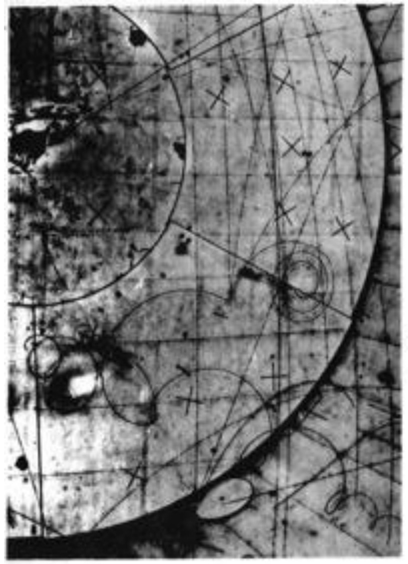
Silicon Detectors :
60 Years of Innovations

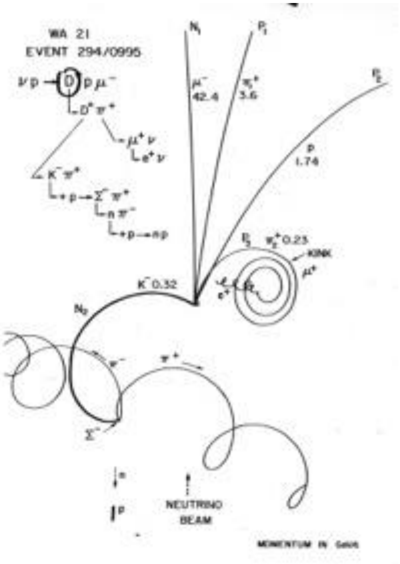
Erik H.M. HEIJNE

EP Detector Seminar

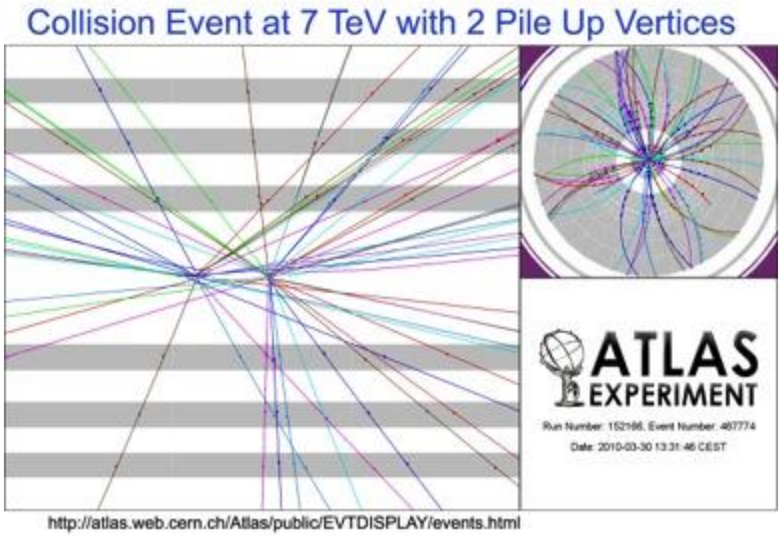
CERN, Genève 16 June 2016

from Bubble Chambers to fully Electronic Imagers





ATLAS experiment 2012



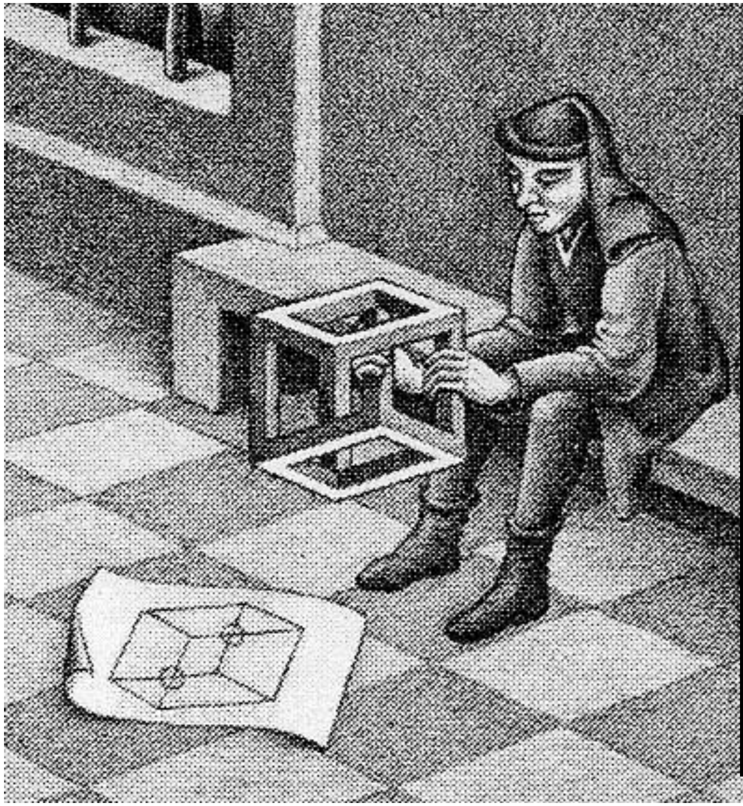
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

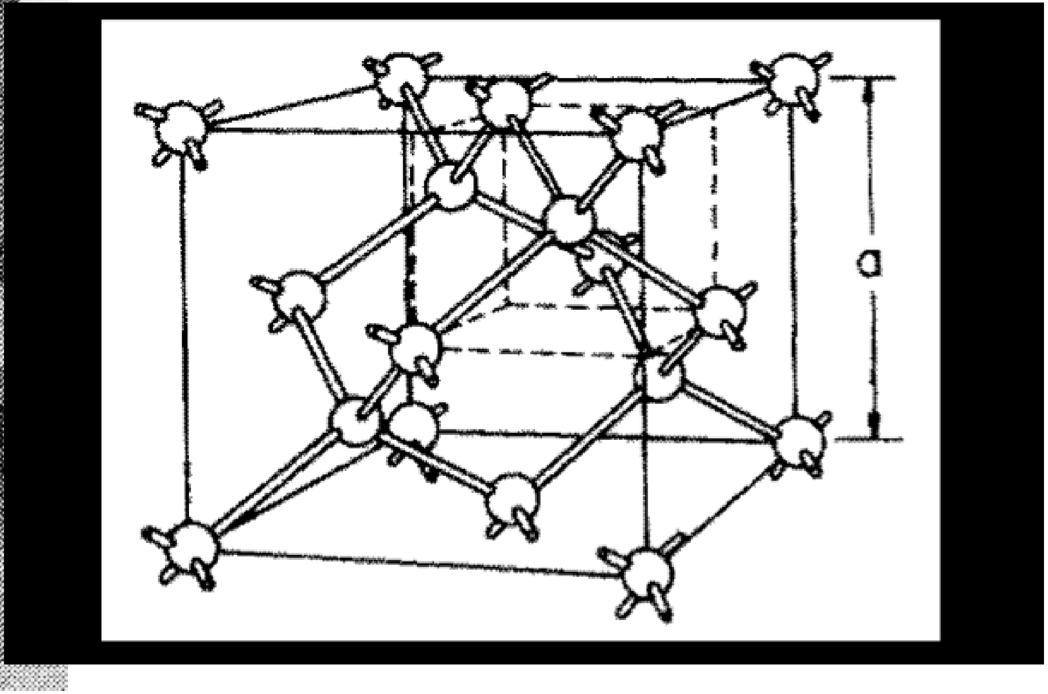
BEBC 1981
photo every ~1s

40 million
records per s

Liquid H → **silicon for vertexing** **(but image information is lost)**

Mono-crystalline semiconductors





Silicon crystal
Imagination and Innovation

- sensitive to visible light (CCD, CMOS camera)
- also all other sorts of radiation (>1.12 eV bandgap)

LOW Z, not efficient for γ >10keV

- conductivity adjustable over 10 orders (x10^{10})
- surface oxide provides high impedance isolation

~1955 Bell,1959 Planar(Hoerni-Fairchild),1970 LOCOS(Kooi,Philips)

Some critical innovations

Surface barrier diodes and the ‘Checker board’ detector

Ion-implanted diodes: the Kemmer patent

Silicon microstrip detector and parallel signal processing

CCD as particle detector

Silicon drift chamber

Introduction of CMOS integrated circuits for readout

Hybrid pixel detector

3D ‘pillar’ diode matrix and 3D stacked detectors

Monolithic/3D CMOS detectors with fully integrated processing

Acknowledgement

Many teams and individuals made essential contributions

in advance my excuses for omitting the major part

here I focus on details of only a few innovations

several were initiated at CERN, in which I was involved

with Pierre Jarron we worked for a long time as a succesful tandem

with the LAA team in 1988, microelectronics really took off:

Anghinolfi, Aspell, Campbell, Christiansen, Marchioro (was already in EF), Meddeler

many other people joined sooner and later, several made their PhD work

the experiments were masters and participants at the same time

too many to list here, some are mentioned in the slides

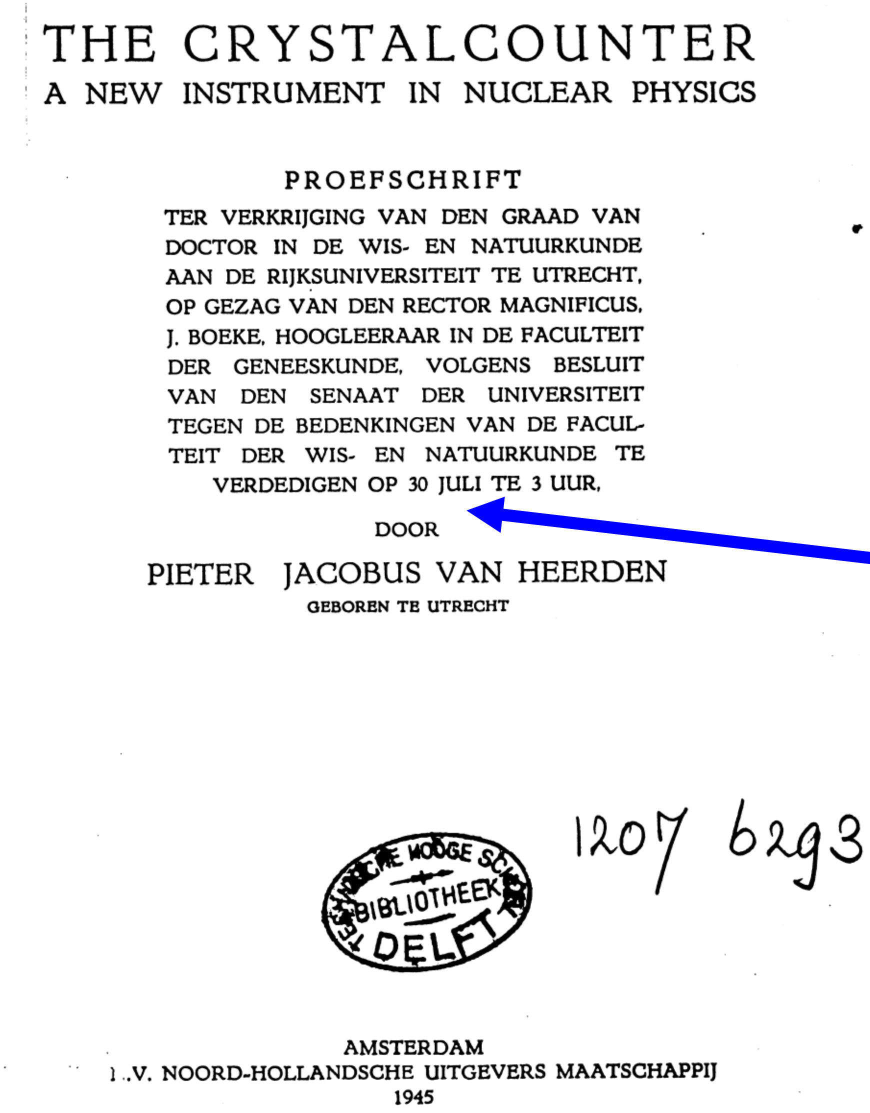
many projects with universities, institutes, manufacturers and industries

do not forget especially the technical people

Directors and Division or group leaders over several decades

The beginning, no silicon at first

First working semiconductor detector 1944



THE CRYSTALCOUNTER
A NEW INSTRUMENT IN NUCLEAR PHYSICS

PROEFSCHRIFT
TER VERKRIJGING VAN DEN GRAAD VAN DOCTOR IN DE WIS- EN NATUURKUNDE AAN DE RIJKSUNIVERSITEIT TE UTRECHT, OP GEZAG VAN DEN RECTOR MAGNIFICUS, J. BOEKE, HOOGLEERAAR IN DE FACULTEIT DER GENEESKUNDE, VOLGENS BESLUIT VAN DEN SENAAT DER UNIVERSITEIT TEGEN DE BEDENKINGEN VAN DE FACULTEIT DER WIS- EN NATUURKUNDE TE VERDEDIGEN OP 30 JULI TE 3 UUR,

DOOR
PIETER JACOBUS VAN HEERDEN
GEBOREN TE UTRECHT

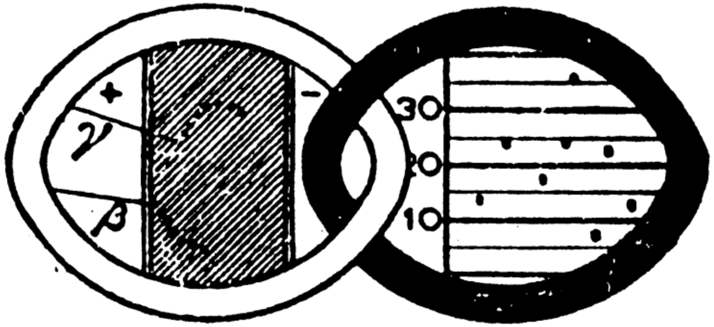
AMSTERDAM
N.V. NOORD-HOLLANDSCHE UITGEVERS MAATSCHAPPIJ
1945

AgCl crystal
is SEMICONDUCTOR
when used at LIQUID AIR temp

at RT conductive, because of
carrier injection at the contacts

PhD 30 July 1945, Utrecht

Pieter J. van Heerden



Result: electron energy spectrum

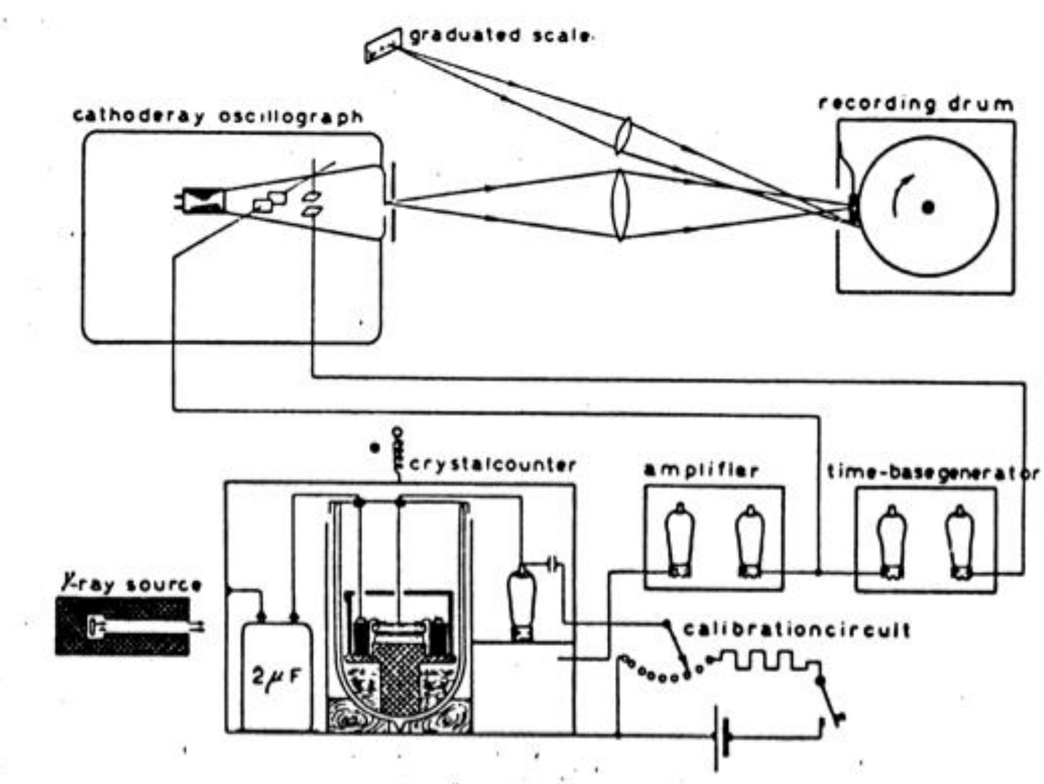
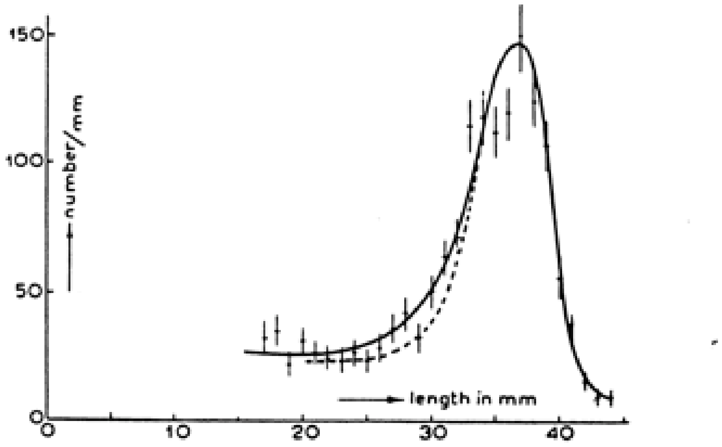
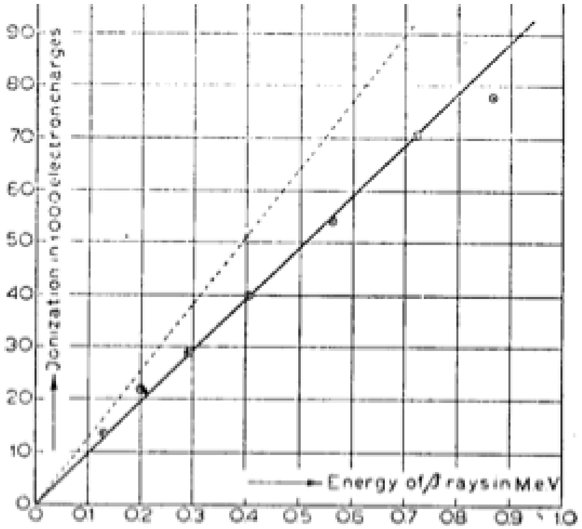


Fig. 11. The experimental arrangement.



g. 30. The distribution curve of the deflections caused by homogeneous β-rays. $H\varrho = 2500$; $E = 0.4$ M.e.V. $V = 200$ volt; 1 mm = 1200 e.c. Dotted: curve expected theoretically.



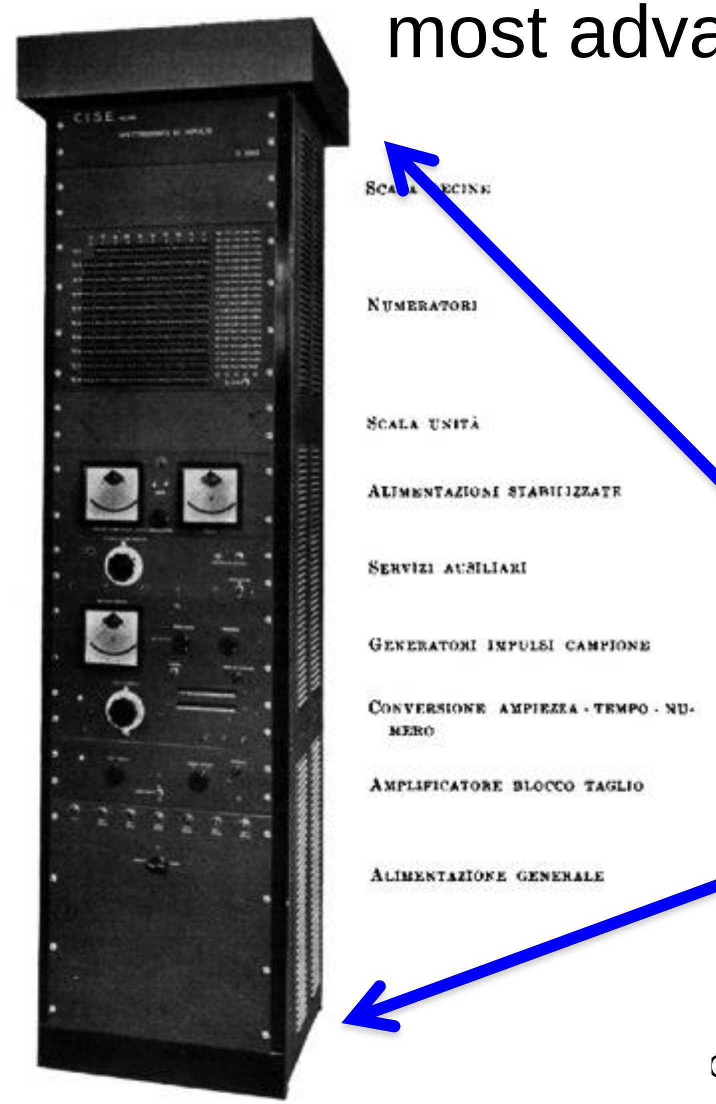
oscilloscope + film used for recording of pulses

1944 no ADCs yet !!!

several sources different energies, linear response, 7.6 eV per e-h pair

Physica16 (1950) 505, 517

ADC: nuclear and particle physics experiments need most advanced technologies for progress



In 1948 Wilkinson introduced signal digitization for nuclear spectrometry

D.H. Wilkinson Proc.Cambridge Phil.Soc.46(1950) 508

Emilio Gatti improved it further (1949)

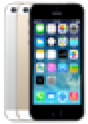
using 2 telephone registers

→ 99 channel digitizer

E. Gatti Nuovo Cimento 7(1950) 655-673

One rack, one ADC !!

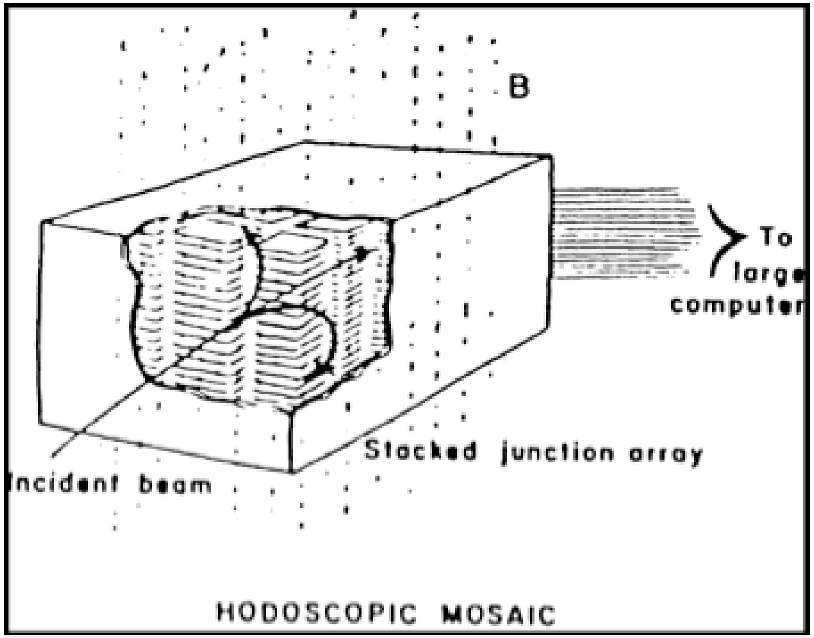
F.Anghinolfi and E. Heijne IEEE-Sol.St Circ Mag.4-3(2012) 24 history of ADC

→  iPHONE >30 ADCs

Innovation:
only if operational prototype
and measurements

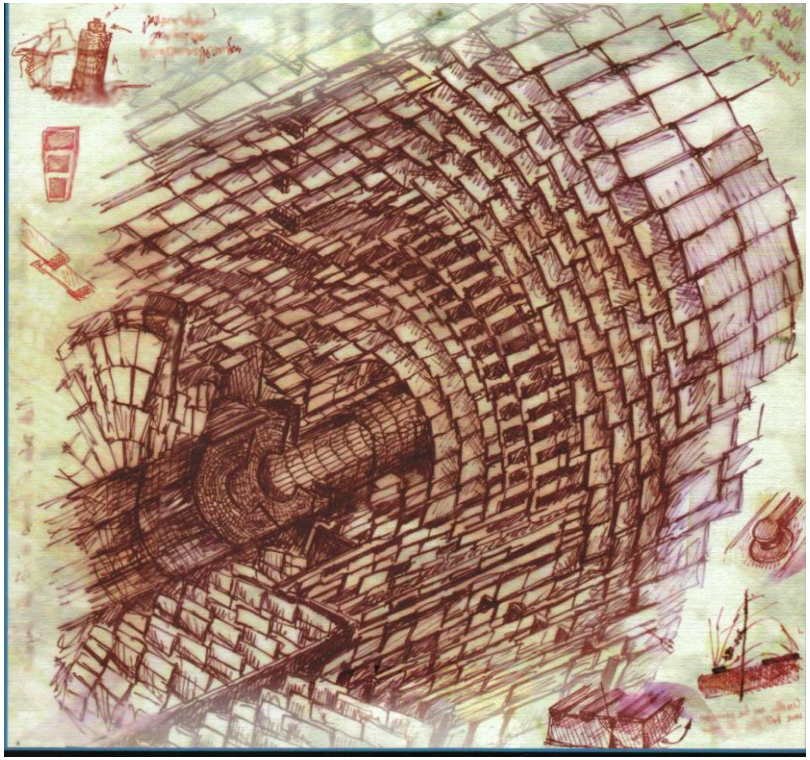
Plans for Si particle tracking systems

1960



~1959 proposal of diode array
suggested at Hughes Aircraft
by Friedmann and Mayer
reported by Bromley in Asheville

