Development and performance of Silicon-drift detectors and their potentials for soft x-ray advanced light sources applications

Andrea Vacchi INFN Trieste

outline

- Few introductory remarks
- The due historical framing
- Our daily SDD; working principle
- tracking & ALICE detector more than 1 m^2 since 2007
- Large Area & soft X-rays:
- Towards X-ray astrophysics
- X-ray astronomy LOFT et.al.
- Some recent results

- G. Zampa presentation at this conference

what’s new?

Know-how diffusion;
parallel developments;
efficiency & optimizatin;
large impact

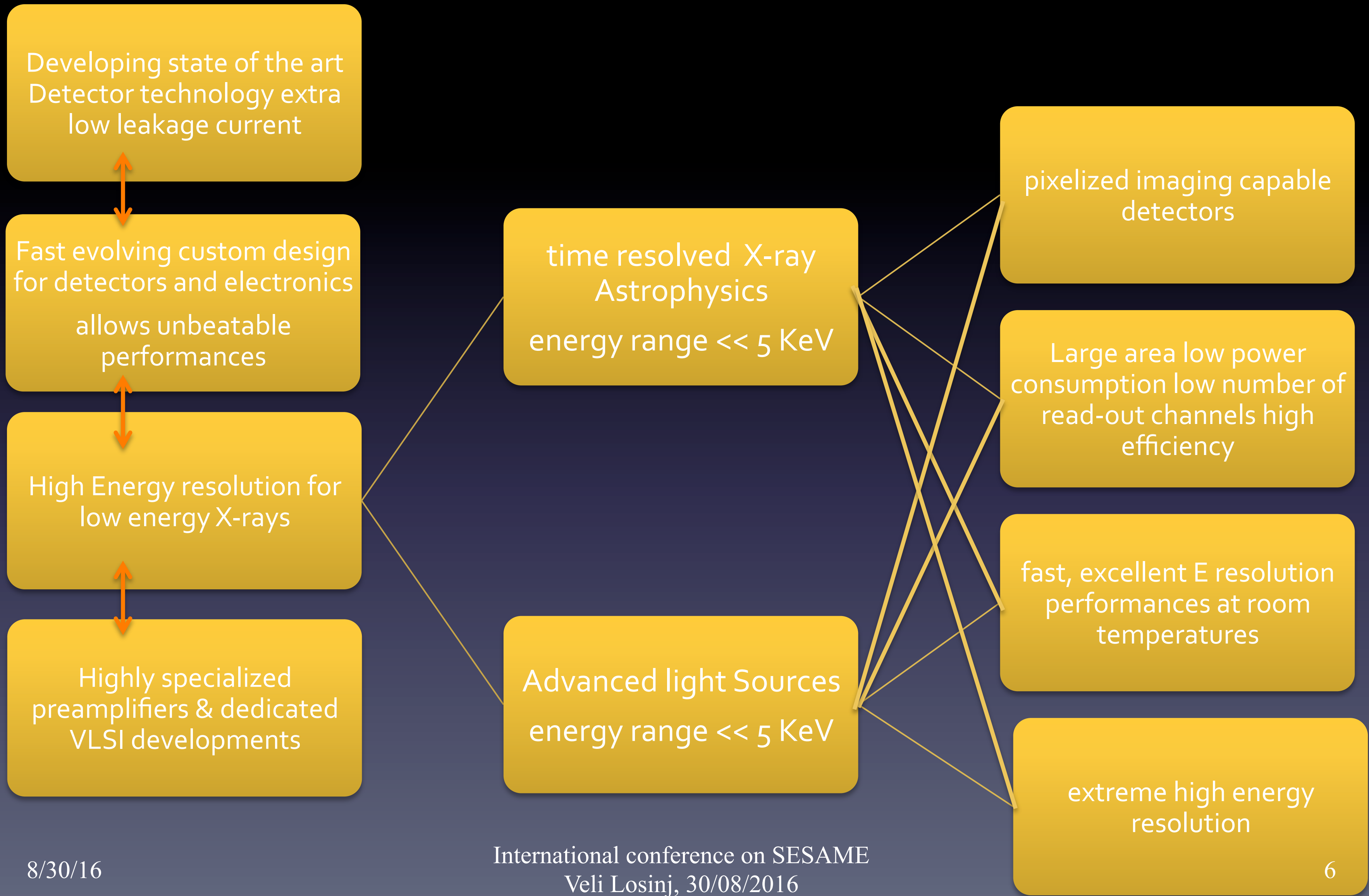
REDSOX collaboration
state of the art SDD

2nd Meeting
on Silicon Drift
Detectors for Low
Energy X-Ray
Applications
9-11 May 2016,
Palazzo Natta,
COMO

The Abdus Salam International Centre for Theoretical Physics

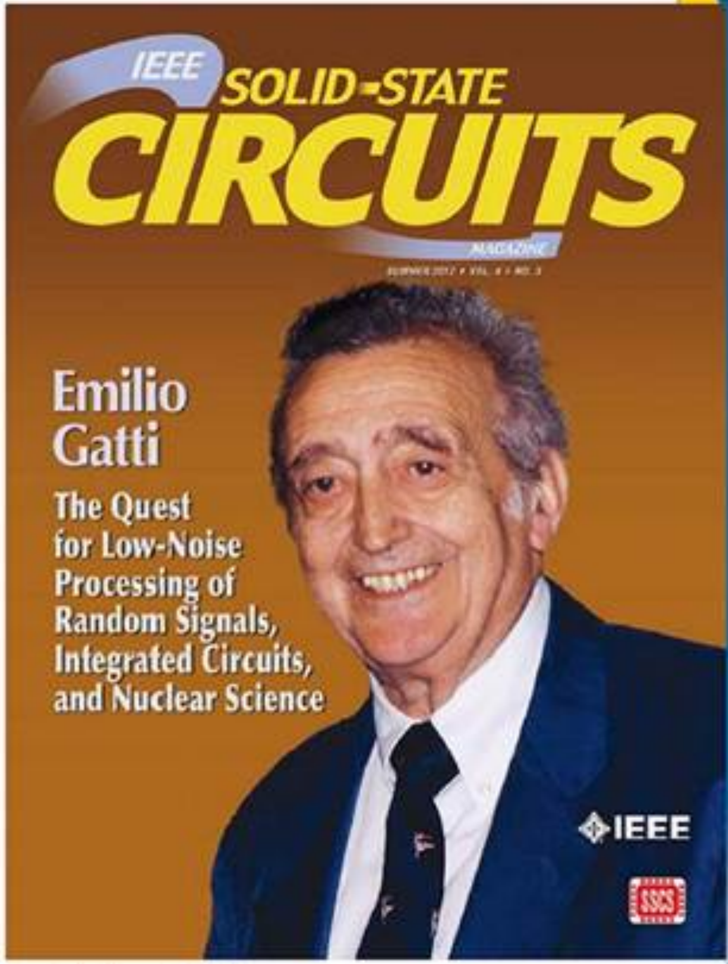
RESEARCH DRIFT FOR SOFT X-RAYS
redsox

continuous flow of front edge developments in two technologically hungry scientific fields



Foreword:

- **E. Gatti and P. Rehak have proposed Silicon Drift Detectors (SDD) in 1983. It is now 33 years** that this very versatile and elegant device evolves in different directions. The SDD operation principle has given rise to the development of a variety of solutions adapted to very challenging specific needs.
- All this was made possible by the planar technology introduced by J. Kemmer dedicated to the field of high performance detectors.
- ***The first large area SDD, for particles tracking in a high multiplicity environment, was published in 1990,*** *while in* ***2007 more than 1 m2 of SDD was made operative in the internal tracking system of the LHC-ALIC****E experiment, demonstrating the possibility of industrial mass production with high production yield.*
- **Far from being exhausted**, large area SDD's continue to evolve.



4 ottobre 2012

In occasione dell'uscita del numero speciale a lui dedicato,

alla presenza e in onore di **Emilio Gatti**

Erik H.M. Heijne terrà il seminario:

Imaging and imagination: the use of nanoelectronics for particle physics experiments

Maggiori dettagli sono disponibili al sito: www. dei.polimi.it

Ore 14.15

Sala Conferenze

Dipartimento di Elettronica e Informazione Politecnico di Milano

POLITECNICO DI MILANO

DIPARTIMENTO DI ELETTRONICA E INFORMAZIONE

PAVEL REHAK

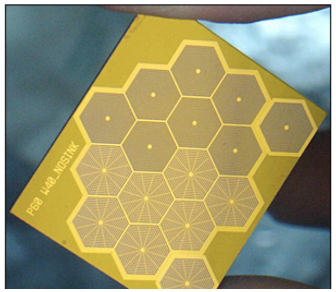
BROOKHAVEN NATIONAL LABORATORY Features Media & Communications Office

News Releases | Features | Photos | Videos | Fact Sheets | Lab History | Contacts

By Satya Shanmugham | December 19, 2008

25th Anniversary of Rehak's and Gatti's Innovative Detector

Brookhaven's Instrumentation Division develops state-of-the-art instrumentation required for experimental research programs at BNL and throughout the world. Much of their work is focused on detectors that track particles after a collision or detectors that identify the energy and location of absorbed x-rays. Some of the current silicon detector developments are for RHIC and ATLAS upgrades, NSLS and NSLS-II, and NASA missions, to name a few.



1983

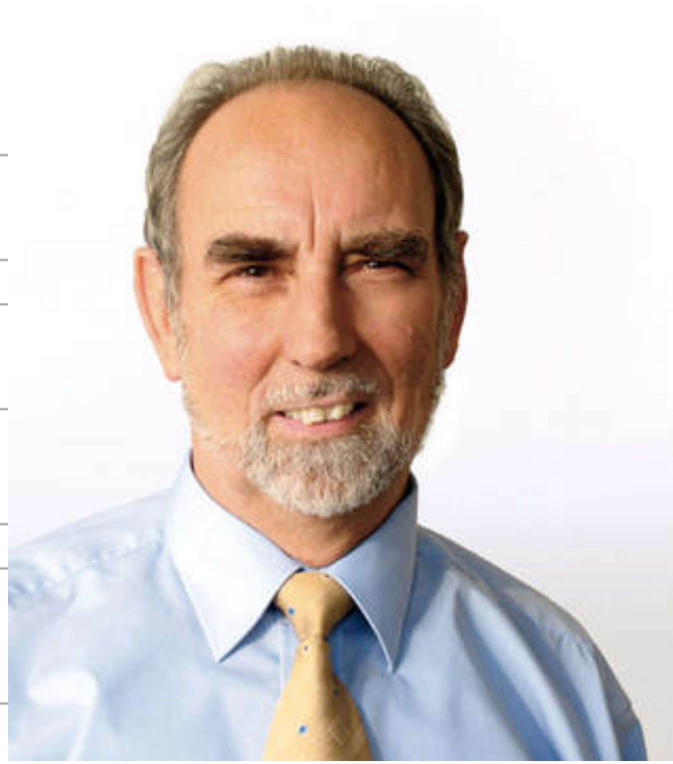
Dr. Josef Kemmer

KETEK
Creative Detector Solutions

HOME PRODUCTS COMPANY DOWNLOADS NEWS CONTACT

1980 Publishes **planar technology** with ion implantation in Nuclear Instruments and Methods (NIM)

HISTORY



Development of the planar technology for the fabrication of silicon radiation detectors by Dr. Josef Kemmer at the Technical University of Munich (TUM).
Fabrication of the first SDDs by Dr. Josef Kemmer at the TUM utilizing the planar process. The detector principle was proposed by Emilio Gatti from Politecnico di Milano and Pavel Rehak from Brookhaven National Laboratory.
Formation of Ketek GmbH by Dr. Josef Kemmer.
Main business of KETEK is technology transfer to industry and to research institutes. Contribution to some of the world's most advanced detector projects in high energy physics and space research like XMM Newton.
Development and launch of the first generation of commercial SDD modules.Introduction of KETEK SDD to the XRF and EDX market within a strong co-operation with Röntec.
Development of monolithic and discrete multi-channel SDD systems.
Manufacturing and delivery of the 1000th commercial SDD Presentation of the 3rd generation of SDD with an energy resolution < 128eV at Mn Kα. Inituation of the electronic product line with the KETEK Analytical X-ray Acquisition System (AXAS) with own development and production.
The MER-Rover in NASA's Mars Lander carries six KETEK alpha particle detectors and a customized SDD.

PATENT Josef KEMMER 1980

United States Patent [19] — **Kemmer**

[11] **4,442,592**
[45] **Apr. 17, 1984**

[54] **PASSIVATED SEMICONDUCTOR PN JUNCTION OF HIGH ELECTRIC STRENGTH AND PROCESS FOR THE PRODUCTION THEREOF**

[76] Inventor: **Josef Kemmer**, No. 41 D, Hauptstrasse, 8041 Haimhausen, Fed. Rep. of Germany

[21] Appl. No.: **225,069**

[22] Filed: **Jan. 14, 1981**

[30] **Foreign Application Priority Data**

Jan. 31, 1980 [DE] Fed. Rep. of Germany 3003391

[51] **Int. Cl.**[3] **H01L 31/18**

[52] **U.S. Cl.** .... **29/572**; 29/576 B; 29/578; 148/1.5; 148/187

[58] **Field of Search** .... 148/1.5, 187; 29/571, 29/572, 569 R, 576 B, 578; 156/643, 662

[56] **References Cited**

U.S. PATENT DOCUMENTS

3,769,109	10/1973	MacRae et al.	148/1.5 X
3,891,468	6/1975	Ito et al.	148/1.5

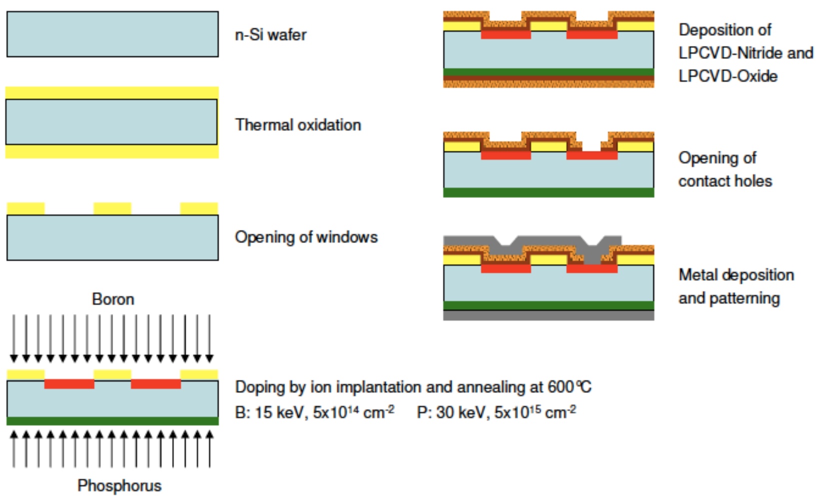
Primary Examiner—Brian E. Hearn
Assistant Examiner—David A. Hey
Attorney, Agent, or Firm—John C. Smith, Jr.

[57] **ABSTRACT**

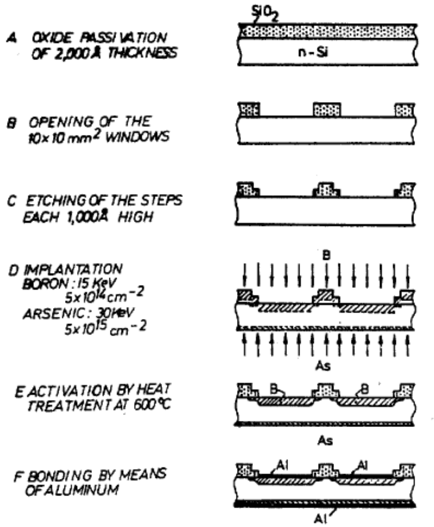
A passivated semiconductor pn junction is provided which has a high electric strength, one area being heavily doped and being very thin, in particular for radiation detectors. The pn junction has an edge zone at which a depletion zone (surface channel) is provided underneath the passivation layer.

12 Claims, 2 Drawing Figures

Planar Technology



PATENT Josef KEMMER 1980



4,442,592

CRITICAL STEPS :

OXIDE GROWTH USING HCl (not mentioned)

OXIDE STEPS

REAR IMPLANT

PATTERNING of Al in CONTACTS (not mentioned)

The First Large-area Silicon Drift Detector (1991)

Nuclear Instruments and Methods in Physics Research A306 (1991) 187–193
North-Holland

1991

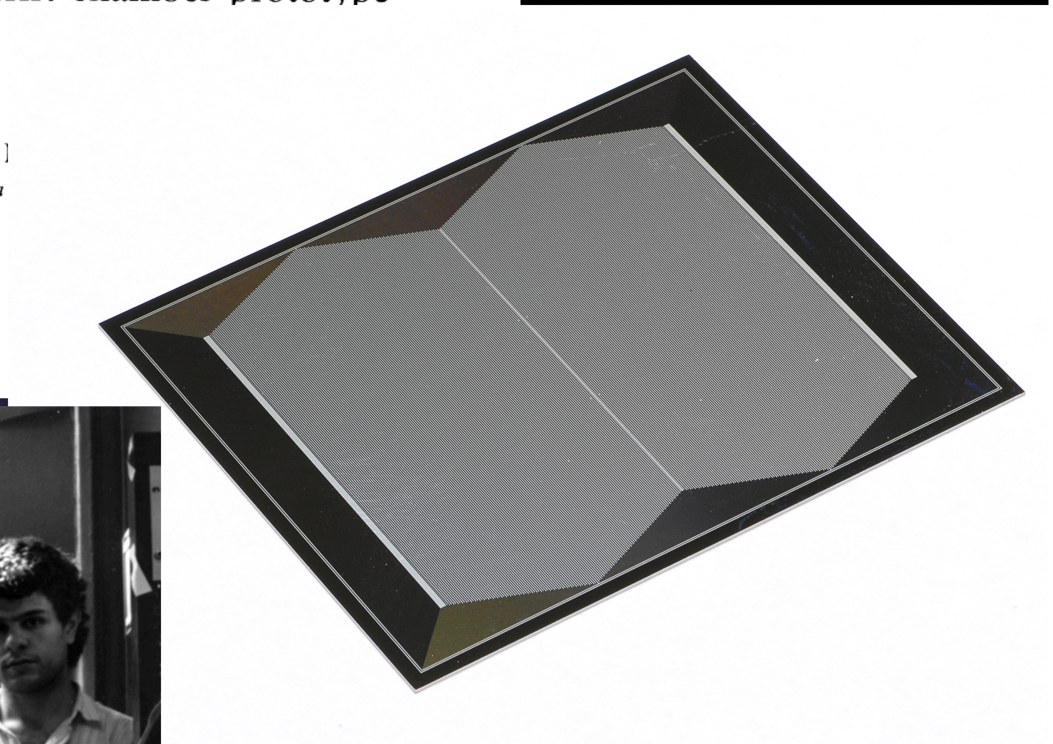
Performance of the UA6 large-area silicon drift chamber prototype

A. Vacchi
The Rockefeller University, New York, NY, USA

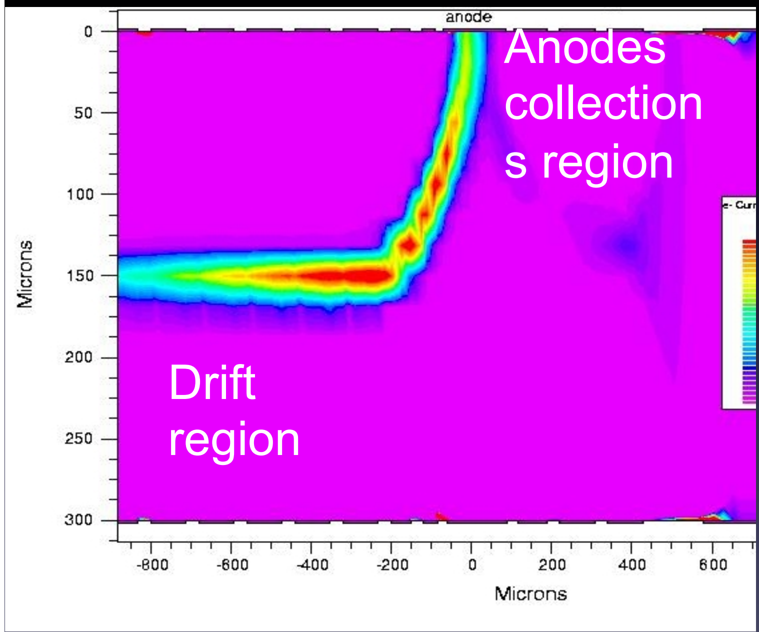
A. Castoldi, S. Chinnici, E. Gatti, A. Longoni, F. Palma and
Politecnico di Milano, Dipartimento di Elettronica and Centro di Elettronica Quantistica

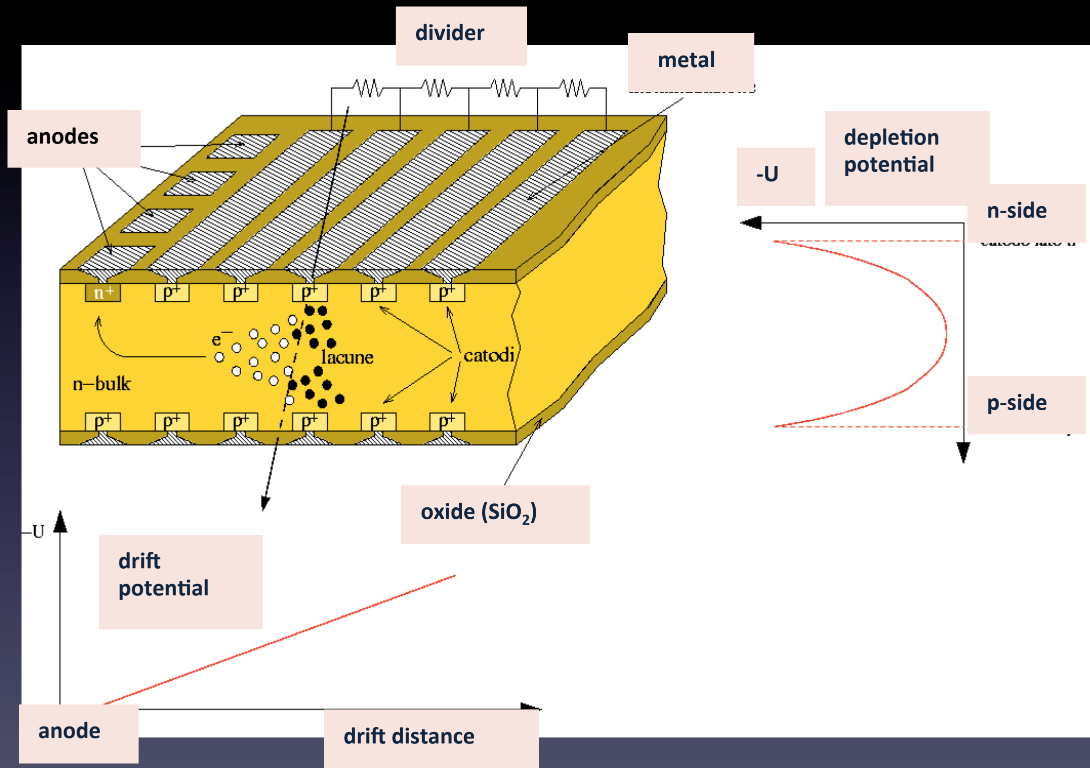
P. Rehak
Brookhaven National Laboratory, Upton, NY, USA

