

## Fermilab 2022 Summer Student School

# *Developing DAQ Systems for Particle Physics Experiments*

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# Where do we do electronics in FNAL ?



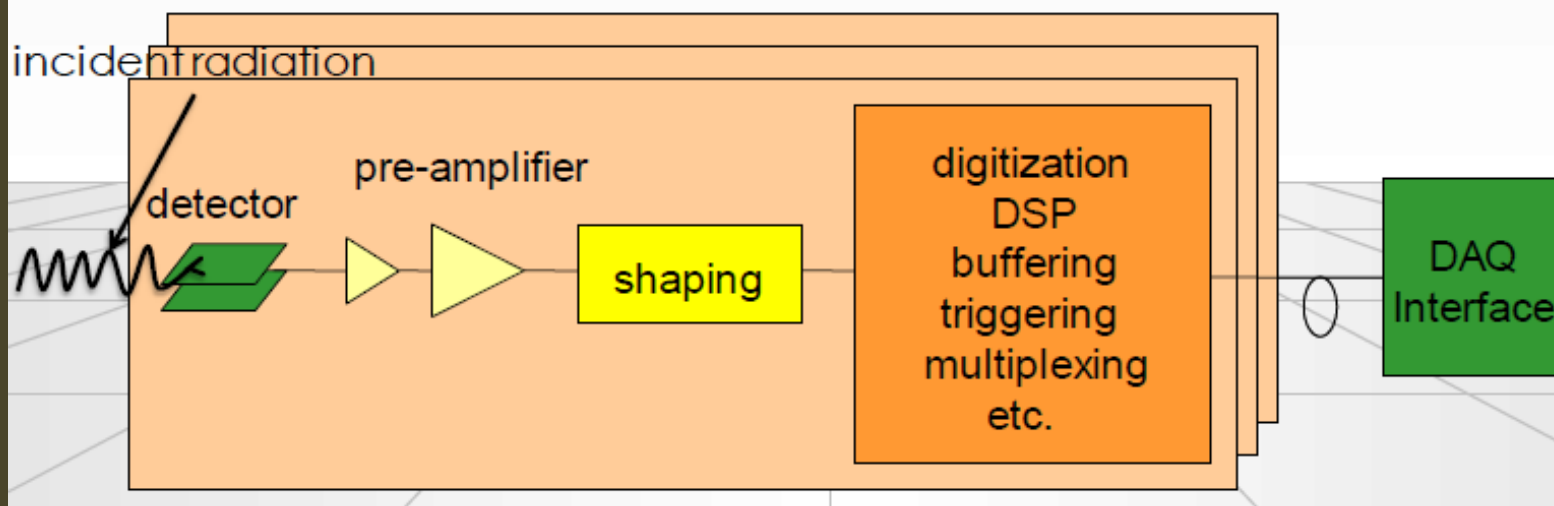
Feynman  
Computing  
Center



High Rise, 14<sup>th</sup> floor

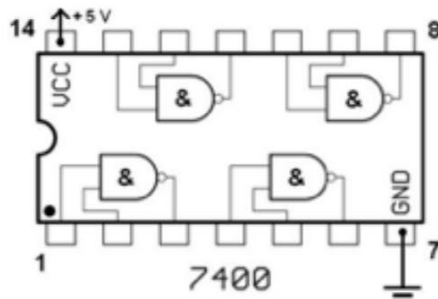
# Readout electronics

- Front-end electronics is the electronics directly connected to the detector (sensitive element)
- Its purpose is to
  - acquire an electrical signal from the detector (usually a short, small current pulse)
  - tailor the response of the system to optimize
    - the minimum detectable signal
    - energy measurement (charge deposit)
    - event rate
    - time of arrival
    - insensitivity to sensor pulse shape
  - digitize the signal and store it for further treatment



# How do we build electronics ?

## Old ways of implementing digital circuits:



- ◆ Discrete logic – based on gates or small packages containing small digital building blocks (at most a 1-bit adder)
- ◆ De Morgan's theorem – theoretically we only need 2-input NAND or NOR gates to build anything
- ◆ Tedious, expensive, slow, prone to wiring errors

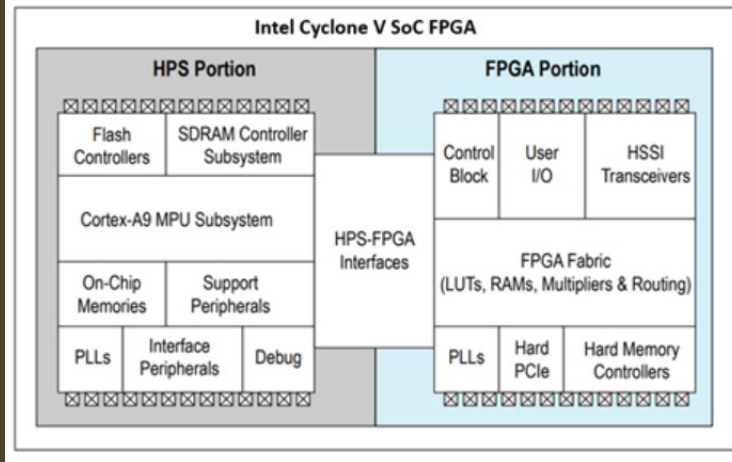
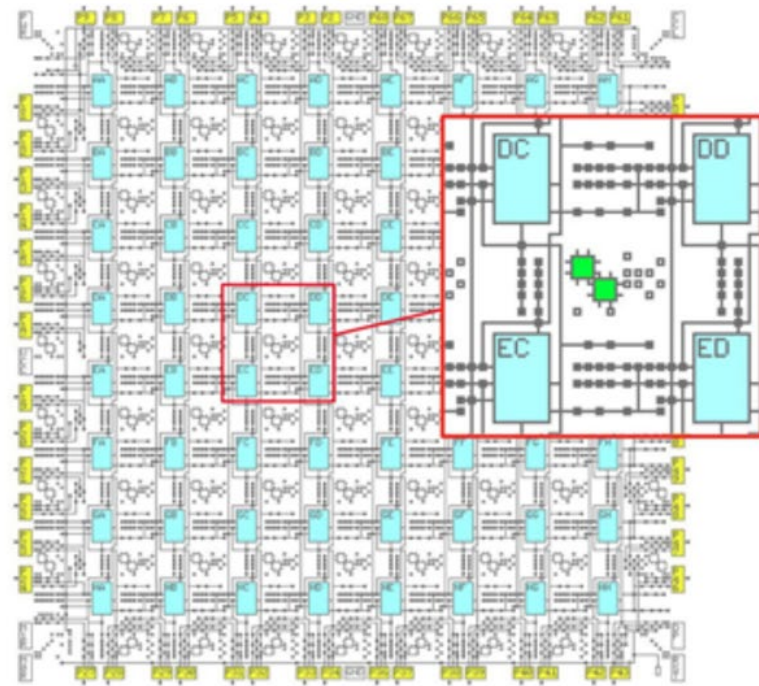


# Modern way: Field Programmable Gate Array (FPGA)

- Integrate millions of simple gates but given to the user the possibility to interconnects these gates in a programmable way.
- The interconnects can be readily reprogrammed allowing an FPGA to accommodate changes to a design or even support a new application during the lifetime of the part.

# FPGA

- Millions of simple blocks named CLB (Configurable Logic Blocks)
- Millions of configurable interconnect structures
- Something more ...



# How do we program FPGA:

## Example: VHDL

```
architecture behavioral of VMEReg is
    signal vme_en_i : std_logic;
    signal Q : std_logic_vector(15 downto 0);

begin -- behavioral

    vme_addr_decode : process (vme_addr, vme_en) is
        variable my_addr_vec : std_logic_vector(vme_addr'high downto 0);
        variable selected : boolean;
    begin -- process vme_addr_decode
        my_addr_vec := std_logic_vector( TO_UNSIGNED ( my_vme_base_address, vme_addr'high+1 ) );
        selected := my_addr_vec(vme_addr'high downto 1) = vme_addr(vme_addr'high downto 1);
        vme_en_i <= '0' ;
        if selected then
            vme_en_i <= vme_en;
        end if;
    end process vme_addr_decode;

    reg: process (vme_clk, reset) is
    begin -- process reg
        if reset = '1' then -- asynchronous reset
            Q <= init_val;
            vme_en_out <= '0';
        elsif vme_clk'event and vme_clk = '1' then -- rising clock edge
            vme_en_out <= vme_en_i;
            if vme_en_i = '1' and vme_wr = '1' then
                Q <= vme_data;
            end if;
        end if;
    end process reg;

    data <= Q;
    vme_data_out <= Q;

end behavioral;
```

- Looks like a programming language
- All statements executed in parallel, except inside processes

# Introduction

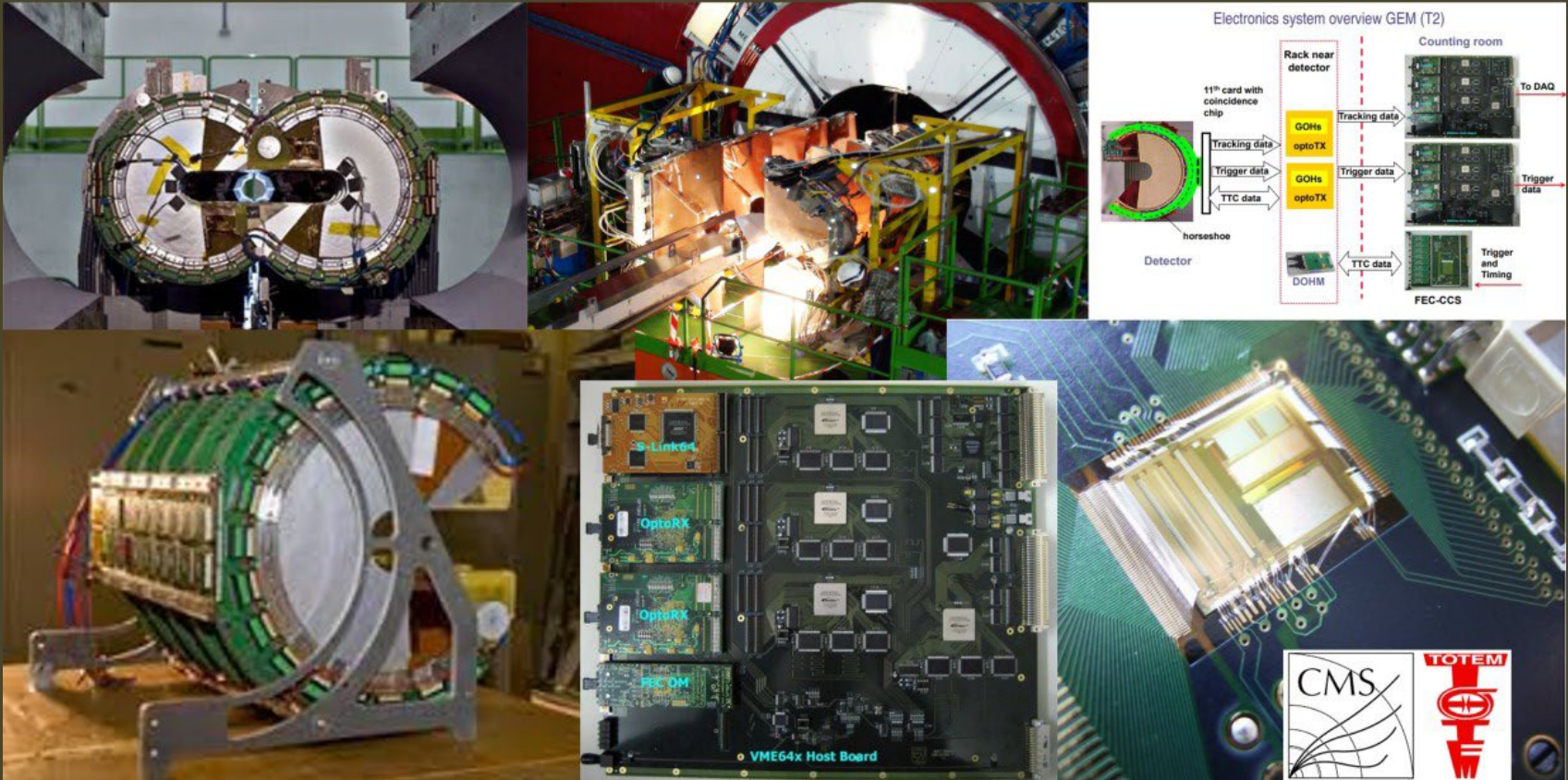
- Electronics is strongly linked to the physical processes that we want to study
- Electronic problems are very complex because:
  - Very high data flow
  - Harsh environment:
    - Temperature
    - Radiative stresses
    - Mechanical stresses

