The SESAME XAFS fluorescence detector project

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TIFPA

XVI International Conference on Science, Arts and Culture
International Conference on SESAME - in honour of Paolo Budinich

Veli Lošinj, Croatia, 29 August - 2 September 2016

Outline

- Introduction
  - XAFS and the fluorescence detector
- The SESAME fluorescence detector
  - The detector design
  - Results from a parallel development: TwinMic at Elettra
- Conclusions

What is XAFS?

XAFS: **X**-ray **A**bsorption **F**ine **S**tructure

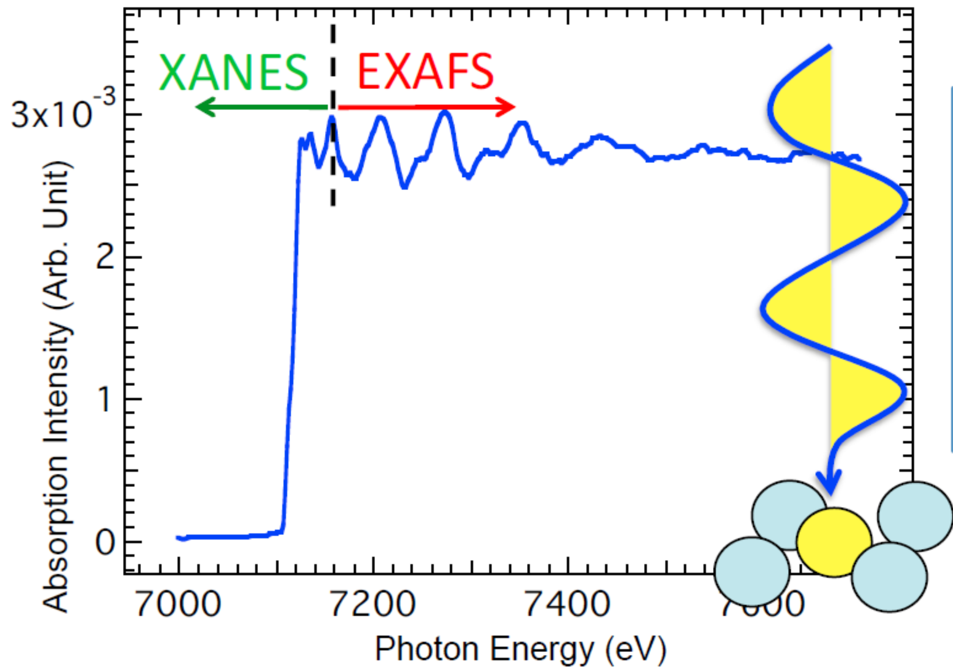
electronic state (valence)

Symmetry

Bond length

Number of surrounding atoms (Coordination number)

Distribution, Thermal vibration



Element specific

to observe **Local structure**

(long range periodicity is not required)

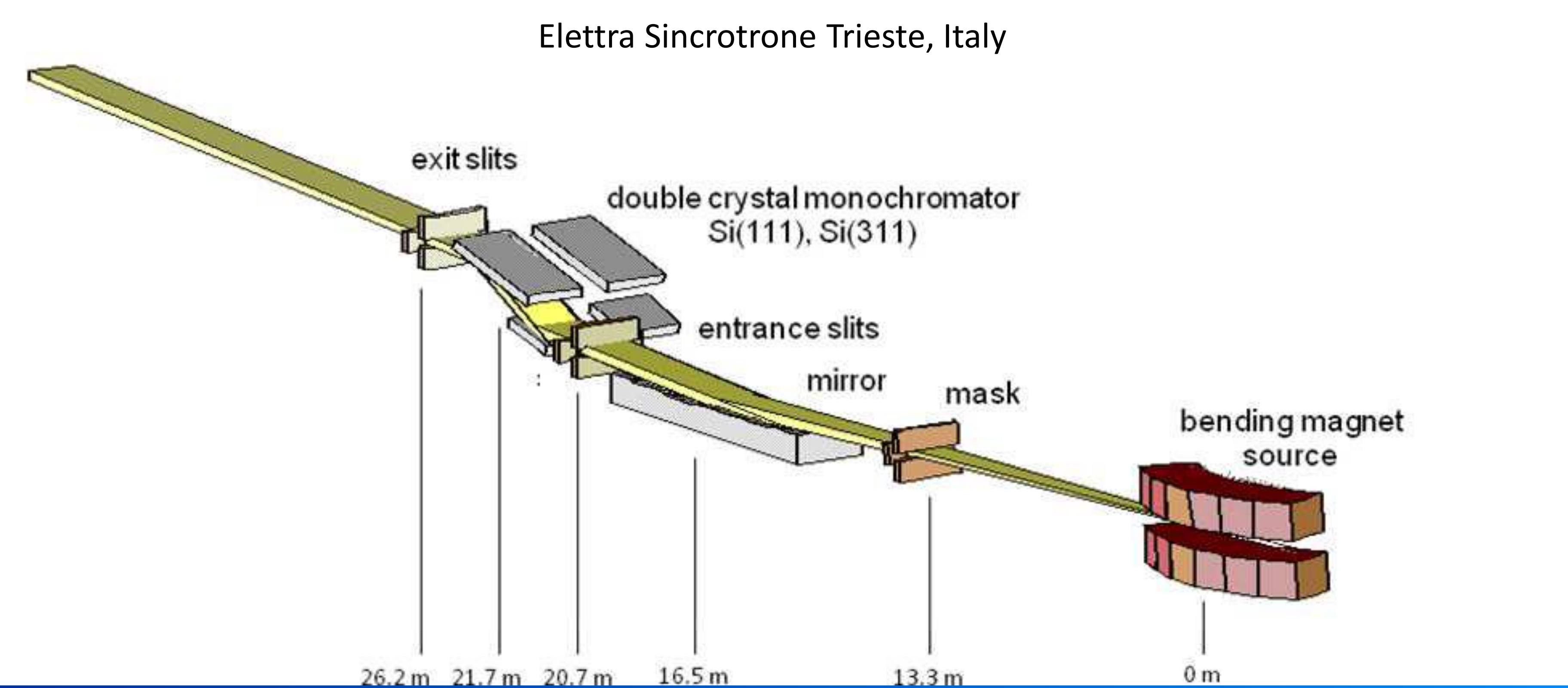
Solid, Liquid, Gas, whatever

XANES: X-ray Absorption Near Edge Structure

EXAFS: Extended X-ray Absorption Fine Structure

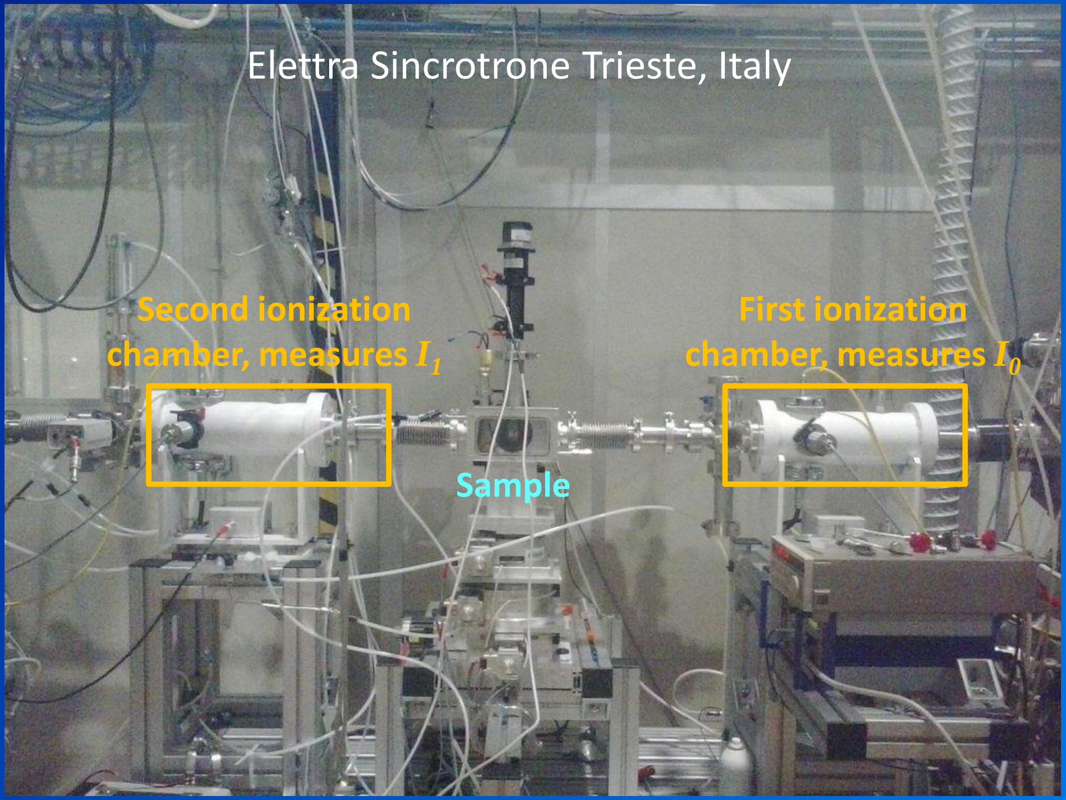
Source: Hitoshi Abe, ***A Brief Introduction to XAFS***
http://www.sesame.org.jo/sesame/images/News/Users_meeting_and_JSPS_School/jsps-lectures/Lec04_Abe.pdf

A typical XAFS beamline



- The energy of the output X-ray beam is precisely set by a double crystal monochromator that provides an energy resolution $\Delta E/E \approx 10^{-4}$
- The beam size at the sample is defined by the exit slits
- The X-ray flux is $\approx 10^{11} - 10^{12}$ ph/s·mm^2

A typical XAFS experimental station

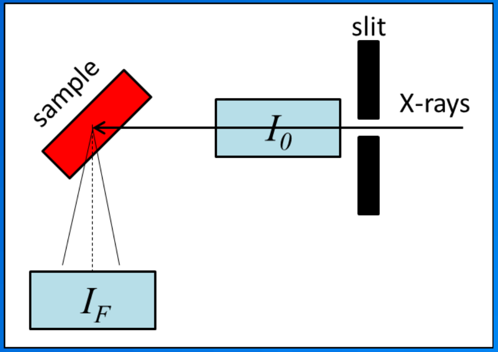


X-ray beam

Absorption coefficient

$$\mu = ln\left(\frac{I_0}{I_1}\right)$$

When the sample is thick but diluted or thin but concentrated, the measurement can be carried out in fluorescence mode



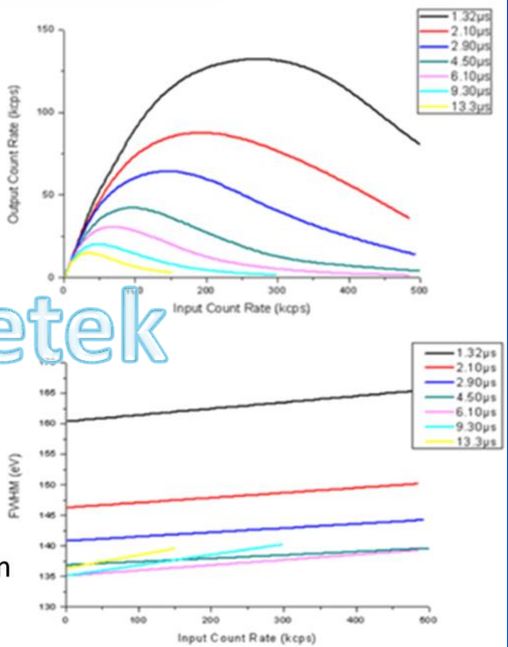
$$\mu = \propto \frac{I_F}{I_0}$$

XAFS fluorescence detector specs?

