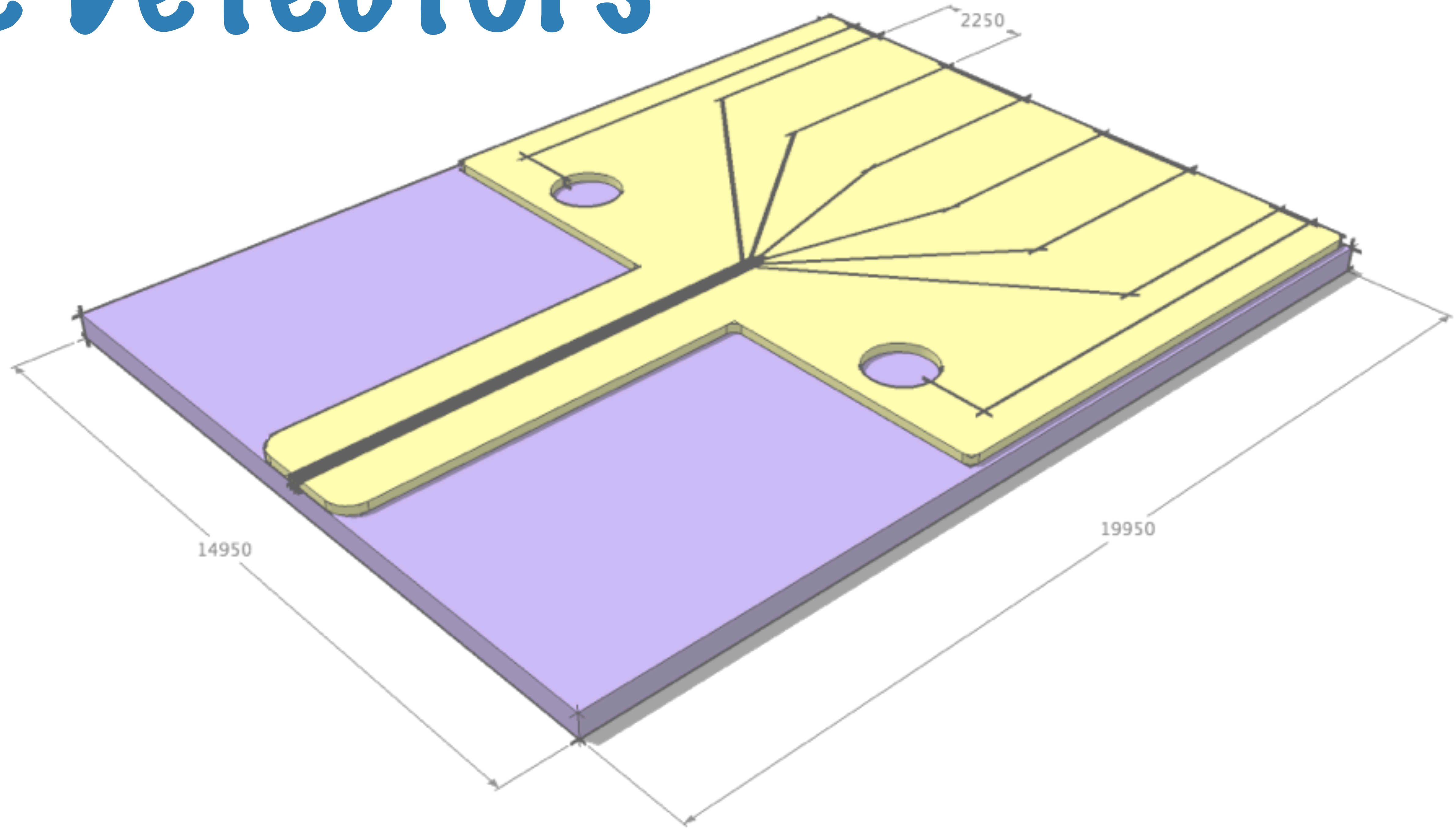
Physics Department
Detector Technologies Group
Engineering Office
Alessandro Mapelli

Microfabrication for Particle Detectors



EPS-TIG Workshop
Erice, Sicilia, Italia
22nd-25th October 2012

Detector Technologies PH-DT

microfabrication projects in PH-DT

- microchannel cooling
- thermo-mechanical mockups
- microfluidic scintillation detectors
- heat transfer of superfluid helium

The devices presented hereafter have been fabricated by our CERN PH-DT group members in the university cleanroom of EPFL, Lausanne, Switzerland.

microfabrication

Miniaturization science is the science of making very small things.

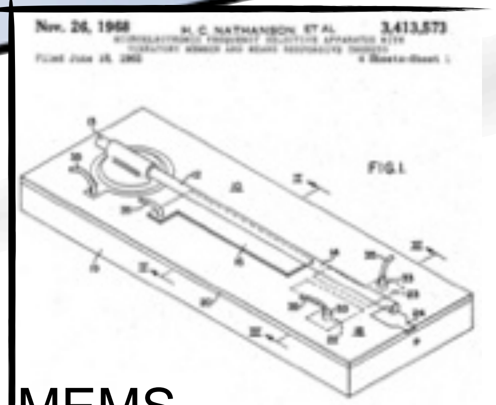
It requires a profound understanding of the intended application, different manufacturing options, materials properties, and scaling laws.

Fundamentals of Microfabrication and Nanotechnology, Marc Madou, 2012

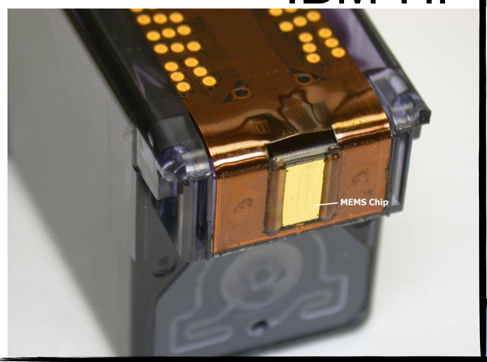
microfabrication milestones

Transistor
Bell
1947

1958
Integrated Circuit
Texas Instrument

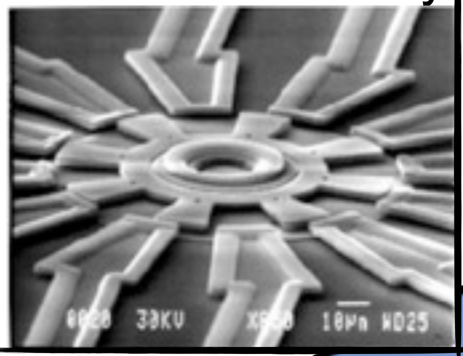


MEMS
H. Nathanson
1967

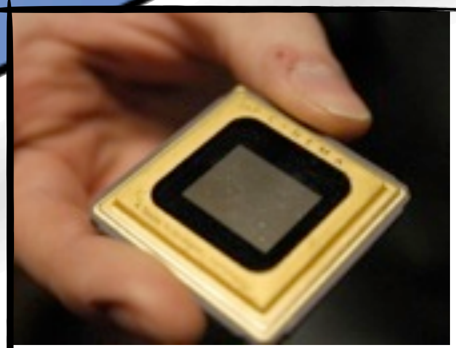


1977
Inkjet nozzle
IBM-HP

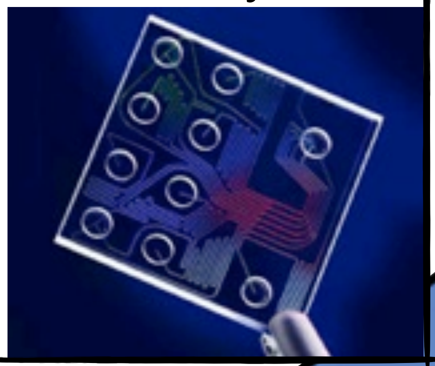
LIGA
W. Ehrfeld
1982



1988
Electrostatic Motor
UC-Berkeley



Digital Mirrors Display
Texas Instruments
1996



1999
DNA microarray
ex. Affymetrix

Optical Switch
Lucent
2002

2004
Dual-axis accelerometer
IBM

microfabrication applications

Electrons in semiconductors	+	MICROFABRICATION	⇒	Microelectronics
Photons in semiconductors	+		⇒	Optoelectronics
Instrumentation	+		⇒	Micromechanics
Chemistry & biotechnology	+		⇒	Microfluidics
Optics	+		⇒	Micro-optics
Quantum mechanics	+		⇒	Nanotechnology
Robotics/mechatronics	+		⇒	Micromachines

Introduction to microfabrication, S. Franssila, 2004

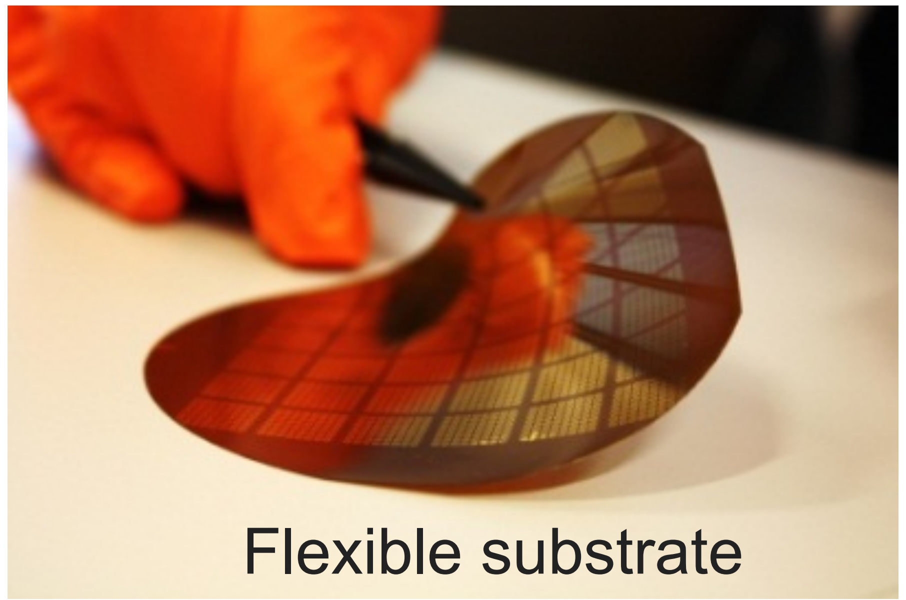
microfabrication technologies

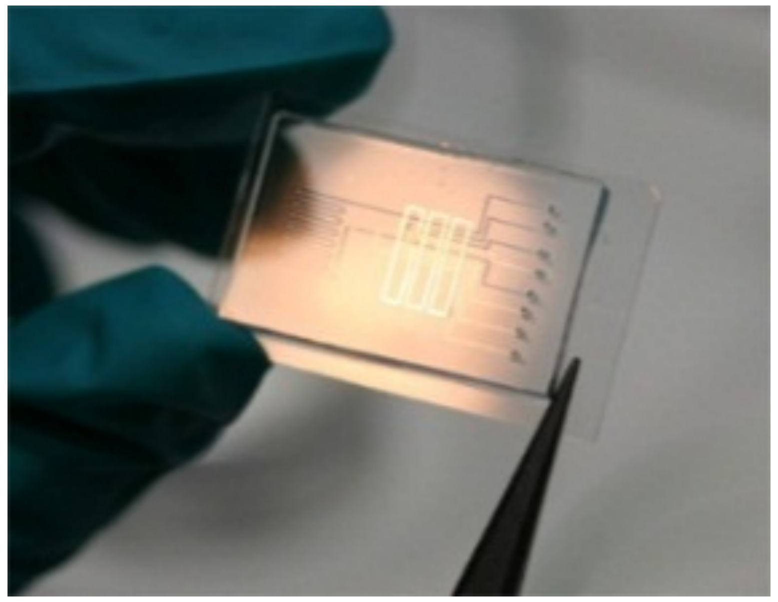
- **Bulk micromachining**
  mechanical structures are etched in the substrate

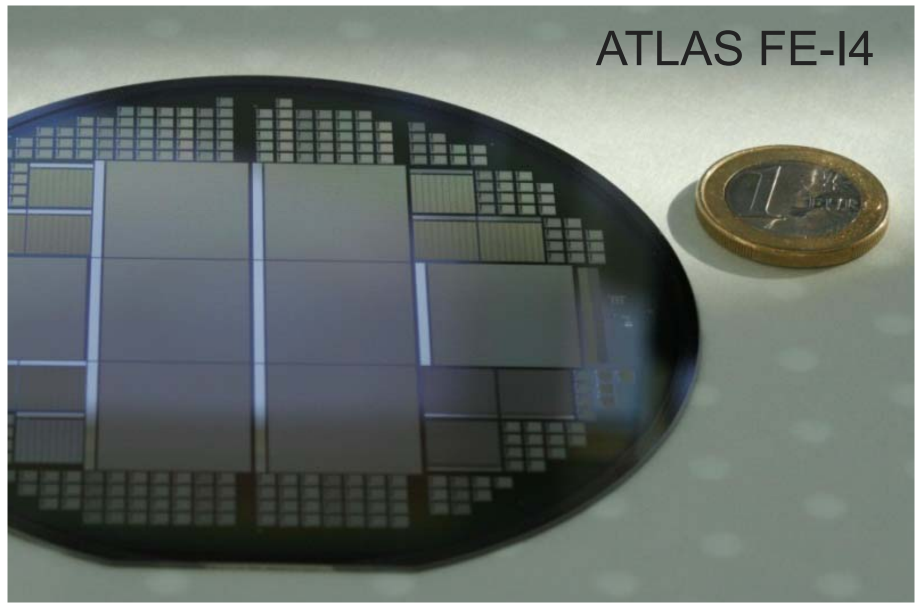
- **Surface micromachining**
  layers of material are deposited on the substrate, patterned and selectively removed

- **Substrates**
  round wafers 3”, 4”, 6”, 8”, 12”...
  Silicon, SOI, glass, GaAs, SiC, Ge, polymers...

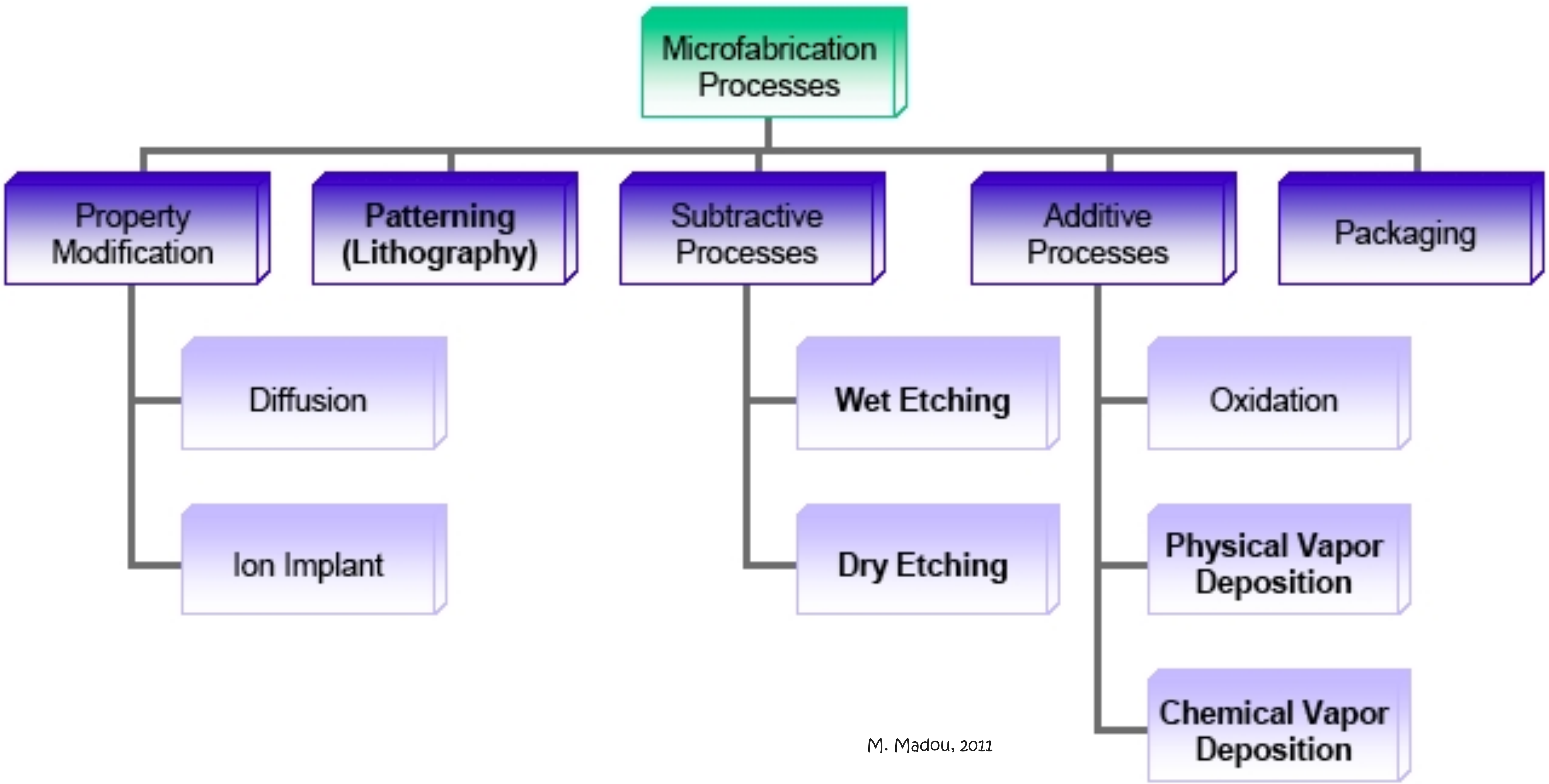

Si ingots and wafers


Flexible substrate

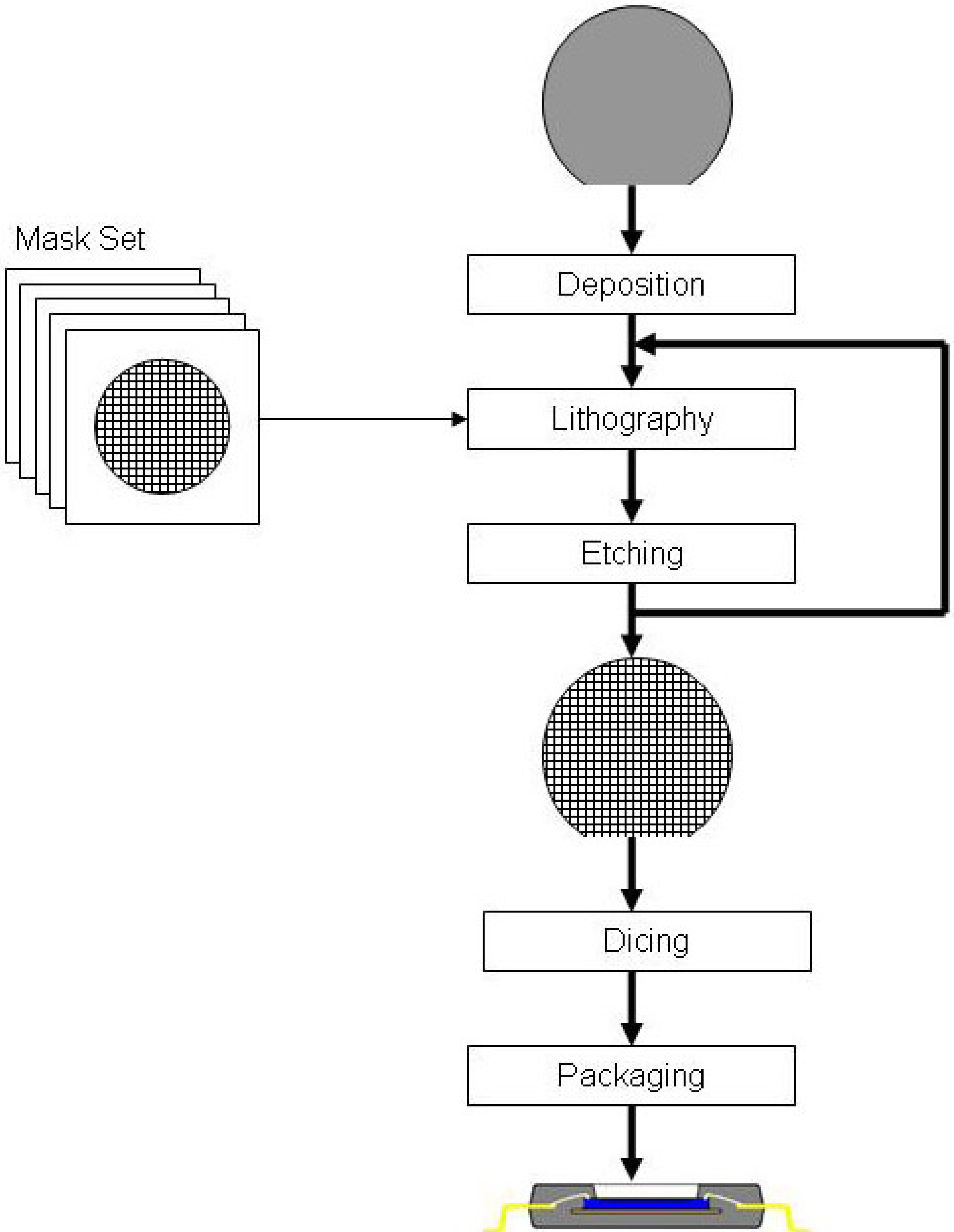



ATLAS FE-I4

microfabrication processes



microfabrication process-flow



http://www.electronicproductsktn.org.uk, 2007

Detector Technologies PH-DT

CERN

microcooling for trackers... long-awaited

Mechanics and cooling of pixel detectors

The most advanced raw materials, the same adopted in aerospace industry, are widely used: Ultra High Modulus carbon fibres with low moisture adsorption cyanate ester resin matrix to minimise swelling due to change in moisture content.

A typical weight of a well designed global support structure ranges from 10% to 15% of the total weight of the detector.

6. Thermal management

The problem to be solved, common to all detectors, is shown schematically in Fig. 4.

The heat is produced quasi-uniformly over the relatively wide module area and has to be efficiently transferred to the coolant flowing inside a small cooling pipe, which must minimise the material.

The thermal design of the local support has to achieve:

- a good temperature uniformity over the module
- a good heat transfer efficiency to minimise the module-to-coolant temperature difference.

To accomplish the temperature uniformity goal the local support structure material has to have a good in plane as well as transverse thermal conductivity.

High X_0 metallic materials, typically beryllium or aluminium, are in principle good options for the module thermal management.

However the metallic materials make the thermal stability issue more critical due to their relatively high CTE, limiting the application range to small structural parts.

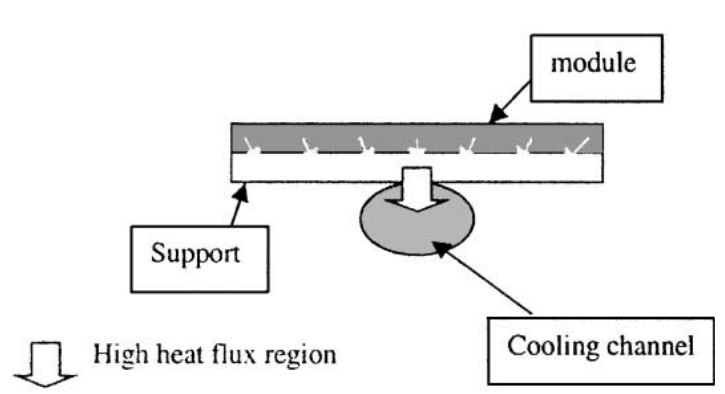


Fig. 4. Module thermal management fundamentals.

Moreover the Al is usually not adopted as stand alone structural material due to its poor mechanical properties.

Attractive alternatives to metals are the carbon-based materials. Standard CFRP are difficult to be adopted in an efficient thermal design due to their poor transverse thermal conductivity.

Carbon–Carbon materials are in principle the best option combining good thermal properties even in transverse direction to fibres (thermal conductivity 1 or 2 order of magnitude better then standard CFRP) with excellent mechanical properties, stability and transparency to particles. The C–C materials have essentially two technological drawbacks limiting the application range: porosity and difficulty to achieve complex and accurate geometry due to the high temperature manufacturing process.

The selection of the material for the cooling channel and of the coupling method to the module support is a critical issue for the local support thermal efficiency and stability.

There are three possible options:

1. pipe material with the same CTE of the support: hard and reliable thermal joint is possible
2. pipe material with different CTE: elastic joint is necessary, but reliability becomes an issue
3. cooling fluid in direct contact with the module support (integrated cooling channel)

Solution 1 is the safest design but possible just in very limited cases.

Solution 2 is the most widely adopted, because it leaves the maximum freedom in the design choices.

Solution 3 minimises the material, but is difficult to be implemented.

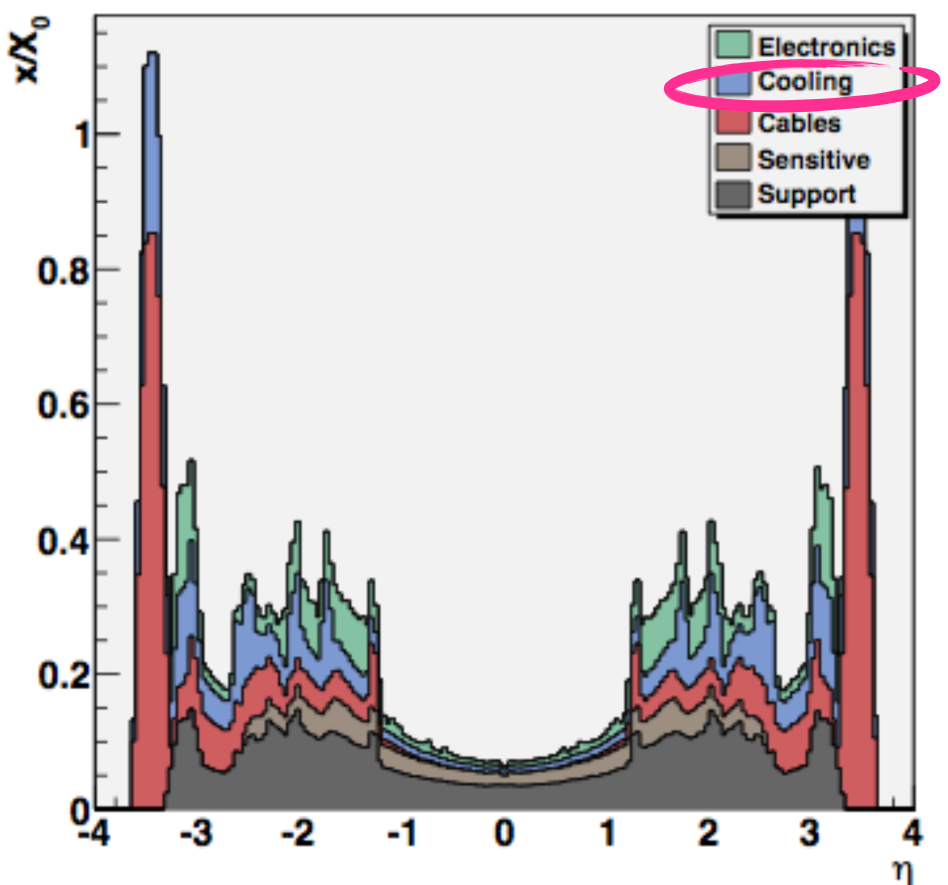
Additional stability constraints as well as specific design solutions will be discussed in the following sections.

7. Cooling options

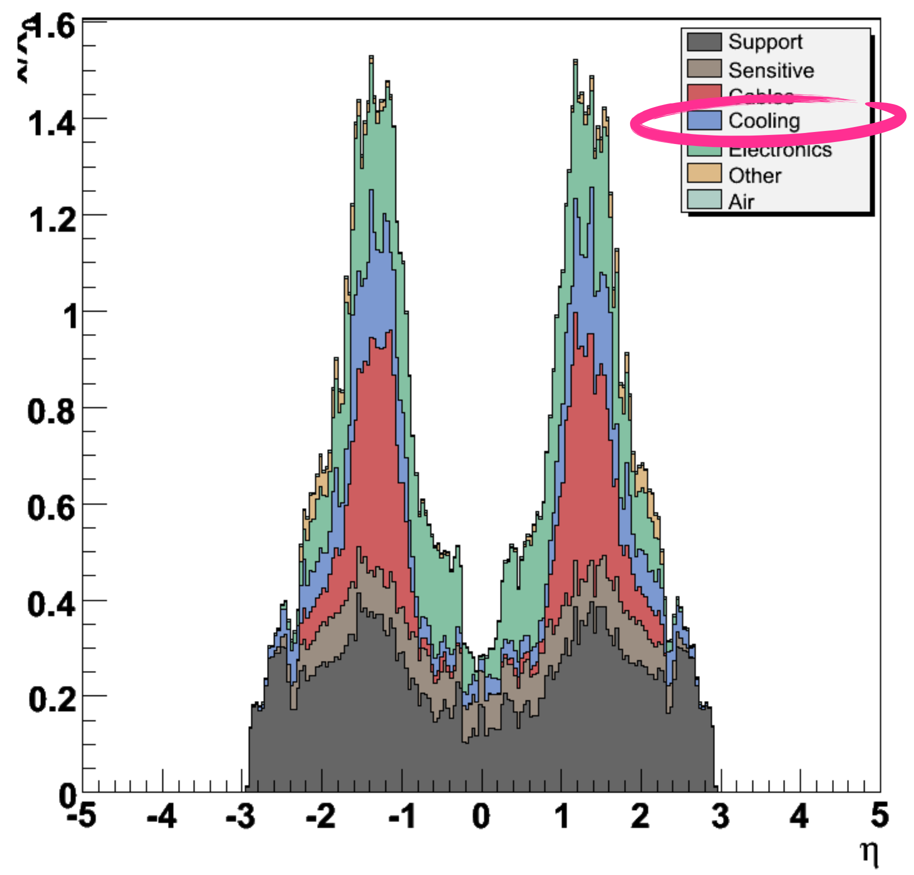
The minimisation of the material of the cooling circuit (pipes, connections) and the need of a good heat transfer efficiency to meet the temperature requirements on the module, restricts the choice to

μ-channel cooling

why silicon microcooling for trackers ?



Material budget of the CMS Si-Pixel tracker (2 layers)



Material budget of the CMS Si-strip tracker (10 layers)

LHC large Si trackers (ATLAS and CMS)
2% X_0 per layer

SLHC "phase II" upgrade:
"significant" reduction needed

Future trackers at ILC
0.1÷0.2% X_0 per layer

no CTE mismatch

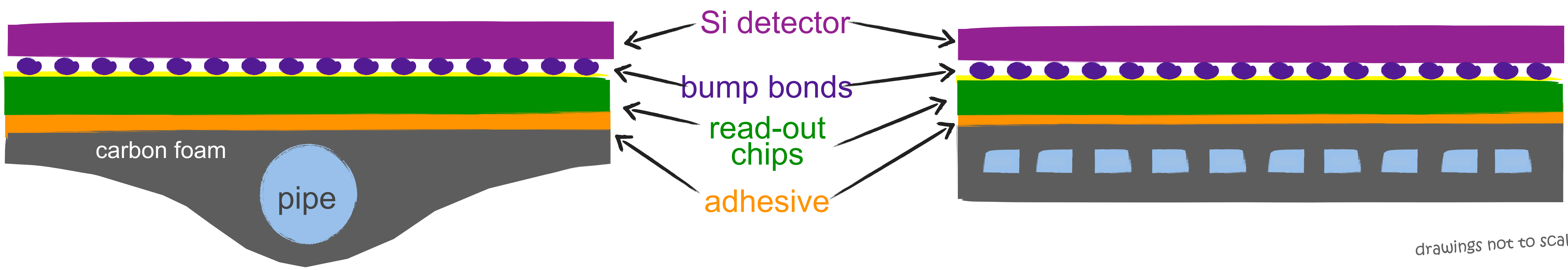
- **Minimization of material budget:**
  - Micro-channel cooling naturally addresses this issue through the use of thin Si cooling plate
- **For a given material budget, increase the cooling power:**
  - High heat transfer coefficients in laminar flows (prop. to 1/Dh with very small Dh)
  - High heat flux with large exchange surface
- **Reduce ΔT between heat source and heat sink:**
  - Micro-channels embedded in Si plate -> large exchange surface
  - Thinned Si plates -> ΔT minimized
  - Local cooling only where heat transfer required

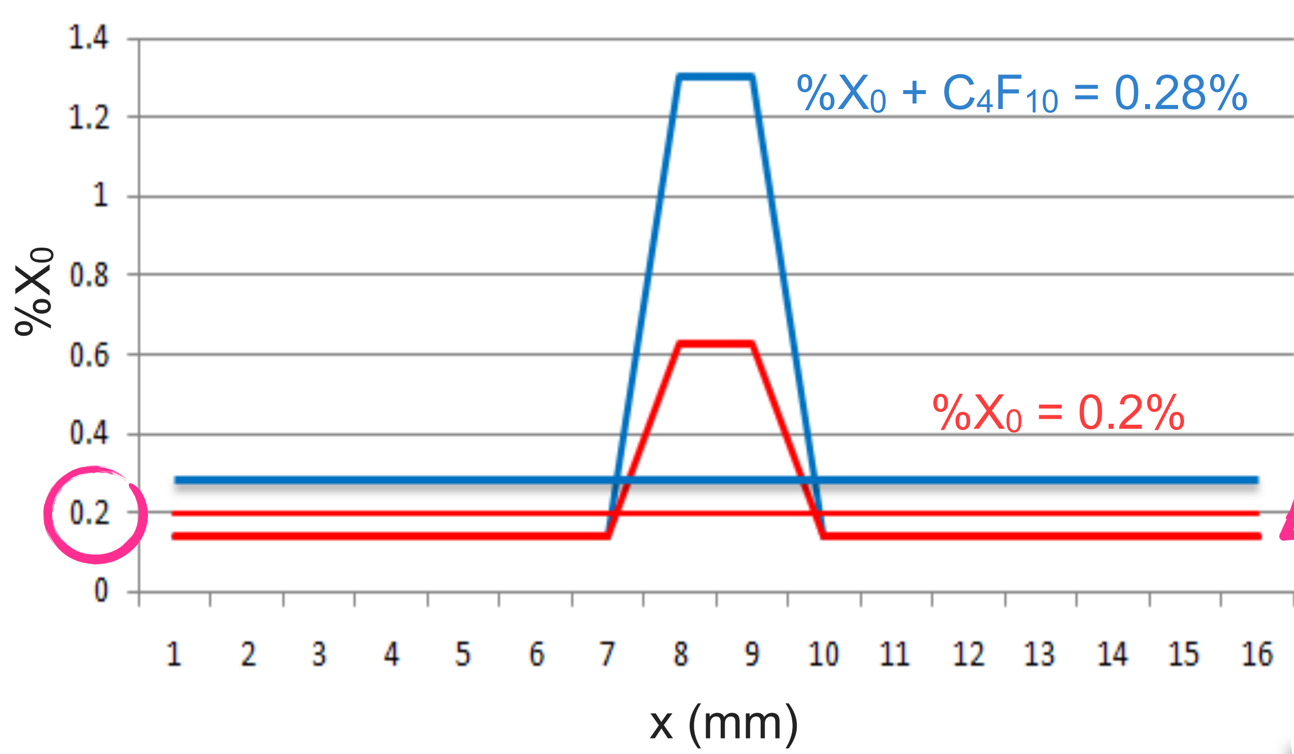
$X_0 = X_0/\rho$ [cm]
Cu: 1.4
Steel: 1.7
Ti: 3.6
Al alloy: 8.9
Si: 9.4
C_6F_{14} @ -20 C : 19.3
CO_2(liquid) @ -20 C: 35.8

