H2020-MSCA-RISE-2015 — Grant Agreement N° 690835

Highlights of the MU2E Calorimeter

S.Miscetti (INFN-LNF) Frascati

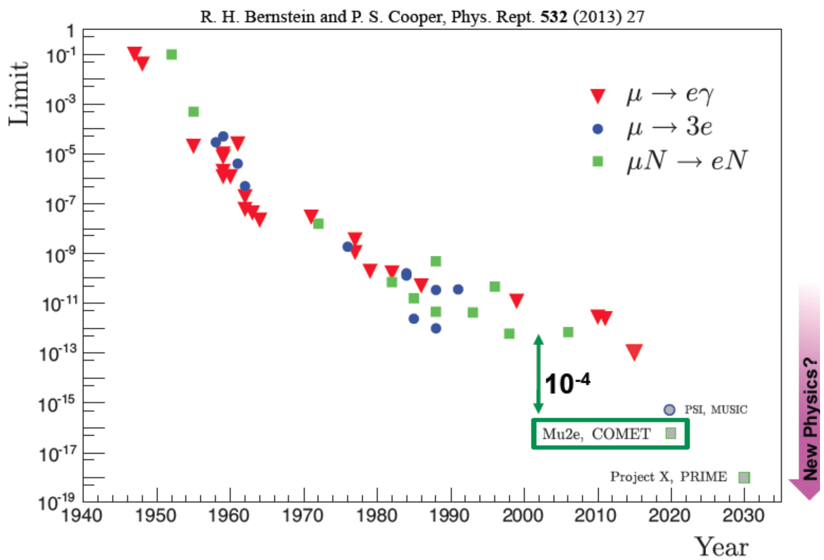
MUSE Mid Term Meeting
Frascati - 11-May-2017

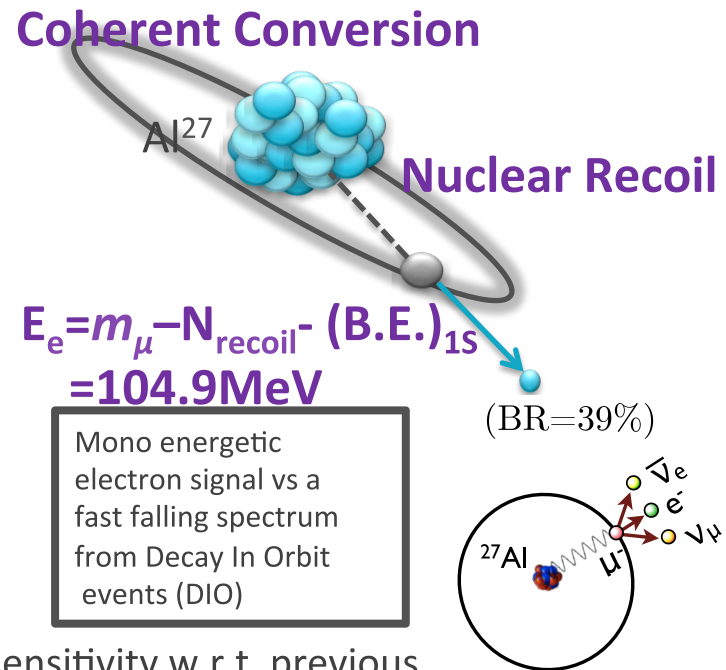
Talk Layout

- Overview of the Mu2e experiment
- Overview of the Mu2e calorimeter system
- Mu2e calorimeter inside MUSE project
- Calorimeter Simulation
- Calorimeter Design Status
- Status of pre-production
- Status of irradiation
- Status of Calibration
- Module-0 and Mockup
- Preparation for production

The Mu2e experiment: physics goal

- 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)

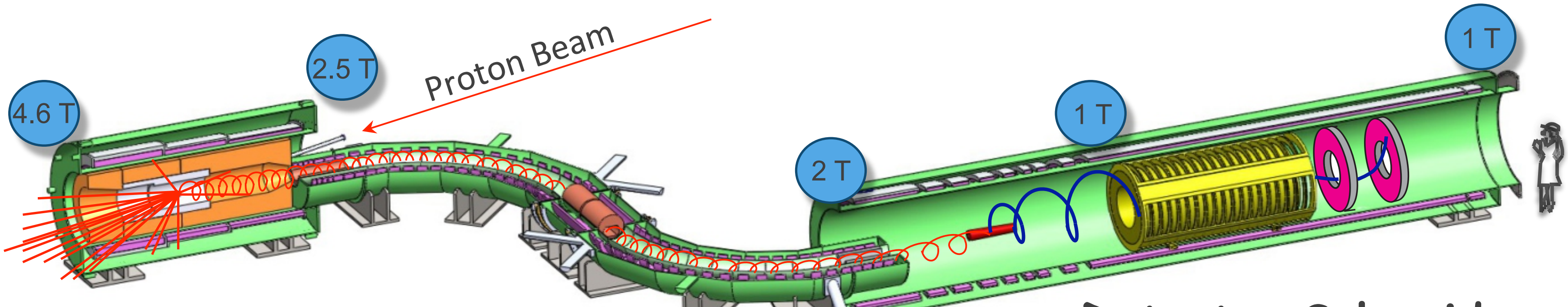
Mu2e goal: improve of 4 order of magnitude the sensitivity w.r.t. previous Conversion experiment (Sindrum-II)

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

The Mu2e experiment: detector and simulation

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



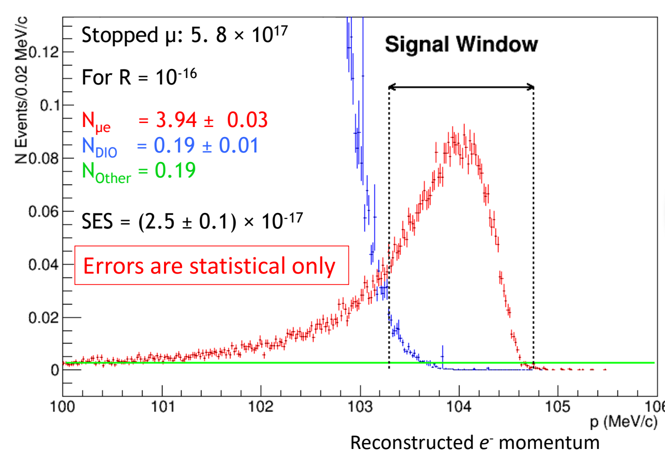
Transport Solenoid (TS)

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

Detector Solenoid

- Capture muons on Al target, Measure momentum in tracker and energy/time in calorimeter
- Cosmic Ray Veto detector surrounds the solenoid

For the sensitivity goal →
~ 6 x 10^{17} stopped muons
in 3 years run (6 x 10^7 sec)
→ 10^{10} stopped muon/sec



For Susy BR=10^{-15}
→ signal of 40 events
with bkg < 0.4

Mu2e Calorimeter Requirements

The Mu2e 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 a high radiation environment (100 krad, 10^{12} n/cm^2)**
- **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 Conversion Electron @ 100 MeV**