1998



1998 artistic concept in
CMS Technical Design Report
for the inner Si tracker

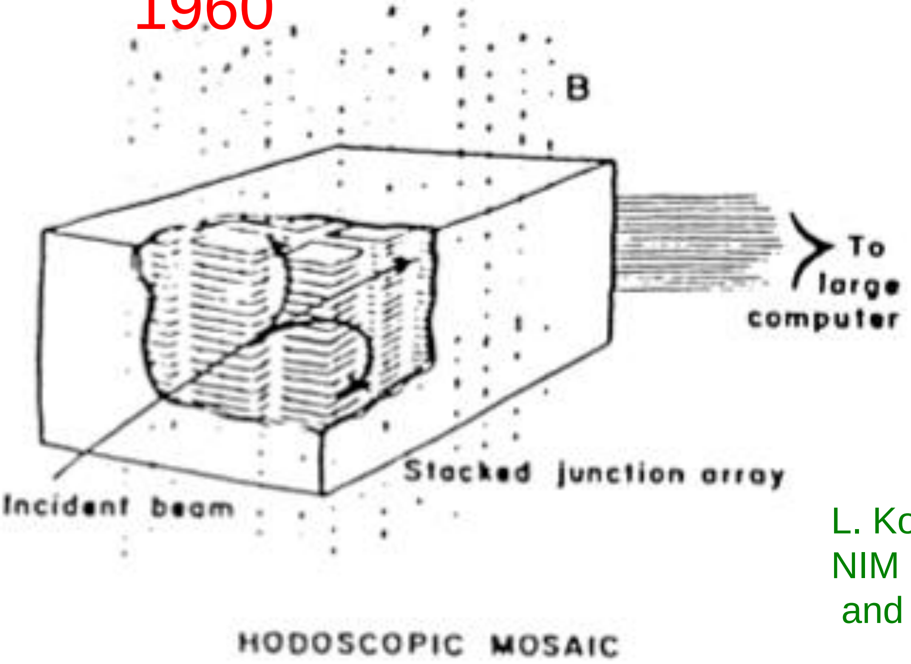
Technology ↔ nuclear science

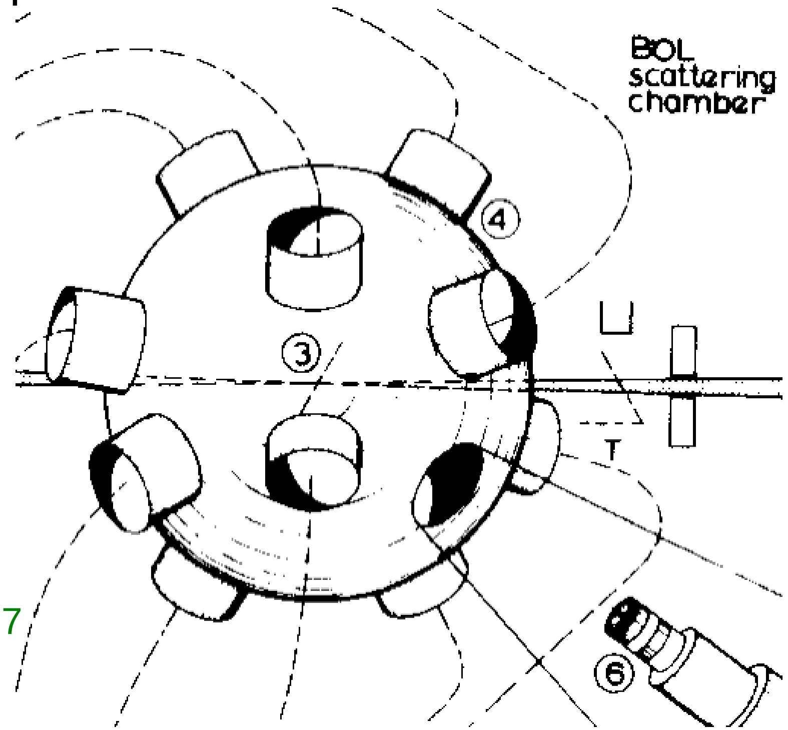
Proposals to use silicon detector arrays for particle tracking:

Bromley, Friedland et al.
was never made
(Asheville Conf p.69)

1965
Koerts et al. BOL Amsterdam
fully implemented

1960

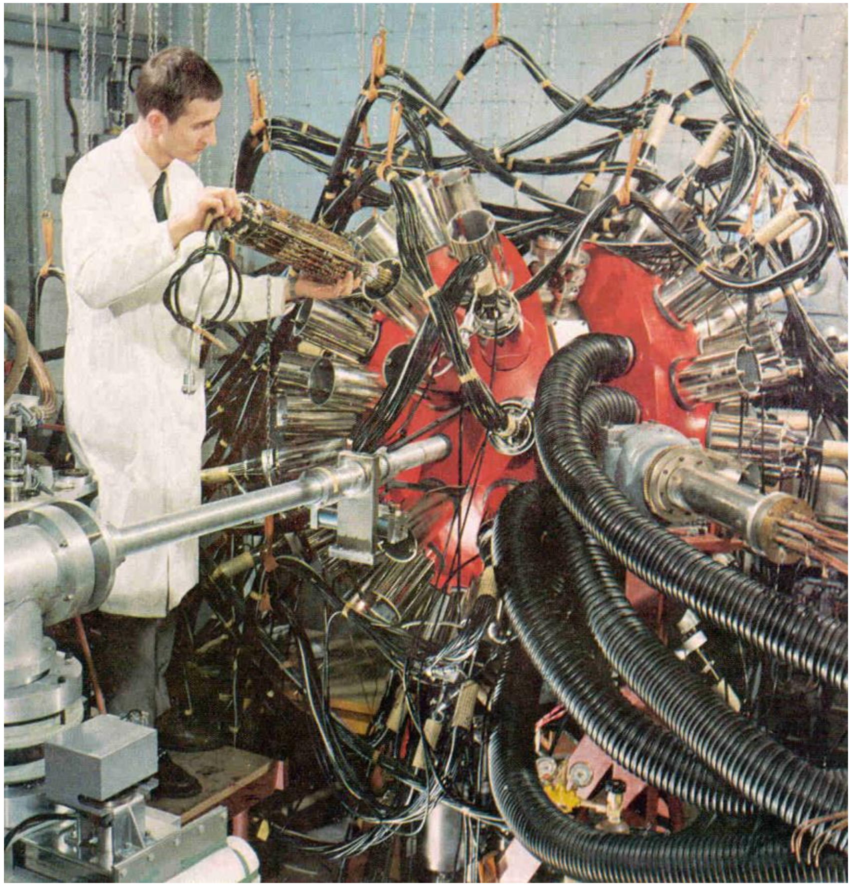




L. Koerts et al.
NIM 92(1971) 157
and following

ADC enables digitization of measurements
of nuclear energy levels only since ~ 1955

IKO BOL 1968-72

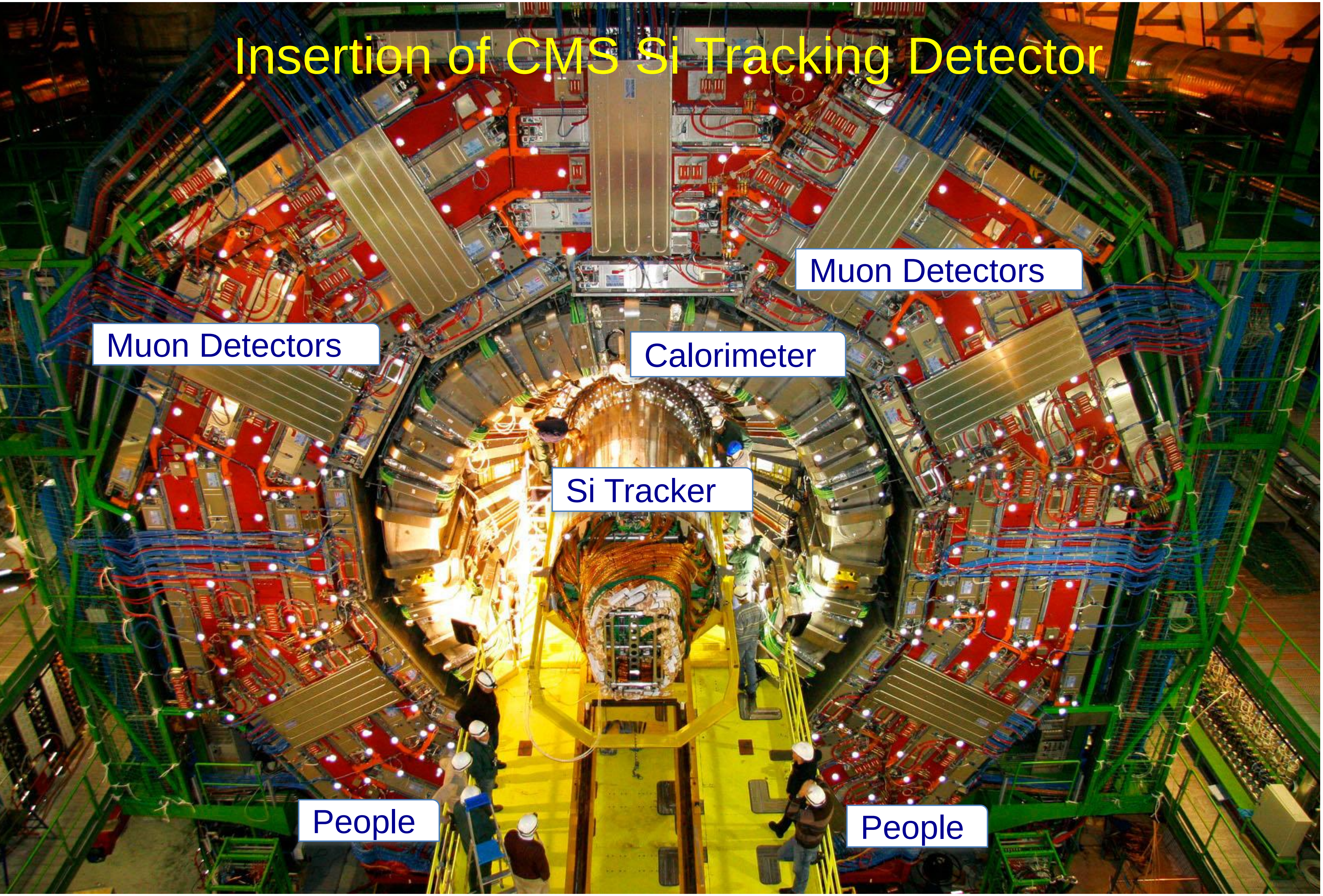


introduced state-of art
silicon technology
2D Si detectors ‘checker board’

unique collaboration
industry+ research institute

Integrated design of
sensors and readout electronics
dedicated data processing,
using on-line computing
powerful computer (1968 !!) for off-line

Insertion of CMS Si Tracking Detector



source: CERN- CMS

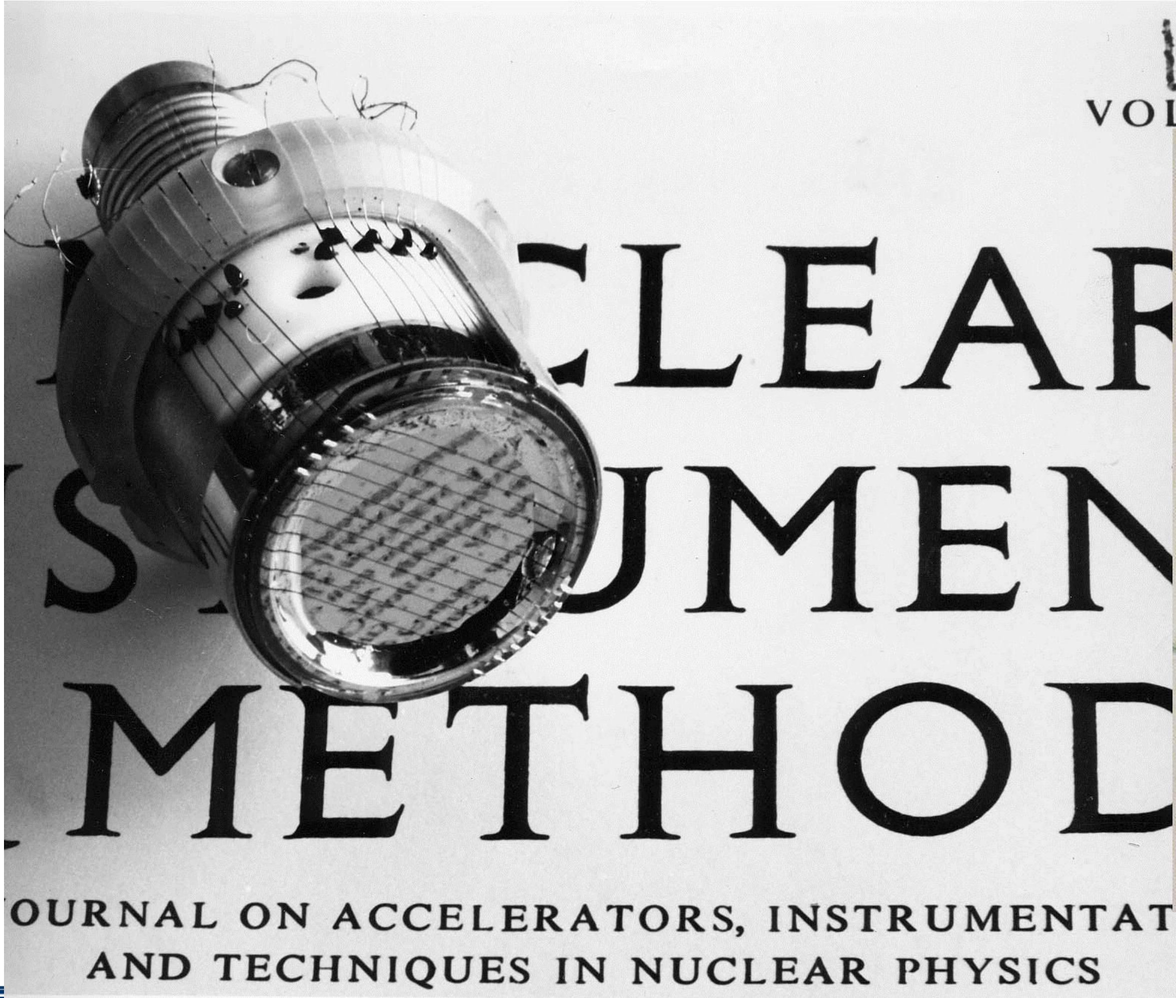
BOL – AMSTERDAM ~1969

Si detectors were the pride of BOL

First double-sided,segmented strip detector (pitch 1.37mm) PHILIPS patent 1967

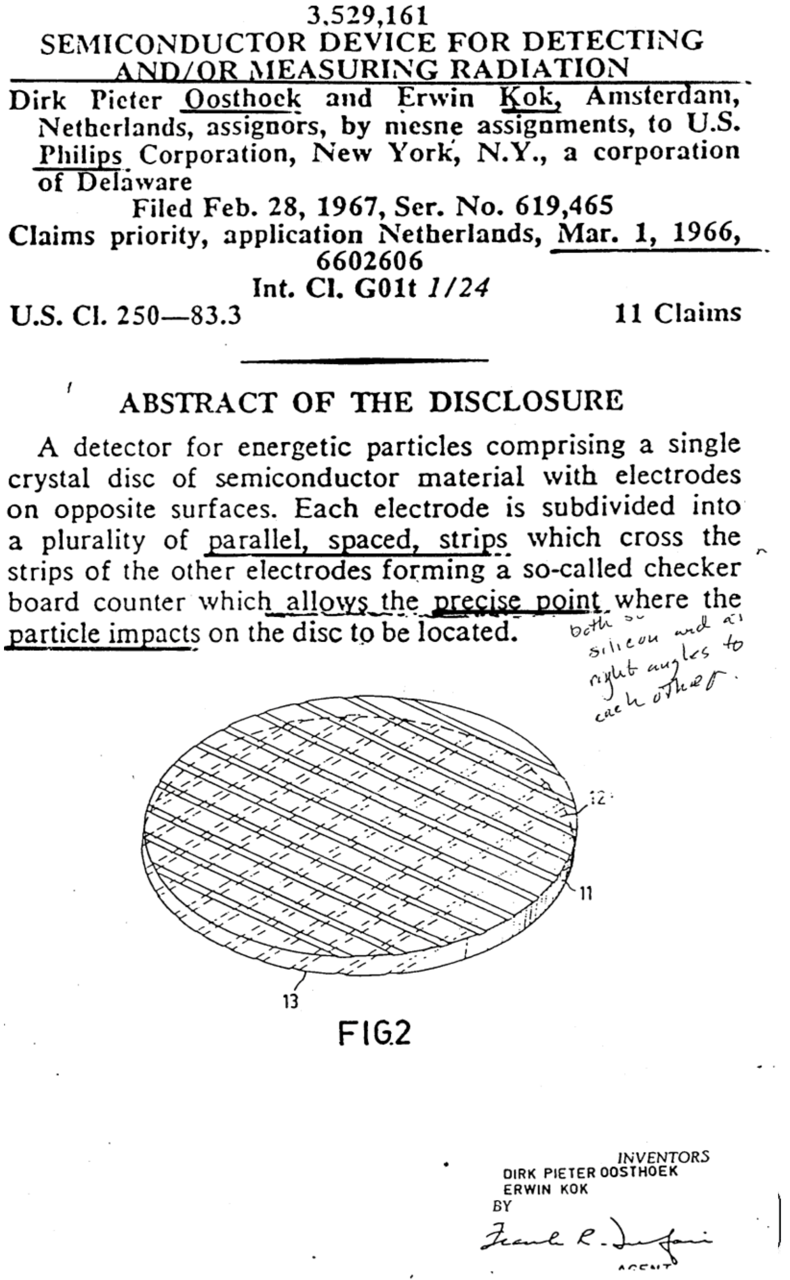
NIM 92 (1971)

Oberski et al.



The patent for double-sided Si strip detector

Oosthoek & Kok
US 3 529 161
1967 filed NL, USA



3,529,161
SEMICONDUCTOR DEVICE FOR DETECTING
AND/OR MEASURING RADIATION

Dirk Pieter Oosthoek and Erwin Kok, Amsterdam, Netherlands, assignors, by mesne assignments, to U.S. Philips Corporation, New York, N.Y., a corporation of Delaware
Filed Feb. 28, 1967, Ser. No. 619,465
Claims priority, application Netherlands, Mar. 1, 1966, 6602606
Int. Cl. G01t 1/24
U.S. Cl. 250—83.3 11 Claims

ABSTRACT OF THE DISCLOSURE

A detector for energetic particles comprising a single crystal disc of semiconductor material with electrodes on opposite surfaces. Each electrode is subdivided into a plurality of parallel, spaced, strips which cross the strips of the other electrodes forming a so-called checker board counter which allows the precise point where the particle impacts on the disc to be located.

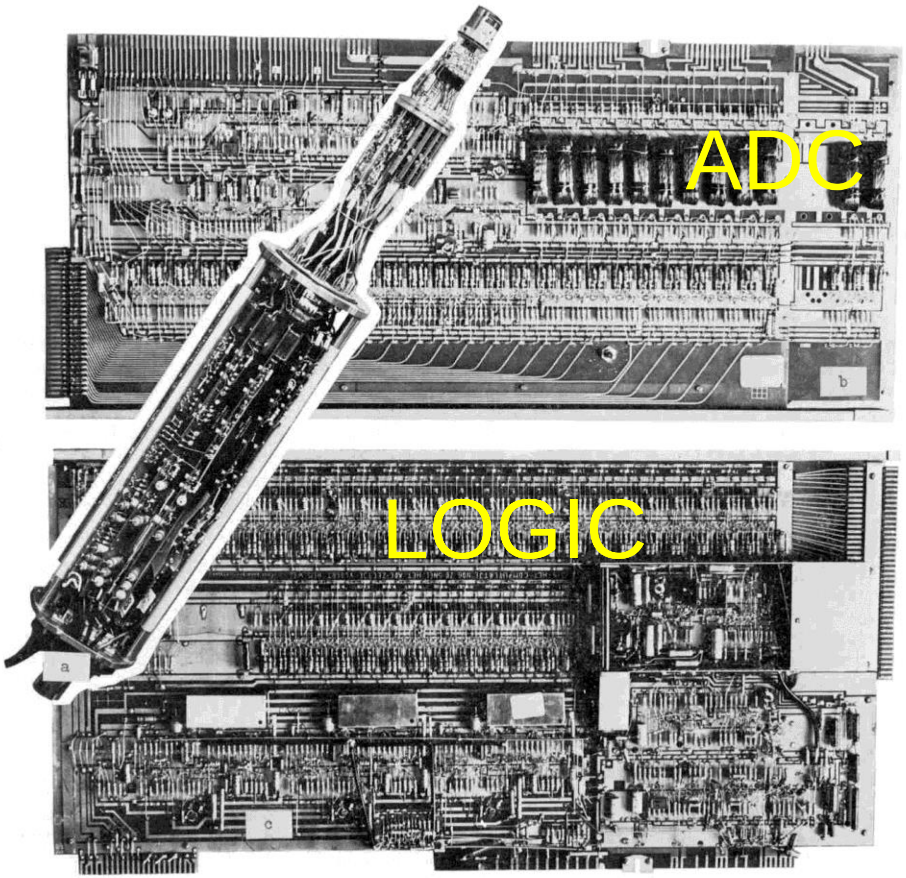
both su silicon and at right angles to each other.

FIG2

INVENTORS
DIRK PIETER OOSTHOEK
ERWIN KOK
BY
Frank R. Trifari
AGENT

~10 years later: Integrated Si telescope

178 J. E. J. OBERSKI et al.



only 2 channels per board

Fig. 1. Composition of the electronic parts of a complete detection channel: a) detection unit; b) logic unit; c) ADC unit.

one, indicating whether the left or the right partner of the pair was hit. Including the edges, this yields a 7-signal position code for each side of the detector (6 pairs of strips and edges + left/right indication). For the generation of this code, the bipolar 30 ns position indication signals from the transformers secondaries are amplified, used to extract a left-indication signal from one polarity and then rectified. To reduce the number of bits of the location code, the edge signal is then encoded as if three innermost pairs of strips were simultaneously activated. The 12 location signal lines are connected to the logic unit. Each line has got its own lower level adjustable discriminator. Remote control of the lower level discriminators is possible in the range from 0.3 MeV to 2 MeV. With the discriminators set to their most sensitive values, 50 MeV protons can be detected[5]). Set to an intermediate value, 25 MeV alpha particles (just stopping in the Checkerboard detector) do not cause significant cross talk between the position indication channels.

NIM 92 (1971)

Oberski et al.

Innovation proceeds in many areas

Sensor material: single crystal growth, purity

Sensor technologies, sensor design

Readout and electronic signal processing

Detector system layout

Complexity of data processing and analysis

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Major innovations in/for silicon detectors

1957 alloyed or diffused n-p and later p-n junctions
(Chalk River, others)
~1959 Gold surface barrier rectifying structure allows preservation of high resistivity
(J. Blankenship, Oak Ridge)
~1960 ¾" and 1" Si crystals commercially available (Monsanto, Wacker, Montecatini)

1960 Lithium drift for very thick depletion volume (>5mm, needs 77K cryo LN)
(E. Pell, General Electric)
1963 Si JFET (cooled 77K) in place of tube-preamp for lower noise (Radeka, BNL)

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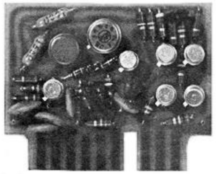
CSP Laben ~1960 from review Bertuccio SSCM



https://upload.wikimedia.org/wikipedia/
commons/8/85/Discrete_opamp.png

Si single-crystal the essence

Silicon single crystal growing

1955 Montecatini, later part of Monsanto

3/4” - 1”

wafer diameter 3/4” - 1”

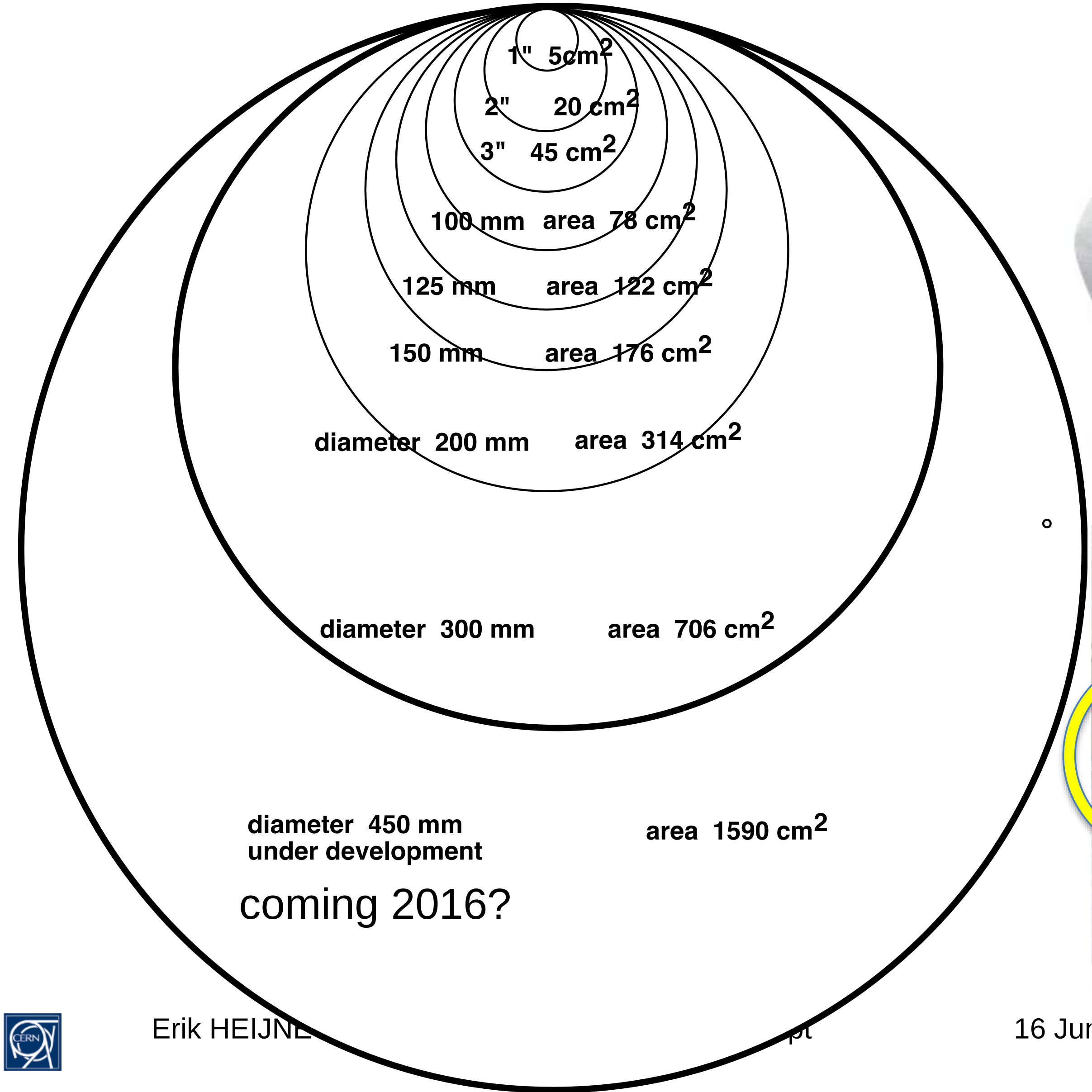
http:/ /www.comp
www.semi.org/en

Silicon single crystal growing

1955-2015

Wafer sizes

Increase of wafer diameter 3/4" - 450mm



1" 5cm^2

2" 20 cm^2

3" 45 cm^2

100 mm area 78 cm^2

125 mm area 122 cm^2

150 mm area 176 cm^2

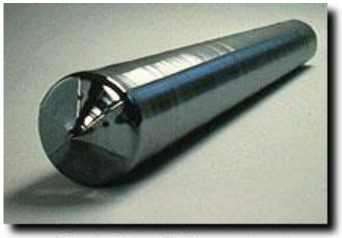
diameter 200 mm area 314 cm^2

diameter 300 mm area 706 cm^2

diameter 450 mm
under development

area 1590 cm^2

coming 2016?