J. Kemmer
Facultät für Physik der Technischen Universität, Munich, Germany



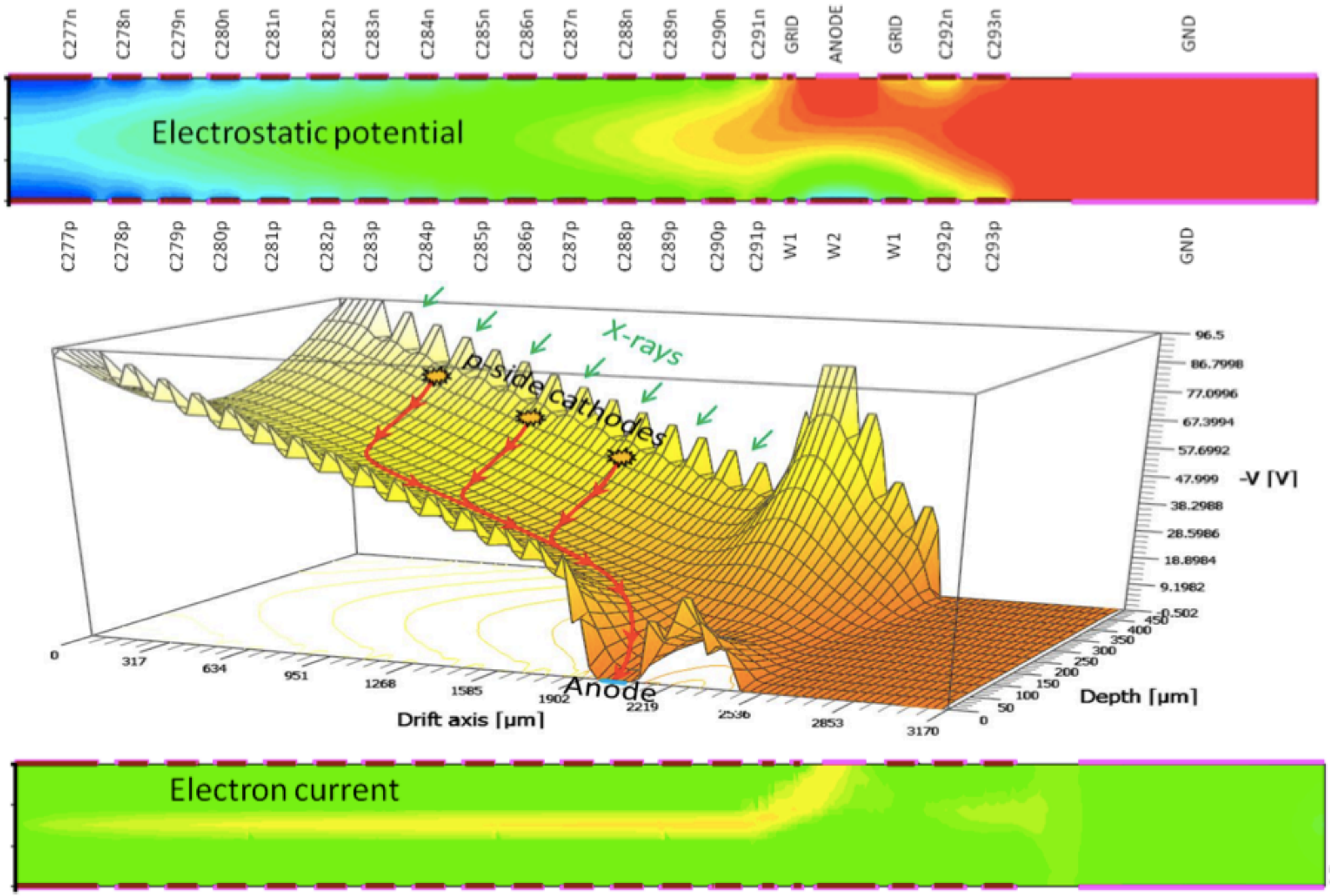
Silicon Drift Detectors (SDD) Basic Principle



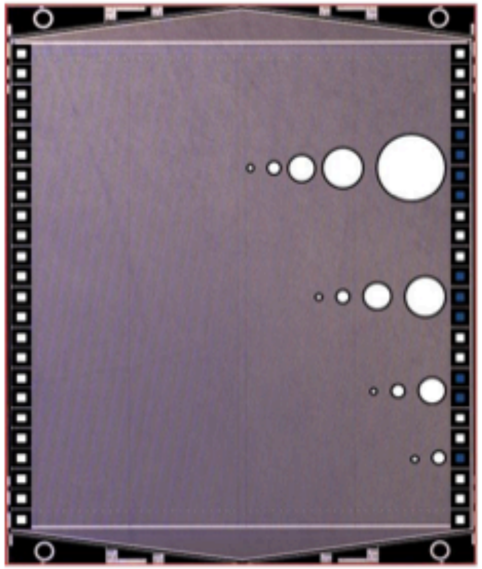


- due to their collection electrode geometry, anodes, SDD have excellent noise performance and are well suited for low-energy X-ray spectroscopy applications.

The linear Silicon Drift Detector



The linear SDD signal and charge diffusion



The charge cloud has a Gaussian shape. Its width depends on the drift time which, for a constant electric field, is a linear function of the drift distance:

$$D = \frac{k_B T}{q}\mu \quad \text{diffusion coefficient}$$

$$v = \mu E \quad \text{drift velocity}$$

$$t = \frac{x}{v} \quad \text{drift time}$$

$$\sigma = \sqrt{2Dt + \sigma_0^2} = \sqrt{2 \cdot \frac{k_B T}{q}\mu \cdot \frac{x}{\mu E} + \sigma_0^2} = \sqrt{2\frac{k_B T}{qE}x + \sigma_0^2}$$

For low energy X-ray photons it is possible to take $\sigma_0 \approx 0$

- Measuring the charge cloud lateral dimension it is possible to derive the drift length with a coarse resolution

→ Several anodes (N) are involved in the signal acquisition: the electronic noise contribution to the energy resolution is multiplied by $\sqrt{N}$

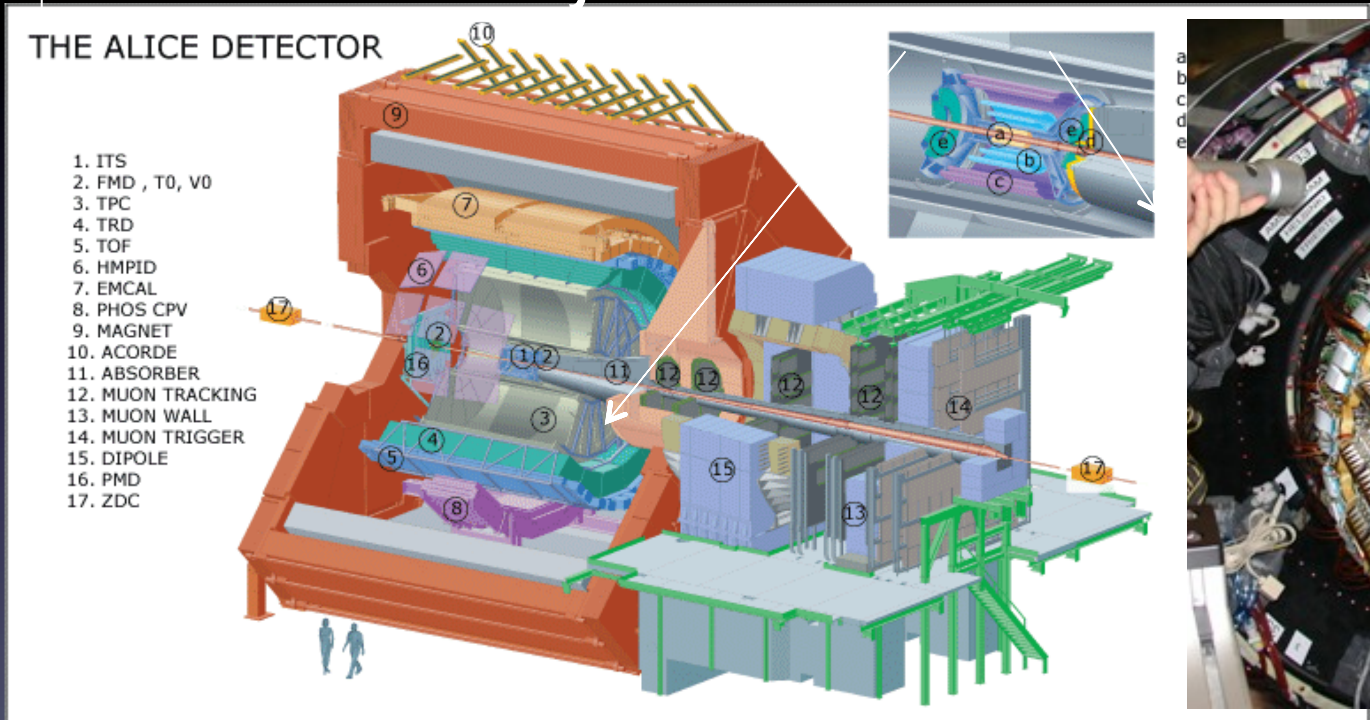
- For the best energy resolution the anode pitch should be large in order to have at most 2 anodes integrating the charge
- For imaging purposes the anode pitch should be small to better estimate the drift distance from the signal shape at the anodes (no prompt trigger with photons!!!)

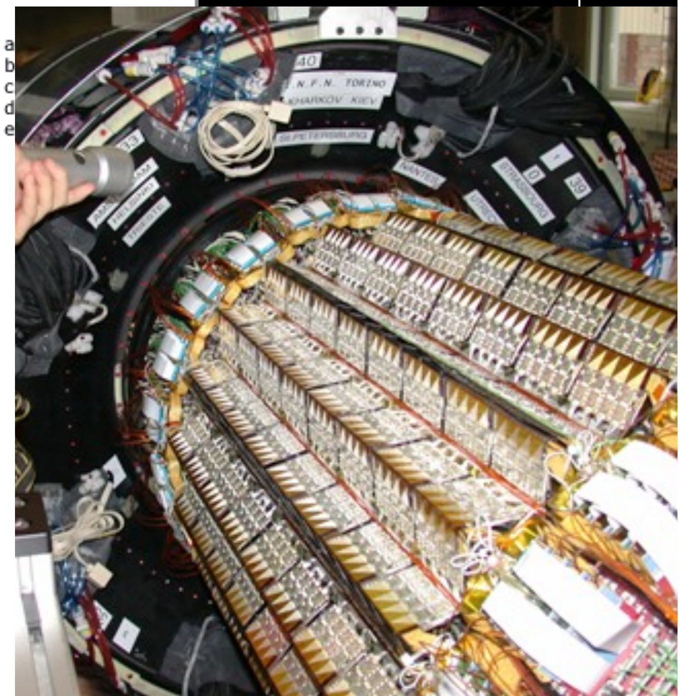
INFN Istituto Nazionale di Fisica Nucleare

ALICE-ITS-SDD

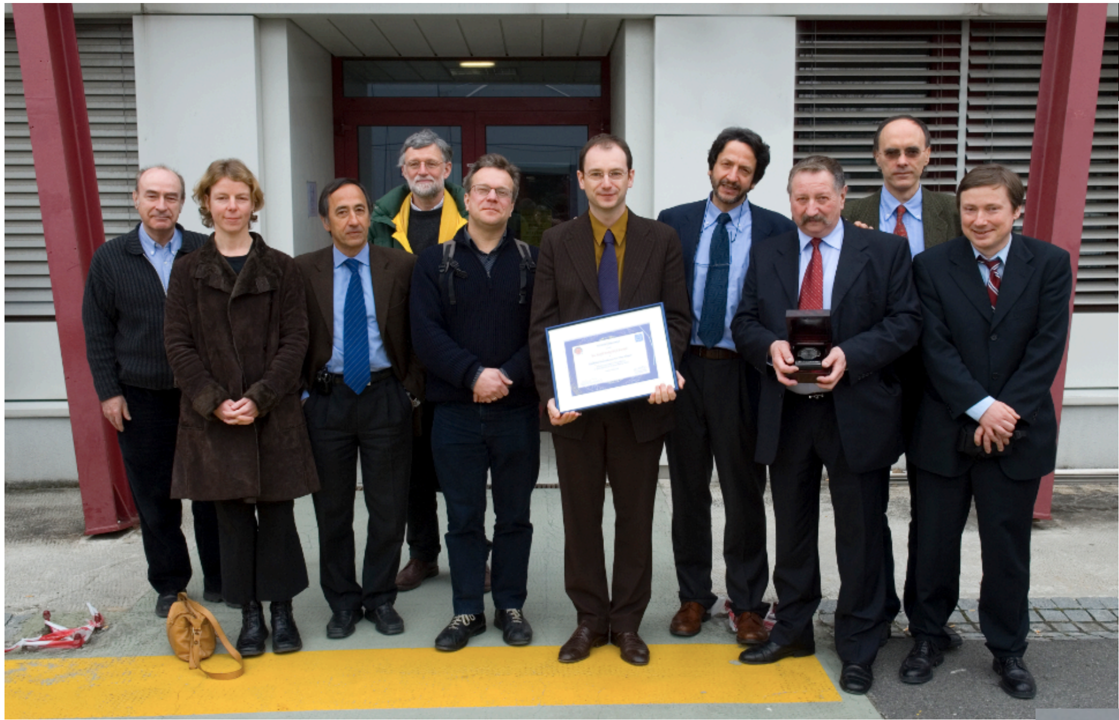
•production yield better than 60%(>90% for last batches)

260 detectors (~1.37 m^2) operational in LHC since 2007 .
Manufactured by Canberra in collaboration with INFN-Ts.





Nuclear collisions at the LHC have allowed experimenters to study strongly interacting matter in unprecedented conditions of temperature and density and with a much enhance range of probes unveiling new features of the quark-gluon plasma in these extreme conditions.



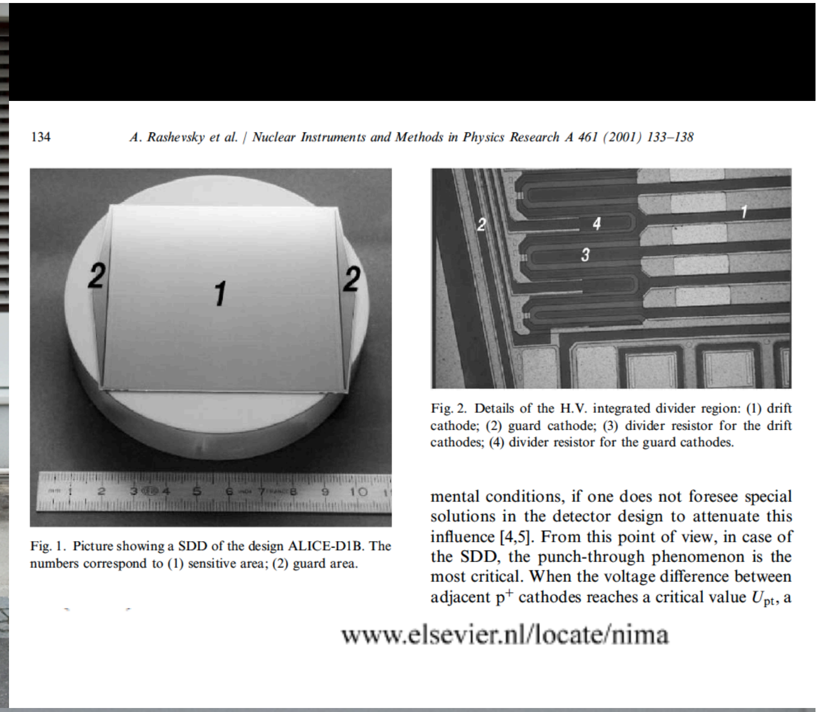


Fig. 1. Picture showing a SDD of the design ALICE-D1B. The numbers correspond to (1) sensitive area; (2) guard area.

Fig. 2. Details of the H.V. integrated divider region: (1) drift cathode; (2) guard cathode; (3) divider resistor for the drift cathodes; (4) divider resistor for the guard cathodes.

mental conditions, if one does not foresee special solutions in the detector design to attenuate this influence [4,5]. From this point of view, in case of the SDD, the punch-through phenomenon is the most critical. When the voltage difference between adjacent p^+ cathodes reaches a critical value U_{pt}, a

www.elsevier.nl/locate/nima

Characteristics of the ALICE

A. Rashevsky[a,*], V. Bonvicini[a], P. Burger[b], P
R. Hernández-Montoya[c,1], A. Kolojvari[c
C. Piemonte[a], F. Tosello[c], A.

one di Trieste, c/o Area di Ricerca, Palazz
[b] *Canberra Semiconductor, NV,*
[c] *INFN Sezione di To*

For the ALICE Coll

(SDD) with an active area of 7.0 × 7
stem. The development of the SDD

SDD for LHC-ALICE experiment

Wafer type:

- 5" Neutron Transmutation Doped <111> 3 kΩ·cm, thickness 300 μm

Area:

- Sensitive: 7.02 × 7.53 ≈ 53 cm^2, divided in 2 drift regions
- total: 7.25 × 8.76 cm^2, (ratio = 0.83)

Each drift region:

- has a length of 35 mm
- has 291 cathodes biased by an integrated voltage divider
- has 256 anodes - pitch of 294 μm
- has 3 lines of 33 MOS charge injectors for the drift velocity calibration

Guard region:

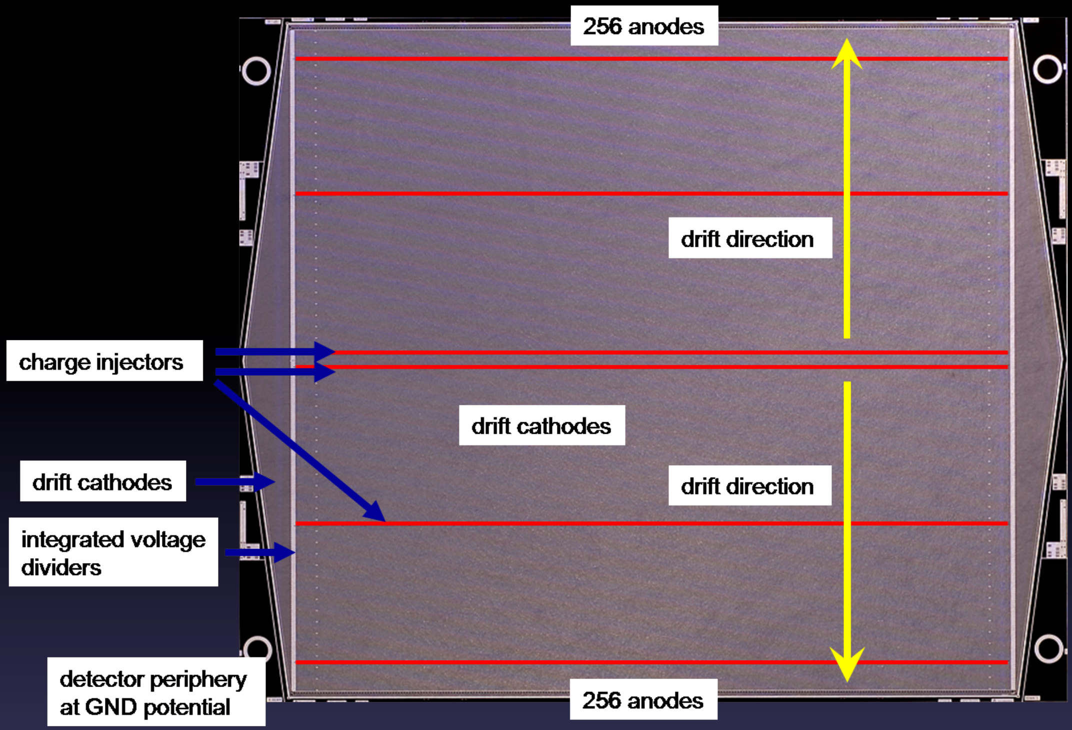
- independent voltage dividers

Integrated dividers:

- Equivalent resistance of all voltage dividers R_{tot} = 4781 kΩ

Each anode:

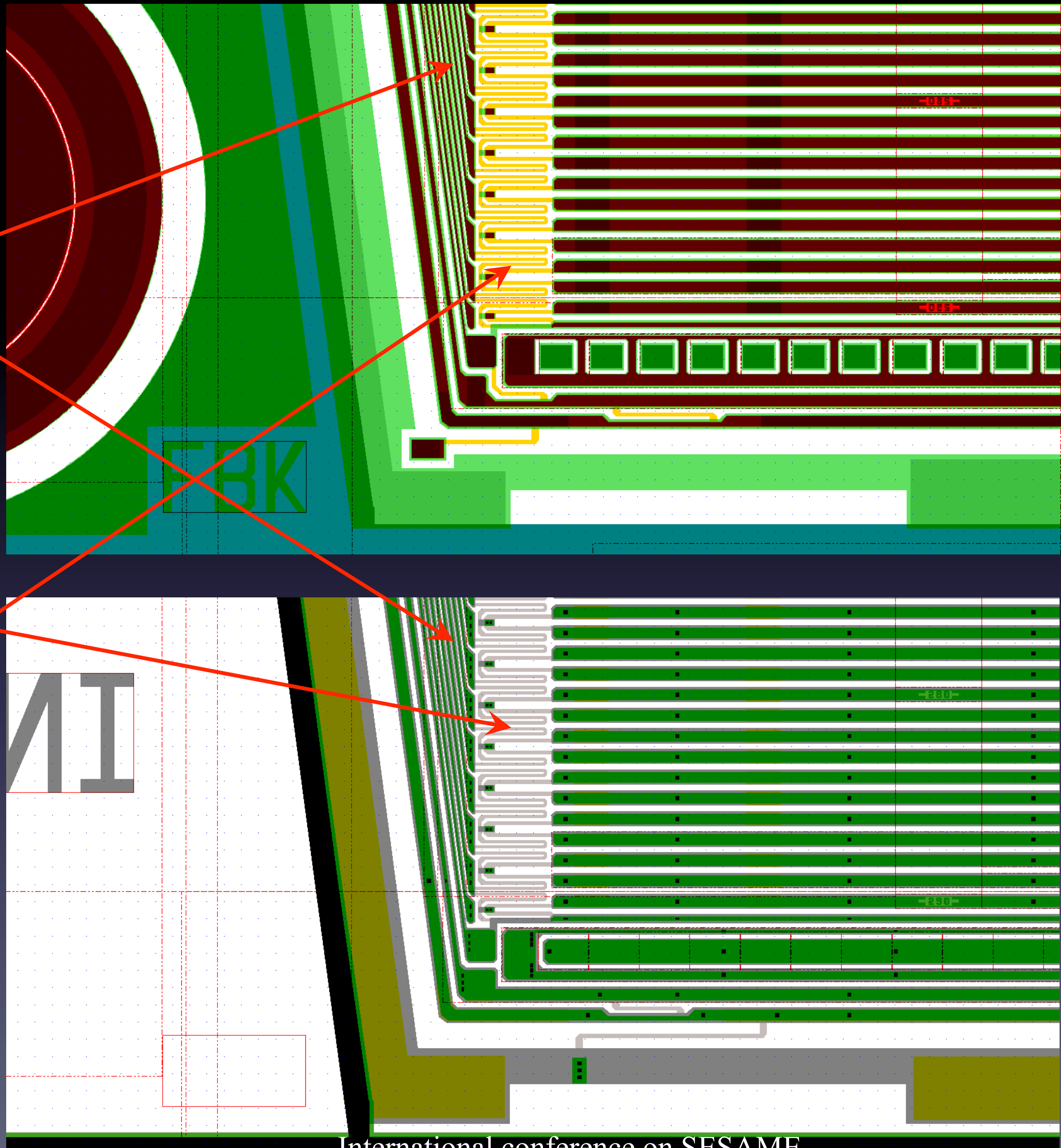
- has a very small capacitance of ~100 f F
- reads an area of 10 mm^2