# AMS-02 -ISS



Harsh environment: Radiation, Vacuum, Temperature and Vibration

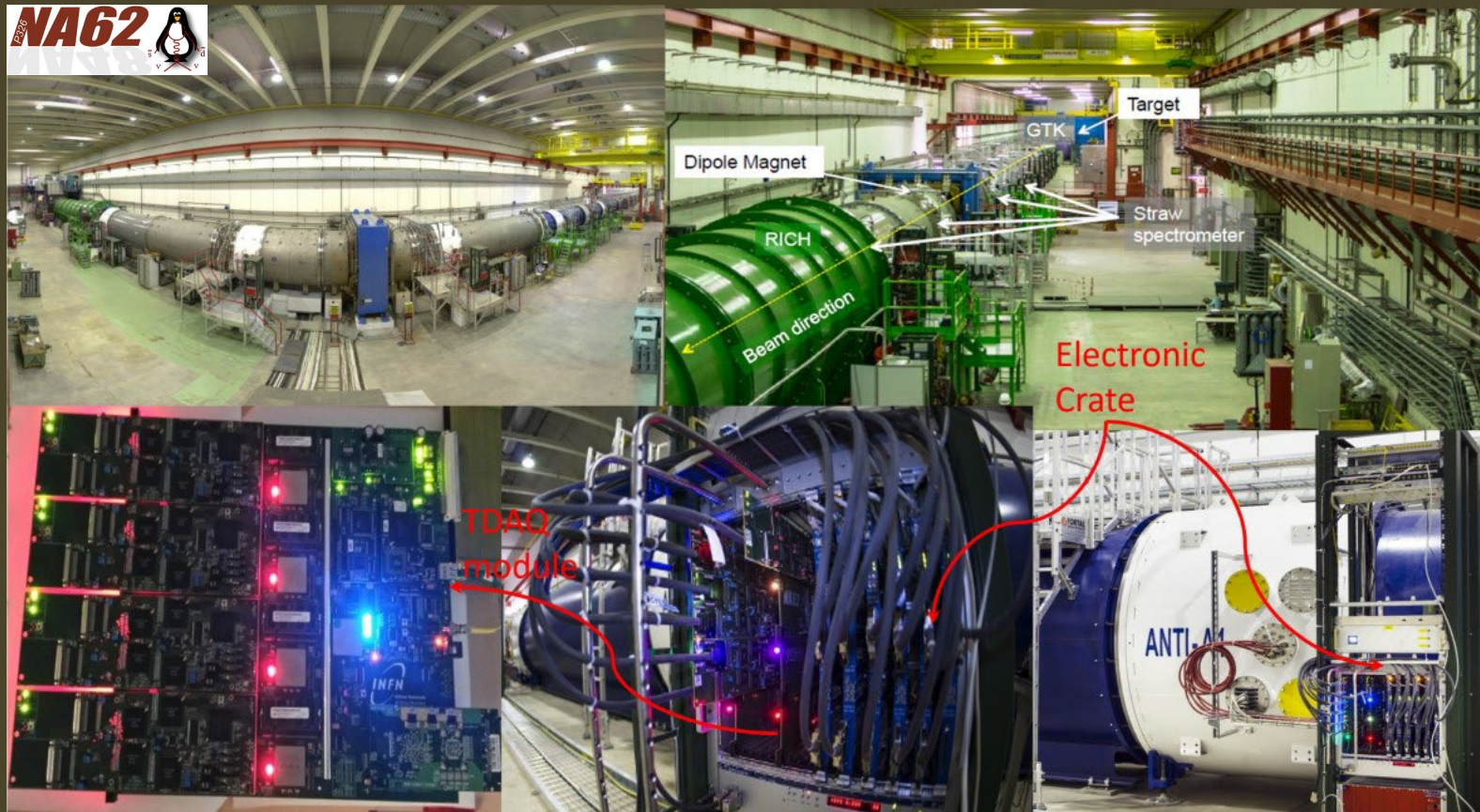
# TOTEM – CMS @ LHC IP5



Harsh environment:

- Radiation Dose  $\approx$  100 Mrad

# NA62 – CERN SPS



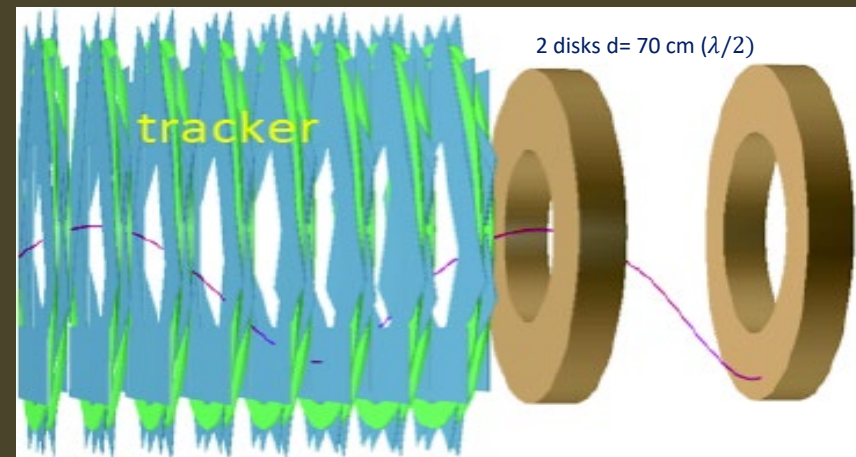
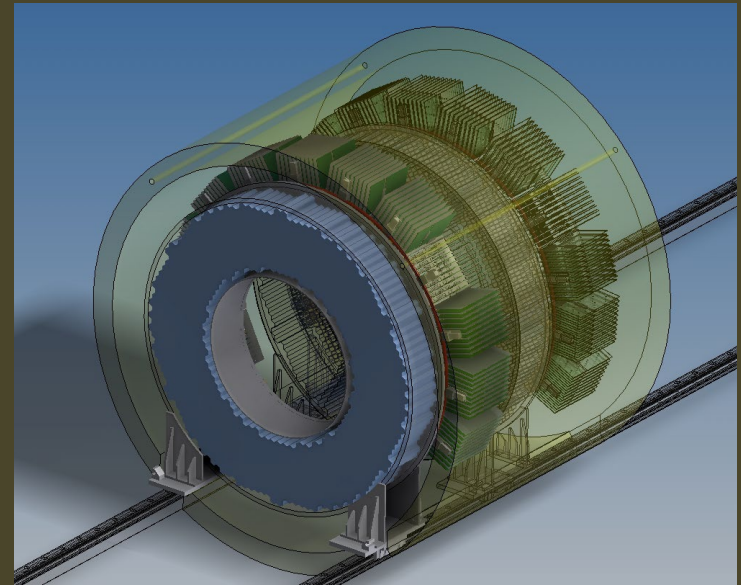
Harsh environment:

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

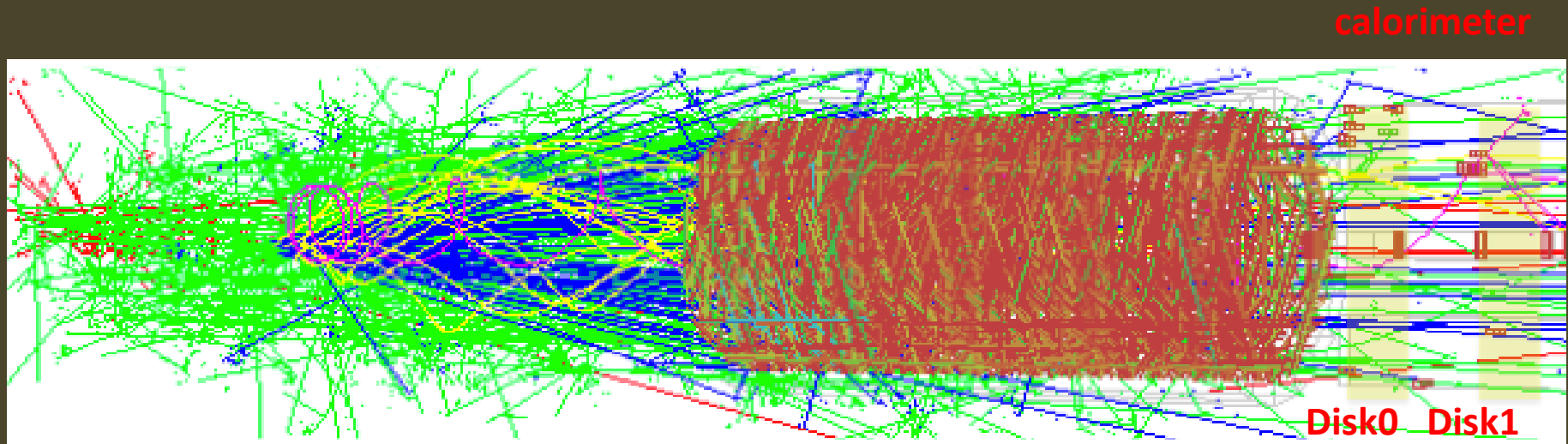
# The Mu2e Calorimeter

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

INFN is in charge of the design and of the construction



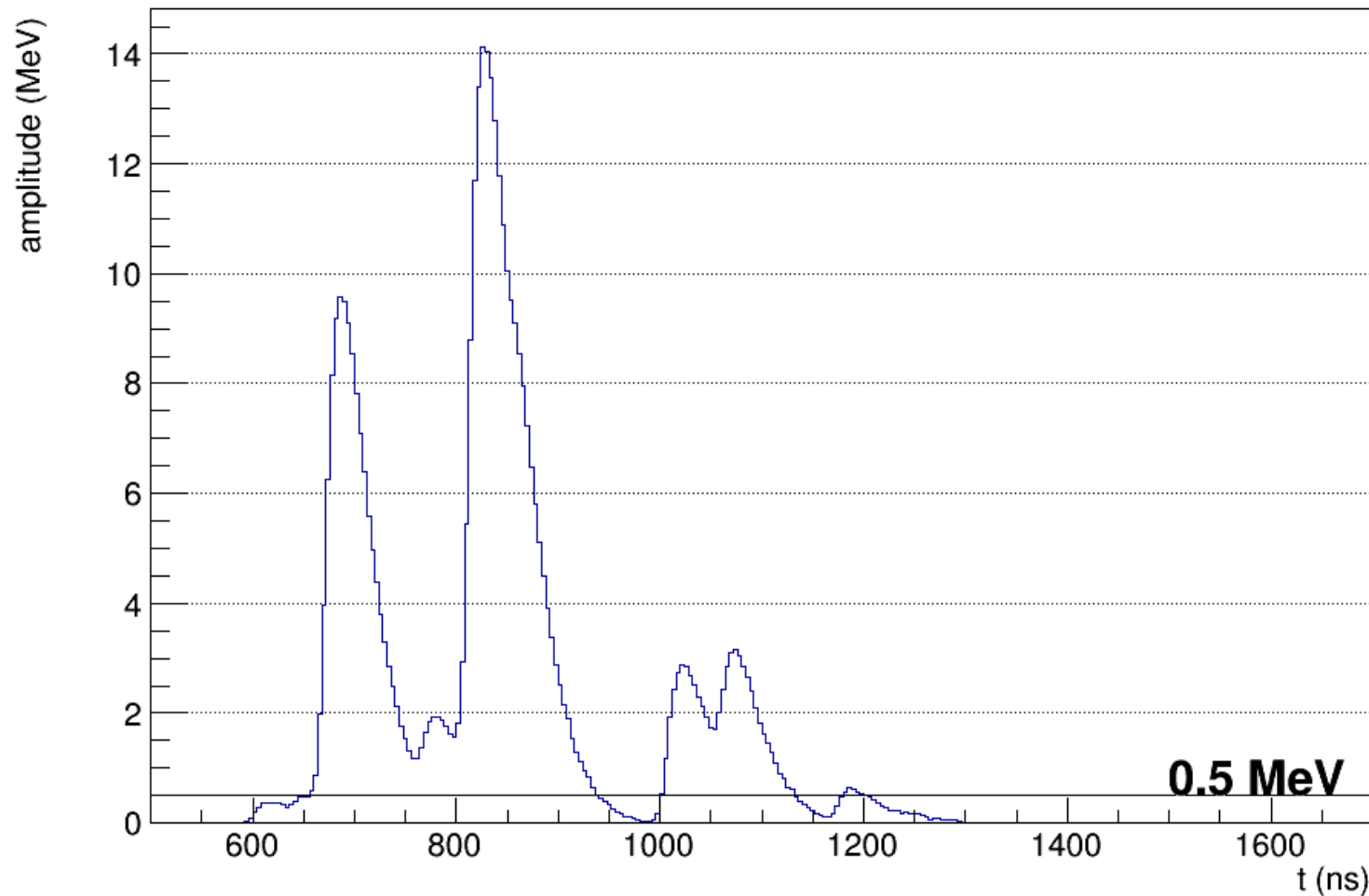
# E, t measurements – Why a digitizer?



## Typical 1.7 $\mu\text{s}$ Mu2e event

- Very intense particle flux expected in the calorimeter

# Example of Front-End output

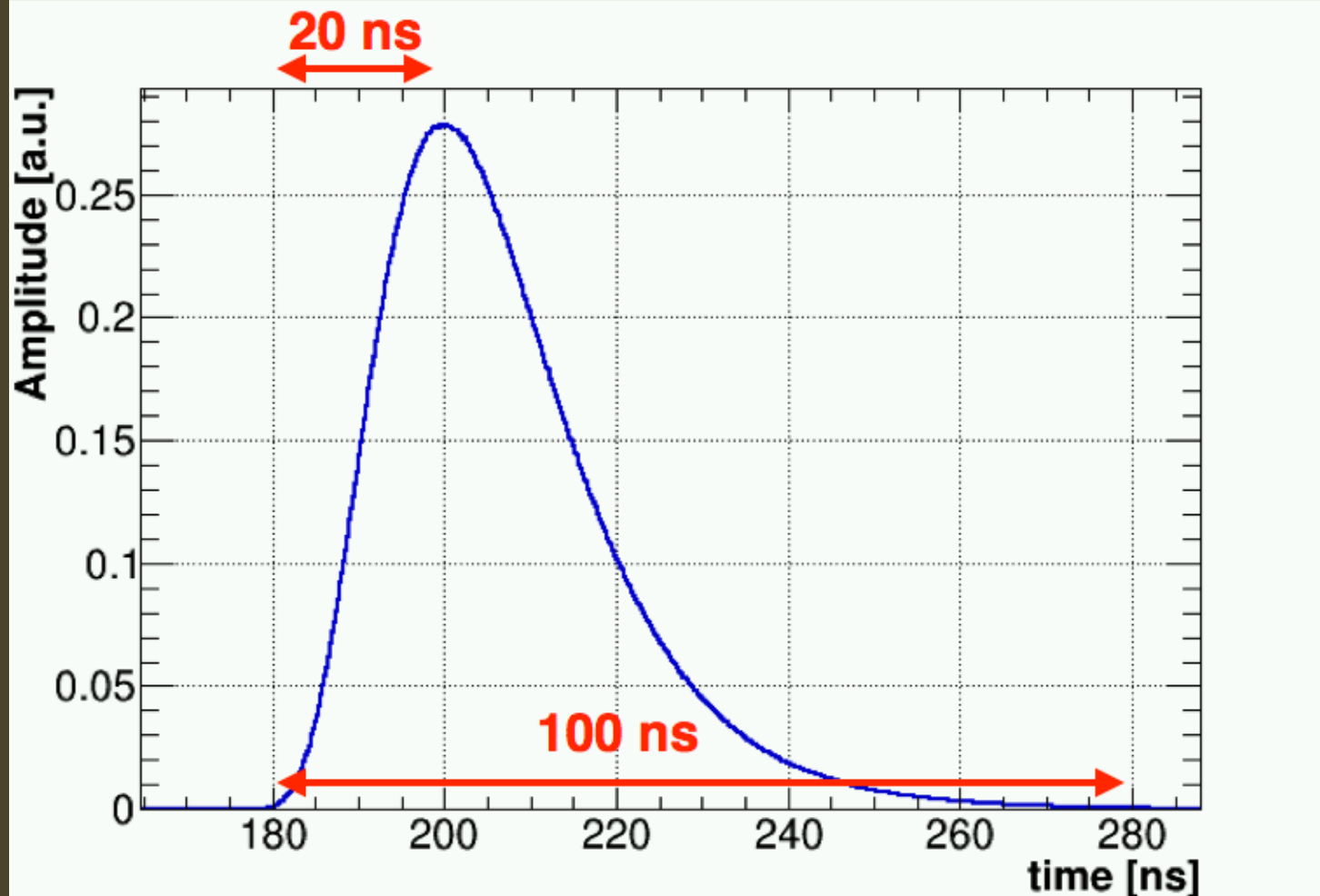


- We need high-sampling rate digitizers to resolve pile-up

# Digitizer requirements

- Digitization requirements are determined by the calorimeter requirements
- **Particle identification:**
  - $\sigma_t < 500 \text{ ps @ } 100 \text{ MeV}$
  - $\sigma_E/E < 10\% @ 100 \text{ MeV}$
- **We require** the additional contribution due to the digitization procedure itself to be:
  - $\sigma_t < 200 \text{ ps @ } 100 \text{ MeV}$

# Analog input: signal waveform

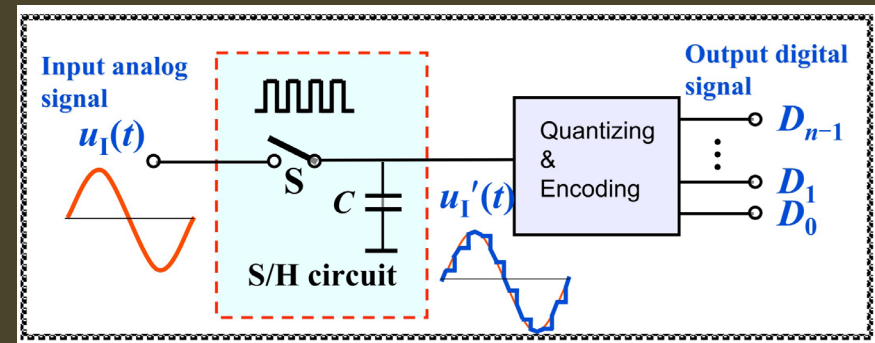


# From Analog to Digital: ADC converters

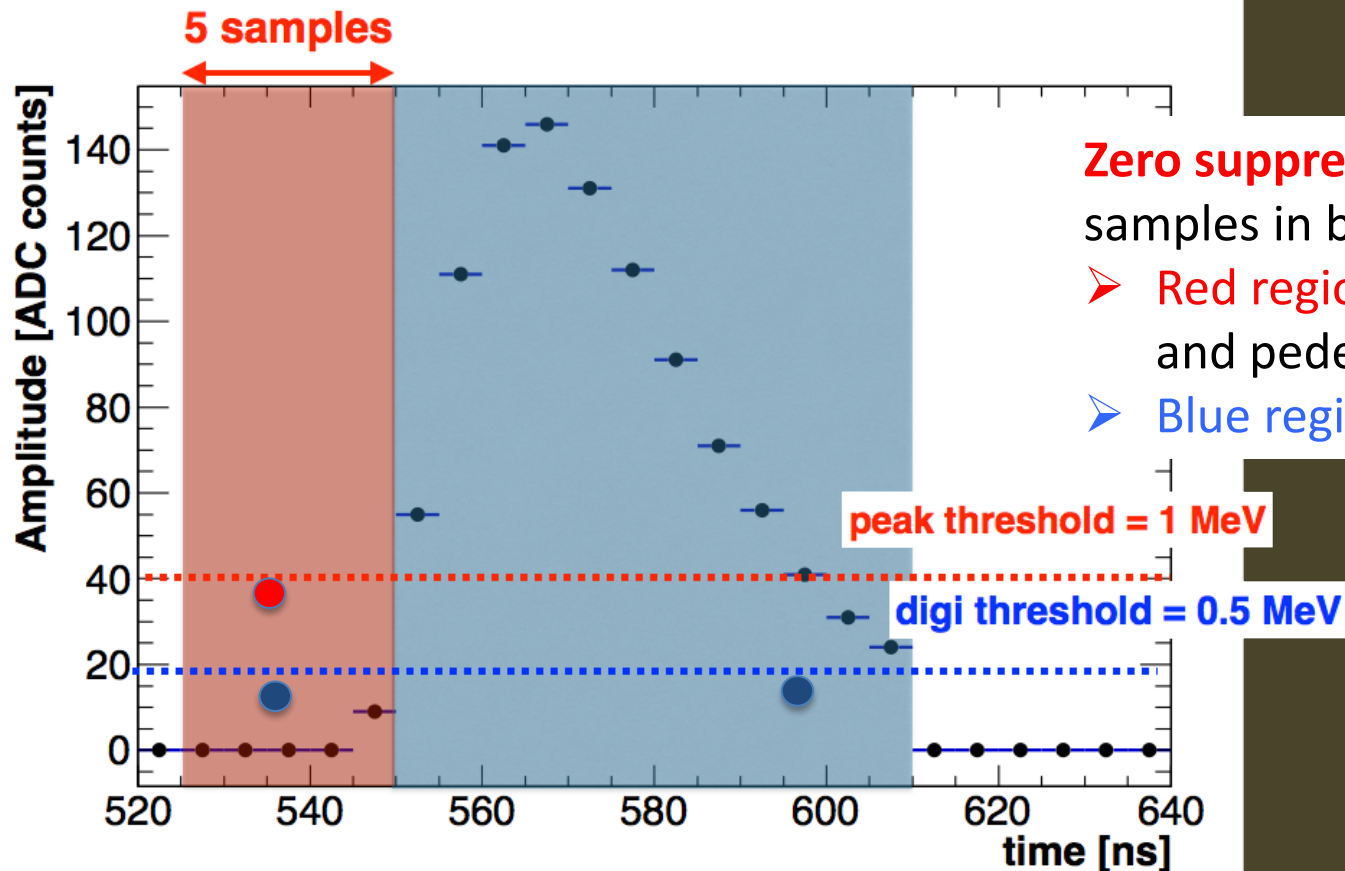
- What is an ADC?
  - An electronic integrated circuit which transforms a signal from analog (continuous) to digital (discrete) form
  - Analog signals are directly measurable quantities
  - Digital signals have only two states
- Why ADC is needed?
  - ADC provides a link between the analog world of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