→ Redundancy in FEE and photo-sensors

Solution: A crystal based disk calorimeter

The Mu2e calorimeter basic design

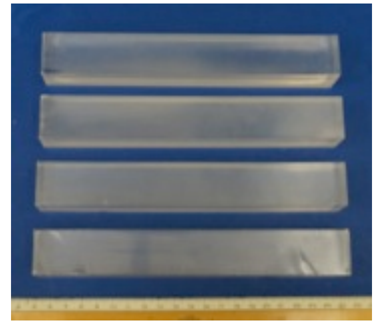
The Mu2e Calorimeter is a state of the art detector consisting of two disks with 674 34x34x200 mm^3 CsI square crystals:

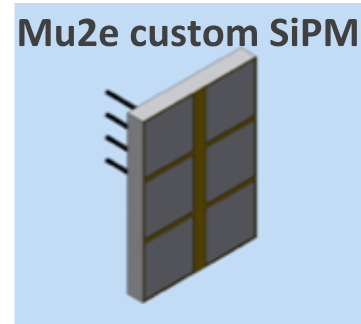
→ R_{inner} = 374 mm, R_{outer}=660 mm, depth = 10 X_0 (200 mm)

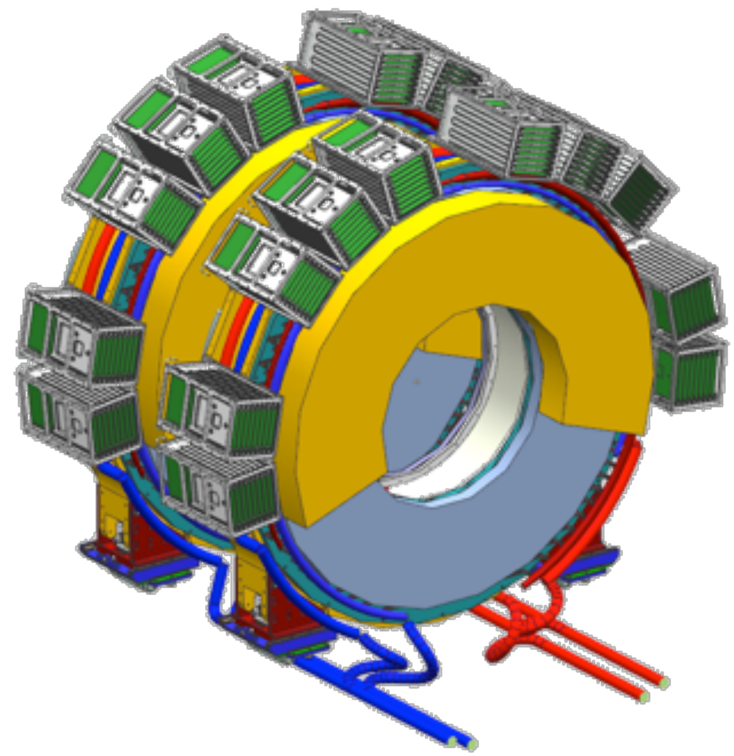
→ Each crystal is readout by two large area UV extended SIPM's (14x20 mm^2)

→ 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







The Calorimeter Team

Calorimeter
L2: S. Miscetti (LNF)
Deputy: D. Hitlin (Caltech)

475.7.1 Project Management
L3 – S. Miscetti – (LNF)

475.7.2 Crystals
L3 – D. Hitlin (Caltech)
S.Giovannella (LNF)

475.7.3 Mechanics
L3 – F. Happacher (LNF), F.Raffaelli (Pisa)

475.7.4 Photosensors
L3 –D.Hitlin (Caltech)**, I. Sarra (LNF)**

475.7.5 FEE and Digitizer
L3 – F. Spinella (Pisa)

475.7.6 Calibration
L3 – F. Porter (Caltech),
M.Cordelli (LNF)

475.7.7 Power
L3 – G. Corradi (LNF)

475.7.8 Assembly and Installation
L3 – **A.Saputi (LNF)**

- **Simulation**: B.Echenard(Caltech), **G.Pezzullo(Pisa), Calibration:** P.Murat(FNAL)
- **Trigger:** B.Echenard(Caltech), **S.DiFalco(Pisa)**

- Large International team: INFN → 25 FTE, Caltech → 8 FTE, JINR → 6 FTE, HZDR → 2 FTE
  - DOE/INFN/JINR share most of the core costs
  - INFN (Italy) provides in-kind: electronics, mechanics, laser.
  - HZDR (Germany) provides simulation/facilities for radiation tests
  - Caltech is fully responsible for the calibration source

Mu2e group composition in MUSE

2 PhD students, 4 post-docs, 2 young Researchers, 8 staff Researcher/Professor, 4 techs

The Mu2e calorimeter in MUSE

The Mu2e calorimeter or pieces of it appear in 3 WPs in MUSE:

→ WP 2 : the Mu2e Calorimeter together with HPGE that is the 2nd relevant European contribution from UK

→ WP 3: Calibration systems together with g-2 Laser system

→ WP 4: Software: together with g-2 software (ART-framework)

I will "transversely report" on calorimeter but concentrate mostly on WP-2 while providing you an overview of the system and describing the related deliverables (done and in progress):

→ **D2.1 (Technical Design Report) Month 12**

→ D3.3 (Design of the Mu2e Laser system) Month 18

→ D4.2 (Development of Mu2e simulation code) Month 32

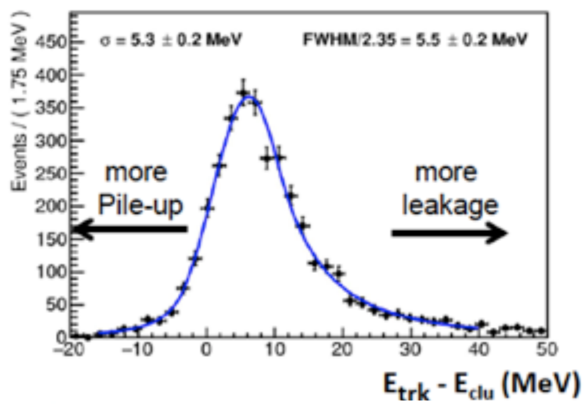
→ D2.2 (Production DB for crystals and sensors) Month 36

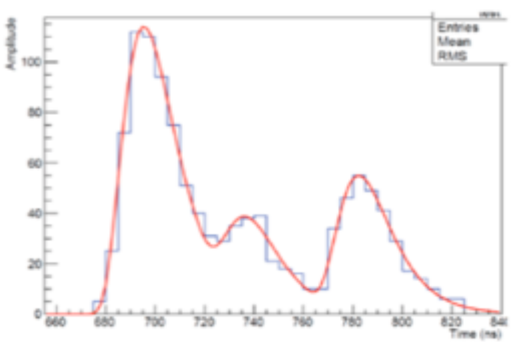
→ D2.5 (Assembly of the first calorimeter disk) Month 42

Calorimeter Simulation

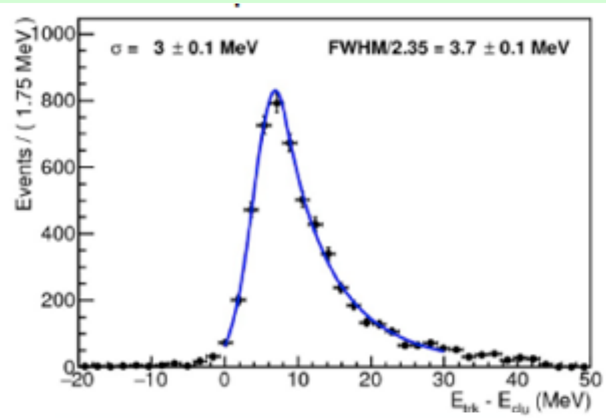
- Calorimeter simulation greatly improved during last year to include realistic shapes for the signals thus proving that our requirements can be met.
- Now continuing the refinement of this work by: simulating the mechanical structure, tuning the reconstruction codeand improving shielding for radiation.

