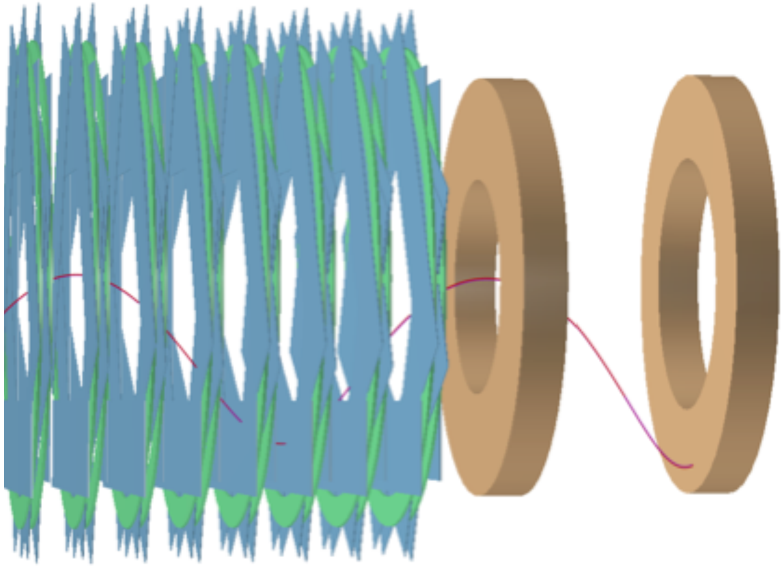
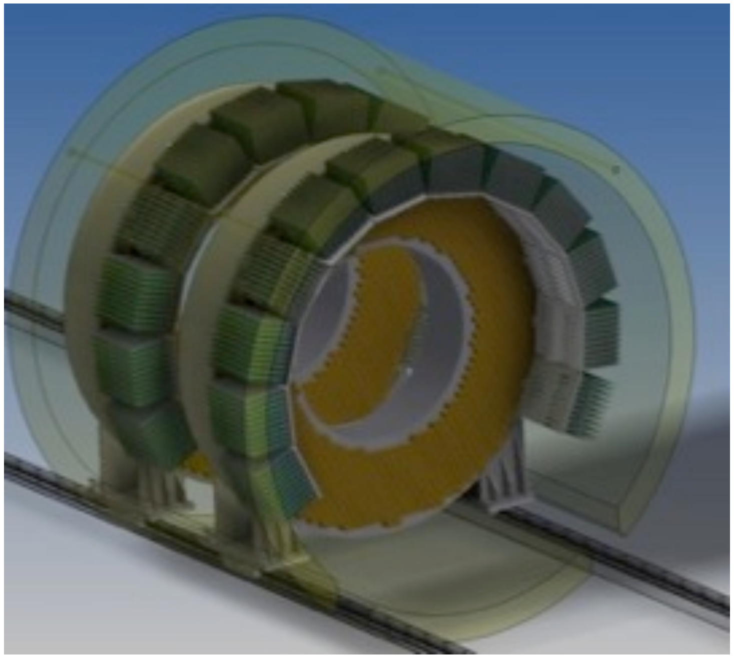
The Mu2e Calorimeter





Stefano Miscetti
Laboratori Nazionali di Frascati
of INFN, Frascati, Italy
on behalf of the MU2E calorimeter group

Frontier Detector for Frontier Physics
13th Pisa Meeting on Advanced Detectors
La Biodola, Isola D'Elba (Italy)
25-29 May 2015

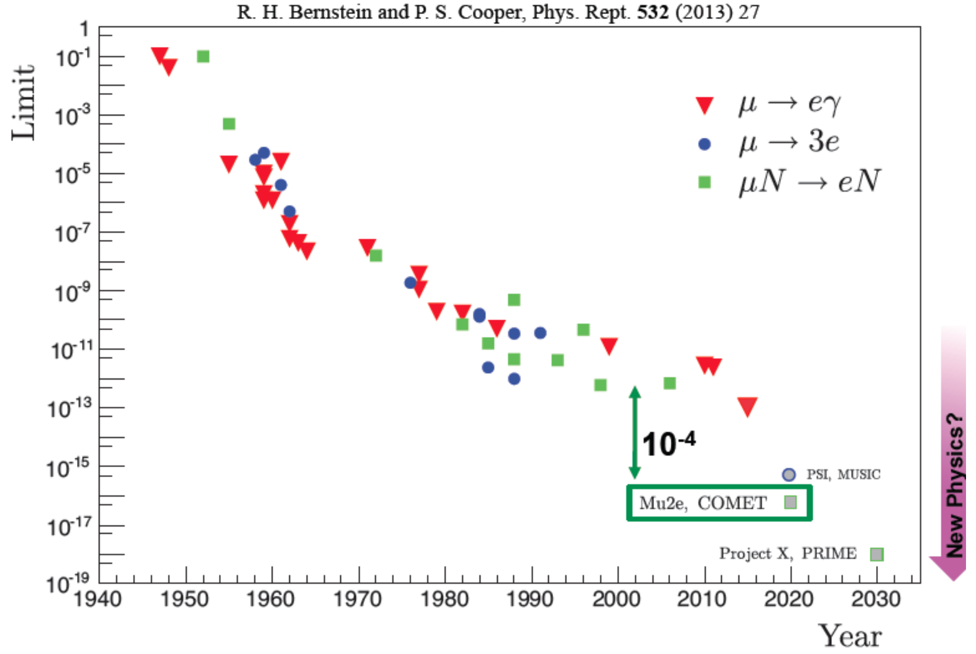
Outline

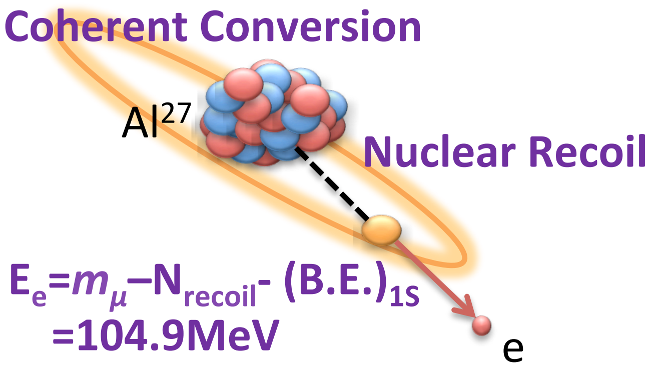
- The MU2E experiment
- Calorimeter Requirements
- Calorimeter Design
  - → Crystal choices and LYSO Legacy
  - → BaF_2 crystal measurements
  - → Solar Blind Photosensors
  - → Calibration System
  - → Mechanics and Electronics
- Tests of backup solution
- **Summary and Plans**

The MU2E experiment (1)

- 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

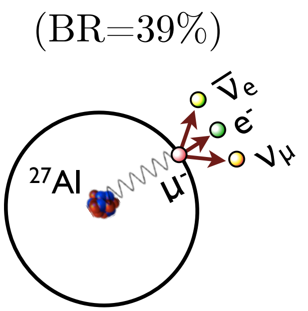
R. H. Bernstein and P. S. Cooper, Phys. Rept. **532** (2013) 27





$E_e = m_\mu - N_{recoil} - (B.E.)_{1S}$
$= 104.9 MeV$

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



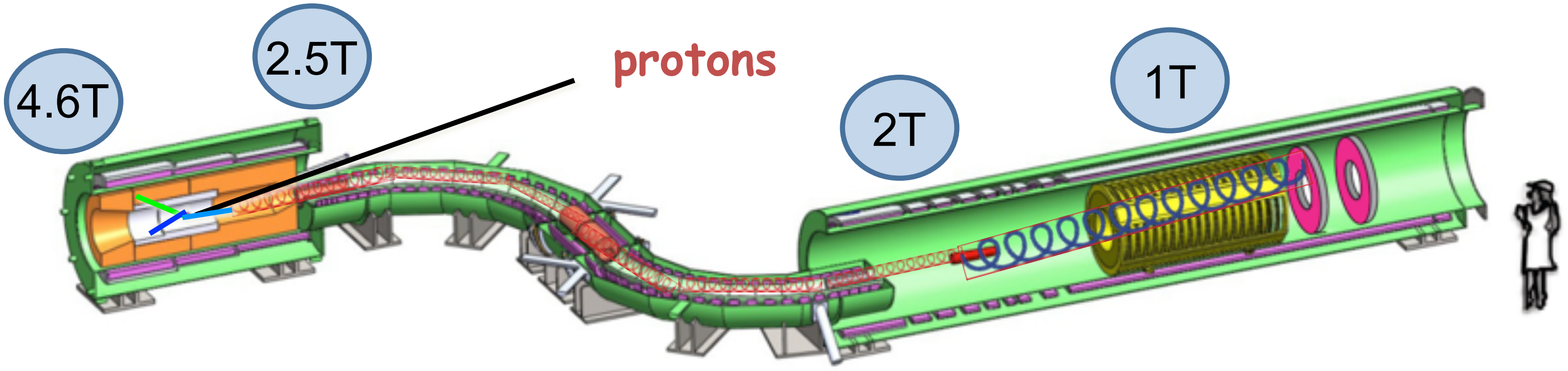
Mu2e goal: improve of 4 order of magnitude the sensitivity w.r.t. previous Conversion experiment (Sindrum-II)

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

The MU2E experiment (2)

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

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

Target, Detector and Solenoid (DS)

- Capture muons on Al target
- Measure momentum in tracker and energy/time in calorimeter
- Cosmic Ray Veto detector surrounds the solenoid to make CR contribution negligible

Calorimeter system: requirements/layout

Calorimeter requirements:

→ Particle Identification to distinguish e/mu
→ Seed for track pattern recognition
→ Tracking independent trigger
→ Work in 1 T field and 10^{-4} Torr vacuum
→ RadHard up to 30 krad, 10^{12} n/cm^2/year

Calorimeter choice:

High granularity crystal based calorimeter with:

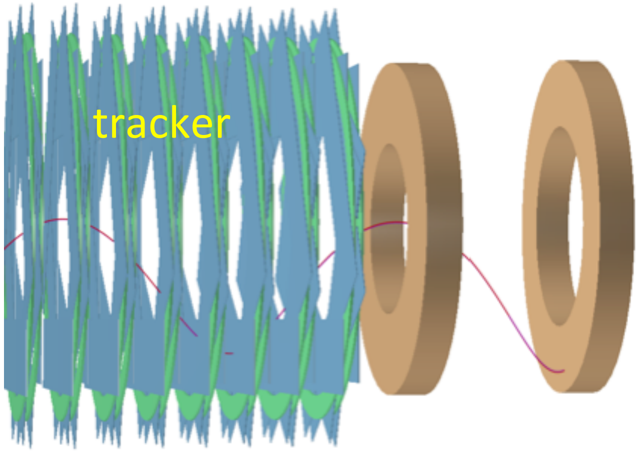
→ σ/E of O(5%) and Time resolution < 500 ps
→ Position resolution of O(1 cm)
→ almost full acceptance