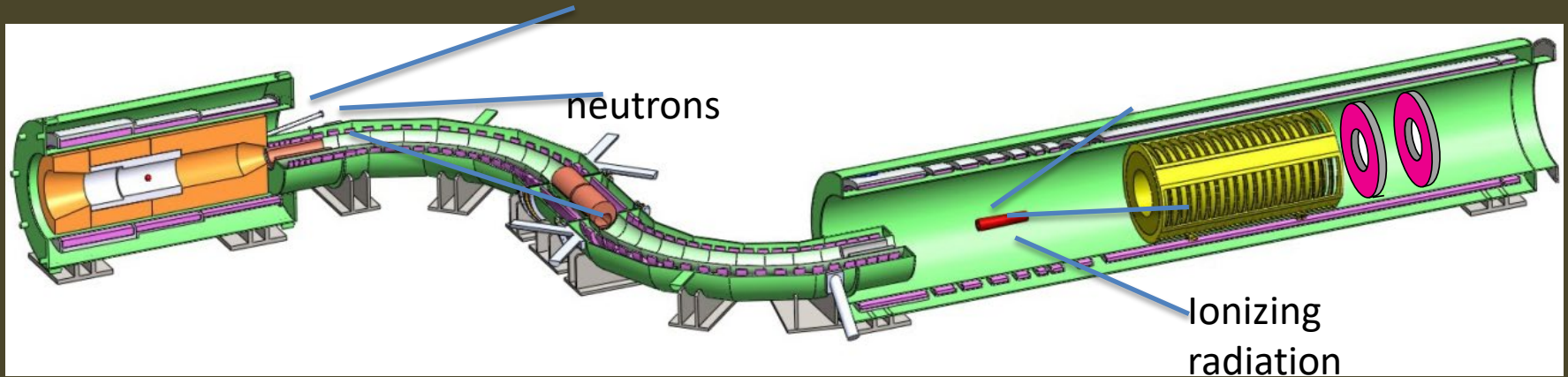
- Radiation (not too high but present) 0,5 Krad/y and high neutron flux ( $\sim 6 \times 10^{11} / \text{cm}^2 \cdot \text{year}$ )  $\rightarrow$  select rad-hard components
- High magnetic field (1T)  $\rightarrow$  problems for magnetic nuclei of DC-DC converters
- All the electronics is in vacuum  $\rightarrow$  degassing problems and need to use only conductive thermal dissipation.
- Maintenance complicated  $\rightarrow$  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  $\sim 0.2 \div 0.5$  krad
- ✓ Expected total dose  $0.5 \times 12 \times 5 = 12 \div 30$  krad
- ✓ Neutron flux  $6 \times 10^{11} / \text{cm}^2 \cdot \text{year}$

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

✓ -

# Radiation Effects on Electronics

- Long Term Effects
  - *Total Ionizing 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 (*SEUs*) 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

The choice is for Microsemi Polarfire FPGA

- Specs:
  - non-volatile 28 nm technology
  - Cost-optimized, lowest power, mid-range density FPGAs
  - 250 Mbps to 12.7 Gbps transceivers
  - 100K to 500K logic elements, up to 33Mbits of RAM
  - Best-in-class security and exceptional reliability
  - SEU immune FPGA configuration cells
- We used the largest and fastest one MPF500T (1152 pins)
- We don't need to qualify this part as a single element



# ADC

- Specs:

- $\geq 200$  Msample
- $\geq 12$  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

	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	-	1.27x 10 <sup>9</sup>	0.8	-	-	-	-	55	60.0	0.7	125	1000	14782	0



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<sub>PP</sub>
- Package: 9-mm × 9-mm, 64-Pin Quad Flat No-Lead (QFN) Package

### 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).

### 2 Applications

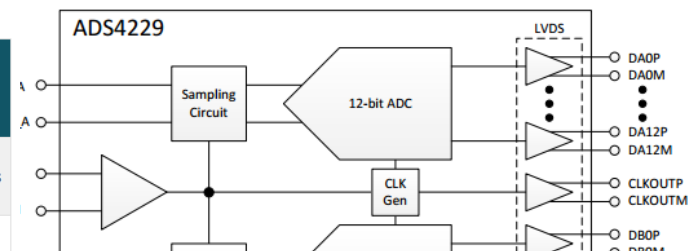
- Wireless Communications Infrastructure
- Software Defined Radio
- Power Amplifier Linearization

#### Device Information<sup>(1)</sup>

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

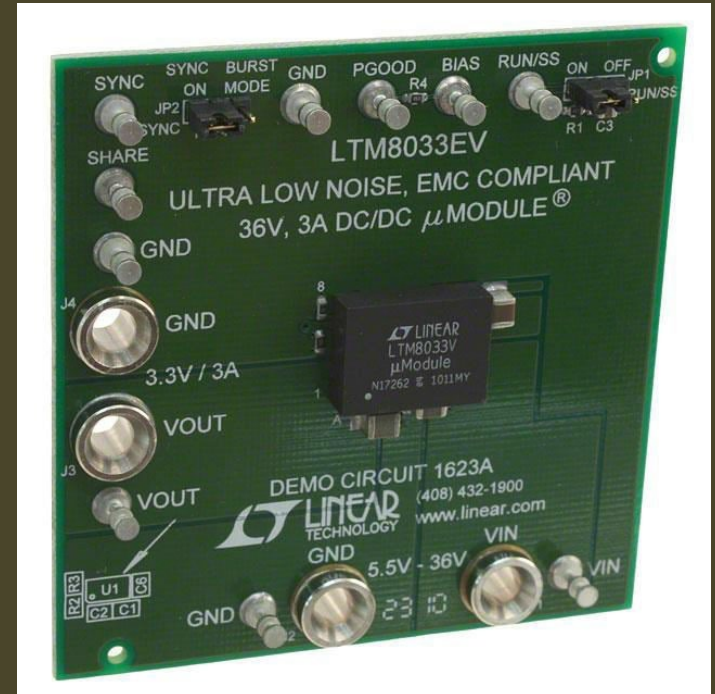
(1) For all available packages, see the orderable addendum at the end of the datasheet.

#### ADS4229 Block Diagram



# DC-DC

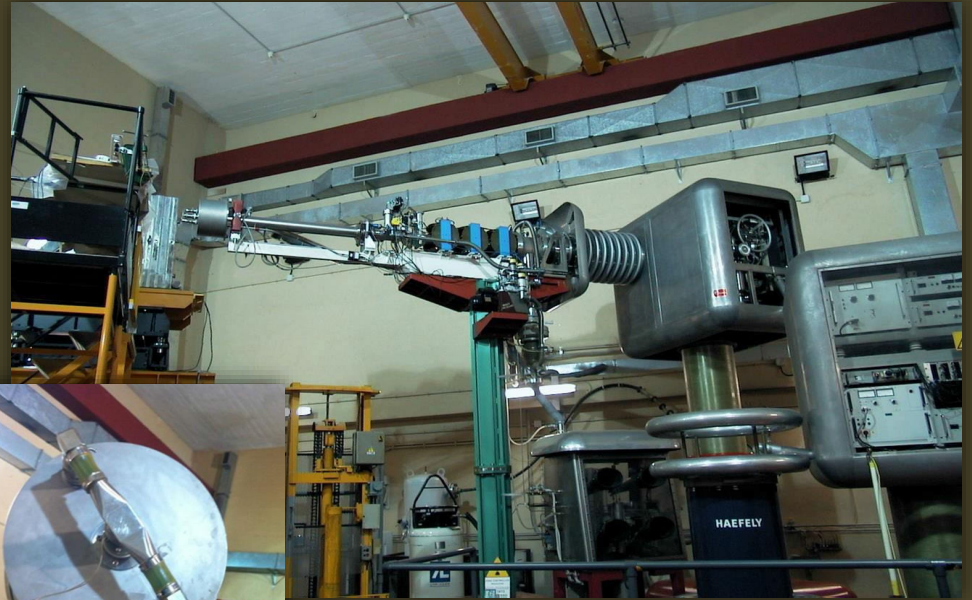
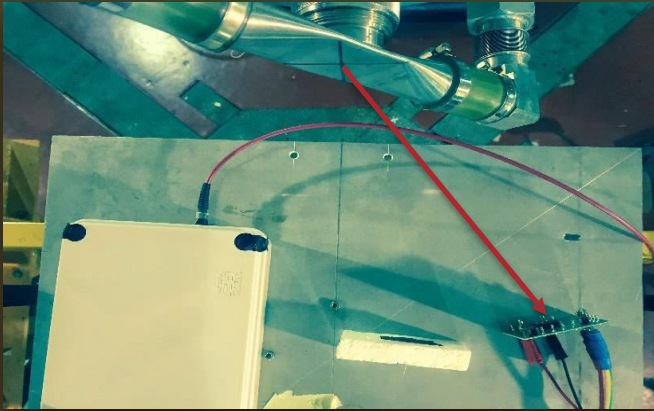
- DCDC converters are quite delicate devices, prone to radiation damage and B field
- INFN has financed a test survey to study which DCDC
- are suitable to be used in HEP environments (LHC ...)
- From these studies the Texas Instruments LMZM36606 seems the best suitable for MU2E environment



# Neutron irradiation test – FNG facility

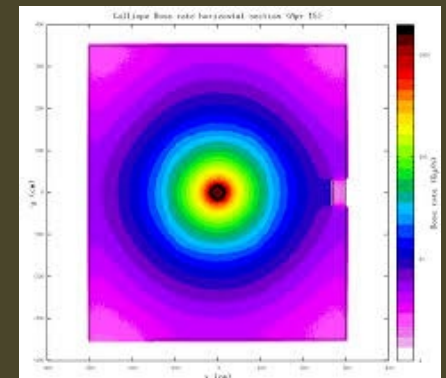
FNG (Frascati Neutron Generator) is a linear electrostatic accelerator in which up to 1 mA D<sup>+</sup> ions are accelerated onto a Tritium target.

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

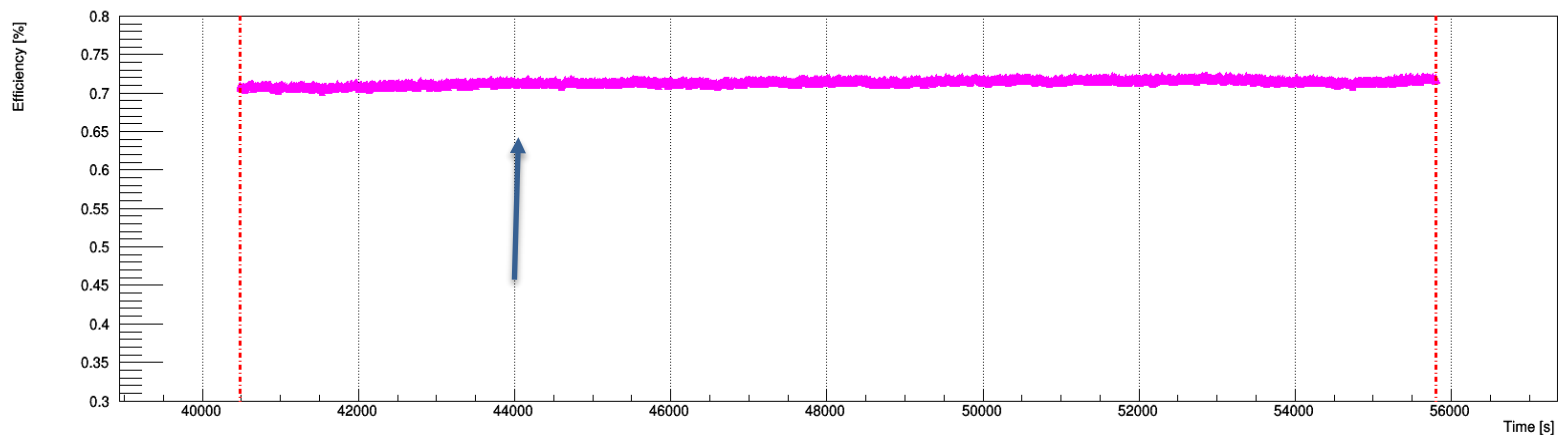
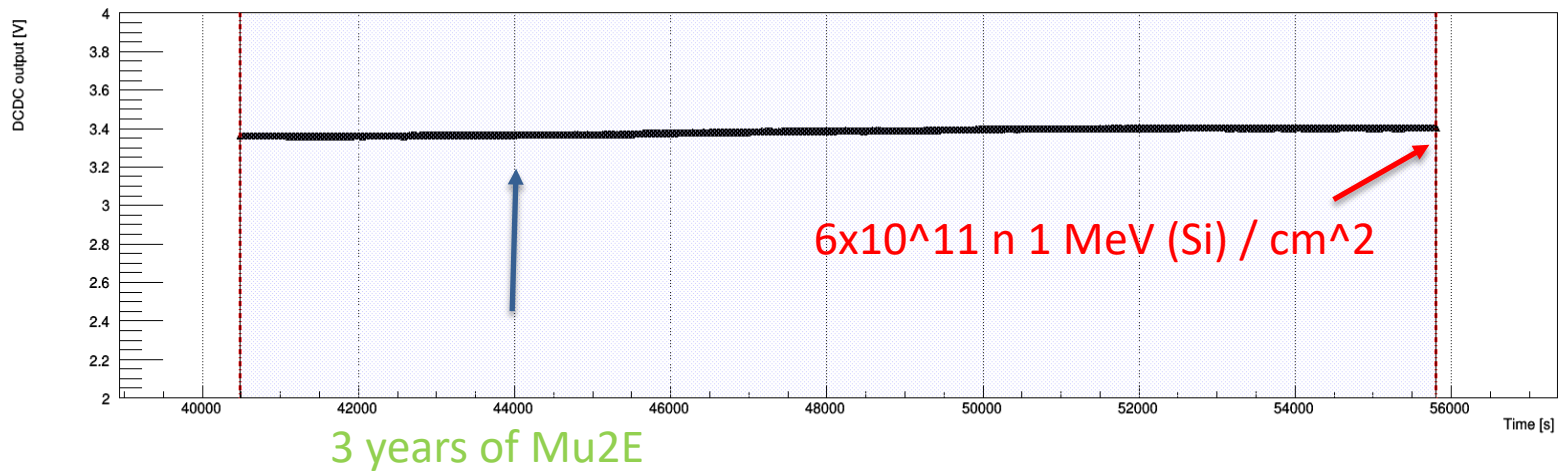


# Ionizing dose test – CALLIOPE facility

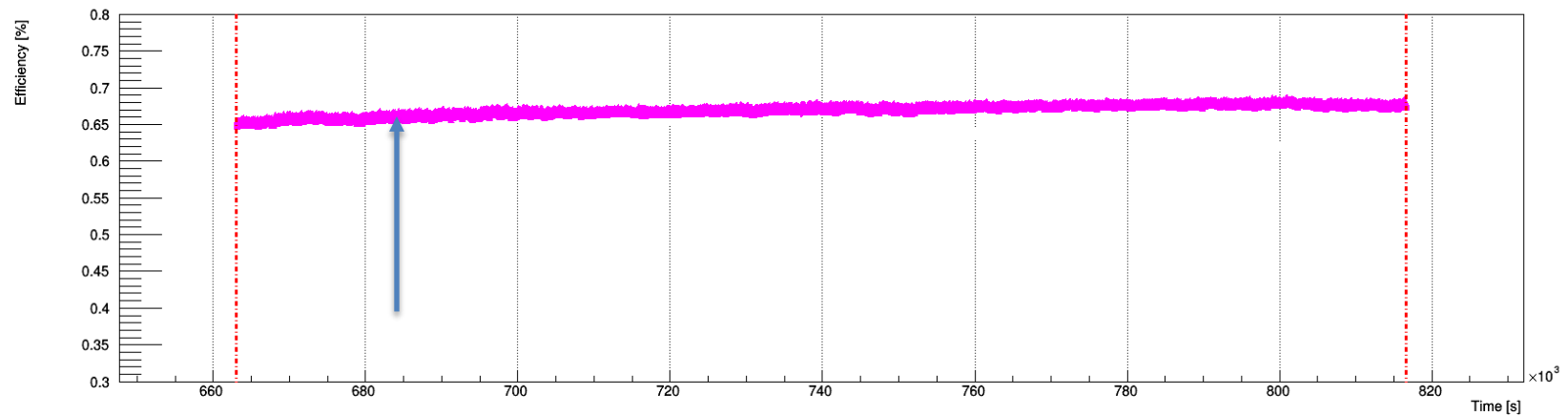
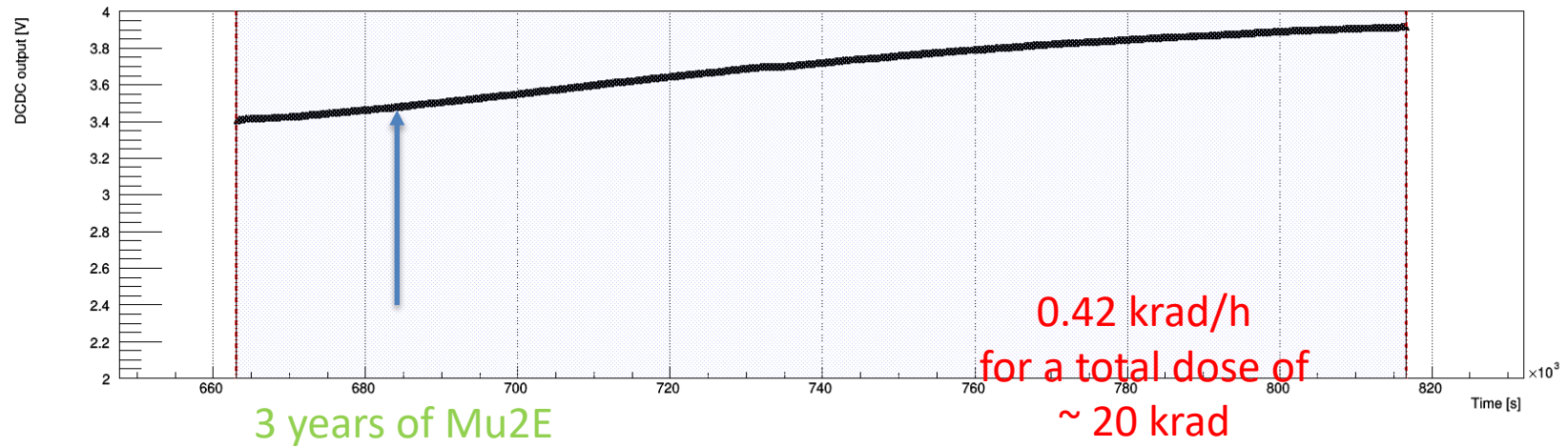
- Gamma rays at 1.17 and 1.33 MeV from Co60.
- $3.7 \times 10^{15}$  Bq of activity.
- Isotropic source, flux scales with  $r^2$ .



# DCDC neutron irradiation test - Results



# DCDC gamma irradiation test - Results

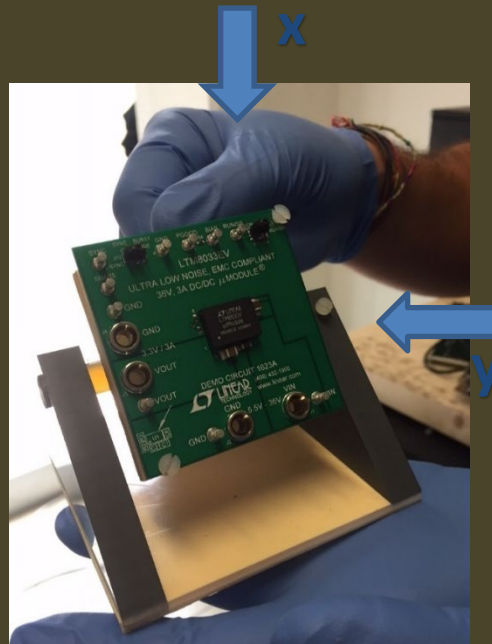


# Magnetic Field exposure test (1)

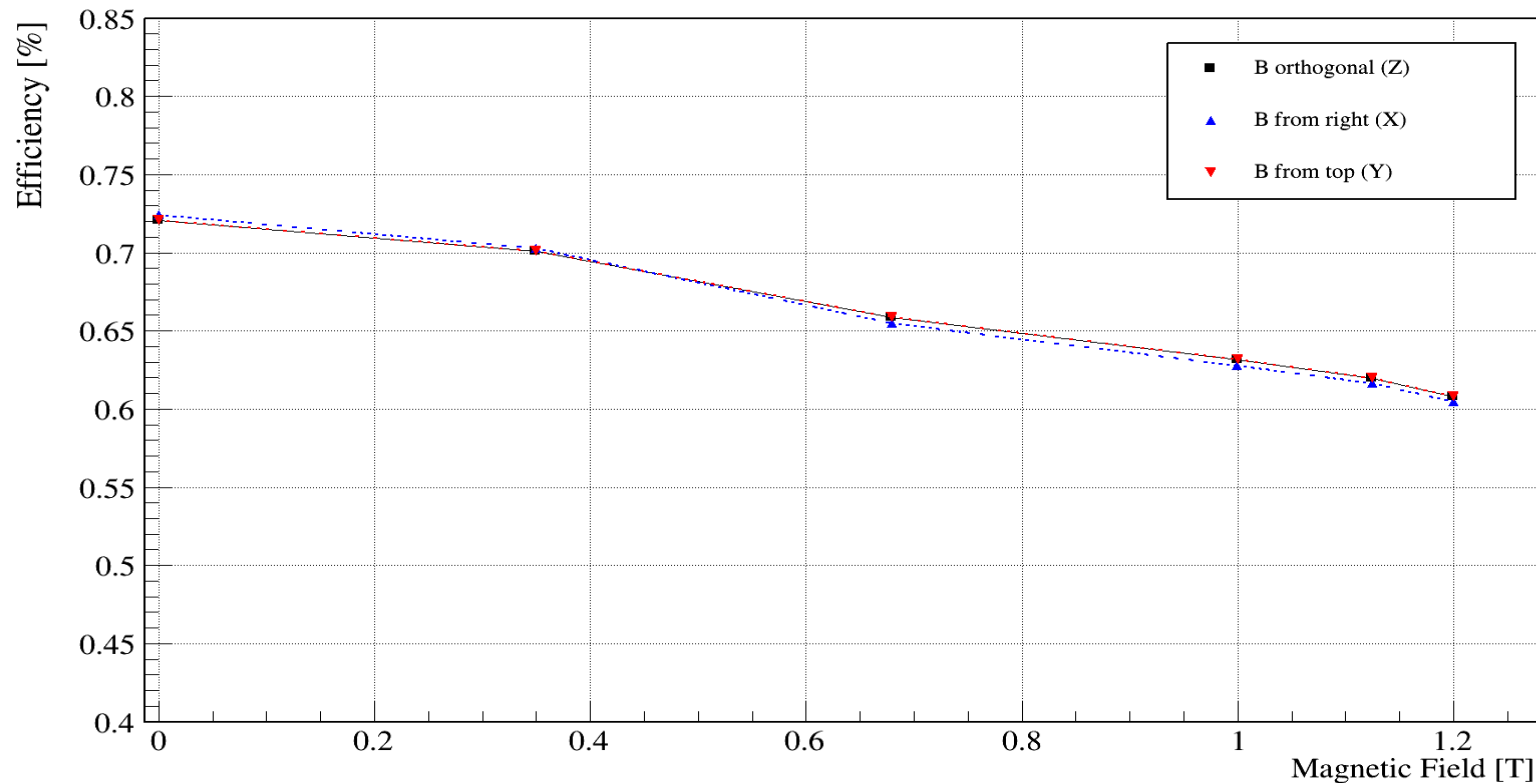
## Laboratorio Acceleratori e Superconduttività Applicata



- 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.

