Silicon drift detectors

Introductory seminar

Gianluigi Zampa

II Seminario Nazionale Rivelatori Innovativi

INFN Sezione diTrieste, 18-22 Ottobre 2010

Where everything begun

E. Gatti, P. Rehak,

Semiconductor drift chamber - an application of a novel charge transport scheme, Nucl. Instr. and Meth., vol. 225, no. 3, pp. 608-614 (1984)

They proposed a bias scheme that allows to decouple the charge transport field from the depletion field, demonstrating the feasibility of a 2D position sensitive Silicon Drift Chamber (SDC) read-out by a linear array of anodes

Nuclear Instruments and Methods in Physics Research 225 (1984) 608–614
North-Holland, Amsterdam

SEMICONDUCTOR DRIFT CHAMBER – AN APPLICATION OF A NOVEL CHARGE TRANSPORT SCHEME

Emilio GATTI [1)] and Pavel REHAK

Brookhaven National Laboratory, Upton, New York 11973, USA

The purpose of this paper is to describe a novel charge transport scheme in semiconductors, in which the field responsible for the charge transport is independent of the depletion field. The application of the novel charge transport scheme leads to the following new semiconductor detectors:
1) Semiconductor drift chamber;
2) Ultralow capacitance – large area semiconductor X-ray spectrometers and photodiodes;
3) Fully depleted thick CCD.
Special attention is paid to the concept of the semiconductor drift chamber as a position sensing detector for high energy charged particles. Position resolution limiting factors are considered and the values of the resolutions are given.

1. Introduction

For many applications, the use of a semiconductor as a detection medium is a great advantage. In low energy radiation spectroscopy, it is well known that semiconductor detectors achieve the best energy resolution.

In high energy physics, however, position sensing is performed today mostly with gas proportional or drift chambers. For several years, there has been an interest in the application of semiconductors as high resolution position sensing detectors for particle physics [1].

Fig. 1 shows an example of a typical position sensitive silicon microstrip detector [2]. It consists of a thin (≈ 300 μm) n-type silicon wafer having a continuous n^+n junction on one side of the wafer and a strip pattern of p^+n junctions on the opposite side. A suitable reverse bias voltage is applied across the wafer, to deplete the detector and to provide the collection field. A fast charged particle passing through the detector produces electron–hole pairs which drift towards the electrodes under the influence of the electric field. The motion of the charge carriers induces the signal in an external amplifier connected between the n^+ and the p^+ contacts.

Position sensing in this kind of configuration is done by the granularity of p^+ contacts. The method, in principle, requires as many amplifiers as the number of individual strips. Using charge division readout (capacitive or resistive), the number of amplifiers can be reduced by up to a factor of 10; a certain price is paid in the complexity of the readout channels and the doubletrack resolution is sacrificed. Nevertheless, the number of readout channels per unit length remains very large (~ 20–500 channels/cm). The practical problems related to the number of readout channels (the volume requirement, the heat dissipation and the connection problems) limit the application of microstrip silicon detectors to a few special experiments.

In this paper, we are going to describe a novel scheme of operation for semiconductor detectors, which is applicable to position sensing in silicon detectors. The new method should be capable of achieving the same position resolution as a very fine microstrip silicon

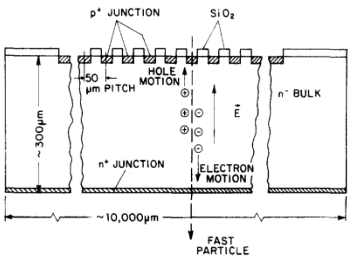


Fig. 1. Structure of a standard parallel microstrip detector. The same voltage provides the depletion of the semiconductor crystal and the drift field for charge carriers produced by ionizing particles.

[1)] Permanent address: Istituto di Fisica, Politecnico di Milano, Piazza Leonardo da Vinci 32, Milano, Italy.

The challenge was to realize a very large SDC (or SDD, silicon drift detector) with a sensitive area of several tens of cm^2…

1990:

Precursor of the ALICE SDD:

Silicon Drift Camber UA6 (4×4 cm^2)

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

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 M. Sampietro
Politecnico di Milano, Dipartimento di Elettronica and Centro di Elettronica Quantistica e Strumentazione Elettronica CNR, Milan, Italy

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

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

Received 30 November 1990

This report presents results on the performance of a large-area silicon drift detector ($\sim 4\times4$ cm^2), which has been designed for use as a high-resolution tracking device in the experiment UA6 at the CERN p–$\bar{p}$ collider. We give here the basic characteristics of the design, and report the first experimental results. The influence, on the detector's performance, of the adopted design criteria and of the quality of the semiconductors has been experimentally determined and is discussed. Results of the first drift-time calibration using an on-board device for charge injection are also given.

1. Introduction

This article is concerned with the development of a large-area semiconductor drift detector for high-resolution measurement of the position of ionizing particles and of the energy deposited in the detector [1,2]. In silicon drift detector (SDC) arrays of p^+ strips implanted on both faces of the detector, suitably biased, deplete the semiconductor and provide the drifting field parallel to the detector's surface. The electrons generated by the ionization in the fully depleted high-resistivity n-type semiconductor are confined in the bulk of the detector and also driven parallel to the large semiconductor surface towards one or more low-capacitance collecting n^+ anodes. The holes are collected at the nearest p^+ electrode. The electron-cloud drift time and the centroid of the distribution of charge collected at the anodes deliver unambiguously the two coordinates of the origin of ionization.

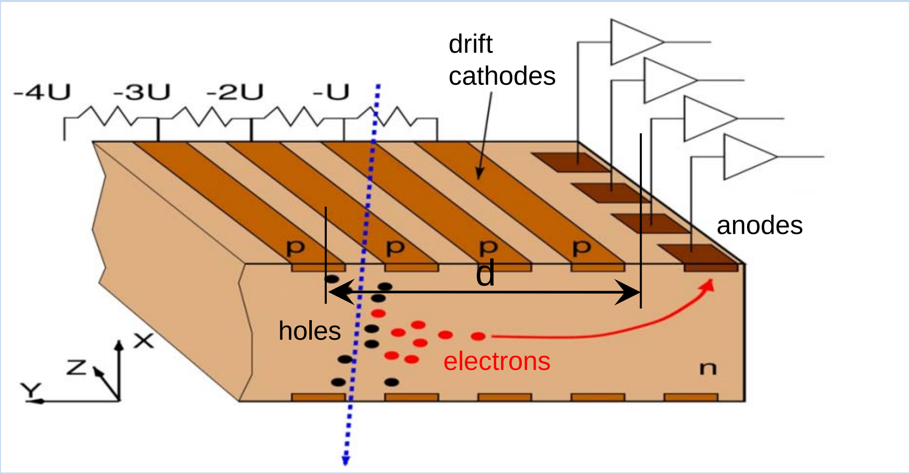
All the noteworthy characteristics of the SDC are important for an application as a tracking device. It places very little material in the path of a particle: a set of two SDC detector planes would contribute only 0.4–0.6% of a radiation length. It delivers the x and y coordinates of interaction points unambiguously. Ghosts due to incorrect x–y combinations, which occur in conventional detectors in the presence of high particle multiplicity, are avoided. The fine position-resolution and double-track separation capability allow precise measurements to be made, even in high-multiplicity environments [3]. Using the excellent energy resolution of the SDC it is possible to resolve one and two minimum-ionizing particles, and hence to identify overlapping tracks. Therefore the SDC can play a decisive role in the event definition, allowing a precise measurement of the track coordinates in the vicinity of the interaction point.

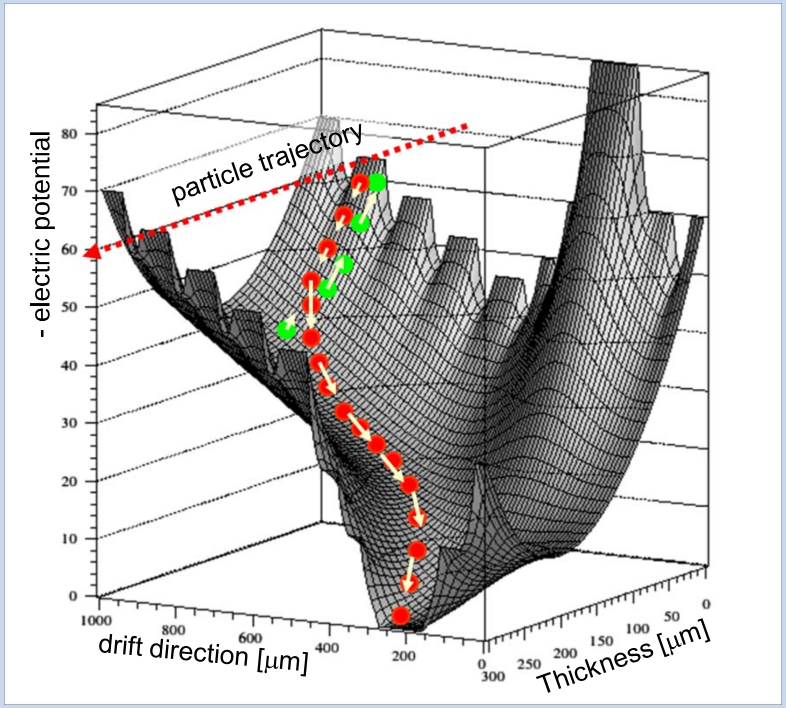
Since the information on the position of the origin of ionization is bound to the speed of the moving charge in a controlled electric field, a precise knowledge of the carrier mobility and of the influence of temperature variations is essential. This implies that the speed of the carriers must be measured continuously with high precision. The most direct way to make this measurement is to inject the charge at a known position in the drift field and then measure the corresponding drift time.

Silicon drift detectors for both position and energy measurement, with an active area of about 1 cm^2, have already been successfully built and tested [1,2]. Here we report results from the first attempt to build a detector

Elsevier Science Publishers B.V. (North-Holland)