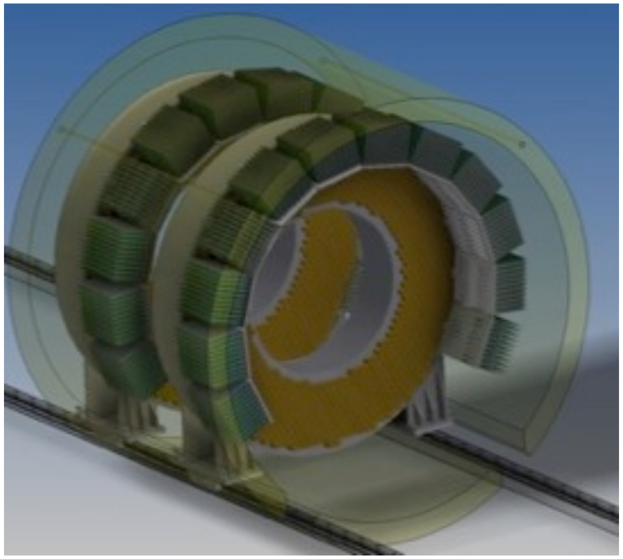
for CE signal @ 100 MeV

Disk geometry

- Square crystals
- Charge symmetric, can measure $\mu^- N \rightarrow e^+ N$

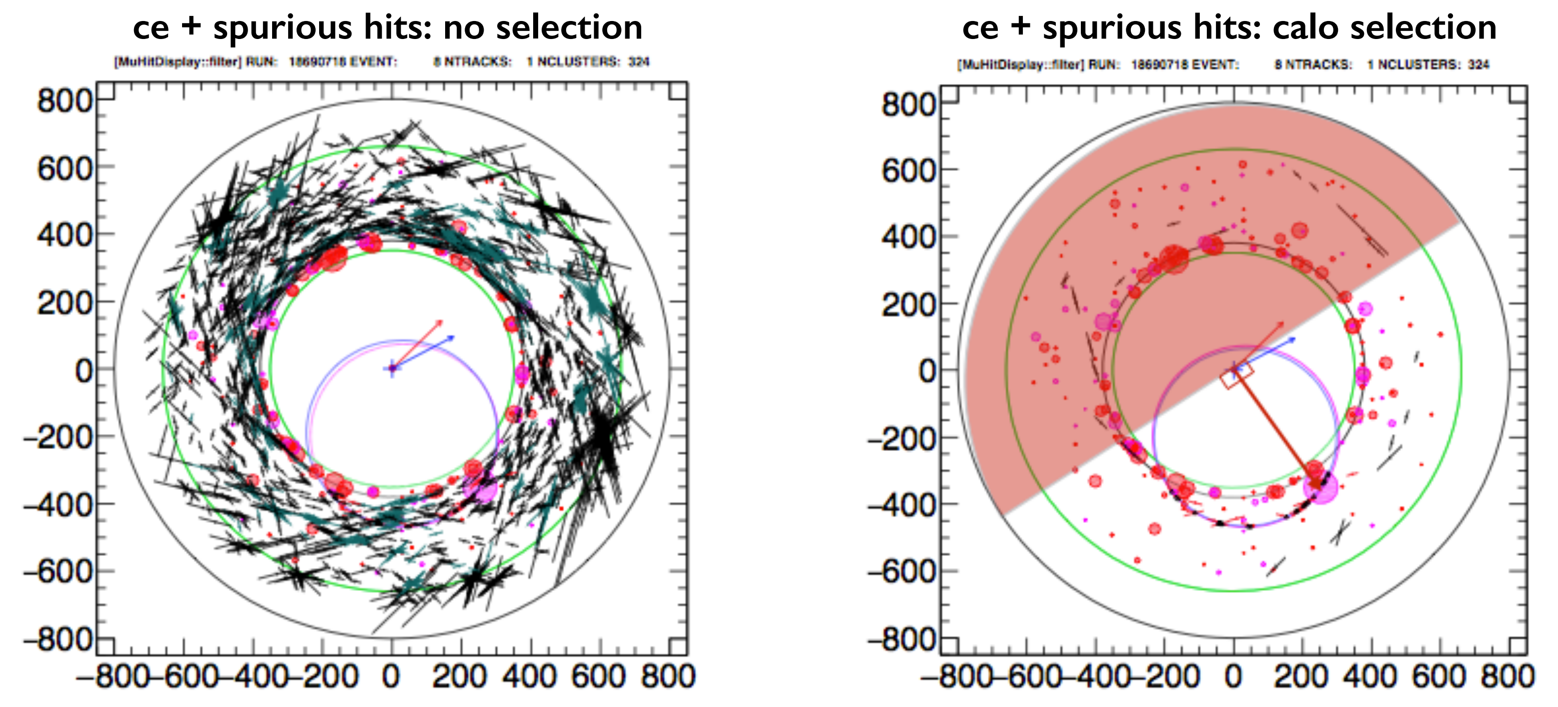
Two disks separated by ½ wavelength (70 cm)





Example of track seeding

Search for tracking hits with time (and azimuthal angle) compatible with the calorimeter clusters (|ΔT| < 50 ns) → great simplification of the pattern recognition



ce + spurious hits: no selection

ce + spurious hits: calo selection

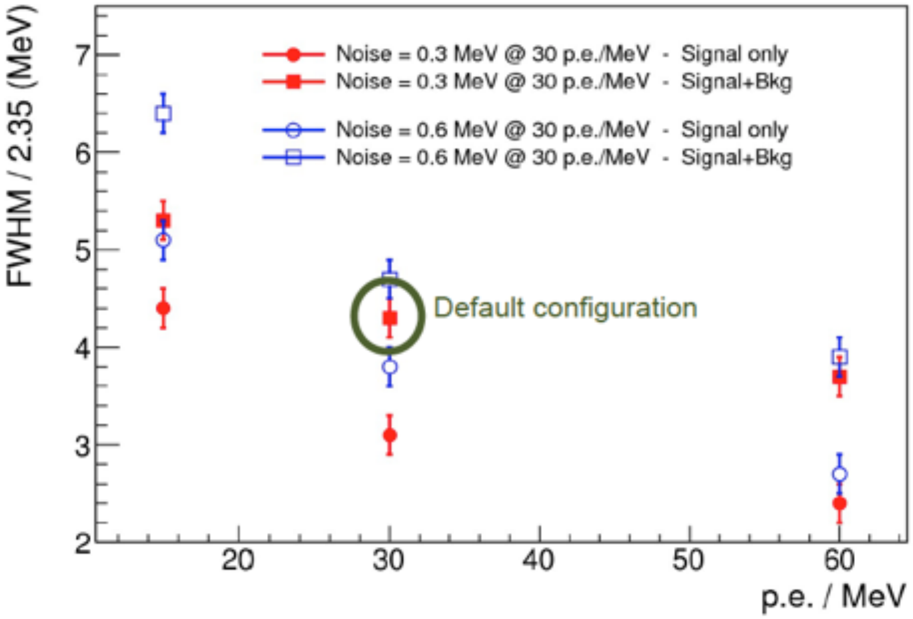
- ❑ Add search of an Helix passing through the cluster and the selected hits
- ❑ Calorimeter time used to calculate tracking Hit drift times.
- ❑ Reduce the wrong drift sign assignments → **smaller positive momentum tail**
- ❑ **Increase relative efficiency of standalone tracking of 9%**

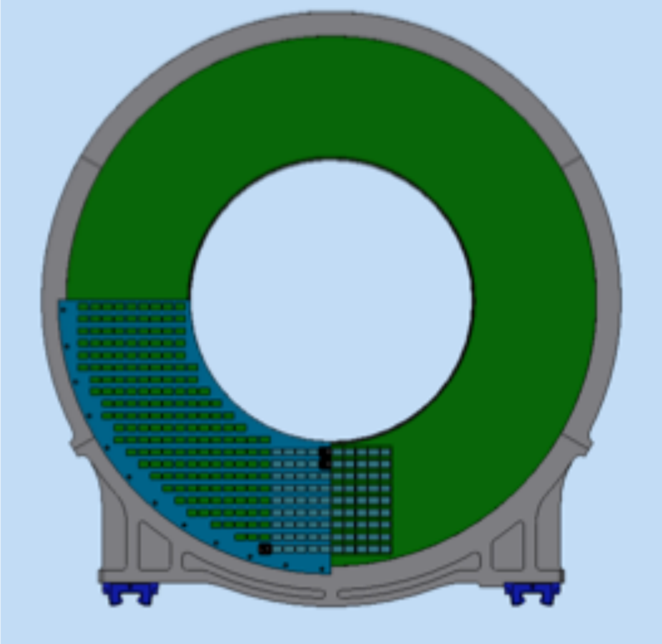
Calorimeter Layout

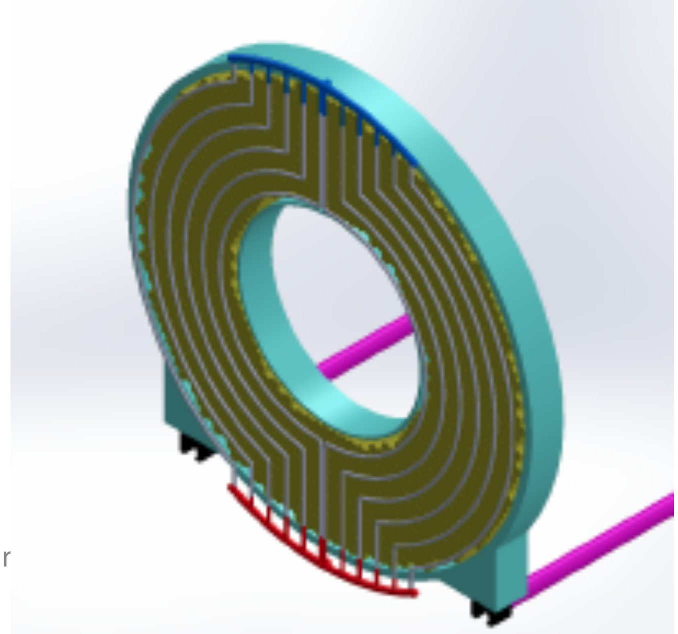
The Calorimeter consists of two disks of 1650 BaF_2 square crystals (30x30x200) mm^3

- R_{IN} = 351 mm, R_{OUT} = 660 mm Depth = 10 X_0 (200 mm)
- Each crystal readout by two APDs (9x9 mm^2) (3300 total) for redundancy and NCE x-check
- FEE and digital electronics located in near-by crates
- Radioactive source provide absolute calibration
- Laser system fast monitoring capability.

