Design, status and test of the Mu2e crystal calorimeter

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On behalf of the MU2E Calorimeter group

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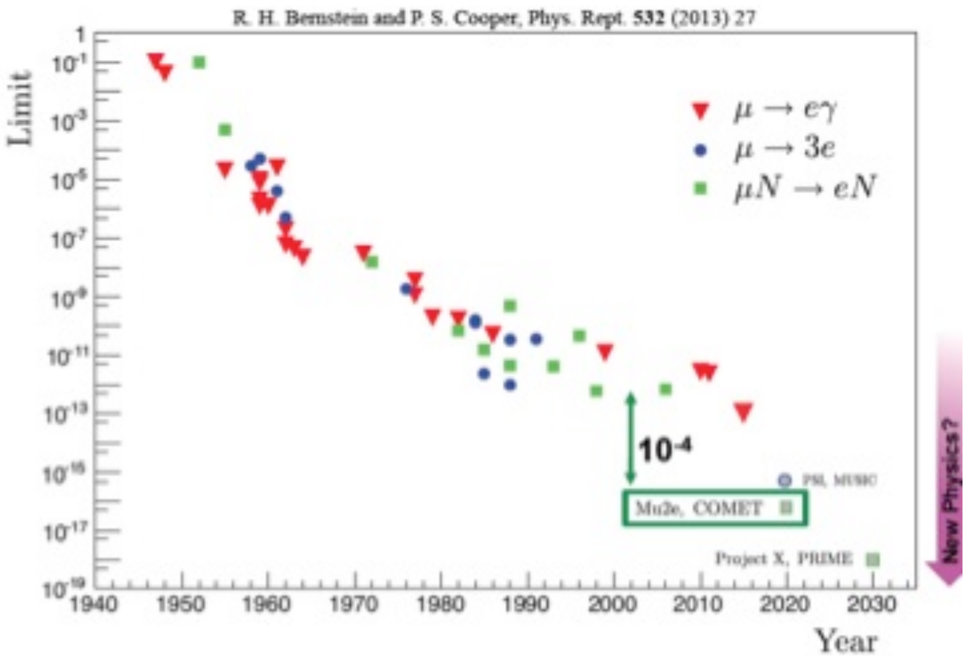
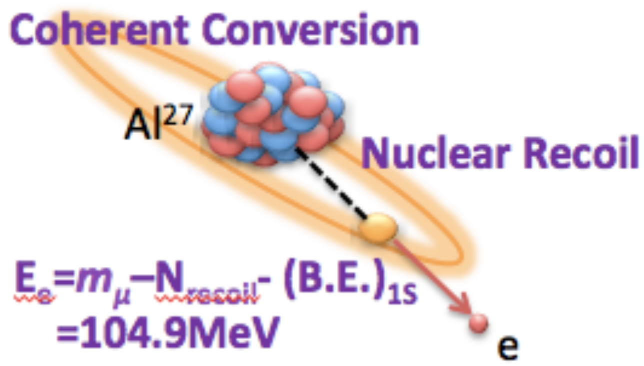
Talk layout

- The MU2E experiment
- Calorimeter requirements
- Calorimeter design
- Test of crystals
- “Mu2e-Custom” UV-extended SiPM
- FEE and WD electronics
- Calibration system
- Mechanical structure

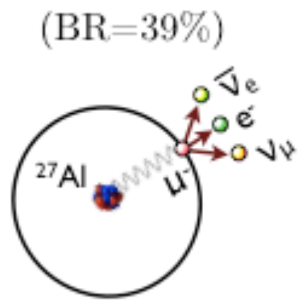
The MU2E experiment

- Detect the CLFV process $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$ i.e. the coherent, neutrinoless **conversion of a muon to an electron** in the field of a nucleus.
- CLFV process. Negligible in the SM (10^{-52} assuming neutrino oscillations)
- A CLFV signal is observation of new Physics





Mono energetic electron signal vs a fast falling spectrum from Decay In Orbit events (DIO)



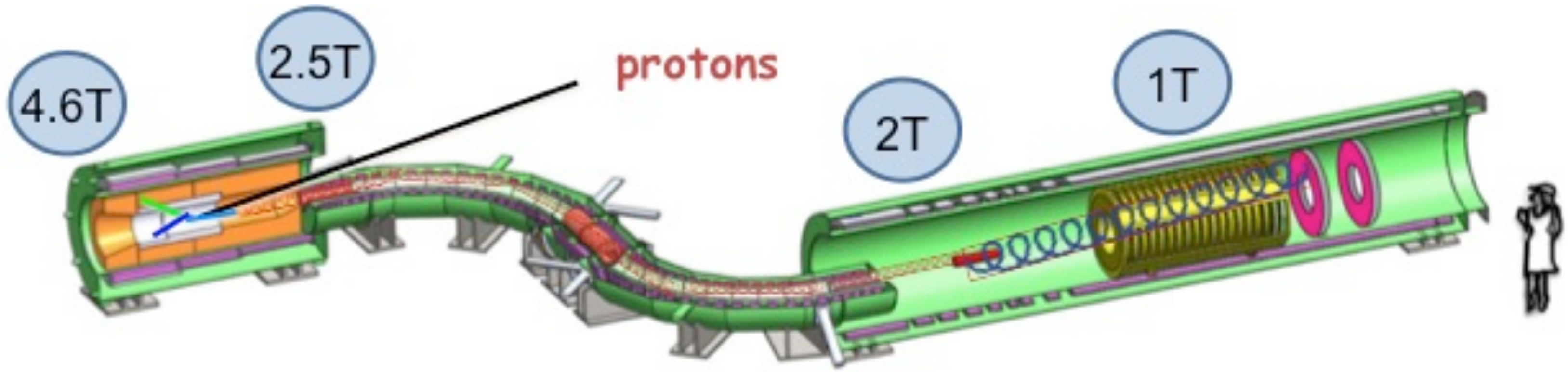
Mu2e goal: improve of 4 order of magnitude the sensitivity w.r.t. previous

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z)) \rightarrow e^- + N(A,Z)}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{ all muon capture})} \leq 6 \times 10^{-17} \text{ (@90\%CL)}$$

The MU2E beamline

Production Target / Solenoid (PS)

- 8 GeV Proton beam strikes target, producing mostly pions
- Graded magnetic field contains backwards pions/muons and reflects slow forward pions/muons



Transport Solenoid (TS)

- Selects low momentum, negative muons
- Antiproton absorber in the mid-section

Target, Detector and Solenoid (DS)

- Capture muons on Al target
- Measure momentum in tracker ($\sigma \approx 120$KeV/c) and energy/time in calorimeter
- Cosmic Ray Veto detector surrounds the solenoid to make CR contribution negligible