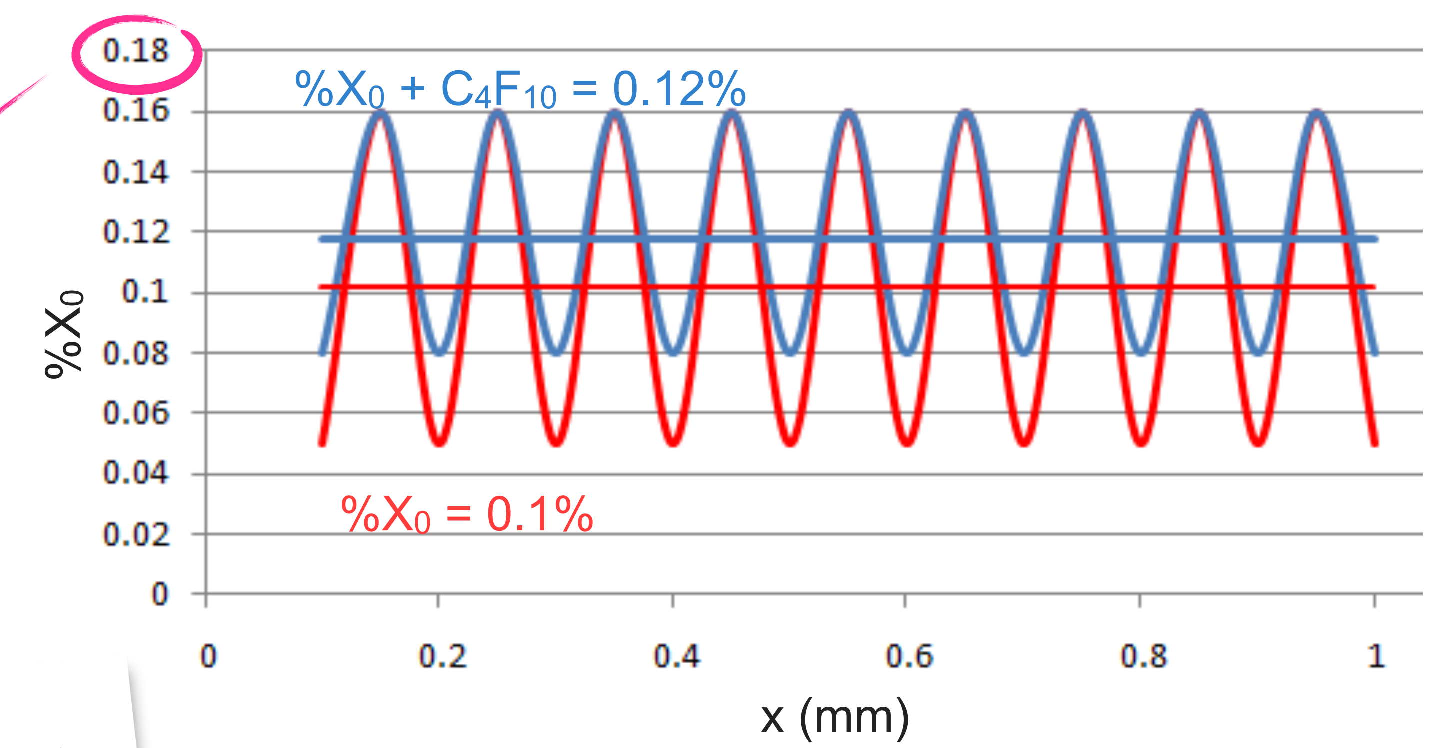
cooling of future detectors

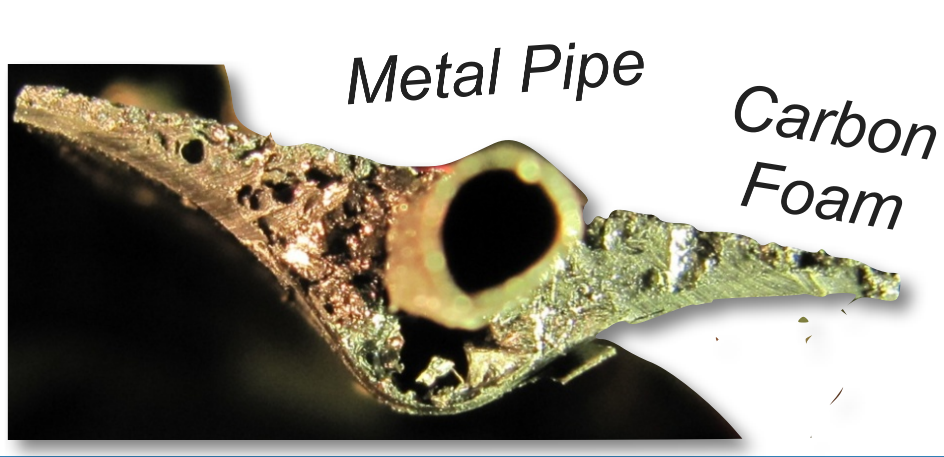
Carbon Foam + Metal Pipe

Silicon Microchannels





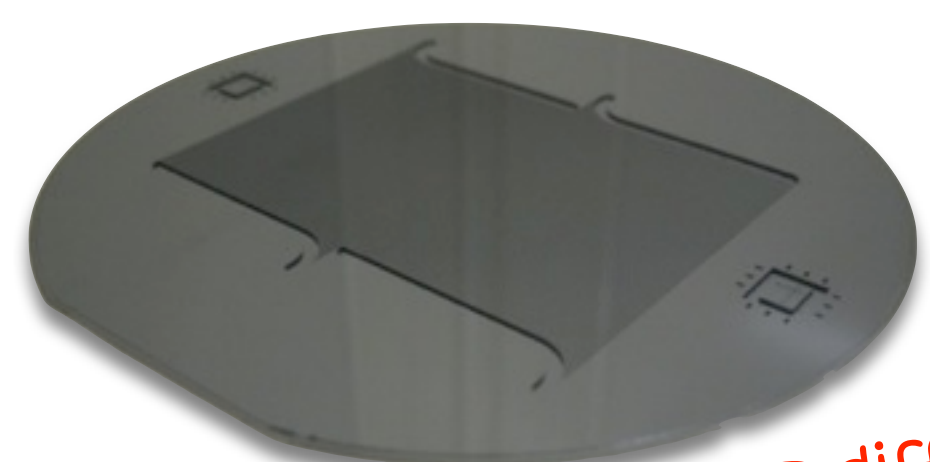




10°C

ΔT between heat source and heat sink for power dissipations of ~1W/cm^2

5°C



no CTE difference

microcool projects

CERN PH-DT
Andrea Catinaccio
Raphael Dumps
Alan Honma
Luc Kottelat
Camille Ligneau
Alessandro Mapelli
Ian McGill
Jérôme Noel
Paolo Petagna
Giulia Romagnoli
Bart Verlaat

ALICE ITS upgrade
Andrea Francescon

ATLAS IBL upgrade
Cinzia Da Via'
Vladyslav Tyzhnevyi

LHCb VeLo upgrade
Jan Buytaert
Paula Collins
Ed Greening
Sasha Leflat
Andrei Nomerotski

Microengineering
Aurélie Pezous

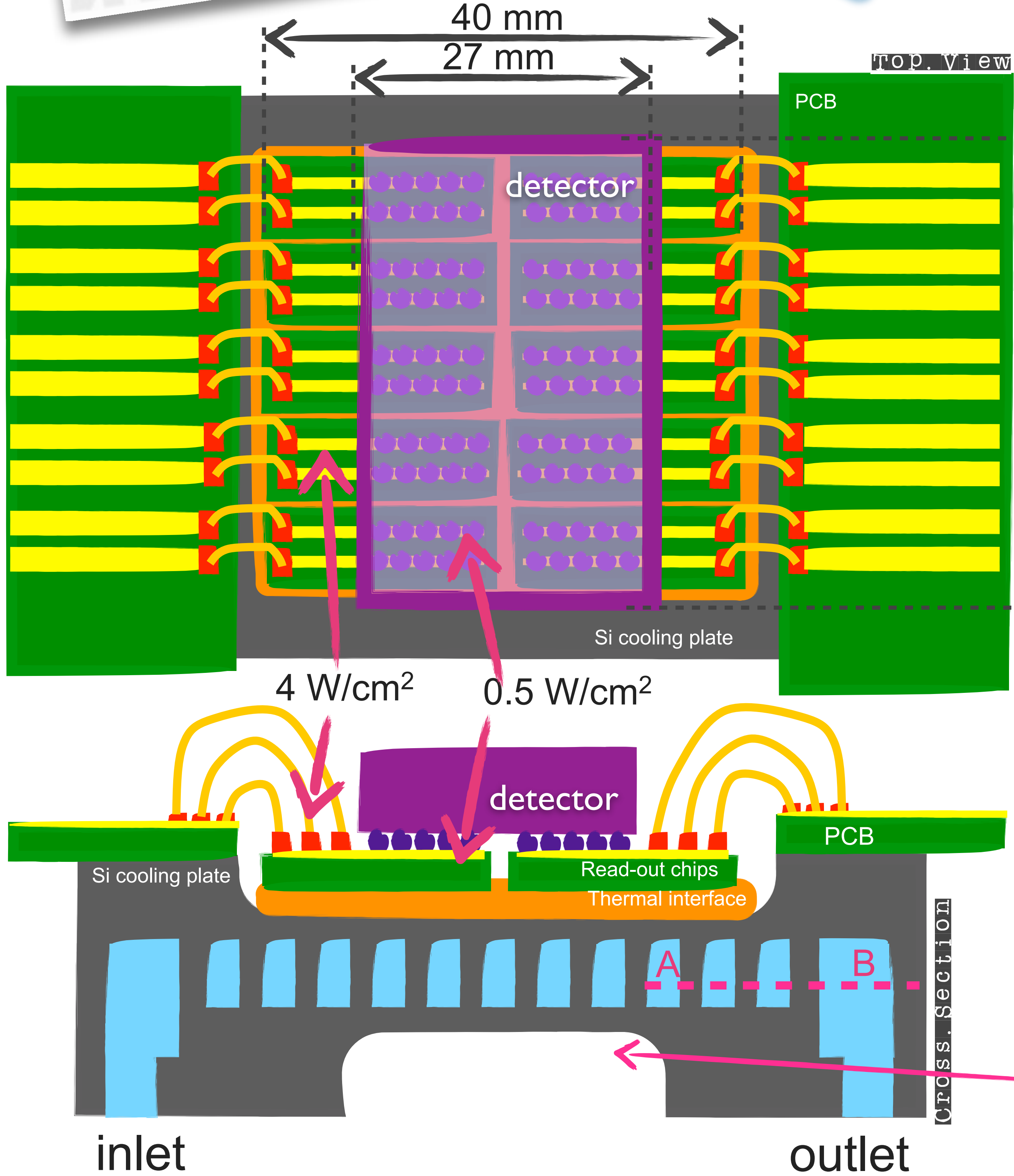
NA62 GTK
Enrico Da Riva
Kaitlin Howell
Alex Kluge
Michel Morel
Georg Nuessle
Vinod Rao

Microsytems Laboratory
Philippe Renaud
Harald van Lintel

experiment	material	temperature	coolant phase	pressure	coolant fluid
ALICE	0	20ºC	evaporative	2 bars	C_4F_{10}
ATLAS	TBD	TBD	TBD	TBD	TBD
LHCb	500 μm	-30ºC	evaporative	60 bars	CO_2
NA62	150 μm	-10ºC	liquid	10 bars	C_6F_{14}

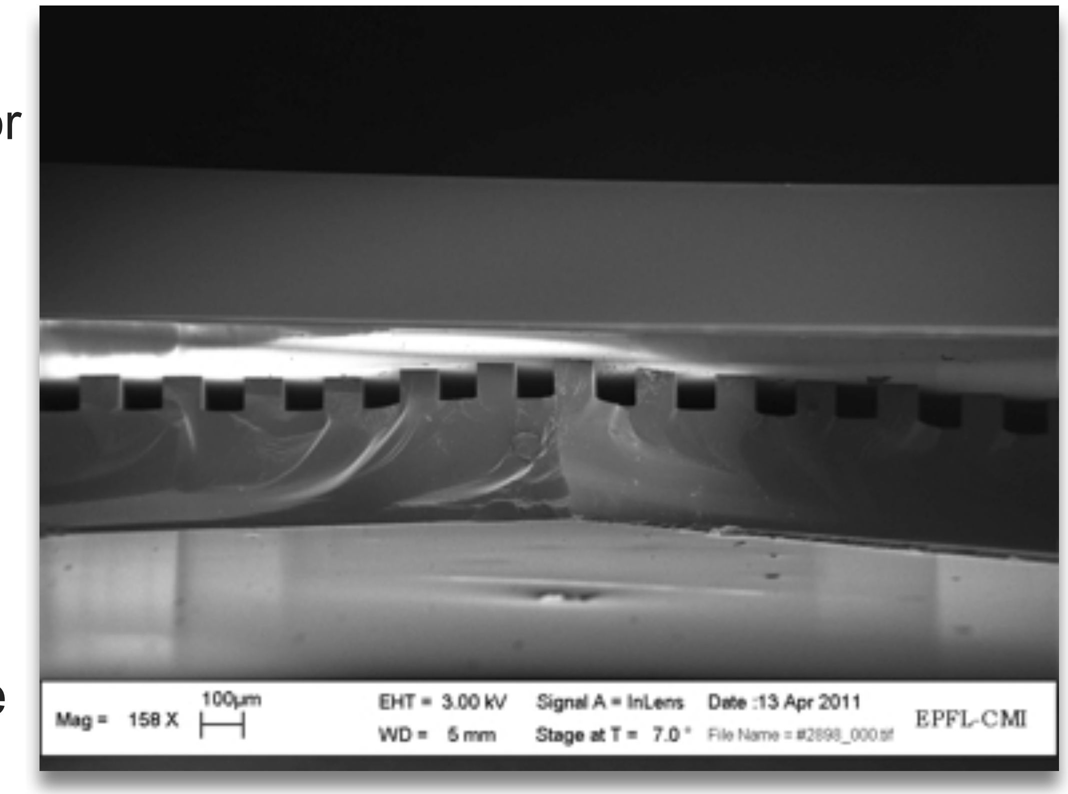
approved !

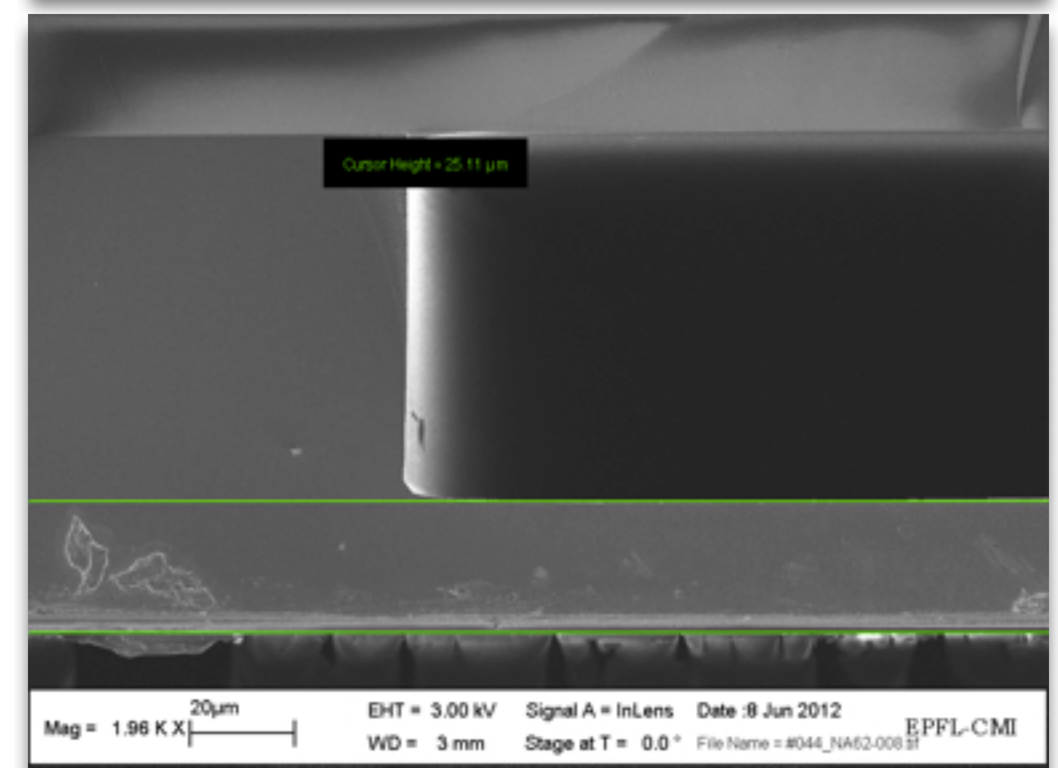
NA62 GigaTracKer silicon pixel detector cooling

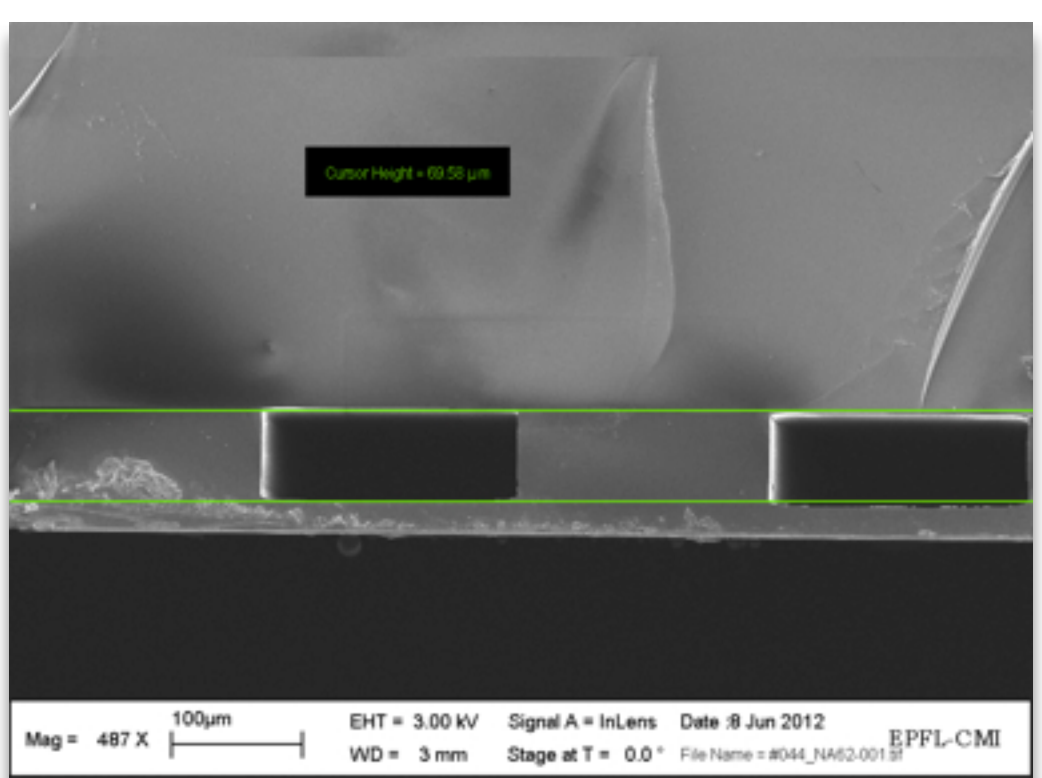


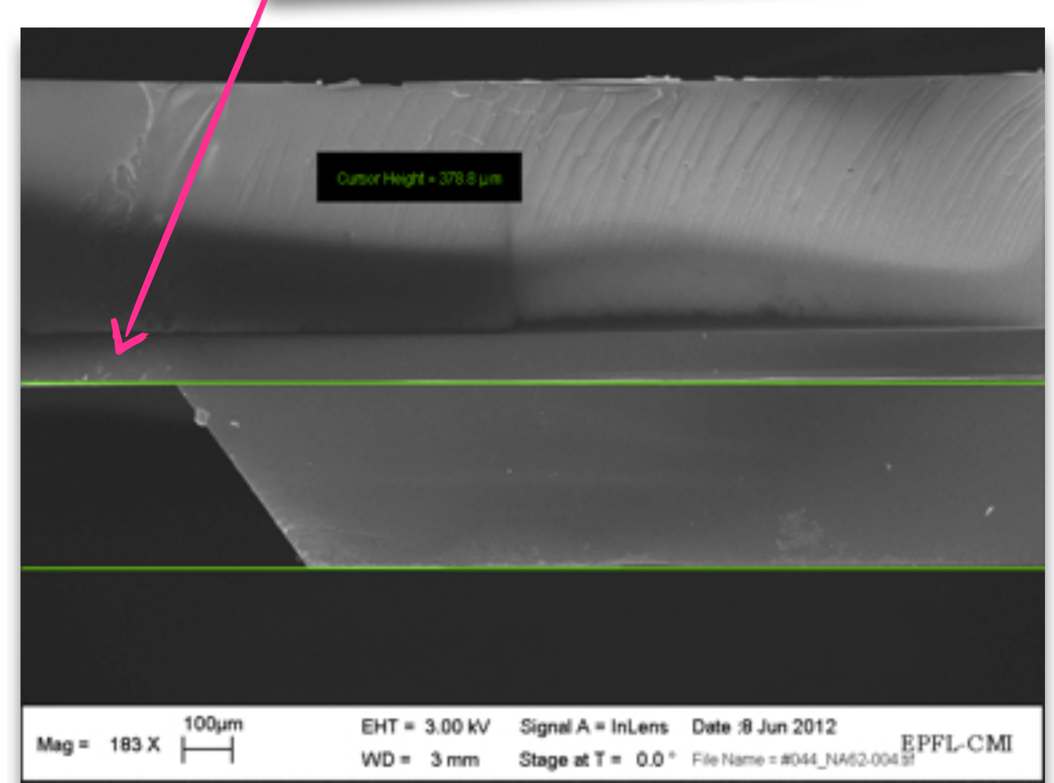
- Cooling requirements
  - minimize material below detector
  - detector area: 60 x 27 mm
  - T on Si detector: -20ºC ÷ 5ºC
  - ΔT over detector: 6ºC
  - Heat dissipation by read-out chips:
    - 4 W/cm² in the periphery (Digital)
    - 0.5 W/cm² in the center (Analog)
    - total 48 W
- Cooling solution adopted by the NA62 collaboration
  - thin silicon plate (130 μm)
  - C_6F_{14} liquid

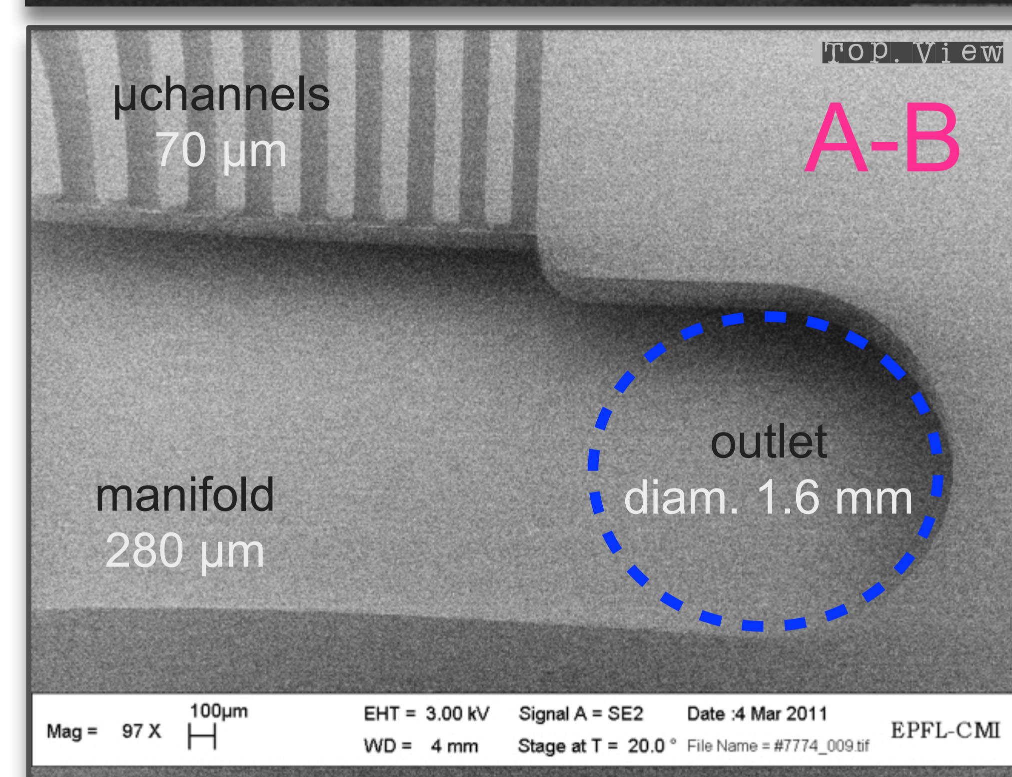
locally thinned to 130 μm in detector acceptance