Simulated energy resolution







Crystal Choice

	~~LYSO~~	BaF_2	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	20
Photosensor	APD	**R&D APD**	SiPM
Wavelength [nm]	402	**220**/300	310

LYSO

CDR

- Radiation hard, not hygroscopic
- Excellent LY
- Tau = 40ns
- Emits @ 420 nm,
- Easy to match to APD.
- High cost > 40$/cc

Barium Fluoride (BaF_2)

TDR baseline

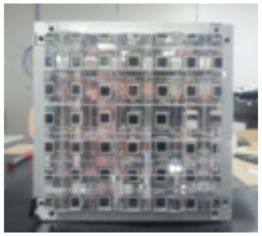
- Radiation hard, not hygroscopic
- very fast (220 nm) scintillating light
- Larger slow component at 300 nm. should be suppressed for high rate capability
- Photo-sensor should have extended UV sensitivity and be “solar”-blind
- Medium cost 10$/cc

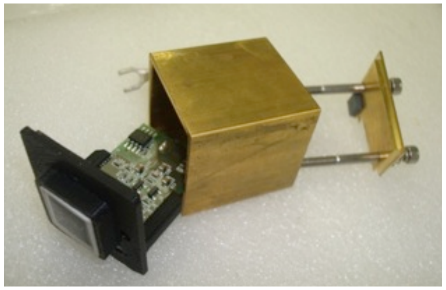
CsI(pure)

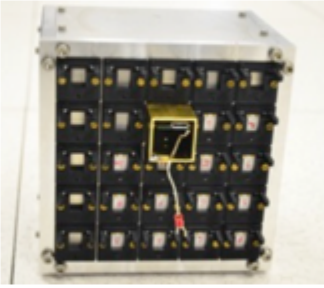
TDR backup

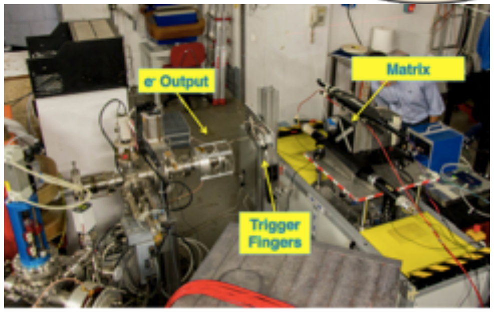
- Not too radiation hard
- Slightly hygroscopic
- 20 ns emission time
- Emits @ 320 nm.
- Comparable LY of fast component of BaF_2.
- Cheap (6-8 $/cc)

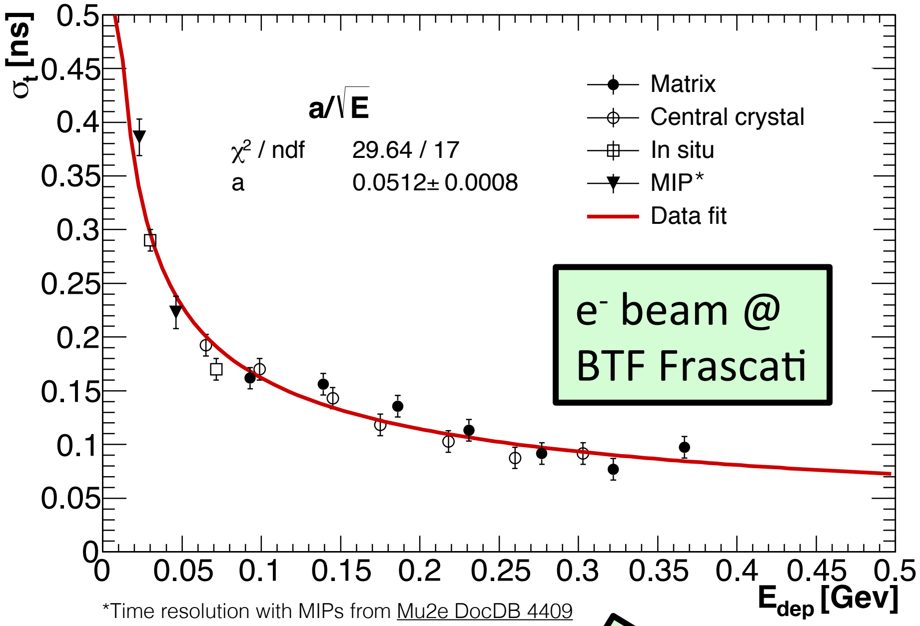
LYSO LEGACY





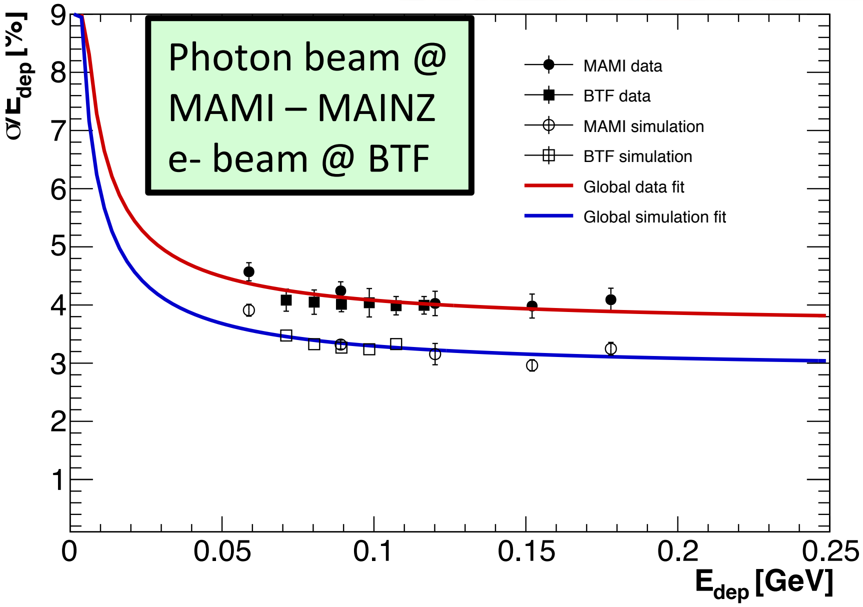






e⁻ beam @ BTF Frascati

*Time resolution with MIPs from Mu2e DocDB 4409



Photon beam @ MAMI – MAINZ e- beam @ BTF

σ_T = 51 ps/sqrt(E/GeV) compare with KLOE ~ 55 ps/sqrt(E/GeV)

Poster from S.Giovannella

Energy resolution as a function of the energy deposition fitted with the function:

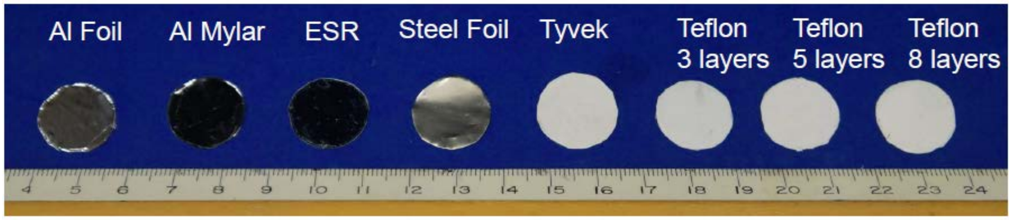
~ 4% @ 100 MeV

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

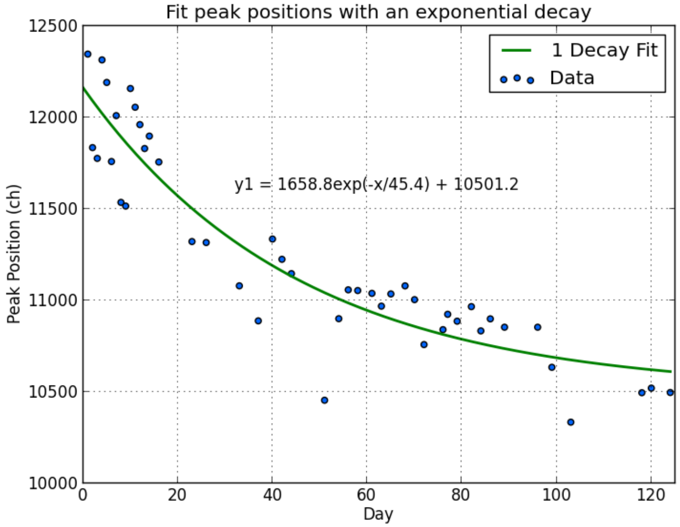
Noise term *b* considered negligible (~0.1% in quadrature).

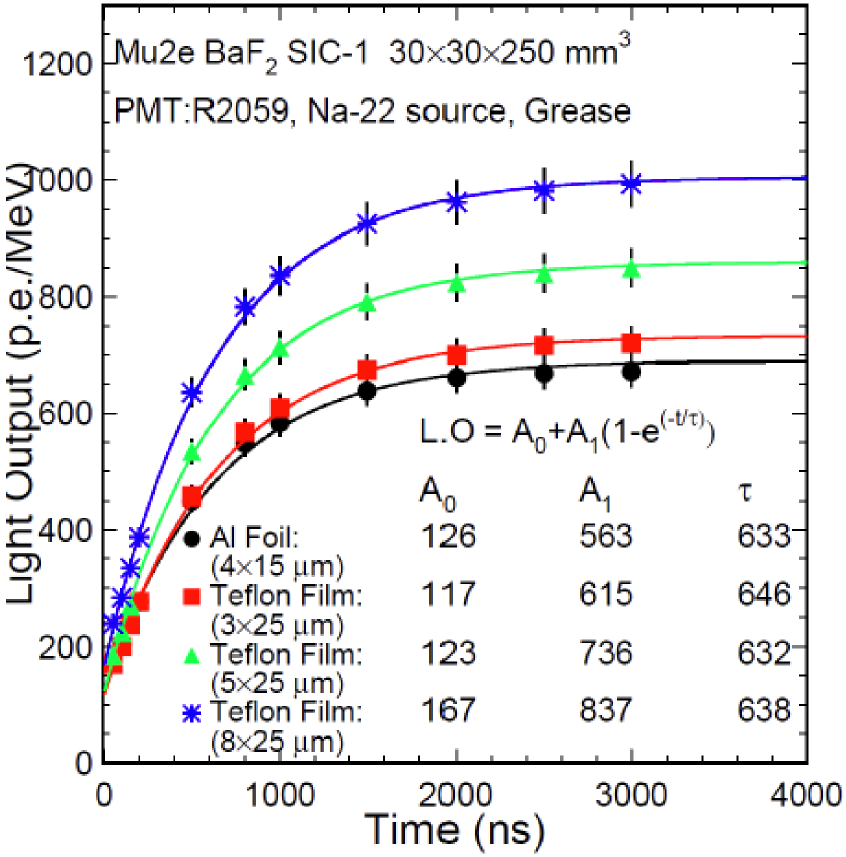
BaF_2 tests

- 20 30x30x250 mm^3 SICCAS BaF_2 crystals characterized for LY, LRU
- **Study of wrapping material also completed** → Teflon foils looks the best candidate