The Linear Silicon Drift Detector – working principle

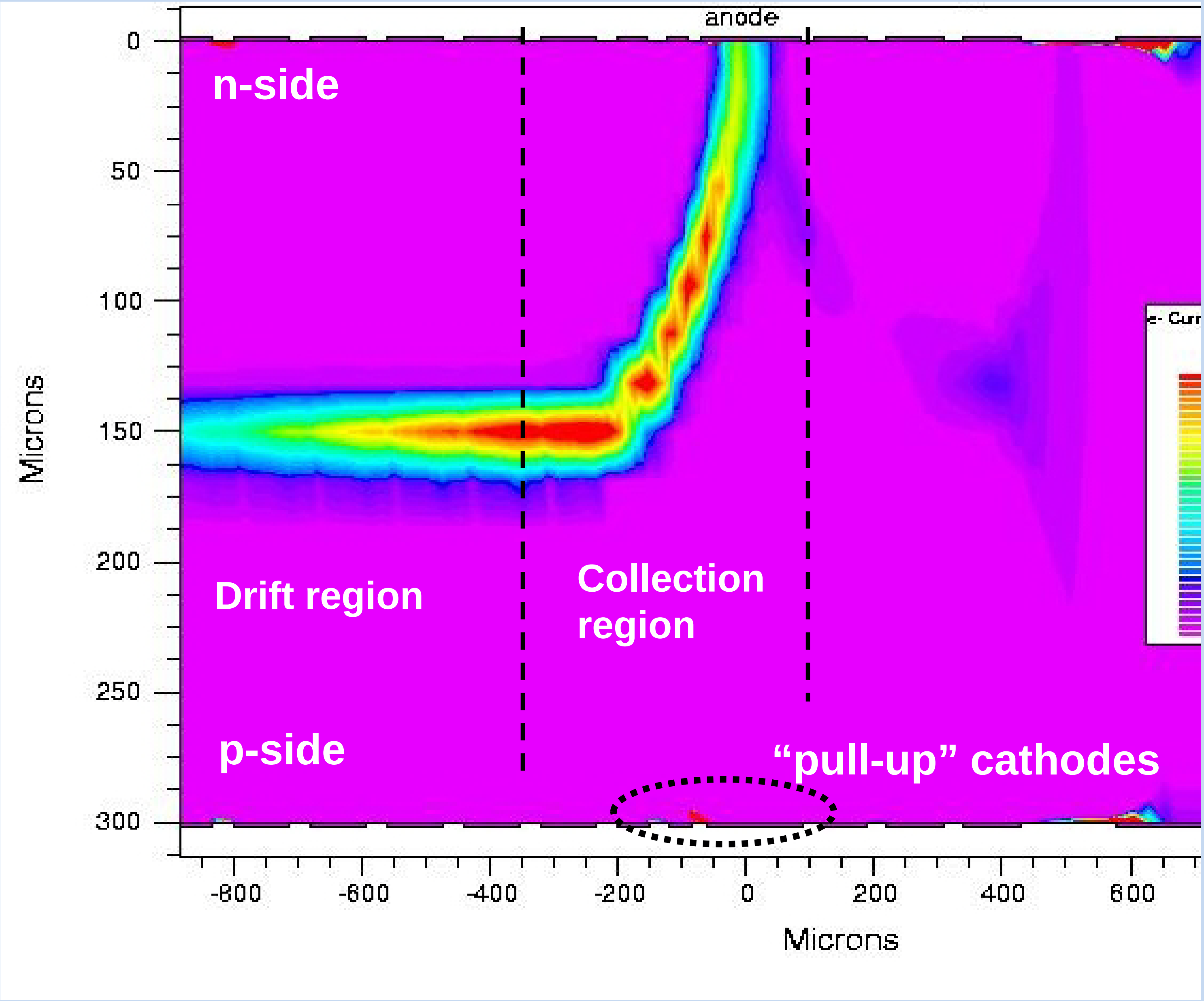




- Designed to provide unambiguous 2D tracking of ionizing particles with very good resolution in a high-multiplicity environment with a very limited number of channels
- Linearly scaling potentials are applied to drift cathodes to generate a constant electric field parallel to the detector surface directed outwards an array of anodes
- Holes are quickly collected by the drift cathodes, while electrons are focused in the middle plane of the detector and drift towards the anodes
- The first coordinate is determined by the center of gravity of the signal at the anodes
- The second coordinate (drift axis) is determined measuring the time required by the electron cloud to reach the anodes

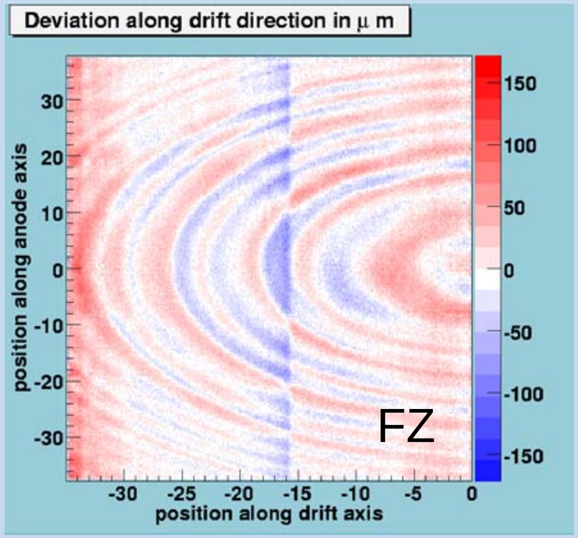
$$v = \mu \cdot E = const. \Longrightarrow d = v \cdot \Delta t$$

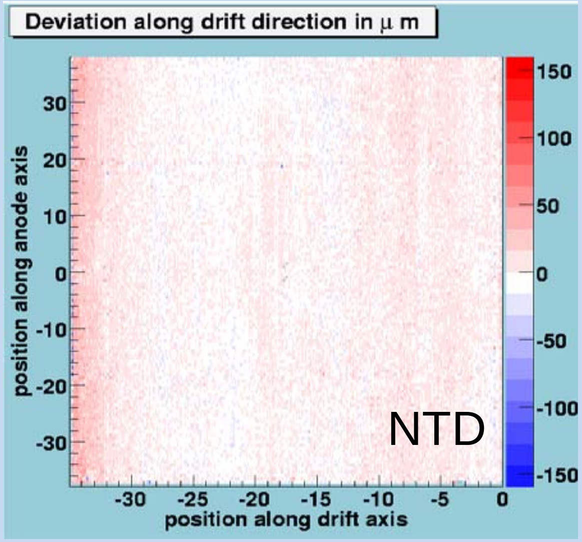
Simulation: drift and collection regions



BUT …

- For high resolution the electric field must be very uniform → Neutron Transmutation Doped (NTD) substrates
- Complication for Float-Zone (FZ) material: corrections must be applied to the reconstructed position (e.g. lookup tables) → precise characterization of every single detector !!!





In 1974 Topsil realized the Neutron Transmutation Doping process: conventionally doped Silicon (FZ), having a very high resistivity is irradiated with thermal neutrons

$$^{30}_{14}Si + n \rightarrow ^{31}_{14}Si + \gamma \xrightarrow{2.6\ hours} ^{31}_{15}P + e^{-} + \overline{\nu}$$

The final product, Neutron Transmutation Doped Silicon, has a lower resistivity than the starting material and a very uniform Phosphorus doping concentration

Why SDDs are attractive?

- In comparison to the pixel detectors:
  - The charge transport mechanism allows to measure the two spatial coordinates of the incoming particles with the same precision, but using a very small number of channels (N instead of N^2)
- In comparison to the micro-strip detectors:
  - There is no ambiguity in the position reconstruction of the impact point of the particles (highly desirable in high particle multiplicity environments)
  - The anodes are very small (lower detector capacitance) → reduced series noise contribution from the preamplifier

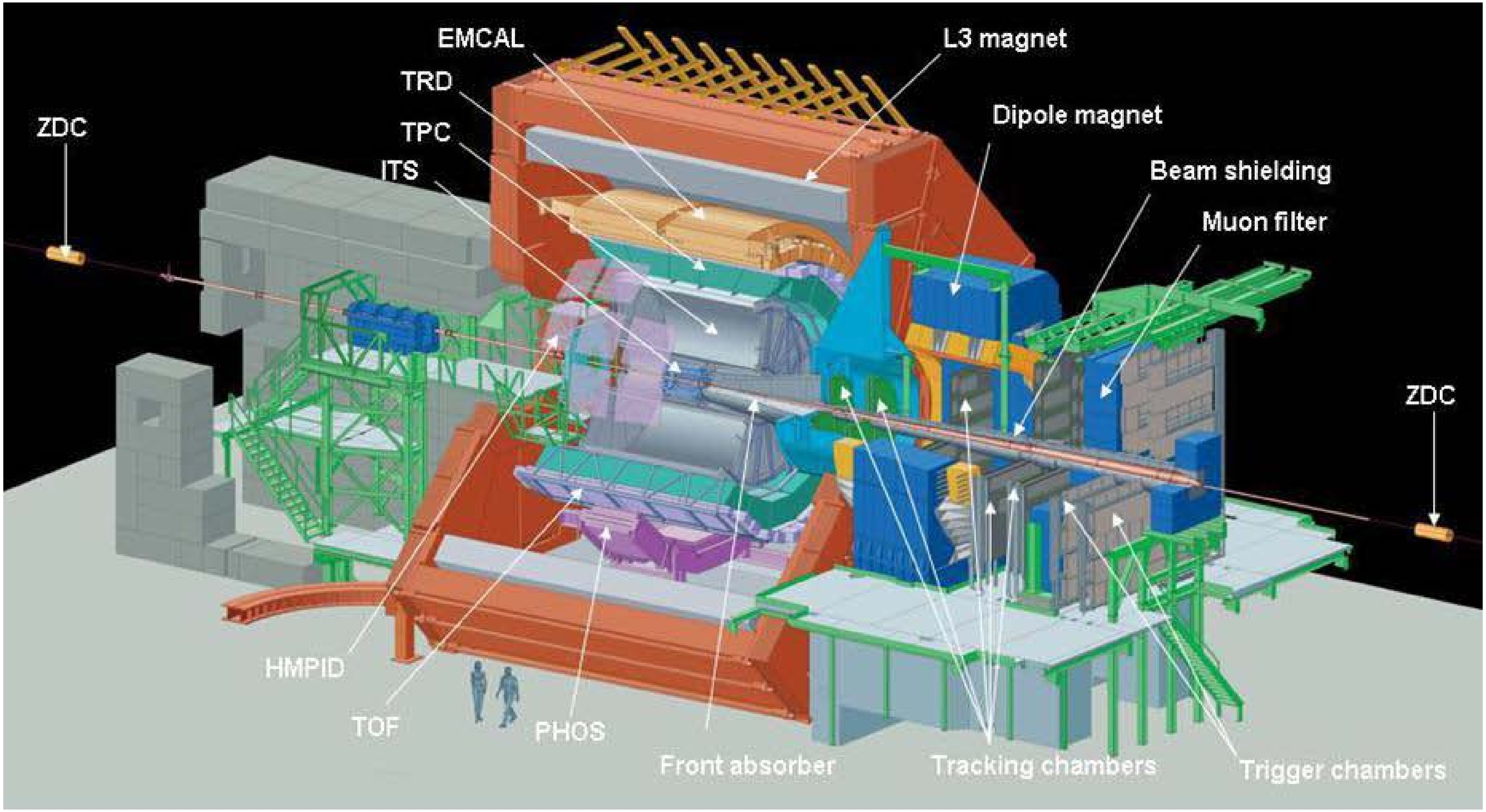
EXAMPLE: the LHC-ALICE experiment design requirements of the Inner Tracking System

Parameter	**Pixels**	**Drifts**	**Strips**
radius (inner plane) cm	3.9	14.9	38.5
radius (outer plane) cm	7.6	23.8	43.6
cell size ($r\phi \times z$) μm^2	50×425	150×224	95×40000
resolution ($r\phi$) μm	**12**	**35**	**15**
resolution (z) μm	**100**	**25**	**730**
max. occupancy %	2.1	2.5	4
max. expected dose (10 years) krad	250	13	2
total area m^2	**0.24**	**1.37**	**4.9**
total no. of channels	**9.8 M**	**133 k**	**2.6 M**
material budget (both layers) % X0	2.06	1.89	1.78
Readout channels density ch./m^2	**40.8 M**	**0.1 M**	**0.53 M**