In our context, a XAFS measurement is the measurement of the fluorescence flux from the sample during a very fine energy scan around the absorption edge of the material under examination, hence:

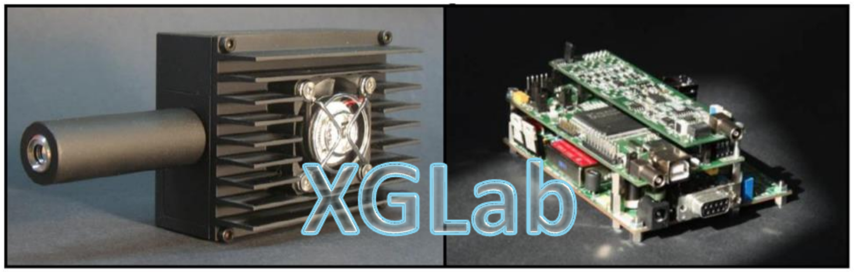
- The detector needs to have a good sensitivity in the whole energy range of the beamline → 3 – 30 keV for SESAME
- The energy resolution of the detector should be good enough to allow for rejection of undesired signals, i.e. scattered beam or other fluorescence lines close to the investigated one → E_{RES} < 150 eV FWHM @ 5.9 keV
- The detector needs to cope with large fluxes of photons
  → small detection units to reduce pileup probability
- The geometric acceptance of the detector should be as large as possible to reduce the measurement time → multi-channel systems

Some commercial systems

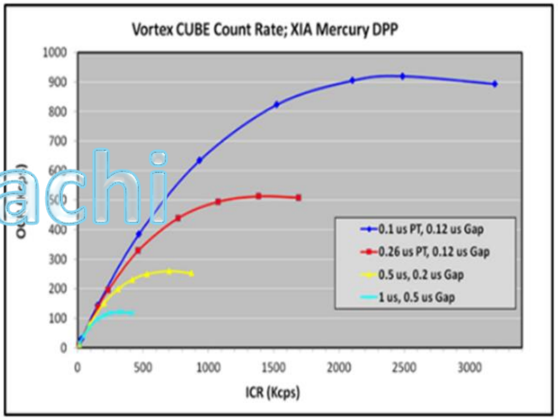


Detector active area from 7 to 100 mm²

- A range of silicon drift detector sizes, from 150 mm² to 20 mm²
- **X-Max**^N provides a superb resolution that is independent of sensor size
- Excellent low energy analysis, including Be detection guaranteed on all sensor sizes
- Up to four X-Max^N can run in parallel on one microscope to create a system with a total active area of 600 mm²



- Top performances SDD with active area from 5mm² to 100mm².
- Equipped with the state-of-the-art Pulsed-reset Charge-preamplifier XGL-CPA-2100.
- Optionally includes the XGL-MCSH-3100 and the XGL POWER SUPPLY to set-up a complete stand-alone **X-ray** spectroscopic system.



- Available in thickness of 0.5 and 1 mm
- Available single detectors in 30, 40, 50, 65, 70, 80 mm²
- Large area, four-element silicon drift detector (total area of 120 mm² - 200 mm²)

Multi-channel commercial solution

Sensor	# of channels			1 to 19		
	Sensor type			SDD		
	Active area (mm²)	10	40	65	100	170
	Thickness			450µm		
	Collimated area (mm²)	7	30	50	80	150
	Resolution (eV)	<133	<133	<133	136	139
	P/B ratio			>10,000 : 1		
	FET or 'CUBE[2]' primary stage			Option		
	Peltier cooled cryostat			Standard		
	Temperature stabilisation			Standard		

Interesting solution, but few drawbacks:

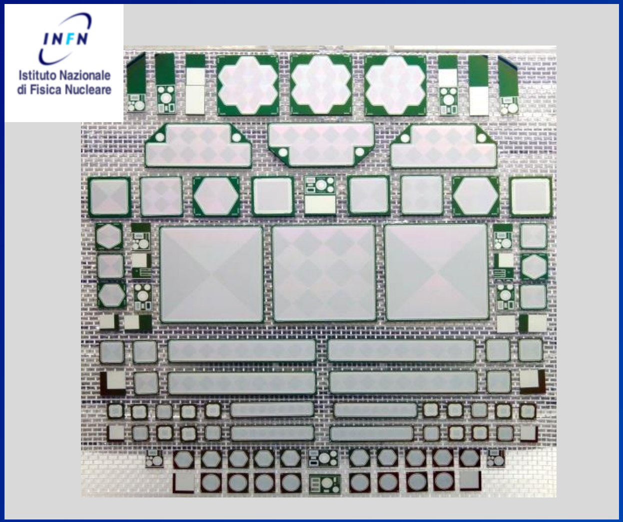
- large area easily obtainable with large sensors, difficult with smaller ones
- made up of single detector systems, each one requires a power supply and a MCA and a lot of cables
- bulky (not necessarily bad)

SESAME detector concept

The detector concept we proposed to SESAME is the result of a thorough discussion with the XAFS beamline scientists at Elettra, for which we are developing the same exact detector:

- a multi-channel system with cells as small as feasible to reduce pileup, the limit is due to the constraints on the hybrid layout
  → 9 mm^2 a good compromise
- the total sensitive area should allow at least an order of magnitude gain on the measurement time → 64 cells, 576 mm^2 (currently 80 mm^2)
- the system should be segmented, rather then monolithic, to allow for redundancy → 8 units, each comprising a detection head and a backend PCB
- the system should be compact and should contain the whole acquisition chain including the MCAs → On board digital signal processing

Heritage – detector R&Ds



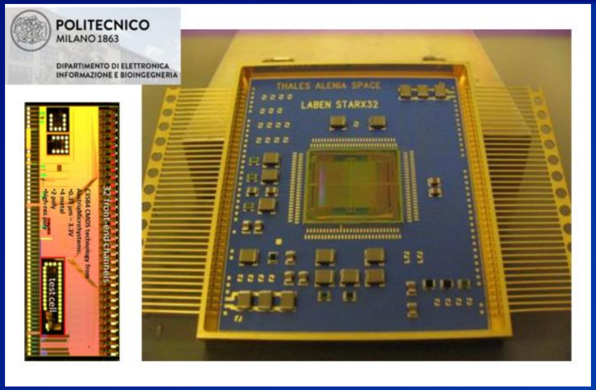
INFN (Trieste, Bologna and TIFPA)

- Silicon detector design: device simulation, layout, characterization, and assembly
- Expertise in optimizing large-area SDDs for applications on different research fields
- Expertise in design and construction of complex multi-channel detector systems
- Expertise in digital signal processing

FBK - Center for Materials and Microsystems

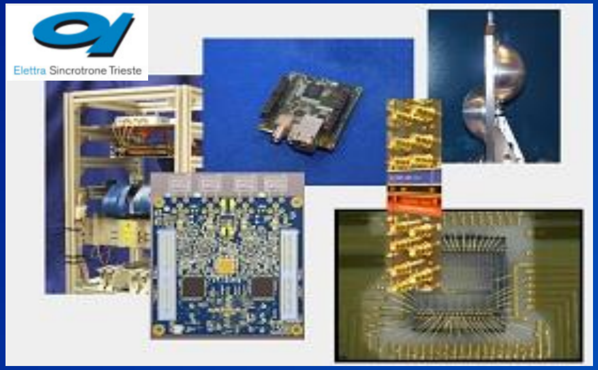
- Expertise in development of advanced solid-state sensors in dedicated technology processes
- Sensor design and simulations, physical design, tuning of the fabrication process, electrical and optical characterization
- 6” wafer microfabrication facility with a 500 m^2, class 10/100 Clean Room and a 0.8 µm CMOS pilot line

Heritage – ASICs and DAQ systems



Politecnico di Milano – DEIB

- Characterization of GaAs, CdTe, CZT, Si and SiC radiation detectors
- Design of ASICs for radiation detectors
- Low-noise Low-Power Electronics



Elettra – Instrumentation and Detectors Laboratory

- Development of special instrumentation and boards for many applications: FAST STM scanning and acquisition electronics, LLRF systems and bipolar HV power supplies, picoammeters, electron energy analyzers and fast feedback electronics
- Deep knowledge of Synchrotron beamlines requirements

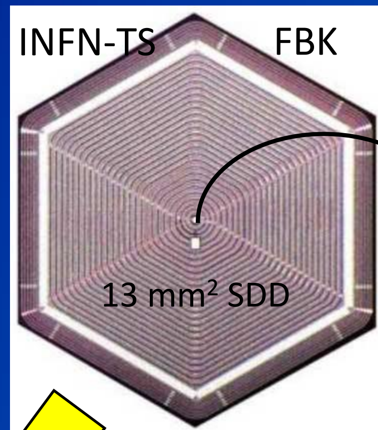
ICTP-INFN Microprocessor laboratory

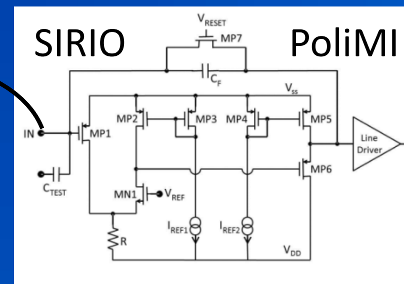
- Expertise in design of FPGA based acquisition systems and digital signal processing for scientific instrumentation
- Expertise in training and education of researchers coming from developing countries

Starting point: state-of-the-art technology

Very-low leakage current production process was developed at FBK

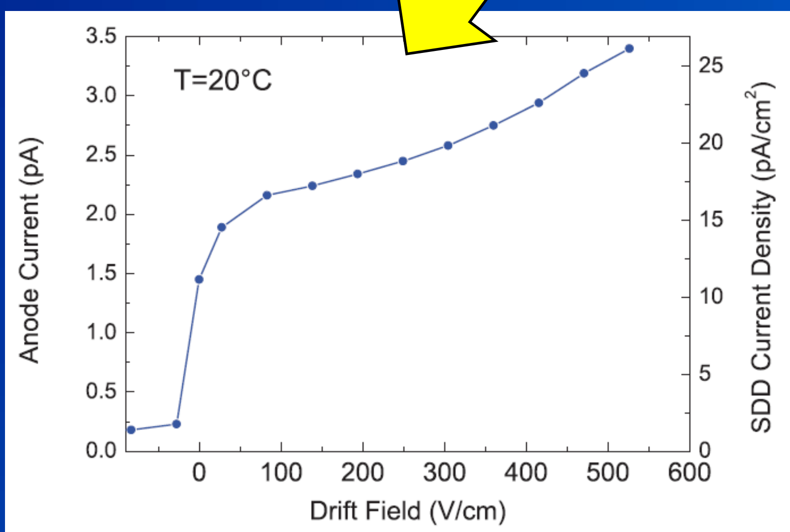
- Typical: < 150 pA/cm^2
- Minimum: 25 pA/cm^2