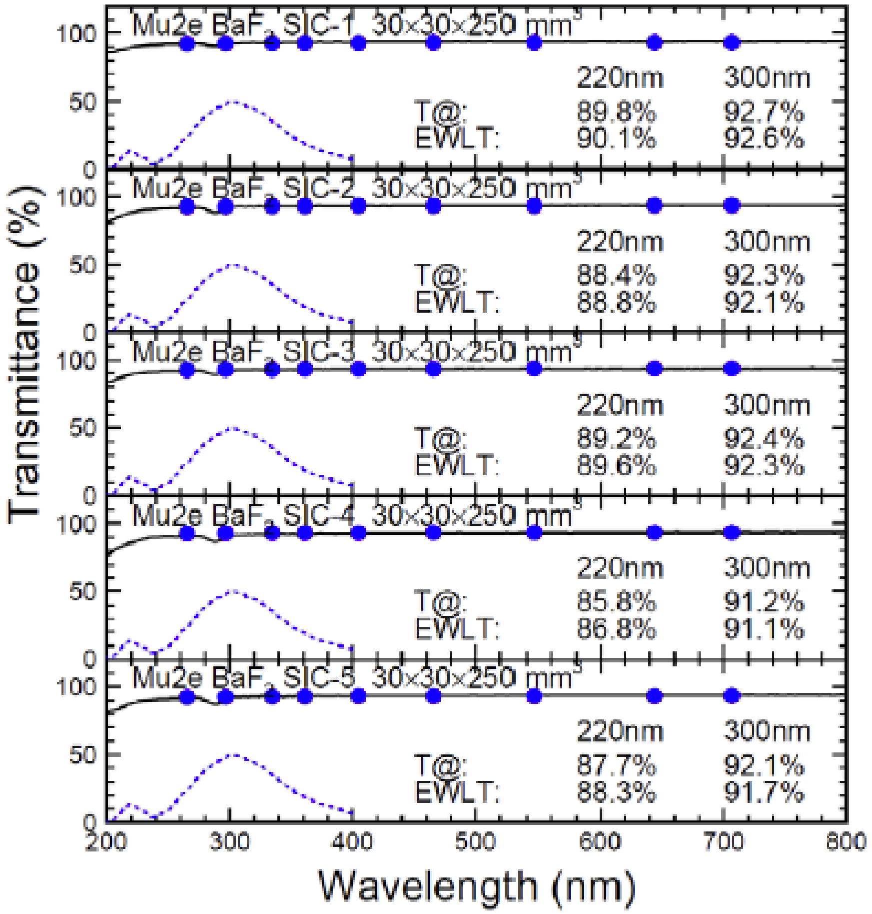


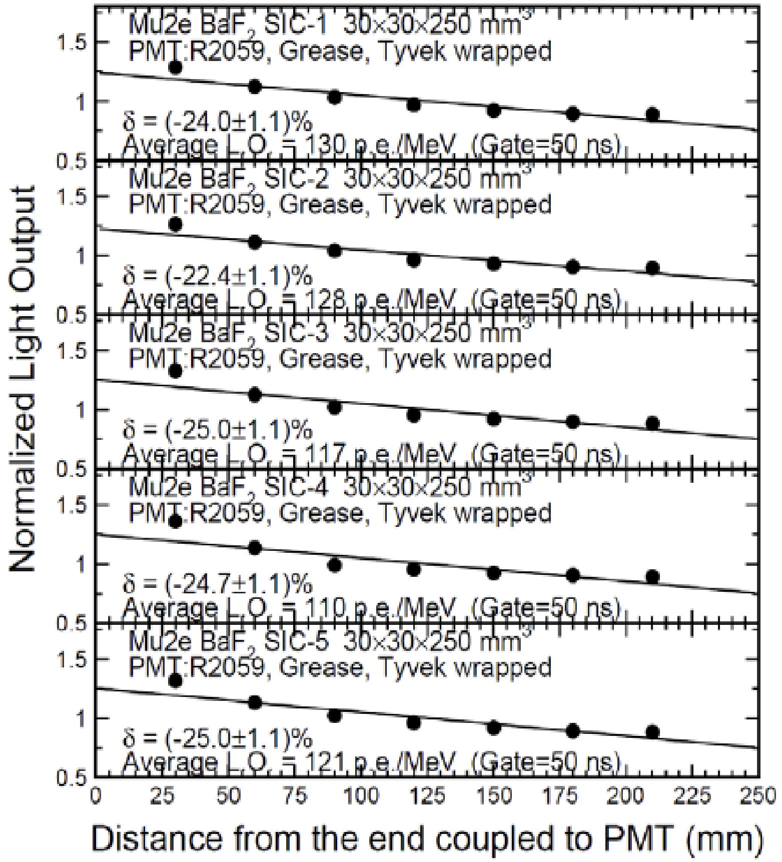
- ☐ Radiation hardness of wrapping tested up to 1 Mrad
- ☐ LY variation of w.r.t. maximum weight load tested





BaF_2 QA: LY, LRU, Transmittance



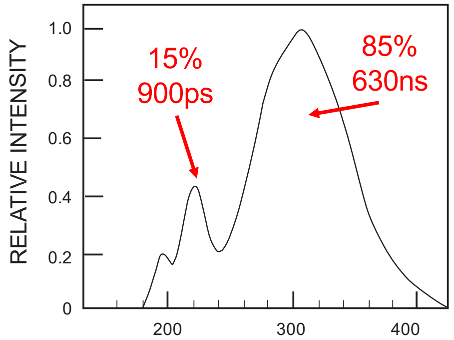


- ✧ SICCAS: LY OK, Transmittance excellent, LRU = too high (+/- 25%)
- ✧ **New crystals under test from BGRI (China) and ISMA (Ukraine)** → much better LRU
- ✧ Radiation test with dose and neutron under way → **TID >> neutrons**

A solar blind UV APD

- ✧ BaF_2 is one of the fastest emitting crystals (900 ps @ 220 nm). However a large slow component exists (630 ns) for wavelength > 280 nm.
- ✧ This component has to be suppressed due to the high event rate in the experiment

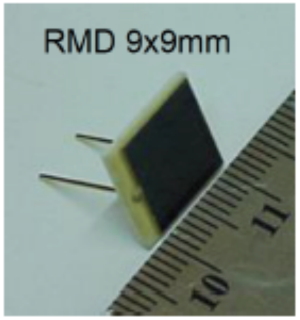
Poster Session:
D.Hitlin

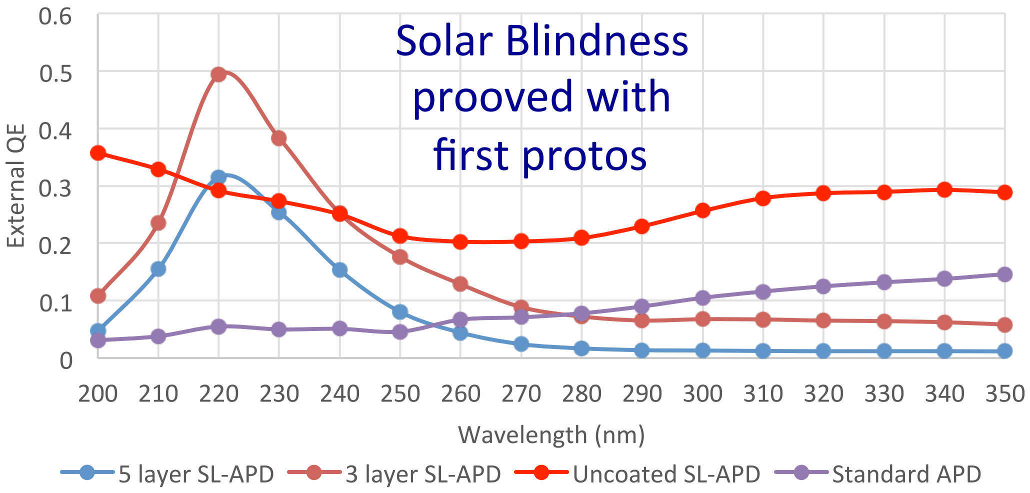


A Caltech/JPL/RMD consortium has been formed to develop a Large area RMD APD **into a delta-doped super-lattice APD with high Q.E. @ 220 nm** incorporating also **an Atomic Layer Deposition antireflection filter** to reduce efficiency for wavelength > 300 nm.

- ✓ 60% QE @ 220 nm
- ✓ ~ 0.1 % QE @ 300 nm
- ✓ capacitance ~ 60 pF (1/5 of Ham S8664)
- ✓ HV ~ 1800 V
- ✓ Operation Gain ~ 500
- ✓ Decay time ~ 25 ns.

deltadoped APD from RMD

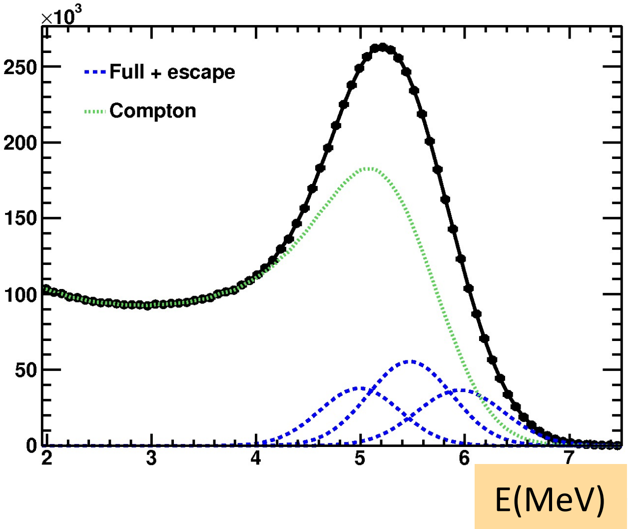


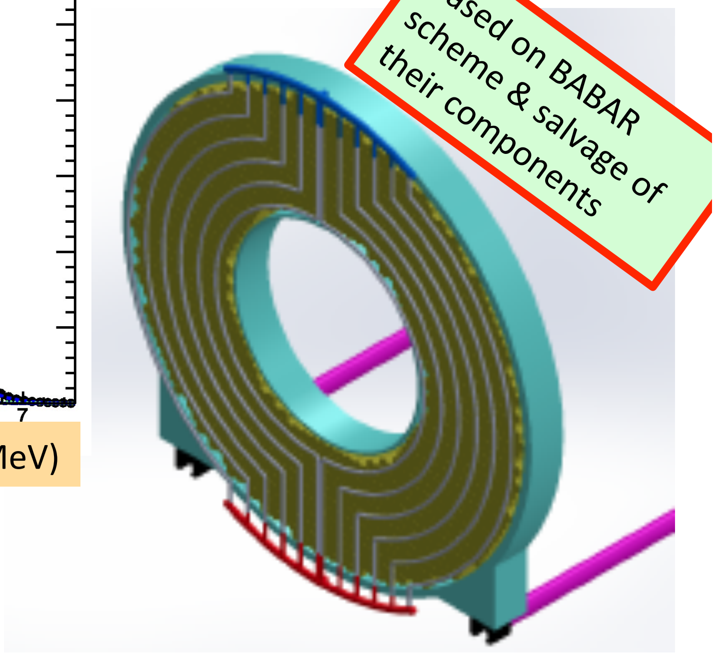


Solar Blindness proove d with first protos

Calibration and monitoring system

- ◆ Neutrons from a DT generator adjacent to the Detector irradiate a fluorine rich fluid (Fluorinert).
- ◆ The activated liquid is piped to the front face of the disks.
- ◆ Few per mil energy scale in few minutes.
- ◆ Final experiment scale (E/P) is set using DIO's.