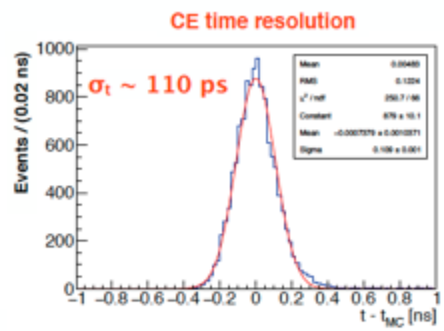
@ CD-3, crude hits digitization





Today: with realistic hits digitization





More details on dedicated MUSE SW talk

Reviews 2016-2017 and .... where are we now?

- Design Review → Feb 2016
- Director review for CD3-C → April 2016
- CD3c → June 2016 → **CD3c approval , July 2016**
- **INFN/Fermilab signature of Statement of Work → Oct 2016**
- Final Design Report: December 2016
- **Mechanical review: March 2017**

- Pre-production started after CD3c
- Now proceeding with Module-0/Mockup
- Upcoming reviews for Construction Readiness (CRR) under planning (2017/2018) → start of production
- INFN/HZDR participation to meetings and reviews increased thanks to MUSE

Calorimeter: Design Status @ May 17

Calorimeter Subsystem	Design Completion	Remaining Work/Risks
Crystals	**100%**	**CsI slow component specified.** Pre-production done. Irradiations done.
Photosensors	**100%**	**SiPM packaging.** Have three qualified SiPM vendors. Pre-production done. Irradiation studies to be continued.
Mechanical Infrastructure	**90%**	**Cooling design being finalized.** Optimizing tradeoffs between noise, radiation damage and operating temperature. x2 headroom
Front End Electronics And Digitizer (WFD)	**90%**	• **PreFEE for CsI/SiPM** done • WFD board design with 20 channels done. Pre-poduction in progress. • Irradiation studies to be completed.
Calibration	90%	Integration of source pipe in progress. Laser optics being finalized.
Overall Design	**94%**	

Prepare for CRR now (Crystals, Photosensors)

CRR @ 2018 (Mechanical Infrastructure, Front End Electronics And Digitizer, Calibration)

Deliverable 2.1: FTDR

- ✓ First deliverable of WP-2 done in time at the end of December.
- ✓ It is a complete Technical Design Report of 128 pages incorporating all final design features of the calorimeter system.
- ✓ It is both a public Mu2e Document (DOCDB # 8429) and a public MUSE document.

Mu2e-doc-8429, December 2016

The Mu2e Calorimeter Final Technical Design Report

N.Atanov[a], V. Baranov[a], J. Budagov[a], S.Ceravolo[b], F. Cervelli[e], F. Colao[b], M. Cordelli [b], G. Corradi[b], E. Dané[b], Yu.I. Davydov[a], S. Di Falco[e;g], S. Donati[e;g], E. Diociaiuti[b;j], R. Donghia[b;k], B. Echenard[c], K. Flood[c], S. Giovannella[b], V. Glagolev[a], F. Grancagnolo[l], F. Happacher[b], D.G. Hitlin[c], M. Martini[b;d], S. Miscetti[b], T. Miyashita[c], L. Morescalchi[e;f], P. Murat[h], D. Pasciuto[e], G. Pezzullo[e], F. Porter [c], T. Radicioni[e] , F. Raffaelli[e], M. Ricci[b;d], A. Saputi[b], I. Sarra[b], F.Spinella[e], D. Tagnani[b;k],G. Tassielli[l], V. Tereshchenko[a], Z. Usubov[a], R.Y. Zhu[c]

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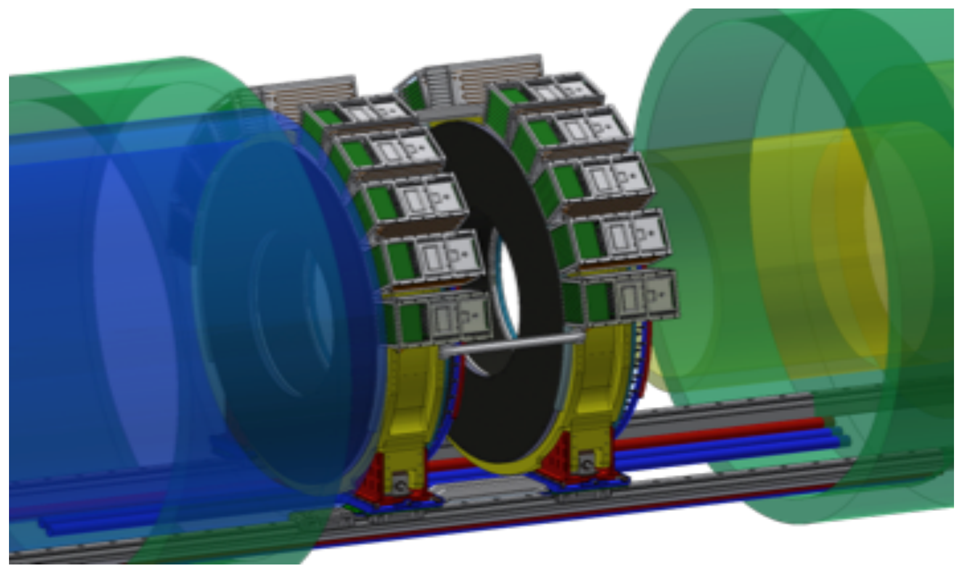
h Fermi National Laboratory, Batavia, Illinois, USA
i INFN Sezione di Lecce, Lecce, Italy
j Dipartimento di Fisica dell'Università di Roma Tor Vergata, Rome, Italy
k Dipartimento di Fisica dell'Università degli Studi Roma Tre, Rome, Italy



Pre-production status: crystals

- The 2 largest bids (3 and 1 M$) are the ones for Crystals and photosensors
- Same technique of "competitive bid" used for both bids:

  → **Use pre-production to rank the vendors**

  → **Final selection with 40% cost, 60% technical**

For crystals, **the international bid has been prepared @ FNAL:**

- 6 vendors participated St.Gobain, Siccas, Amcrys, OptoMaterial, Hilger, Khineng. **3 vendors selected for preproduction**