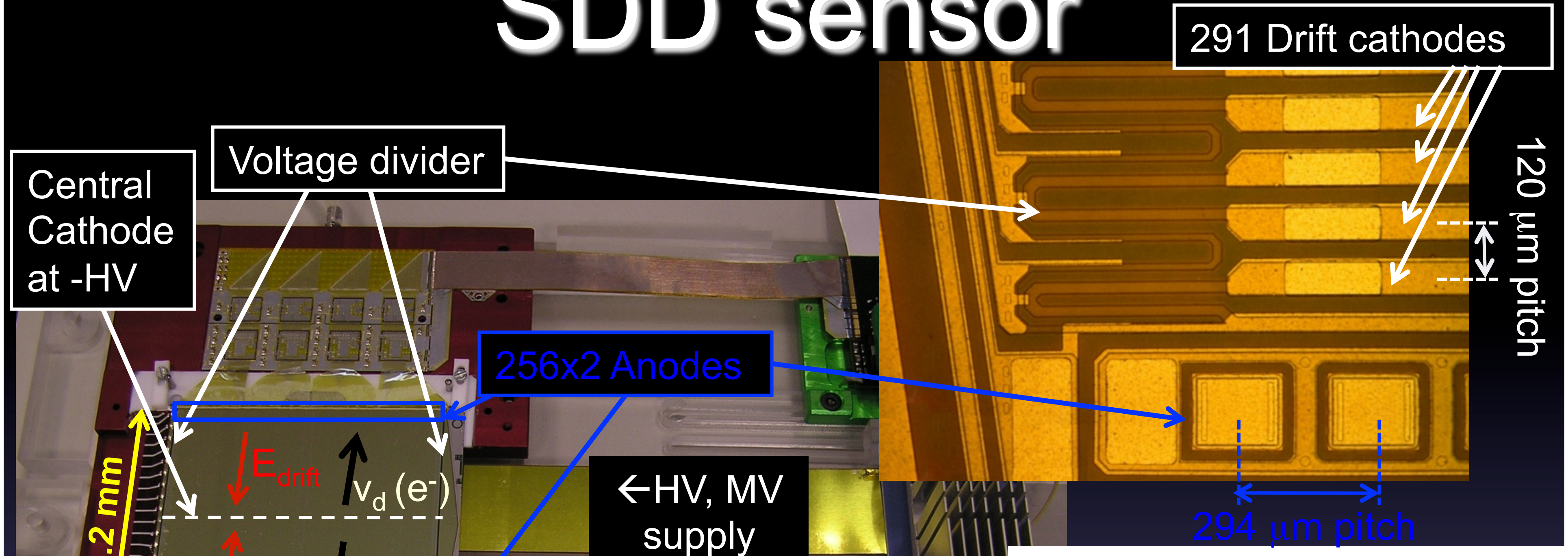
Specs for the detector :

- HV bias: -2.4 kV, 8V/cathode E = 670 V/cm
- 35mm in a drift time of 4.3 μs, v_d = 8 μm/ns
- total current on the voltage dividers ~0.48 mA
- on board power consumption: 1.15 W

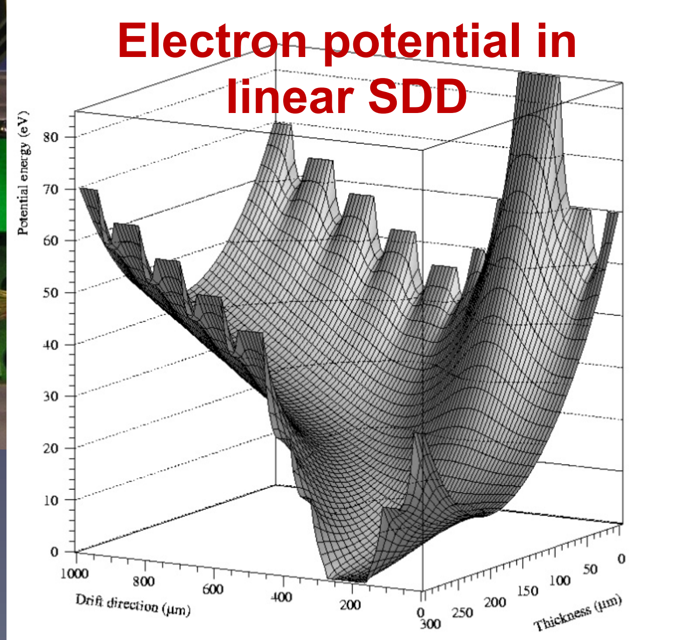
SDD layout details and terminology



SDD sensor

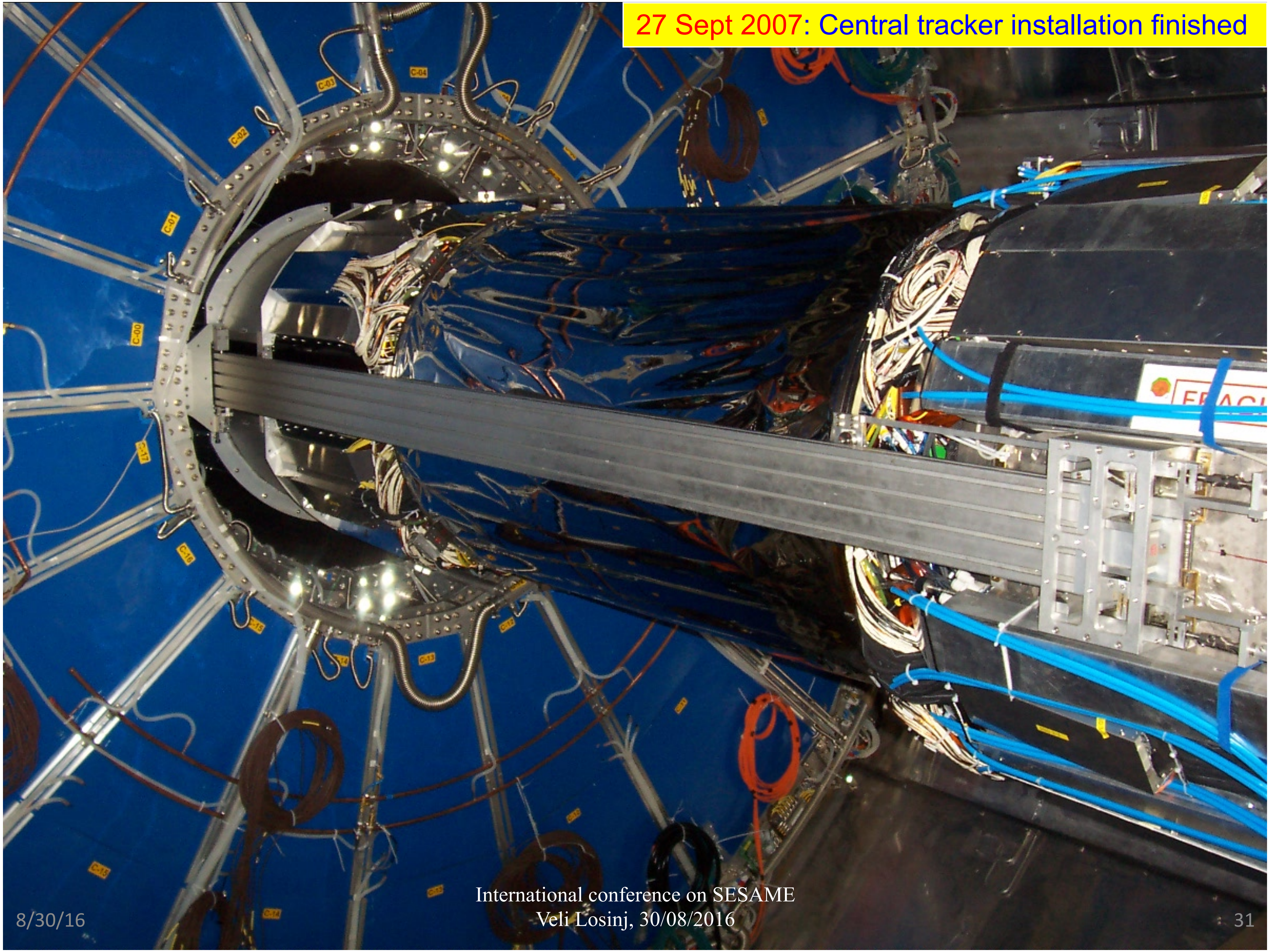


291 Drift cathodes
120 μm pitch
Voltage divider
Central Cathode at -HV
256x2 Anodes
294 μm pitch
70.2 mm
E_{drift}
v_d (e^-)
E_{drift}
v_d (e^-)
←HV, MV supply
←LV supply
←Commands
←Trigger
Data →
Hybrid with front-end electronics (4 pairs of ASICs)



Electron potential in linear SDD
Potential energy (eV)
Drift direction (μm)
Thickness (μm)

27 Sept 2007: Central tracker installation finished

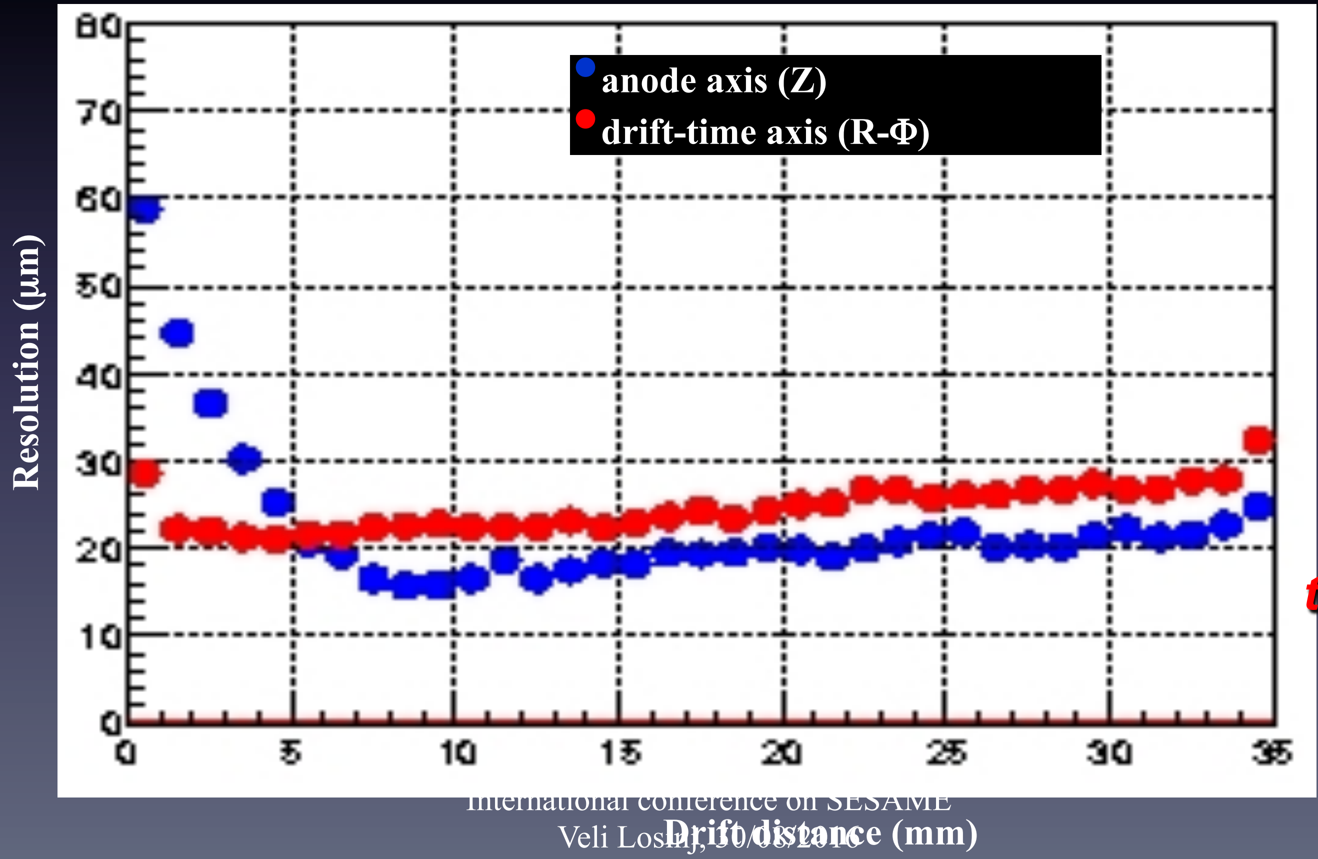


The spatial precision

along the drift direction, is better than 30 μm over the whole detector surface.

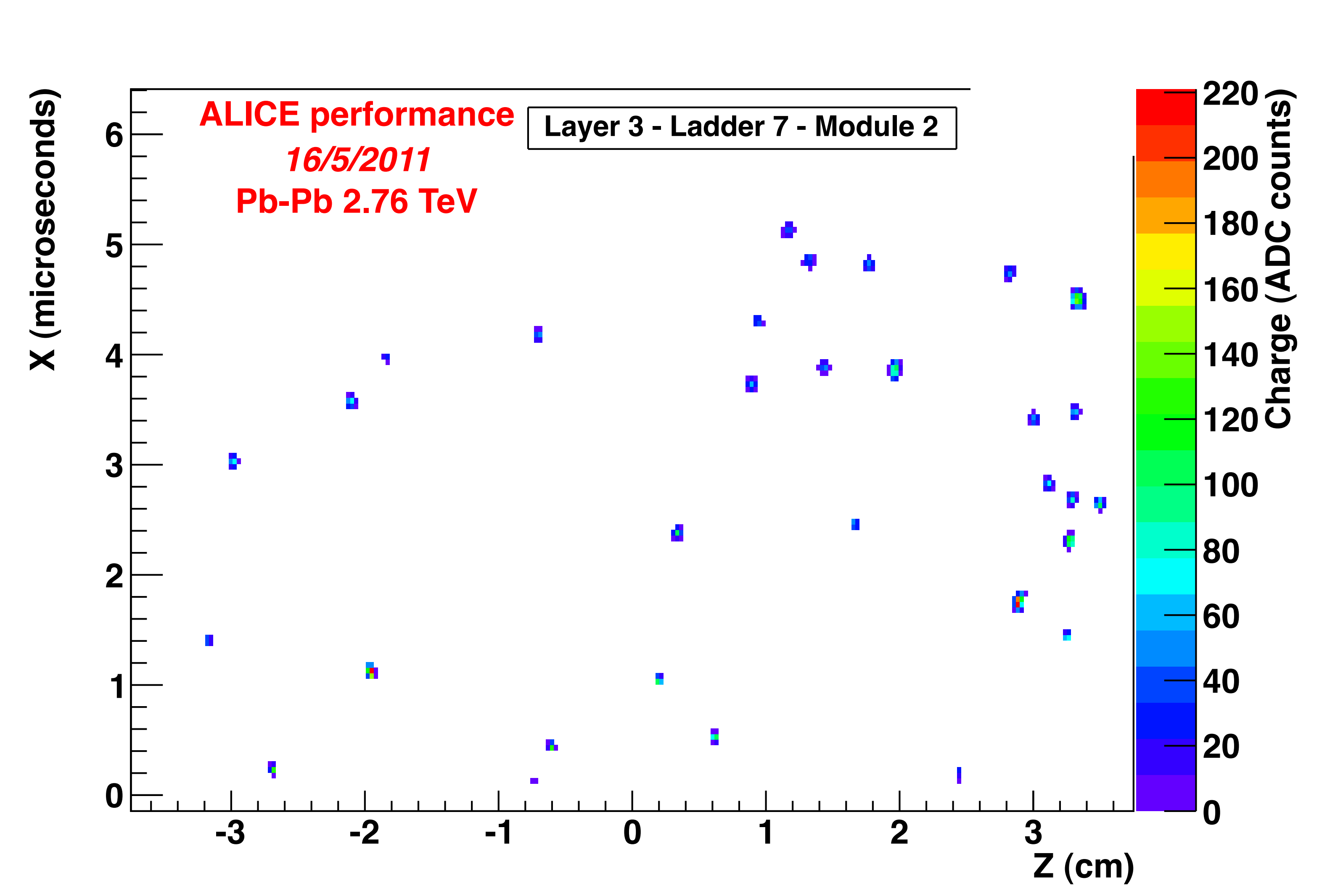
The precision along the anode, is better than 30 μm over 94% of the detector surface and reaches 60 μm close to the anodes, where a fraction of clusters affects only one anode.

The average values are 35 μm x 25 μm respectively.

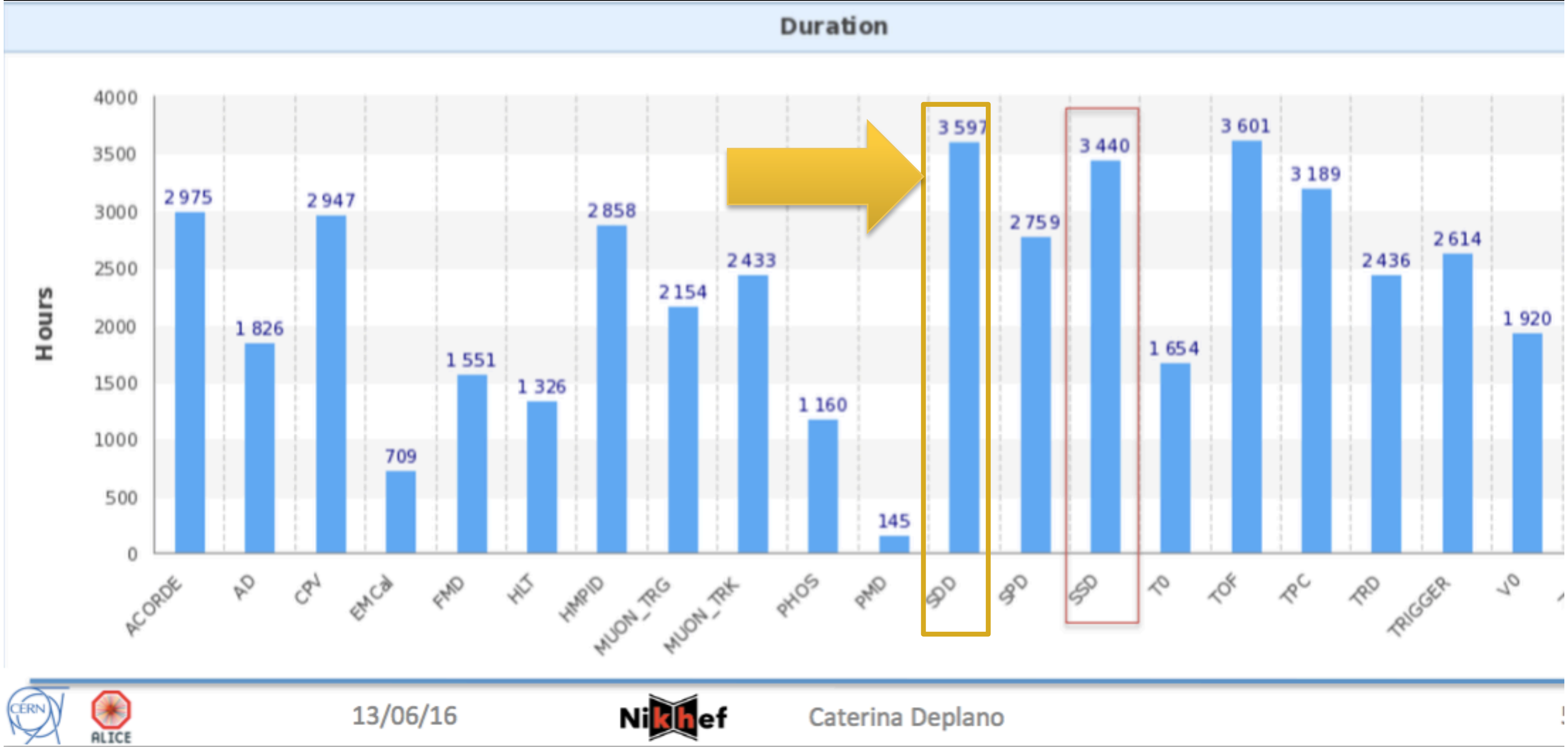


test beam data

High multiplicity two coordinates delivered Clean!



Alice SDD detection system run active time since 2016 year beginning



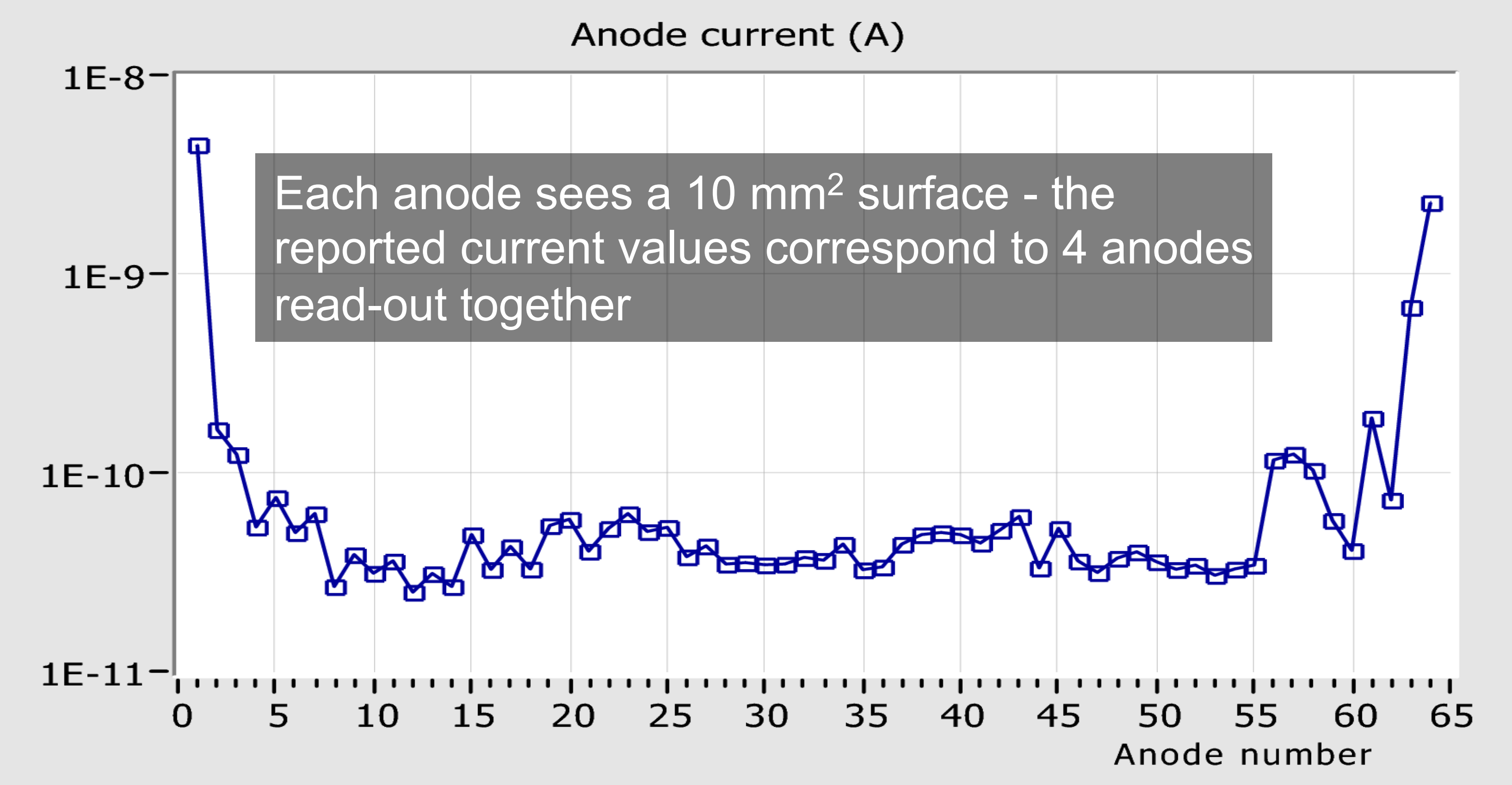
suitable for low-energy X-ray spectroscopy applications:

+ anode capacitance is about 50 fF,

+ the leakage current at the anode measured at room temperature is very low.

