Summer School "Summer Students at Fermilab and other US Laboratories"

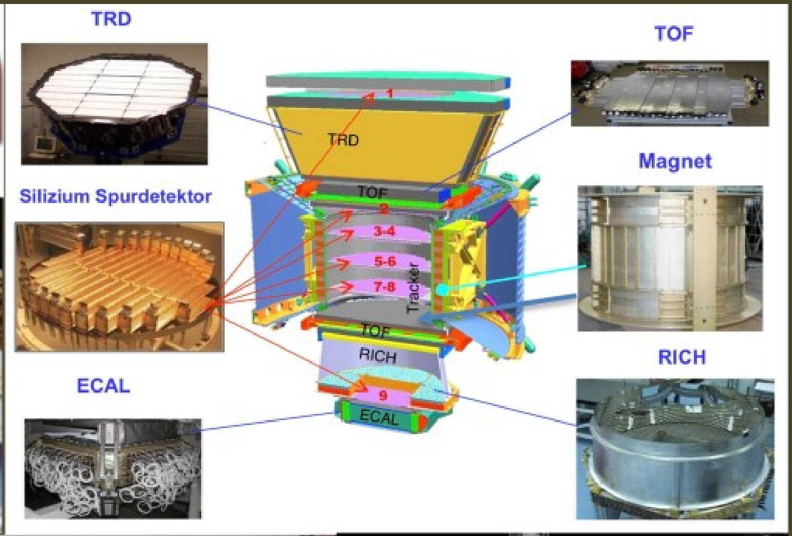
Digital electronics techniques for particle physic experiments at accelerators

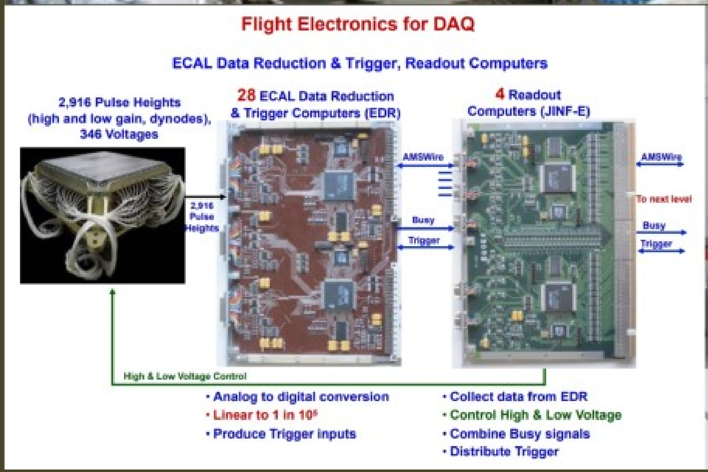
Elena Pedreschi

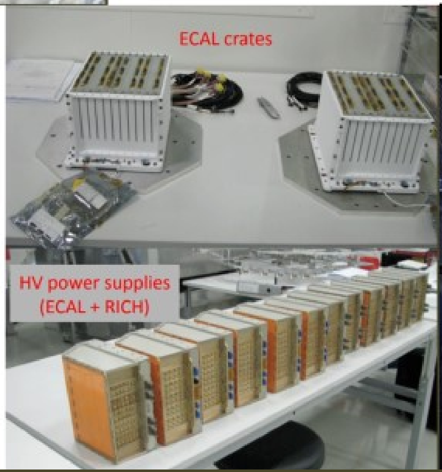
Introduction

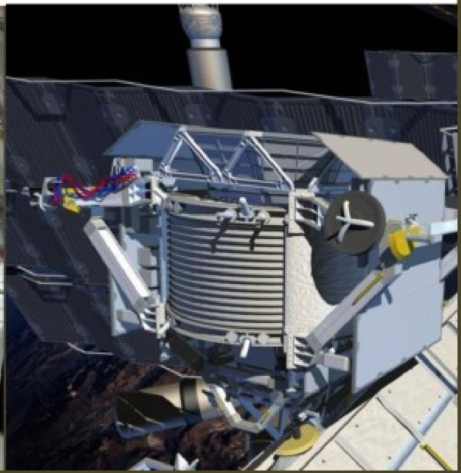
- Elettronics is strongly linked to the physical processes that we want to study
- Elettronic problems are very complex because:
  - Very high data flow
  - Harsh environment:
    - Temperature
    - Radiative stresses
    - Mechanical stresses
- Since 2002 I designed the electronics for many INFN experiments

AMS-02 -ISS



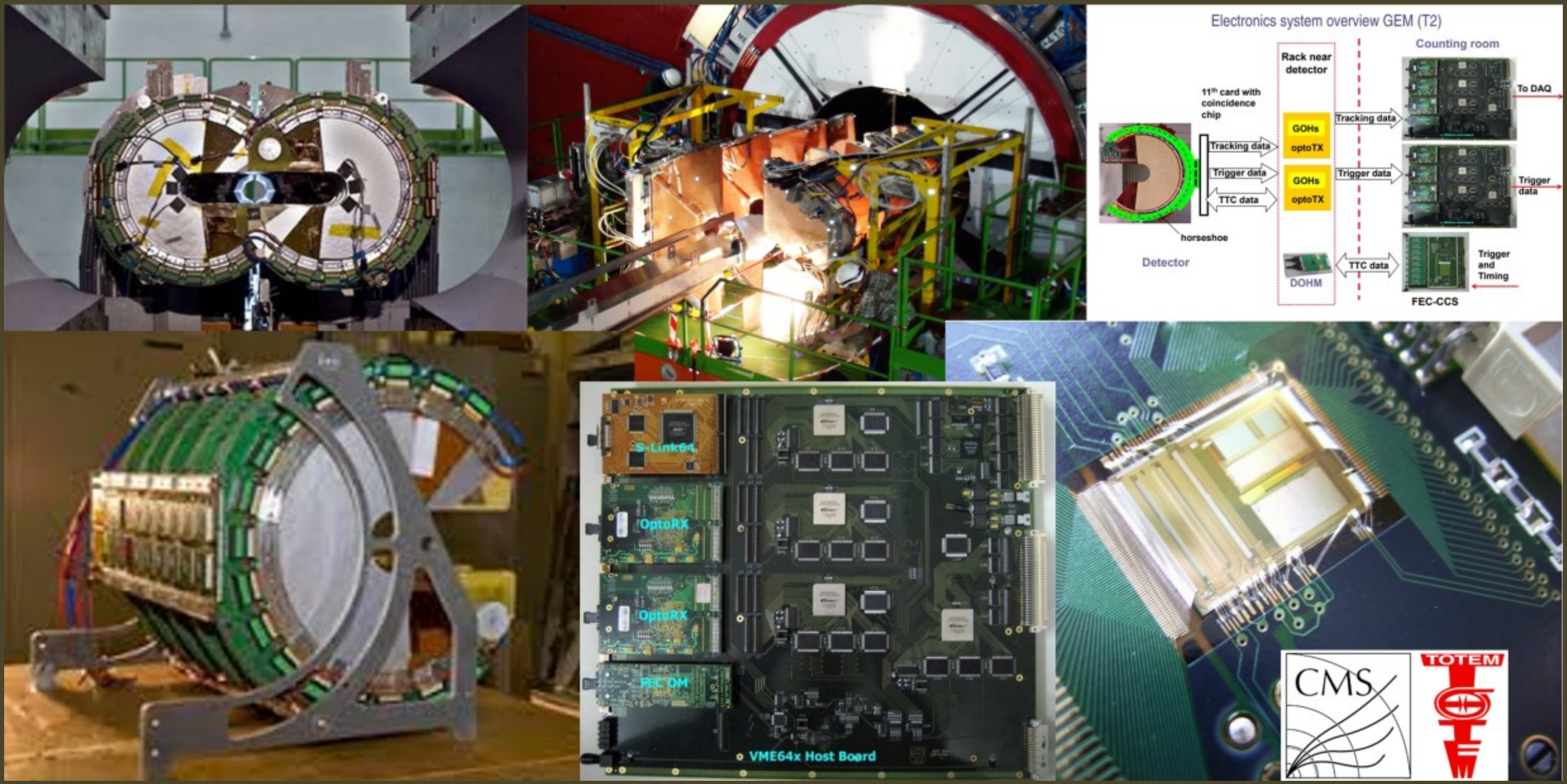






Harsh environment: Radiation, Vacuum, Temperature and Vibration

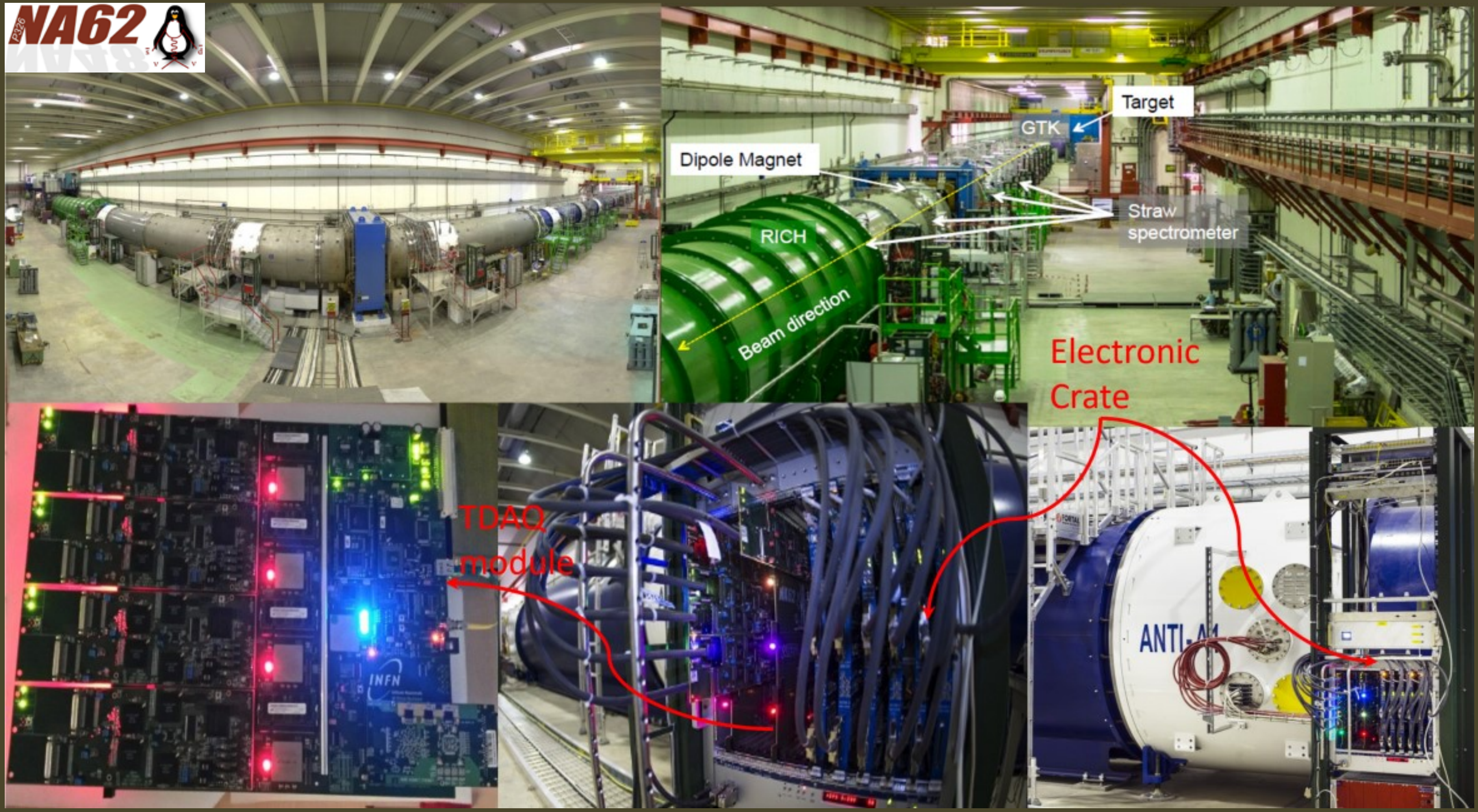
TOTEM – LHC IP5



Harsh environment:

- Radiation Dose < 50 Mrad

NA62 – CERN SPS



Harsh environment:

- Electronics near the beam → sensitive to radiation
- Very high data flow → high trigger efficiency

Mu2e - Fermilab

- Mu2 is an High Energy Physics experiment @ FNAL laboratory in USA
- I am involved in the design of the data acquisition system for the electromagnetic calorimeter

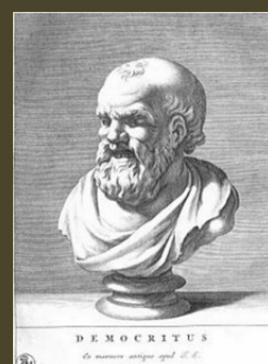
What is High Energy Physics?

It is a branch of science

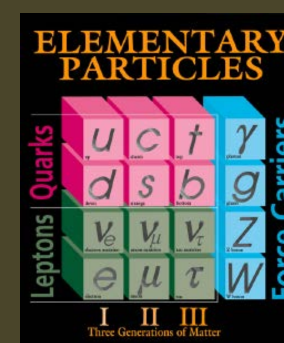
What is the goal of High Energy Physics?

- Identify the fundamental particles … and the forces that govern their interaction
- What are things made of?
- Why they do behave the way they do?