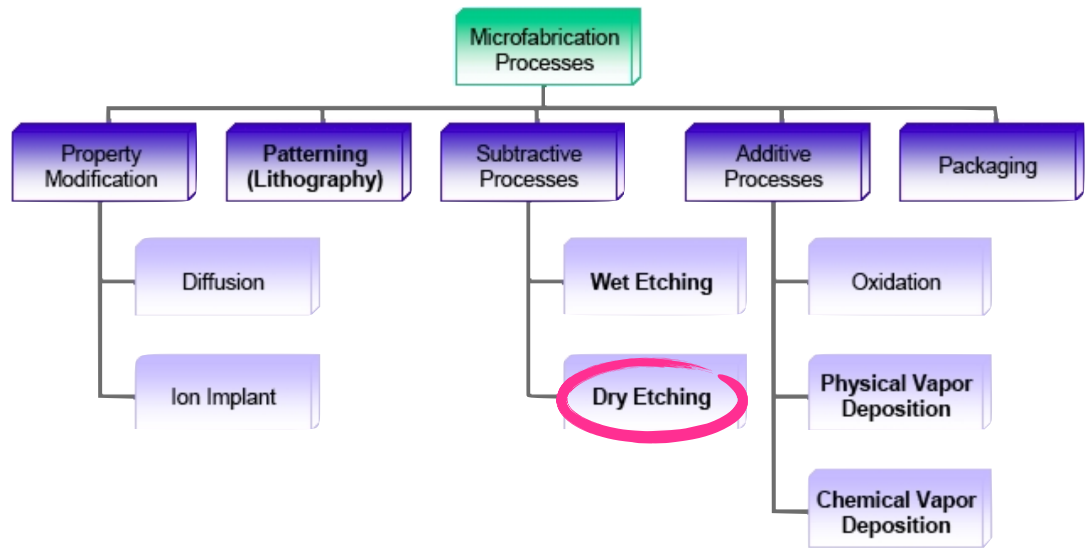


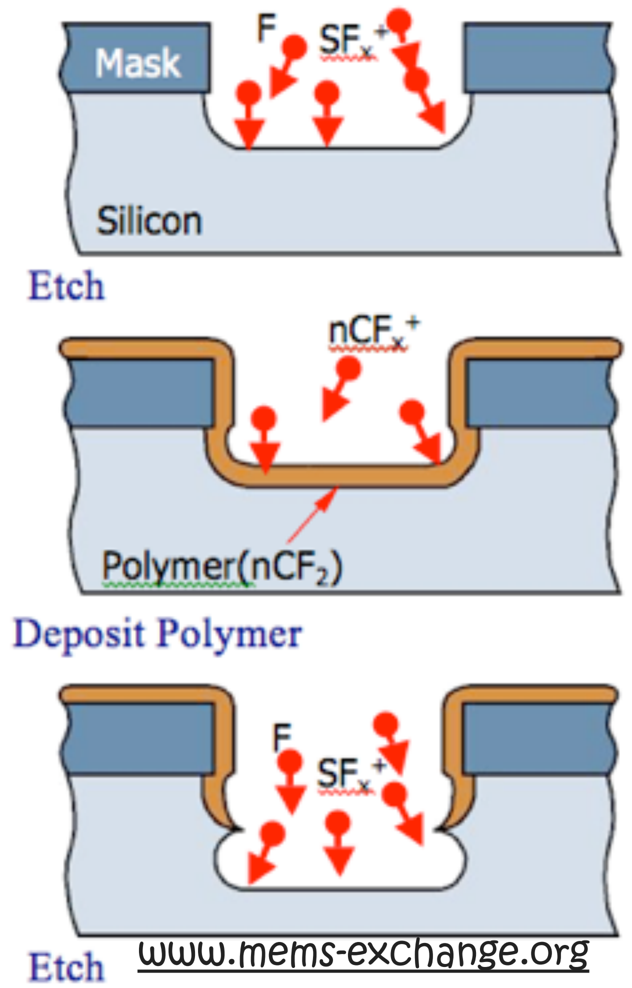


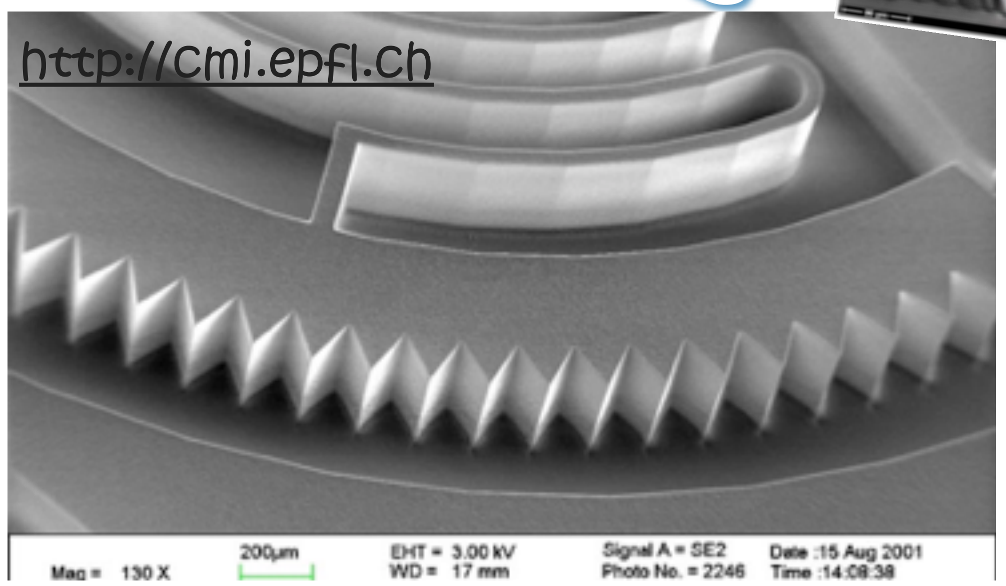


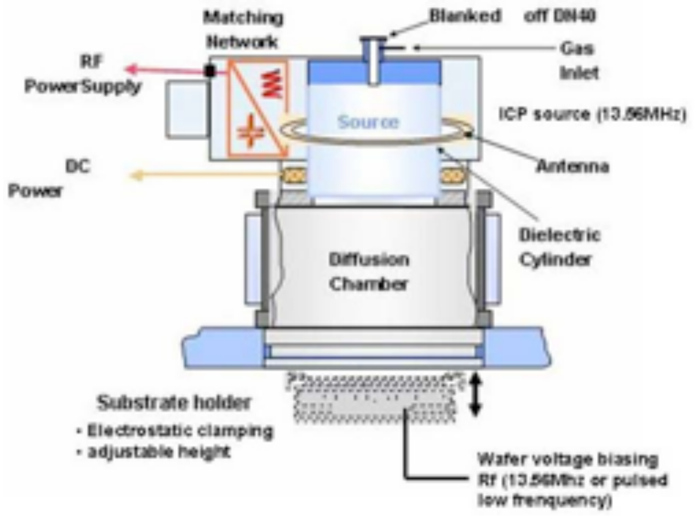


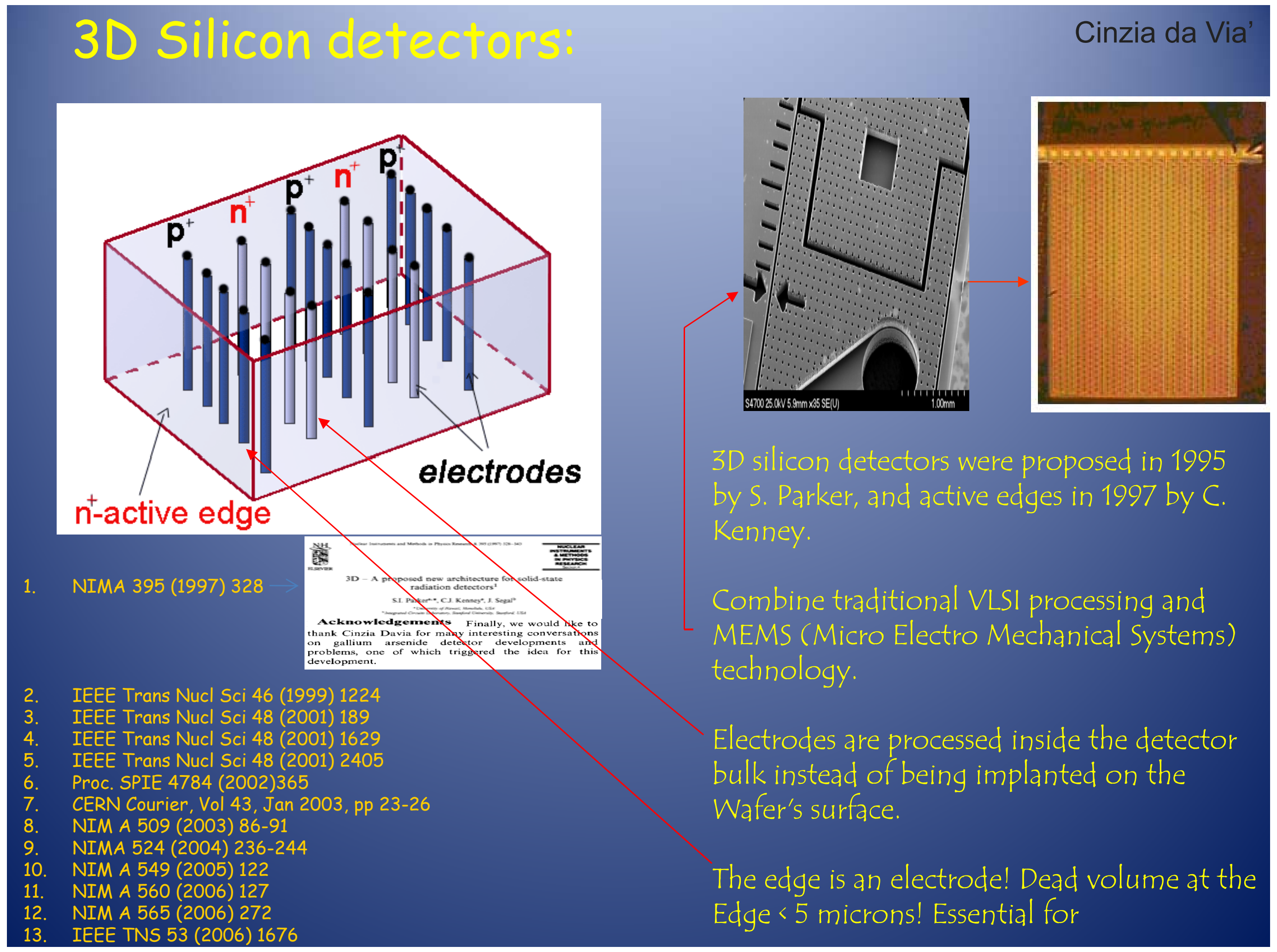
DRIE: Deep Reactive Ion Etching

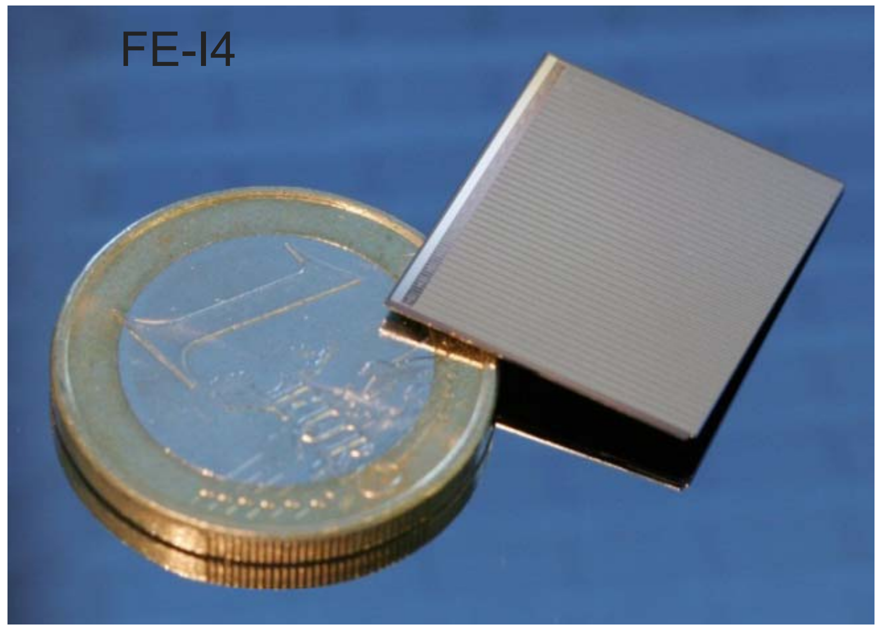


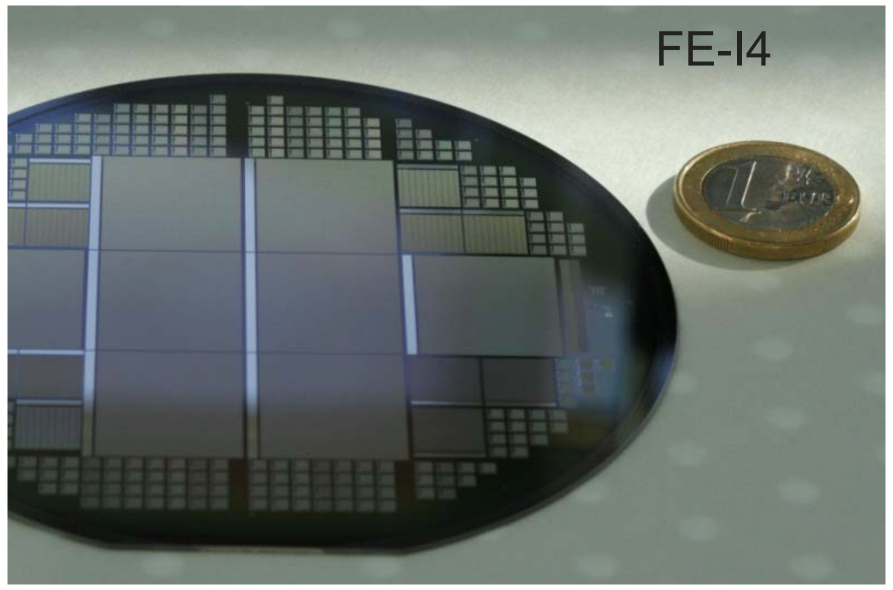


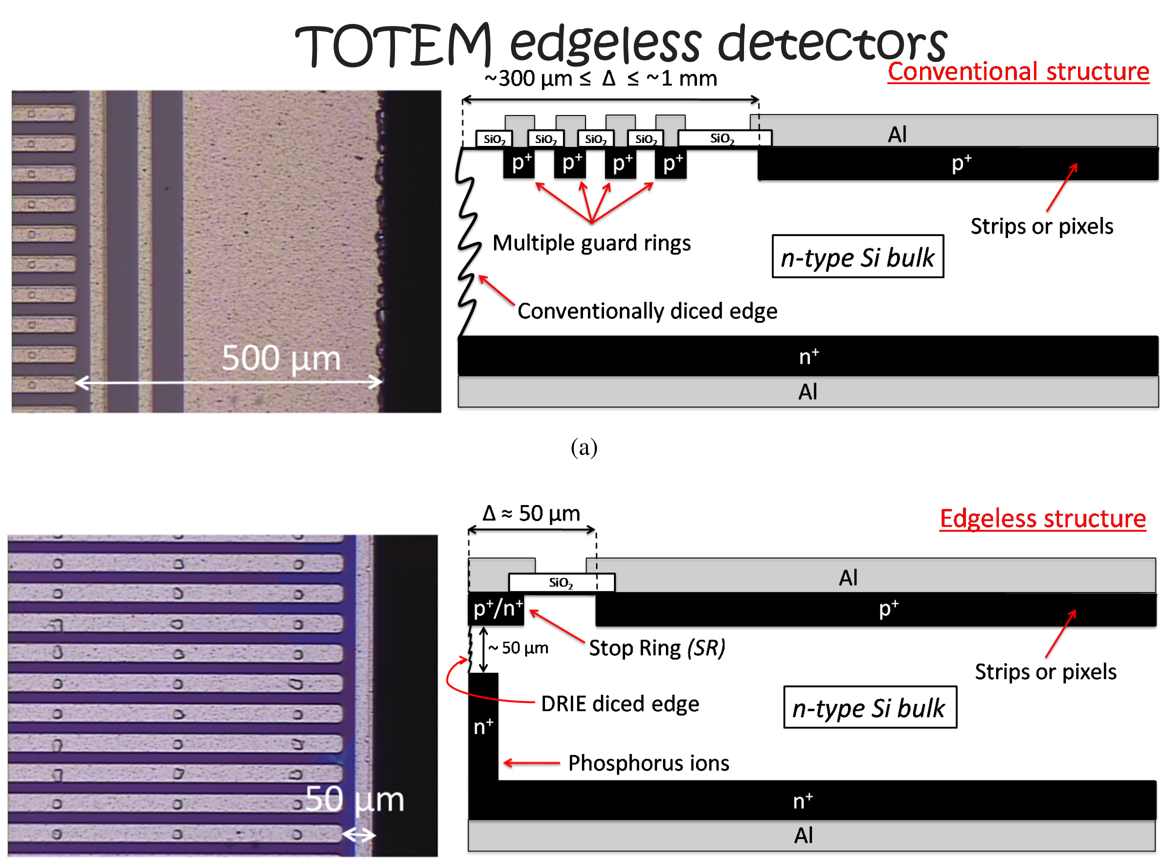




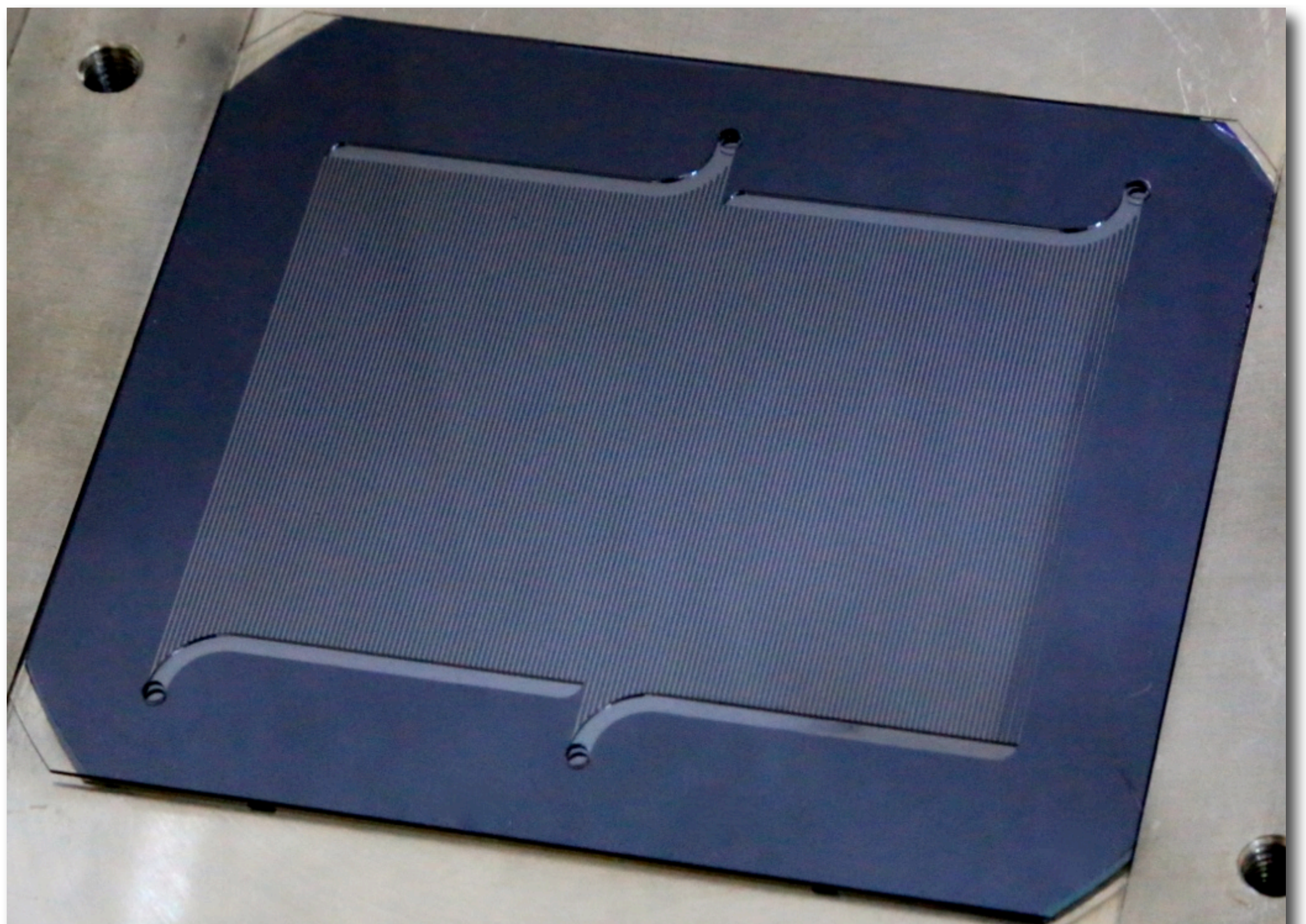




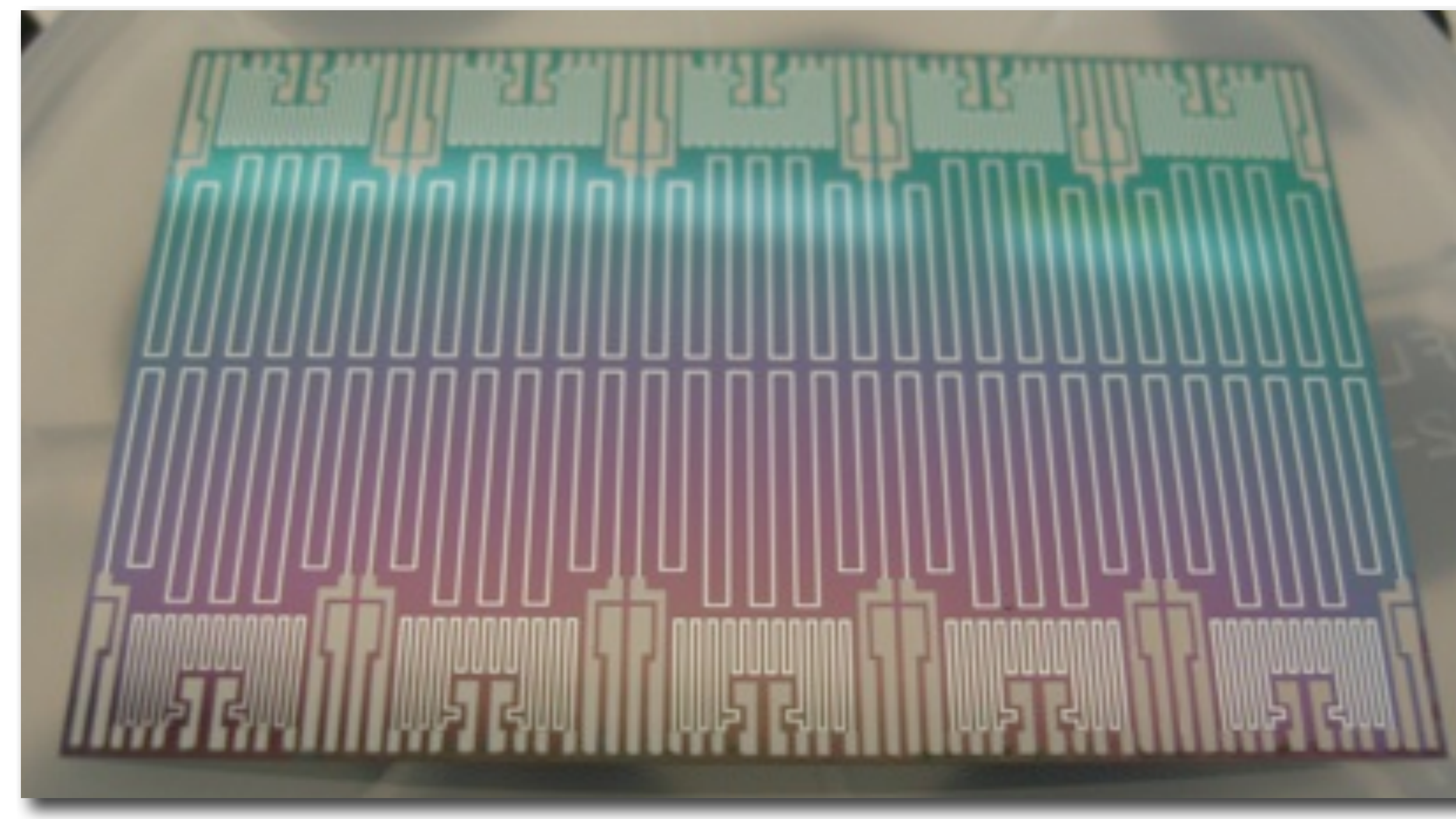




NA62 silicon prototypes



Silicon microchannel cooling plate



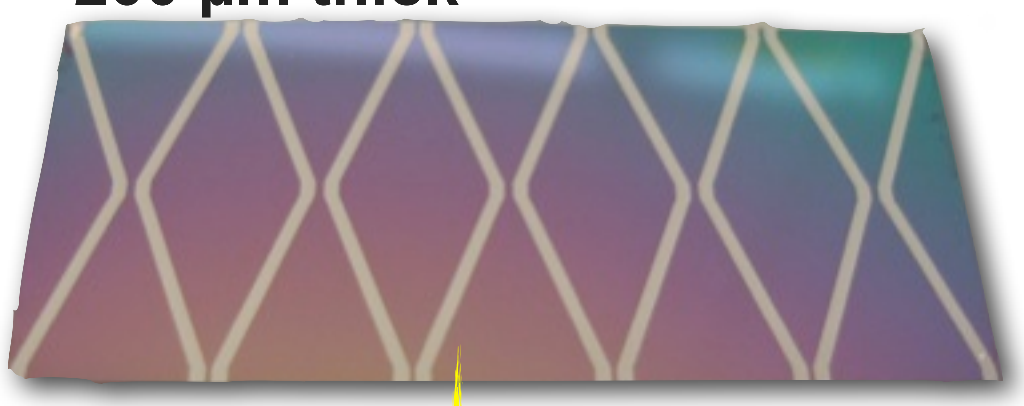
100 μm thick mock-up fabricated with CSEM

Silicon thermo-mechanical mock-ups

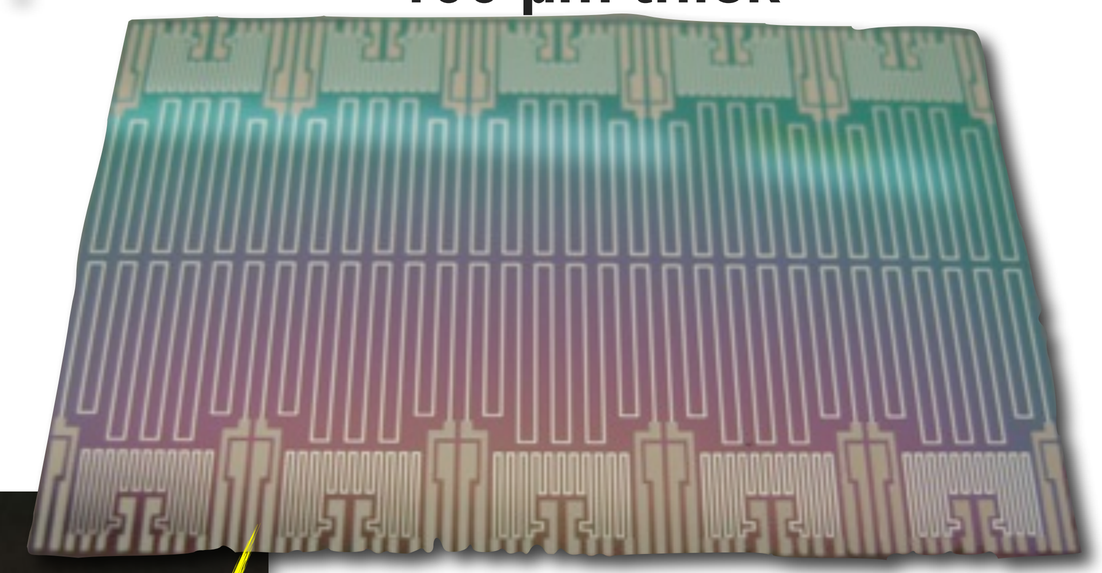
CERN PH-DT is working with major european actors for the fabrication of silicon cooling plates (CEA-LETI, IceMOS...) and is actively collaborating with CSEM on the development of a 6” platform integrating cooling, thermo-mechanical simulationsof detector and read-out with Through-Silicon Vias (TSV).

silicon thermo-mechanical mock-ups

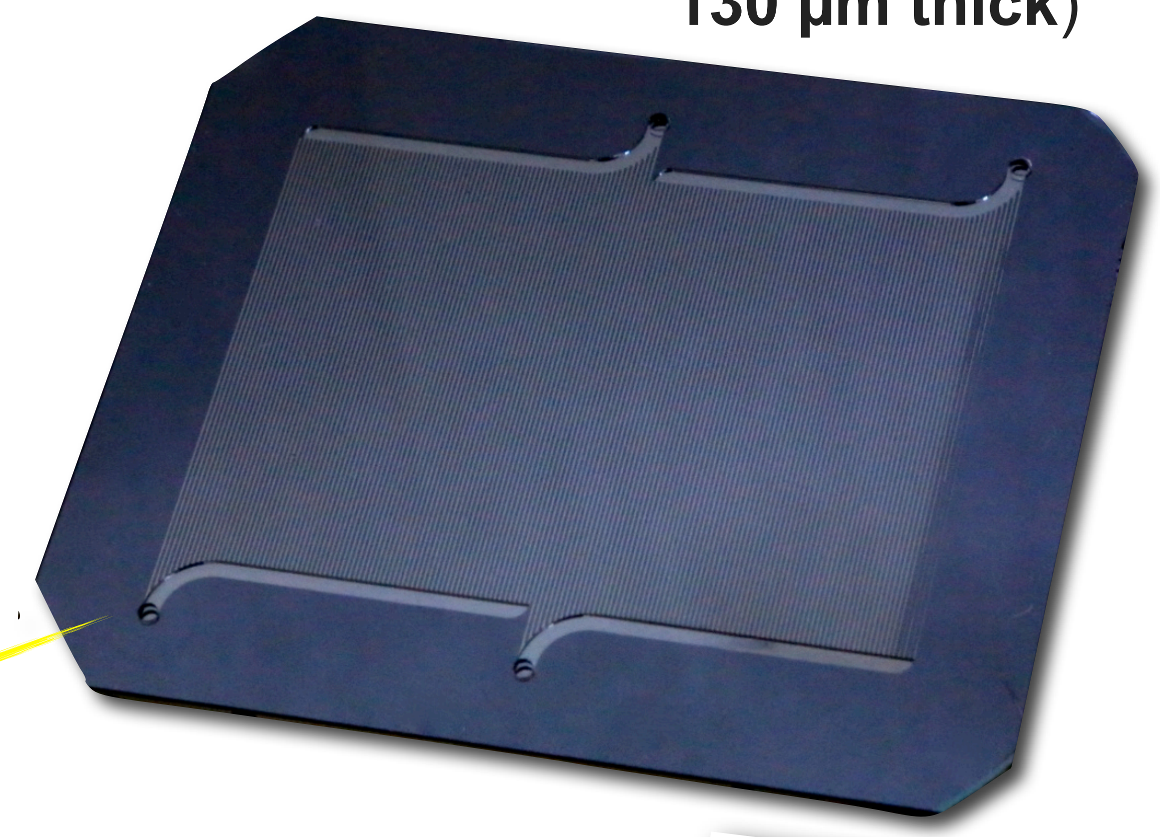
tracker mechanical mock-up
(silicon + metal)
200 μm thick

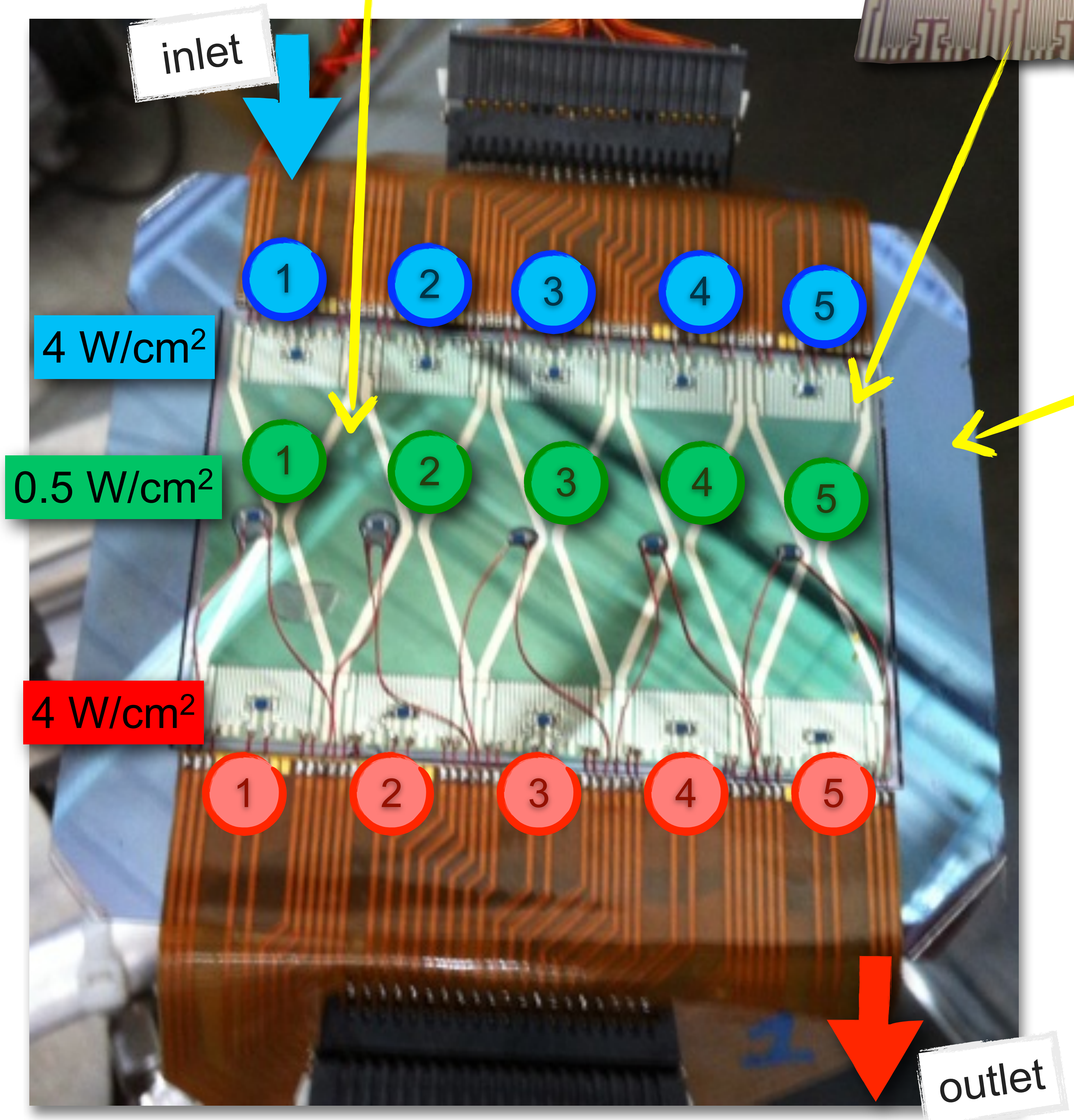


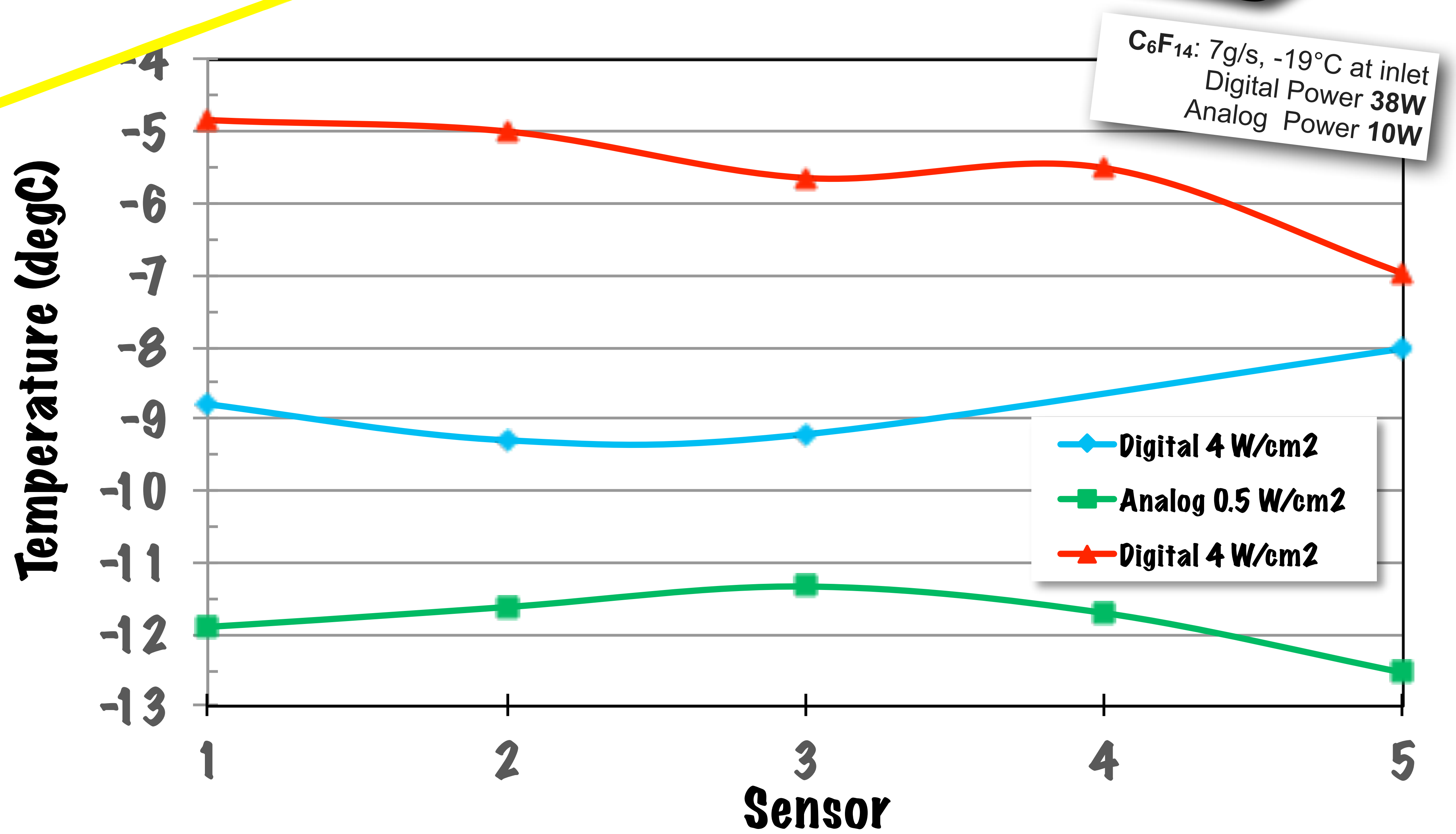
r/o electronics thermo-mechanical mock-up
(silicon + metal)
100 μm thick



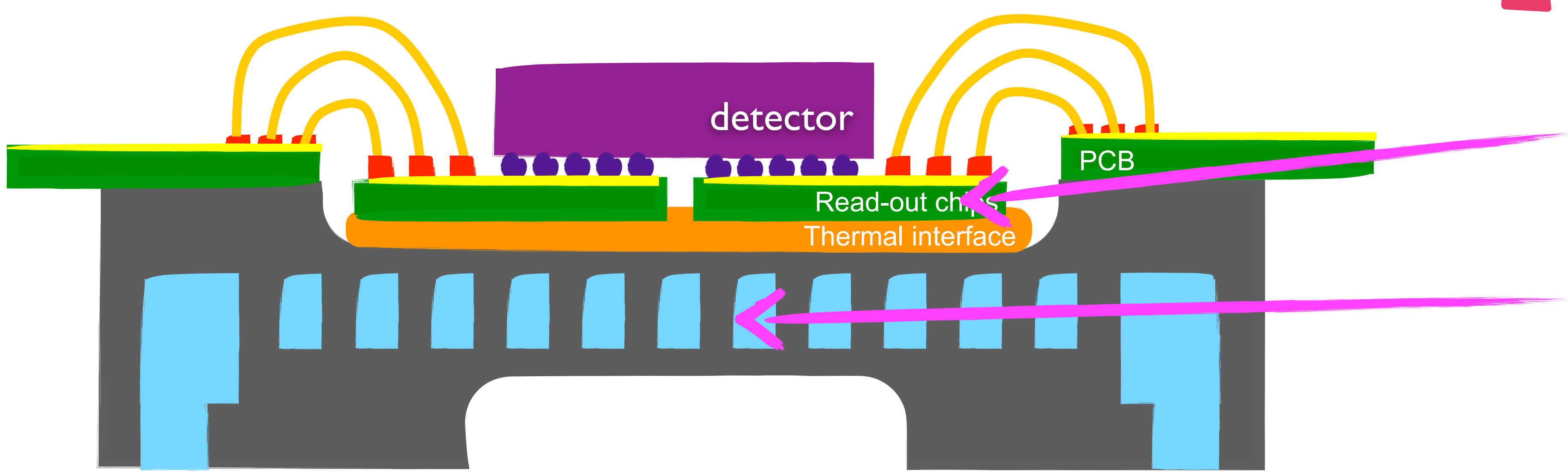
cooling plate
(silicon)
130 μm thick)



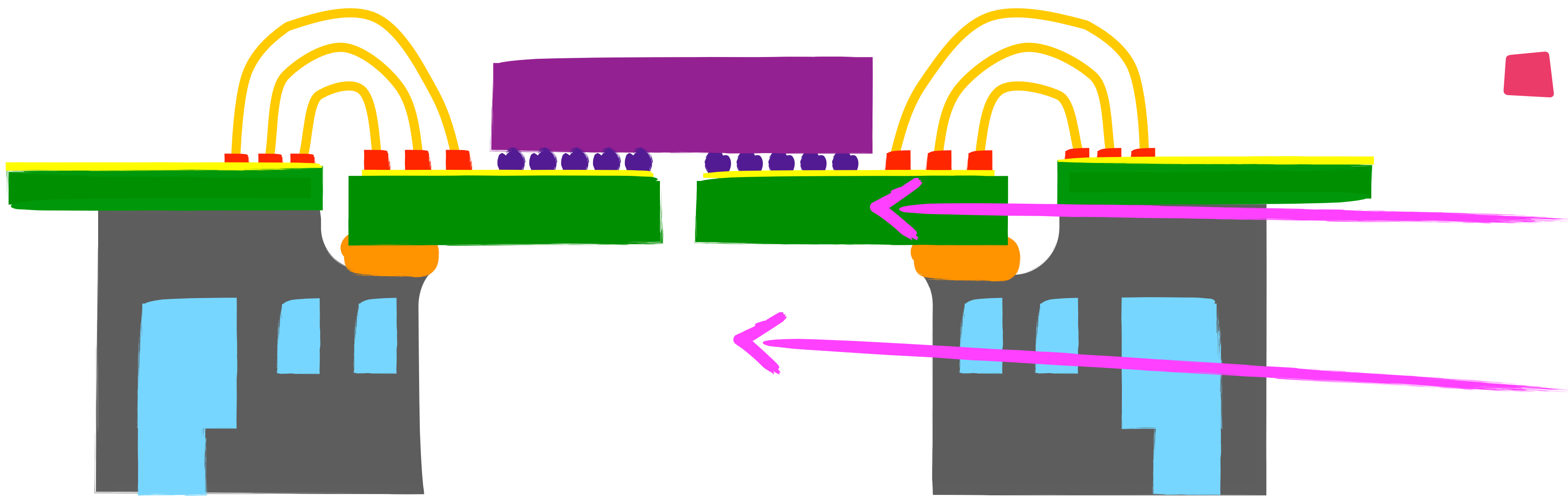




NA62-GTK alternative cooling proposal



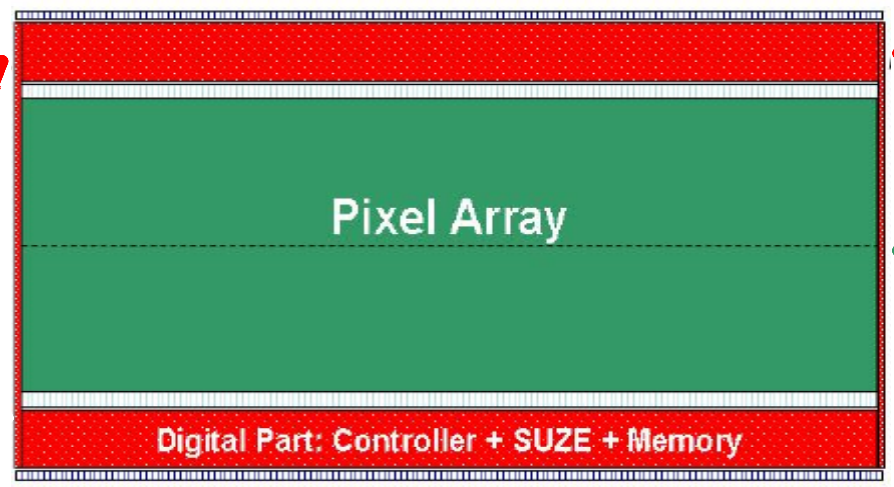
- baseline (**thin plate**)
  - thin electronics (100 µm)
  - thin cooling (130 µm)



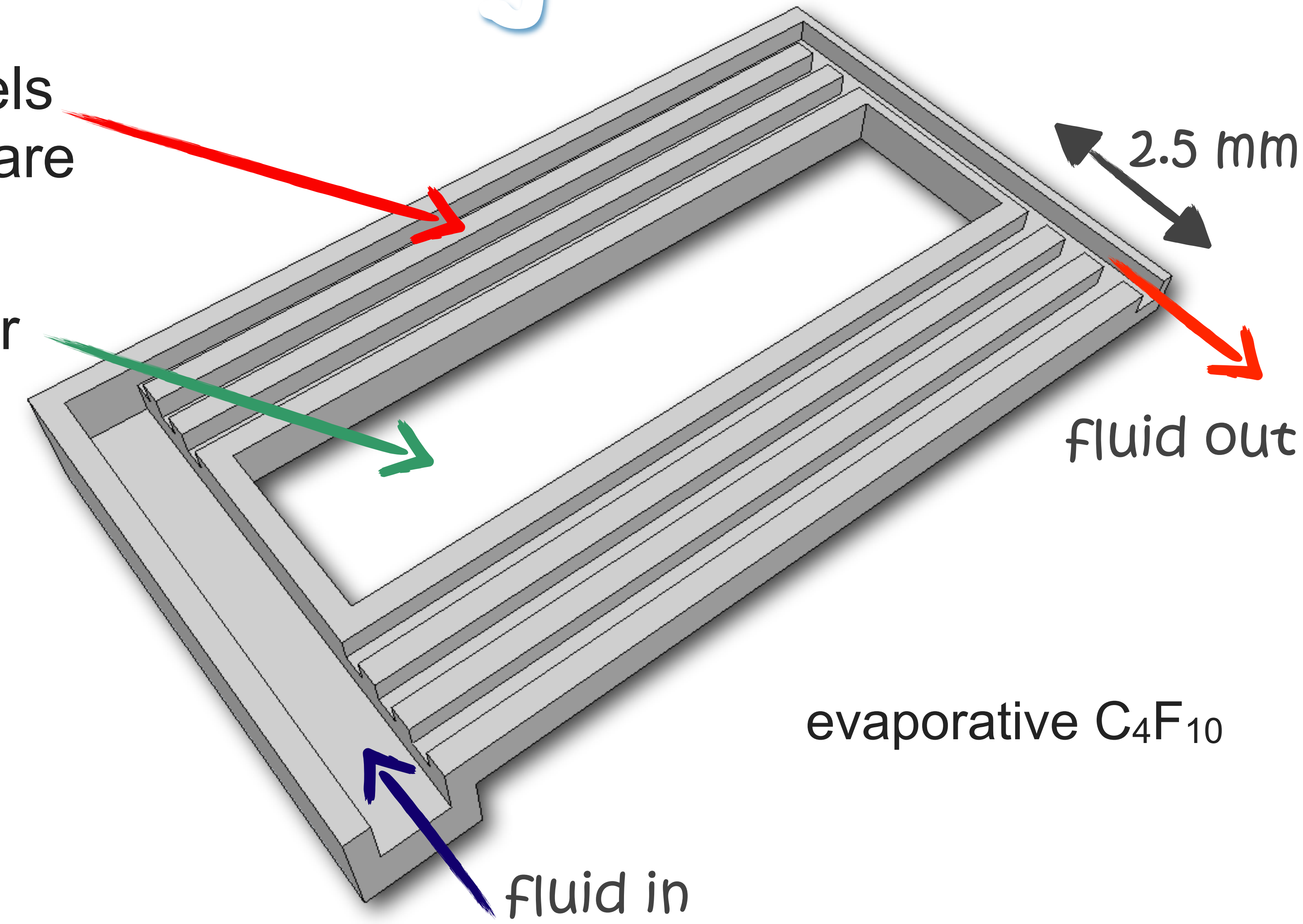
- alternative (**frame**)
  - thicker electronics (200 µm)
  - no silicon in acceptance (0 µm)