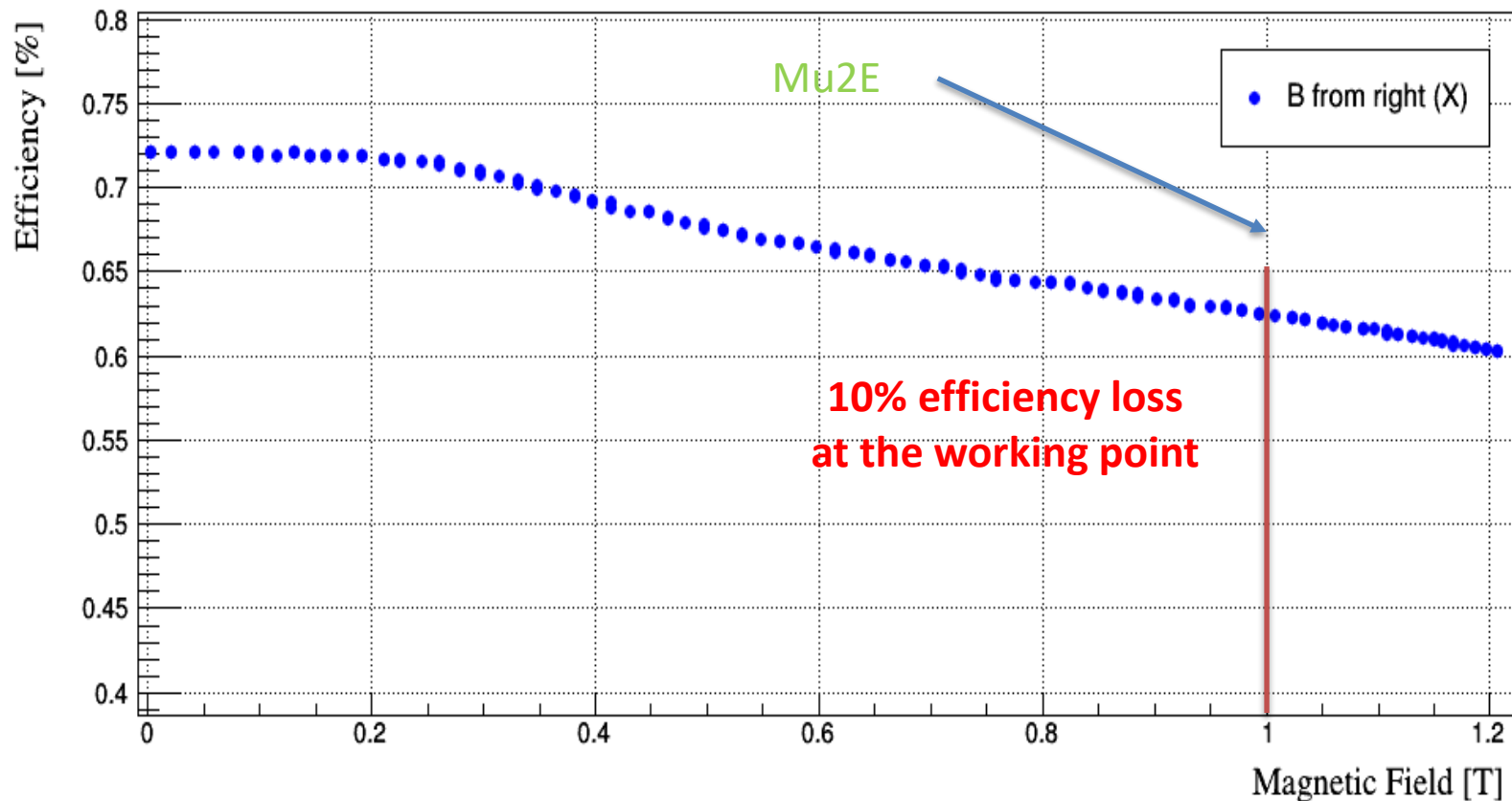


# DC-DC magnetic field exposure test—3 axis



No significant differences between orientations.

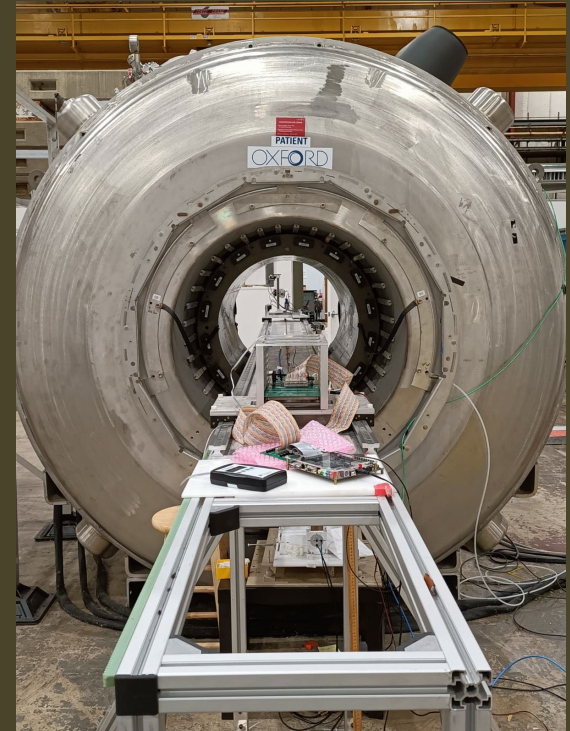
# DC-DC magnetic field exposure test – x axis



# Magnetic Field exposure test (2)



- Uniform Magnetic Field up to 1.4 T.
- We tested different orientations of the electronics with respect to the magnetic field.
- Same setup of the radiation tests.
- Same results of DC-DC converters B test

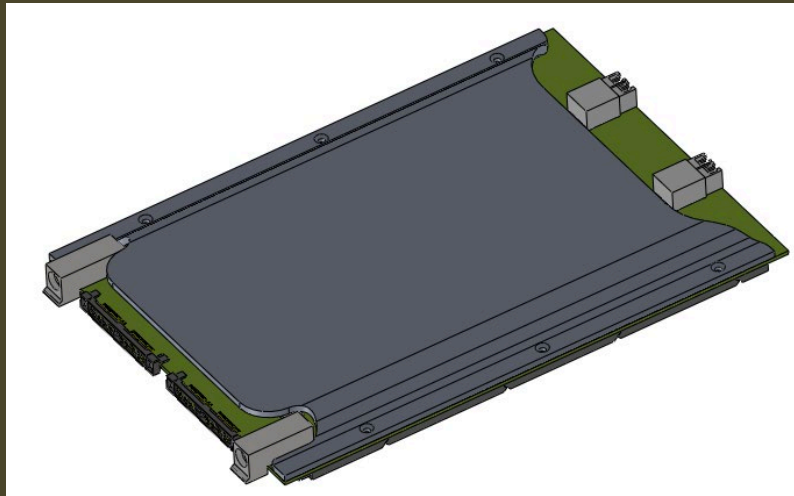


# Heat Transfer in vacuum

- The fundamental modes of heat transfer are:
  - Conduction → transfer of energy between objects that are in physical contact
  - 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*!

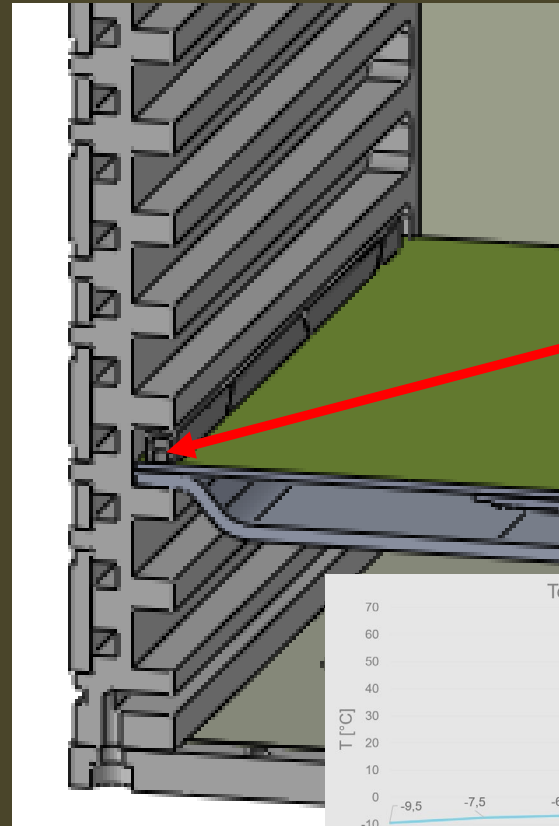
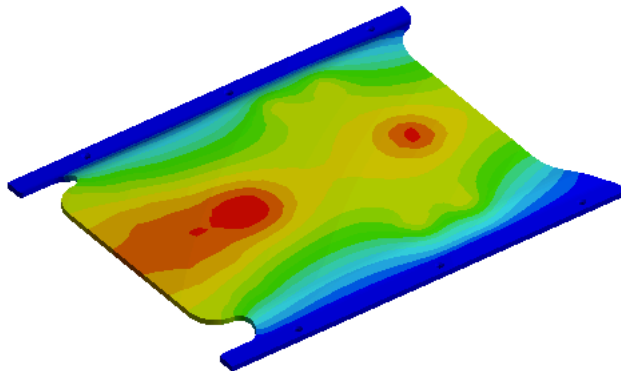
# Heat transfer - preliminar studies



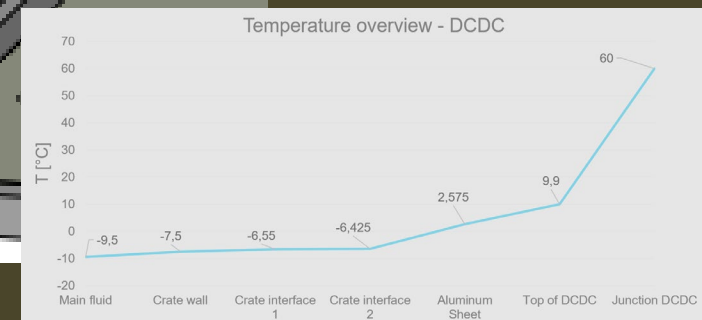
**B: Modulo Piastra Termica**

Temperature  
Type: Temperature  
Unit: °C  
Time: 1  
28/03/17 10:15

1.7662 Max  
1,1466  
0,52696  
-0,09265  
-0,71226  
-1,3319  
-1,9515  
-2,5711  
-3,1907  
-3,8103  
-4,4299  
-5,0495  
-5,6632  
-6,2888  
-6,9084 Min

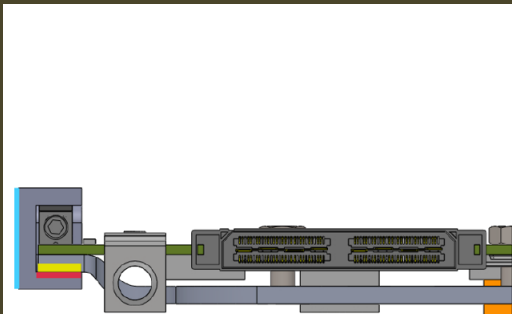
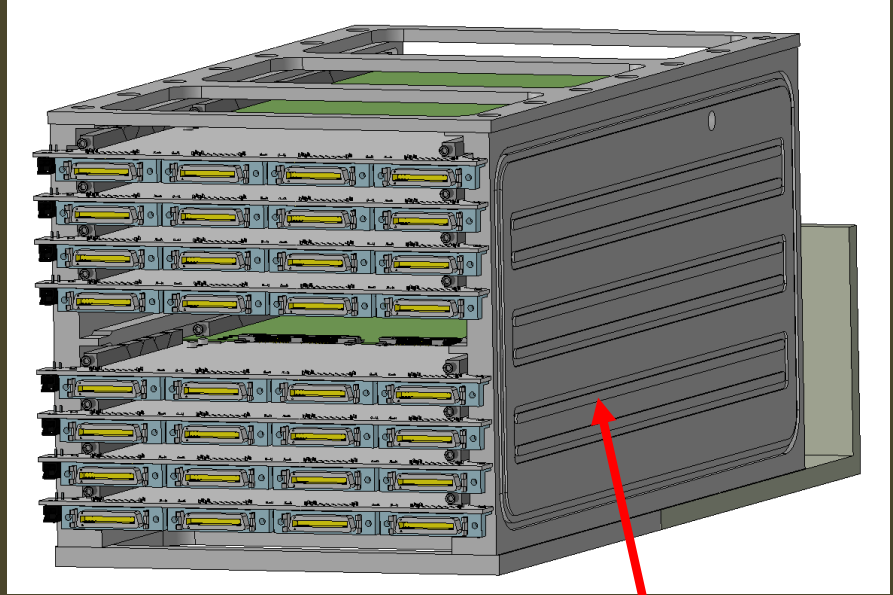
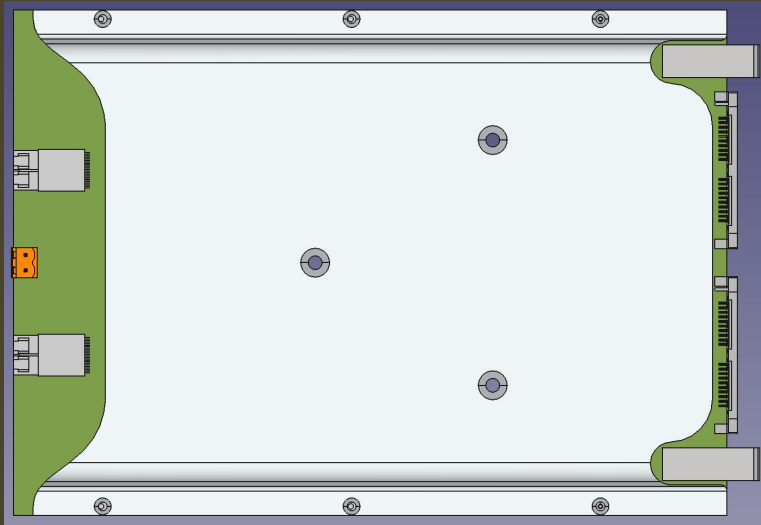


Card-lok

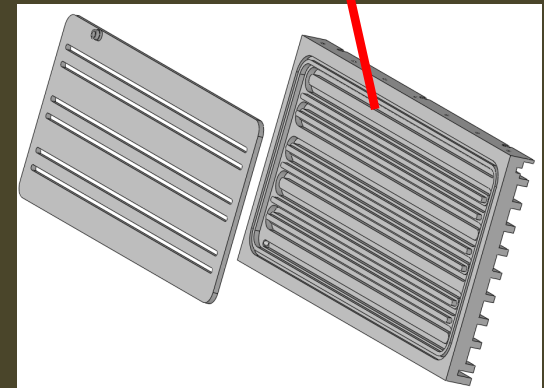
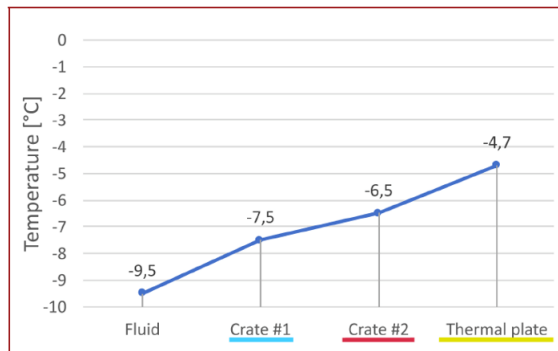


# Cooling

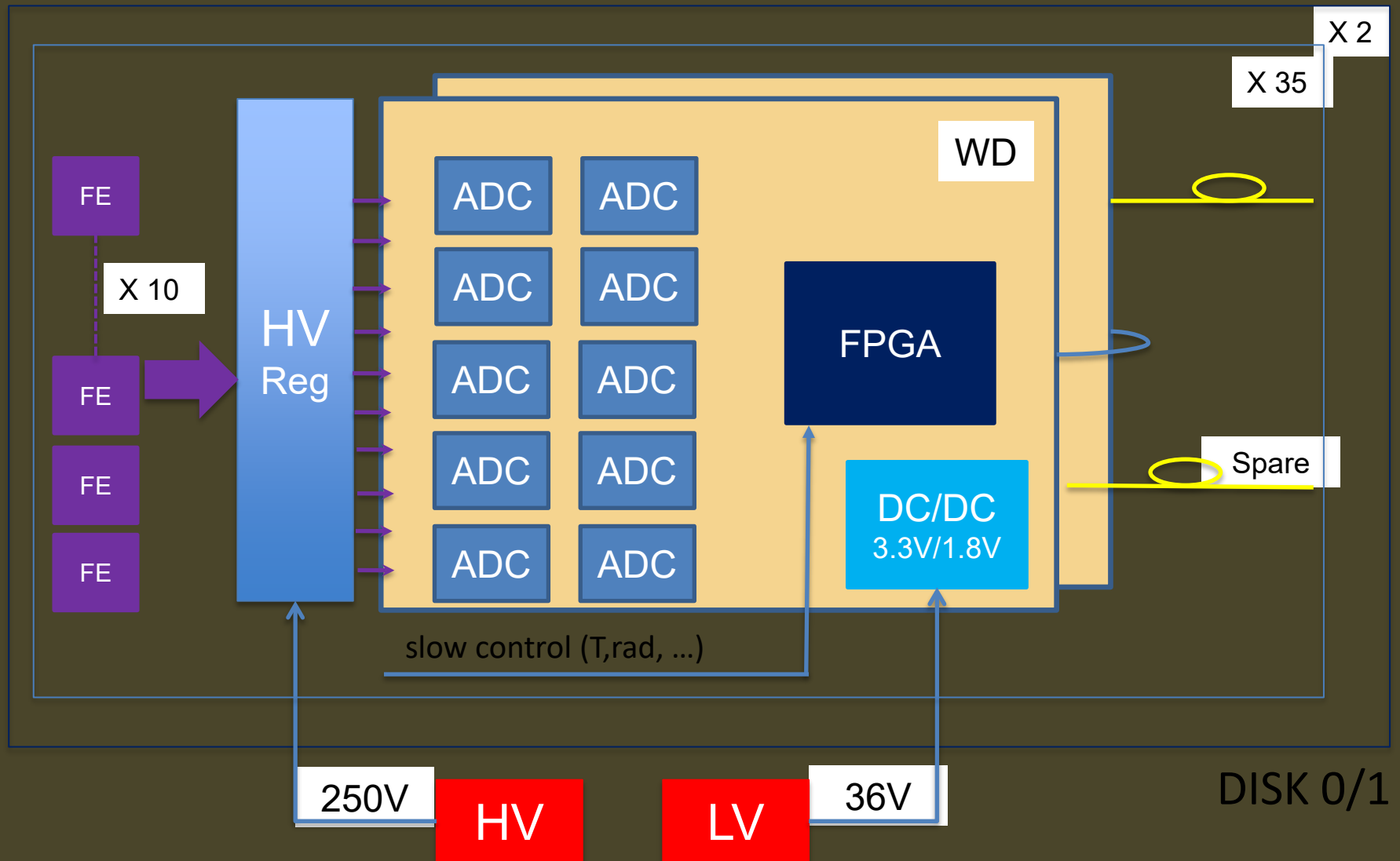
## DAQ cooling



Max T. spec

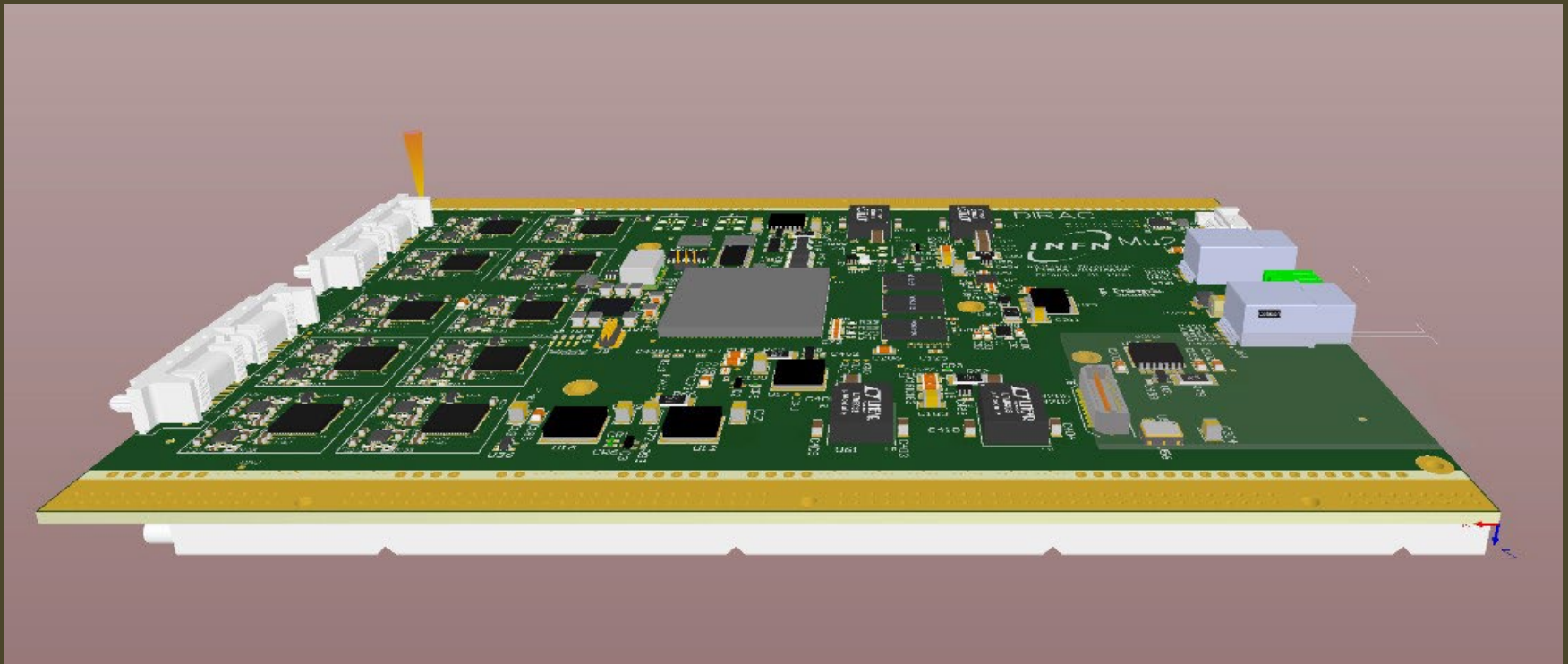


# Finally the design

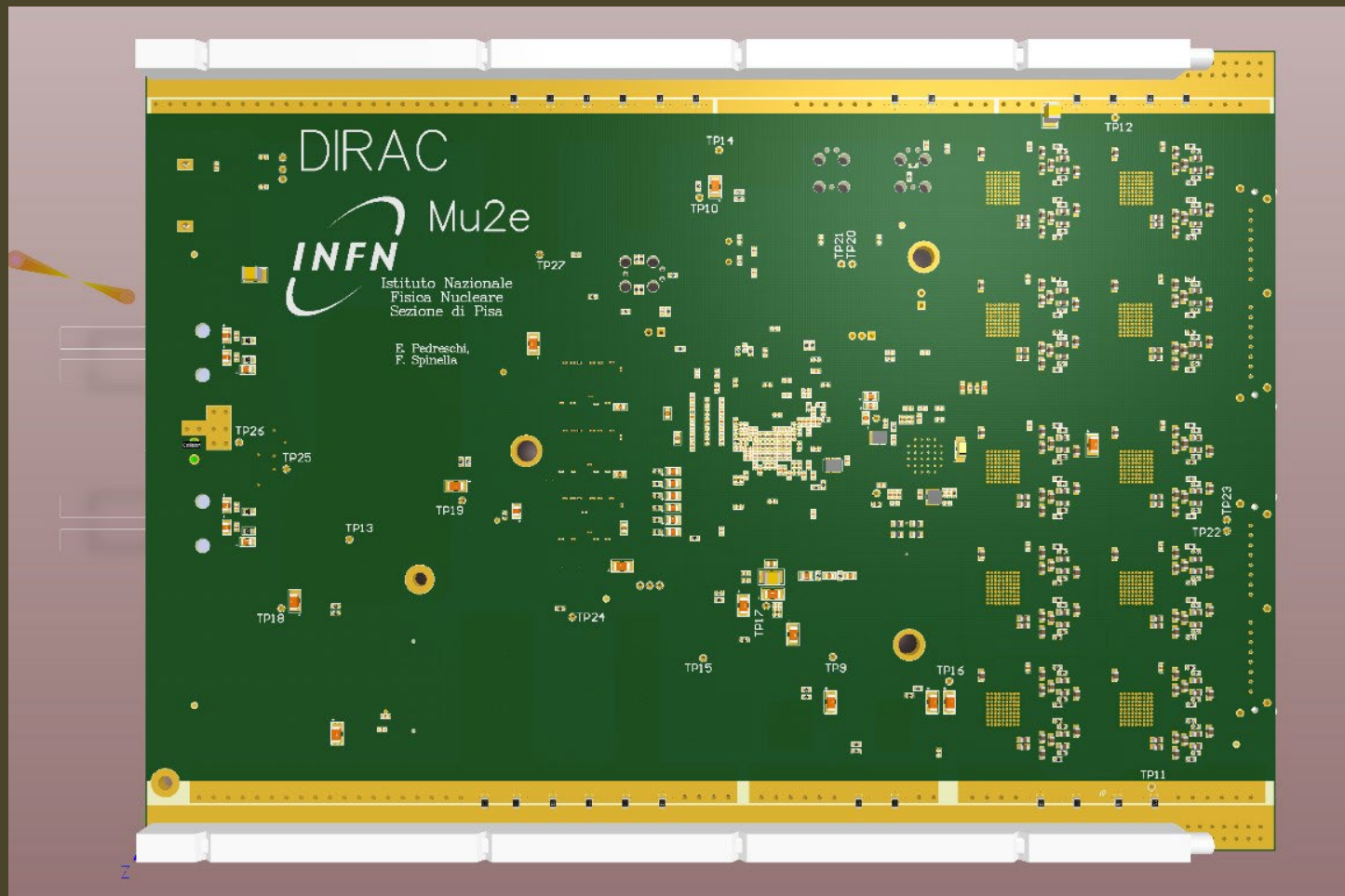


# Digitizer ...

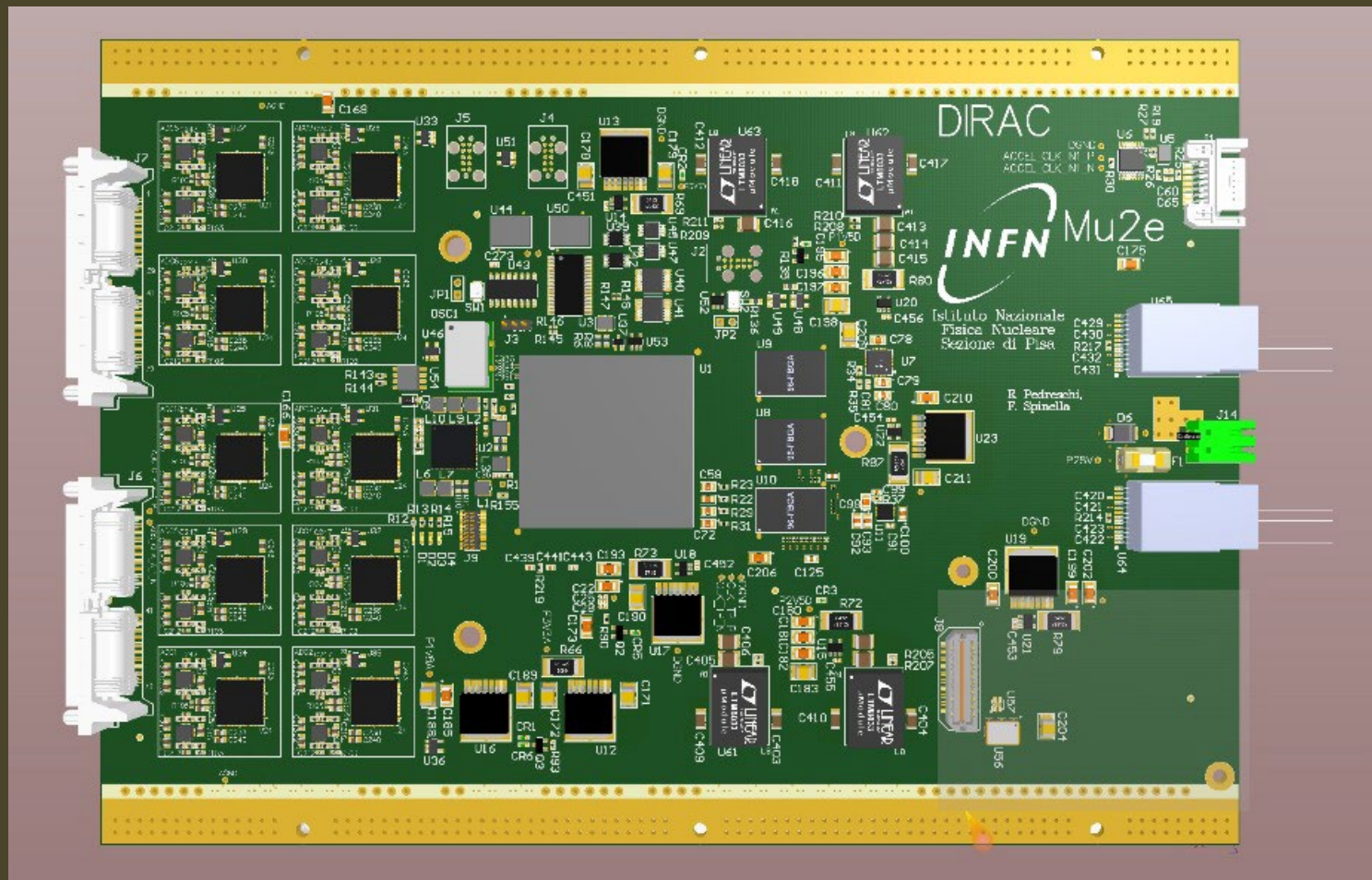
- 20 channels/ board
- 160 boards



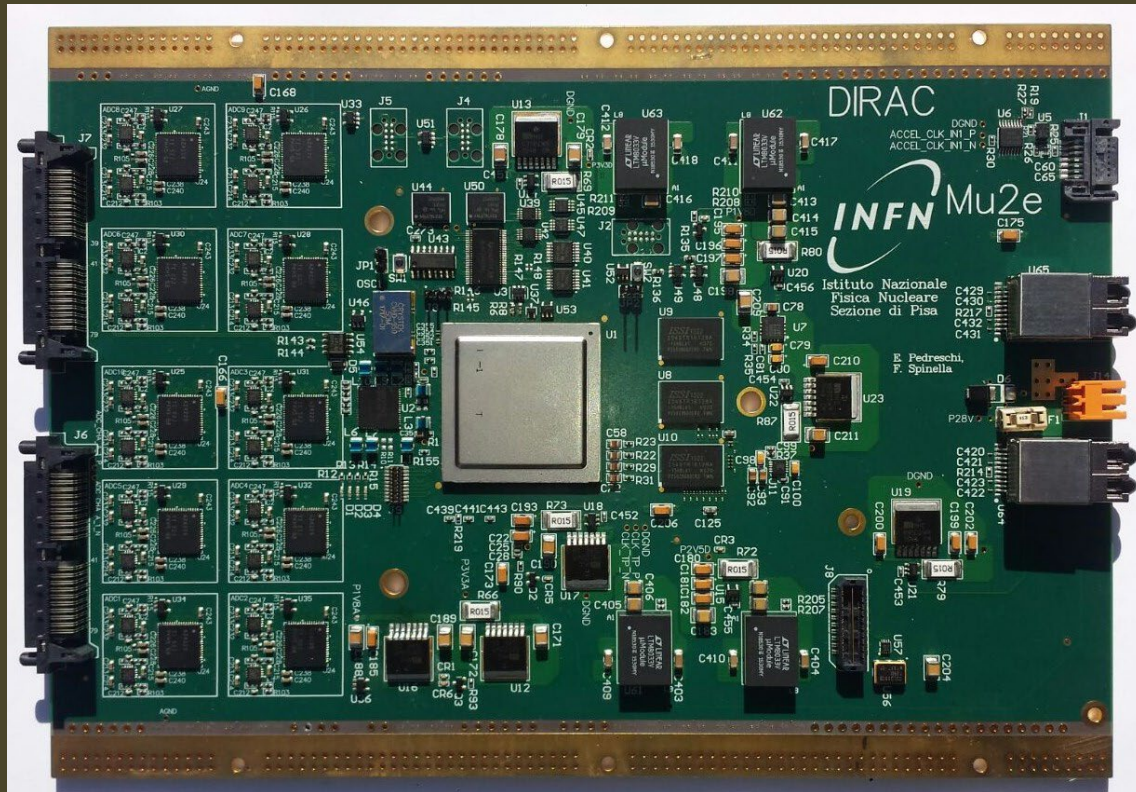
# Digitizer ...



# Digitizer ...



# Digitizer-DIRAC



# 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!