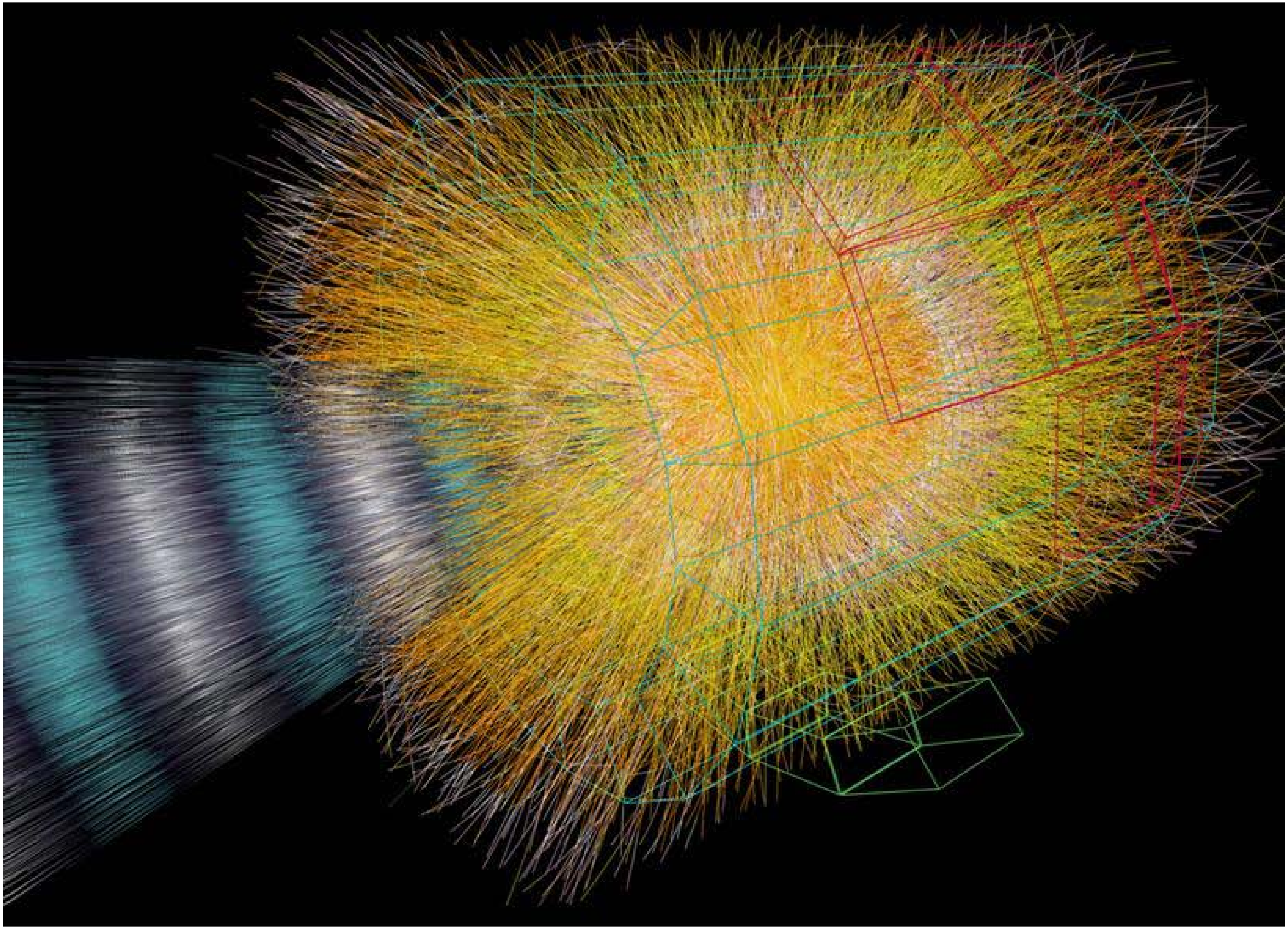
What are the shortcomings?

- High bias voltage (→ high power consumption in the detector)
- High data throughput (for the drift coordinate reconstruction)
- Slow detector (event rate limited by the maximum drift time)