ALICE silicon cooling frame

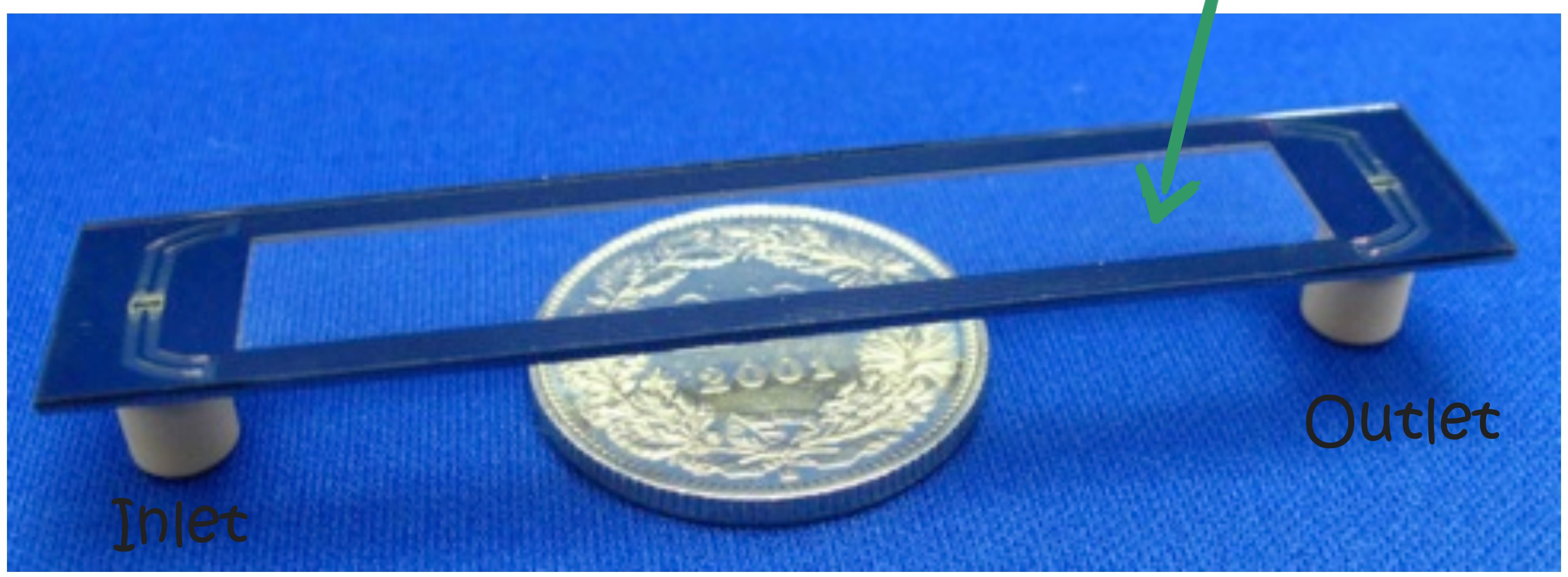
heat sources
0.5 W/cm^2

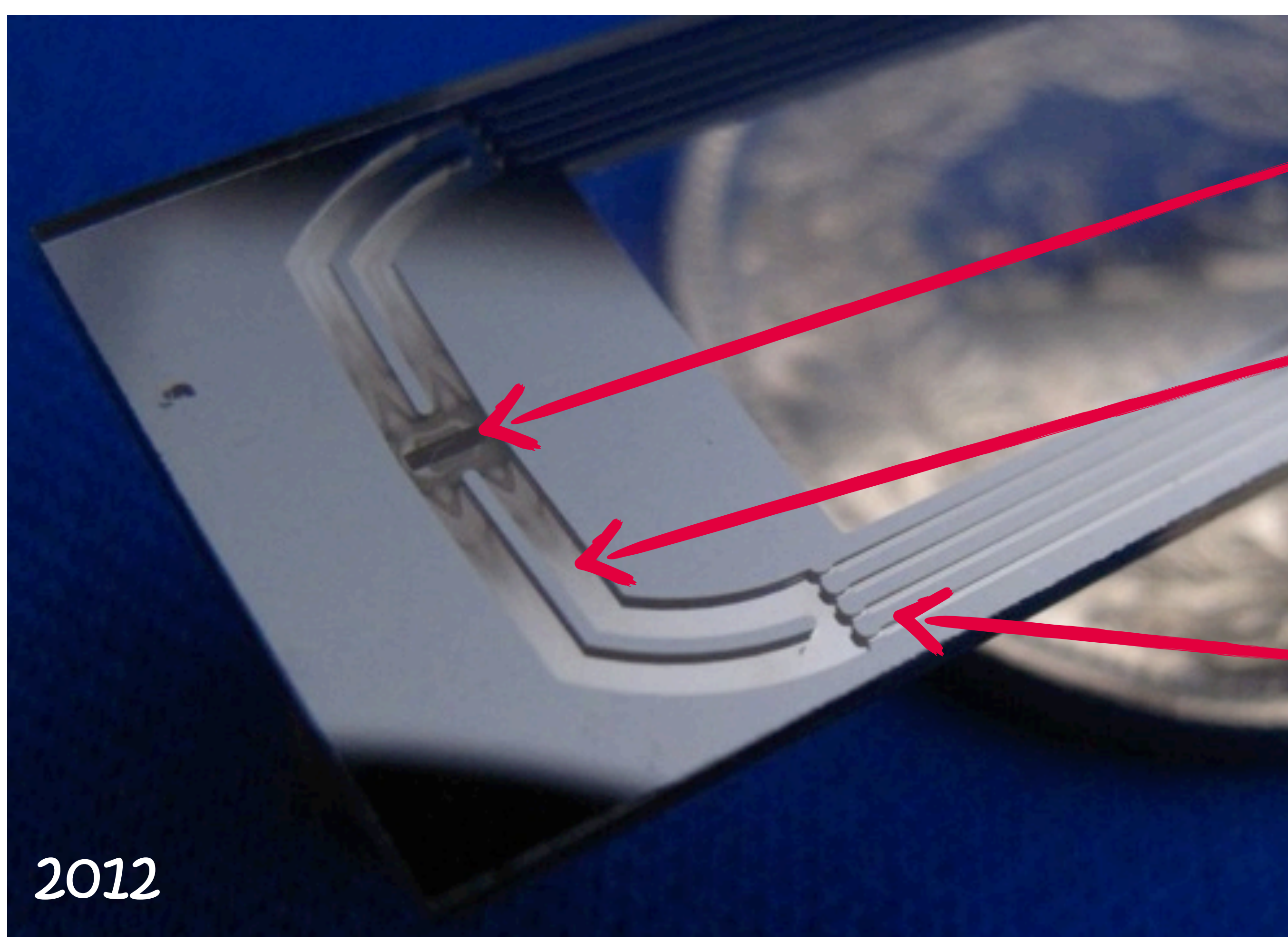


- cooling μ-channels only where they are needed
- no material under detector

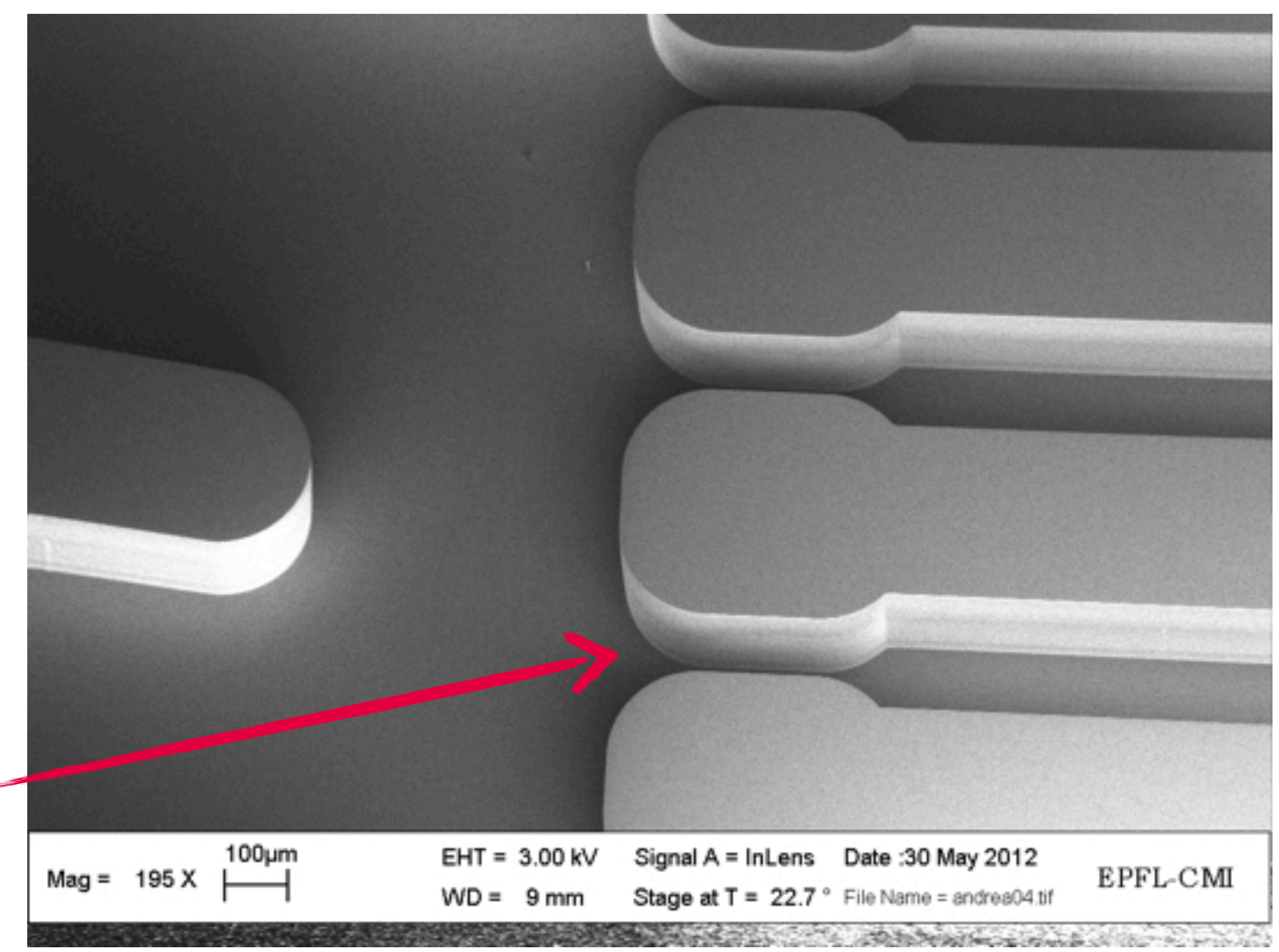


evaporative C_4F_{10}



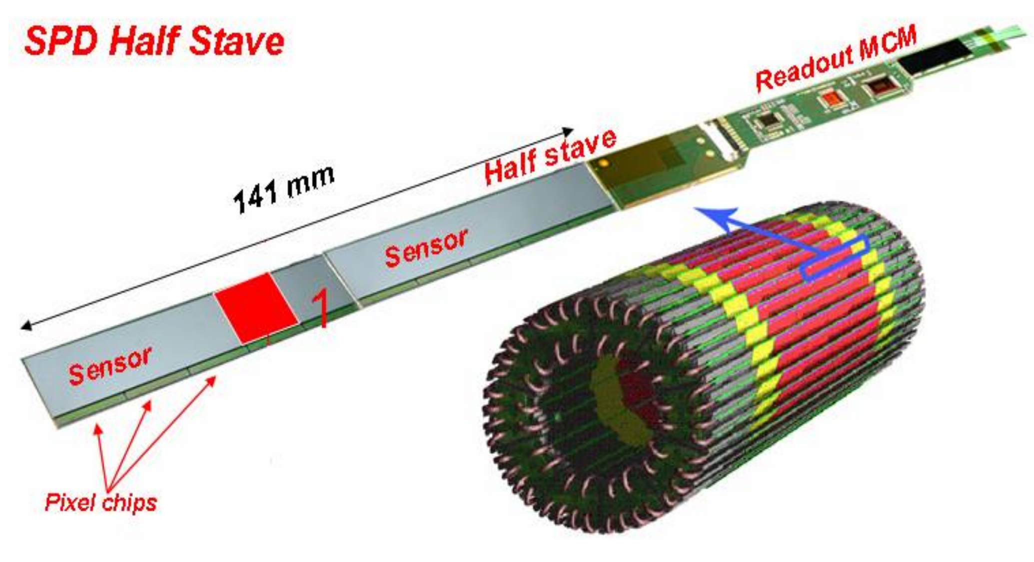


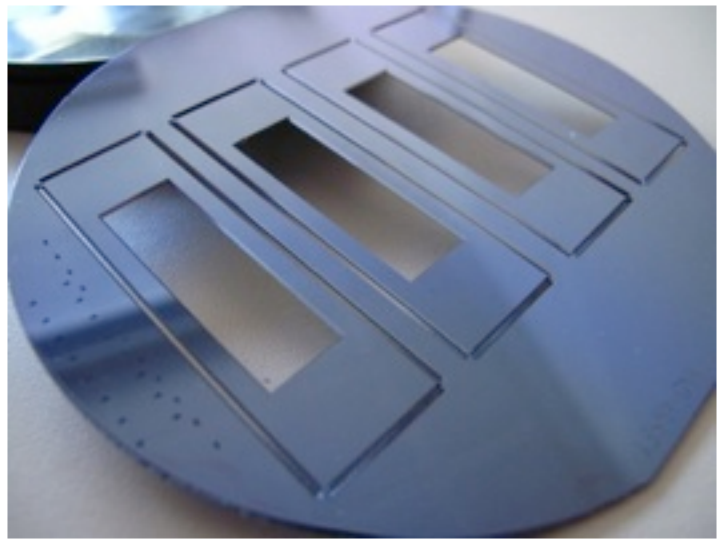
- Inlet
- distribution manifold
- μ-channels restrictions



ALICE.. towards a stave

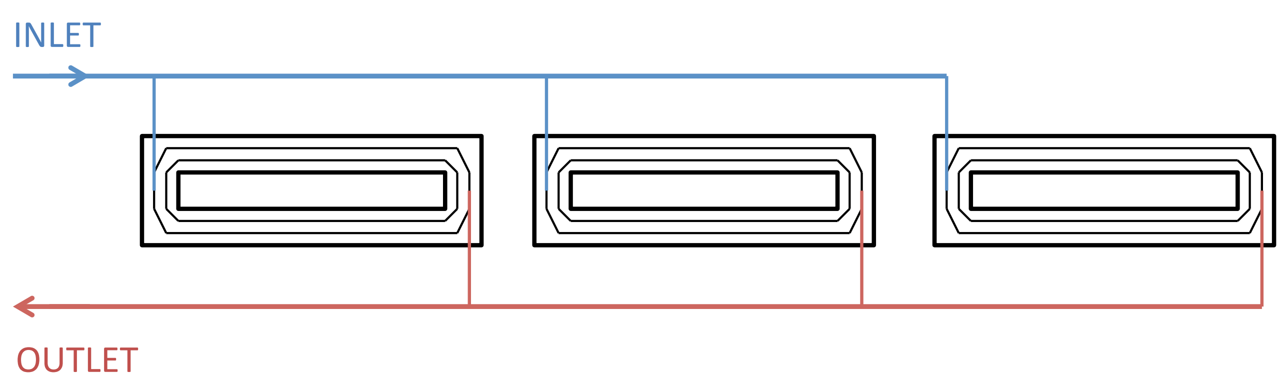
The cooling has to be performed on about 300 mm but the length of the cooling frames is limited by the diameter of the Si wafers.

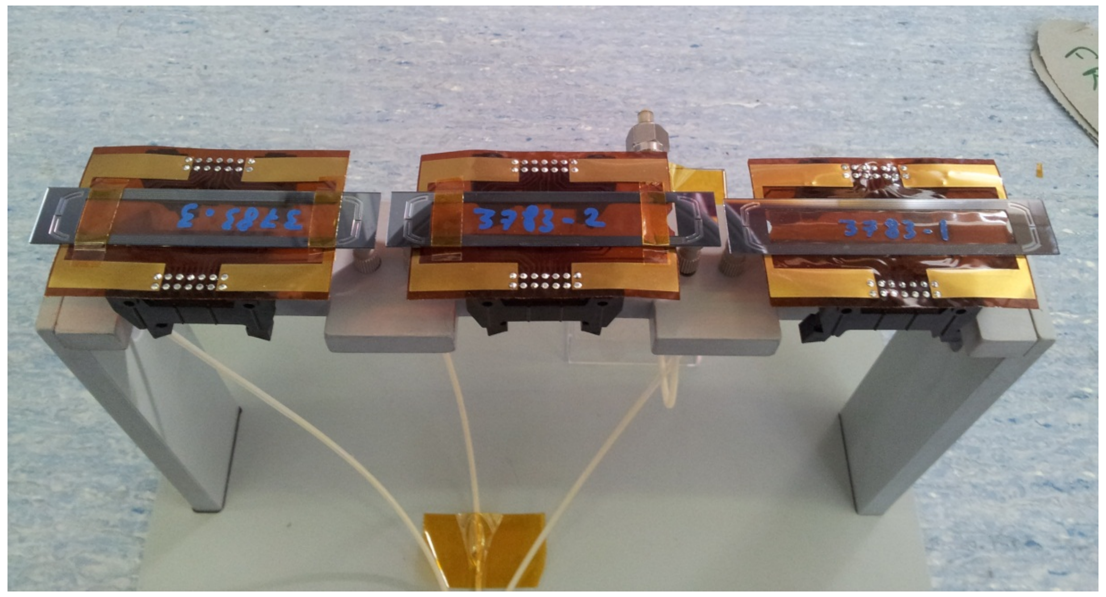




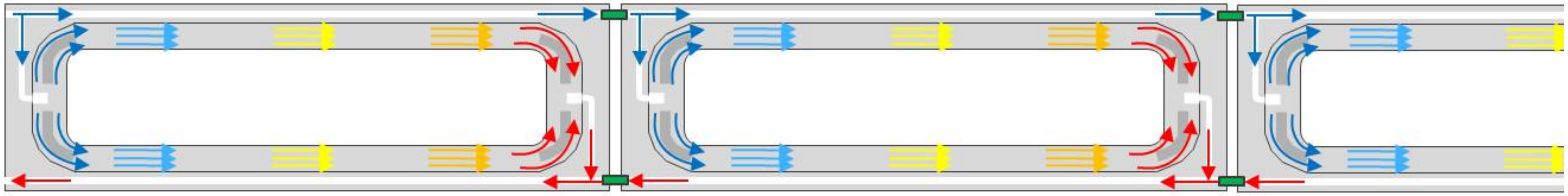
Si wafers, 100 mm diameter.

The proof of principle is performed by daisy-chaining several frames.





A new fabrication process is being developed to connect the frames in-plane with needles.



publication of latest results

to appear in Microelectronics Journal

JINST

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Microfluidic cooling for detectors and electronics

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ABSTRACT: Micro-channel cooling is gaining considerable attention as an alternative technique for cooling of high energy physics detectors and front-end electronics. This technology is being evaluated for future tracking devices, where material budget limitations are a major concern. It is currently under investigation as an option for the cooling of the NA62 Gigatracker silicon pixel detector, where a micro-fabricated silicon cooling plate would stand directly in the beam. Other possible applications are also being studied in the context of LHC detectors upgrades. In this paper, the current status of this R&D at CERN is presented.

KEYWORDS: Detector cooling and thermo-stabilization; Particle tracking detectors (Solid-state detectors)

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Application of Micro-channel Cooling to the Local Thermal Management of Detectors Electronics for Particle Physics

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ABSTRACT:

Micro-channel cooling is gaining considerable attention as an alternative technique for cooling of high energy physics detectors. This is of particular interest for future trackers, where large surfaces are involved and the amount of material must be drastically reduced. Combining the flexibility of standard micro-fabrication processes with the high thermal efficiency typical of micro-fluidics, it is possible to produce effective thermal management devices well adapted to different specific applications. The first case presented is the NA62 GTK silicon pixel detector, where low temperature liquid fluid will be circulated in a micro-fabricated silicon plate locally thinned to 130 µm in the detector sensitive area. Other applications are presently being developed for evaporative cooling in the context of the ALICE and LHCb detector upgrades at LHC. In the former case the devices are being optimized for low pressure/room temperature evaporation; in the latter for high pressure and temperature below 0°C.

KEYWORDS: electronic cooling, micro-channels, thermal management.

1 MICRO-CHANNEL COOLING IN HEP

Local thermal management through micro-fluidic devices is already under study for possible implementation in future 3D architectures for high power computing. In this context, highly effective micro-fabricated cooling devices, capable of dealing with power densities up to 700 W/cm^2 have been recently proposed. Examples span from 2 mm thick silicon assemblies designed for single phase water cooling [1] to few-mm thick copper plates optimized for two-phase refrigerants [2].

When designing the on-board cooling for High Energy Physics (HEP) tracking detectors, the power densities involved are two order of magnitude lower than in high power computing (typically in the range 0.5÷4 W/cm^2). However, large surfaces of silicon detectors are used and, depending on the detector size, a total heating power up to few tens of few kW must be removed. For this kind of application several important issues must be addressed, including the minimization of:

- The amount of material crossed by particles;
- The temperature difference between heat source and heat sink for a given quantity of heat to be removed;
- The temperature gradients on the surface of the sensor.

Furthermore, the detector layout is often very packed and geometrically complex, thus only limited space is available for piping and connections. In many cases, in order to preserve the silicon sensor from severe degradation caused by the high level of radiation, it is also necessary to operate and maintain the detectors at negatives temperatures (typically in the range -10÷-20°C) [3]: this increases the impact of CTE mismatch problems between the silicon heat source and a metal heat sink. The thermal management of today's trackers is based on complex networks of mm-size metallic pipes (Fig. 1). The pipes are locally brought in connection with the region where the highest concentrated heat sources are located through heat spreaders, specifically designed to be compliant with mutual displacements due to CTE mismatch. Due to the small contact surfaces and the long chains of thermal resistances typical of these configurations, the temperature difference between the module surface and the coolant ranges typically between 15 and 20°C (see e.g. [4]).

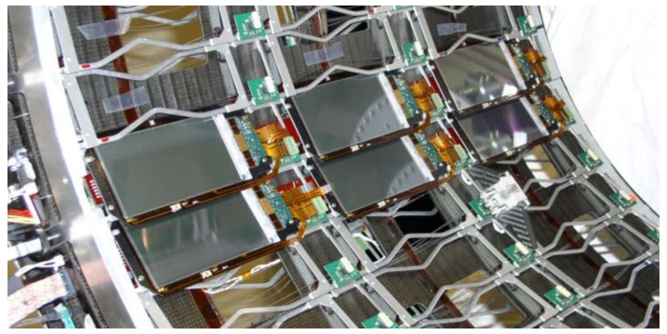
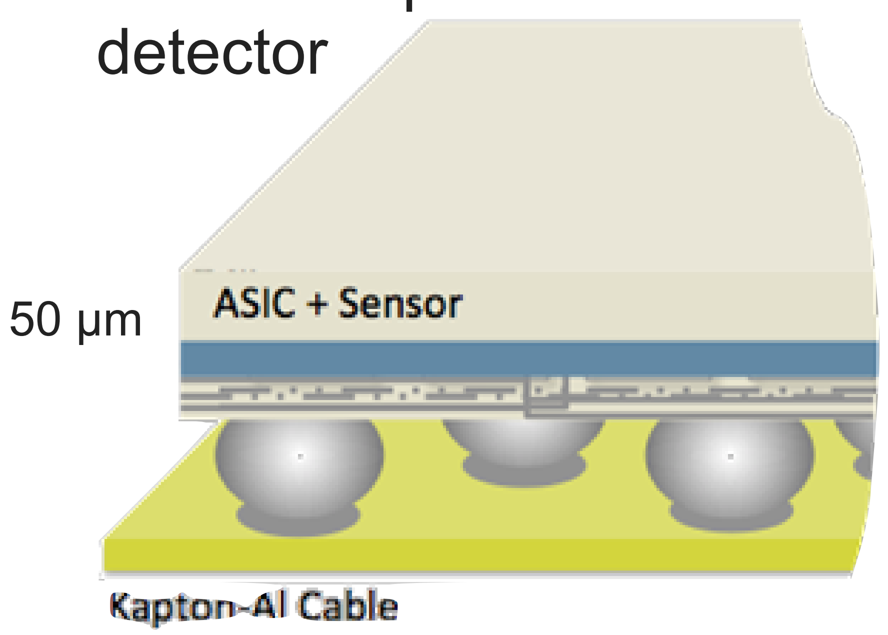


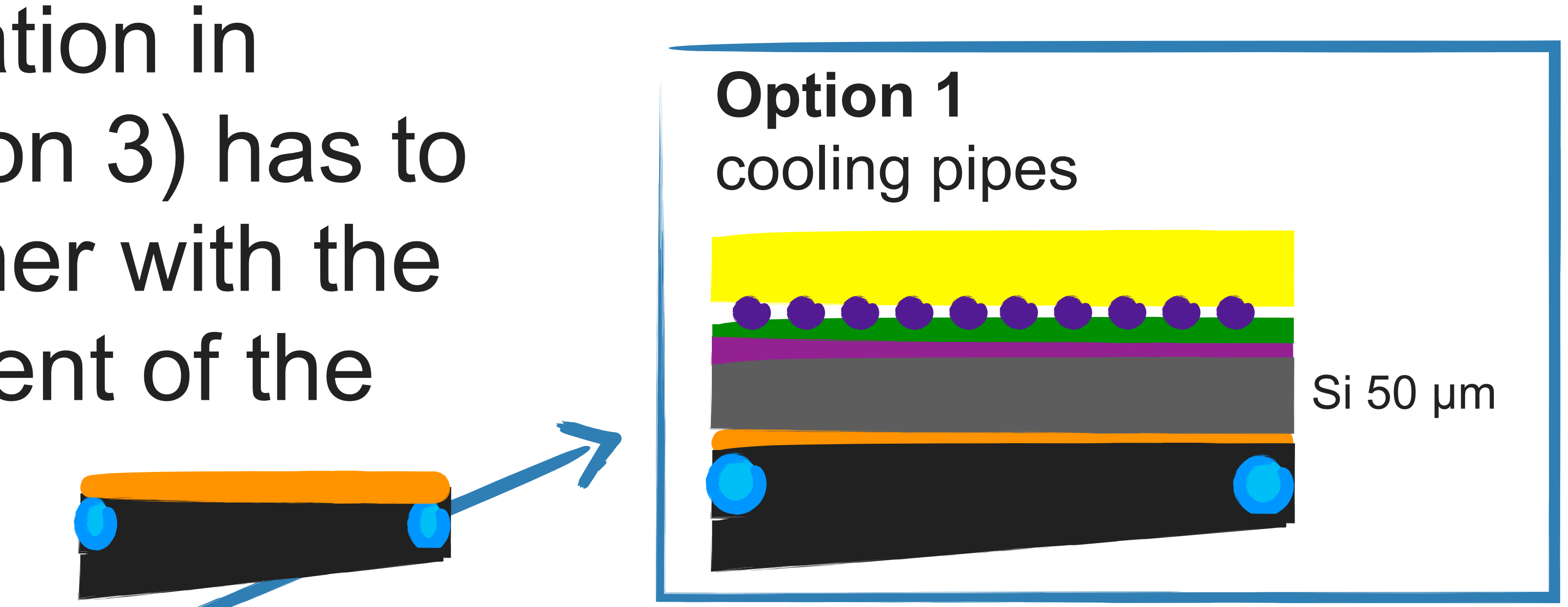
Figure 1: Typical cooling pipe network in today's trackers

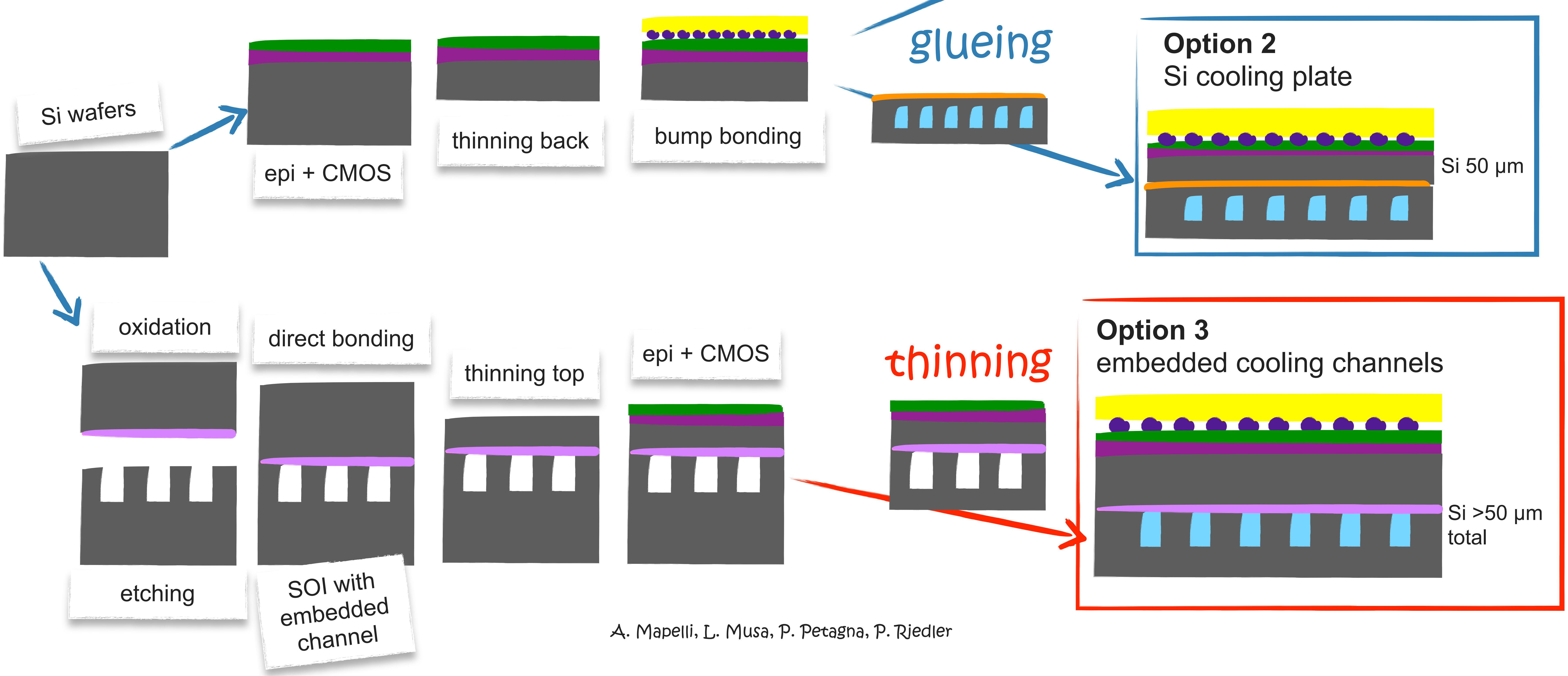
Local thermal management through silicon micro-fluidic devices, in connection with either single-phase or two-phase flow, is a good candidate for solving all the above mentioned issues [5], [6]. The concept, schematically depicted in Fig. 2 for the case of a Pixel tracking detector, is extremely simple: a thin micro-structured silicon plate with the same shape and size of the detector module to be cooled is placed in contact with the heat source by an adhesive layer. As the contact surface between the heat source and the heat sink is maximized and the power density is not

towards integrated cooling



Microchannels integration in silicon detectors (option 3) has to be investigated together with the design and development of the detectors.





A. Mapelli, L. Musa, P. Petagna, P. Riedler

SOI: Silicon-On-Insulator

How SOI wafers are made

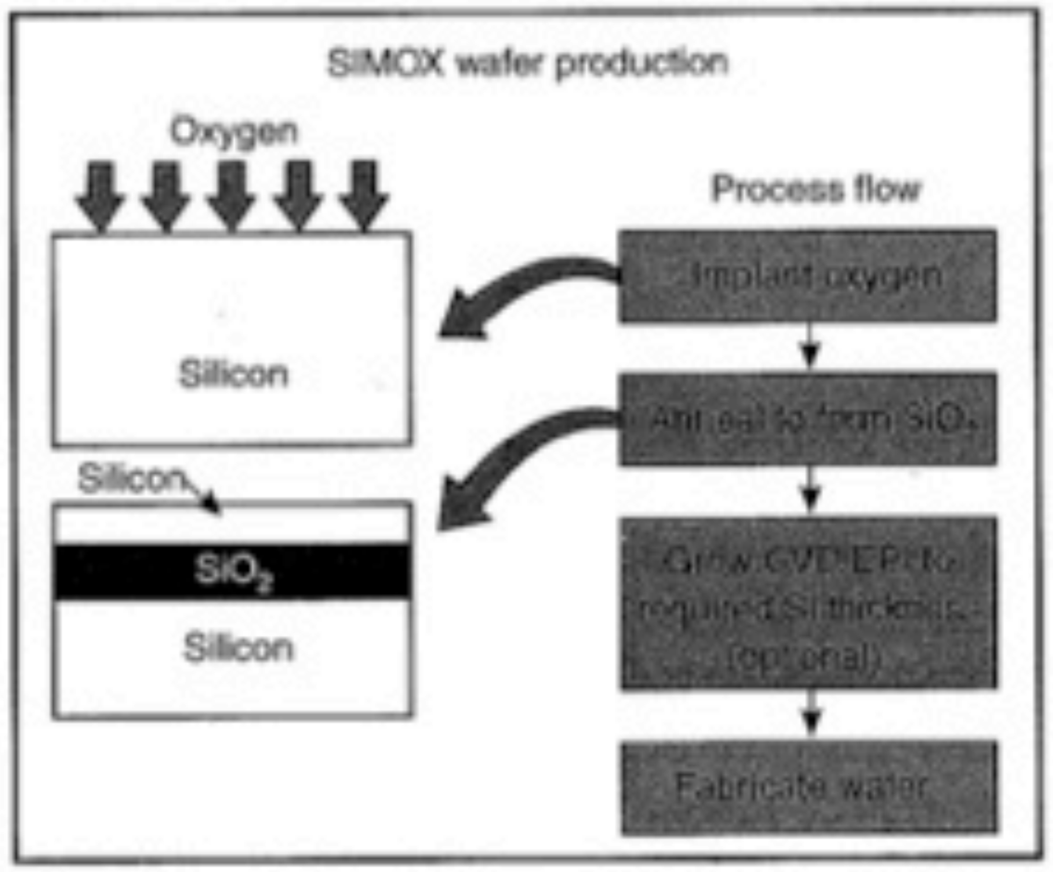
[From P. N. Dunn, *Solid State Technol.*, October, 32–35 (1993). Copyright 1993 PennWell Publishing Company, with permission.]

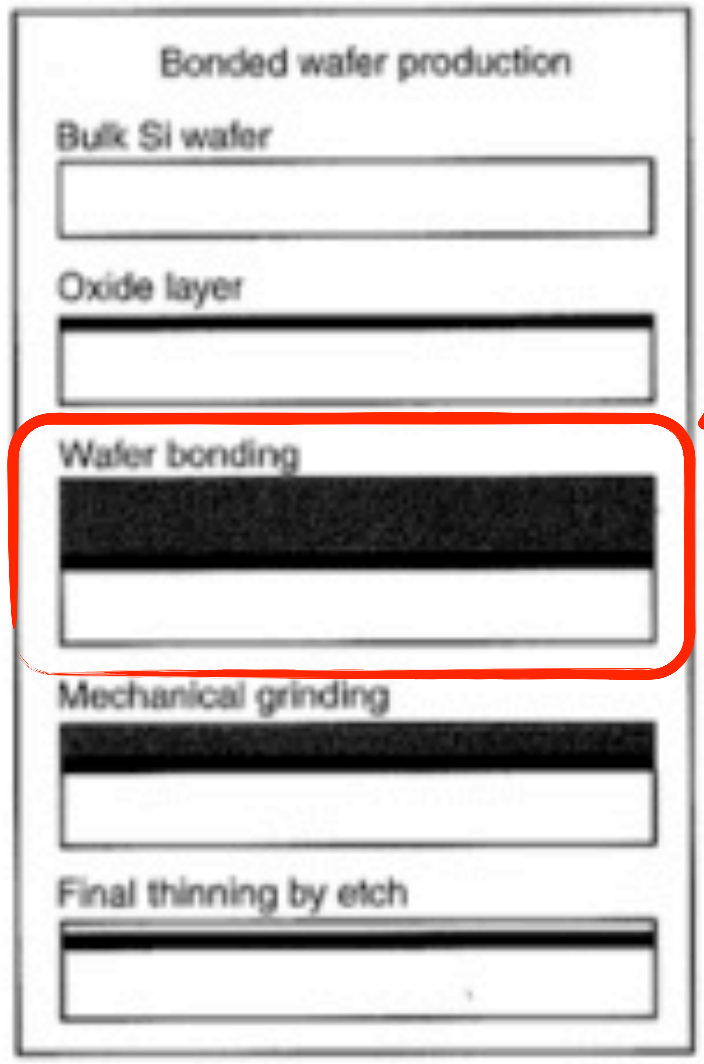
Many different silicon-on-insulator materials have been developed over the years, but two are currently being used for IC production: SIMOX (Separated by IMplanted OXygen) and bonded wafers.