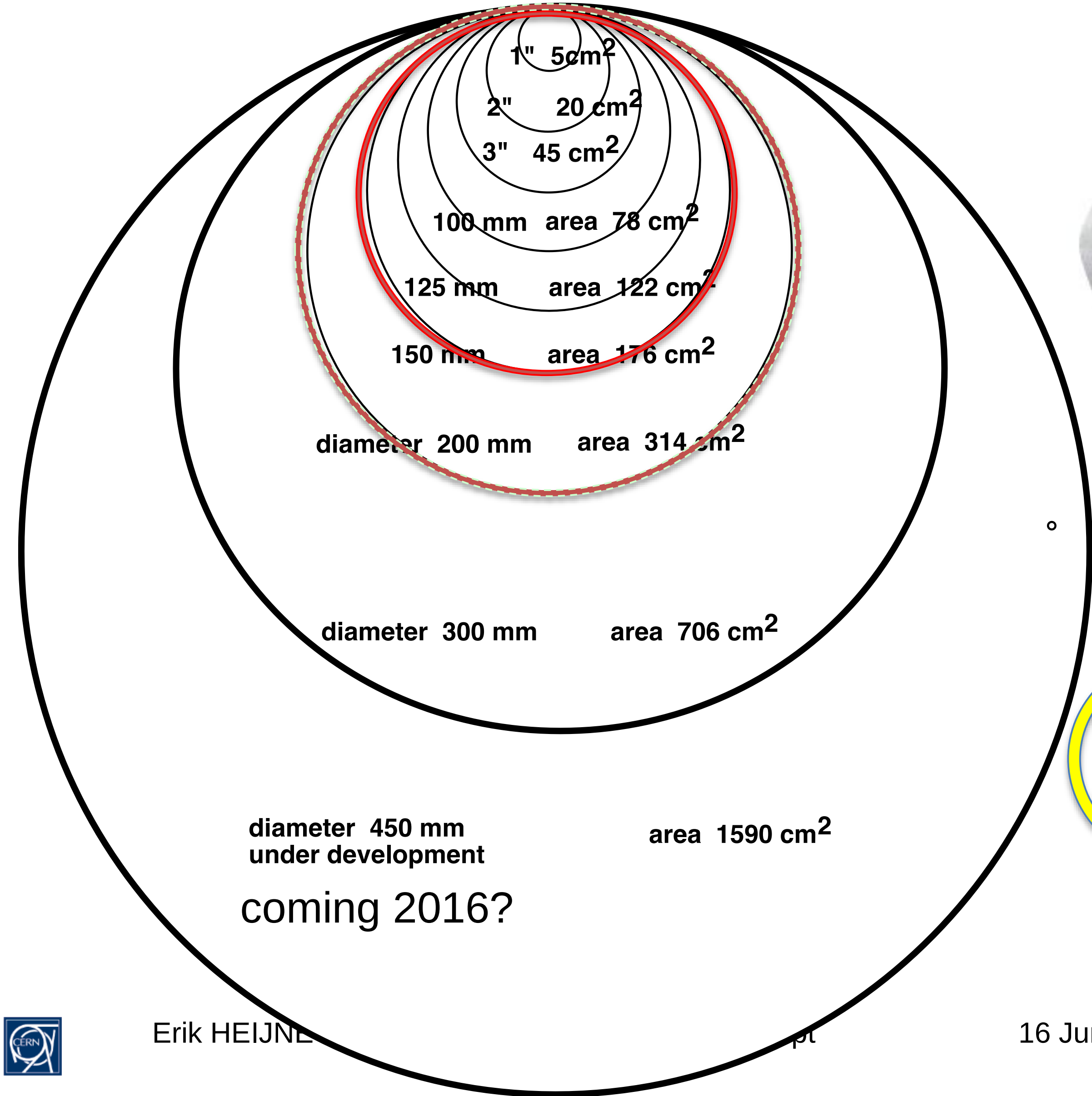
Single Crystal Silicon Ingot

CZ Crystal Pullers
(Mitsubishi Materials Silicon)

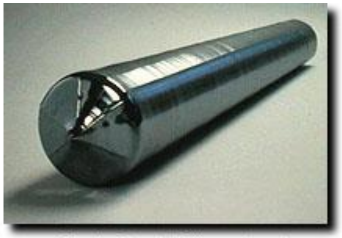
Silicon single crystal growing

1955-2015

Wafer sizes



Increase of wafer diameter 3/4" - 450mm



Single Crystal Silicon Ingot

CZ Crystal Pullers
(Mitsubishi Materials Silicon)

Silicon single crystal growing

450mm still not widely accepted as next standard, in 2020 maybe only 2-4 CMOS foundries worldwide

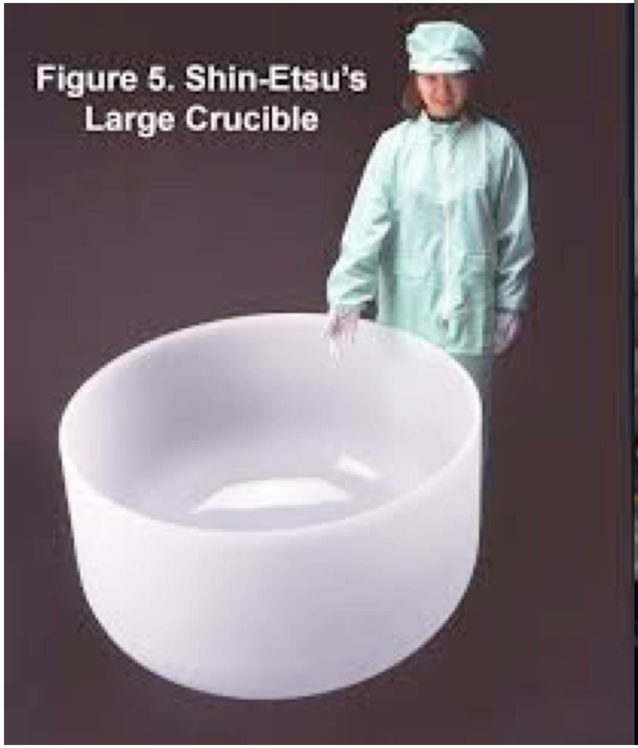
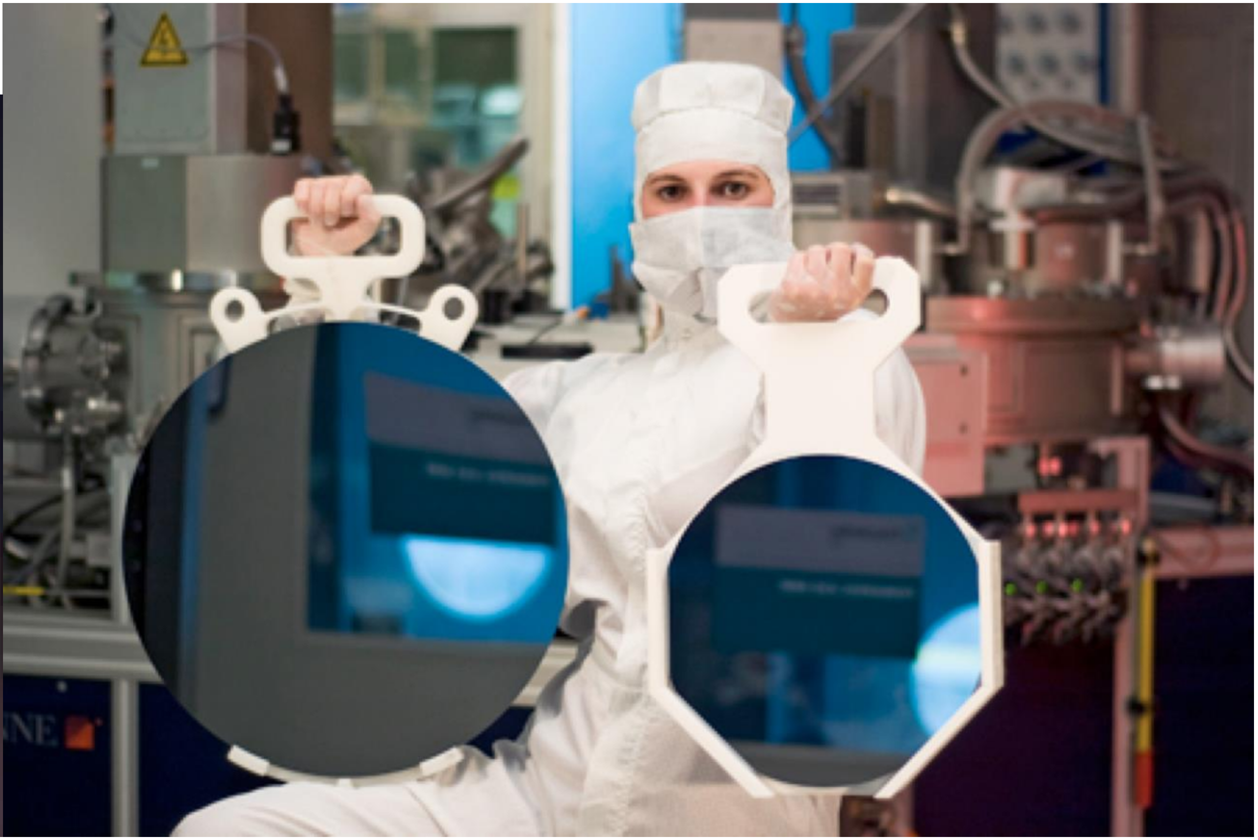


Figure 5. Shin-Etsu's Large Crucible



Silicon single crystal growing

Some economics approximate, just to get a feel:

Worldwide production of Si wafers 2015 was 67x10^9 cm^2 (6.7 km^2)
corresponds to 96 million wafers of 300mm diameter (700 cm^2)
Revenue in Si only was 7.2 B$, amounts to average of 10.7 cents per cm^2
or average ~75$ for a polished 300mm wafer

High resistivity Si much more expensive,available up to Ø150mm (200mm?)

Typical number of wafers in major foundry: some thousands/day, 1M/year

Worlwide sales of semiconductor devices in 2015
revenue 333.7 B$ if all Si area used -> average 5$ per cm^2
the raw Si enters for <u>only 2.1%</u> in the cost of the devices

data from SEMI website

Main periods in silicon detectors

1945 – 1960 Discovery of the field of semiconductor detectors

1960 - 1970 Nuclear physics and applications

1970 – 1980 Consolidation and commercialization

1980 Revolution : somehow the field is turned over

1980 – 1995 Planting the seeds

1995 – 2005 Constructing large systems for HEP & Space

radiation hardness for CMOS readout and for sensors

2005 – 2016 Harvesting results, new applications

A few more cases in detail

~~Si single crystal growth, purity ~1965~~

done

~~BOL: first full system with segmented Si devices ~1969~~

Succesful ion-implanted detectors: Josef Kemmer 1979

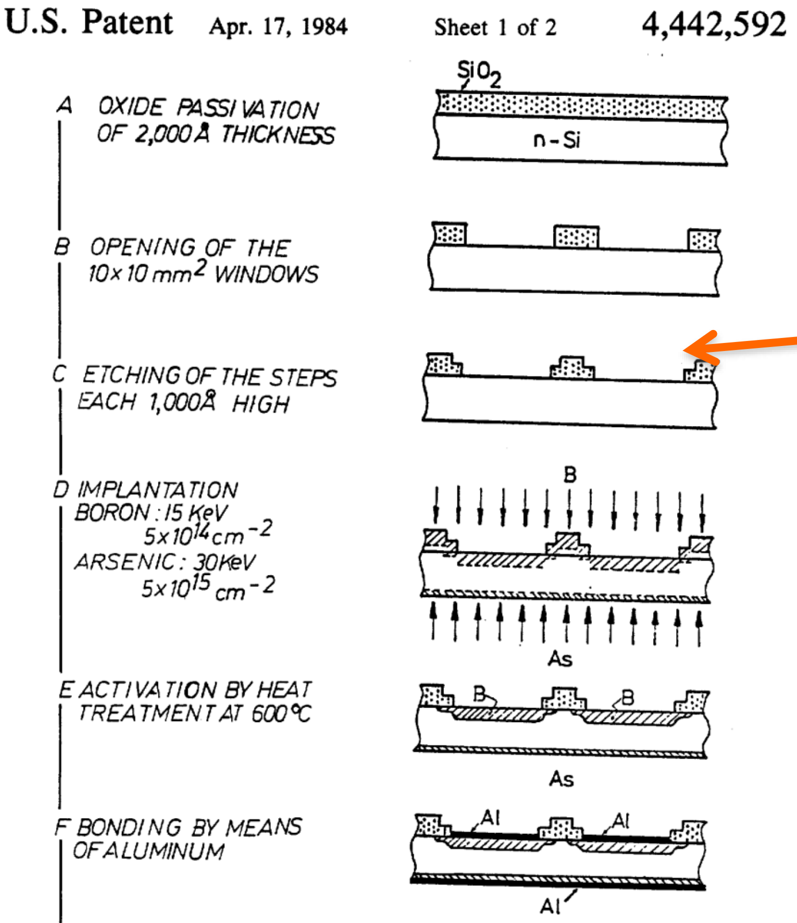
Microstrip detectors 1980, year of the ‘Revolution’

The first colliders & chip readouts: UA2, Mark II, LEP....

Begin of pixel detectors 1986-1989

The Kemmer patent for Si p-n junction detector

filed DE, 31 January 1980



U.S. Patent Apr. 17, 1984 Sheet 1 of 2 4,442,592

A OXIDE PASSIVATION OF 2,000Å THICKNESS

B OPENING OF THE 10×10 mm^2 WINDOWS

C ETCHING OF THE STEPS EACH 1,000Å HIGH

D IMPLANTATION
BORON : 15 KeV
$5\times10^{14} cm^{-2}$
ARSENIC : 30KeV
$5\times10^{15} cm^{-2}$

E ACTIVATION BY HEAT TREATMENT AT 600°C

F BONDING BY MEANS OF ALUMINUM

Edge dopant profiling helps to withstand
higher electric field and
reduces reverse diode current.
Kemmer achieved ~nA cm^{-2}
surface barrier detectors had >0.1 μA cm^{-2}

The step etching is not shown in NIM 169 :

Essential improvement by Kemmer in fact was the adoption of ~1975 silicon manufacturing technology with extreme cleanliness.

The high-dose implant of As^+ ions at the rear was MOST important. $pn=10^{20}$ with $n=10^{12}$

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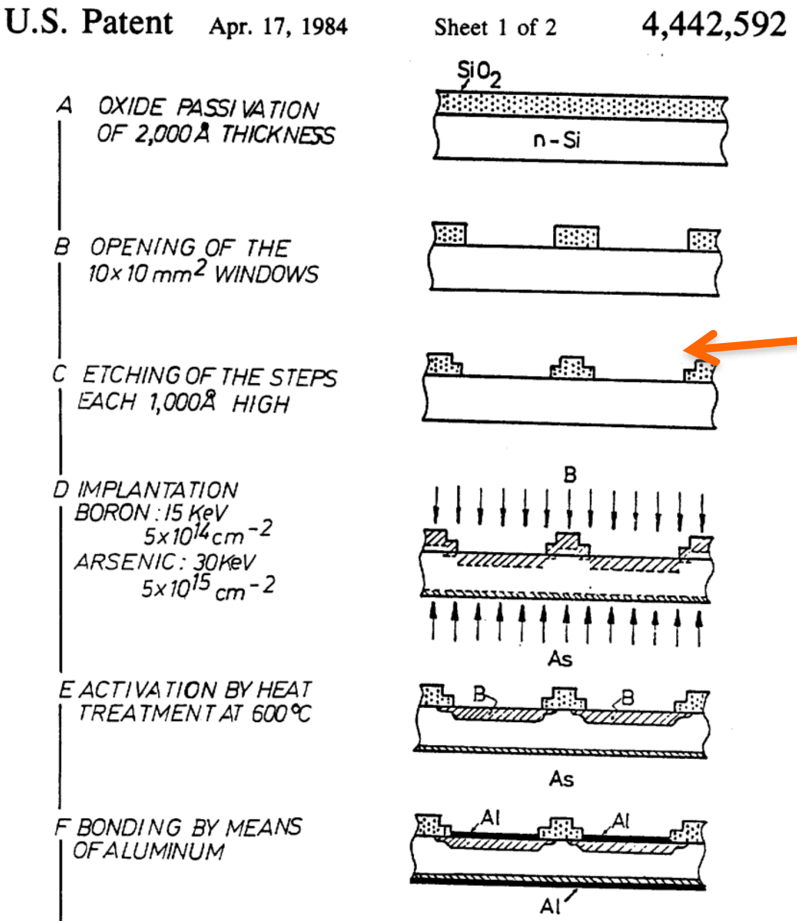

U.S. Patent Apr. 17, 1984 Sheet 1 of 2 4,442,592

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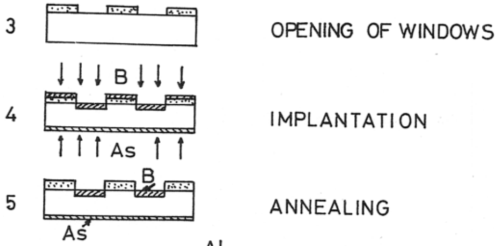

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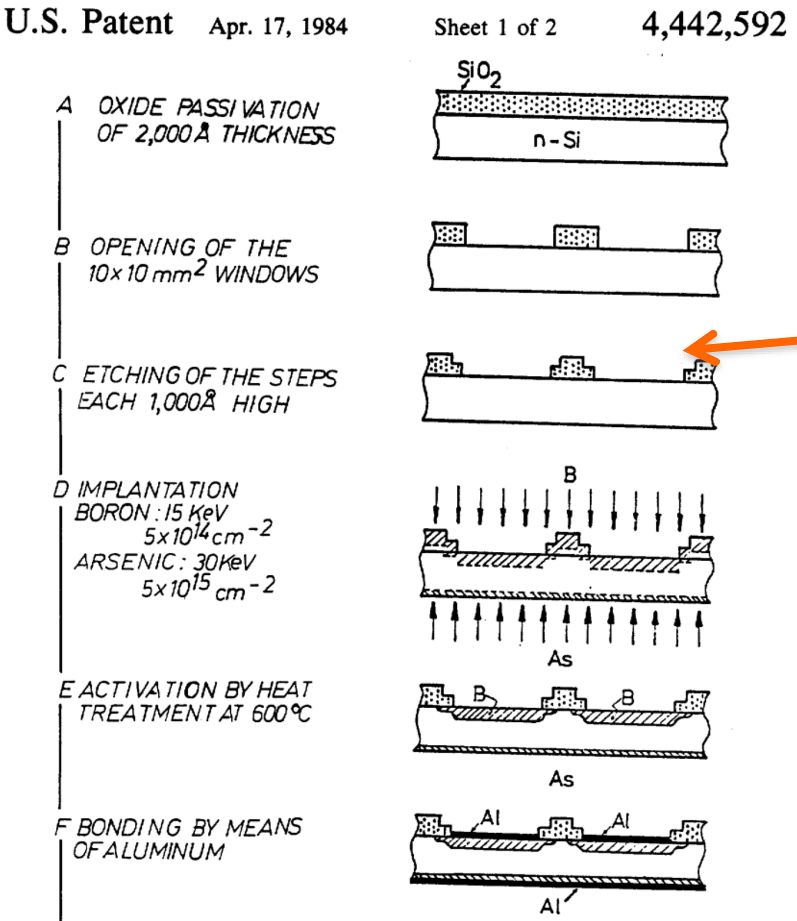

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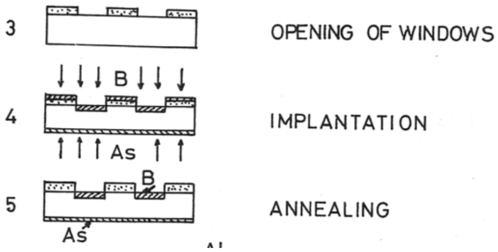
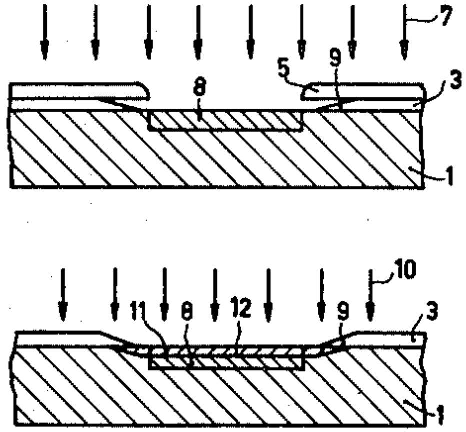


Philips'patent on profiling by beveled edge oxide of implanted p-n junction
filed NL, 11 November 1975



more details in Kemmer
NIM A226 (1984) 89-93

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The high-dose implant of As^{+} ions at the rear was MOST important. pn=10^{20} with n=10^{12}

The 1980 Si revolution

The 1980 revolution in Si detectors

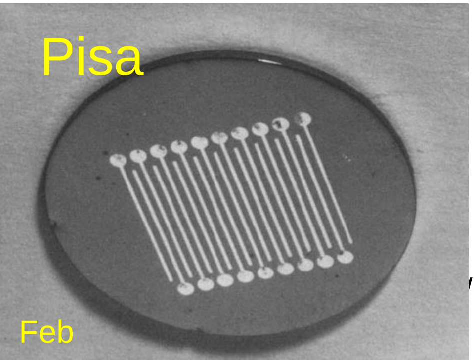
In 1980 several 'revolutionary' innovations took place, that were to shape silicon detectors for future applications in particle physics and other fields

1. **Segmented surface barrier detector,19 strips, pitch 0.6mm made in Pisa.**
   NIM 176 (1980) 457, Amendolia et al. (Menzione, Bosisio,..) readout 2-ch, in beam at CERN

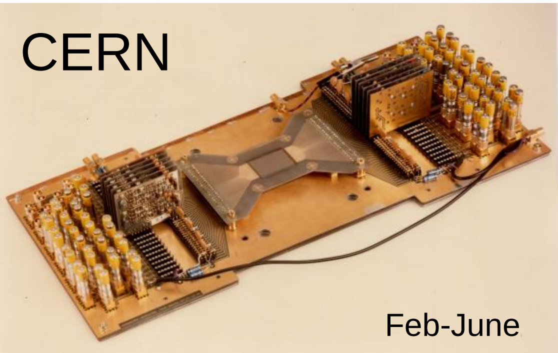
2. **Si microstrip detectors, 100 strips, pitch 0.2mm, Heijne, Burger, Jarron, CERN made at Enertec, Strasbourg; tested May at CERN, with full readout and a first vertex reconstruction by Jos Vermeulen and Andrew Wylie, NIM 178**

3. **Publication in NIM 169 of planar passivated Si diodes with low noise/current by Josef Kemmer, Techn. Univ. München (~nA/cm^{-2}, see before).**
   Process commercialized by Enertec/Strasbourg in 1981.

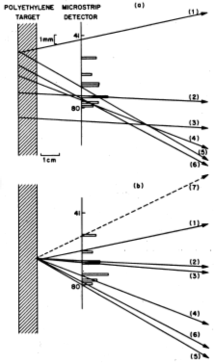
4. **December 1980, first Si microstrip by planar process made by Kemmer, in collaboration with Heijne/Burger; simultaneously with Klanner/Lutz of MPI**
   IEEE Trans.Nucl.Sci. 29 (1982) 733 (Kemmer, Burger, Henck, Heijne at Nucl Science Symp 1981