Earth, wind, fire, water



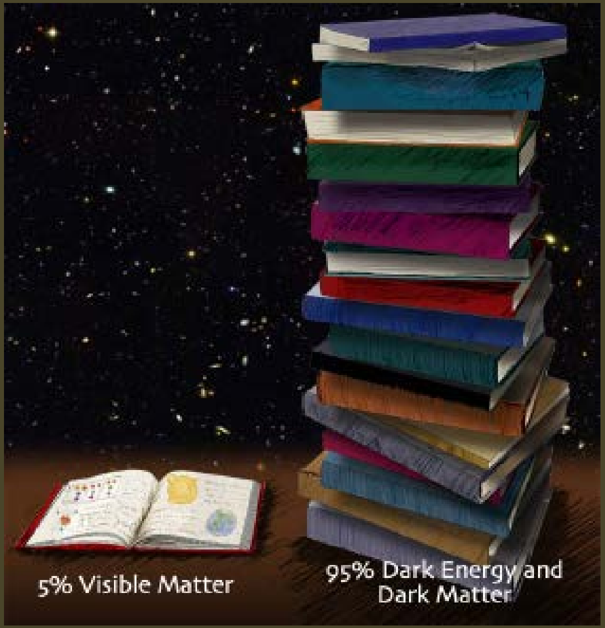
All things are made of “atoms”



Standard Model

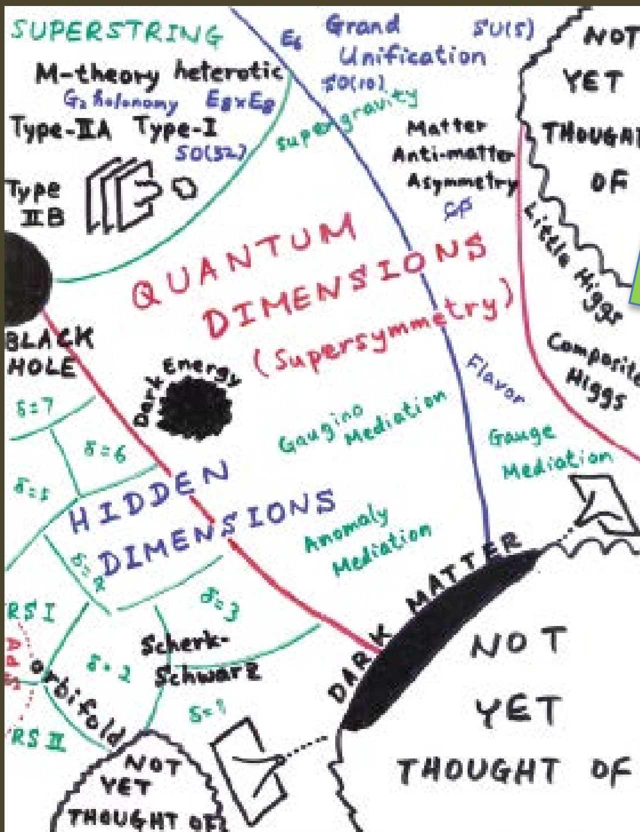
But there is a catch

- We know the Standard Model is incomplete

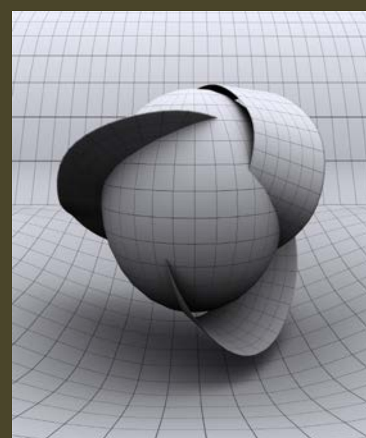


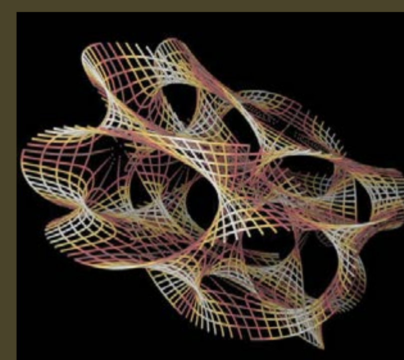
- The Standard Model describes 5% of Universe

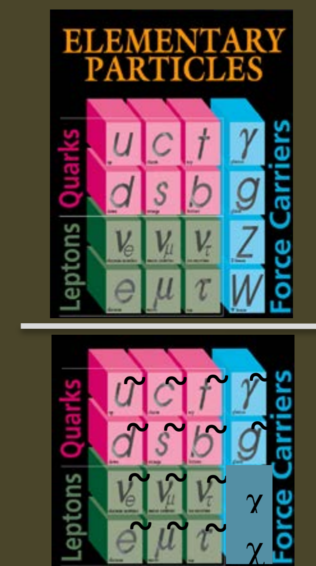
Possibilities



- We have a lot of ideas of what a more complete theory look like…
- We don’t know which one (if any) is correct

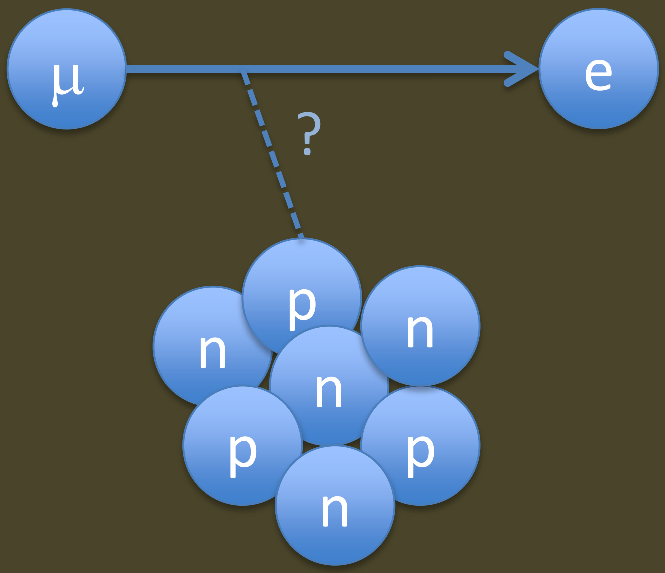






Extra Dimensions Super Strings Super Symmetry

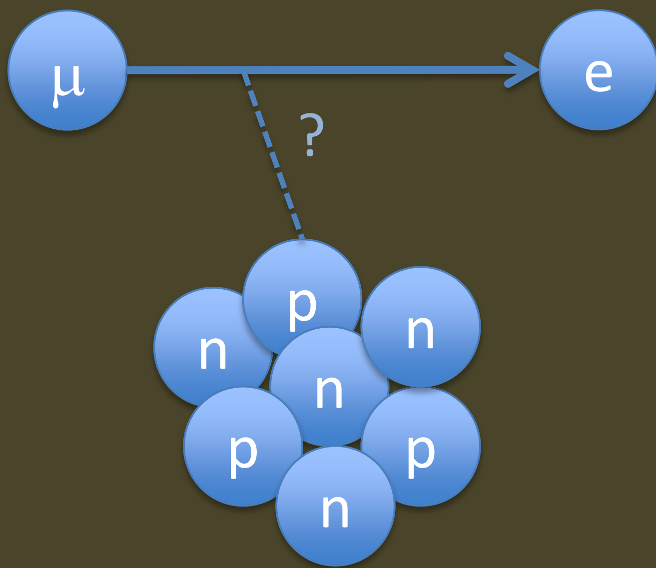
Why is Mu2e important?

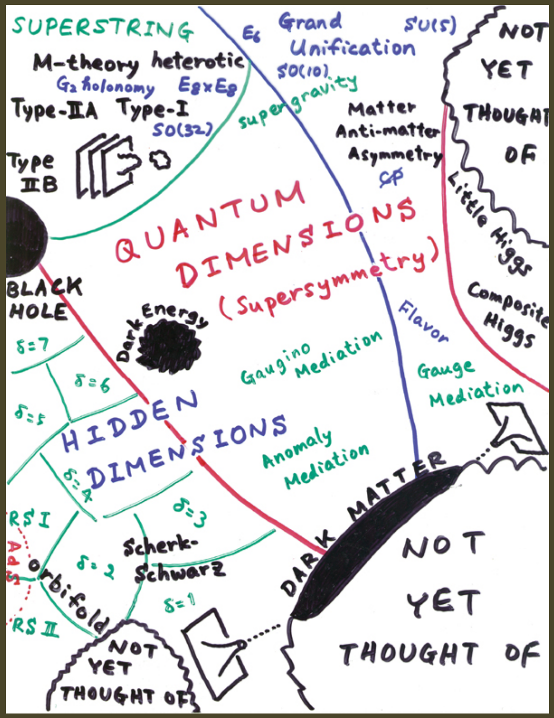


There are many ways this process can occur…

but *none* of them are in the Standard Model!

Why is Mu2e important?





So, by measuring the rate of the μN→eN process we can test these new theories

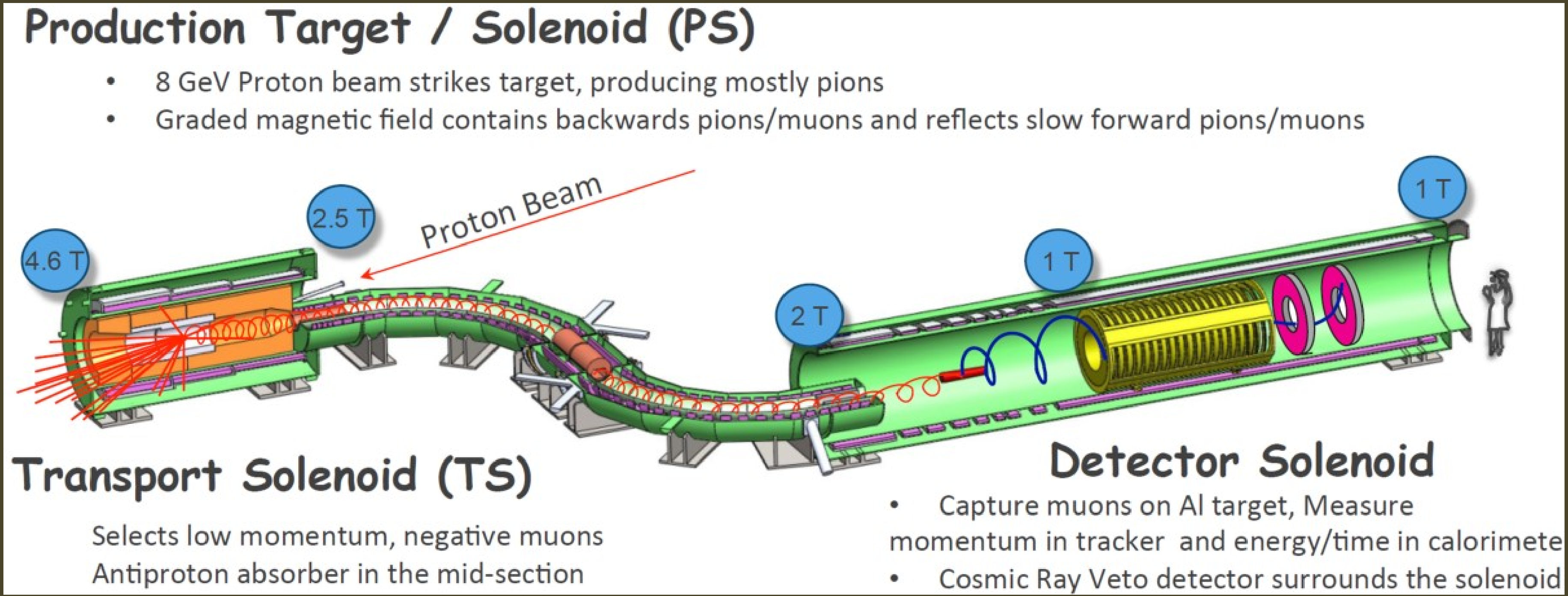
Very difficult measure…

- Will use current Fermilab accelerator complex to reach a sensitivity 10 000 better than current world's best
- Expected limit: $R_{\mu e} < 7 \times 10^{-17}$ @ 90% CL
  - Requires about 10^{18} stopped muons

Some Perspective

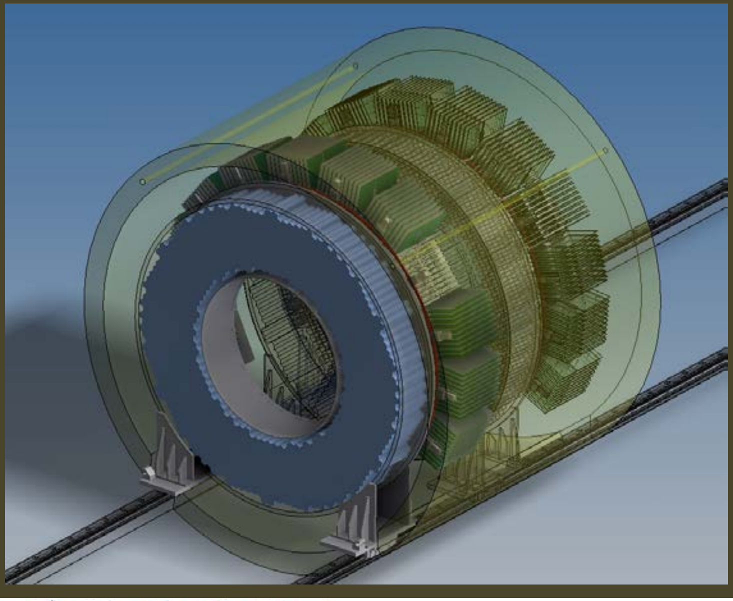
1,000,000,000,000,000,000
= number of stopped Mu2e muons
= number of grains of sand on earth