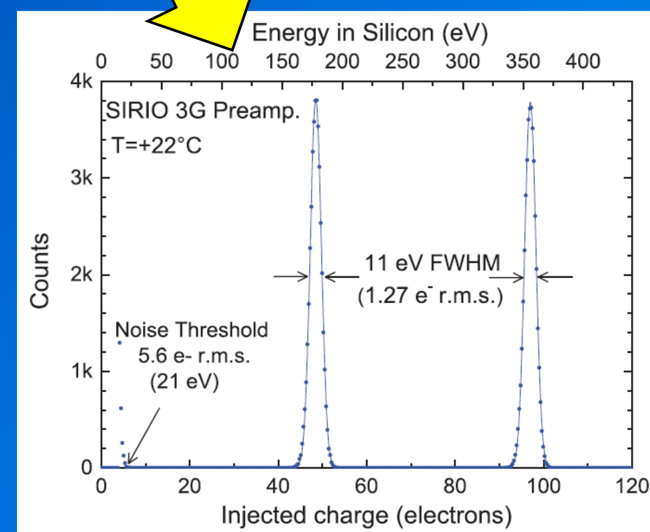




Low-power and very-low noise optimized preampl. in sub-micron technology

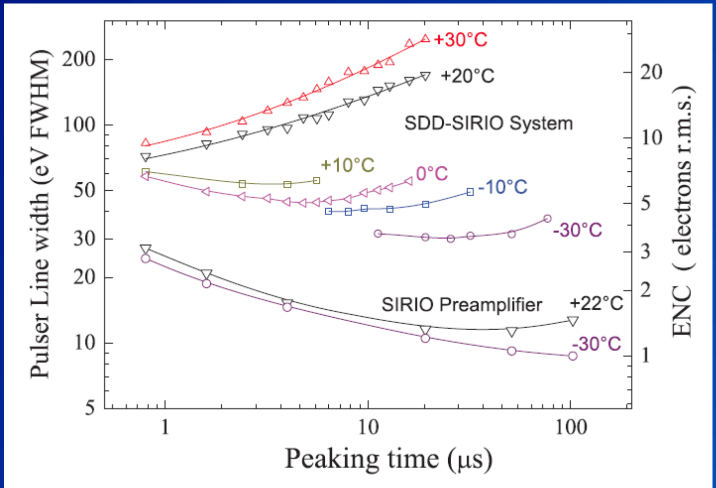
- Power: 10 mW including the output buffer
- ENC of 1.27 e$^-$ r.m.s. at20 °C

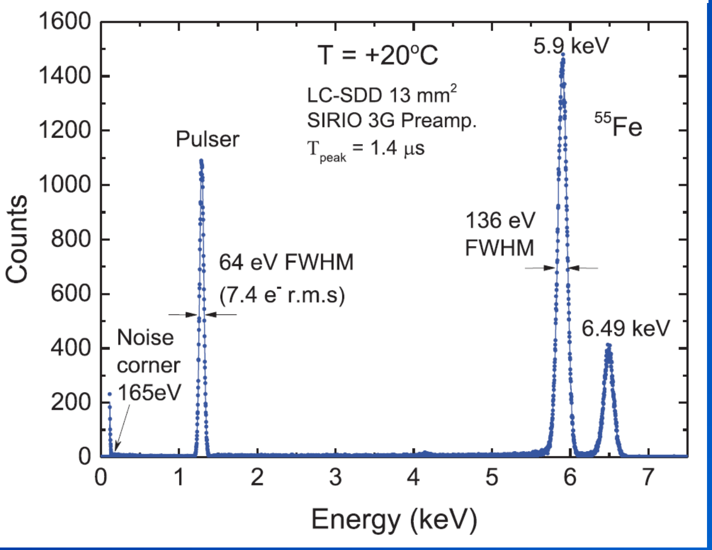




G. Bertuccio, et al., IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 63, NO. 1, FEBRUARY 2016

Room temperature spectroscopy in sight





T (°C)	^{55}Fe 5.9 keV LINE WIDTH (eV FWHM)	PULSER LINE WIDTH (eV FWHM)	ENC (e- r.m.s.)	Peaking Time (µs)
+30	148	82	9.4	0.8
+20	136	64	7.4	1.4
+10	133	53	6.1	2.4
0	129	44	5.0	4.8
-10	129	41	4.7	9.6
-30	123.7	29	3.3	19.2
READOUT ELECTRONICS				
+22	--	11	1.27	51.2
-30	--	8.7	1.0	102.4

- Very-low noise preamplifiers allow the reduction of the shaping time, hence
  - ✓ increased throughput
  - ✓ less sensitivity to leakage current
- Very-low leakage detectors then allow to avoid bulky and power-hungry cooling systems

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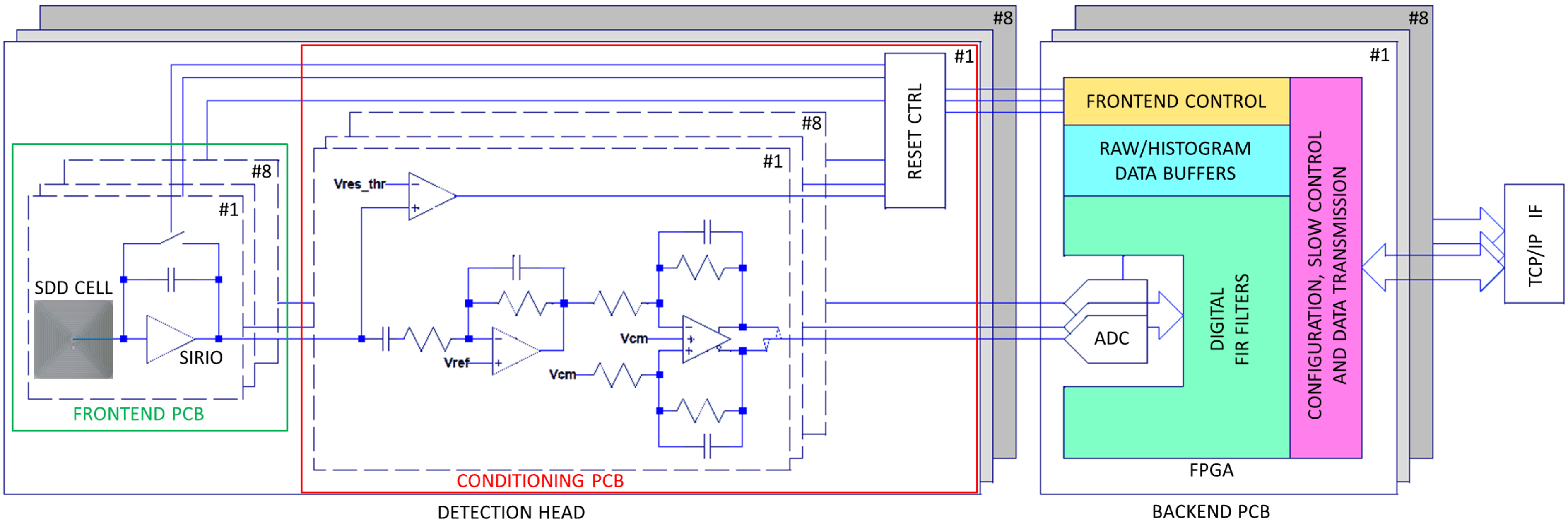
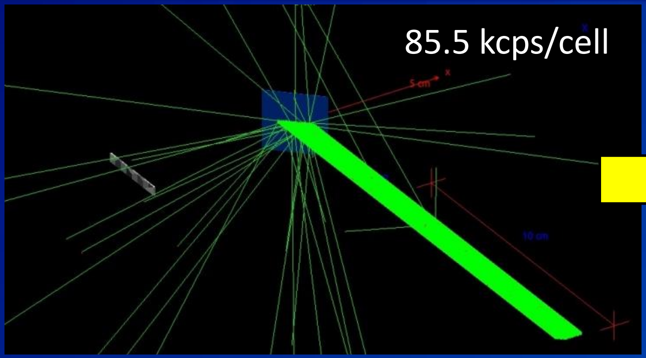
SESAME detector block scheme

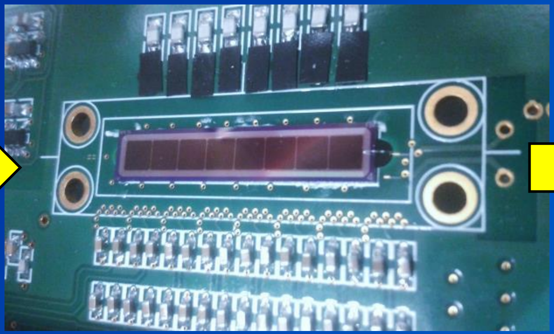


- Each unit comprises a detection head and a backend section
- The detection head hosts the frontend PCB and signal conditioning circuitry (CR-RC^2)
- The detector is controlled by a PC through a TCP/IP connection

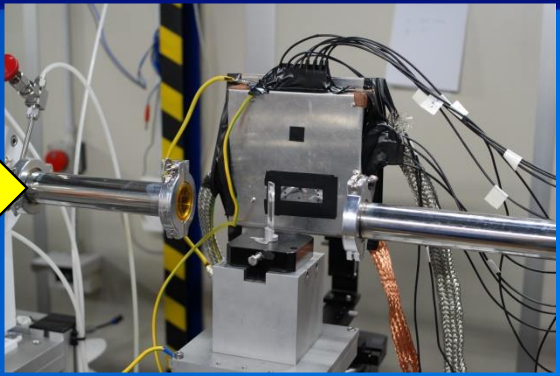
Detection head: sensor cell sizing



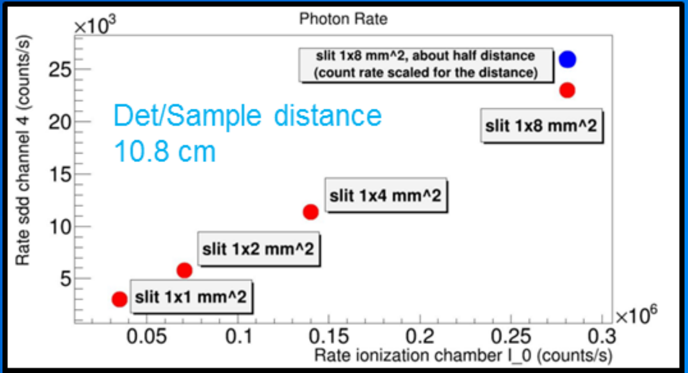
GEANT4 simulation

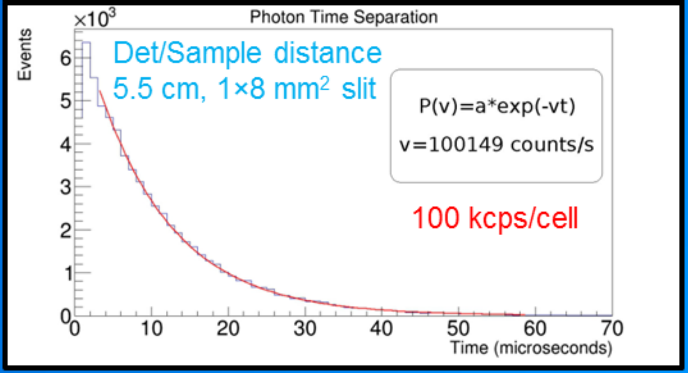


Prototype



Beamline test





Prototype detector:

- the analogue signals from the 8 preamplifiers are sampled by a 40 MSPS,12 bit, 8-channel ADC
- the digital data is transmitted to a PC and saved to disk
- a LabVIEW acquisition software is used to control the detector and acquire raw spectra (filtering not yet optimized)

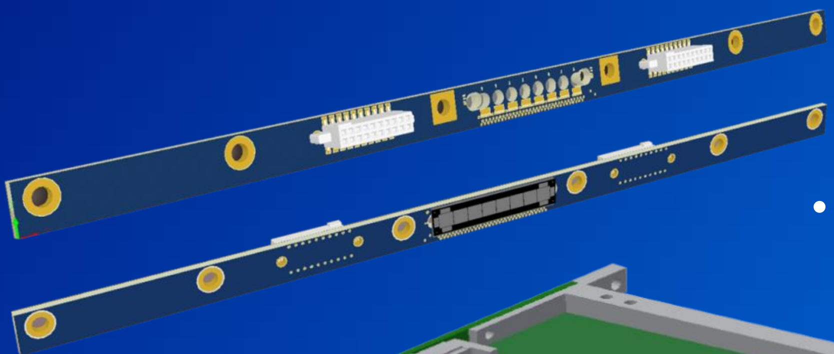
Beam test condition:

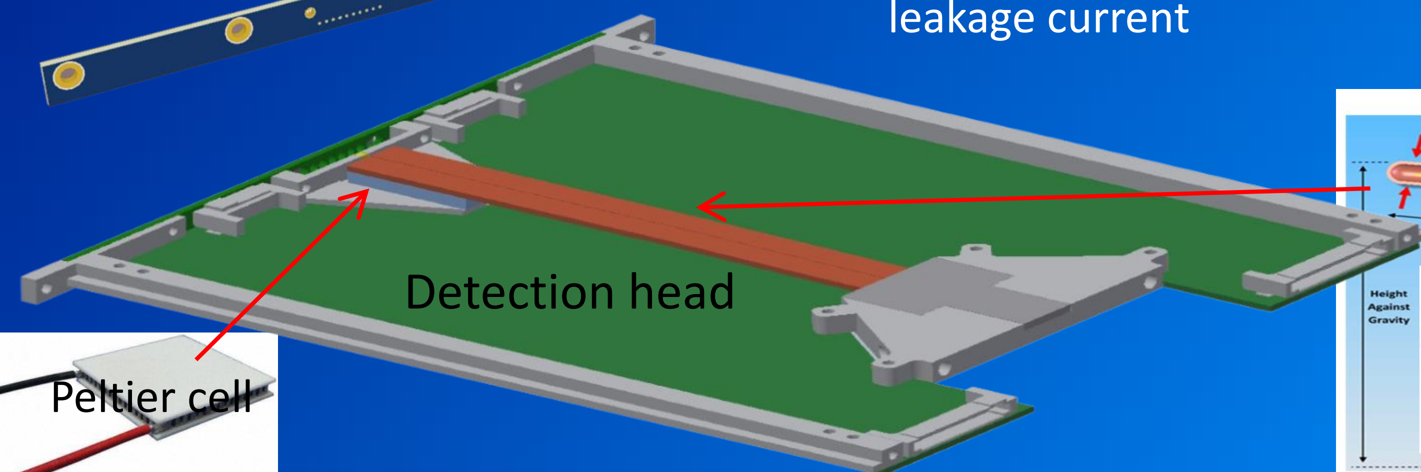
- detector operated near room temperature
- Worst measurement conditions: laminated samples of Mn (K_α @ 5.89 keV, K_β @ 6.49 keV) and Zr (K_α @ 15.75 keV , K_β @ 17.67 keV)

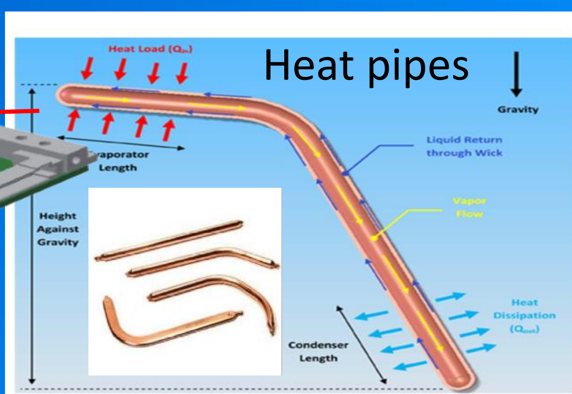
Pileup events: 18% for t_R = 1 µs (9% for a count rate of 50 kcps/cell)

Detection head design

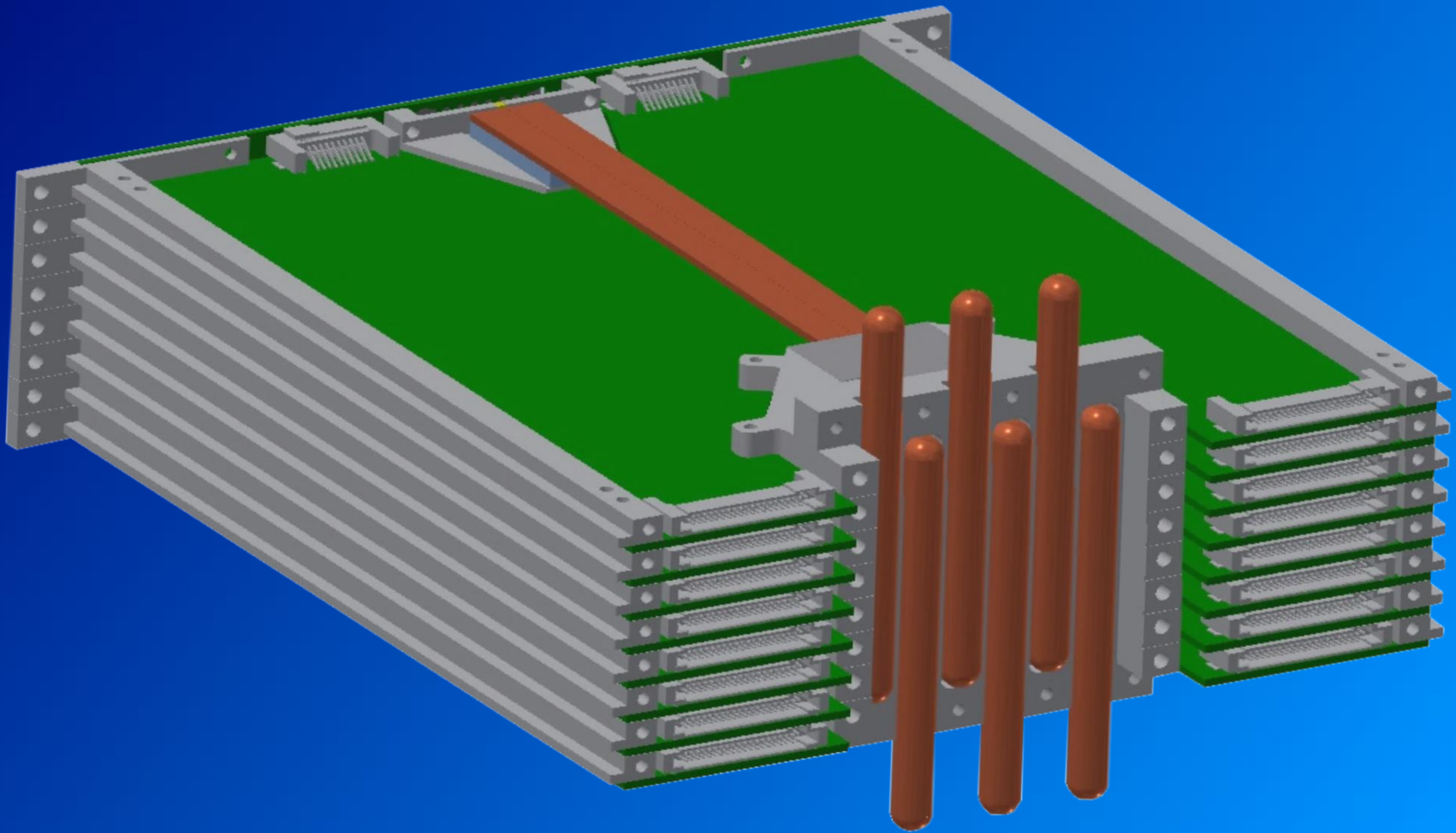
- Improved detector layout:
  - better defined sensitive area
  - on-board thermistors for temperature control
- Tungsten collimator to minimize “split” events
- New SIRIO preamplifier prototypes optimized for SESAME now under test at Politecnico di Milano
  - A low frontend PCB profile allows for compact stacking of detection heads
- Thermoelectric cooling is employed to reduce the leakage current



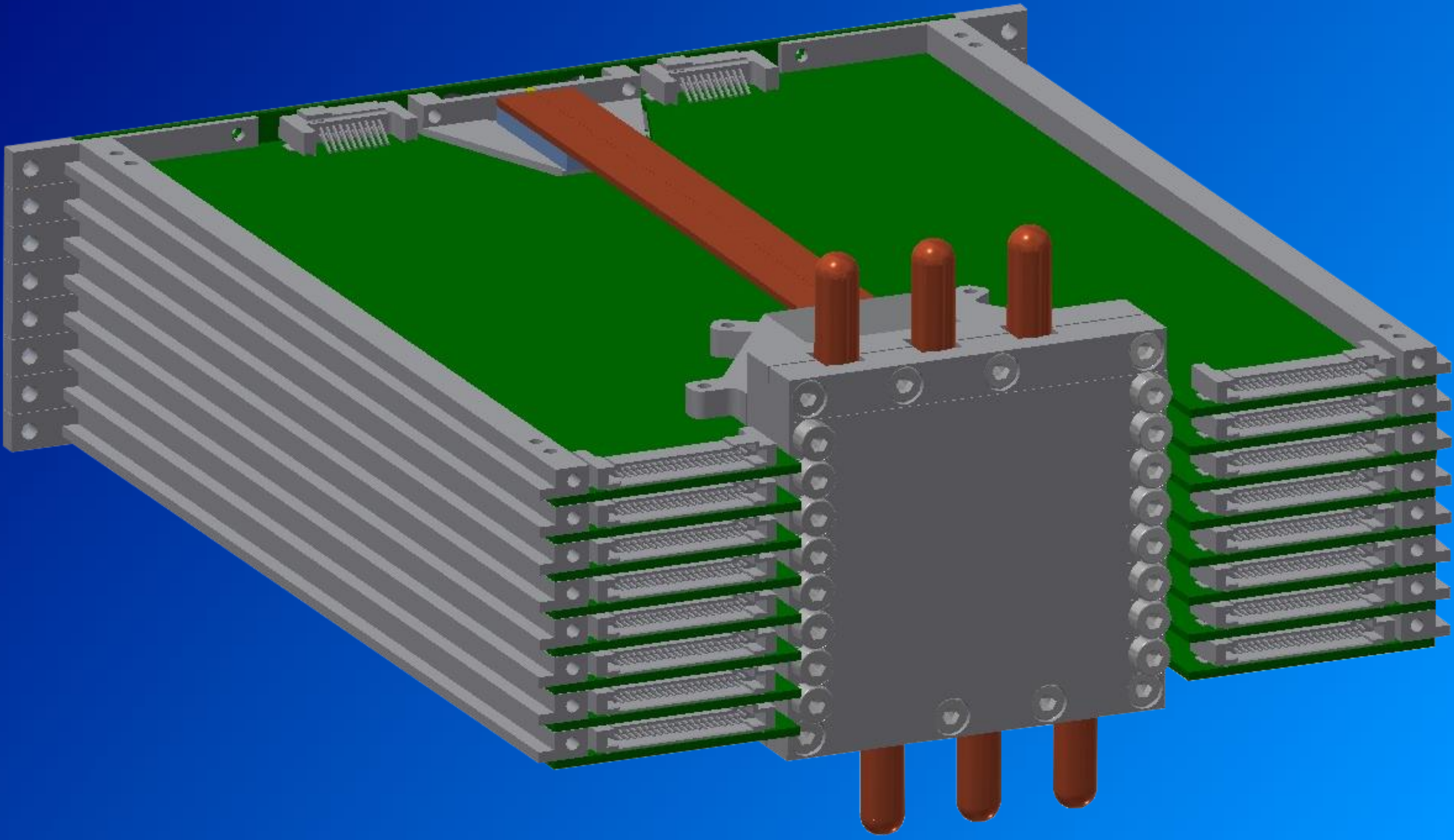




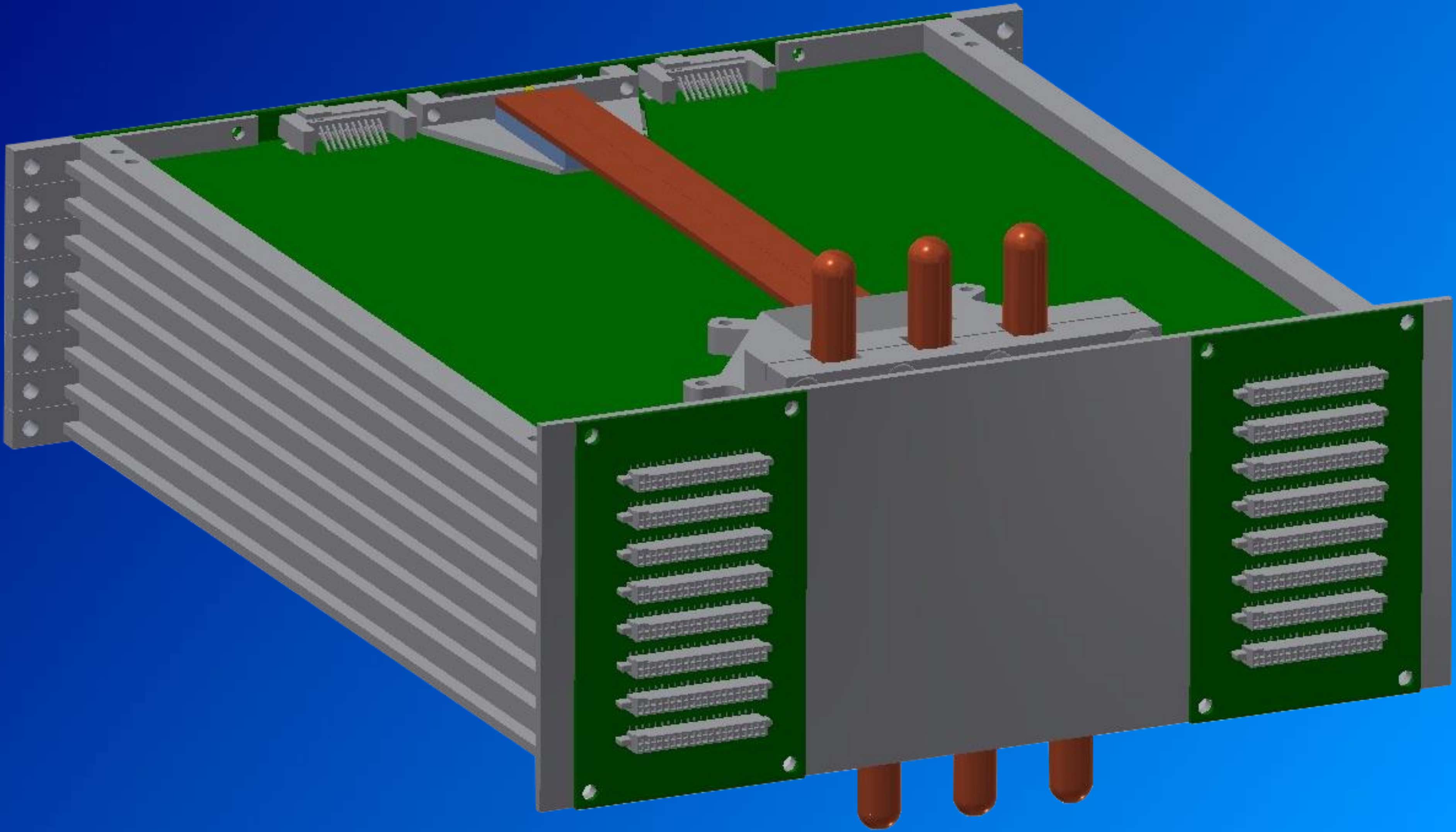
Detection head stack



Detection head stack



Detection head stack



Backend electronics

- Its purposes are
  - the configuration of the instrument
  - the digitization and elaboration of the analog signals
  - the acquisition of histograms or raw data for system analysis
  - the communication with the controlling computer

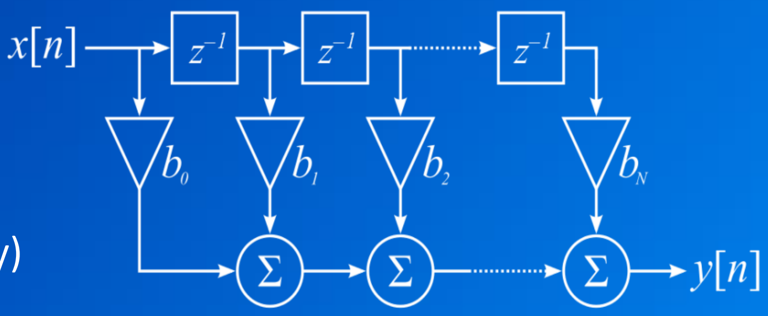
- It features an 8 channel, 40 MSPS, 12 bit ADC. Depending on the conditioning circuit bandwidth it can allow for shaper rise times as fast as 250 ns

- Noise filtering is accomplished by means of a low-power, high-performance ALTERA Cyclone 5 FPGA, which implements also the data buffers and the configuration and control logic

- It features an Ethernet port (possibly in a separated board) for network communication with a host computer

Digital filtering

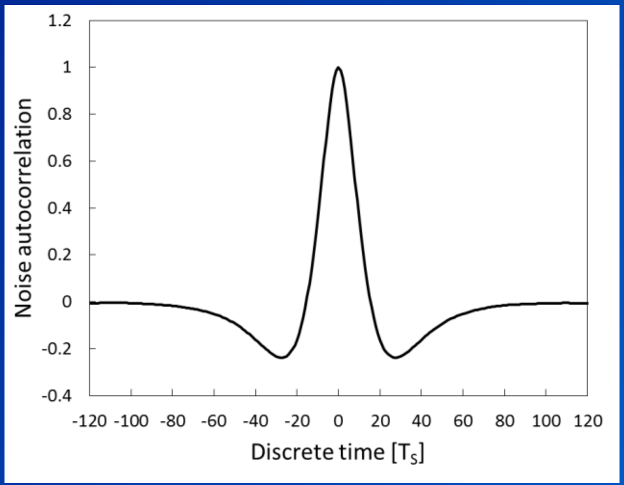
- Several options available, we selected the Finite Impulse Response (FIR) class because of its flexibility

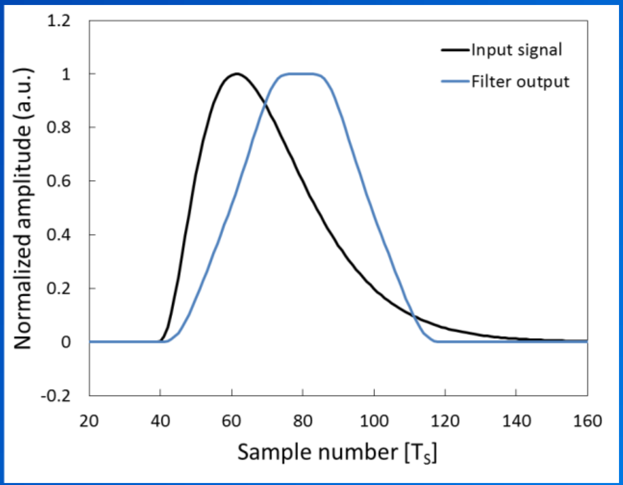


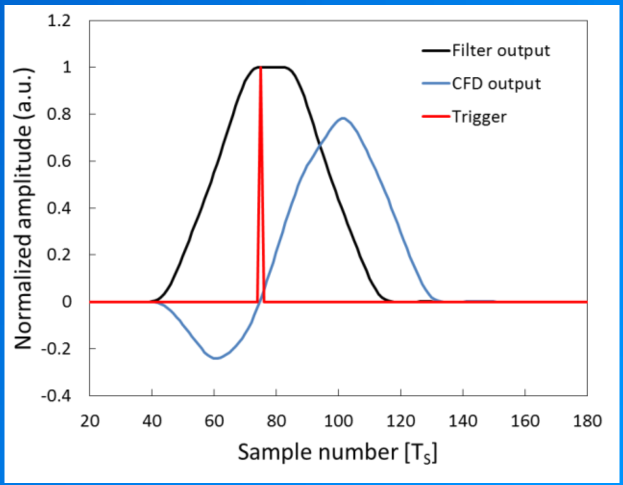
$$y(n) = b_0 \cdot x(n) + b_1 \cdot x(n-1) + \cdots b_N \cdot x(n-N)$$

- Possible to constrain the filter synthesis
  - accounting for the input signal noise
  - optimizing the output shape (duration, flat top, symmetry)
  - requiring rejection of low frequency pedestal variations
  - minimize the ADC quantization noise

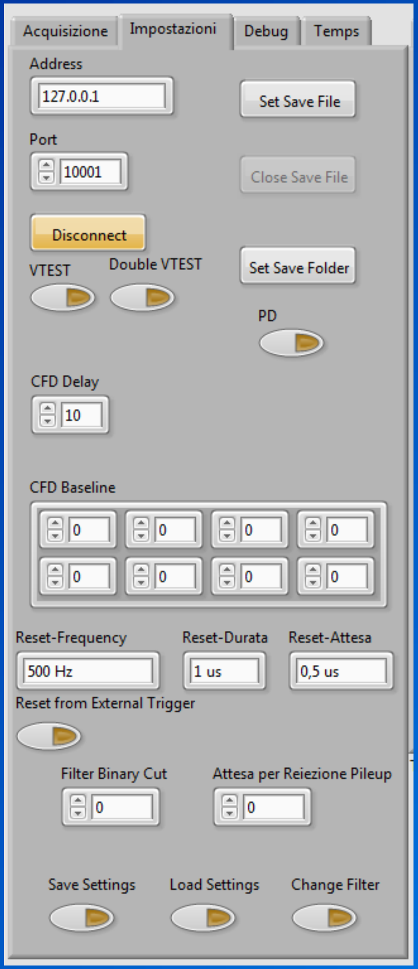
- Digital filtering allows for exotic trigger functions, e.g. constant fraction discrimination



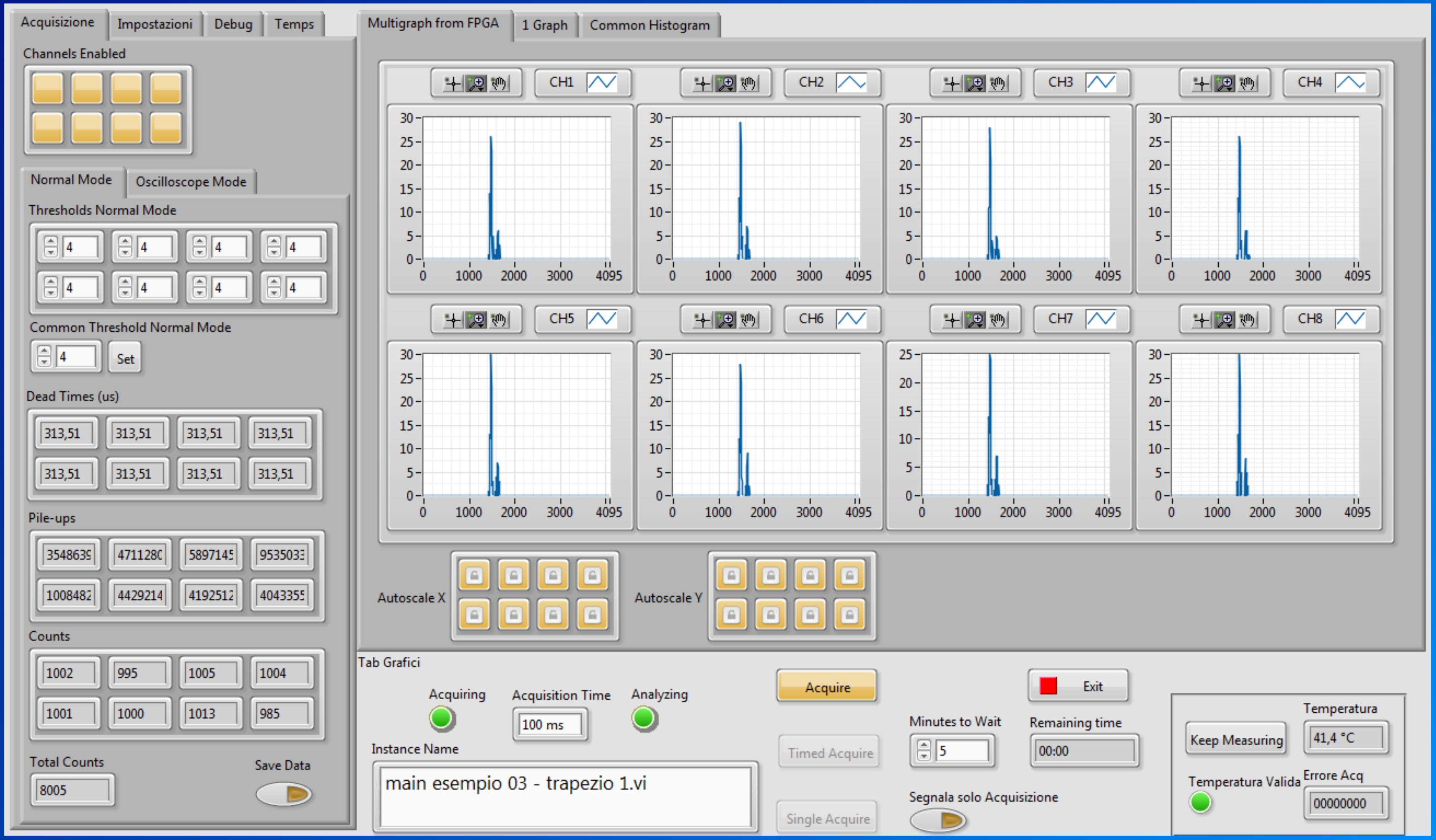




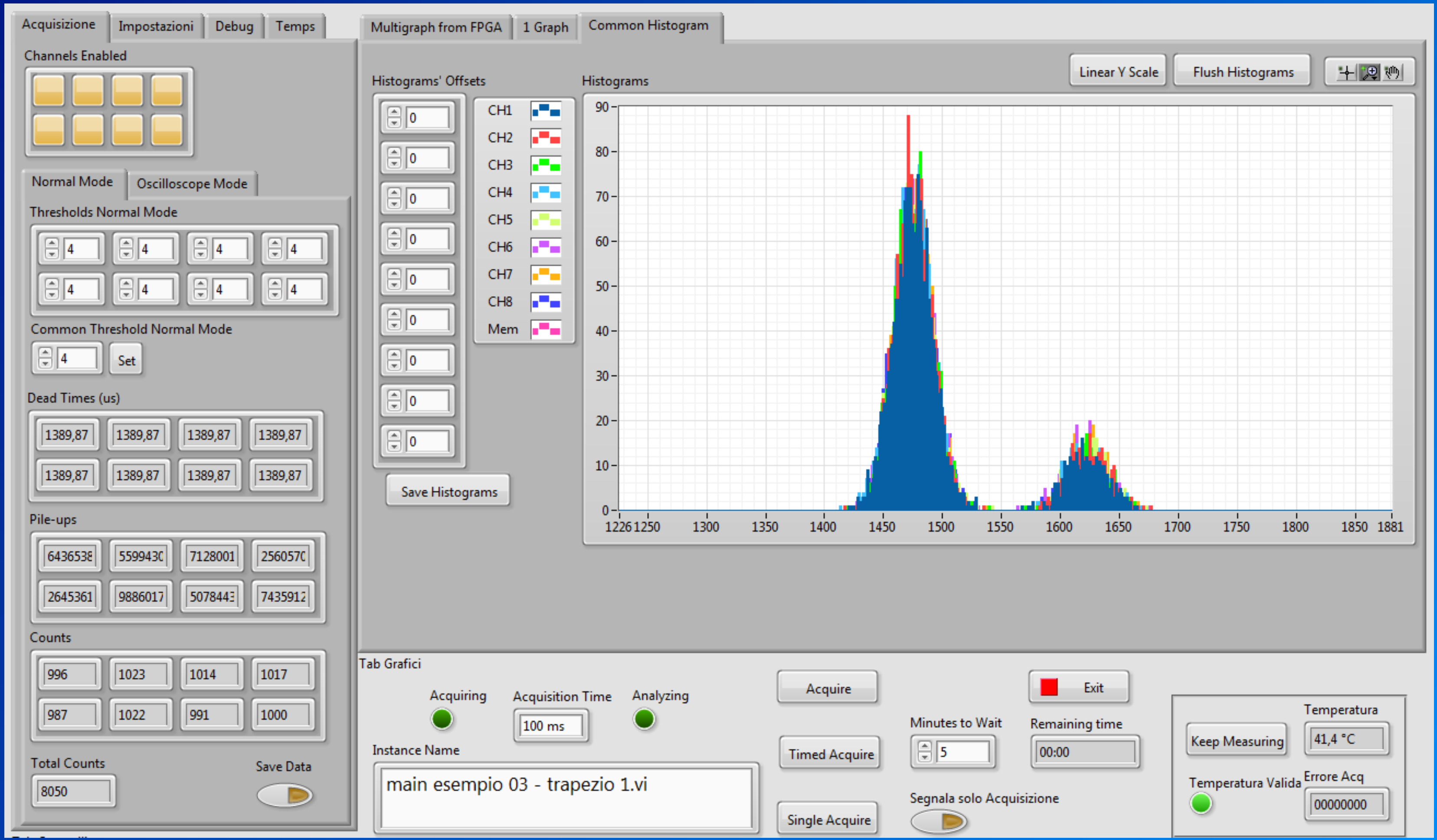
LabVIEW DAQ – detector setup



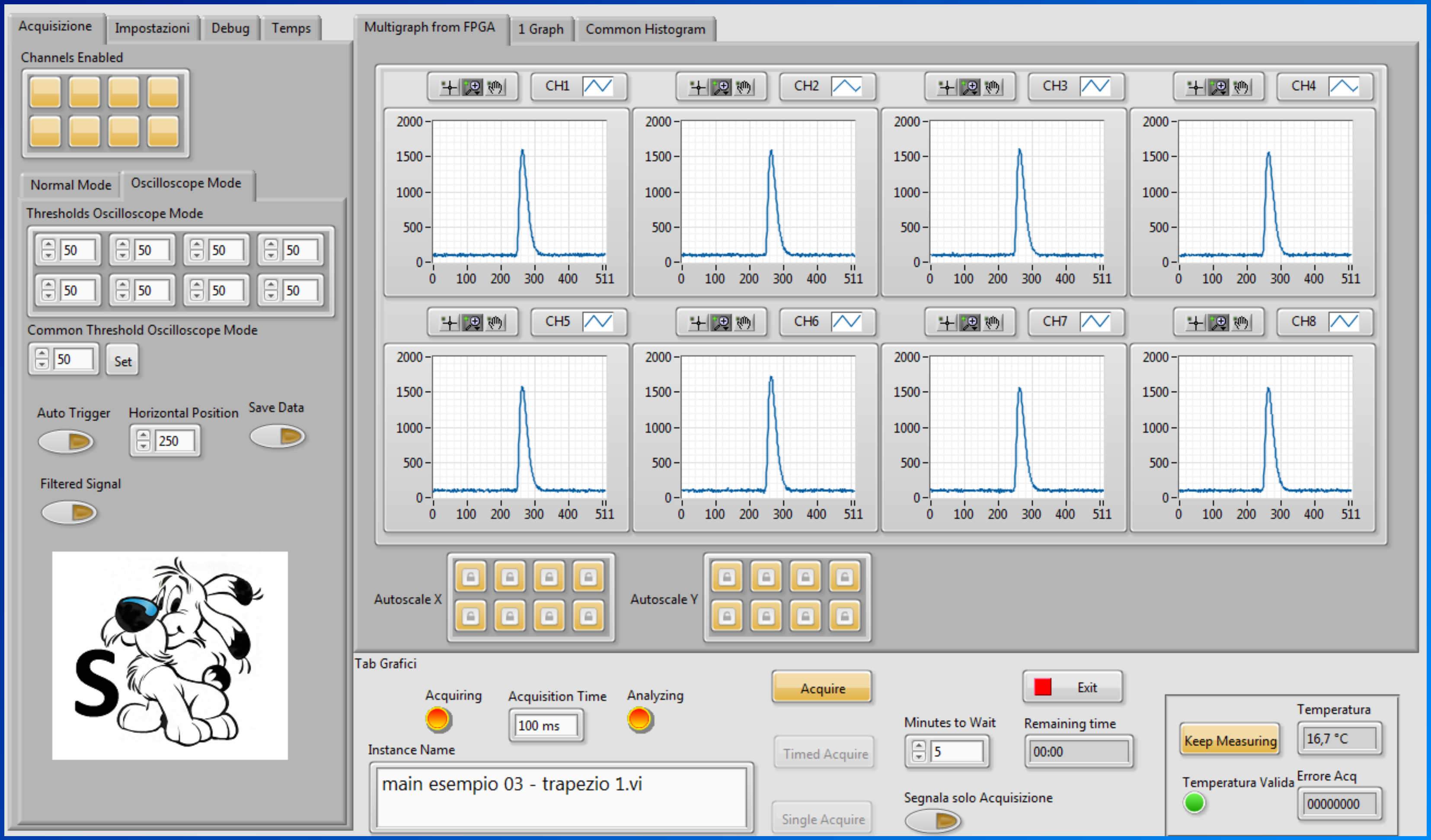
LabVIEW DAQ – normal mode



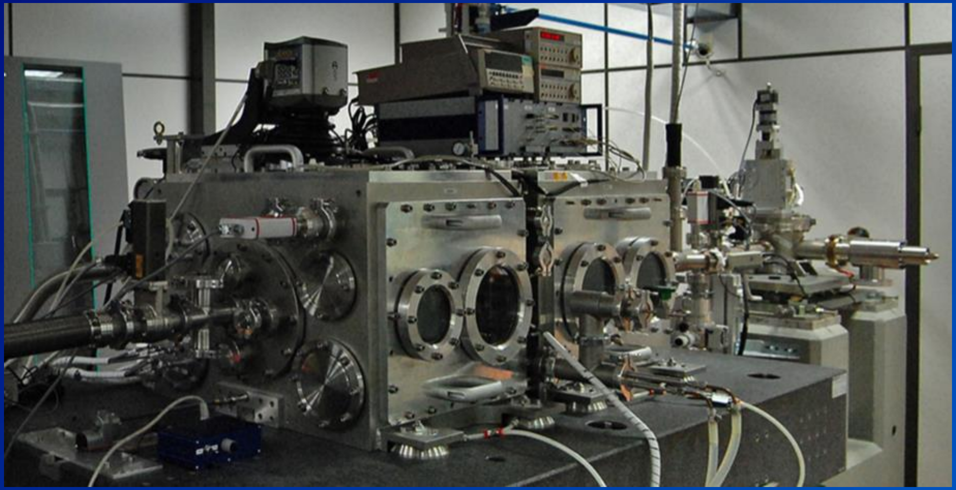
LabVIEW DAQ – histogram mode



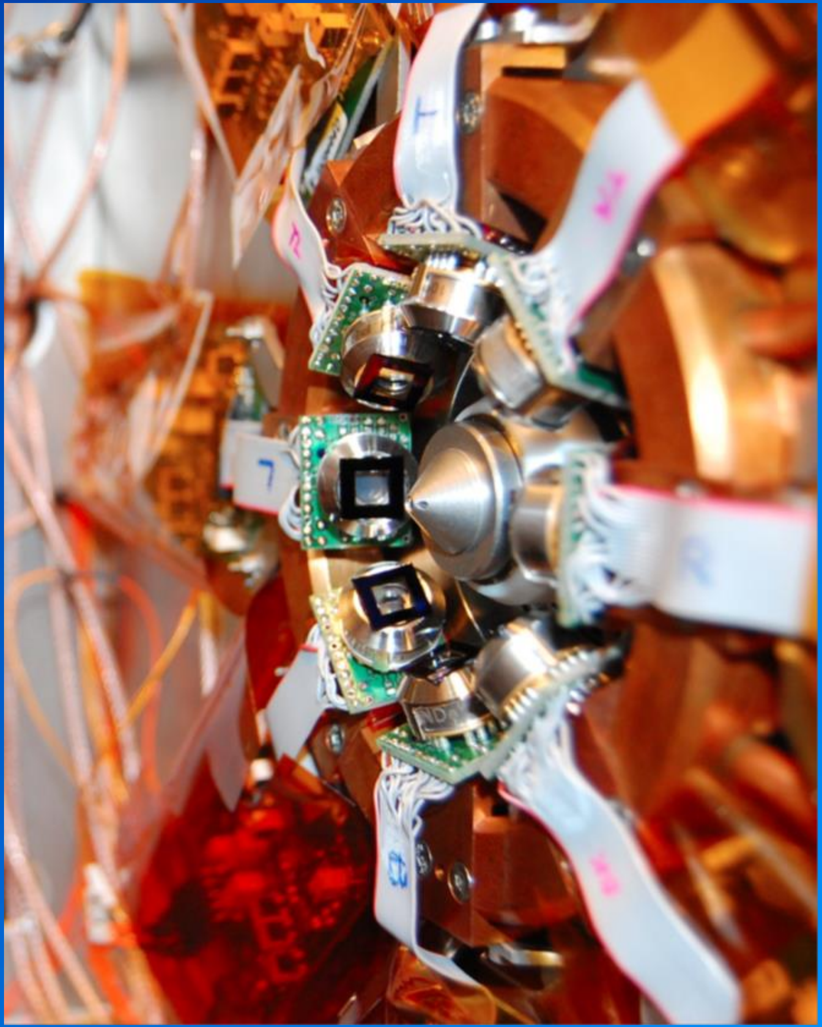
LabVIEW DAQ – oscilloscope mode



Development for Elettra/TwinMic



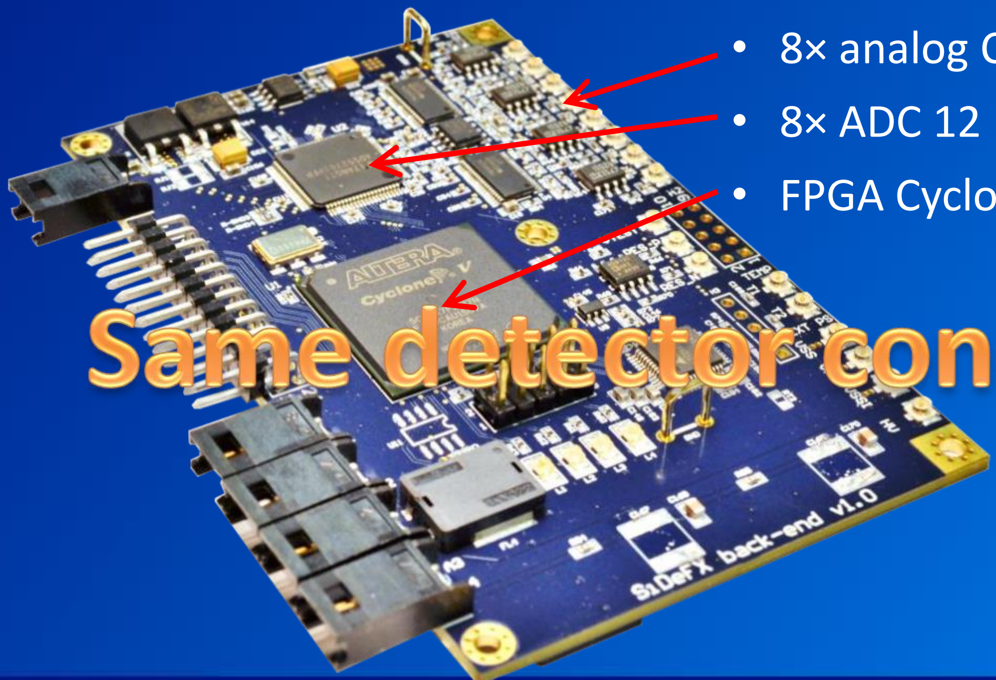
- Combination of scanning and full-field imaging in a single instrument
- Energy range 400 – 2200 eV, lateral resolution of 30 nm – 1 mm
- Goal of the project: an order of magnitude reduction of the measurement time
  - Improved measurement throughput
  - Reduced damage to the sample
  - Alternatively, acquire larger maps



8× PNSensor SDDs (collimated 20 – 30 mm^2) arranged on a copper ring used for cooling

The new TwinMic detector system

- 6 <u>not collimated</u> hexagonal pixels (total area of 182 cm^2) read out by SIRIO preamplifiers

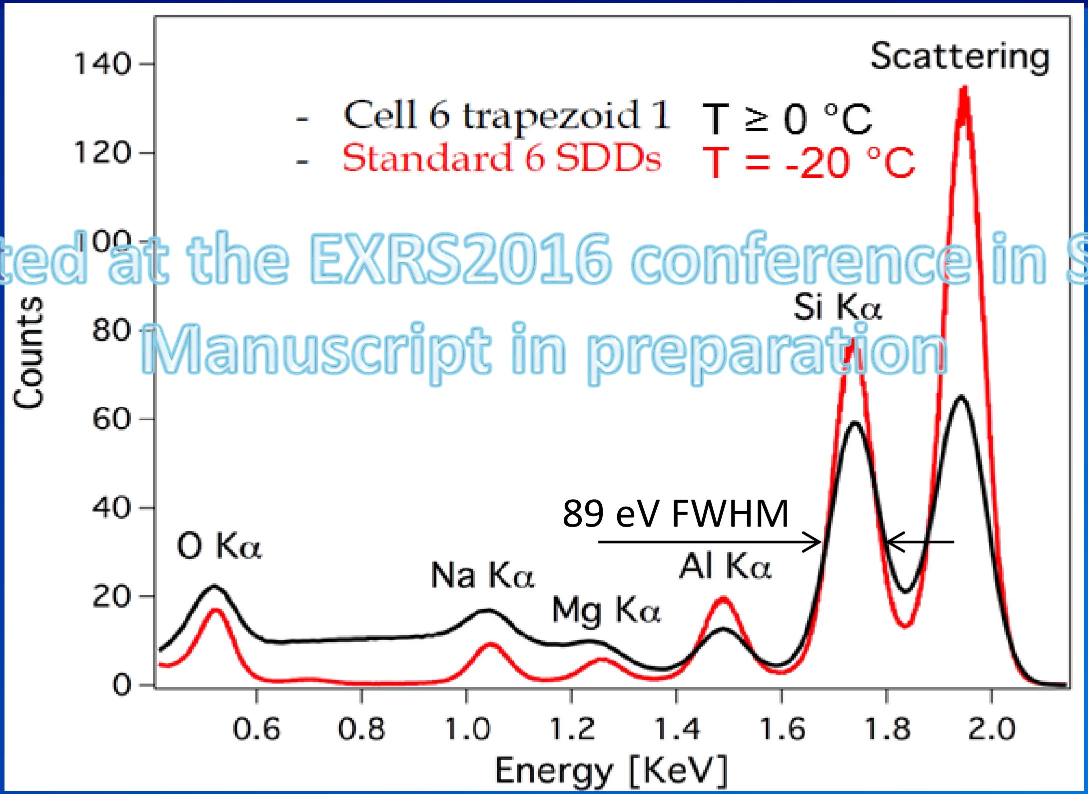


- 8× analog CR-RC^2 filters
- 8× ADC 12 bit 40 MSPS
- FPGA Cyclone 5

Same detector concept of SESAME

Four detectors mounted in the experimental chamber in vacuum conditions; for the test the distance from the sample was not yet optimal

Beamline measurements



Presented at the EXRS2016 conference in Sweden

Manuscript in preparation

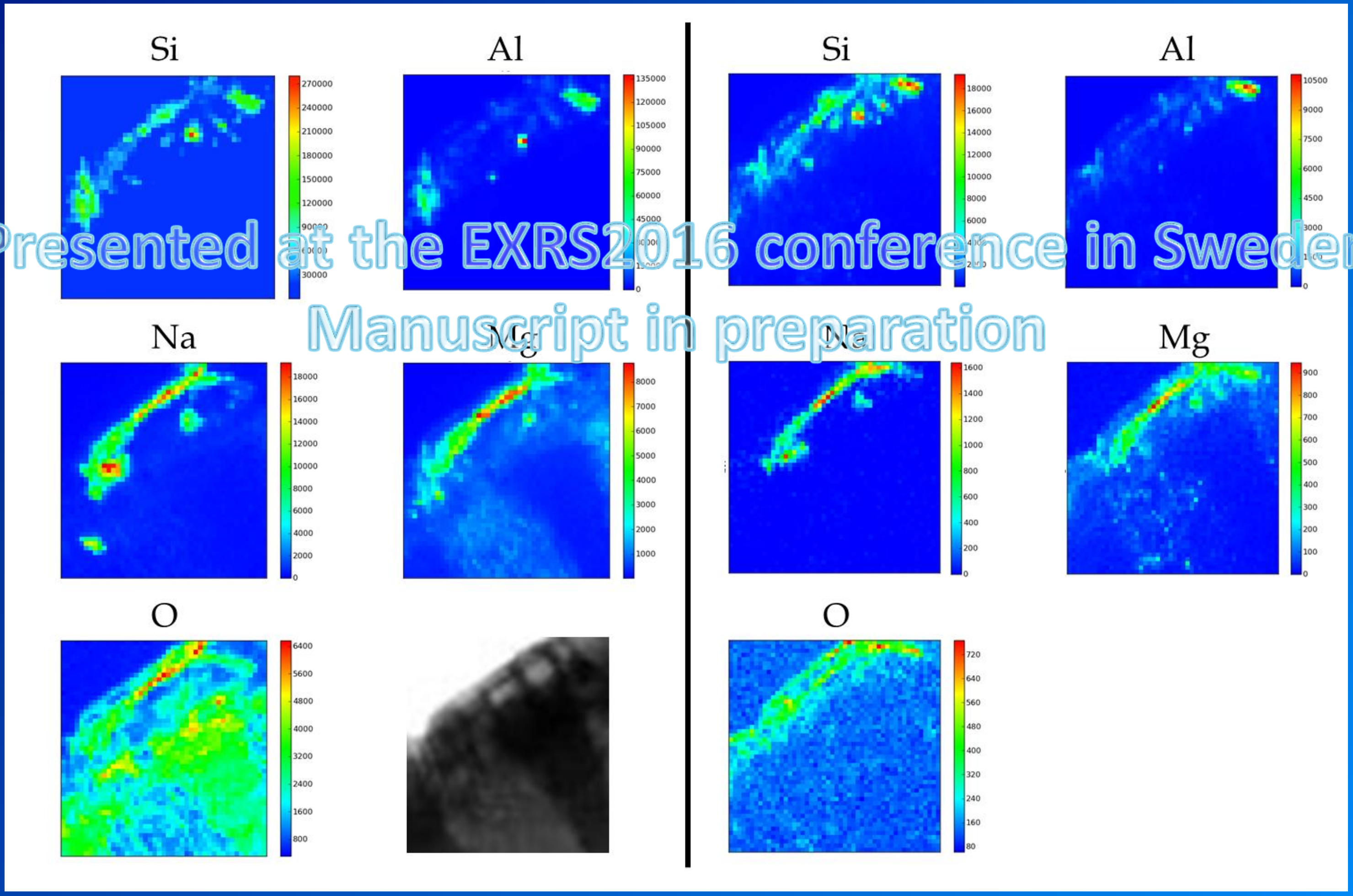
Si-Al-Mg-Na-O spectra of a *euphorbia pityusa* plant section acquired with one cell of the new TwinMic detector and with 6 SDDs of the standard system

- Optimized digital filtering not yet available at that time, t_R = 0.95 µs
- Relevant background below 1.4 keV (electrons extracted from the sample?)
- Successive test with new mechanical support showed a doubling of the rate

Beamline measurements

6 cells of the standard detector

Cell #1 of trapezoid #1

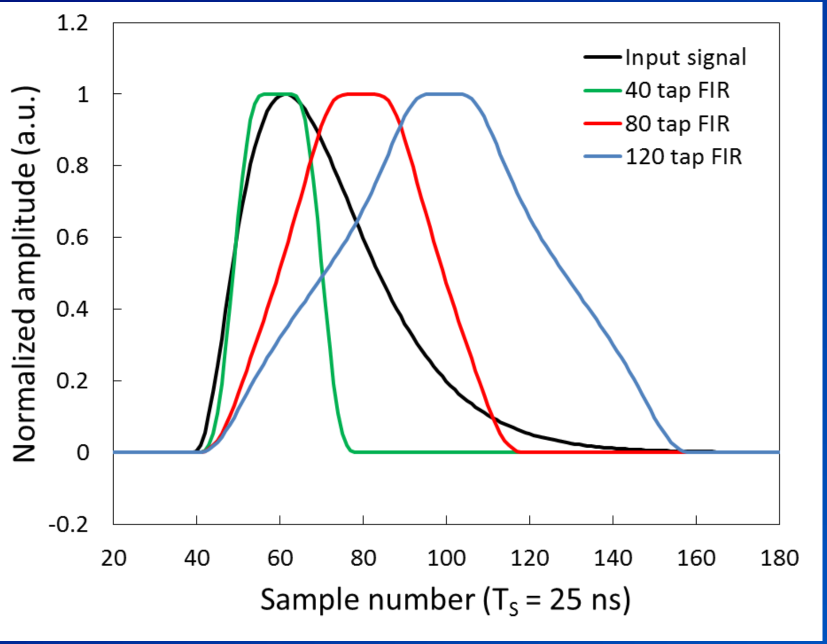


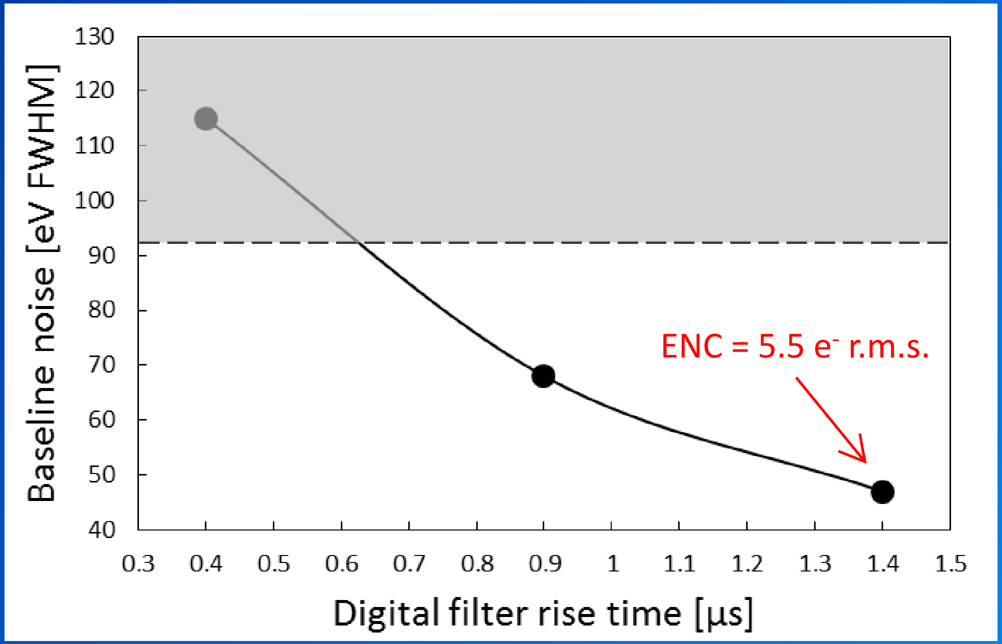
Presented at the EXRS2016 conference in Sweden

Manuscript in preparation

Elemental maps of the *euphorbia pityusa* plant section together with the corresponding absorption image

Laboratory measurements at 0 °C





- Energy calibration with a ^{55}Fe radioactive source
- Digital filter coefficients optimized considering the noise autocorrelation function
- Distortion present on the analog signal → noise evaluated from the baseline fluctuations
- Fast filter worsens the resolution of the analog pre-shaper because of the unmatched frequency bands, the other two filter performances are within SESAME specifications

Conclusions

- The SESAME XAFS fluorescence detector under development is a state-of-the-art instrument:
  - it will sustain a rate of at least 50 kcps/cell (≈ 560 kcps/cm^2)
  - It will have a total sensitive area of 576 mm^2 allowing for a total rate of at least 3.2 Mcps
  - It will have an energy resolution < 150 eV FWHM @ 5.9 keV, 0 °C with a peaking time ≤ 1 μs
- The detector concept is being tested and optimized by way of two parallel developments for Elettra Sincrotrone Trieste (XAFS and TwinMic beamlines) with good results
- The timeframe set for this project forced us to consider conservative solutions, nonetheless further optimizations and improvements of such detector are possible and will be pursued in future developments