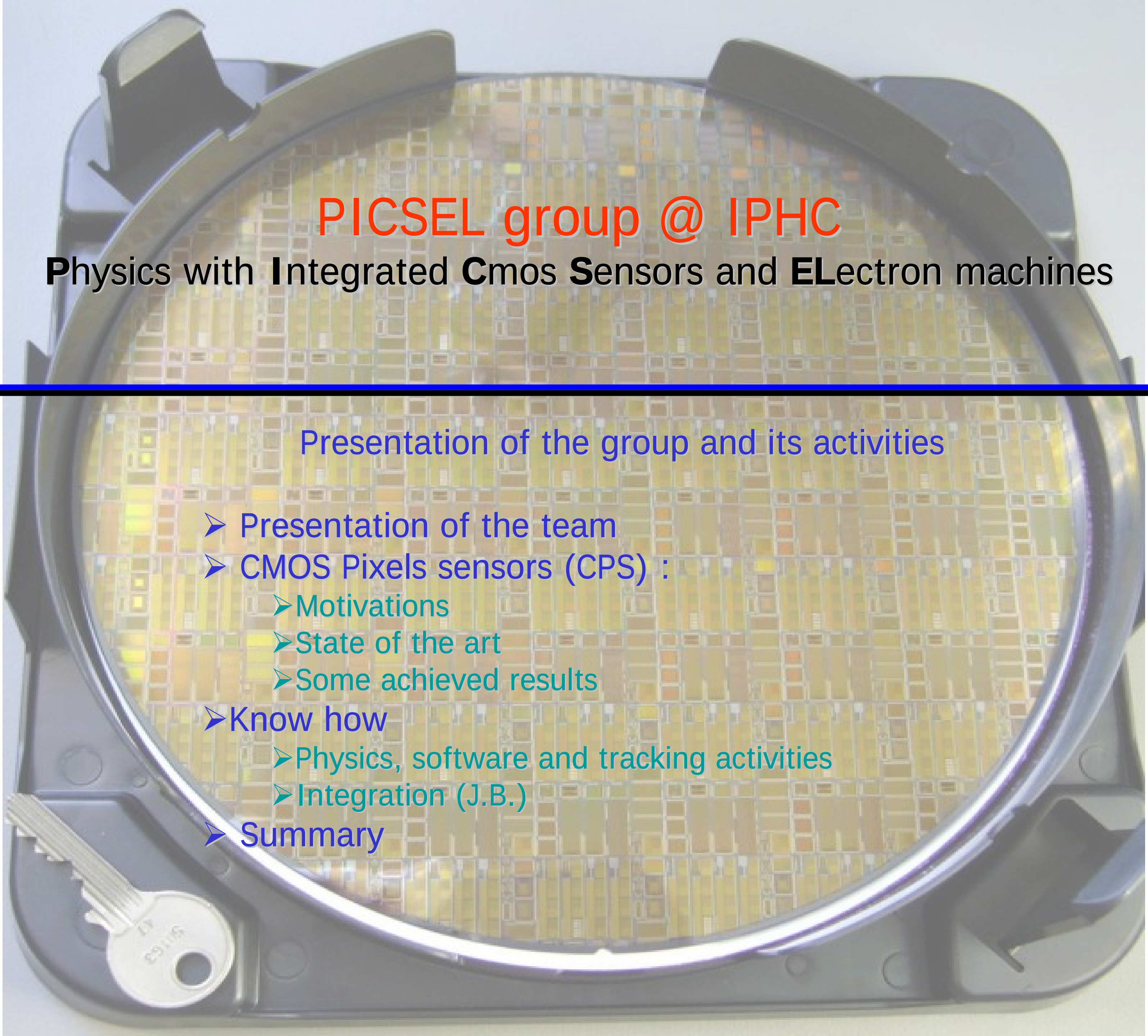


PICSEL group @ IPHC

Physics with **I**ntegrated **C**mos **S**ensors and **EL**ectron machines

---

Presentation of the group and its activities

- Presentation of the team
- CMOS Pixels sensors (CPS) :
  - Motivations
  - State of the art
  - Some achieved results
- Know how
  - Physics, software and tracking activities
  - Integration (J.B.)
- Summary

PICSEL: Group history & composition

PICSEL

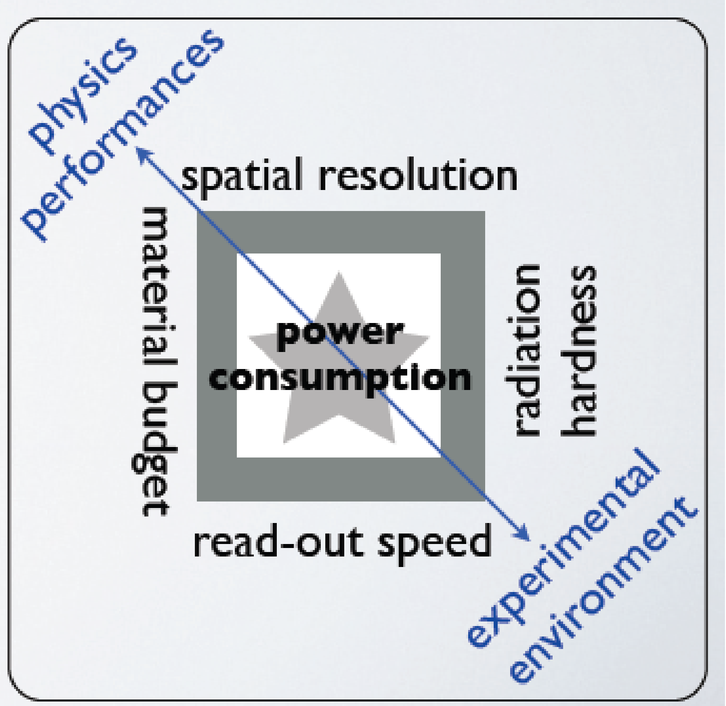
- Physicists
  - Permanents
    - ➢ Marc WINTER (Project coordinator), since 1999 ⇨ (..., DELPHI, PICSEL)
    - ➢ Jerome BAUDOT (Professor), since 2006 ⇨ (DELPHI, STAR, ALICE, PICSEL)
    - ➢ Isabelle RIPP-BAUDOT (researcher), since 2010 ⇨ (DELPHI, CMS, D0, SuperB, PICSEL)
    - ➢ Auguste BESSON (Assistant Professor), since 2003 ⇨ (D0, CMS, PICSEL)
  - Post-doc
    - ➢ Serhiy SENYUKOV (leaving dec.2013) ⇨ (ALICE, PICSEL)
    - ➢ Luis Alejandro PEREZ PEREZ (Sep.2013 – Sep.2016) ⇨ (Babar, CKMfitter, SuperB, PICSEL)
  - PHD students
    - ➢ Loic COUSIN (Sep 2011-Sep 2014) ⇨ (AIDA and alignment studies + double layers @ILD studies)
    - ➢ Robert MARIA (Sep 2012- Sep 2015) ⇨ (Time dependent asymmetry in D0 decays and plume + tracking in Belle 2)

µelectronics

- Microcircuit designers and support
  - 12 permanents (See Claude Colledani’s presentation)
- Test Experts
  - 6 permanents

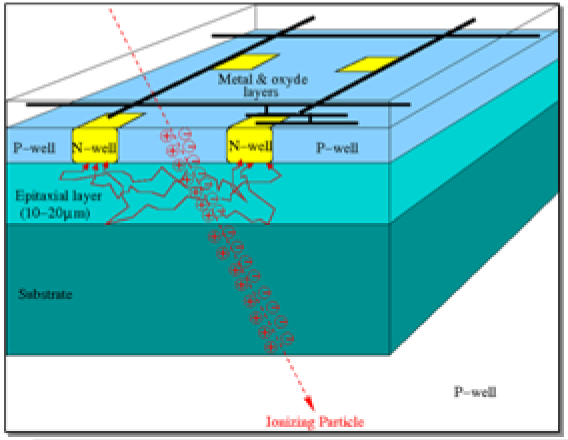
CPS and vertex detector optimisation: squaring the circle

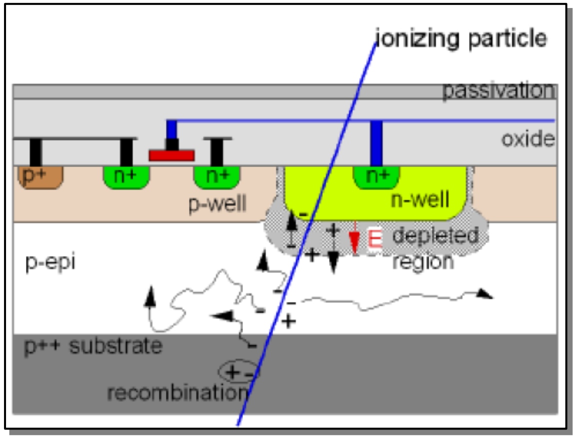
- Early 2000s
  - Different approach compared to hybrid pixels & LHC
  - Focus on resolution and material budget
- Vertex detector design and specifications
  - Physics performances
    - ➢ Spatial resolution
    - ➢ Material budget ⇦⇨multiple scattering
  - Experimental environment constraints
    - ➢ Radiation hardness (ionising and non ion. rad.)
    - ➢ Occupancy ⇦⇨Read-out speed
    - ➢ Power dissipation ⇦⇨ cooling ?
  - Other parameters
    - ➢ Costs, fabrication reliability and flexibility
    - ➢ Mechanical integration
    - ➢ Geometry
    - ➢ Alignment issues
- Interdependance of these parameters
  - e.g. lower radius of inner layer
    - ➢ Better $\sigma_{i.p.}$ but larger occupancy, higher rad.
    - ➢ Needs higher read-out speed and/or granularity ⇨ power dissipation