In the SIMOX process, a standard silicon wafer is implanted with oxygen ions and then annealed at high temperatures; the oxygen and silicon combine to form a silicon oxide layer beneath the wafer surface. To minimize wafer damage, the oxygen is sometimes implanted in two or more passes, each followed by an anneal. The oxide layer's thickness and depth are controlled by varying the energy and dose of the implant and the anneal temperature. In some cases, a CVD process is used to deposit additional silicon on the top layer.

The bonded wafer process starts with an oxide layer of the desired thickness (typically 0.25 to 2 microns) being grown on a standard silicon wafer. That wafer is then bonded at high temperatures to another wafer, with the oxide sandwiches between. One of the wafers is then ground to a thickness of a few microns using a mechanical tool.

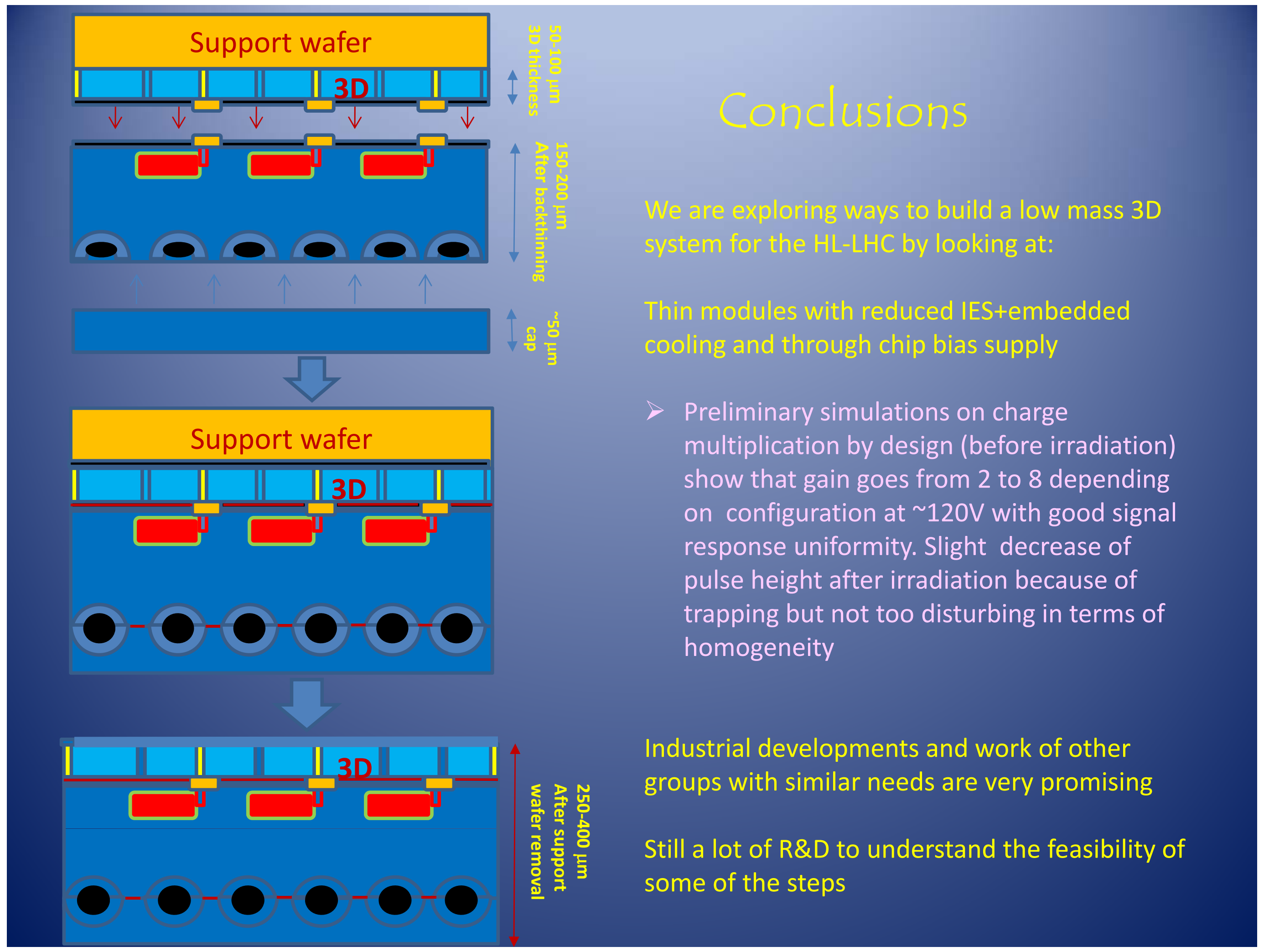
Because advanced devices require an even thinner layer, more silicon must be removed. The wafer may be etched with a confined plasma, between 3 and 30 mm wide, which is stepped across the wafer surface. A film thickness map is made for each wafer and used to compute the dwell time for the plasma etcher at each stop. The process can be repeated for additional precision. Silicon thicknesses of a little as 1000 to 3000 Å, with total thickness variation of 200 Å have been achieved. IBM has also developed an etch-back process for bonded wafers.



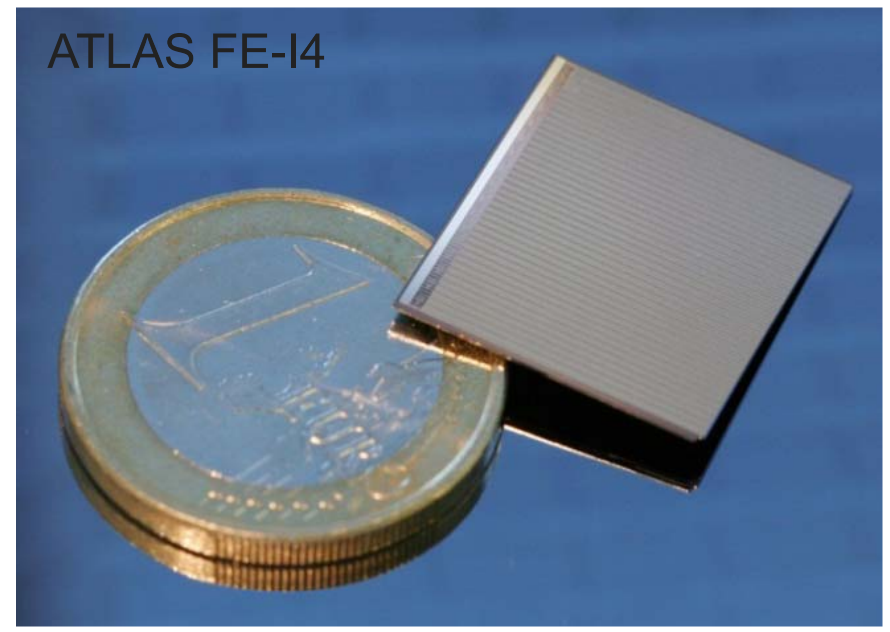


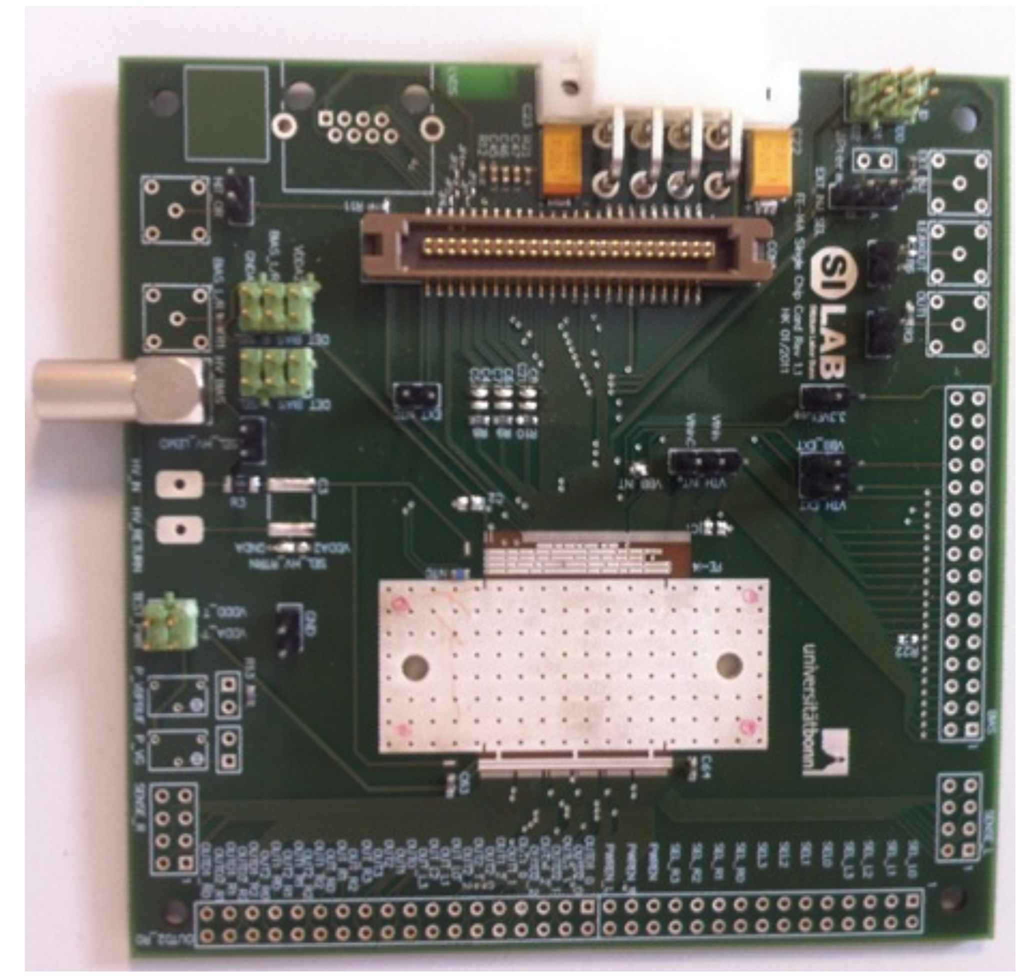
bonding of a wafer with microchannels instead of bulk silicon

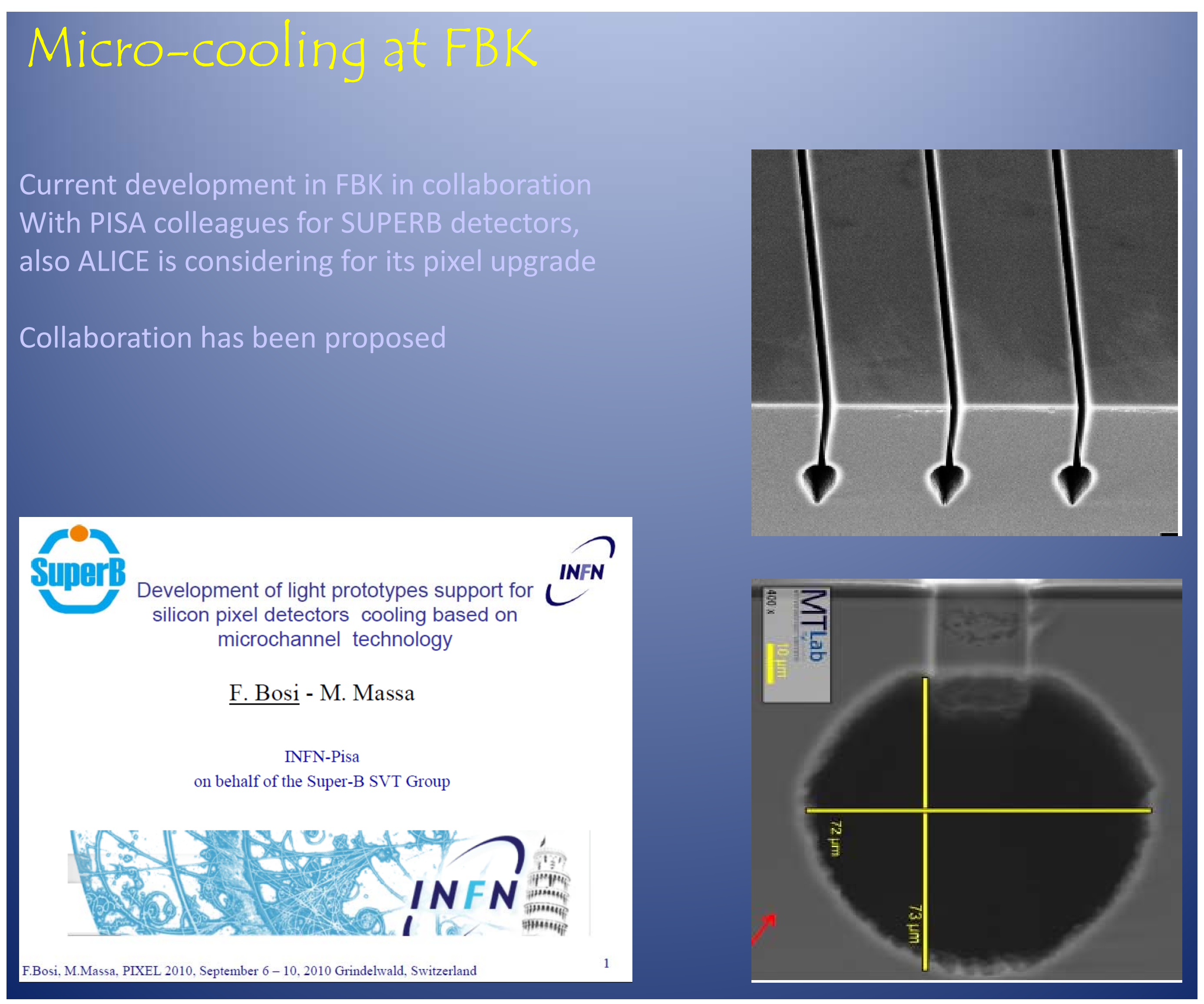
micro-cooling studies for future inner layers of ATLAS Pixels



the heat dissipated by the electronics chip is 1.1W/chip and 0.24W/3D sensor, i.e., overall heat dissipation would be ~1.35W/hybrid. These values are valid for IBL. ATLAS upgrade will result in much higher fluences and, hence, in higher sensor current consumption and, consequently, much higher heat dissipation. Thus, we will also try to make tests with heat dissipation higher than 1.35W/hybrid.

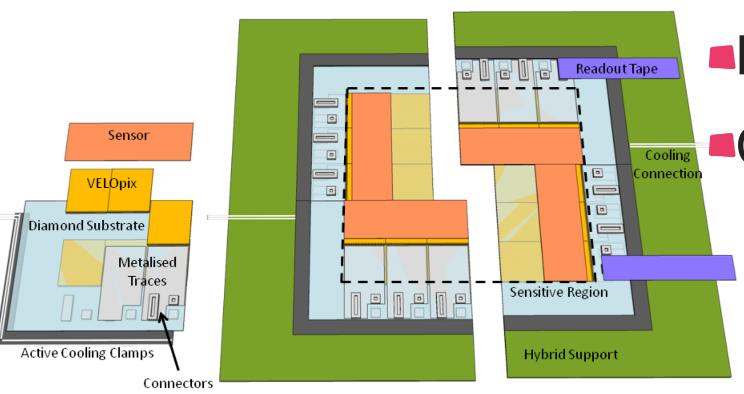






First batch of silicon microcoolers finished.
To be tested in the coming days.

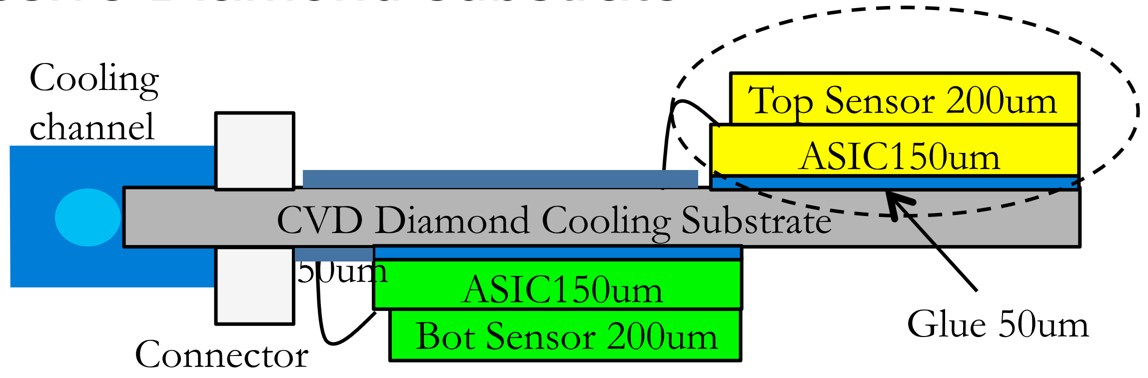
LHCb VeLo upgrade..CO_2 in microchannels



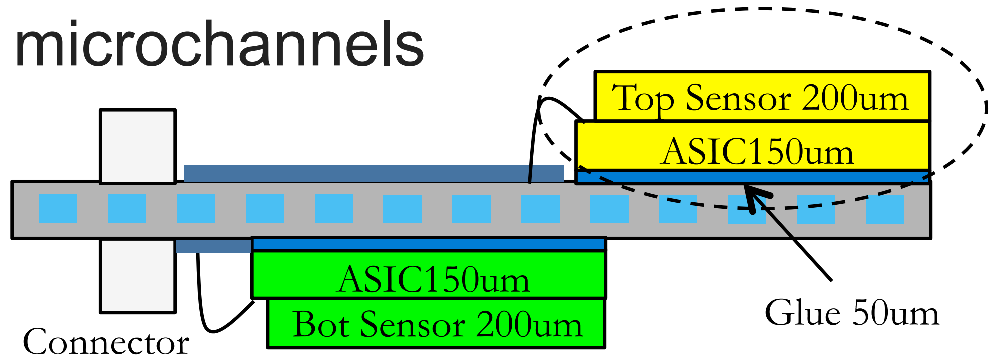
Cooling requirements

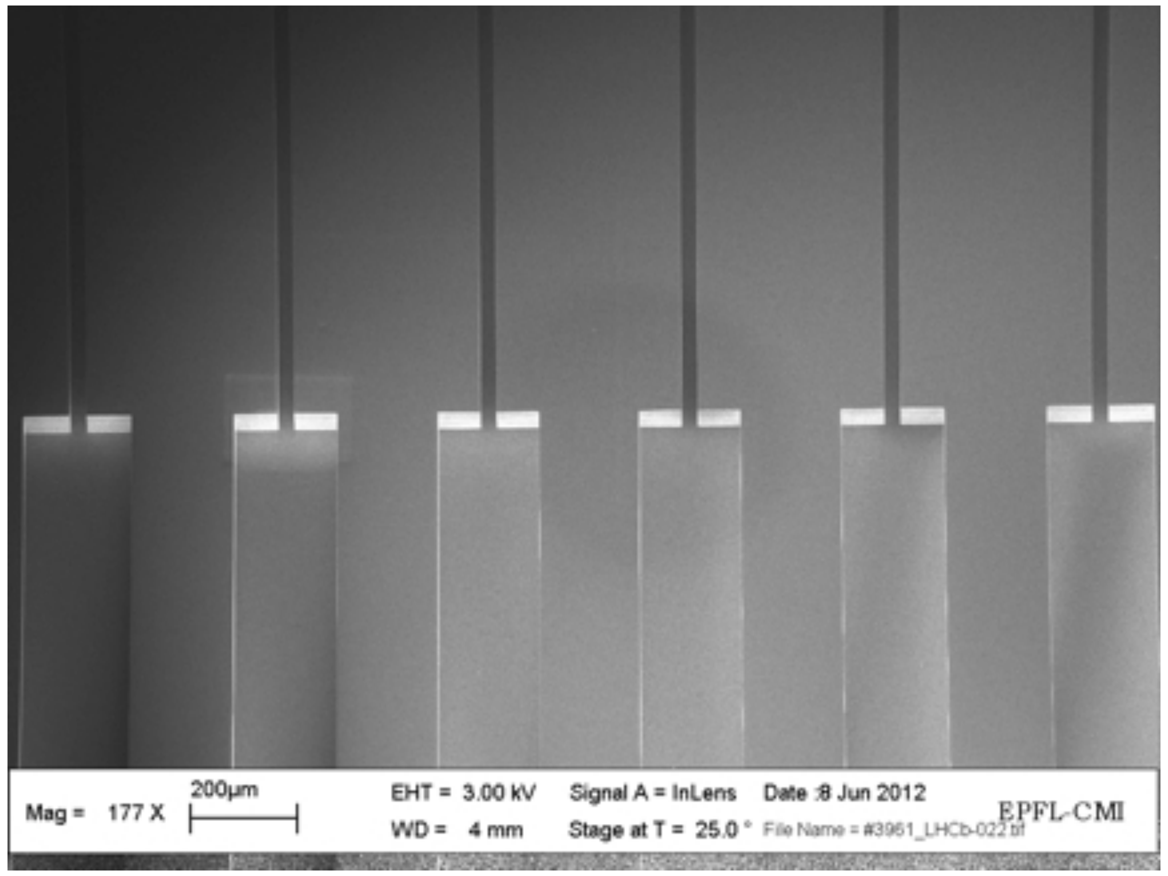
- Diss. power:~2 W/cm^2
- Cooling substrate
  - in acceptance: <500 μm
  - out of acceptance: 1mm

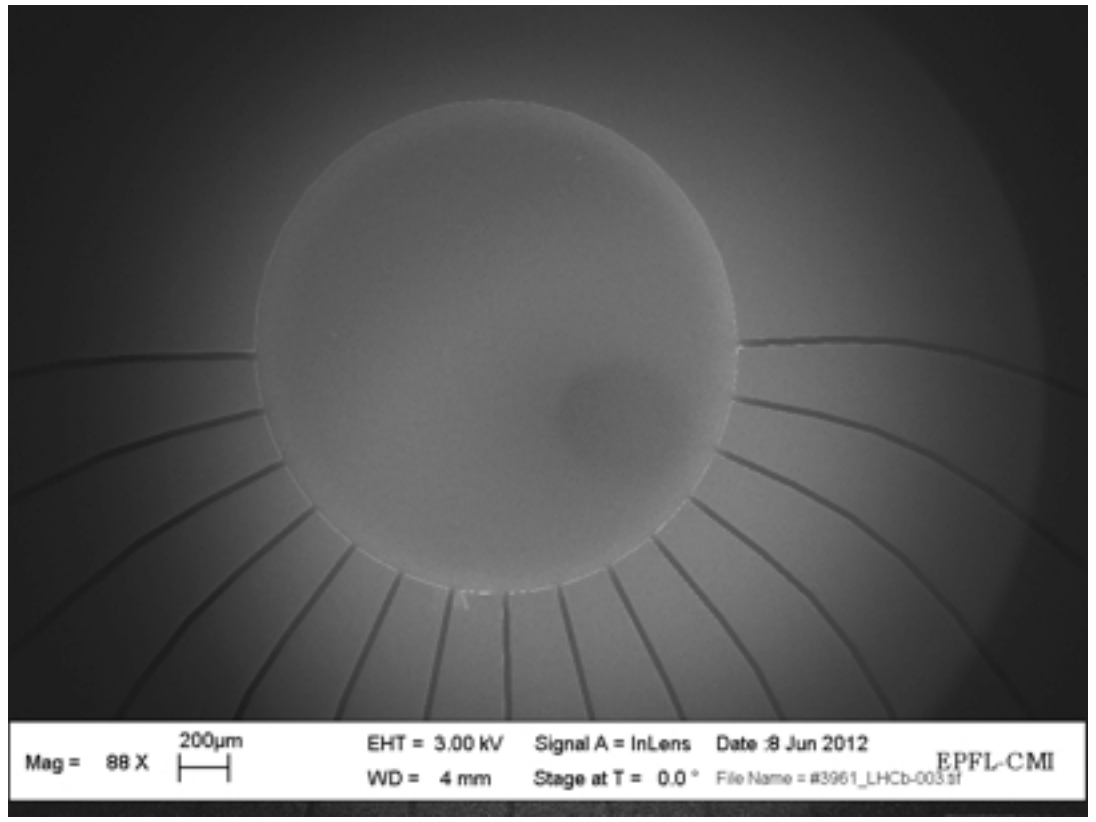
passive Diamond substrate

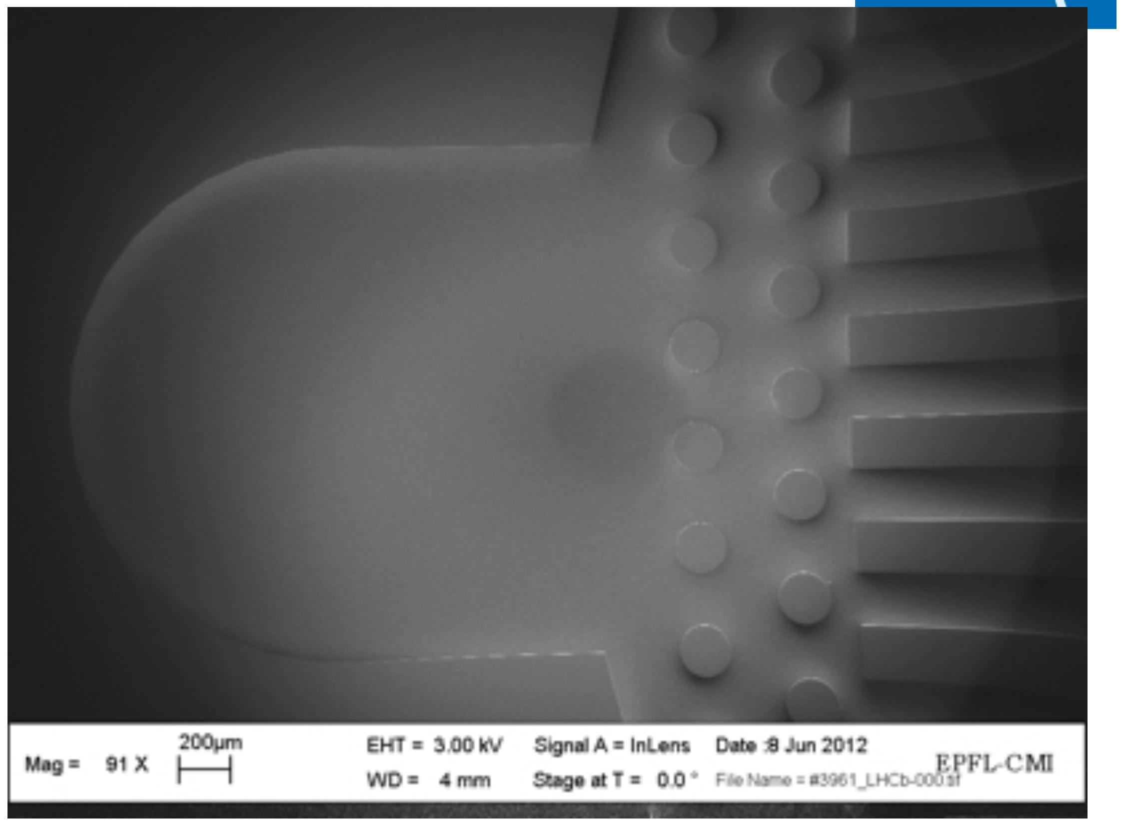


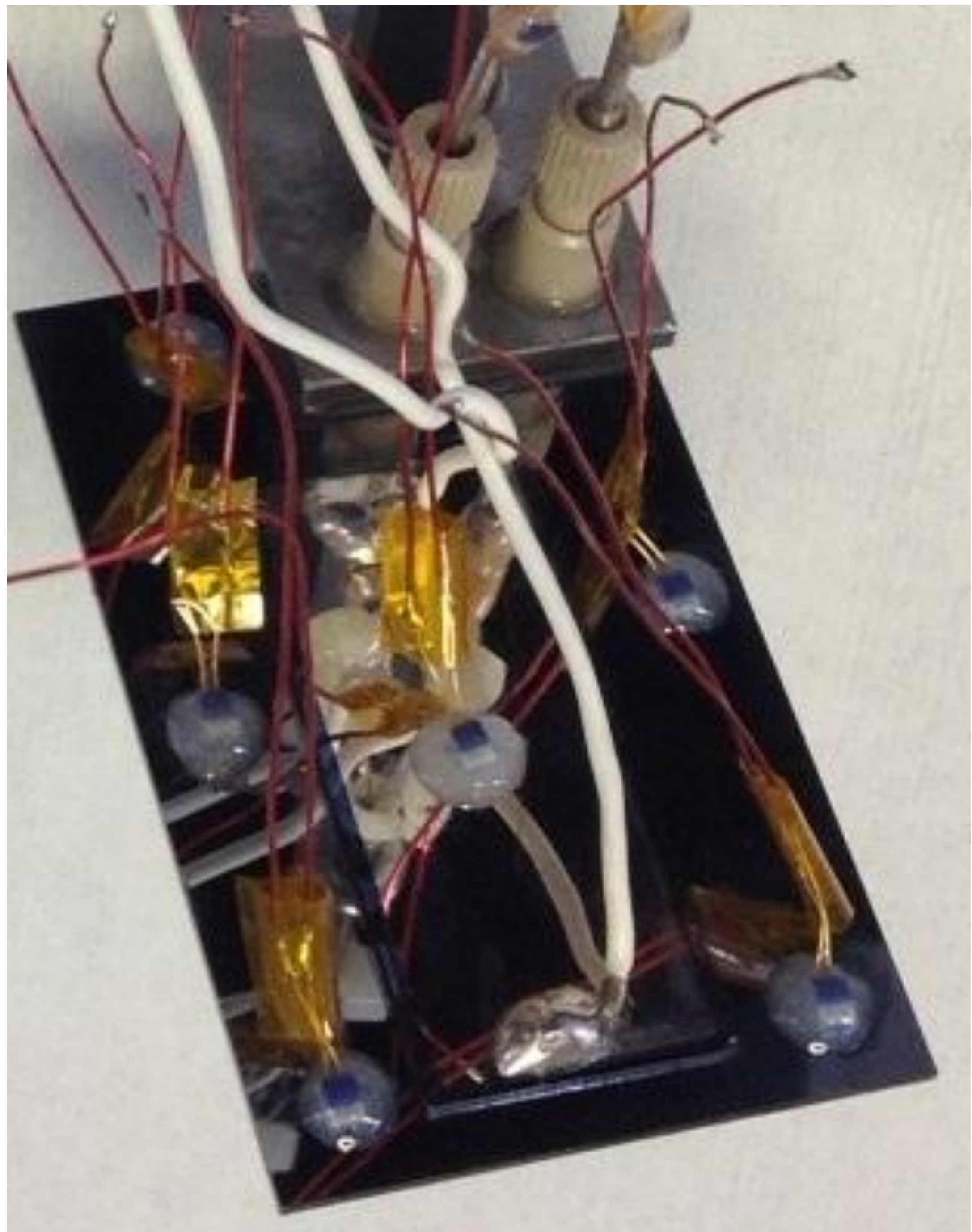
Silicon microchannels











LHCb VeLo upgrade..CO_2 in microchannels

First experimental results submitted to NIM

Evaporative CO_2 cooling using microchannels etched in silicon for the future LHCb vertex detector

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Abstract

The extreme radiation dose received by vertex detectors at the Large Hadron Collider dictates stringent requirements on their cooling systems. To be robust against radiation damage, sensors should be maintained below -20°C and at the same time, the considerable heat load generated in the readout chips and the sensors must be removed. Evaporative CO_2 cooling using microchannels etched in a silicon plane in thermal contact with the readout chips is an attractive option. In this paper, we present the first results of microchannel prototypes with circulating, two-phase CO_2 and compare them to simulations. We also discuss a practical design of upgraded VELO detector for the LHCb experiment employing this approach.

Keywords: Silicon sensor; vertex detector; CO_2 cooling; microchannel

CLIC.. preliminary discussions

NUCLEAR ELECTRONICS & COMPUTING

XXIII International Symposium
Varna, Bulgaria, September 12-19, 2011

Proceedings of the Symposium

NEC'2011

ЯДЕРНАЯ ЭЛЕКТРОНИКА И КОМПЬЮТИНГ

XXIII Международный симпозиум
Варна, Болгария, 12-19 сентября 2011 г.