Mu2e Experimental Apparatus

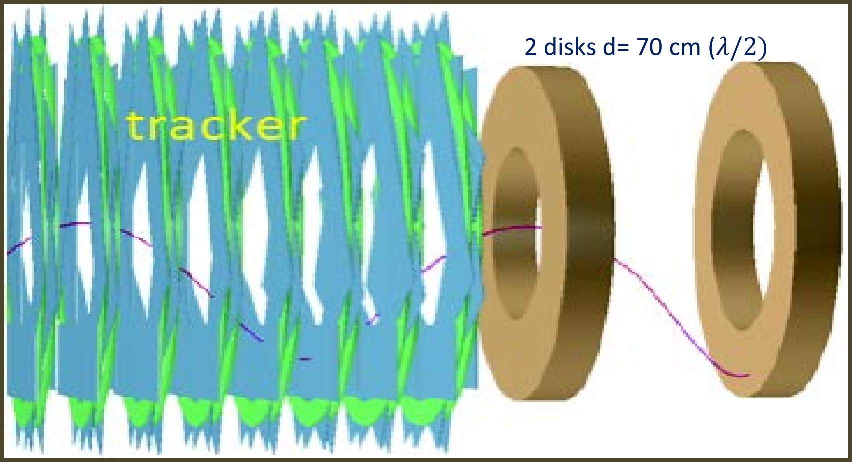


The Mu2e Calorimeter

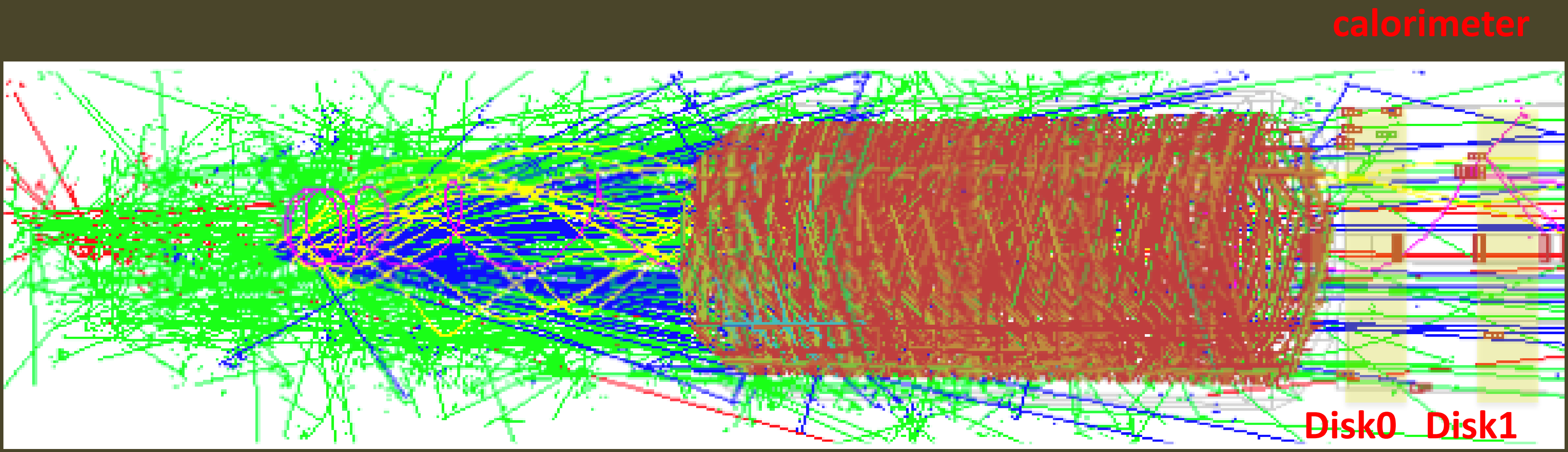
- Crystal calorimeter
  - Compact
  - Radiation hard
  - Operated in vacuum



INFN is in charge of the design and of the construction



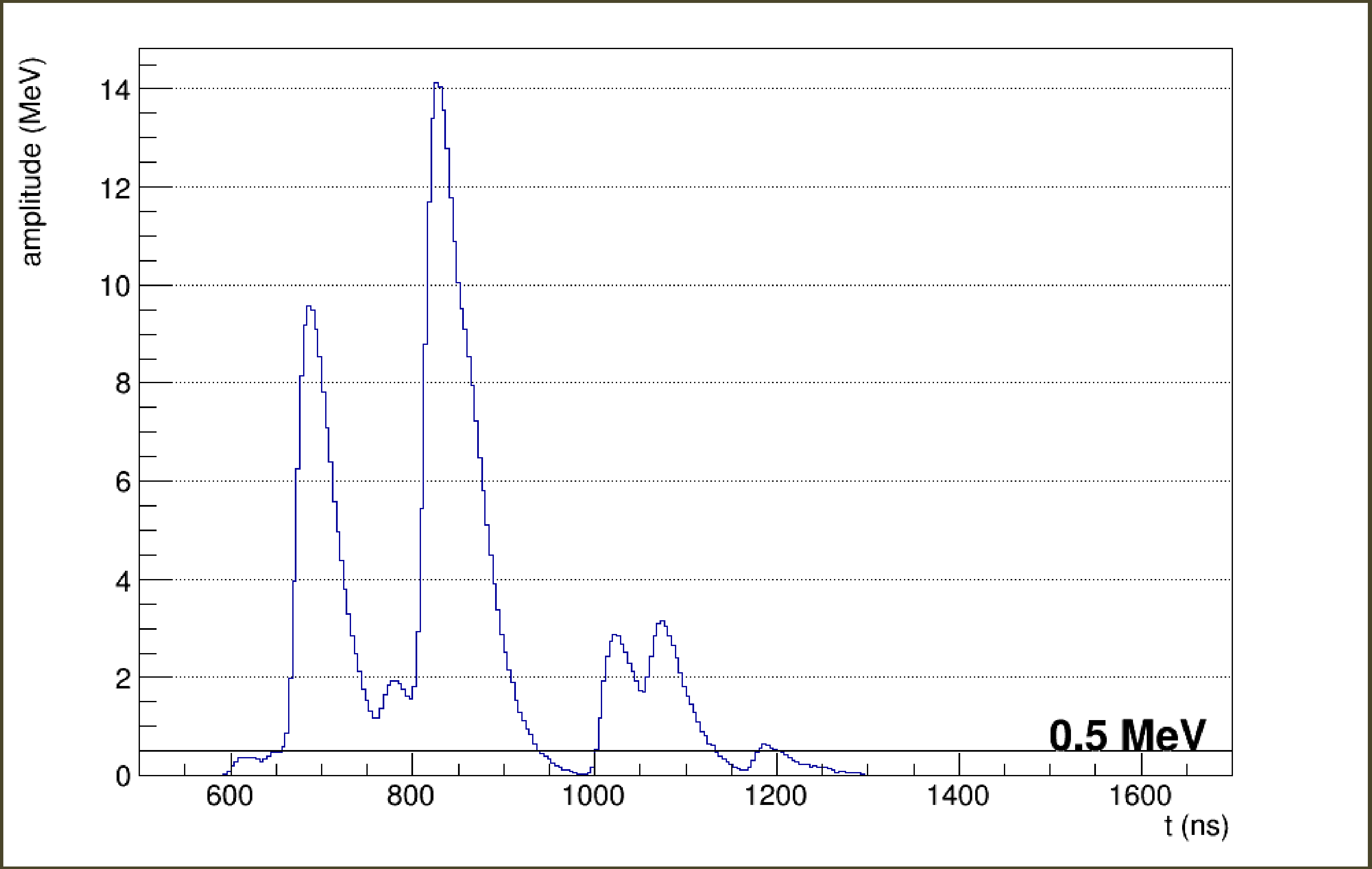
E, t measurements – Why a digitizer?



Typical 1.7 μs Mu2e event

- Very intense particle flux expected in the calorimeter

Example of front end output



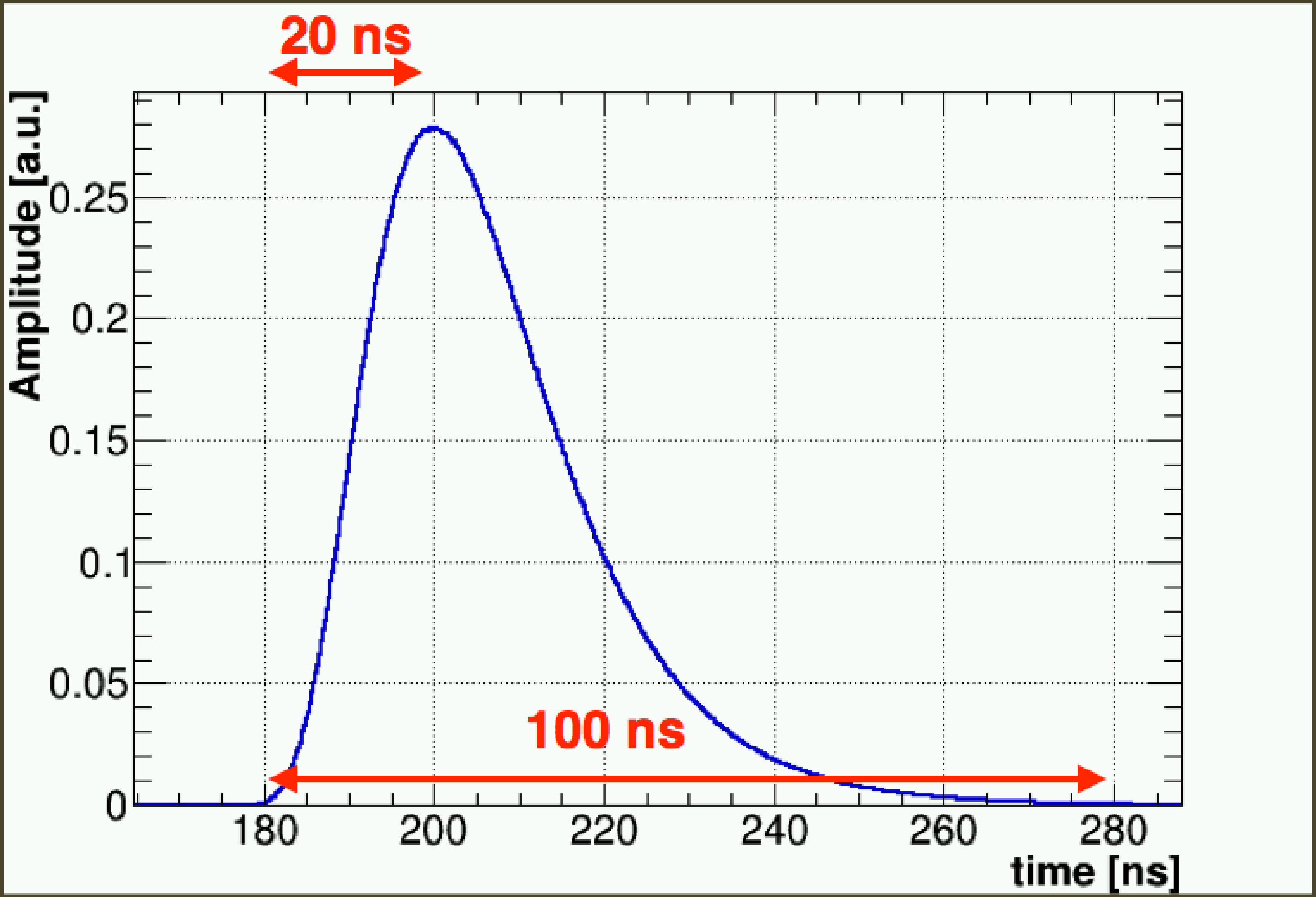
- We need high-sampling rate digitizers to resolve pile-up

Digitizer requirements

- Digitization requirements are determined by the calorimeter requirements
- **Particle identification**:
  - $\sigma_t < 500$ ps @ 100 MeV
  - $\sigma_E/E < 10\%$ @ 100 MeV

- **We require** the additional contribution due to the digitization procedure itself to be:
  - **$\sigma_t < 200$ ps @ 100 MeV**

Analog input: signal waveform

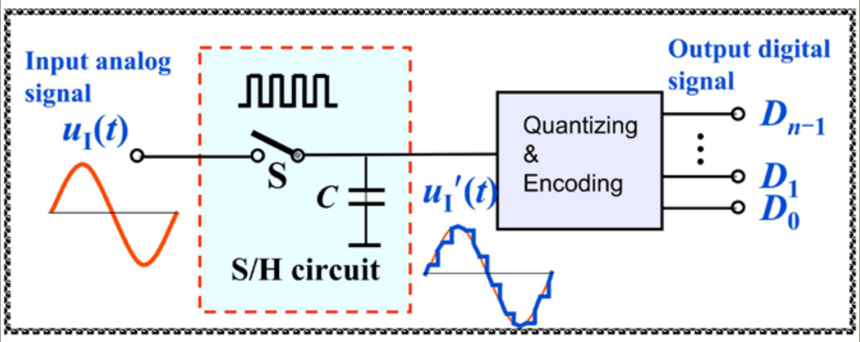


From Analog to Digital: ADC converters

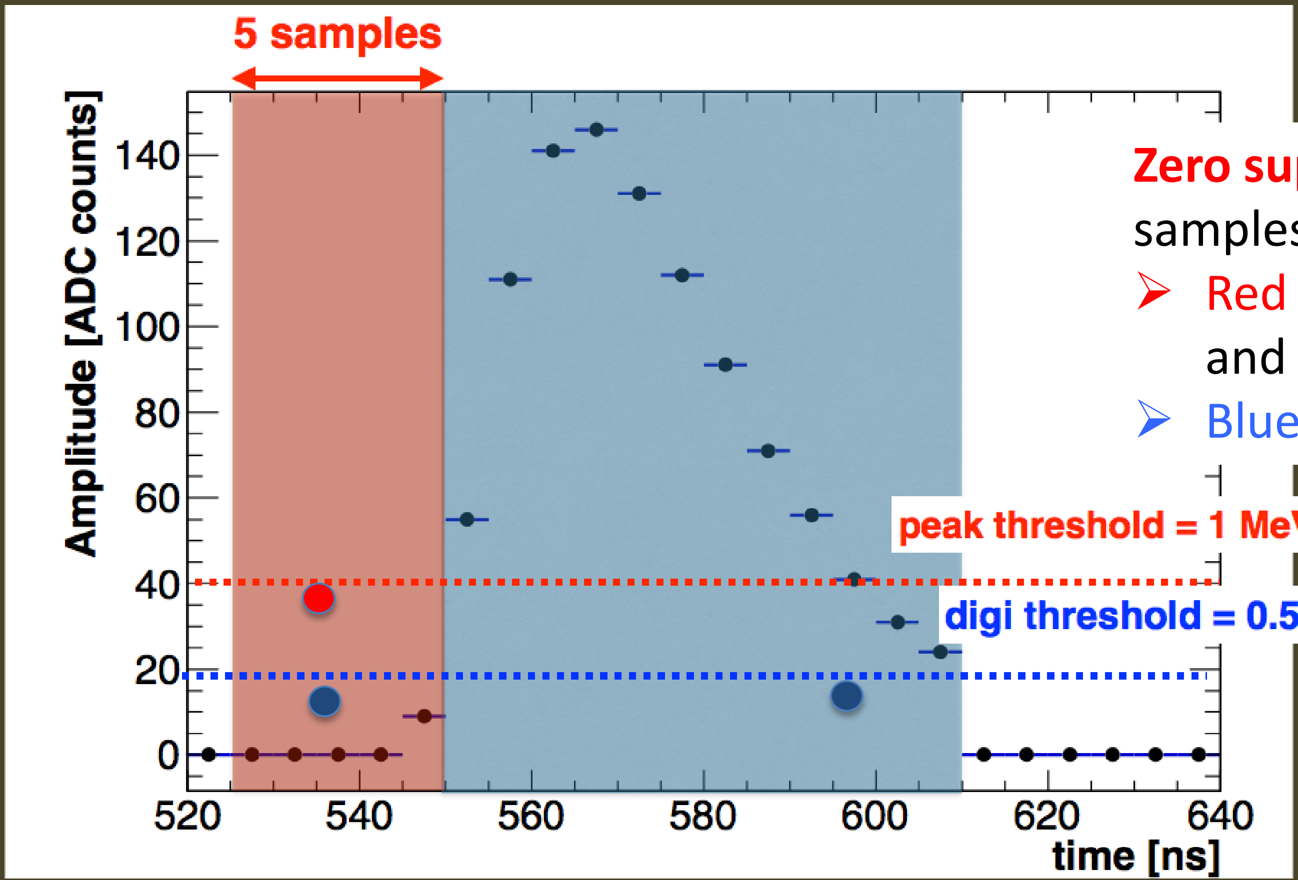
- What is an ADC?
  - An electronic integrated circuit which transforms a signal from analog (continuous) to digital (discrete) form
  - Analog signals are directly measurable quantities
  - Digital signals have only two states
- Why ADC is needed?
  - ADC provides a link between the analog world of transducers and the digital word of signal processing
- Application of ADC
  - ADC are used virtually everywhere an analog signal has to be processed

From Analog to Digital: ADC converters

- 2 steps:
  - Sampling and Holding
  - Quantizing and Encoding
- 2 ways to improve the accuracy of A/D Conversion:
  - increasing the resolution which improves the accuracy in measuring the amplitude of the analog signal
  - increasing the sampling rate which increases the maximum frequency that can be measured



Calorimeter digitization scheme



Zero suppression: acquire **only** samples in blue and red regions

- Red region needed for time and pedestal calculation
- Blue region for energy

- **Sampling frequency** and number of **ADC readout bits** impact time and energy resolution
- Thresholds impact the total data throughput and Energy resolution

Time resolution versus sampling frequency and ADC-bits

- **Time** is reconstructed by fitting the leading edge

	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

Energy resolution versus sampling frequency and ADC-bits

- **Energy** is reconstructed from the total number of ADC counts

	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

Mu2e environment

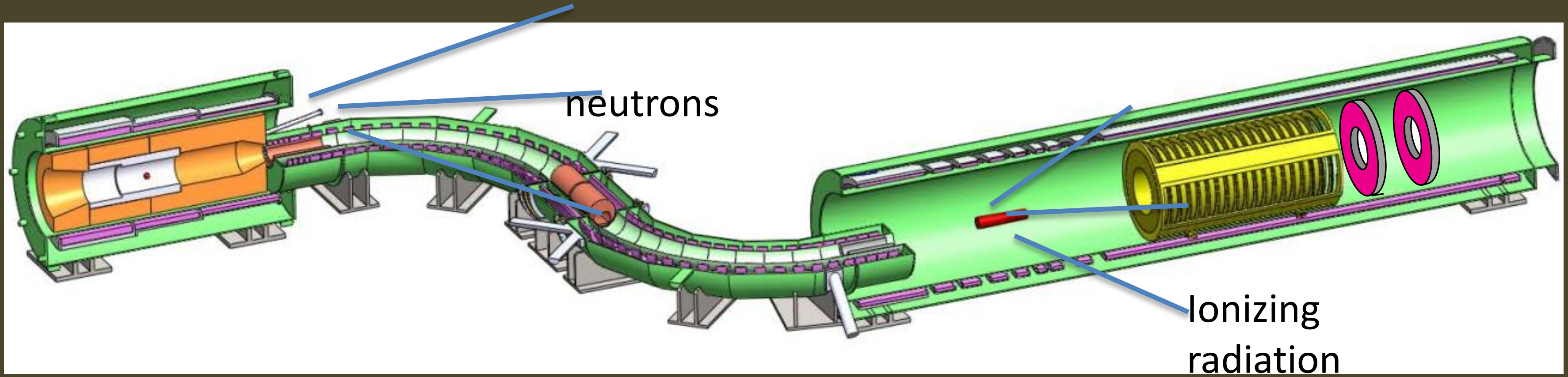
- Radiation (not too high but present) 0,5 Krad/y and high neutron flux (~ 6x10^11 / cm^2 * year) → select rad-hard components
- High magnetic field (1T) → problems for magnetic nuclei of DC-DC converters
- All the electronics is in vacuum → degassing problems and need to use only conductive thermal dissipation.
- Maintenance complicated → cryostat will not be opened more often than once per year

Project must be realized in "high reliability mode",
like an experiment in the space

Challenging …

Mu2e environments: principal problems for electronics

- Radiation



Radiation on calorimeter electronics:

- ✓ Expected dose per year ~ **0.5 krad**
- ✓ Expected total dose 0,5 x 12 x 5 = **30 krad**
- ✓ Neutron flux 6x10^11 / cm^2 * year

- Saturation effects on ferromagnetic nuclei (high magnetic field)
- Heat transfer (vacuum)

Radiation Effects on Electronics

- Long Term Effects
  - *Total Inizing Dose* → cumulative long term *ionizing* damage due to protons & electrons
  - *Displacement Damage* → cumulative long term *non-ionizing* damage due to protons, electrons & neutrons
- Transient or single particle effects (SEE) → caused by a *single charged particle* as it passes through a semiconductor (heavy ions & protons)
  - Effects on electronics:
    - Soft errors such as upsets (*SEU*s) or transients (SETs)
    - Hard (destructive) errors such as latchup (*SEL*), burnout (SEB), or gate rupture (SEGR)

Component choice

- The presence of radiation, B field and vacuum pose stringent requirements on the components.
- The main components are the FPGA, ADCs and DCDC converters
- As a first step towards the prototype we need
  - Choose components that meet the specifications
  - Qualify independently all the main components
  - Test if they are compatible one to the other

FPGA-SoC

- The choice is almost unique (at moment)
- Microsemi SmartFusion2 family (SoC: FPGA + CPU)
  - Specs:
    - Flash (and not RAM) based
    - SEL free (see tables)
    - Configuration Flash SEU free(up to 90 MeV ions)
    - Data SEU low
    - Very low power
- We used the largest and fastest one SM2150T-1 (1152 pins)
- In principle we don't need to qualify this part as a single element

Table 1: Single Event Latch-Up Summary

Run	Device Tested	Number of Parts Tested	Test Facility	Test Temperature	Total Test Fluence	Number of SEL Events LET <= 20	Number of SEL Events LET > 20
1	M2S050	3	LBNL	Room Temperature	2.20×10^8	0	0
2	M2S050	3	LBNL	Room Temperature	4.09×10^8	0	0
3	M2S050	8	TAMU	100°C	4.41×10^8	0	2
Total		14			1.07×10^9	0	2

Table 4: Configuration Single Event Upset Boundary of FIT rates

Environment	Upper Boundary of Configuration SEU FIT Rates
Ground Level (Sea Level, New York City)	Immune
Aviation (40,000 feet, New York City)	Immune
Space (Low Earth Orbit, 800 km circular, 85° inclination)	Immune

Table 5: Data SEU Summary (Single Bit Upsets)

Feature	Test Fluence (Neutrons/cm^2)	Error Rate Ground Level (Sea Level, NYC, FIT)	Error Rate Aviation (40,000', NYC, FIT)
Flip-flop	4.35×10^{11}	218.3 FIT / million flip-flops	1.13×10^5 FIT / million flip-flops
LSRAM	1.7×10^{11}	340.6 FIT / million bits	1.75×10^5 FIT / million bits
uSRAM	1.7×10^{11}	175.3 FIT / million bits	9.04×10^4 FIT / million bits

ADC

- Specs:
  - >= 200 Msample
  - >= 12 bit
  - Ultra Low power
  - Not enough serializers on the FPGA
    -> Parallel readout
    -> Possibly DDR (2 bits/pin) -> half pins
    requested
  - Not too expensive
  - High (and given) MTBF
  - ⇒ TI ADS4229

We need to qualify for radiation

TEXAS INSTRUMENTS

ADS4229

SBAS550C – JUNE 2011 – REVISED MAY 2015

ADS4229 Dual-Channel, 12-Bit, 250-MSPS Ultralow-Power ADC

1 Features

- Maximum Sample Rate: 250 MSPS
- Ultralow Power with Single 1.8-V Supply:
  - 545-mW Total Power at 250 MSPS
- High Dynamic Performance:
  - 80.8-dBc SFDR at 170 MHz
  - 69.4-dBFS SNR at 170 MHz
- Crosstalk: > 90 dB at 185 MHz
- Programmable Gain Up to 6 dB for SNR and SFDR Trade-off
- DC Offset Correction
- Output Interface Options:
  - 1.8-V Parallel CMOS Interface
  - DDR LVDS With Programmable Swing:
    - Standard Swing: 350 mV
    - Low Swing: 200 mV
- Supports Low Input Clock Amplitude Down to 200 mV_{PP}
- Package: 9-mm × 9-mm, 64-Pin Quad Flat No-Lead (QFN) Package

2 Applications

- Wireless Communications Infrastructure
- Software Defined Radio
- Power Amplifier Linearization

3 Description

The ADS4229 is a member of the ADS42xx ultralow-power family of dual-channel, 12-bit and 14-bit analog-to-digital converters (ADCs). Innovative design techniques are used to achieve high dynamic performance, while consuming extremely low power with a 1.8-V supply. This topology makes the ADS4229 well-suited for multi-carrier, wide-bandwidth communications applications.

The ADS4229 has gain options that can be used to improve spurious-free dynamic range (SFDR) performance at lower full-scale input ranges. This device also includes a dc offset correction loop that can be used to cancel the ADC offset. Both double data rate (DDR) low-voltage differential signaling (LVDS) and parallel complementary metal oxide semiconductor (CMOS) digital output interfaces are available in a compact QFN-64 PowerPAD™ package.

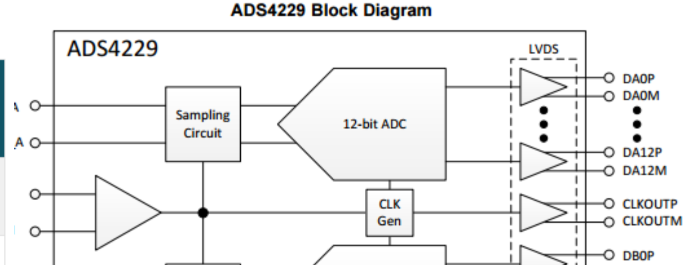
The device includes internal references while the traditional reference pins and associated decoupling capacitors have been eliminated. The ADS4229 is specified over the industrial temperature range (–40°C to +85°C).

Device Information(1)

PART NUMBER	PACKAGE	BODY SIZE (NOM)
ADS4229	VQFN (64)	9.00 mm × 9.00 mm

(1) For all available packages, see the orderable addendum at the end of the datasheet.