- **For the sensitivity goal → ~ 6×10^{17} stopped muons**
- **in 3 year run , 6×10^{7} sec → 10^{10} stopped muon/sec**

The MU2E calorimeter

The calorimeter should:

- Provide high e- reconstruction efficiency for μ rejection of 200
- Provide cluster-based seeding for track finding
- Provide online software trigger capability
- Survive in the radiation environment of Mu2e
- Operate for 1 year w.o. interruption in DS w/o reducing performance

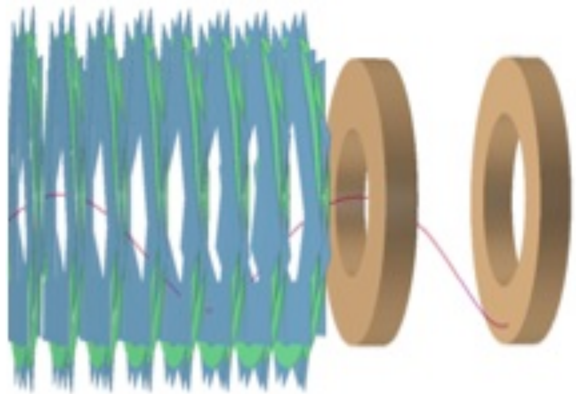
In order to do so the calorimeter should have the following capability

→ Provide energy resolution σ_E/E of O(5 %)
→ Provide timing resolution $\sigma(t) < 500$ ps
→ Provide position resolution < 1 cm
→ Provide almost full acceptance **for CE signal @ 100 MeV**
→ Redundancy in FEE and photo-sensors

Solution: A crystal based disk calorimeter

Calorimeter Requests

High granularity crystal based calorimeter with:



- 2 Disks (Anuli) geometry to optimize acceptance for spiraling electrons
- Crystals with high Light Yield for timing/energy resolution → **LY(photosensors) > 20 pe/MeV**
- **2 photo-sensors/preamps/crystal** for redundancy and reduce MTTF requirement → now set to 1 million hours/SIPM
- Fast signal for Pileup and Timing resolution → **τ of emission < 40 ns + Fast preamps**
- **Fast WFD to disentangle signals in pileup**
- **Crystal dimension optimized** to stay inside DS envelope → reduce number of photo-sensor, FEE, WFD (cost and bandwidth) while keeping pileup under control and position resolution < 1 cm.
- Crystals and sensors should work in 1 T B-field and in vacuum of 10^{-4} Torr and:
  - → **Crystals survive a dose of 100 krad and a neutron fluency of 10^{12} n/cm^2**
  - → **Photo-sensors survive 20 krad and a neutron fluency of 3×10^{11} n_1MeV/cm^2**

Calorimeter Structure

The Calorimeter consists of two disks with 674 34x34x200 mm^3 CsI crystals:

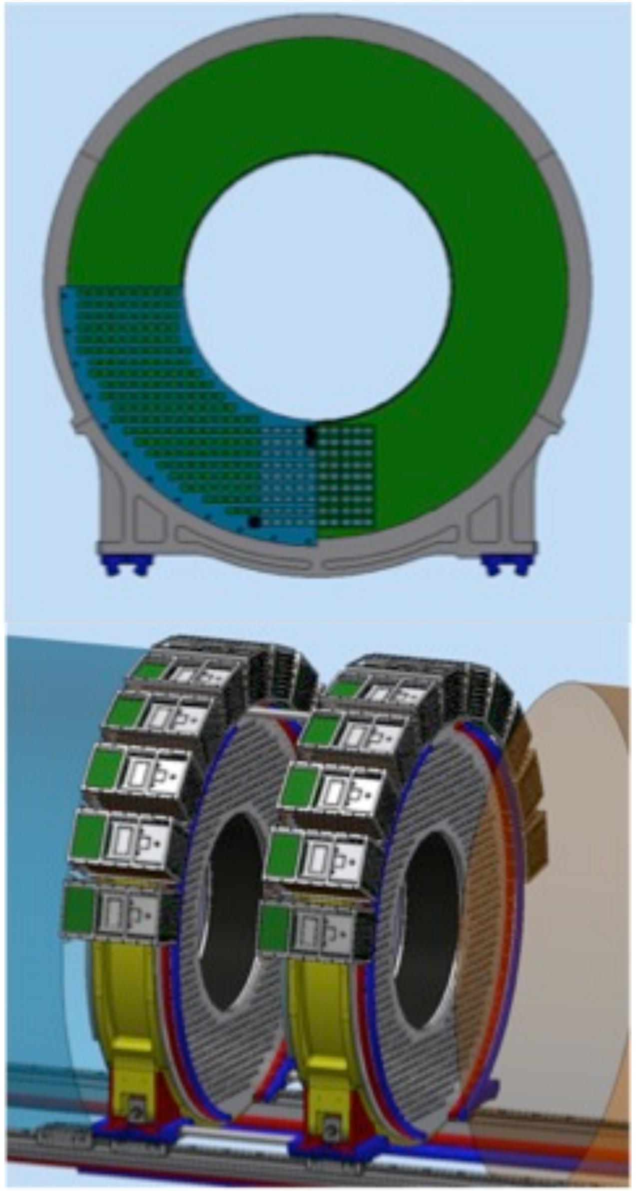
→ R_{inner} = 374 mm, R_{outer}=660 mm, depth = 10 X_0 (200 mm)

→ Disks separated by 75 cm

→ Each crystal is readout by two large area UV extended SIPM's (14x20 mm^2)

→ Analog FEE is on the SiPM and digital electronics located in near-by electronics crates

→ Radioactive source and laser system provide absolute calibration and monitoring capability



Crystal Requirement

- High light output (LO) > 100 p.e./MeV by standard bialkali PMT with air gap and crystal wrapped with two layers of Tyvek paper

- Good light response uniformity (LRU) > 10%

- Fast signal with small slow component: τ <40ns and

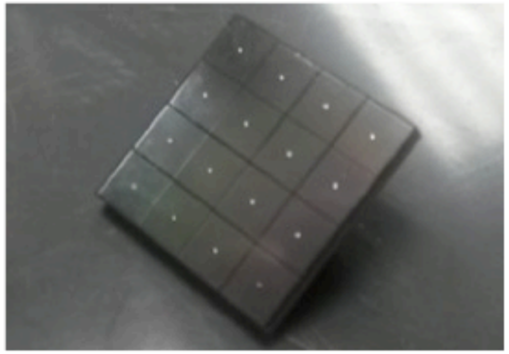
  Rt = F(Integral in 200 ns)/T(Integral in 3000 ns) >75%

