R&D challenges and technical specifications for the Mu2e-II calorimeter

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Introduction

This presentation aims to describe the main differences between the already designed Mu2e calorimeter and the needs for an upgraded version that could satisfy Mu2e-II environment and running conditions.

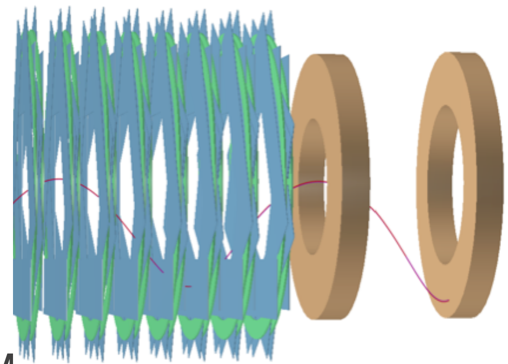
- I start from the simple consideration that **this should be an upgrade** and, **if possible**, use whatever existing, or at least reduce modifications → thus minimizing the time for integration and interfaces with the rest of detector and beam-line.

- **The main differences w.r.t. Mu2e will be the increase:**
  → by a factor of ~10 in total rate (and therefore total doses/neutron fluence)
  → by a factor of 3 in the detector occupancy (assuming same shielding).

Calorimeter requirements

- We aim to get same energy (< 10%) and time (< 500 ps) resolutions as in Mu2e.
- Aiming to provide standalone trigger, track seeding and PID as before.
- Work in vacuum @ 10^{-4} Torr, keep a low level of outgassing.
- Resistant to the strong radiation environment

Mu2e Calorimeter technical specs and design



High granularity crystal based calorimeter with:

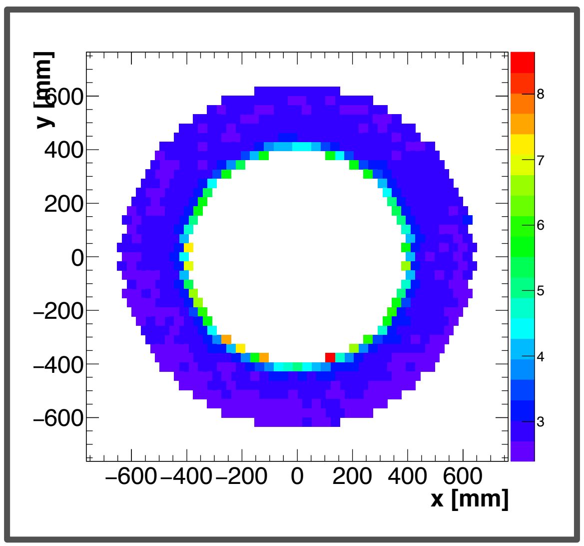
- ❑ 2 Disks (annuli) geometry
- ❑ Crystals with high Light Yield for timing/energy resolution → **LY(photosensors) > 20 pe/MeV**
- ❑ **2 photo-sensors/preamps/crystal** for redundancy and reduce MTTF requirement → 1 million hours/SIPM
- ❑ Fast signal for Pileup and Timing → **τ of emission < 40 ns + Fast preamps**
- ❑ **Fast Digitization (WD) to disentangle signals in pileup**
- ❑ **Crystal dimension optimized** to stay inside DS envelope → reduced number of photo-sensor, FEE, WFD (cost and bandwidth)

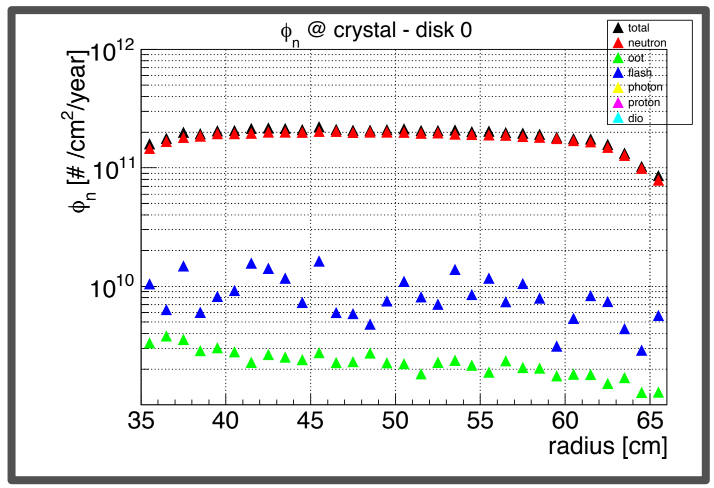
Final Mu2e Design:

- Two annular disks: each one with 674 un-doped CsI crystals of 34x34x200 mm^3
- 2 Mu2e SiPMs (UV extended to 300 nm, parallel of 2 series of 3 6x6 mm^2 SiPMs)
- Fast Amplifiers + Digitization @ 200 Msps

Irradiation problems @ Mu2e

- Crystals and sensors should work in 1 T B-field and in vacuum of 10^{-4} Torr and:
  - → **Crystals should survive a dose of ~~90~~ → 45 krad**
  - → **Crystals should stand neutron fluence of 2×10^{12} n/cm^2**
  - → **SiPMs should survive 20 krad and a fluence of 1.2×10^{12} n_1MeV/cm^2**
- DOSE on FEE is similar to the one for SiPMs
- DOSE on WD up to 10-15 krad (after proper shielding)
- Radiation induced noise corresponding to 200 uA and a energy noise of 300-500 keV
- Dose irradiation is worse on the first disk
- **Higher illumination/occupancy and Radiation on the innermost rings**





Irradiation problems @ Mu2e-II

Safety Factors included

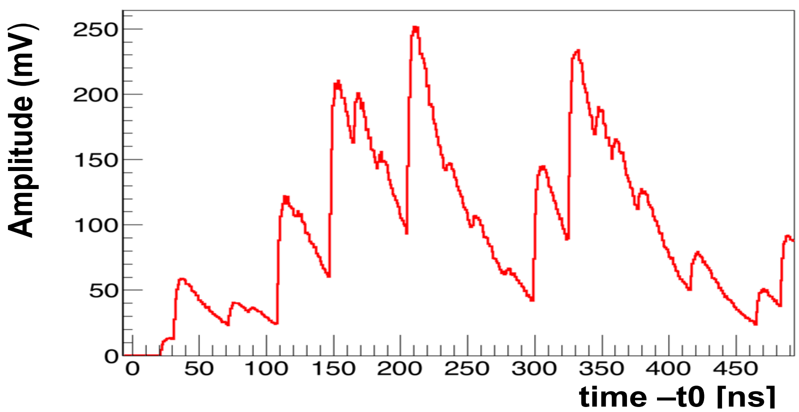
In 5 years running we roughly expect a factor of 10 worsening:

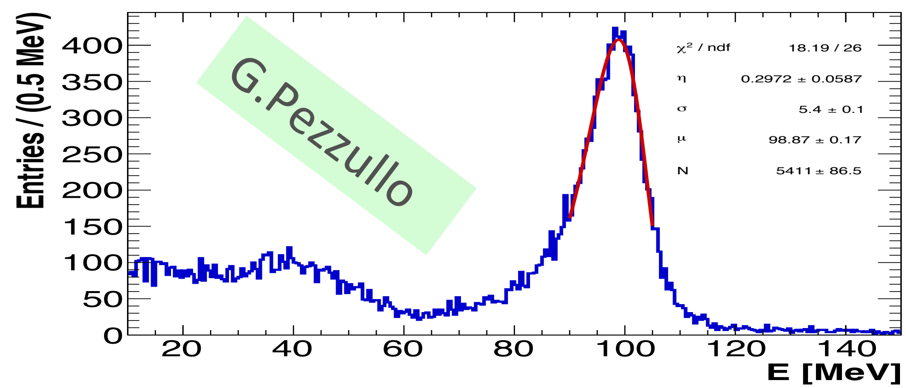
- ✓ Crystals in the hottest region (first disk) will see **a dose up to 500 krad**
- ✓ Crystals in the first disk will see a **neutron fluence up to 2x10^{13} n/cm^2**
- ✓ Instantaneous doses up to 20 rad/h (dominated by beam flash)
- ✓ Instantaneous neutron fluences of 10^5 n/cm^2/sec (neutron capture)

- ✓ In the hottest region **SiPMs will see up to 1.5x10^{13} n_1MeV/cm^2**
- ✓ In same regions, doses on **SiPMs and FEE up to 100-200 krad.**
- ✓ **Localization of FEE will be important**

- ✓ Dose on **Digitization system will be also large (> 100 krad)**

Mu2e-II: occupancy/rec in the first rings (100 ns)





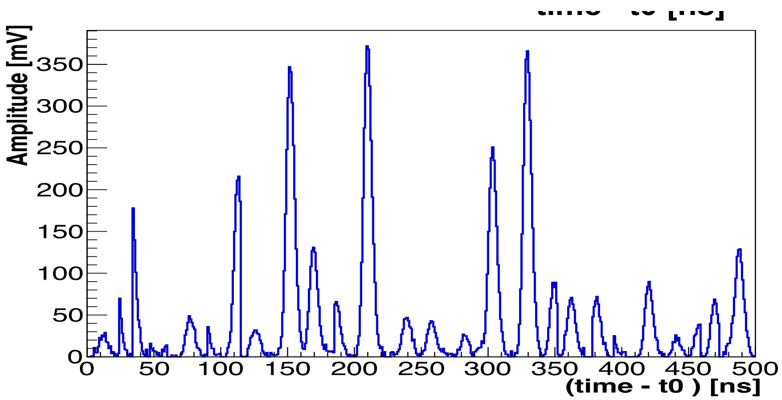
- ❑ The average **value of occupancy** in an event (MicroBunch) **in Mu2e-II** will be roughly **of a factor x 3 wrt Mu2e** (the additional factor x3 in intensity is in the better duty cycle)

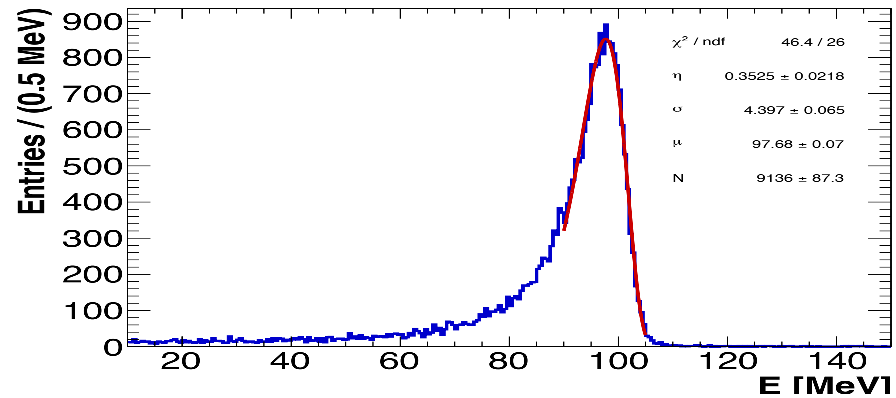
- ❑ A **typical Mu2e-II event in a channel of the calorimeter innermost rings** is in Top-left plot. (obtained by increasing x3 the background overlay in Mu2e simulation)

- ❑ The hits have been smeared in signal shape **assuming a well performing CsI calorimeter** with 100 ns full width signal. **The continuous pileup observed is really difficult to be resolved.**

→ **The energy reconstruction** of the main cluster is spoiled by the breaking of the clusters, wrong pileup separation, **failing in more than 50% of the cases**.

Mu2e-II: occupancy/rec in the first rings (20 ns)





- The same events of previous page were reconstructed by applying a smearing of 20 ns (full width). **A high density set of hits is observed but they are pretty simple to be resolved.**

- **The energy reconstruction of the main cluster is not spoiled by pileup.**

Conclusions:

In Mu2e-II we need a calorimeter with signals having

20-30 ns total width (**10 ns rise time**, **10-20 ns decay time**)

Mu2e-II technical specifications: hottest regions

- It is clear that **at least the calorimeter innermost region** (first 3-4 rings) needs to have better scintillation and photo-sensors.
- **More simulation studies needed to decide** if the whole calorimeter has to be replaced or not.

The following requirements apply to the hottest regions :

→ Still optimal to have scintillators with a high light yield (20 pe/ MeV)
→ Scintillators should be able to stand 0.5 Mrad in 5 years of running
→ Fast scintillation time / Cherenkov (< few ns)
→ Fast photosensors able to stand a dose of 200 krad, 1.5×10^{13} n/cm^2
→ Fast electronics in order not to spoil the fast photosensors
→ Keep a high system reliability with 2 sensors/crystals

Even so the requirement is an MTTF of 10^6 hours!