ADS4229 Block Diagram



	Early life failure rate	MTBF / FIT		Early life failure rate supporting data				MTBF / FIT supporting data						
Part number	ELFR-DPPM	MTBF	FIT	Conf level (%)	Test temp (°C)	Sample size	Fails	Usage temp (°C)	Conf level (%)	Activation energy (eV)	Test temp (°C)	Test duration (hours)	Sample size	Fails
ADS4229IRGC25	-	1.27×10^9	0.8		-	-	-	55	60.0	0.7	125	1000	14782	0

DC-DC

- DCDC converters are quite delicate devices, prone to radiation damage and B field
- INFN has financed a test survey to study which DCDC
- are suitable to be used in HEP environments (LHC …)
- From these studies the Linear Technologies LTM8033 seems the best suitable for MU2E environment

Qualification Test for single components

- **Neutron irradiation test @FNG** facility in Frascati:
  May 2015, up to → LTM8033 ☑
  -> total neutron flux of 1.2 x10^12 n 1 MeV (Si) / cm^2
  November 2015 → LTM8033 and ADS4229 ☑
  -> total neutron flux of 6x10^11 n 1 MeV (Si) / cm^2

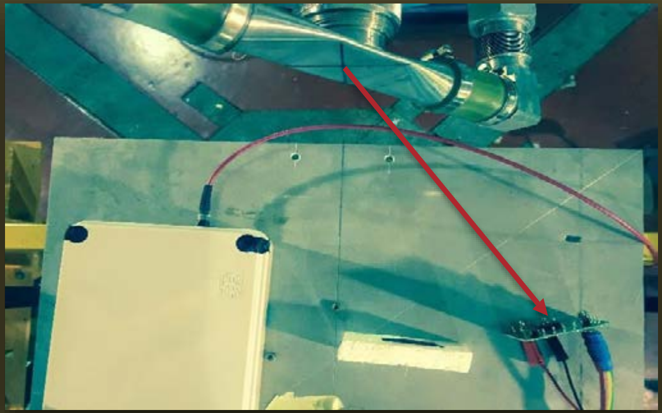
- **Gamma irradiation test @CALLIOPE** in Bracciano:
  November 2015 → LTM8033 e ADS4229 ☑
  -> total ionizing dose (TID) of 20 krad

- **Magnetic field exposure test @LASA** in Milano:
  July 2015, up to 1 T → LTM8033 ☑
  -> up to 1.2 T of magnetic field for different spatial orientations

Neutron irradiation test – FNG facility

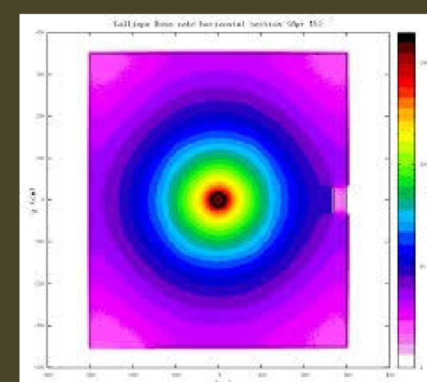
FNG (Frascati Neutron Generator) is a linear electrostatic accelerator in which up to 1 mA D+ ions are accelerated onto a Tritium target.

- Up to 10^11 **14 MeV** neutrons/s.
- almost isotropic source, flux scales with r^2.
- calibrated at 3% level using alpha particles.

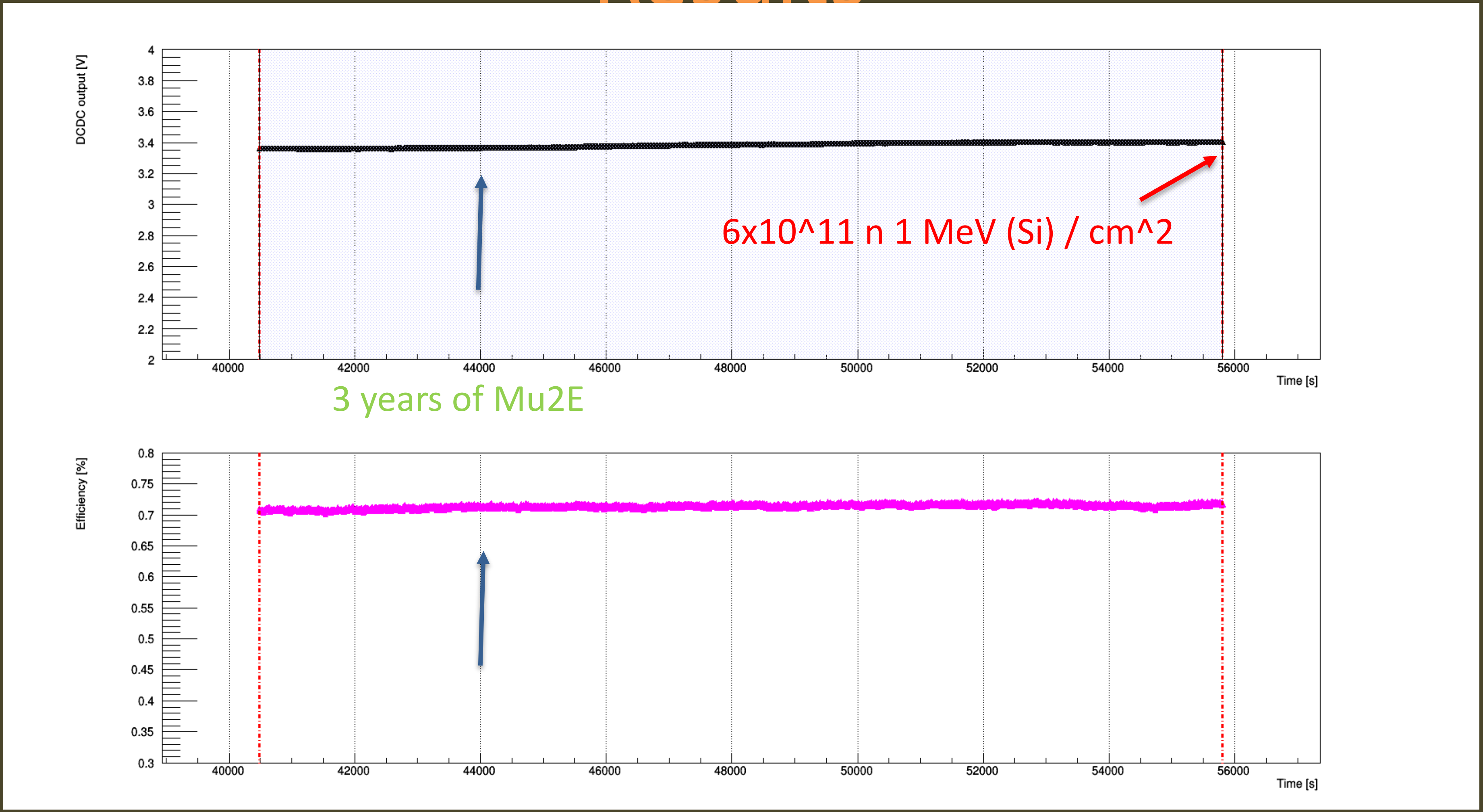


Ionizing dose test – CALLIOPE facility

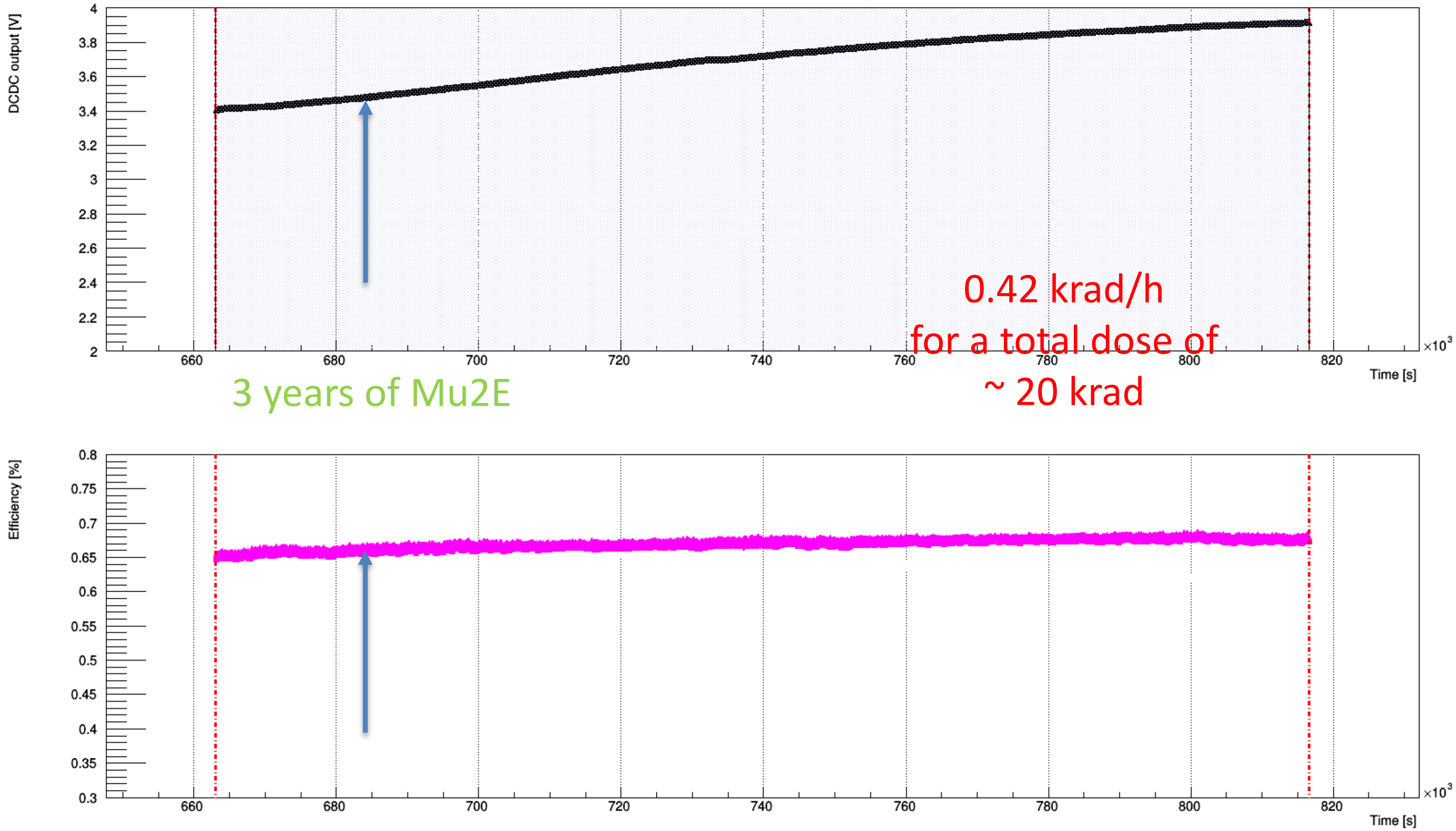
- Gamma rays at 1.17 and 1.33 MeV from Co60.
- 3.7x10^15 Bq of activity.
- Isotropic source, flux scales with r^2.



DCDC neutron irradiation test - Results

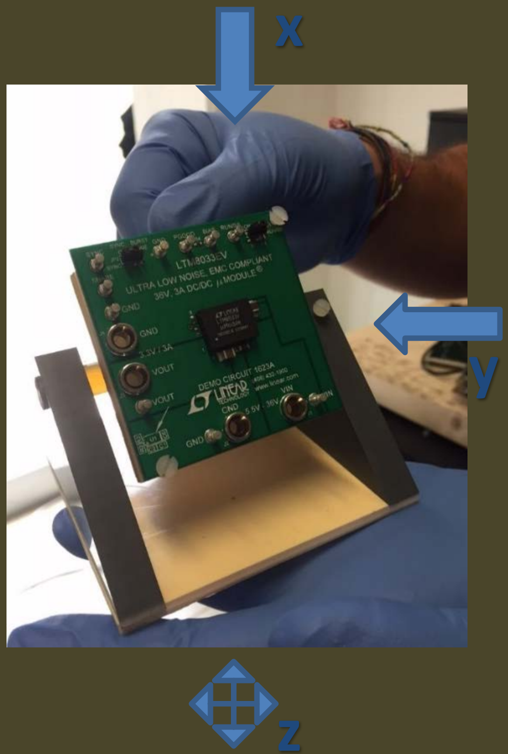


DCDC gamma irradiation test - Results

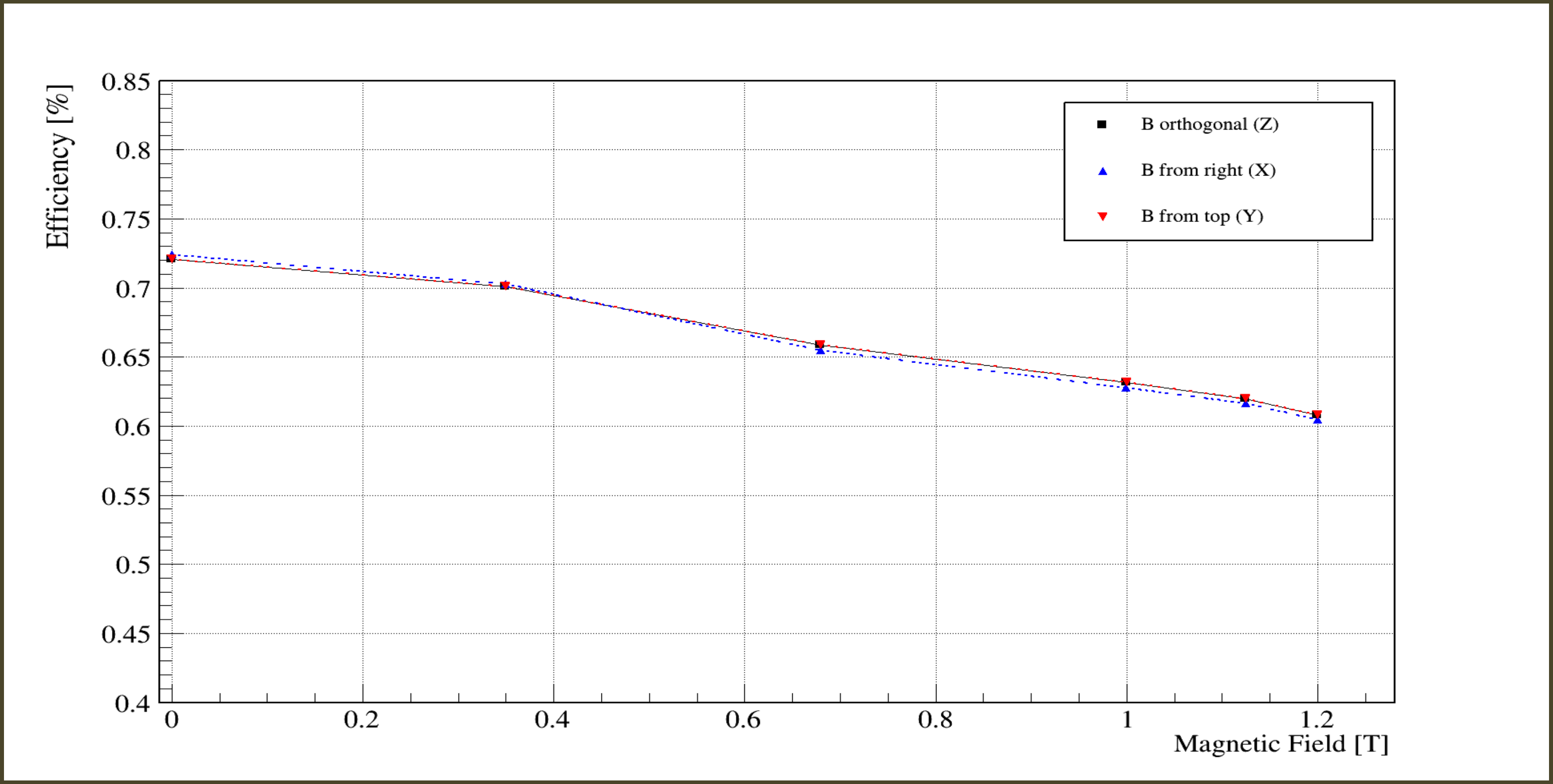


Magnetic Field exposure test

- 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.

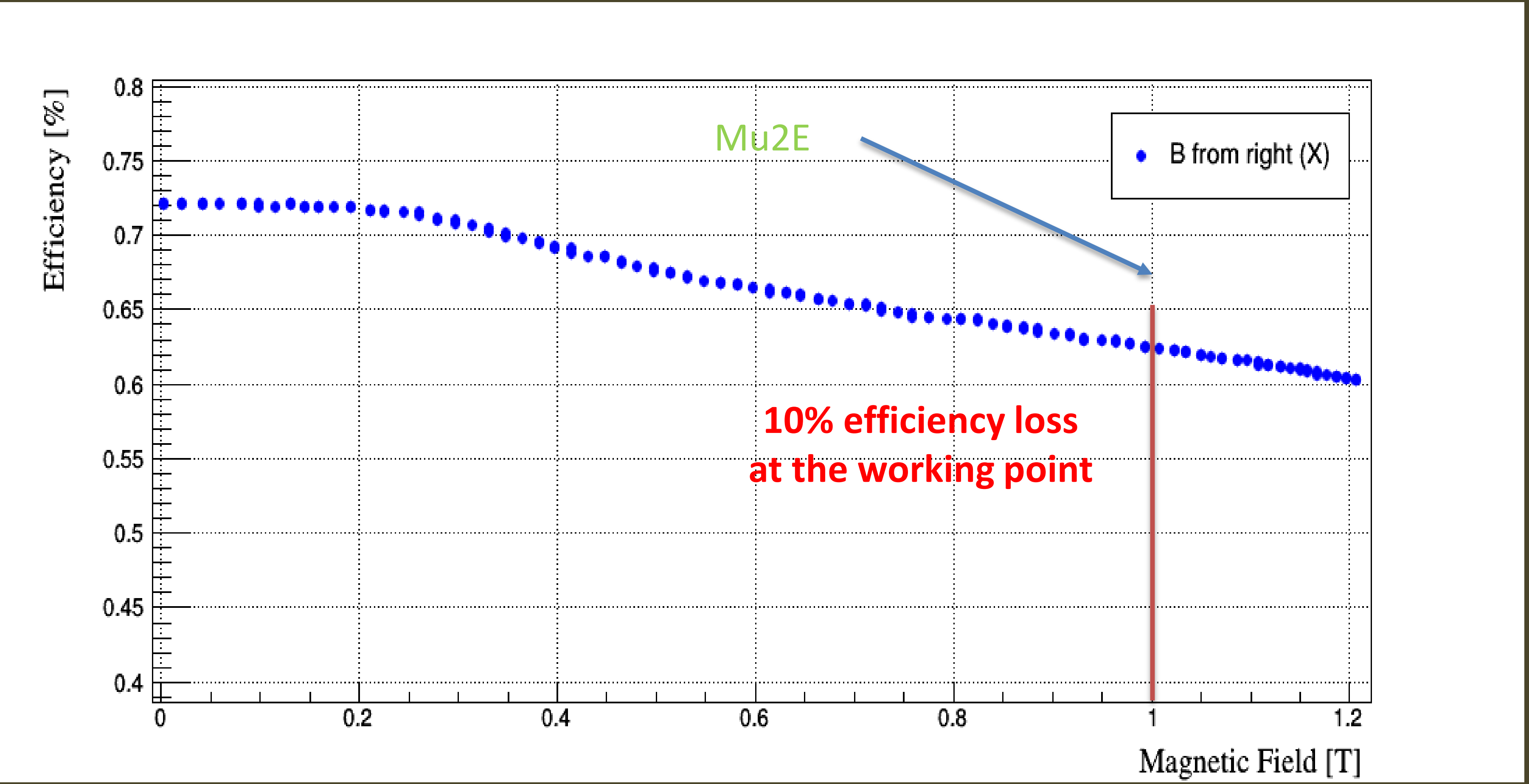


DC-DC magnetic field exposure test–3 axis

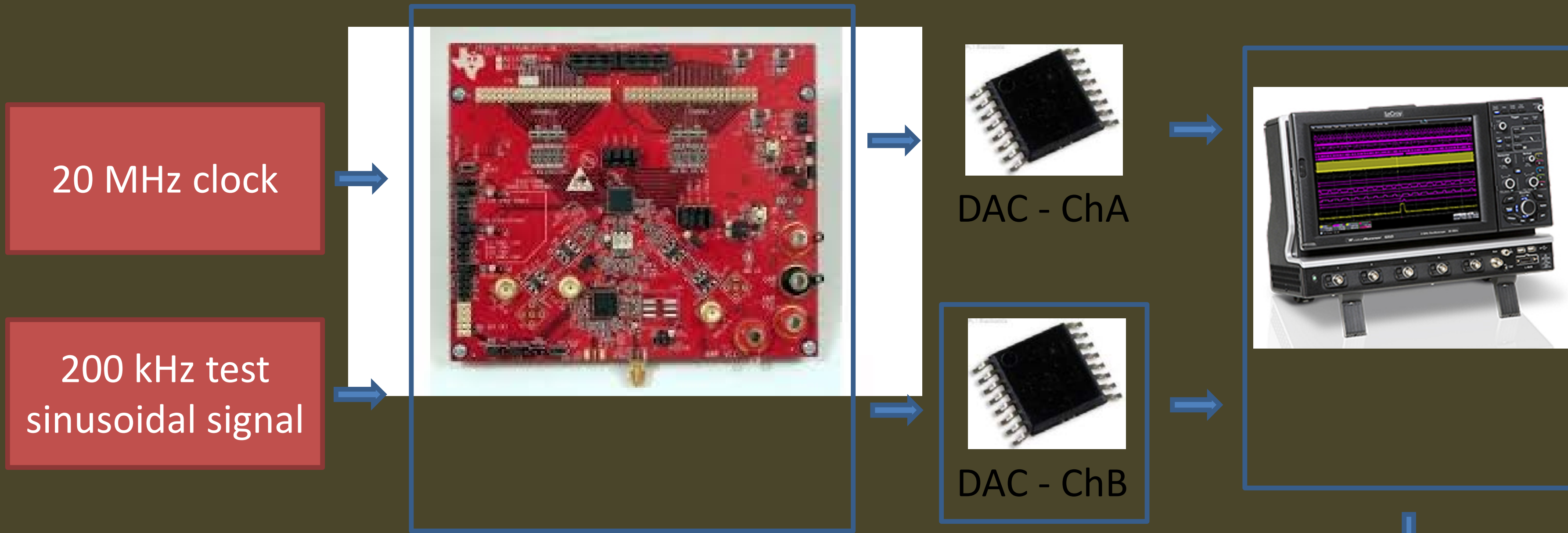


No significative differencies between orientations.

DC-DC magnetic field exposure test – x axis



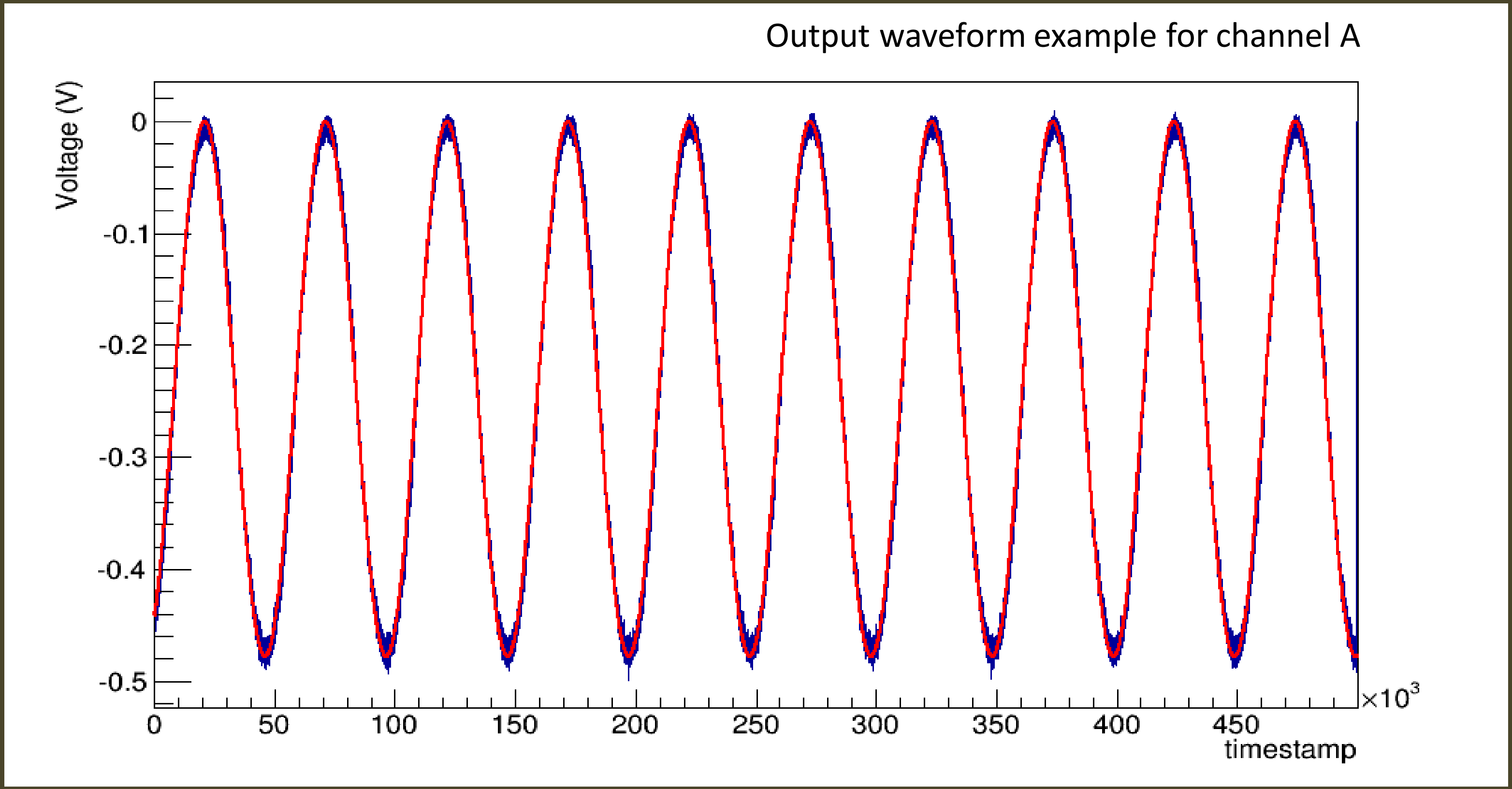
ADC irradiation tests – The experimental setup



We acquire at 10Hz a 50 us sample of the DAC output waveform for both channels. We wanto to monitor:

- Bit Flip occurrency.
- Waveform shape variations.

ADC test results



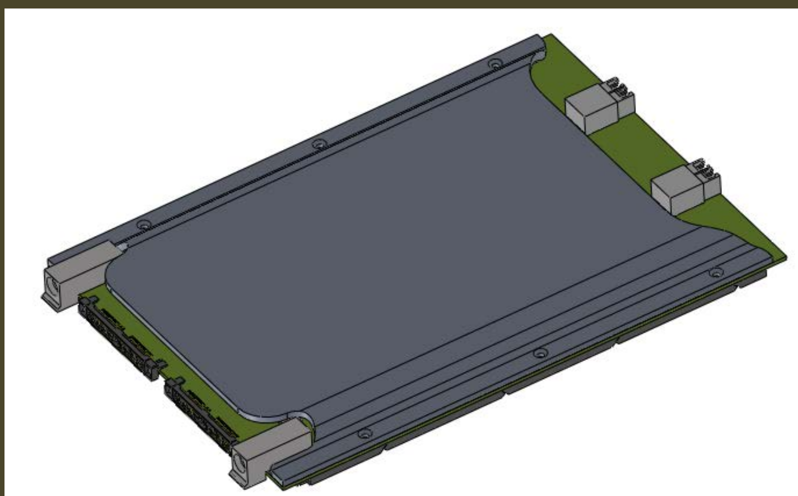
We acquired more than 300 GB of data in both neutron and gamma-ray tests, with no evidence of bit flips or waveforms shape variation. (neutron test 6x10^11 n 1 MeV (Si) / cm^2 , gamma ray 20 krad TID)