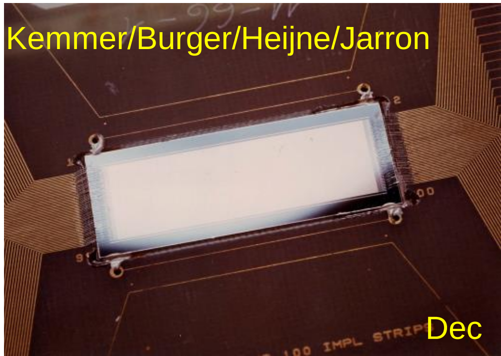

Pisa

Feb


CERN

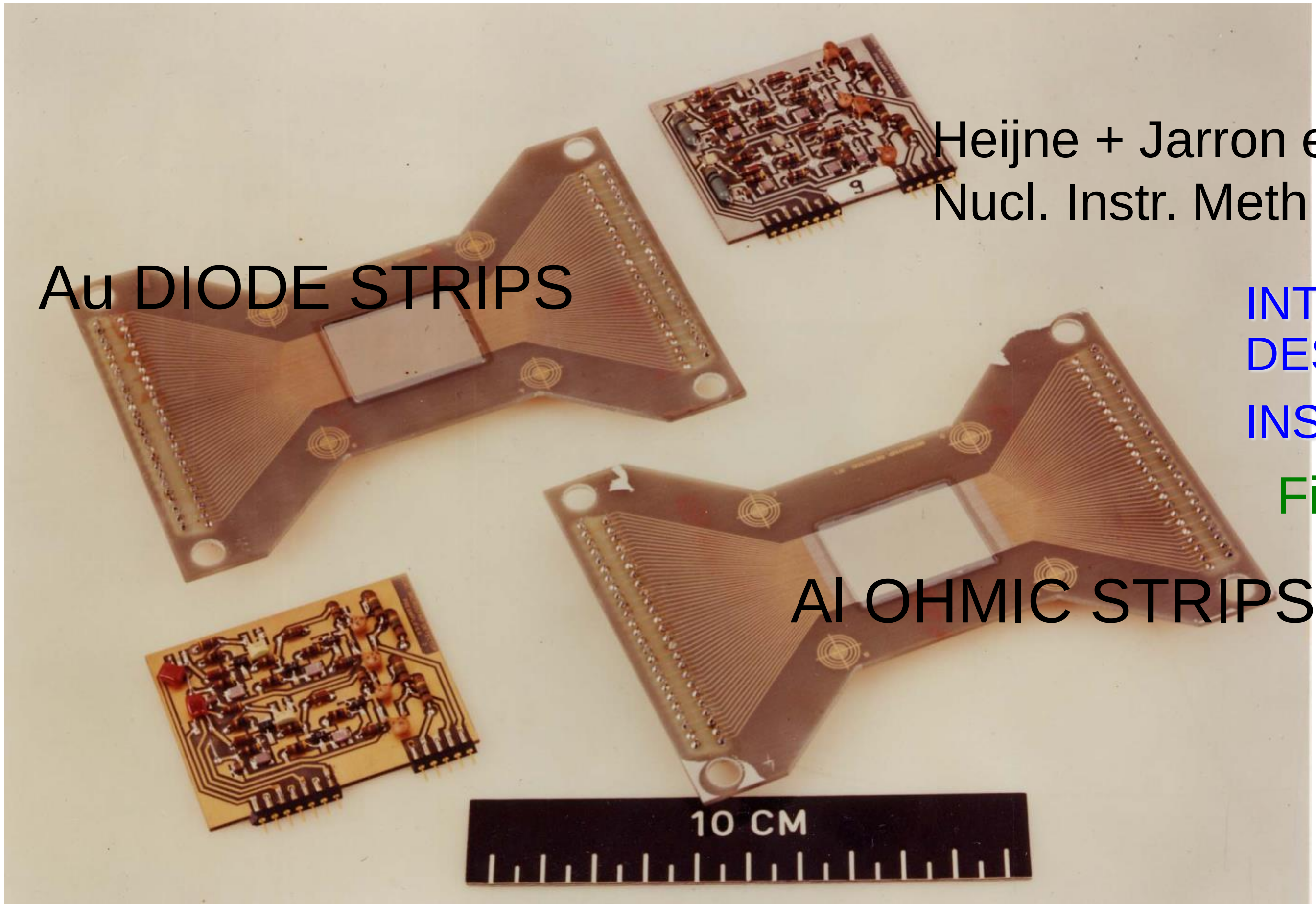
Feb-June




Kemmer/Burger/Heijne/Jarron

Dec

First CERN Si microstrip detectors 1980



Heijne + Jarron et al.
Nucl. Instr. Meth 178 (1980) 331

INTEGRATED
DESIGN

INSPIRED BY IKO-NL

First step : Jan - June 1980

surface barrier strips

either side

100x200 µm

full parallel readout

discrete components

fast and dense

rectangular shape: unusual at the time
but essential for future

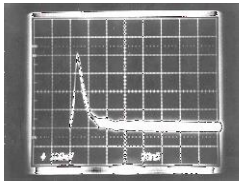
First CERN Si microstrip detectors 1980

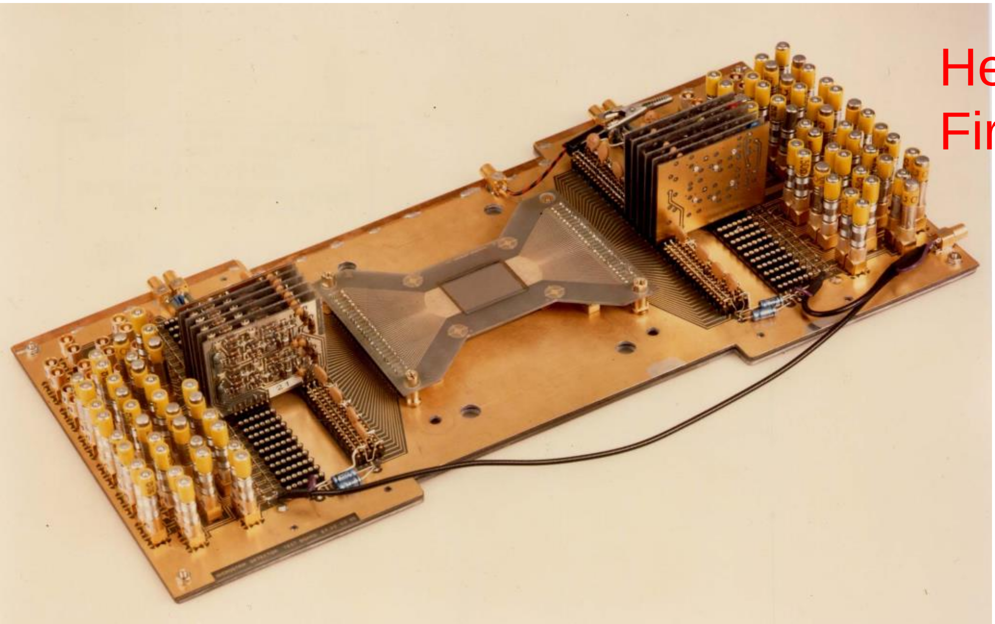
Progressive changes in matched readouts

1980 DISCRETE COMPONENTS on DUAL CARDS

1984 HYBRID QUADS on CERAMIC THICK FILM

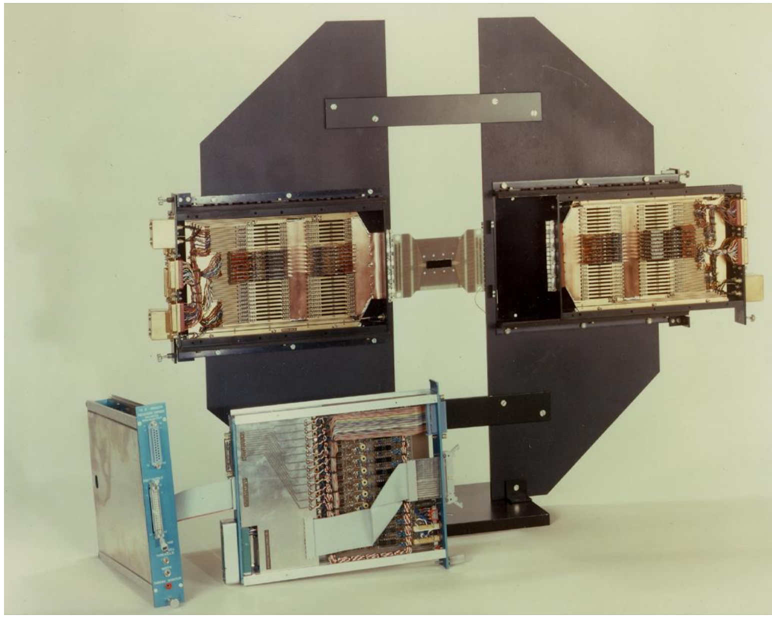
1987 AMPLEX CHIP CERN, MICROPLEX SLAC





Heijne-Jarron 1980

First test beam setup 100 x 200 µm

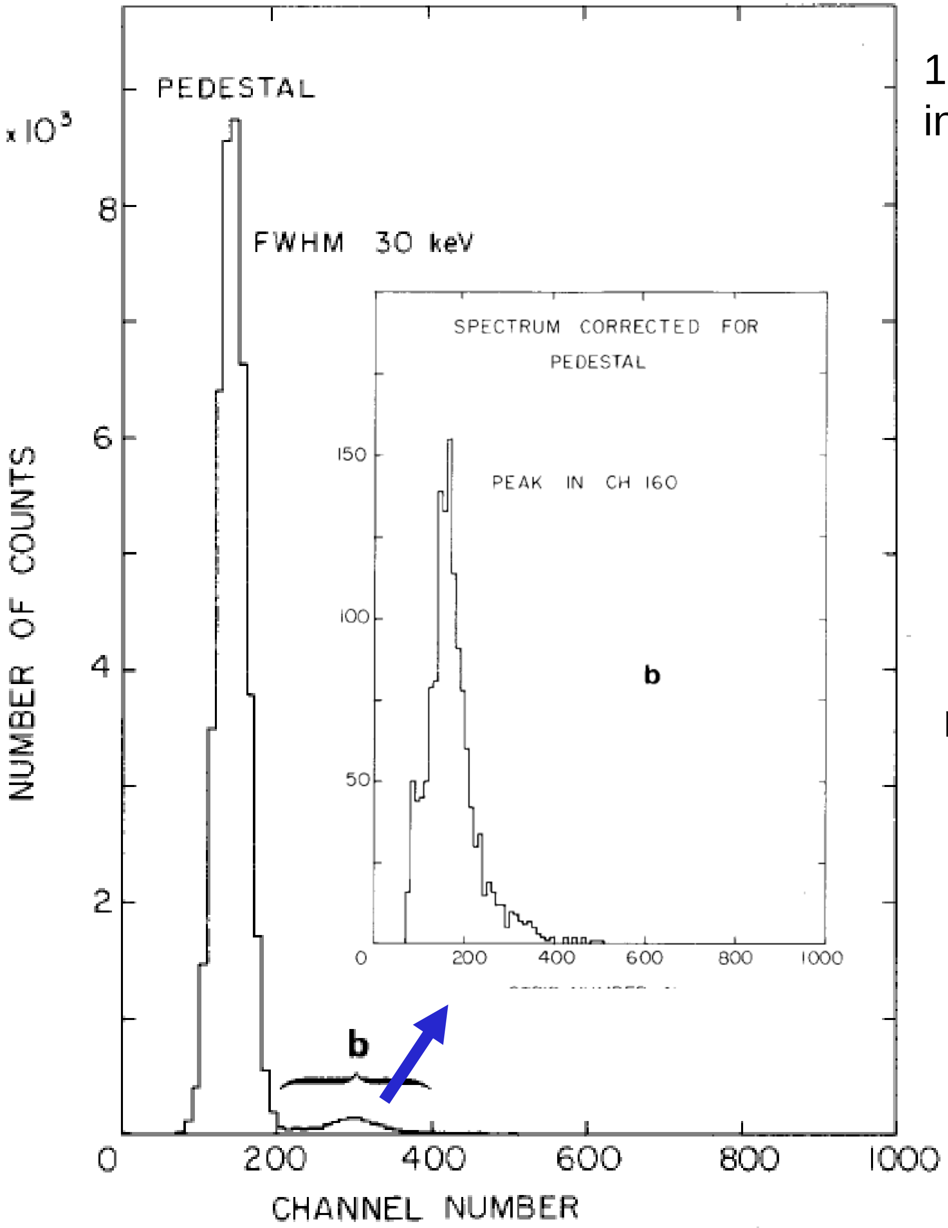


Heijne-Jarron-Hyams 1981

NA11 hodoscope

sensor now 100 x 50 µm

Signal spectrum from first Si Microstrip in 10 GeV beam



10 GeV pions/protons, in setup F. Piuz
in 400 µm Si ~110 keV or ~30ke$^-$

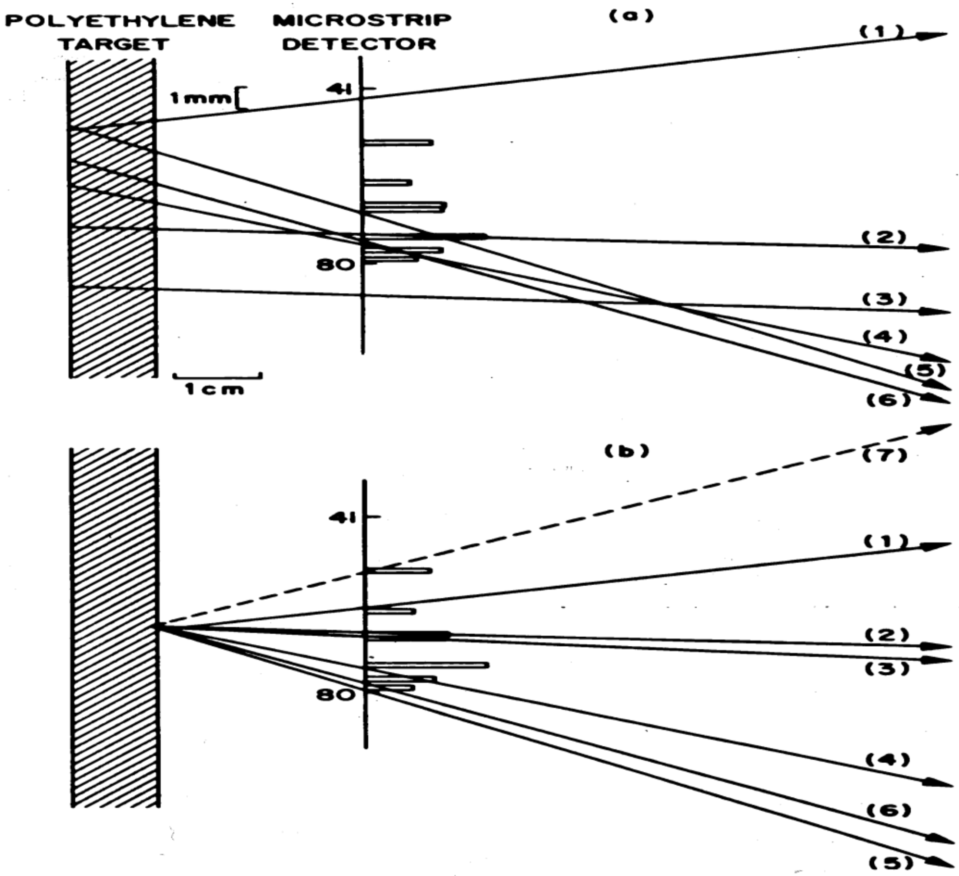
shows noise distribution
around ‘zero’ pedestal channel
FWHM 30 keV **s**=12.7 keV
or 3500 e$^-$ rms
readout by charge integration
over a 60ns gate,
following the beam trigger

note: - tail at low energy
- double hits visible ch 320
- signals not yet
well-separated from noise

First Si microstrip detector, May 1980:
NIM 178 (1980) 331-343
probably first Si Landau curve for GeV

First CERN Si microstrip detectors 1980

First vertex reconstruction (by Vermeulen & Wyllie)
of tracks directly behind target NA11



June 1980

Tracks as reconstructed
in NA11 spectrometer
using the wirechambers

Tracks ordered, using the Si
microstrip points
+ new track (7)
a precise vertex found !!!

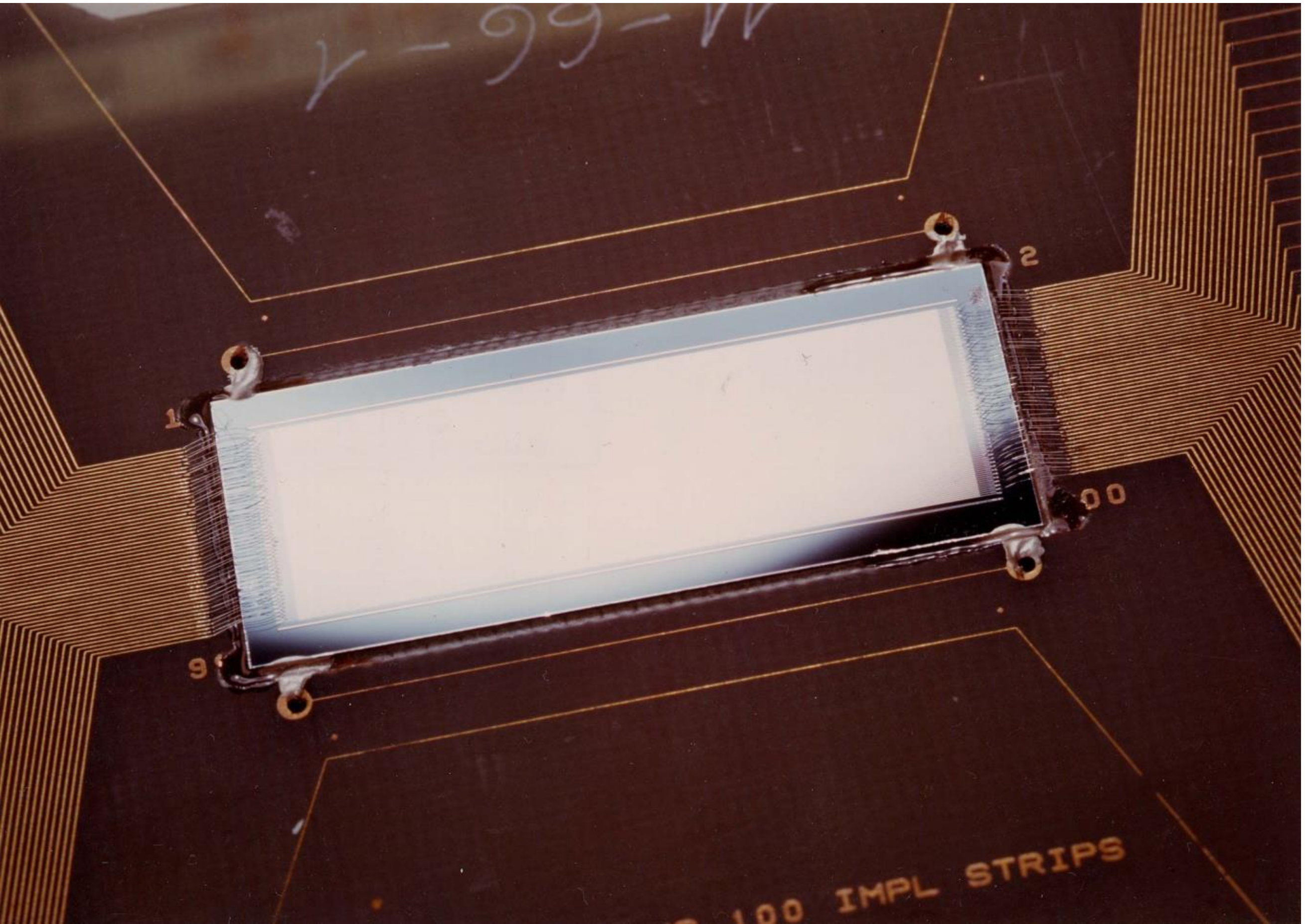
NIM 178 Heijne, Jarron. Hubbeling
Hyams, Piuz, Lazeyras,Vermeulen, Wyllie

First ion-implanted Si microstrip detector 1981

3rd generation CERN design 1981

Ion implantation Kemmer TU München, 200 µm pitch and 50µm pitch,
ultrasonic Al wirebonding (K&S), alternating left/right

Collaboration CERN- Enertec/Burger+Josef Kemmer

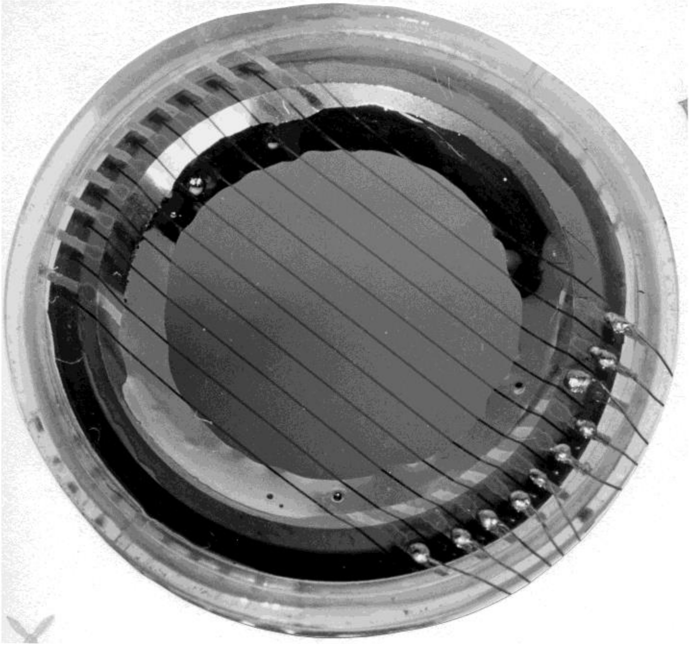


Kemmer, Burger, Henck, Heijne
IEEE Trans.Nucl.Sci.
29 (1982) 733
Performance and applications of passivated ion-implanted silicon detectors

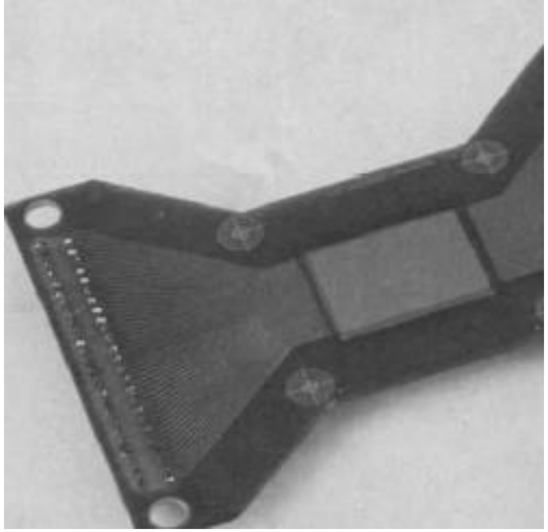
presented at
IEEE Nucl Science Symp 1981

note: Josef Kemmer simultaneously made Si microstrip detectors for the HEP group at MPI München with Robert Klanner and Gerhard Lutz
publ. Hyams et al.
NIM A205(1983)99

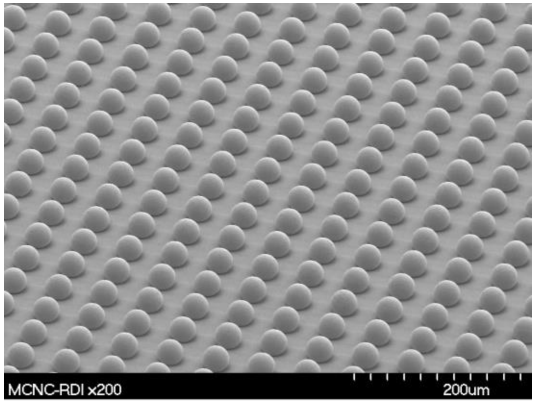
Progressive microscopic segmentation diode arrays



~1965
PHILIPS / IKO
80 squares 1370umx1370um



1980
CERN / ENERTEC
100 strips x 4000umx200um



2000
CERN / MEDIPIX
65000pixels x 55umx55um

Inventions of monolithic segmented Si diode arrays

1. HARWELL: ajacent structures on 1” slice
   1958 not continuous

2. SACLAY: a few continuous (‘jointives’) diodes 1963
   they find full charge collection (Colloquel Liège)

3. IKO/PHILIPS: front/rear strips 1.2 mm (Hofker) 1965
   projected 2-D US patent 1970

SEVERAL PROJECTS 1970 - 1980, ELECTRONICS proves main LIMITATION

4. CERN + Enertec, München TU + MPI
   1980 smaller dimensions 200 um, 50 um
   ion implantation (Kemmer, Burger)
   with matched (micro) electronics !!!!

A few more cases in detail

~~Si single crystal growth, purity ~1965~~

done

~~BOL: first full system with segmented Si devices ~1969~~

~~Succesful ion-implanted detectors: Josef Kemmer 1979~~

~~Microstrip detectors 1980, year of the 'Revolution'~~

just briefly: CCD; Si drift chamber; VERY important for X-ray

The first colliders & chip readouts: UA2, Mark II, LEP....

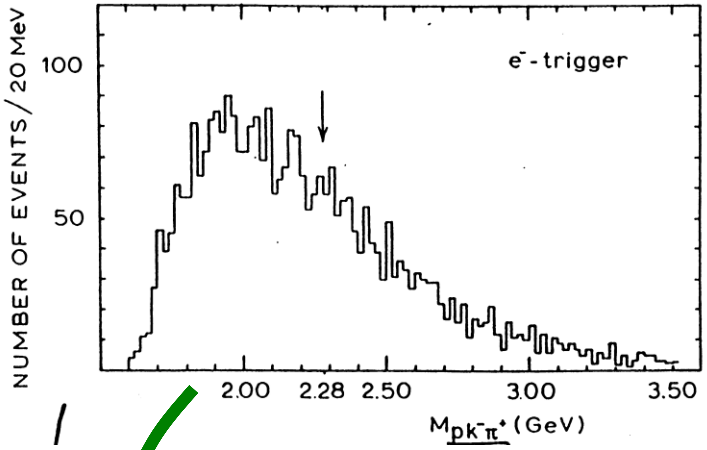
Begin of pixel detectors 1986-1989

Charmed particle 2nd vertex recognition

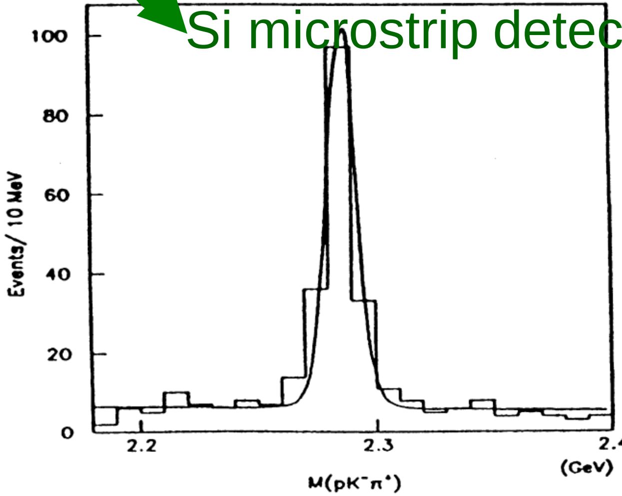
NA11 CHARM EXP

Λ_c --> $p K^- \pi^+$

Invariant mass distribution Lambda
with wirechamber spectrometer only
in spite of large statistics, ‘NO’ selectivity



using new technology :
Si microstrip detectors + CCD



much less background events, so
much improved sensitivity
NA11 can run at reduced beam intensity

DRAMATIC IMPROVEMENT !