⇨ CPS presents an attractive trade off with respect to all these parameters

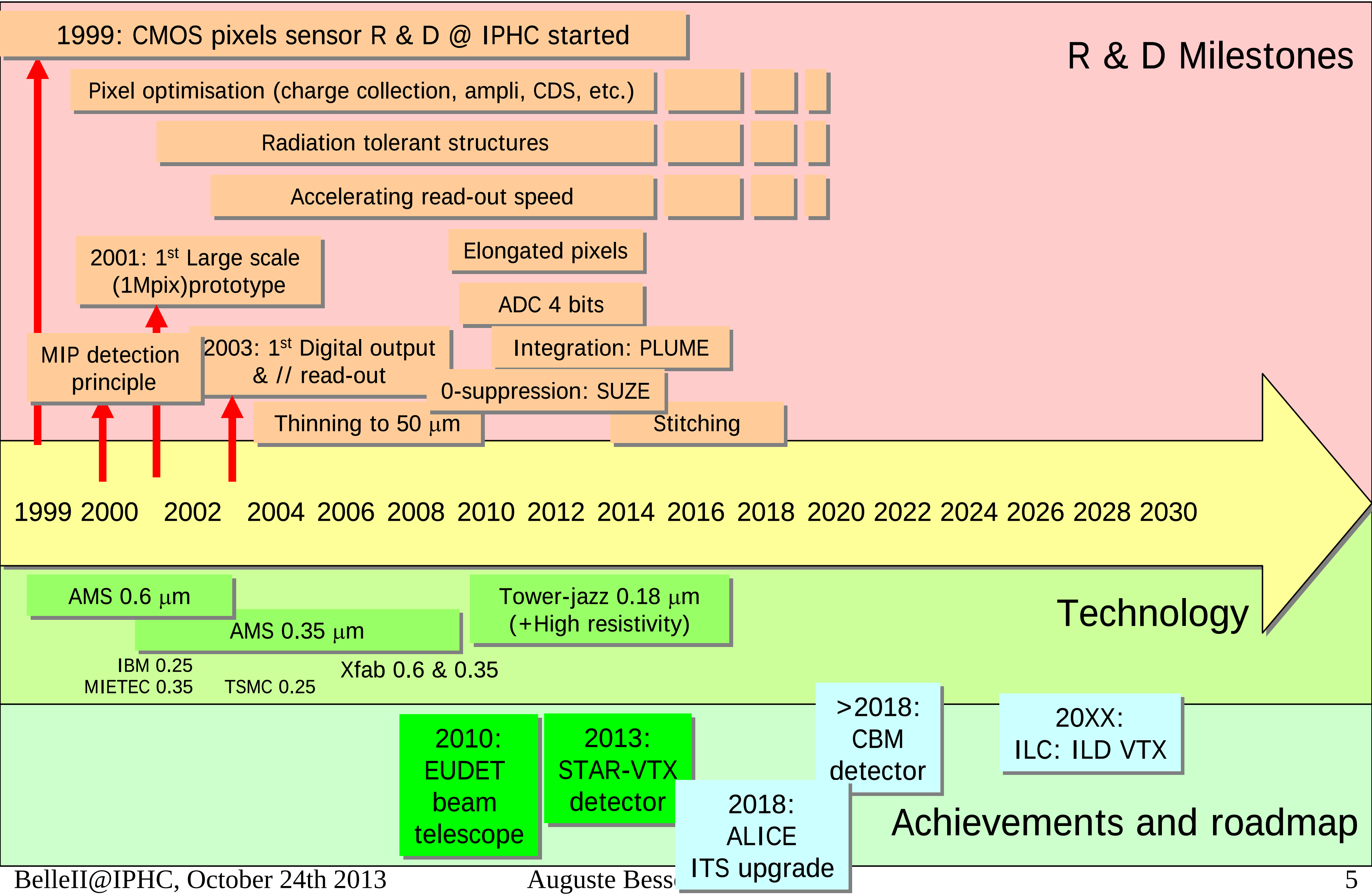
CMOS pixel sensor (CPS) for charged particle detection





- Main features
  - Monolithic, p-type Si
    - ➢ Signal created in low doped thin epitaxial layer ~10-20 μm
    - ➢ ~ 80 e- /μm ⇨ total signal ~ O(1000 e-)
  - Thermal diffusion of e-
    - ➢ Limited depleted region
    - ➢ Interface highly P-doped region: reflection on boundaries
  - Charge collection: N-Well diodes
    - ➢ Charge sharing ⇨ resolution
  - Continuous charge collection
    - ➢ No dead time
- Main Avantages
  - Granularity
    - ➢ Pixel pitch down to 10 x 10 μm^2 ⇨spatial resolution down to ~ 1 μm)
  - Material budget
    - ➢ Sensing part ~ 10-20 μm ⇨ whole sensor routinely thinned down to 50 μm
  - Signal processing integrated in the sensor
    - ➢ Compacity, flexibility, data flux
  - Flexible running conditions
    - ➢ From ≤ 0°C up to 30-40°C if necessary
    - ➢ Low power dissipation (~ 150-250 mW/cm^2) ⇨ material budget
    - ➢ Radiation tolerance: >~100s kRad and O(10^{12} n_{eq}) ⇨f(T,pitch)
  - Industrial mass production
    - ➢ Advantages on costs, yields, fast evolution of the technology, Possible frequent submissions
- Main limitation
  - Industry adresses applications far from HEP experiments concerns
    - ➢ Different optimisations on the parameters on the technologies
  - Recently: new accessible processes:
    - ➢ Smaller feature size, adapted epitaxial layer
    - ➢ Open the door for new applications

CMOS: Past, present and future: 15 years of R & D



R & D Milestones

1999: CMOS pixels sensor R & D @ IPHC started

Pixel optimisation (charge collection, ampli, CDS, etc.)

Radiation tolerant structures

Accelerating read-out speed

2001: 1st Large scale (1Mpix)prototype

MIP detection principle

2003: 1st Digital output & // read-out

Thinning to 50 µm

Elongated pixels

ADC 4 bits

Integration: PLUME

0-suppression: SUZE

Stitching

1999 2000 2002 2004 2006 2008 2010 2012 2014 2016 2018 2020 2022 2024 2026 2028 2030

Technology

AMS 0.6 µm

AMS 0.35 µm

IBM 0.25

MIETEC 0.35

TSMC 0.25

Xfab 0.6 & 0.35

Tower-jazz 0.18 µm (+High resistivity)