→ Keep coupling in air (?) between photosensors and crystals to minimize outgassing and thermal gradients

Comparison between crystals

Specs/Crystal	Pbw0$_4$	PbF_2	BaF_2	CsI	LYSO
Light Yield (pe/MeV)	**10**	**2**	100 (400)	100	2000
Wavelength (nm)	420	UV-Blue	220 (350)	315	420
Emission time (ns)	10	prompt	0.9 **(600)**	**30**	**40**
Rad-hardness LY loss @ 1 Mrad	**80%**	**Not well known**	50%	**80%**	50%
Density (g/cm^3)	7.0	7.0	4.6	4.6	7.0
Radiation Length (cm)	0.9	0.9	1.8	2.0	0.9

- **BaF_2 is the best crystals for the hottest places.**
- It matches all requirements .. .. apart the existence of a slow component.
- **It has also the same density of CsI → good for mechanical replacement!!**

First candidate: BaF_2 + fast sensors

BaF_2 is an excellent candidate as you have seen (will see) during this workshop. Many studies and combinations with sensors have already been tried or are being investigated:

- BaF_2 with/without doping
- Suppression of long components by means of:
  → ALD interference to get solar blind windows on the sensors
  → Nanoparticle coatings on sensors
  → External interference optical filters
- Different kind of fast sensors, insensitive to B-Field:
  → APDs
  → SiPMs
  → MCPs/LAAPD

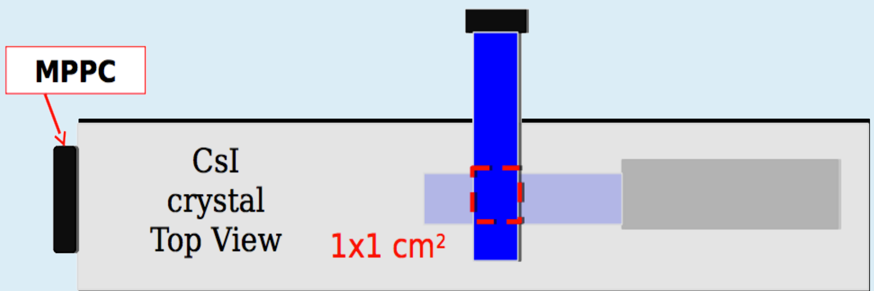
A first look to BaF_2 + SiPMs (1)

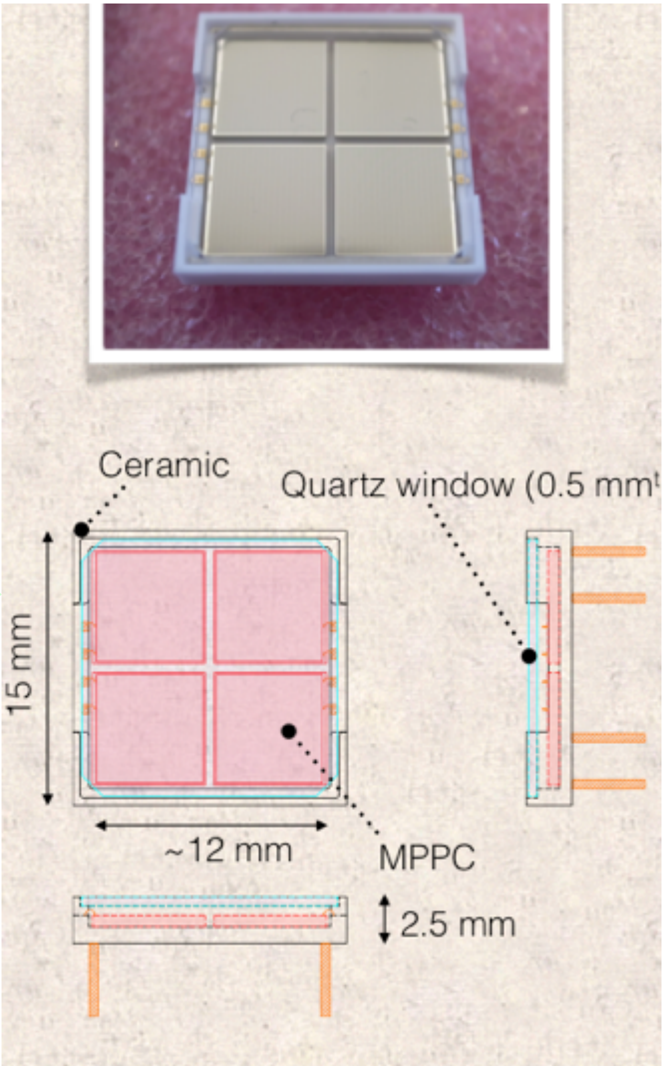
A good indication of the BaF_2 capability was shown by the work done in Mu2e when we carried out the Technical Choice between CsI and BaF_2. Measurement of BaF_2 with MPPC (MEG UV extended version with quartz-window).

The four 6x6 mm^2 SiPM cells were used in Series configuration.

LNF-group

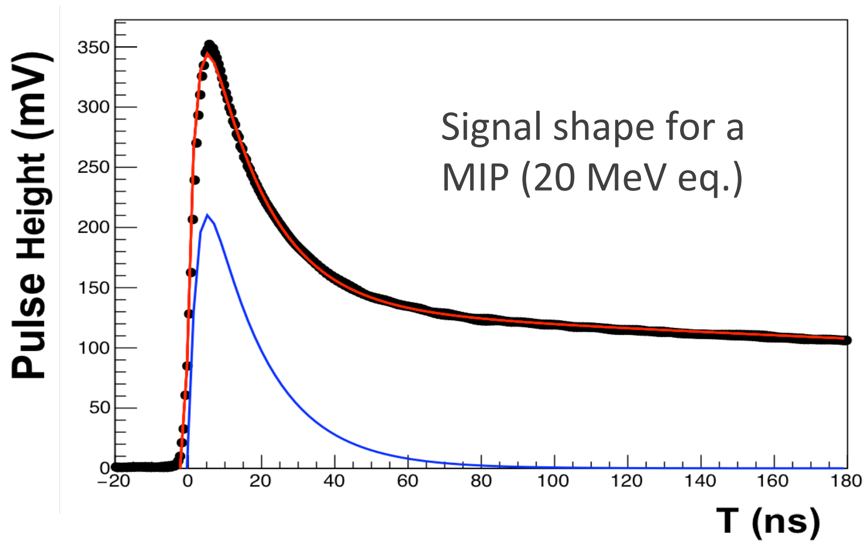
- Crystals between two scintillation counters
- MPPC readout

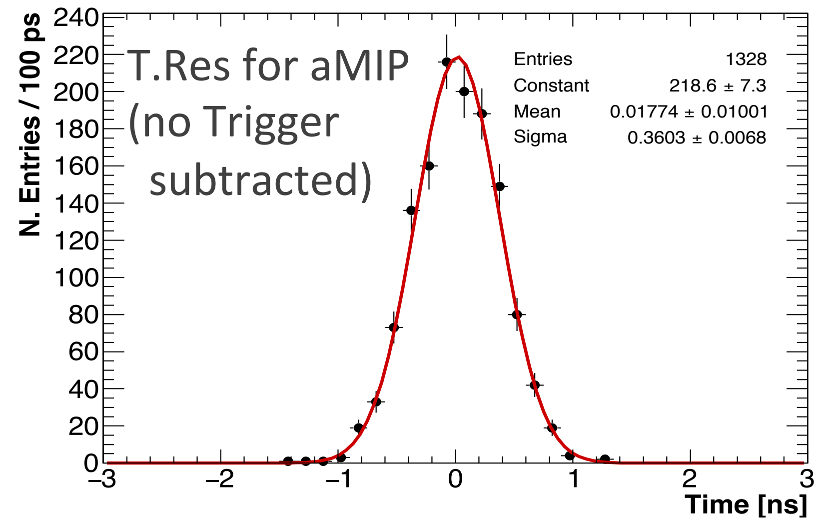




All measurements performed w.o. any optical grease

A first look to BaF_2 + SiPMs (2)





<u>SiPMs indeed are still a highly favorite choice:</u>

1) They present a fast rise time (< 10 ns)
2) Without too much effort we have got a signal full width < 60 ns
3) They present large gains and high MTTF
4) They can work in combination with external optical filters or with Solar Blind interference filters

SiPMs @ Mu2e-II: Radiation hardness and cooling

❑ Cooling and Irradiation

→ SiPMs suffer from neutron irradiation. Their leakage current linearly increases with fluence. In Mu2e, at 0 °C we expect to reach 2 mA/channel in the hottest regions at the end of data taking.