2D position measurement in Si detectors: from ~1982

After the 1980 revolution several innovations aim at 2D precision measurement

1. **'Standard' CCD for m.i.p.s in NA11 by Chris Damerell, Steve Watts + GEC**
   NIM 185 NIM 213 (1983) 201 Bailey et al. first testing in H6 at CERN

2. **Si drift chamber: lateral movement of signal charge to low capacity node**
   NIM 225 & NIM 226 (1984) 129 Gatti, Rehak and Walton

3. **Early report on use of (military) hybrid CMOS imagers for ionizing radiation**
   IEEE Nucl. Sci. Symposium 1984 Steve Gaalema/Hughes IEEE TNS 32,p 417

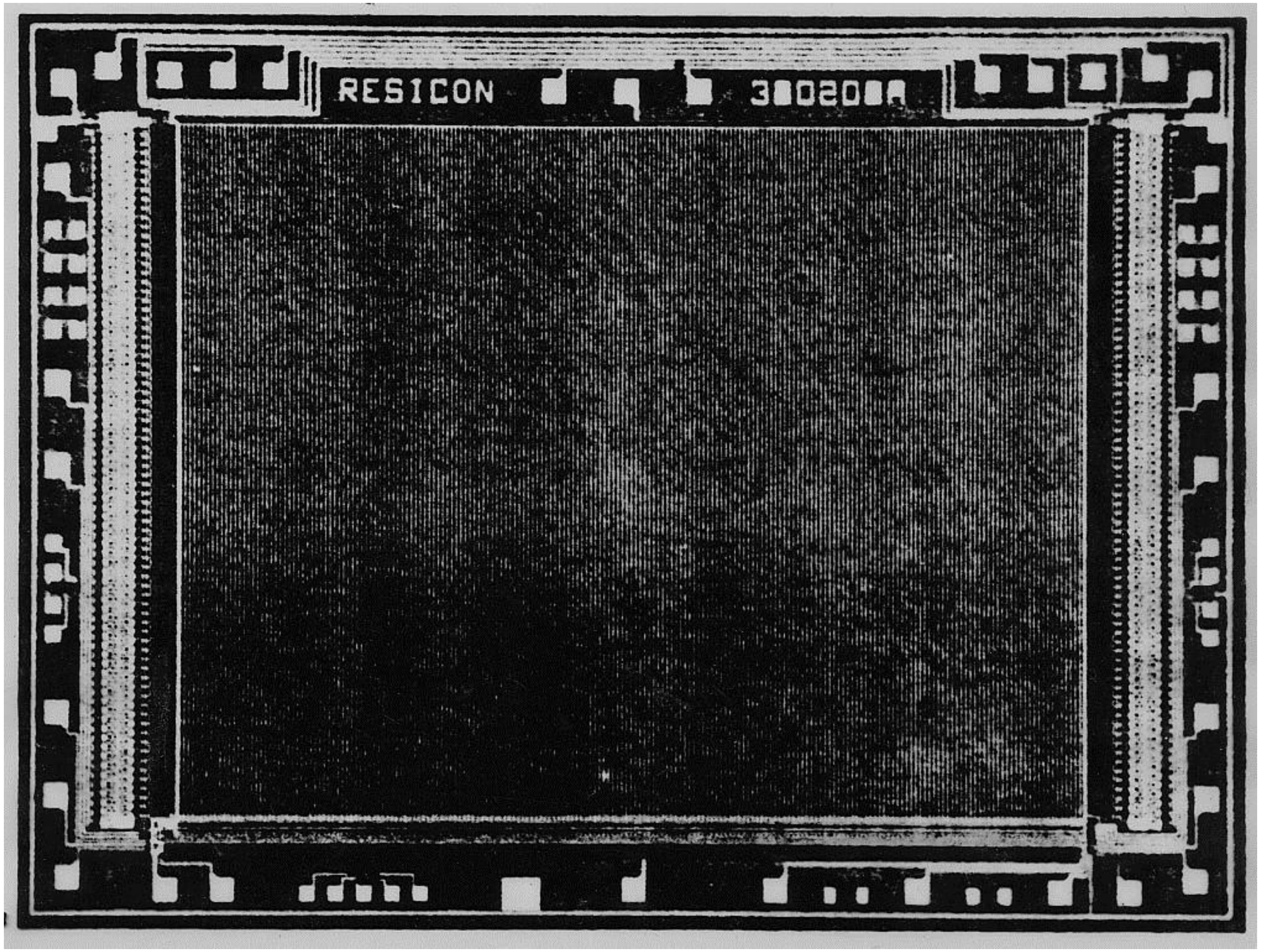
4. **2 barrels of Si pad detectors for 2D tracking in UA2: NIM 253(1987)**
   NIM 279 (1989)388 Clark, Gildemeister, Goessling, Jarron, Heijne

5. **December 1989, first 2D CMOS readout chip for hybrid pixel detector**
   Enz, Krummenacher, Vittoz (EPFL) with Campbell, Heijne, Jarron (CERN)
   NIM 288 (1990) & NIM 290 (1990) 149
   First 6 plane system in WA94 Omega experiment 1992 NIM 332 (1993) 188

6. **Monolithic pixel detector test, Sherwood Parker, Walter Snoeys, Chris Kenney**
   IEEE Trans.Nucl.Sci. 39 (1992)1263

Silicon drift chamber/ detector

Resistive Channel CCD lateral E-field moves electrons to contacts



H. Heyns et al, Philips Techn. Rev. 37, 1976

~1975 CCD

by PHILIPS

300 x 200 pixels

50 Hz Framerate

active area ~0.25 cm^2

Pixel
14 μmx 28 μm

Differences:
carrier transport
in depleted well
close to surface,
no deep depletion

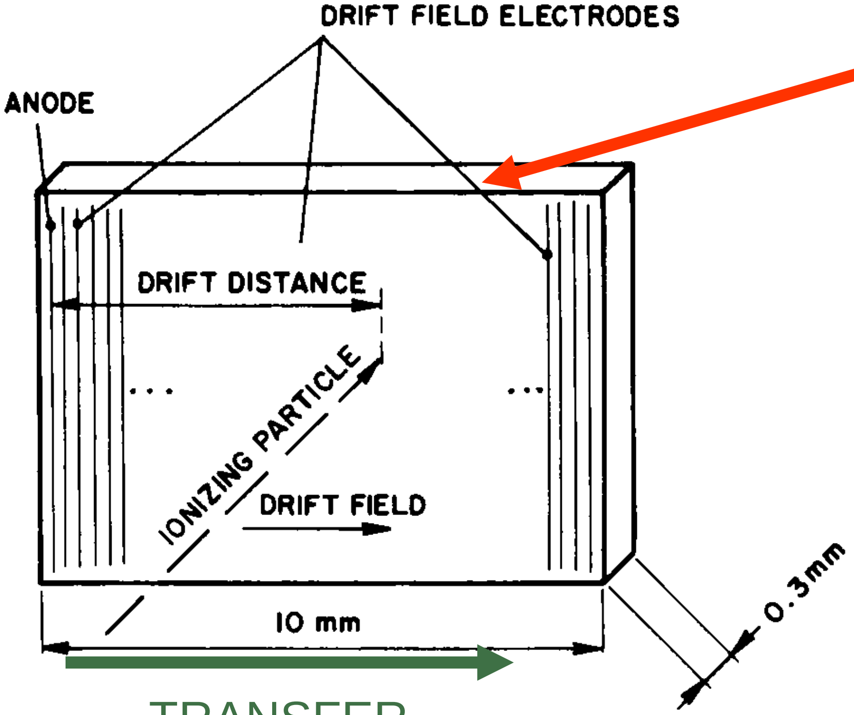
Gatti/Rehak drift in
depleted bulk

HIGH ρ SILICON DRIFT DETECTORS 1983

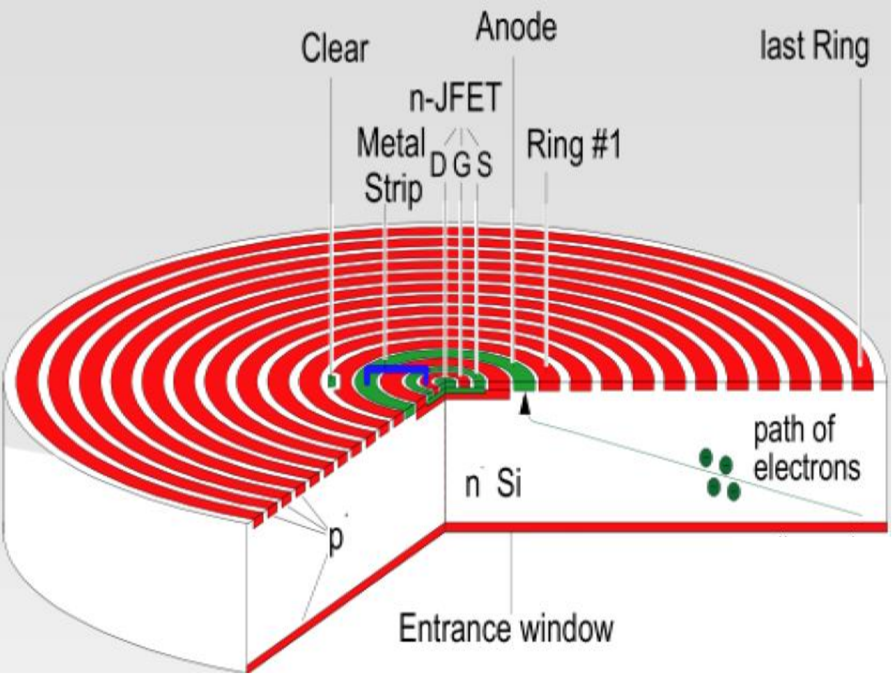
X-ray conversion directly in the sensor

DRIFT FIELD IS CONTINUOUSLY APPLIED

Fully depleted volume, potential well at ~mid-depth



TRANSFER

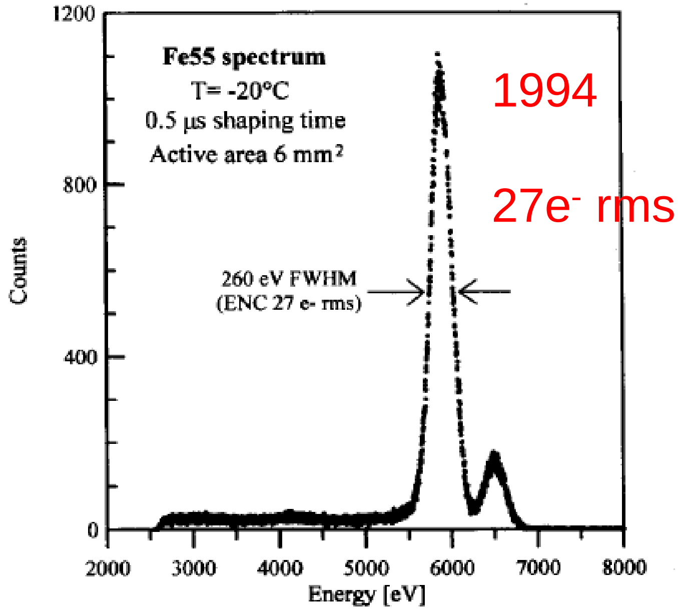


Emilio Gatti & Pavel Rehak, NIM A225 (1984)

LOW CAPACITANCE OUTPUT NODE
very low noise, n-JFET integrated
((drift-time --> position))

Si drift detector: very low noise, large area

BNL: Pinotti et al. IEEE Trans. Nucl.Sci. 42(1995) 12

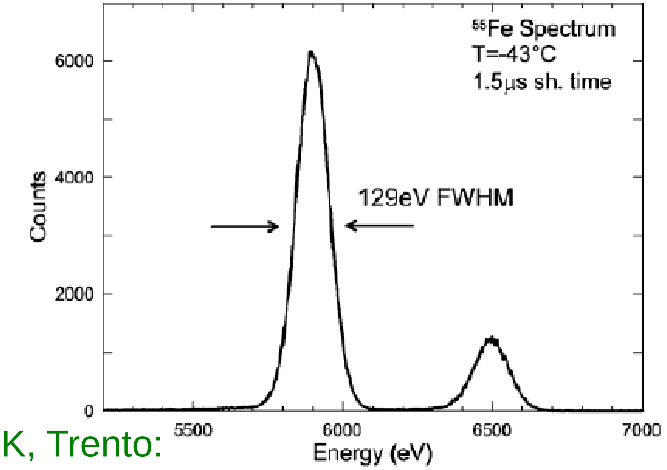


1994

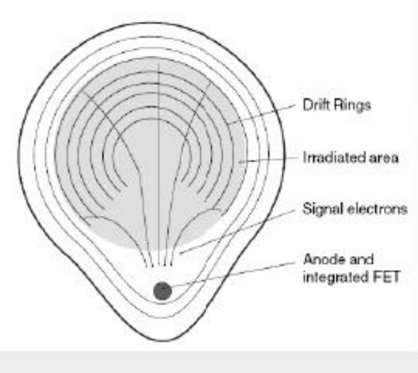
27e$^-$ rms

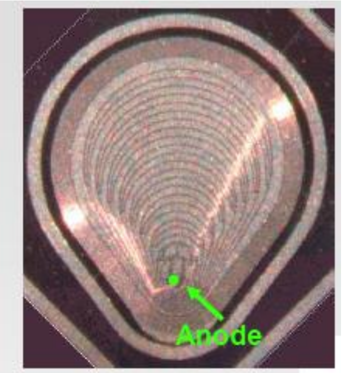
Fig. 4. ^{55}Fe spectrum taken at low temperature. At 4.1 keV, barely visible in the continuum, is the Si escape peak.

X-ray spectroscopy



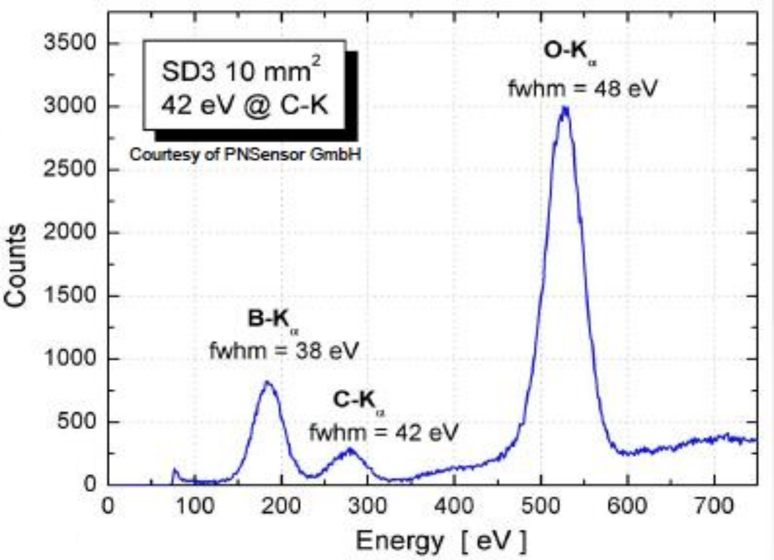
production FBK, Trento:
Fiorini et al. IEEE Trans. Nucl.Sci. 60(2013)2923





Droplet
drift detector
pnSensor
200fF->120fF
(from C. Guazzoni talk EPS Ravenna)

~2013
4e$^-$ rms



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CMOS integrated circuits for particle detector readout
introduction of chip design teams in HEP

Si microstrip detectors obviously need ICs, but how to do this?

Lucky coincidence: 1979 Mead & Conway design, using multi-project

Carver Mead and Lynn Conway, Introduction to VLSI systems,Addison-Wesley New York 1980

Bernard Hyams asks SLAC, begins Microplex with Sherwood Parker

aims at DELPHI tracker 128 channels NIM A226 (1984)

Gerhard Lutz initiates CAMEX64 with in Dortmund/Duisburg

used in ALEPH and elsewhere 64 channels IEEE TNS 36 (1989)

Erik Heijne and Pierre Jarron begin CCD-based readout with Philips Heijne

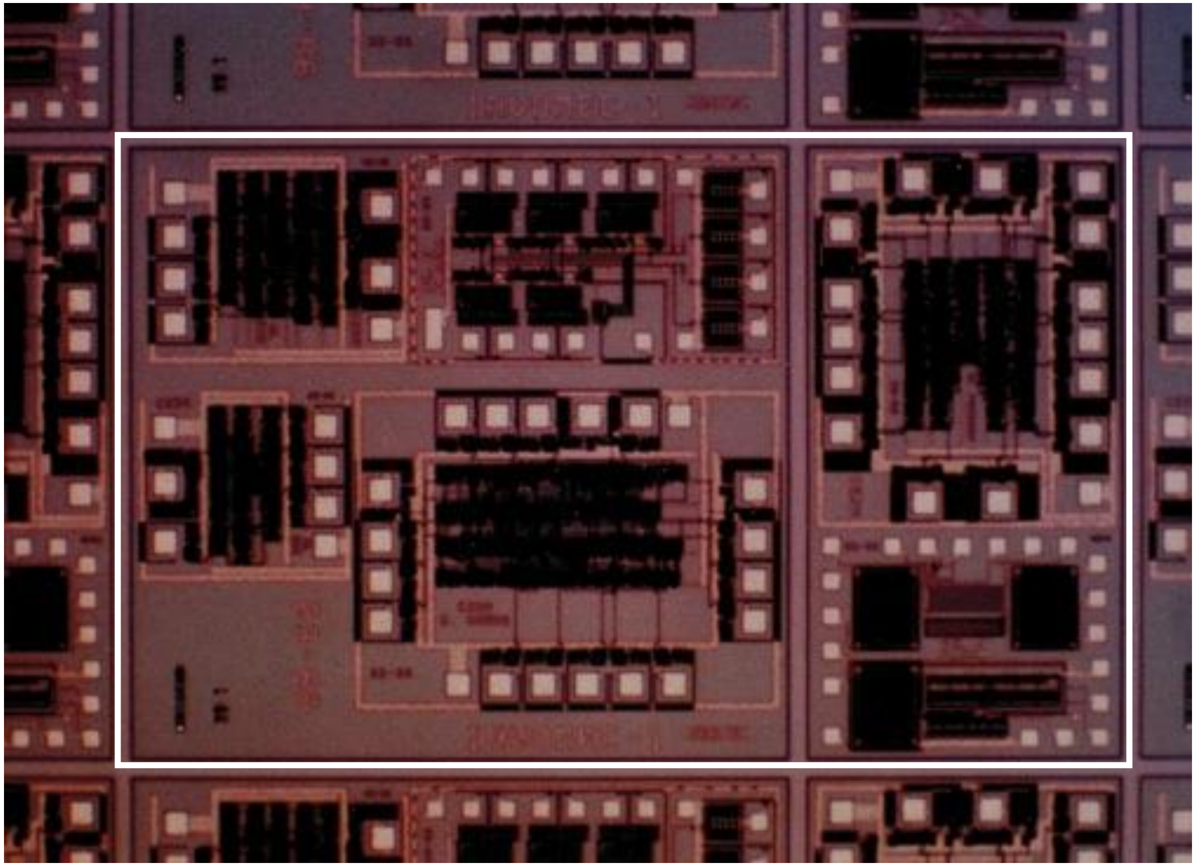
first try to include pipeline memory, no good result

begins collaboration ESAT/IMEC (Leuven) resulting in AMPLEX Stuart

used in UA2

Kleinfelder and David Nygren at LBL: Microplex 2 for CDF

CERN multi-project chip 1986



in collaboration with
IMEC Leuven (B)
Carl Das & Bart DeMey
3µm CMOS
MIETEC, Oudenaarde (B)

had circuits designed by:
Björn Hallgren
Pierre Jarron
Mike Letheren
George McPherson
+ Alessandro Marchioro
Bert van Koningsveld

2 weeks training in Leuven
+ leased telephone-line (25kCHF !)
to access IMEC design software

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Early <1990 readout chips for segmented Si detectors

Chips NOT to scale

SLAC/(DELPHI)

Microplex 1983

Walker, Parker, Hyams, Shapiro

NIM A226 (1984) 200

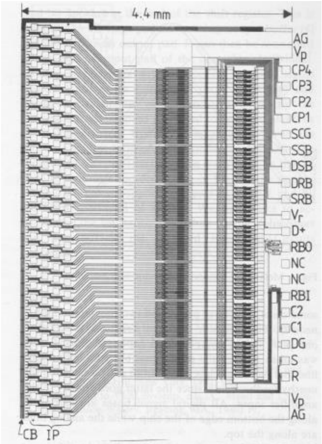


Fig. 3. Enlarged view of chip layout; AG = Analog Ground; D+ = Digital + 5; V_p = Analog + 5 (Pulsed); RBO = Read Bit Out; CP4 = Calibrate Pulse 4; NC = No Connection; CP3 = Calibrate Pulse 3; RBI = Read Bit In; CP2-Calibrate Pulse 2; C2 = Clock 2; CP1-Calibrate Pulse 1; C1 = Clock 1; SCG = Storage Cap Ground; DG = Digital Ground; SSB = Source, Signal Bus; S = Store; DSB = Drain Signal Bus; R = Reset; DRB = Drain, Ref Bus; IP = Input Pads; SRB = Source, Ref Bus; CB = Calibrate Buses; $V_r = V_{ref}$.

RAL/DELPHI

MX1 MX2 1987

Seller, Allport, Tyndel

IEEE TNS 35(1988) 176

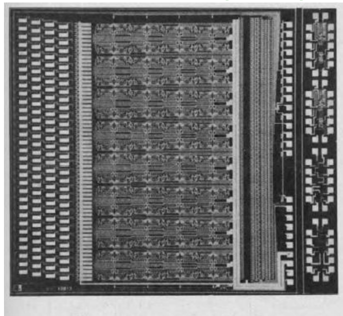


Figure 1. The MX1 Chip 6.4mm by 6.4mm.

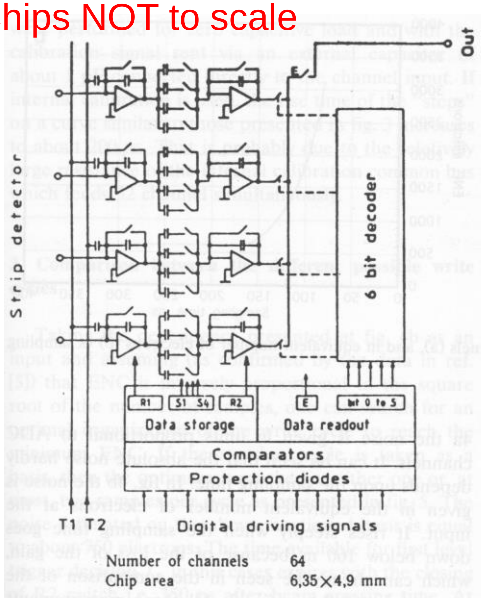


Fig. 1. The layout of the CAMEX chip [5].

CAMEX64/ALEPH-MPI

Buttler, Lutz, Hosticka

Becker et al. IEEE TNS 36(1989) 246

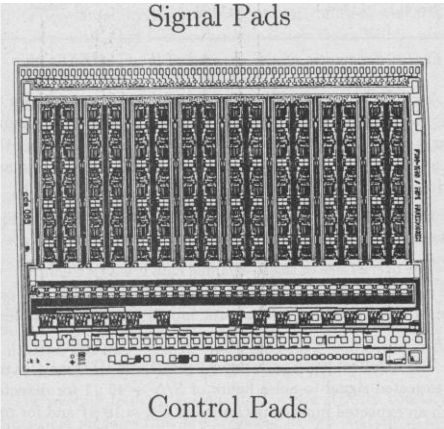
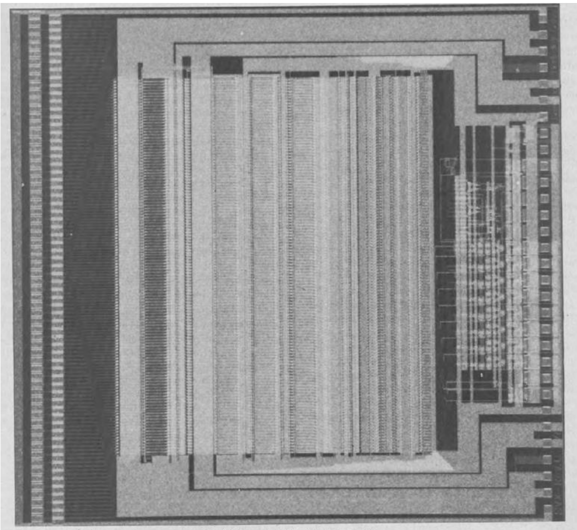


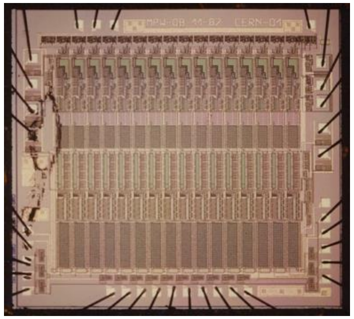
Fig. 5: A picture of the complete 64 channel chip



9. SVX readout I.C. die photograph.

CDF-SVX Kleinfelder 1988

Kleinfelder et al. IEEE TNS 35(1988) 171



AMPLEX (UA2)

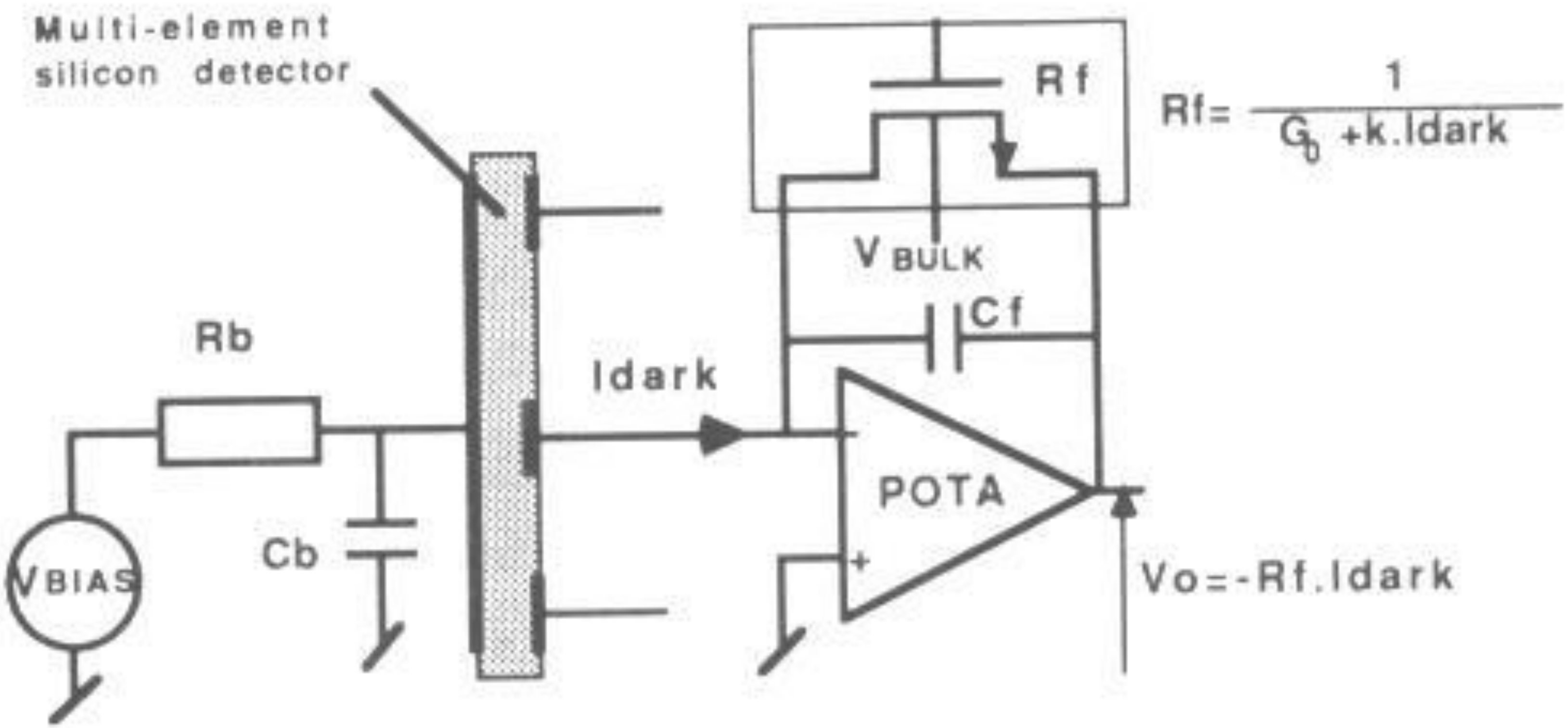
Pierre Jarron 1987

classical, continuous feedback

actually the first in a collider:1988

Beuville et al. NIM A288 (1990) 157

‘AMPLEX’ Schematic - Leakage current compensation



AMPLEX cicuit can COMPENSATE dark current up to ~ 800nA per channel

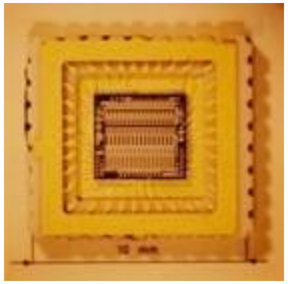
Sensor segmentation in ‘n’ cells already reduces dark current per channel by 1/n

Hermetic Si pad detector for UA2

Cylindrical detector array
collaboration with
Claus Gößling and Alan Clark
U. Dortmund, U. Genève

FIRST Si barrel detector
in collider experiment
FIRST Si array with
IC chip readout

~5 mm thin CILINDER around beam pipe
ONLY POSSIBLE using "AMPLEX" chip
16-channel circuit design **Pierre Jarron**



R. Ansari et al. NIMA279(1989) 388

1986 – 1988 in LAA microelectronics project

Microelectronics essential for experiments
vice versa: CMOS chips impossible without accelerators

major tools for CMOS manufacturing:
- ion implanters
- analysis equipment: X-ray, RBS, fluorescence, e-beam scanning SEM/TEM

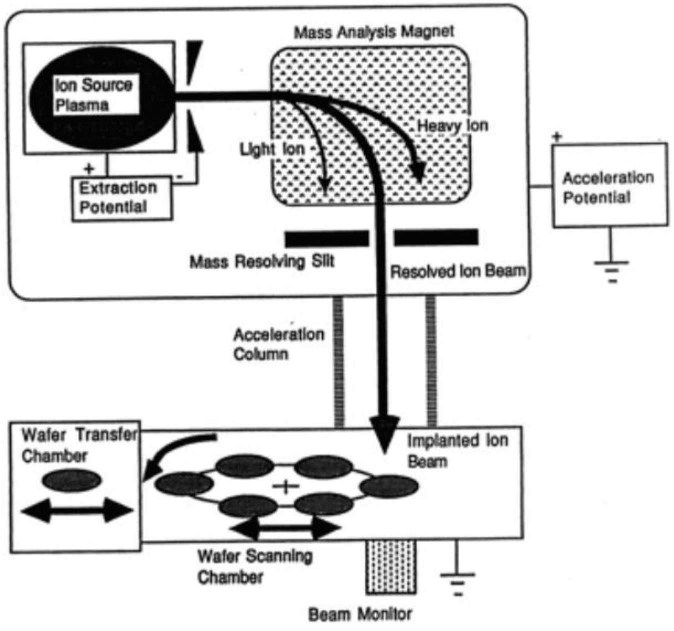
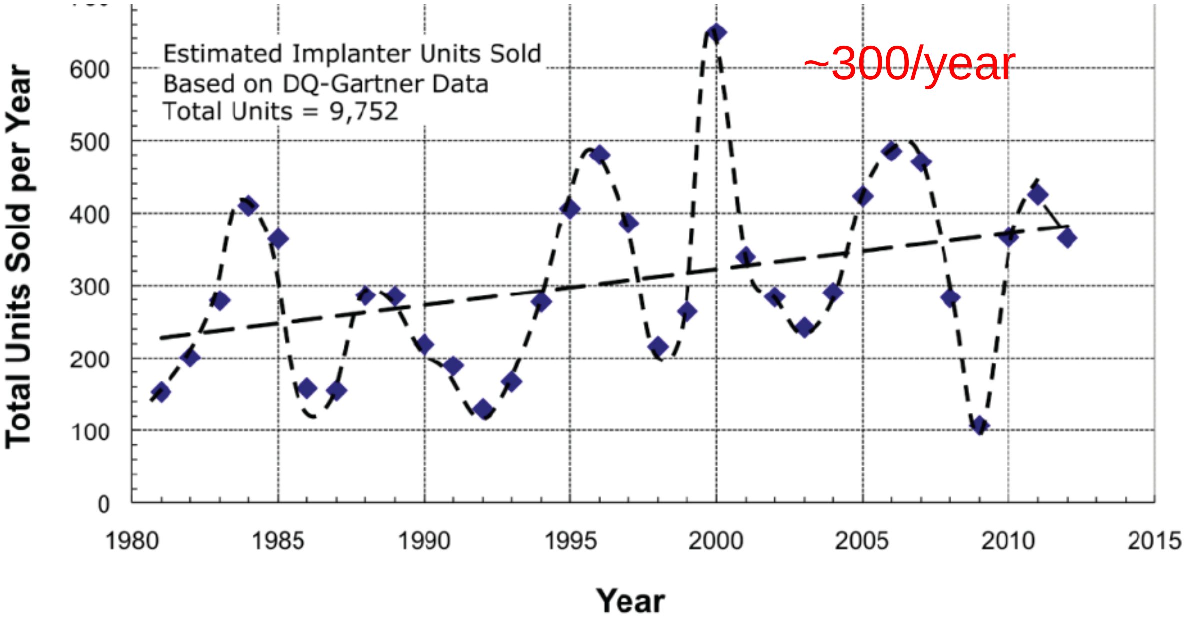


Figure 4: Major ion implantation beamline components.