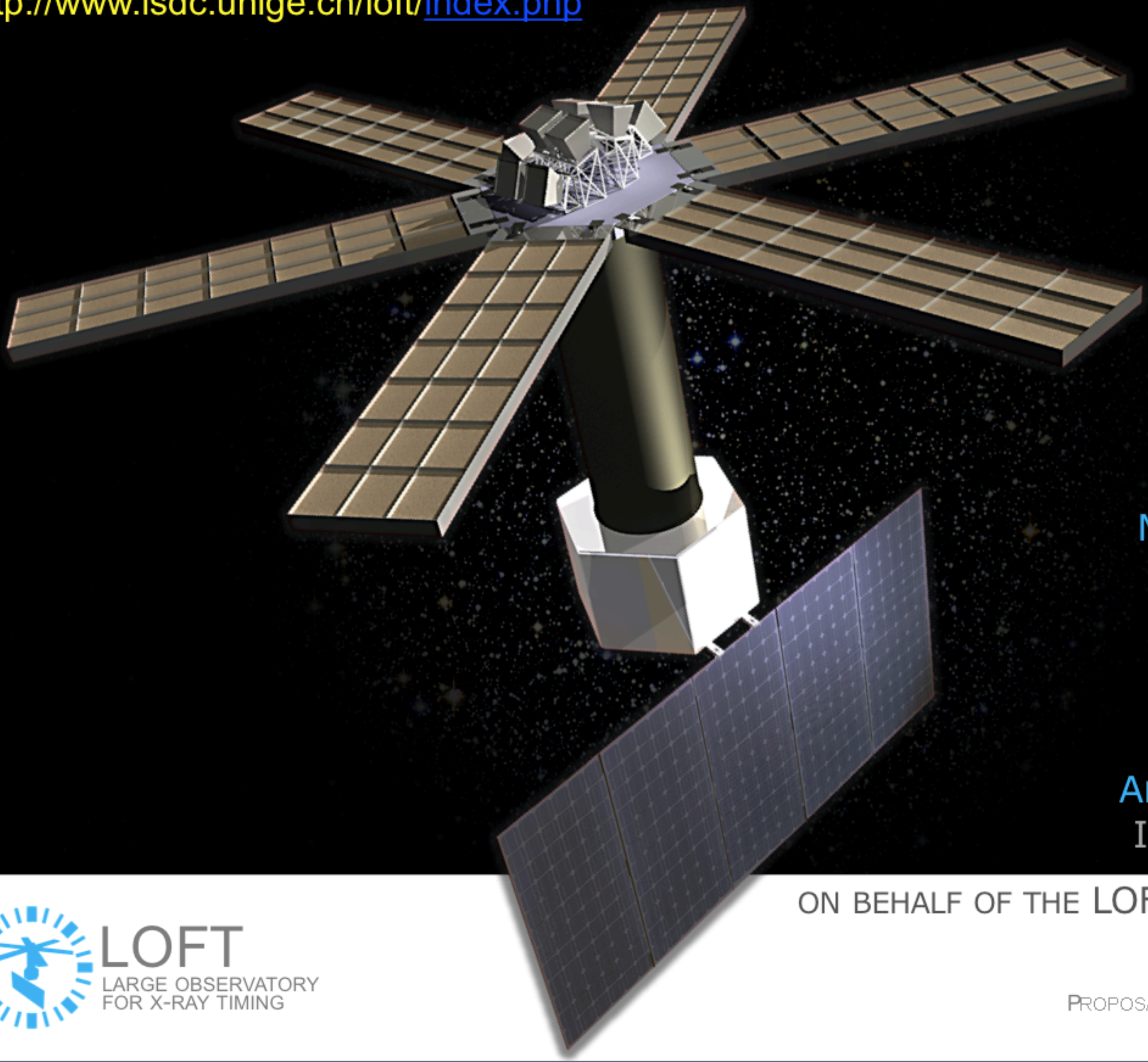
This allows a very-low noise contribution from the front-end electronics.

More than two order of magnitudes larger sensitive area than standard spectroscopic SDDs, this detector can open the way to application areas of the X-ray spectroscopy that require wide surface coverage.



LOFT concept

http://www.isdc.unige.ch/loft/index.php



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INAF, ROME

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INAF, ROME

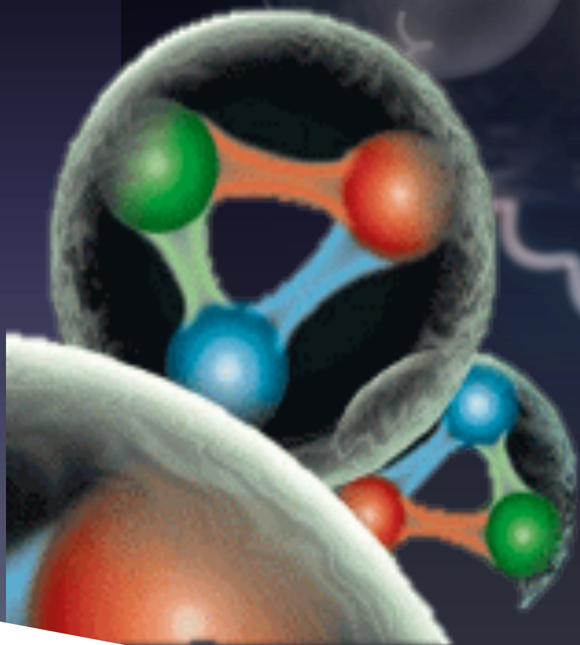
ANDREA VACCHI
INFN, TRIESTE

ON BEHALF OF THE LOFT CONSORTIUM

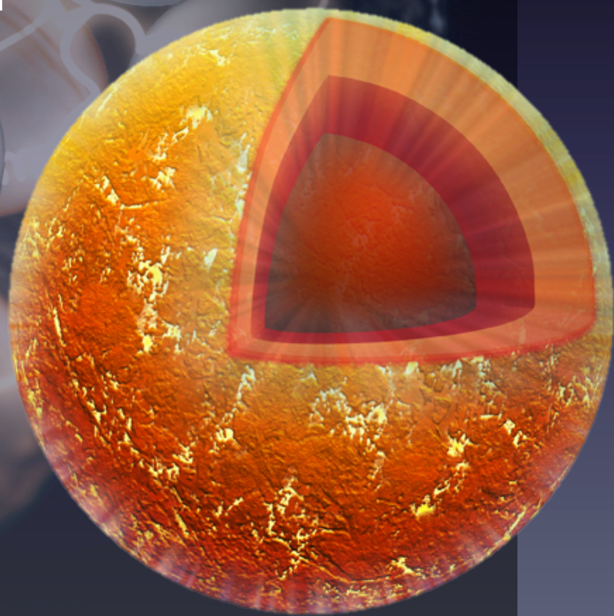
LOFT
LARGE OBSERVATORY FOR X-RAY TIMING

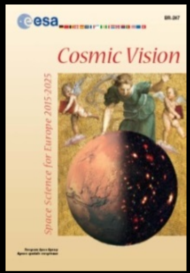
The strong force determines the state of nuclear matter - from atomic nuclei to neutron stars.

It is a major problem within modern physics.



PROGRESS IS DRIVEN BY **LABORATORY EXPERIMENT** AND **ASTROPHYSICAL OBSERVATION**.



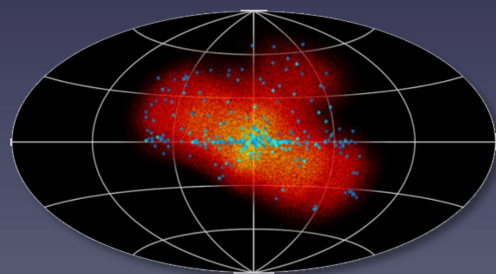


LOFT ADDRESSES THE COSMIC VISION THEME *"Matter Under Extreme Conditions"*

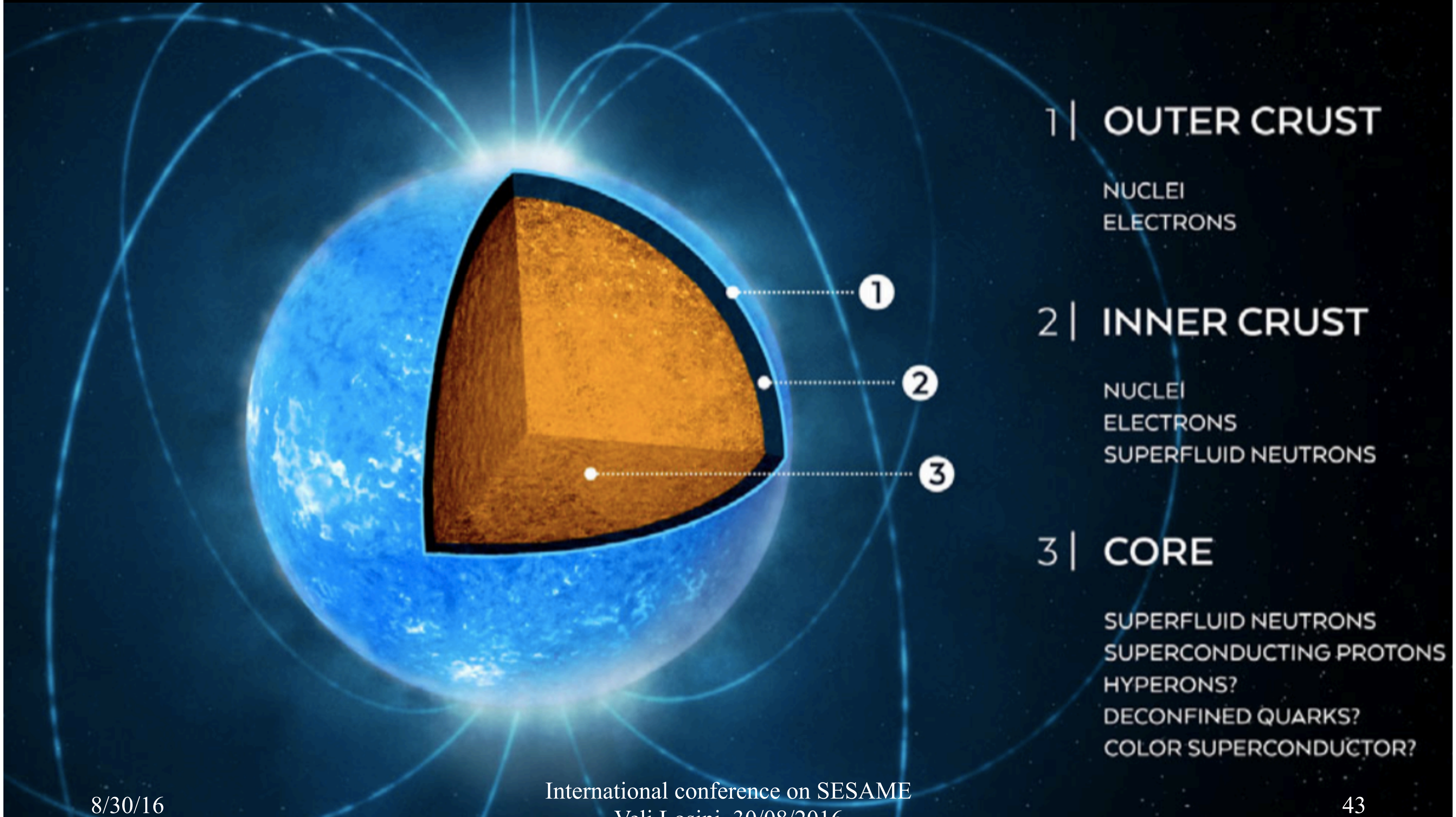
Probe the state of matter at supra nuclear densities in Neutron Stars ("**Dense Matter**")

Probe gravity theory in the very strong field environment of Black Holes ("**Strong Gravity**")

Probe physics of hundreds of galactic and bright extragalactic cosmic sources ("**Observatory Science**")

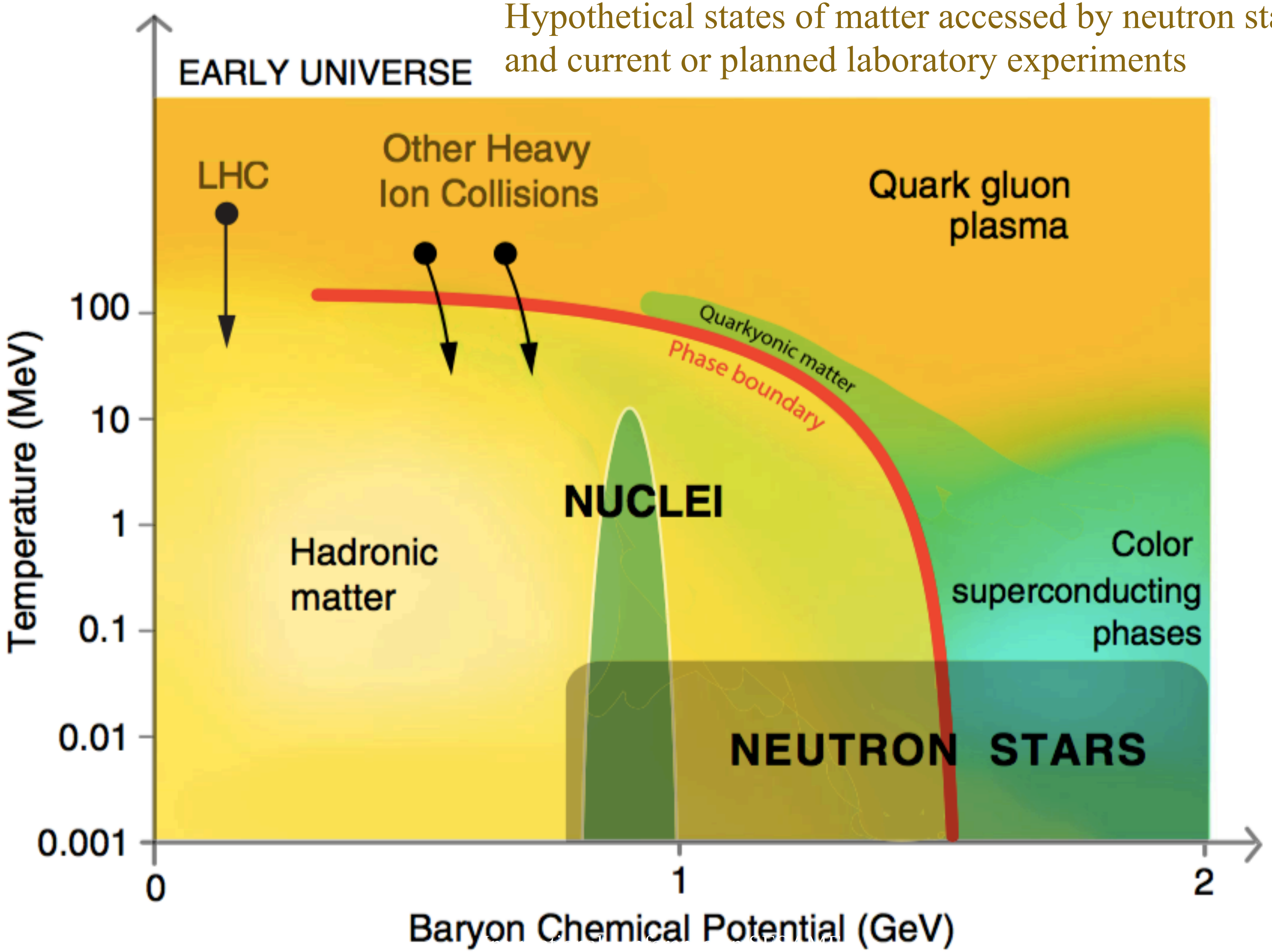


Measuring the neutron star equation of state using x-ray timing

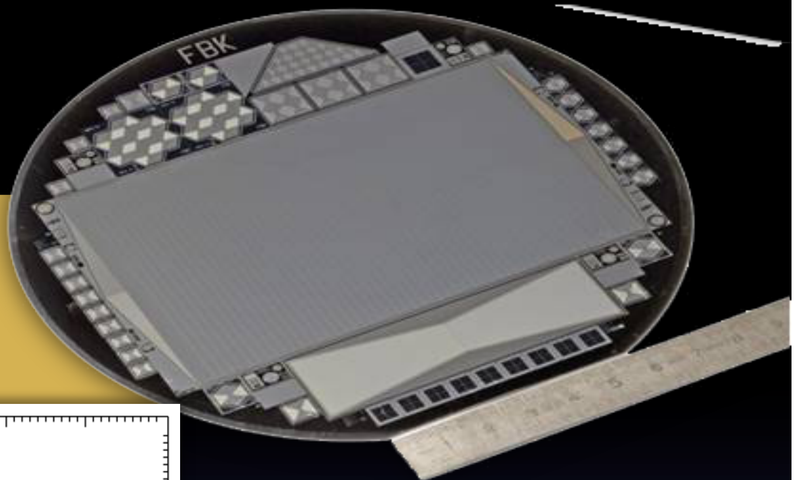


REVIEWS OF MODERN PHYSICS, VOLUME 88, APRIL–JUNE 2016

Hypothetical states of matter accessed by neutron stars and current or planned laboratory experiments

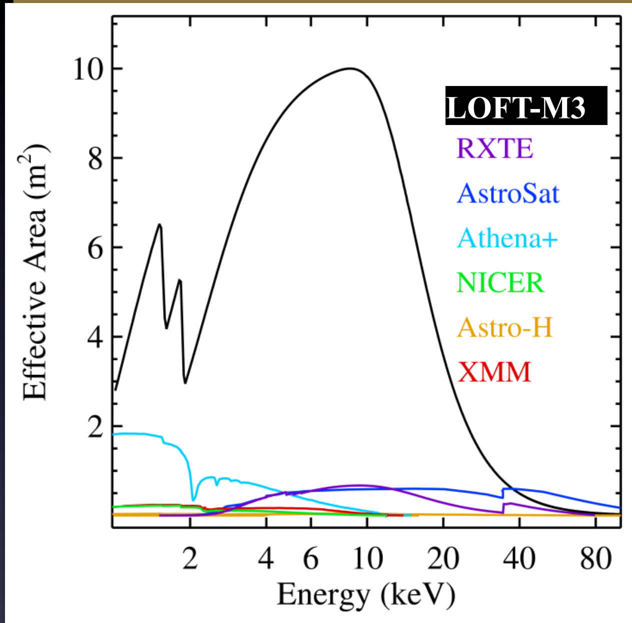


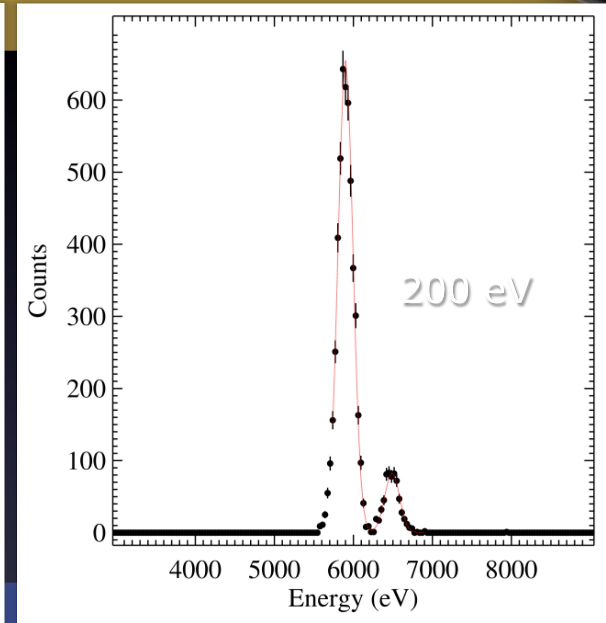
The LOFT Approach



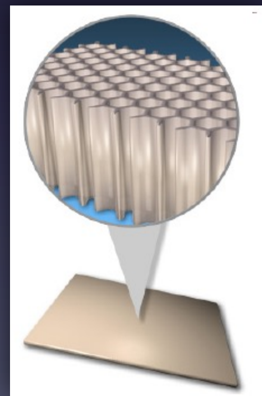
SDD Detectors Heritage

Large Collecting Area

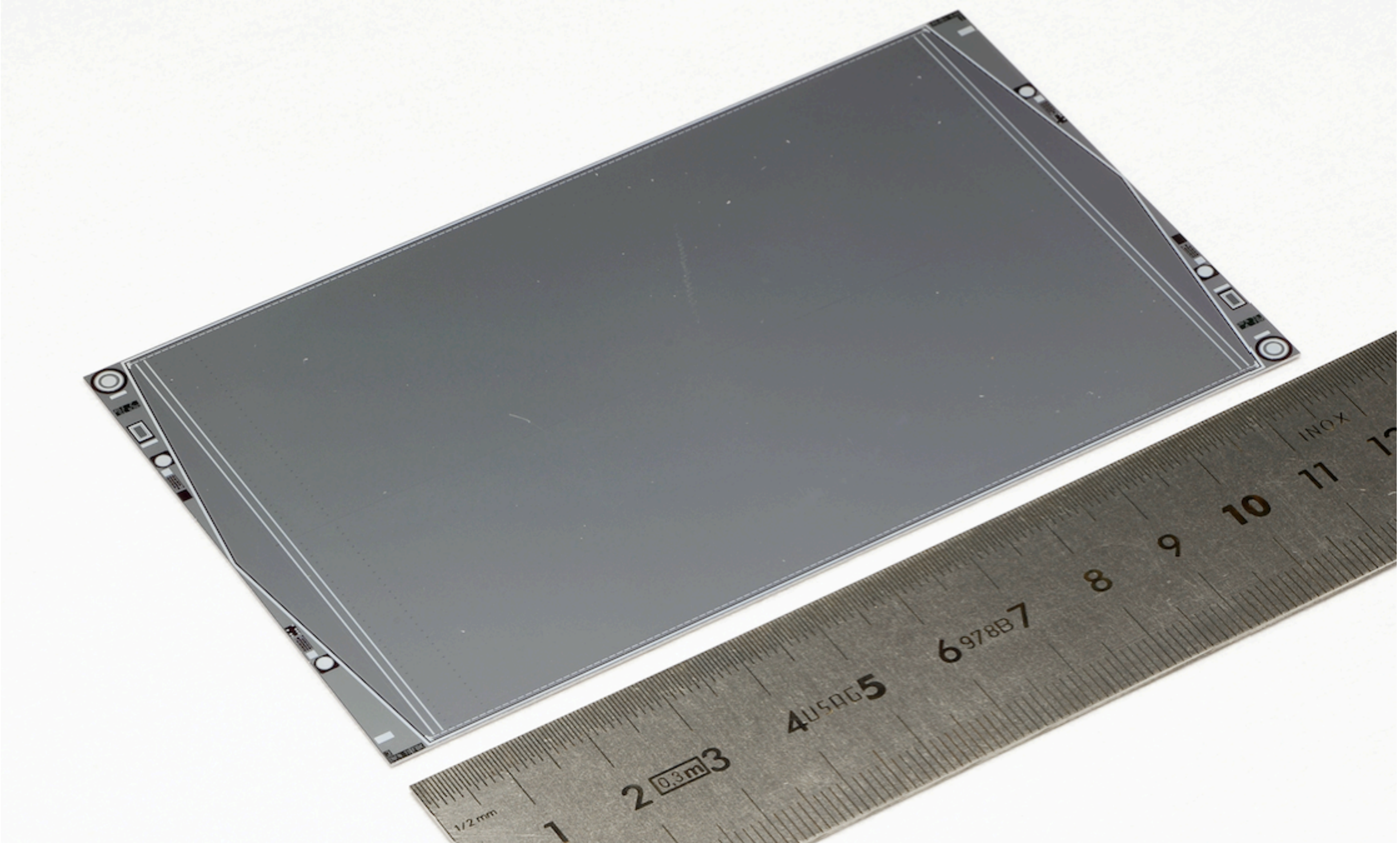


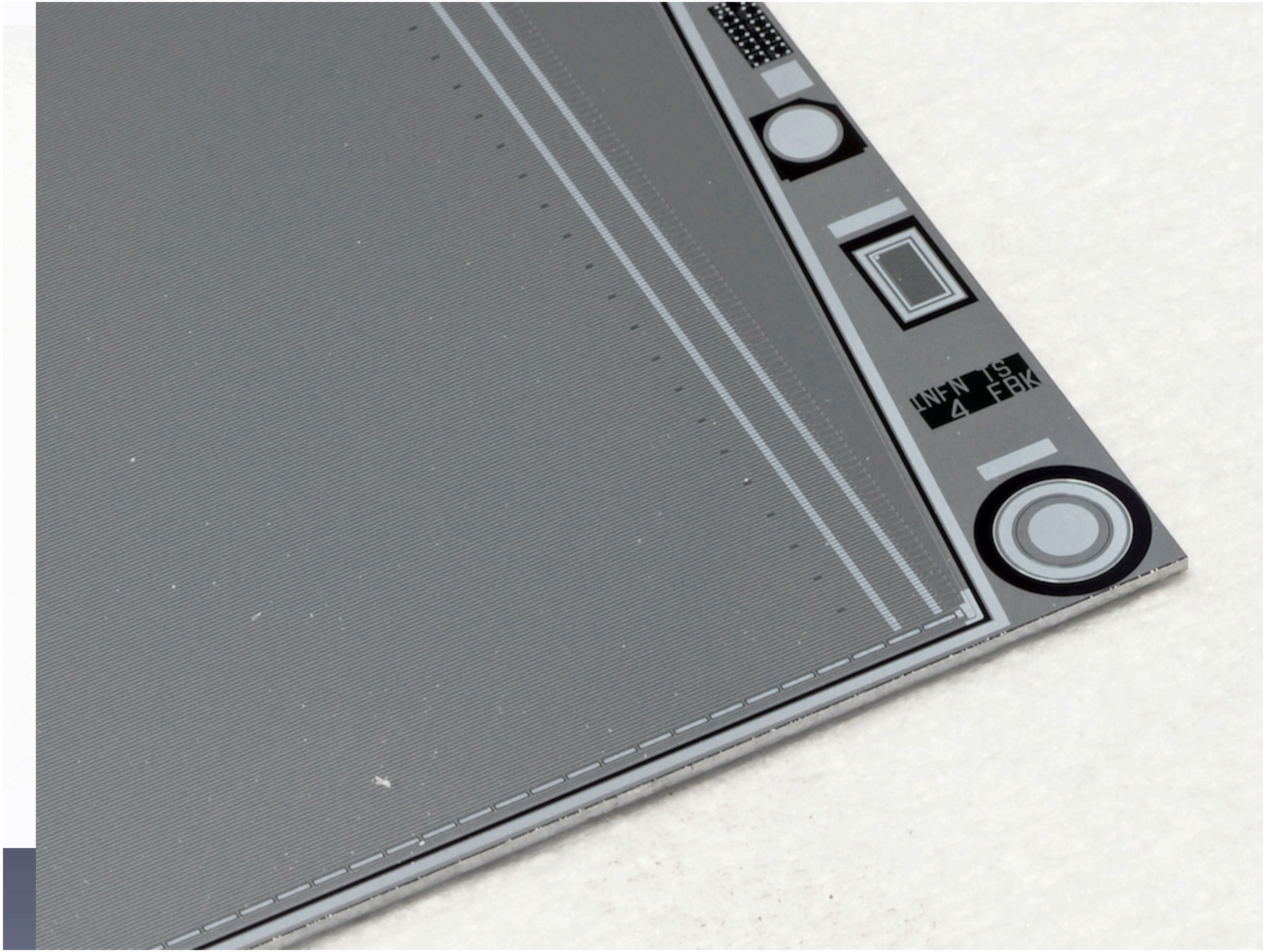


Good Energy Resolution (XMM-class)



