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The final JRA1 beam telescope chip and its successors

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- Where did we start from ?
- The demonstrator sensor
- The road to high speed (I&SDC)
- Performances of the final TC
- Improving the final TC
- Outlook

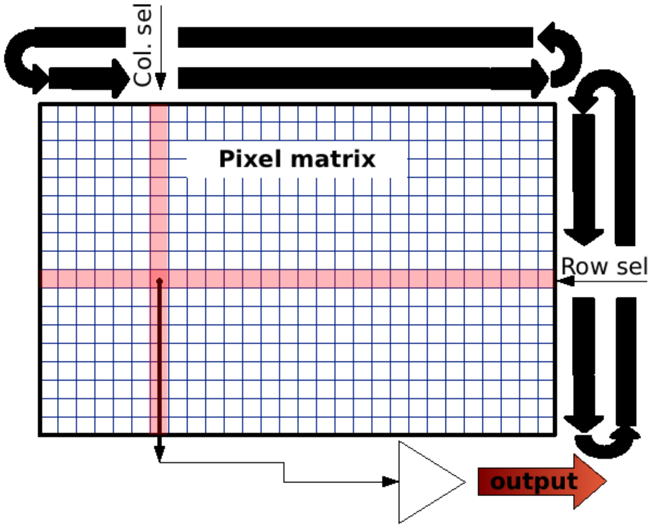
Where did we start from?

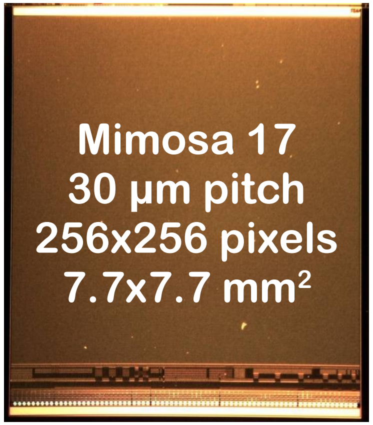
- Requirements on the telescope chip (TC)
  - Single point resolution 2-4 µm
  - Thickness in the sensitive area < 100 µm
  - Readout time 5-10 kHz
  - Operation at controlled temperature ~20 °C
  - Radiation induced by 10^{11} e^- or 10^{12} π^- per year
    - $\leq$ 100 Krad
    - $\leq 10^{12}\ n_{eq}/cm^2$
  - Quantity: 6 planes and some spares
- Time-line
  - 2007: Provide a readily available sensor for the demonstrator telescope
  - 2009: final Telescope Chip

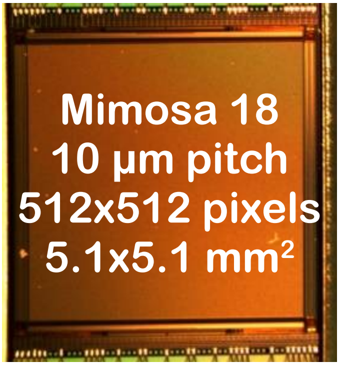
The demonstrator chips

Demonstrating the resolution

- No need (yet) for fast readout speed
  → allow to use analog output
- Minimal sensitive area 5x5 mm^2
- Provide standard res. for telescope arms and high res. for proximity reference

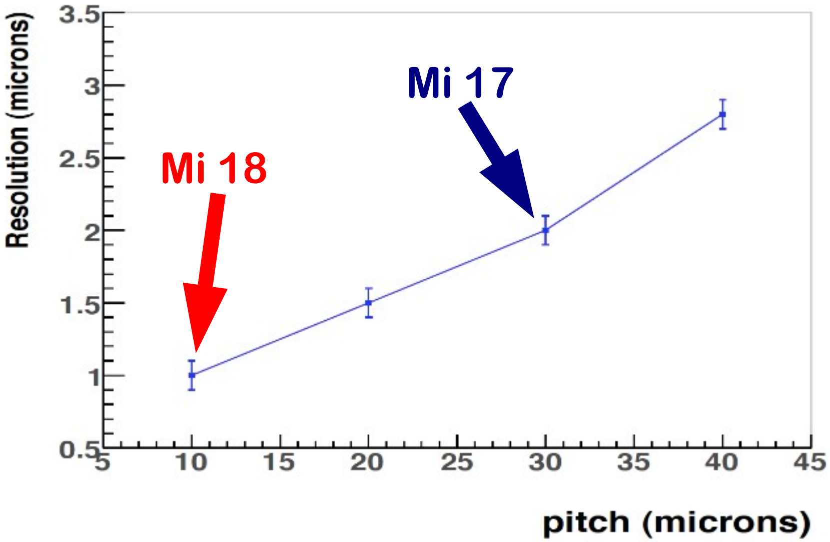


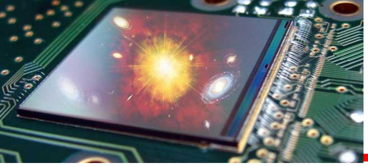




MIMOSA 17, 18

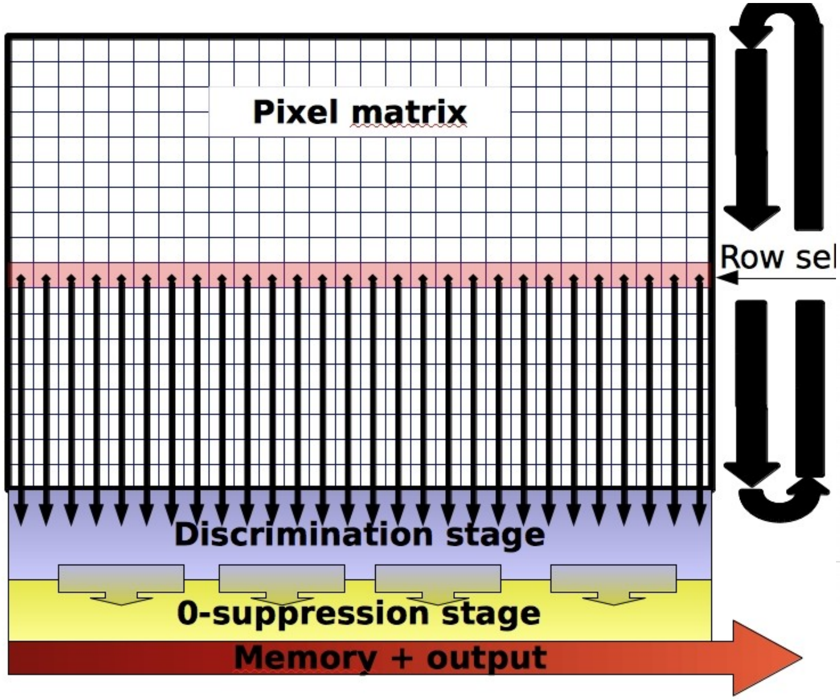
- Process AMS 0.35 µm OPTO
- 14µm epitaxial layer
- “self-bias” pixel
  → 1 readout = 1 frame ([n]-[n-1])
- Fabricated in 2006
- Clock frequency 20 MHz
  & 4 parallel outputs
  → 860 µs readout time for M17
  → 3276 µs readout time for M18

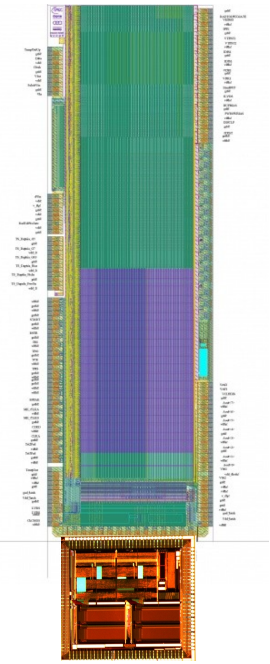




The road to high speed

- **Read only the necessary information**
  - Include CDS (correlated double sampling) in pixel
  - Discriminate pixel output
  - Suppress zeros
  - ⇒ column parallel binary output
- **A new sensor architecture needed**
  - 2 intermediate chips for each functionality
  - Process AMS 0.35 µm OPTO
  - Fabricated 2007 & 2008



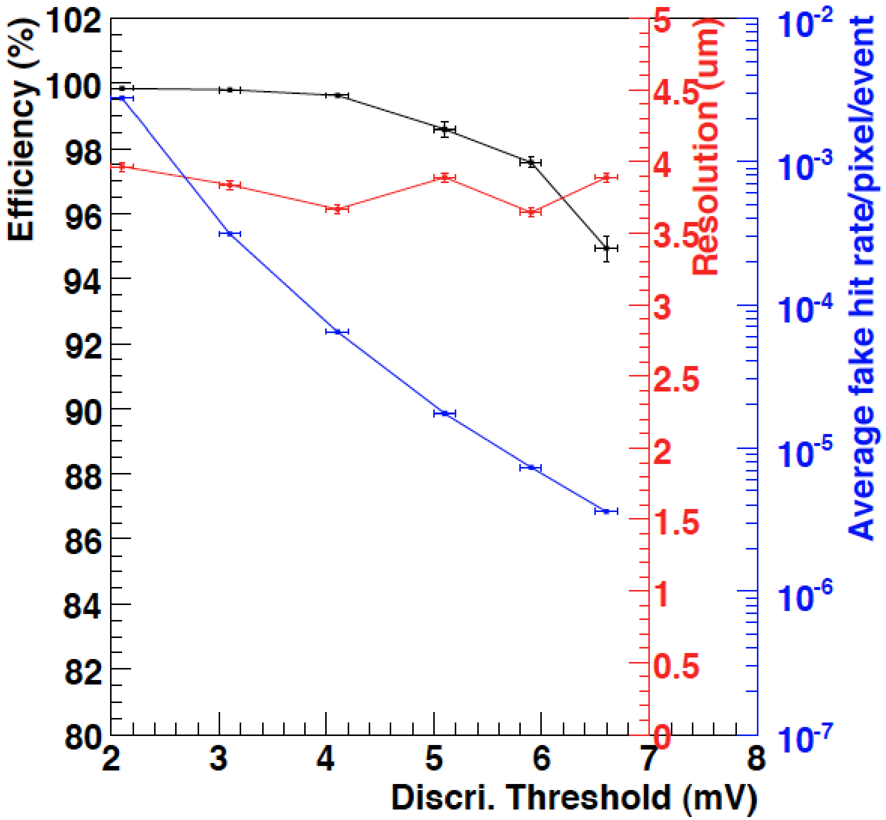


- **IDC = MIMOSA 22**
  - pixels with CDS + discriminator
  - 128 columns x 576 rows
  - pixels with 18.4 µm pitch
  - JTAG protocol for external tuning of steering voltages
- **SDC-2 = SUZE 01**
  - zeros suppression logic
  - 4 memories for readout

Intermediate chips performances

IDC / Mimosa 22 & 22bis

- Results from the evolution of several precursors (MIMOSA 8, 16)
- ~30 pixel variants to optimize ampli.
  - for CDS
  - for homogeneity / discrimination
  - for radiation tolerance
- Operation: $t_{r.o.}$ = 92.5 µs (80 MHz), T=20 °C
- Tested in beam with 120 GeV π- in 2008
  - Efficiency >99.8% with fake <10^{-4} hits/pixel
  - $\sigma_{s.p.}$ = 3.5 µm
  - Perf. Unaffected after 150 kRad

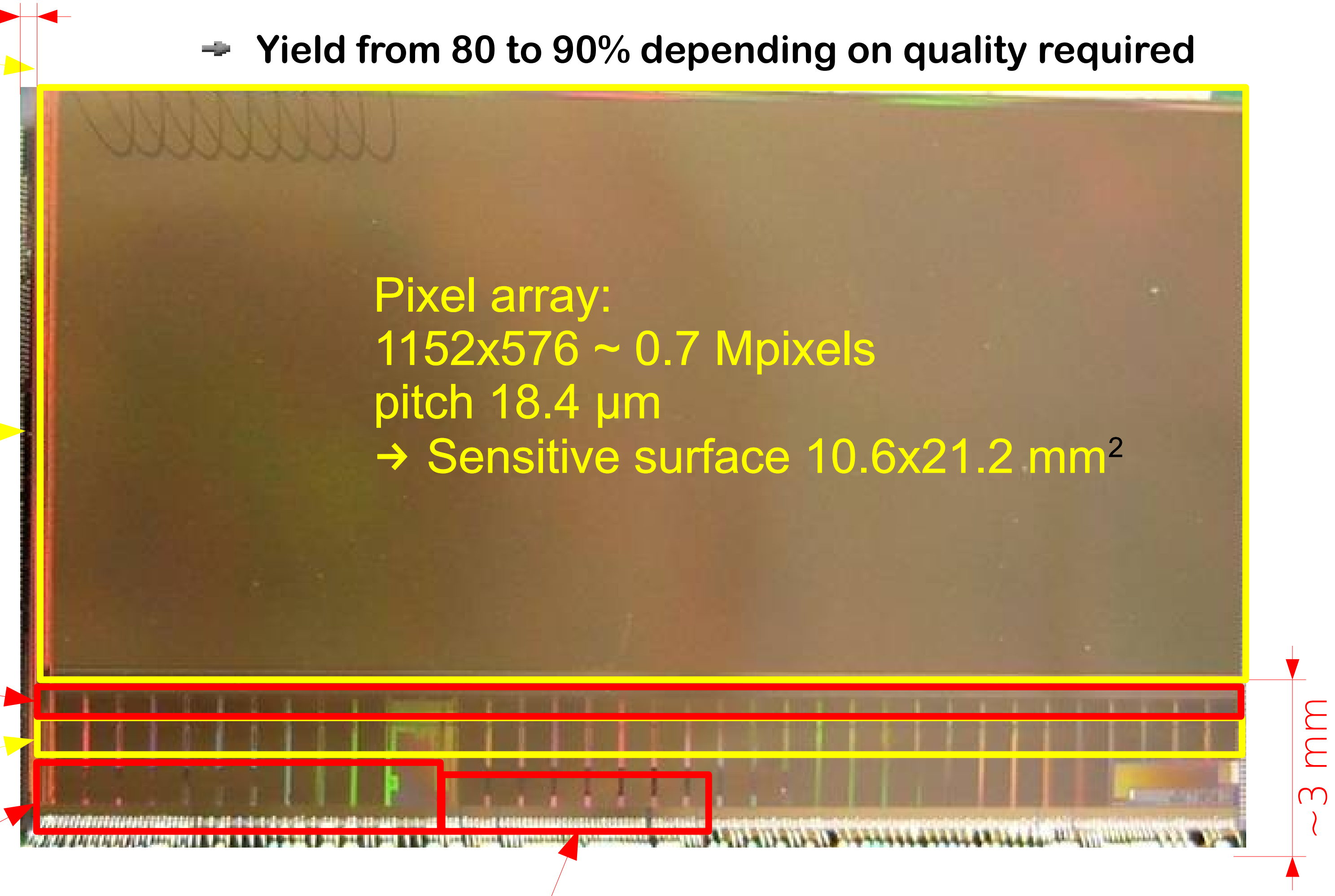


SDC-2 / SUZE 01

- Input patterns to mimic discriminator outputs
- Millions of inputs tested w/o errors
- Frequency 100 MHz = 1.15 x nominal
- Validated to handle > 100 hits/ frame @ 10^4 frame/s → 10^6 hits/s

The final Telescope Chip

- **TC / MIMOSA 26 ~ 10x MIMOSA 22 + 18x SUZE 01**
  - **Process AMS 0.35 µm OPTO**
  - **Fabricated end 2008 and thinned down to 120 µm**
  - **Yield from 80 to 90% depending on quality required**



300 µm

Analog outputs for test only

Row sequencer

Pixel array:
1152x576 ~ 0.7 Mpixels
pitch 18.4 µm
→ Sensitive surface 10.6x21.2 mm^2

1152 discriminators

zero-suppression

control (JTAG+DAC)

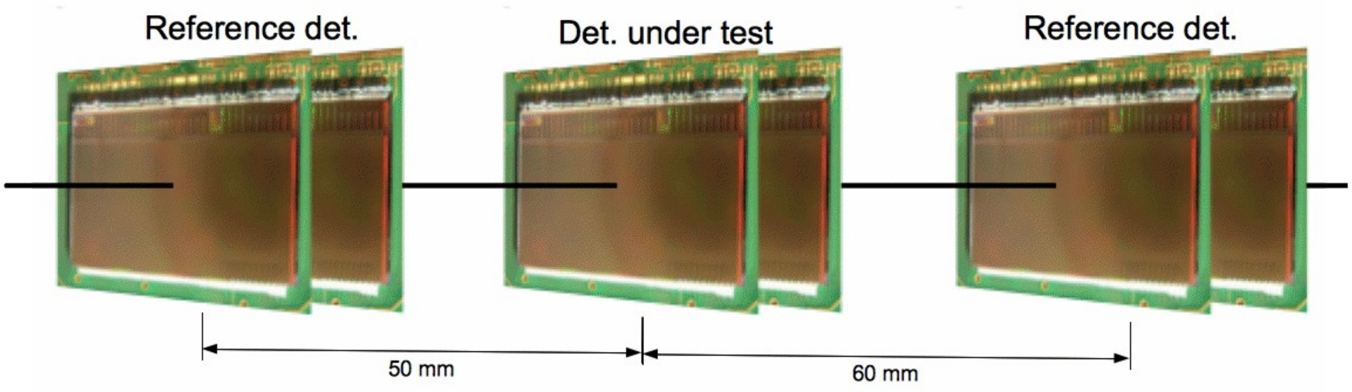
~3 mm

Memory for binary out

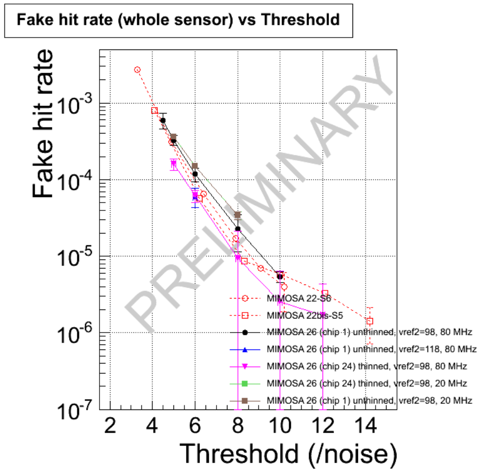
TC performances in Beam tests

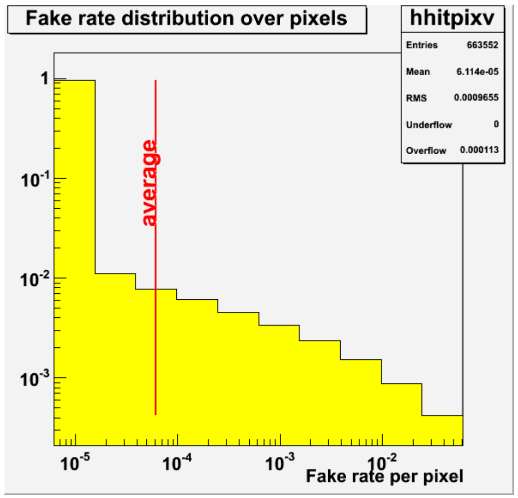
Beam test setup

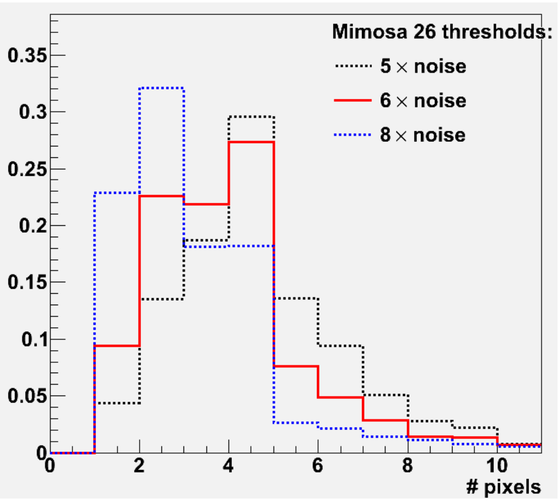
- 2009 & 2010 campaigns at CERN SPS with 120 GeV π-
- Using IPHC DAS based on NI-PXI digital IO board → event rate ~ kHz
- Operating at 80 MHz ($t_{r.o.}$ = 115 µs) and T=20 °C (80 Mbits/s @ output)

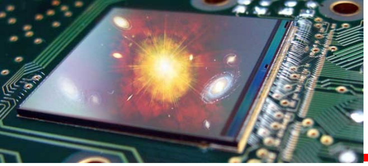


Thresholding strategy validation

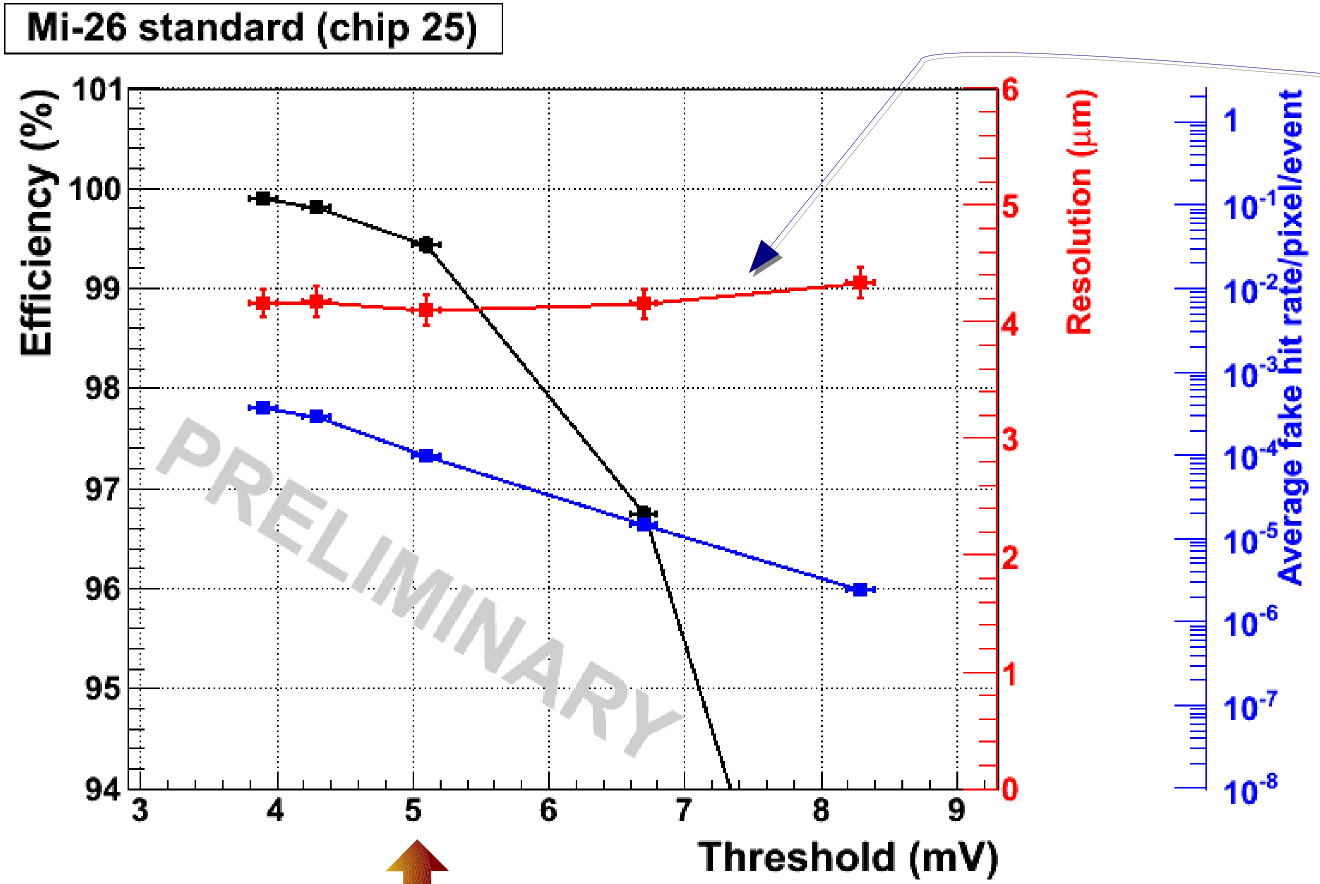








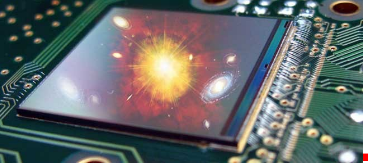
TC performances



! shift of .5 µm in resolution understood (alignment)

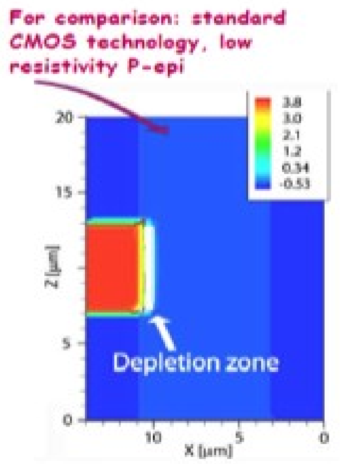
6 x noise ≡

- **Final TC / MIMOSA 26 performances**
  - With typical threshold ~6 x noise
    - Effi ~ 99.5 %, fake ~ 10^{-4} hits/pixel, $\sigma_{s.p.}$ ~ 3.5 µm
  - Used in EUDET telescope since summer 2009

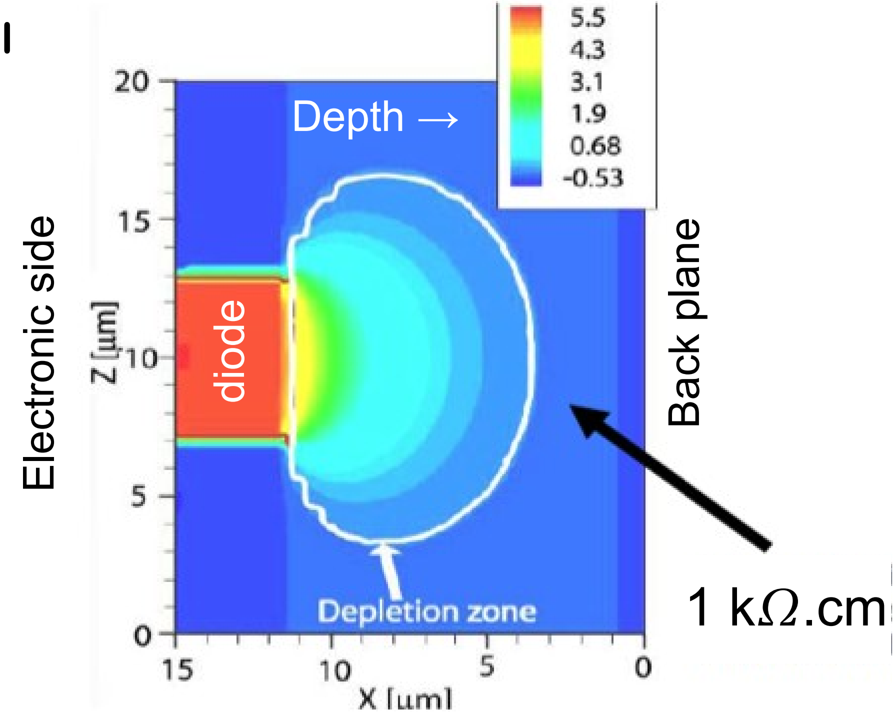


Improving the q-collection effi.

- **High resistivity (HR) epitaxial layer**
  - In standard CMOS process:
    - Epitaxial layer P-doped $O(10^{15})$ atom/cm^3 → resistivity ~10 Ohm.cm
    - charges drift thermally
  - Newly available low-doped $O(10^{13})$ atom/cm^3 epitaxial layer
    - increases the resistivity $\gg$100 Ohm.cm → deeper depletion (still largely incomplete)
    - Note: depletion level depends on diode voltage
  - Expected shorter collection time & more focused
    → better non-ionizing radiation tolerance
    → larger signal-over-noise ratio on single pixel
    → better resolution ?
- **TCAD simulation for one pixel**

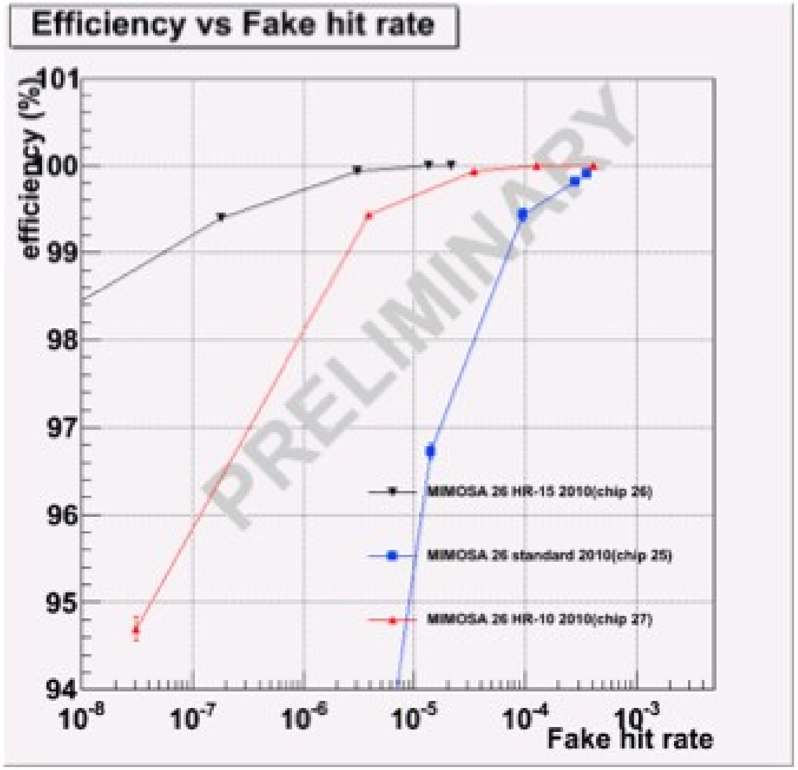


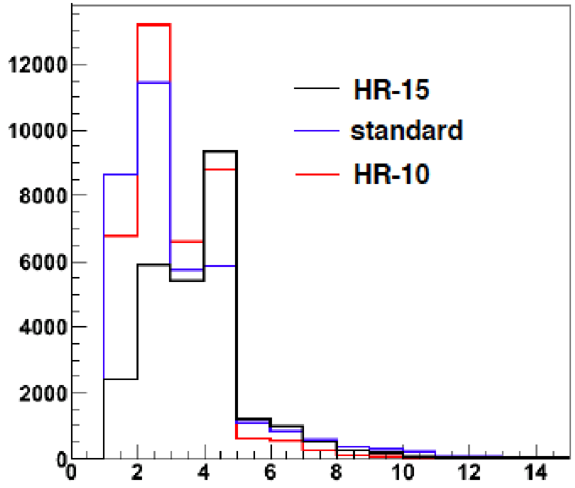
For comparison: standard CMOS technology, low resistivity P-epi



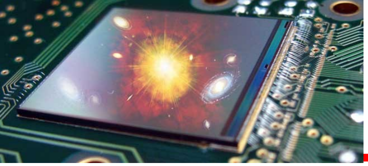
Better TC performances

- **Final final TC = MIMOSA 26-AHR**
  - Process AMS 0.35 µm OPTO with 400 Ohm.cm resistivity epi. layer
  - Exact same layout / MIMOSA 26
  - Fabricated in 2009 with 3 composite epi.: 10, 15 & 20 µm thick
  - Yield at least as good as std. Epi. layer
  - Thinned down to 50 µm
- **Characterization**
  - Operating @ $t_{r.o.}$ = 115 µs and T=20 °C
  - Test in lab with Ru source (MIP-like β)
    S/N x 1.5 to 2 from std to HR epi.
    (depending on epi. thickness)
  - Beam test in summer 2010 with 120 GeV π^-
  - Irradiated sensors at
    - 150, 300, 500, 1000 kRad
    - 3., 6., 10., 30. 10^{12} n_{eq}/cm^2



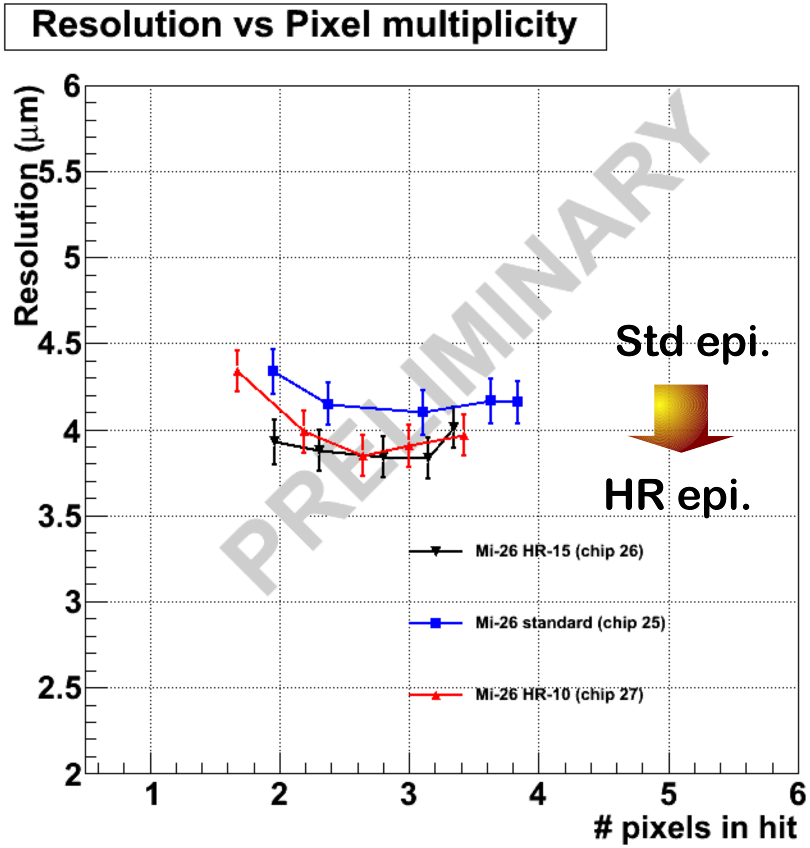


Pixel multiplicity in hit at fake rate 10-5 hit/pixel



Better TC performances

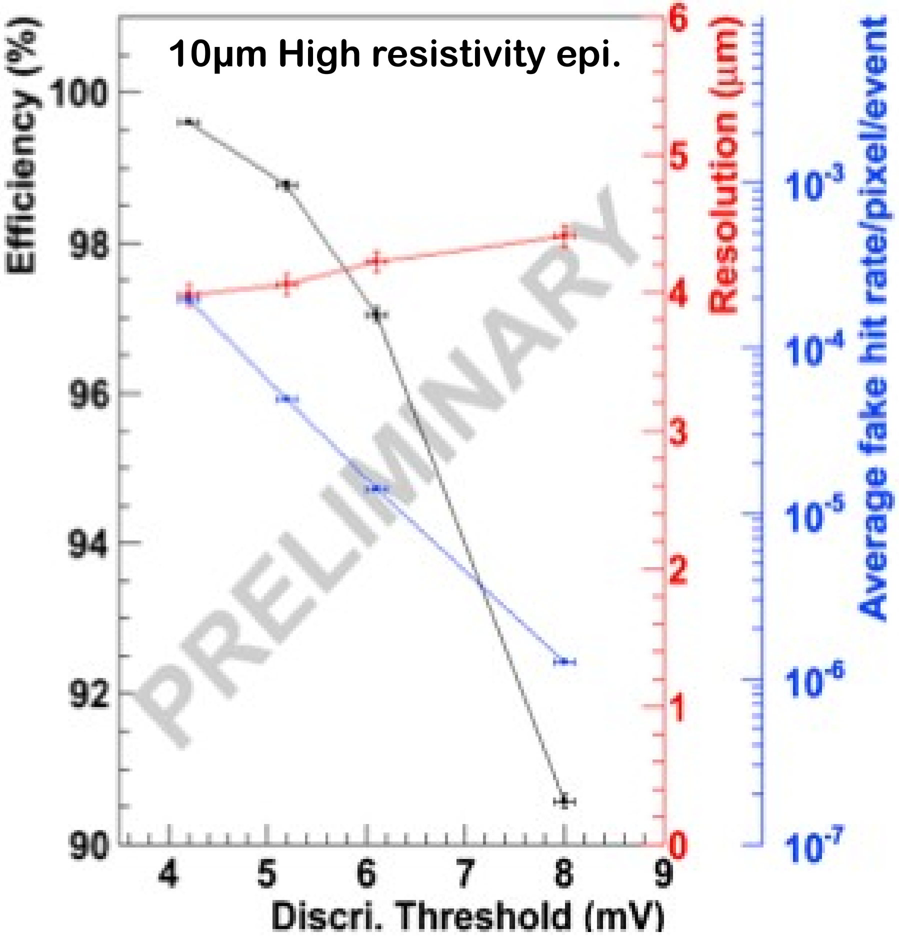
- **Resolution vs pixel multiplicity**
- **After irradiation at 1.10^{13} n$_{eq}$/cm^{2}**
  - Test at 0 °C



Std epi.

HR epi.

Note: overall shift of .5 µm in resolution (alignment)

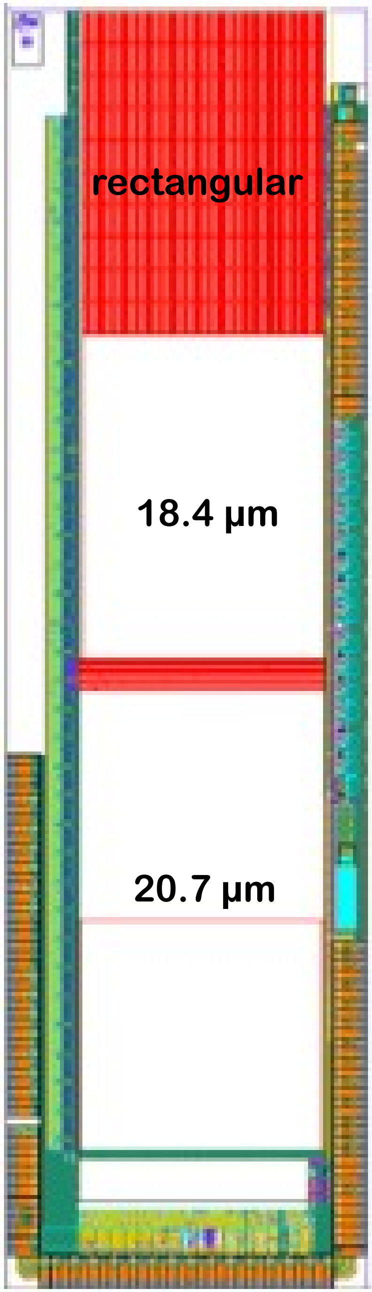


10µm High resistivity epi.

Beyond the TC

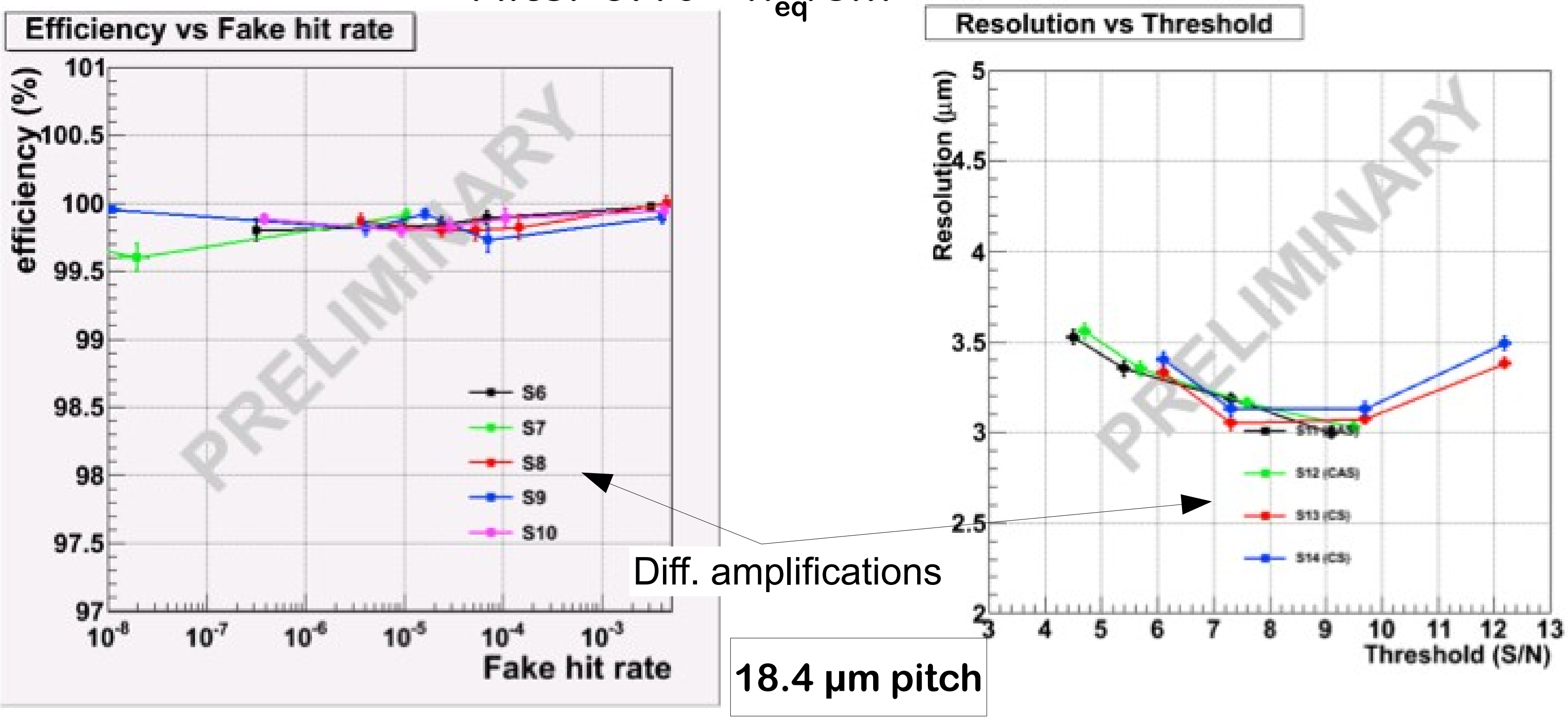
IDC / MIMOSA 22-AHR

- Process AMS 0.35 µm OPTO
  with 400 Ohm.cm resistivity
- Same global geometry / MIMOSA 22
  - 128 columns x 578 rows
- Fabricated 2010 with 3 epi: 10, 15 & 20 µm thick
- New pixel designs
  - Different amplification schemes & diode biasing
  - Different pitch 18.4, 20.7 µm & rectangular pixels
- Irradiated sensors at
  - 150 kRad
  - 3. and 6.10^{12} neq/cm^2
  - Combined 150 Krad+3.10^{12} n_{eq}/cm^2
- Operation $t_{r.o.}$= 92.5 µs (80 MHz), T=20 °C
- Beam test in late summer 2010 with 120 GeV π^-



Newest IDC performances

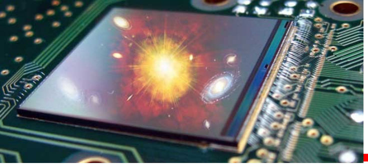
After 3.10^{12} n_{eq}/cm^2



Diff. amplifications

18.4 µm pitch

- **Improvements observed**
  - **Lower fake hit rate achievable @ ~100% efficiency below 1 hit/frame on the full matrix**
  - **Spatial resolution reaches 3µm: -0.5 µm with same pixel pitch**
  - **Performances stability with irradiation under study**



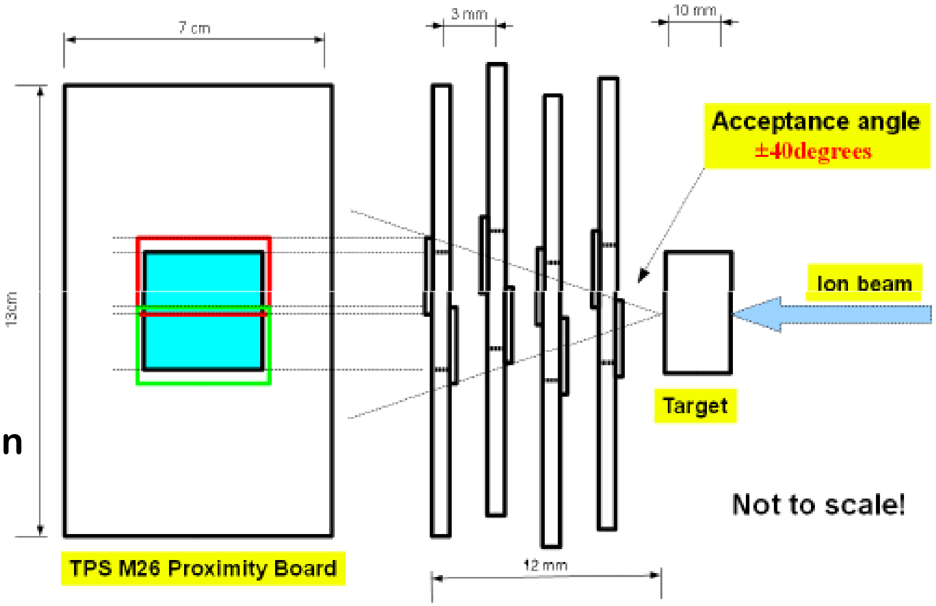
Outlook - 1 : direct applications

Facilities

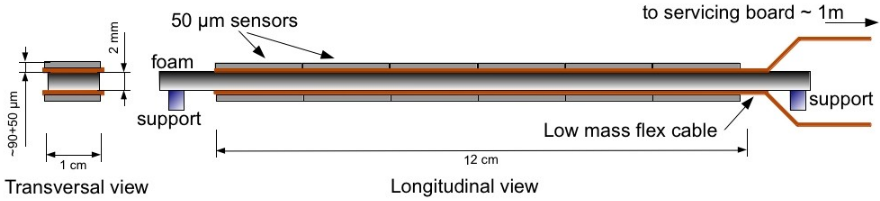
- Several telescope replications (ATLAS)
- Mass spectrometry (Bristol)

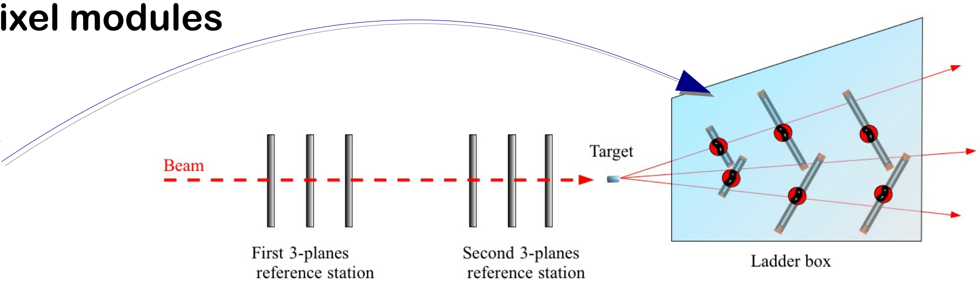
Vertex detectors

- FIRST @ GSI: hadrontherapy
  - low energy fixed target collisions
  - Doubly diff. Xsections measurement for carbon
  - data taking in summer 2011
  - With INFN (E.Spiriti)

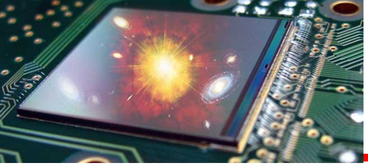


- PLUME Pixelated Ladder with Ultra-low Material Embedding (Bristol U., DESY, IHC, Oxford U.)
  - Demonstrator for <.3% X0 double-sided pixel modules
  - Ready by 2012





AIDA setup



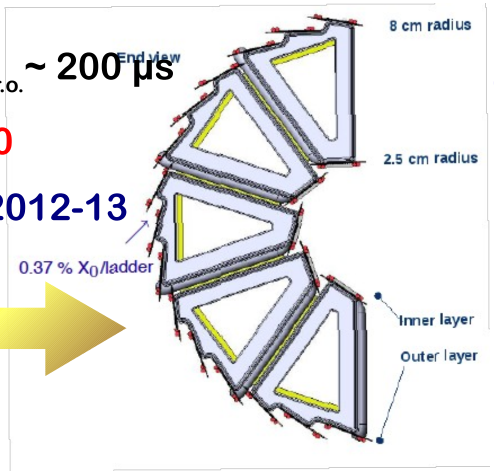
Outlook - 2 : extensions

Telescope facility

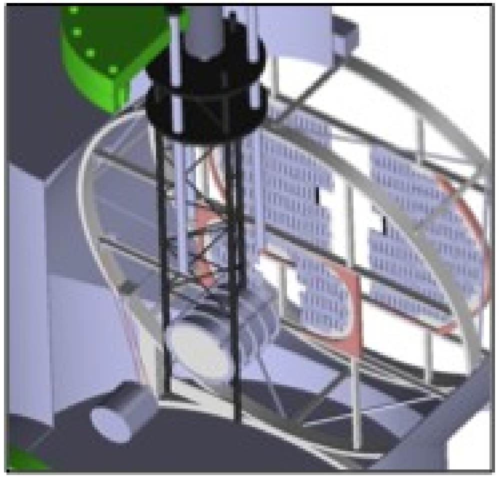
- AIDA
  - Larger surface 5x5 cm2
  - Timestamping

Vertex detectors

- STAR @ RHIC: heavy ion collisions
  - With LBNL
  - ULTIMATE sensor ~2x2 cm^2 @ $t_{r.o.}$ ~ 200 µs
  - Single material budget ~0.3% X0
  - Submission 2010, first data by 2012-13

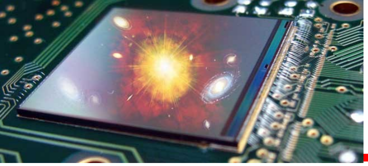


- CBM @ SIS: heavy ion collisions
  - With IK-Frankfurt
  - MIMOSIS sensor, $t_{r.o.} \leq 10 \mu s$, $\sigma_{s.p.} \leq 5\ \mu m$
  - Rad. tol. required ~MRad and $\geq 10^{13}\ n_{eq}/cm^2$
  - SIS100 running in 2016 , SIS300 for 2020



Calorimetry

- ALICE @ LHC: heavy ion collisions
  - FOrward CALorimeter project with NIKHEV & Bergen
  - W+Si compact sandwich < 80cm
  - 50 m^2 cumulated sensitive area !
  - 100 µm pitch, $t_{r.o.}$ < 50 µs
  - Prototype in ALICE: 2011 (using STAR sensor)
  - Final installation: 2016



Conclusion

Development path

- Benefited from the quick turn-over of the CMOS technology
- Demonstrator Chip version in 2007, a final TC version in 2008, and improved final TC version in 2010 (<u>thanks to the additional EUDET year</u>)

Final performances of the TC

- Efficiency $\geq$ 99.8% for a fake rate $\leq 10^{-6}$ hit/pixel/frame
- Single point resolution ~3.5µm
- Manage 10^4 frames/s and 10^6 hits/cm^2/s
- Performances unaltered after at least 150 kRad and 3.10^{12} n_{eq}/cm^2

Promises for future applications

- TC readily usable for a number of experiments (2011)
- Evolution of TC (sensitive area, readout speed, radiation tolerance) will pave the way to more demanding experiments for 2013 and beyond