Achievements and roadmap

2010: EUDET beam telescope

2013: STAR-VTX detector

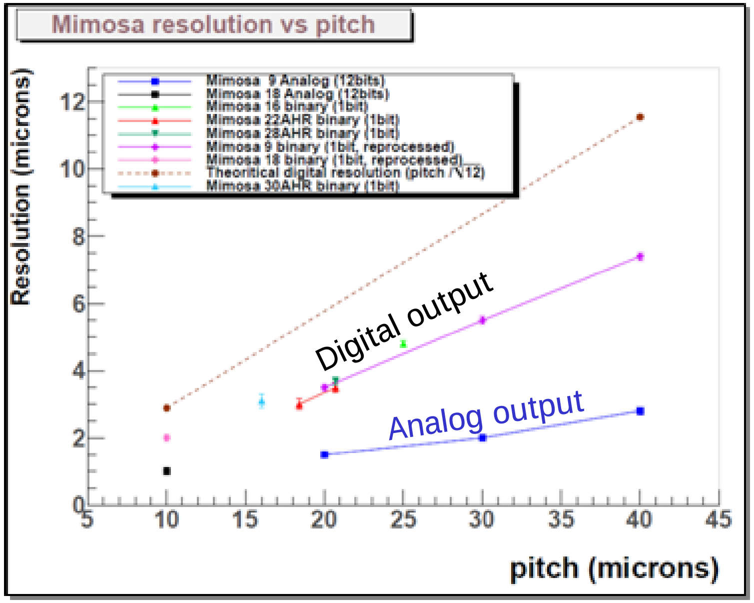
2018: ALICE ITS upgrade

>2018: CBM detector

20XX: ILC: ILD VTX

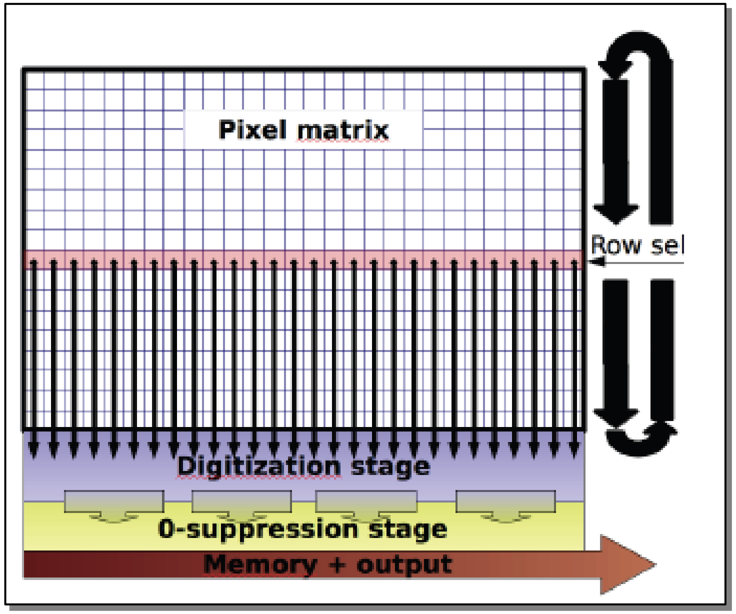
State of the art

- IPHC-Strasbourg and collab.
  - CPS developped since ~ 1999
    - 4-5 fabricated prototypes /year
    - 2-3 test beam campaigns /year
    - ~ 50 conferences
    - ~ 60 publications
    - ~ 15 PhD
  - Typical performances in AMS 0.35 μm technology
    - Detection efficiency ≥ 99.9% with fake rate ~≤ 10^{-5}
    - Typical spatial resolution (20 μm pitch) :
      - ~1.5 μm (analog output)
      - ~3.5 μm (digital output)



- Read-out architecture with digital output
  - In pixel preamplification and CDS
  - Column parallel rolling shutter read-out
    - Continuous read-out
    - Integration time = #rows x row r.o. time (100ns)
    - End-of-columns discriminators
    - Data sparsification (0-suppression)

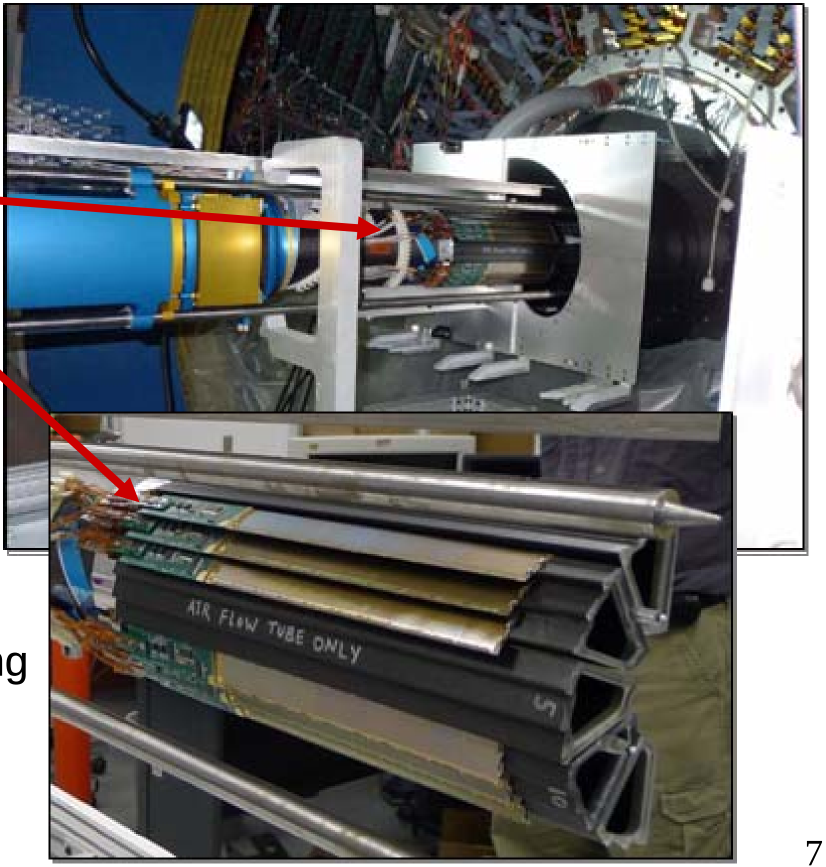
⇨enhances r.o. speed with preserving material budget, granularity and power comsumption



State of the art (2): current applications

- EUDET pixel telescope
  - Beam telescope (FP6 project)
    - ➢ 6 x Mimosa-26 planes (// r.o. and dig output)
    - ➢ Successfully operating since 2008

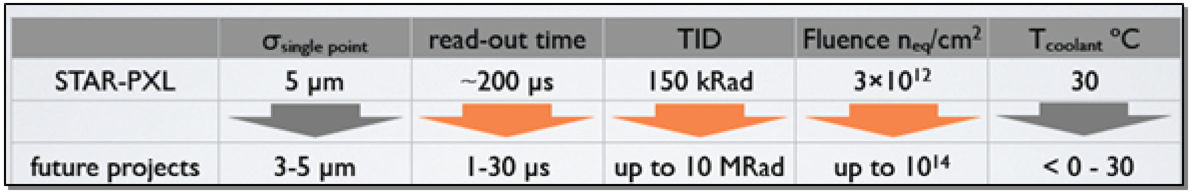
- STAR PXL detector
  - First vertex detector equipped with CPS
    - ➢ 2 layers = 40 ladders x 10 sensors
    - ➢ First sectors (3/10) installed May 2013
    - ➢ Commissioning completed
    - ➢ End of construction under way



- Prototype: Mimosa-28 (Ultimate)
  - ➢ AMS 0.35 μm techno with high resisitivity epitaxial layer
  - ➢ 960 x 928 pixels, 20.7 μm pitch ➩ 3.8 cm^2
  - ➢ In pixel CDS & ampli, collumn parallel read-out
  - ➢ End of column discri. and binary charge encoding
  - ➢ On chip zero suppression

Upgrade for more demanding applications

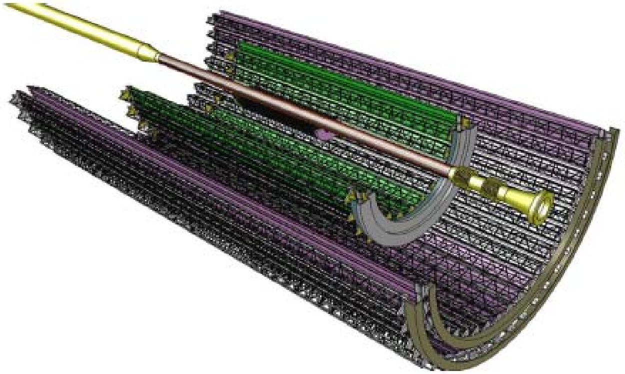
- CPS are also considered by forthcoming projects
  - ALICE @ LHC: baseline for ITS upgrade
  - CBM @ FAIR (>2018): baseline
  - ILD @ ILC@ 500 GeV: TDR option



	$\sigma_{\text{single point}}$	read-out time	TID	Fluence n_{eq}/cm^2	T_{coolant} °C
STAR-PXL	5 µm	~200 µs	150 kRad	3×10^{12}	30
	⬇	⬇	⬇	⬇	⬇
future projects	3-5 µm	1-30 µs	up to 10 MRad	up to 10^{14}	< 0 - 30

⇨ higher particles rates

- Goal: ALICE ITS upgrade (cf. TDR draft) ⇨scheduled for 2017-18 LHC shutdown
  - Addionnal L0(22mm) + replacement of inner layers
  - scheduled for 2017-18 LHC long shutdown
    - ➢ 0.25-1 MRad + 0.3-1x$10^{13}n_{eq}/cm^2$
    - ➢ Chip sensitive area 1x3 cm^2



- ➢ Inner layers ⇨0.3% X0
- ➢ Spatial resolution ~ 4 μm
- ➢ Read-out speed ~ 10-30 μs

MISTRAL

- ➢ Col. // read-out with in pixel ampli.
- ➢ Read-out speed ~ 30 μs

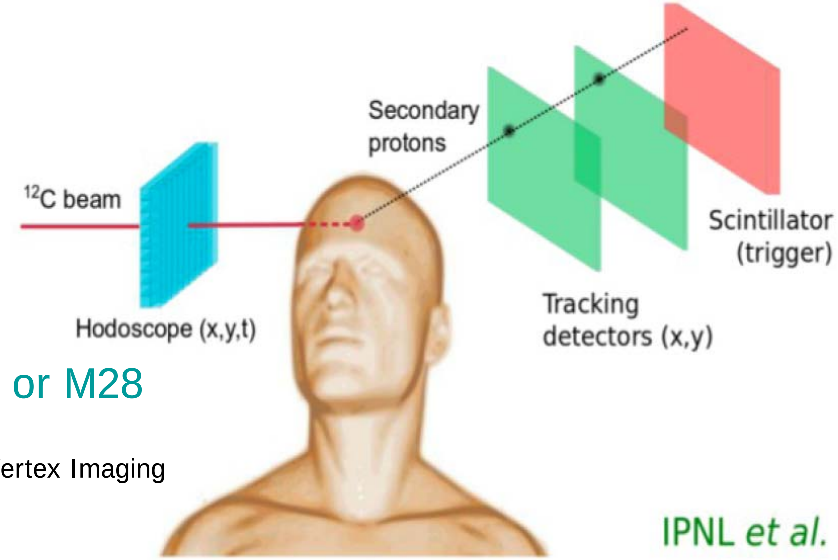
ASTRAL

- ➢ In pixel discri & 2/4-row encoding

(cf. C. Colledani's talk)