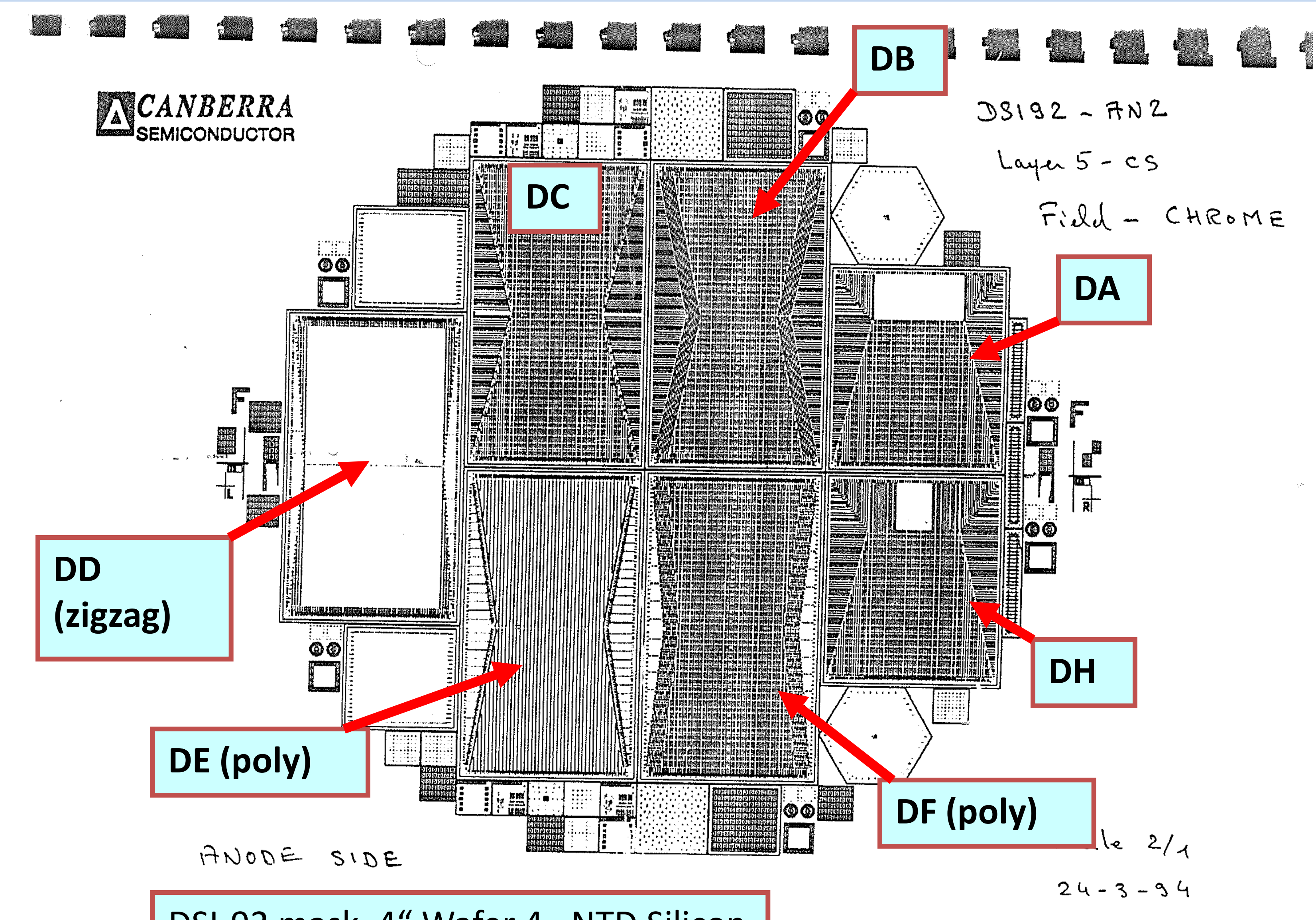
The ALICE-D4 detector in the ALICE-ITS



A typical interesting ALICE event !!! - Simulation

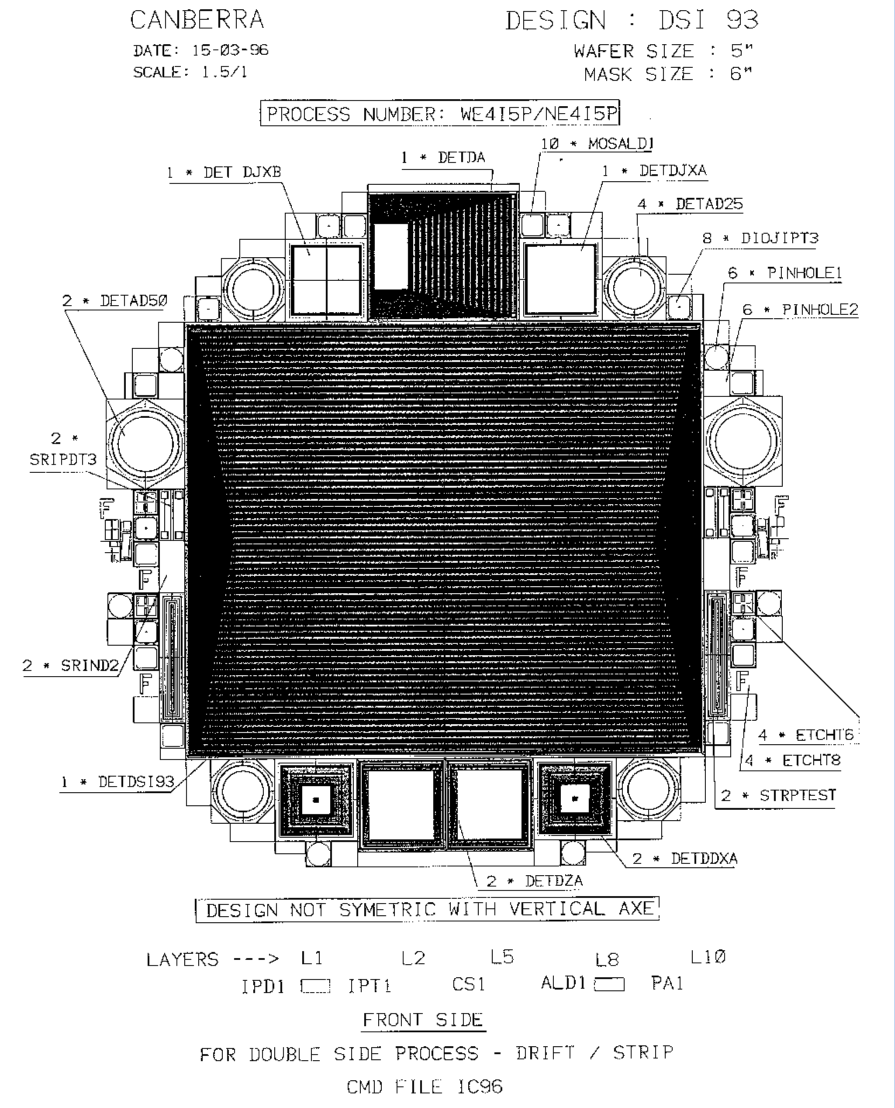


1992. INFN project Drift Silicon (DSI)



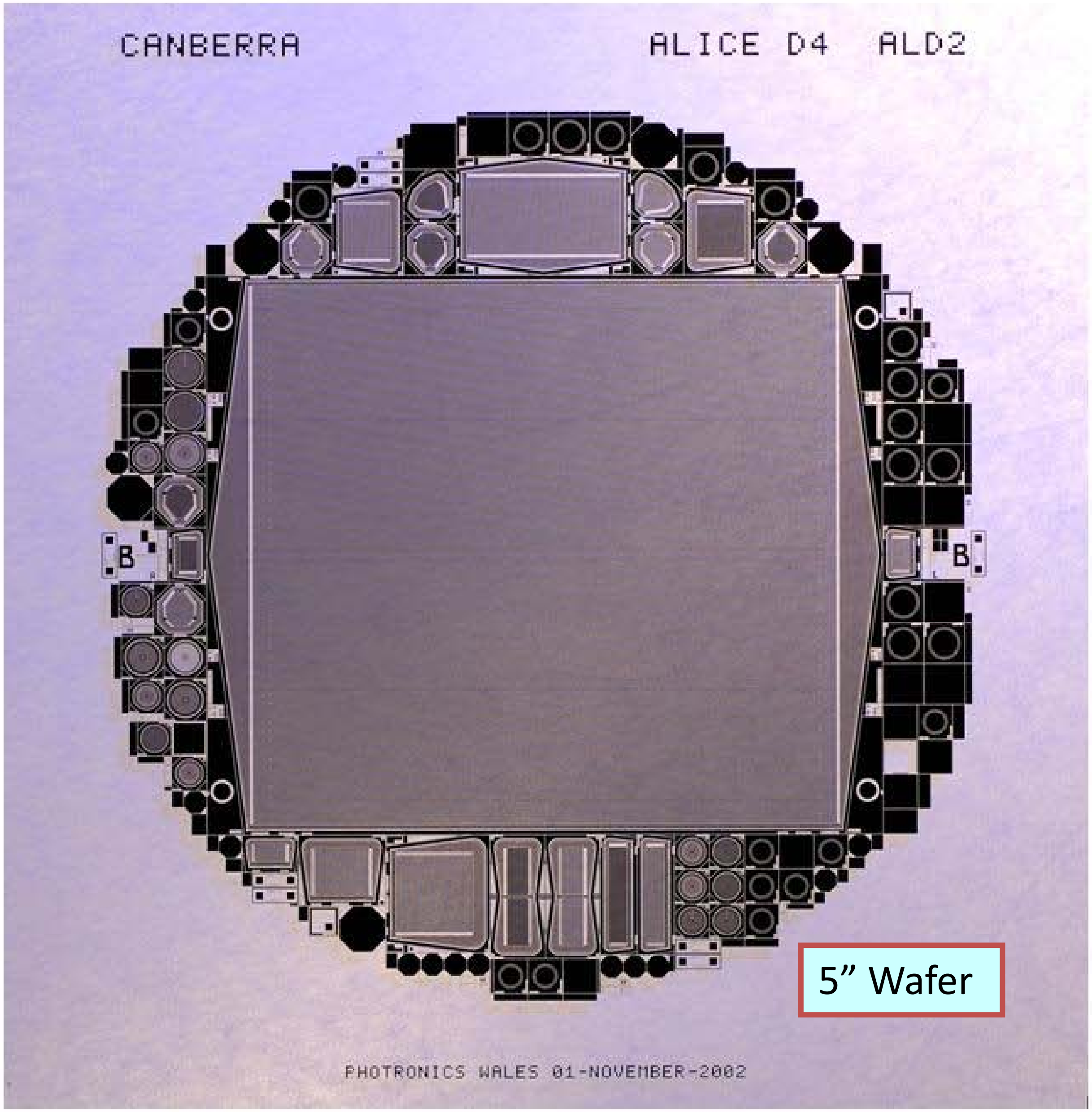
DSI-92 mask. 4“ Wafer 4 , NTD Silicon

1996. First large-area prototype



DSI-93 mask. 5" Wafer

2002. Final version of the ALICE SDD (ALICE-D4 mask)



ALICE-D4 for the LHC-ALICE experiment

Wafer type:

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

Area:

- sensible 7.02 × 7.53 ≈ 53 cm^2, <u>divided in 2 drift regios</u>
- 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:

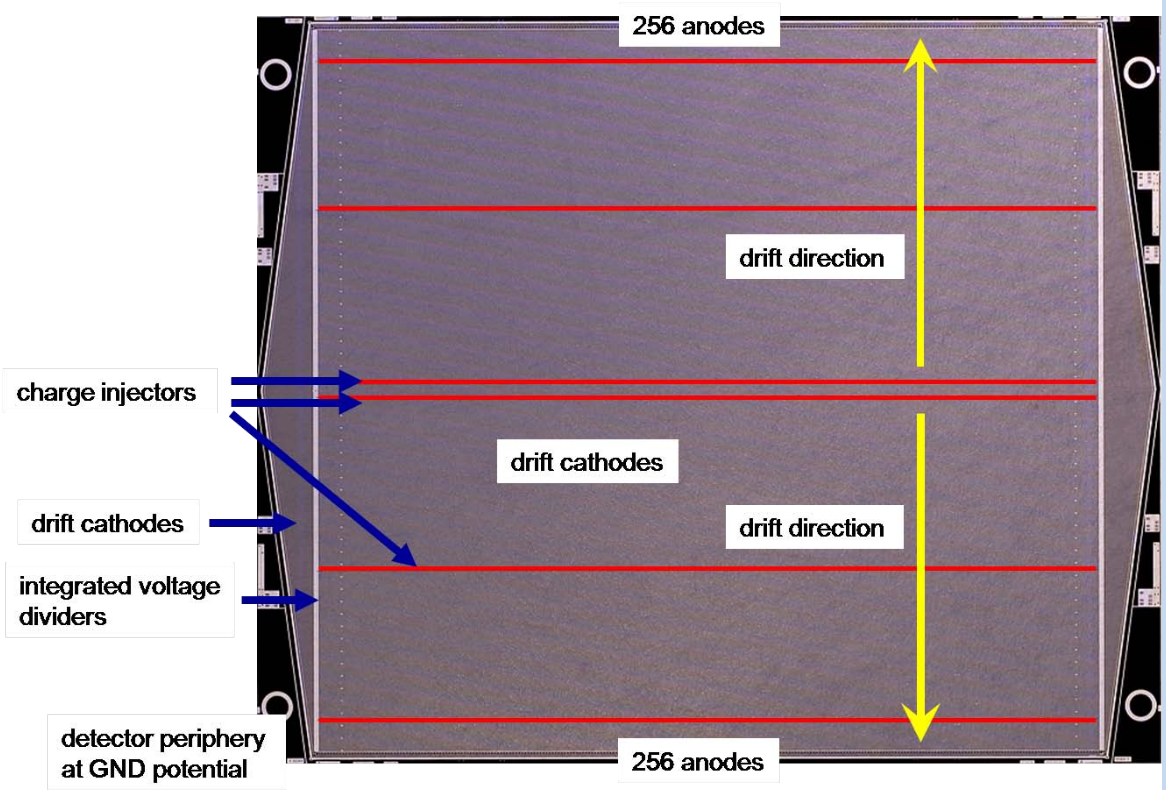
- independent voltage dividers

Integrated dividers:

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

Each anode:

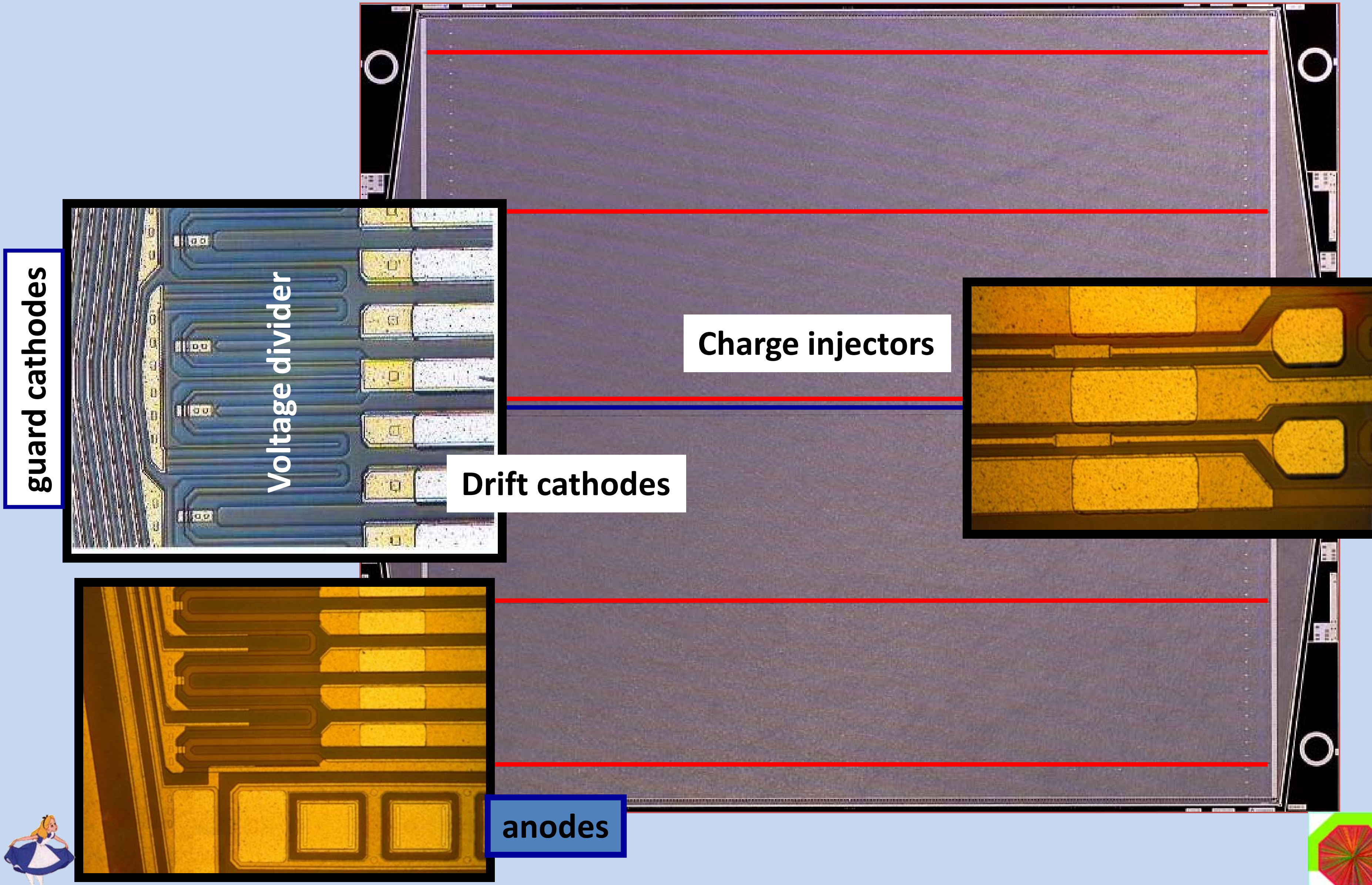
- has a very small capacitance of ~50 fF
- reads an area of 10 mm^2



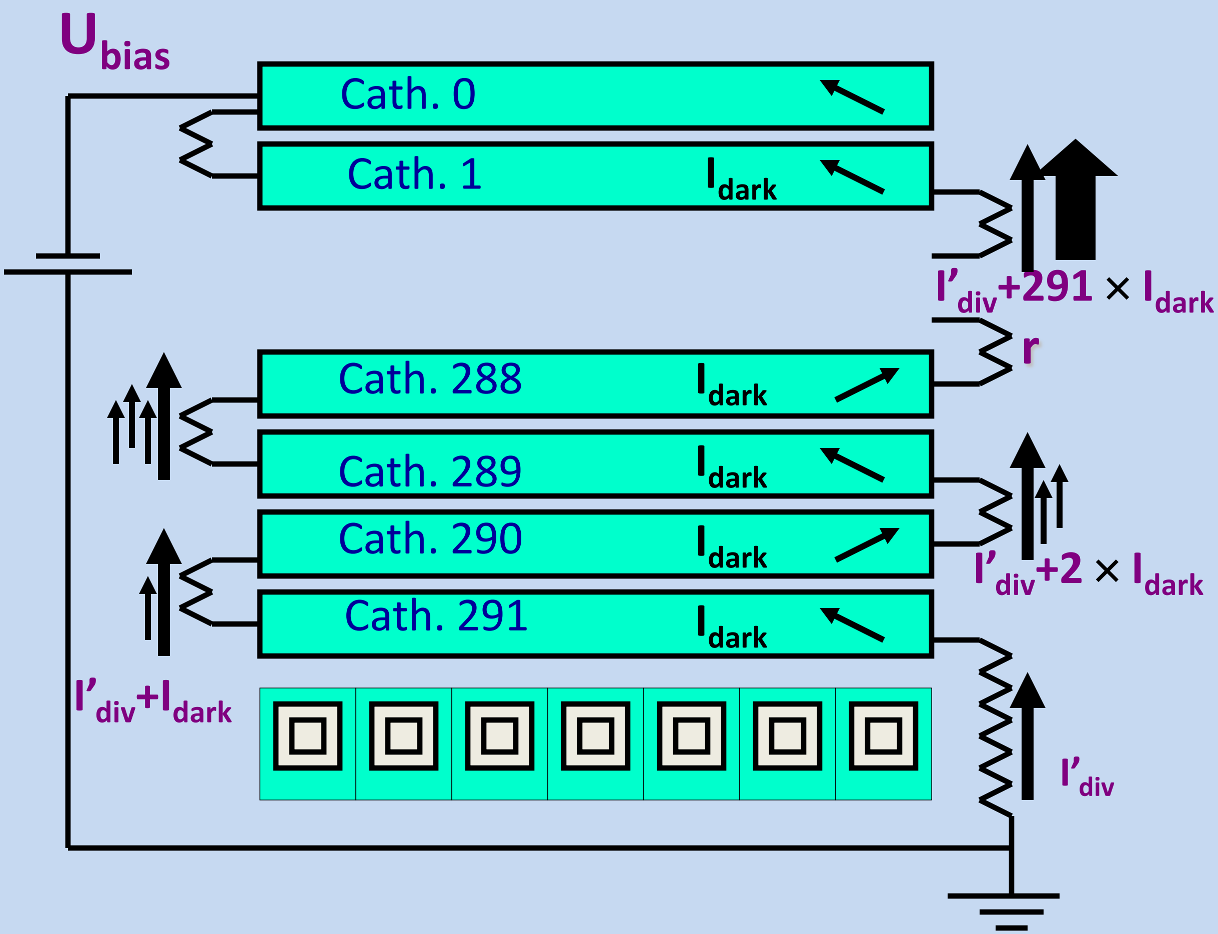
Maximum ratings for the detector bias:

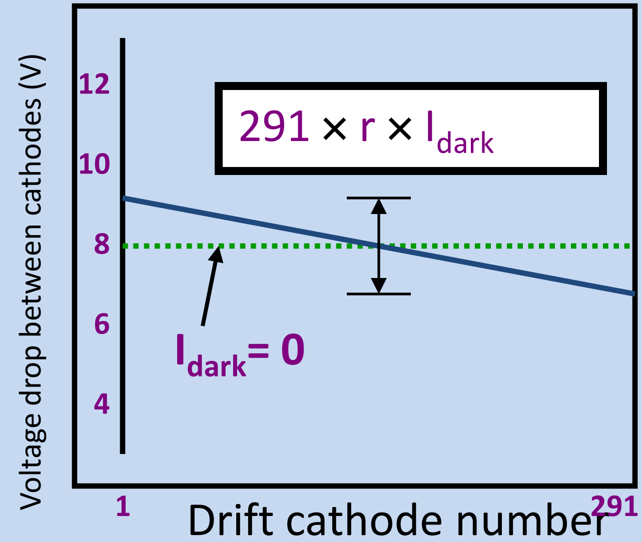
- HV bias: -2.4 kV, 8V/cathode E = 670 V/cm
- for a drift time of 4.3 μs, v_d = 8 μm/ns
- total current on the voltage dividers ~0.48 mA
- on board power consumption: 1.15 W

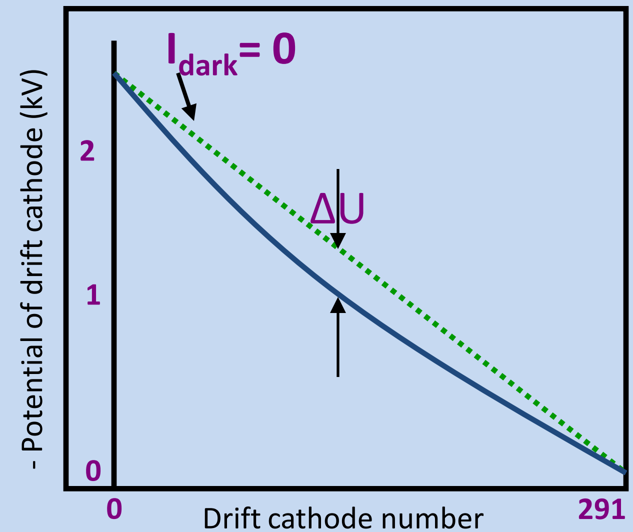
ALICE-D4 structures at the microscope



ALICE-D4 integrated voltage divider - 1



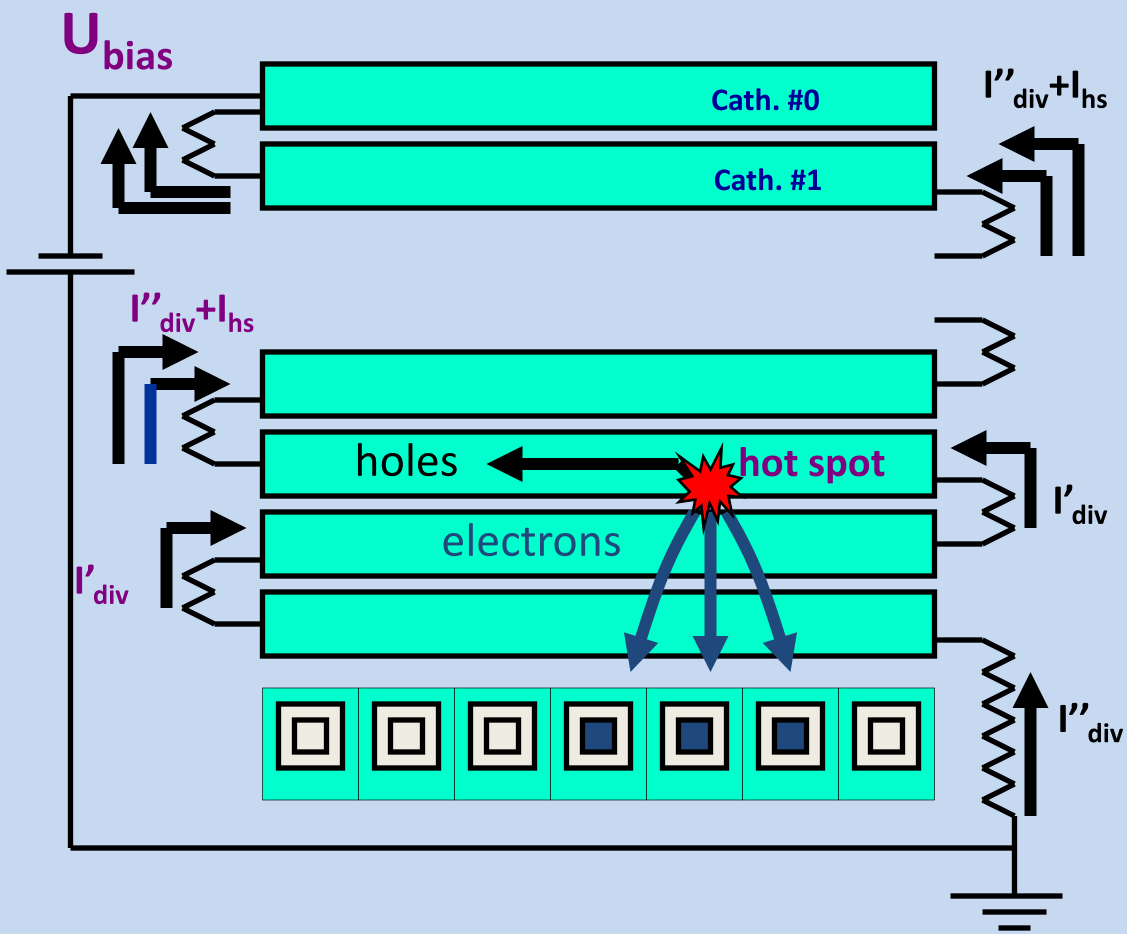


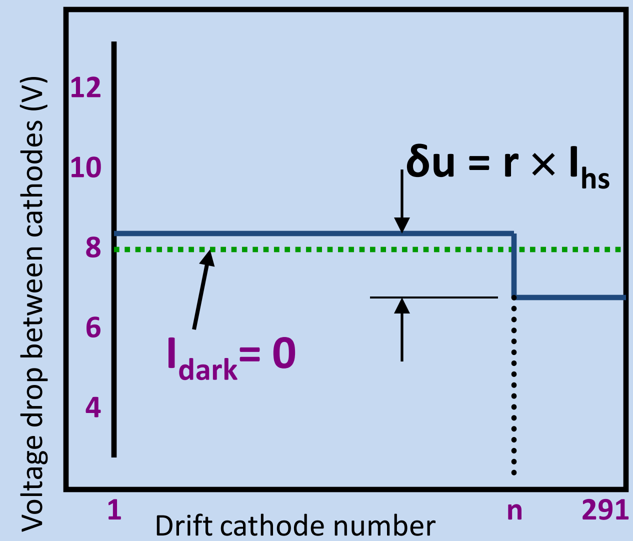


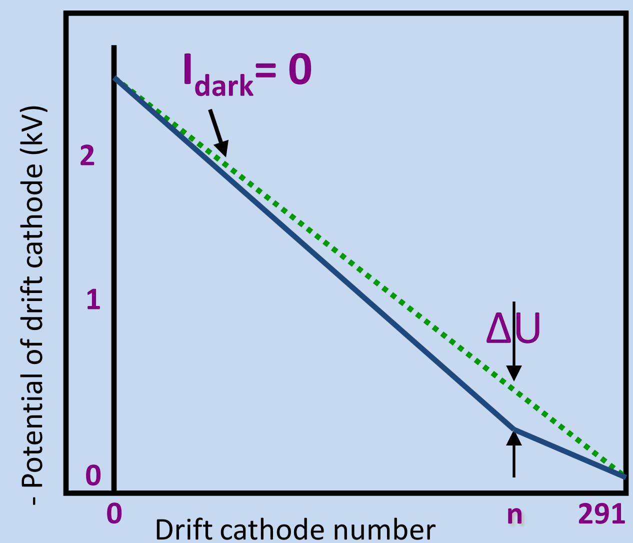
$$U_{bias} = 291 \times r \times (I'_{div} + 146 \times I_{dark})$$

N.B. I_{div} **– divider current, when** $I_{dark} = 0$

ALICE-D4 integrated voltage divider - 2







$U_{bias} = 291 \times r \times I''_{div} + n \times r \times I_{hs}$

(I_{hs} – "hot spot" current that enters the divider through the drift cathode n)

N.B. I_{div} – divider current, when $I_{dark} = 0$

ALICE-D4 charge injectors - 1

$$x = v \cdot \Delta t$$

$$v = \mu \cdot E \overset{?}{=} const.$$

NO !!!