→ To survive, we have to reduce temperature and bias voltage. The thumb rule is a factor 2-2.5 reduction in current when lowering the temperature (reducing operating voltages) of 10 degrees (1 V).

→ To keep a situation similar to Mu2e, **we estimate that in Mu2e-II we need to reach an operating temperature of -25/-30 °C**.

This should be taken into account in the design

SiPMs @ Mu2e-II: Radiation Induced Current

- ❑ In Mu2e, there is a current drawn by the sensors that is due to the direct illumination by low gamma irradiation or by induced phosphorescence.

- ❑ **For CsI and BaF_2 this has been measured during Mu2e R&D path**

→ The highest RIC source is the dose, a smaller contribution from neutrons.
→ In Mu2e, we expect to have a RIC of 200-300 uA dominated by beam-flash dose.

→ In Mu2e-II, this situation could be reversed, neutron fluence coming from capture on the target could be the highest source.

- ❑ **This RIC is independent from the photosensor cooling** and depends only on the crystal "induced" light

→ **In Mu2e-II, the average current induced by neutrons could reach 2 mA/channel**

SiPMs @ Mu2e-II: Radiation Induced Noise

- From the RIC we estimate the radiation induced noise (RIN) in MeV looking at the fluctuation of the photoelectrons in a given gate.

- In Mu2e we evaluated the RIN (with SiPM) in a 200 ns gate
  - → We estimate around 300-500 keV / channel
  - →The noise factor is proportional to SQRT(Npe−rin) i.e. to SQRT(RIC)
  - → In Mu2e-II, we expect a factor SQRT(10) = 3 of increase in RIC
  - → This means a factor of 3 on RIN → **1-1.5 MeV noise per channel.**

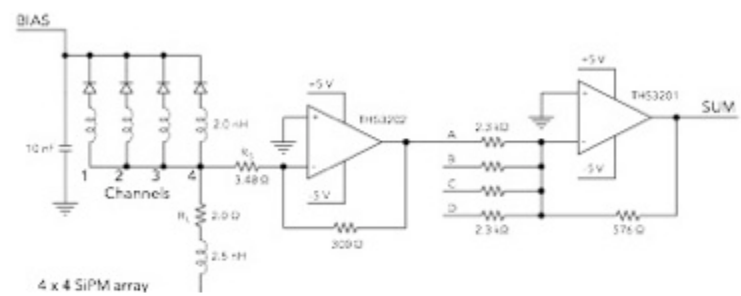
- **Fortunately the technical requirement of requiring for Mu2e-II narrow signals helps to reduce the noise contribution:**
  - → In MU2E we evaluate the noise in 200 ns.
  - → In MU2E-II we can do that in 20-30 ns
  - → The noise scales down with SQRT(DT-Gate) → it will be reduced to 1/3

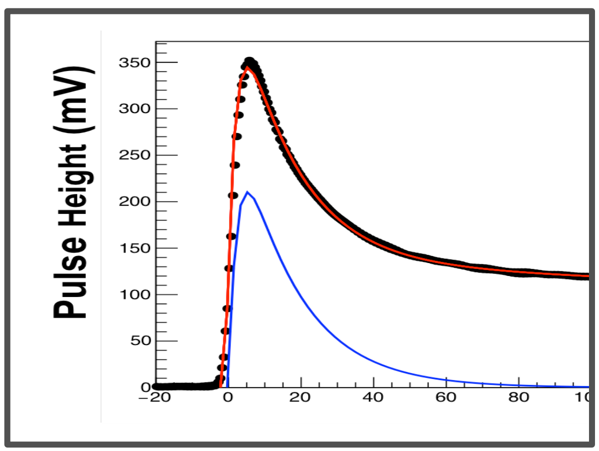
The RIN noise in Mu2e-II will be comparable to Mu2e

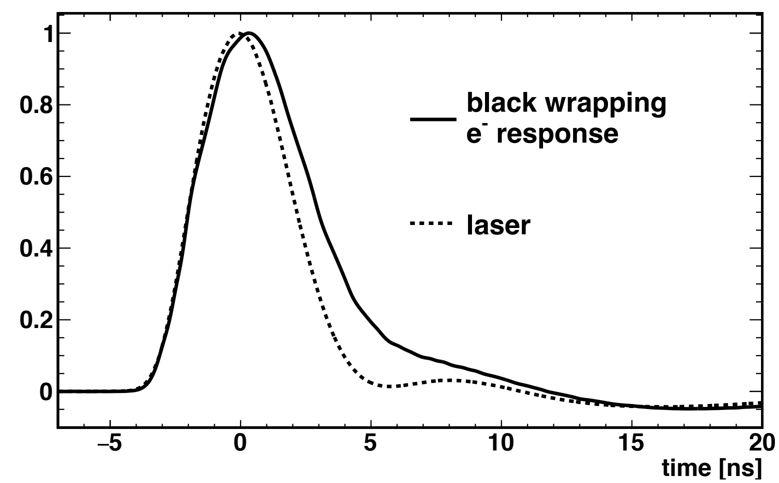
SiPM preamplification

Corradi/Miscetti

- 4 6x6 mm^2 SiPM in series + Preamp + Shaper (ala Mu2e) ..
- 16 3x3 mm^2 SiPM in Parallel configuration +
  2 stages of operational sum (4 x 4) + single pole shaper (ala g-2)







For Mu2e-II → BaF_2 + SiPMs matched with the g-2-like solution is favored

Possible digitization scheme (1)

- In Mu2e we are digitizing signals with Waveform sampling at 200 Msps
- This is working nicely in Mu2e but has to be abandoned for Mu2e-II

- The sampling will be too slow for pileup separation and timing resolution for the "much narrower" envisaged signals of 20 ns → **at least 1 Gsps needed!**
- Increasing the sampling will drastically increase power consumption
- X 10 radiation hard

<u>Possible scheme solution: fan-out signals at MB level</u>

→ First copy discriminated and digitized with multi-hits TDC (picoTDC of CERN)

https://indico.cern.ch/event/548960/contributions/2225641/attachments/1303647/1947295/DT_elec_up_DR.pdf

→ Second copy readout with a lower rate FADC

→ Find RadHard components
POLARFIRE FPGA and DCDC converters (FEAST of CERN)

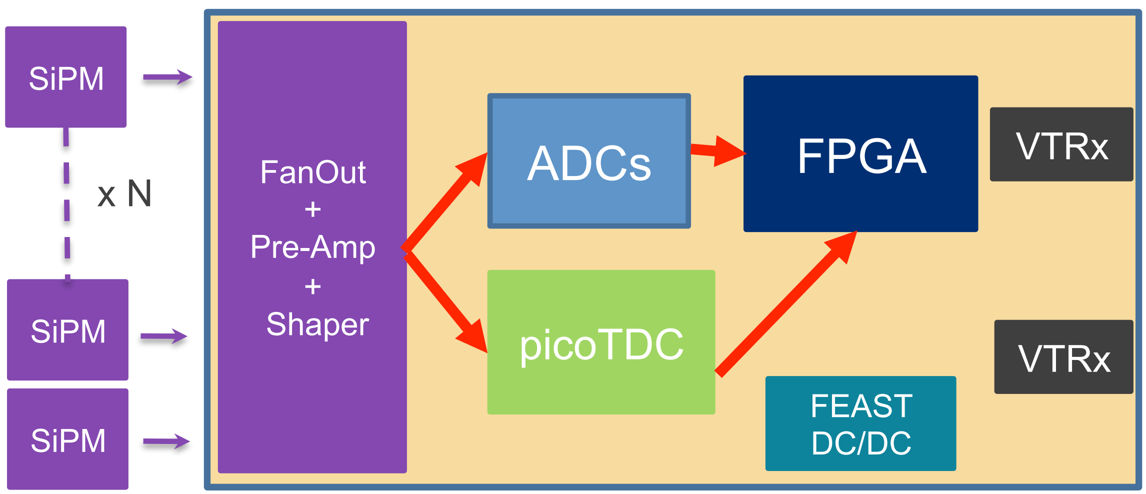
Spinella/Pezzullo

http://project-dcdc.web.cern.ch/project-dcdc/public/Documents/FEAST%20datasheet.pdf

Possible digitization scheme (2)

- Instead of sampling the waveform we want to use TDCs for:
  - Precise time reconstruction
  - Charge evaluation using time over threshold
- Rad hard ADC @ 50-100 MHz for charge reconstruction? **(simulation needed)**
- The **PolarFire** FPGA should be sufficiently rad hard
- **VTRx** optical transceivers
- **The board could also include the PreAmp + shaper section**
  (thanks to the SiPM or MCP-LAPPD high gain)
  - TID reduction & neutron flux by a factor of ~ 10
  - simplified cooling system

Spinella/Pezzullo



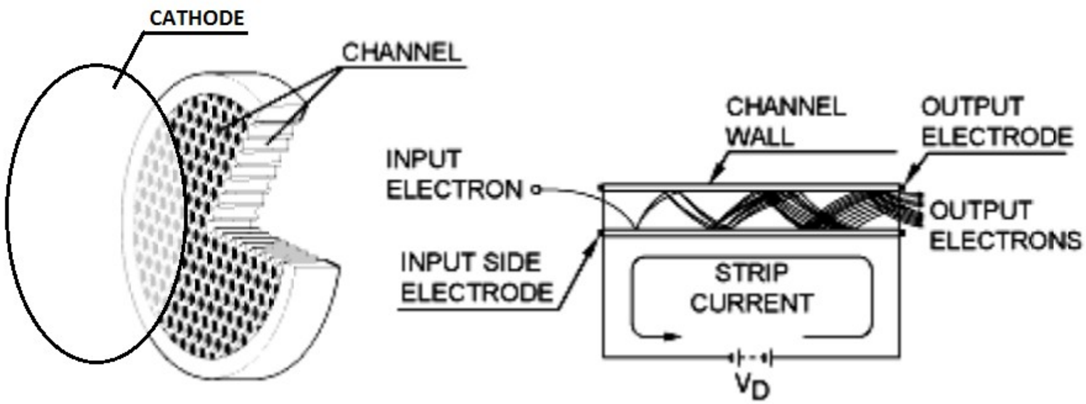
Mu2e-II Calor R&D studies at JINR

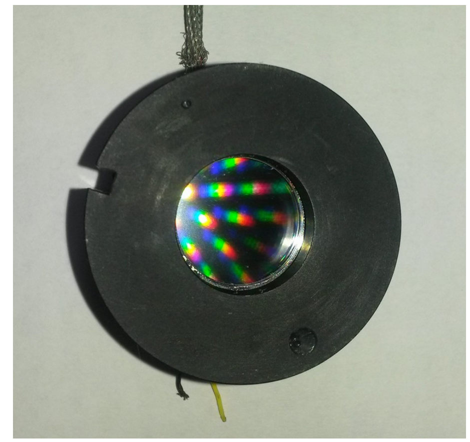
I was asked to present these three slides from JINR group, to summarize two possible R&D developments:

1) The first is a work on prototypes of AlGan cathodes + MCP.
   This has been presented by N.Atanov at the NTHEP 2016 conference in Montenegro and has been reported as DocDb# 8287.

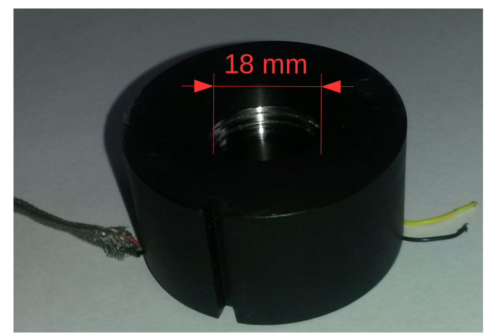
2) The second one is a proposal of Y.Davydov & V.Glagolev of production of optical filters in collaboration with INCROM and with the Valivov GOI (State Optical Institute) of St. Petersburg.

JINR-1: prototype of AlGan photocatodes+MCP (1)



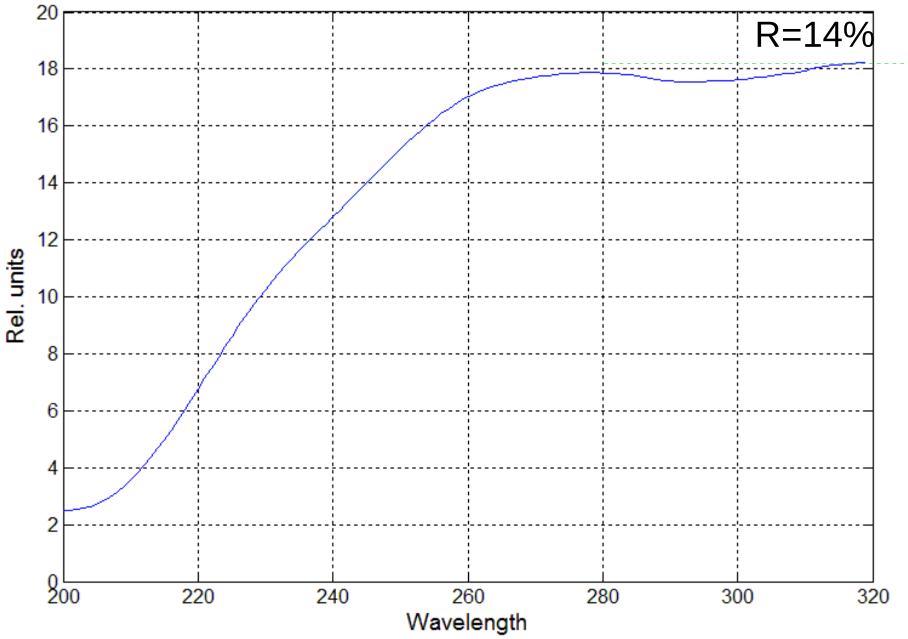


MCP consists of a two-dimensional periodic array of very-small diameter glass capillaries (channels) fused together and sliced in a thin plate. A single incident particle enters a channel and emits an electron from the channel wall.

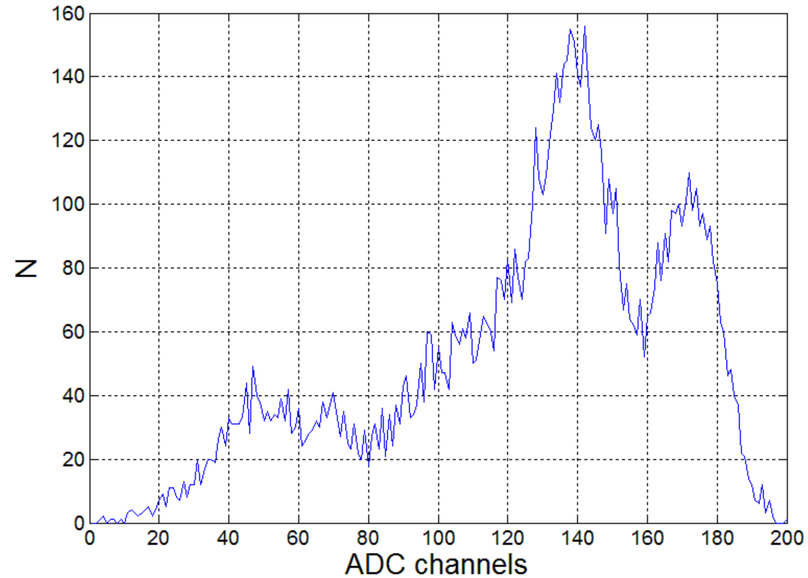


AlGaN photocathode with 320 nm long-wavelength edge was combined with MCP in a single device with 18 mm window diameter.

JINR-1: prototype of AlGan photocatodes+MCP (2)



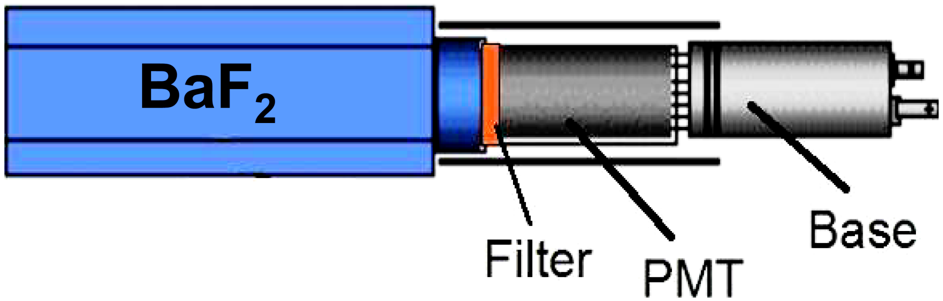
a) AlGaN structure with edge ~260 nm

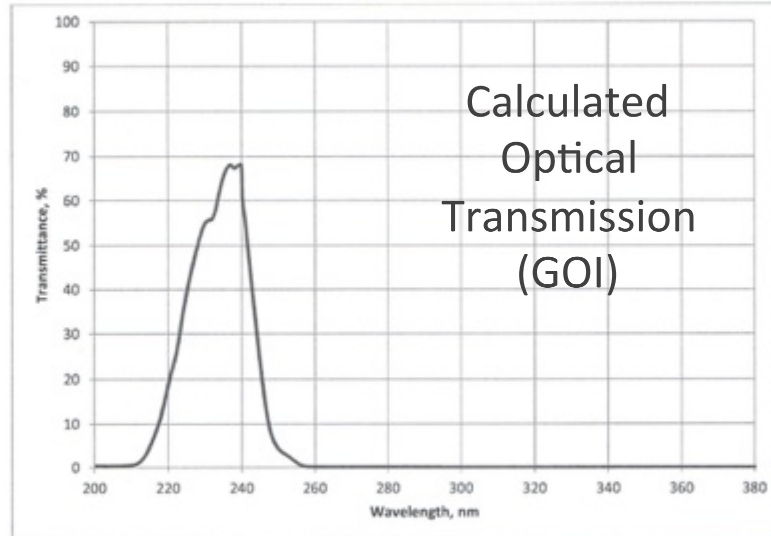


Photomultiplier with BaF_2 crystal was used to measure Co60 spectrum. For mixed signal (fast + slow component, 2 ns gate) we can obtain energy resolution ~10% FWHM.

- Solar-blind photocathodes with long-wavelength edge 260 nm and 280 nm, regulated by Al mass fraction in AlGaN alloy, were successfully tested.
- One should build photomultipliers with these photocathodes to exploit time resolution of fast BaF_2 component

JINR-2: proposal of using an external optical filters





- Collaboration with INCROM firm (Piotr Rodnyi & Eugeny Garibin) and GOI of St. Petersburg to develop an external optical filter, highly efficient on UV and Solar Blind
- Short term goal is to test the optical filter with BaF_2 and UV PMTs
- If working, an optical coupling with quartz SiPMs or other device is possible.
- This could be a simple device to use in combination with other options (BaF_2 doping, nanoparticle-coating, MCP .. and so on)

Summary table between options → FOM

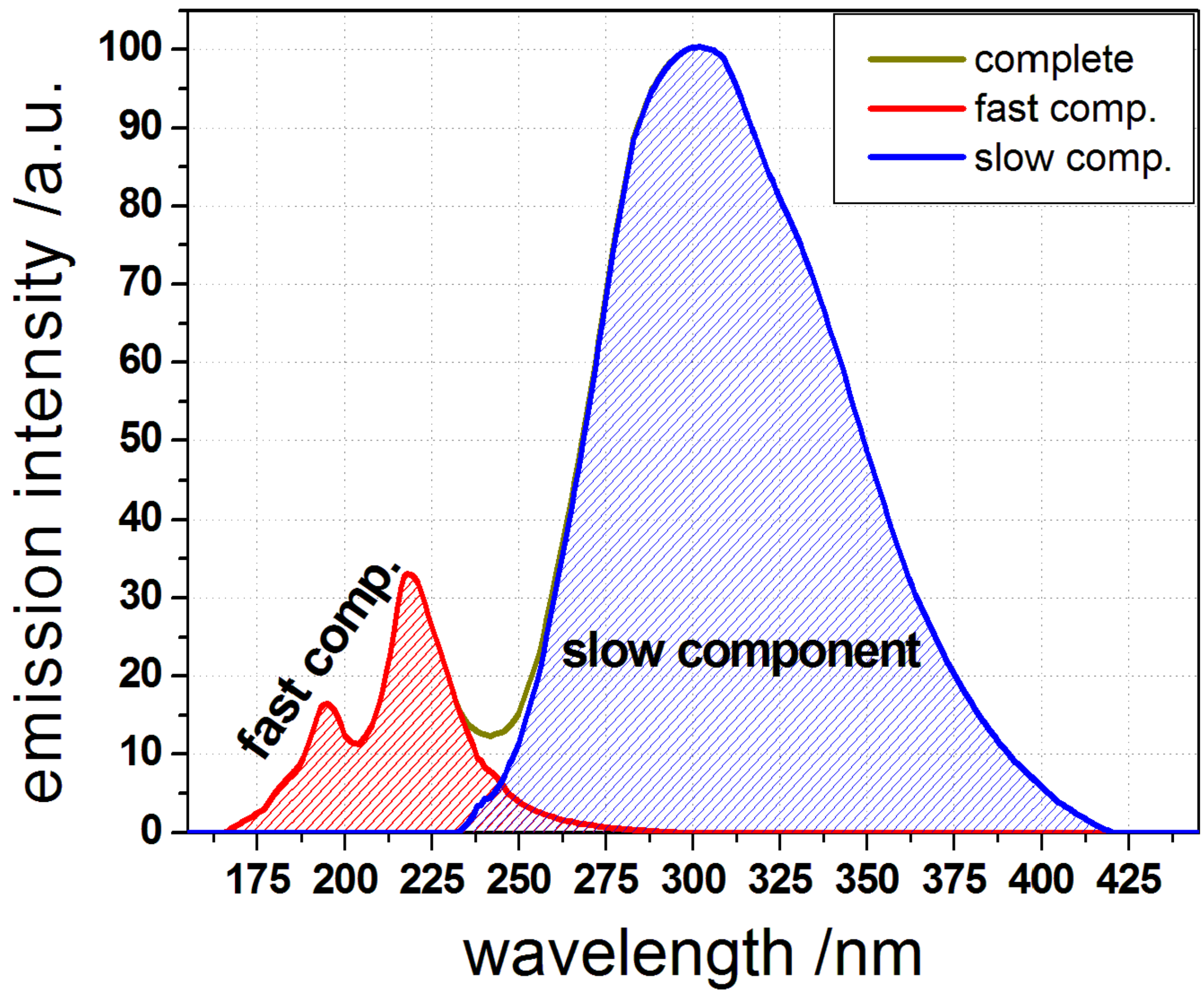
	Speed/ Timing	Pileup	LY	Noise	Rad-Hardness	RIC and RIN
PbF_2	***	***	*	*	???	???
LeadGlass	***	***	*	*	*** / ?	???
BaF_2	***	*	***	***	***	**
BaF_2+Y	***	***	**	**	???	**
SB APD	***	**	***	*	???	???
SB SiPM	***	**	***	***	*** (- 25 C)	?
NanoSiPM	**	???	***	***	*** (- 25 C)	?
AlGan MCP Or LAAPD	***	***	***	***	???	???

I believe that, whenever ready to start with a Mu2e-II R&D process, the various options on the floor should be evaluated/compared following a list of technical requirements **similar** to this table in order to build a FIGURE OF MERIT for down-select → **costs/integration considerations can then be added.**

Nice examples of such a list of options on the next talks …

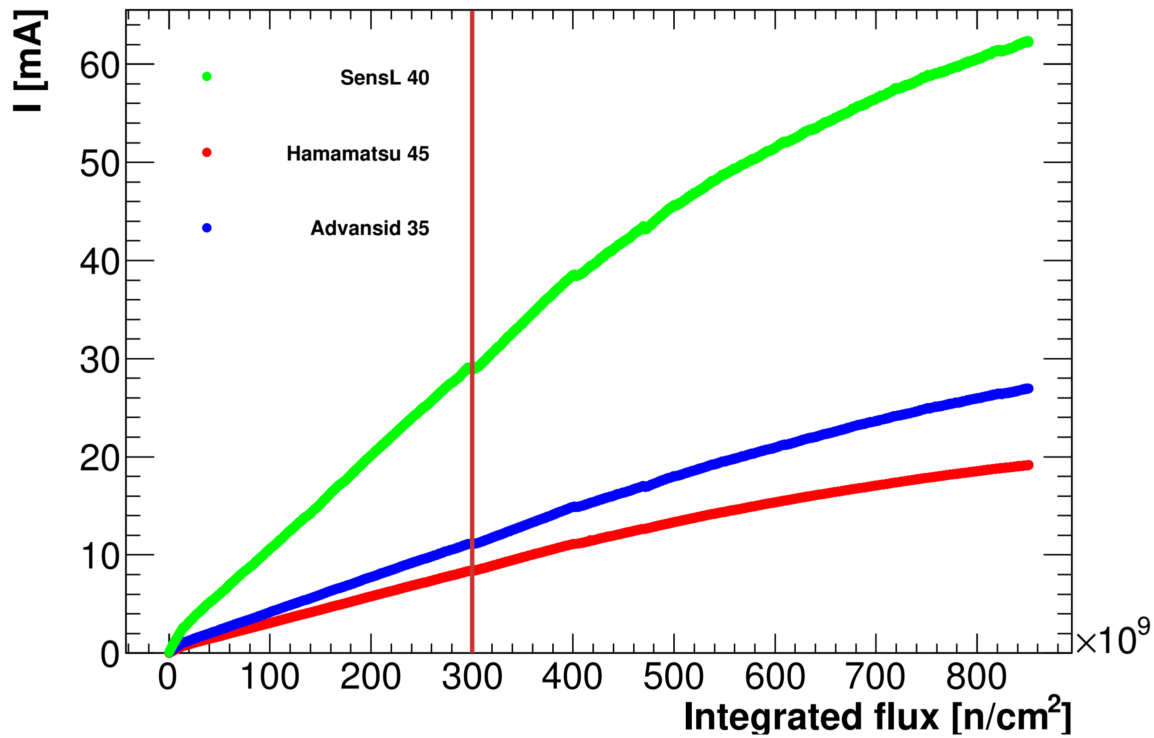
Additional material

BaF_2 fast and slow components

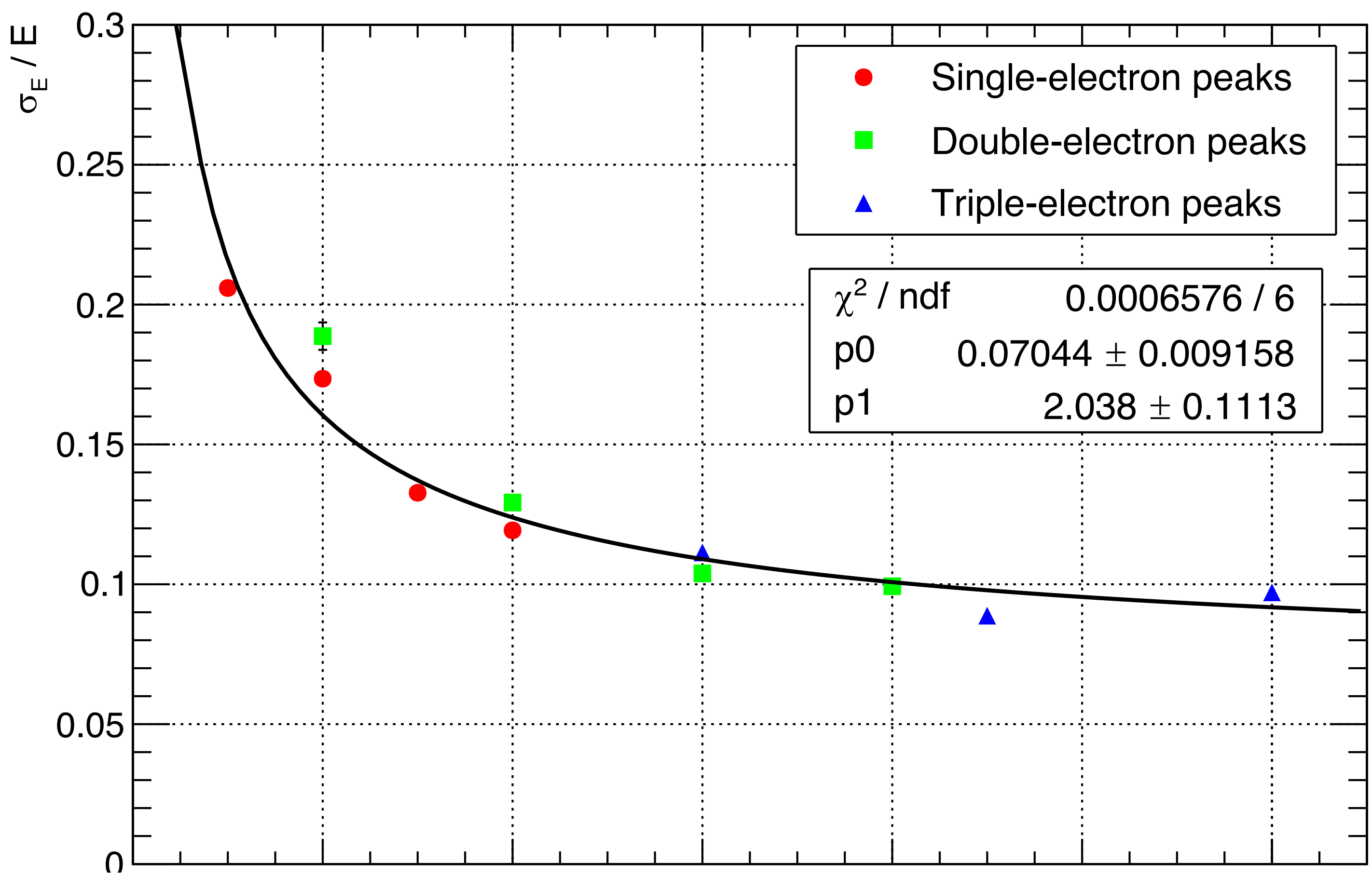


Mu2e SiPM status

- Custom design of Large Area UV-extended Silicon Photomultipliers (SiPMs) array
- Array of two series of 3 (6x6) mm^2 monolithic SiPMs with 50 mum pixels



I. Sarra: Padme SAC Test beam



PbF2 crystals with UV PMT readout .. 5 ns signal width

FEAST DC/DC converter

- The current best candidate is the **FEAST** DC/DC converter developed @ CERN:

Features

- Input voltage range 5 to 12V
- Continuous 4A load capability
- Integrated Power N-channel MOSFETs
- Adjustable switching frequency 1-3MHz
- Synchronous Buck topology with continuous mode operation
- High bandwidth feedback loop (150KHz) for good transient performance
- Over-Current protection
- Under-voltage lockup
- Over-Temperature protection
- Power Good output
- Enable Input
- Selectable Power Transistor size ($5/5^{th}$ or $2/5^{th}$) for improved efficiency at small loads (<600mA)
- Radiation tolerant: TID up to >200Mrad(Si), displacement damage up to $5\text{-}8{\cdot}10^{14}n/cm^2$ (1MeV-equivalent), no destructive SEEs up to $>30MeVcm^2mg^{-1}$, SEFI (reset) cross-section in a 230MeV proton beam $\sim 2.8{\cdot}10^{-13}$ cm^2

http://project-dcdc.web.cern.ch/project-dcdc/public/Documents/FEAST%20datasheet.pdf

picoTDC from CERN

- The current best candidate is the **picoTDC** under development @ CERN

Interfaces

- Power: 1.2v, ~1.0W (64ch, 3ps),
  ~0.5W (64ch, 12ps)
  ~0.3W (32ch, 12ps)
- Hits: Differential SLVS (LVDS “compatible”)
- Time reference: 40MHz SLVS
  - Low jitter reference critical for high time resolution
- Trigger/BX-reset/reset: Sync Yes/No, Encoded protocol
- Control/monitoring: GBT E-link and I2C
- Readout SLVS: 4 readout ports of 1-8 signals
  - To be interfaced with GBTX or FPGA
- Packaging: ~300 FPBGA

ACES Workshop
picoTDC

Readout

- 1 or 4 readout ports
  - 4 ports: High rate applications (e.g. non triggered)
    16 TDC channels per port
  - 1 port: Low-medium rate
    64 channels (or 32channels in 32 channel mode)
- Readout data: 32bit words
  - Headers, trailers, TDC data, status, etc.
- Readout ports interface
  - Byte wise:
    - 40, 80, 160, 320 MHz
  - Serial:
    - 8B/10B or 64B/66B encoding
    - Low speed: 40, 80, 160, 320 Mbits/s
    - High speed: 1.28 Gbits/s
- TDC readout bandwidth:
  - Max:
    320MHZ x 8 x 4 = 10Gbits/s (~4Mhits/s per channel without triggering)
    1.28Gbits/s x 4 = 5Gbits/s
  - Min: 1 x 40Mbits/s= 40Mbits/s

ACES Workshop
08.03.2016
picoTDC

https://indico.cern.ch/event/548960/contributions/2225641/attachments/1303647/1947295/DT_elec_up_DR.pdf