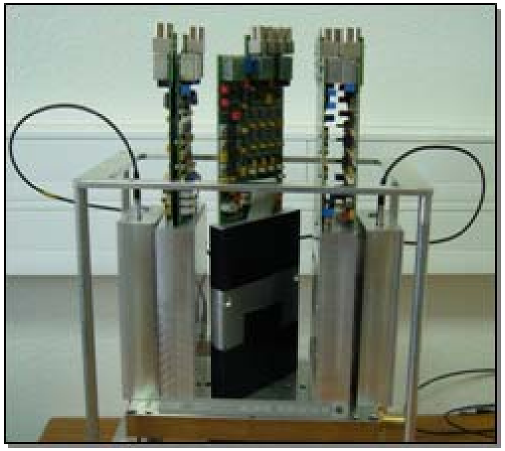
Spin off

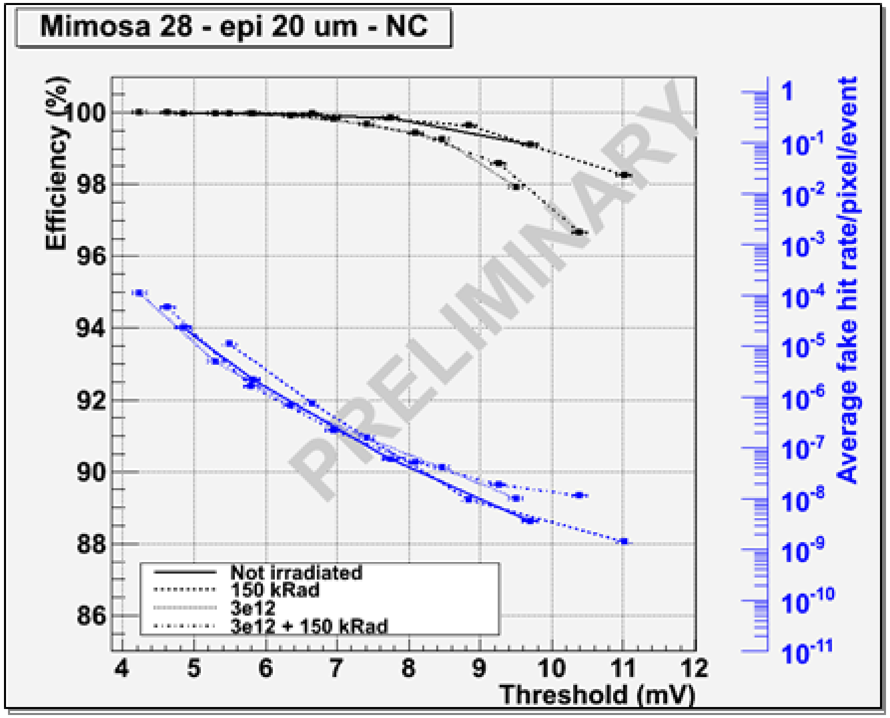
- Visible photon detection
  - design of a specific electron bombarded CMOS (LUCY)
    - collab. with IPN-Lyon and PHOTONIS
    - goal = hybrid photo-detector with
      * sensitivity to single photons
      * spatial resolution in the 10 microns range
    - paper: NIM A 648 (2011)266–274, doi:10.1016/j.nima.2011.04.018
- X-rays
  - concept studies, no practical applications
    - Explore high res. Process, single photon counting, 1 PhD.
- Radiation monitor
  - Dosimeter for space application
    - Ongoing thesis and prototype
- Beta detection
    - Nucl.Phys. B (Poc.Suppl.) 125 (2003) 133
- Hadrontherapy
  - proton telescope based on thinned MIMOSA 26 or M28
    - FIRST experiment at GSI: Carbon cross-sections measurement
    - Online dose monitoring for carbon-therapy with Proton Interaction Vertex Imaging
    - http://hal.archives-ouvertes.fr/hal-00838442



Tracking, Alignement, Software

- Tools
  - –Software for test beam analysis (TAF/MAF)
    - ➢Track matching, efficiency, resolution, clustering, etc.
  - –Digitisation tool
    - ➢(DIGMAPS) standalone tool to build a digitizer
  - –GEANT 4 full simulation
    - ➢AIDA & self alignement (L.Cousin)
- e^+e^- Physics and tracking
  - –ttbar-H Yukawa coupling @ ILC
  - –Tracking ILD-VTX @ ILC
    - ➢(Y.Voutsinas + B.Boitrelle)
    - ➢Tracking studies @ ILD
    - ➢Standalone tracking with VTX
  - –See I.Ripp Baudot’s talk





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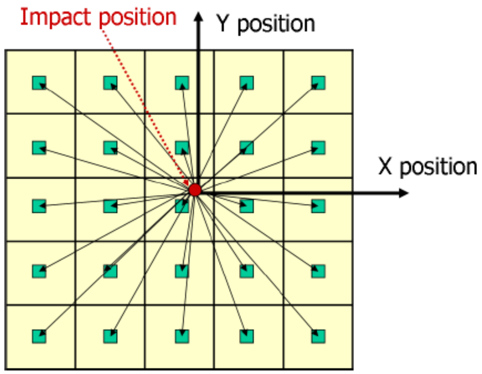
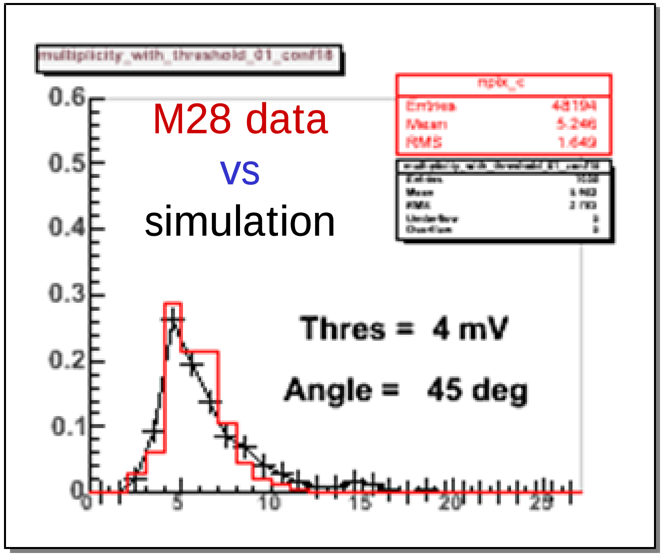


Energy deposition,
charge transport,
charge collection
discriminator simulation

⟺

Efficiency
Resolution
Multiplicity



M28 data
vs
simulation

Thres = 4 mV

Angle = 45 deg

Tracking, Alignement, Software

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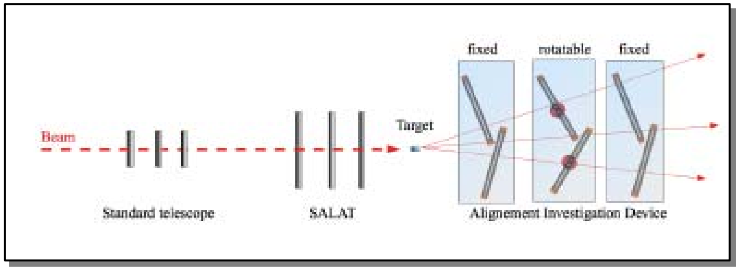
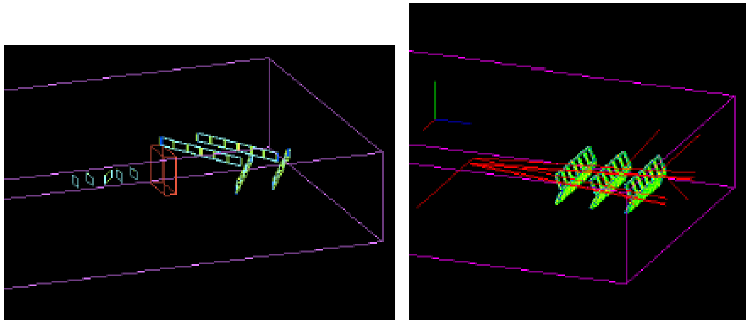
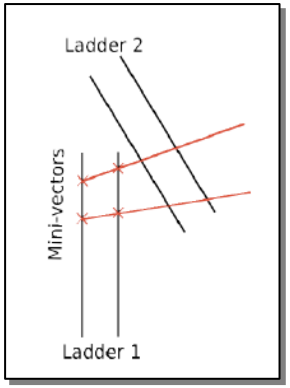



Examples of simulated AIDA-like setup



Tracking, Alignement, Software

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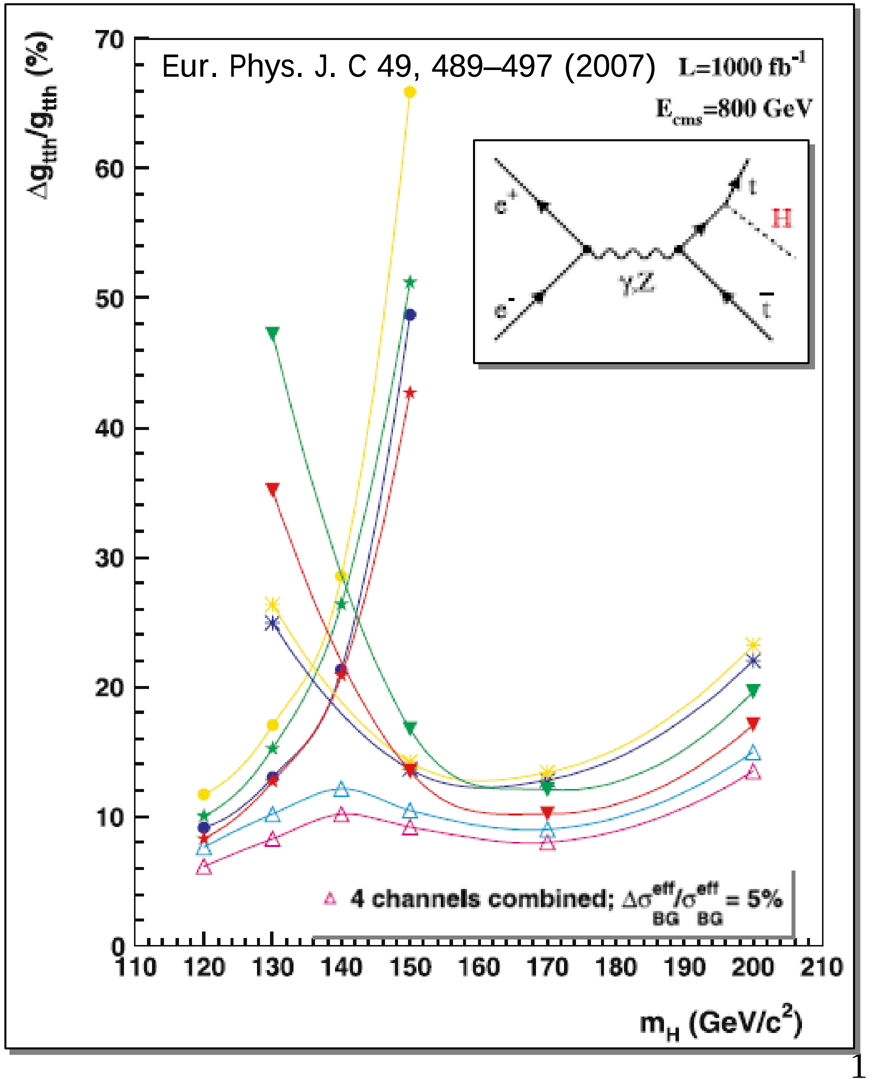
Eur. Phys. J. C 49, 489–497 (2007)

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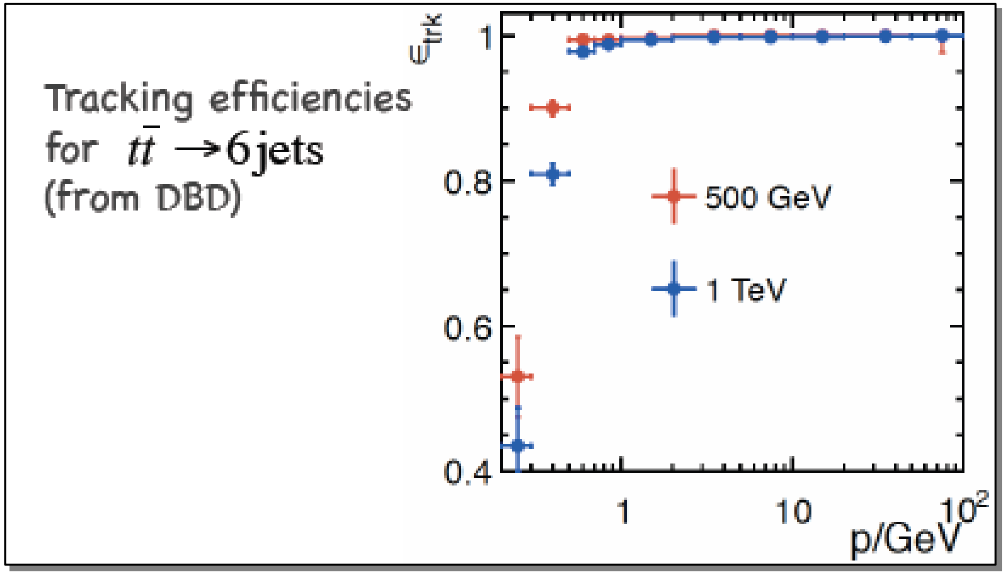
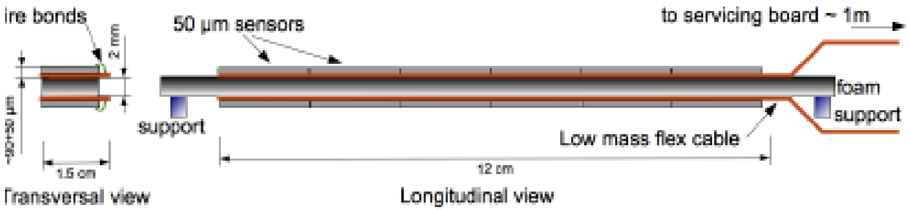


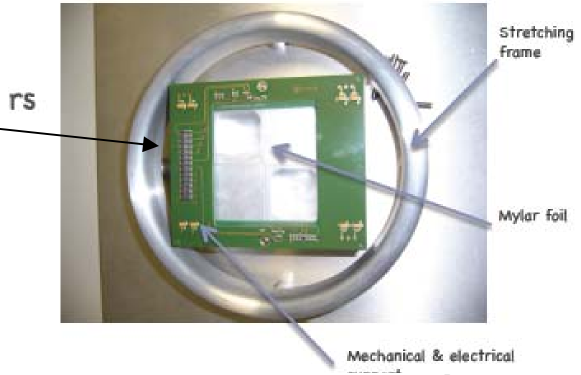
Tracking efficiencies for $t\bar{t} \rightarrow 6\text{jets}$ (from DBD)

Integration activities

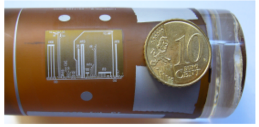
- PLUME
  - Double sided ladders
    - ➢ Collab. Bristol & DESY
    - ➢ Double sided ladders with ~ 0.35% X0
    - ➢ First prototype built in 2011
    - ➢ See J.Baudot's talk.

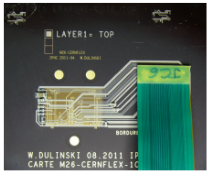


- SALAT in AIDA project
  - Large surface detectors (stitching)
    - ➢ First demonstrator built
    - ➢ Goal: 6 x 4 cm²
    - ➢ Applications: Large area telescope, forward discs



- SERNWIET
  - Sensor embedding in kapton
    - ➢ Collab. CERN





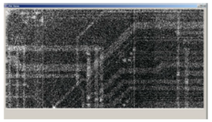
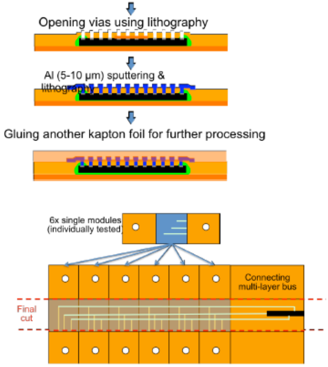


Image obtained with 55Fe source, X-rays detected by MIMOSA-26



Summary

- Group founded with the starting CPS R&D in early 2000s
- Motivations
  - Lepton collider physics
  - Exploit fully the potential of CPS
    - ➢ Pursuing the R&D and prototypes fabrications
    - ➢ Integration developpements (PLUME, etc.)
    - ➢ Algorithms & tracking optimizations
- Know how
  - Physics & tracking
    - ➢ Resolution, clustering, digitisation, alignment, etc.
    - ➢ Interests: e.g. low momentum tracks, VTX standalone tracking, c-tagging, etc.
  - Hardware Expertise
    - ➢ Microelectronics, Mechanical integration, Microtechnics (probe tests, bounding), PCB designs
  - Test experts
    - ➢ DAQ systems, Lab tests, Beam test = 2 telescopes + 2-3 campaigns/year (@ DESY & CERN)

⇨ Mastering the complete fabrication chain (from design to validation) on site.