Труды симпозиума

Дубна 2011

Detector challenges at the CLIC multi-TeV e^+e^- collider

D. Dannheim[1]
CERN, European Organisation for Nuclear Research, Geneva, Switzerland

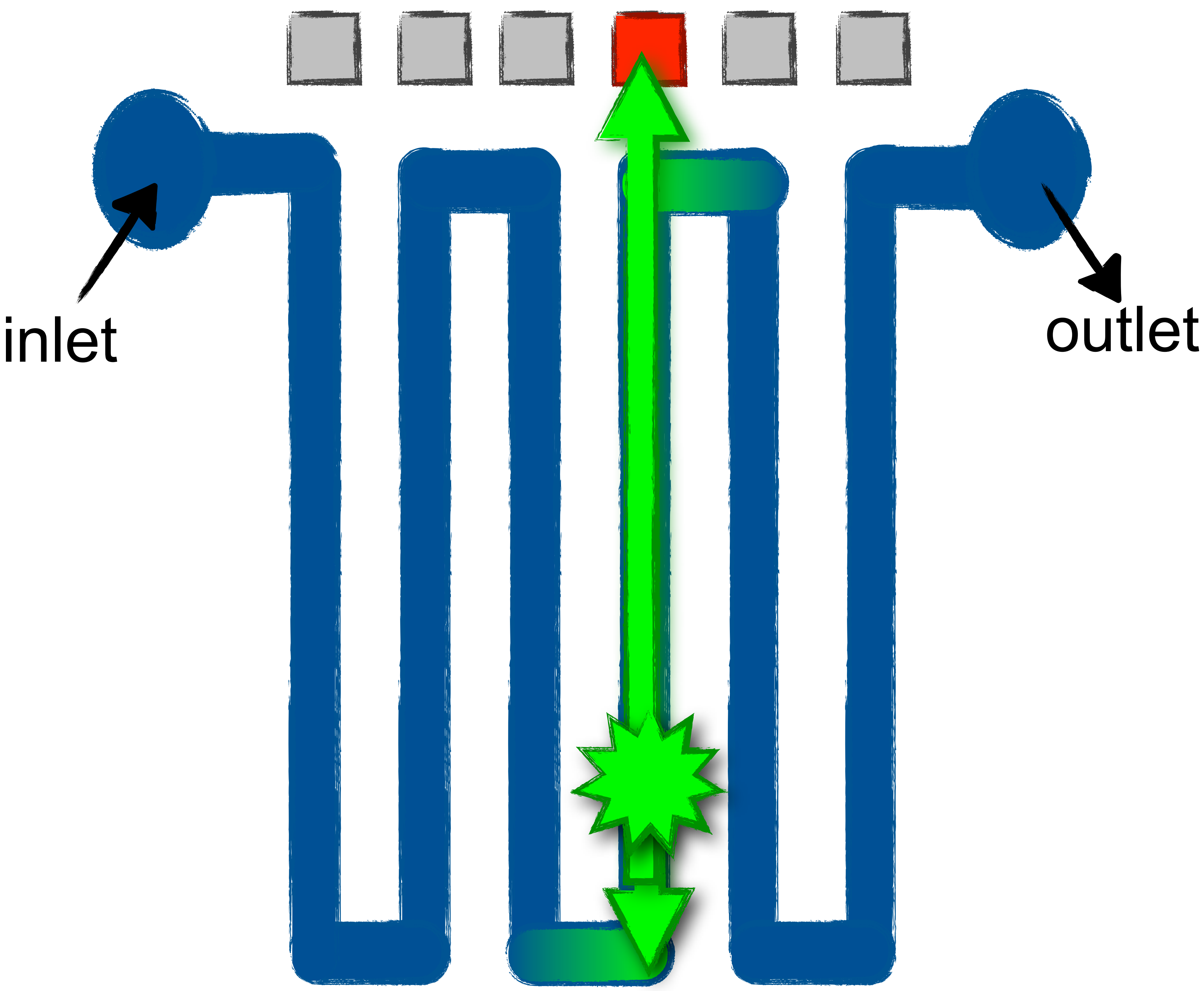
- *Low-mass cooling solutions*. A total power of approximately 500 W will be dissipated in the vertex detectors alone. The small material budget for the inner tracking detectors constrains severely the permitted amount of cooling infrastructure. For the vertex barrel layers, forced air-flow cooling is therefore foreseen. Fig. 6 shows a calculation of the temperature distribution inside the barrel layers of the CLIC_SiD vertex detector in dependence of the air-flow rate. A flow rate of up to 240 liter / s, corresponding to a flow-velocity of 40 km/h, is required to keep the temperatures at an acceptable level. Further R&D is required to demonstrate the feasibility of this air-flow cooling scheme. Possible vibrations arising from the high flow velocities are of particular concern. Supplementary micro-channel cooling [6] or water-based under-pressure cooling may be required in the forward vertex regions;

[6] A. Mapelli et al. Low material budget microfabricated cooling devices for particle detectors and front-end electronics. Nucl. Phys. Proc. Suppl., 215, 2011, pp. 349–352.

microfluifidic scintillation detectors

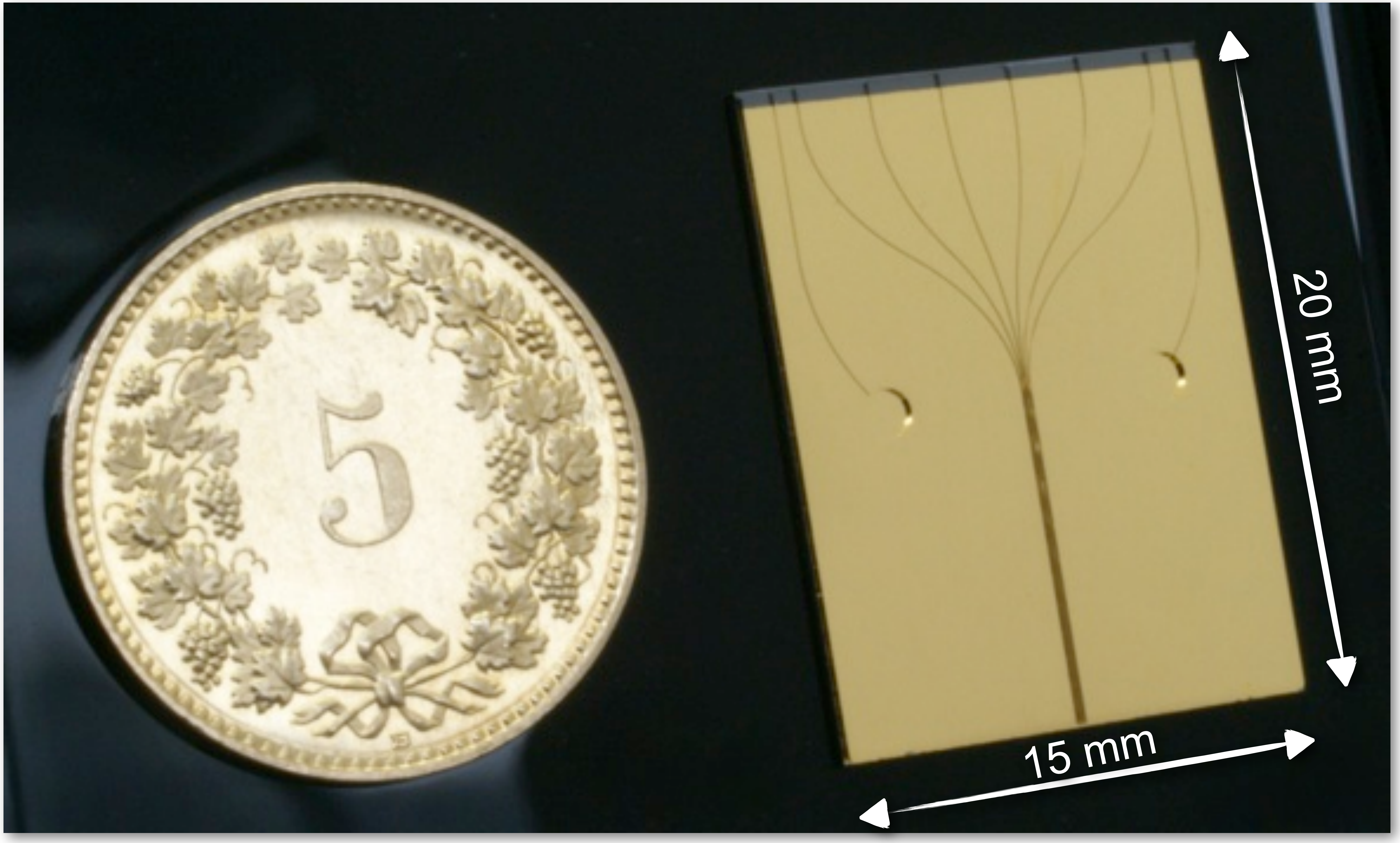
a single μ-fluidic channel

defines an array of scintillating waveguides



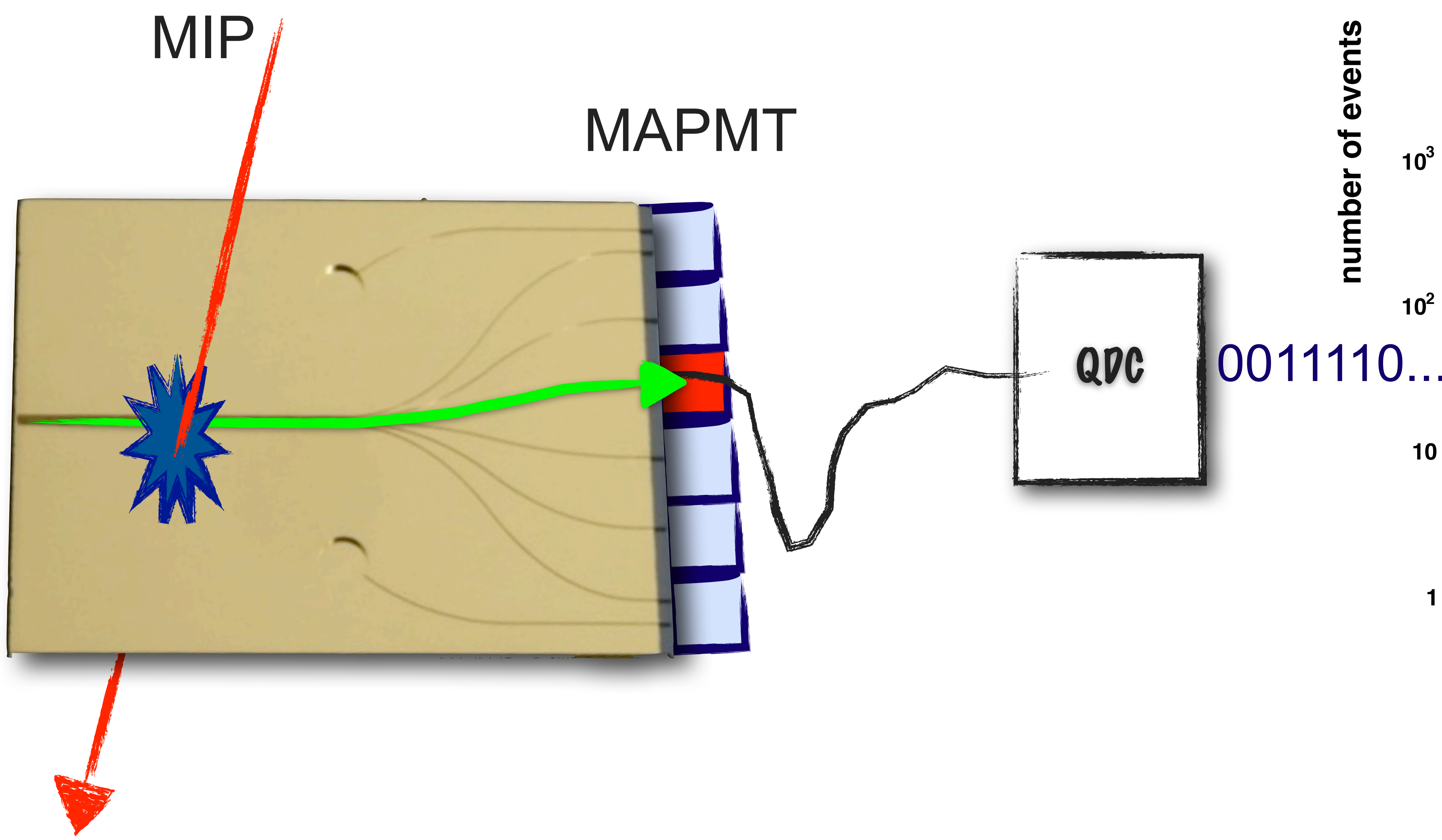
- simple construction
  - standard μ-fabrication processes
- low material budget
  - thin μ-fluidic devices
- high spatial resolution
  - dense arrays of μ-channels
- high radiation resistance
  - liquid scintillator can be circulated and renewed

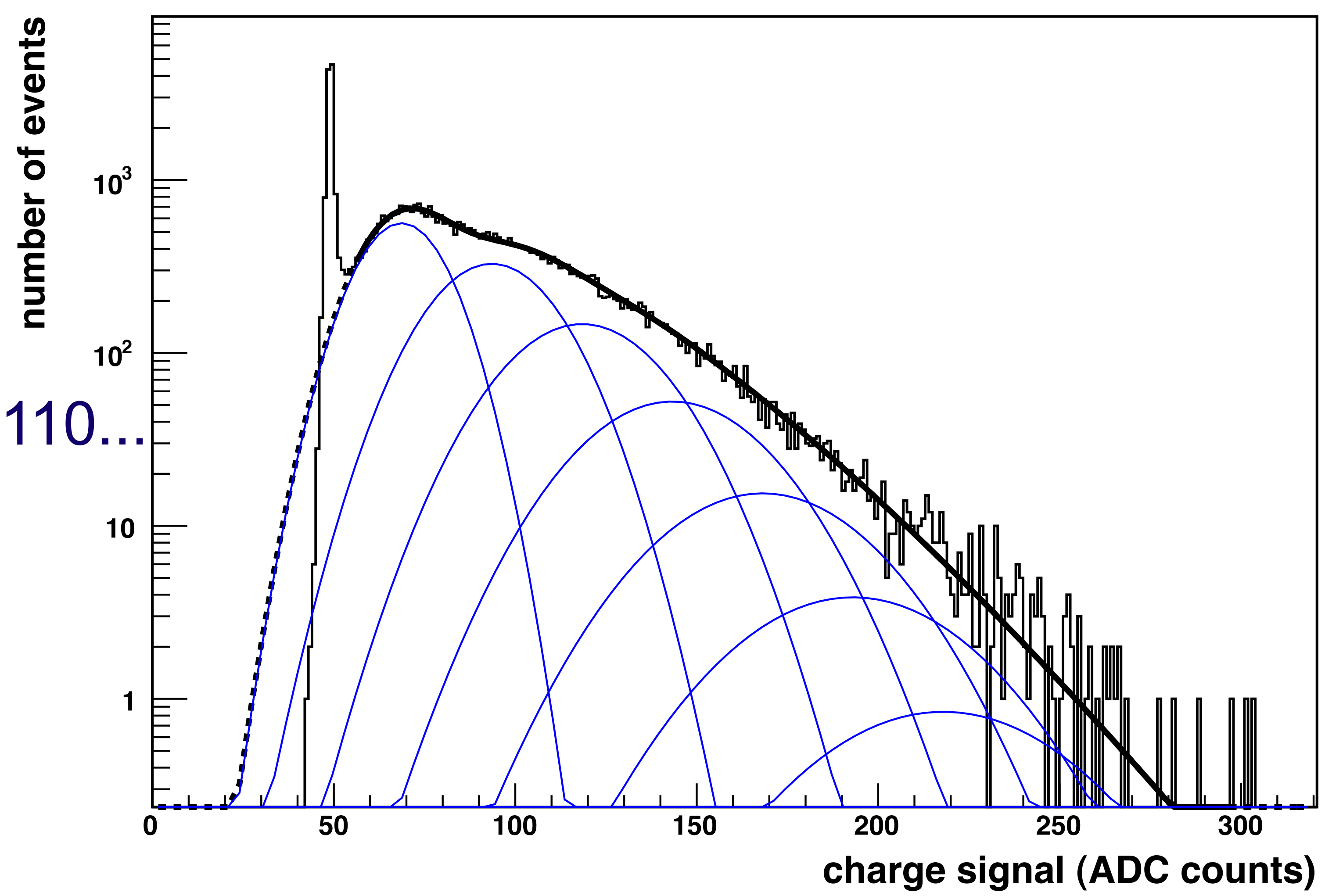
microfluidic scintillation detector



single photolithography step
200 µm thick micro-channels
50 µm wide channels separated by 10 µm walls

experimental results

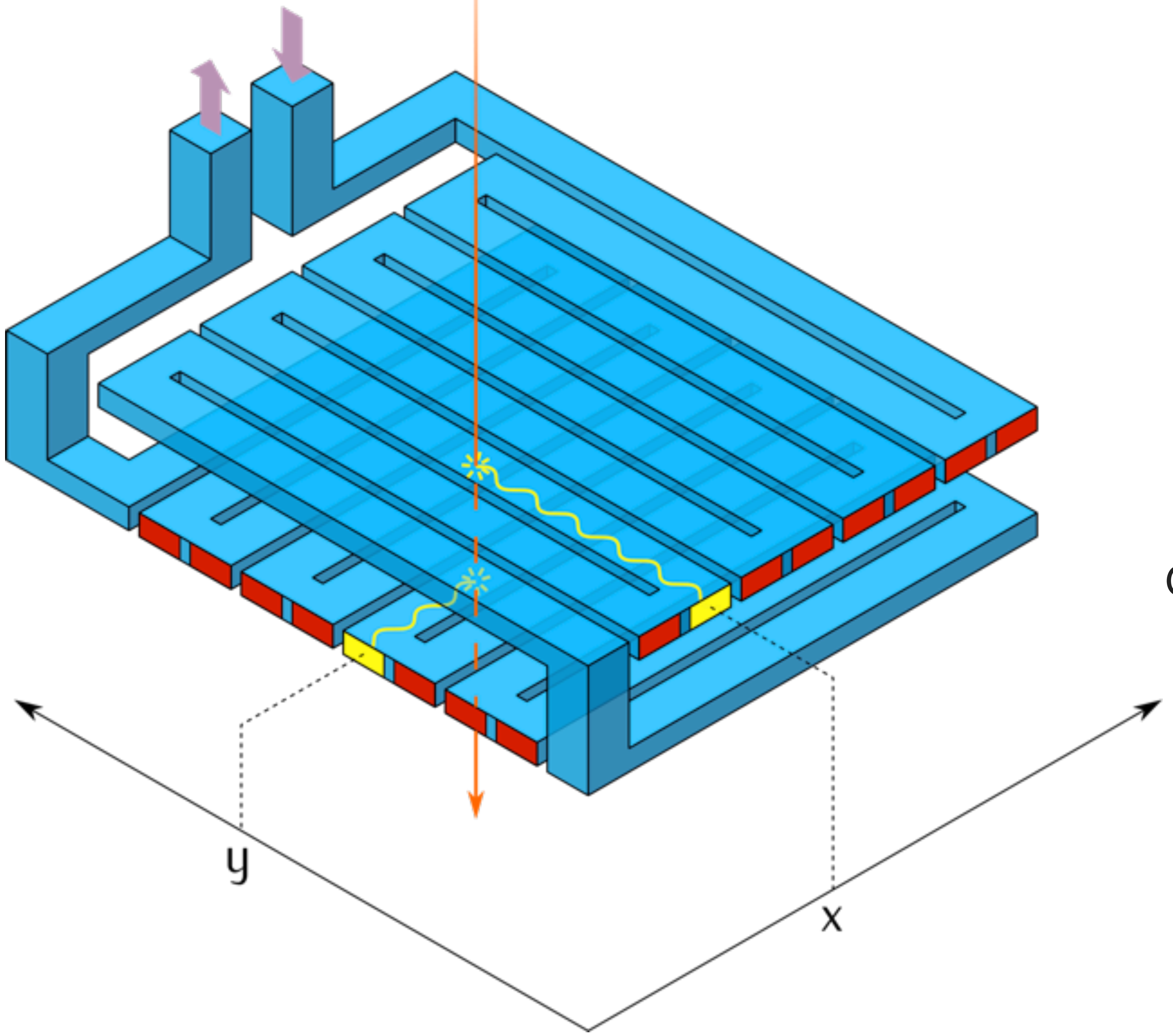




light yield = 1.6 pe
detection efficiency 80%

A. Mapelli *et al.*, *Sens. Act. A 162 (2010) 272-275*

XY.. bi-layer microfluidic device



CERN group
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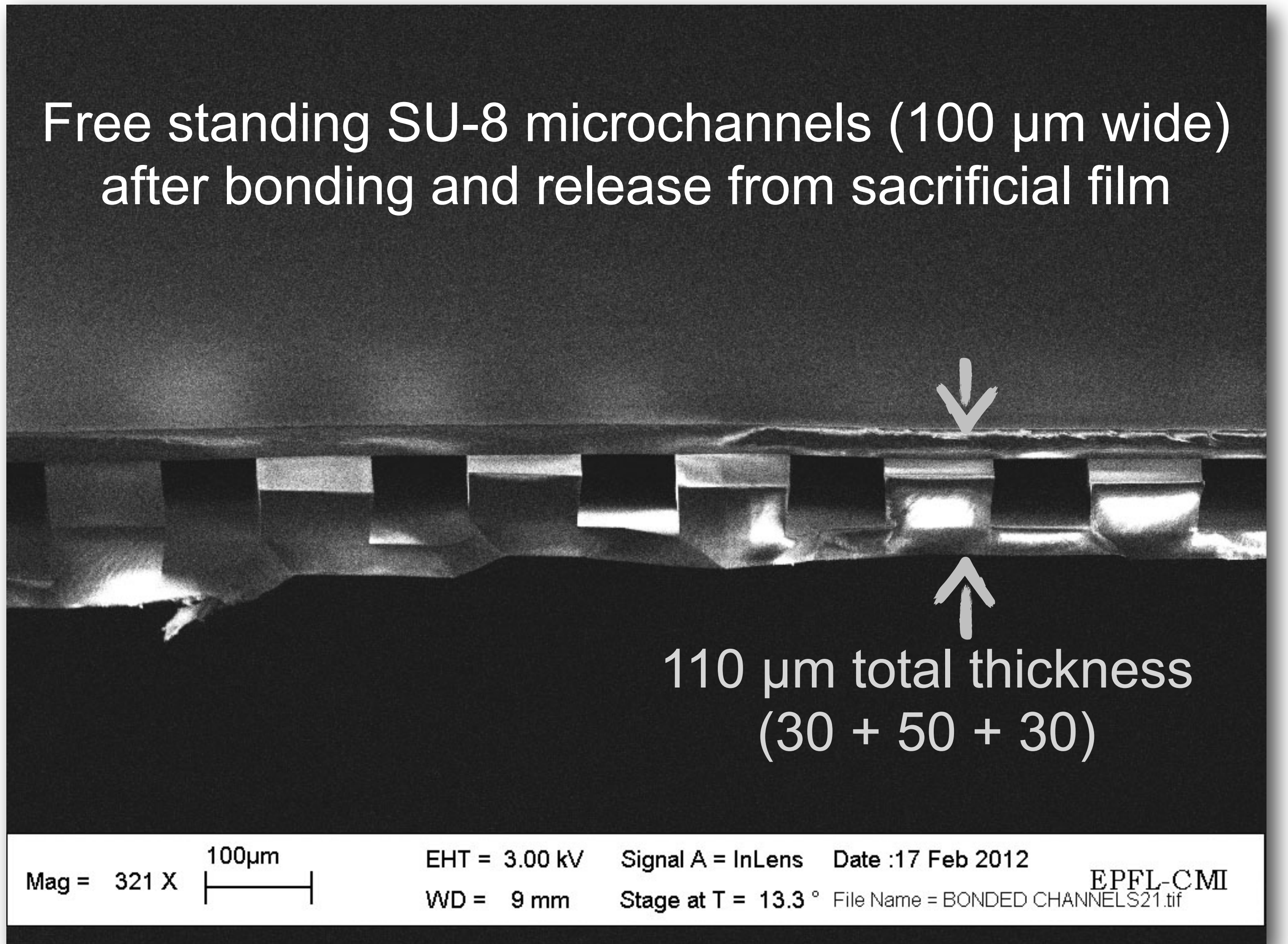
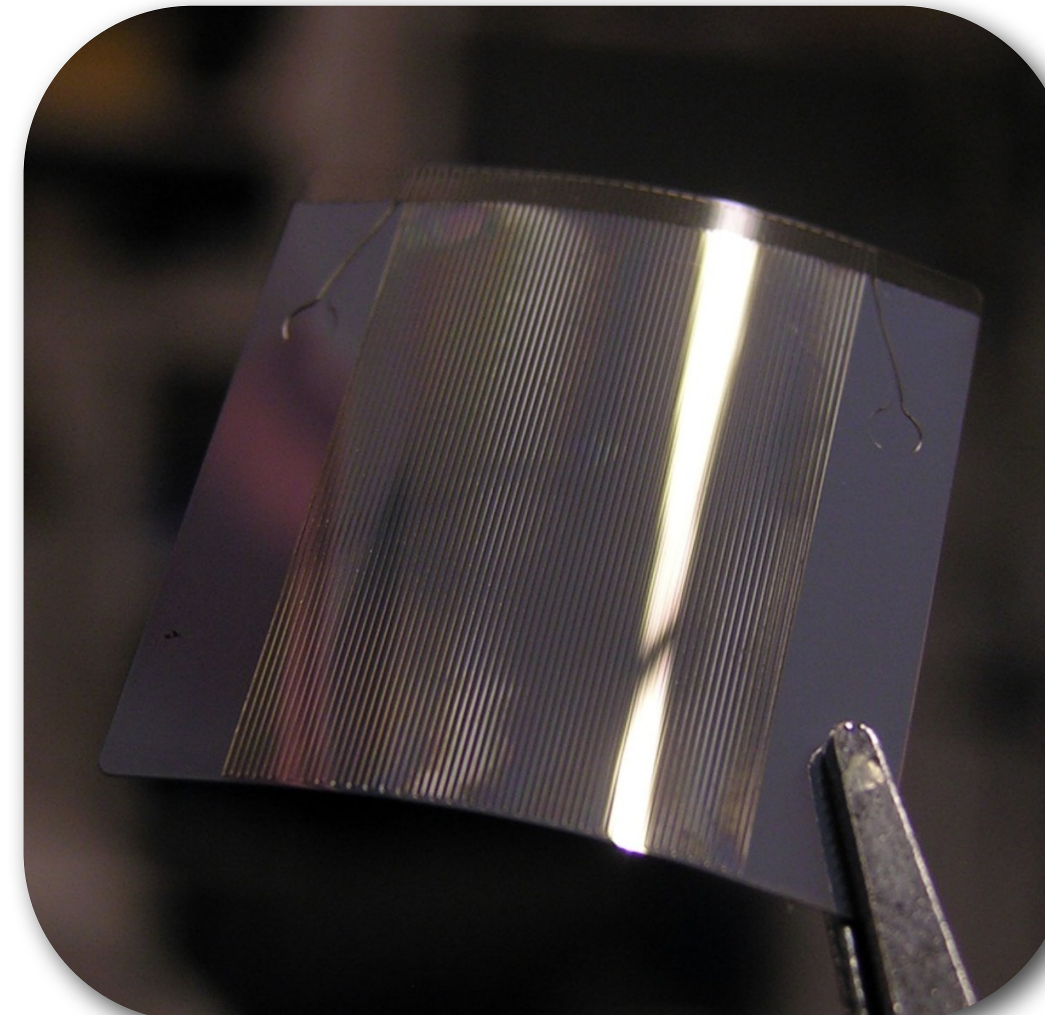
INFN group
Guglielmo Gemignani, Daniele Ruggieri, Francesco Safai-Tehrani, Riccardo Vari, Stefano Veneziano

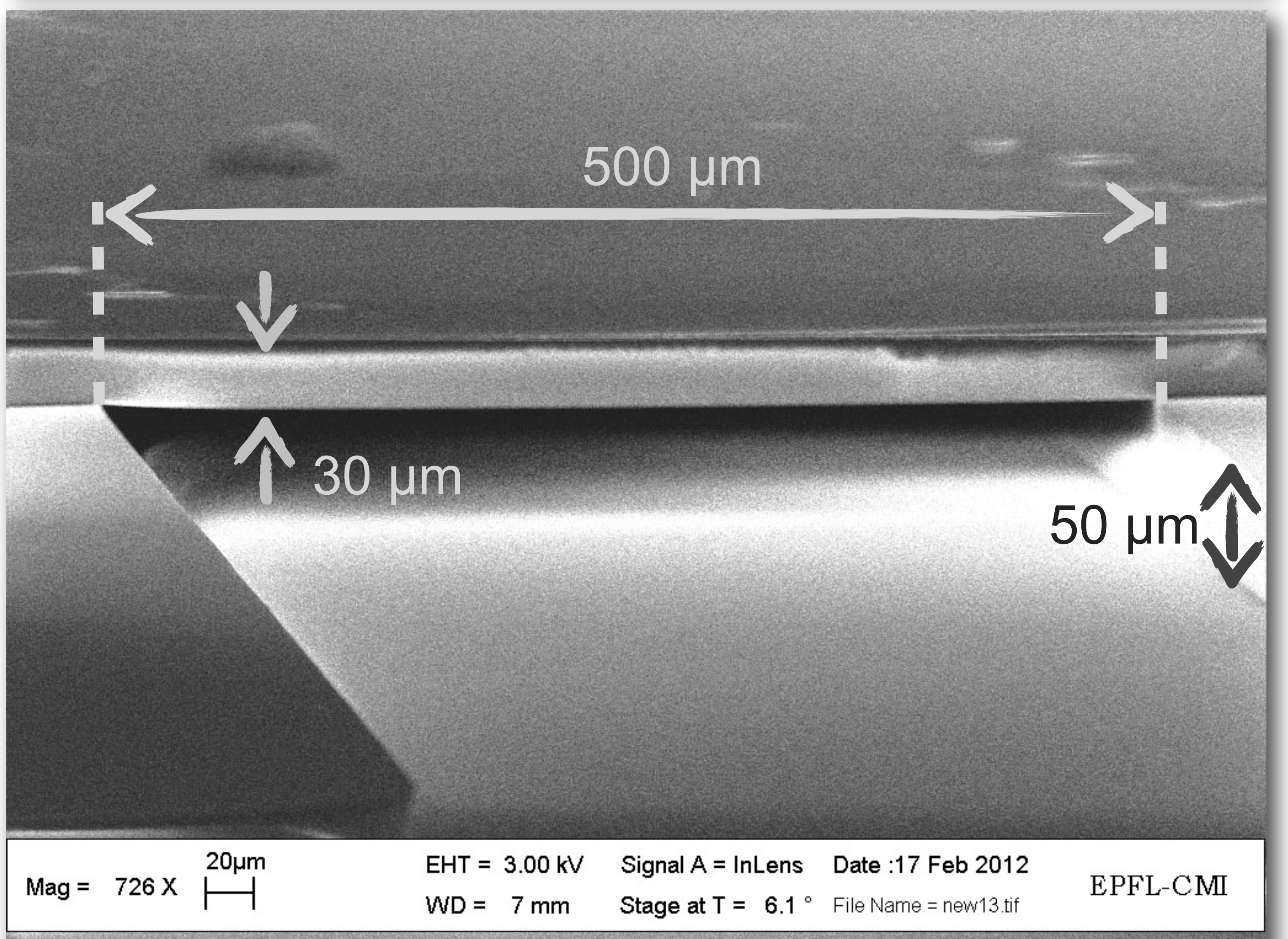
Under investigation for tracking, calorimetry for **HEP** and online beam monitoring for **hadrontherapy with KT funds**.

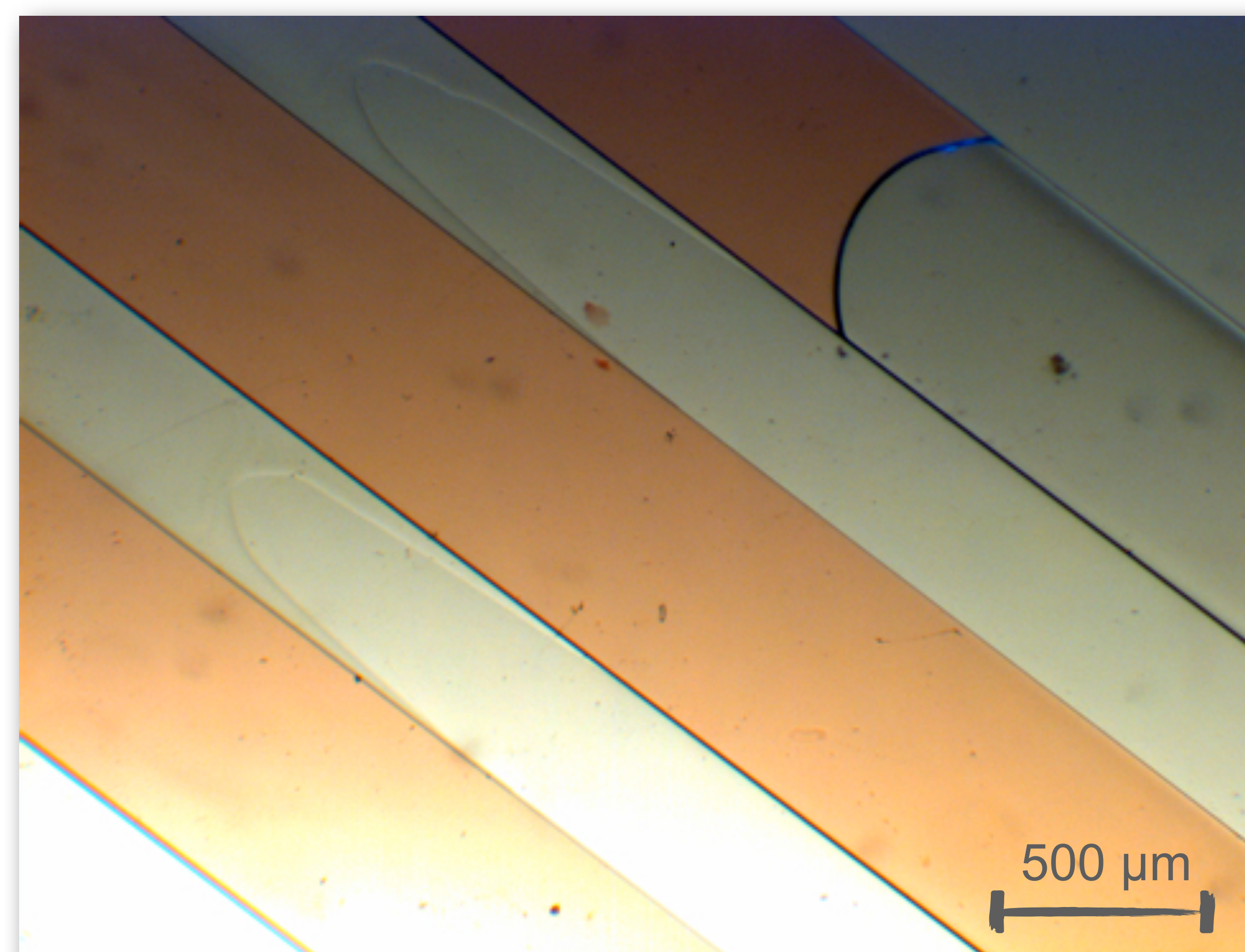
Patent filed May, 8th 2012
PCT/EP2012001980

embedded microchannels



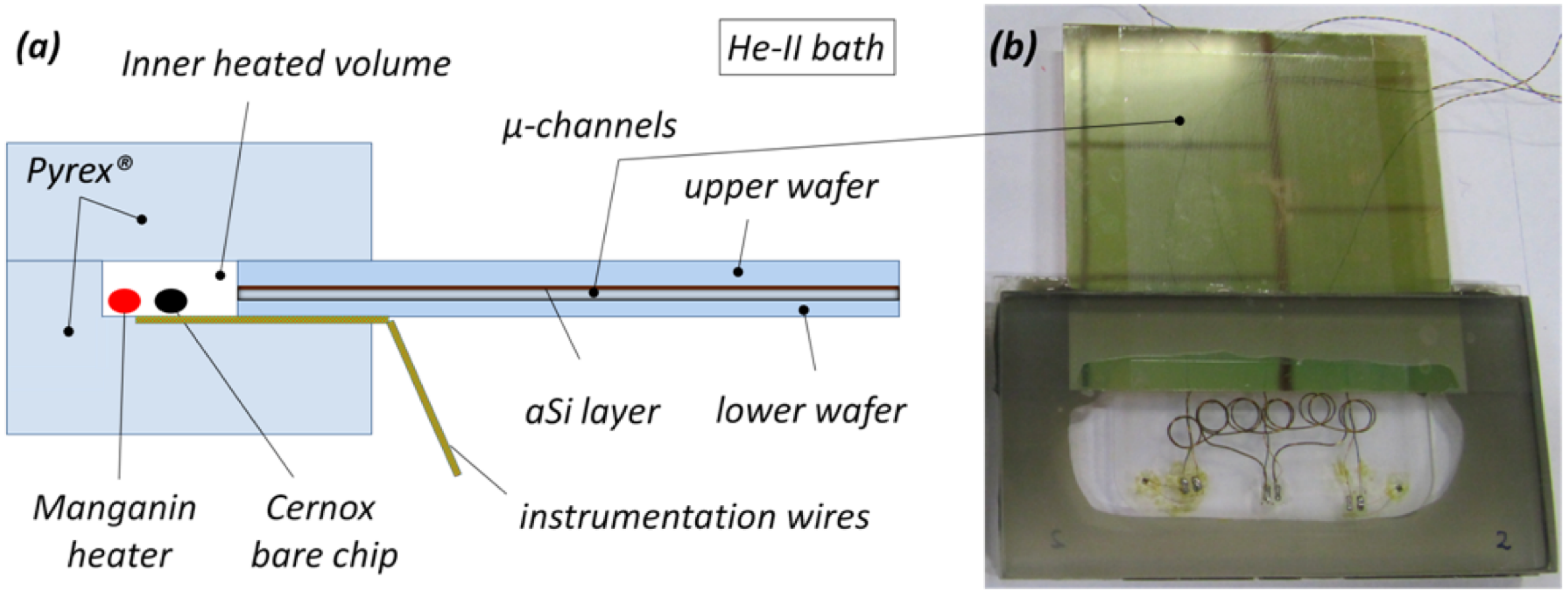




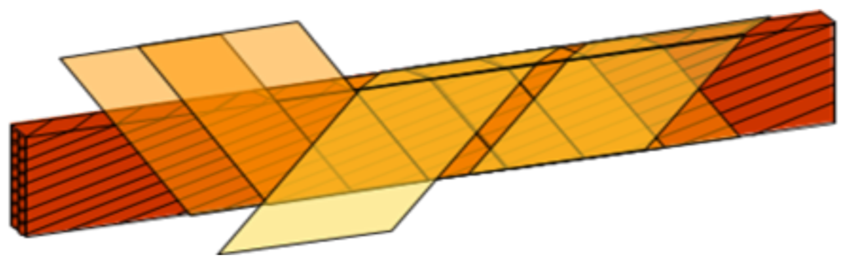


μHeII.. superfluid He in glass microchannels

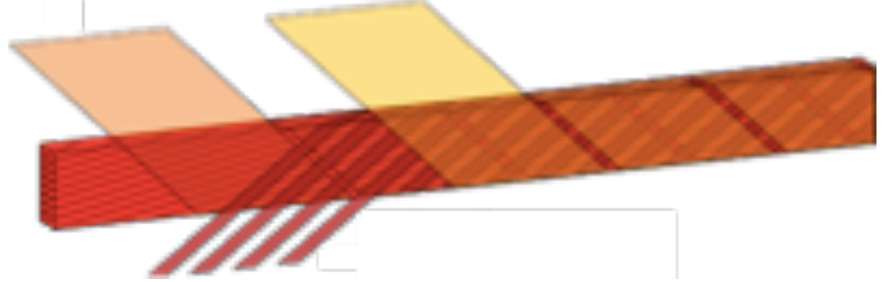
- study the heat transfer of superfluid He in microchannels
- improve the insulation of LHC magnets for upgrade plans.