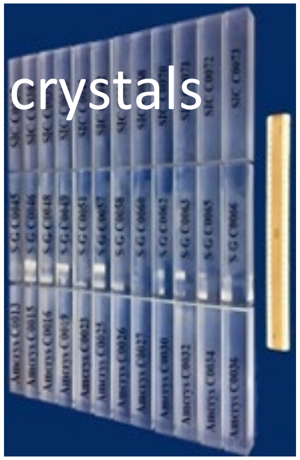
  St. Gobain, Siccas, Amcrys
- We have received 24 pieces/each for module-0 (Oct-Dec 20160
- We will receive additional 50 crystals from Amcrys as JINR (Dubna)

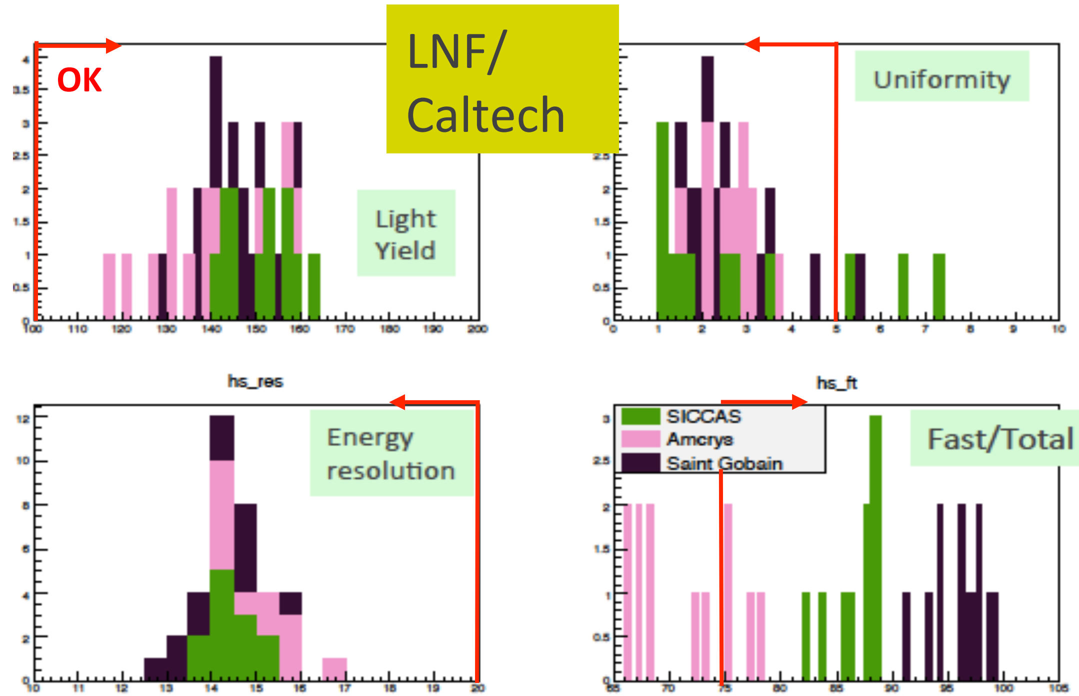
→ **Quality assurance performed on all pieces (see next page)**

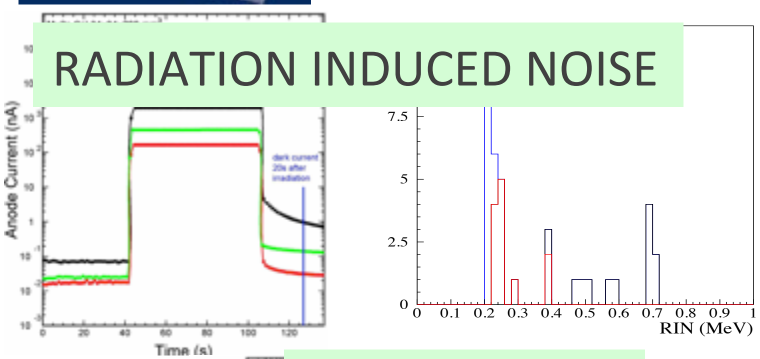
→ **Great contribution from PRISMA people for definition of QA procedures and first version of Hardware DataBase**

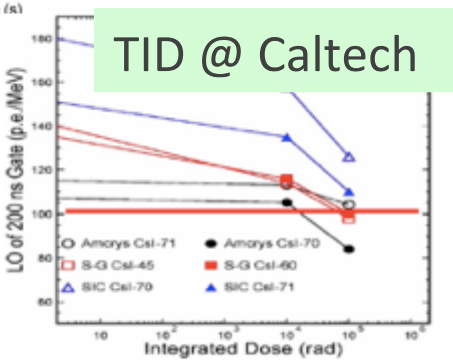
More details on MUSE ToK talk

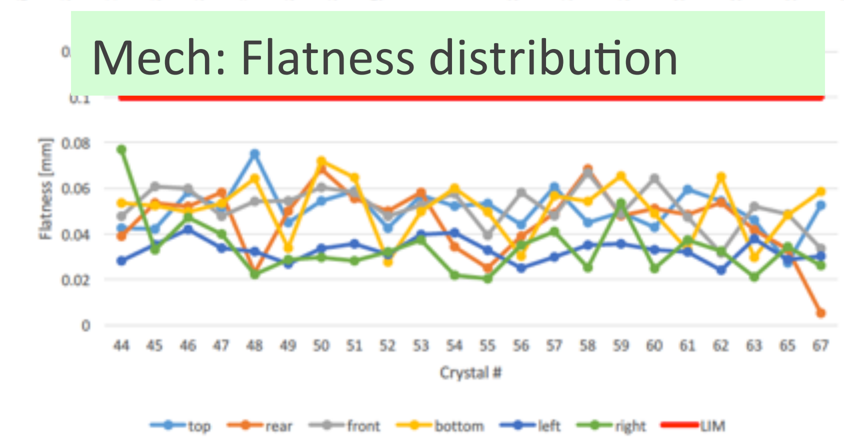
QA of crystals











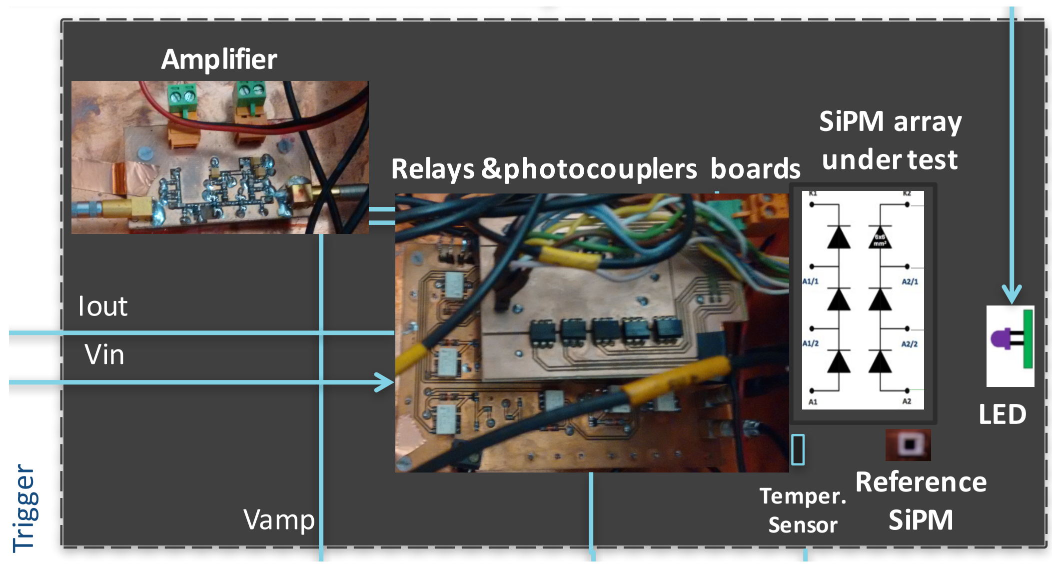
Pre-production status: sensors

For photosensors, the international bid has been prepared @ INFN:

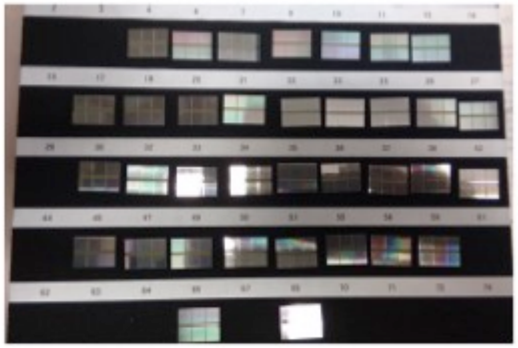
- 3 vendors participated
- **3 vendors selected for preproduction of the Custom Mu2e SIPM**

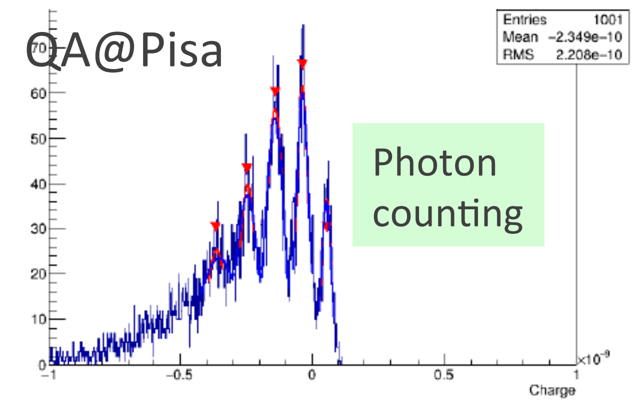
  Hamamatsu, SensL, Advansid. Each of them produced 50 prototypes
- Delivered on schedule in the middle of October
  - → We have spent > 4 months for the evaluation.
  - → 3 months of Quality Assurance in Pisa
  - → Longer time for Irradiation and MTTF

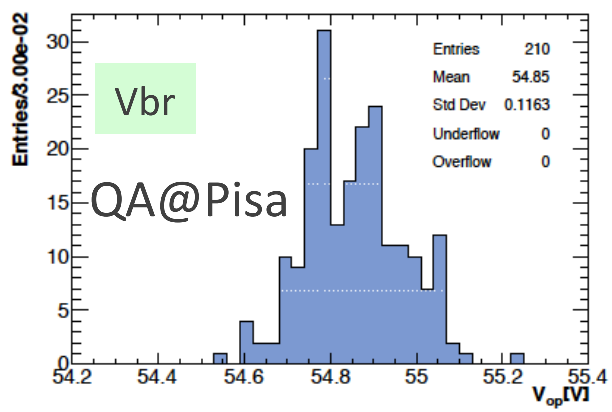
Pisa QA station got also the help of Prisma engineers for the design and assembly of the Relays board

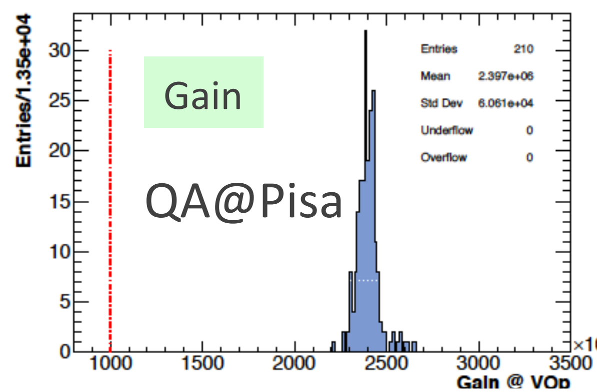


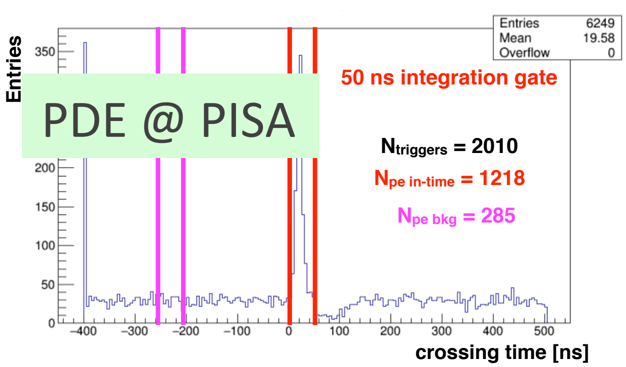
QA of Silicon Photomultipliers

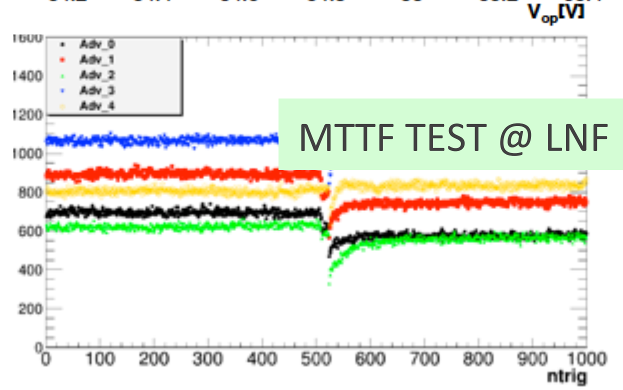


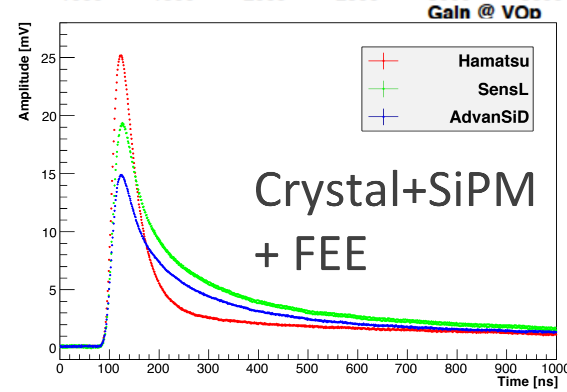










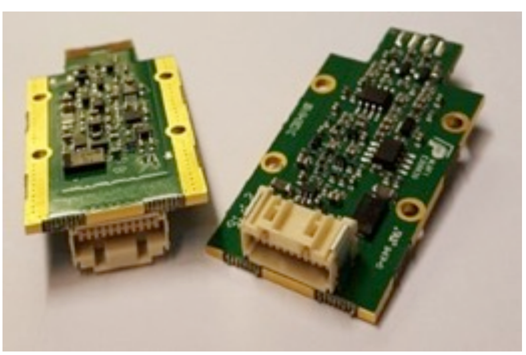


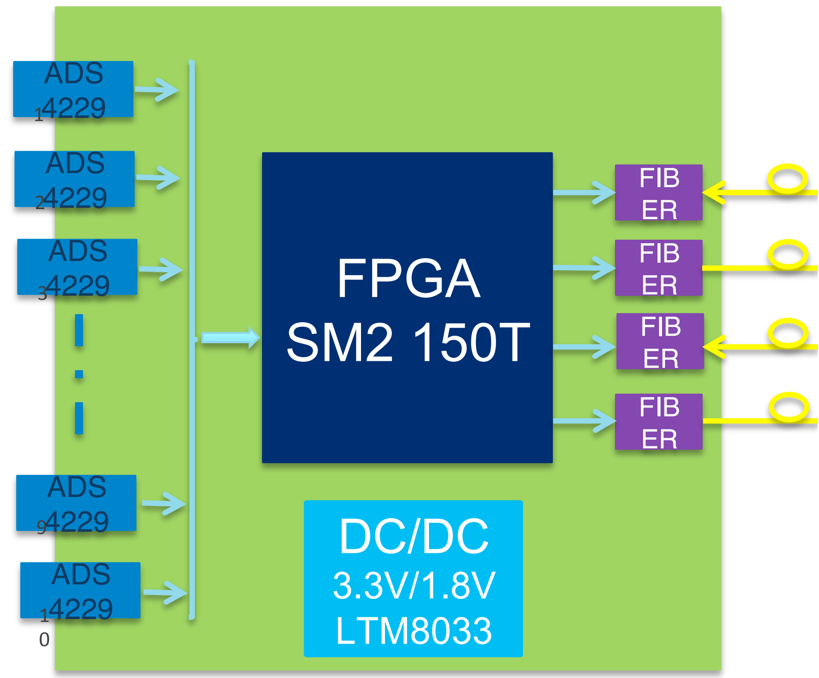
Pre-production status: FEE/WD

The electronics is composed of 3 parts:

1) The FEE chips closed to the sensors (amplification, HV regulation)
2) The Mezzanine Board (MB) to set/read HV , temperature and currents
3) The Waveform Digitizer (WD) board to digitize the signals at 200 Msps.

- ✓ 130 FEE pieces produced
- ✓ 5 MBs produced
- ✓ WD design completed.
- ✓ WD PCB in routing.
- ✓ 2 WD prototypes under construction
- ✓ Additional 5 WDs expected for the fall





Irradiation/simulation and implication for MUSE

- ❑ Crystals tested up to 100 krad, 10^{12} n @ 14 MeV, slow neutron hig[h]
- ❑ SIPMs tested up to 20 krad, $4x10^{11}$ n_1MeV eq/cm^2
- ❑ WD (FPGA OK) ADC+DCDC tested up to 20 krad, $6x10^{11}$ n_1 MeV eq/cm[…]

Safety factors of 3 used so far

Increased Safety factors ask for:

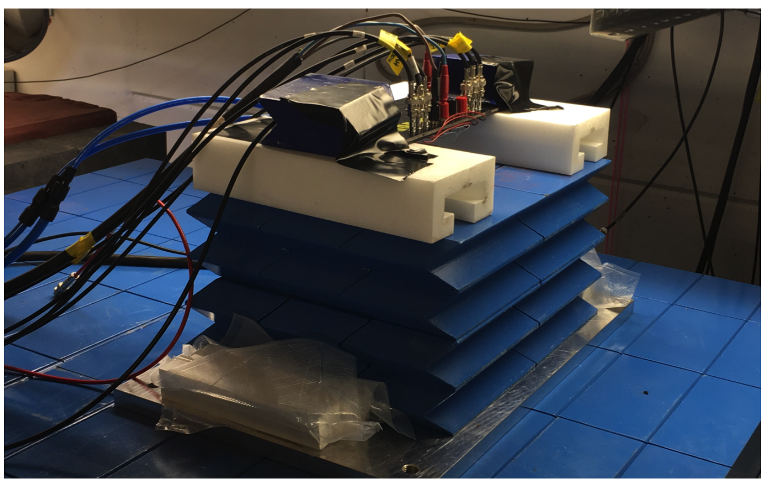
→ Testing SiPM/FEE up to 10^{12} n/cm^2 and FEE/MB/WD up to 90 krad

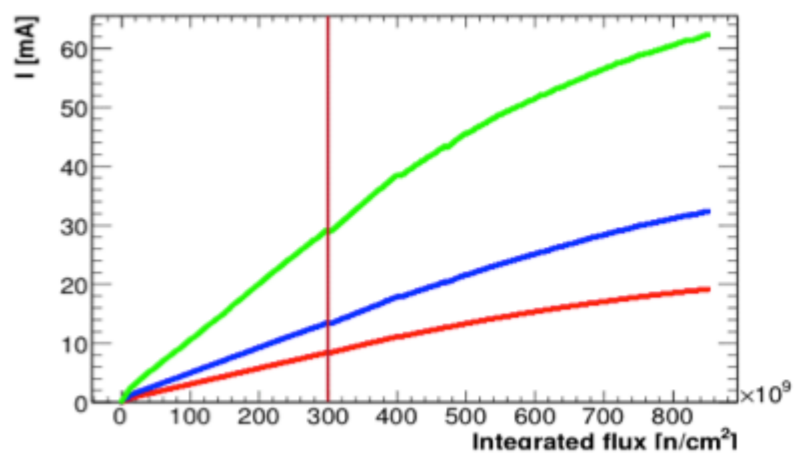
→ Improving shielding by means of a detailed simulation

→ Organizing a new irradiation campaign with neutrons and Dose

Great collaboration inside MUSE for usage of HZDR facility (P-ELBE) for neutron irradiation, (G-ELBE) for gamma irradiation

More details on MUSE Irradiation talk



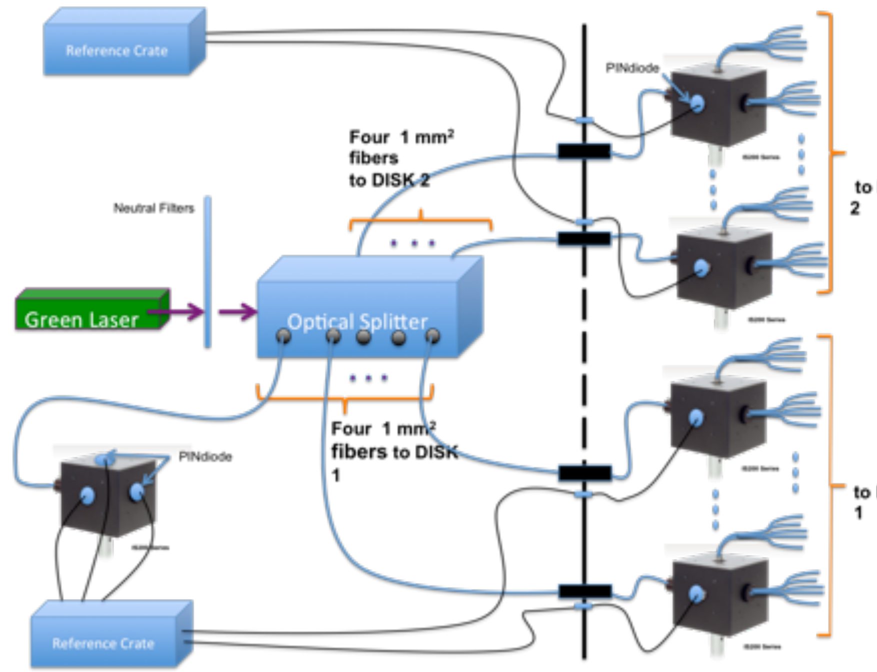


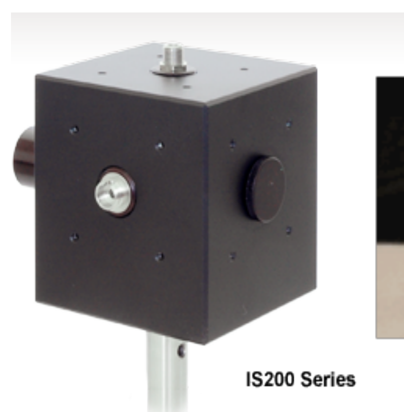
The Mu2e calorimeter calibration system

- The Laser calibration system has the goal to monitor the changes of the SiPM gain and of their resolution by distributing 315 nm Laser light to each sensor.

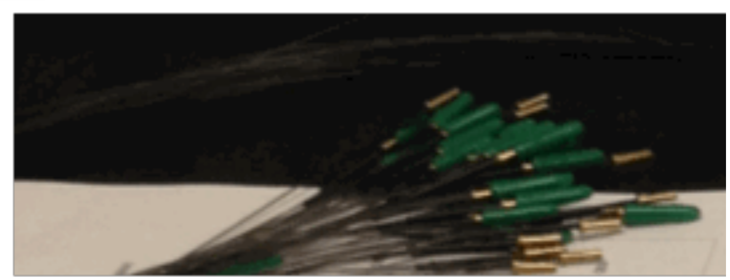
- The distribution system is based on optical lenses and diffusing sphere.

We have done few meetings with our g-2 MUSE colleagues to learn details and tricks used on their calibration system. **Good collaboration established on this.**

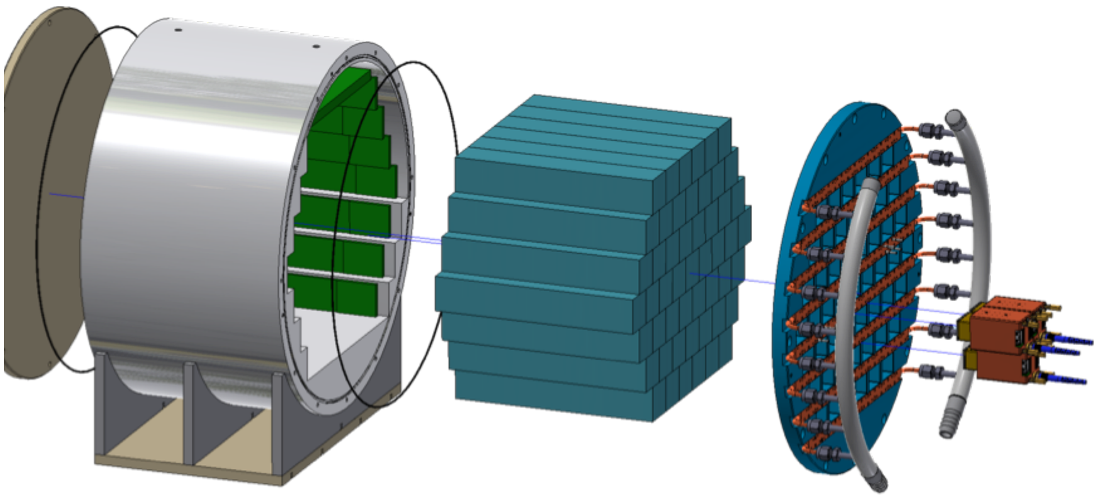




IS200 Series



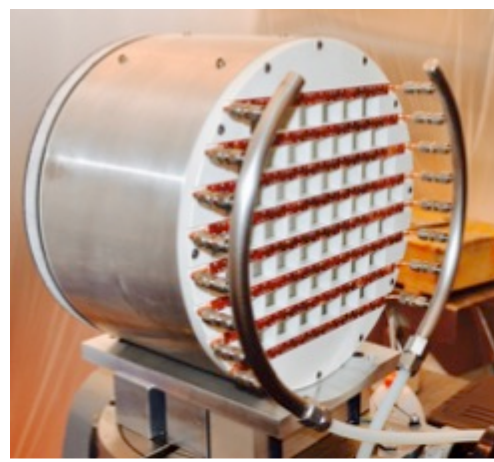
The Module-0 : from CAD to reality

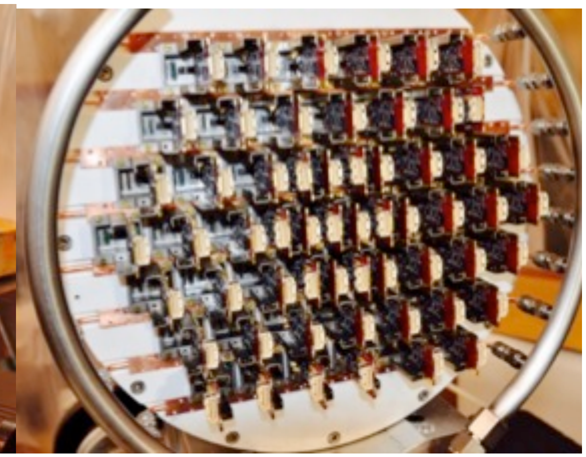


A large size prototype of the disk with final components.

- 51 crystals, 102 sensors,
- 102 FEE chips, cooling lines and readout.
- Completed 1 week ago

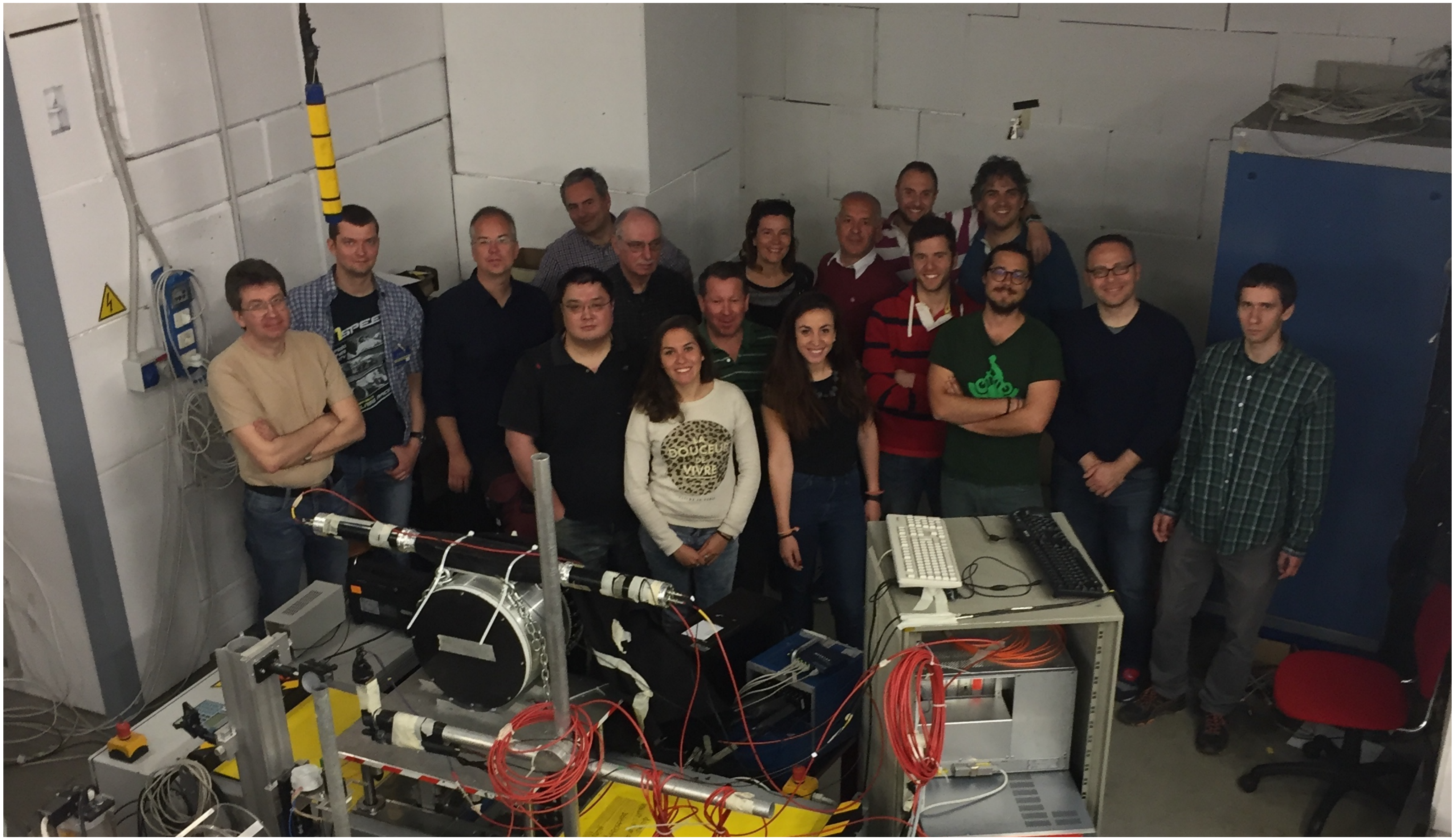
A great achievement!



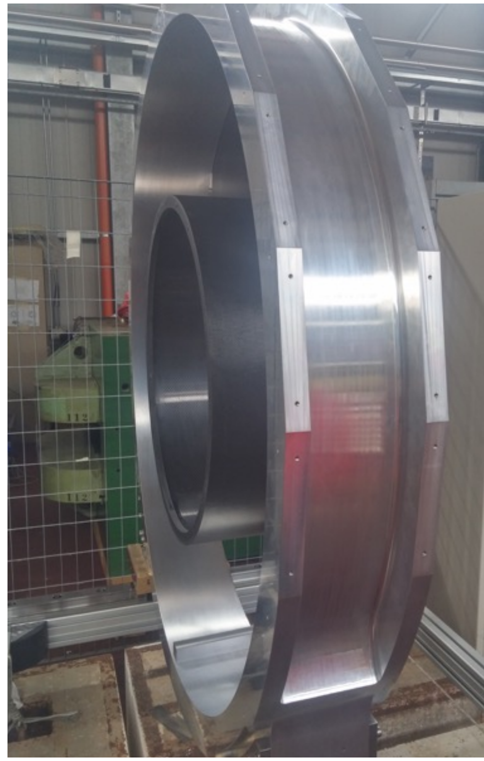


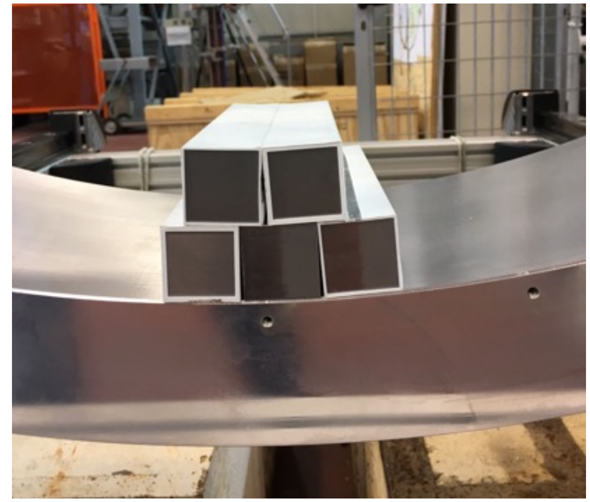
Test beam of Module-0

Last Friday, module- 0 has been transported to the area for an electron beam test @ LNF.
16 people (INFN, Caltech, JINR) are working on this test that is being carried out this week.



The calorimeter full size Mockup





- Mockup is standing on its feet
- CF rings mounted
- Crystal supports being prepared
- Fake crystals (700) being wrapped

Preparation for production/long term deliverables

- The conclusion of the **international bids for crystals/sensors will happen this summer** after their CRR planned for middle of June.

- **Production of crystals/sensors will start on the fall** with a delivery schedule of 1.5/1 year respectively. Tools for QA have been prepared and proved to work on pre-production → **Most of the final QA will be located @ FNAL.**

- For the disk assembly we had a successful Mechanical Design Review in March. Construction of Module-0 and completion of Mockup are the first steps to be completed before producing the final full-size pieces.
  → **Assembly area at FNAL is being prepared.**

→ D2.2 (Production DB for crystals and sensors) Month 36
→ D2.5 (Assembly of the first calorimeter disk) Month 42

Conclusions

- **The Mu2e calorimeter is a state of the art detector** that will provide a very important contribution to the identification and reconstruction of the Conversion electron candidates.

- **The calorimeter is progressing well and in schedule.**

- **The EU contribution to this system has been remarkable and has improved from beginning of 2016 thanks to MUSE network**:

  → Our presence is constantly increased
  → The network between Research Institutions works well for irradiation, simulation and calibration
  → The collaboration with our SME partners is proceeding well
  → We are on schedule and on-budget for MUSE deliverables.
  One completed. One being completed. Two in progress. One still long term.

Calorimeter "Sketched" schedule