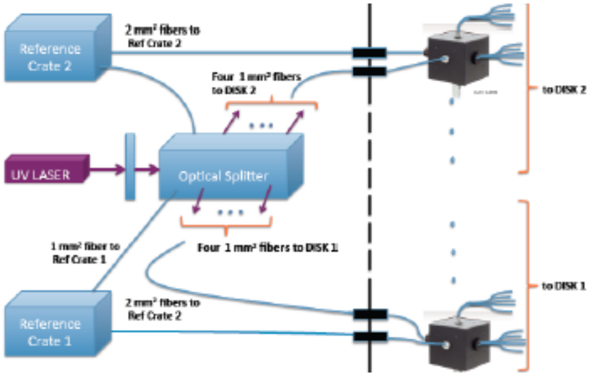


Based on BABAR scheme & salvage of their components

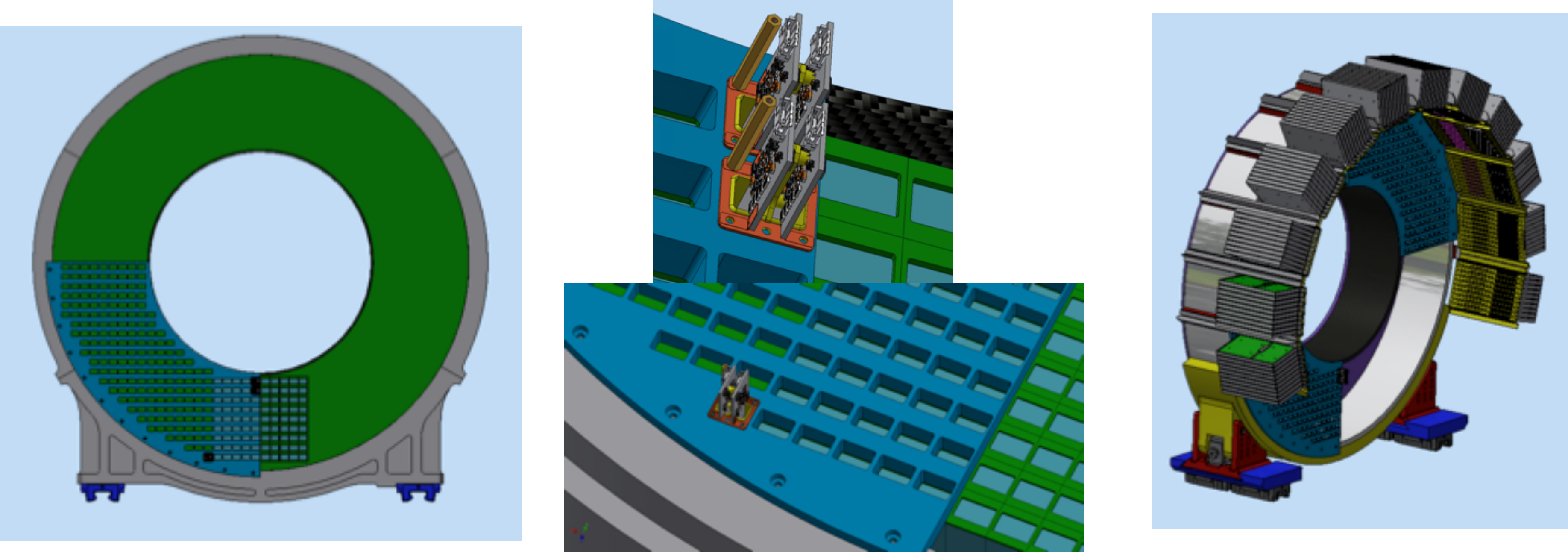
→ Salvage of BABAR DT generator done @ Caltech
→ Integration of pump,mechanics and controls done
→ **First tests expected in June**

Laser system adapted from CMS calibration system.
UV light to monitor continuously the variation of the APD gain

→ Green laser prototype used for LYSO test
→ Distribution system with Silica optical fibers developed
→ **UV laser and monitoring system still to be optimized.**

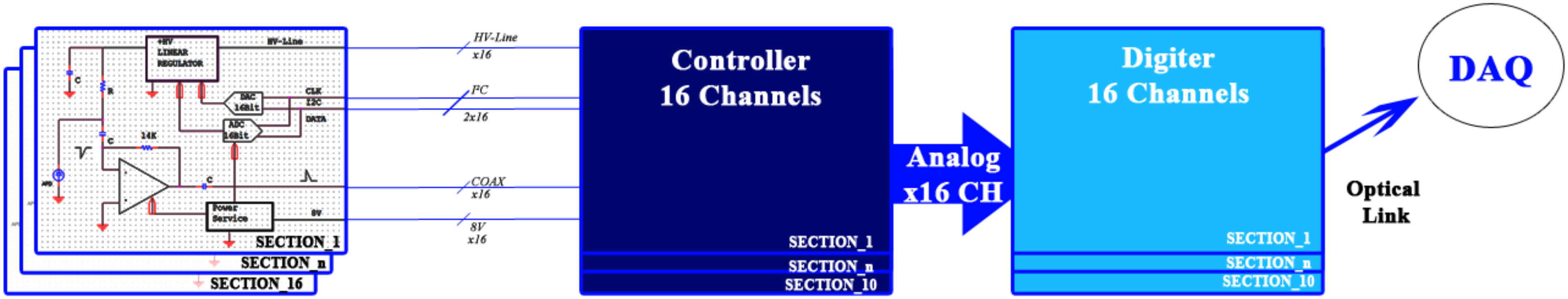


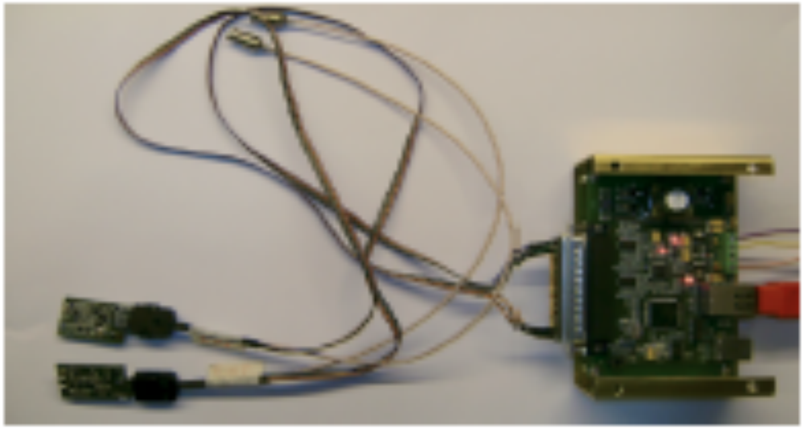
Mechanical support



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

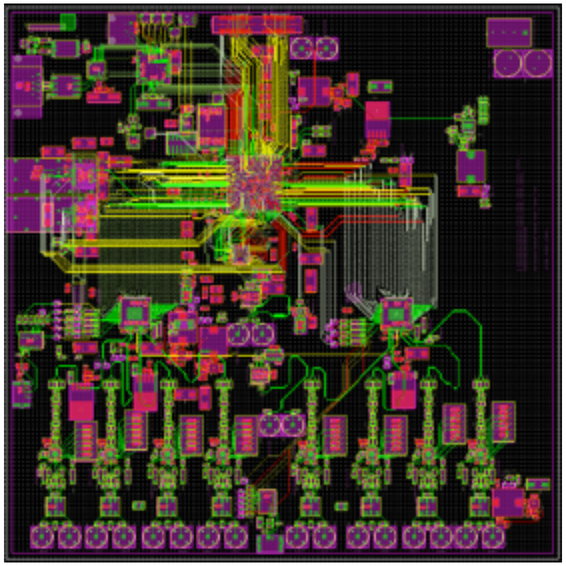
Electronics scheme and FEE





- FEE is a discrete chip connected to the photo-sensor: V preamp & Local V-bias regulator.
- Amplification layer consists of a low noise, high gain trans-impedance voltage preamplifier
- 16 FEE channels driven by an ARM-controller to generate/distribute Vbias and low voltages
- 50 FEE channels and 5 ARM controllers produced by INFN-Frascati for LYSO test beam array.
- FEE being adapted to the solar blind APD (HV from 500 to 1800 V, C_D from 270 to 60 pF)
- Prototype expected in two weeks to make the first slide test.

WF digitizers



In order to cope with the high rate and to allow separation of pileup hits on the same channel we need Digitizer boards @ 200 msps, 12 bits resolution:

- ☐ Zero suppression on board
- ☐ Rings of optical links (2 Gbits/link)
- ☐ 5 prototypes 8 channels built with Xilinx FPGA @ University of Illinois

Upgraded version in progress (PISA):

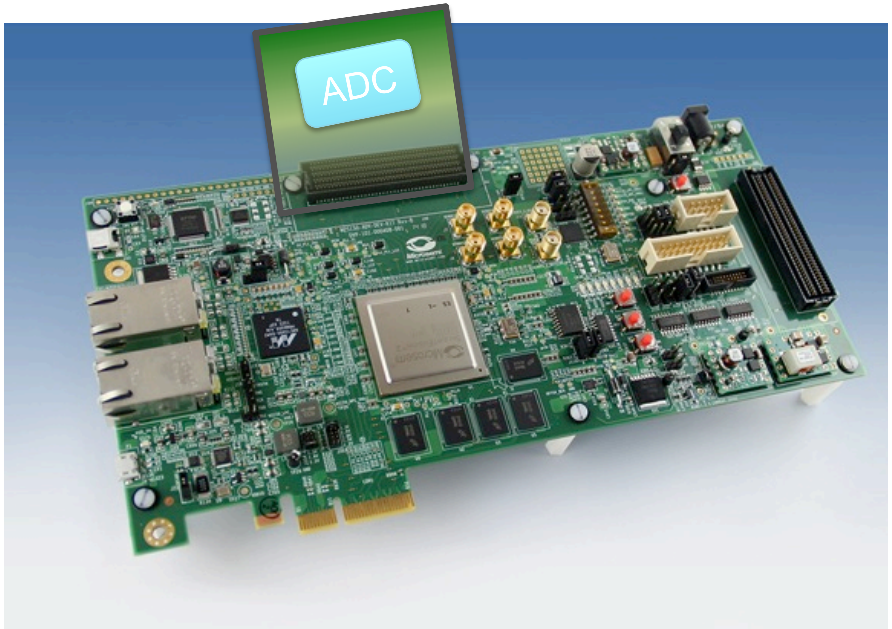
→ From 8 to 16 differential channels

→ FPGA: from Xilinx to Smart Fusion2 M2S150T that is SEU immune.

→ ADC: new version under study
Analog Devices: AD9230

→ **DC-DC converter: LTM8033**

→ Board dimensions 6U VME (23x16 cm^2)



Backup: CsI + MPPC tests

Backup alternative:
pure CsI with UV extended MPPC

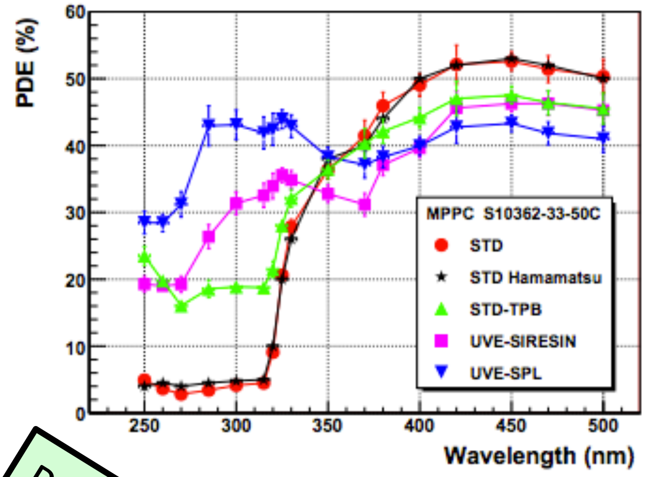
- ❑ 10 new SLP MPPC received on March.