Microchannel Plate Collimators

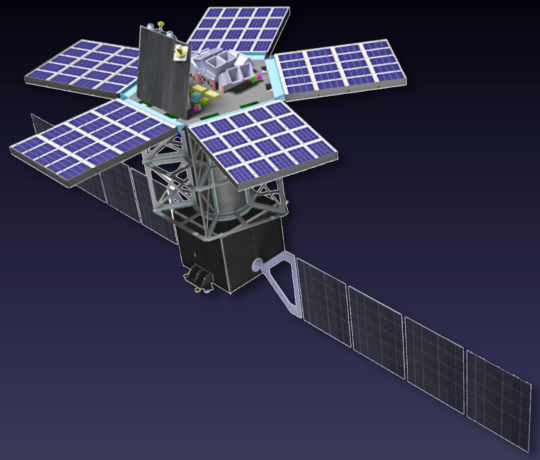

INOX
0,3m
1/2 mm


INFN TS
4 FBK

Three possible mission approaches

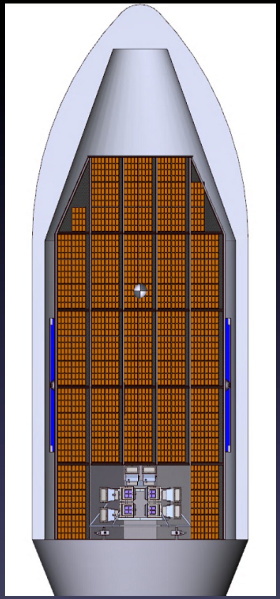
LOFT

Large Observatory For x-ray Timing (ESA)



LOFT-P

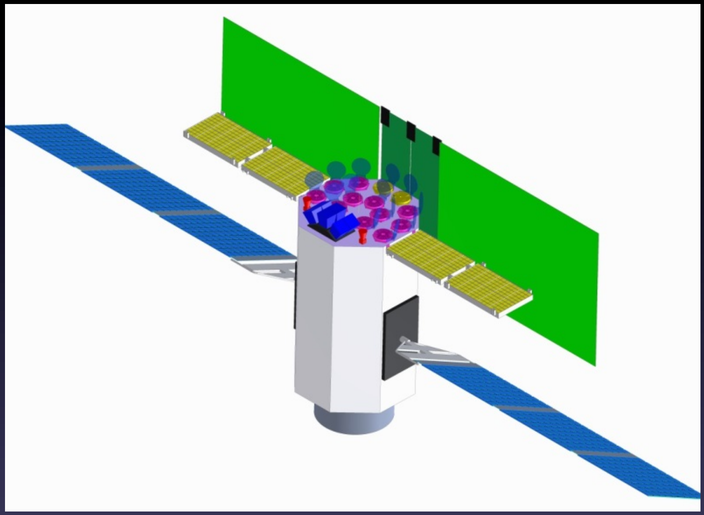
LOFT-Probe (NASA)



Bright sources: Large Collimated Area

eXTP

enhanced X-ray Timing and Polarization mission (CAS)

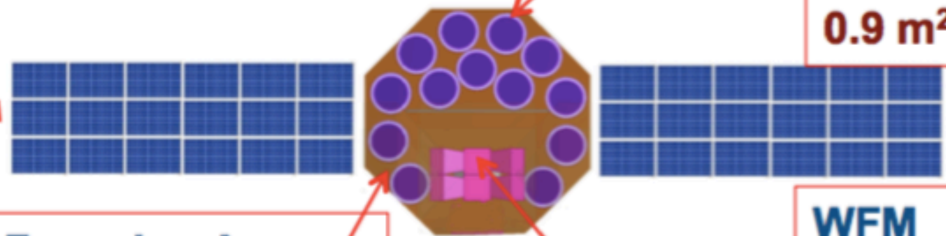


Weak/soft sources: Collimated Area + Telescopes. And Polarimeter

Payload

LAD
40 arrays SDD
Energy band：2-50 keV
Collimated FOV 1deg FWHM
Time resolution: 1us
Energy res.: 200eV@ 6keV
Sensitivity：0.01 uCrab（10^4s）
Effective area：3.4m^2@6keV

Soft Focusing Array
11 arrays: focal length 4.5m,
Diameter 450 mm, SDD
Energy band: 0.5-20 keV
FOV：12 arcmin
Time resolution：10 us
Energy res.: 180eV@6keV
Angular resolution: 1 arcmin
Sensitivity：0.16uCrab（10^4s）
Effective area: 6500cm^2@6keV
0.9 m^2 between 1-2 keV



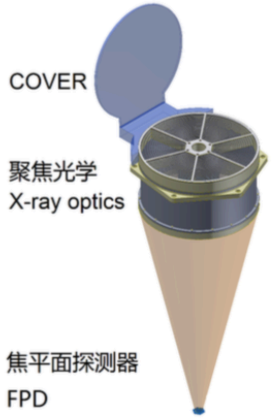
Polarimetry Focusing Array
2 arrays focal length 4.5 m,
diameter 450 mm
Energy band: 2-10 keV
FOV:12 arcmin
Time resolution: 500us
Energy res: 1.8keV@6keV
Angular resolution：15 arcsec
Sensitivity：5 uCrab（10^4s）
Effective area：250cm^2@2keV

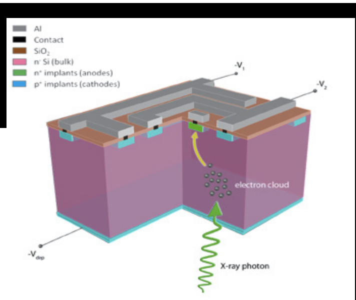
WFM
3 arrays，SDD
Energy band：2-50 keV
FOV：1.33PI
Time resolution：2 us
Energy resolution：
300eV@6keV
Angular resolution：4.5 arcmin
Sensitivity：3uCrab（2x104s）
Effective area：170cm^2@6keV

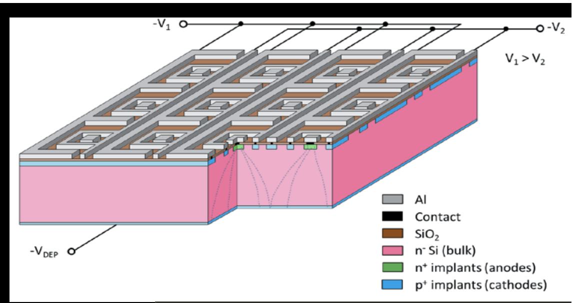
Pixel SDD

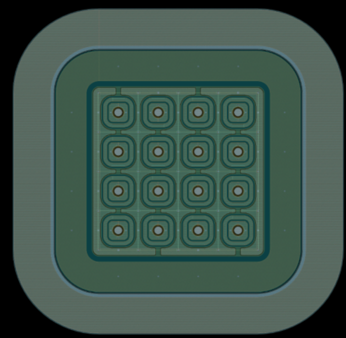
- SFA for spectroscopic and timing measurement with imaging capability.

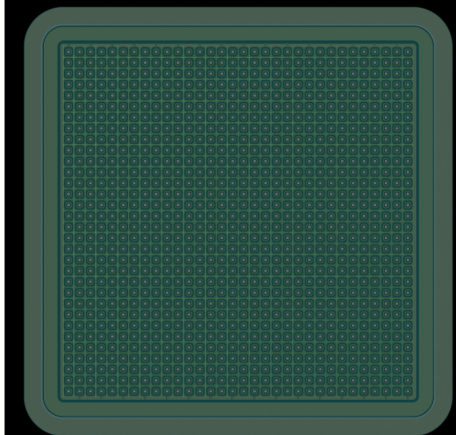
Focal length	4.5 m
Area	>500 cm^2 @ 6 keV, 1 module >6000 cm^2 @ 2-6 keV, in total
Energy range	0.5~20 keV
Field of View	+/-6 arcmin
Angular res.	HEW≤1’, W90≤3’
Energy res.	<180eV@6keV
Timing res.	10 us





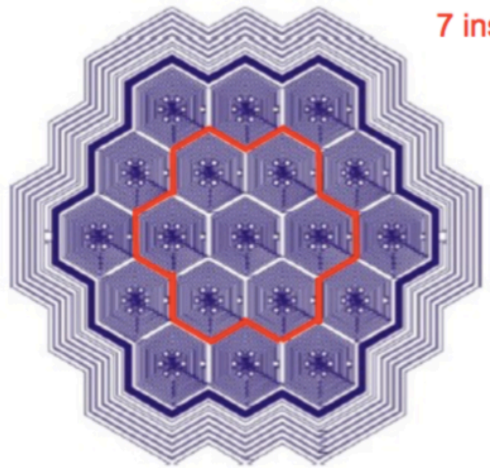




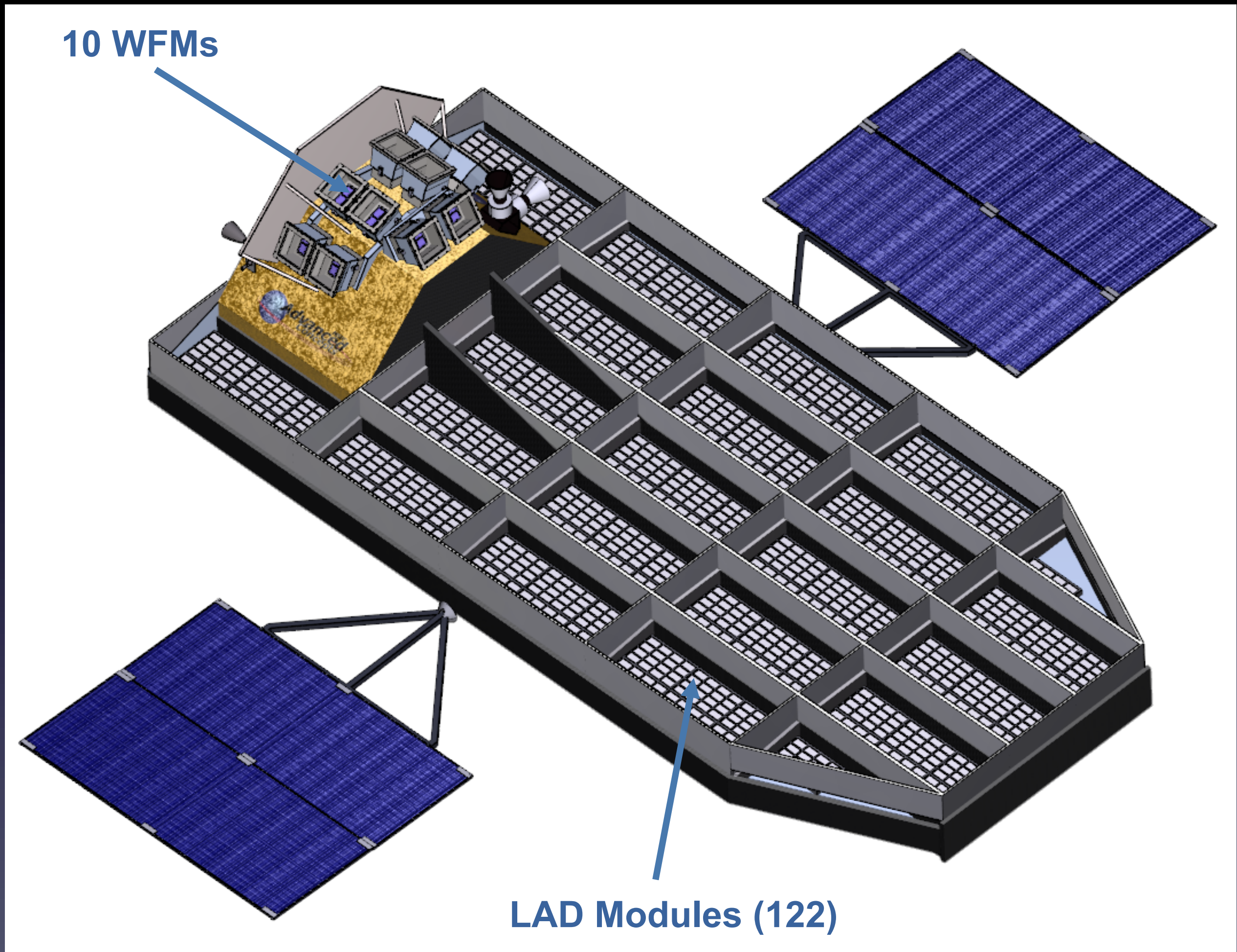


- The baseline for the SFA focal plane detector (FPD) is a 7 pixels SDD. The pixel size shall not exceed 3’.
- It is agreed that the baseline FEE is based on discrete components.

7 instead of 19 pixels

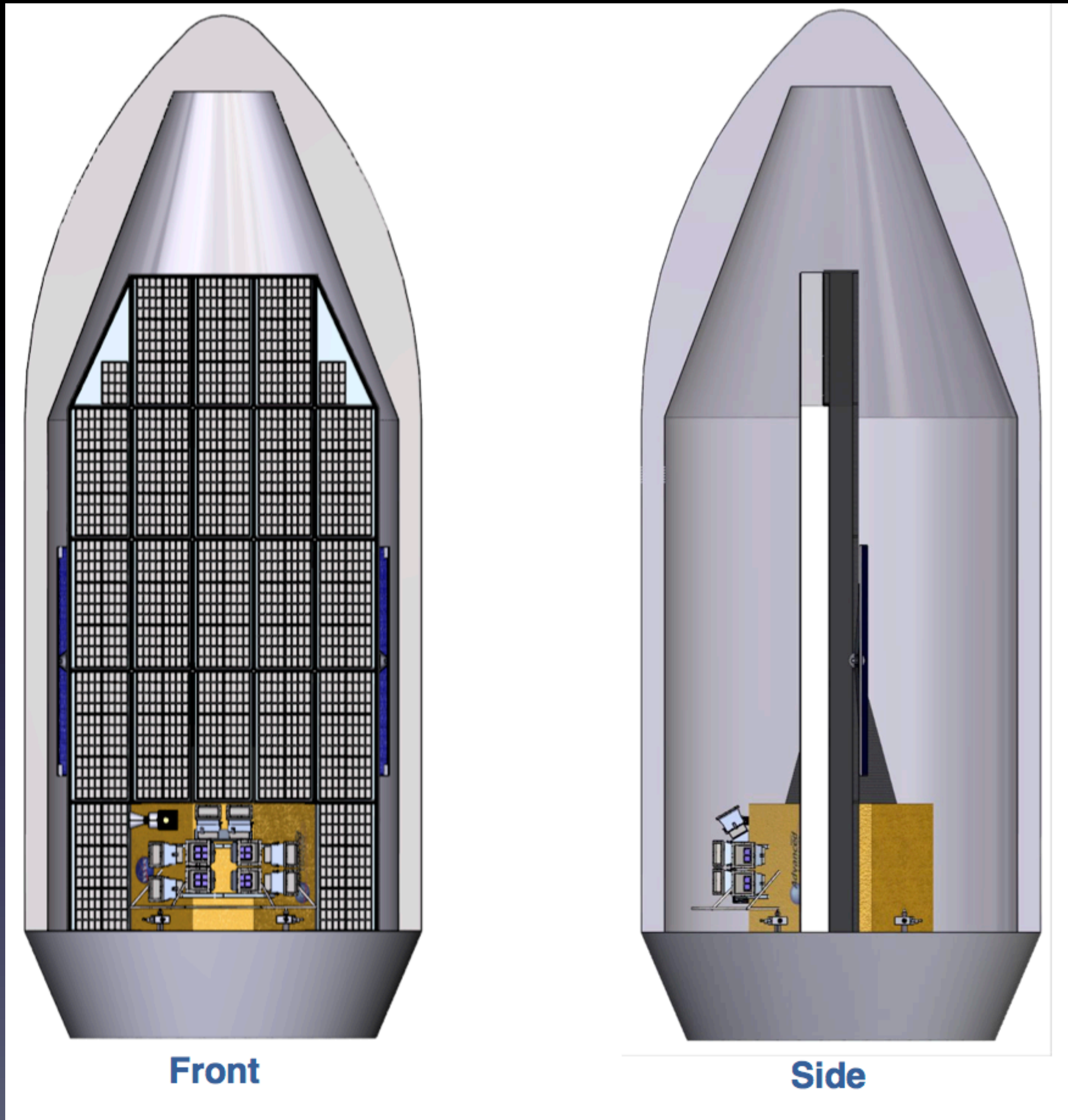


LOFT-P



Credits: NASA/MSFC and ACO

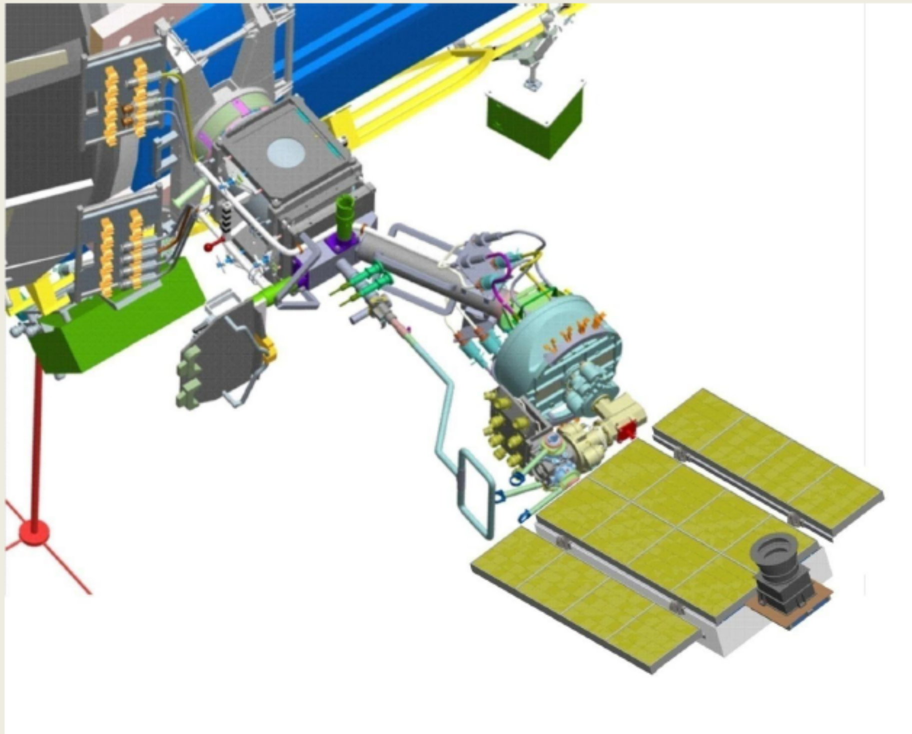
LOFT-P



LOFT-pathfinder

1-m^2 experiment on ISS (Russian segment) to be launched in 2020

Rotary pointing system on the Russian segment of the ISS



At the moment the Canadian telescopes successively operates eXTP

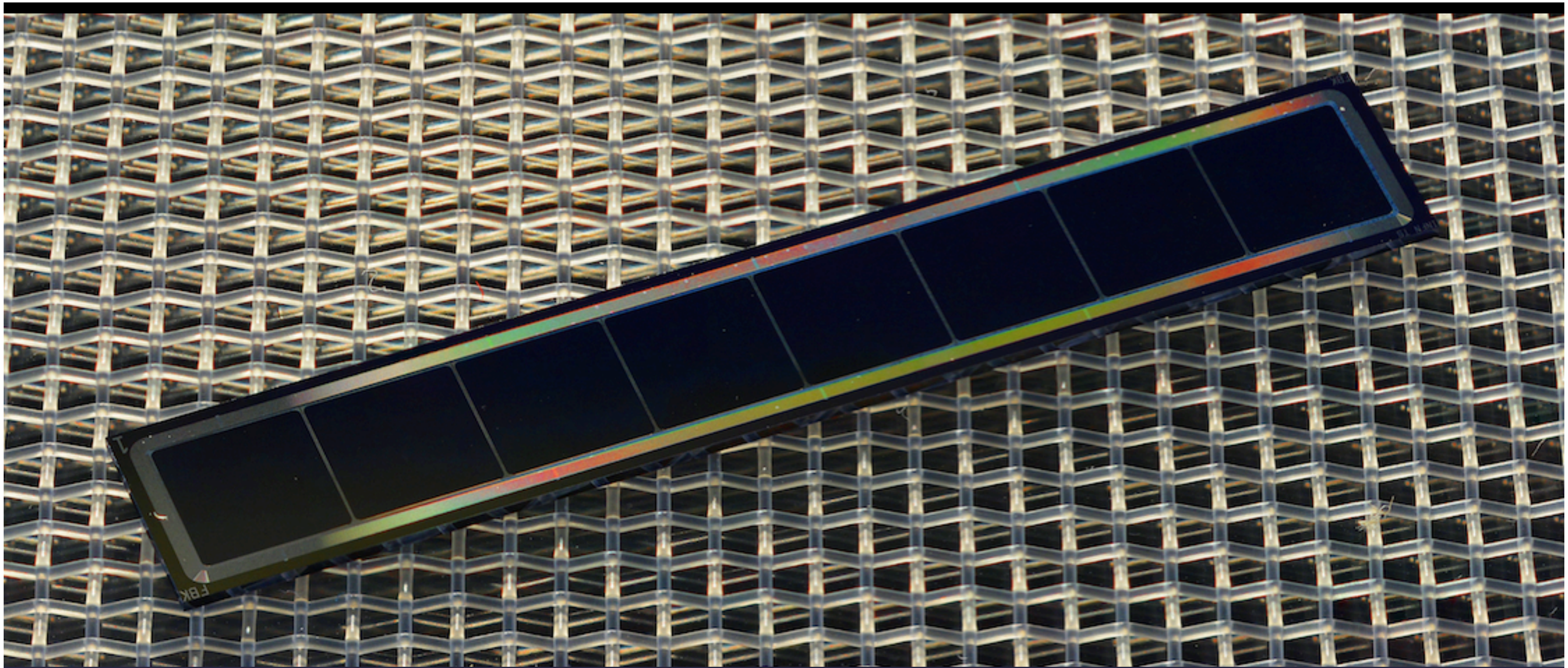
- Pre-selected in China, currently in phase 0/A. Possible selection in 2016 or 2017, for a launch in 2024-2025. Participation of the whole LOFT consortium + INAF/OAB + MPE.

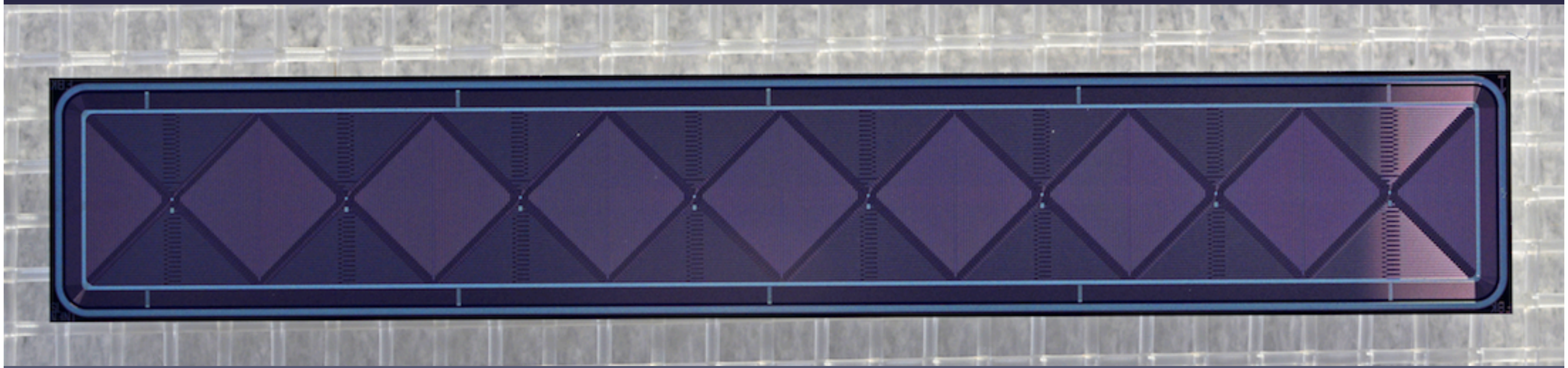
LOFT-P

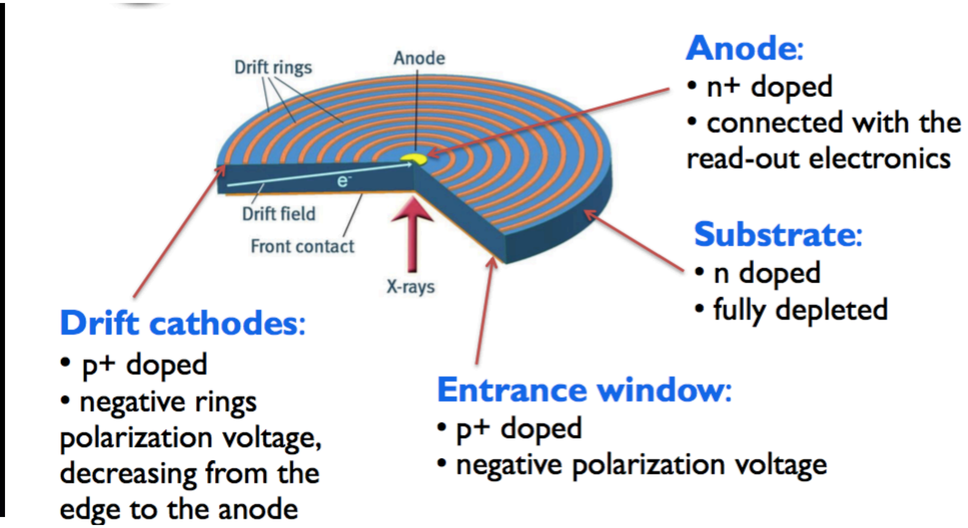
- Preparation activities for the Decadal Survey 2020. NASA/ MSFC-funded mission study currently ongoing. Probe-class. Possible notional mission call end-2016/early-2017. Real mission call early-2020's. Launch in late-2020's.

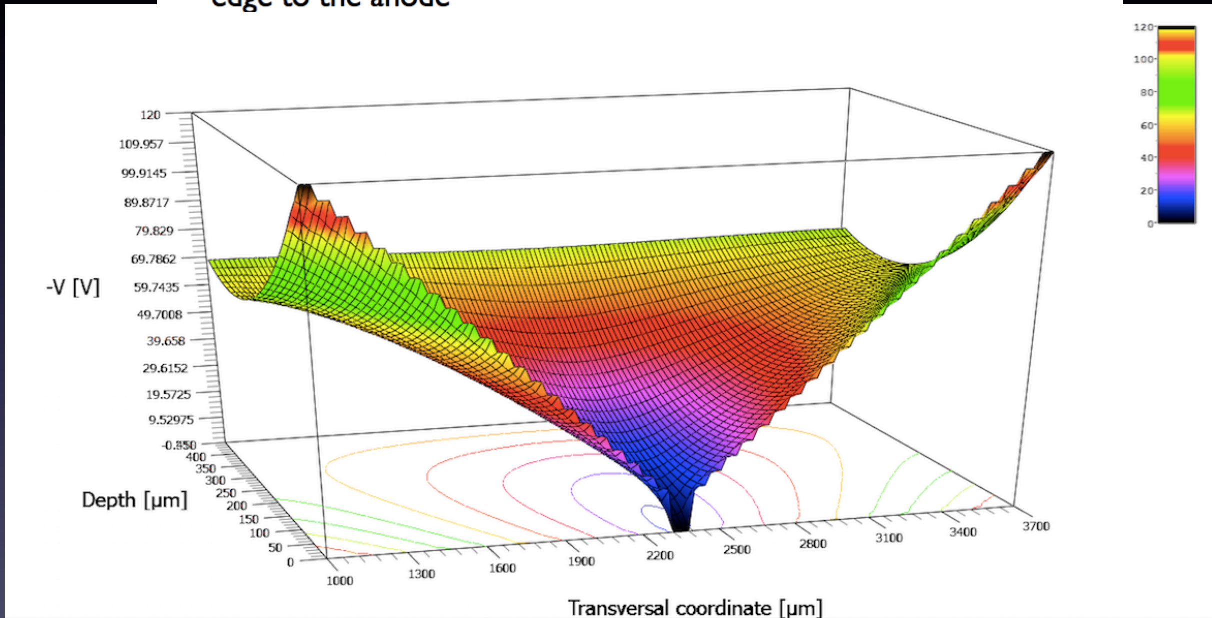
MVN-M2 on ISS

- Experiment led by IKI (Academy of Sciences, Moscow). PI: M. Pavlinski. ROSCOMOS industrial partner: Energya. Approved and funded in Russia. Phase 0/A/B1: Jan 2016 – Nov 2017. Launch end-2020.

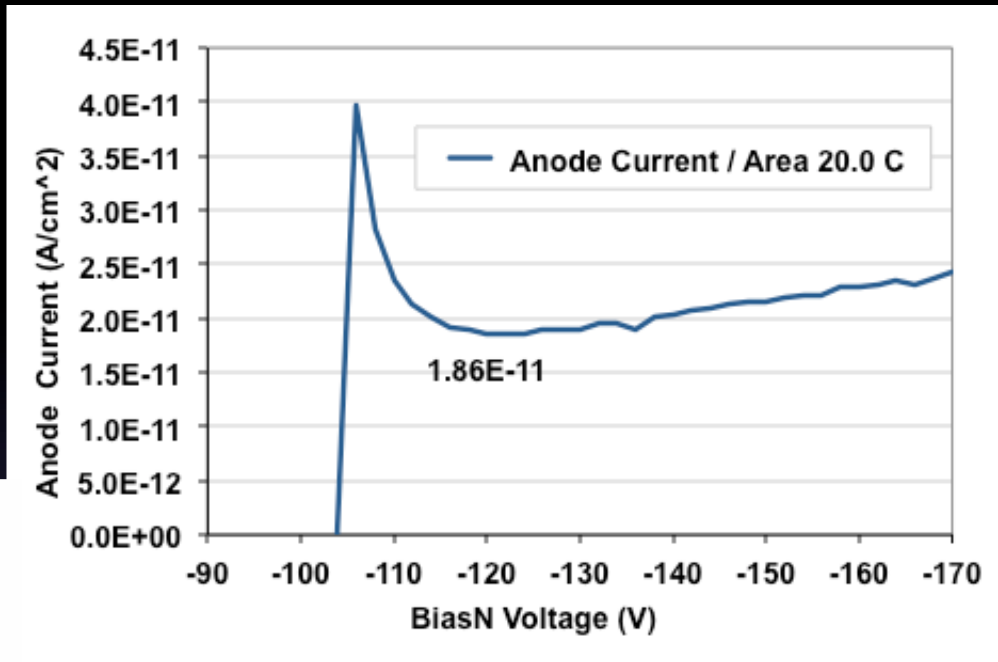


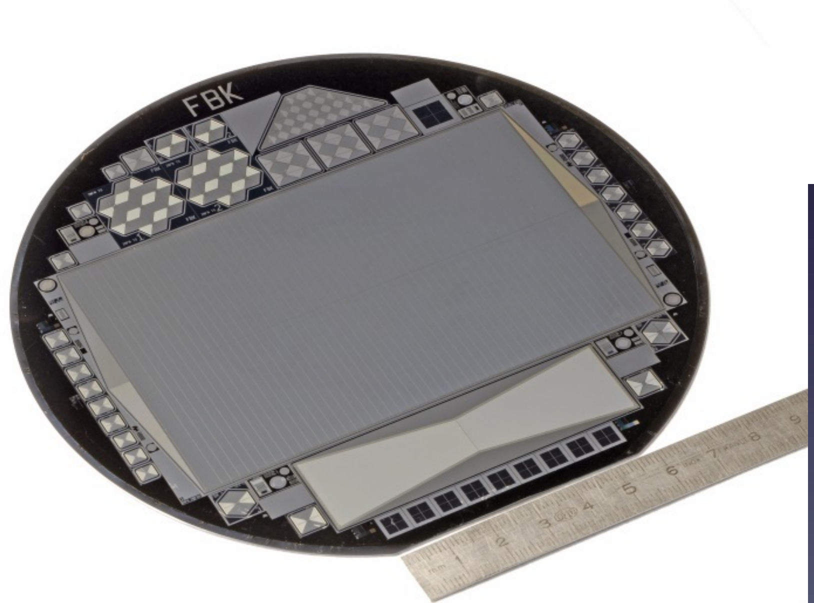



Drift rings
Anode
e-
Drift field
Front contact
X-rays
Anode:
• n+ doped
• connected with the read-out electronics
Substrate:
• n doped
• fully depleted
Drift cathodes:
• p+ doped
• negative rings polarization voltage, decreasing from the edge to the anode
Entrance window:
• p+ doped
• negative polarization voltage


-V [V]
Depth [μm]
Transversal coordinate [μm]

FBK Trento Low leakage current





The SDD, with an active area of 13 mm, has been manufactured by optimizing the production processes in order to reduce the anode current, successfully reaching leakage current densities between 19 pA/cm and 25 pA/cm at 20 C.

TABLE I
X-RAY SDD PERFORMANCE AT ROOM TEMPERATURE

Reference	year	Detector area (mm^2)	Temperature (°C)	5.9 keV ^{55}Fe FWHM (eV)	ENC (e- r.m.s.)	Peaking time (µs)
This work	2015	13	+20	136	7.4	1.4
[8]	2014	13	+21	141	8.6	0.8
[9]	2012	25	+25	260	27	0.1
[10]	2001	10	+25	300	--	--
[11]	1996	3.5	+27	220	21	0.5
[12]	1994	2	+24	(374)	41	--
[13]	1994	1.5	+20	327	--	7
[13]	1994	0.5	+20	267	--	7
[14]	1992	78	R.T.	940	110	0.25

room temperature state of the art, our collaboration

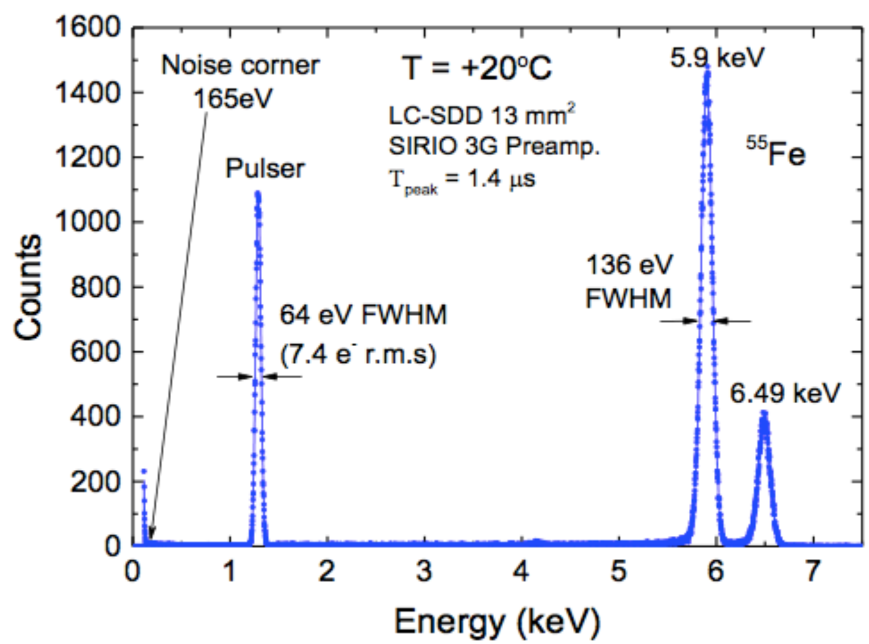


Figure 6 ^{55}Fe acquired at +20°C amd optimum peaking time (1.4 µs). The pulser line width is 64 eV FWHM, corresponding to 7.4 electrons r.m.s..

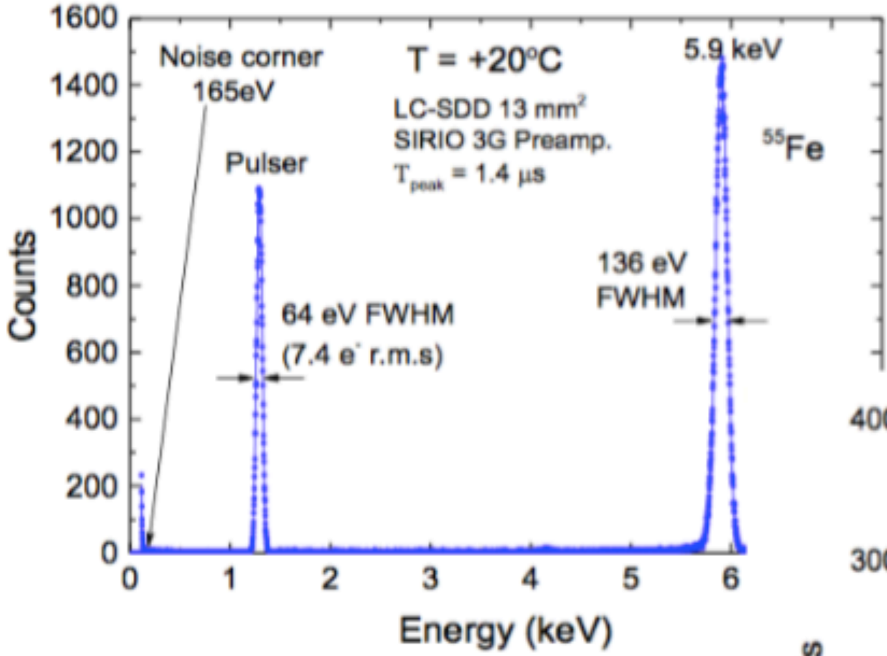


Figure 6 ^{55}Fe acquired at +20°C amd optimum peaking ti
The pulser line width is 64 eV FWHM, corresponding to 7
r.m.s..

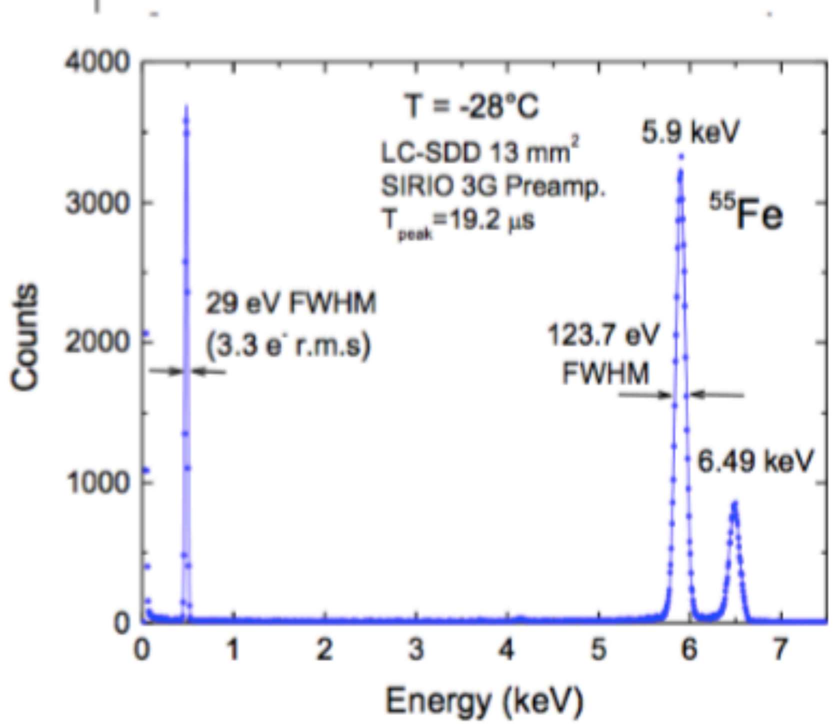
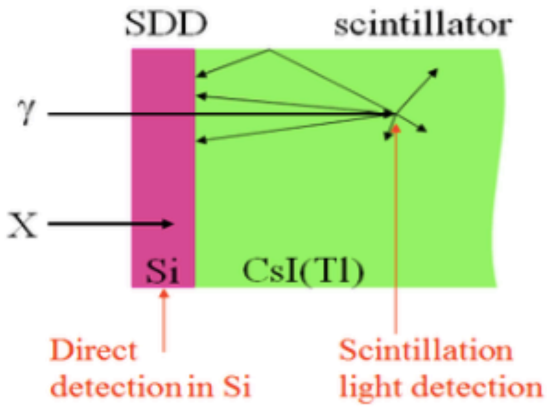
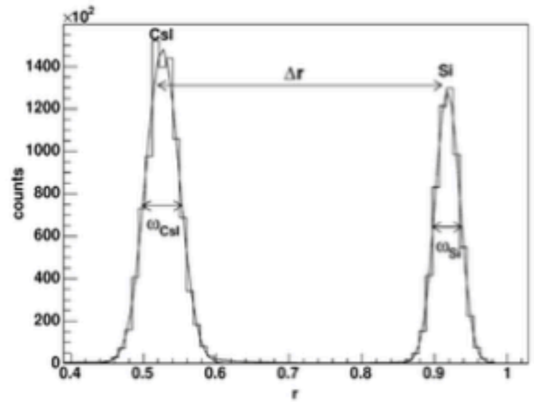


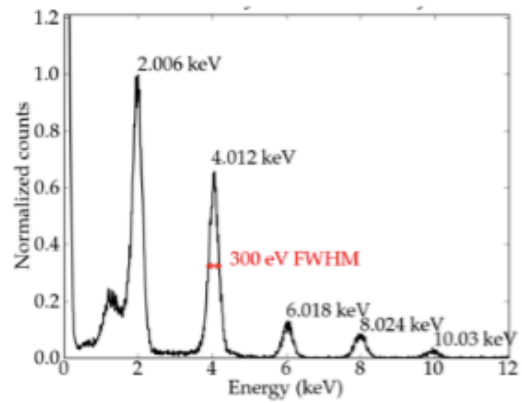
Figure 7. ^{55}Fe acquired at -28°C and optimum peaking time (19.2 µs)..
The pulser line width is 29 eV FWHM, corresponding to 3.3 electrons
r.m.s..