LHC standard insulation



Enhanced insulation for LHC upgrade



P.P. Granieri, A. Mapelli et al., "Steady-state transfer through micro-channels in pressurized HeII"
Presented at CEC/ICMC 2011
(http://cdsweb.cern.ch/record/1416393/)

new field of application

Electrons in semiconductors	+	MICROFABRICATION	⇒	Microelectronics
Photons in semiconductors	+		⇒	Optoelectronics
Instrumentation	+		⇒	Micromechanics
Chemistry & biotechnology	+		⇒	Microfluidics
Optics	+		⇒	Micro-optics
Quantum mechanics	+		⇒	Nanotechnology
Robotics/mechatronics	+		⇒	Micromachines
HEP	+		=>	to be defined...

Introduction to microfabrication, S. Franssila, 2004

summary

- Looking closer into microfabrication techniques could lead to
  - integration of services (*e.g.* cooling in silicon,..)
  - novel particle detectors
  - anticipation of problems and issues in the development phase
    - at the moment, silicon thermo-mechanical mock-ups allow to gain expertise in manipulating and operating thin silicon devices waiting for the real objects to be fabricated by external partners
- At CERN, several projects have been launched in PH-DT in collaboration with various experimental groups
  - micro-channel cooling
    - adopted by NA62 for the GigaTracker
    - experimental results published by LHCb for the VeLo upgrade
    - under consideration by ATLAS, ALICE... and CLIC collider
  - micro-fluidic scintillating detection
    - single particle trackers and calorimeters for HEP
    - beam monitors for hadrontherapy
- At long term, the formation of a centre of competence in microfabrication within the PH Department, with synergies with the existing excellence in microelectronics design and wire-bonding module integration, would crucially advance the development of novel detectors for LHC and future projects.

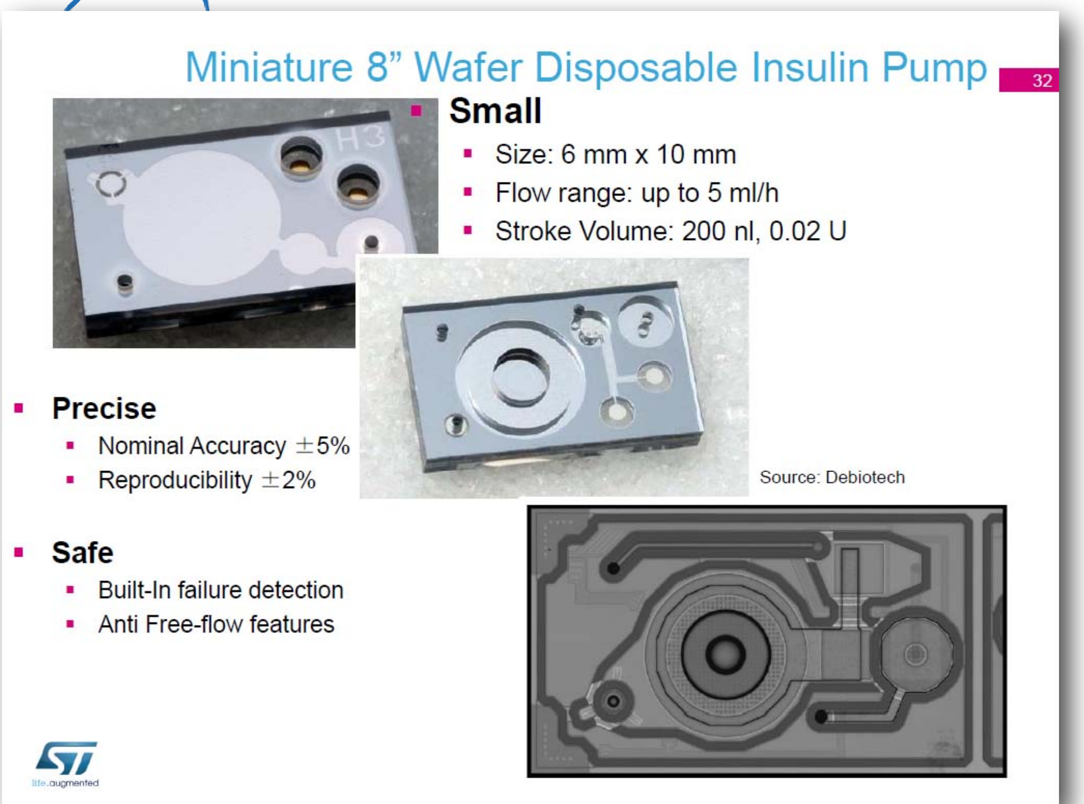
back-up slides

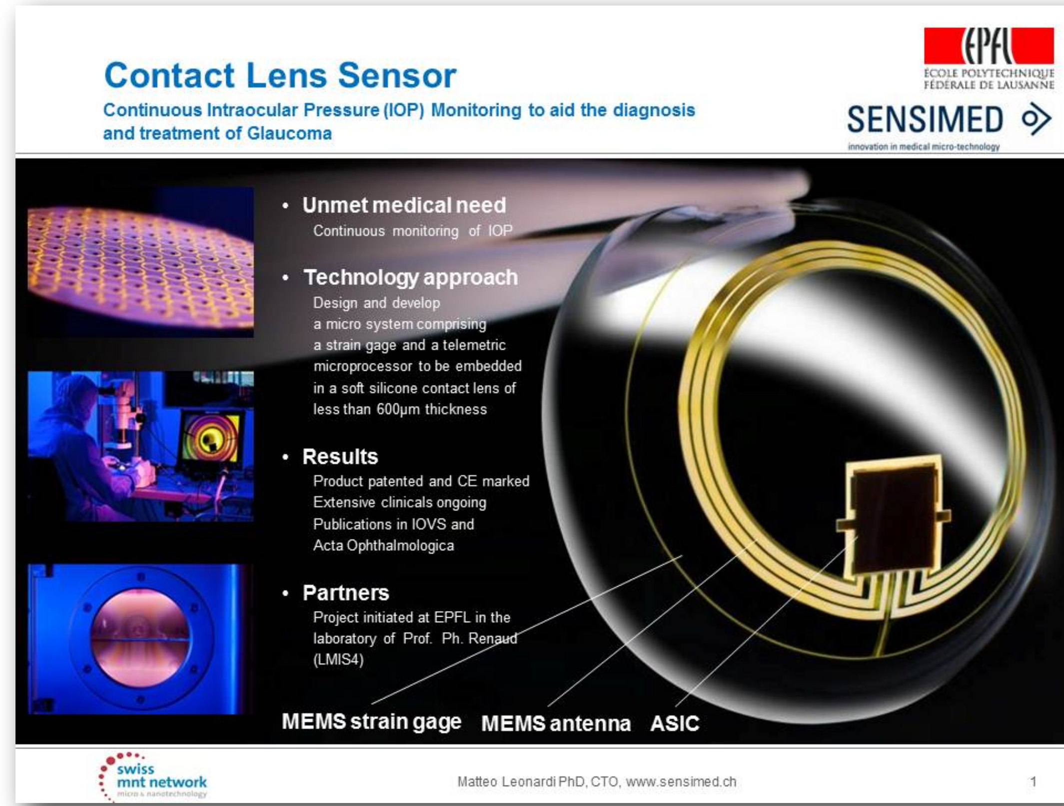
The Micromegas technology research and development

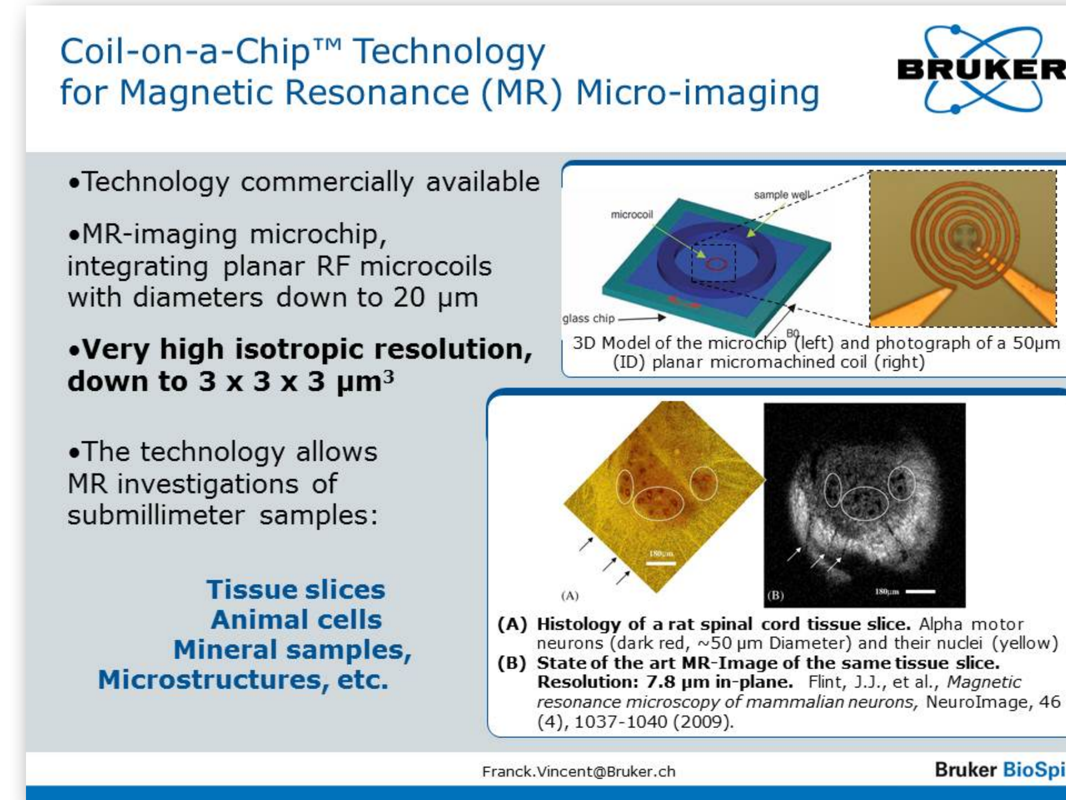
- Since 1992, at the CEA Saclay and at CERN, the Micromegas technology has been developed in order to obtain more stable, reliable, precise and faster detectors. In 2001, twelve large Micromegas detectors plane of) were used for the first time in a large scale experiment at COMPASS situated on the Super Proton Synchrotron accelerator at CERN. Since 2002 they have been detecting millions of different particles per seconds and still continue today.
- Another example of the development of the Micromegas detectors is the invention of the “bulk” technology. The **“bulk” technology** consists of the integration of the micro-mesh with the printed circuit board (that carries the readout electrodes) in order to build a monolithic detector. Such a detector is very robust and can be **produce within an industrial process** (a successful try has been conducted with the 3M firm in 2006[5]) allowing public applications. For instance, by modifying the micro-mesh in order to make it photo-sensitive to UV light, the Micromegas can be used to prevent forest fires[6].

http://en.wikipedia.org/wiki/Micromegas_detector

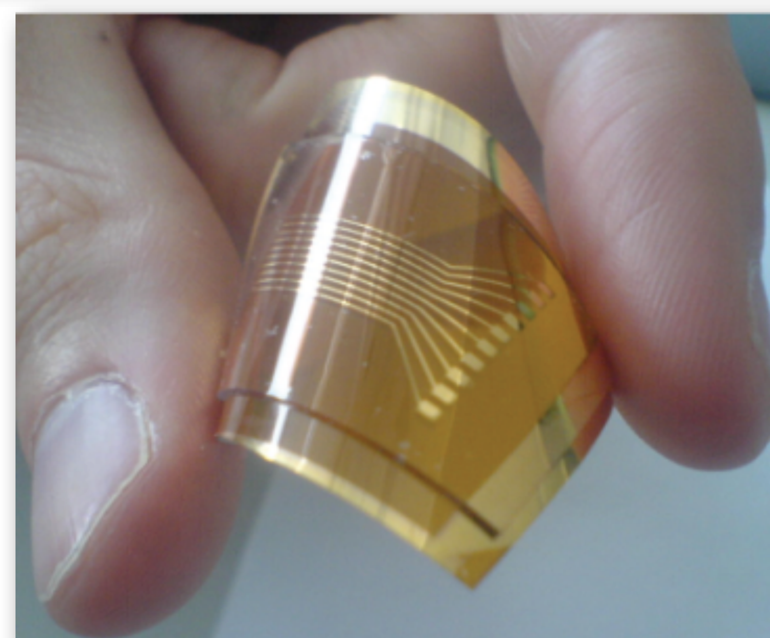
examples of micro-fabricated stuff

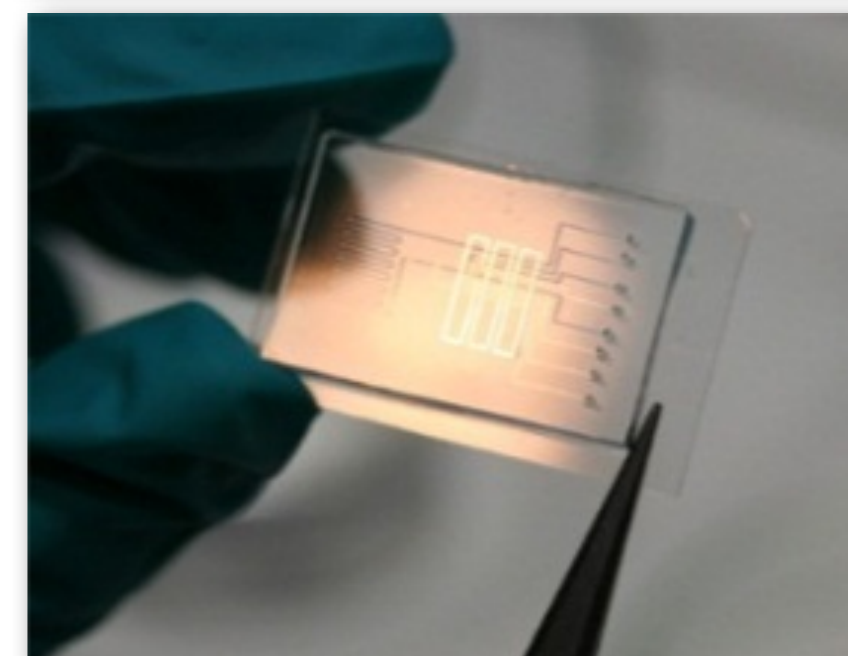


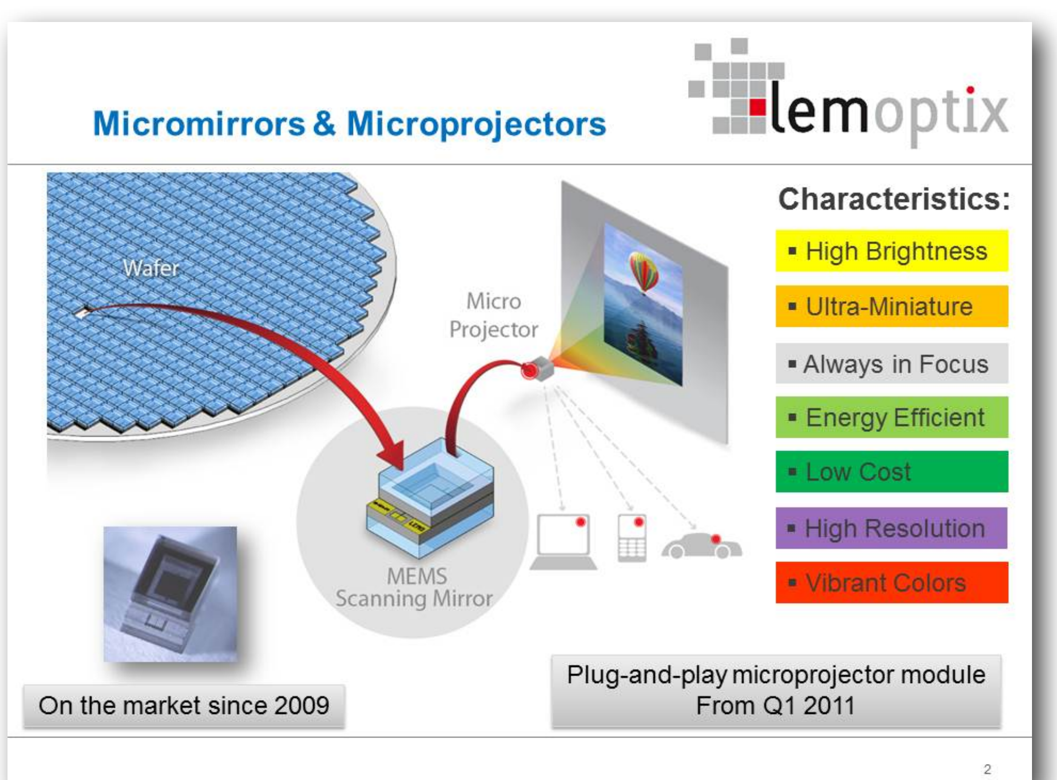


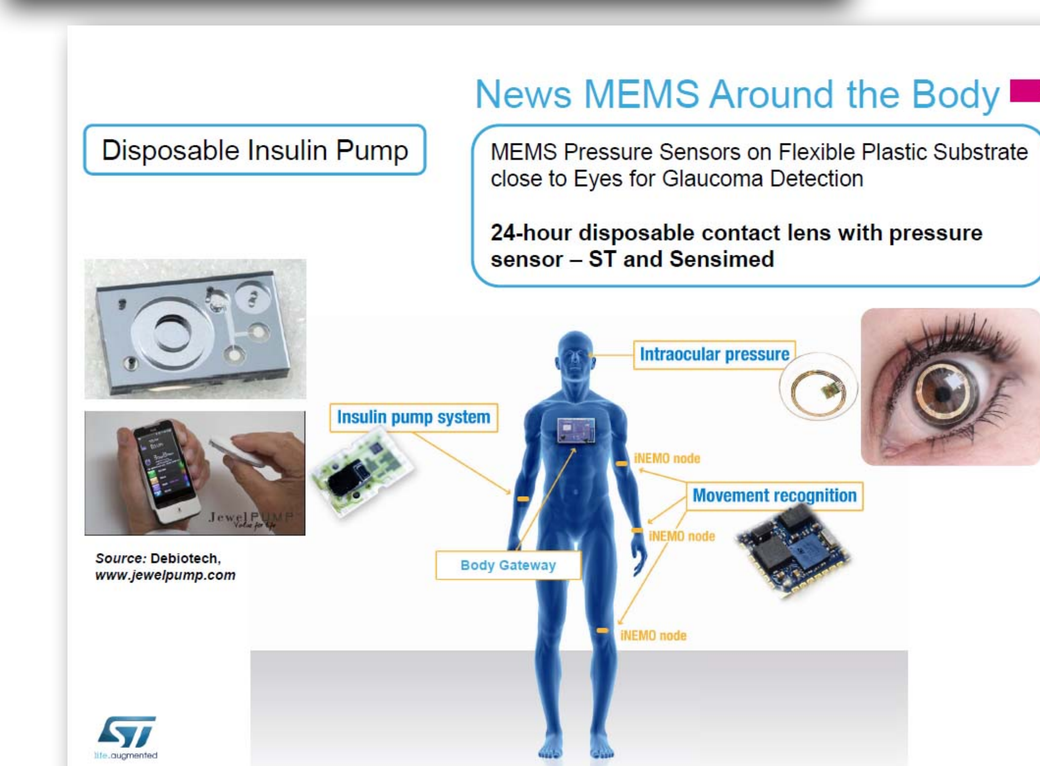


μ-chip pump (6 x 10 mm)

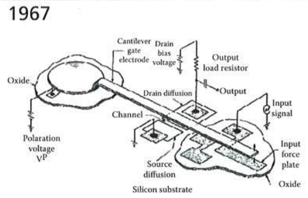




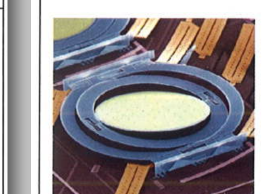




microfabrication milestones

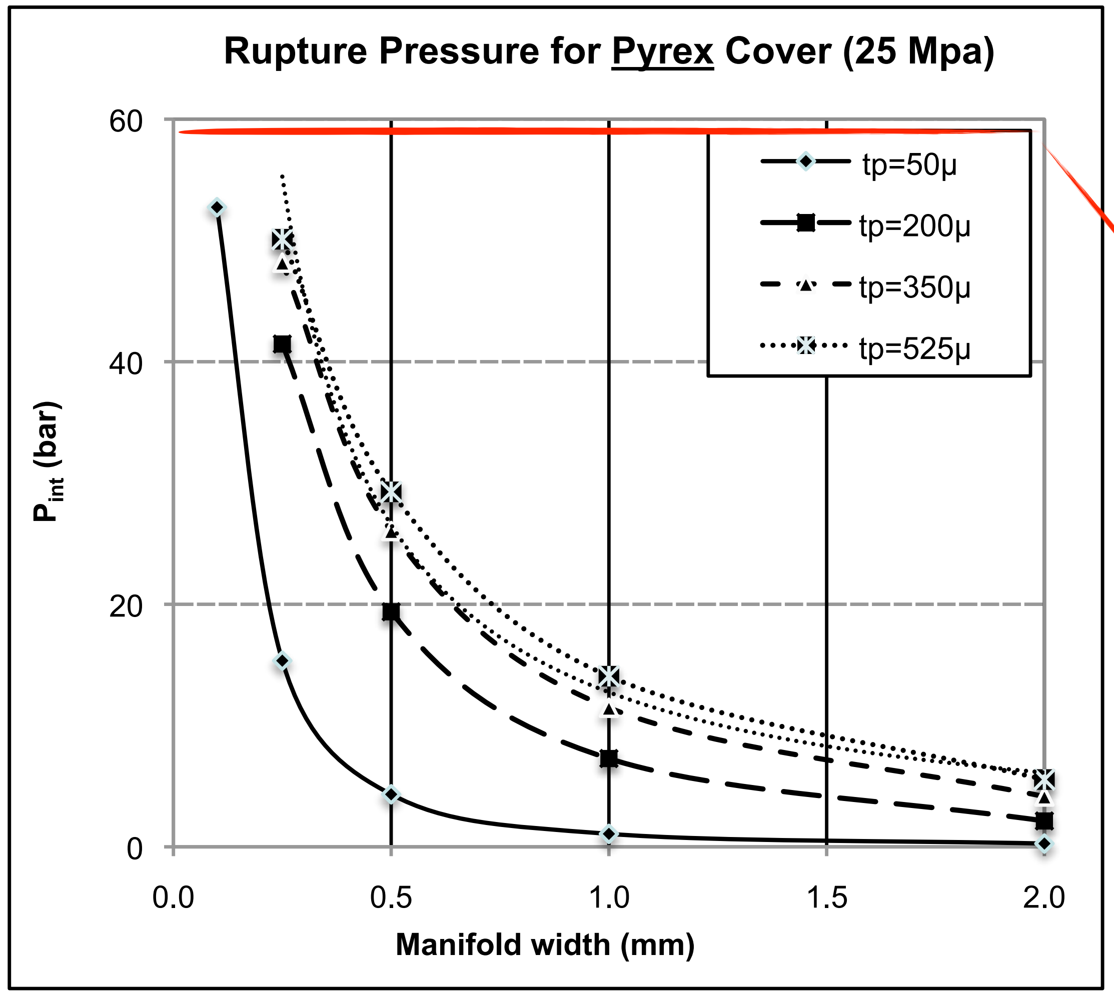
Year	Fact
1824	Berzelius discovers Si
1910	First patent on the MOS transistor concept
1927	Field effect transistor patented (Lilienfield)
1939	First pn junction transistor (J. Bardeen, W.H. Brattain, W. Shockley)
1947 (23 December) 	Invention of the transistor made from germanium at Bell Telephone Laboratories
1954	Evidence of piezoresistive effect in Si and Ge by Smith[9]
1956	An early milestone for the use of single-crystal silicon in MEMS was the discovery of porous Si by Uhlir[8]
1958  1960s IC (1st Monolithic BJT IC, 4BJT)	Jack Kilby of Texas Instruments invents the IC, using GE devices. A patent was issued to Kilby in 1959. A few months later, Robert Noyce of Fairchild Semiconductor announced the development of a planar Si IC
1958	Silicon strain gauges commercially available
1958	First IC (oscillator)
1959	R. Feynman famous talk: "There's Plenty of Room at the Bottom"[7]
1961	Fabrication of the first piezoresistive sensor, pressure (Kulite)
1967	Anisotropic deep silicon etching (H.A. Waggener[12])
1967 	First surface micromachining process (H. Nathanson[28]): resonant gate before it was called MEMS
1969–1970	Anodic bonding of glass to Si[13]
1972	National Semiconductor: commercialize a Si MEMS pressure sensor
1975	Gas chromatograph on a Si wafer by S.C. Terry, J.H. Jerman, and J.B. Angell at Stanford University[23]
1977	First capacitive pressure sensor (Stanford)[16]
1977 	IBM–HP: micromachined ink-jet nozzle[24]
1980	K.E. Petersen, silicon torsional scanning mirror[24]

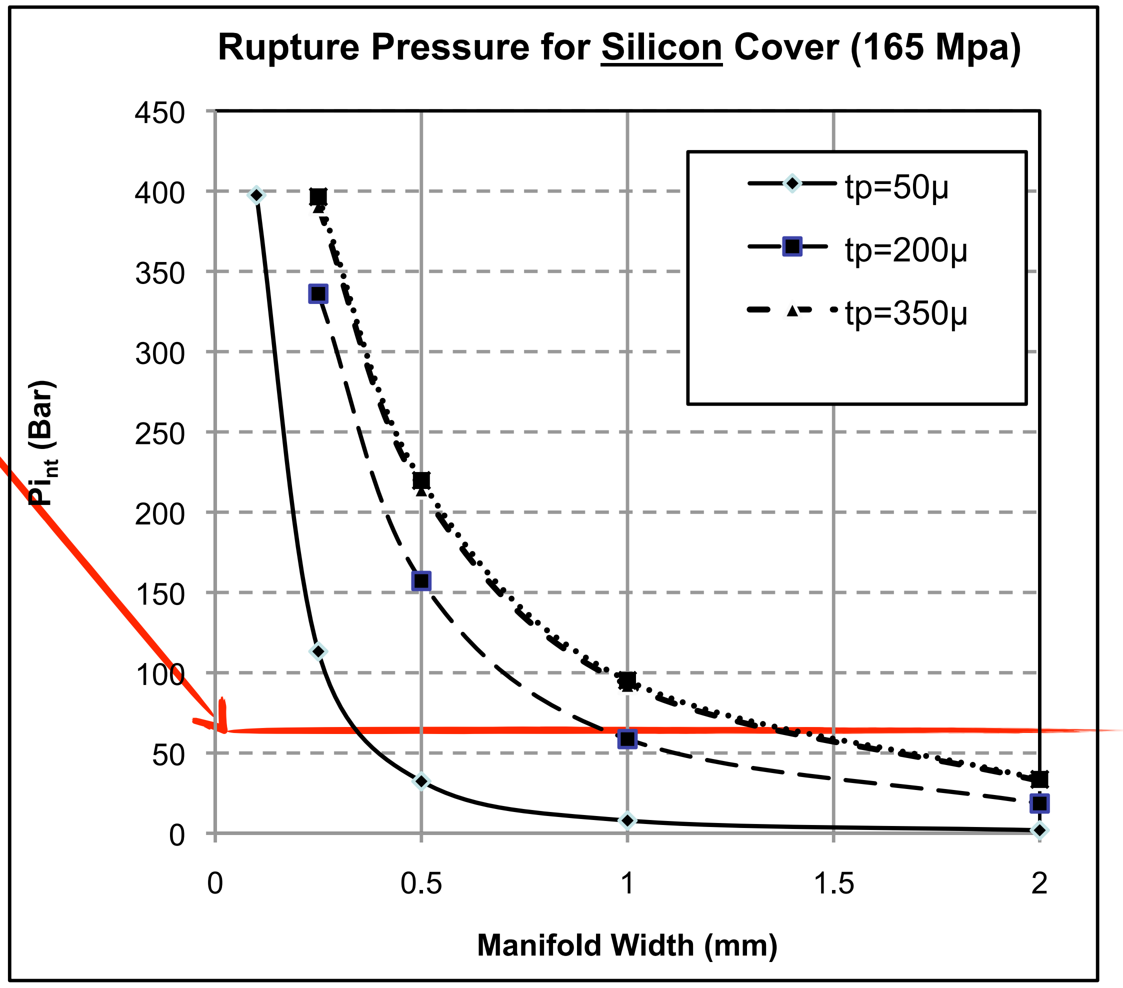
Year	Fact
1982	Review paper "Silicon as a mechanical material" published by K.E. Petersen[25]
1982	Disposable blood pressure transducer (Foxboro/ICT, Honeywell, $40)
1982	The use of x-ray lithography in combination with electroplating and molding (or LIGA), introduced by Ehrfeld and his colleagues[29]
1983	Integrated pressure sensor (Honeywell)
1983	"First" polysilicon MEMS device (Howe, Muller UCB[26]); see also Nathanson in 1967[28]
1986	Silicon to silicon wafer bonding (M. Shimbo[14])
1987	Texas Instrument's Larry Hornbeck invents the digital micromirror devices (DMDs)
1988	Rotary electrostatic side drive motors (Fan, Tai, Muller[30]) Electrostatic micromotor (UC-Berkeley BSAC)
1988	First MEMS conference (first transducers conference held in 1987)
1989 	Lateral comb drive (Tang, Nguyen, Howe[31])
1990	The concept of miniaturized total chemical analysis system or μ-TAS is introduced by Manz et al.[32] This may be seen as the beginning of BIOMEMS
1992	Grating light modulator (Solgaard, Sandejas, Bloom)
1992	First MUMPS process (MCNC) (with support of DARPA). Now owned by MEMSCAP
1992	First MEMS CAD tools: MIT, S.D. Senturia, MEMCAD 1.0 Michigan, Selden Crary, CAEMEMS 1.0
1992	Single-crystal reactive etching and metallization (SCREAM) developed at Process (Cornell)
1993	Analog devices: commercialize multiaxis accelerometer integrating electronics (ADXL50)
1995	Intellisense Inc. introduces MEMS CAD IntelliSuite. MEMCAD 2.0 is launched, and ISE introduces SOLIDIS and ICMAT
1996  TI's VGA (640 × 480), the SVGA (800 × 600), and the XGA (1024 × 768)	The first digital mirror device (DMD)–based products (Texas Instruments) appear on the market
1996	DRIE (Bosch Process)
1997	Printing meets lithography when George M. Whitesides et al. at Harvard discover soft lithography[27]
1998	First PCR-microchips
1998	Sandia's ultraplanar multilevel technology SUMMiT-IV and -V technologies. Four- and five-level poly-Si processes

Year	Fact
1999  Affymetrix genechip	DNA microarray techniques
1999	Electrokinetic platforms (Caliper, Aclara, and Agilent)
2000	Nortel buys Xros for $3.25 billion
2002  Lucent 3D optical switch	The telecom recession puts many things on standby
2004	MEMS rebuilds. First application of accelerometer in consumer electronics (CE) to hard drive protection in notebooks. IBM puts dual-axis accelerometer in the notebook (now Lenovo)
2006	Sony (PS3) and Nintendo (Wii) introduce motion-based game controllers
2007	Apple announces the iPhone with motion-based features

Fundamentals of Microfabrication and Nanotechnology
Marc Madou, 2012

structural resistance Pyrex and Si





what is micro-fabrication?