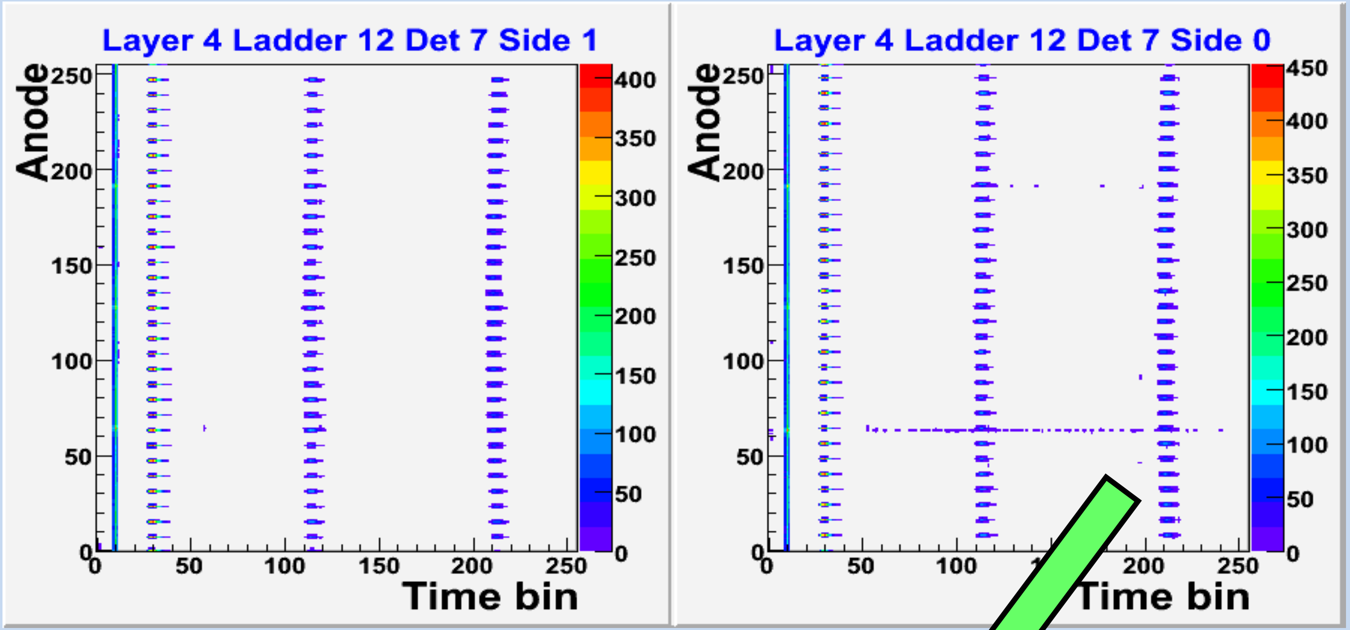
$$\mu \propto T^{-2.4}$$

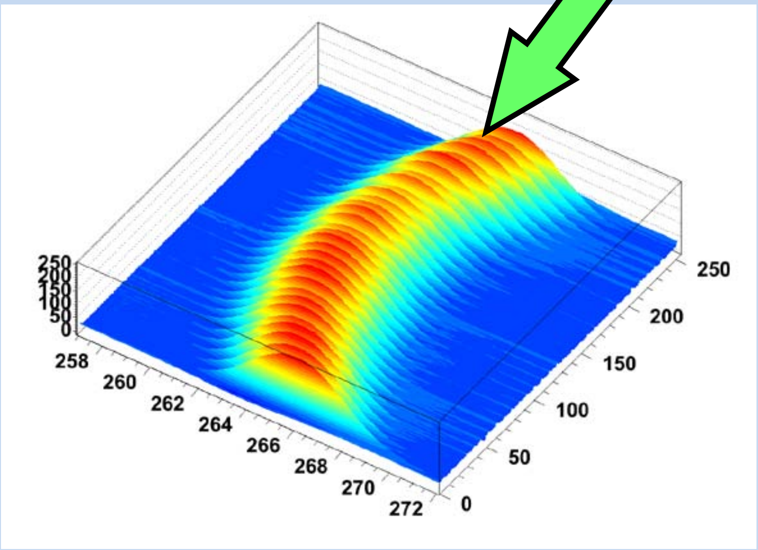
The SDD are extremely sensitive to temperature variations: 0.8 %/K at room temperature!!

To require a spatial res. of 35 µm we need to know the drift velocity with a precision of 0.1%
→ charge injectors

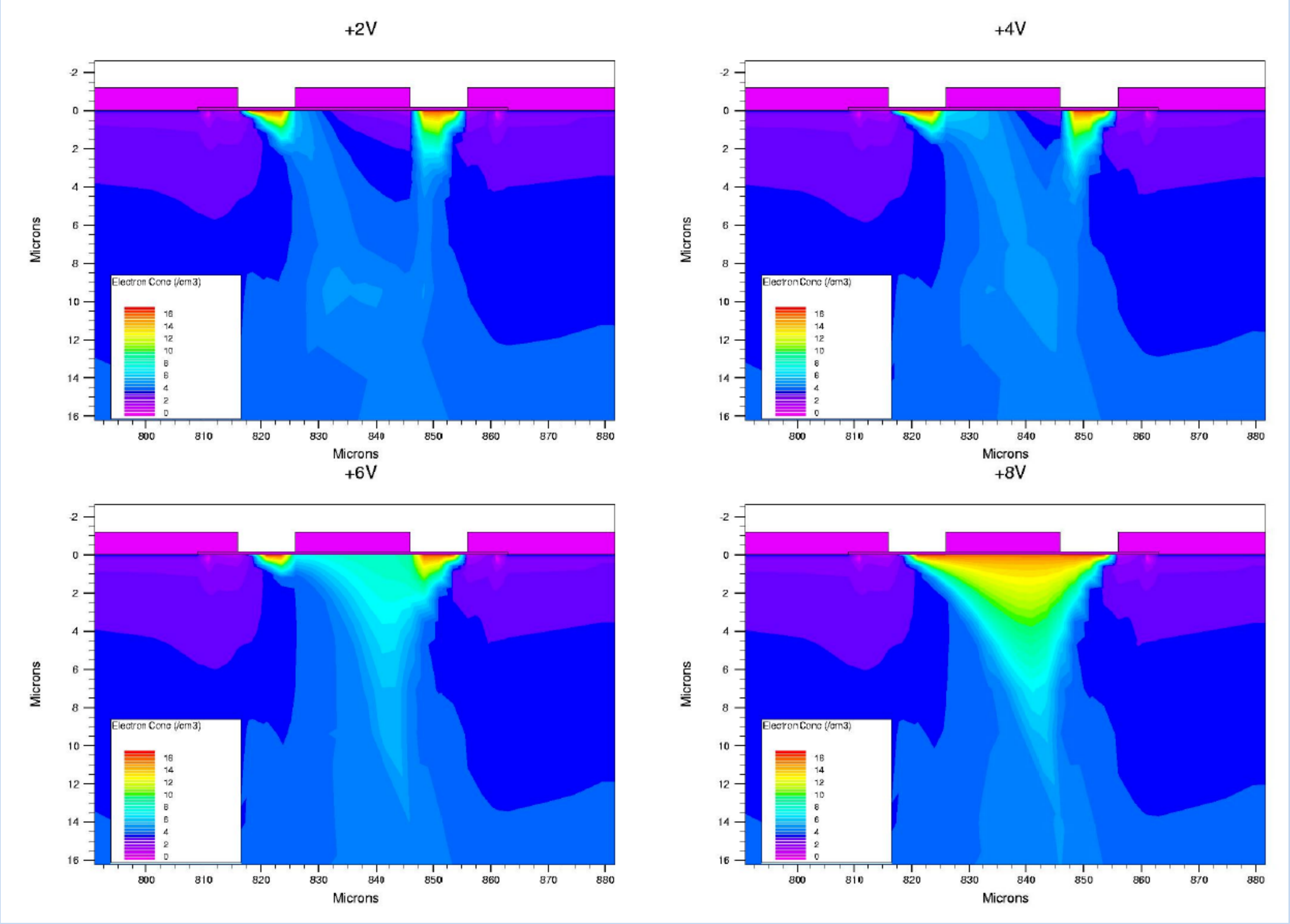
The SDD is a very good (but expensive) thermometer:

$$T[K] = 293.15 \cdot \left(\frac{v/E}{\mu_{293.15\,K}} \right)^{-\frac{1}{2.4}}$$



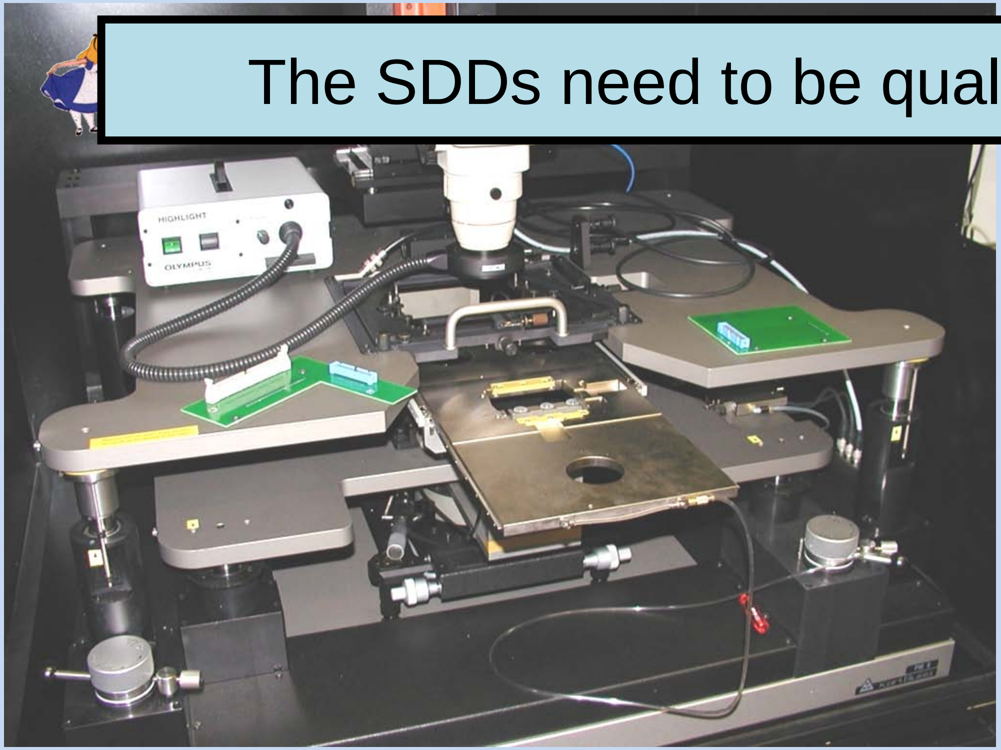


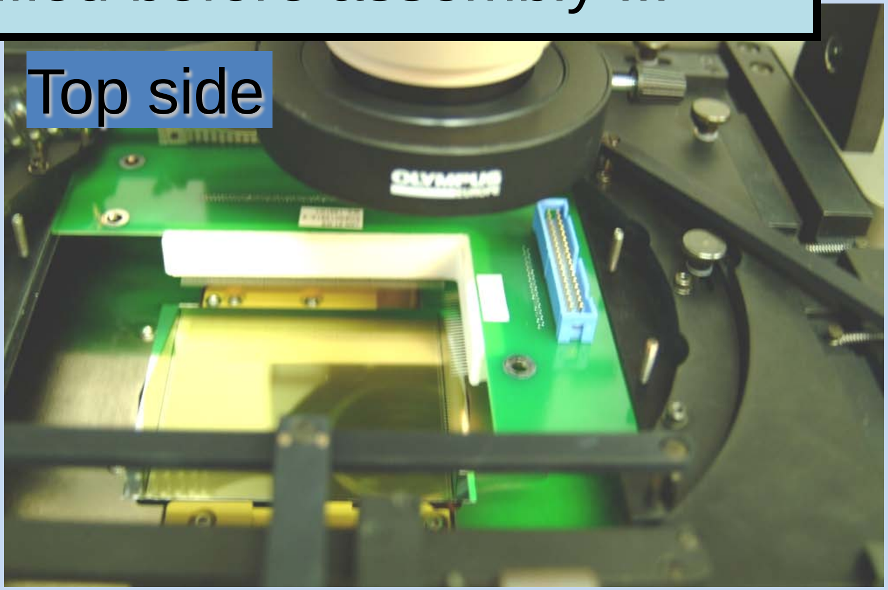
ALICE-D4 charge injectors – 2



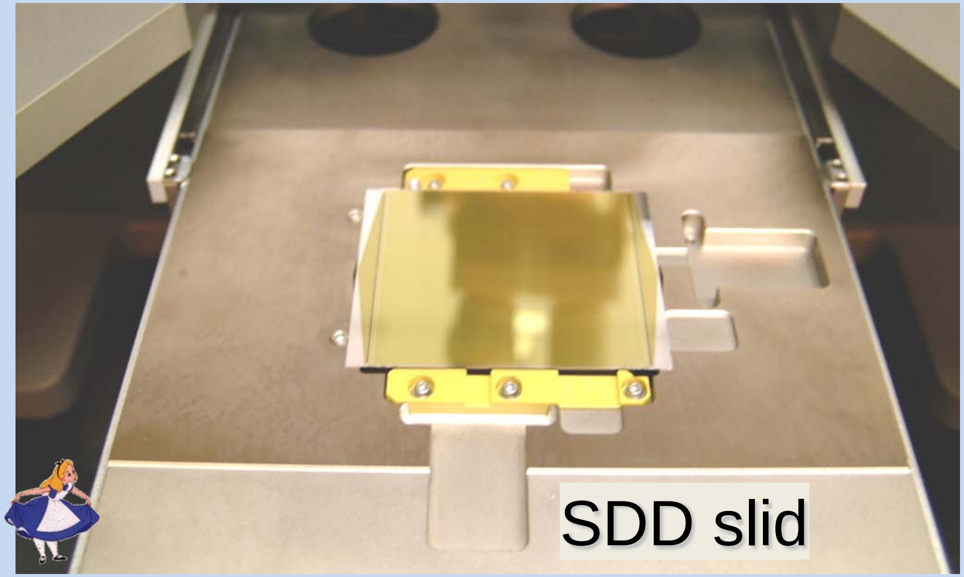
e^- concentration in the transversal section. Qox = 2.0E+11 q/cm^2

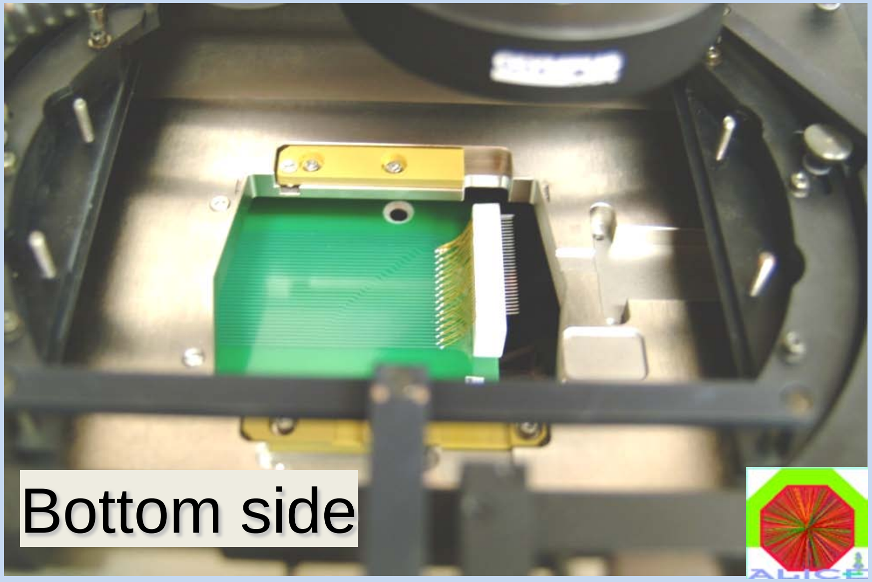
The SDDs need to be qualified before assembly !!!





Double sided probe station at INFN Trieste

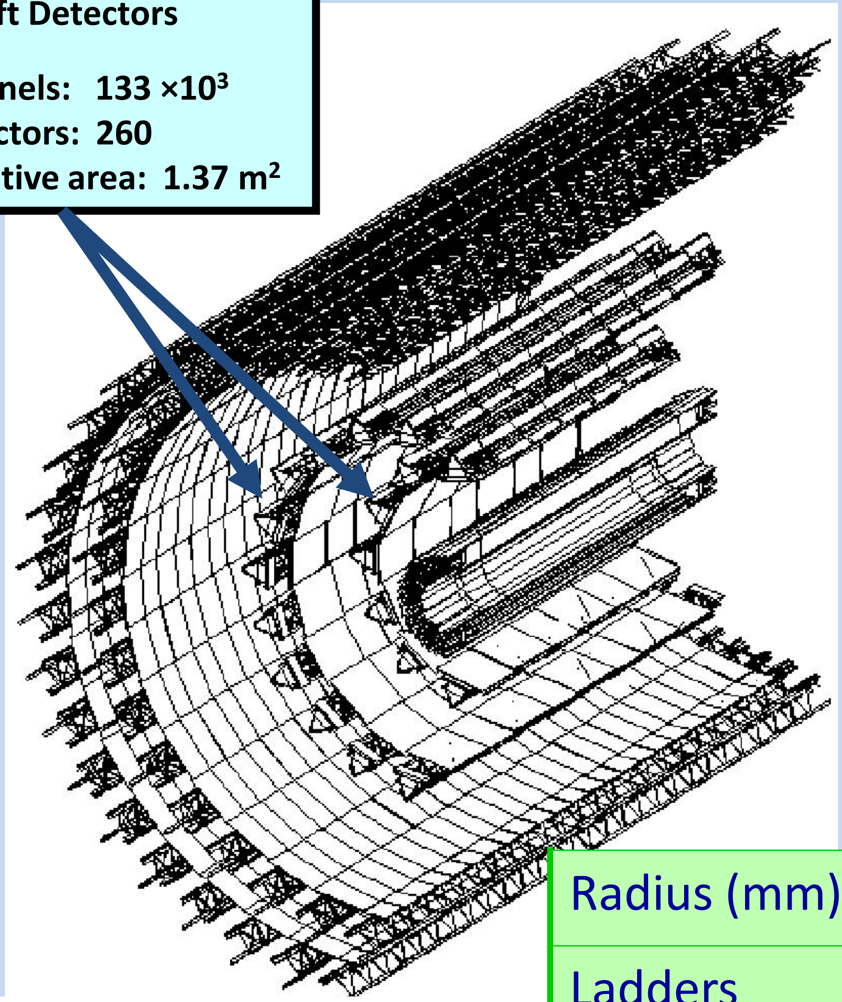


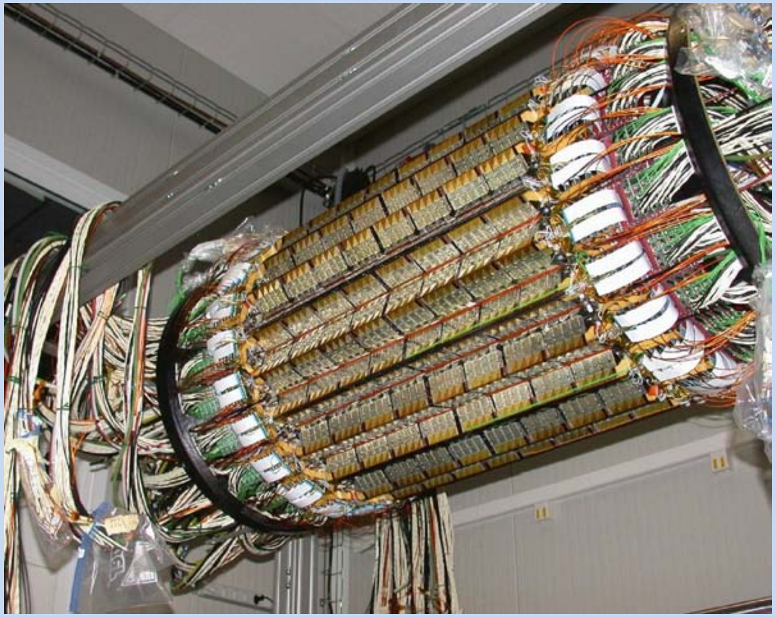


The ALICE-D4 detector in the ALICE-ITS

Silicon Drift Detectors

Total channels: 133 ×10^3
Total detectors: 260
Total sensitive area: 1.37 m^2

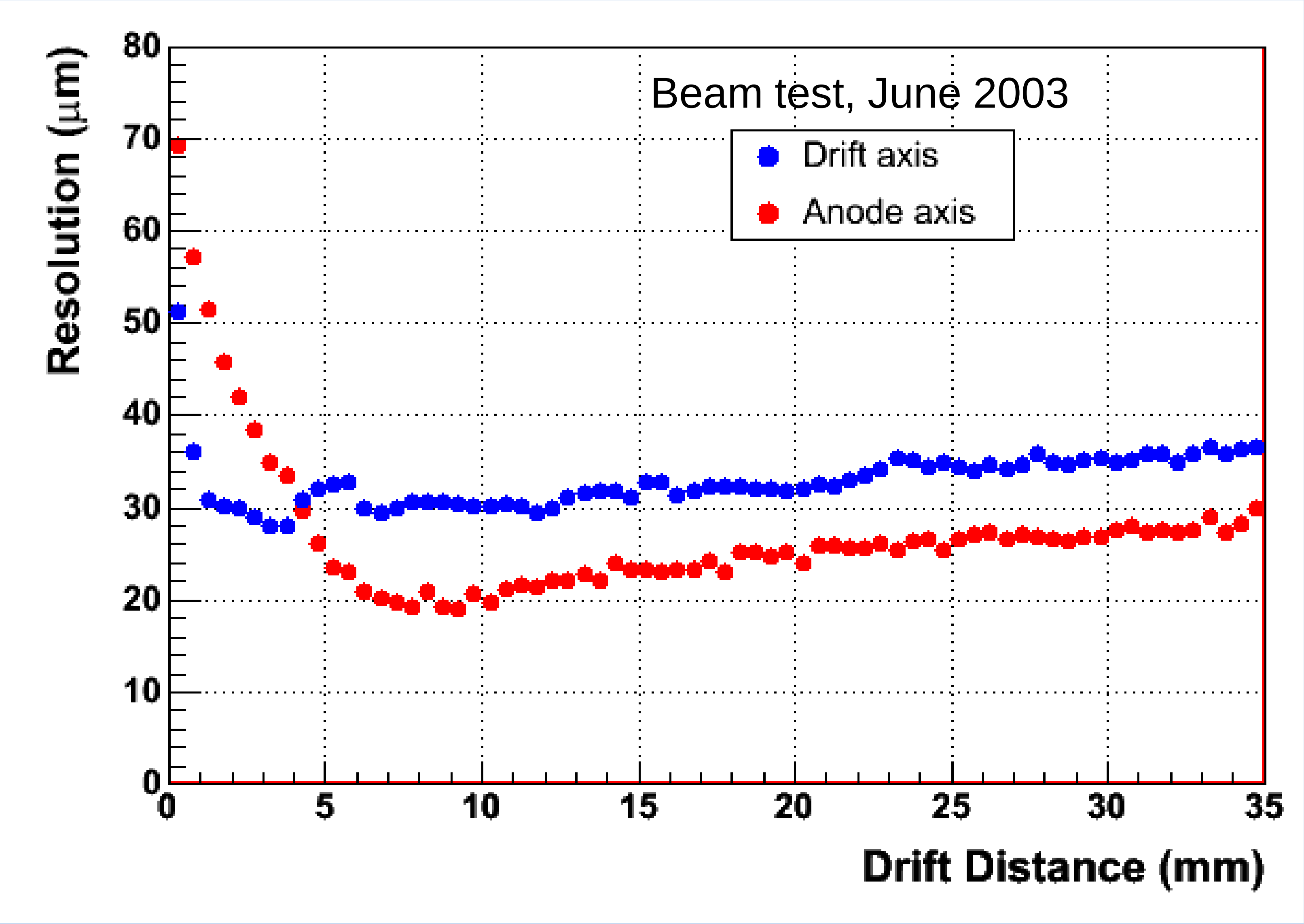




- 600 detectors realized and tested for compliance with specifications
- production yield better than 60%

	Layer 3	Layer 4
Radius (mm)	14.9	23.8
Ladders	14	22
SDDs per ladder	6	8

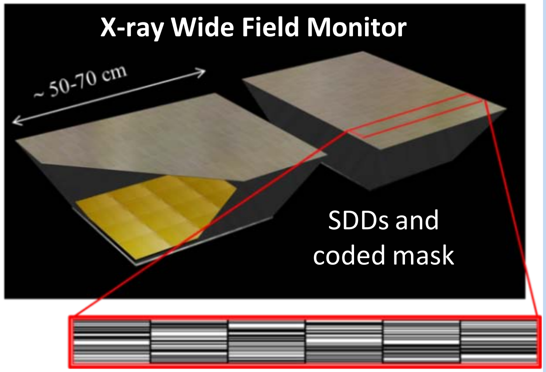
The ALICE-D4 detector in the ALICE-ITS: spatial resolution