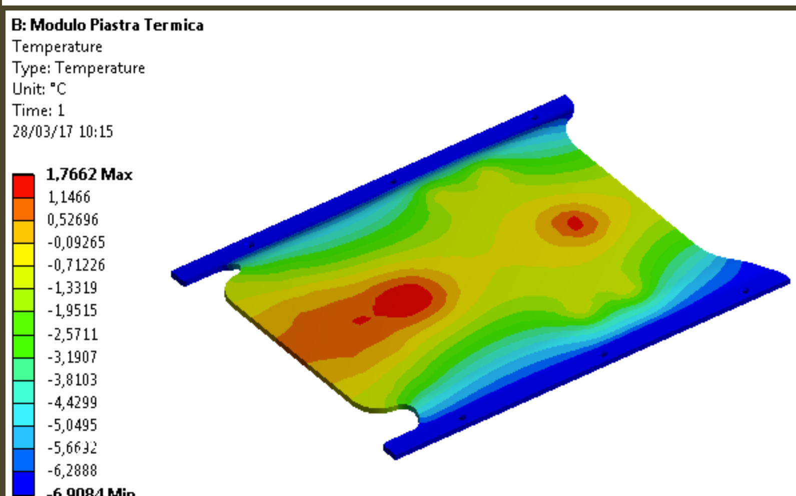
Heat Transfer in vacuum

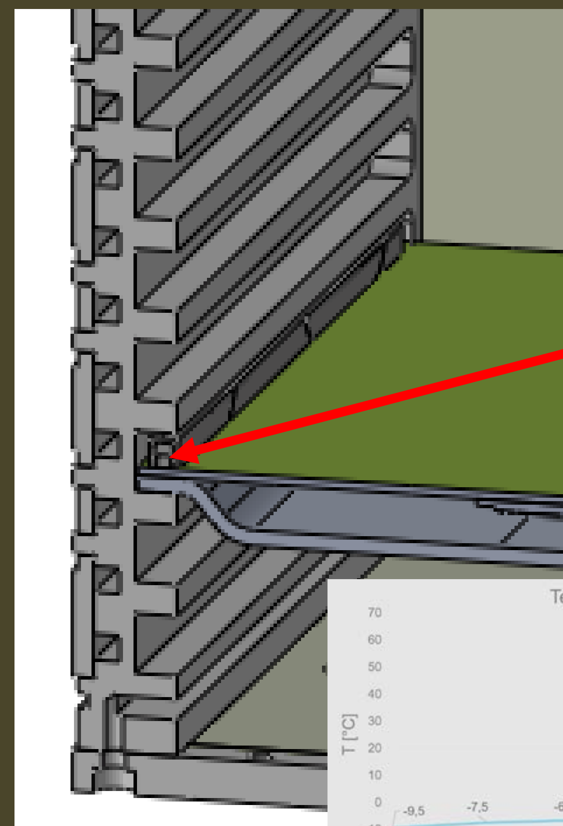
- The fundamental modes of heat transfer are:
  - Conduction → transfer of energy between objects that are in physical contac
  - Convection → transfer of energy between an object and its environment, due to fluid motion
  - Radiation → transfer of energy by the emission of electromagnetic radiation

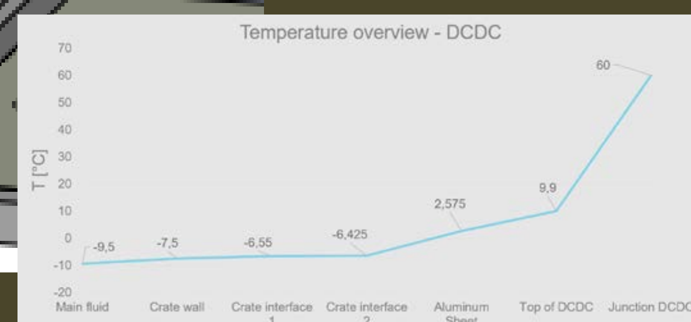
In vacuum the heat is dispersed basically by *conduction* because there is *no convection*!

Heat transfer - preliminar studies



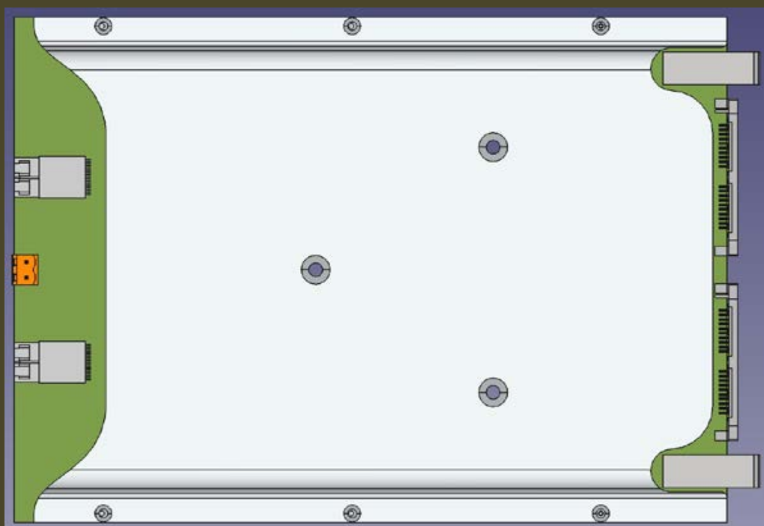


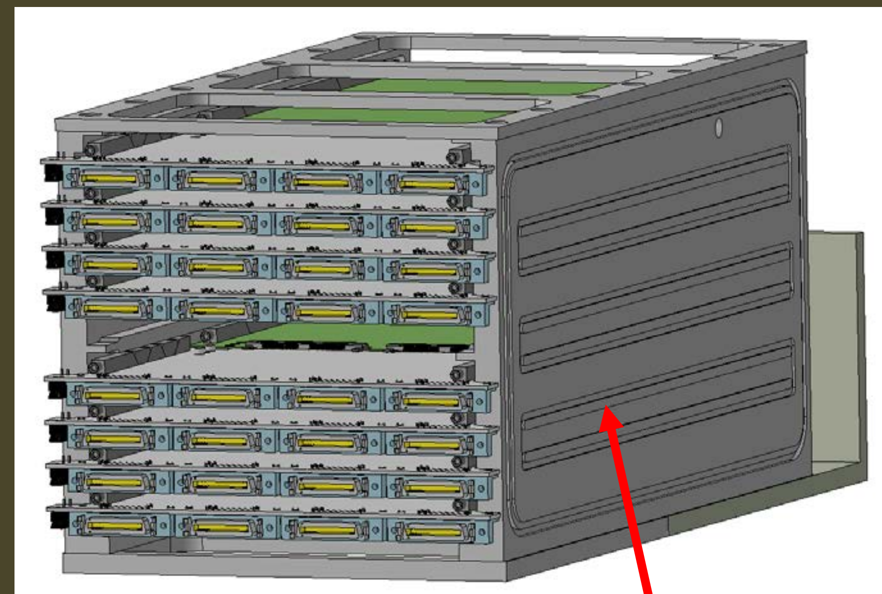


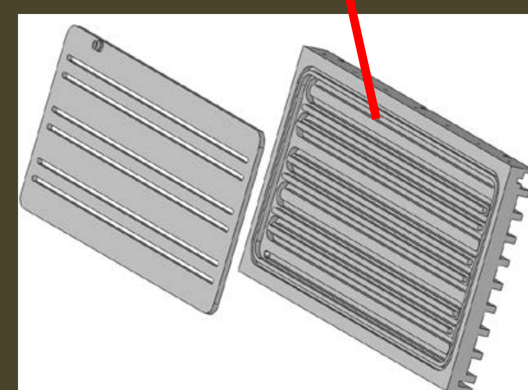


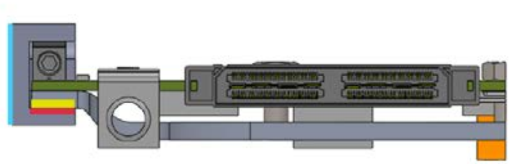
Cooling

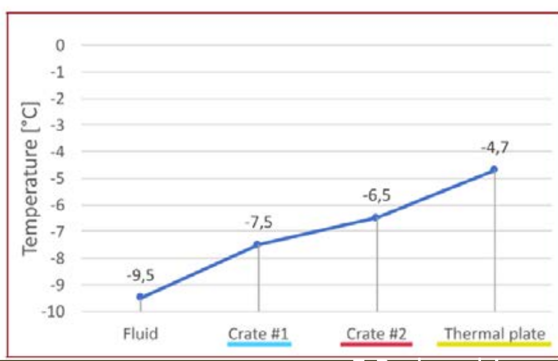
DAQ cooling



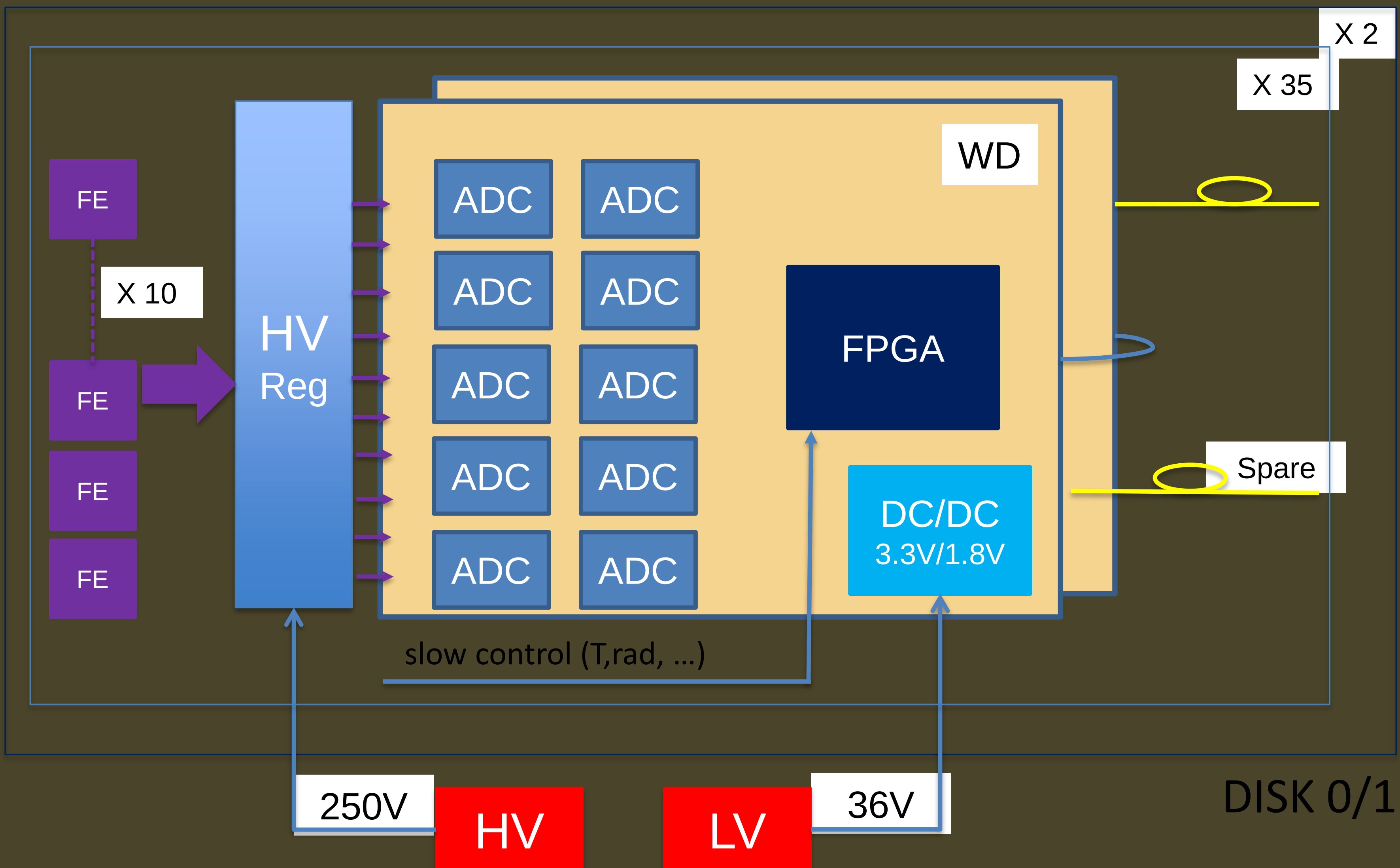




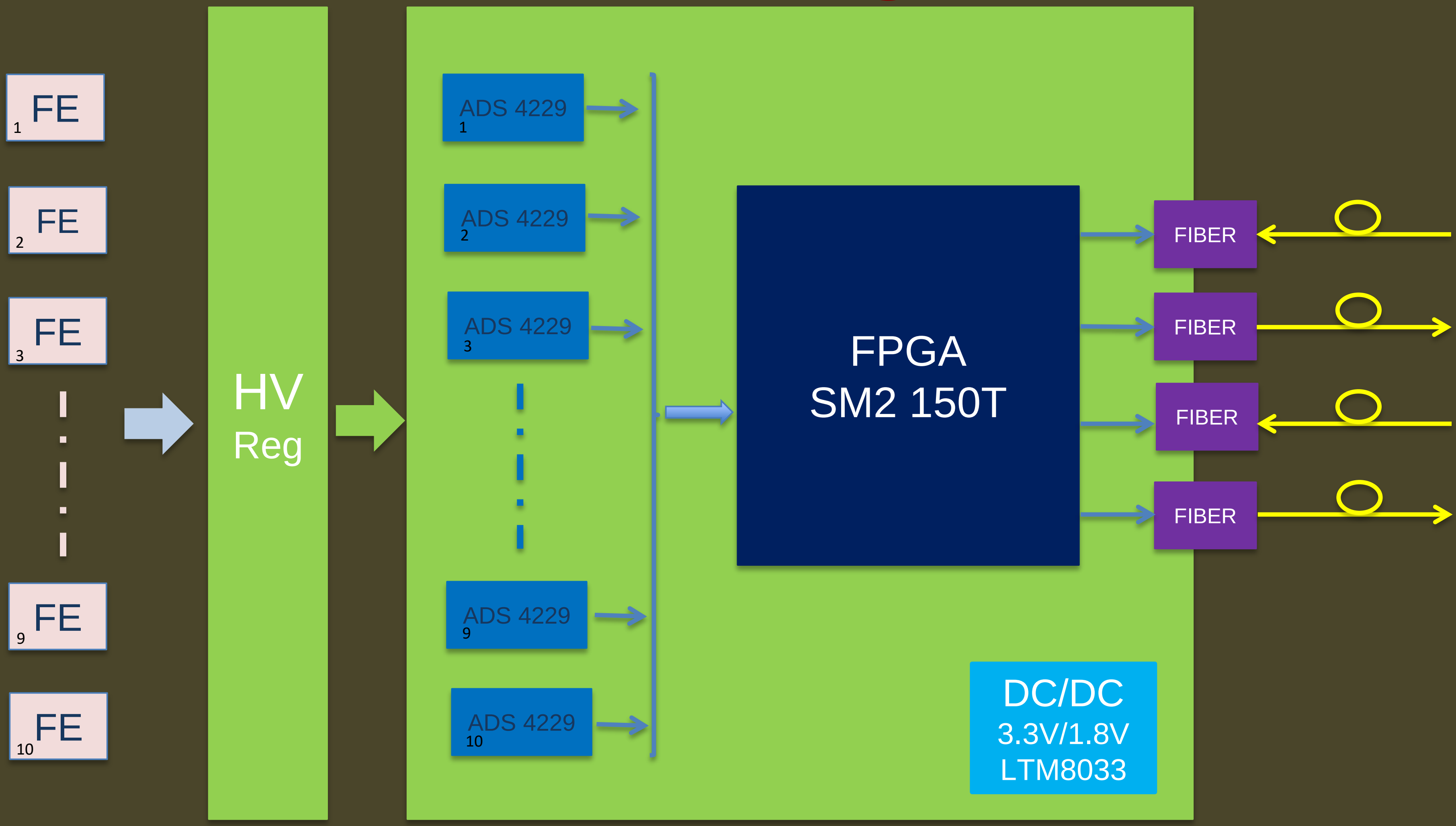




Finally the design

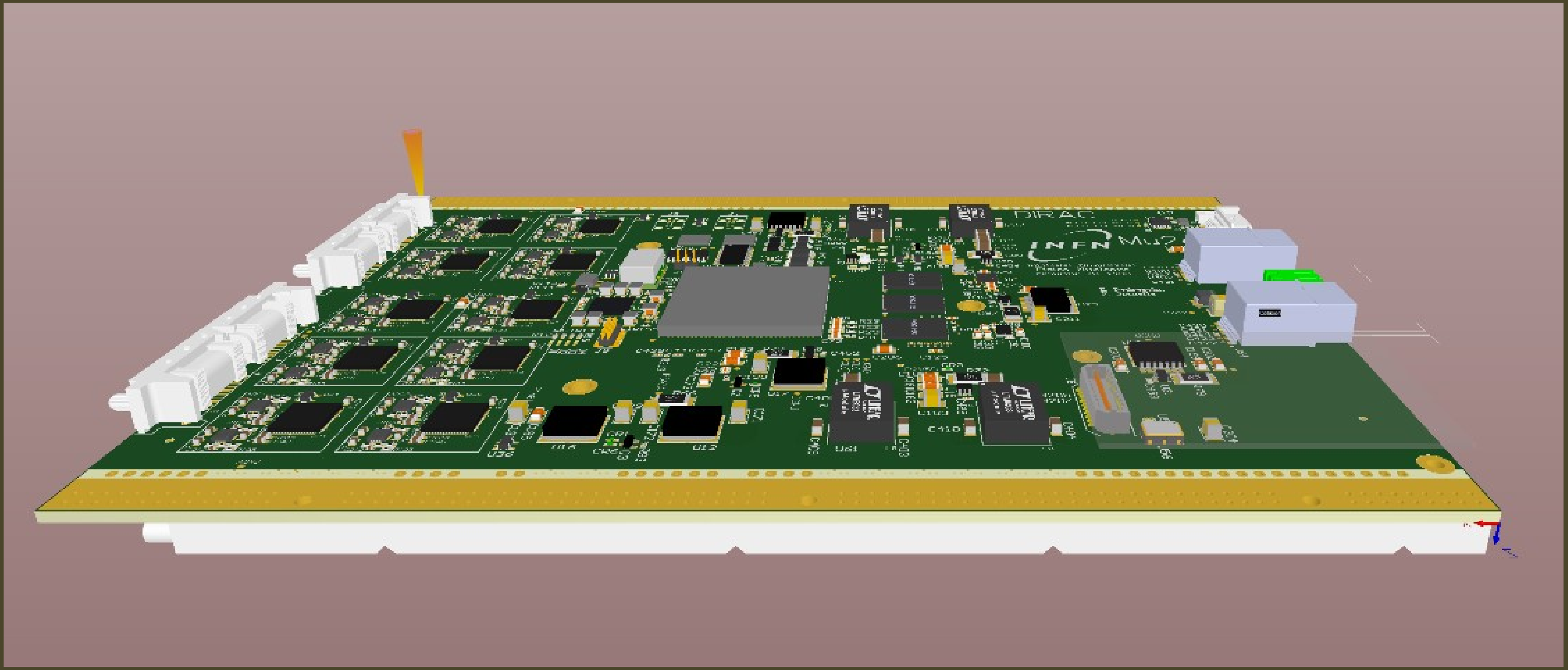


WD block diagram

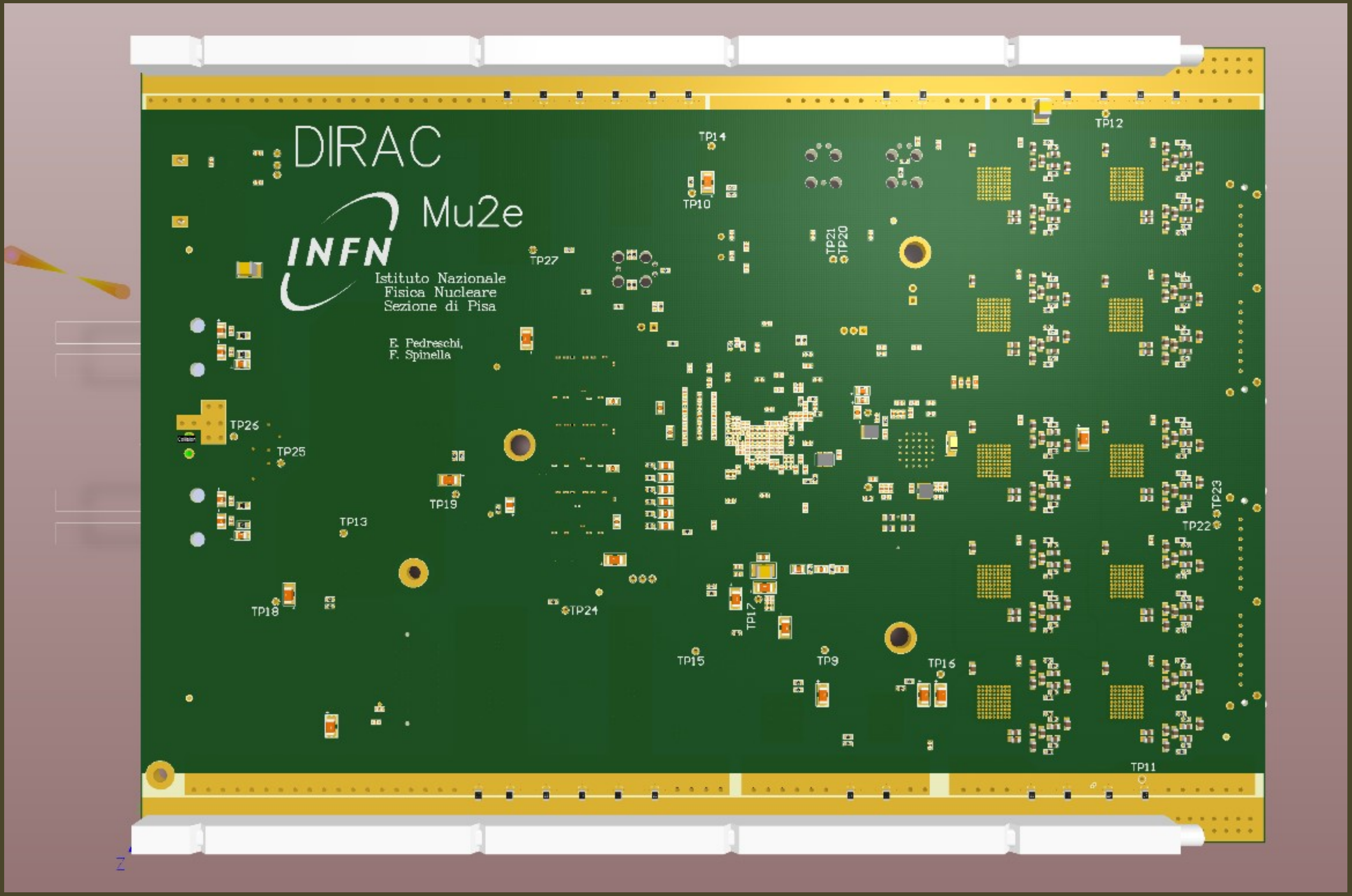


Digitizer …

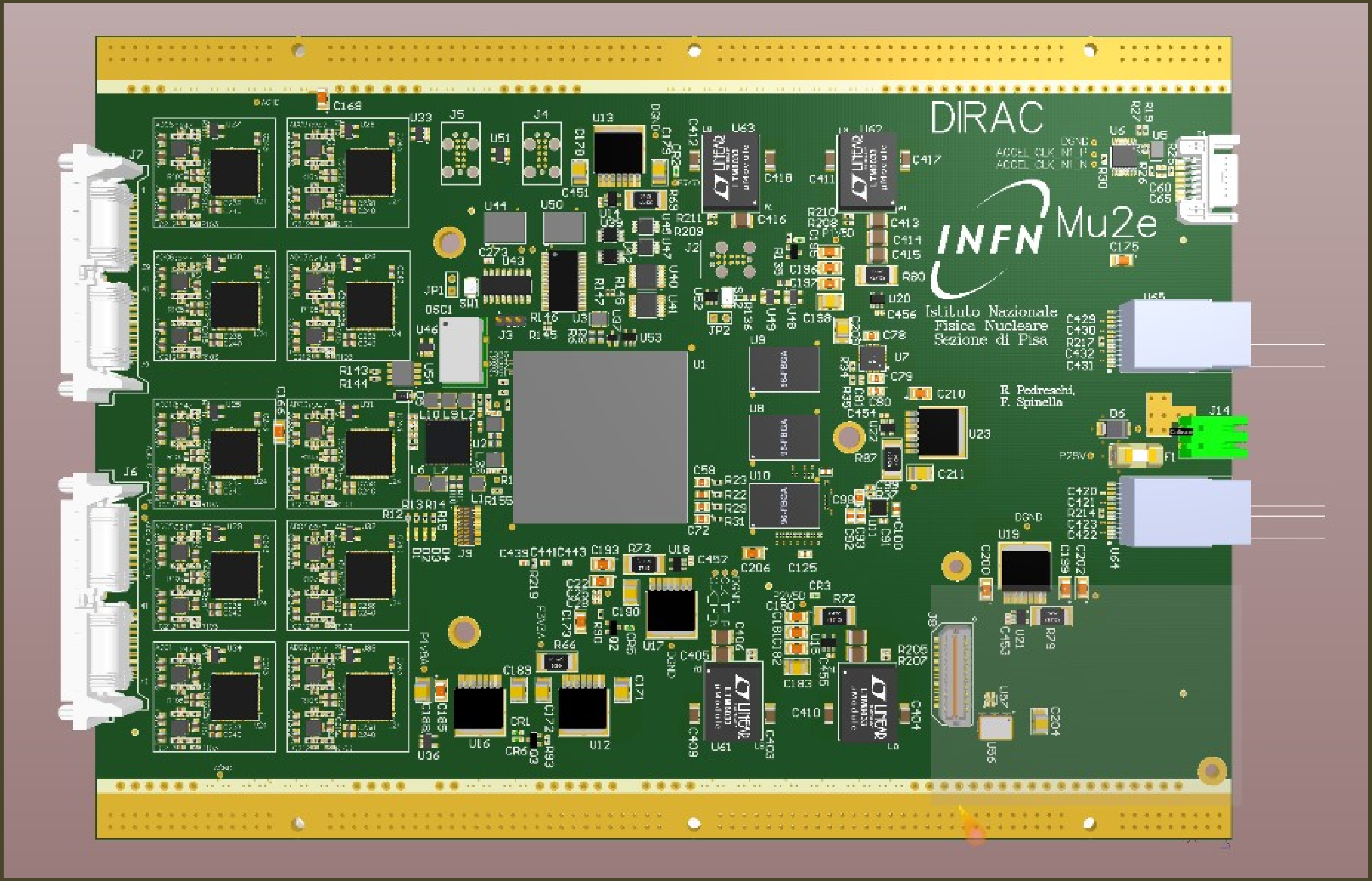
- 20 channels/ board
- 160 boards



Digitizer …


DIRAC
Mu2e
INFN
Istituto Nazionale
Fisica Nucleare
Sezione di Pisa
E. Pedreschi,
F. Spinella
TP14
TP10
TP12
TP27
TP21
TP20
TP26
TP25
TP19
TP13
TP23
TP22
TP18
TP24
TP17
TP15
TP9
TP16
TP11

Digitizer …


DIRAC
INFN
Mu2e
Istituto Nazionale
Fisica Nucleare
Sezione di Pisa
R. Pedreschi,
F. Spinella

Conclusions

- Elettronics is strongly linked to the physical processes that we want to study
- Elettronic problems are very complex because:
  - Very high data flow
  - Harsh environment:
    - Temperature
    - Radiative stresses
    - Mechanical stresses
- the cooperation among physicists, electronics and mechanical engineers is necessary for the success of the experiment

Thank you!