→ Amplifier done

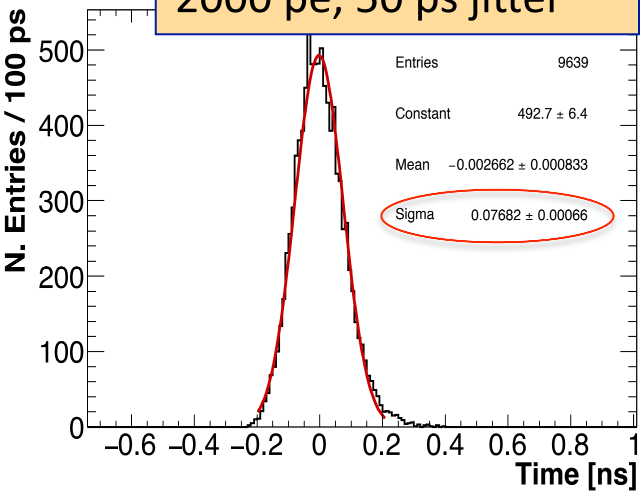
→ Test with Laser for time Jitter test successful < 70 ps

→ New crystals from OptoMaterial (Italy), ISMA (Ukraine) more uniform & with better transmittance than SICCAS ones (China)

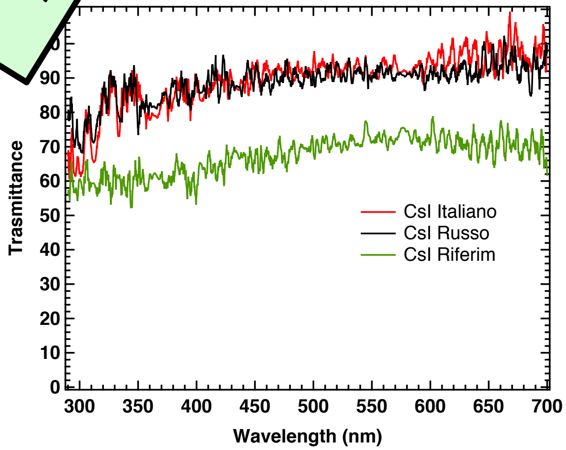
Imaging with SiPMs in noble-gas detectors: arXiv 1210.4746

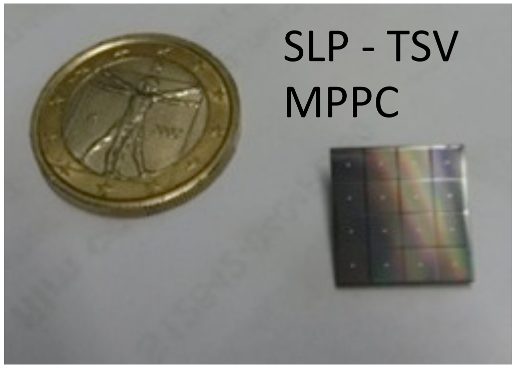


Jitter with laser source
2000 pe, 50 ps jitter

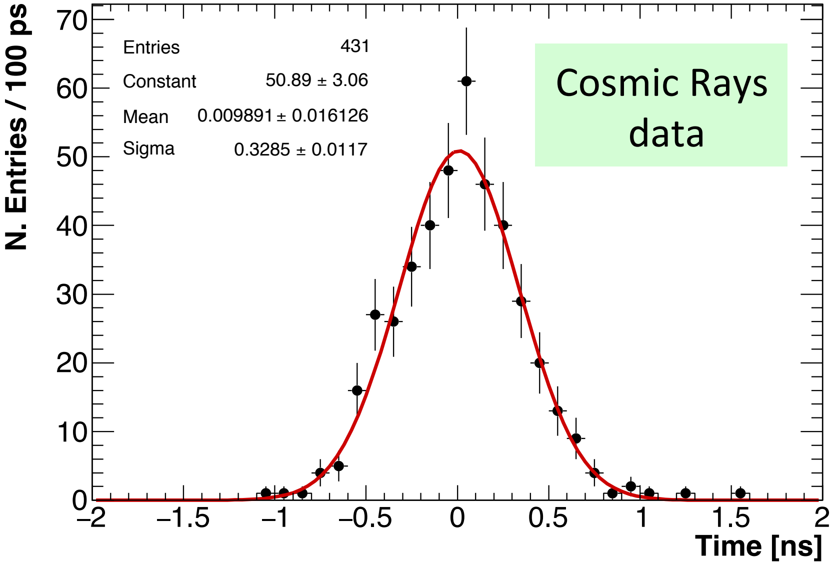


Poster from R.Donghia





CsI + MPPC: preliminary tests



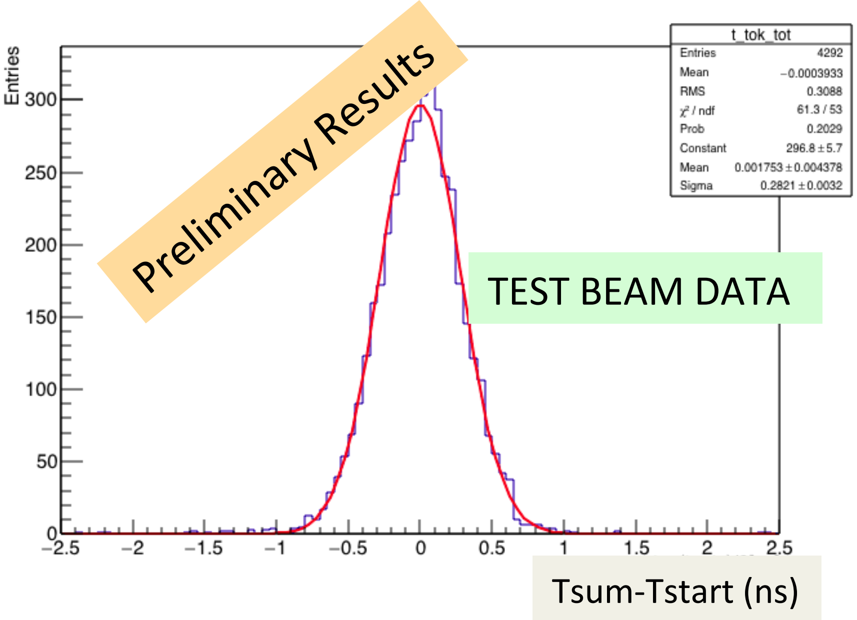
@ 22 MeV energy deposition with a MIP

- ☐ In air: ENE 270 keV (8 pe), **410 ps**
- ☐ With Bluesil 7 : 190 keV noise , **330 ps**

- ☐ **Test beam data (e^- beam @ 100 MeV) with a 3x3 crystal matrix**

→ **7% energy resolution**

→ **280 ps at 50 degrees incidence**
(as in the experimental condition)



Plans/summary

- **The MU2E calorimeter will provide complementary information to the tracker and will be be used for PID, seeding of tracks and triggering.**

- CD-2 has been obtained in March 2015

- EMC Baseline consists of two disks of 1650 BaF_2 crystals, each one read out by two SL solar blind APDs.

- Technology choice Review will be carried out this summer to freeze the available options and complete the engineering design.

- **An irradiation program with ionization dose and neutrons is under way to complete characterization of the EMC components.**

- **CD-3 review is expected in March 2016 to allow start of construction**

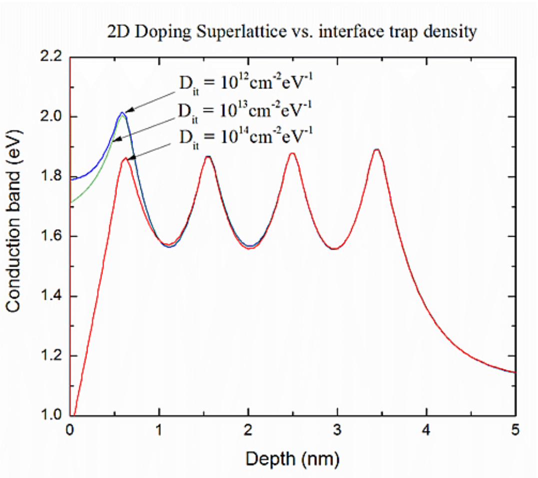
- We expect to complete construction at the end of 2018 and start installation in the DS during 2019.

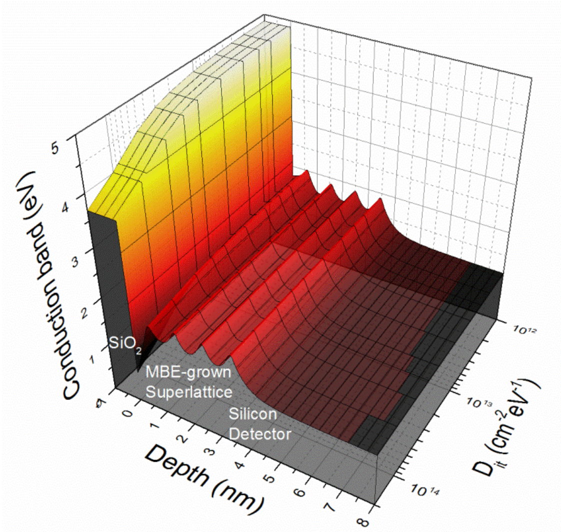
ADDITIONAL INFORMATION

Superlattice microstructures

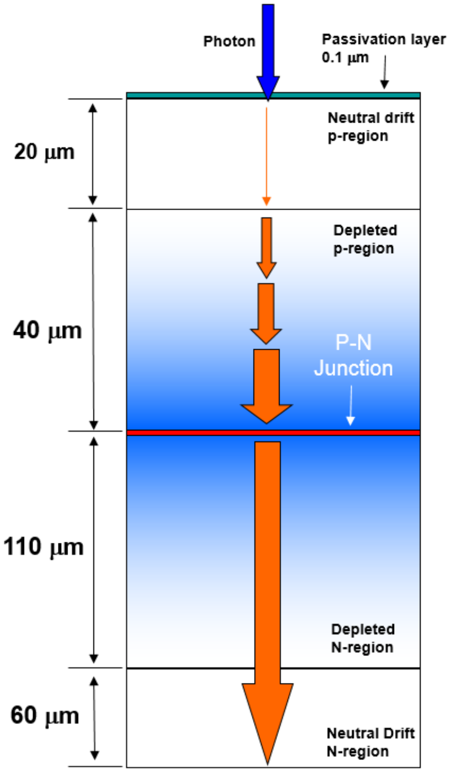
JPL has developed superlattice microstructures, built on the surface of silicon photosensors, that provide greatly enhanced quantum efficiency and improved time response

- These have been successfully employed to enhance the UV performance of CCDs and APDs used from UV astronomy in satellites and balloons
- Monoatomic layers of boron are implanted beneath the (thinned) photosensitive surface of the Si device using molecular beam epitaxy (MBE) (2D doping)
    - Equivalent dopant density > $10^{21}/cm^3$
- Conduction band remains stable with varying surface charge
- Recombination is suppressed by quantum exclusion
- Close to 100% internal QE
- Stable against high intensity UV illumination





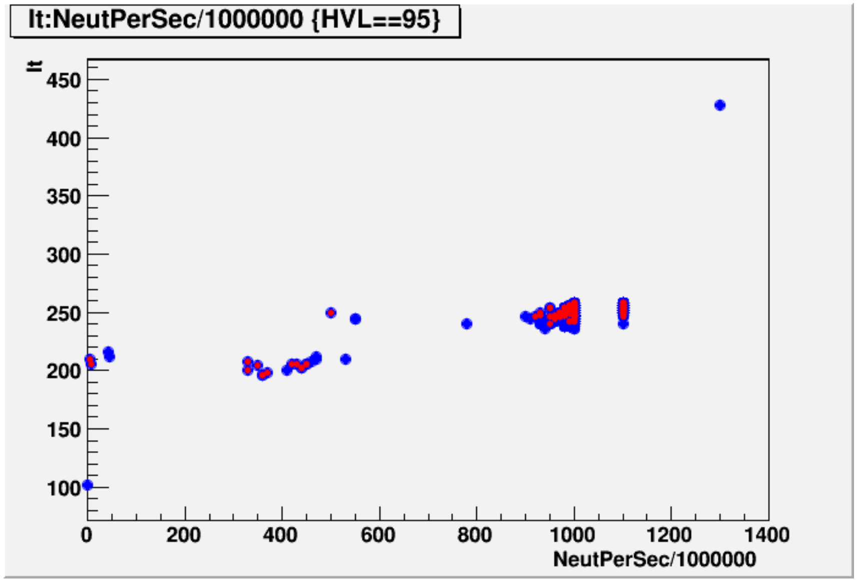
- Eliminating the potential well at the surface and reducing (or removing) the drift region improves the detector UV QE and speed



Source system

Prototype construction at Caltech is almost finished

- Electrical work is done, lead shielding put in place and neutron generator installed in bunker. **Neutron Generator being Qualified.**
- Neutron flux: using Ag, Rh, Co activation foils analysis. Correction factors have still to be implemented for a final calculation.
- **Parts to refurbish salvaged circulation arrived last week**. Power/pump load protection system. Solution for plumbing elements found.
- Expect completion: end of may.
- Integration of full system (June).