WEYB2 Proceedings of PAC2013, Pasadena, CA USA

ION IMPLANTATION FOR SEMICONDUCTOR DEVICES: THE LARGEST USE OF INDUSTRIAL ACCELERATORS

S.B. Felch, Susan Felch Consulting, Los Altos Hills, CA 94022, USA
M.I. Current, Current Scientific, San Jose, CA 95124, USA
M.C. Taylor, Taylor Consulting, Lake Oswego, OR 97034, USA



~300/year

A few more cases in detail

~~Si single crystal growth, purity ~1965~~

done

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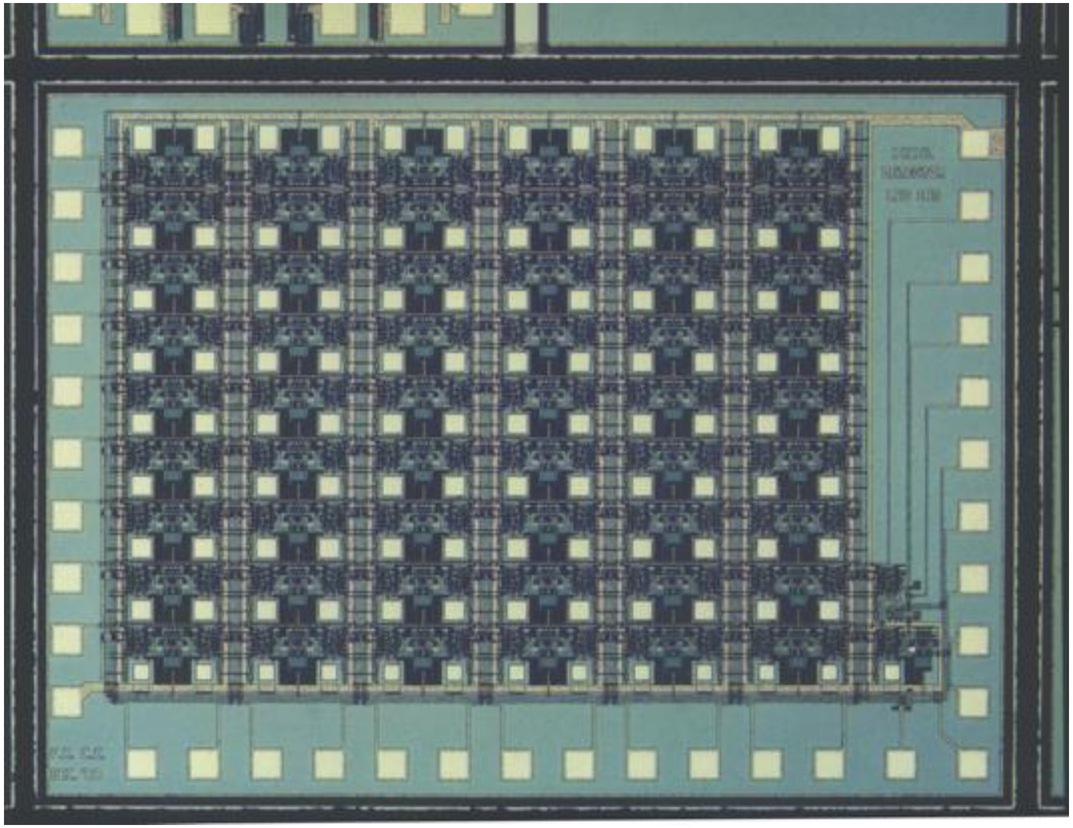
~~Microstrip detectors 1980, year of the ‘Revolution’~~

~~The first colliders & chip readouts: UA2, Mark II, LEP....~~

Begin of pixel detectors 1986-1989

Hybrid pixel detector

our 2nd component in LAA project micropattern pixel detector



Chip layout Dec 1988
Krummenachher & Enz   EPFL

First design in collaboration with EPFL

Krummenacher et al.
NIM A288(1990)176
(presented at Munich Symp Feb 1989)

Chip ready
Summer 1989
published at IEEE
Nucl Sc Symp 1989

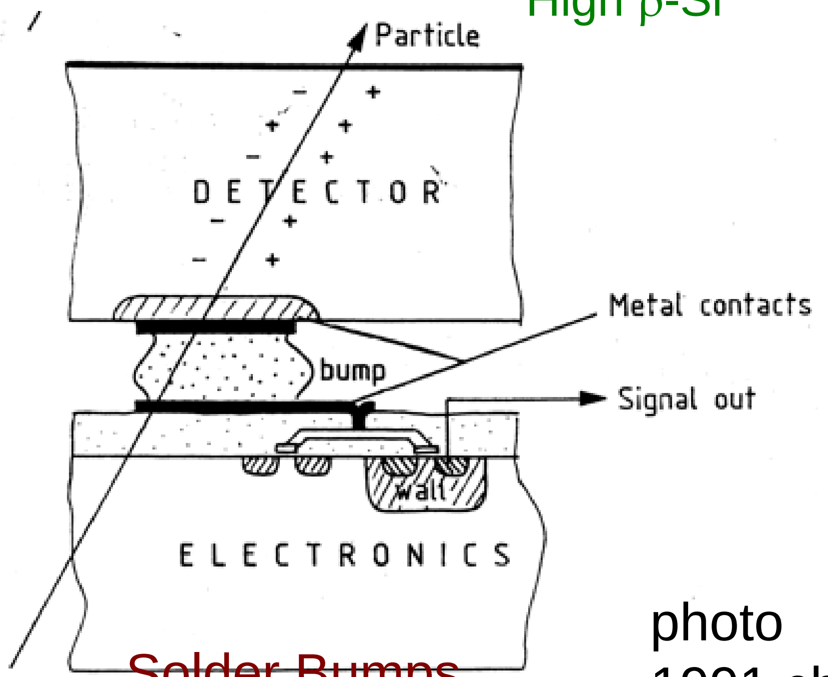
Campbell et al. NIM A290 (1990) 149
(presented at IEEE Nucl Sc. Symp. 1989)
results including spectra
taken with radioactive sources

Complete hybrid Si pixel detector 1989

CERN : Campbell, Heijne + EPFL Vittoz, Enz, Krummenacher + ETHZ: Viertel

True 2 – D sensor matrix (ladder design)

High ρ-Si



Solder Bumps
+

CMOS electronics readout matrix

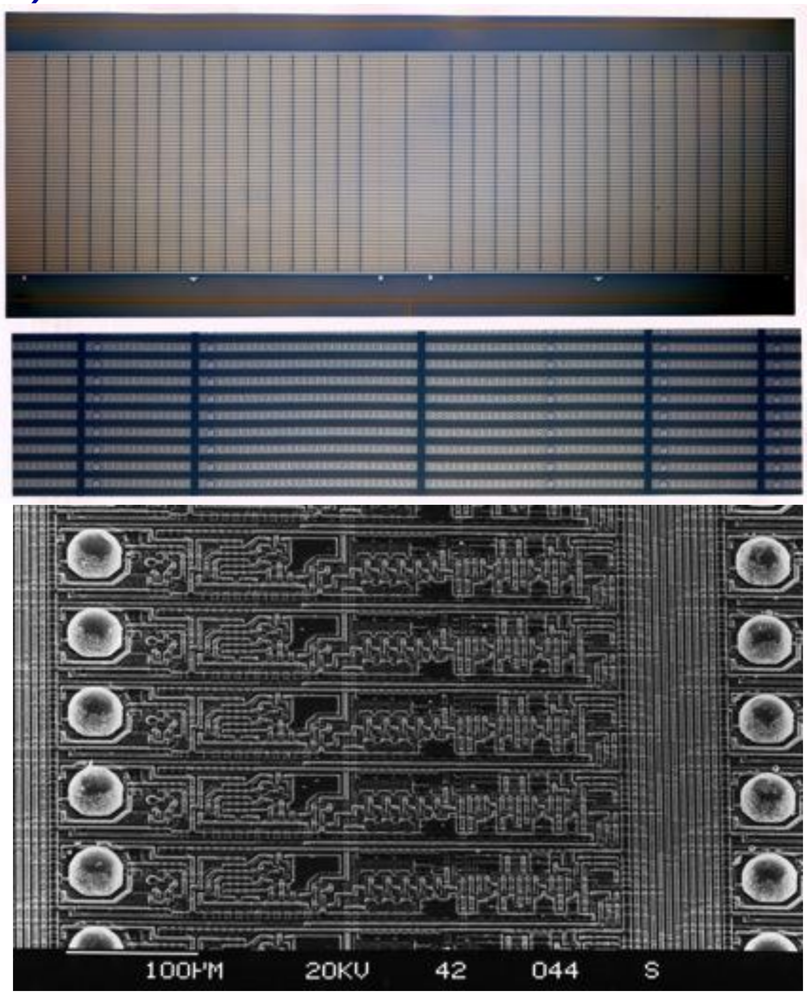
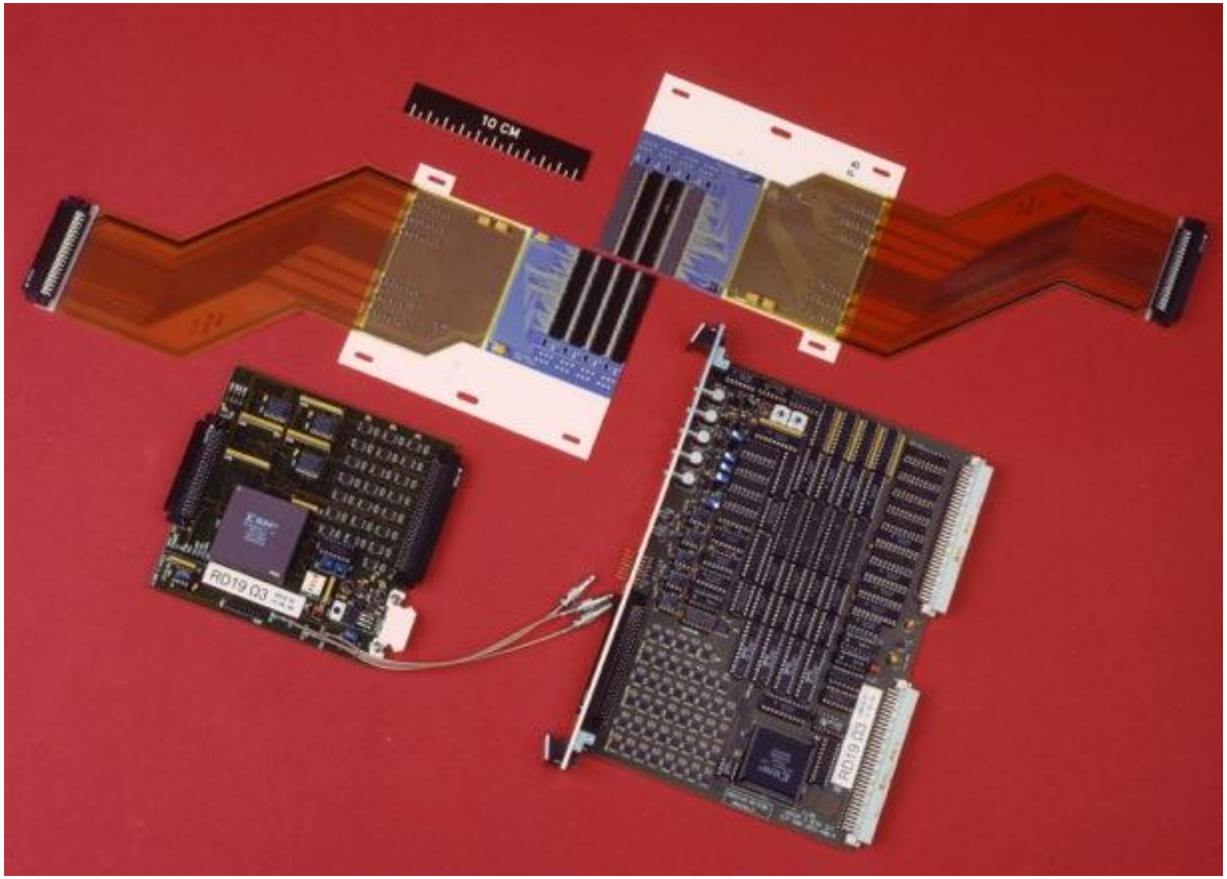


photo
1991 chip
‘Omega2’

Sept 1991: Tested in H6 beam & in Omega magnet

2nd generation pixel arrays ‘LHC1’ 1995



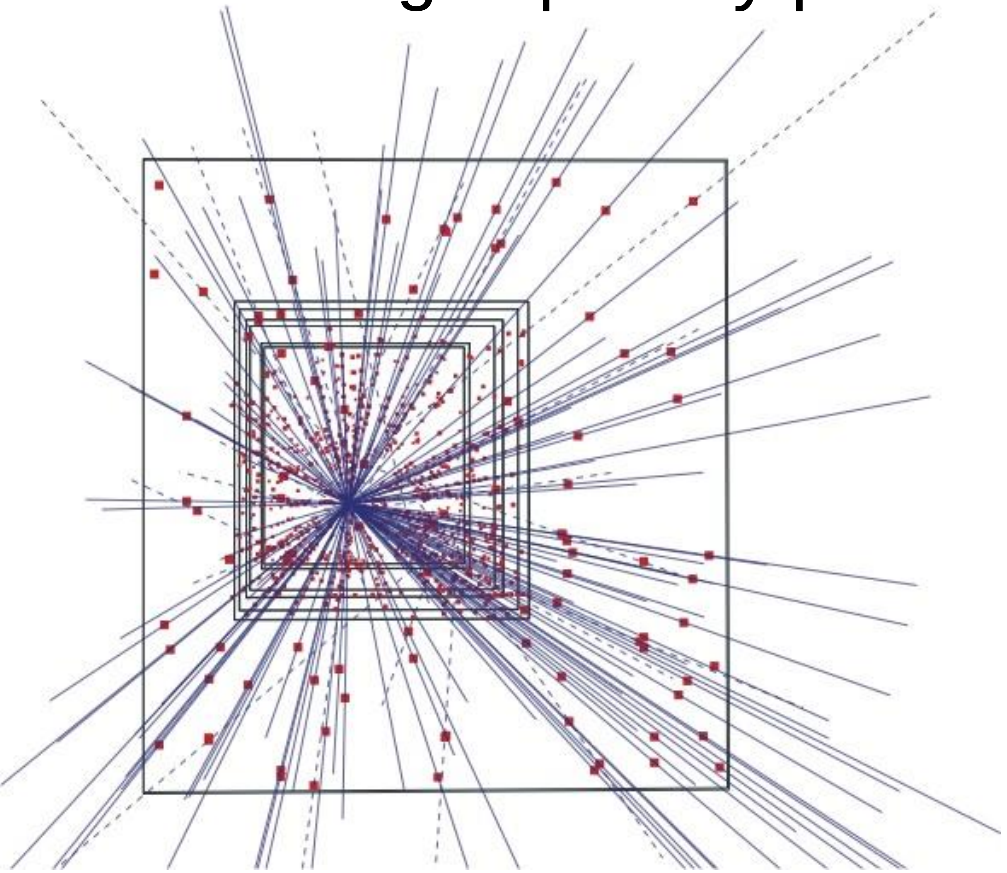
2 x 4 ladders
using overlap for
covering full
5 x 5 cm^2

telescope of
14 such planes
contructed 1992-7

Telescope in heavy ion experiments Omega Spectrometer at CERN
design by CERN RD19 collaboration in view of LHC

this pixel chip was first presented in Hiroshima Symposium 1995
E.H.M. Heijne et al. NIM A383 (1996) 55

Tracking capability pixels proven in WA97 Pb ion



RD19 1995

7 planes

1.1 M pixels

153 tracks reconstructed

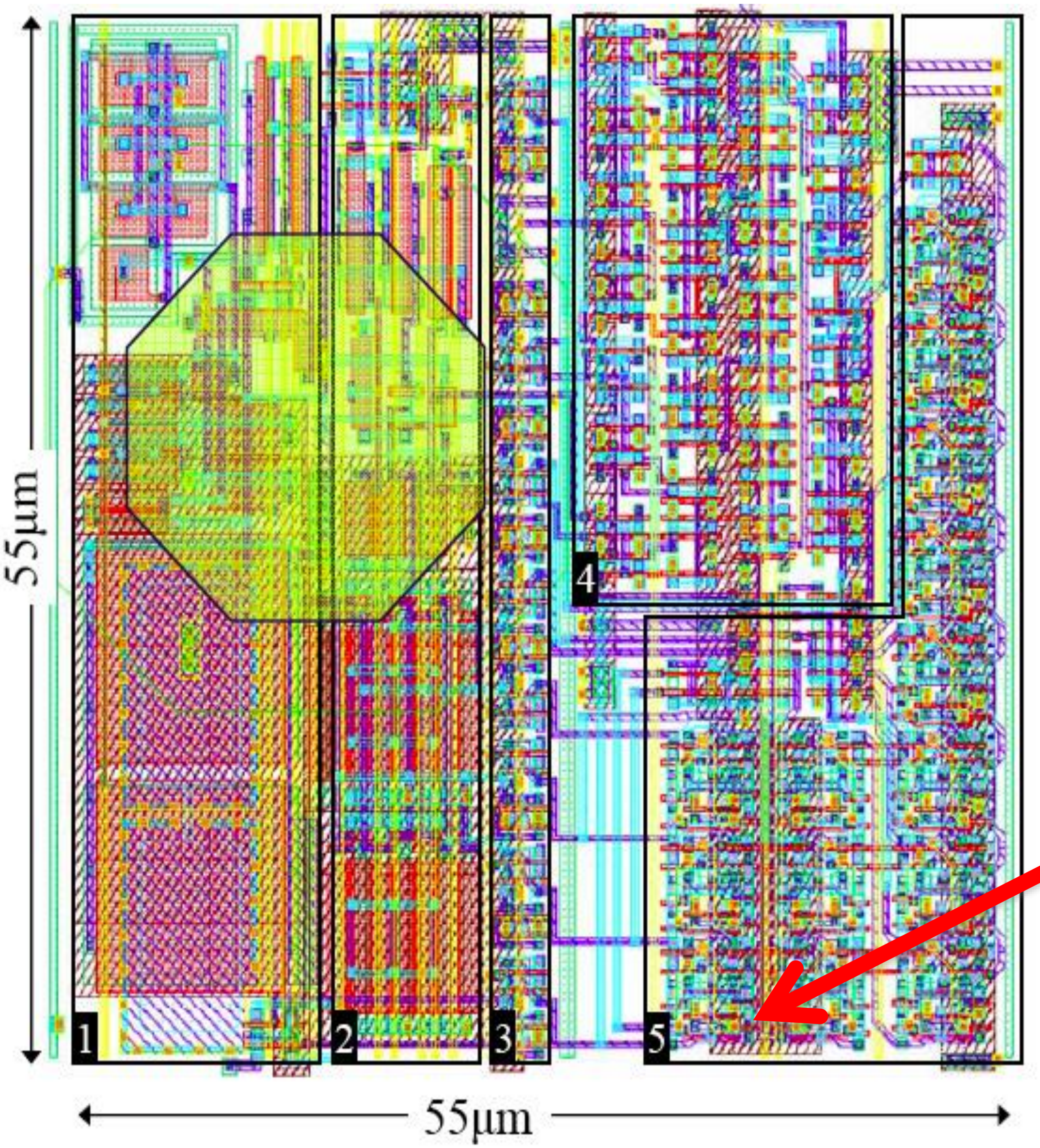
B-field OFF

^{208}Pb ion at 158 A GeV/c on Pb target

Millions of EVENTS ANALYZED

Obvious: noise-free space points , high multiplicity

TIMEPIX cell layout



design by
Xavier Llopart
and colleagues
PhD Thesis p. 107
CERN 2007

1. PREAMPLIFIER CSA
2. THRESHOLD, 4-BIT TUNING
3. 8-BIT CONFIG REGISTER
4. REF_CLK & SYNCHR LOGIC
5. 14-BIT COUNTER

includes Time-Over-Threshold
signal amplitude digitizer
in each pixel

TIMEPIX silicon ’emulsion’/portable ‘bubble chamber’

H6 120 GeV p/ π beam 2007

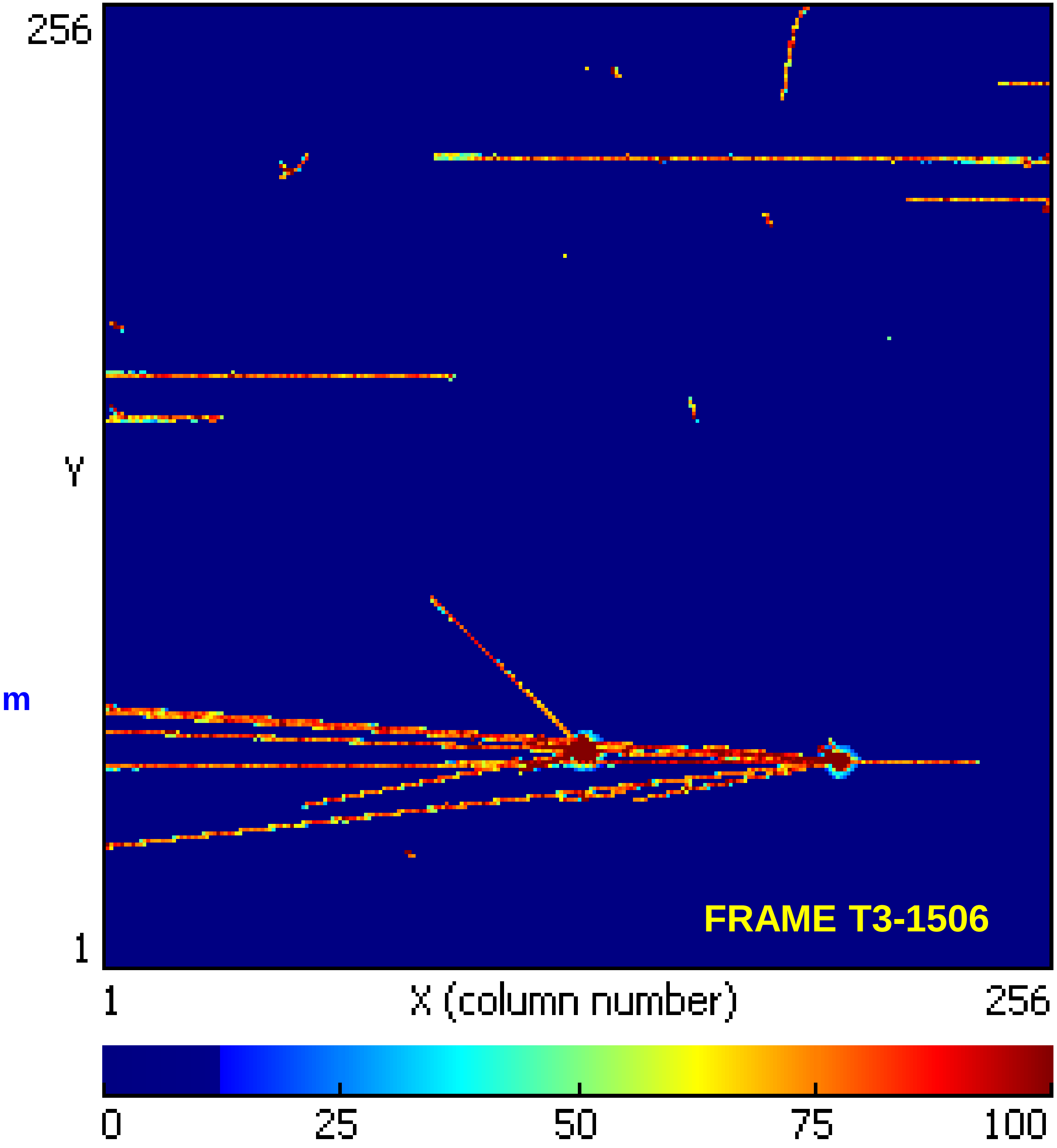
incident from the right

Beam ←

pion interacts with Si,
one secondary pion again, after ~3mm

Trails to the front or to the back ?
ambiguity can be solved if
2 adjacent planes are used
-> stack of pixel detectors

beam test with help of
John Idarraga / then Montréal



Major innovations silicon detectors (repeat)

1957 alloyed or diffused n-p and later p-n junctions

.... (Oak Ridge, Chalk River, Harwell, Saclay, Strasbourg)

in the meantime, **great advances** in silicon crystal growing

some time later this allowed rectangular detectors, instead of circular devices

1983 first experiments use mostly **commercial** detectors from

Enertec Schlumberger (Paul Burger from Strasbourg, using the Kemmer patent),

Micron Semiconductor (Colin Wilburn, originally from Chalk River)

Hamamatsu (Keio Yamamoto)

from ~1985 and later, some additional companies:

Canberra (again Paul Burger, now with Walter Schoenmaekers in Belgium)

SINTEF (Oslo, Thor-Erik Hansen and Berit Avset)

CiS (Erfurt, Ralf Röder)

etc.