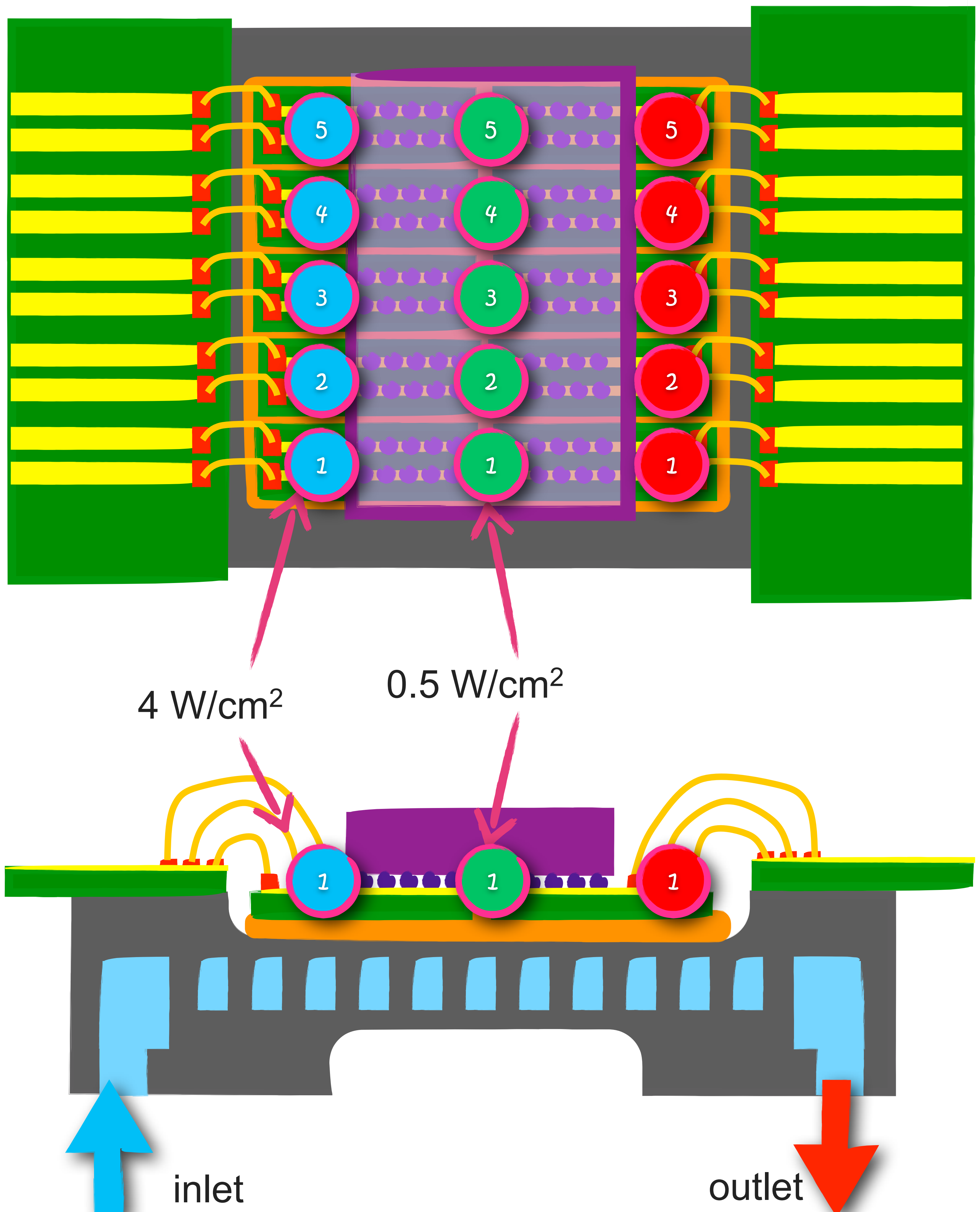
- same technologies used in micro-electronics but for new applications
  - micro-electronics
  - opto-electronics
    - light emission devices, light detectors, light transmission
  - Micro-optics
    - movable mirrors (e.g. TEXAS INSTRUMENTS PROJECTORS)
    - integrated waveguides
  - Micro-fluidics
    - micro-channels (e.g. LAB-ON-CHIP)
    - micro-pumps (e.g. DRUG DELIVERY, INKJET PRINTER NOZZLES)
  - MEMS: Micro-Electro-Mechanical Systems
    - micro-mechanics (Pressure sensors, resonators, gyroscopes, switches,...), micro-machines, micro-sensors, actuators
    - micro-accelerators (e.g. CAR AIR-BAGS)
  - Nanotechnology
    - AFM tips, nano-electronics, bottom-up approach
  - ...
- Typical dimensions
  - around 1 μm in the plane of the wafer (from 0.1 μm to 100 μm)
  - vertical dimensions from atomic-layers (0.1nm) to hundreds of micrometres
- processes can be transferred out of cleanroom environment

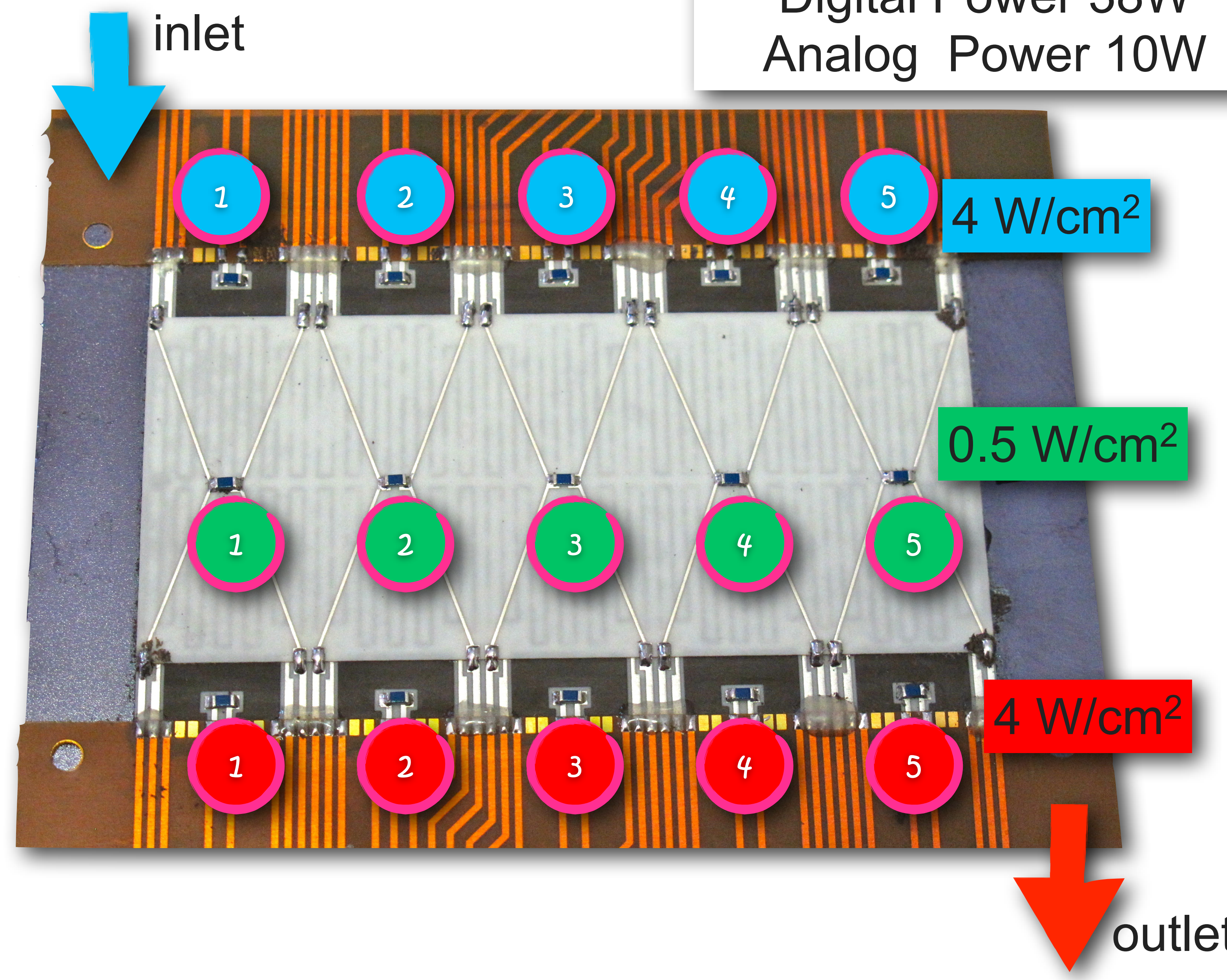
microfabrication

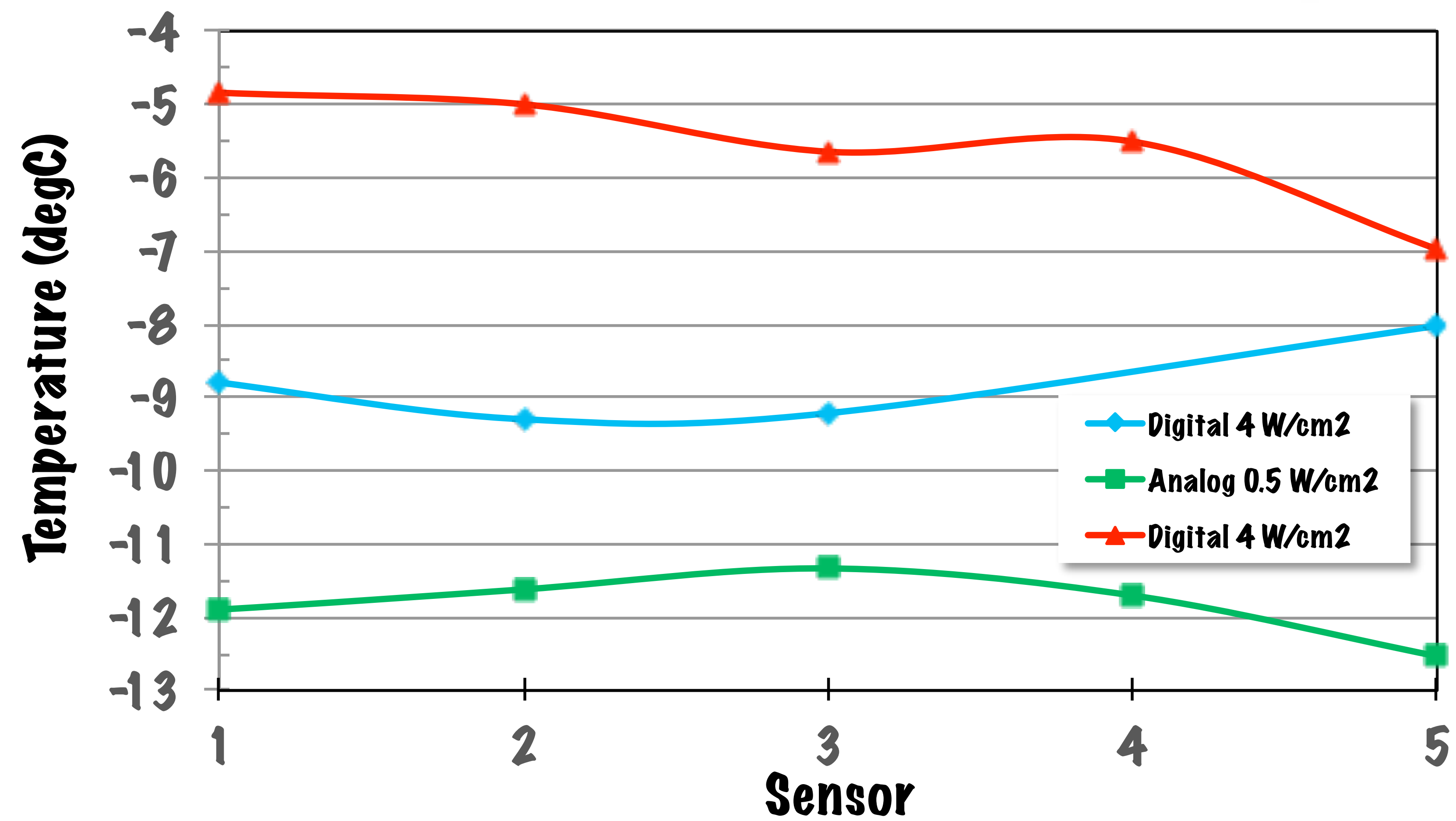
- Miniaturization techniques are
  - top-down methods, in which one builds down from the large to the small, and
  - bottom-up methods, in which one builds up from the small to the large.
- Micromachining, also microfabrication, micromanufacturing, or micro electromechanical systems (MEMS) refers to the fabrication of devices with at least some of their dimensions in the micrometer range.
- In the early years, this discipline was almost exclusively based on thin and thick film processes and materials borrowed from IC fabrication labs.
- Although the term MEMS is still very popular, a much more apt description today for microfabrication and the other techniques described below is miniaturization engineering, a discipline based on a thorough knowledge and understanding of intended applications, different micromanufacturing options, the behavior of materials, and scaling laws. The latter describes the laws that express how structures scale when all their dimensions are isomorphically reduced.
- MEMS: MicroElectroMechanical Systems (US)
- MST: MicroSystems Technology (Europe)
- Micromachining (Japan)
- Microengineering (UK)

NA62 thin Si cooling plate

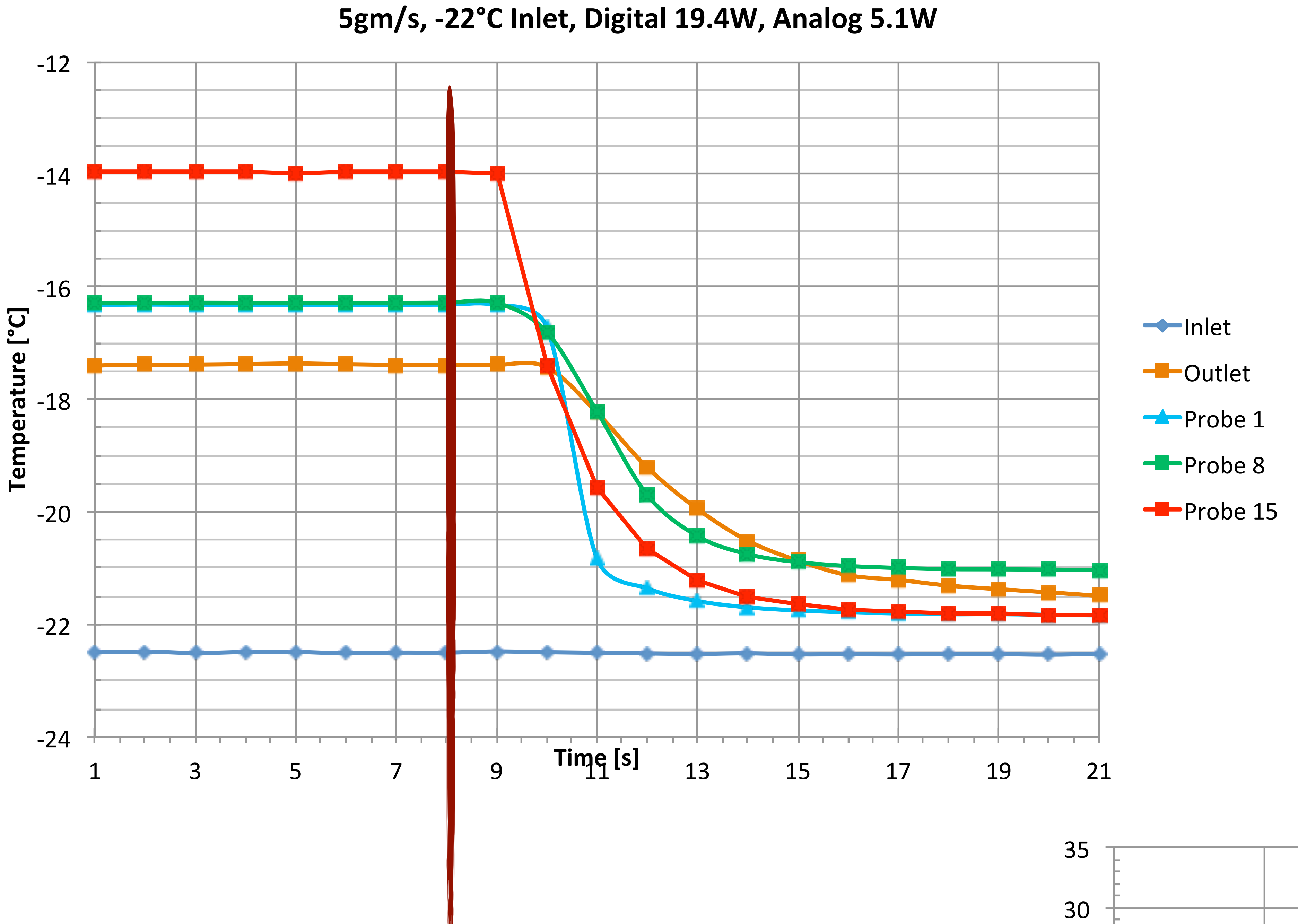
C_6F_{14}: 7g/s, -19°C at inlet
Digital Power 38W
Analog Power 10W





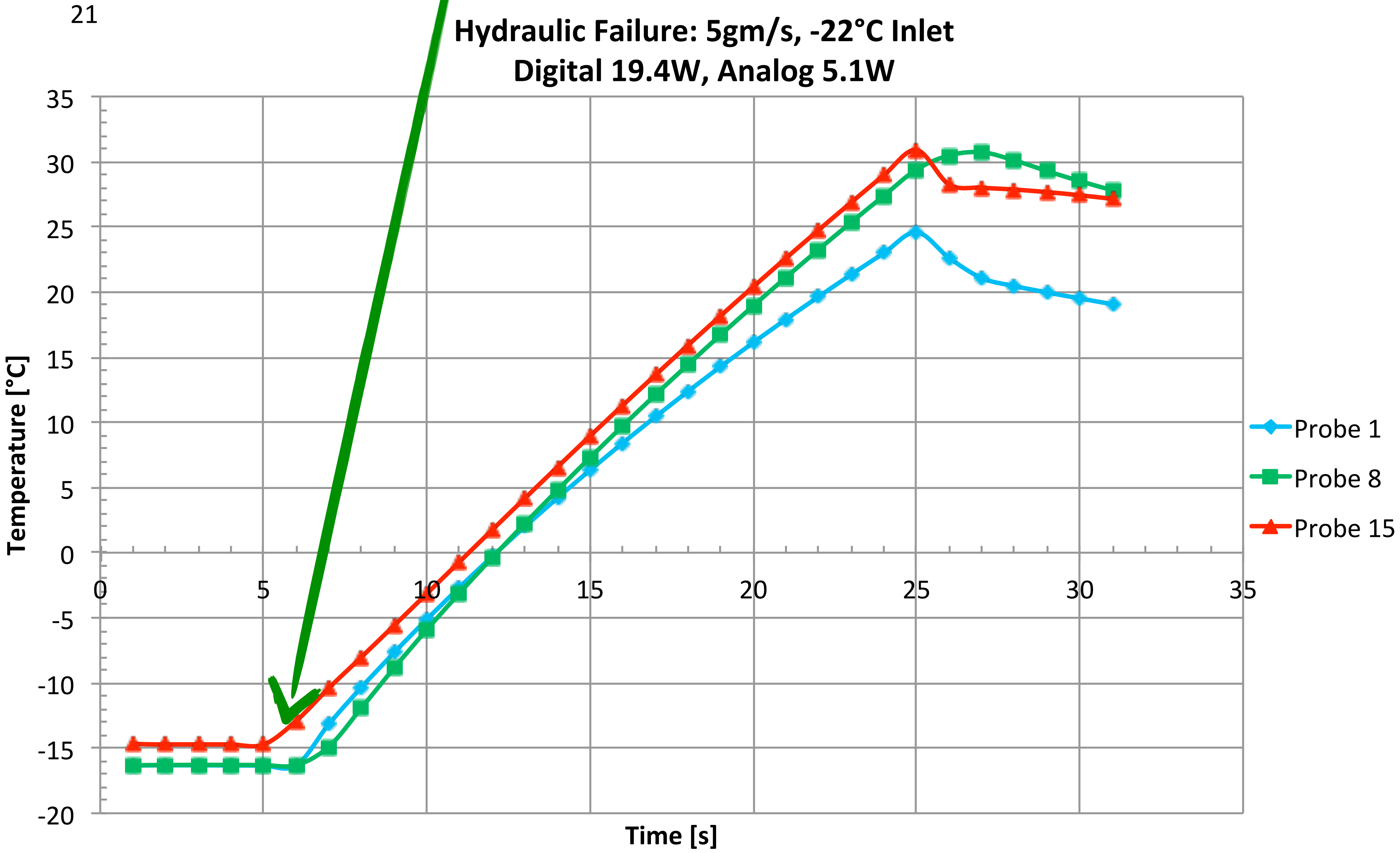


NA62 thin Si cooling plate

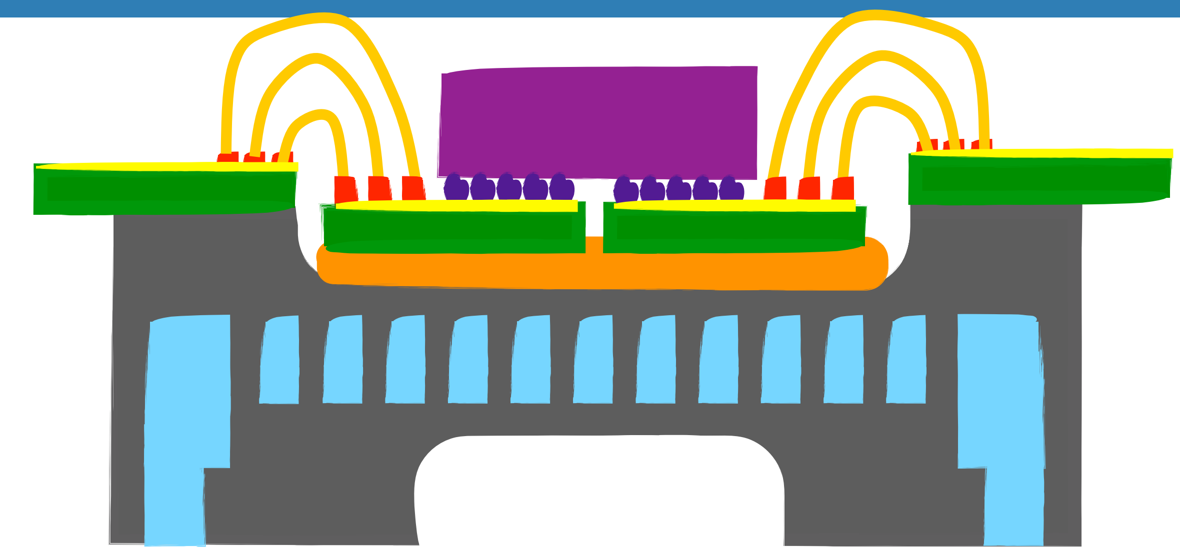


Power Failure
Temperature stabilizes in 8 s

Hydraulic Failure
Temperature rises at 2.3ºC/s

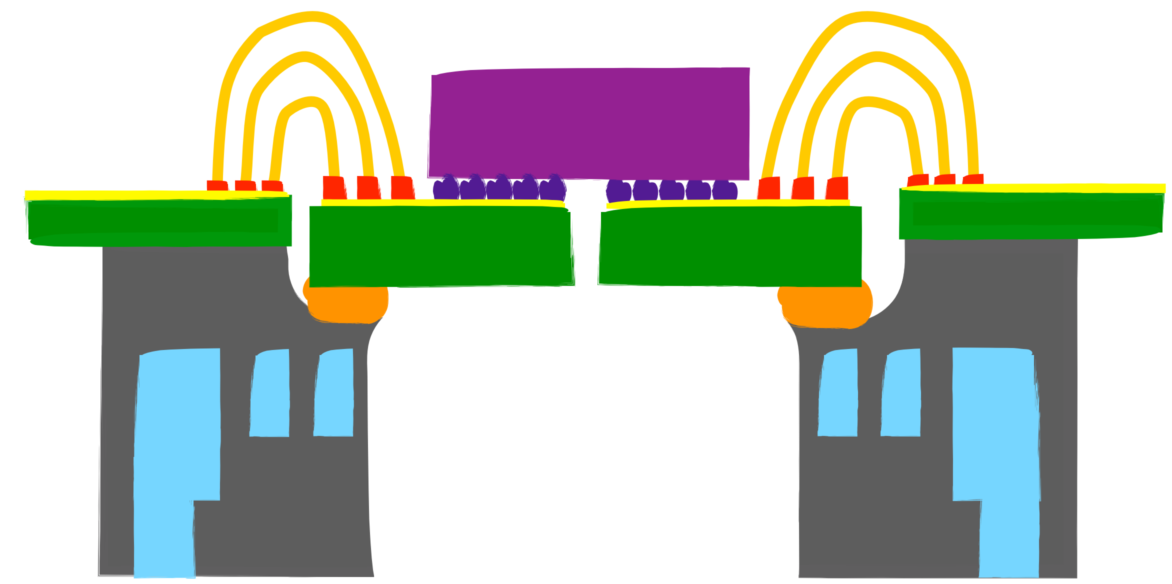


towards integrated micro-cooling



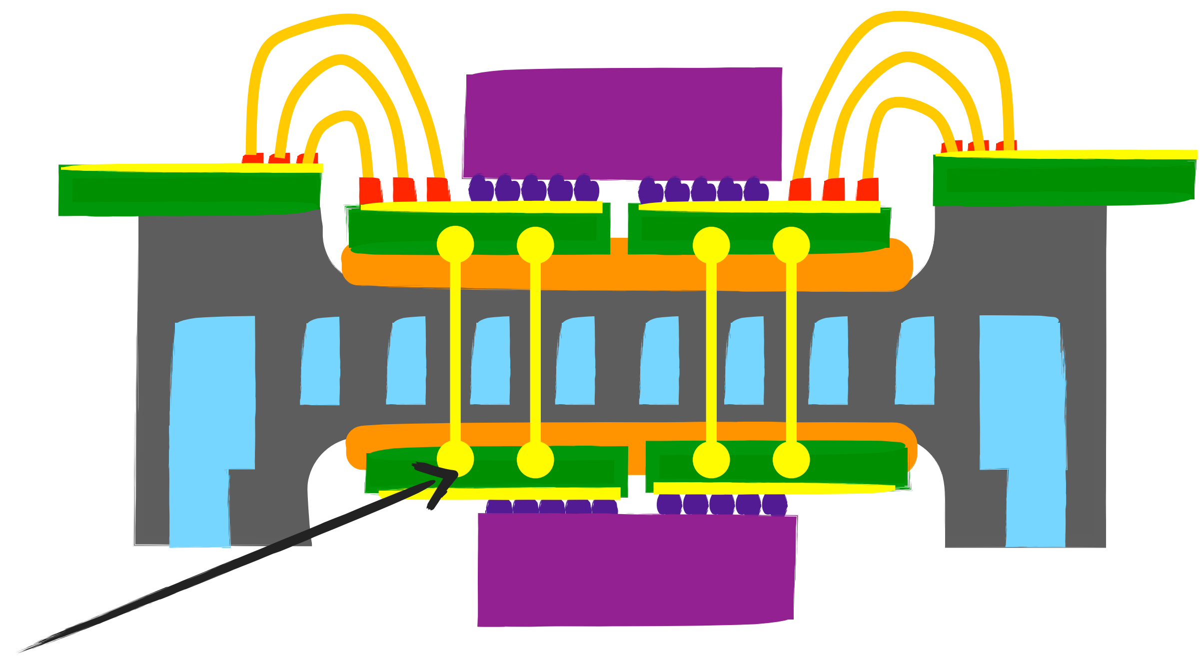
1. thin silicon cooling plate

NA62
LHCb



2. silicon cooling frame

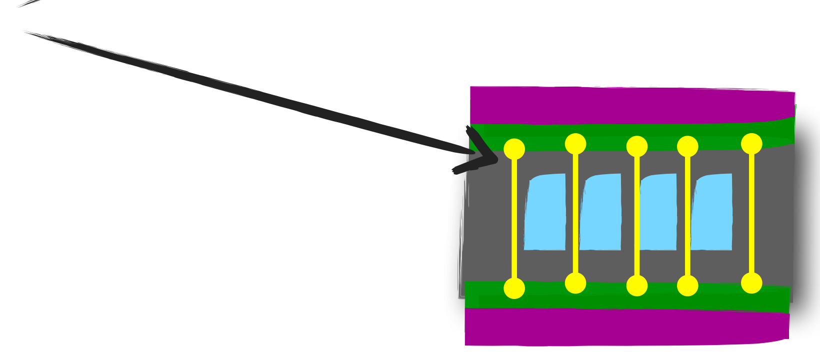
NA62
ALICE



3. silicon cooling plate with TSVs

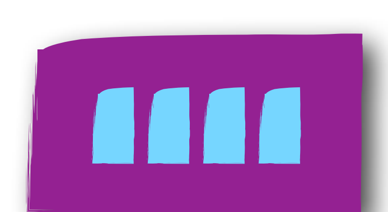
3D architectures
project will start in Sept. 2012

TSV: Through Silicon Via

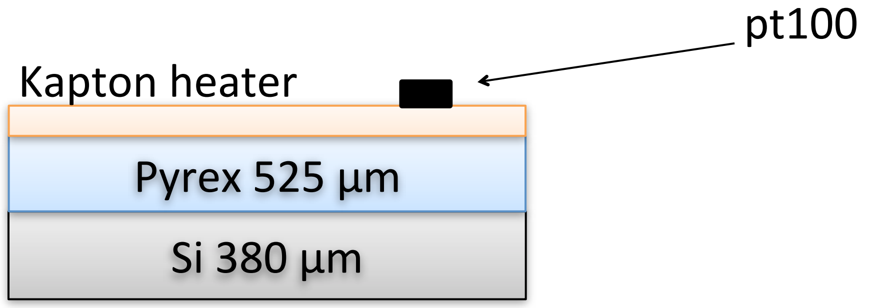


... integration of the μ-channels

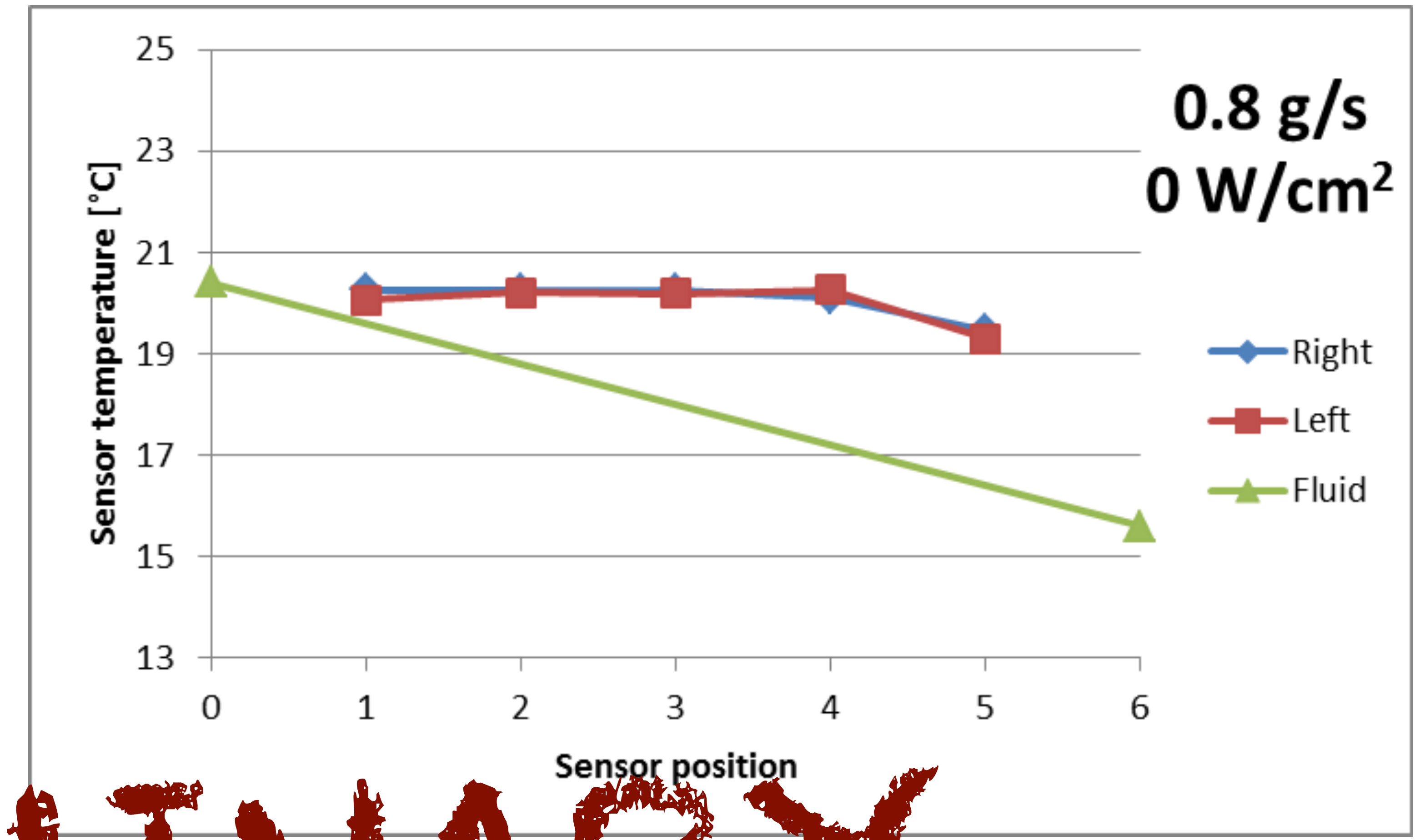
in-plane connectivity
in the bulk of the Si detector
in the read-out chips



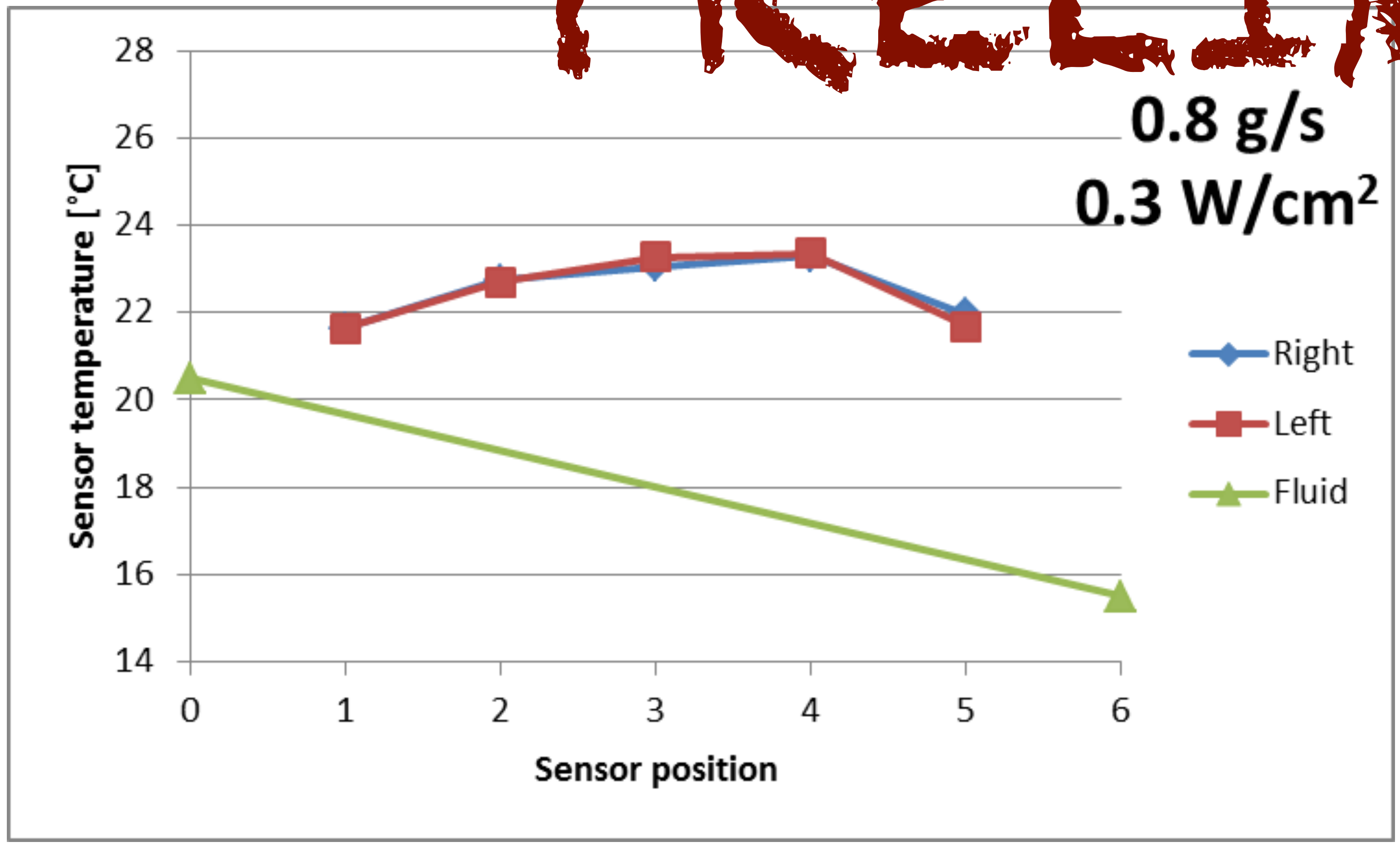
preliminary results.. evaporative!

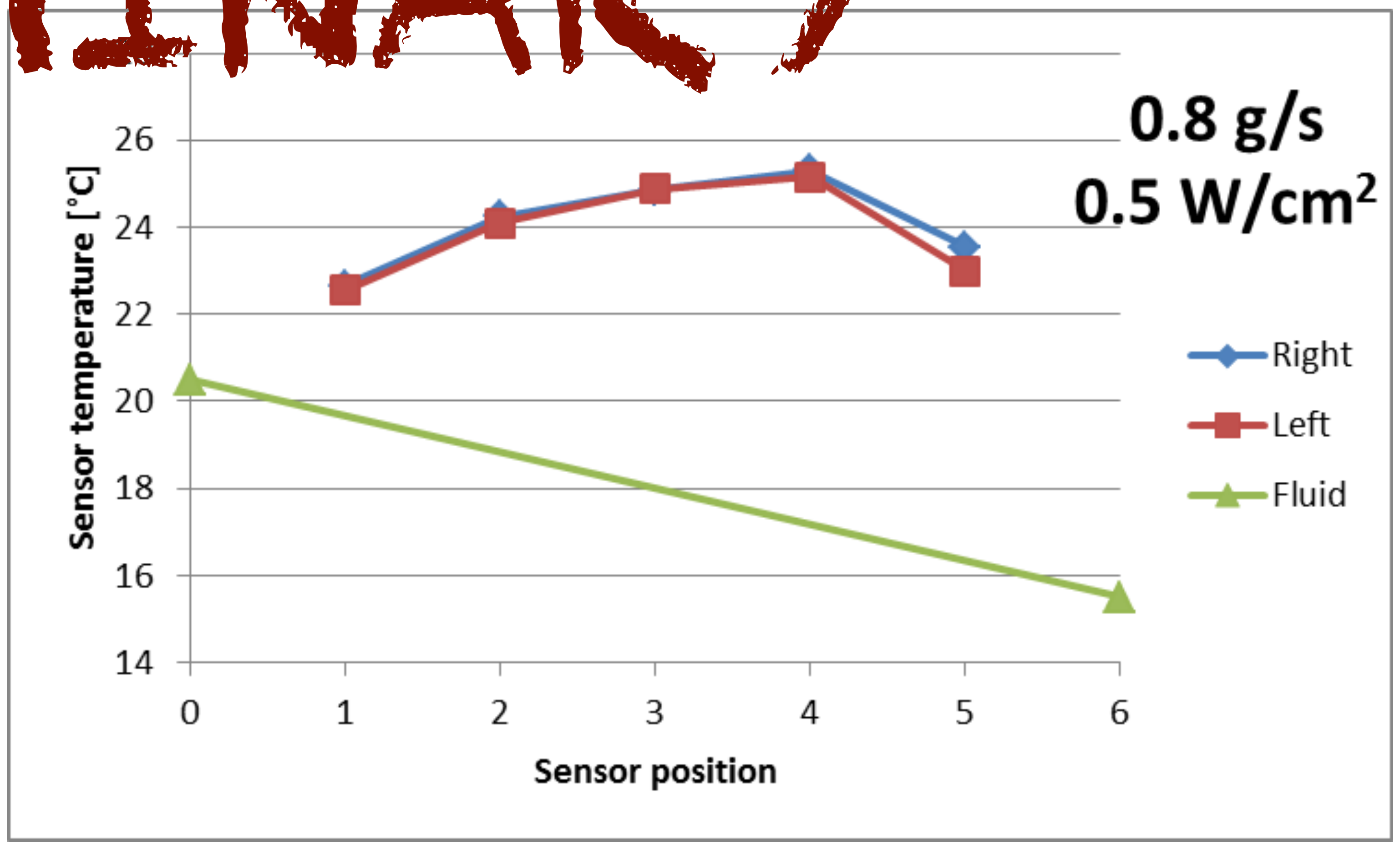


Preliminary tests using the first frame available: due to fabrication problems this frame has the heater glued on the pyrex side (high thermal resistance).
Future tests with the heater on silicon side.



PRELIMINARY





micro-scint people

- CERN group
  - Andrea Catinaccio
  - Benedetto Gorini
  - Maurice Haguenauer
  - Zoe Lawson
  - Giovanna Lehmann Miotto
  - Pietro Maoddi
  - Alessandro Mapelli
  - Raul Murillo Garcia
  - Paolo Petagna
  - Wainer Vandelli
- EPFL group
  - Sébastien Jiguet
  - Philippe Renaud
  - Noelia Vico Triviño
- INFN group
  - Guglielmo Gemignani
  - Daniele Ruggieri
  - Francesco Safai-Tehrani
  - Riccardo Vari
  - Stefano Veneziano