⇨ Faster fabrication/validation cycles (typically < 1 year)

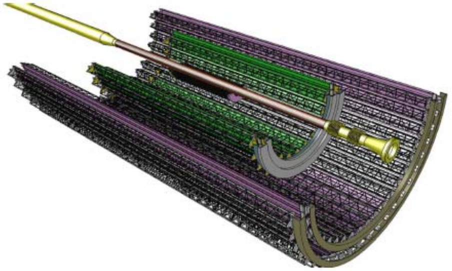
Back up

Read-out speed

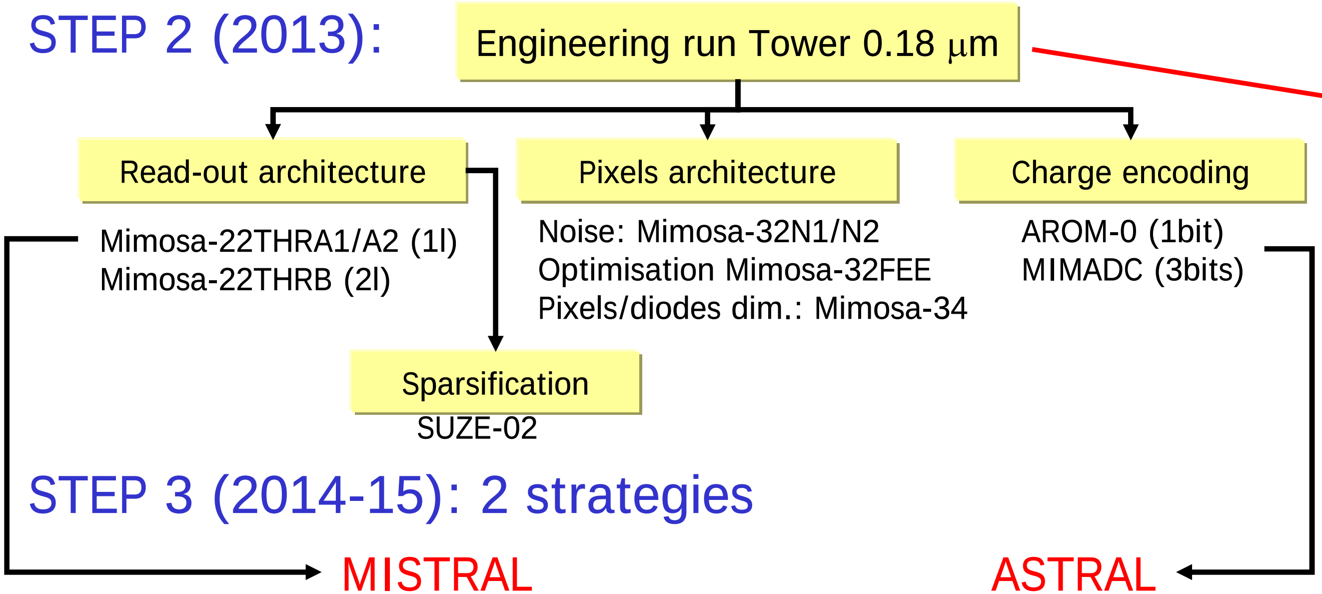
- ILC motivations
  - Robustness with respect to predicted beam background ⇨occupancy
  - Capabilities to stand the increased occupancy @ 1 TeV (x3-5)
  - Stand alone tracking capabilities (low momentum tracks)
- How to improve read-out speed ?
  - Elongated pixels (+staggered pixels)
    - ➢ Less row per column
    - ➢ Allow in pixel discriminator ⇨ r.o ≥ 2 x faster
  - More parallelisation
  - ➢ 2 or 4 rows read out simutaneously ⇨ r.o ≥ 2-4 x faster
  - ➢ Sub arrays read out in // ⇨ r.o ≥ 2-4 x faster
  - ➢ Only possible in smaller feature size process (0.18 μm) see next slide

Validation of the 0.18μm technology roadmap

- Goal: ALICE ITS upgrade (cf. TDR draft) ⇨scheduled for 2017-18 LHC shutdown
  - Addionnal L0(22mm) + replacement of inner layers
  - scheduled for 2017-18 LHC long shutdown
    - ➢ (See talks by Beolè and Bufalino)
    - ➢ 0.25-1 MRad + 0.3-1x$10^{13}$$n_{eq}$/$cm^2$
    - ➢ Chip sensitive area 1x3 cm^2
    - ➢ Inner layers ⇨0.3% X0
    - ➢ Spatial resolution ~ 4 μm
    - ➢ Read-out speed ~ 10-30 μs



- STEP 1 (2012): First prototypes ⇨Validation of MIP detection performances
- STEP 2 (2013):



Engineering run Tower 0.18 μm

Read-out architecture

Mimosa-22THRA1/A2 (1l)
Mimosa-22THRB (2l)

Pixels architecture

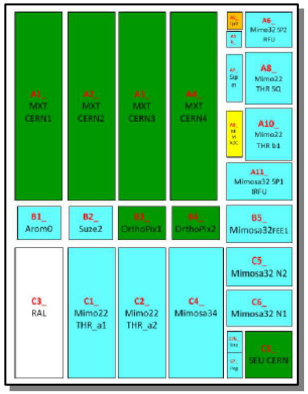
Noise: Mimosa-32N1/N2
Optimisation Mimosa-32FEE
Pixels/diodes dim.: Mimosa-34

Charge encoding

AROM-0 (1bit)
MIMADC (3bits)

Sparsification

SUZE-02



- STEP 3 (2014-15): 2 strategies

MISTRAL

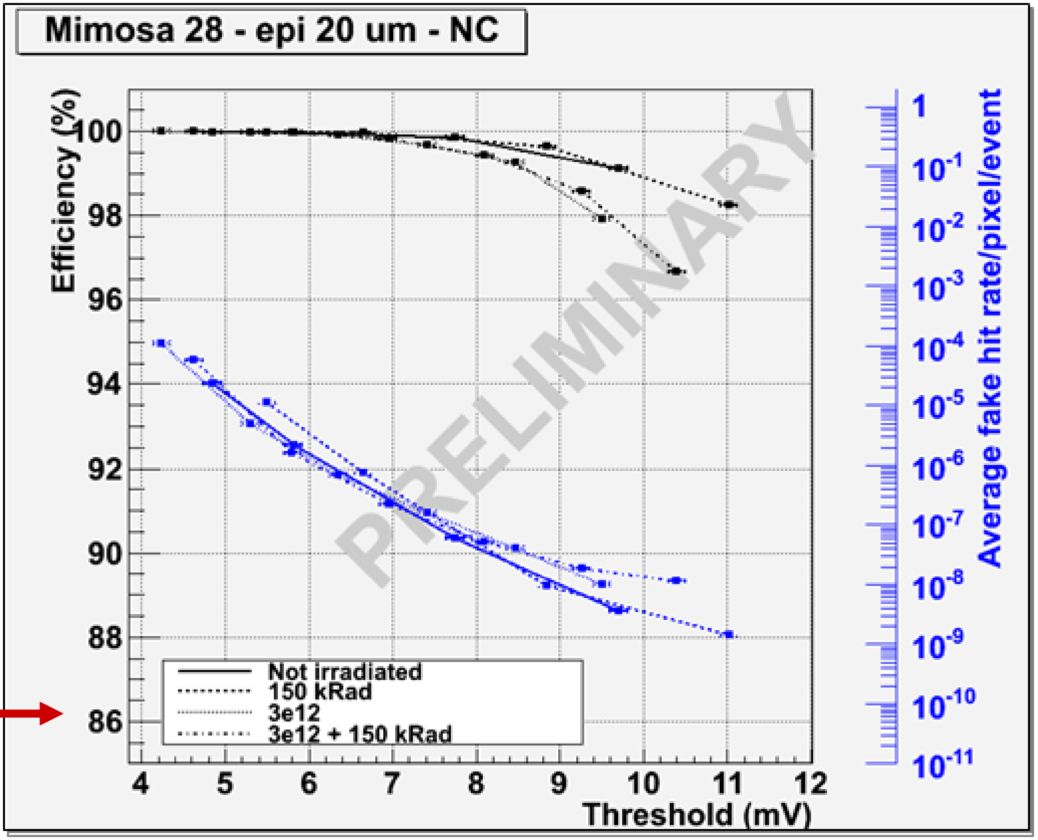
- ➢ Col. // read-out with in pixel ampli.
- ➢ Simultaneaous 2 rows encoding (x2 faster)
- ➢ Read-out speed ~ 30 μs

ASTRAL

- ➢ In pixel discri & 2/4-row encoding
- ➢ 2-4 x faster than M22THR ⇨ r.o. speed ~ 10-20 μs
- ➢ P_{diss} ~< 150-200 mW / cm^2

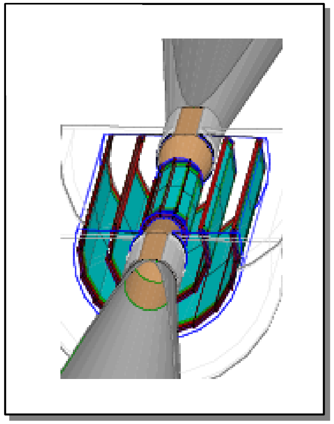
Mimosa-28 (=Ultimate) performances

- Operating conditions
  - JTAG + 160 MHz
  - Temperature
    - ➢ 35°C
  - Read-out time = 200 µs
    - ➢ Suited to $\geq 10^6$ part/cm^2/s
  - Power comsumption
    - ➢ 150 mW/cm^2
- Performances
  - Noise ~ 15 e- ENC @ 35°C
  - Eff vs fake rate
  - Spatial resolution
    - ➢ charge sharing
    - ➢ $\sigma_{sp} \geq\sim 3.5\ \mu m$
  - Radiation tolerance
    - ➢ $3.10^{12} n_{eq}/cm^2$ + 150 kRad @ 35 °C

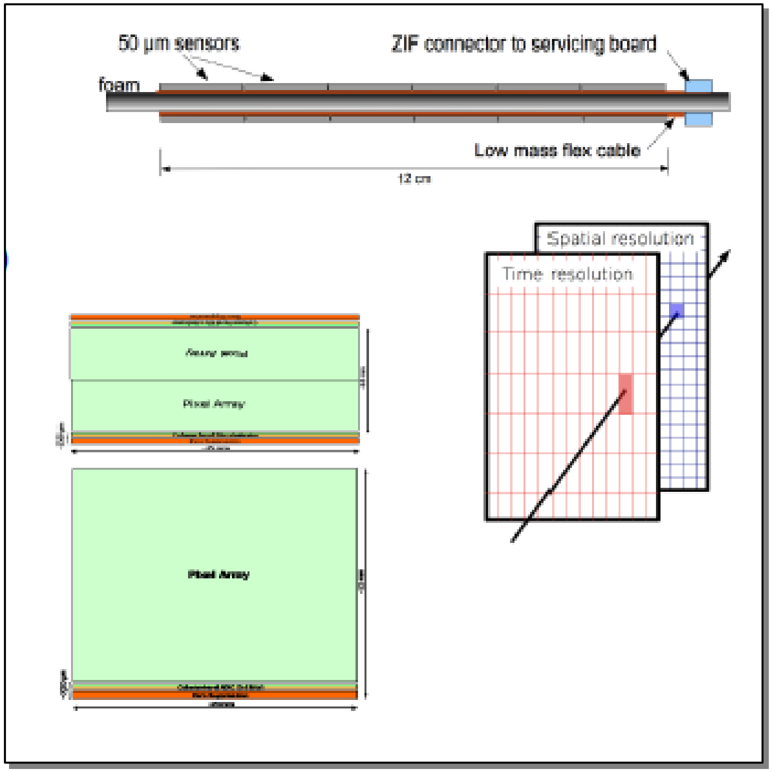


⇨ reached performances meets specifications

An example of vertex detector optimisation: ILD @ ILC



- Baseline: *(cf. ILC - Detector Baseline Document)*
  - Spatial resolution/material budget ⇨ $\boxed{\sigma_b < 5 \oplus 10/p\beta\sin^{3/2}\theta\ \mu m.}$
  - Occupancy 1st layer: ~ 5 part/cm^2/BX ⇨ few % occupancy max
  - Radiations: O(100 krad) et O(1x10^{11} n$_{eq\ (1MeV)}$) / year
  - Power dissipation: 600W/12W (Power cycling, ~3% duty cycle)
- Proposed geometry:
  - 3 x double sidded ladders
    - ➢ Optimize material budget / alignment.
- 2 designs:
  - Double sidded inner ladders :
    - ➢ Priority to r.o. speed & spatial resolution
    - ➢ 2 faces: resolution / speed (elongated pixels)
    - ➢ Pitch 16x16μm^2/ 16x64μm^2 + binary charge encoding
    - ➢ $t_{read\text{-}out}$ ~ 50μs/10μs ; σ_{res} ~ 3 μm/6μm
    - ➢ 2012: Mimosa-30 prototype (AMS 0.35 μm) with 2 sided read-out
  - Outer ladders: power dissipation
    - ➢ Minimize P_{diss} while keeping good spatial resousion
    - ➢ Pitch ~ 35x35 μm^2 + ADC 3-4 bits
    - ➢ $t_{read\text{-}out}$ ~ 100 μs
    - ➢ 2012: Mimosa-31 prototype (AMS 0.35 μm) with 4-bit ADC

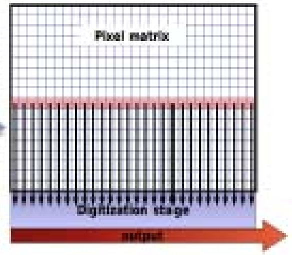


Ongoing evelopments

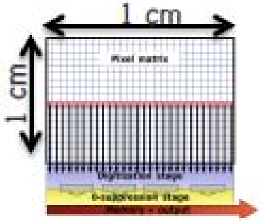
- **Applications driving the R&D**
  - ALICE Internal Tracking System: 50 μs with 4 μm and 10^7 hits/cm^2/s
    - Require readout acceleration
  - AIDA Single Arm Large Area Telescope: Sensor sensitive area = 25 cm^2
    - Require stitching
  - CBM Micro-Vertex Detector
    - Require acceleration & radiation tolerance

- **Upgrading the technology**
  - Change from to *Tower-Jazz* 0.18 μm CIS 2D process
  - First validation in 2011-2012: see Auguste Besson’s talk

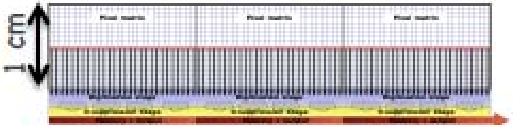
- **Advanced functionalities**
  - MIMOSA-32/34: further optimisation of q-collection, noise, ampli.
  - MIMOSA-22-THR: pixel matrix + col-level discriminators
    - single and double rows read-out
  - SUZE-02: zero-suppression circuitry
  - AROM-0: matrix with in-pixel discriminator
  - MIMADC: matrix with in-pixel 3-bits ADC



- **Full Scale Basic Blocs (FSBB)**
  - = complete functionality over $\sim$1 cm^2
  - Q4/2013: col-level discri. approach (→MISTRAL)
  - Q4/2015: in-pixel discri. approach (→ASTRAL)



- **Final sensors**
  - Q4/2014: MISTRAL 22x33 μm2 pitch with 30 μs integration time (15 μs possible)
  - Q4/2016: ASTRAL 15 μs integration time (2 μs possible)
  - 2015: AIDA large area (4 × 6 cm2) beam telescope sensor



Evolving to an optimal process: Tower-Jazz 0.18 µm

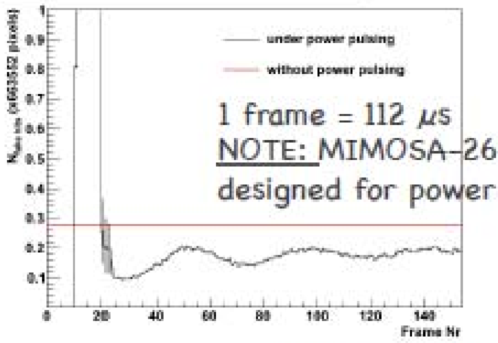
- CMOS 0.35µm process does not allow to fully exploit the potential of CPS
- Main limitations of 0.35µm:
  - Feature size ⇨ in pixel circuitry, r.o. speed, power comsumption, radiation hardness
  - Number of metal layers ⇨ in pixel circuitry, r.o. speed, insensitive area
  - Clock frequency ⇨ data output
  - Epitaxial layer flexibility: (thickness and resistivity) ⇨Charge collection/sharing
- Tower-Jazz 0.18 µm
  - Smaller feature size process
  - Stitching ⇨ multi chips slabs (yield ?)
  - 6 metal layers ⇨in pixel discri.
  - Deep P-well ⇨ small pitch in pixel discri.
  - higher epitaxial resistivity (1-6 kΩ.cm), epi thickness 18-40 µm
    - ➢ Enhances signal

⇨ Higher read-out speed, higher radiation tolerance

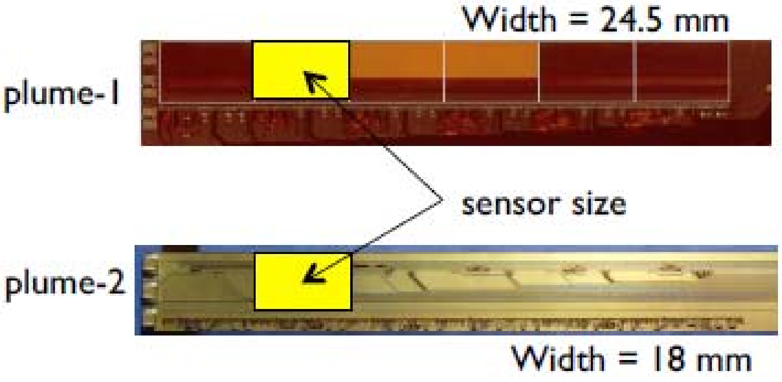
⇨ Faster and smarter pixels

The PLUME project

- Collaboration with
  - DESY + University of Bristol
  - Formerly with University of Oxford
- Previous achievements ≲ 2012
  - Ladders with material budget 0.6 % X_0
    - Full VTX inner layer geometry
  - Operated with air cooling on beam test
  - Operation with power pulsing in preparation (single sensor achieved)
- Moving toward final goal
  - Expected material budget 0.35 % X_0
    - Lighter (alu) flex cable & mechanical support
    - Two flex designs for symmetry and final ladder geometry
  - Readiness
    - First cables validated, rest to be produced
    - New assembly setup in production
    - First ladder by end of summer 2013



1 frame = 112 µs
NOTE: MIMOSA-26 not designed for power-pulsing



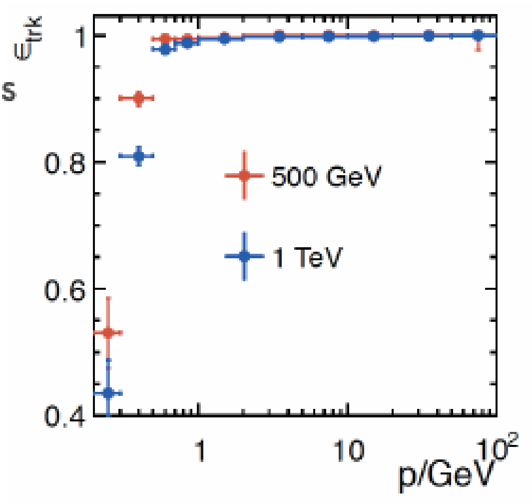
Rationale for double-sided ladders

- **Mechanics**
  - One support for 2 sensitive layers ➡ benefit material budget hence resolution
- **Safety**
  - Hit redundancy ➡ benefit efficiency
- **Technology**
  - Mixing 2 different sensor optimizations ➡ alleviate technology limitation

- **Alignment**
  - Additional geometric constraints ➡ benefit #tracks needed for a given precision
- **Tracking**
  - 2-hits make a mini-vector ➡ additional angular information
    ➡ improve hit-track association

Tracking @ ILD

Tracking efficiencies for $t\bar{t} \rightarrow 6\text{jets}$ (from DBD)



- **Silicon standalone tracking**
  - The problem at low p_T is track-seeding
    - 3 real 3D hits needed
  - With current strip-SIT configuration
    - Either not efficient enough 80% at p_T 500 GeV/c
    - Either two slow (270 s /event) when considering all combinations
  - Pixelated-SIT with 2 double-layers option
    - Offers 4 3D hits & mini-vectors
    - Cellular automaton algorithm under evaluation

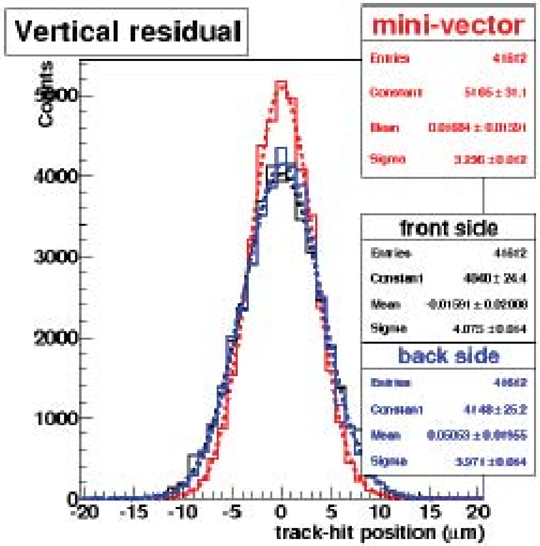
- **Track extrapolation TPC➛SIT➛VTX**
  - Impact of pixelated-SIT (double-layers)

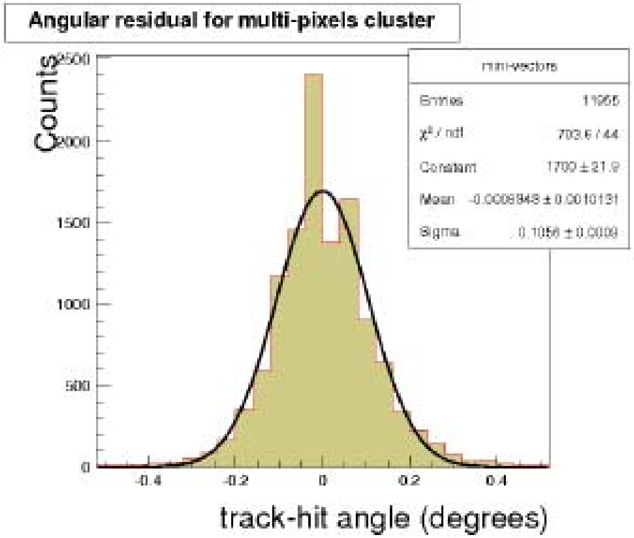
	strip		pixel	
	$\sigma_{s.p.}$ (μm)	t_{int} (μs)	$\sigma_{s.p.}$ (μm)	t_{int} (μs)
SIT - 1	7(R-ϕ) 50 (z)	< t_{BunchX}	4/15	100/7
SIT - 2			4	100

  - Efficiency TPC➛SIT strips > pixels
    - Benefit of short t_{int} / beam Background
  - Efficiency SIT➛VTX similar / both options
    - BUT pixel timestamping layer mandatory

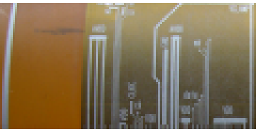
Beam test results on Ladder

- Beam test with 120 GeV π in November 2011
  - → efficiency > 99% for fake hit rate<10^{-4}/pixel
  - → σ(point)=3 μm
  - → σ(angle)=0.1°
  - Analysis ongoing / alignment & cracks



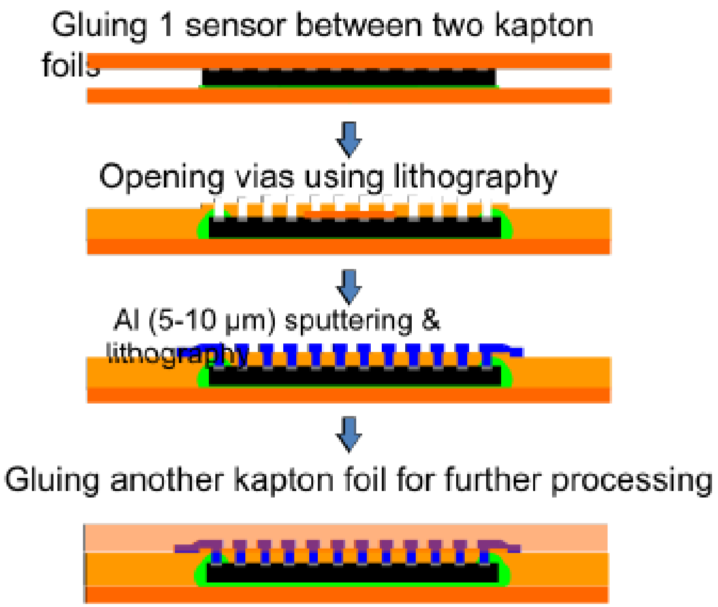


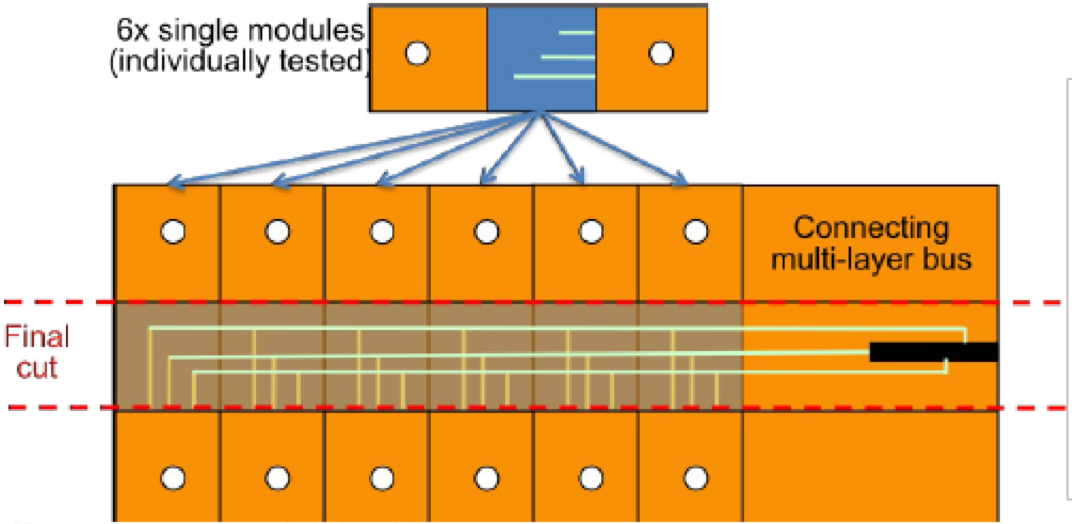
- Further beam test
  - With next 0.35% X0 prototype
  - Power pulsing in magnetic field
    - Check impact Lorentz forces



Sensor embedding: CERN

- **Idea from R. De Oliveira, W.Dulinski**
  - ✗ Embed sensor one at time
    - ➔ Alleviate alignment difficulty
    - ➔ Allow individual testing before assembly (yield)
  - ✗ Processing of further metal layers decoupled from sensor embedding
- **Questions**
  - ✗ Insensitive area in-between sensors?
    - ➔ Possibility to overlay embedded sensors





- **Material budget**
  - ✗ Embed sensor one at time
    - ➔ Alleviate alignment difficulty
    - ➔ Allow individual testing before assembly (yield)
  - ✗ Processing of further metal layers decoupled from sensor embedding