1988 first Si array of 1.1 m^2 operational in collider experiment UA2 at CERN

using AMPLEX 16-ch CMOS readout, Jarron

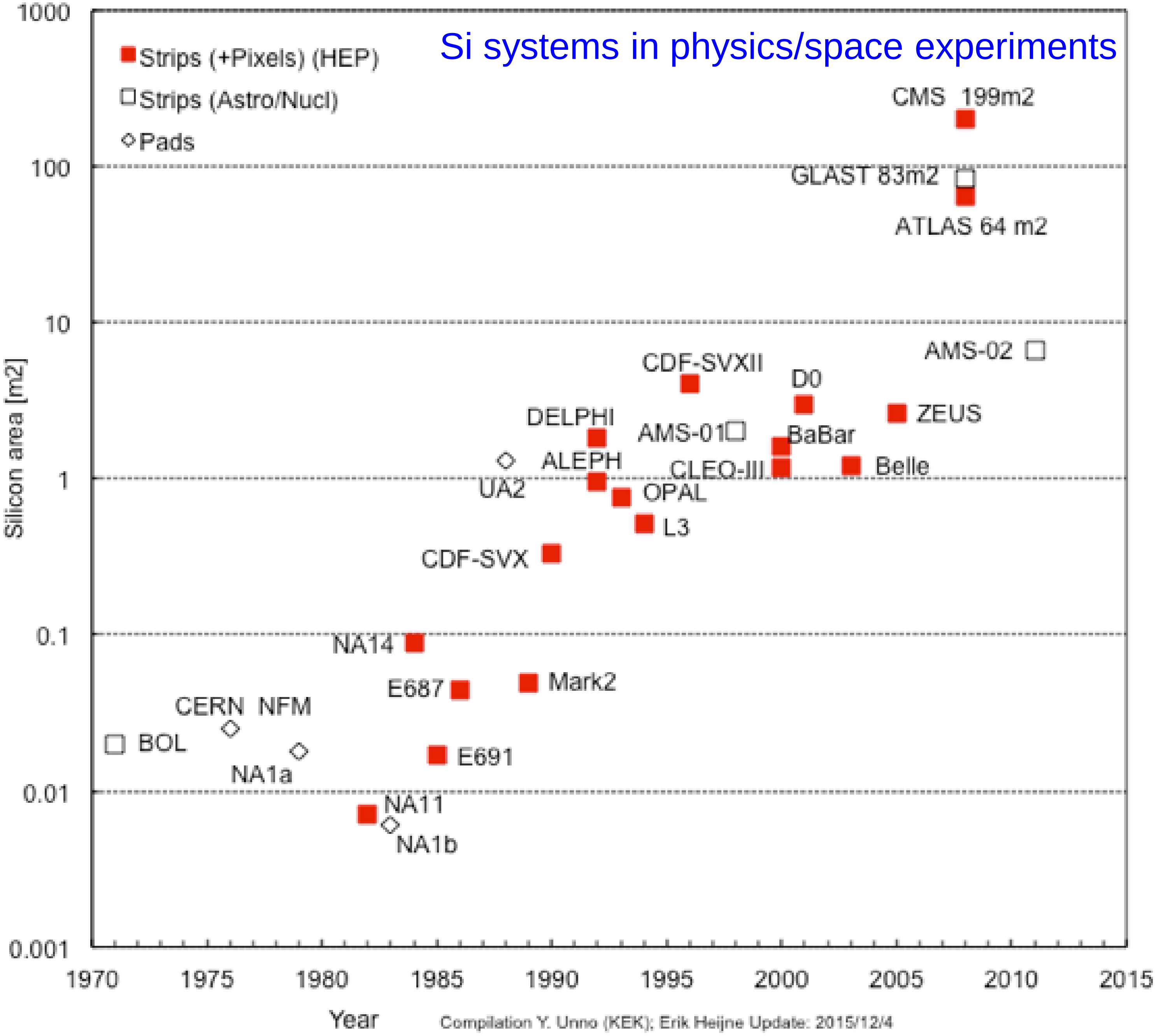
1989 Si micropattern pixel detector chip (Heijne, Campbell, Enz, Krummenacher)

1991 hybrid pixel detector bump-bonded with 1006 cell CMOS chip IEEE-TNS 39

1997 3D ‘pillar’ structure proposed by Sherwood Parker, LBL NIM 39

exponential increase in area of Si arrays in physics experiments and space

Si systems in physics/space experiments



Compilation Y. Unno (KEK); Erik Heijne Update: 2015/12/4

Large silicon systems with 1000’s of chips

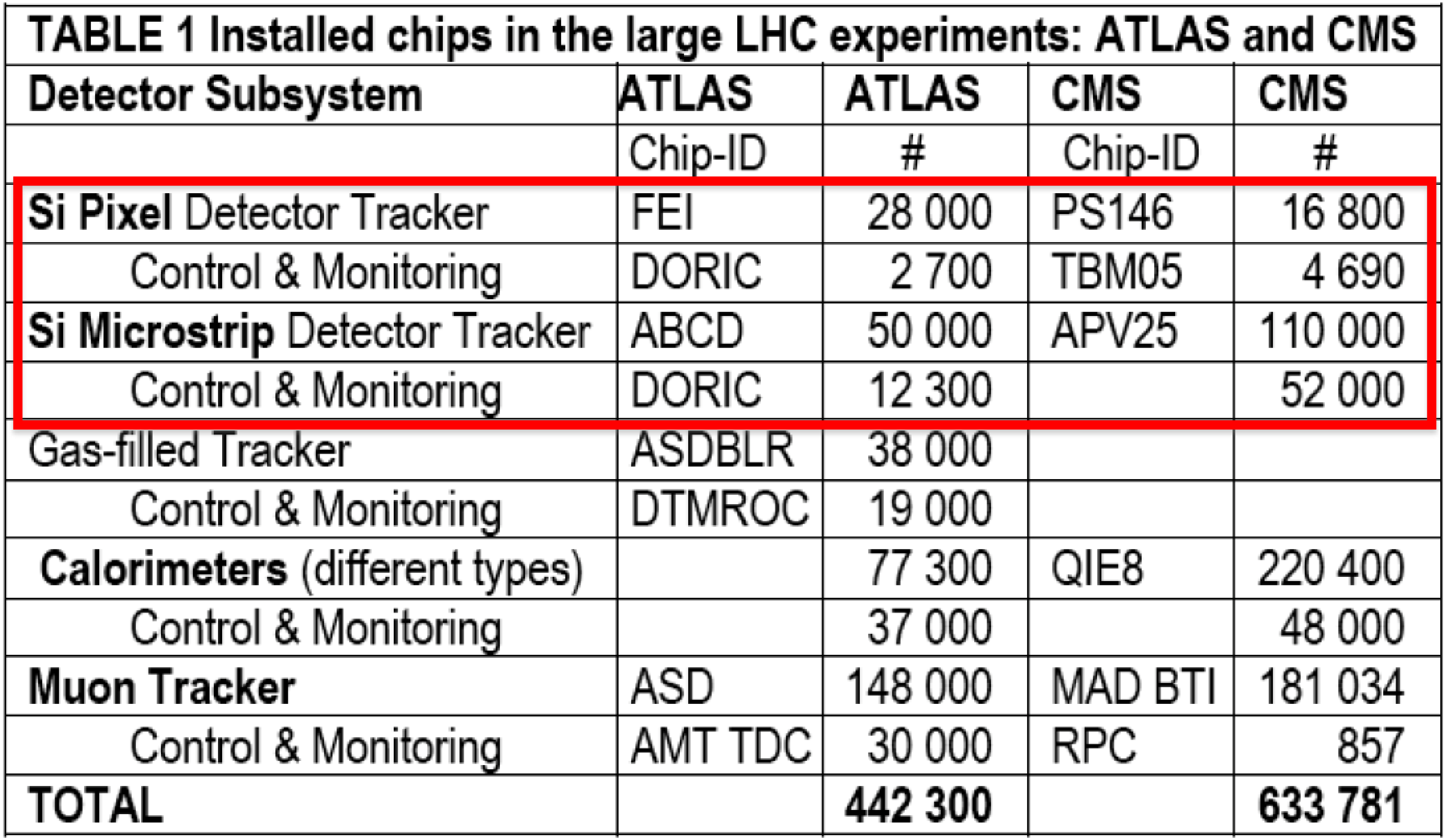


TABLE 1 Installed chips in the large LHC experiments: ATLAS and CMS

Detector Subsystem	**ATLAS**	**ATLAS**	**CMS**	**CMS**
	Chip-ID	#	Chip-ID	#
Si Pixel Detector Tracker	FEI	28 000	PS146	16 800
Control & Monitoring	DORIC	2 700	TBM05	4 690
Si Microstrip Detector Tracker	ABCD	50 000	APV25	110 000
Control & Monitoring	DORIC	12 300		52 000
Gas-filled Tracker	ASDBLR	38 000		
Control & Monitoring	DTMROC	19 000		
Calorimeters (different types)		77 300	QIE8	220 400
Control & Monitoring		37 000		48 000
Muon Tracker	ASD	148 000	MAD BTI	181 034
Control & Monitoring	AMT TDC	30 000	RPC	857
TOTAL		**442 300**		**633 781**

Exploitation of Si systems in space experiments

Large Si telescopes use expertise from HEP experiments

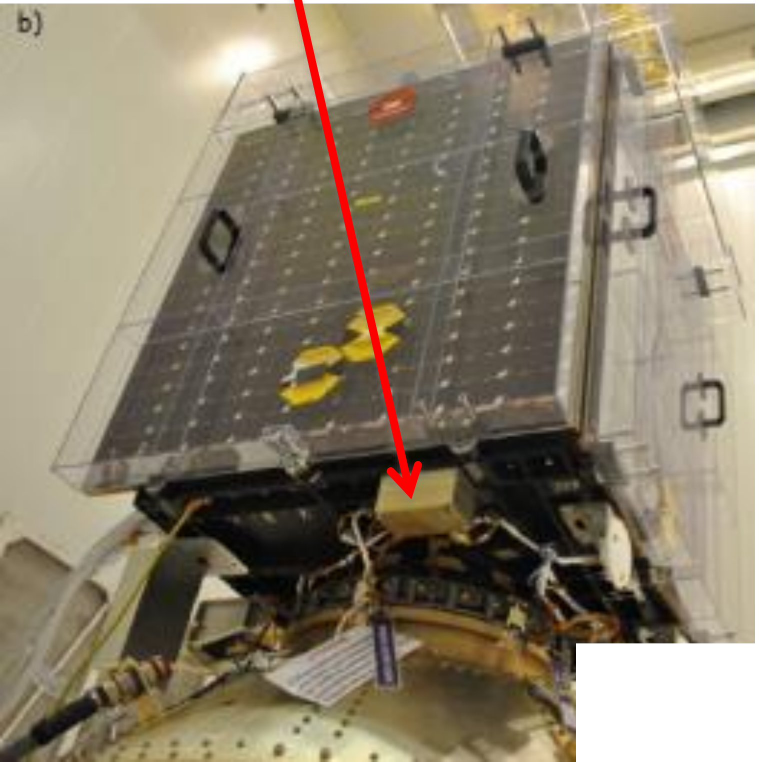
AMS primarily aimed at antimatter

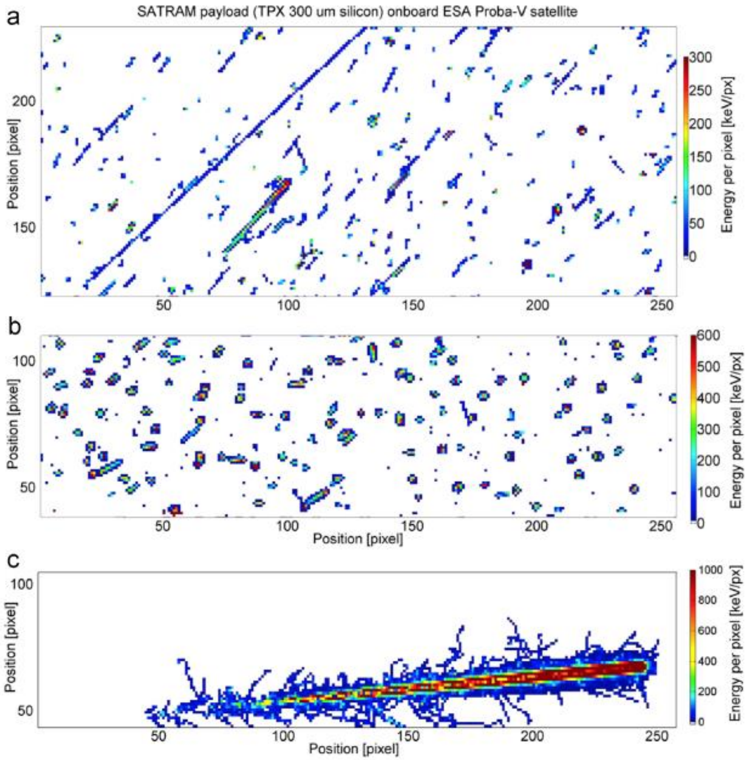
Fermi/GLAST study of energetic photons
gamma bursts

Small Si pixel devices allow radiation studies "in a nutshell"
perfect for pico-satellites

C. Granja et al.
Planetary Space Sci 125(2016) 114

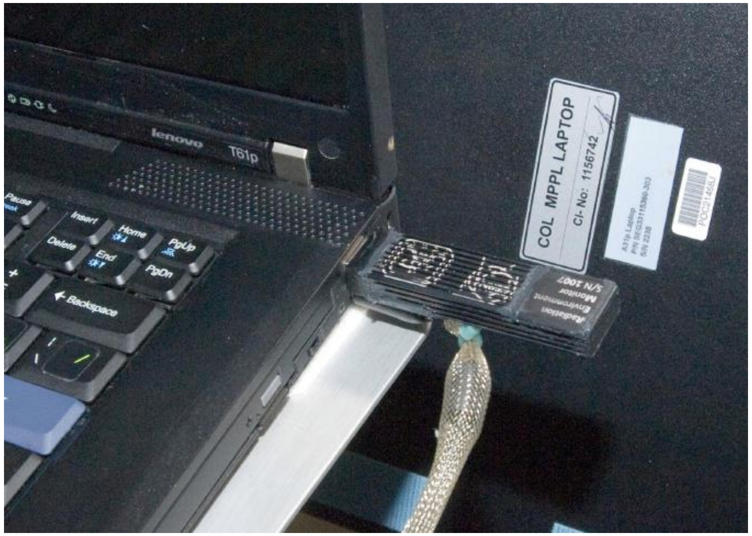
SATRAM (Timepix) on PROBA-V satellite from ESA at ~800km altitude



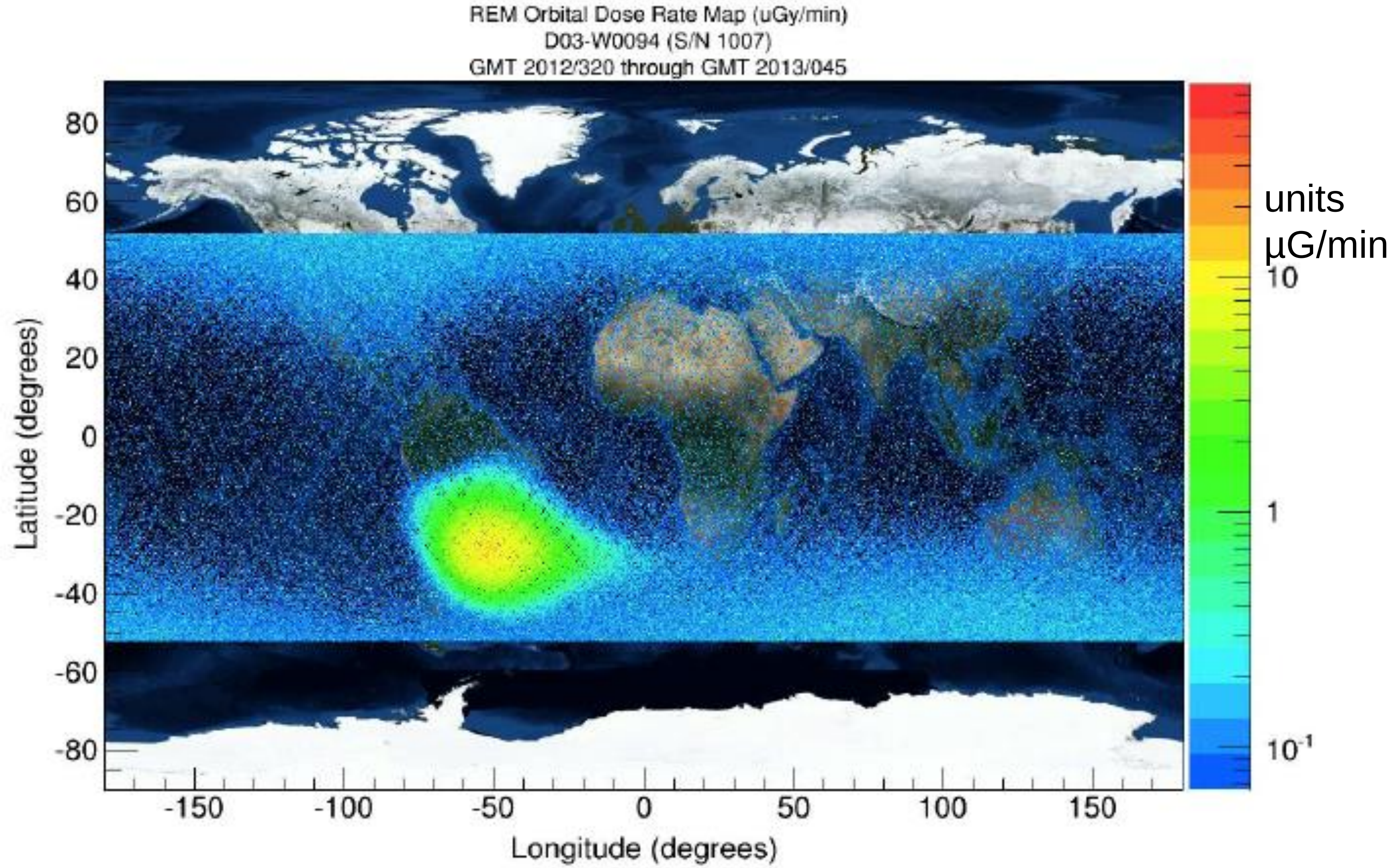


heavy ion
+ d rays

Pixel chips for dosimetry in Int Space Station ISS



Dosimetry at the Int Space Station ISS



Innovation in radiation hardness for Si chips and sensors

Radiation effects in equipment have been an issue for spacecraft since Telstar

Dose levels even much higher inside collider experiments: krad -> Mrad
~1988 only 'iron-ball' experiment looked possible, what to do?

Understanding of the particle interactions in Si and Si-oxide + beam testing

The 3 main radiation effects require 3 main solutions:
oxide threshold shift disappears due to tunneling, if oxide <5nm
suggestion based on work Nelson Saks, NRL Washington
edge leakage current under thick oxide avoided by enclosed layout
solution implemented ~1978 at RCA Princeton by Ron Smeltzer
single event effects (upset, burnout,..) avoided by triplication
standard approach in avionics, visit by Eugene Normand Boeing
These 'innovations' allowed financially acceptable radiation hard chips

A serious situation avoided by learning from specialists 1984-1997

Radiation hardness improvement of sensors has also been achieved
segmentation helps for dark current and signal loss

Many important innovative steps could not be discussed...

many hours would be needed

Double-sided Si detectors
Charge sharing & understanding of current signal generation
DC vs AC coupling
Bias schemes
Power and cooling
Integration of front-end components
Signal processing architecture
Safety systems
...
~recent innovations such as 3D ‘pillar’ diode matrix

Future innovations? Look at the past

Future ???

Recent nanoCMOS technology for sensors, 3D stacking

Smaller pixel capacitance: 100 e^- on 0.1 fF -> 160mV

ultrapixels of ~$2x2 \mu m^2$ need only charge from ~3µm Si; 32nm CMOS +fast

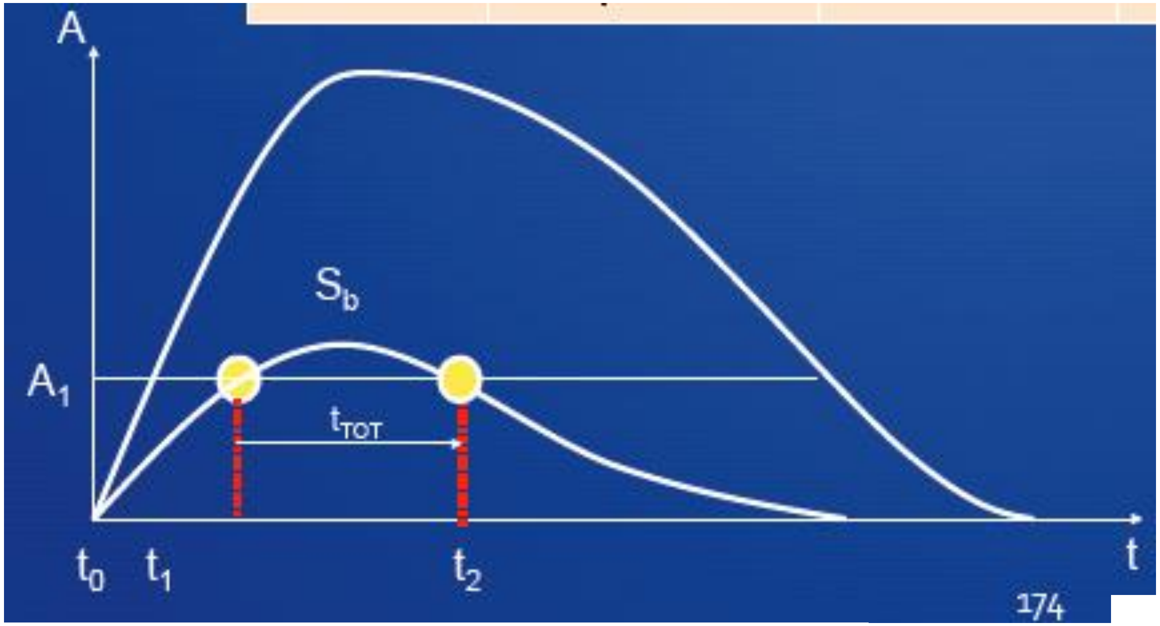
Larger wafersize could be used if signal/noise improves

Faster signals allow timestamps ‘inside-crossing’ <20ps?

CMOS readout circuits in 32nm, 14nm, etc.???