On-going SDD developments in photon detection (XDXL project)

Compact instruments for X-rays in the 3 to 50 keV energy range

- Angular res: 5 arcmin
- Module sensitivity: 2.3 mCrab @ Δt=50 ks
- FoV: 4.6 steradiants
- Mask distance: 150 mm
- Total weight: 28 kg



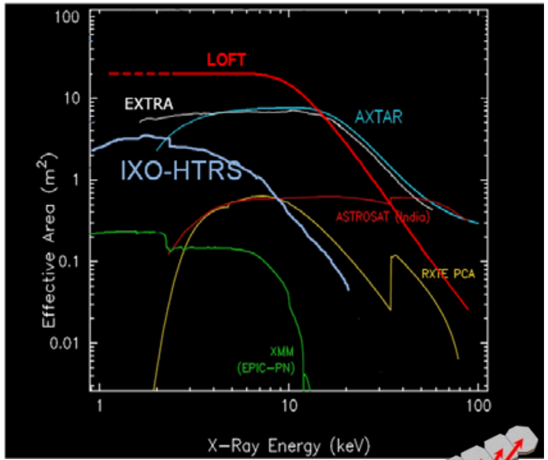
Flying missions	Energy Range (keV)	Angular Resolution (arcmin)	1-day Sensitivity (mCrab)	Field of View (deg^2)	Area (cm^2)	Detector Position Res. (mm)	Mask-Detector Dist. (mm)	Weight (kg)
INTEGRAL/IBIS	20-2000	12	~3-5	29 x 29	2600	4.6	3200	700
Swift/BAT	15-150	17	~5 (*)	100 x 60	5240	4	1000	>200 (*)
ISS/MAXI	2-30	6	2	1.5 x 160	5350	1	770	490
BeppoSAX/WFC	2-28	5	~5	40 x 40	140	0.5	700	43
RossiXTE/ASM	2-12	12	10	12 x 110	90	0.5	300	>30 (*)
HETE-2/WXM	2-25	36	N/A	90 x 80	175	1	187	>20 (*)
AGILE/SuperAGILE	18-60	6	~15	106 x 68	1444	0.121	140	5.5

(*) Not available from literature: "reasonable guess" based on the instrument/mask properties

LOFT

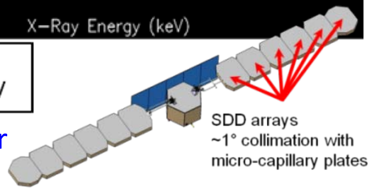
Based on the SDD technology, a timing mission with an effective area of 20 m^2

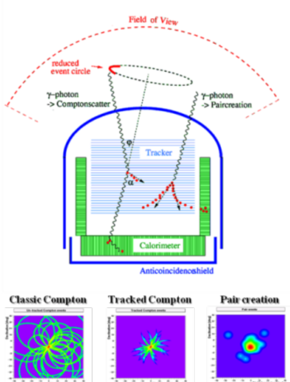
Lead glass micro-capillary plates used to collimate X-rays to limit the FOV to 1° FWHM

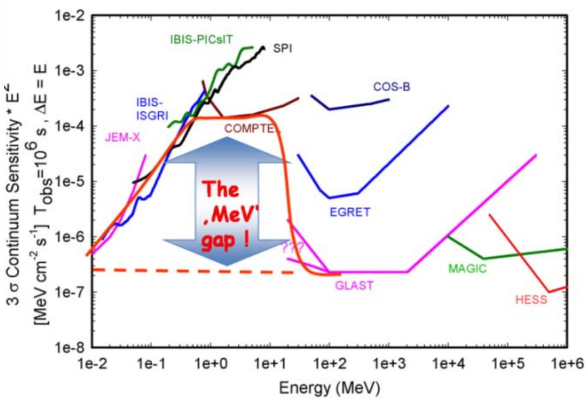


Dead-time	Energy Resolution	Band
negligible	300 eV (room temp.)	3-30 keV

5 sigma sensitivity @ 3-30 keV one order of magnitude better than RXTE

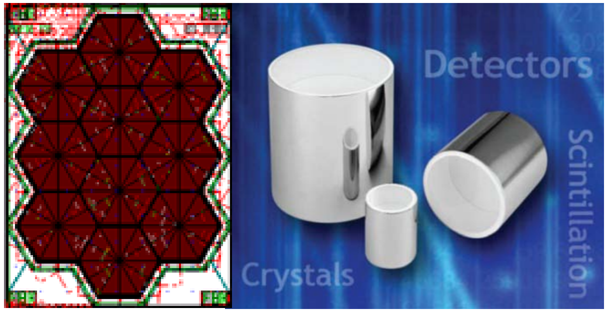






- A detector to address the so-called "MeV energy gap"
- γ-ray photons scatter on a high resolution tracker (linear SDD) and are absorbed by a segmented calorimeter
- The calorimeter provides a precise time reference to allow high resolution drift time measurement

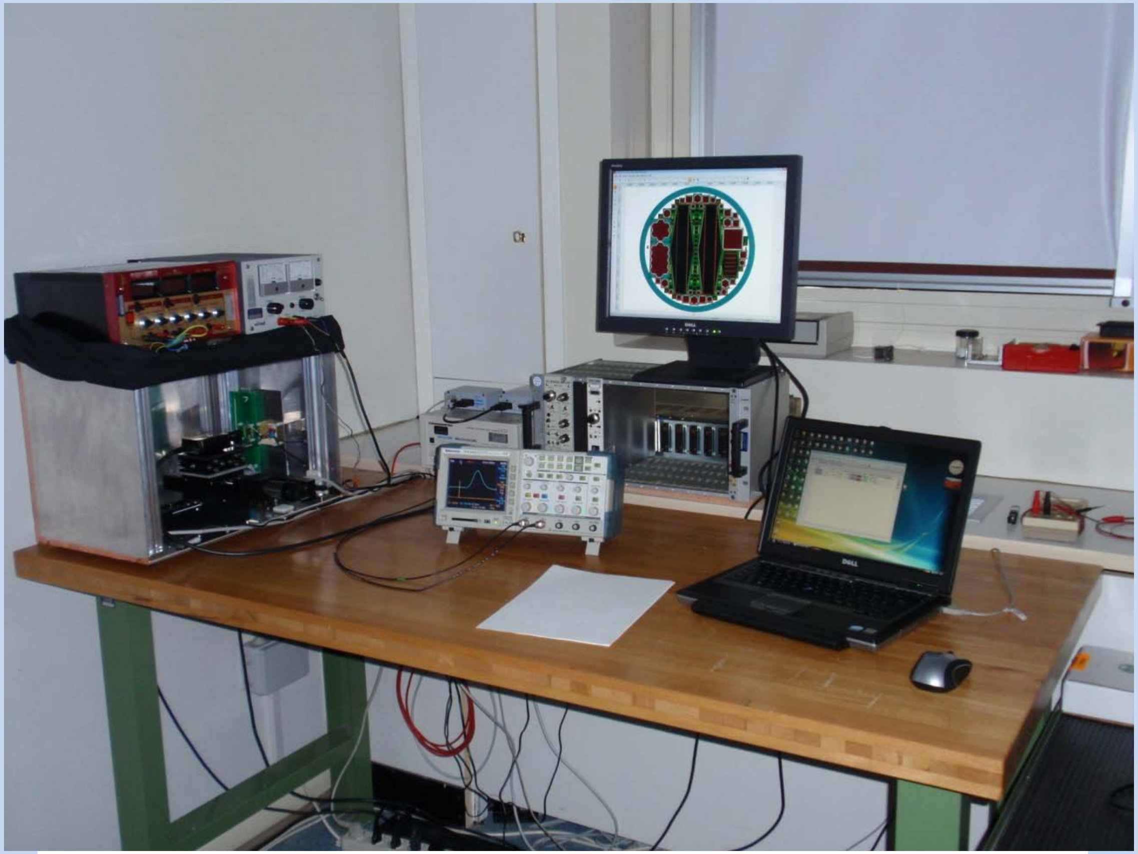
$LaBr_3(Ce)$ crystals coupled with SDD arrays realize γ-ray detectors reaching the best energy resolution with the highest detection efficiency

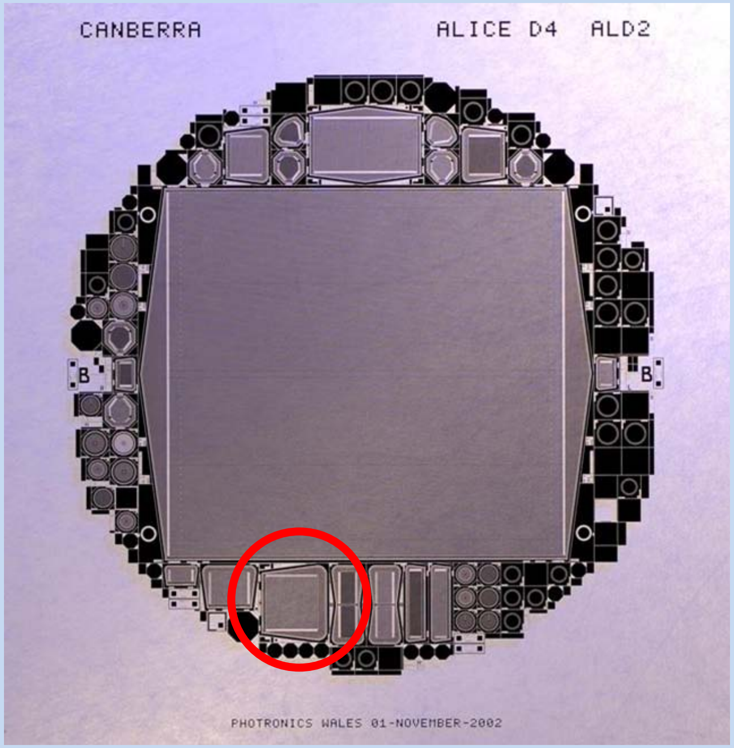


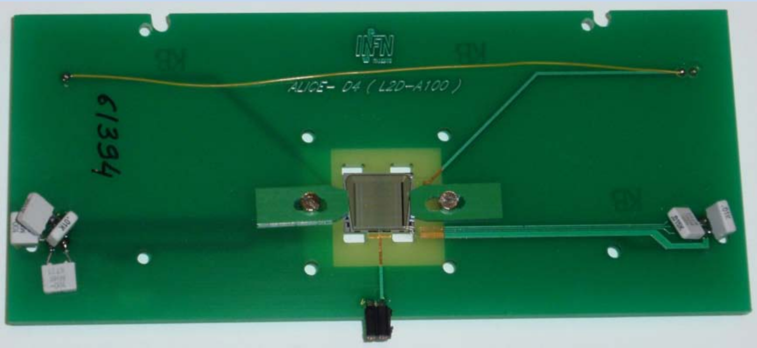
XDXL is pursuing this development within

- INFN-E project: assessment of the integrity of radioactive waste depots, ambient radioactivity monitoring…
- ESA technological tender : AO/1-6476/10/NL/CP – Silicon Drift Detectors for Gamma-Ray Scintillators for space missions (**proposal to be submitted by 2010/09/30**)

Your SDD laboratory







- Demonstration of the SDD working principle with a smaller, single-anode device
- Discussion of the issues related to the multi-anode detector and the charge transport mechanism
- X-ray spectroscopic performances of the ALICE-D4 detector with the data taken at the INAF/IASF X-ray facility in Rome

Enjoy the LAB