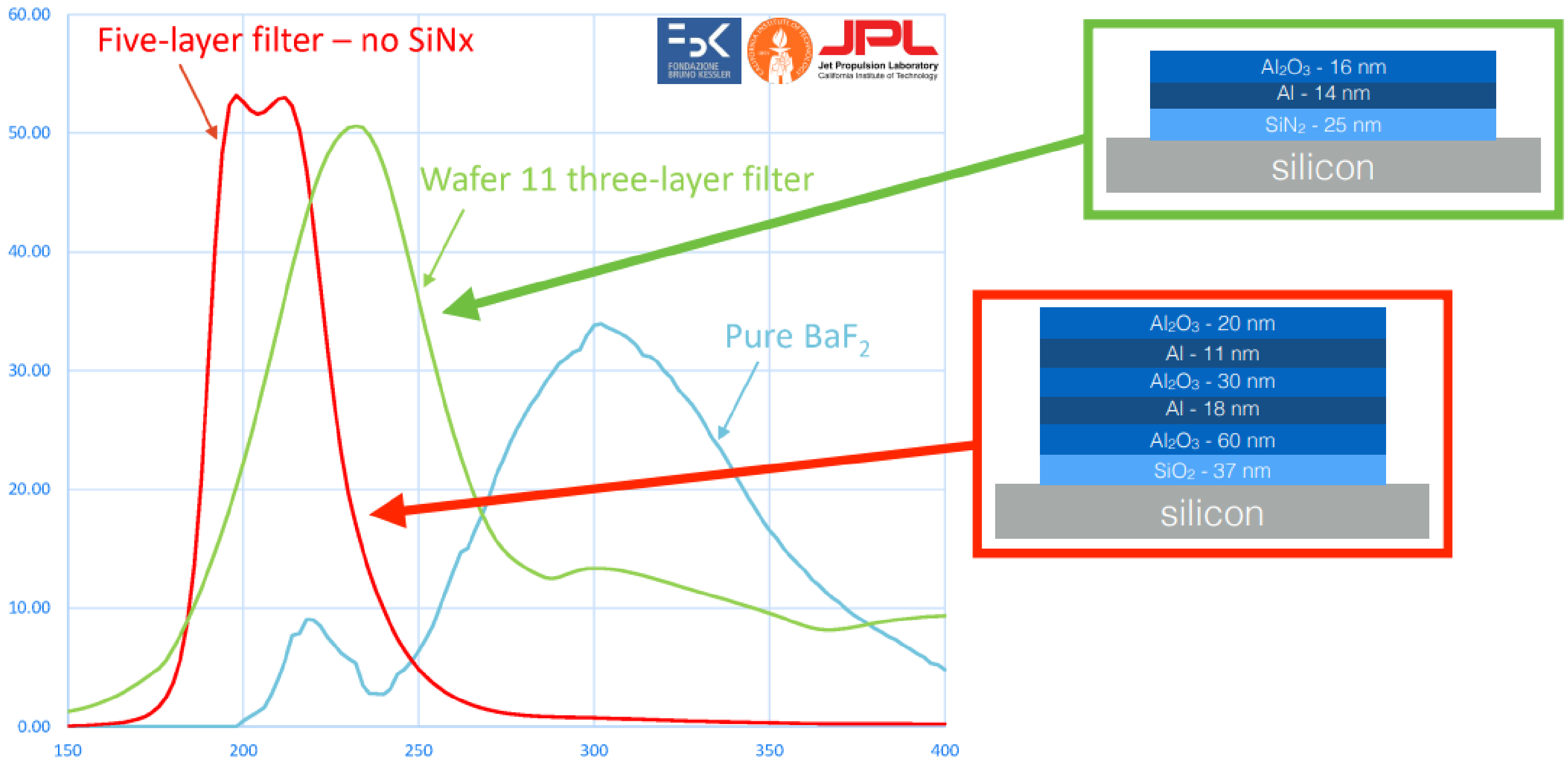
To suppress the detection of the BaF2 slow component, an intense R&D campaign is ongoing..





Y doping can suppress slow scintillation component of BaF2

Solar Blind SiPMs R&D



- Caltech-JPL-FBK consortium is working on delivering developing a special coating for SiPMs to suppress the detection of the BaF2 slow component:

  - Sandwich of Al, SiN2 and Al2O3 layers deposited on the active material

Conclusions

- The Mu2e CsI+SiPM Calorimeter demonstrated excellent energy (< 10 %) and timing (< 500 ps) resolution @ 100 MeV as proven with electron beams
- **Production of crystals, SiPMs and FEE completed**
- **Production of mechanical parts completed for disk-0**
- **Assembly room at FNAL is being completing**
- **Mass production and installation of electronics will start in 2023**
- **A Vertical Slice Test is planned at FNAL in 2023 to verify the integration of the electronic chain with the DAQ of the experiment**
- **Commissioning of the calorimeter in 2024**
- **The R&D on the Mu2e-II calorimeter is converging into a viable conceptual design based on BaF2 crystals readout by Solar Blind Silicon PhotoMultipliers**