VECTORS and SUBMICRON TRACKING in SILICON DETECTORS

INSTRUMENTATION DIVISION SEMINAR
BROOKHAVEN NATIONAL LABORATORY

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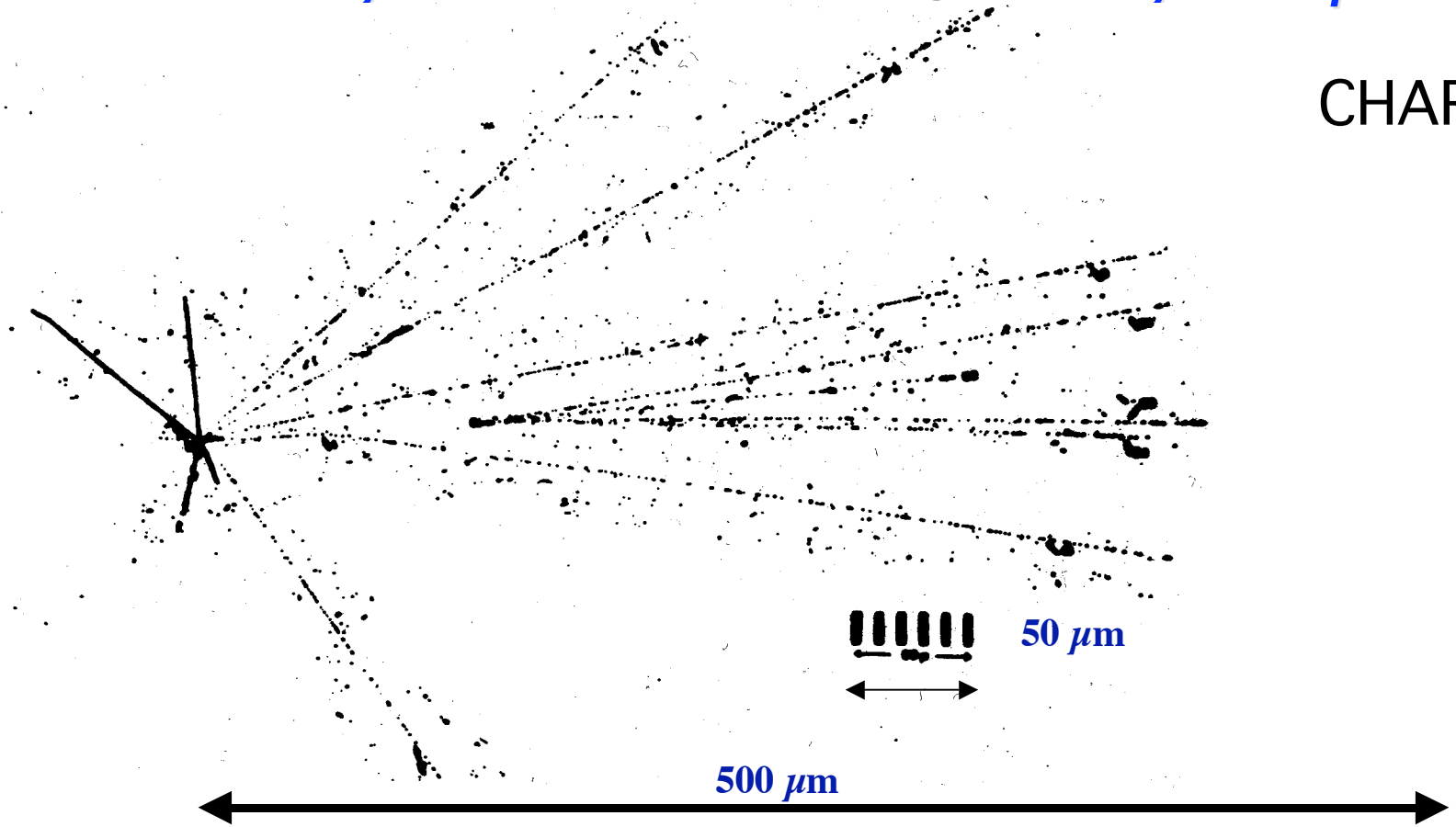
CERN Genève

25 June 2008

NUCLEAR EMULSION

SPECIAL, THICK FILM AgBr 3D, sub μm PRECISION

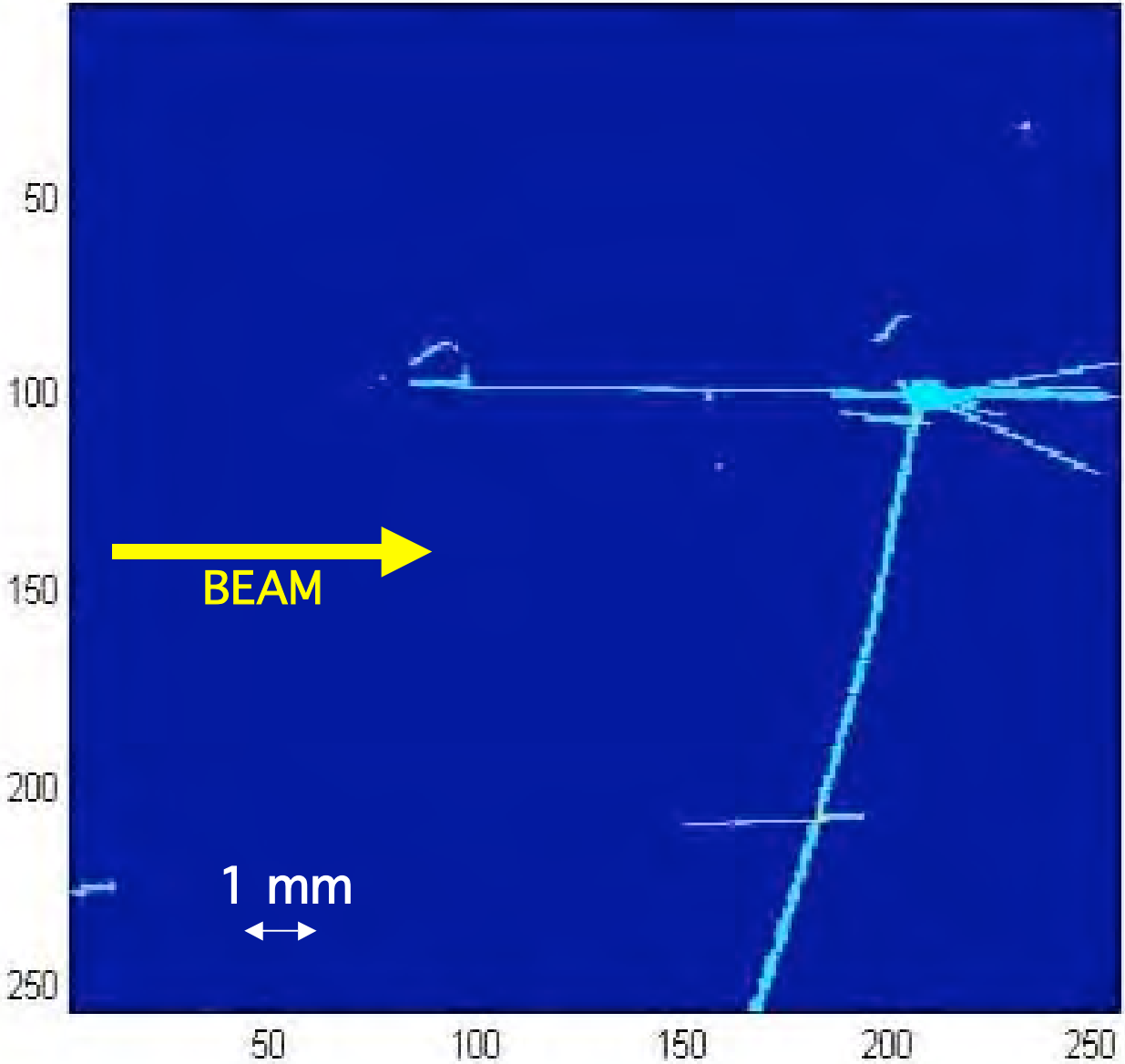
CHARM DECAY



ENERGY TRANSFERS TO GRAINS CREATE LATENT IMAGE OF TRACKS

Emulsion Event WA59 ~ 1985

CERN H6 beam 120 GeV PIONS



SILICON PIXEL ASSEMBLY
256x256 55um pixels
EXPOSURE TIME 50 ms

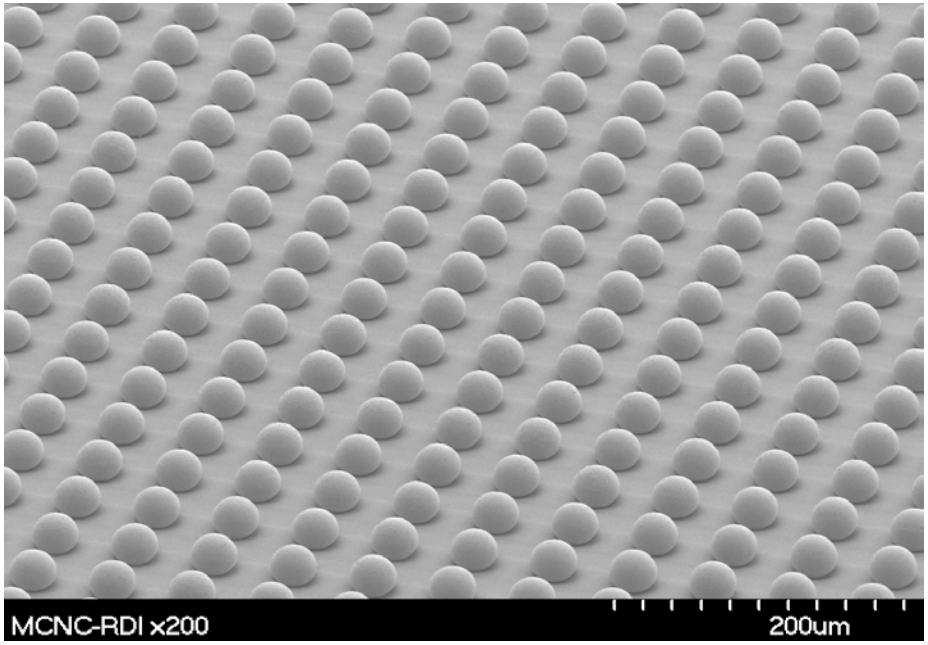
BEAM HODOSCOPE
&
TARGET
&
DETECTOR

14.08 mm

256 pixels

Medipix2 FRAME P04-0356

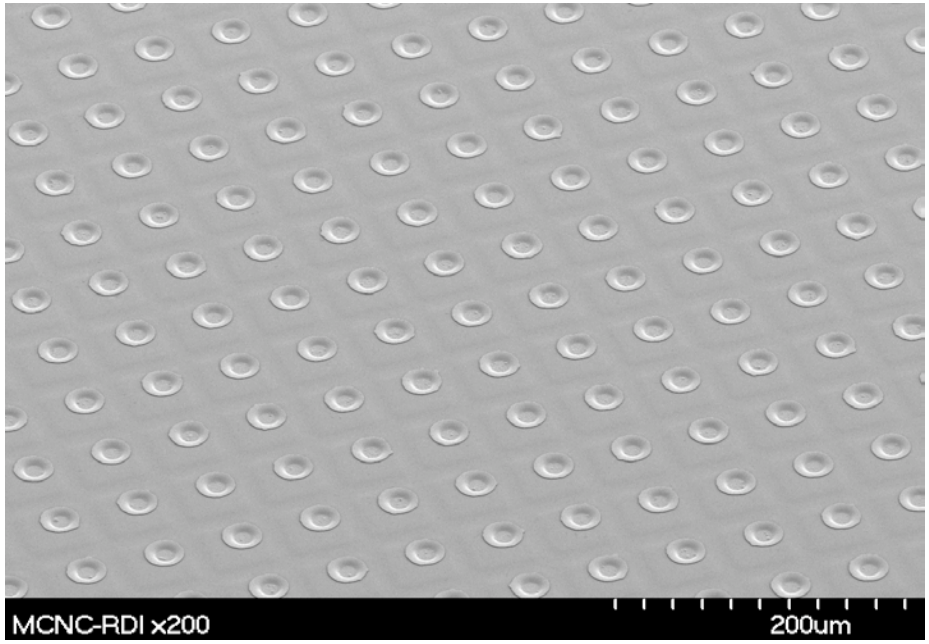
BUMP BONDING Medipix2



BUMP DEPOSITION
& SEM PHOTOS
COURTESY MCNC-RDI DURHAM NC

PITCH 55 μm

HIGH RESISTIVITY
Si SENSOR MATRIX
CANBERRA SEMICONDUCTOR



0.25 μm CMOS CHIP
CERN 2001
CAMPBELL & LLOPART
256 COLUMNS x 256 ROWS
pixel 55μm x 55 μm

DISCUSS SEVERAL DEVICES from MEDIPIX FAMILY

MEDIPIX2

TIMEPIX

MEDIPIX3

INTENDED for 2D X-RAY IMAGING

MAIN FUNCTIONALITY

SIGNAL PROCESSING in EACH PIXEL
TUNABLE THRESHOLD SETTINGS
13 bit REGISTER in EACH PIXEL
ADJUSTABLE FRAME EXPOSURE TIME μs - min

MEDIPIX2 COUNTING SIGNALS between LOWER/UPPER THRESHOLD

TIMEPIX CLOCK 10 MHz - 100 MHz to EACH PIXEL :
COUNTS from FIRST SIGNAL ARRIVAL TIME DRIFT TIME
COUNTS TOTAL TIME of SIGNAL(S) over THRESHOLD TOT

MEDIPIX3 SPECTROSCOPIC MODE,
SUMMING of COINCIDENT SIGNALS in ADJACENT PIXELS

MEDIPIX2 PARTNERS

- U INFN Cagliari
- CEA-LIST Saclay
- CERN Genève
- U d'Auvergne Clermont
- U Erlangen
- ESRF Grenoble
- U Freiburg
- U Glasgow
- IFAE Barcelona
- Mitthoegskolan
- MRC-LMB Cambridge
- U INFN Napoli
- NIKHEF Amsterdam
- U INFN Pisa
- FZU CAS Prague
- IEAP CTU in Prague
- SSL Berkeley

http://medipix.web.cern.ch/MEDIPIX/

SPOKESMAN Michael CAMPBELL
Deputy Jan VISSCHERS

THANKS TO

R&D, DESIGN WORK by the CERN MEDIPIX team

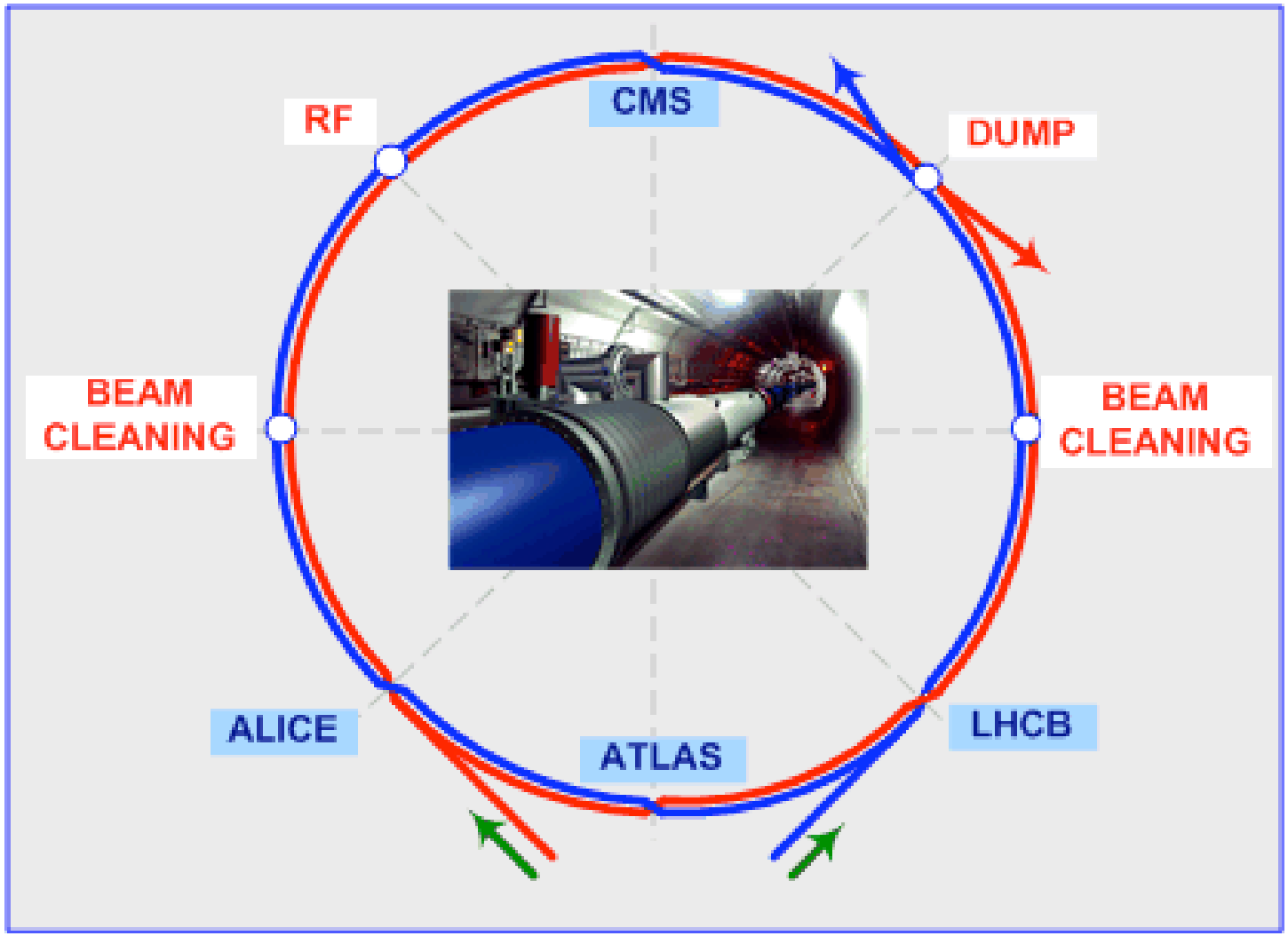
MICHAEL CAMPBELL, team leader
XAVI LLOPART
LUKAS TLUSTOS
RAFA BALLABRIGA
WINNIE WONG
EH

& CERN-MICROELECTRONICS GROUP

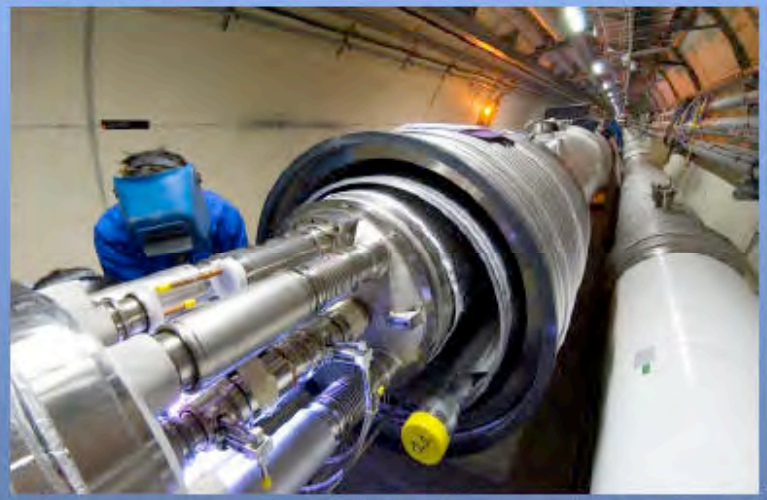
8-YEAR R&D EFFORTS by MEDIPIX COLLABORATION

WORK in the BEAM **2006: RYAN FIELD, SUMMER STUDENT NCSU**
2007: JOHN IDARRAGA, MONTREAL, DOMINIC GREIFFENBERG, FREIBURG
2008: DAAN BOLTJE, NIKHEF

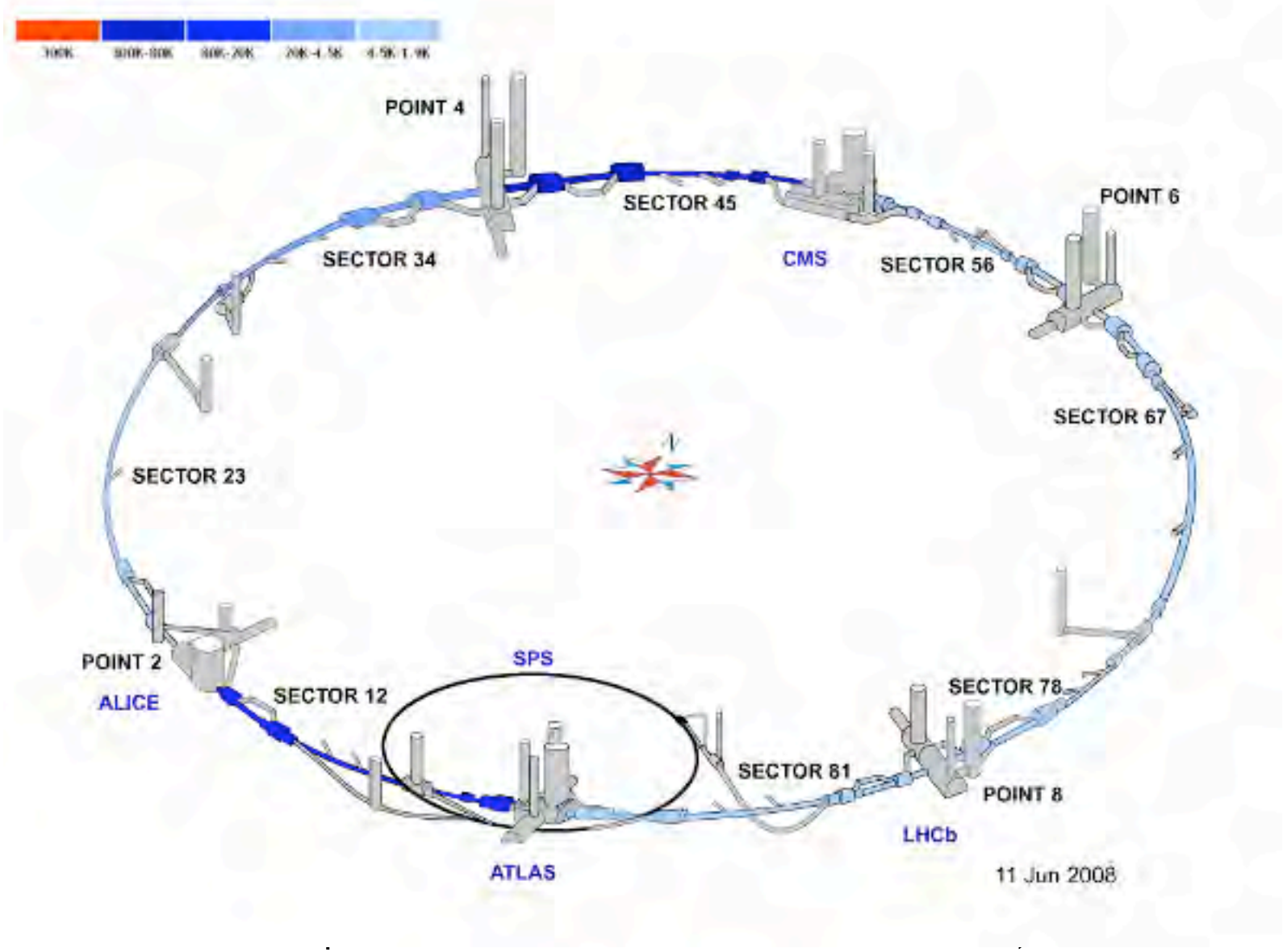
SCHEMATIC LHC



Underground



CERN LHC COOLING DOWN

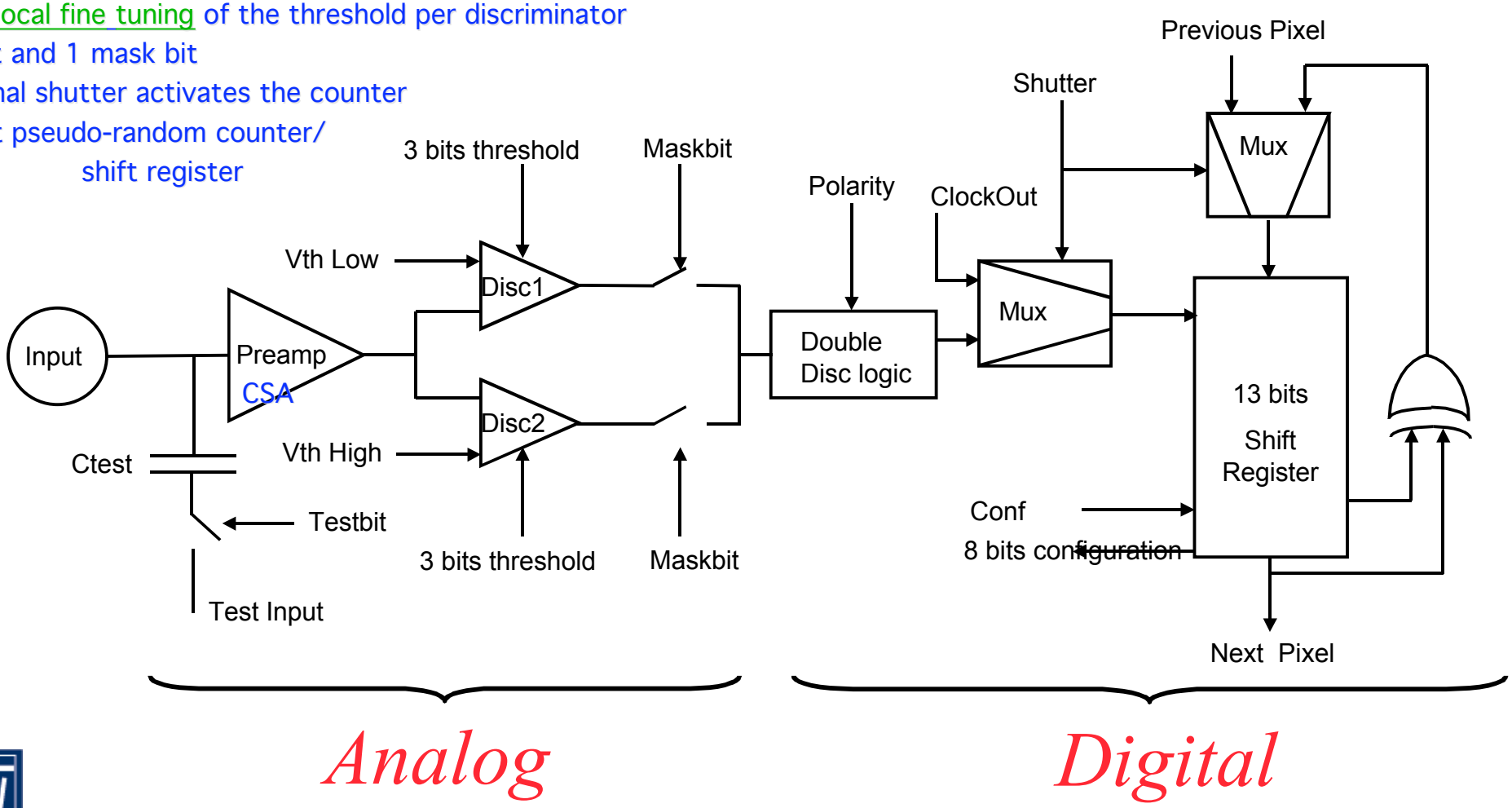


LOW NOISE
(relative to microstrips)
ELECTRONICS READOUT

MEDIPIX2 PIXEL BLOCK DIAGRAM

accepts positive and negative input _ different detector materials
charge sensitive preamplifier with individual leakage current compensation CSA
2 discriminators with globally adjustable threshold
3-bit local fine tuning of the threshold per discriminator
1 test and 1 mask bit
external shutter activates the counter
13-bit pseudo-random counter/
shift register

65 536 x



Medipix2 PIXEL CELL LAYOUT

CMOS technology 0.25μm

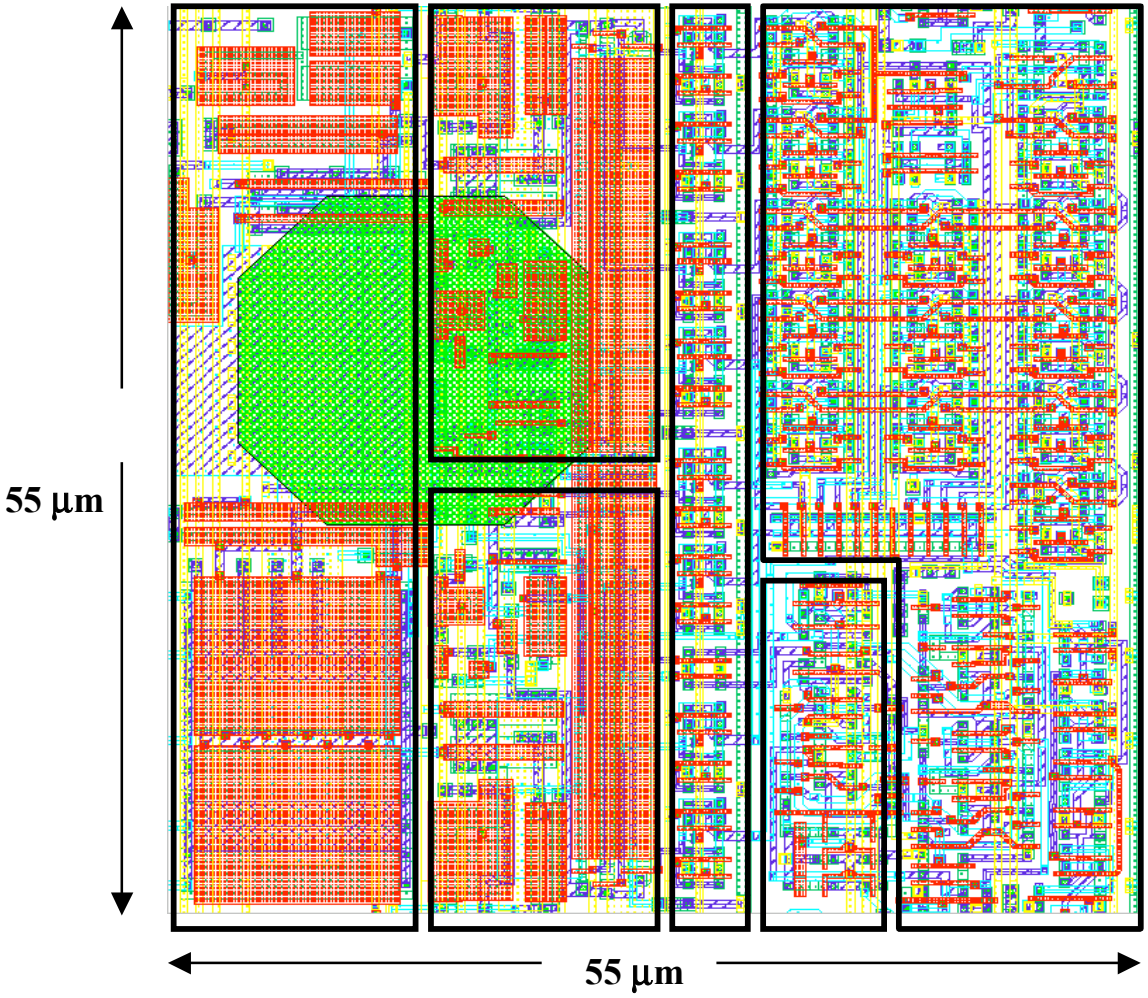
6 metal layers

pixel cell has ~500 transistors ⇒
chip ~33 million transistors

Static power consumption:
~8μW/channel @ 2.2 V

Amplifier Gain: ~11 μV/e⁻

Electronic Noise: ~100 e⁻ rms.



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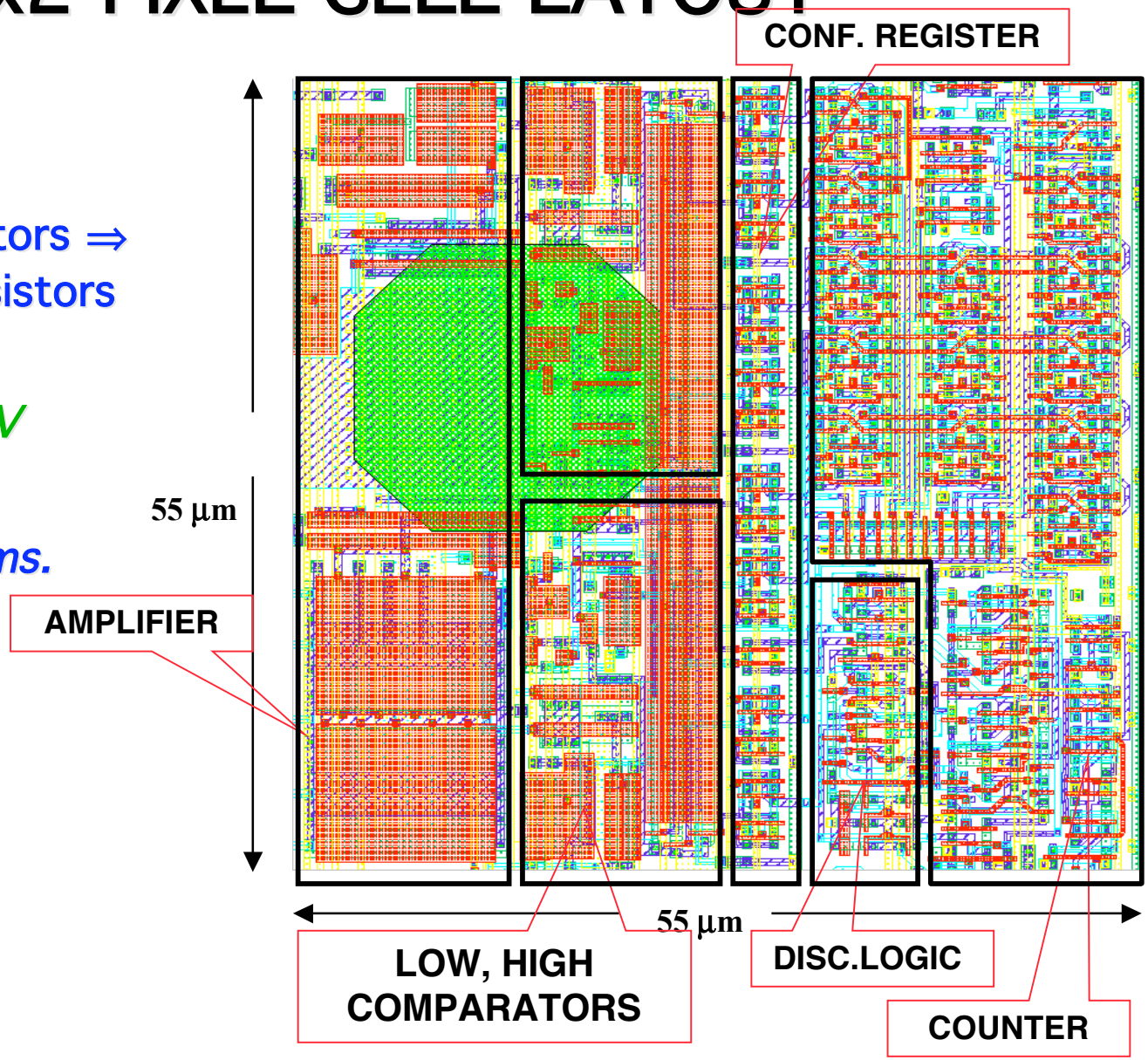
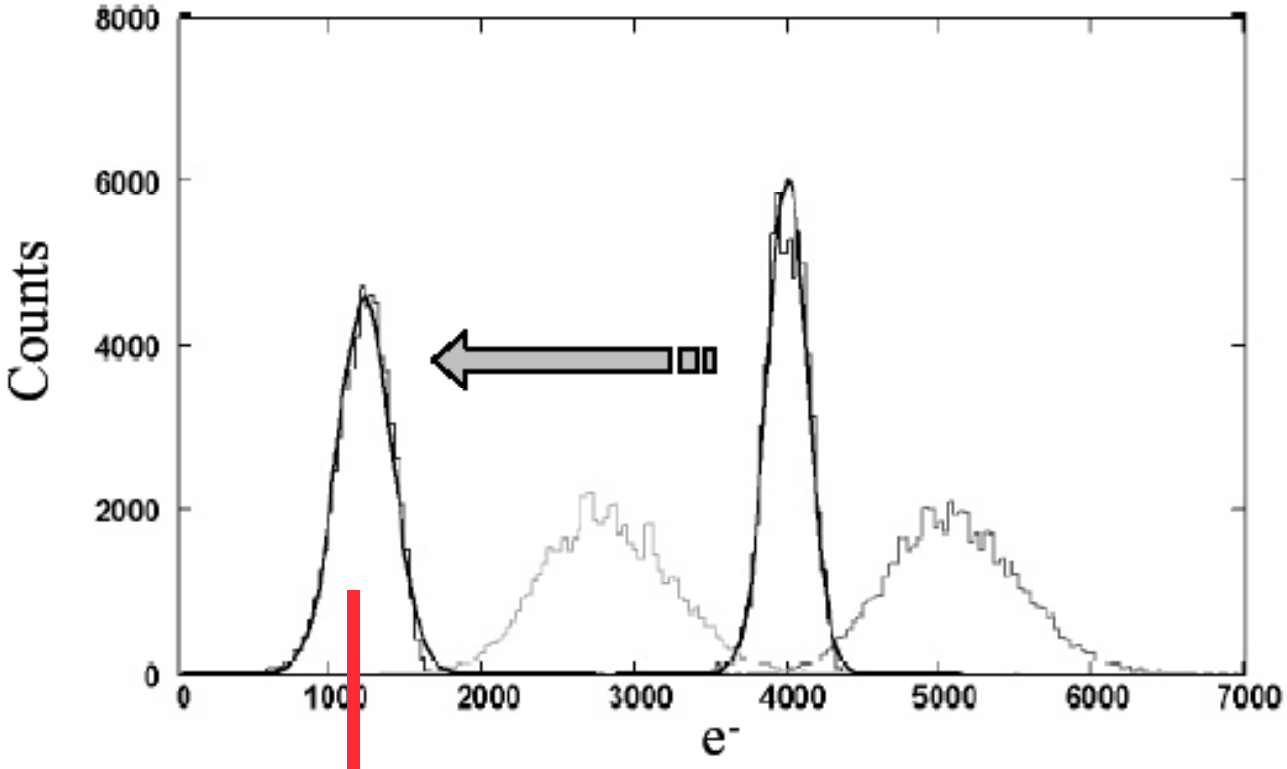


EVEN SMALL SIGNALS CAN BE USED



SMALL PIXEL CELL
55μm x 55μm

THRESHOLD TRIMMING

TRIMMED THRESHOLD DISPLACED to 'LOW' VALUE

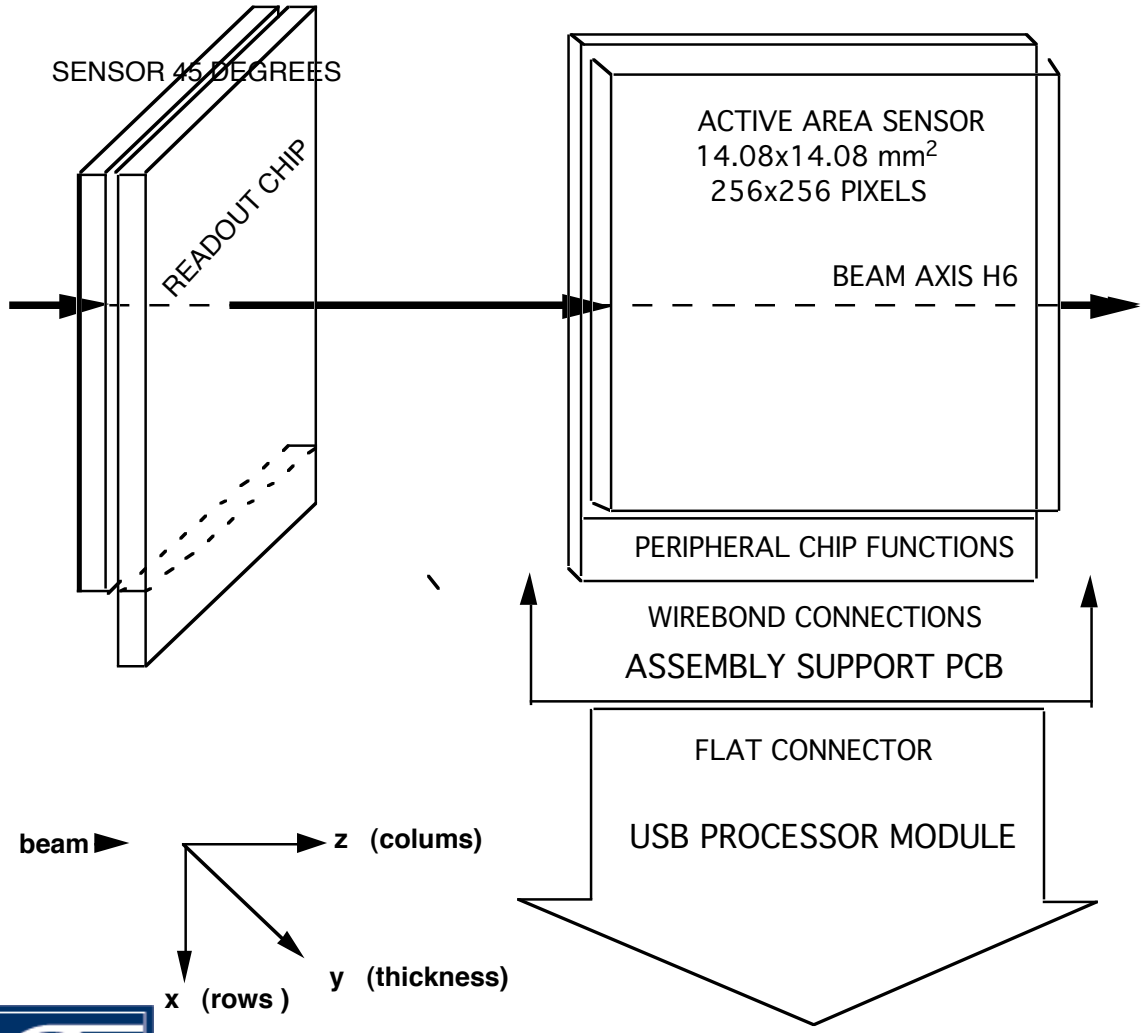
1100 e^- or 4 keV in Si

GENERATED by M.I.P. in ~16 μm Si

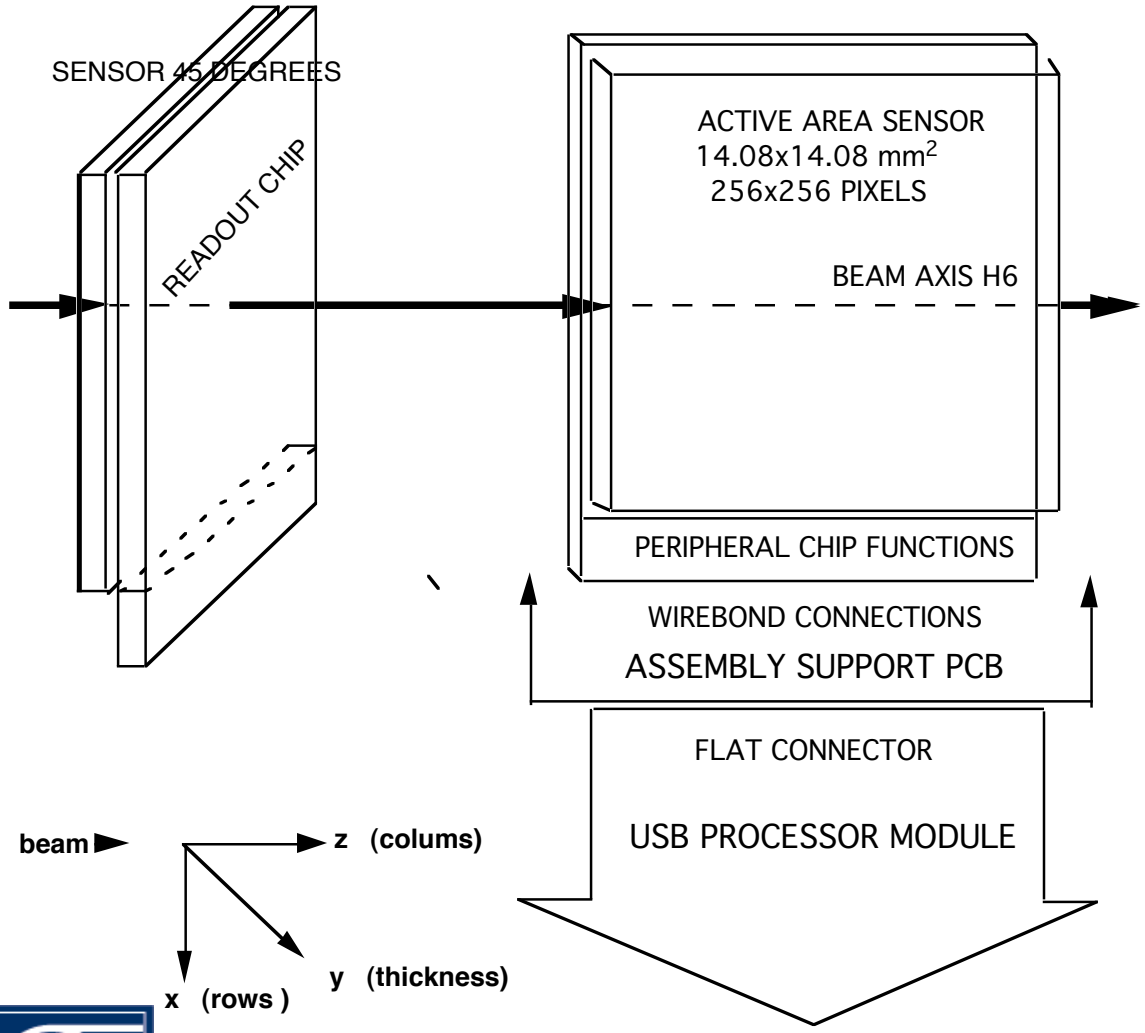
IN BEAM TEST 800 e^- to 1000 e^-

TRUE 3D TRACKING INFORMATION from Si VOLUME

SETUP in H6 BEAM CERN



SETUP in H6 BEAM CERN



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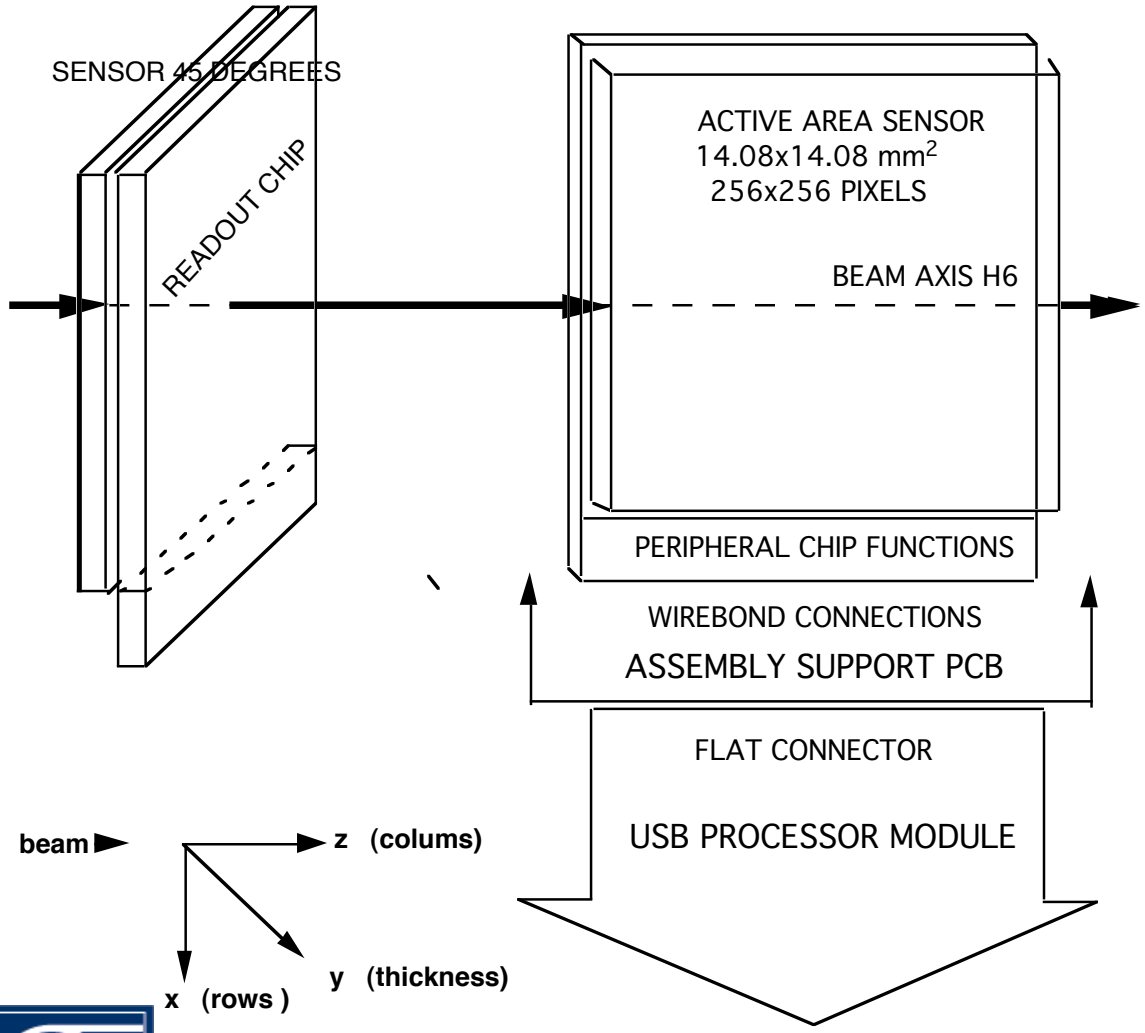
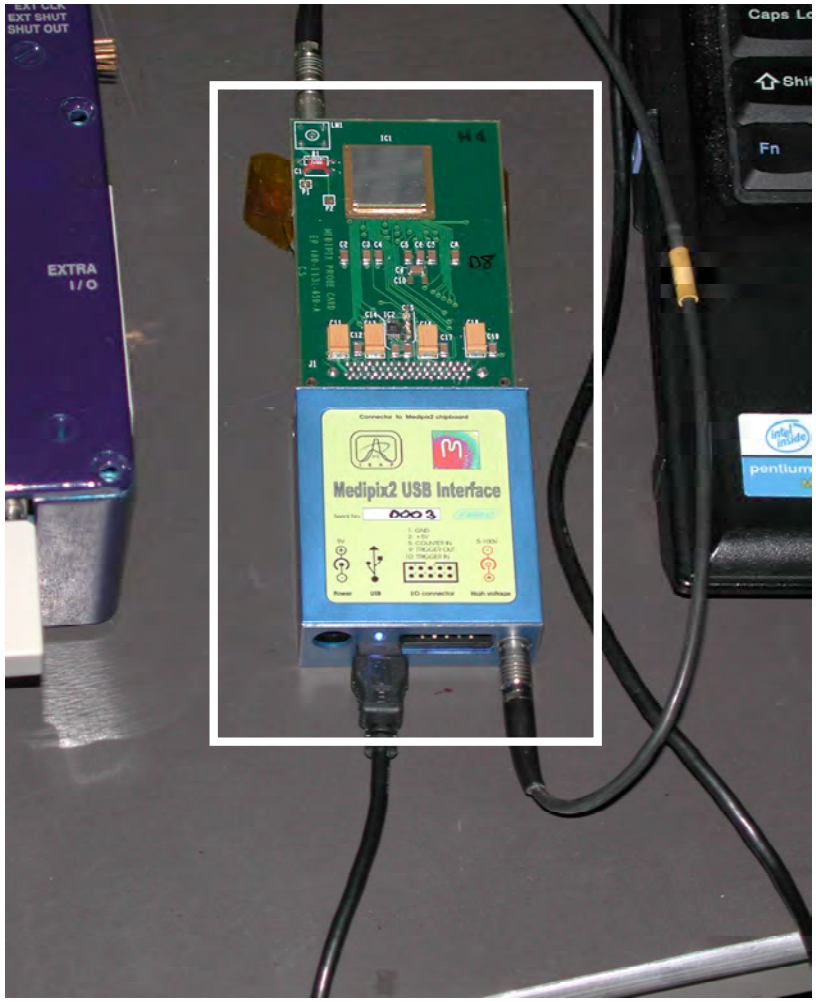
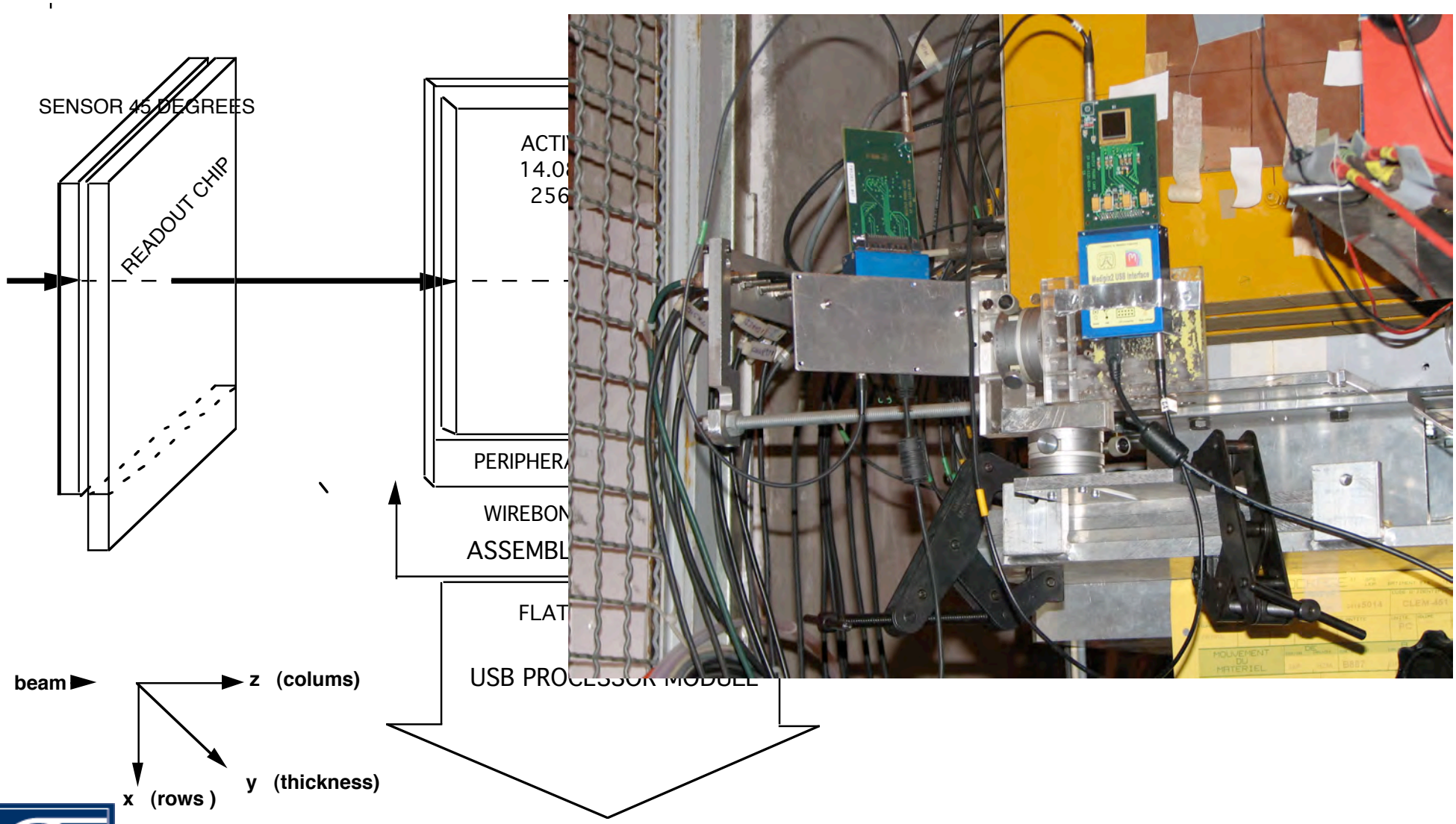
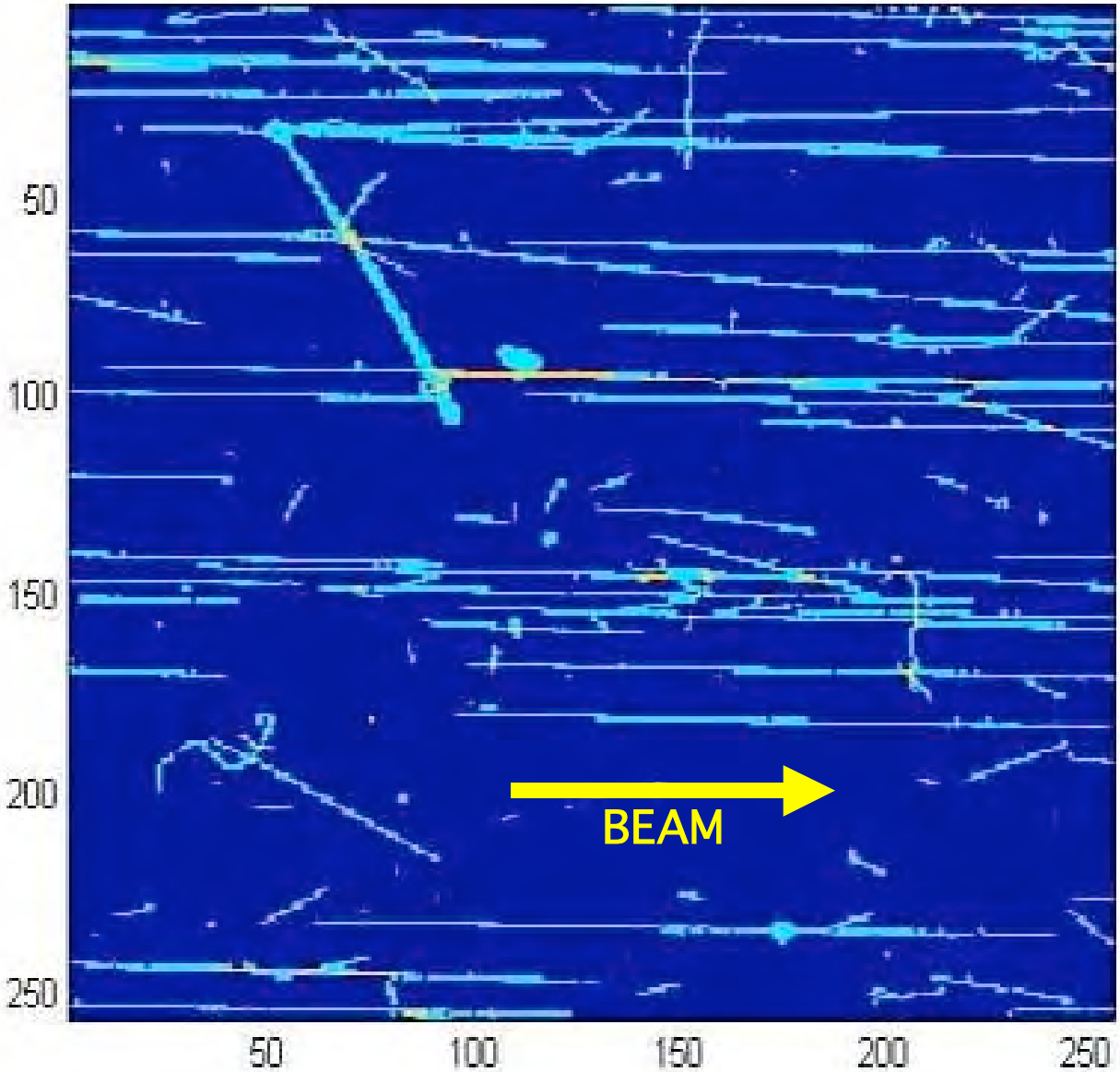




SETUP in H6 BEAM CERN



H6 120 GeV PIONS



EXPOSURE 1 s

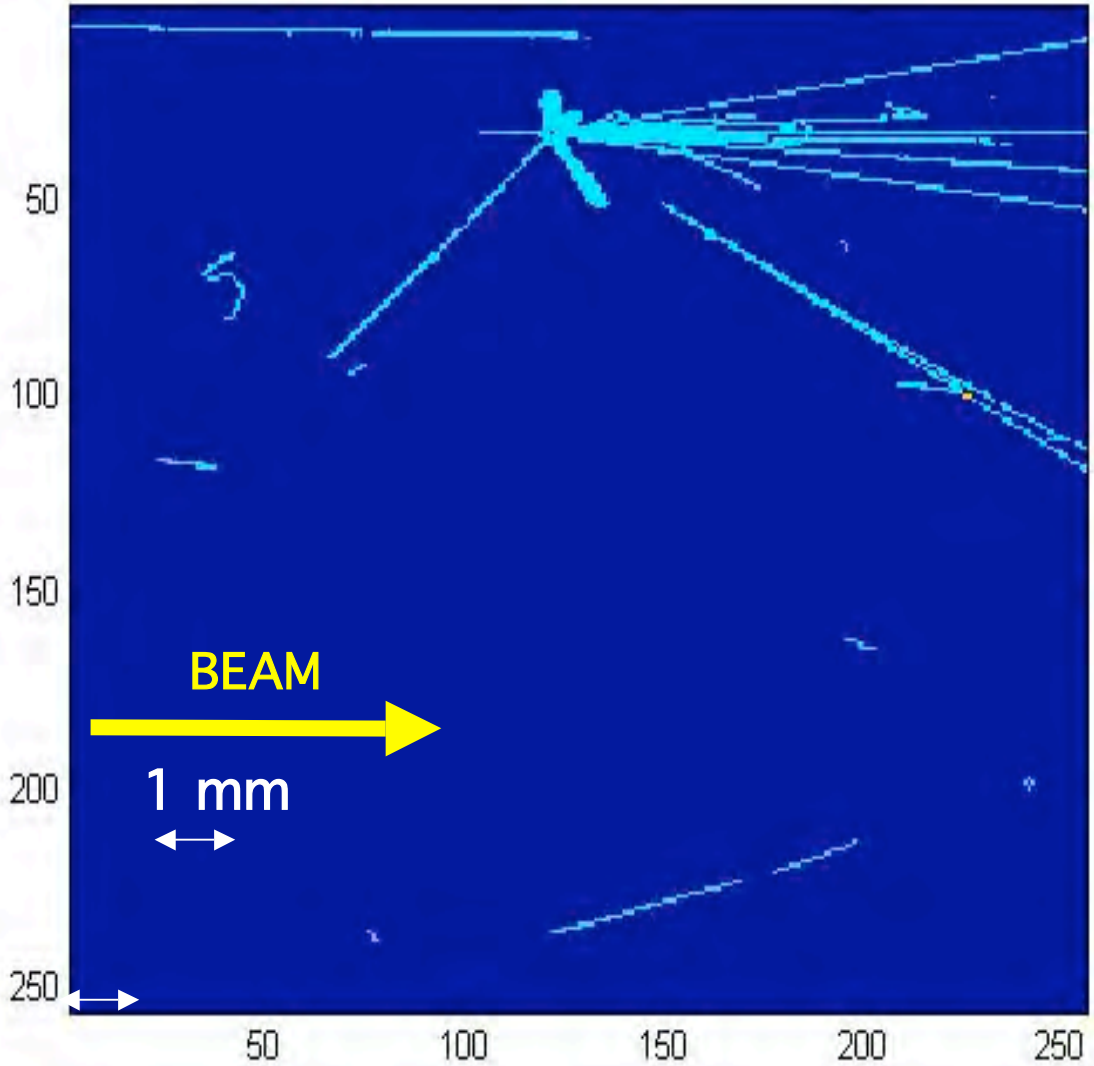
14.08 mm

256 pixels

PARTICLE 'TRAILS' ~ PARALLEL

Parallel Medipix2 P-02-0668

120 GeV PIONS



INTERACTION in Medipix DETECTOR
Si 'EMULSION'

DECAY of NEUTRAL K ?

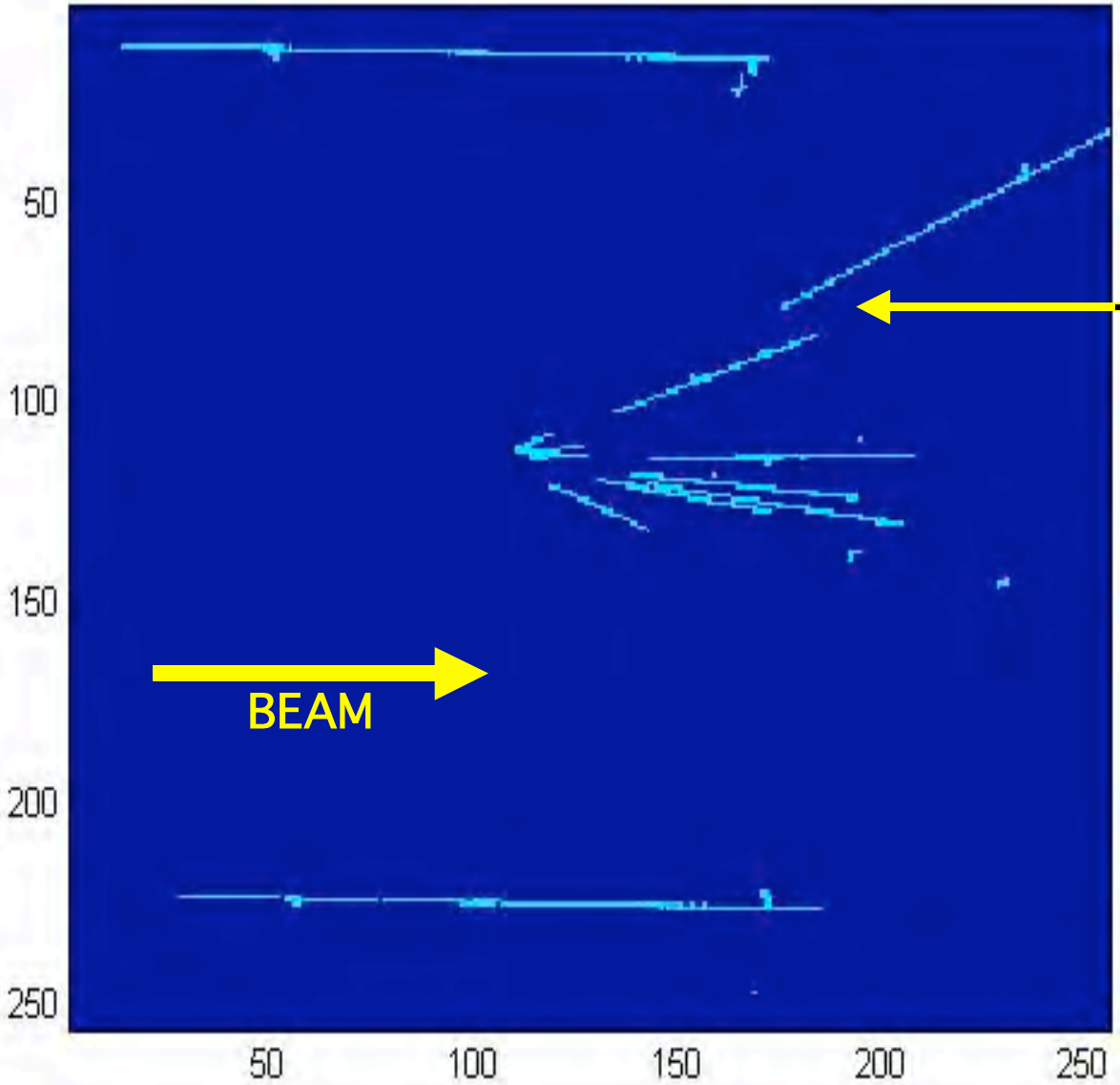
WHICH DIRECTION HAS TRAIL ?
PROJECTION CAUSES
AMBIGUITY : TOWARDS/AWAY

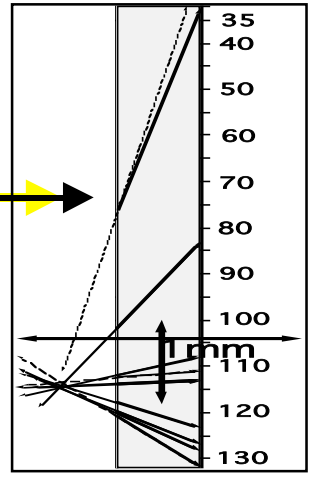
500 μm

July 2006 Parallel Medipix P-05-0583

120 GeV PIONS

ALL TRAILS in SAME DIRECTION





3-D RECONSTRUCTION

INTERACTION
190μm behind SENSOR

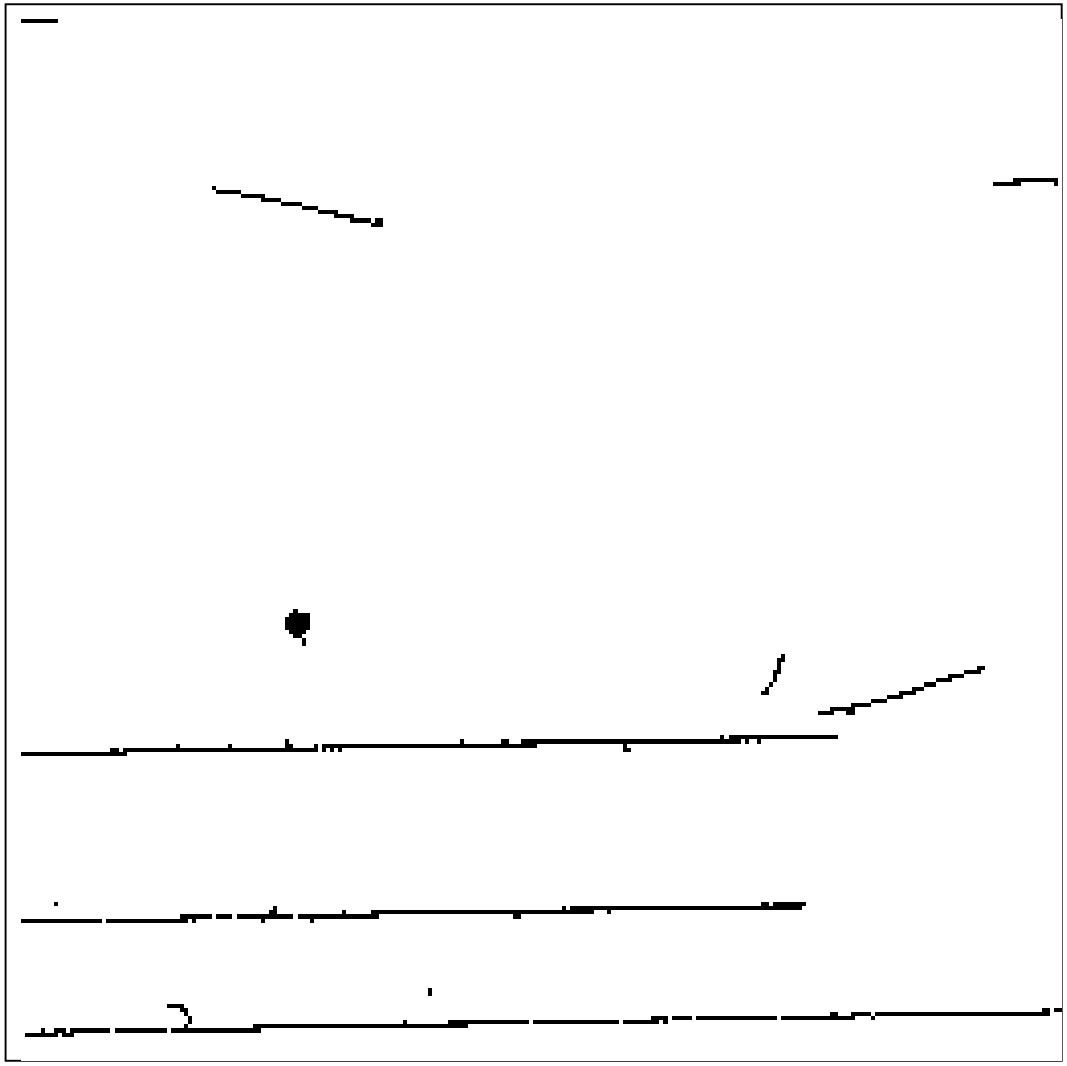
Parallel Medipix2 0016

MUONS from π, K DECAY

MEASUREMENTS MEDIPIX 2006

VECTORS & SUBMICRON PRECISION

H6 BEAM DECAY MUONS + BACKGROUND



ELECTRONS

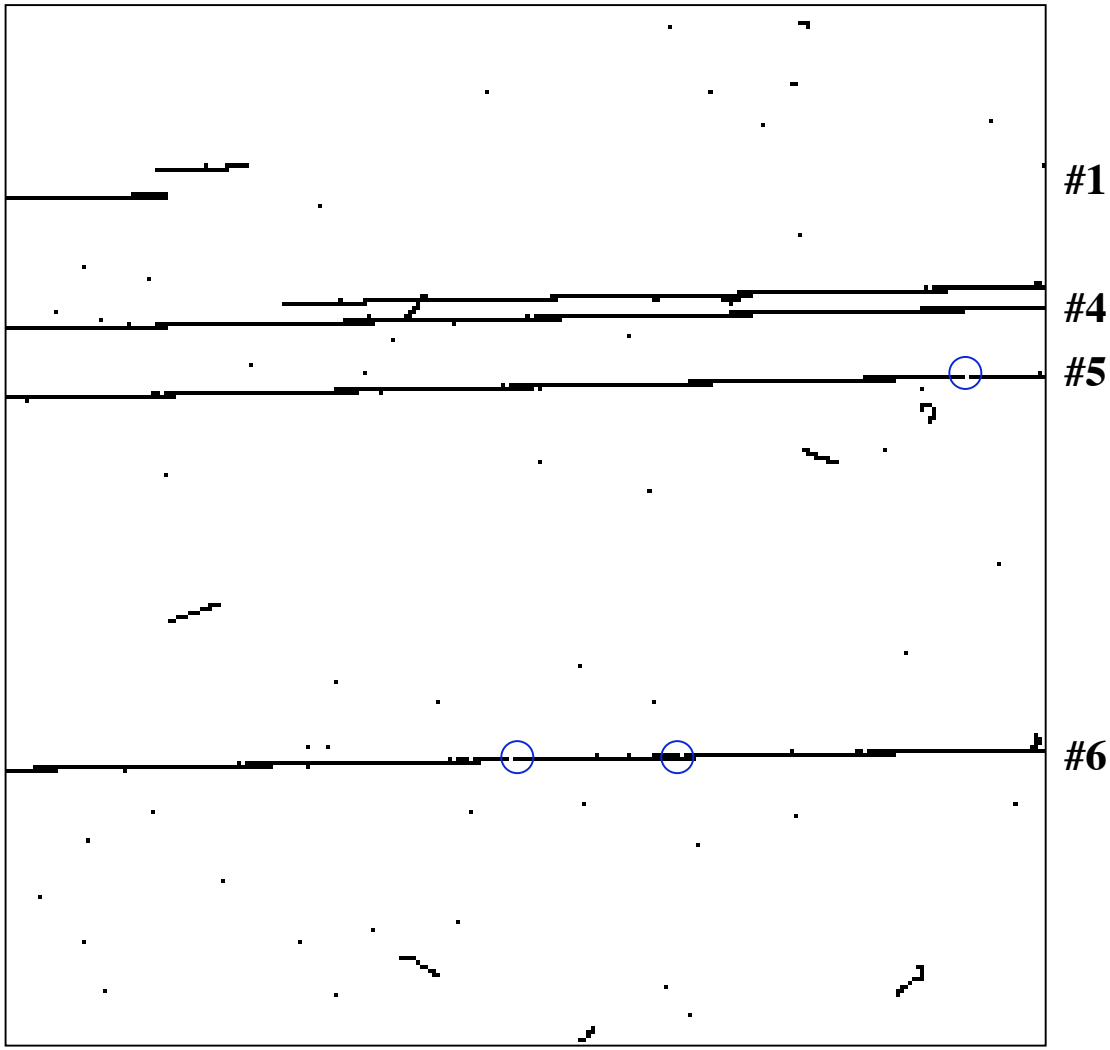
ALPHA or NEUTRON

3 MUONS

(a few dead pixels)

Parallel Medipix M-01-0025

H6 DECAY MUONS : EFFICIENCY

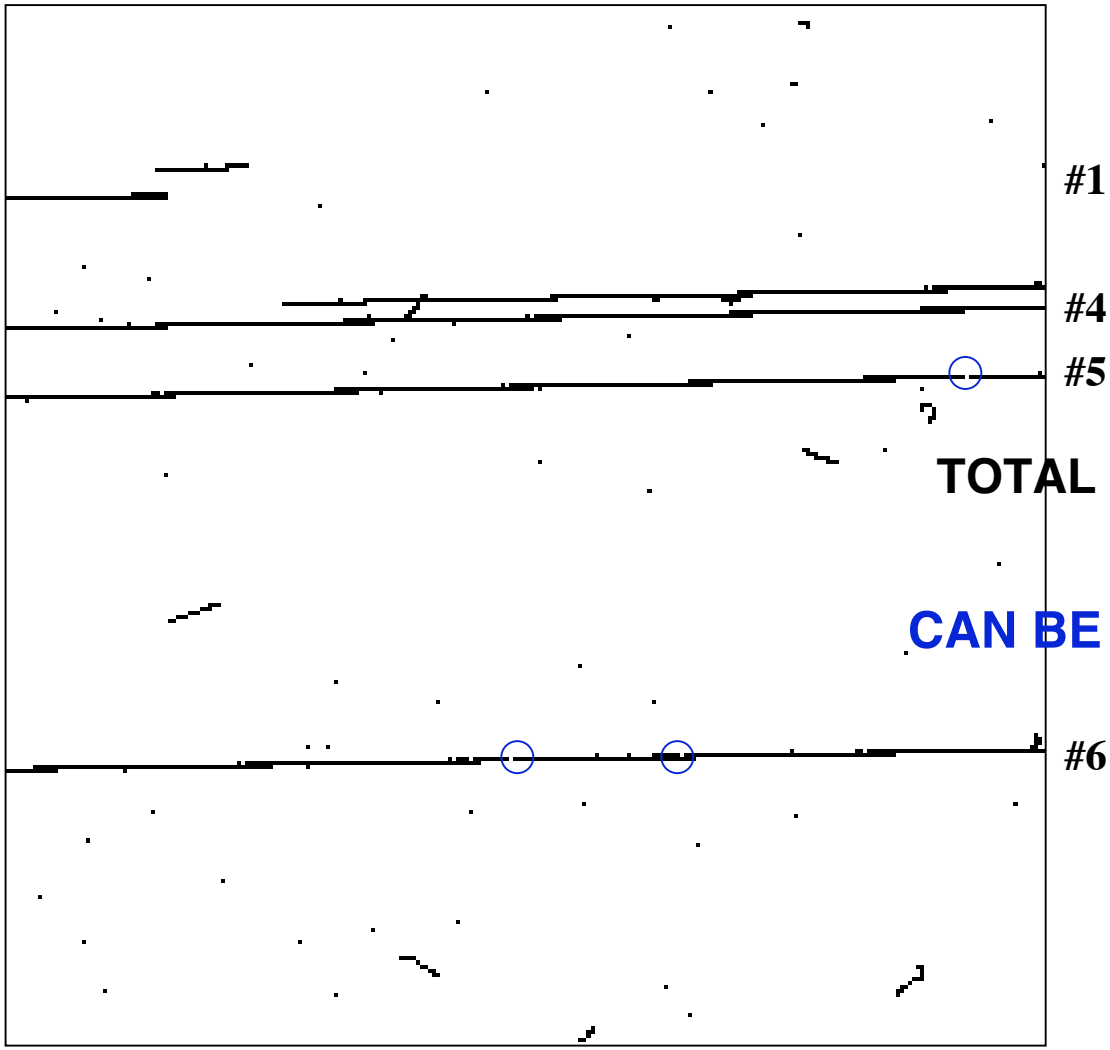


A FEW DEAD PIXELS

NO EFFECT on EFFICIENCY

Parallel Medipix M-01-0013

H6 DECAY MUONS : EFFICIENCY



TOTAL ENERGY/CHARGE in a TRAIL

3.4 MeV or ~1M e^-

CAN BE USED FOR TIMING/TRIGGER

A FEW DEAD PIXELS

NO EFFECT on EFFICIENCY

Parallel Medipix M-01-0013

SMALL-PIXEL CHARGE SHARING

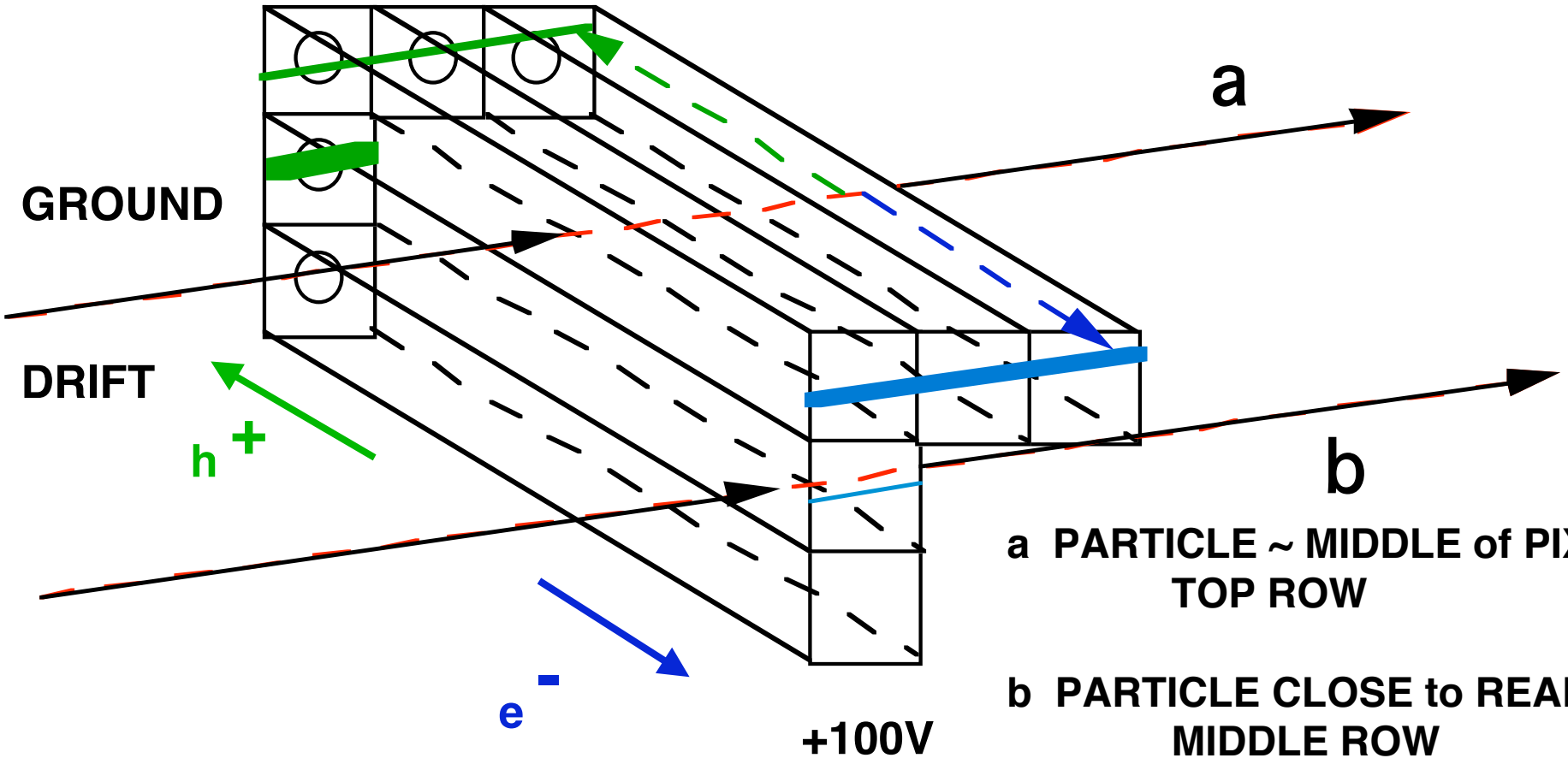
CHARGE-SHARING & SINGLE - QUANTUM PROCESSING

MULTIPLE HITS for BINARY OPERATION if
SMALL PIXEL DIMENSIONS
THICK SENSOR MORE DIFFUSION DURING DRIFT
LOW TRESHOLD

EFFECTS on ENERGY SPECTRAL DISTRIBUTION
REDUCTION of PEAK
INCREASE LOW - ENERGY TAIL

TO BE SIGNFICANTLY REDUCED in MEDIPIX3

CHARGE COLLECTION & LATERAL DIFFUSION

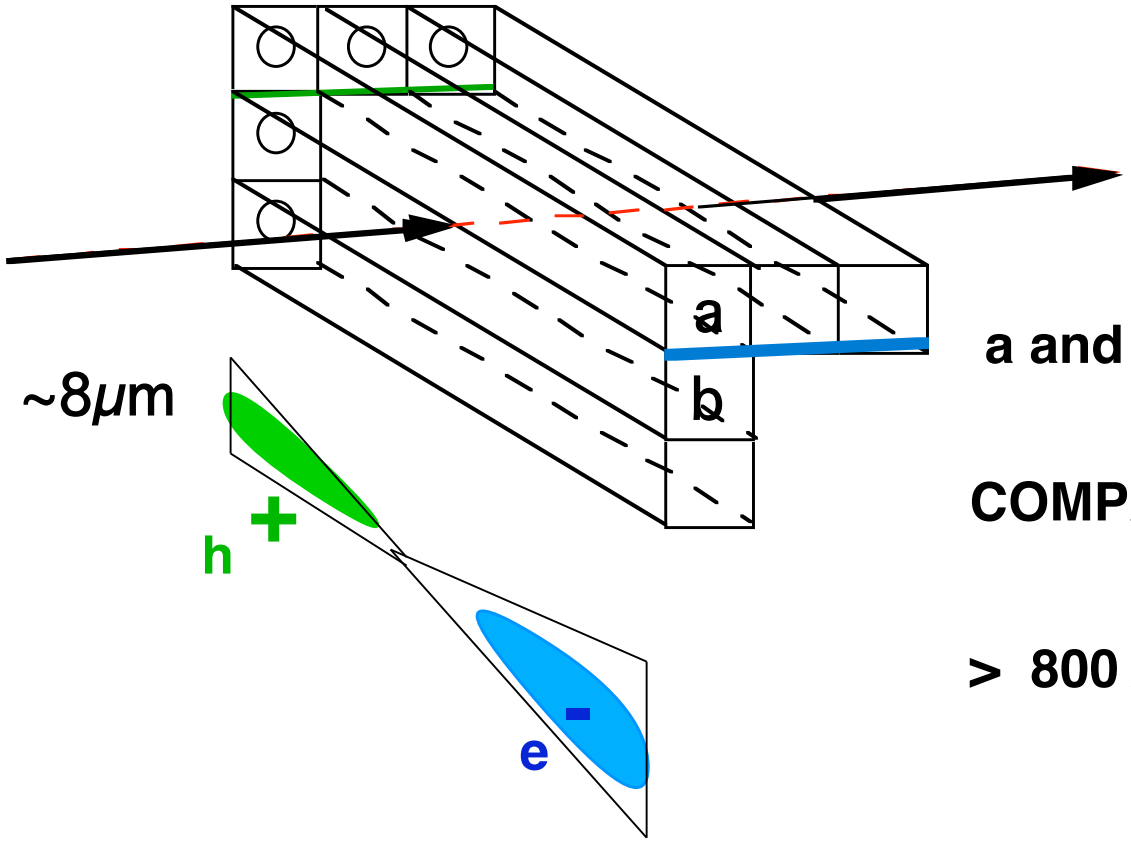


a PARTICLE ~ MIDDLE of PIXELS TOP ROW

b PARTICLE CLOSE to REAR MIDDLE ROW

DIFFUSION width shown EXAGGERATED

CHARGE SHARING



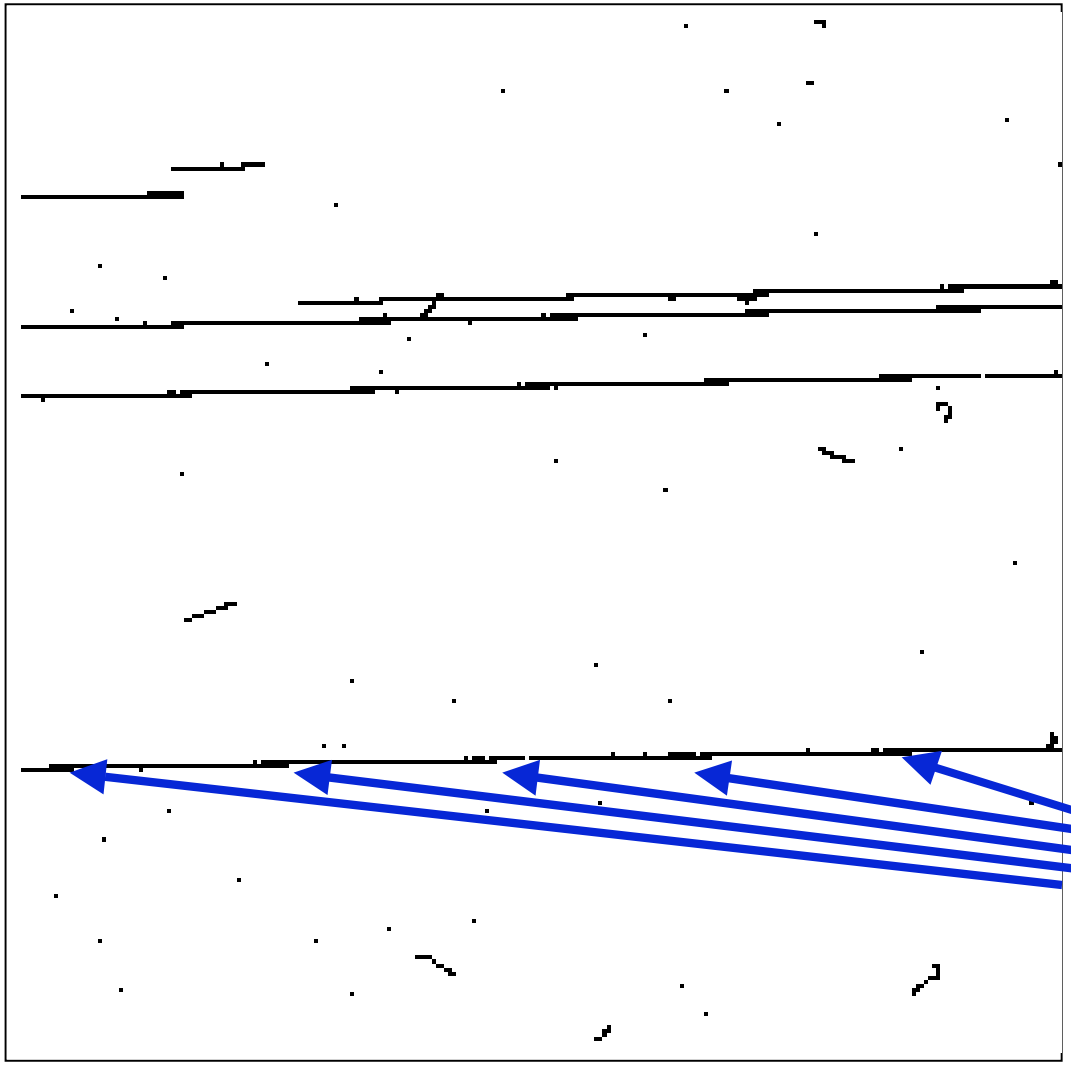
a and b SHARE SIGNAL CHARGE

COMPARATOR SIGNAL if > ~ 800 e^-

> 800 / 3800 e^- > 20% PARTITION

DIFFUSION PRODUCES DOUBLE HITS

MUON TRAILS : 'CLOSED' SEGMENTS



#4

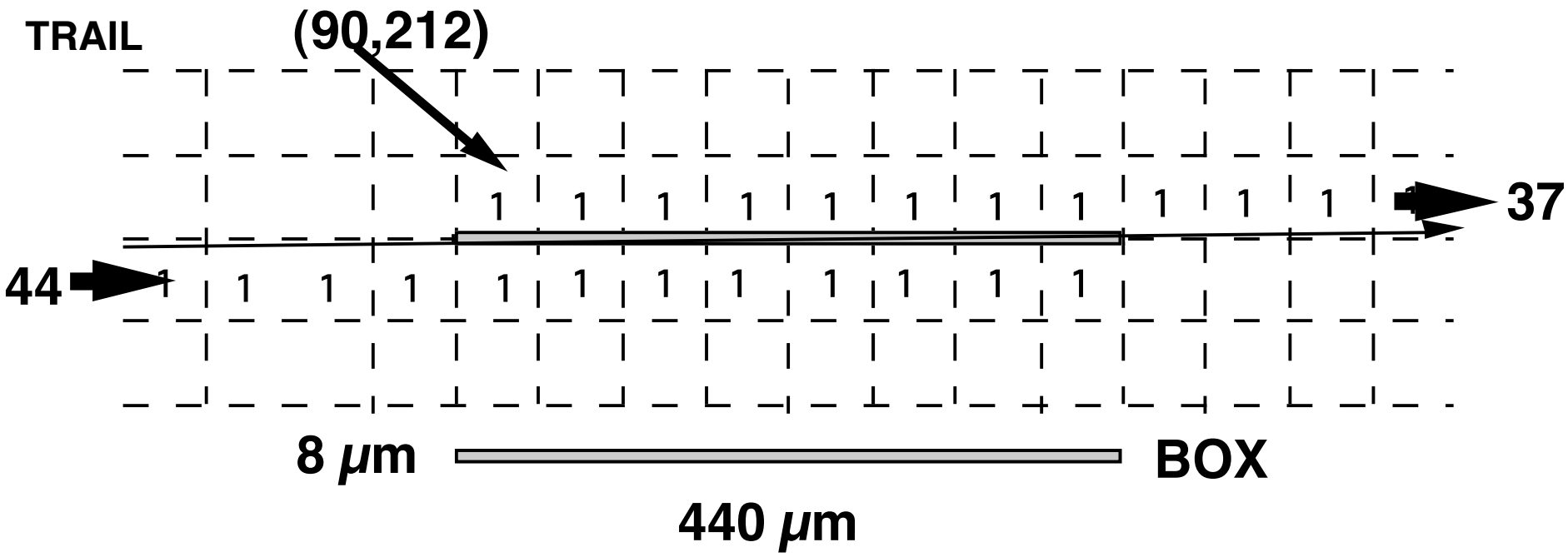
VECTOR MEASUREMENTS from 'CLOSED SEGMENTS'

BOUNDED by SEQUENCES of DOUBLE HITS

ROW TRANSITION POINTS

Parallel Medipix M-01-0013

HIGH RECONSTRUCTION PRECISION with MUONS

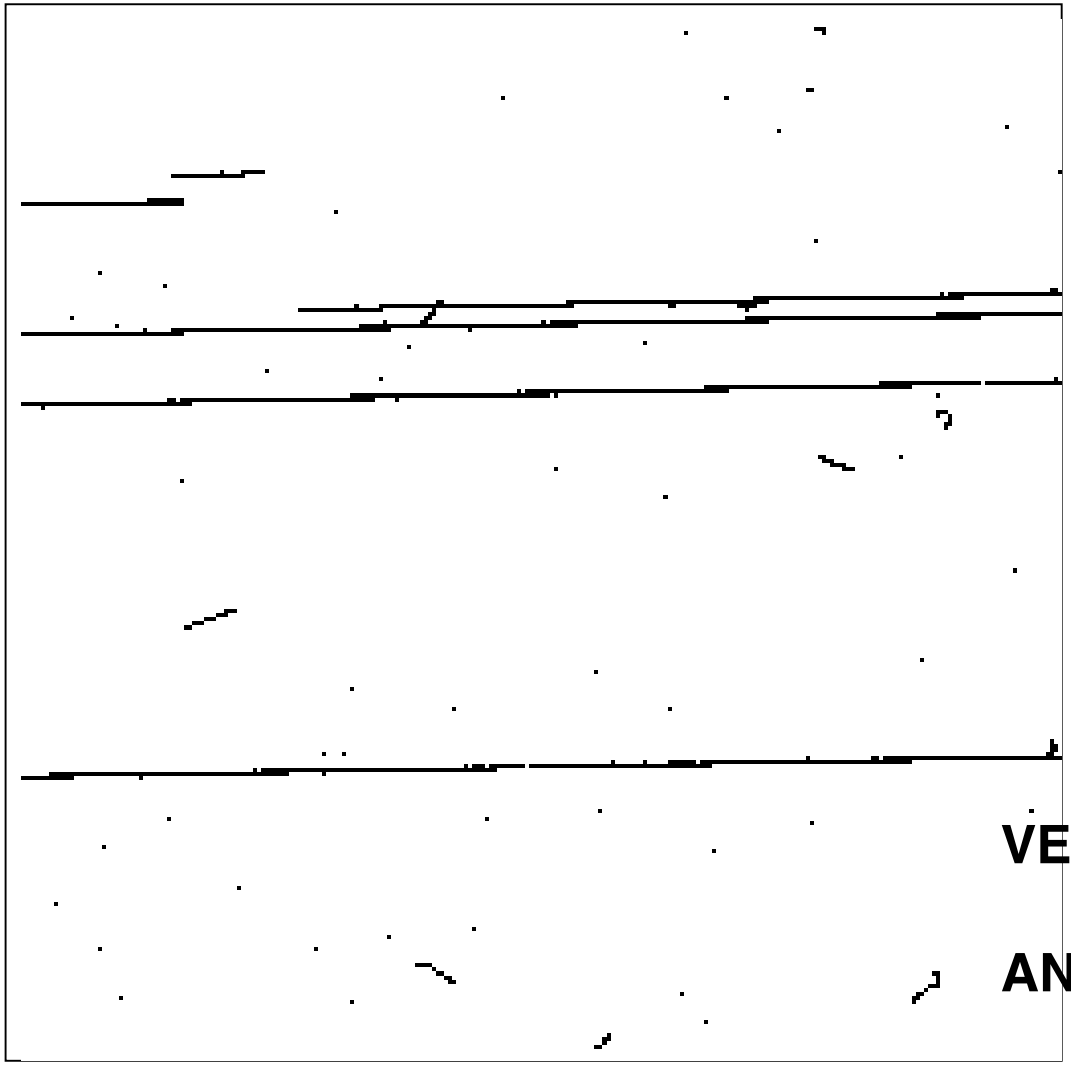


DOUBLE HITS ---> PRECISE ROW TRANSITION POINTS
CONSTRAIN TRAJECTORY to~ 0.05 μm (??)

HOW to DEAL with SUCH DATA

Parallel Medipix M-01-0013

H6 DECAY MUONS



HIGH PRECISION
at OVERLAP POINTS

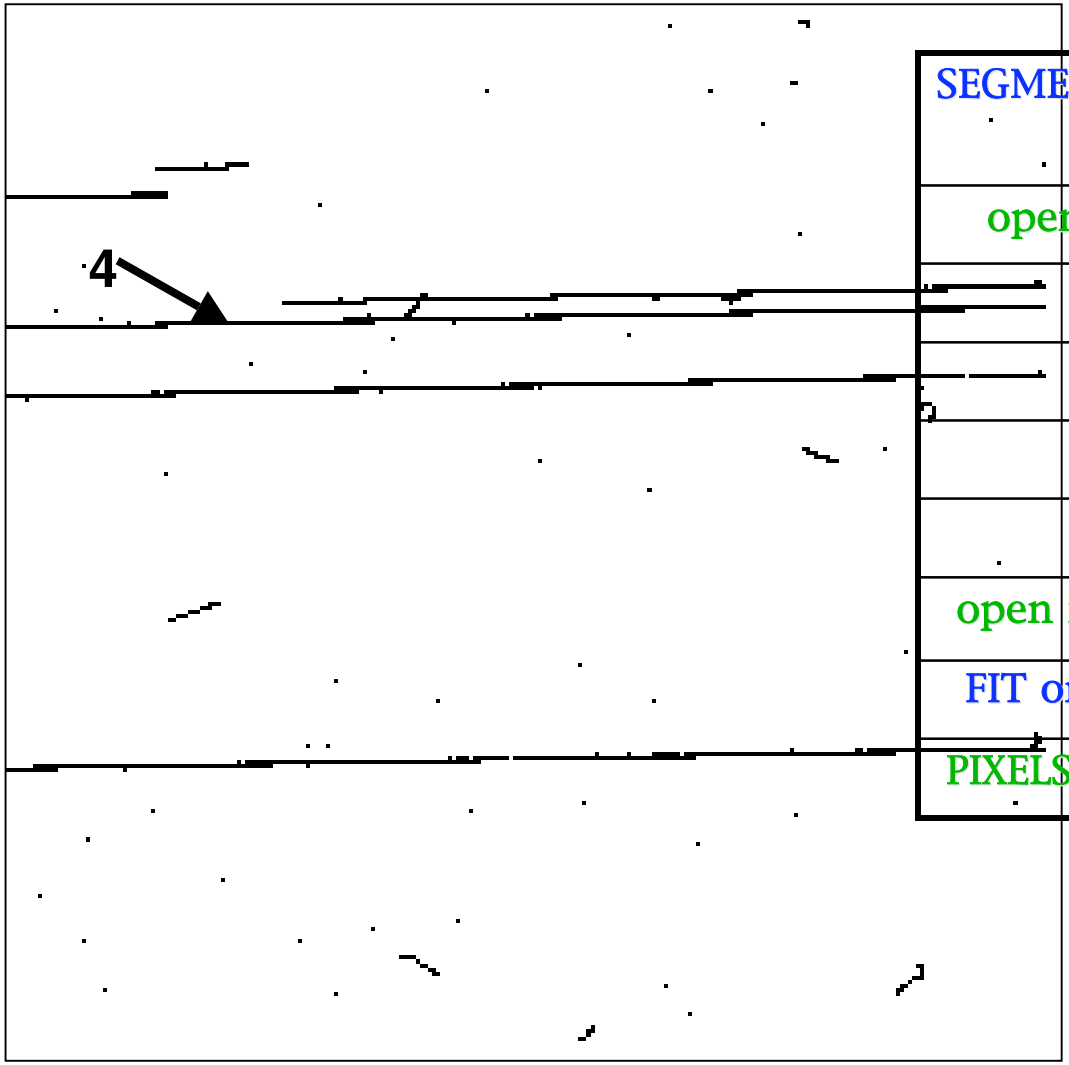
VECTOR MEASUREMENTS

ANGULAR DISTRIBUTIONS

Parallel Medipix M-01-0013

MUON VECTORS

Comparison of Tilt Angles for segments of Trail #4 in frame M01-013

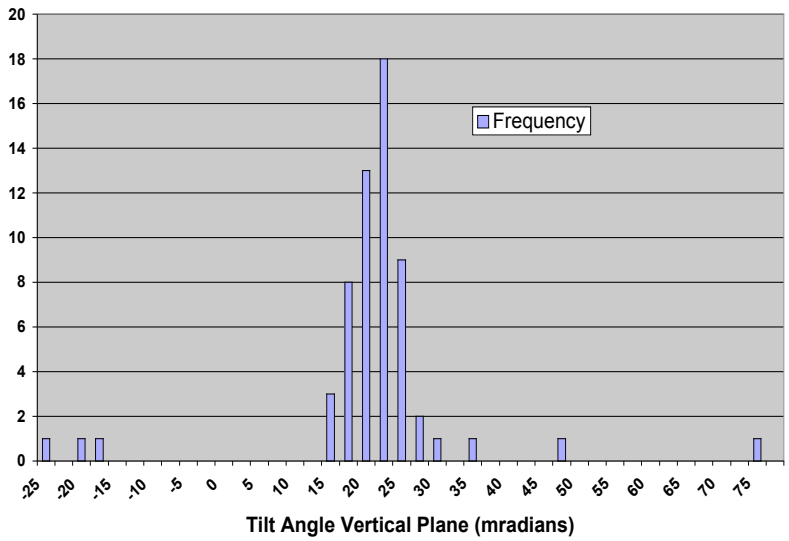


SEGMENT	SINGLE HIT PIXELS	INCL. OVERLAP	TILT mradian
open left 1	37	38.5	26.0
2	43	48.5	20.6
3	37	45.5	22.0
4	41	48.5	20.6
5	41	49.5	20.2
open right 6	20	25.5	39.2
FIT on 5 pts			20.92
PIXELS 1-256	219	256	23.4

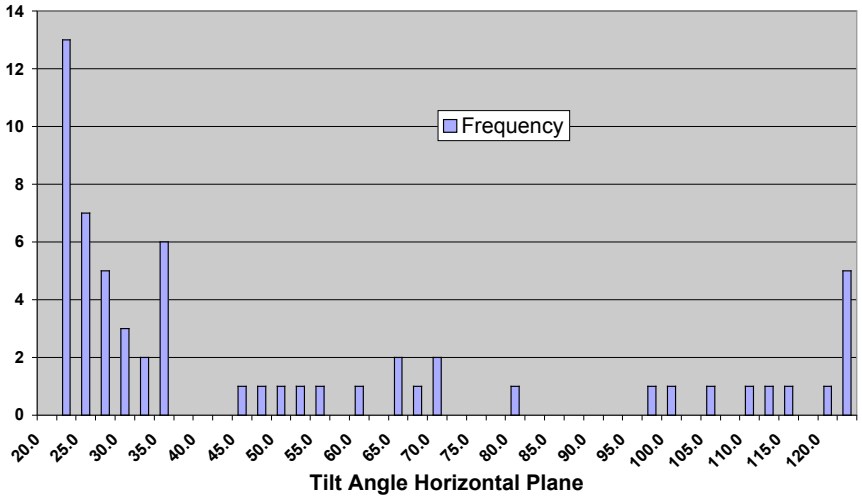
VECTOR MEASUREMENTS

Parallel Medipix M-01-0013

H6 MUON ANGULAR DISTRIBUTION



ANGULAR DISTRIBUTION
VERTICAL PLANE
CONE of 15 mradians

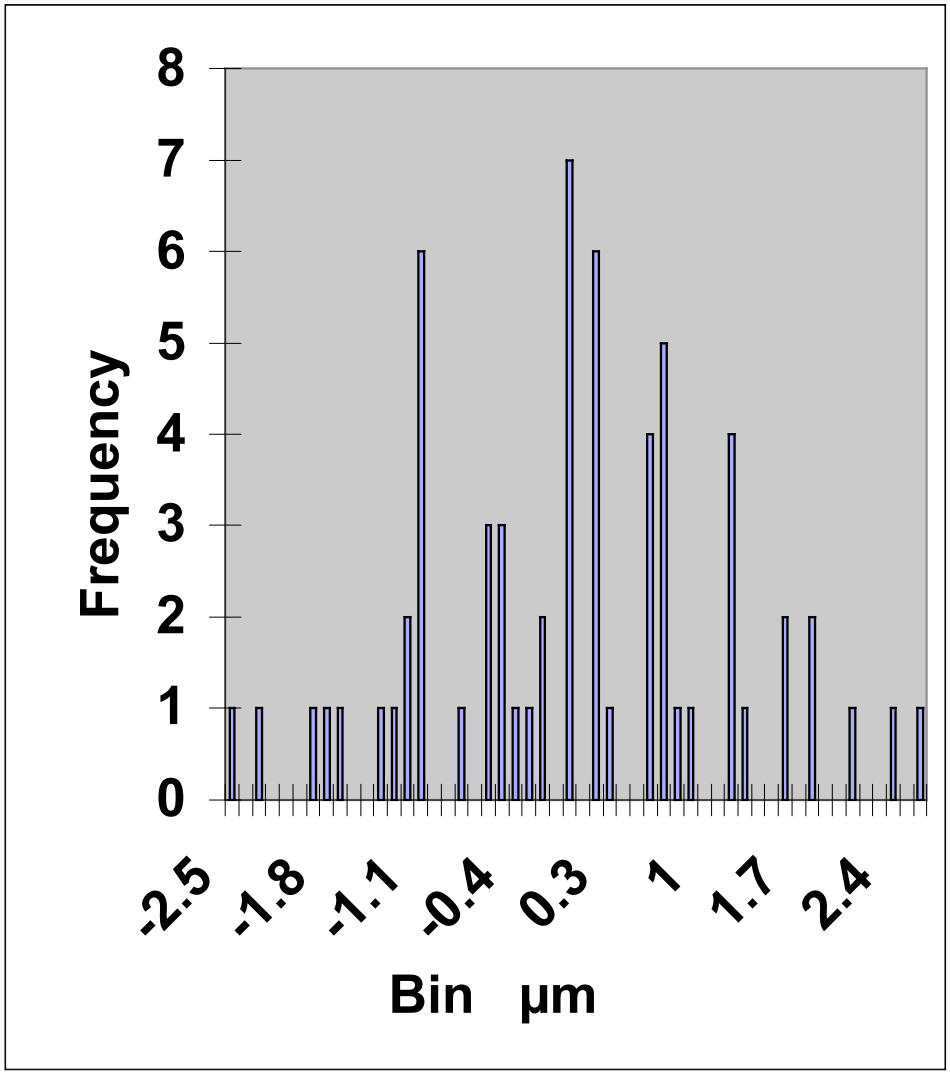


ANGULAR DISTRIBUTION
HORIZONTAL PLANE
+ and - mixed

CONE of > 40 mradians

+ wide background

AUTO - RESIDUALS



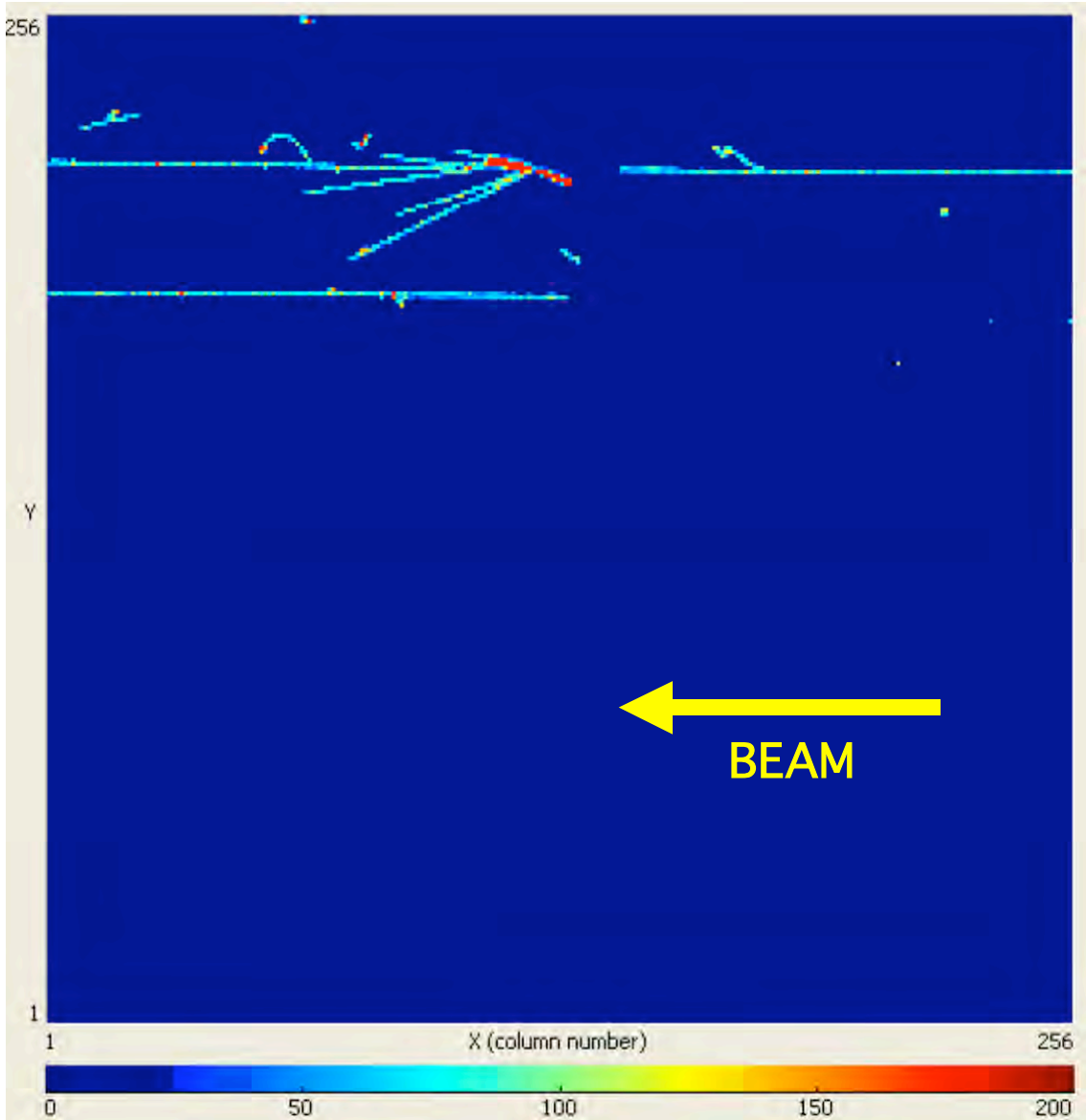
USE MUON TRAIL SEGMENTS TO PREDICT POSITIONS in ROW OVERLAP POINTS

(TAKE ALWAYS MIDDLE OF SEQUENCE)

RESIDUAL DISTRIBUTION

RANGE ± 2.5 μm → σ = 0.8 μm

TIMEPIX-TOT in H6 PION BEAM



QUASI-ANALOG SIGNALS

INTERACTION

+ RECOILS

NOTE :

+ DELTA RAYS

+ BRAGG PEAK in ENERGY DEPOSIT at END of TRAILS

JOHN IDARRAGA
DOMINIC GREIFFENBERG
ERIK HEIJNE

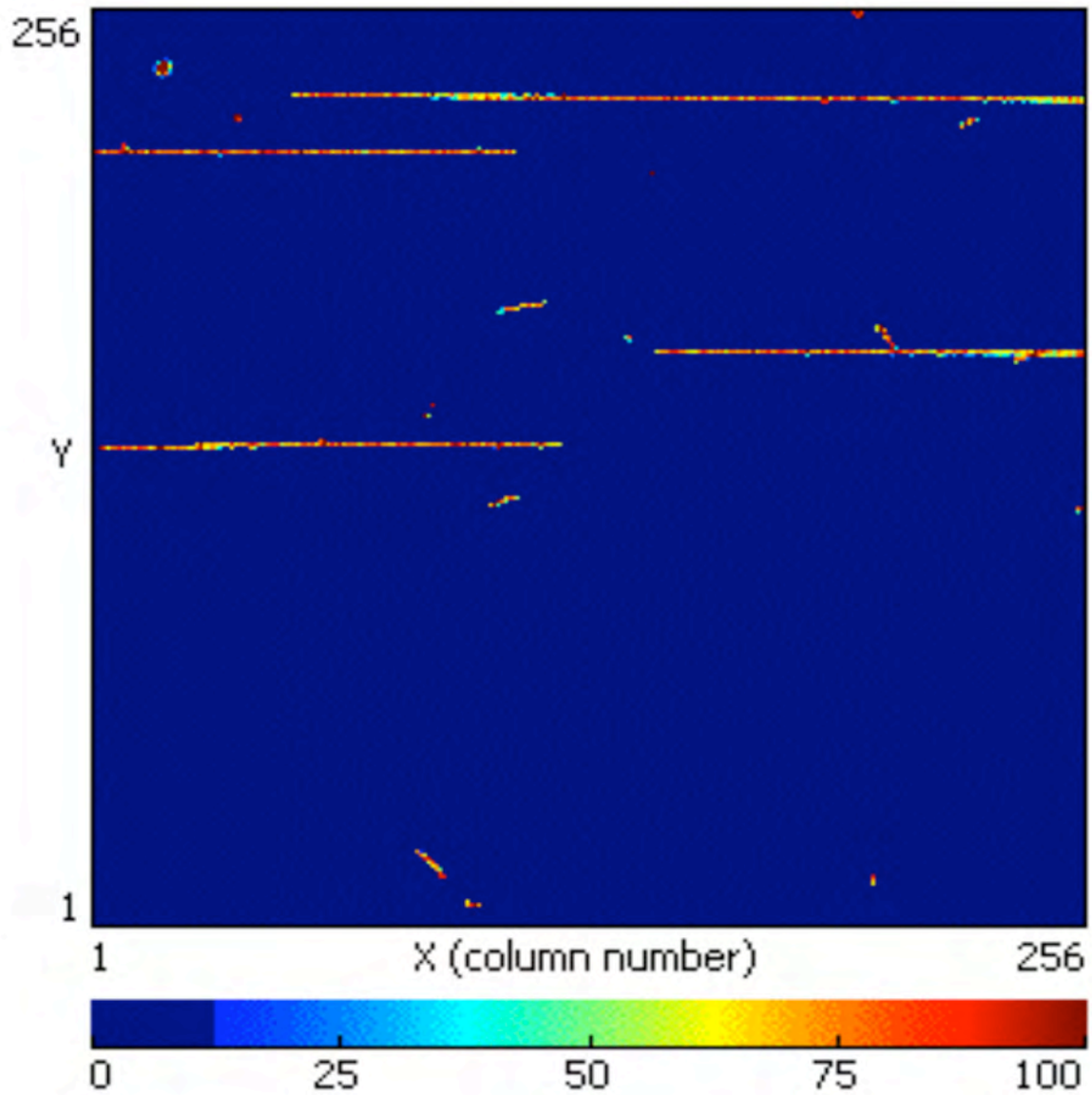
DELTA ELECTRONS in SILICON

June 2007

INCIDENT from RIGHT

BEAM

TIMEPIX MODE TOT



JOHN IDARRAGA
DOMINIC GREIFFENBERG
ERIK HEIJNE

MEASUREMENTS with MIPs in Si TIMEPIX (2007)

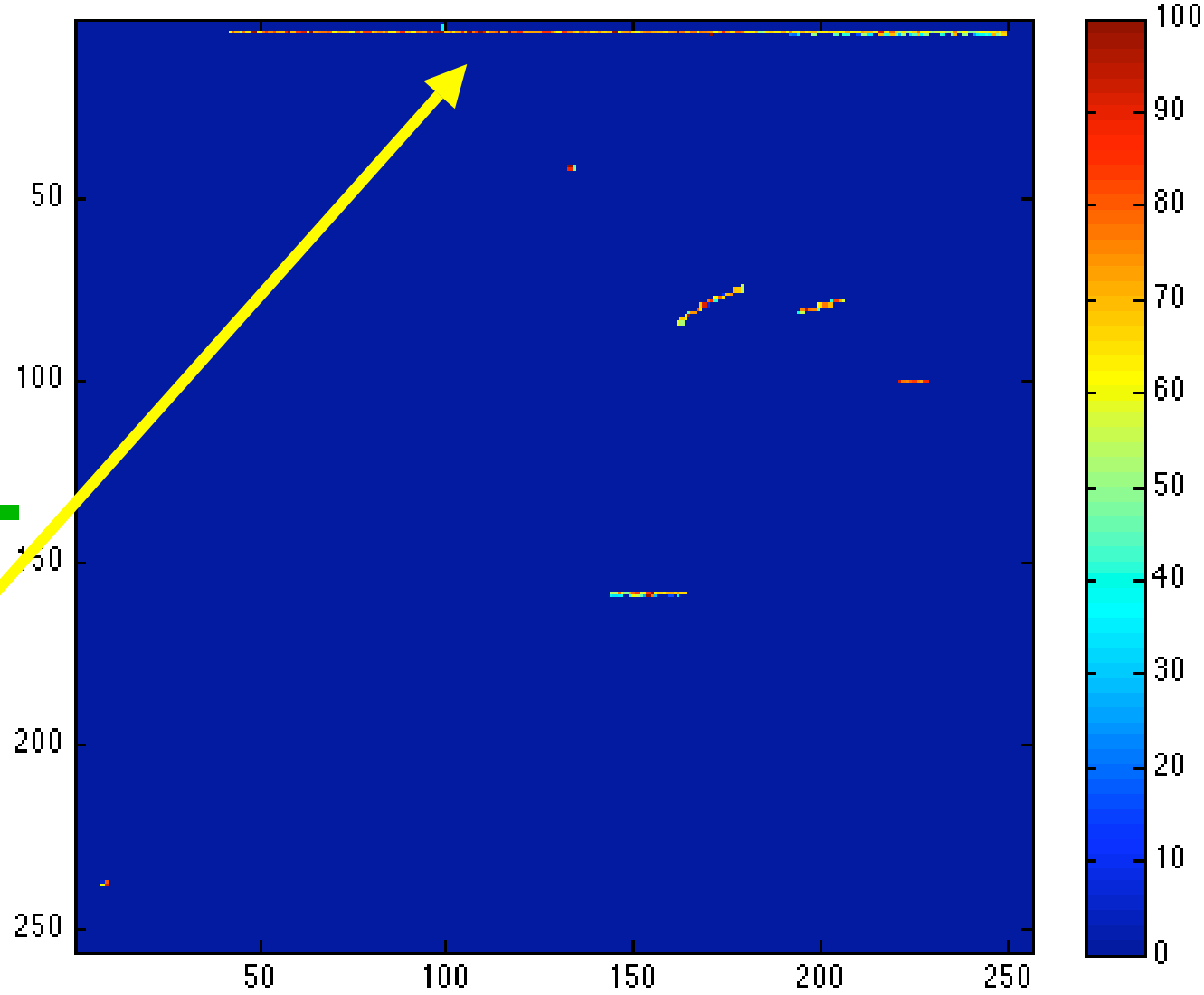
MUONS
H6 in EHN1

June 2007

INCIDENT from RIGHT

BEAM

ANALYZED TRAIL



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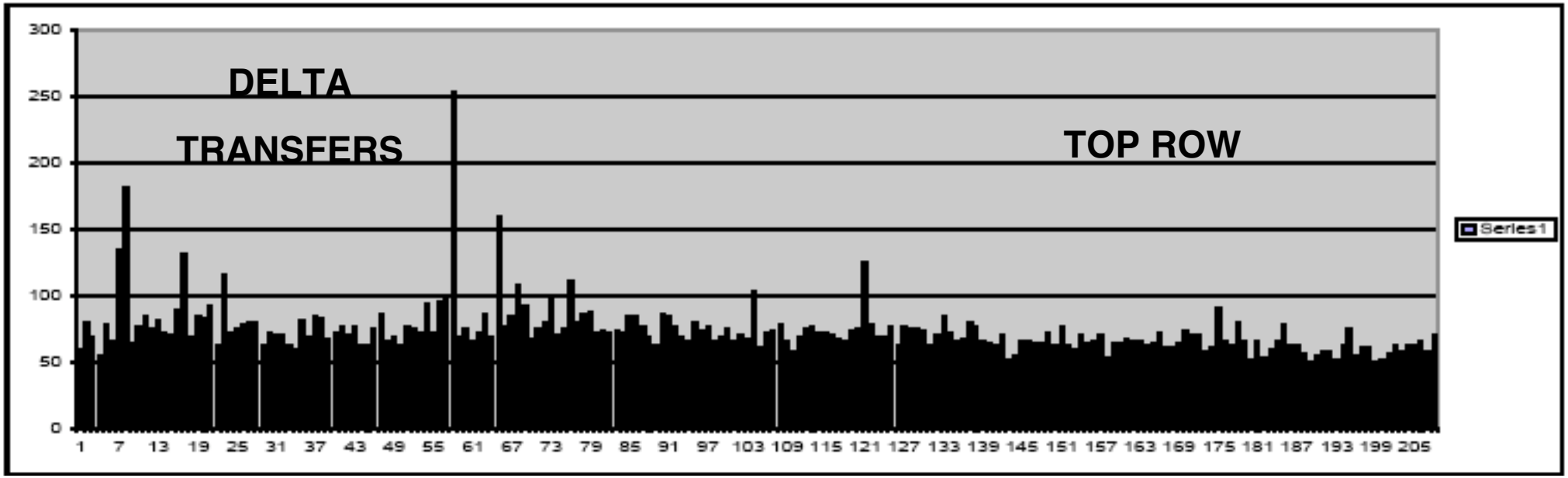
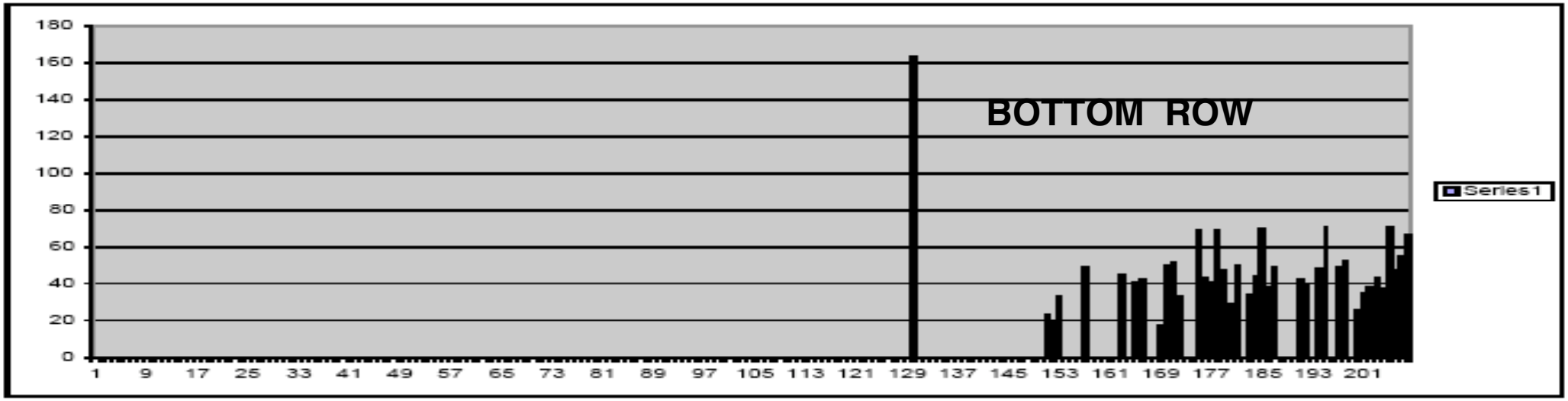
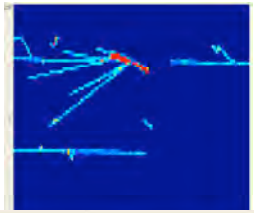
ERIK HEIJNE

TRAIL ANALYSIS FRAME 29853

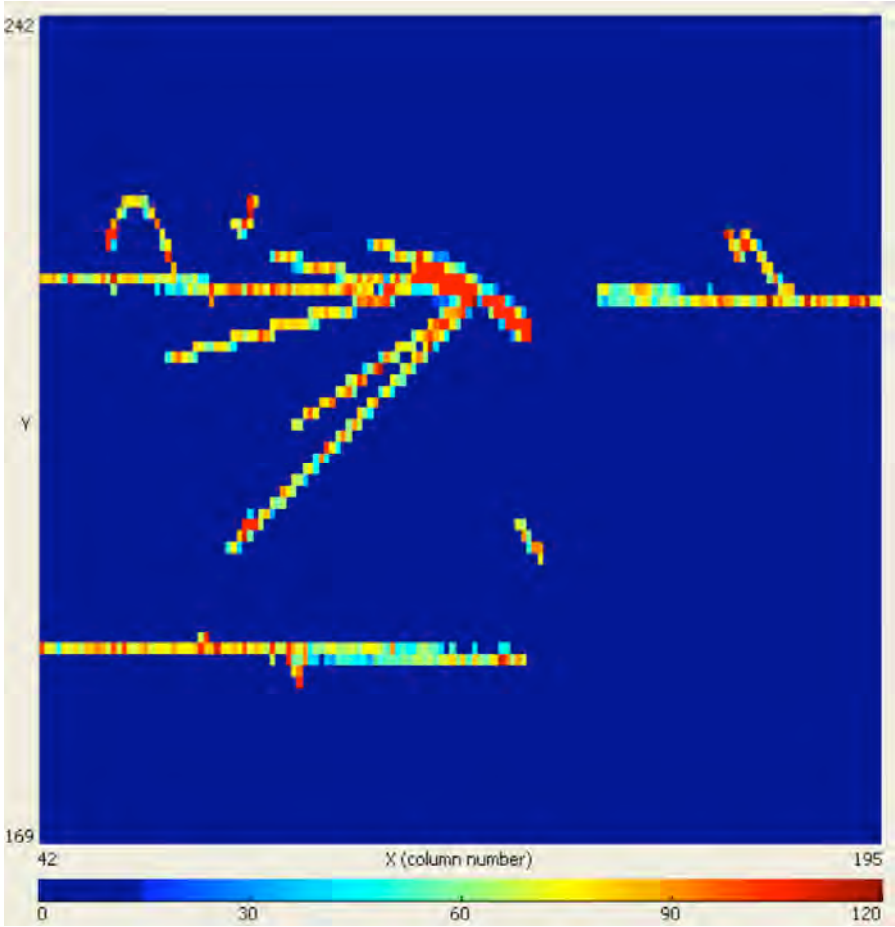


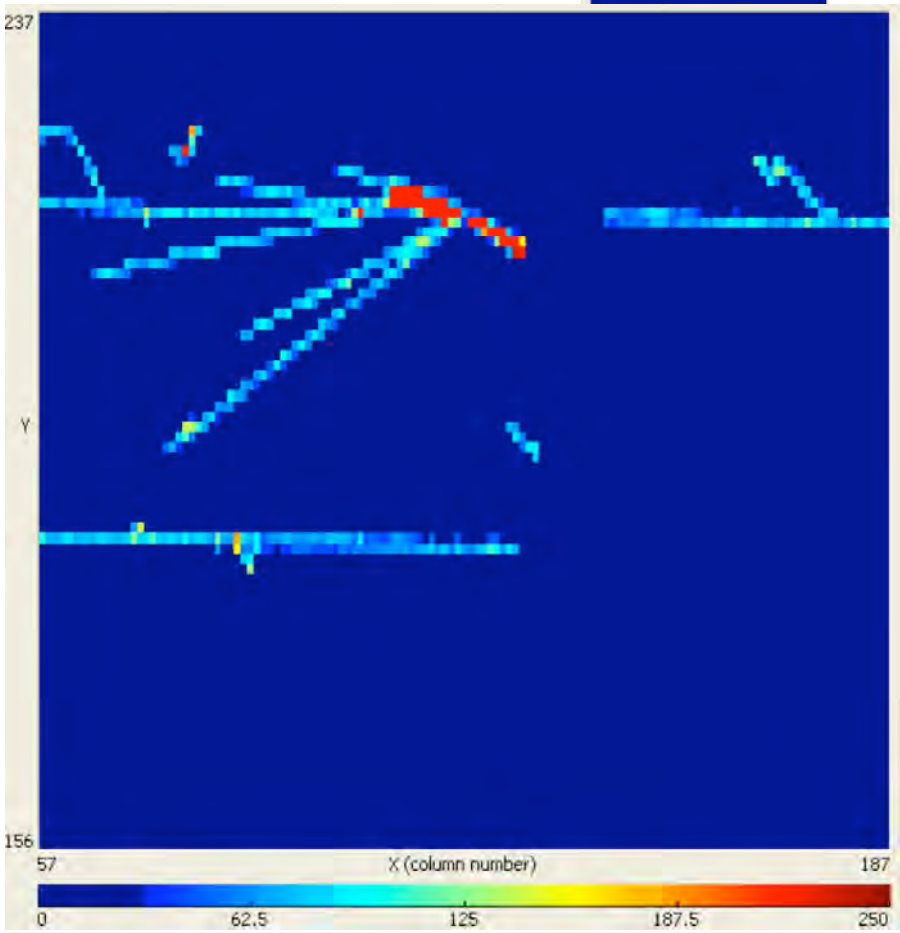


TIMEPIX-TOT in H6 PION BEAM



SAME FRAME ENLARGED, DIFFERENT FULL SCALE



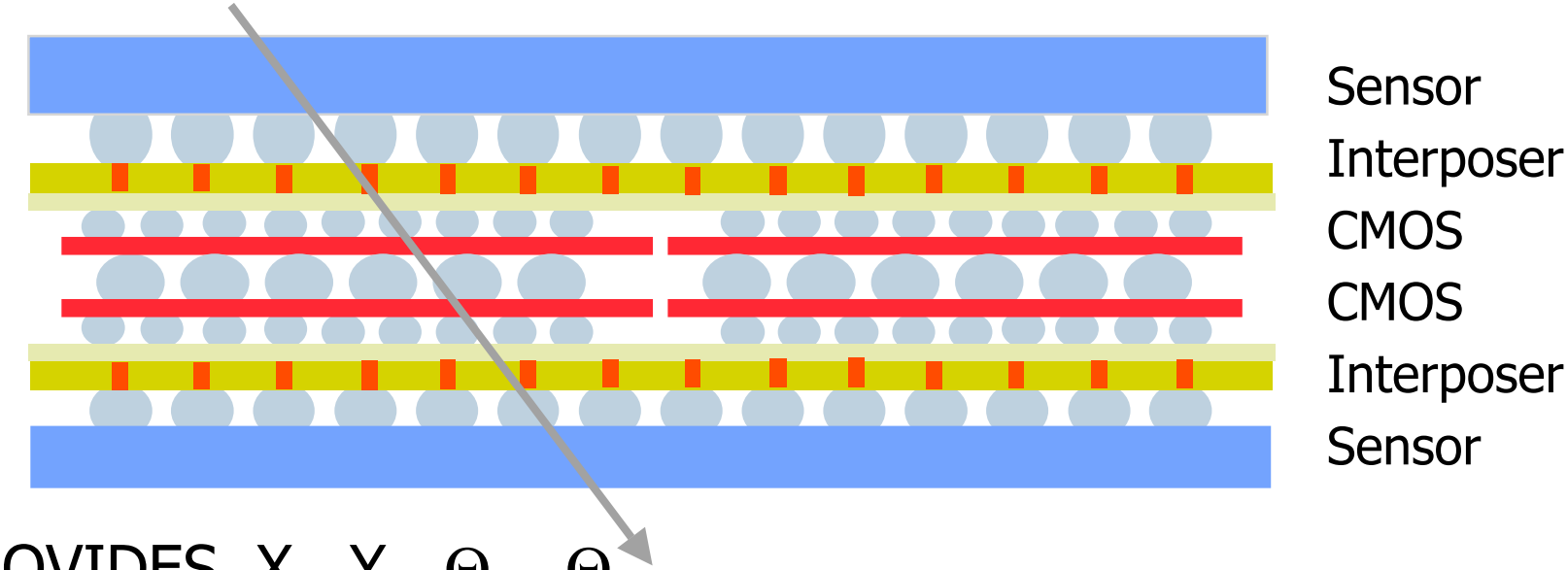


M.I.P. TYPICALLY DEPOSITS 200 - 300 eV per um
11- 16.5 keV in PIXEL TOT RANGE 70-95 (1 keV~6)

ARE THERE APPLICATIONS ?

TRACK VECTOR DETECTOR

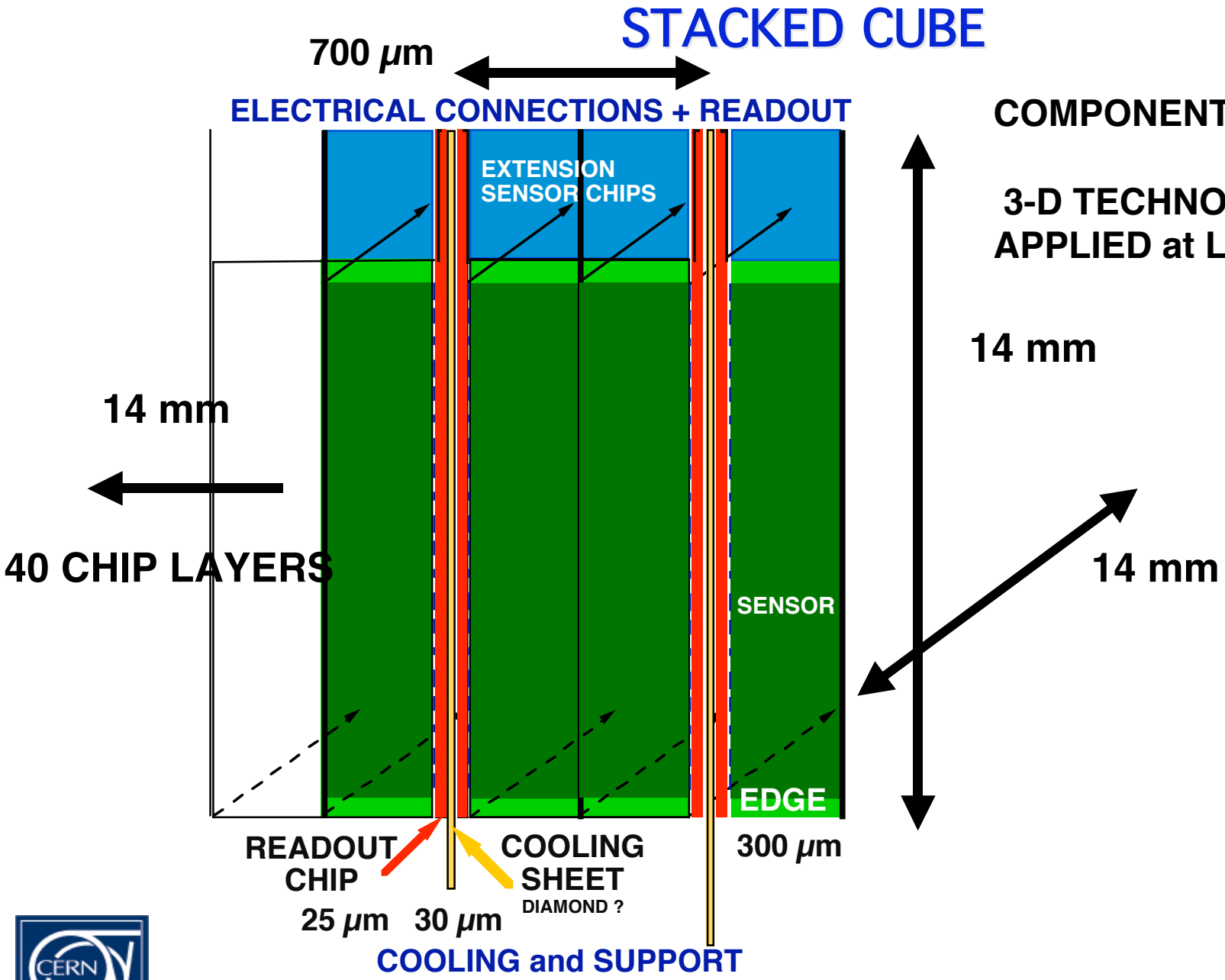
3D TECHNOLOGY* MULTILAYER ASSEMBLY



PROVIDES X , Y , Θ_X , Θ_Y

intersecting position + angular direction

STACKED CUBE

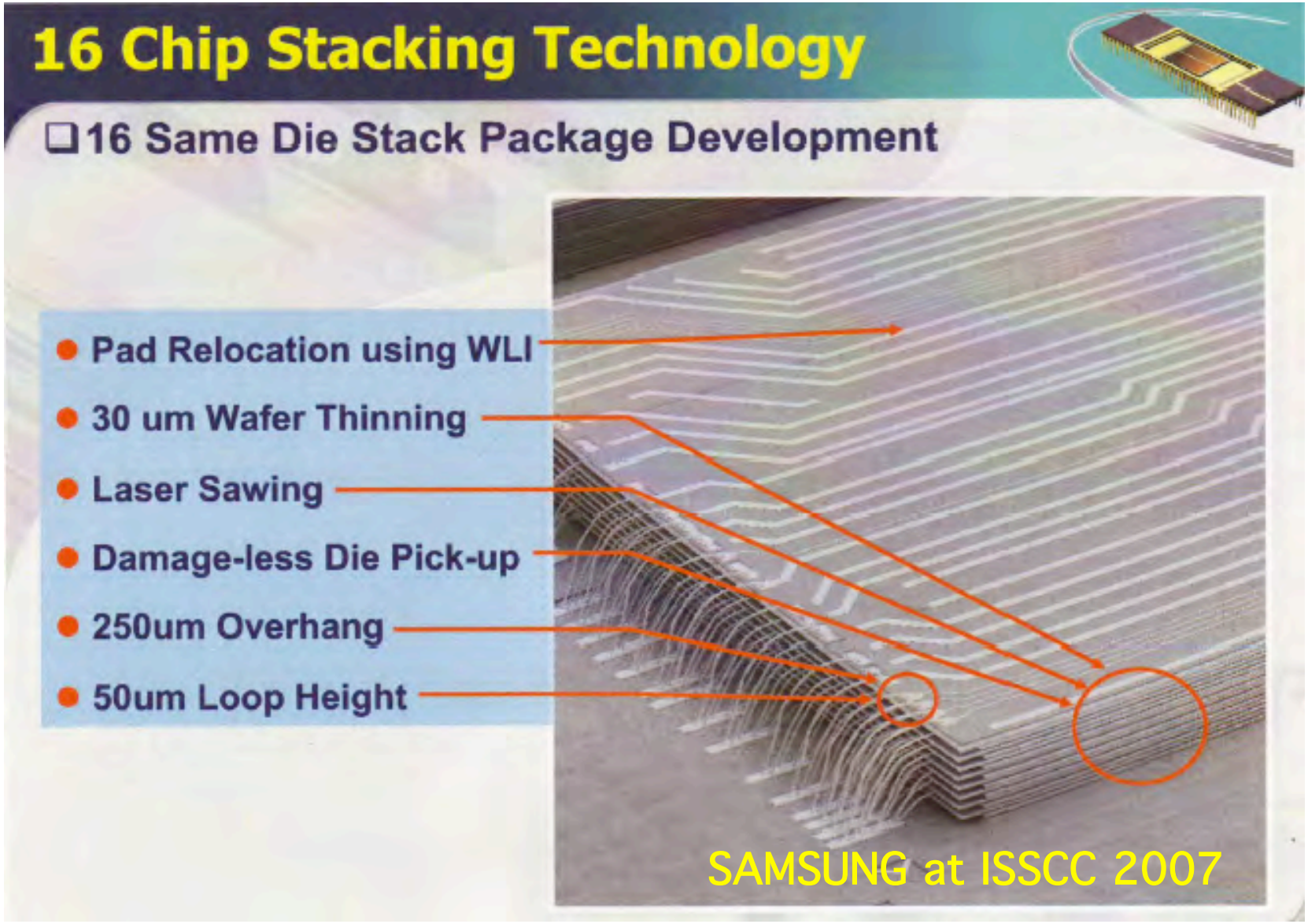


COMPONENTS 'EXIST'

3-D TECHNOLOGY ALREADY APPLIED at LOS ALAMOS

3D STACKING
MAJOR EFFORTS in INDUSTRY

3D STACKING TECHNOLOGY



SUPER ADVANCED TECHNOLOGY

TSUKUBA ASET K. Takahashi et al, Microel. Rel. 2003

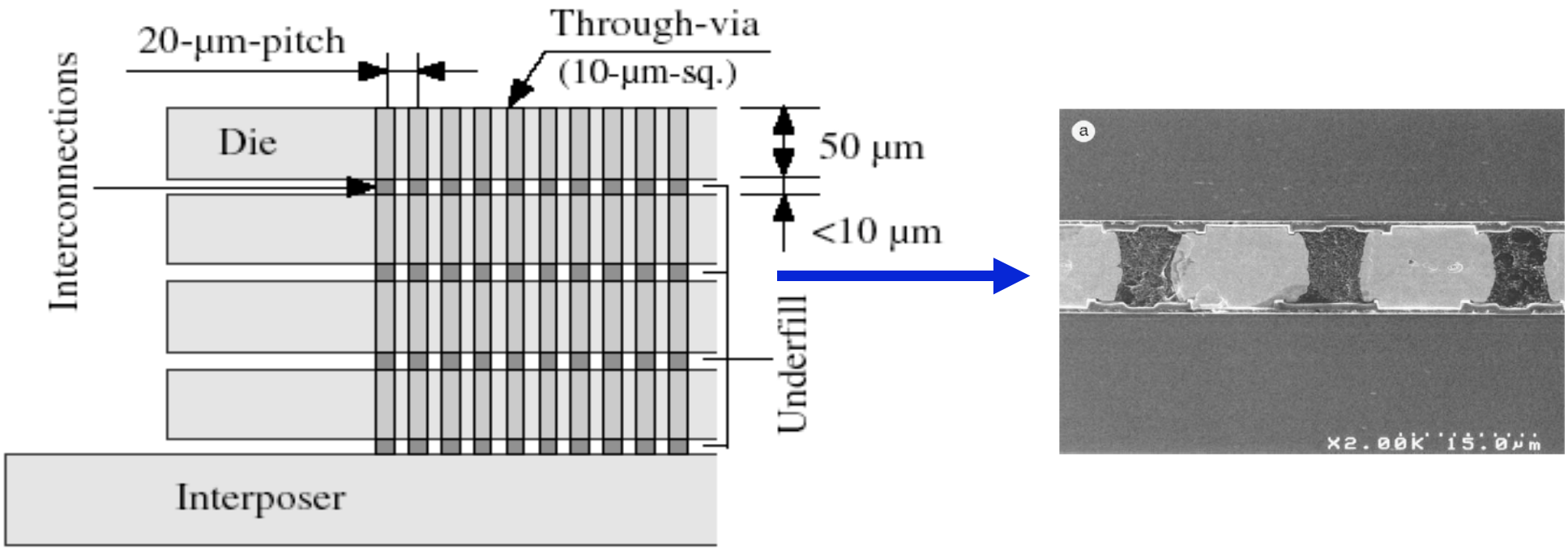
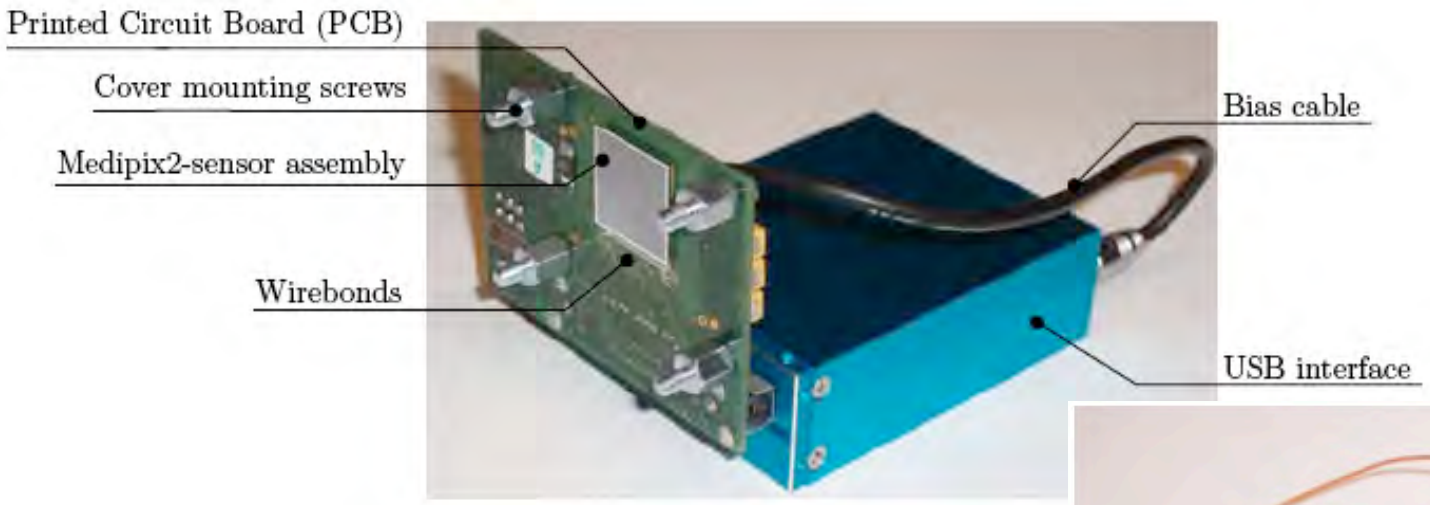
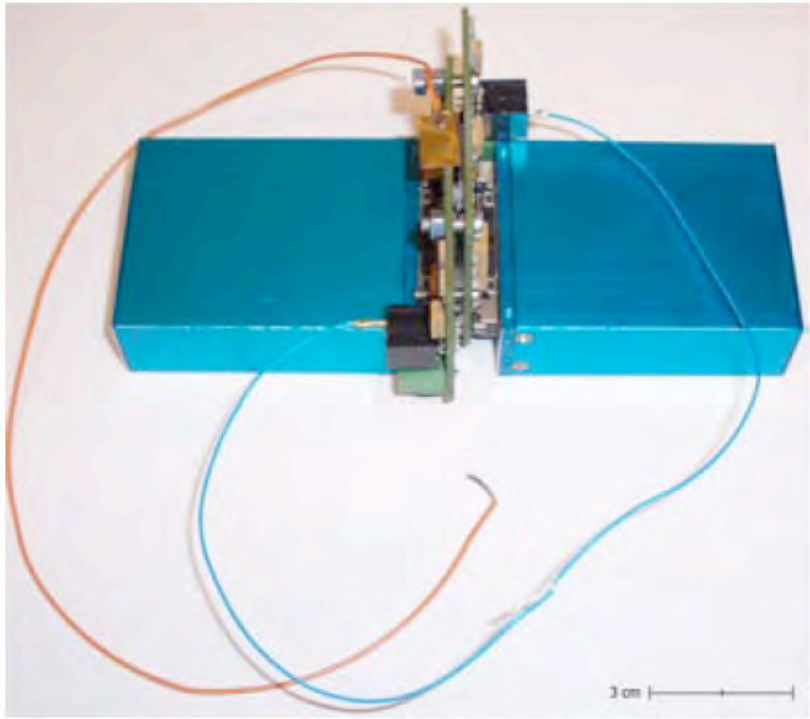


Fig. 2. 3D LSI chip stacking structure.

INCREASE of FUNCTIONAL DENSITY REQUIRES 3D STRUCTURES

MEDIPIX STACKING & TILING : FIRST TRY

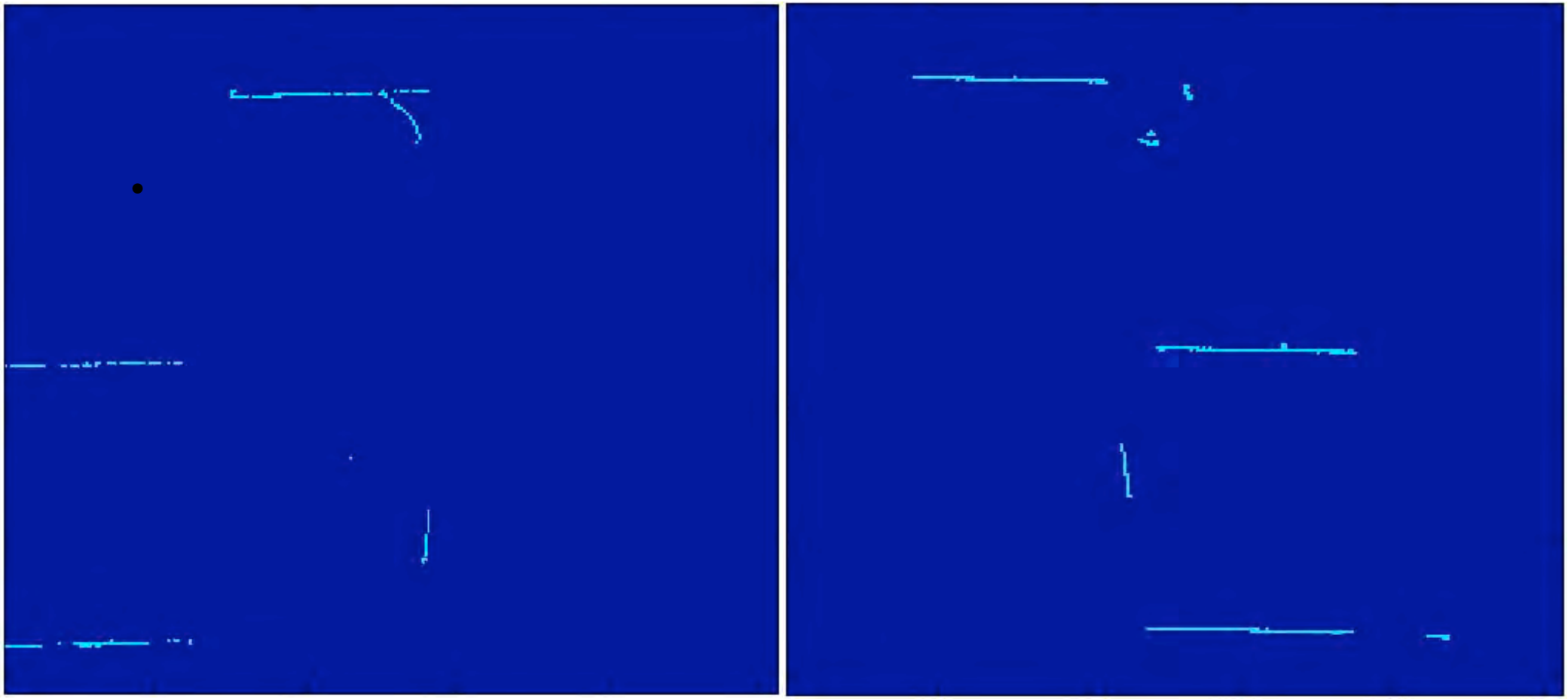




(a) The stacked prototype

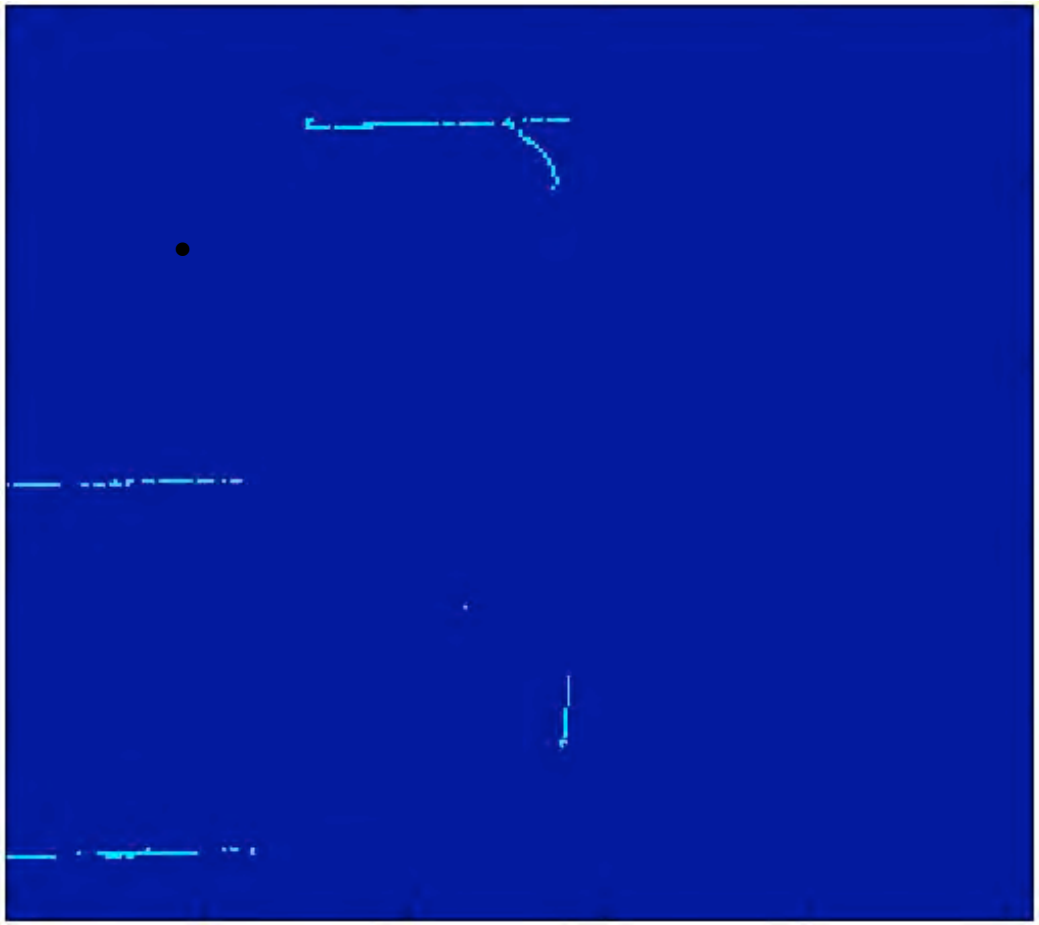
JAN VISSCHERS
DAAN BOLTJE
NIKHEF

223 3 beam 1 cosmic



E I

223 3 beam 1 cosmic



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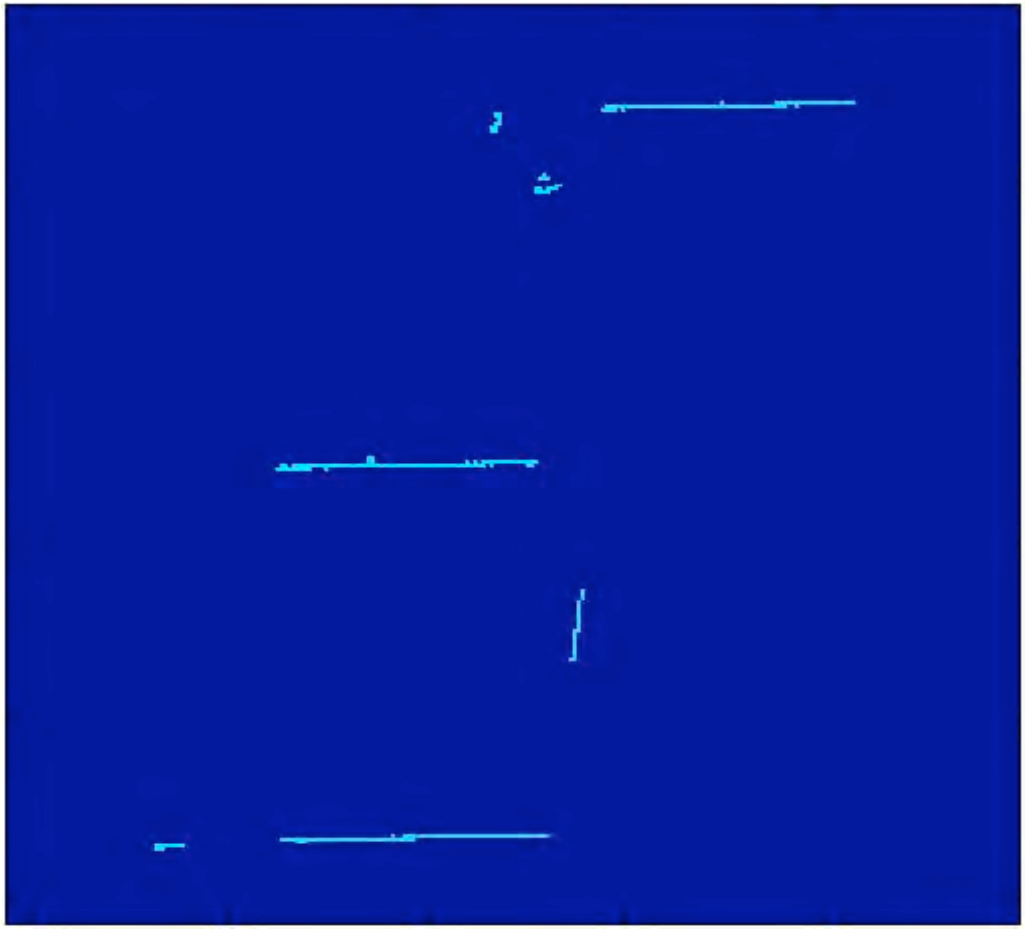
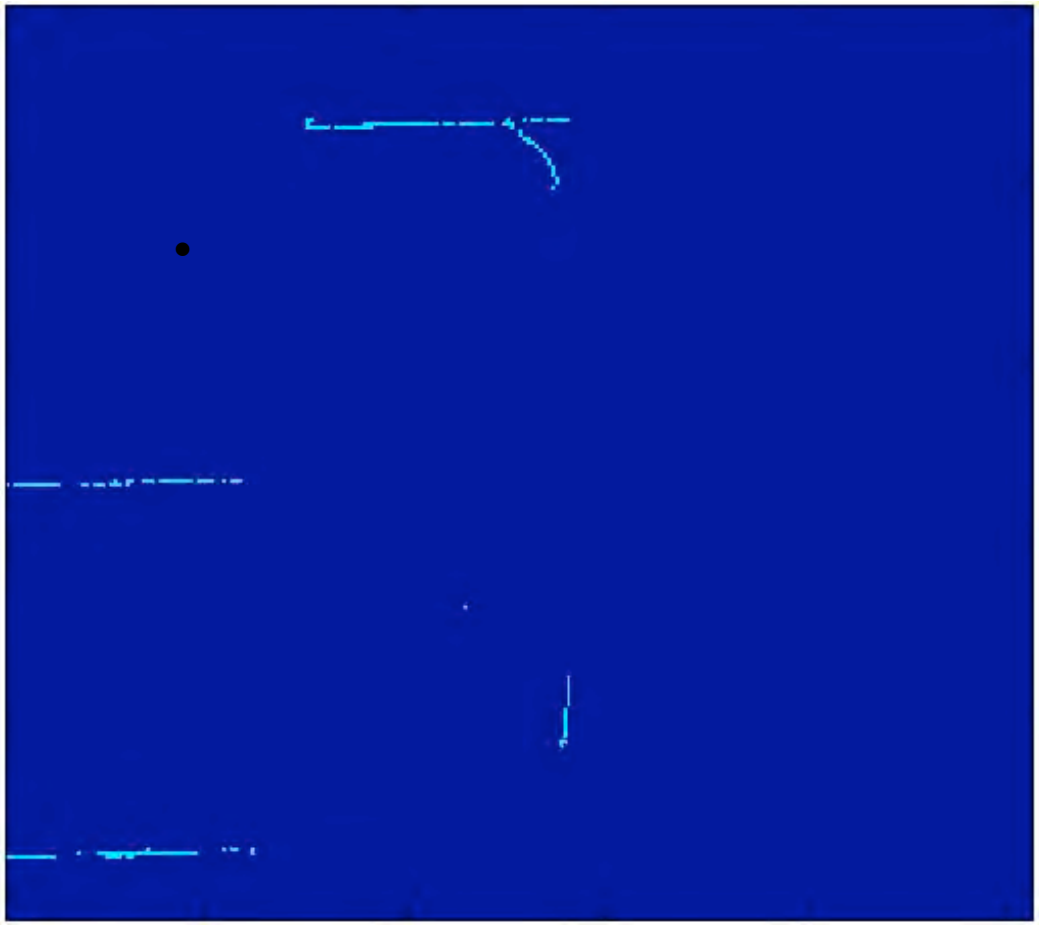


I flipped

223 3 beam 1 cosmic



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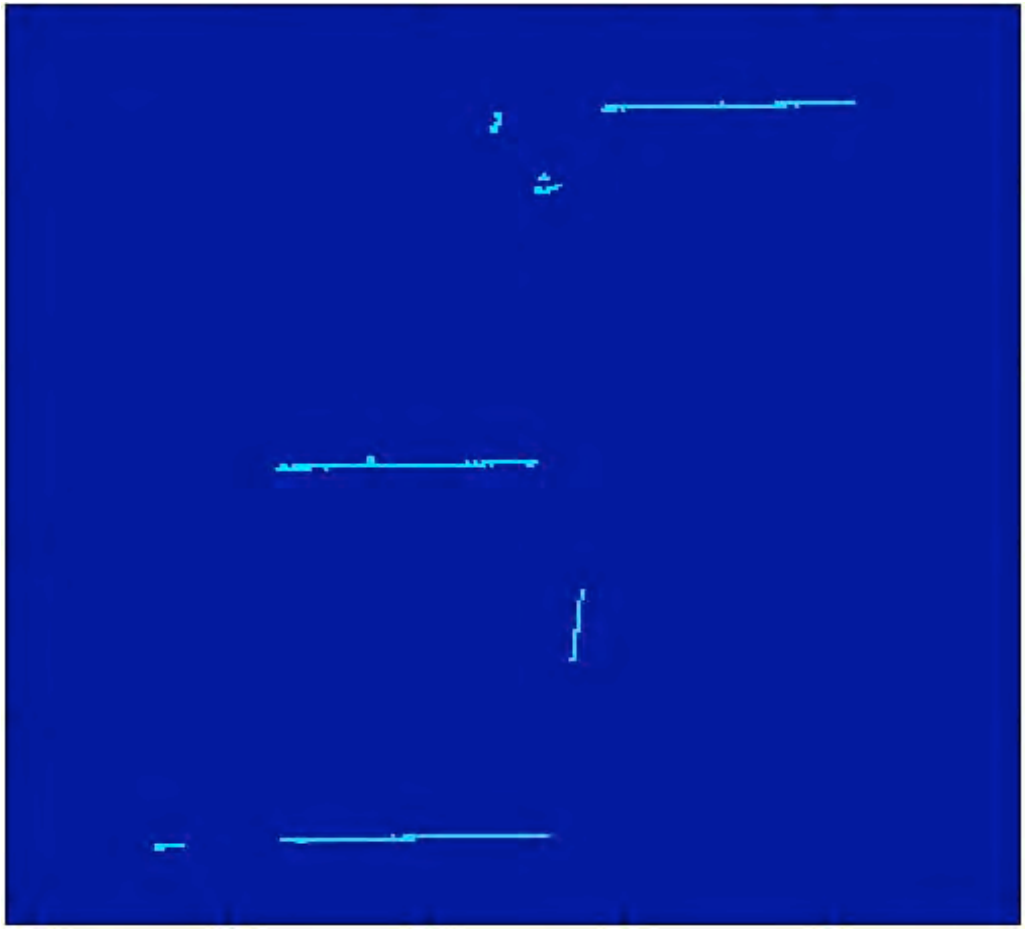
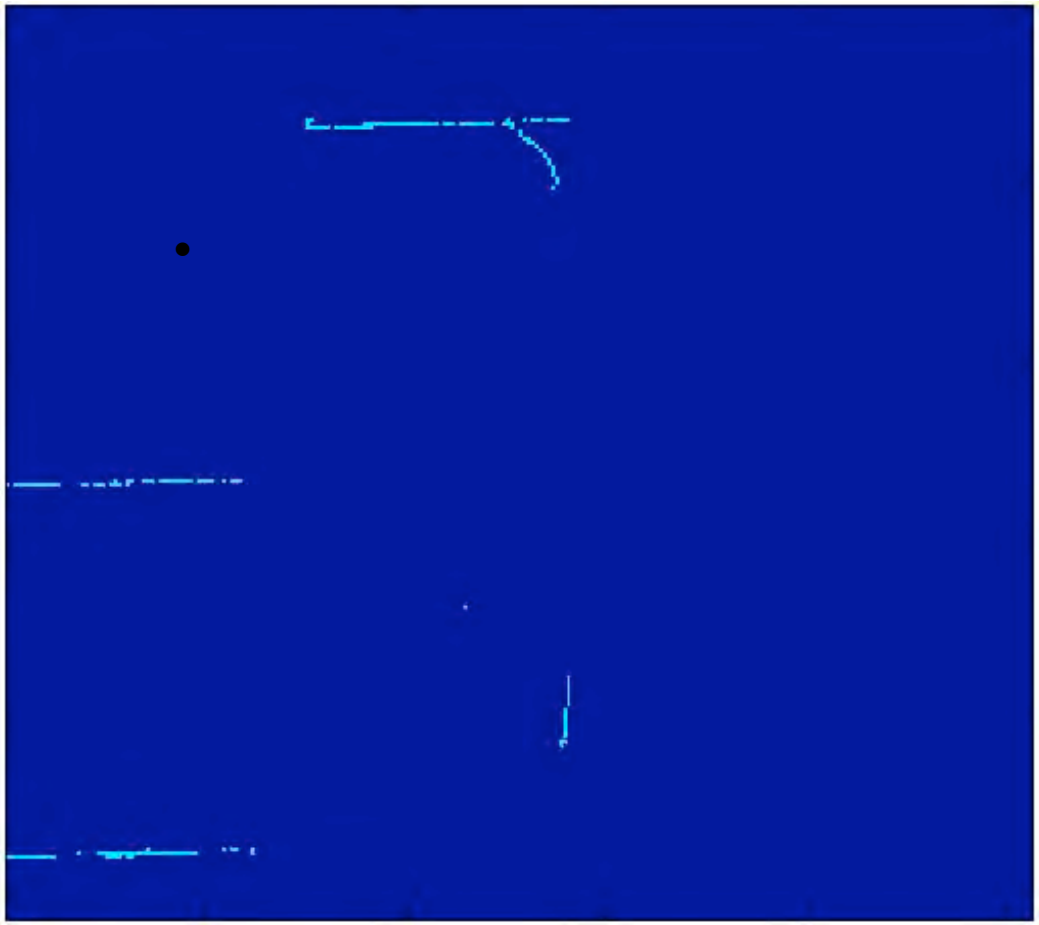


I flipped

223 3 beam 1 cosmic



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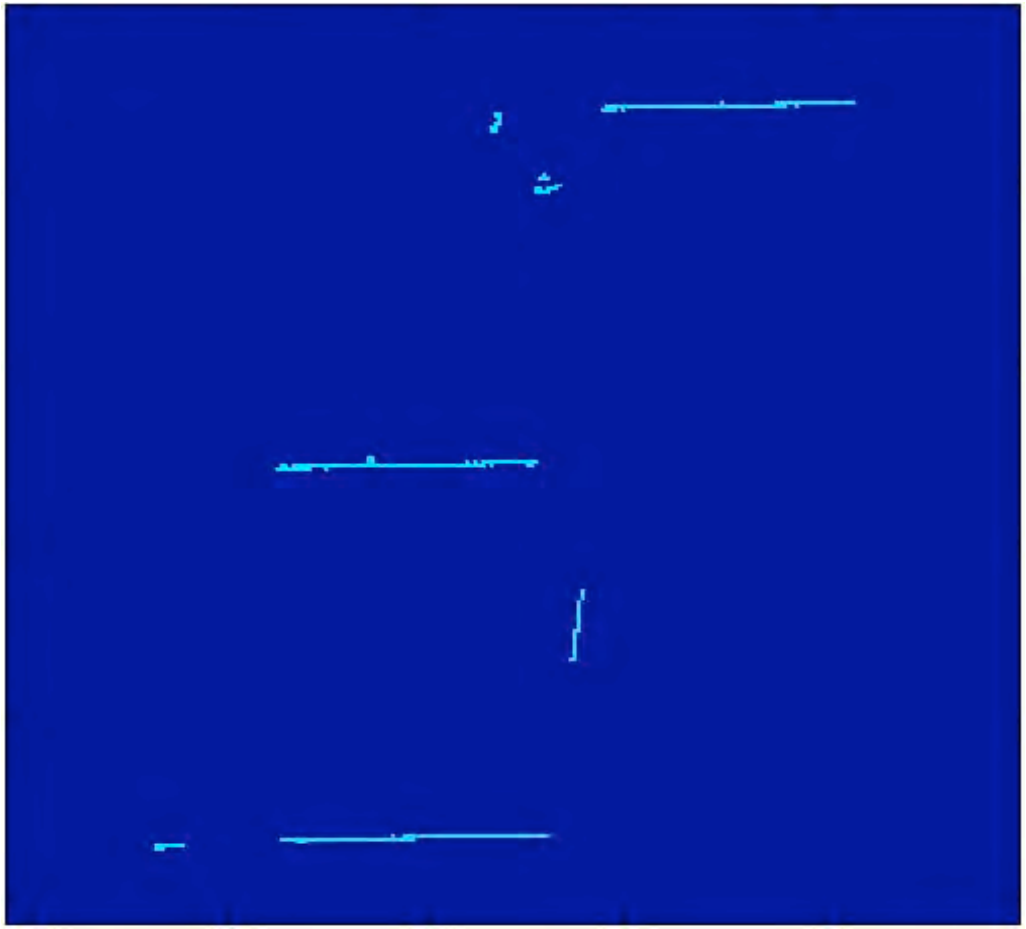
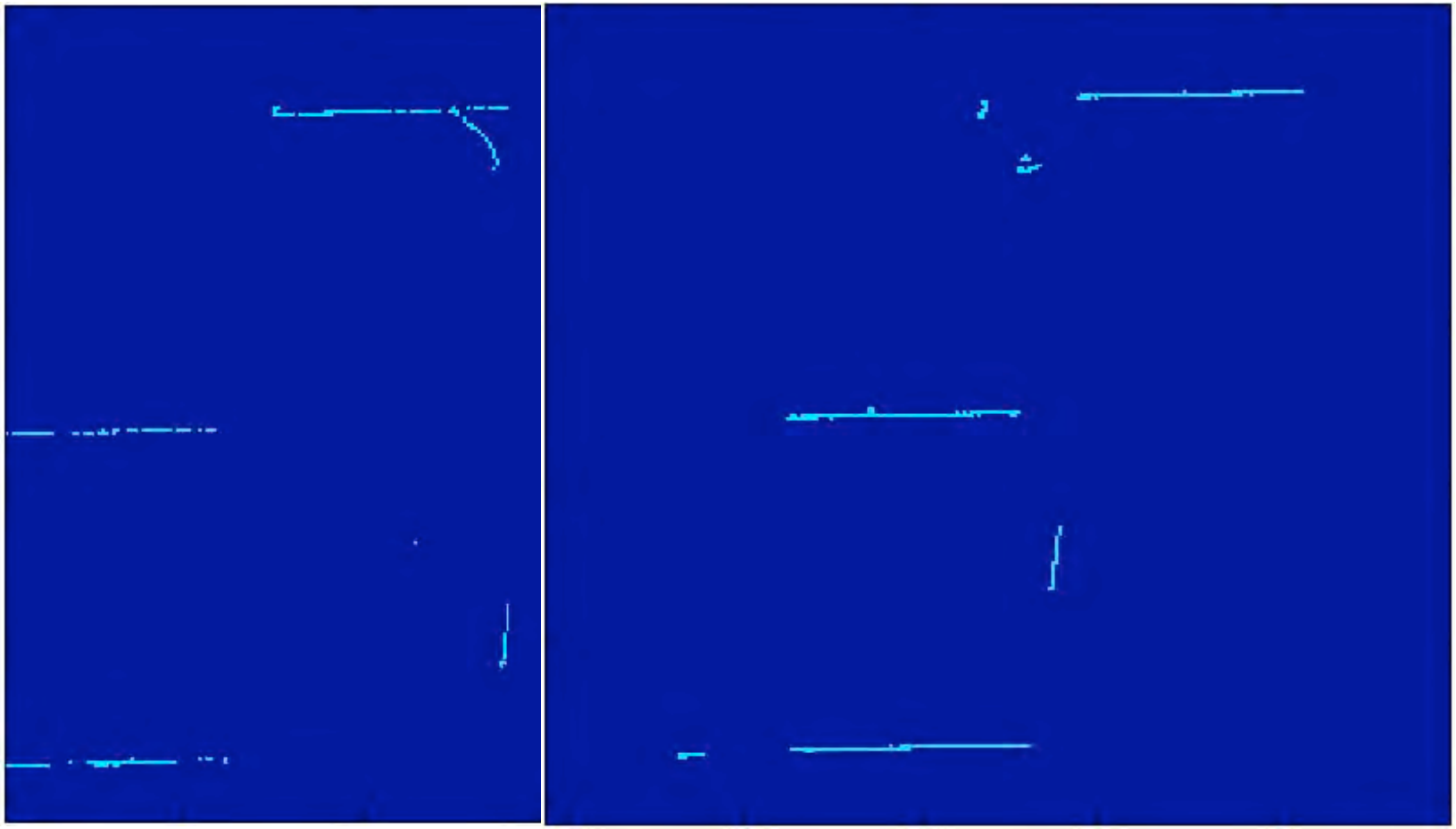


I flipped

223 3 beam 1 cosmic



E I flipped

223 3 beam 1 cosmic

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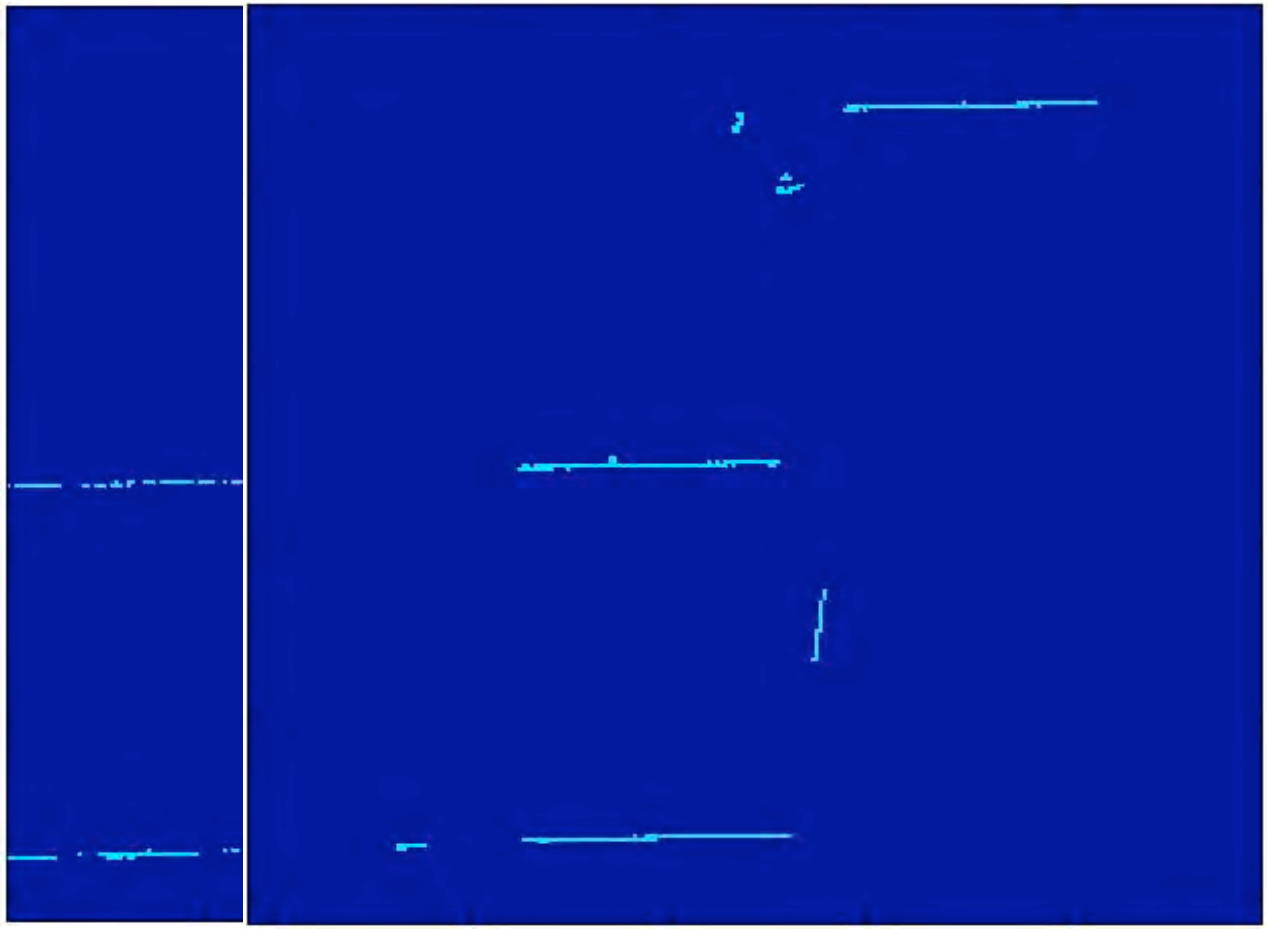

E I flipped

223 3 beam 1 cosmic

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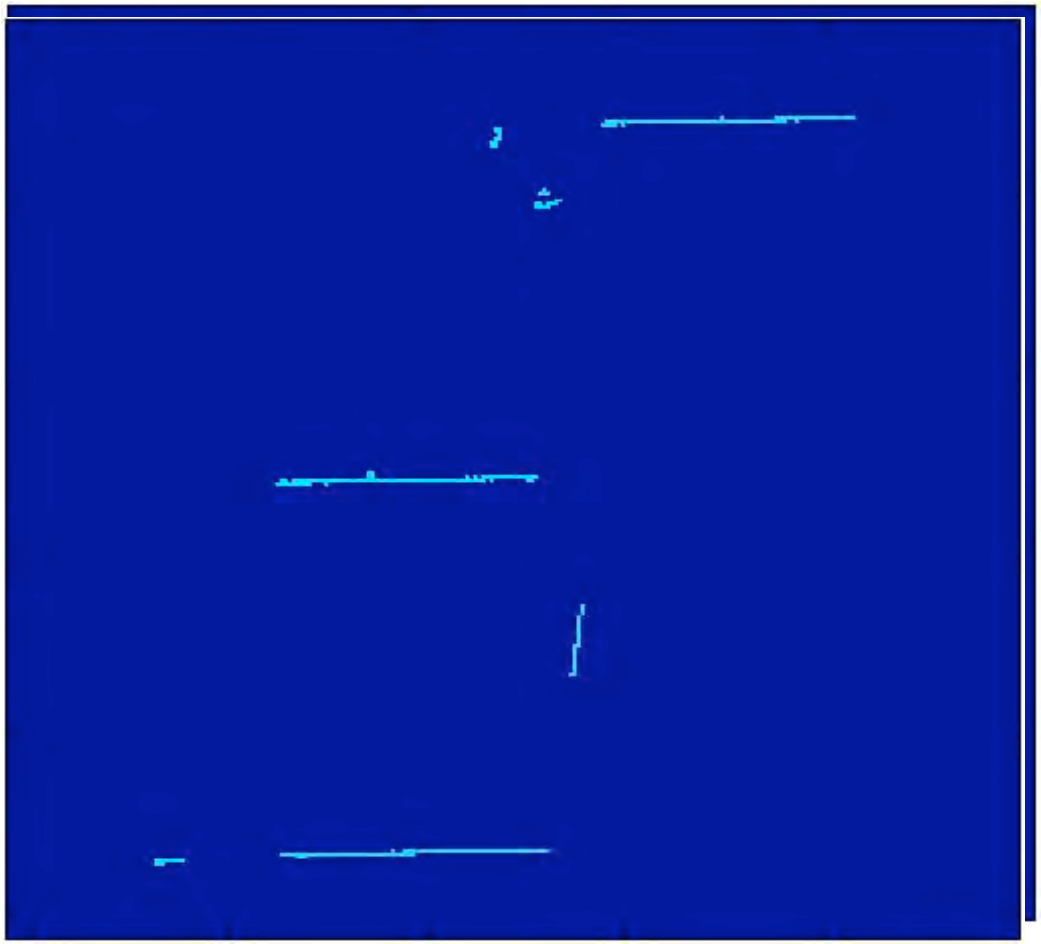


E I flipped

THE ROLE of CMOS TECHNOLOGY STEPS

TRANSISTORS

SMALLER

FASTER

POWER

LITHO

PROPERTIES
WHICH TOOLS & TRICKS

SOI TRANSISTOR LETI

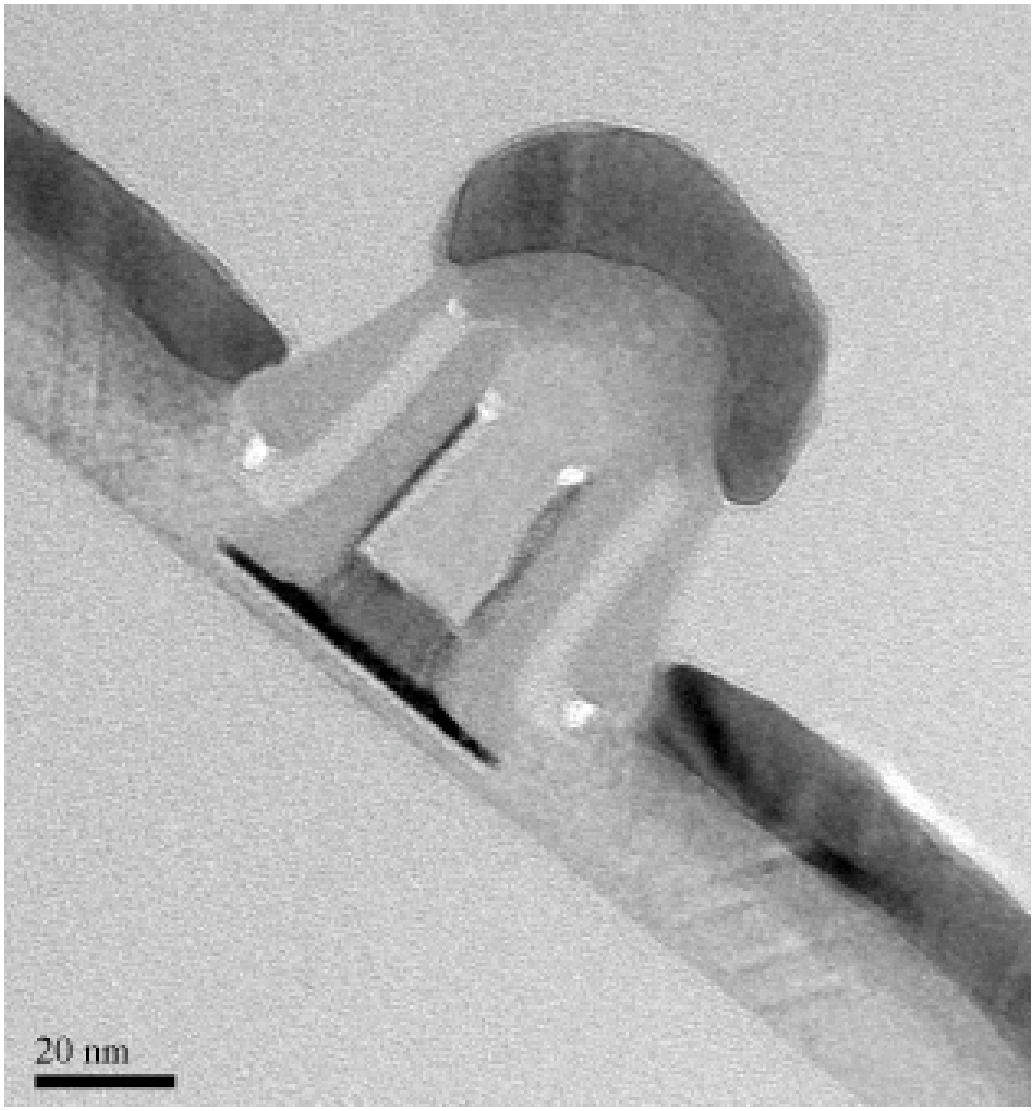


Fig. 1 - TEM cross section of 18nm gate length n-sSOI MOSFET.

LETI-SOITEC 3.4

SOI TRANSISTOR 18 nm

SOI TRANSISTOR LETI

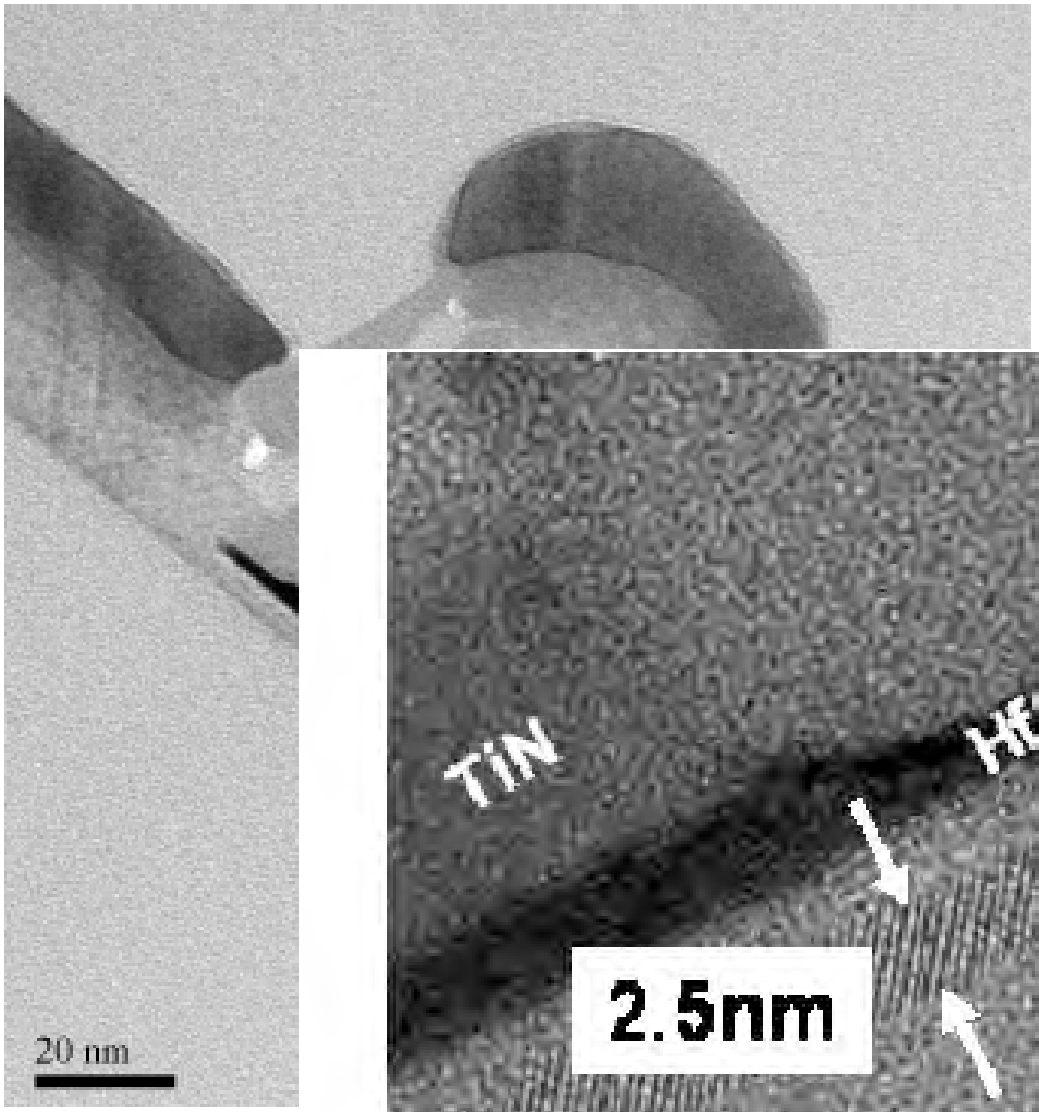


Fig. 1- TEM cross section o

LETI-SOITEC 3.4

SOI TRANSISTOR 18 nm
+ EPITAXIAL Si GROWTH

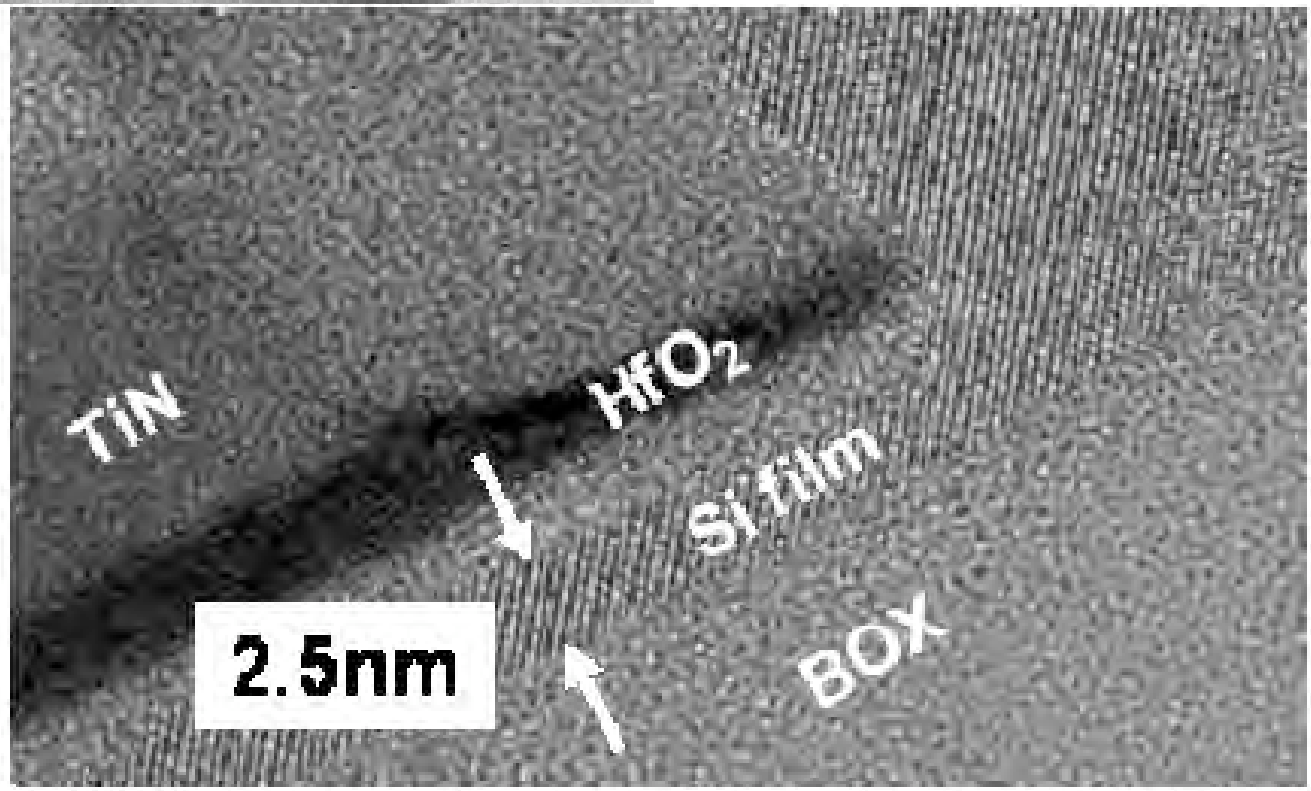


Fig. 2- HRTEM cross-section showing the detail of the channel edge. The Si film thickness is 2.5nm.

IBM PRODUCTION in 65 nm
TSMC 45 nm
INTEL 45 nm

SOME DATA from
IEEE - IEDM Washington Dec 2007

TRANSISTORS SMALLER

ITRS ROADMAP NODES 65 - 45 - 32 - 22 - nm

IMPROVEMENT NEEDED

SOME ROADS TAKEN :

< 65 MOBILITY ENHANCEMENT by STRAIN

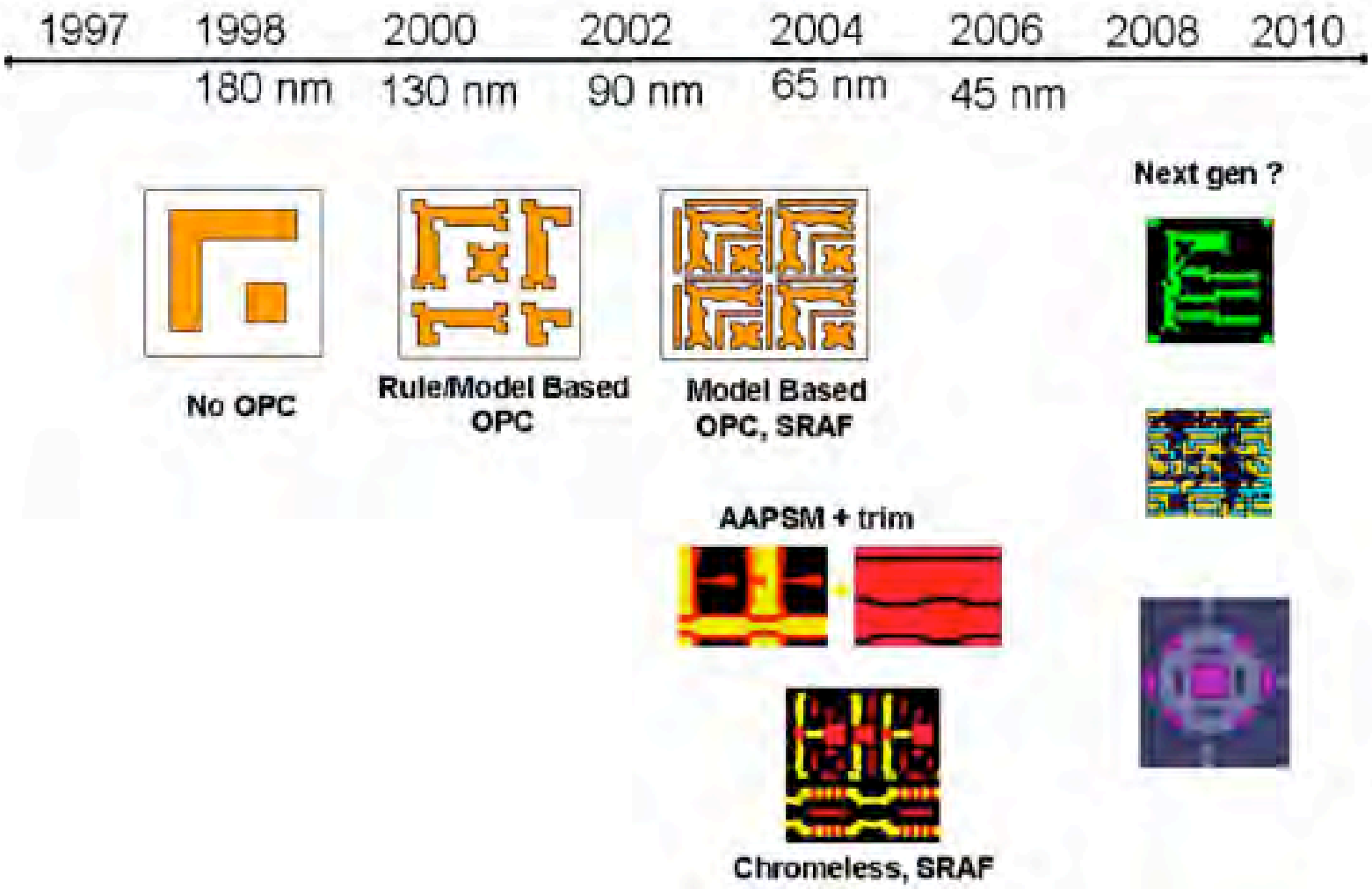
< 45 LEAKAGE REDUCTION by HIGH k + METAL GATE

< 22 MULTI GATE DEVICES

PROGRESS in LITHOGRAPHY

MASK TECHNOLOGY 130 nm - 35 nm

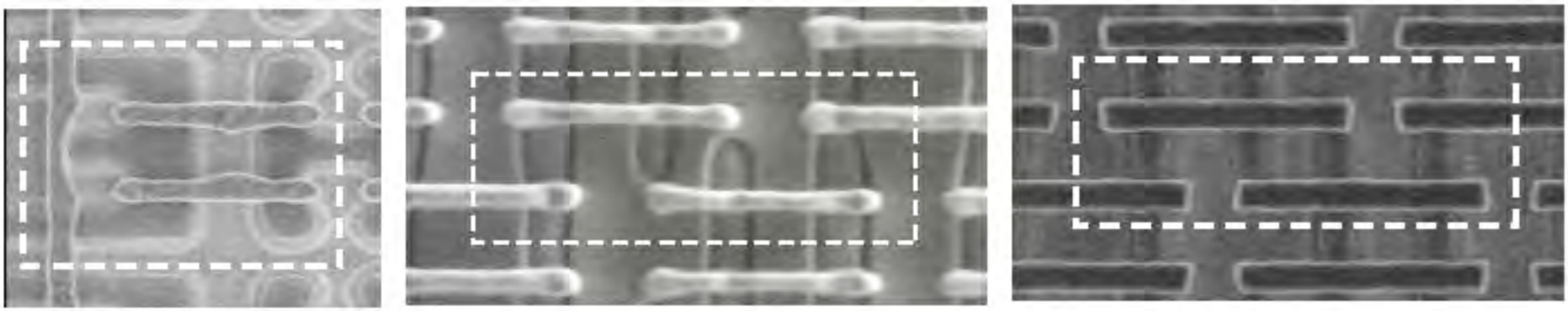
Optical view of masks (patterns)



45 nm INTEL : BETTER LITHOGRAPHY

Mrs Kelin KUHN, INTEL 18.2

SRAM CELL



90nm – tall
1.0 μm^2

65nm – wide
0.57 μm^2

45nm – wide
w/ patterning enhancement 0.346 μm^2

Fig.7 Cell topology enhancements for mismatch improvement

45 nm INTEL IN PRODUCTION : NEW GATE

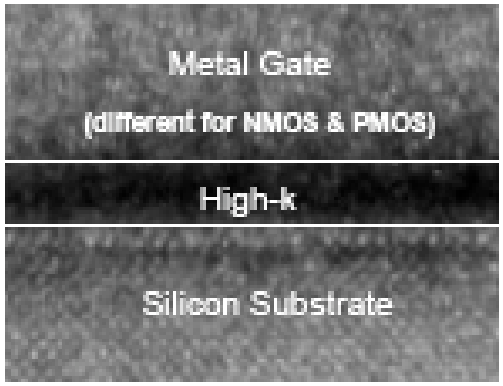


Fig. 2 TEM of High-k + Metal Gate transistor stack

CHANGE in TREND

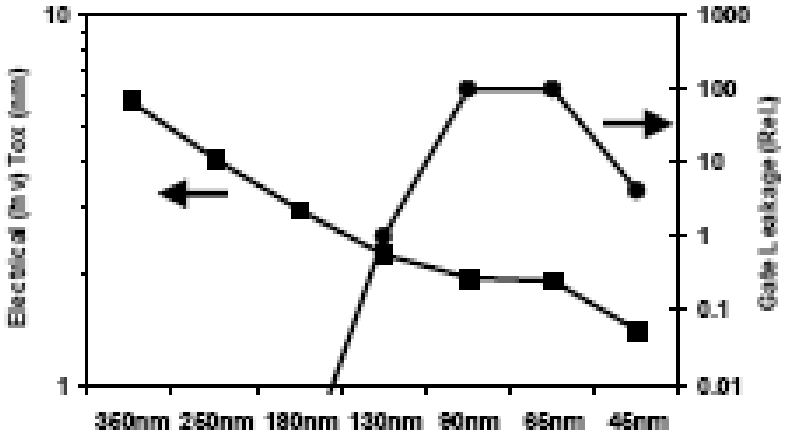
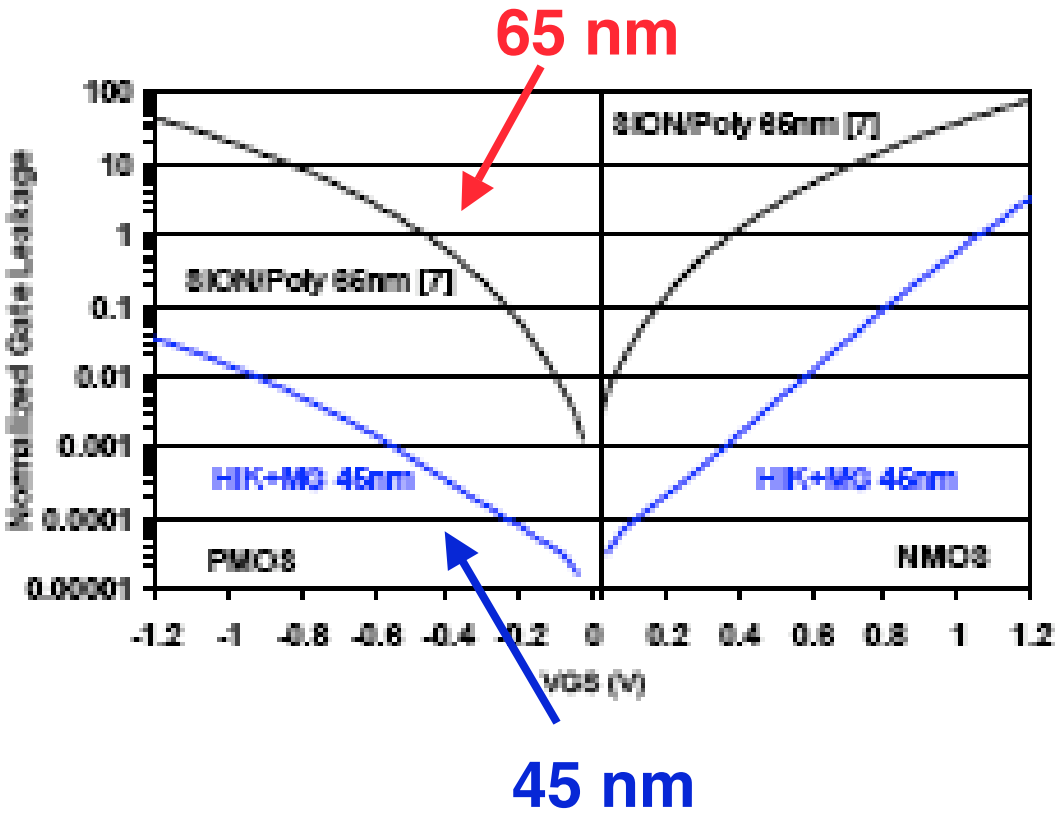


Fig. 1 Intel scaling trend for inversion electrical T_{ox}



'Effective Oxide Thickness'

45 nm INTEL IN PRODUCTION : DRIVE

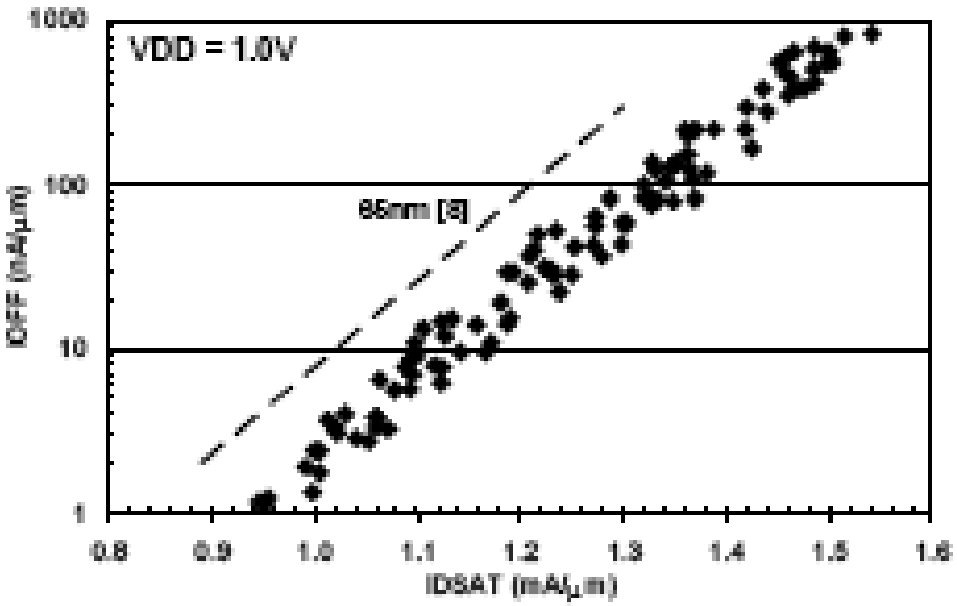


Fig.11 NMOS I_{DSAT} vs. I_{OFF} shows 1.36mA/µm at 1.0V & 100nA

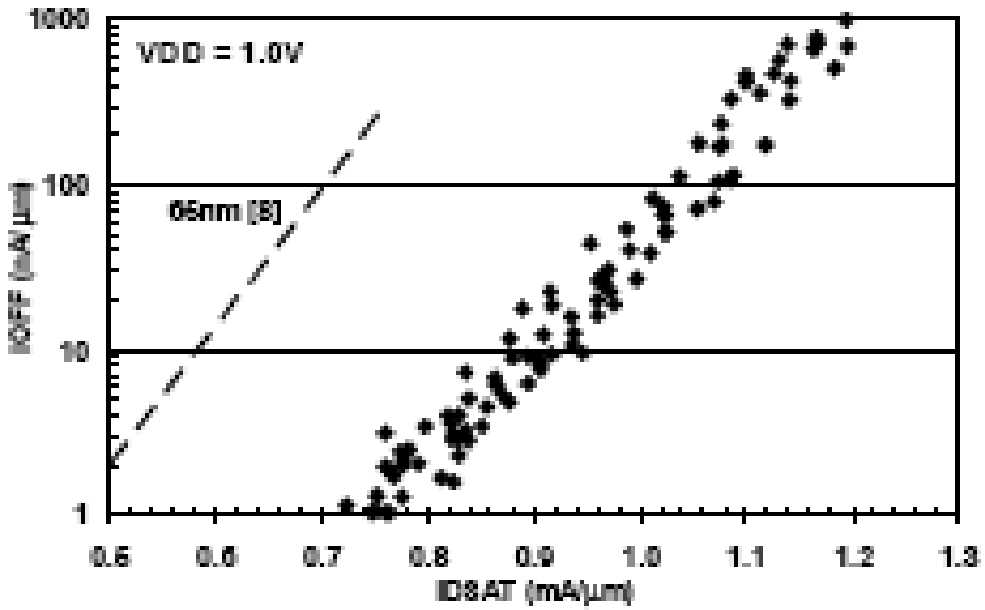


Fig.10 PMOS I_{DSAT} vs. I_{OFF} shows 1.07mA/µm at 1.0V & 100nA

1V

45 nm TRANSISTORS IMPROVED compared to 65 nm

45 nm INTEL IN PRODUCTION

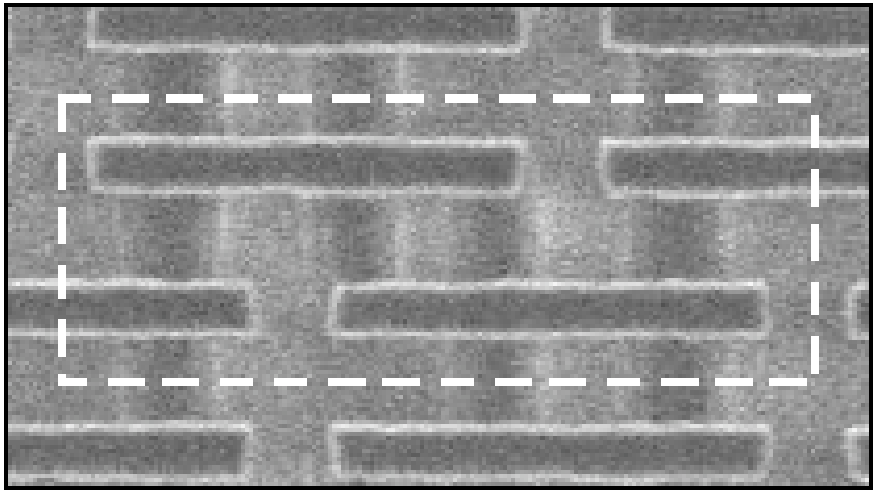


Fig. 4 Diffusion and poly layers of 0.346 μm^2 6-T SRAM cell

SRAM CELL

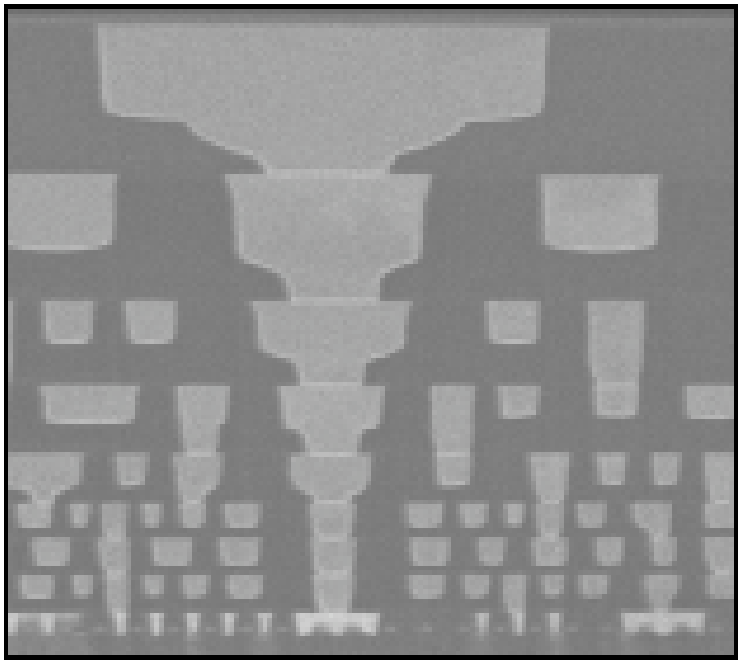


Fig.16 Cross-section of 8 of the 9 Cu interconnect layers

9 METAL STACK

45 nm TSMC IN PRODUCTION

STRAIN, <110>

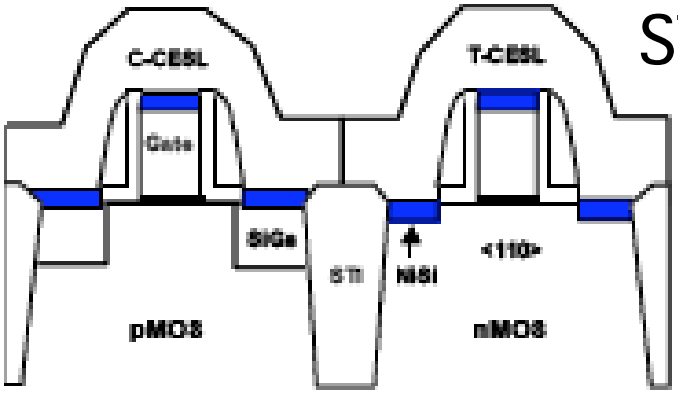


Fig. 3 Schematic illustration of strain-optimized CMOS structures, utilizing <110> channel, e-SiGe, SMT and d-CESL.

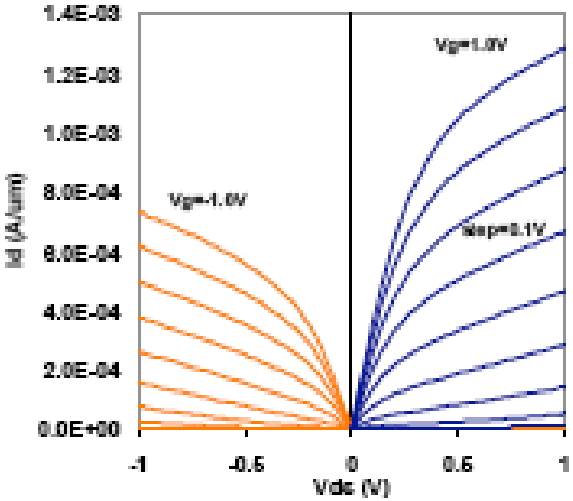


Fig. 7 N/P-MOS output characteristic.

1 V

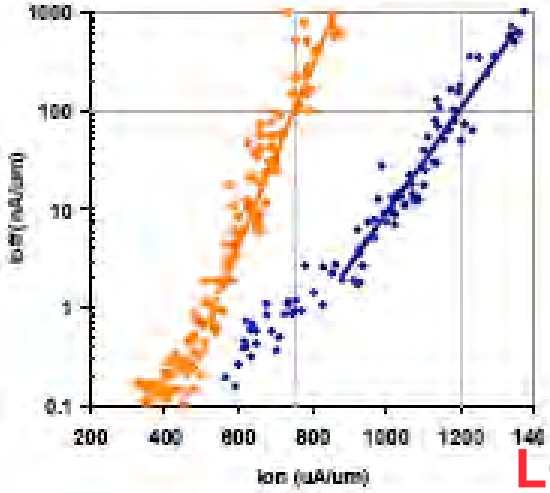


Fig. 5 The 45nm CMOS Ion-Ioff performance at 1.0V.

LOW LEAKAGE

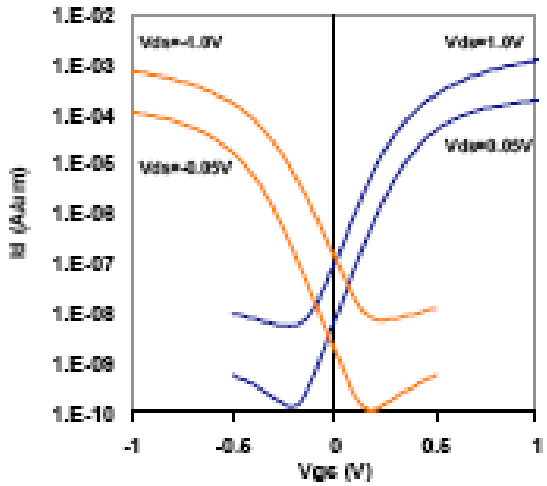


Fig. 6 N/P-MOS sub-threshold characteristic at Vd=1.0 & 0.05V.

45 nm TSMC IN PRODUCTION

SMALL SRAM CELL

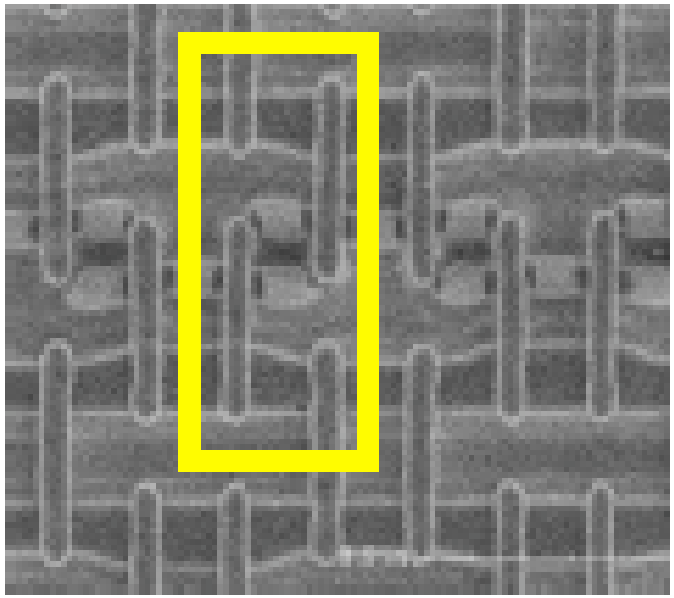


Fig. 10 0.242 SRAM bit-cell top-view SEM

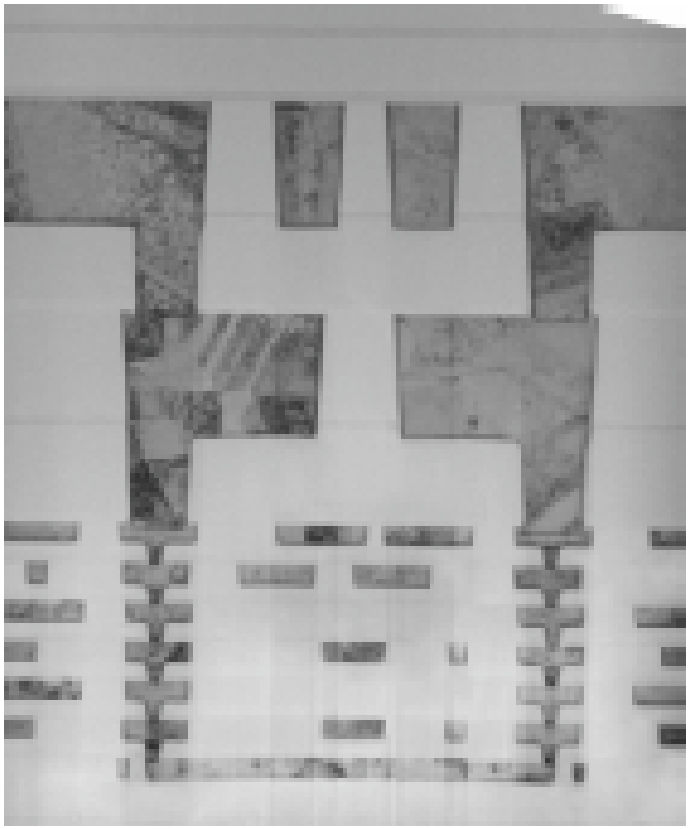


Fig. 12 X-TEM of 7+2M BEOL process.

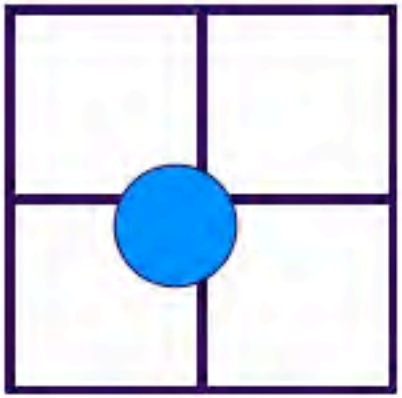
9 METAL STACK

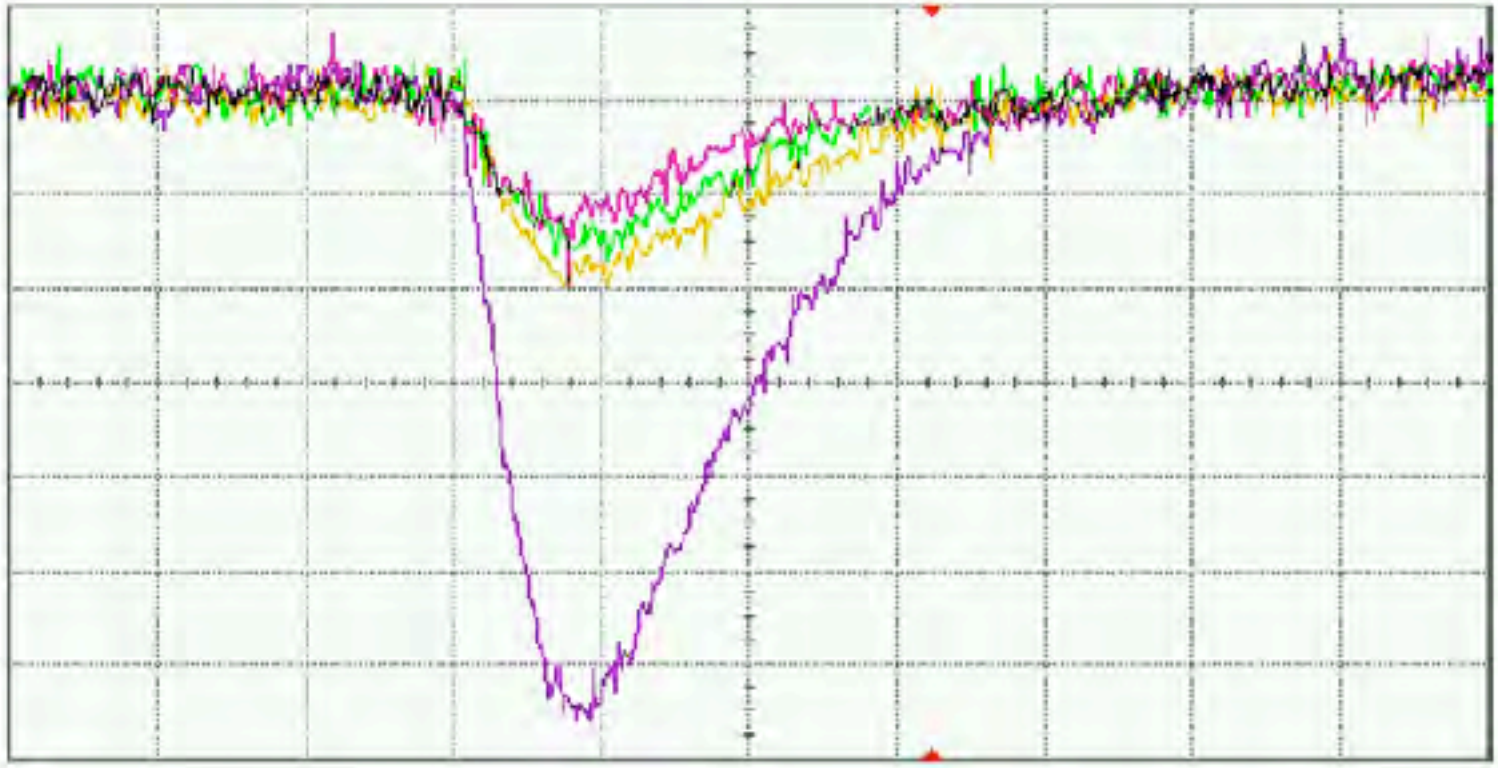
MEDIPIX3

ATTACKS CHARGE SHARING

NEED for MORE TRANSISTORS

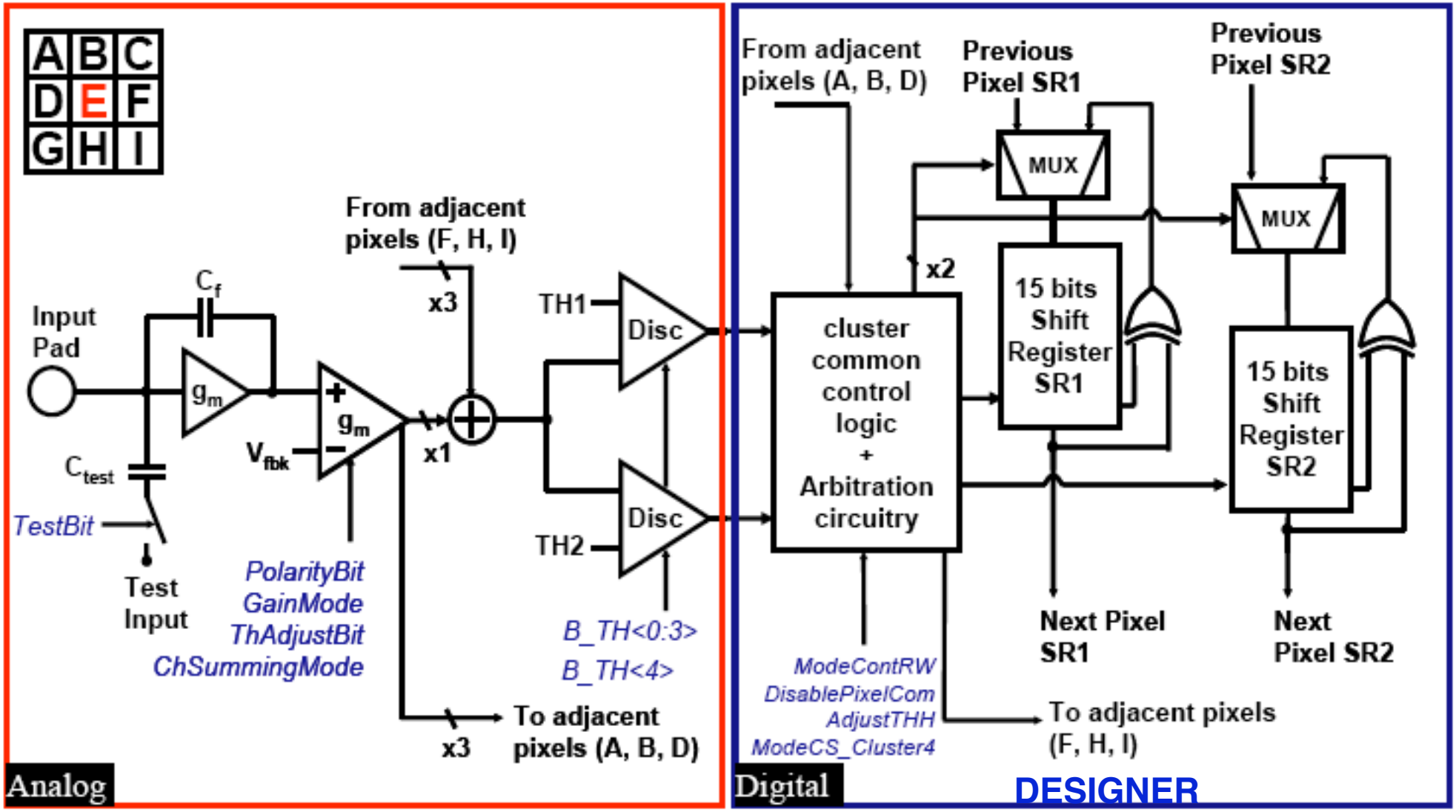
CHARGE SPREAD



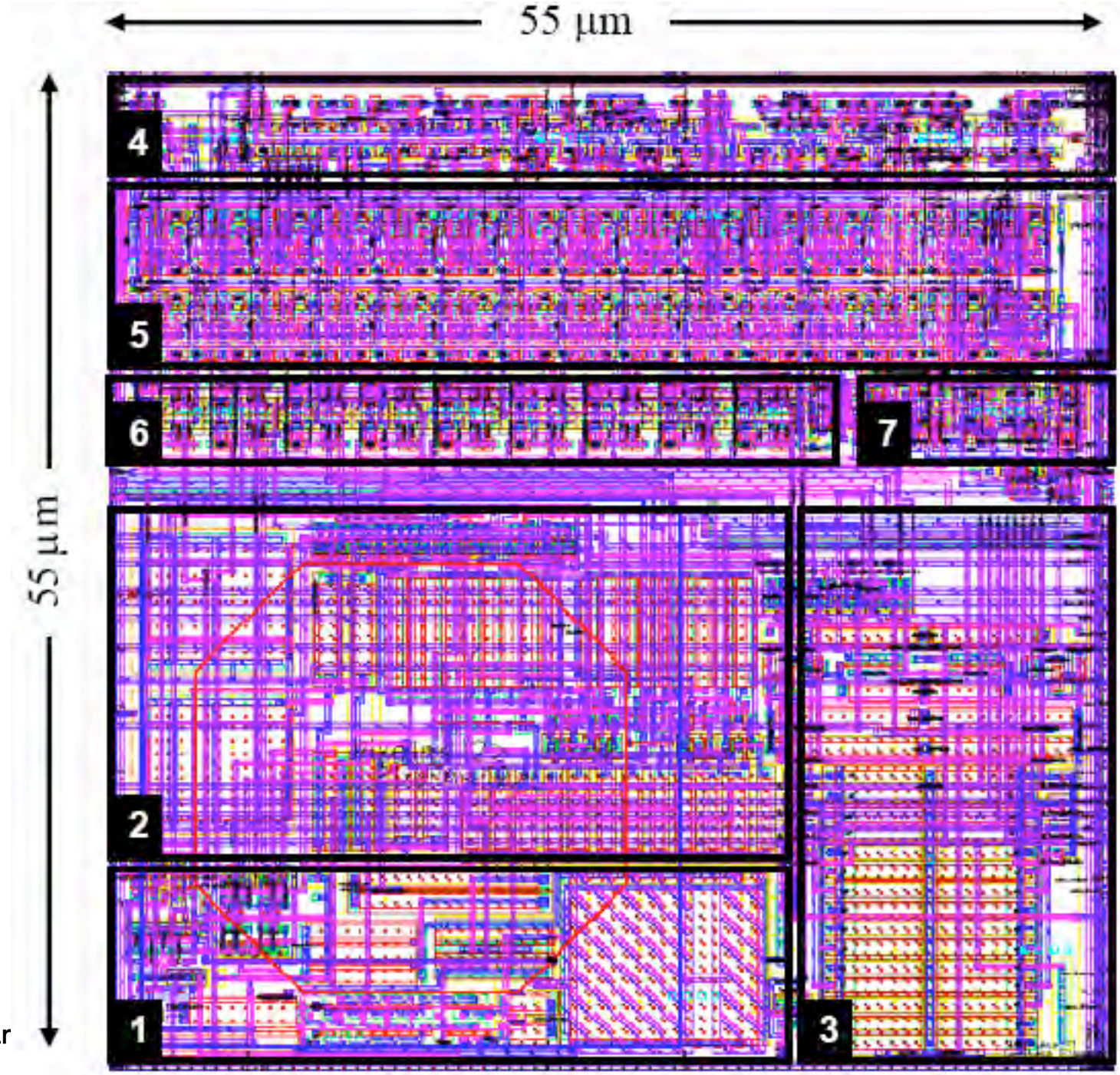


ANALOG SHARING

MEDIPIX3 PRELIMINARY SCHEMATIC



DESIGNER
Rafael BALLABRIGA
CERN


55 µm
55 µm
4
5
6
7
2
1
3

PROGRESS in Si SENSORS

DEPENDS on AVAILABLE INDUSTRIAL TECHNOLOGY

0-D	SINGLE DIODE		1955
1-D	SEGMENTED DIODE	mm	1960
QUASI 2-D	DOUBLE-SIDED STRIPS		1965
TRUE 2-D	CCD/MOS MATRIX		1971
	PIXELS	MONO or HYBRID	1989
	PILLARS	'3D'	1998
TRUE 3-D	VOXELS	next step	?

END