- Radiation hard with LO loss <40% for:
  - Ionization dose: 100 krad @10krad/year in hottest areas
  - Neutrons: 10^{12} n/cm^2 @ 2x10^{11} n/cm^2/year in hottest areas

- Small radiation induced readout noise: <0.6 MeV

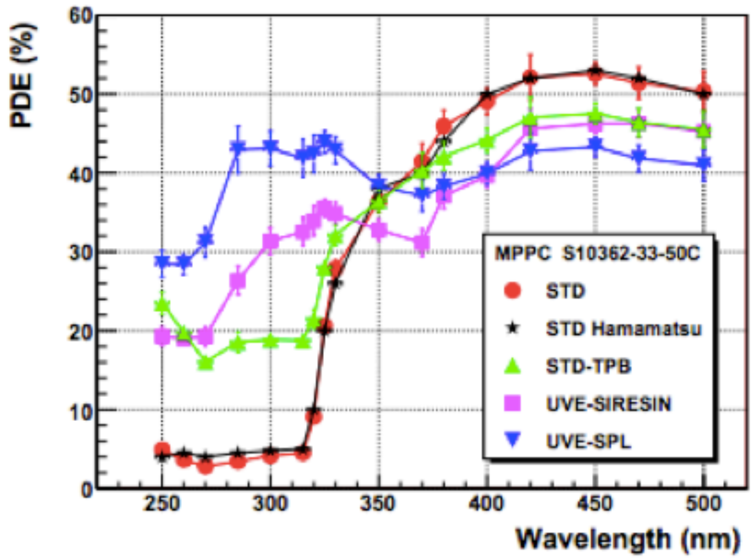
Crystal choice

	~~LYSO~~	~~BaF2~~	CsI
Radiation Length X_0 [cm]	1.14	2.03	**1.86**
Light Yield [% NaI(Tl)]	75	4/36	**3.6**
Decay Time[ns]	40	0.9/650	**30**
Photosensor	APD	RMD APD	**SiPM**
Wavelength [nm]	402	220/300	**310**



CsI(pure)

- Adequate radiation hardness
- Slightly hygroscopic
- 30 ns emission time, small slow component.
- Emits @ 310 nm.
- Comparable LY of fast component of BaF_2.
- Lower cost (6-8 $/cc)



CsI crystals test

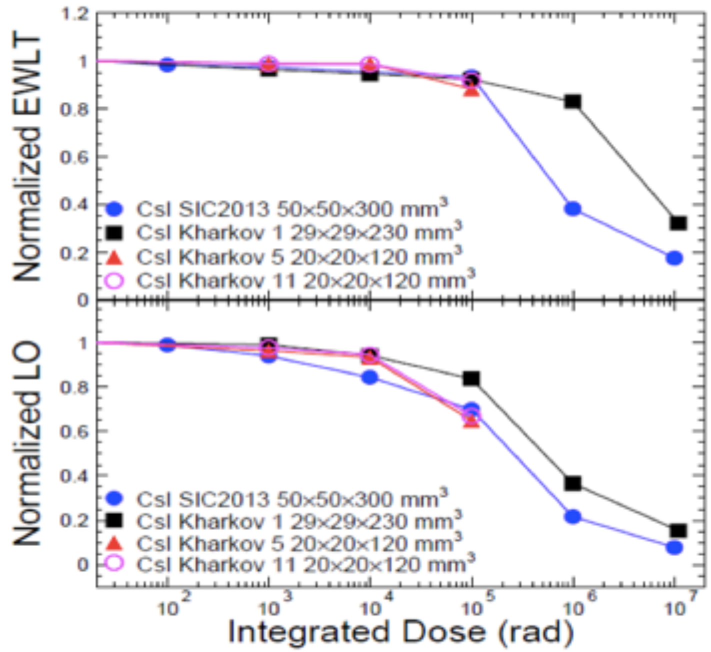
Test on different vendors performed:

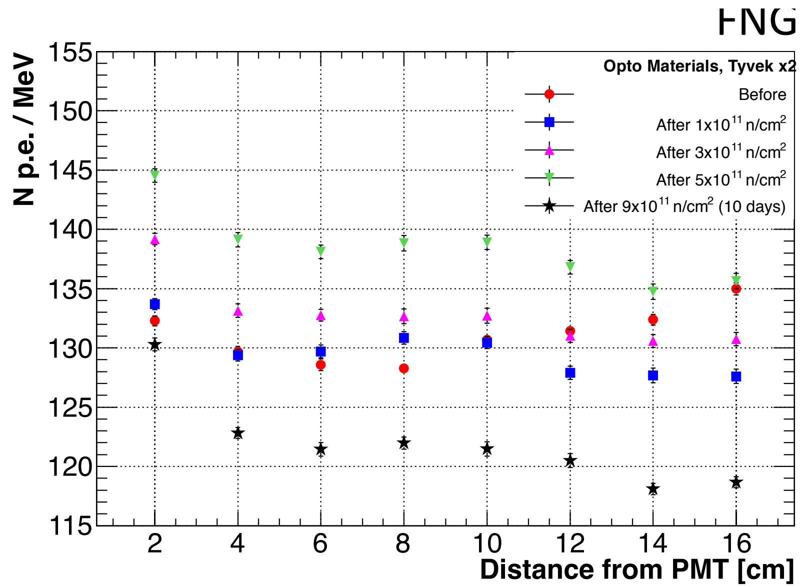
- ISMA (Ukraine)
- SICCAS (China)
- OptoMaterial (Italy)

- CsI crystals irradiated up to 900 Gy and to a neutron fluency up to 9×10^{11} n_{1MeV}/cm^2 @Caltech (USA) and CALLIOPE and FNG in ENEA(Italy)

- The ionization dose does not modify LRU while a 20% reduction in LY is observed at 900 Gy.

- Similarly, the neutron flux causes an acceptable LY deterioration (< 15%).





UV-extended SiPM

We have tested arrays of 16 3x3 mm^2 Hamamatsu TSV MPPCs (12x12 mm^2)

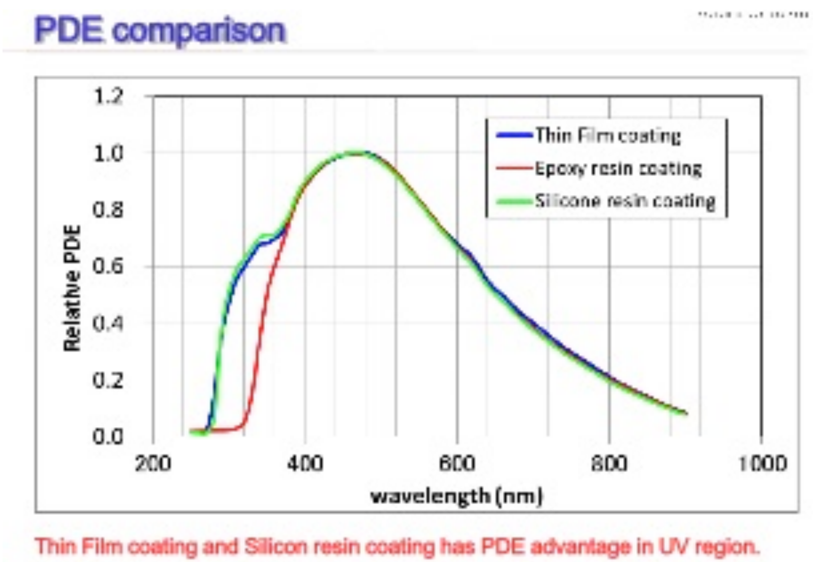
- These have silicone and thin film protection layers
- SiPMs are coupled to pure CsI crystals (30x30x200) mm^3

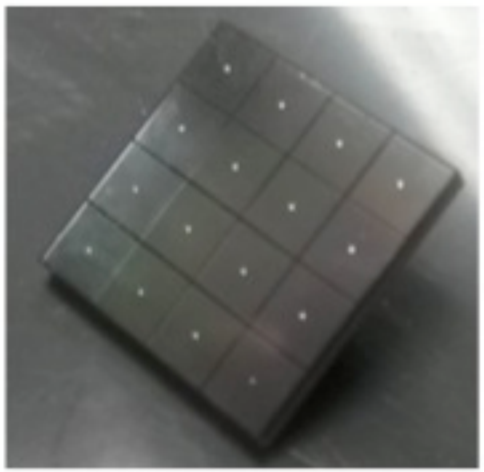
→ ~ 30 (20) p.e./MeV with (without) optical grease with Tyvek-wrapped crystals

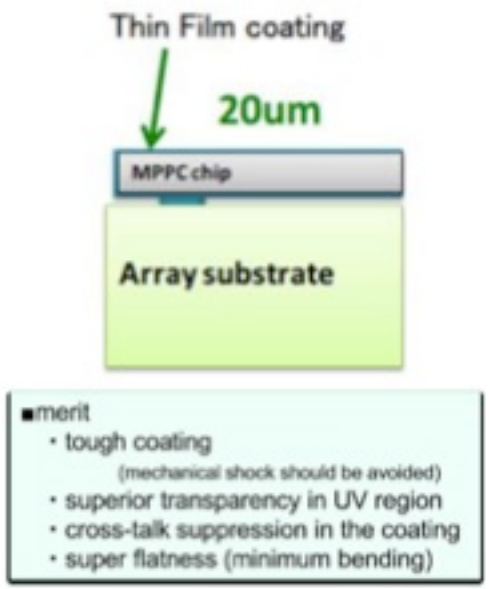
→ Time resolution < 150 ps @ 100 MeV with 45° e^- impact angle

→ Energy resolution better than 7% at 100 MeV (leakage dominated)

→ Equivalent noise ~ 100 keV

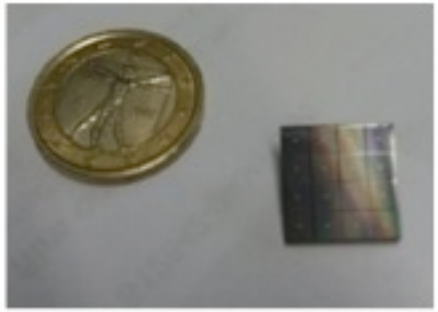


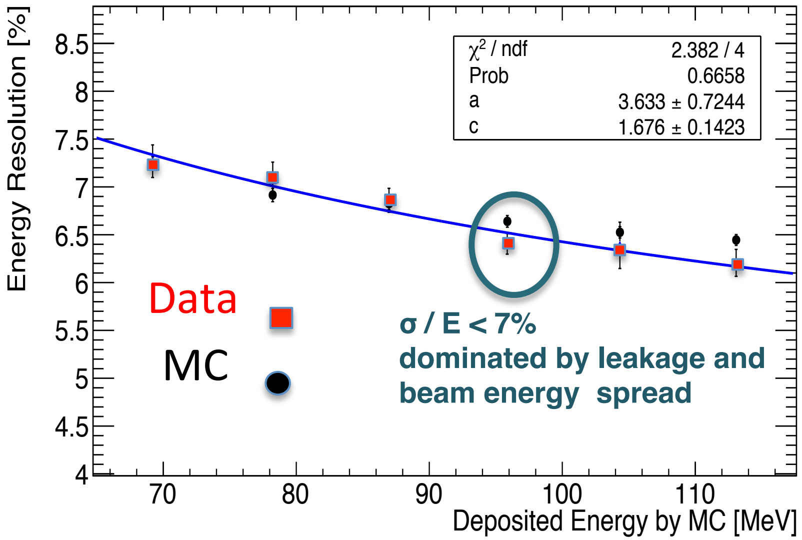


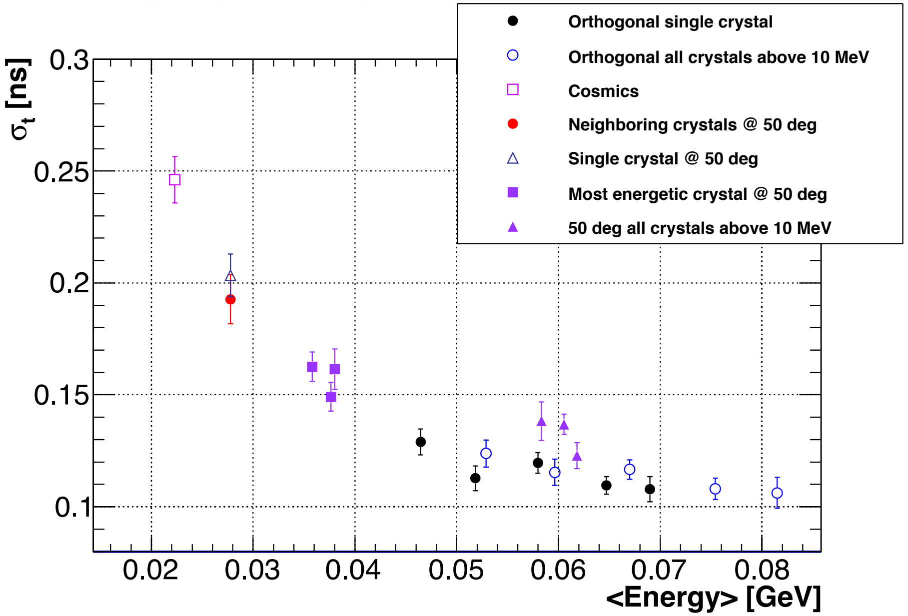


CsI+MPPC test

- A small crystal prototype has been built and tested in Frascati in April 2015
- 3x3 matrix of 3x3x20 cm^3 un-doped CsI crystal coupled with UV-extended MPPC.
- Test with e- between 80 and 120 MeV



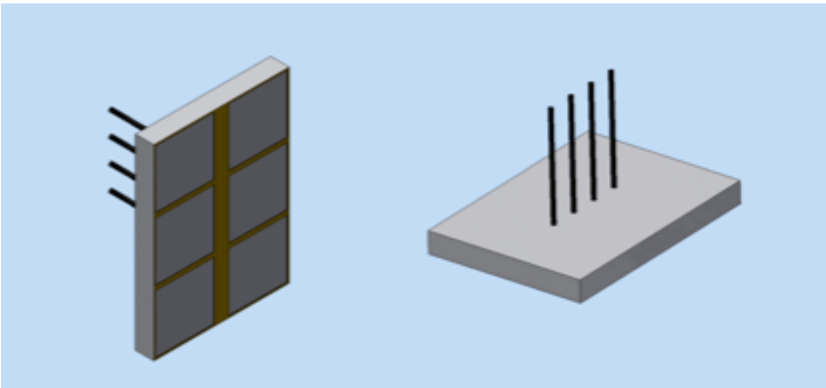


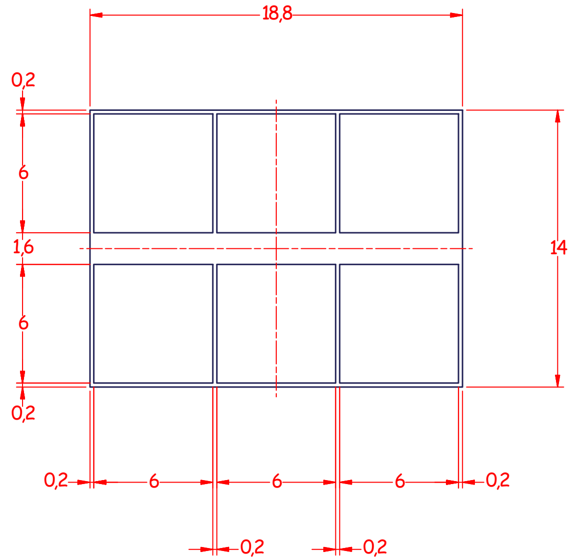


- Good energy (7%) and timing (110 ps) resolution
  Matching EMC requirements

Custom UV-extended SiPM array

- We have chosen a modular SiPM layout that allows us to enlarge the active area, maximizing the number of collected photoelectrons.
- The crystal dimension, increased from 30x30 to 34x34 mm^2, now accommodates a 2x3 array of individual 6x6 mm^2 SiPM modules
- This allows us to work with an air-gap while satisfying the p.e./MeV requirement with a single SIPM → **2 SIPMs/crystal are used for redundancy**
- The SiPM will be made of a 2x3 matrix (6 cells) of 6x6 mm^2 UV extended SiPMs
- We use a parallel arrangement of two groups of three cells biased in series

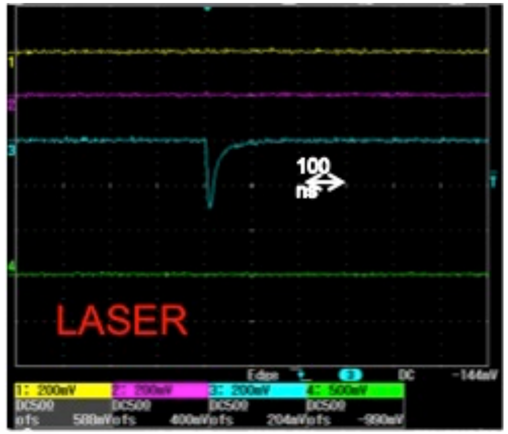


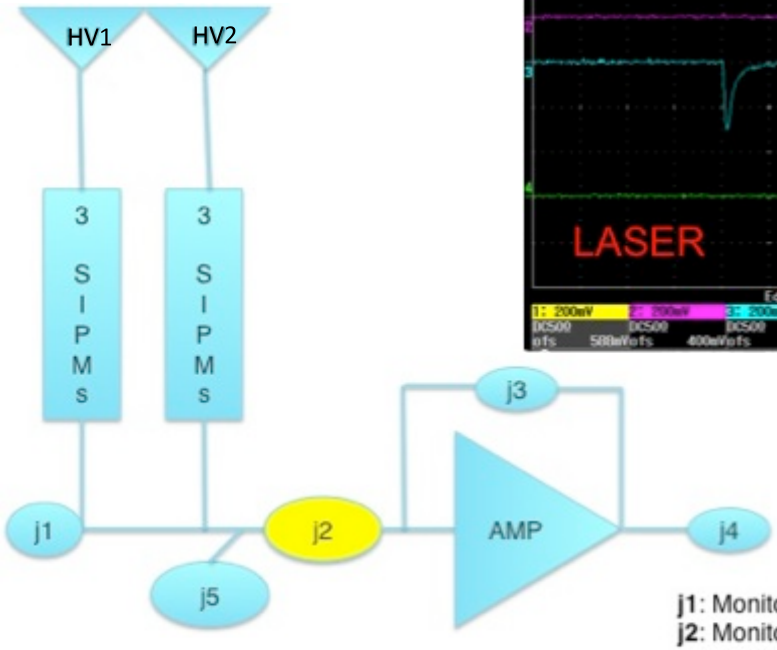


Custom UV-extended SiPM array

We have procured 7 monolithic MPPCs of 6x6 mm² dimensions:

- **→ 6 of them have been used to build a 2x3 array with our packaging, 1 for irradiation.**
- **→ UV extended by SPL technique**
- **→ TSV technique**





j1: Monitoring of the temperature
j2: Monitoring of the current
j3: Settable Gains
j4: Differential output
j5: Pulse Signal

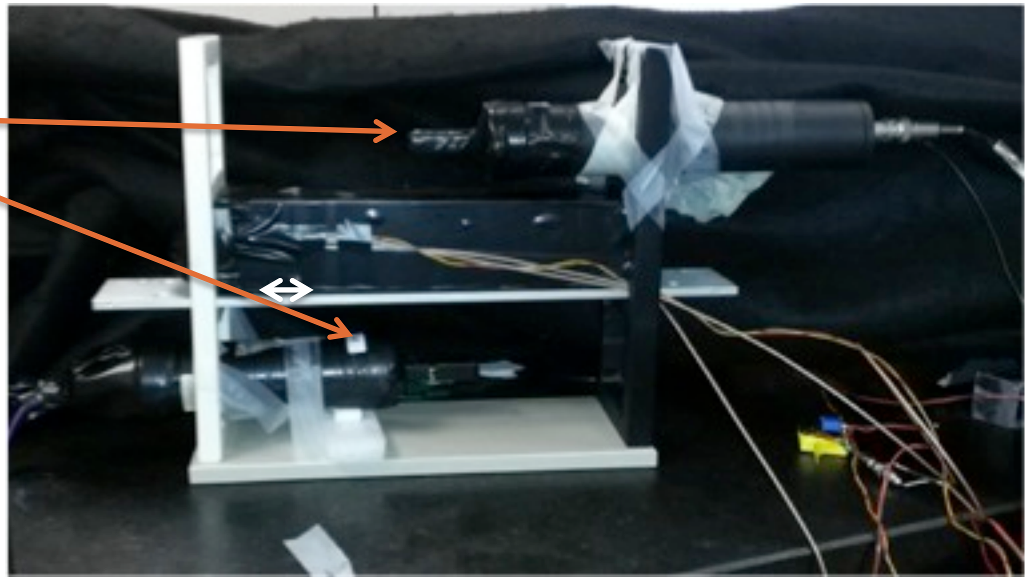
Specifications:

- PDE ~ 30% @ 315 nm;
- Gain > 10^6 at $V_{op} = V_{br} + 3V$
- the series connection of the three 6x6 mm^2 SiPMs should produce a signal width of about 70 ns (τ_r ~ 15 ns) to minimize pileup

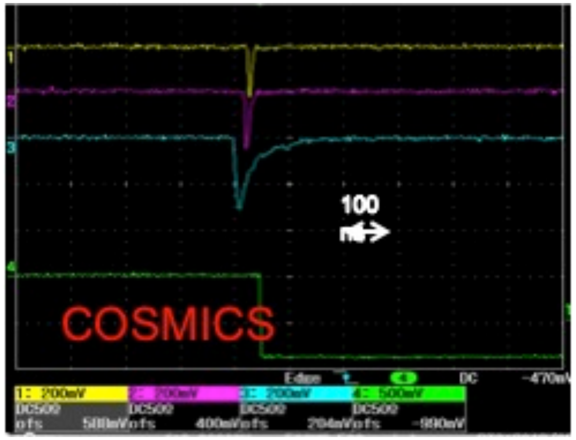
Cosmic test of CsI+2x3 array

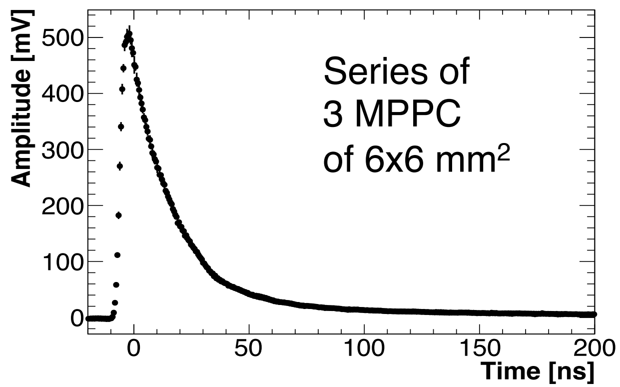
Crystal+ custom SiPM array between two plastic scintillation finger counters:

- TRG: counters coincidence
- Crystal wrapped with 150 μm Tyvek + coupled with an air-gap to the 2x3 SiPM array



- ❖ Trigger Resolution ($\Delta t\_fingers$) = 255 ps
- ❖ Final resolution for 1 MIP (~20 MeV) → ~ 170 ps

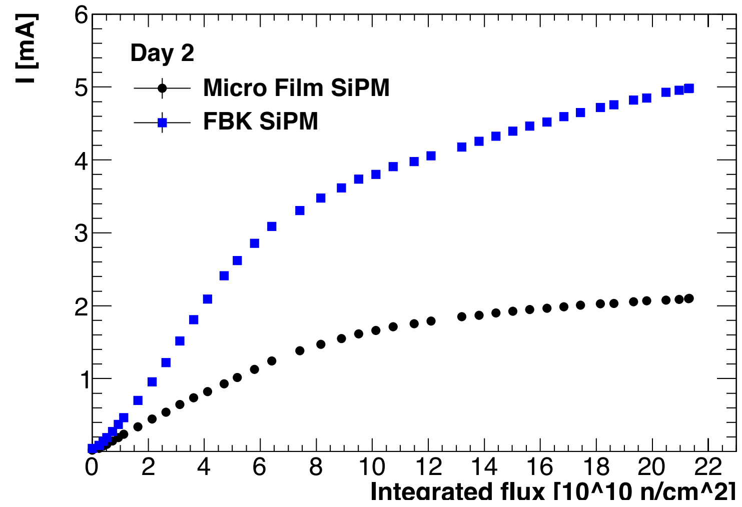




SiPM irradiation

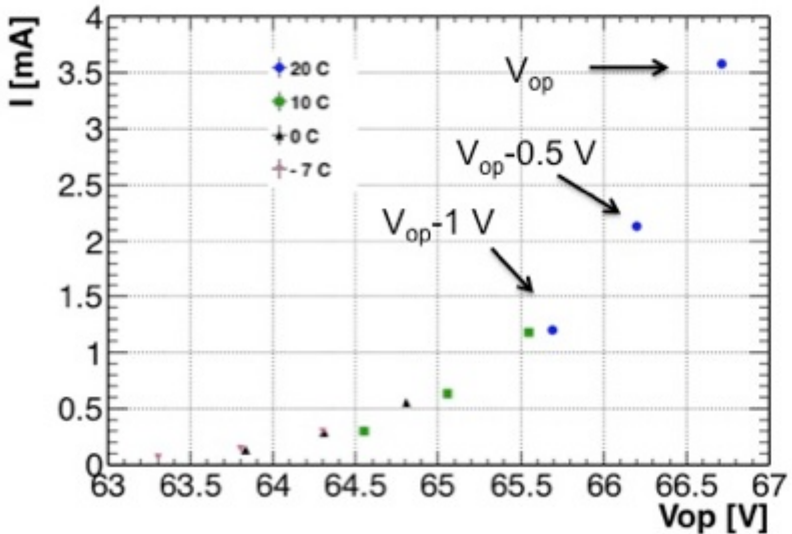
SiPM irradiated at ENEA Casaccia with 20krad ^{60}Co photon source producing negligible effect on the response and on leakage current

- Neutron irradiation tested at ENEA Frascati (FNG) with 14 MeV neutrons.
- Total flux 2.2×10^{11} n/cm^2 (2.2 times the experiment lifetime)
- Test Hamamatsu 3x3 mm^2 and FBK 6x6 mm^2 SiPMs
- Leakage current increases to too high values asking for cooling at lower temperatures the sensors.



By measuring the dependence of the leakage current as a function of temperature, we observe a factor of 10 reduction in Idark when working at T = 0 °C that is acceptable.

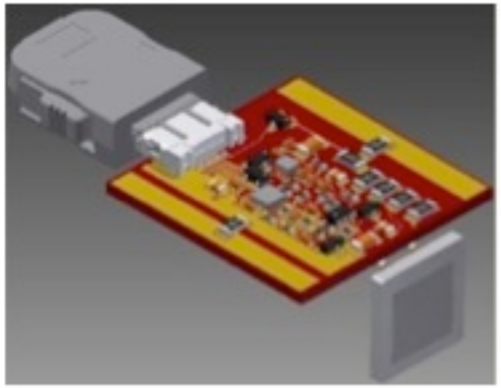
So, we require to cool down all SIPM to a running temperature of ~ 0 °C.

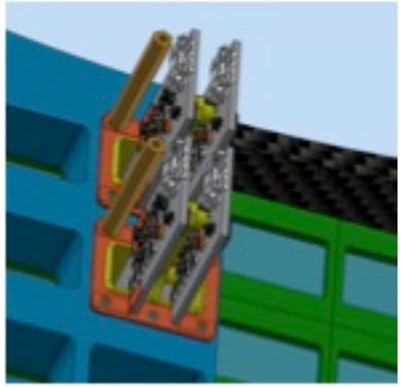


FEE and WFD

Dedicated board on each SiPM for:

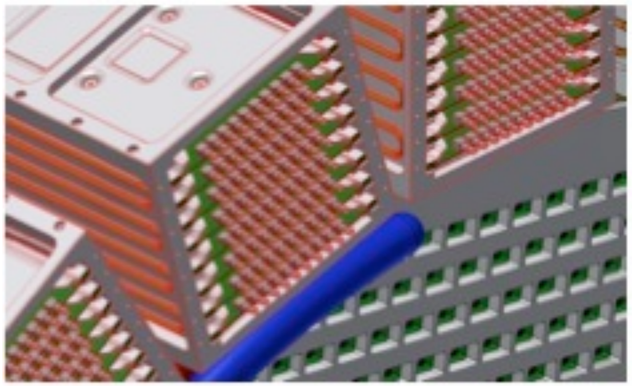
- Amplification stage (x15, x30)
- Linear regulation of bias
- Rise time 15 ns
- Dynamic range 2V
- Monitoring of the current
- Pulse signal for testing
- Therma-Bridge to dissipate heat

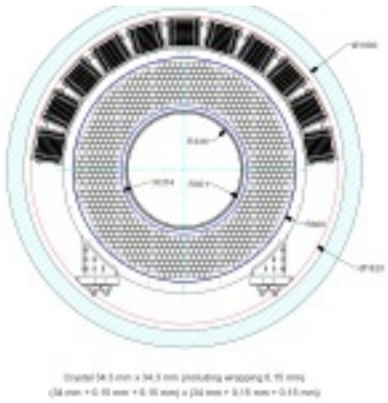




11 crate per disk with 20 differential channels boards:

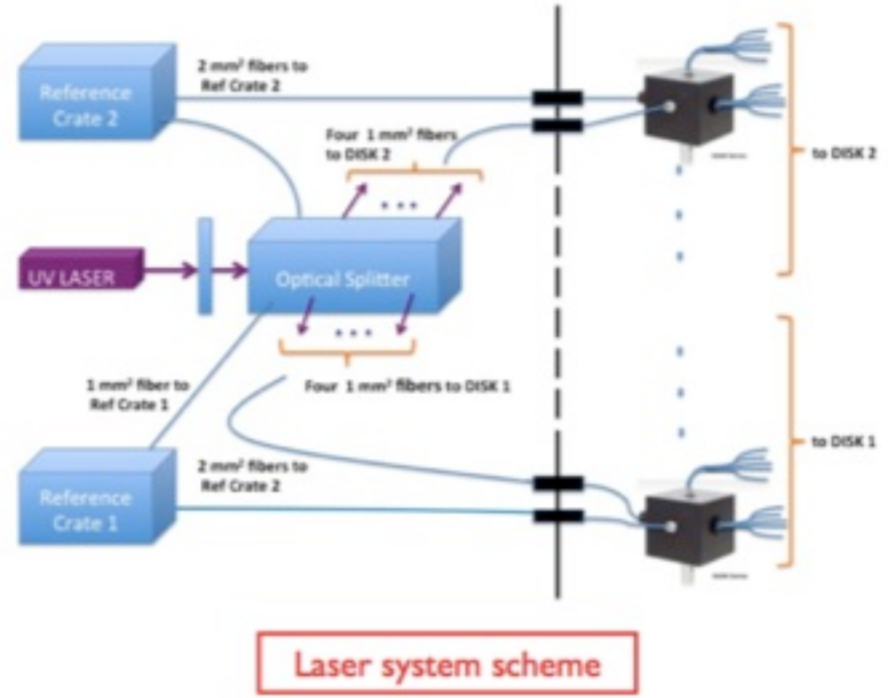
- HV regulator
- WD boards with:
- Smartfusion II FPGA
- 200 Msps-12 bit ADC
- DCDC converter
- Optical connection

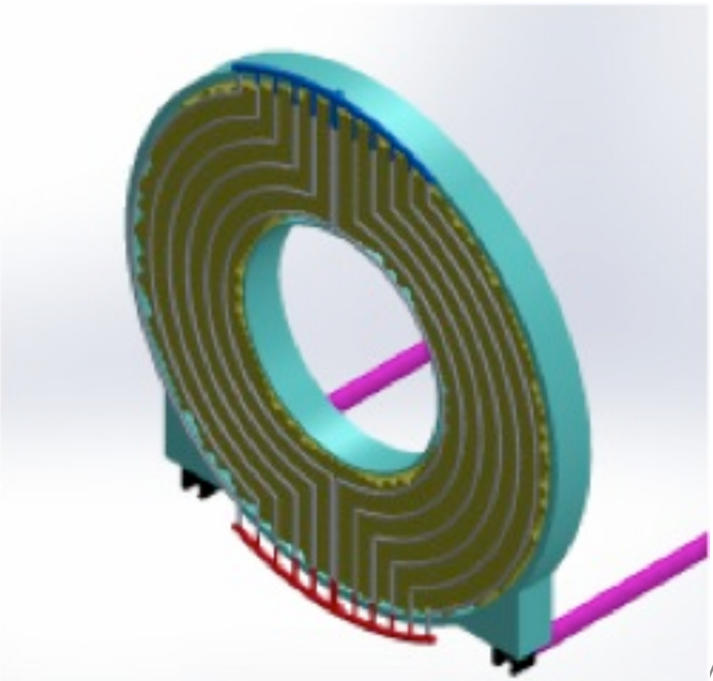




Calorimeter calibration

- **Pre-insertion calibration with 6 MeV source**
- **Weekly crystal-by-crystal calibration with 6 MeV source**
- **Monitor readout on shorter time scale with Laser system**
- **Monitor electronics gains with pulser**
- **Monitor temperatures**



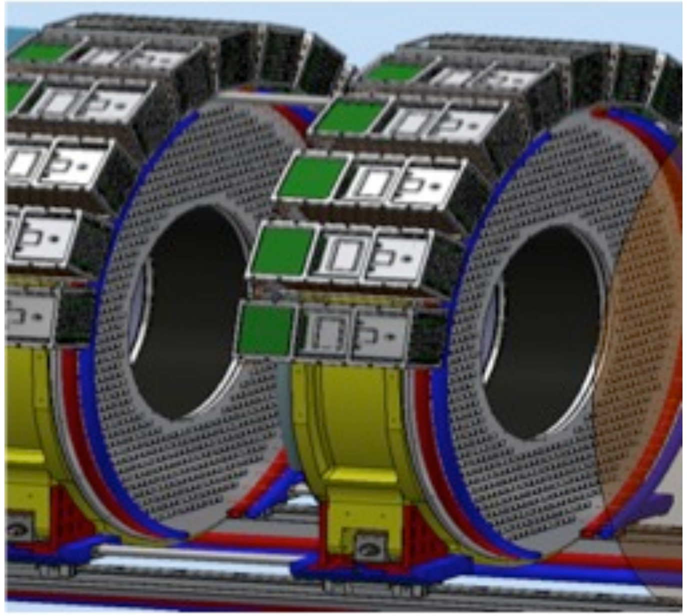


6 MeV gamma source:
Low energy neutron from DT generator irradiate Fluorinert fluid outside detector

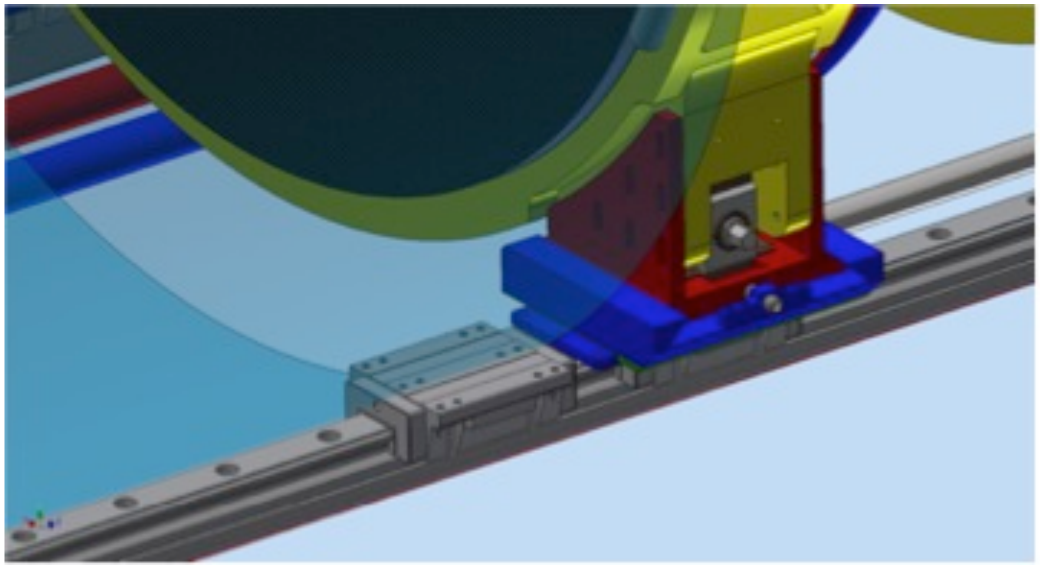
$$^{19}F + n \rightarrow \ ^{16}N + \alpha$$
$$^{16}N \rightarrow \ ^{16}O^{*} + \beta \quad t_{1/2} = 7\ \mathrm{s}$$
$$^{16}O^{*} \rightarrow \ ^{16}O + \gamma(6.13\ \mathrm{MeV})$$

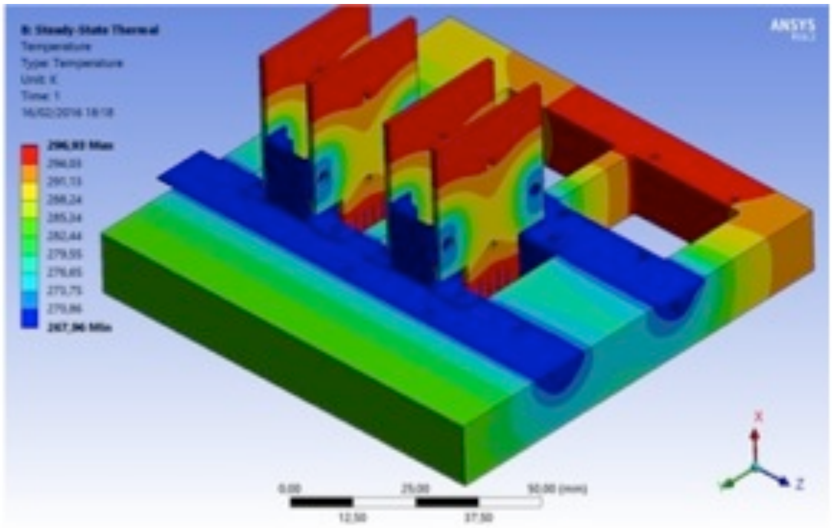
DT generator: d+t→ n(14.2 MeV): 10^9 n/s

Mechanical structure



- Square crystals stacked from the bottom for increasing rows in an external stainless steel cylinder
- Inner cylinder in composite material
- FEA completed, good stability of the system, small stress on legs
- Readout back plate will be used for positioning FEE and cooling them to low temperature.
- Front face is being integrated with Source Tubing
- FEE crates will be connected to the external cylinder
- Full Size mockup is underway





Summary and plans

- Mu2e goal: improve of 4 order of magnitude the sensitivity w.r.t. previous Conversion experiment
- **EMC Baseline consists of two disks with 674 34x34x200 mm^3 un-doped CsI crystals each readout by custom UV extended 2x3 6x6 mm^2 SIPMs each**
- Results from Test beam and irradiation program with ionization dose and neutron show that this solution fulfills requirements both for timing and energy resolution
- We expect to complete construction in the middle of 2019 and complete installation in the DS beginning of 2020.