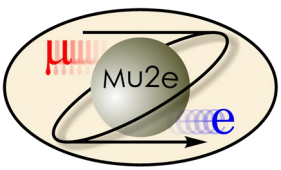# Development of the Mu2E electromagnetic calorimeter front-end and readout electronics

Franco Spinella
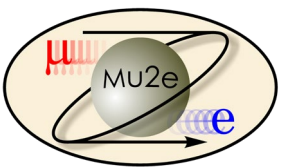## On behalf of the Mu2e calorimeter group

INFN Pisa

Outline

- The Mu2E experiment: goal and experiment layout
- The Electromagnetic Calorimeter
- Calorimeter electronics scheme
- Front End electronics
- Why a digitizer?
- Which requirements?
- Digitizer spec, architecture and design
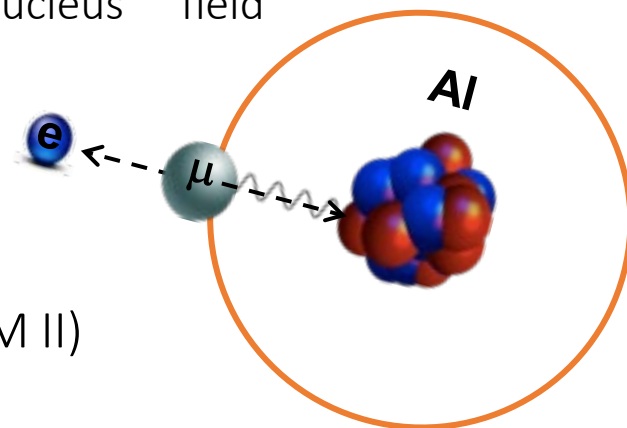- Qualification tests
- Conclusions

Mu2e goal

- CLFV strongly suppressed in SM: Branching Ratio $\leq 10^{-54}$
  → Observation would indicate New Physics

  $E_{CE} = m_\mu c^2 - E_b - E_{recoil} = $
  $= 104.97$ MeV

- *CLFV @ Mu2e*: μ- e conversion in a nucleus field
  → discovery sensitivity to many NP models

Al

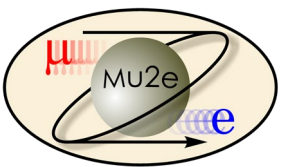## Goal:
10^4 improvement w.r.t. current limit (SINDRUM II)

μ-e conversion in the presence of a nucleus

$$R_{\mu e} = \frac{\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)}{\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1)} < 8.4 \times 10^{-17}$$

Nuclear captures of muonic Al atoms

(@ 90% CL, with ~ 10^{18} stopped muons in 3 years of running)

More information at mu2e.fnal.gov

Mu2e experiment layout

Production Solenoid (PS)/Target

- An 8 GeV proton beam hits a tungsten target and *produces* mostly π

- A *graded magnetic* field reflects slow forward μ/π and contains backward μ/π
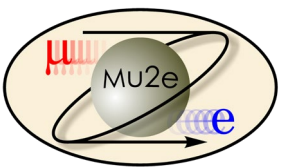
Detector Solenoid (DS): stopping target and detectors

- Stops μ^- on Al foils (decay time ~ 864 ns)

- *Events reconstructed by detectors, optimized for 105 MeV momentum*

- 1 T B field and 10^{-4} Torr vacuum in the detector zone
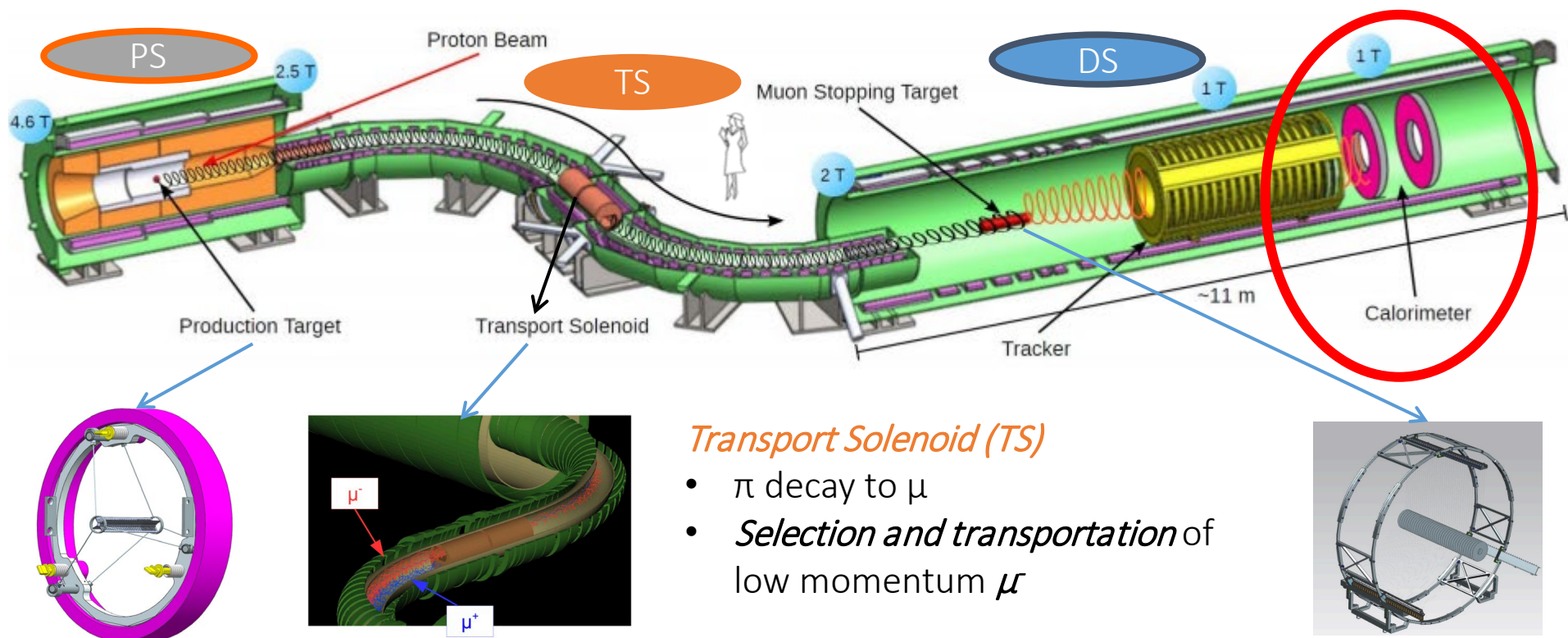
Transport Solenoid (TS)

- π decay to μ
- *Selection and transportation* of low momentum μ

The Electromagnetic Calorimeter

Calorimeter provides:

- *Particle Identification*: e/μ separation → reject μ background
- Improve the track pattern recognition
- Standalone trigger

@ 105 MeV

Calorimeter requirements

- energy resolution σ_E/E <10%
- timing resolution $\sigma(t)$ < 200 ps
- position resolution < 1 cm
- Work in vacuum @ 10^{-4} Torr
- 1 T Magnetic Field

1. **CsI Crystals coupled with Silicon PhotoMultipliers(SiPM)**
- Light Yield(photosensor)>20 pe/MeV
- Fast signal for pileup and timing
2. **Detector must Survive high radiation environment**
- TID of 90 krad/5 year for crystal
- TID of 75 krad/5 year for sensor
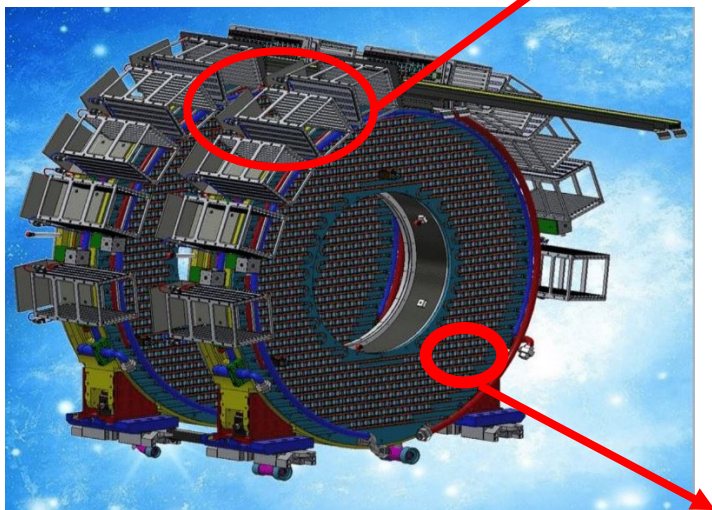- 3×10^{12} n/cm² for crystal
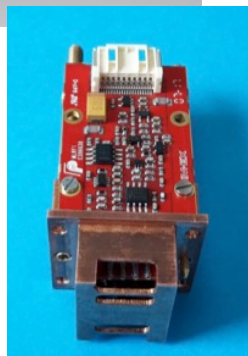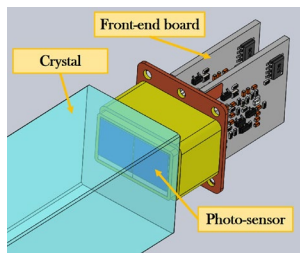- 1.2×10^{12} n/cm² for sensor
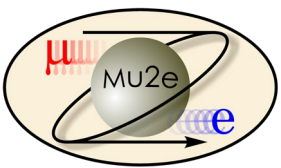
Calorimeter design
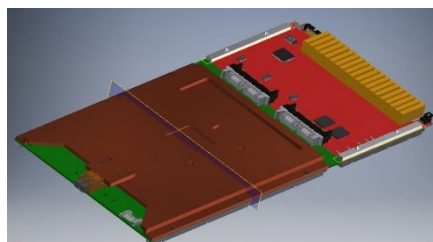
DIRAC + Mezzanine
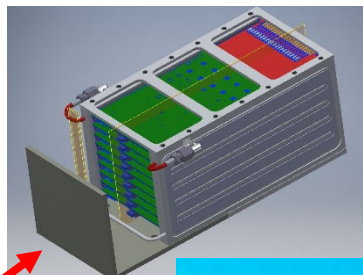
CRATE

Calorimeter disks

CsI crystals

CsI + SiPM + Holder + FEE

SiPM + Holder + FEE
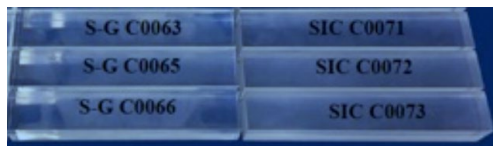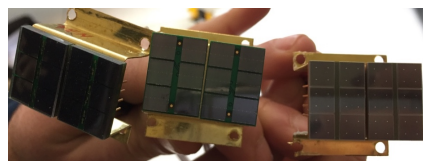
UV-extended SiPMs

- **High granularity** → 1348 undoped CsI crystals (3.4x3.4x20 cm^3)
- *Crystals arranged in 2* disks (inner/outer radius 37.4 cm / 66 cm, separation between disks 75 cm)
- *1 crystal coupled to 2* UV-extended *SiPMs* (14x20 mm^2 area) → 2696 electronic channels
- SiPM packed in a parallel arrangement of 2 groups of 3 cells biased in series
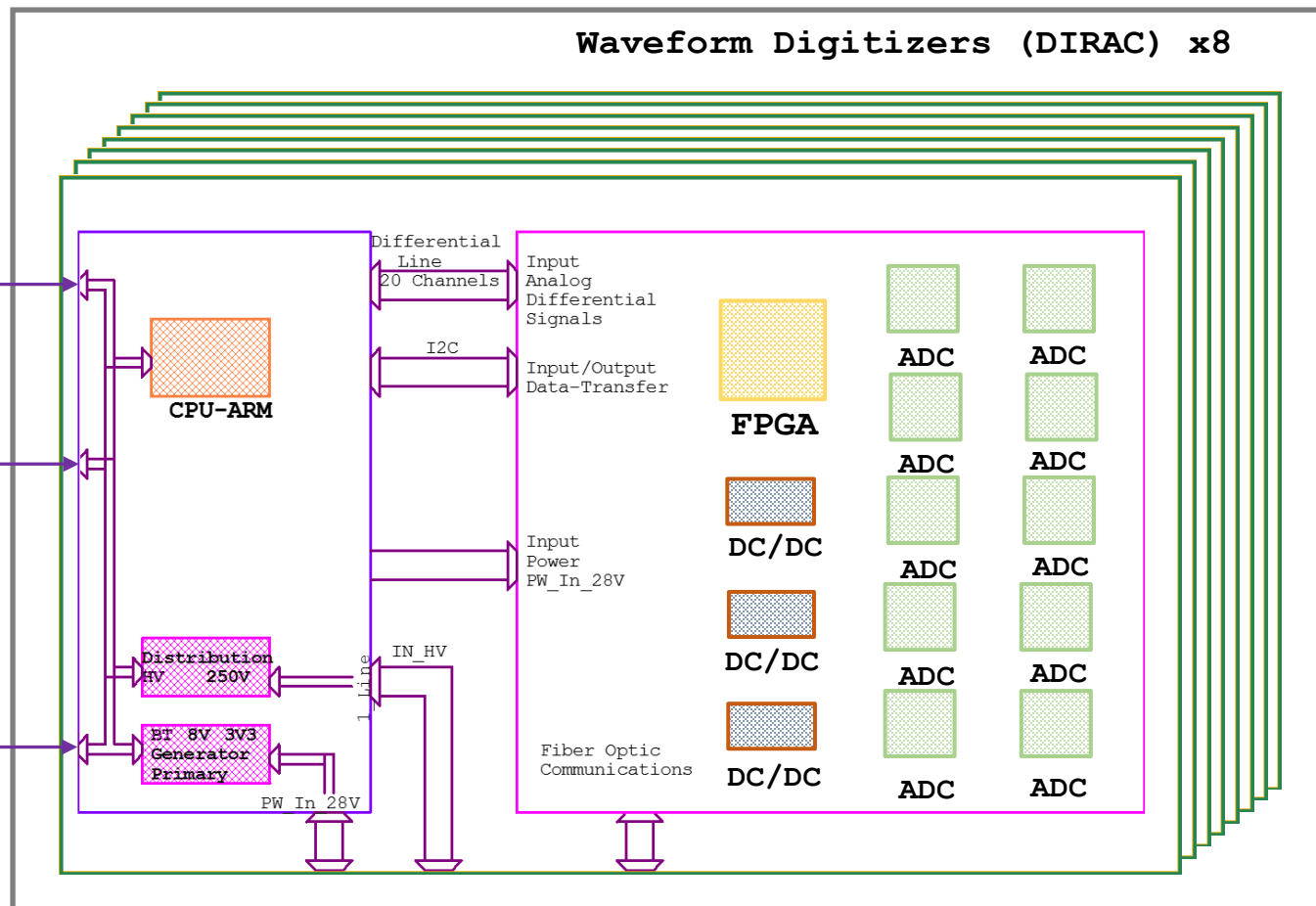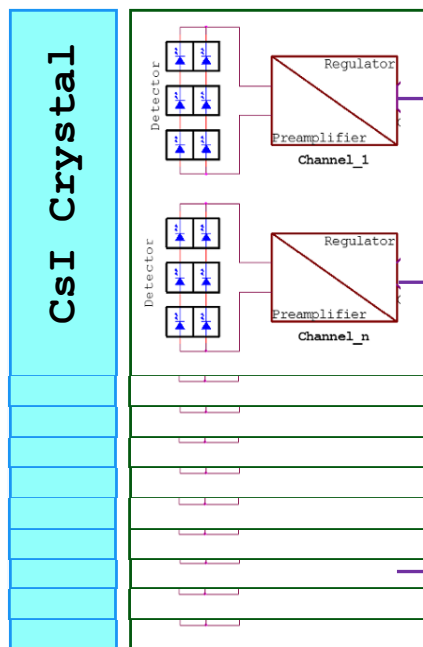- DAQ *crates located* inside the **cryostat** to limit the number of pass-through connectors
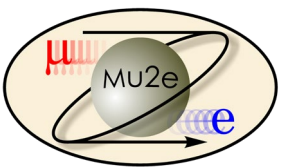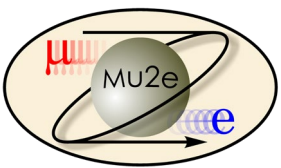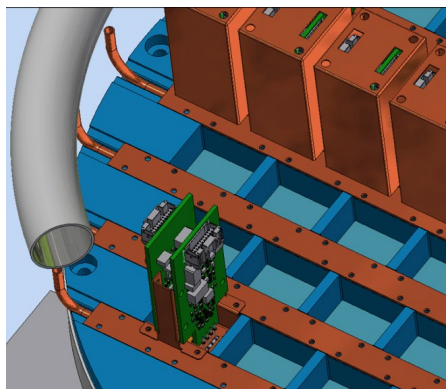
Calorimeter electronics scheme

Disks x2

Crate x10

Waveform Digitizers (DIRAC) x8

FEE x10 / board
(MPPC x2 / FEE)

CsI Crystal

Detector
Channel_1
Regulator
Preamplifier

Detector
Channel_n
Regulator
Preamplifier

CPU-ARM

Differential Line 20 Channels

Input Analog Differential Signals

I2C

Input/Output Data-Transfer

FPGA

ADC   ADC

ADC   ADC

DC/DC

Input Power PW_In_28V

ADC   ADC

Distribution HV   250V

IN_HV

1 line

DC/DC

ADC   ADC

BT 8V 3V3 Generator Primary

DC/DC

ADC   ADC

PW In 28V

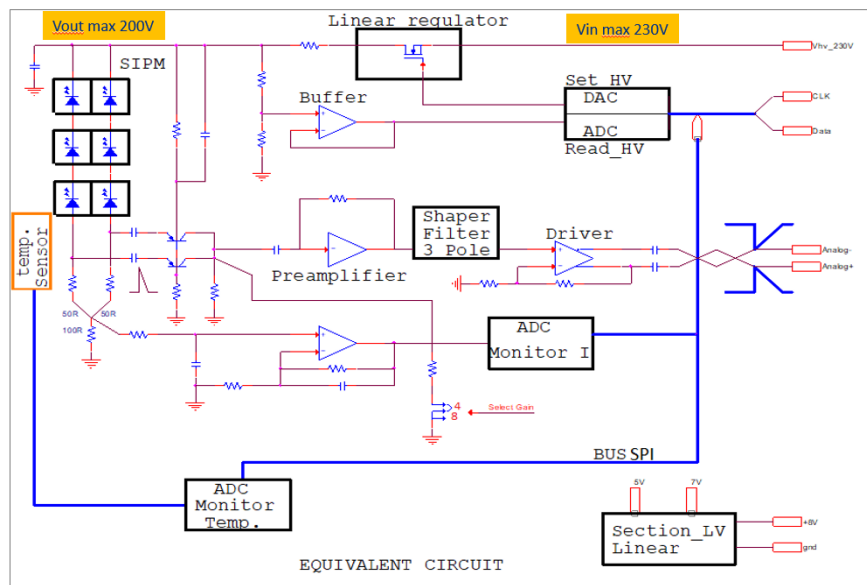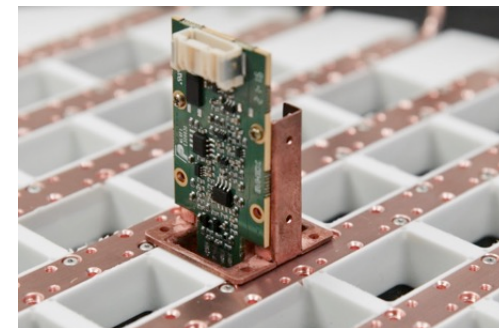Fiber Optic Communications

ADC   ADC

Front End Electronics

- FE boards connected to SiPMs to provide:
  - *Amplification & shaping*
  - Local **linear regulation** of the *bias voltage*
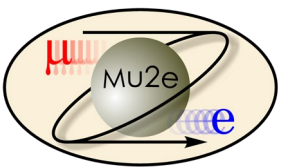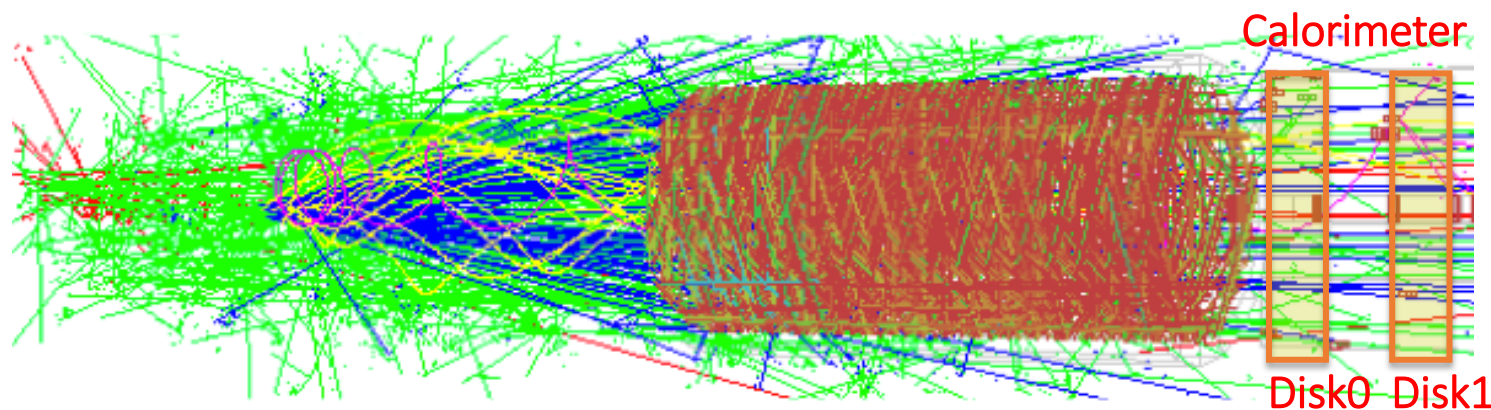 - Monitoring of current and temperature
  - Test pulse

FEE (X20)

MB + DIRAC (X8)

CRATE + DIRAC +MB X20 (10 + 10)
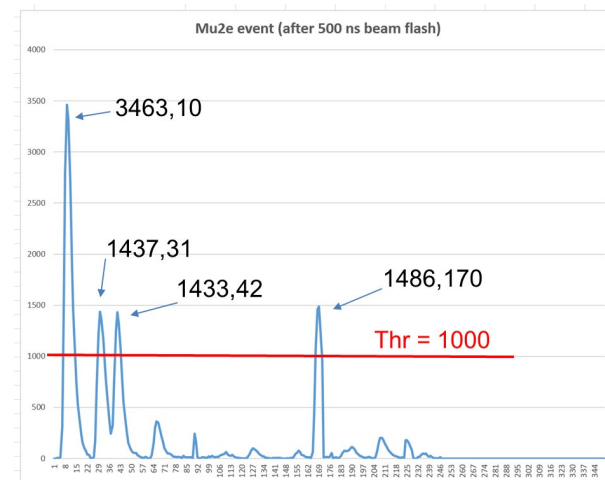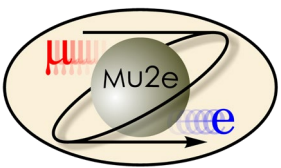
Why a digitizer?

Calorimeter

Disk0 Disk1

Typical 1.7 μs Mu2e event

Very intense particle flux expected in the calorimeter

Pile Up Example (Front End output)

We need *high-sampling rate* digitizers to resolve pile-up
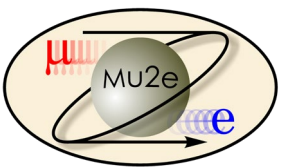
«Physics» requirements:

- Digitization requirements = function (calorimeter requirements)
- *Particle-Id*:
  - $\sigma_t < 200$ ps @ 100 MeV
  - $\sigma_E/E < 10\%$ @ 100 MeV
- We need to define:
  - *Sampling frequency* and number of *ADC readout bits* (impact time and energy resolution)
  - **Thresholds** (impact the total data throughput and Energy resolution)
  - **Zero suppression algorithm** (big amount of data)
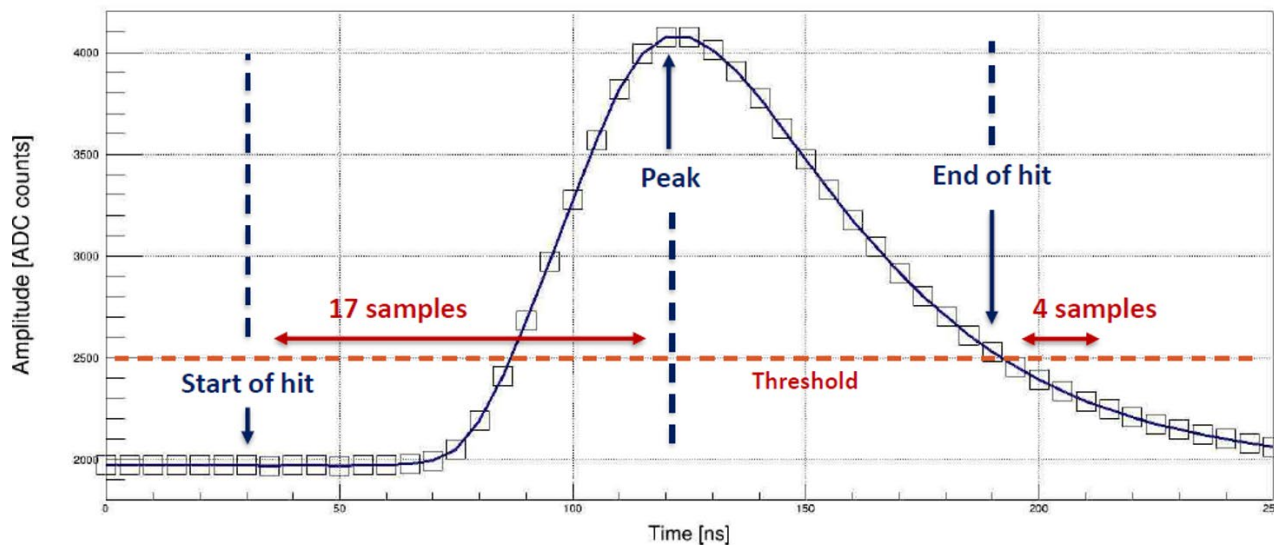
- Simulation results show that a digitizer with:
  - Sampling frequency of *200 MHz*
  - ADC with *12 bits resolution*

Matches the calorimeter requirements on time and energy resolution

|	150 MHz	200 MHz	250 MHz
8 bits	470 ps	440 ps	440 ps
10 bits	370 ps	250 ps	250 ps
12 bits	300 ps	**170 ps**	170 ps

Time resolution versus sampling frequency and ADC-bits

- *Time* is reconstructed by fitting the leading edge
- Time resolution for Conversion Electrons (~105 MeV)

	150 MHz	200 MHz	250 MHz
8 bits	9.8 MeV	8.0 MeV	7.8 MeV
10 bits	6.5 MeV	5.5 MeV	5.5 MeV
12 bits	6.2 MeV	5.5 MeV	5.5 MeV

Energy resolution versus sampling frequency and ADC-bits

- *Energy* is reconstructed from the total number of ADC counts
- Energy resolution (FWHM/2.35) for Conversion Electrons (~105 MeV)
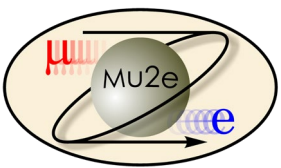
Environmental requirements?

- System located inside the cryostat → *Harsh Environment*:
    - o *Magnetic field of 1 T and 10^{-4} Torr vacuum*
    - o *Total Ionizing Dose (TID):*
        - ➢ *0.2 krad/yr (from simulation)*
        - ➢ *12 Safety factor (requested from collaboration)*
        - ➢ *5 years data tacking*
            - ➢ *TID 12 krad*
    - o *Neutron flux 5×10^{10} 1 MeV (Si)/yr (from simulation)*

- Mechanical constraints → DAQ crates located inside the cryostat:
    - o *Limited space →* 20 ADC channels/board
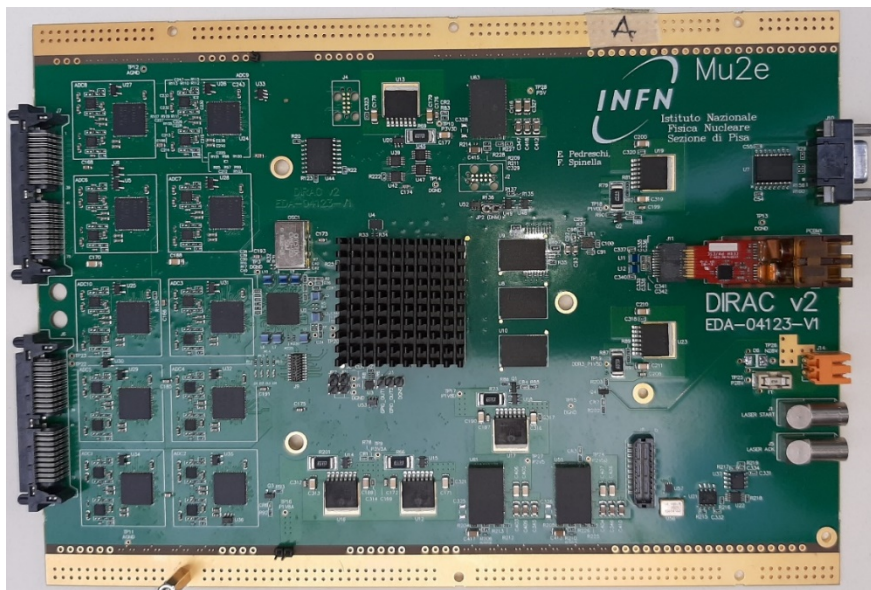   - o Limited access for maintenance → *Highly Reliable Design* mandatory
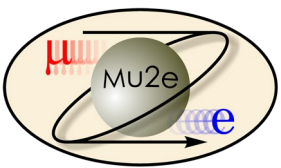
DIRAC architecture
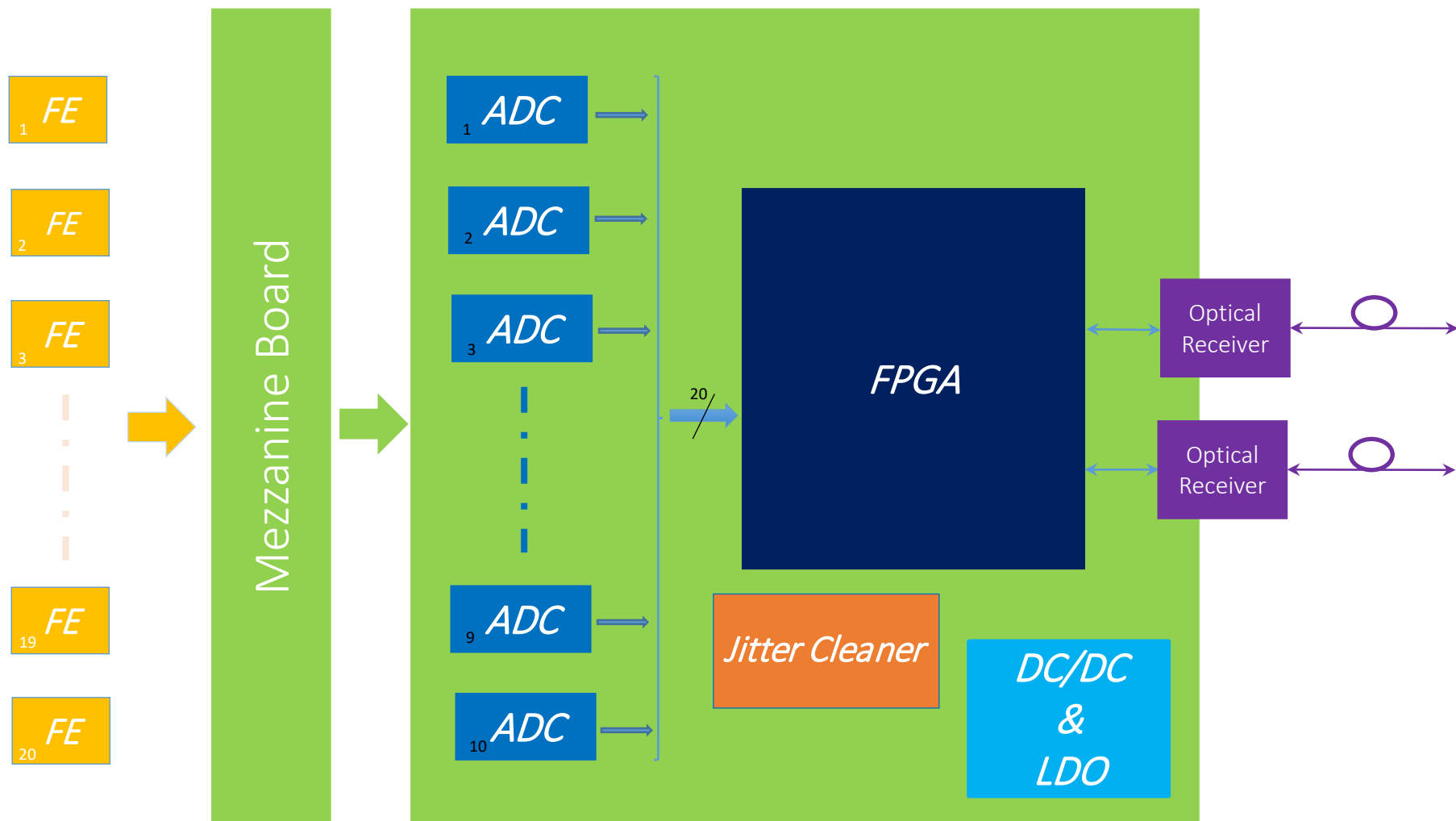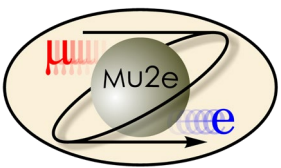
DIRAC design

PCB specs:
- *Material:* FR408-HR
- *Layers:* 16
- *Dimensions:* 233x165 mm
- *Thickness:* 2.127 mm
- *Differencial lines*: 100 Ω
- *Single ended lines*: 50 Ω

After an intense campaign of tests:
- *ADC*: ADS4229 (Texas Instruments®)
- *FPGA*: Polarfire MPF300 (Microsemi®)
- *DC-DC*: LMZM33606
- *LDO*: MIC69502 (Micrel®)
- *Jitter Cleaner*: LMK04828 (Texas Instruments®)
- *Optical Transceiver*: CERN VTRX
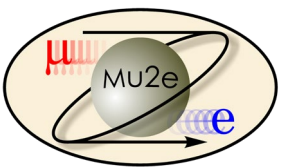
# DIRAC qualification tests

Several test campaigns were performed:

- *Total Ionizing Dose (TID)* → requested 12 krad:
  - YELBE @HZDR
    - γ from Bremsstrahlung (0<E<14MeV)
    - Extimated dose ≈ 20 krad/h @ 600μA
    - Single components test
  - Calliope @ENEA
    - Co60 source
    - Dose in function of distance: Max 2krad/h, requested 1krad/h
    - Full board test
- *Magnetic Field (B)*:
  - LASA @INFN Milano (1T)
- *Neutron irradiation test*
  - FNG @ENEA
    - Total neutron flux of 1.2×10^{12} n 1 MeV (Si) / cm^2
    - Total neutron flux of 6×10^{11} n 1 MeV (Si) / cm^2
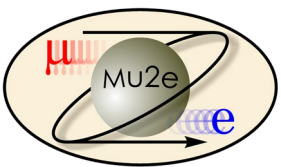   - LMZM33606 test
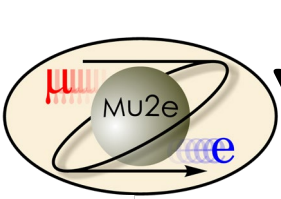
YELBE facility, HZDR lab, Dresden
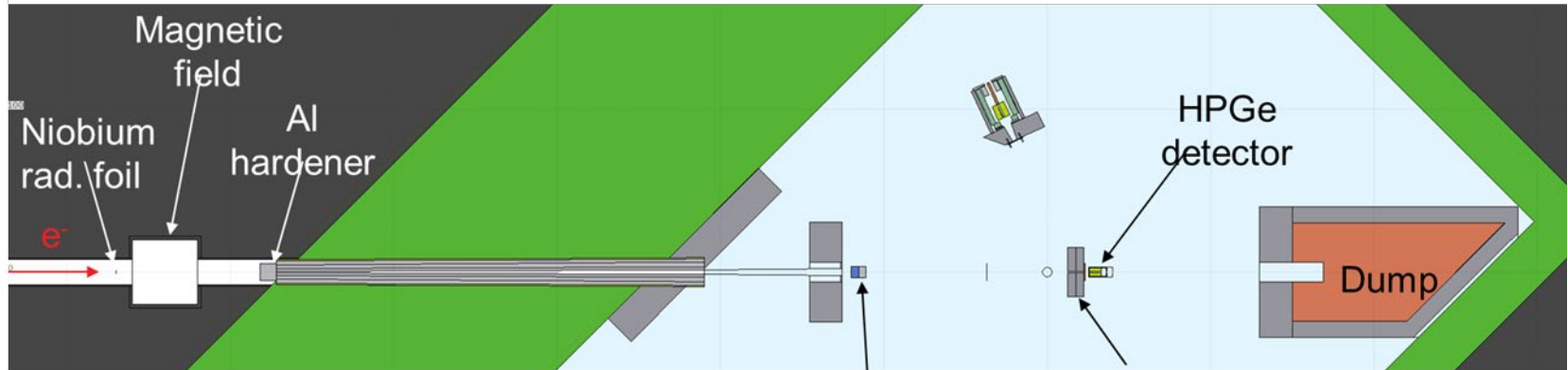
- Photons is produced per Bremsstrahlung by the electron beam hitting a niobium foil in the accelerator hall
- Nominal beam conditions: 17 MeV electrons, 600uA, 12.4 um niobium radiator foil

- Simulated *dose rate ≈ 18.6 krad/h*

- Active dosimetry used to confirm simulated dose rate
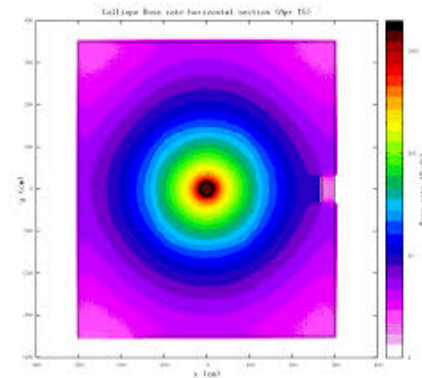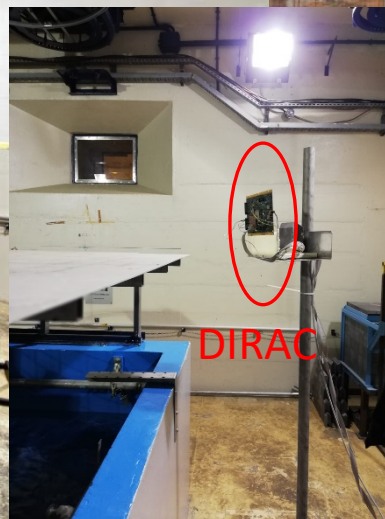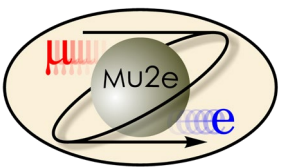

Photon fluence rate @ 1 uA e- beam
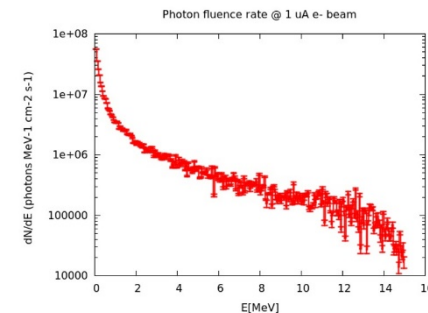
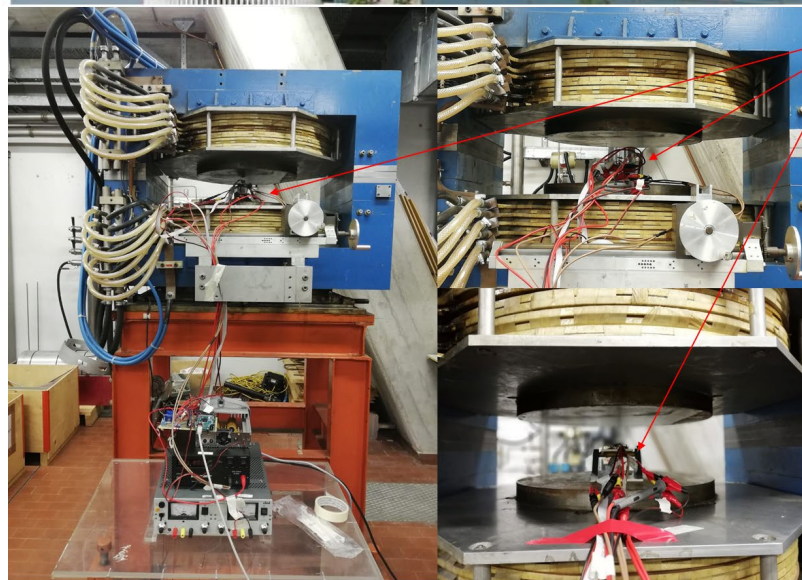# Calliope facility, ENEA Lab (Bracciano-Rome)

- Gamma rays at 1.17 and 1.33 MeV from *Co60*.
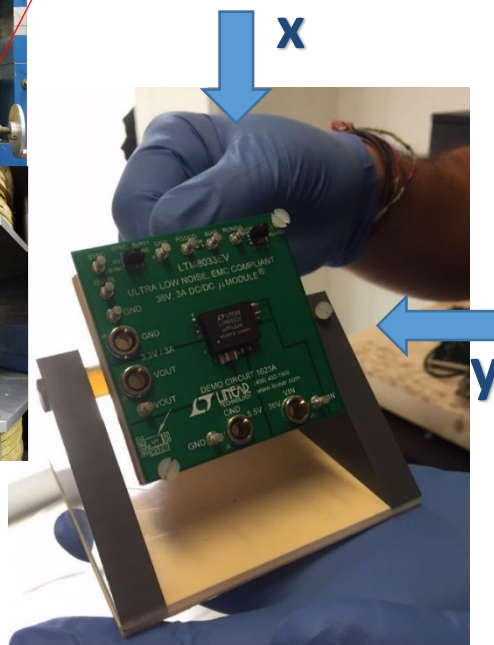- 3.7x10^15 Bq of activity.
- *Isotropic source*, flux scales with r^2
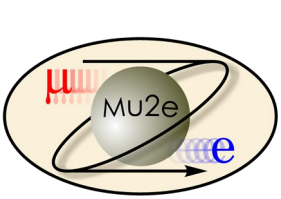

DIRAC

LASA facility, INFN Milano lab.

Laboratorio Acceleratori e Superconduttività Applicata

INFN-LASA

Istituto Nazionale di Fisica Nucleare

DCDC DEMO BOARD

x

y

z

- *Uniform magnetic field up to 1.2 T*
- We tested different orientations of the DCDC with respect to the magnetic field
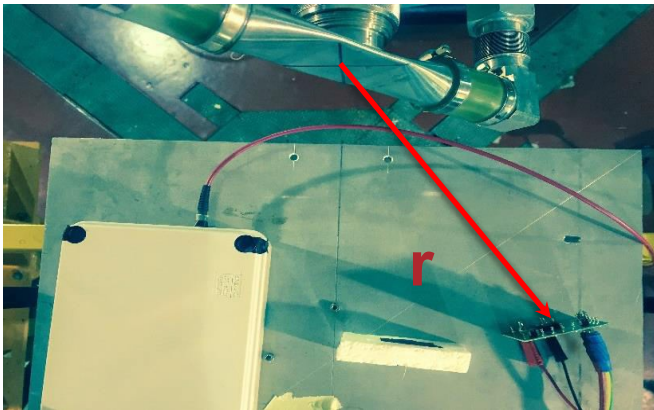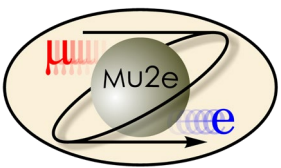- Same setup of the radiation tests

FNG facility, ENEA Frascati lab (Rome)

Frascati Neutron Generator (FNG) is a linear electrostatic accelerator in which up to 1 mA D+ ions are accelerated onto a Tritium target
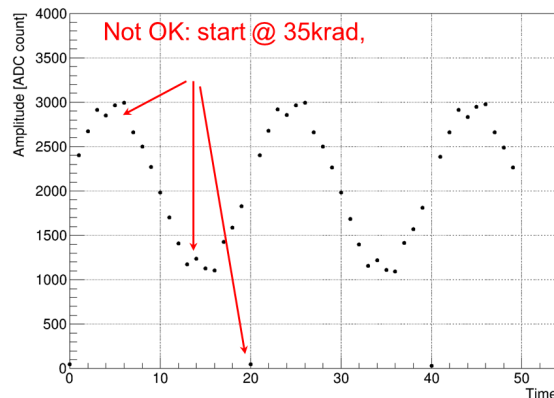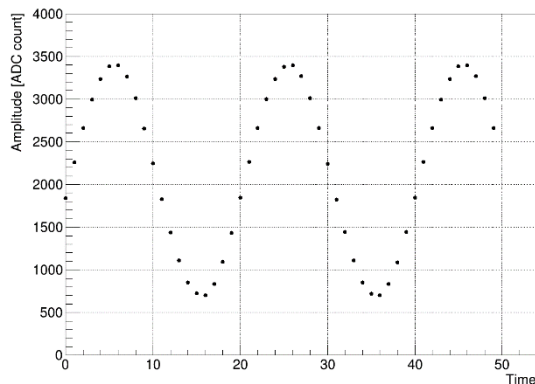
- *Up to 10^11 14 MeV neutrons/s*
- almost *isotropic source*, flux scales with r^2
- calibrated at 3% level using alpha particles

r

D+T→ α +n

DIRAC: TID test results

- Input waveform →4.5@10MHz, readout waveform:

Not OK: start @ 35krad,

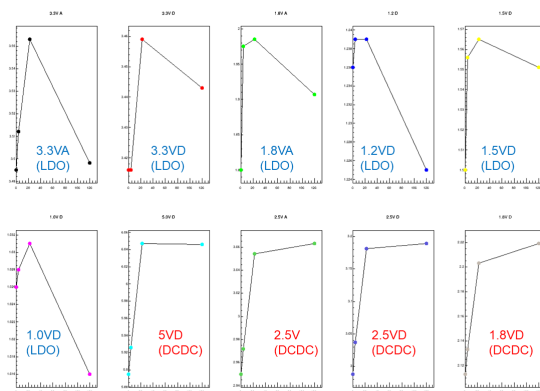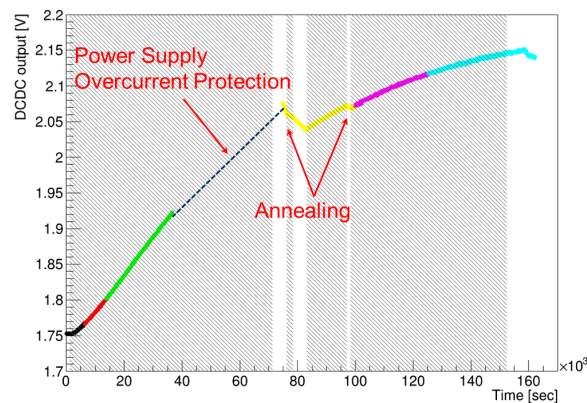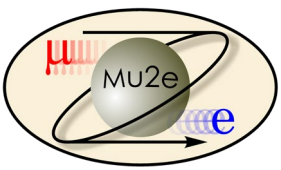*Conclusions*:
- 41 h beam time
- Nominal Dose Rate ≈ 1krad/h
- TID ≈ 41krad
- No evidence of broken components up to 35 krad
- LDO small increase, fast recover if no beam

- LMZM33606 and MIC69502 Vout(rad;t)

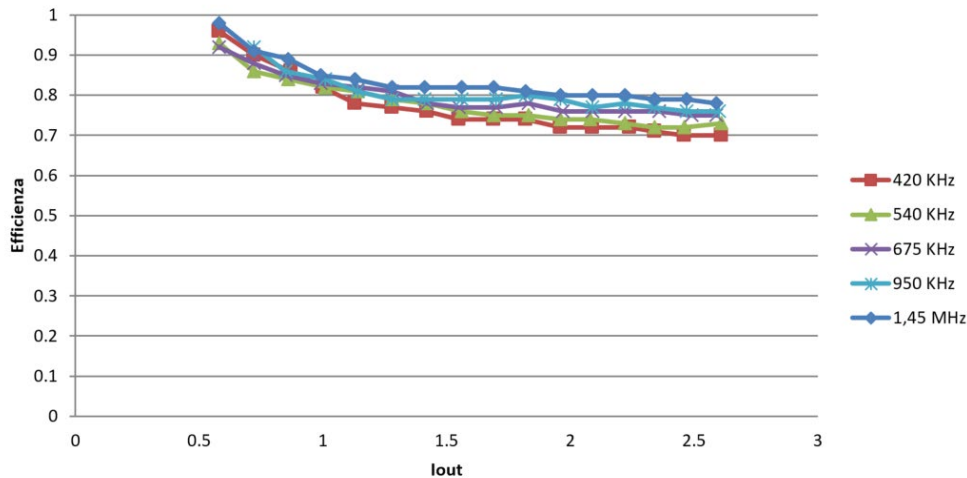# Tests in magnetic field results
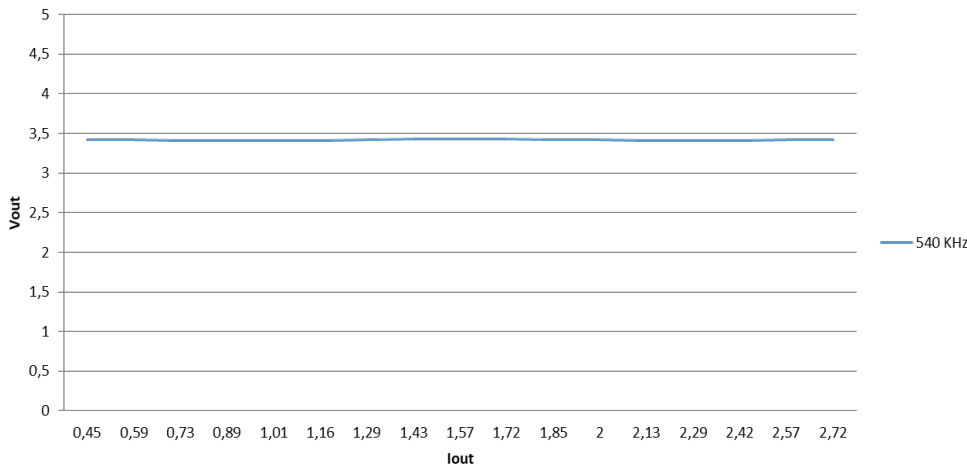

Vin 28V - Vout 2.5V

Test conditions:

- View X (parallel to B)
- Vin 28V, Vout 2.5V
- Variable load
- Switching frequency

Efficiency quite low (still acceptable), higher if Vin lower
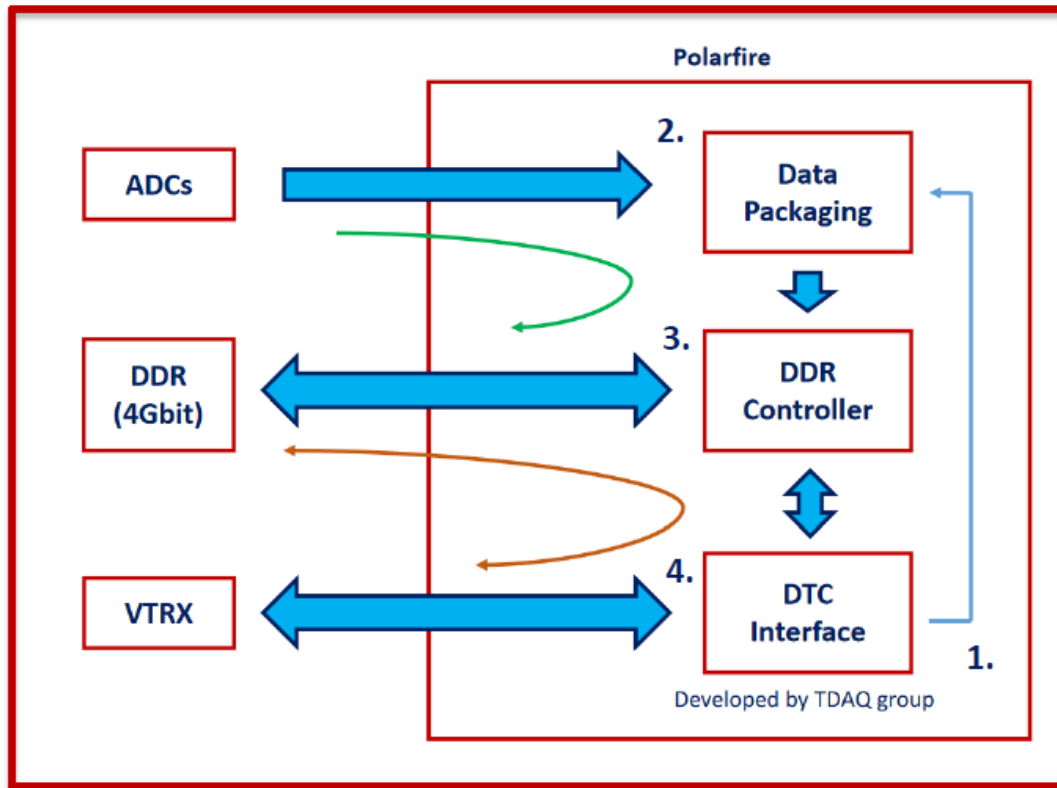

Vin 28V - Vout 3.3 V

Test conditions:

- View X (parallel to B)
- Vin 28V, Vout 3.3V
- Variable load
- Constant frequency

Vout constant

Main firmware flow ... 6 Gbyte/sec ...

1. TDAQ sends Heartbeat packet that contains EVENT TAG and EVENT WINDOWS

2. DiRAC builds the calo hit applying a zero suppression and pre-processing data

3. Data are stored in the DDR

4. TDAQ sends Data Request for a specific EVENT TAG, and DiRAC retrieve requested Data Packet from DDR and sends it out to DTC

Firmware block diagram
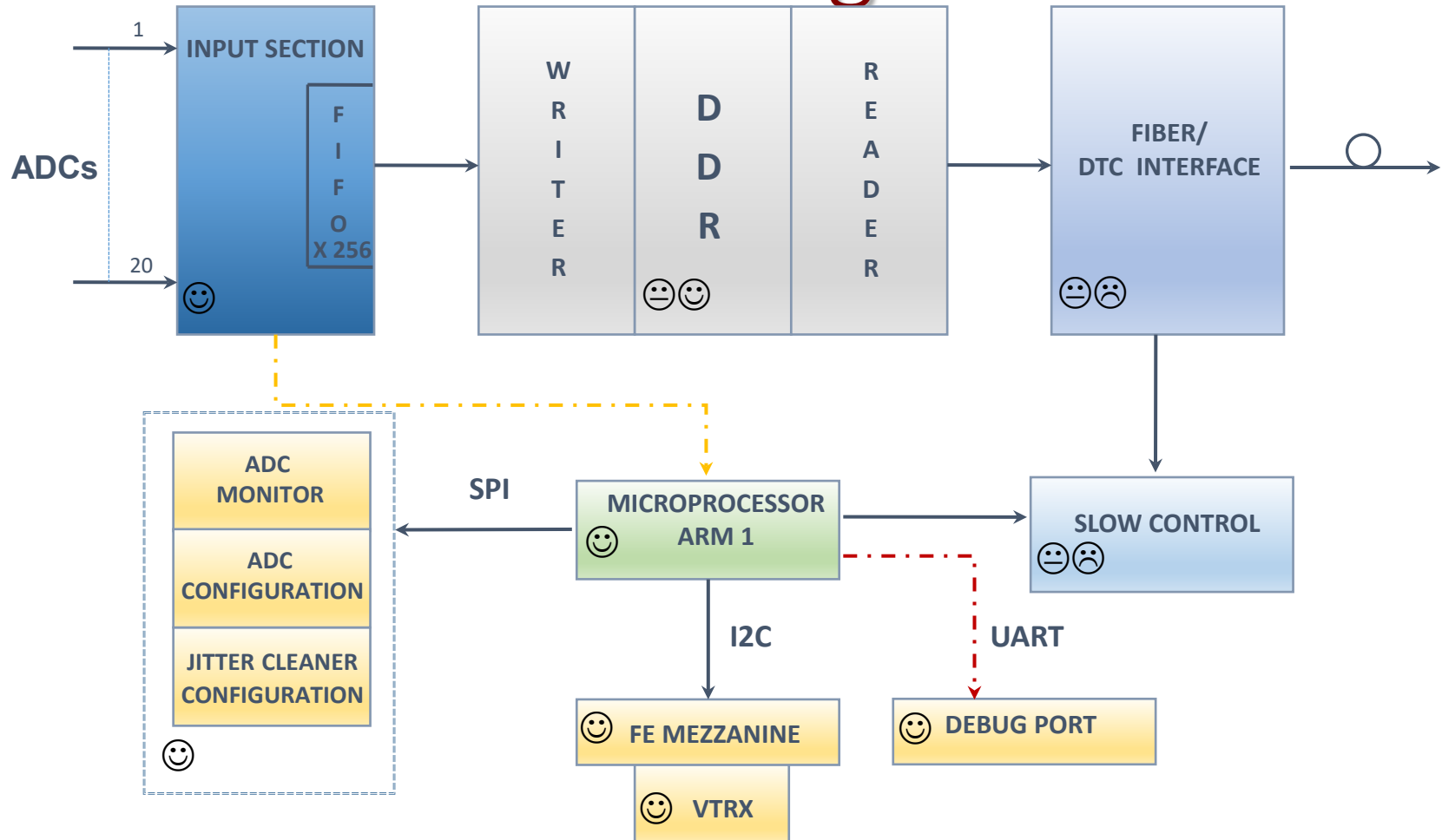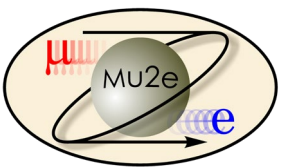
Slice test results

An example of the resulting waveform (Fig.A) and the distribution of the peak amplitude versus the integrated charge (Fig.B) is shown
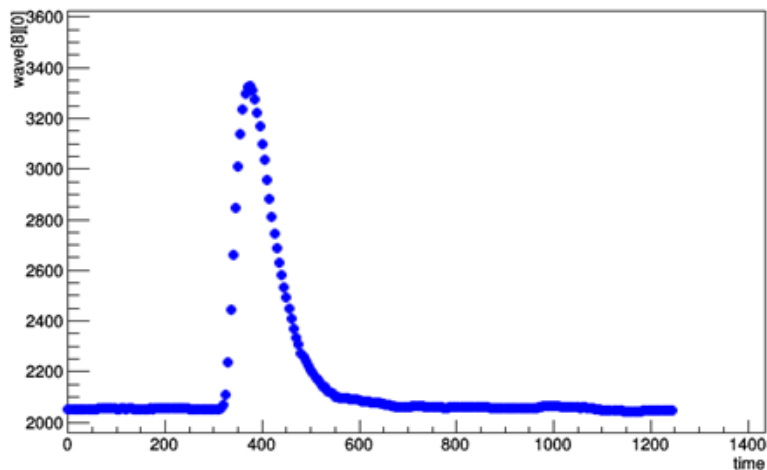

ADC 3 CH 0

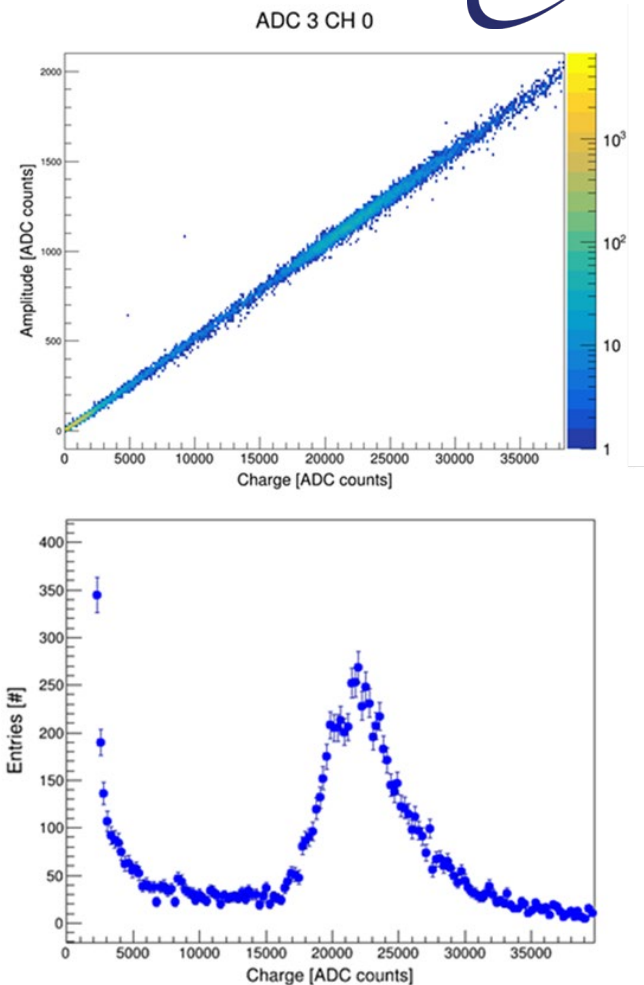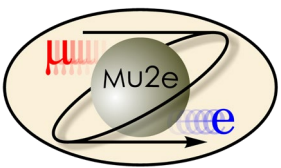

Fig.A: Resulting waveform

Fig.B: Energy distribution deposited by cosmic rays (ADC counts)

Conclusions

- A waveform digitizer designed to operate in Mu2e hostile environment has been presented. Named DIRAC.
- The DIRAC is designed to sample @200 MHz differential signals coming from SiPM and amplified by a custom FEE.
- The presence of vacuum (10^{-4} Torr), high magnetic fields (1T) and radiation (Non-Ionizing Energy Loss 5×10^{10} n/cm^2 @ 1 MeV_{eq} (Si)/y and Total Ionizing Dose 12 Krad) makes the environment particularly harsh and the design of the board very challenging
- We described the apparatus, the design specification, the architecture and all the technical choice
- The system has been qualified
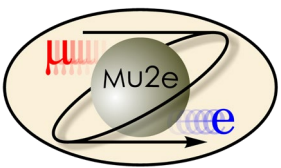
Thank you!

franco.spinella@pi.infn.it