95% HV

SLAC: all Run 7 calibrations

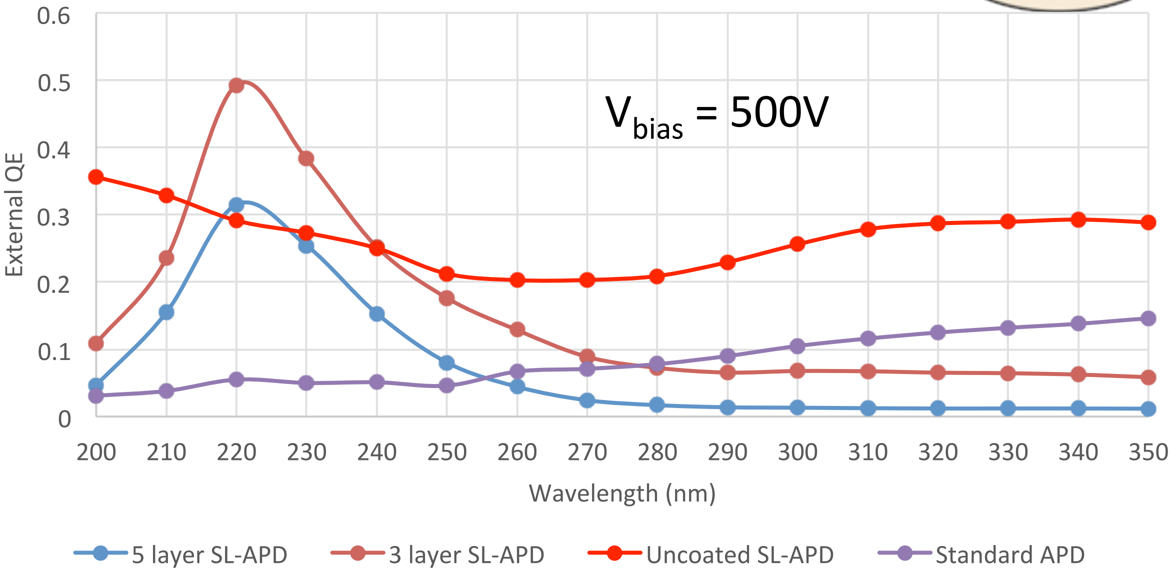
Caltech: all 95% HV

Development at FNAL of final system

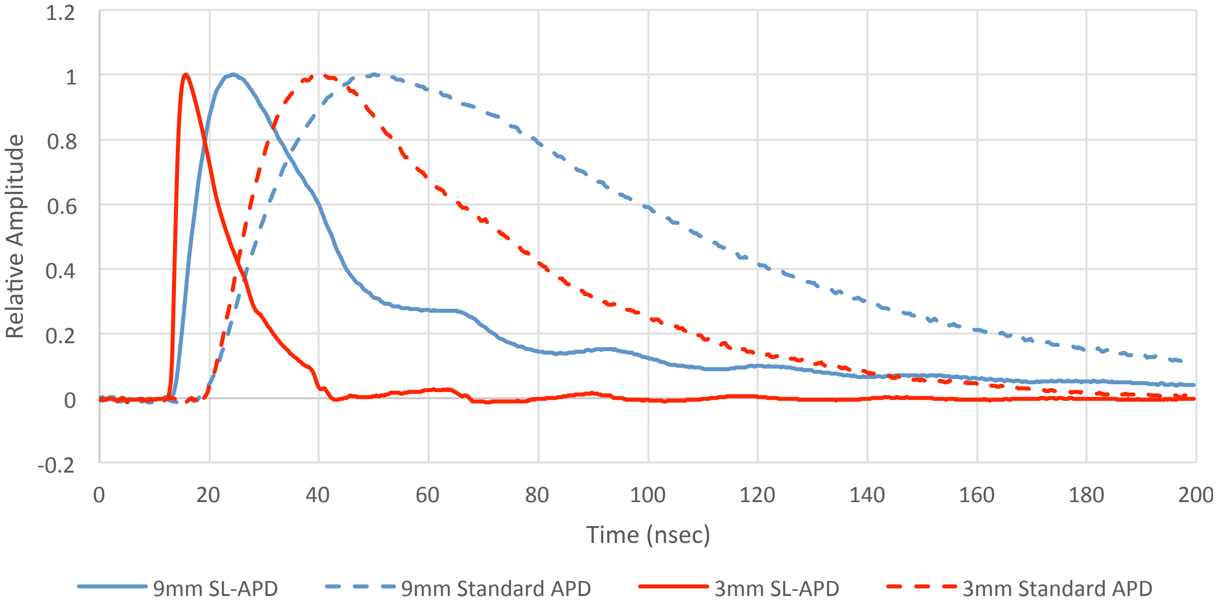
- Source system integrated in civil engineering model, few details being fixed

Measurement on Solar Blind Devices

- Solar Blindness proved
- High Q.E. proved with SL-APD
- 5 Layers ALD



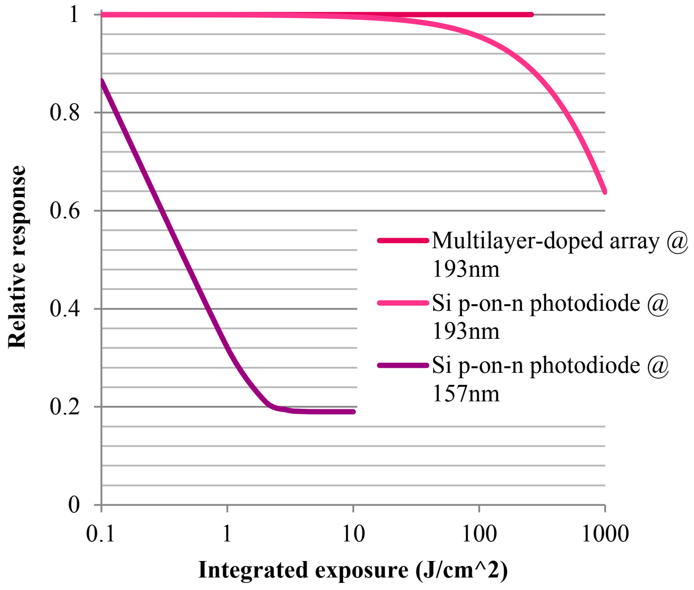
☐ Excellent rise-time of the APD pulses and overall "narrow" pulse-width.



How much UV energy does the sensor see?

- UV photons have sufficient energy that an integrated dose can cause a significant number of lattice dislocations over time
- The JPL superlattice design protects against degradation due to this effect

Accelerated Lifetime Test of Multilayer-doped D11C at 193nm

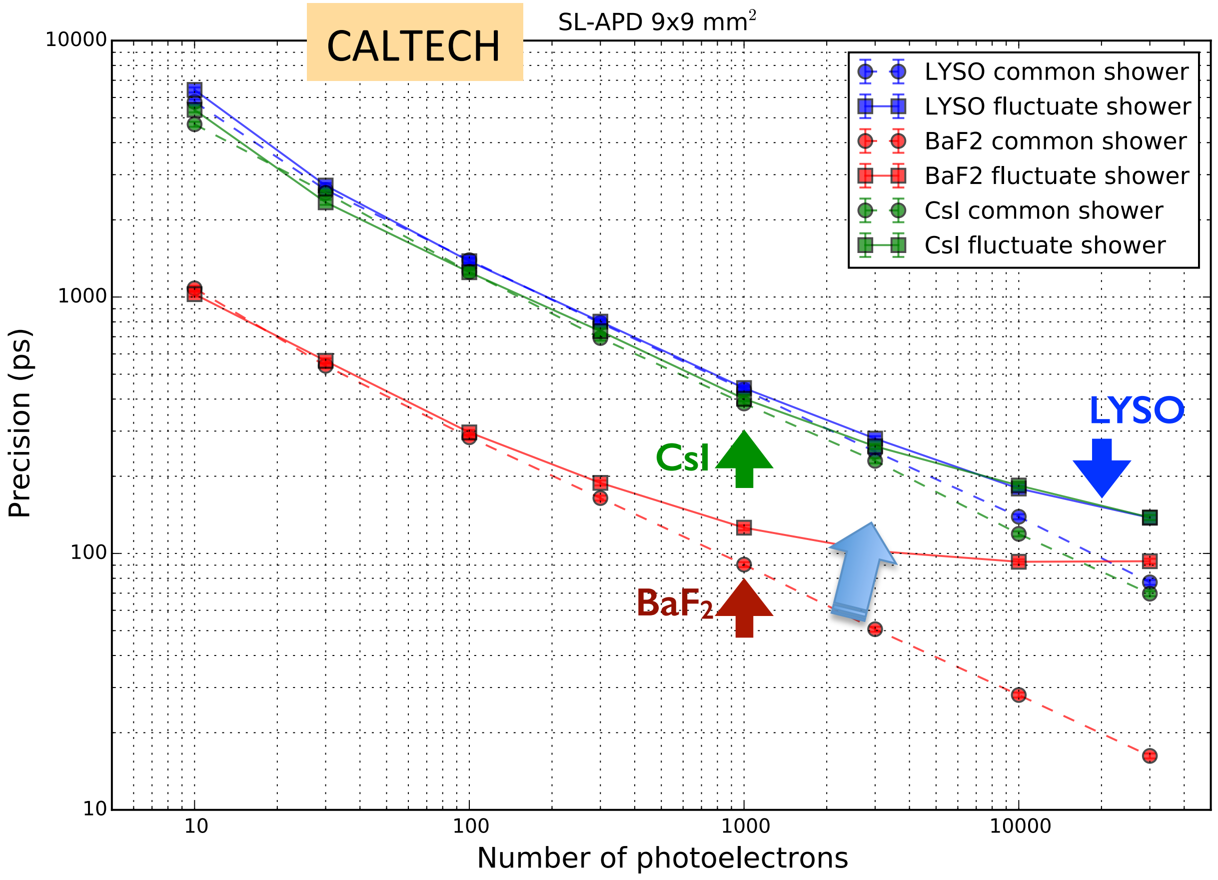


Total Dose	kRad	Joules
Average front disk	3	1.8
Average rear disk	0.5	0.3
Worst case	50	30

- Assumptions
  - 15 pe/MeV/sensor with QE of 50%
  - Photon energy 10^{-18} J
  - Crystal 1 kilogram

Conclusion: we can likely survive without the protection of the superlattice, but the superlattice also increases QE and improves time response

Simulation of timing resolution

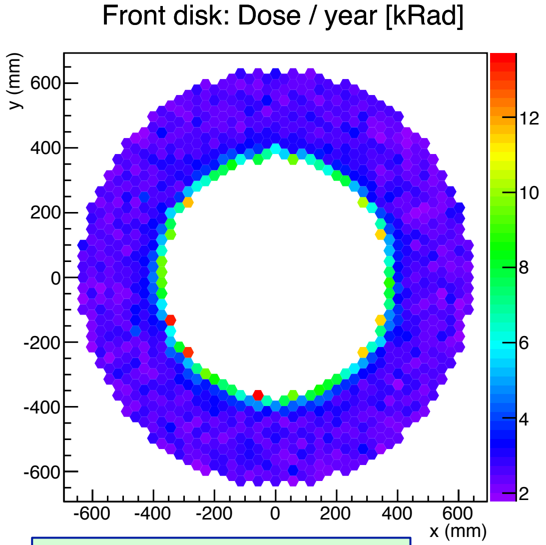


- Simulation of ray tracing on the crystal, pulse shape on the APD + shower fluctuation.
- Shower fluctuation count as 100 ps. **FEE contribution not included. No irradiation.**

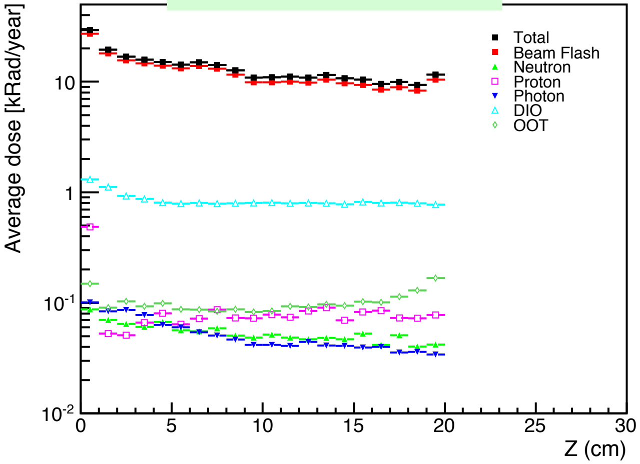
☐ Estimate for BAF2 scaled at 100 MeV (~ 6000 pe) → 100 ps
☐ Estimate for CsI scaled at 100 MeV (~ 4500-6000 pe) → 250 ps

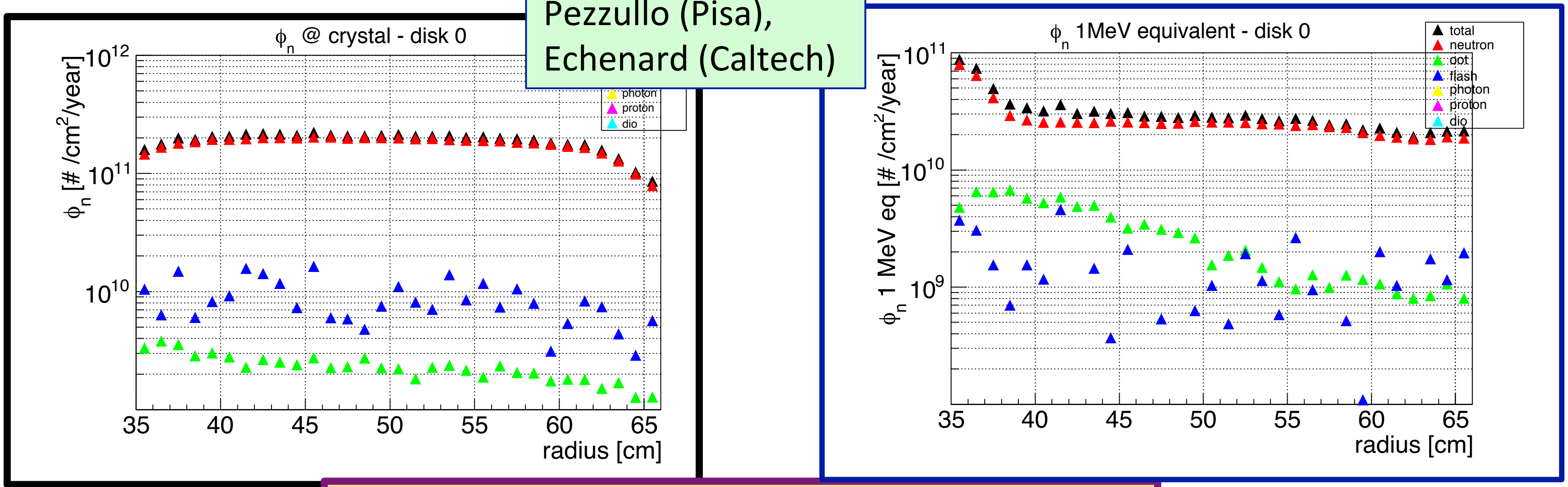
Radiation Hardness (simulation)

- ☐ Radiation dose driven by Beam flash (300 ns from interaction on target). **Dose from Muon capture x 10 smaller**
- ☐ Strongly limited to inner radius (up to 400 mm)
- ☐ **Highest dose/year ~ 10 krad**
- ☐ **Highest n flux/year on crys. ~ 2x10 ^{11} n/cm^2**
- ☐ **Highest dose/year on APD ~ 6x10^{10} n_1Meveq/cm^2**



Radius = 36 cm

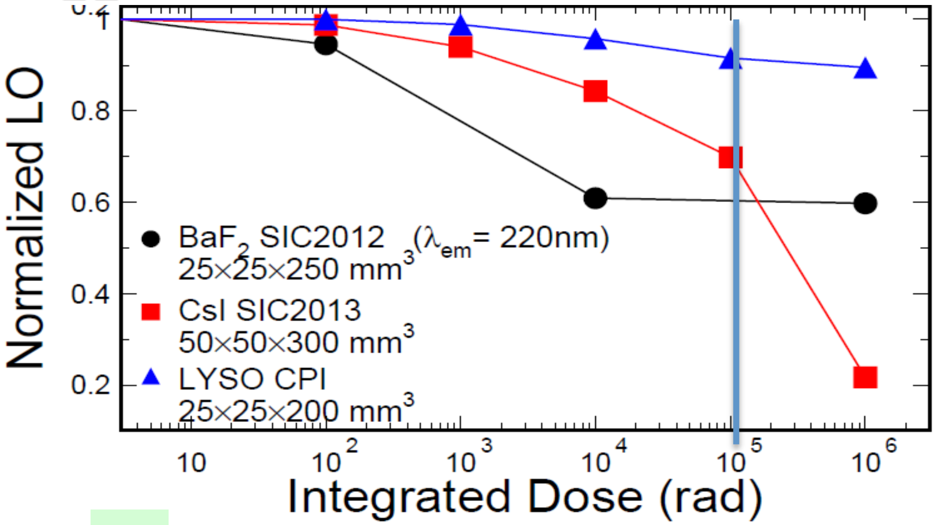




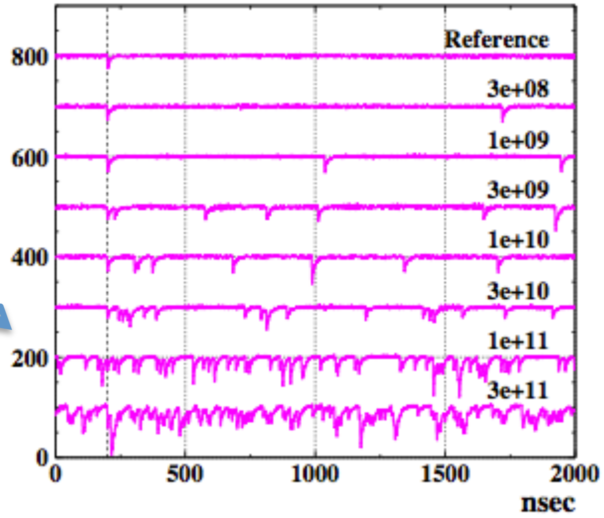
Pezzullo (Pisa), Echenard (Caltech)

Rad-Hard test: qualify crystals up to 100 krad , 10 ^{12} n/cm^2
Qualify photo-sensors up to 10^{11} --- 3x10^{11} n_1MeV/cm^2

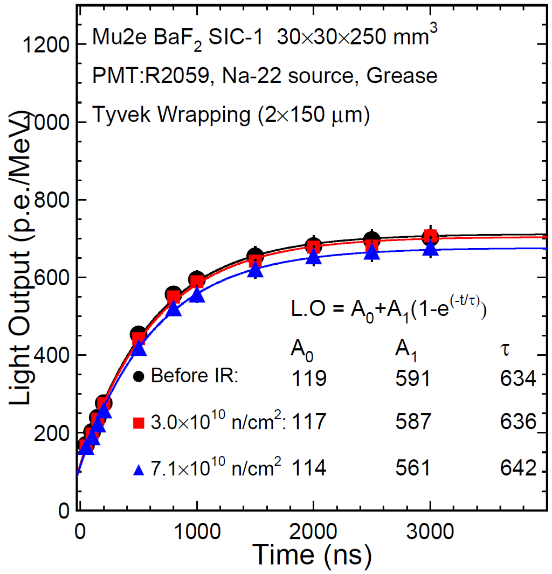
Radiation Hardness (Measurement)



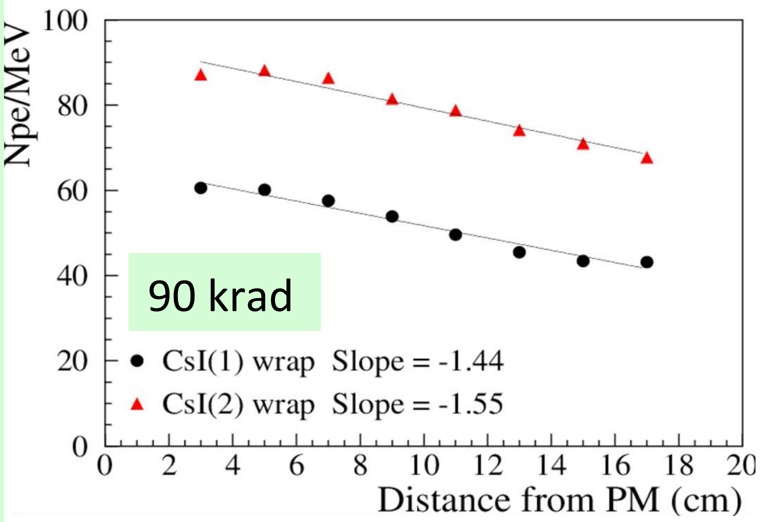
MPPC response
n flux/year
worst case



- Neutron test on BaF_2 (Caltech)



Dose on CsI at Calliope (ENEA-INFN)



90 krad

A round of measurement with neutrons planned for May 2015

Rad Hardness plans

First irradiation tests with dose on CsI provide good results:

- LY reduction of 20% after 90 krad
- After irradiation, Npe 80/MeV @ crystal center using Teflon wrapping and grease
- LRU between 20 and 50% (no wrap, no grease)
- Not negligible fluorescence after large irradiation dose

New irradiation tests planned for :

1) 4 kind of crystals (1 BaF_2 (IMCROM) +
3 CsI (Siccas, Optomaterial, AmCrys)

2) 3 MPPC

3) DC-DC converter, optical fibers and FEE
   - May-July 2015 @ ENEA-Frascati (FNG, neutrons)
   - Test with neutron at N-Elbe facility @ HZDR (Dresda) being planned (probably September)