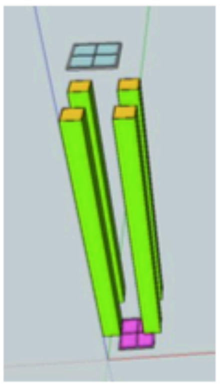
5/10/16 41

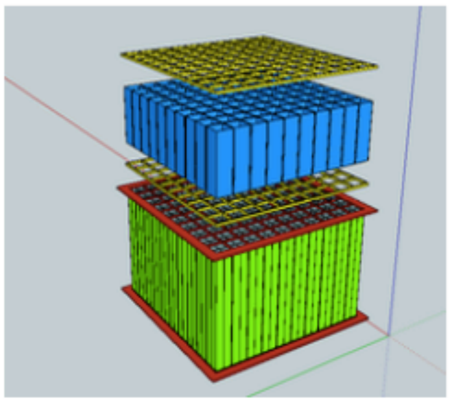
The X-Gamma-rays spectrometer (XGS)



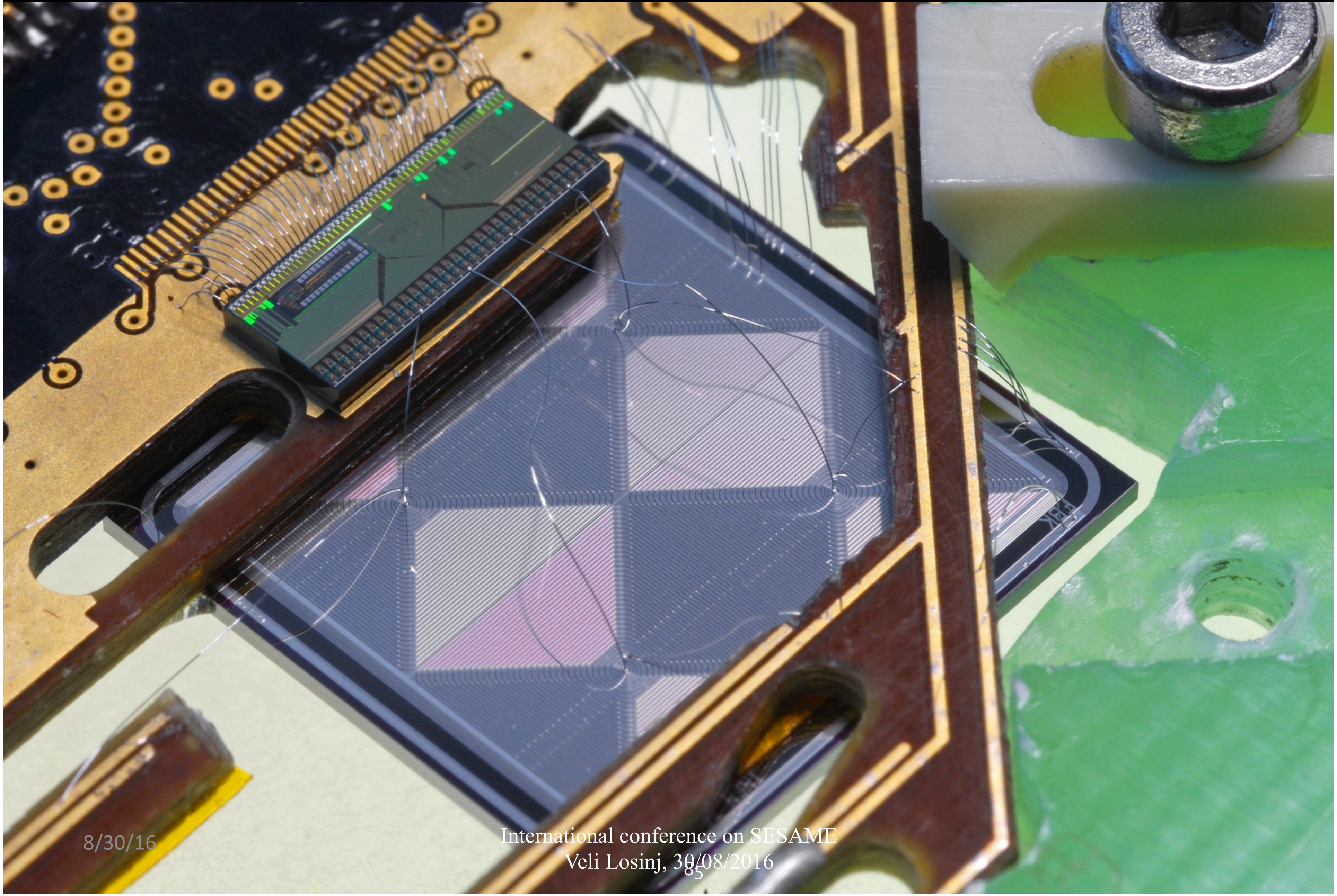




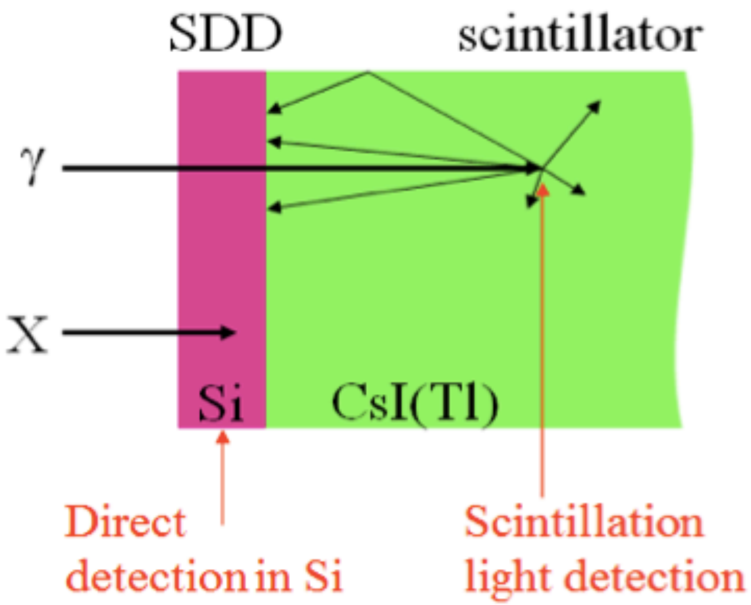


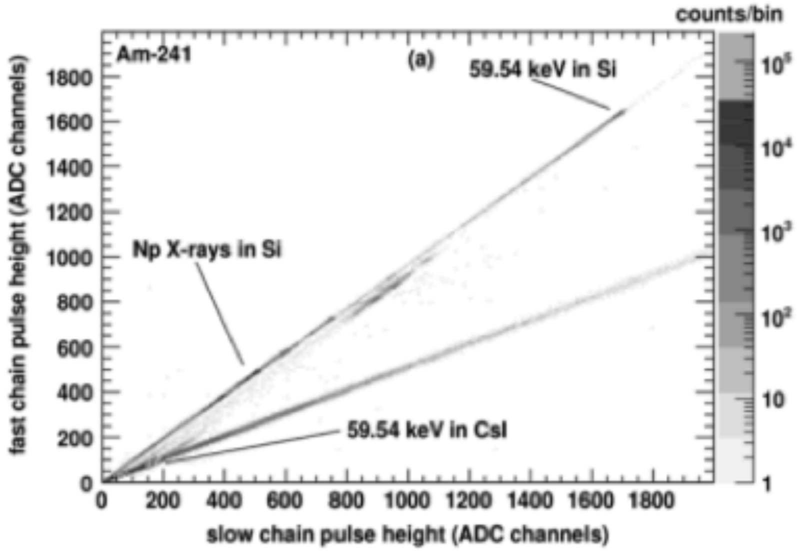


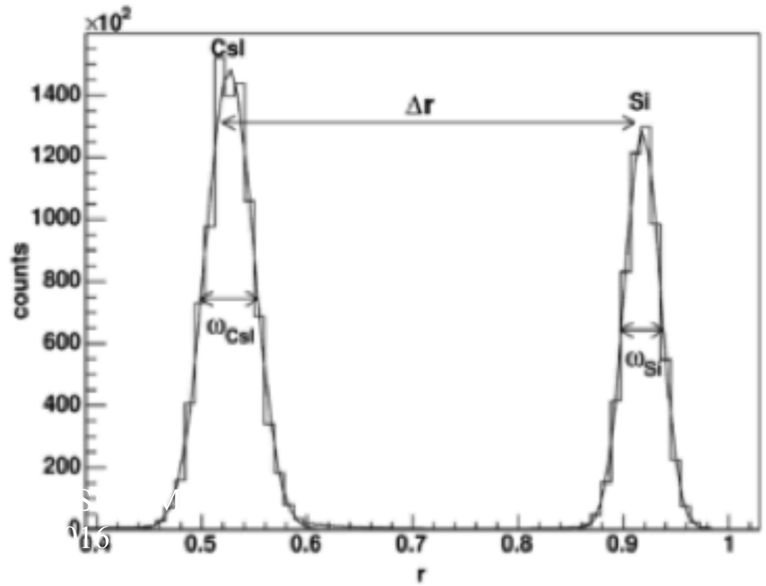
Energy band (keV)	2-20000
Detection principle	Siswitch
Low-energy detector	Silicon Drift Detector
High energy detector	CsI(Tl)
Separation of energy losses in Si and CsI(Tl)	Pulse shape analysis
Number of modules	25
Size of each module (mm^3)	130x130x100
Lateral passive shielding/module	0.5 mm W
Slat collimator/module	0.5 mm W
Overall collimator FOV (FWHM)	
Average useful area in the SXI FOV (cm^2)	~2000

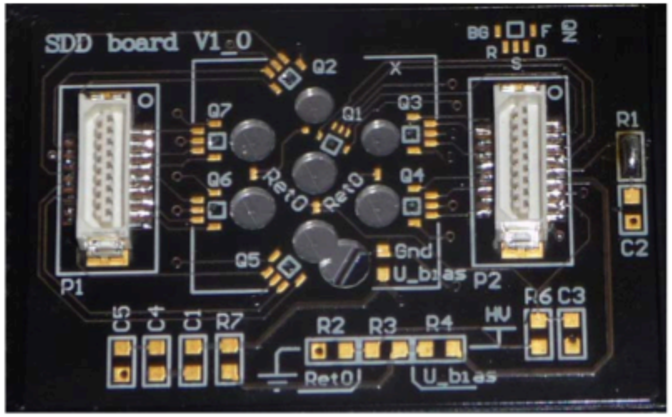


XGS – X and Gamma-ray Spectrometer detection principle



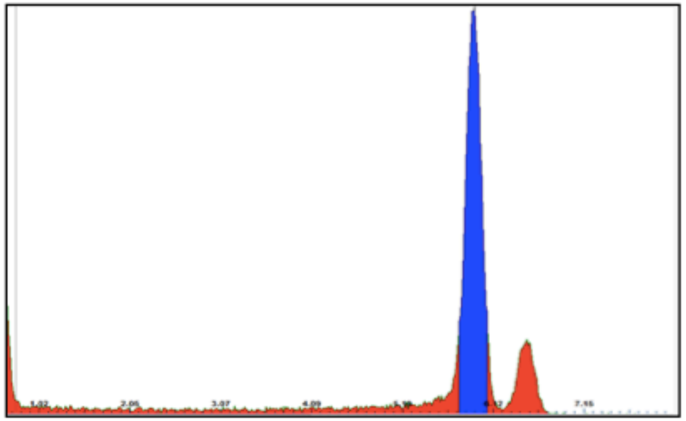


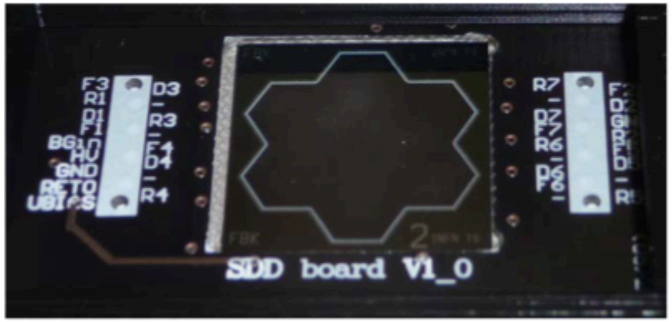




SDD only
Fe55
@253K

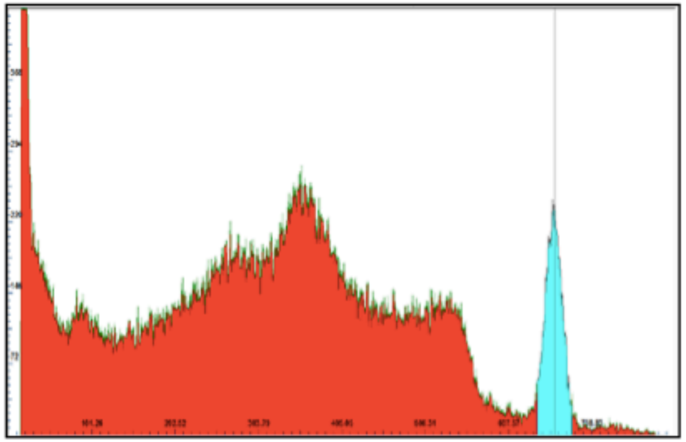
170 eV

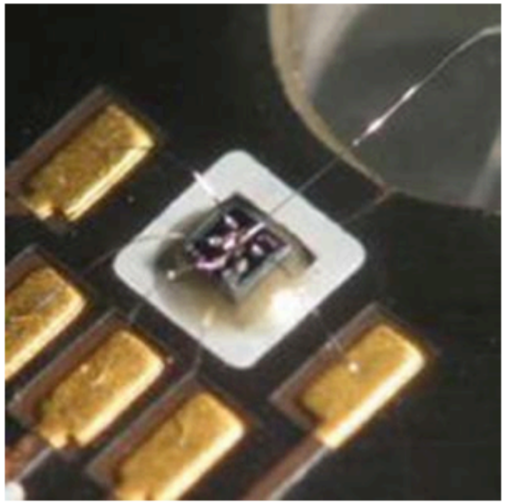


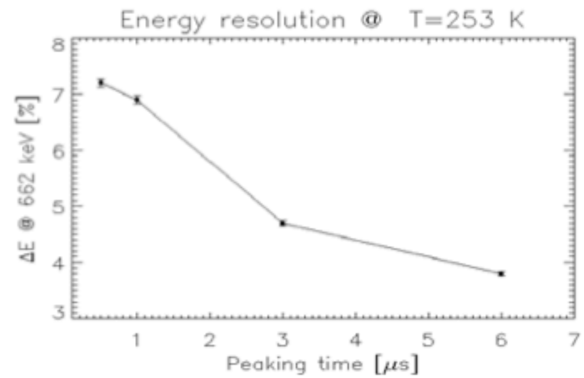


SDD+CsI
Cs137
@253K

3.8%

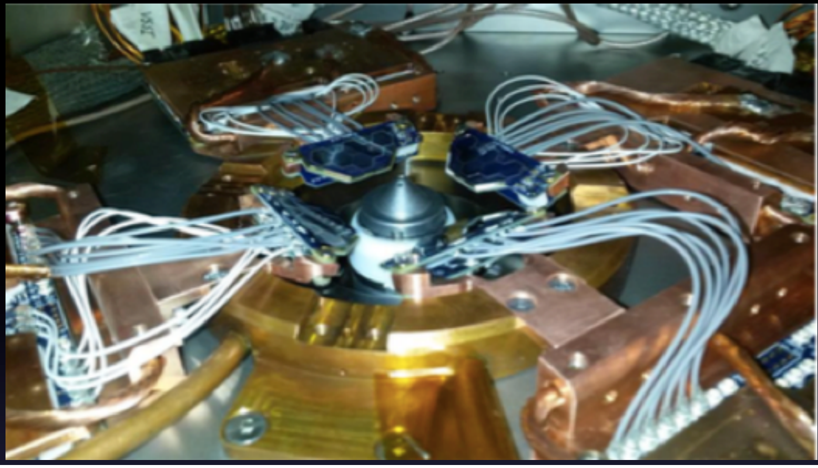


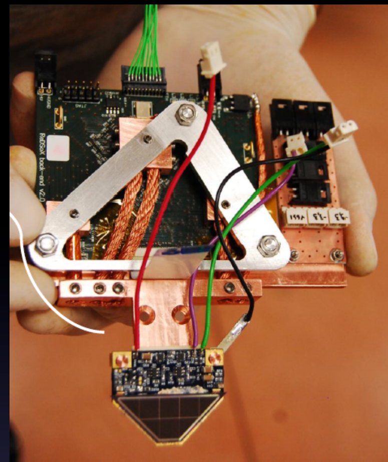


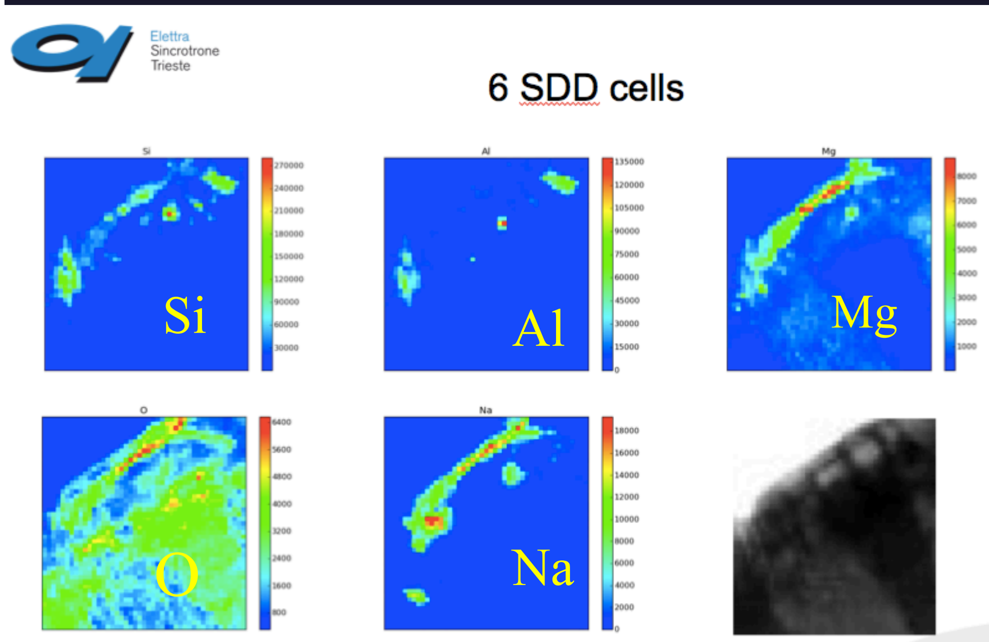


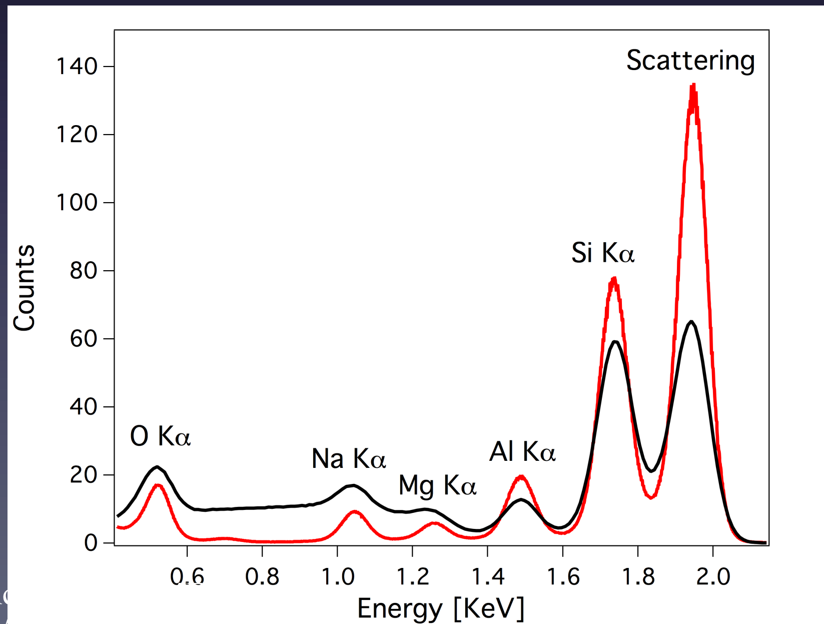
0.4 0.5 0.6 0.7 0.8 0.9 1
r

TwimMic (Elettra) beam line
maps of a soybean root section acquired with the new detector system, realized within the REDSOX collaboratio



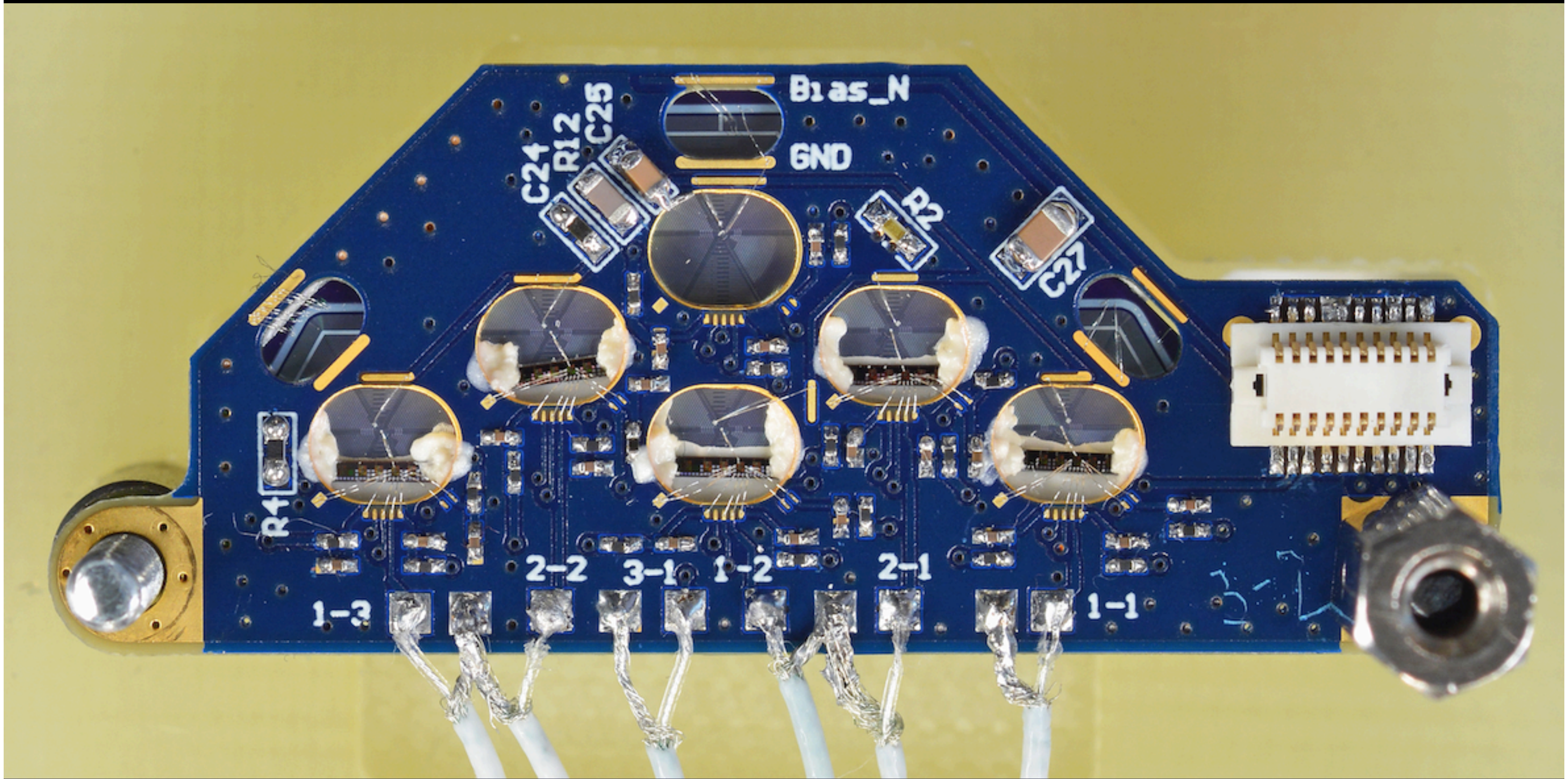


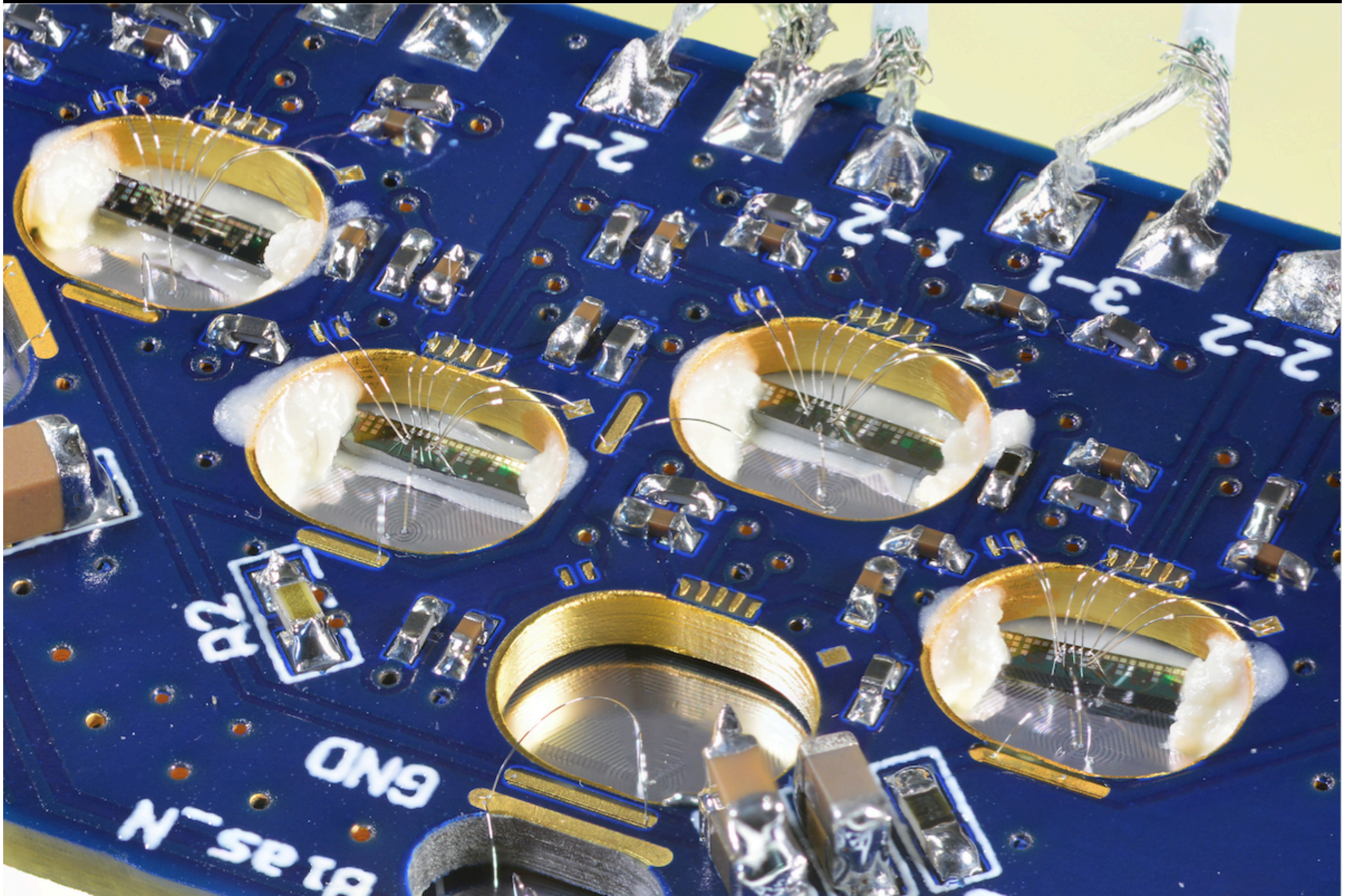




Al-Mg-Si-O-Na spectrum of a soybean root section acquired with the new TwinMic detector system.


INFN TS
FBK
C19
DT
Rs
RT
C18
FBK
INFN TS
2


Bias_N
GND
C24
R12
C25
R2
C27
R4
2-2
3-1
1-2
2-1
1-3
1-1


2-1
1-2
3-1
2-2
R2
GND

Bruxelles, 30th May, 2016

For the International Center for Synchrotron-light for Experimental Science and Applications in the Middle East

Khaled Toukan

Prof. Khaled Toukan,
Director

For Istituto Nazionale di Fisica Nucleare

Prof. Fernando Ferroni
President

ISTITUTO NAZIONALE FISICA NUCLEARE
PRESIDENTE
INFN

Our INFN collaboration specialized in the development of state of the art Silicon Drift Detectors will carry out the work for SESAME

Outline

1) front edge unique results

2) working principle

3) SESAME detector

INFN Trieste

FBK Trento

Elettra Sincrotrone Trieste

INAF IASF INFN Roma 2

INFN INAF Bologna

INFN Pavia

INFN TIFPA Trento

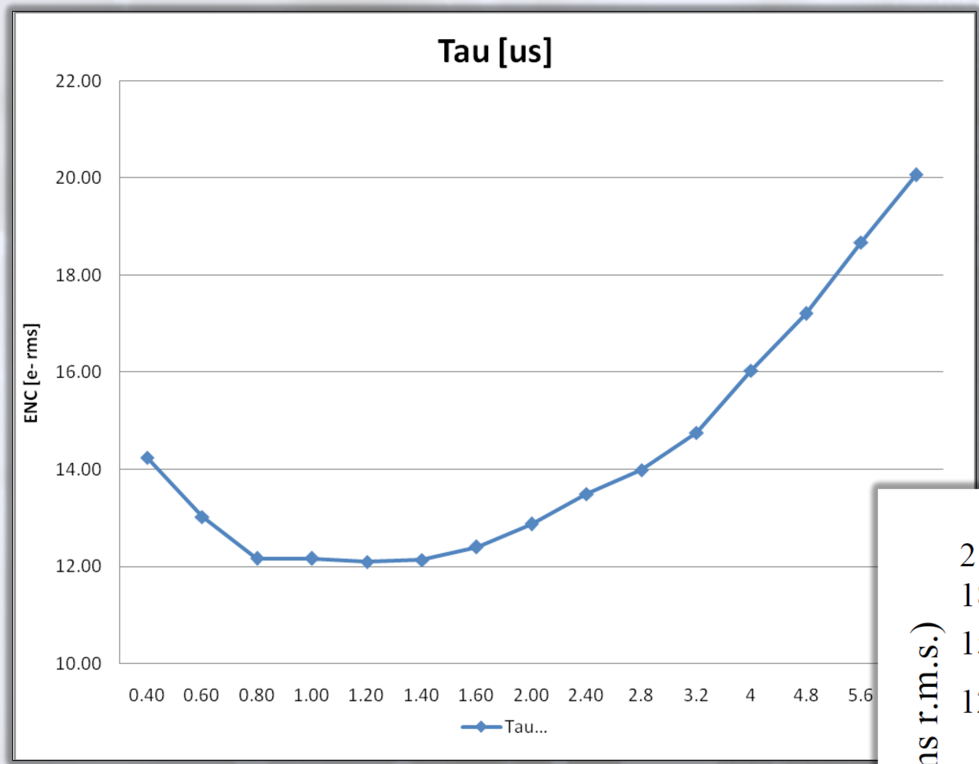
ICTP Mlab Trieste

INFN Firenze Labec

Poli Milano El.&Det.

INFN Istituto Nazionale di Fisica Nucleare

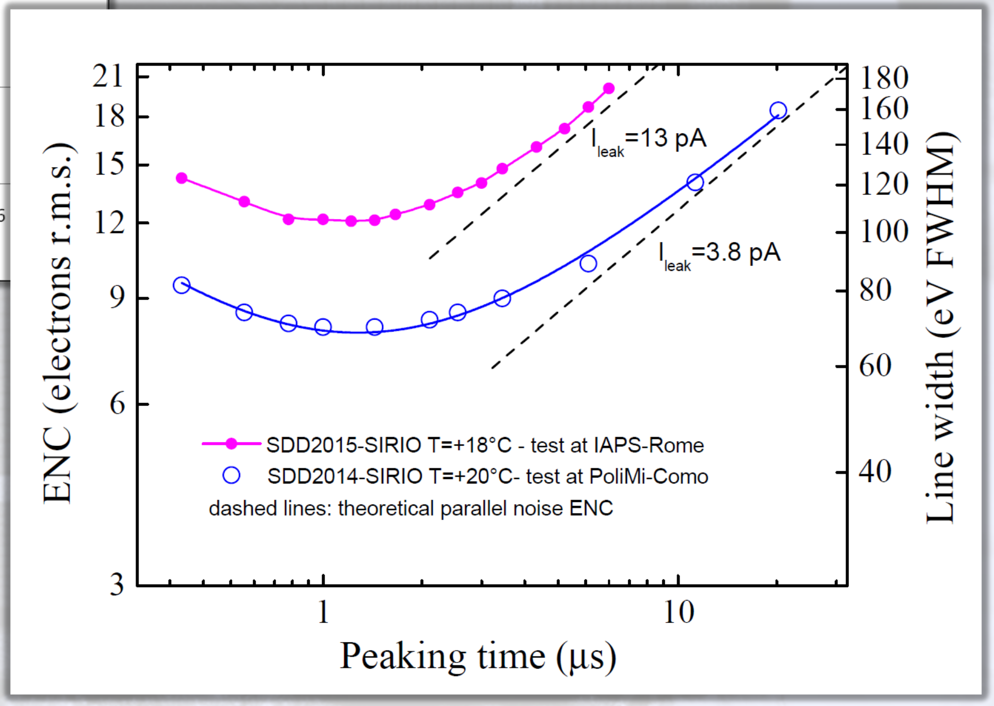
The new detectors for XAFS beamlines



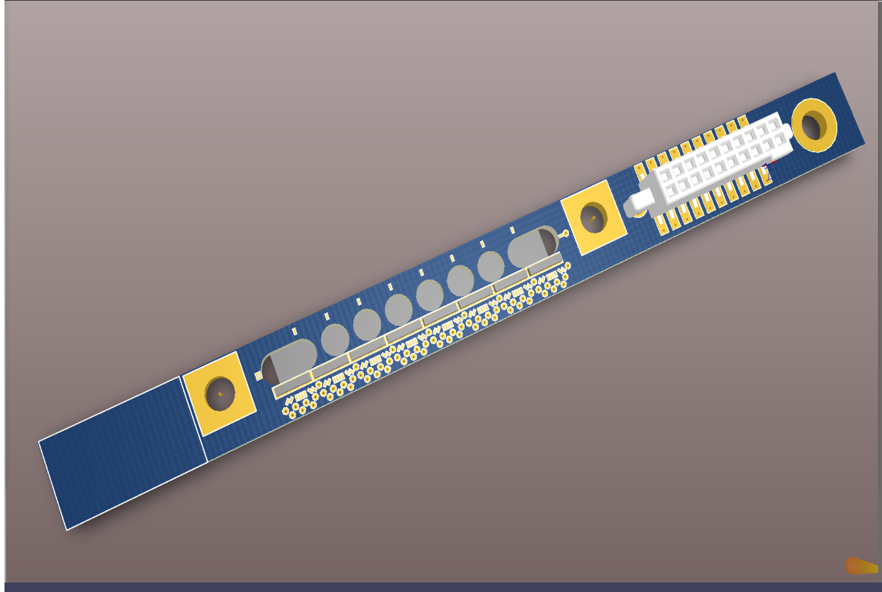
ENC vs τ @ 18° C

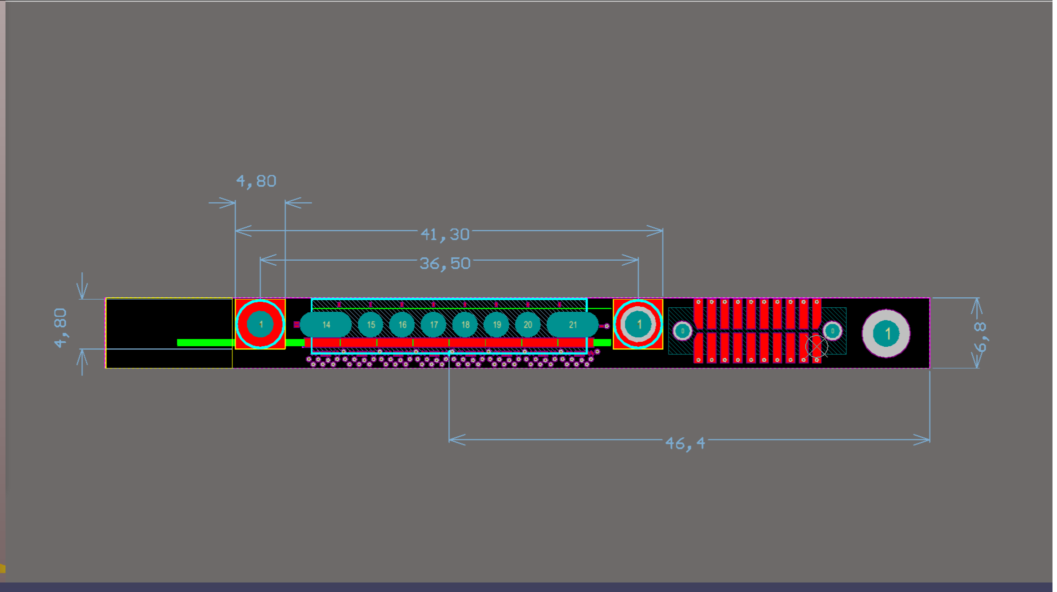
Trapezoidal shaping (flat-top 200ns)

Pulse amplitude 4.98 keV (eq.).



Prototype – 2 : work in progress

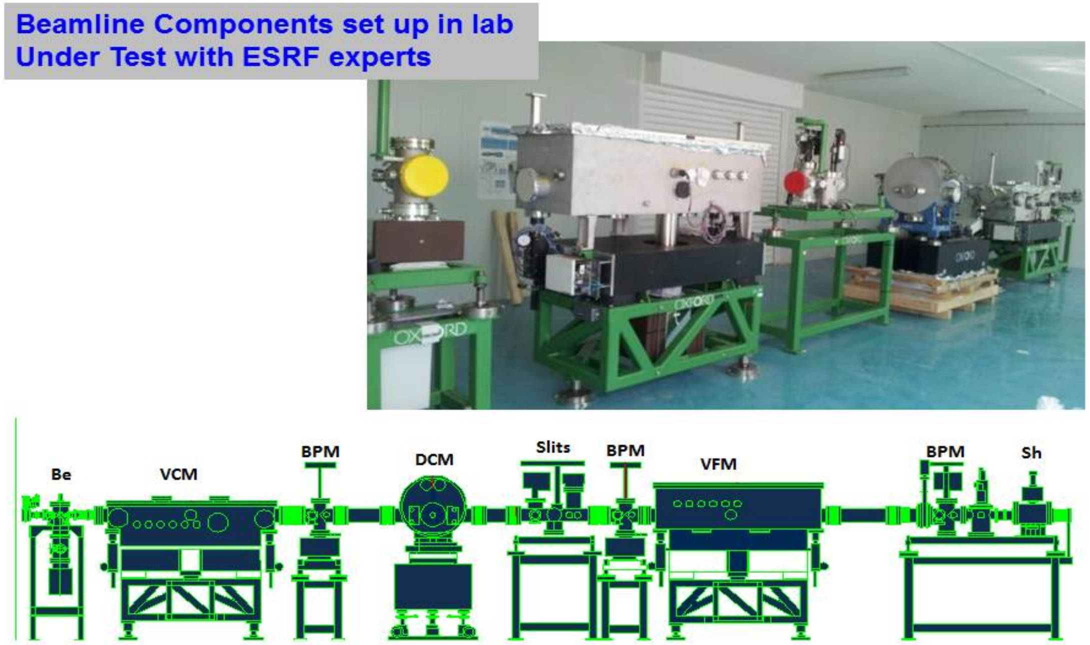




- Tungsten collimator 100 micron thick

SESAME

XAFS-Beamline (ROBL-ESRF)



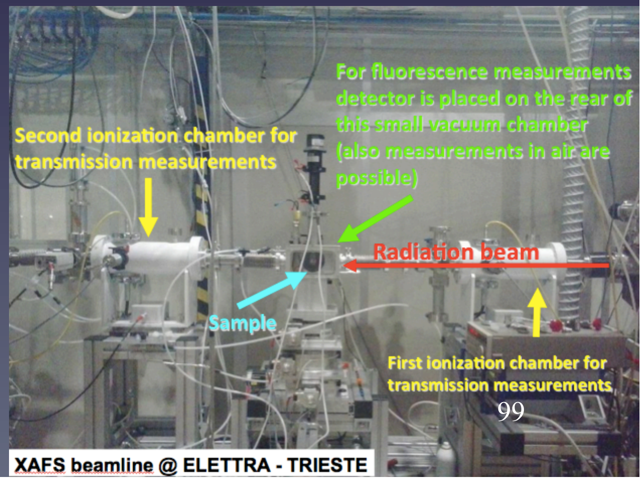
XAFS and μ-XAFS
(X-ray absorption fine structures),

(AFS beam-line combines X-ray
ıbsorption
pectroscopy and X-ray diffraction
o provide chemically specific
tructural information of
naterials.

ournal of Physics: Conference Series 689 (2016) 012017

among the XAFS applications: cultural heritage,
environmental analysis

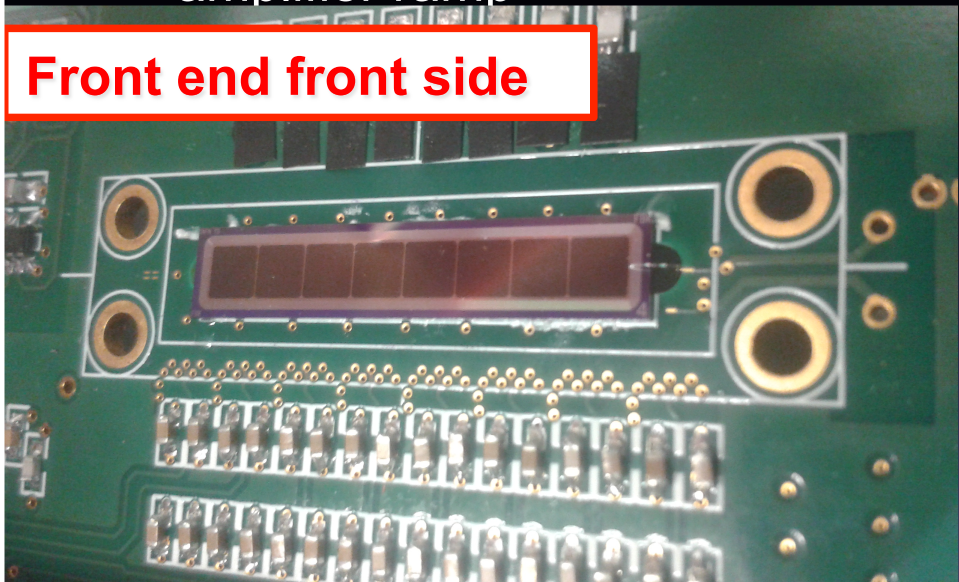
Paleolithic paintings from caves in Spain

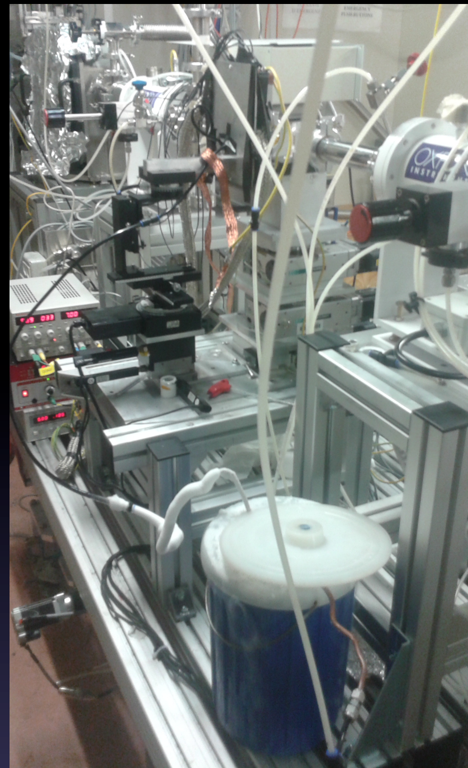


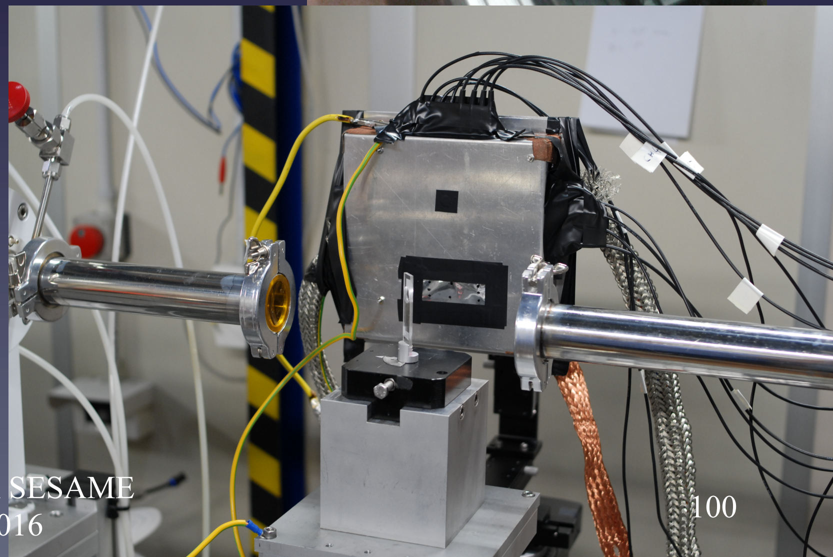
SESAME Prototype - 0 : the first beam test at XAFS Elettra

The **prototype** comprises:

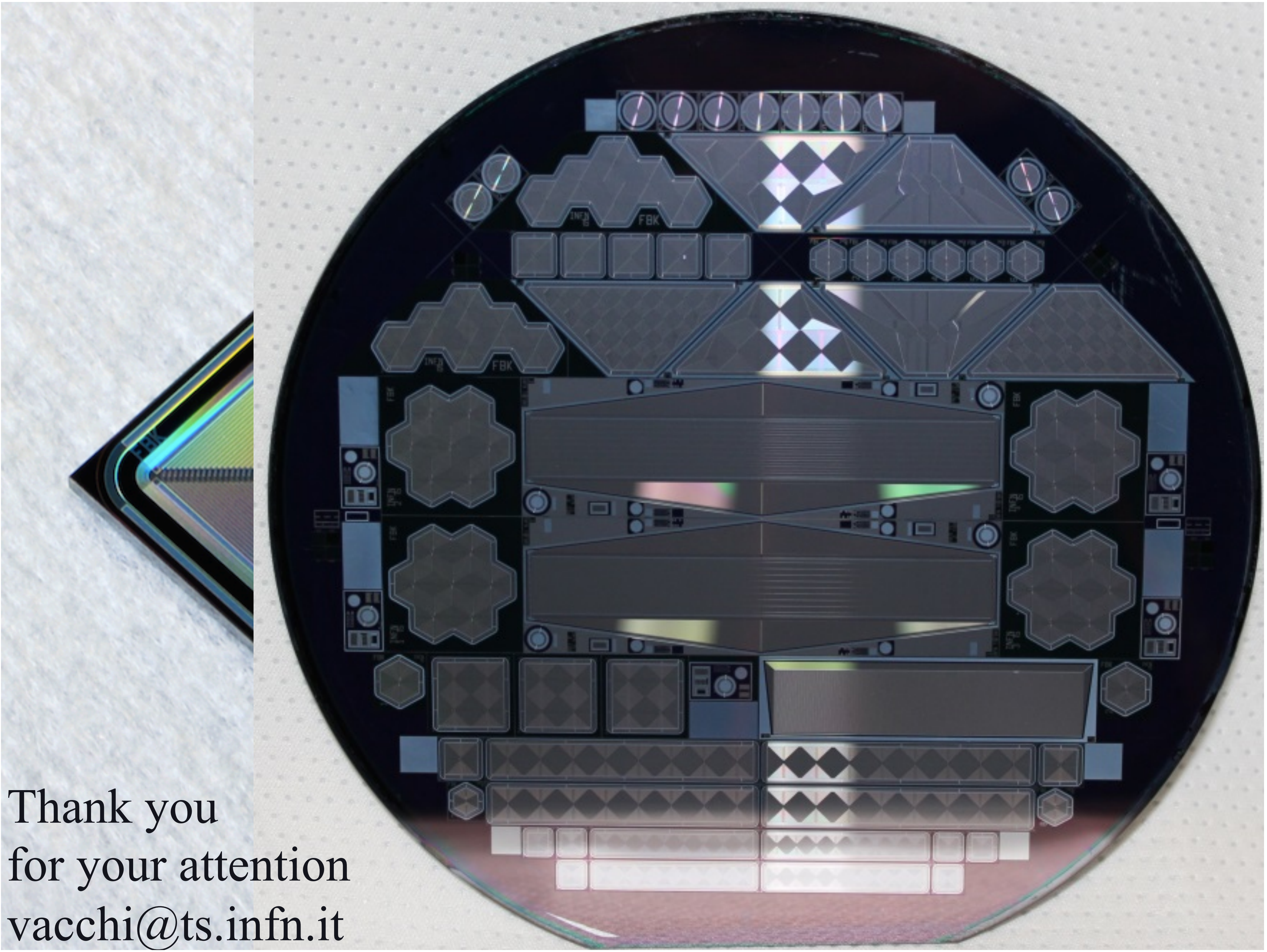
1 SDD with 8 cells mounted on a font end electronics (by INFN-Ts) Signal output unplified pre-amplifier ramp







back end electronics equipped with 8 ADCs for each independent channel and an FPGA (by Elettra)



Thank you
for your attention
vacchi@ts.infn.it