Monolithic detector chips in CMOS instead of hybrid ......

ps timing is new frontier: ~70ps in NA62



200µm Si DETECTOR

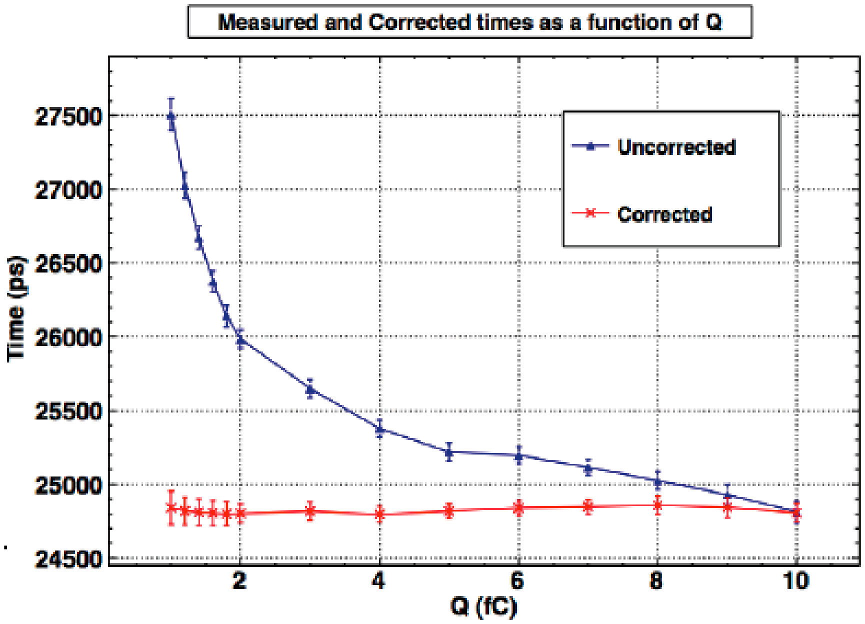
pixels 300µmx300µm

CORRECT the TIMEWALK

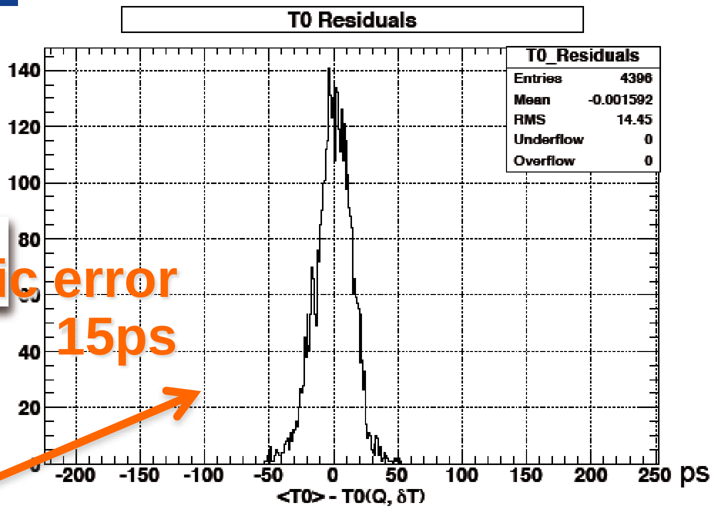
real-time in the readout chip

measured TOT of shaped signals

from a LASER



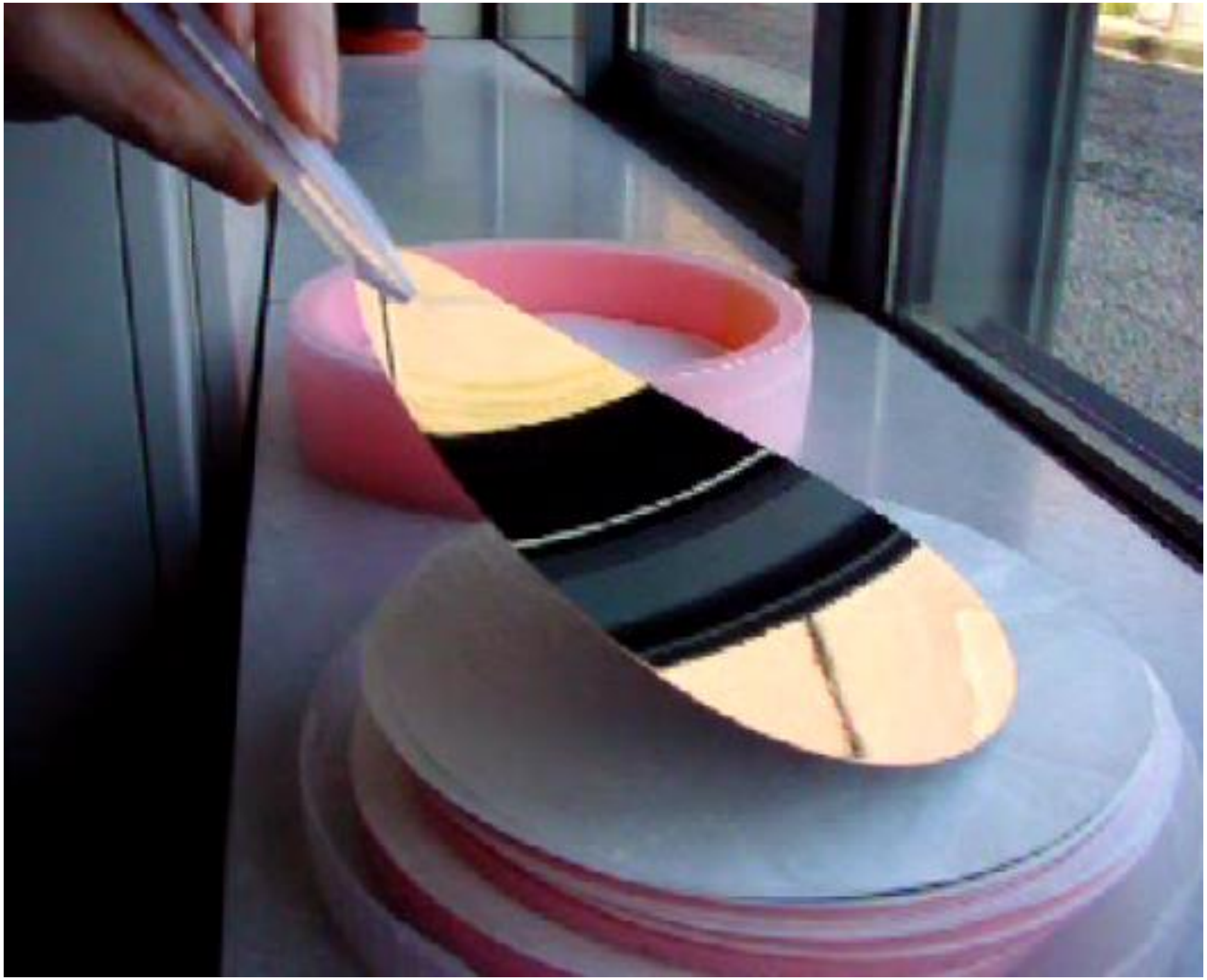
systematic error 15ps



ept

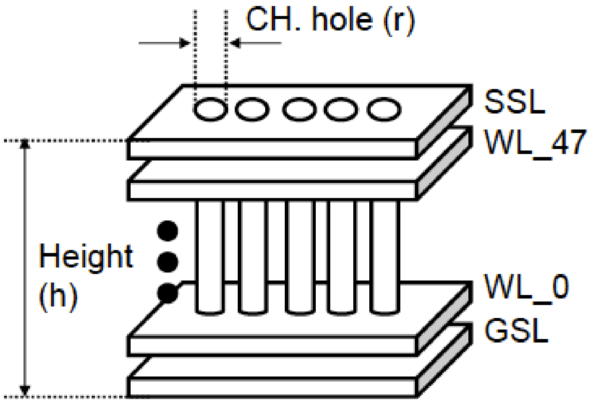
GigaTracKerteam NA62

Thinned wafers and ‘Through Si Via’ TSV



IMEC

256Gb 3b/Cell V-NAND Flash Memory with 48 Stacked WL Layers



CH. Hole increase

→ Easier to fabricate

→ Poor WL resistance

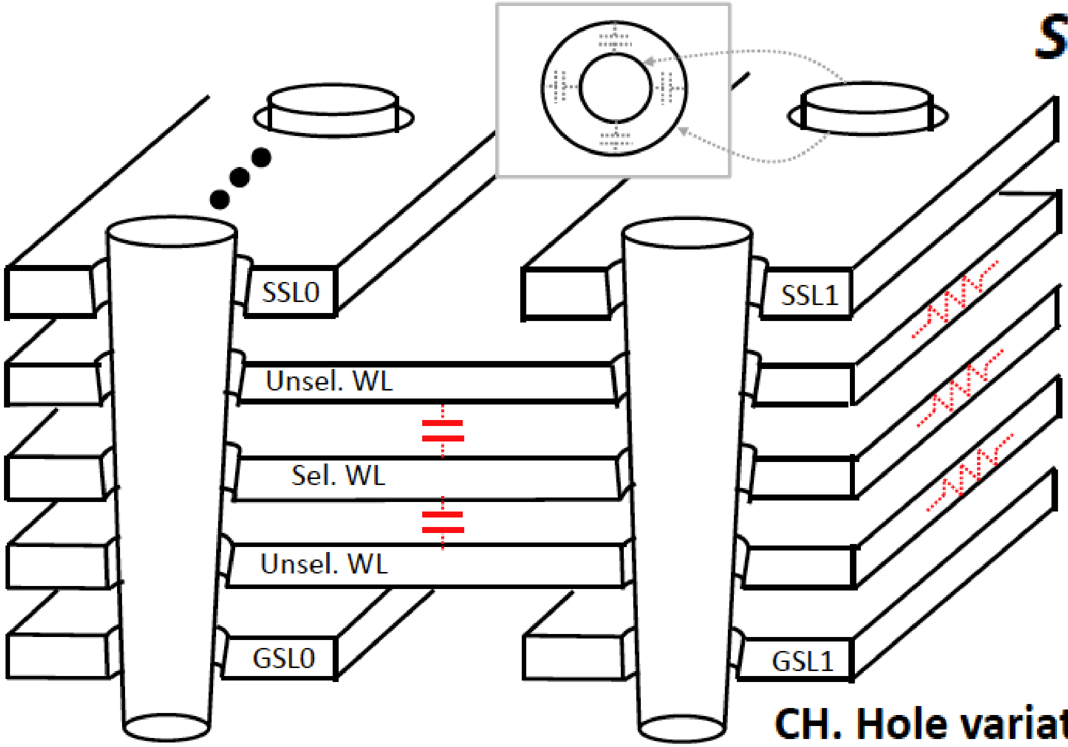
Height shrink

→ Easier to fabricate

→ Poor cell char.

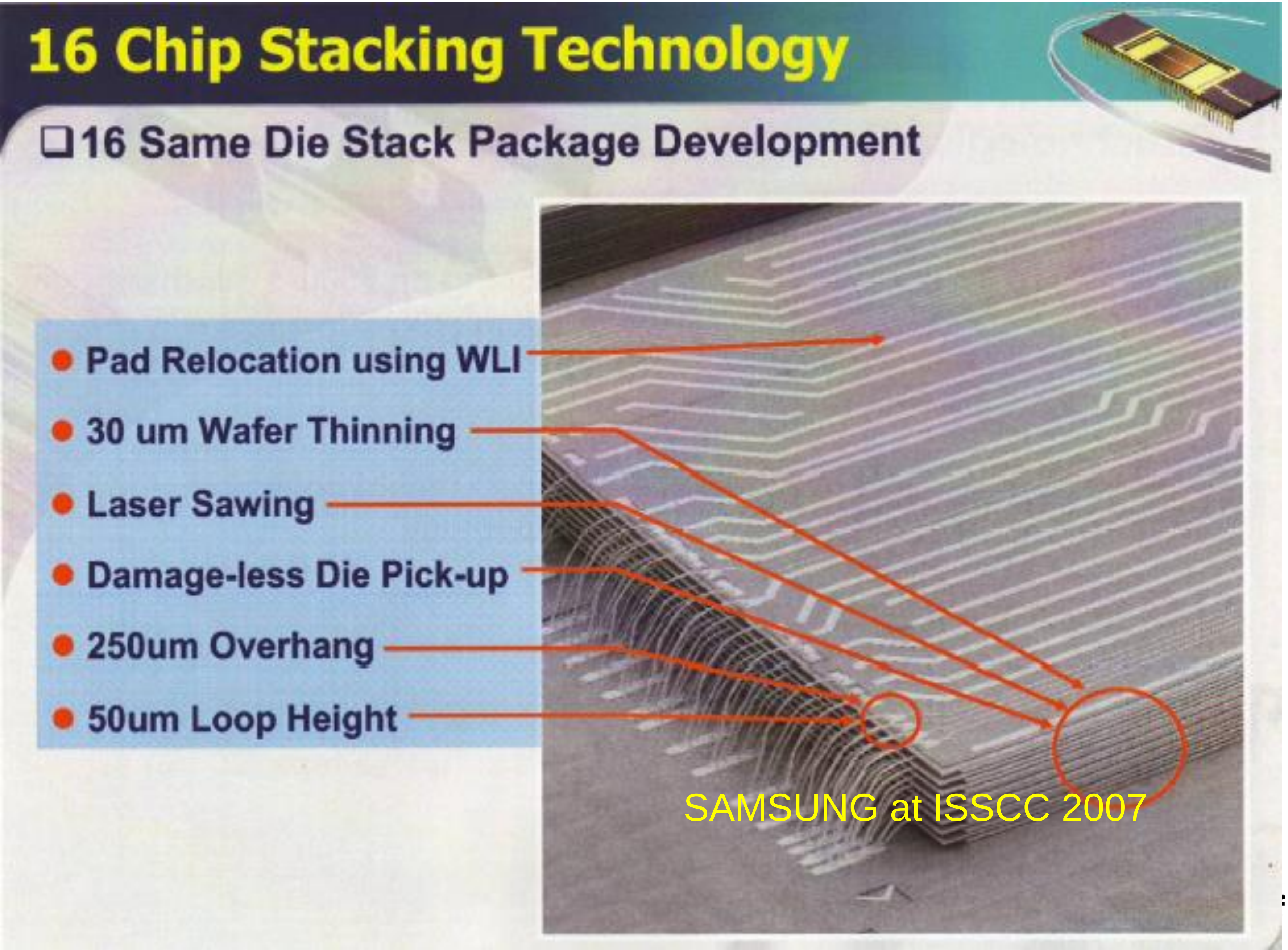
→ Poor WL-WL Couple

Samsung Electronics, Korea



CH. Hole variation is unique characteristic for 3D NAND.

‘old’ example of 3D memory stacking; 48 layers in 2016



16 Chip Stacking Technology

❑ 16 Same Die Stack Package Development

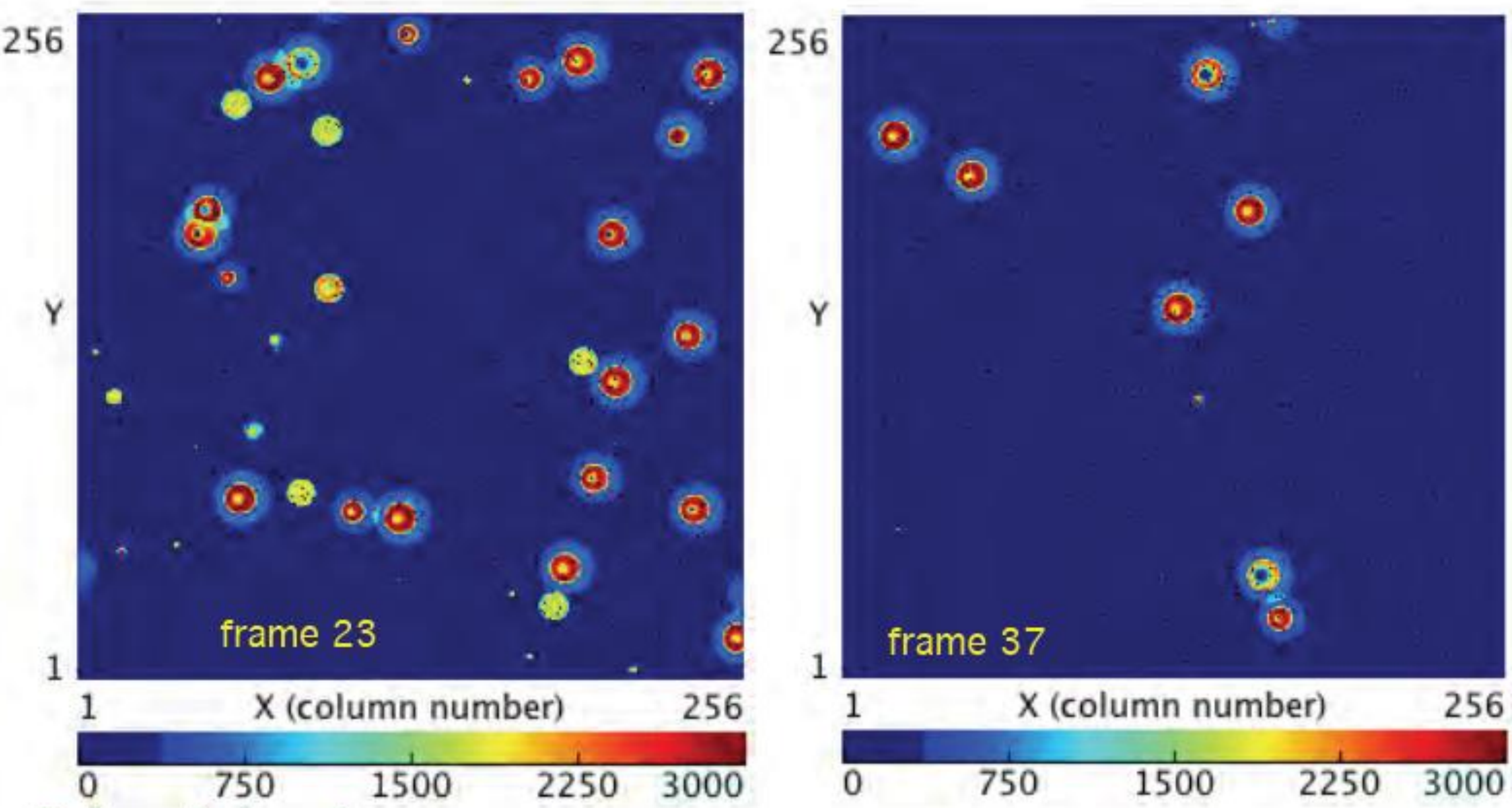
- Pad Relocation using WLI
- 30 um Wafer Thinning
- Laser Sawing
- Damage-less Die Pick-up
- 250um Overhang
- 50um Loop Height

SAMSUNG at ISSCC 2007

Images with redundancy can show unexpected objects

Different kinds of GeV ions, perpendicular on Timepix, are recognizable

(1mm sensor bias 2V)



Pixelman display software

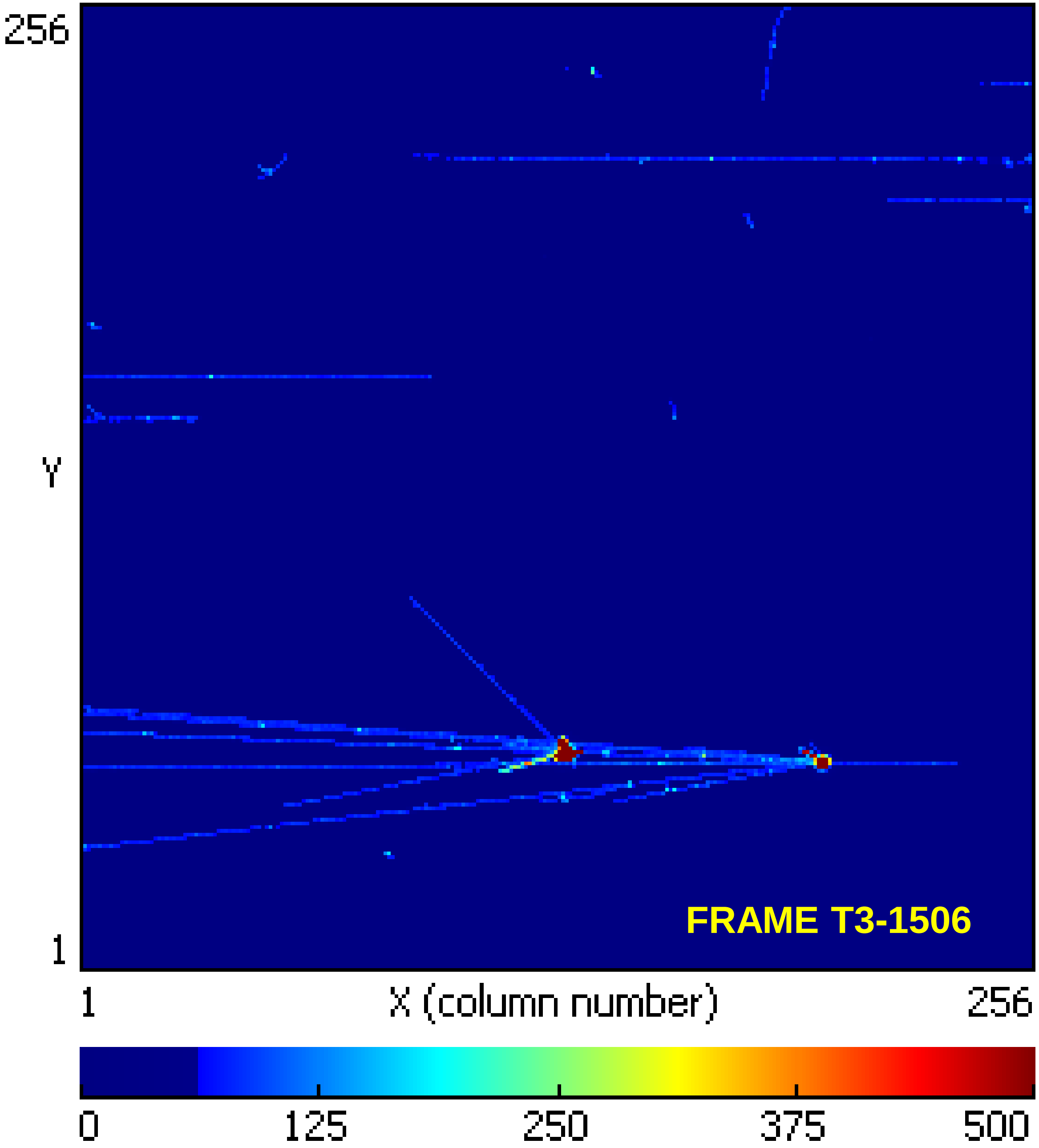
Imaging and energy measurement in Timepix

H6 120 GeV p/ π beam 2007

BEAM ←

as shown earlier:
different color code
highlights
“large” energy deposits

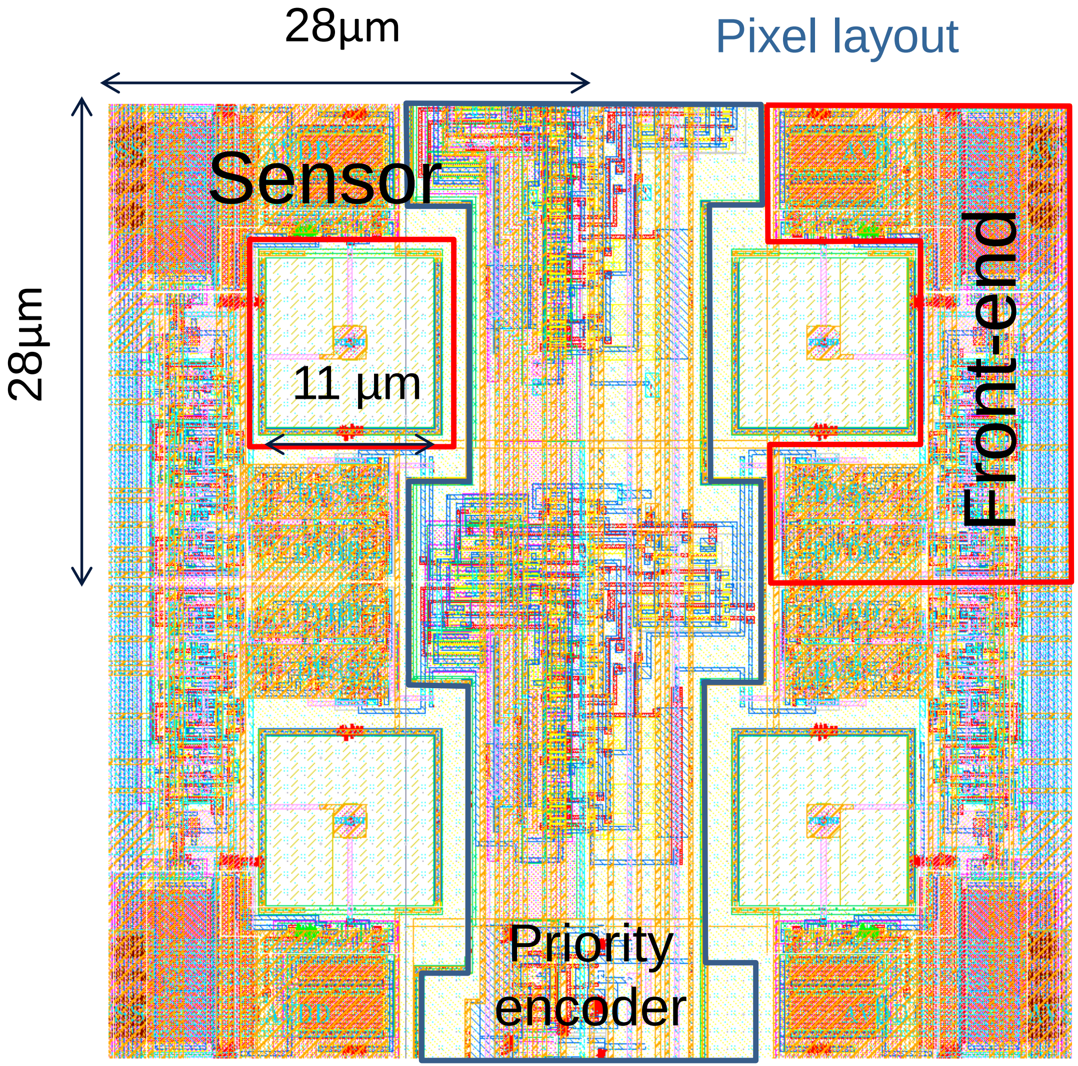
small compared to
‘new particle’



ALPIDE pixel

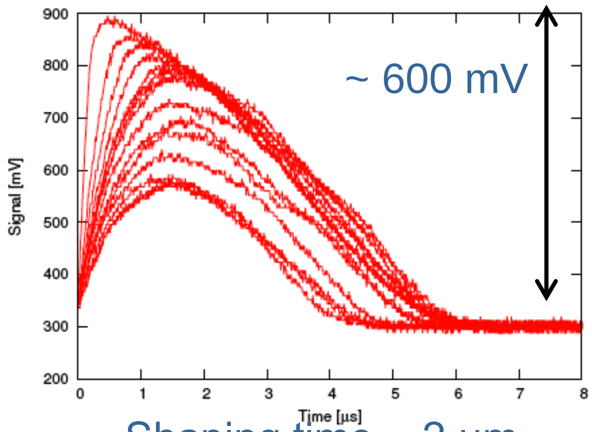
example of development monolithic CMOS pixel detectors

Pixel layout



Analogue output of one pixel under ^{55}Fe

(result from small scale prototype)



~ 600 mV

Shaping time ~ 2 µm

from Walter Snoeys

CONCLUSION

Technical innovation essential for physics progress

- silicon replaced liquid and gas; rates go from Hz to kHz to MHz

Electronics determines sensors and systems

- ultrapixels in advanced nanotechnologies?

Low noise achieved by sensor segmentation

- pixel detectors for multiplicity and precise positions
- Si drift detectors for precise energy spectra, extreme signal/ noise

Timing at ps precision next frontier

- silicon not adapted? light is faster than electrons

Other technologies?

- stacking of active layers integrated cooling real µm imaging

1960, on the future of silicon detectors

The progress of science has always followed the development of the experimental arts, and this has been as true in nuclear physics as it has been in astronomy, chemistry and biology. One has only to mention the ionization counter, the cloud chamber, the scaling circuit, nuclear emulsions, magnetic spectrometers, the modern scintillators, and the bubble chamber to bring to mind the historical framework of experimental nuclear physics. To this distinguished lineage we may now have to add the semi-conductor detector. [Its characteristics] place it in a class by itself, and [as such it] is likely to go a long way.

Arthur H. Snell
Chairman, Subcommittee on Instruments and Techniques
USA National Academy of Sciences

Proceedings Conference Semiconductor Nuclear Particle Detectors
Asheville NC, USA, 28-30 September 1960 NAS-NRC Pub 871

END

3rd Munich Symposium on Semiconductor detectors 1983

something funny......

Pierre Jarron ??

3rd Munich Symposium on Semiconductor detectors 1983

Pierre Jarron !

Many of the innovators in Si detectors:

Josef Kemmer, München
Paul Burger, Strasbourg
Marie-Odile Lampert, Strasbourg
Koei Yamamoto, Hamamatsu
Colin Wilburn, Southampton
Thor-Erik Hansen, Oslo
Veljko Radeka, Brookhaven
Emilio Gatti, Politecnico
Pavel Rehak, Brookhaven
Pierre Jarron, CERN
Chris Damerell, Oxford
Paul Siffert, Strasbourg
Bernard Hyams, CERN
Wojciech Dulinski, Strasbourg
Lothar Strüder, München

Guido Tonelli, Pisa
Craig Woody, Brookhaven
Franco Manfredi, Pavia
Tom Ludlam, Brookhaven
Luciano Bosisio, Pisa
Marcello Giorgi, Pisa

total ~90

Symposium Organizers: Erik Heijne, Robert Klanner, Gerhard Lutz

earlier Munich Symposia in 1971 and 1973, the later 1986, and every 3 years: