Overview & Organisation of the PICSEL Group Activities

M.Winter, on behalf of J.Baudot & A.Besson / IPHC, 8 March 2019

PICSEL: Physics with **I**ntegrated **C**mos **S**ensors at **EL**ectron machines

(http://www.iphc.cnrs.fr/-PICSEL-.html)

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Origin of CMOS Pixel Sensors

- **CMOS Pixel Sensors are derived from ASICS**

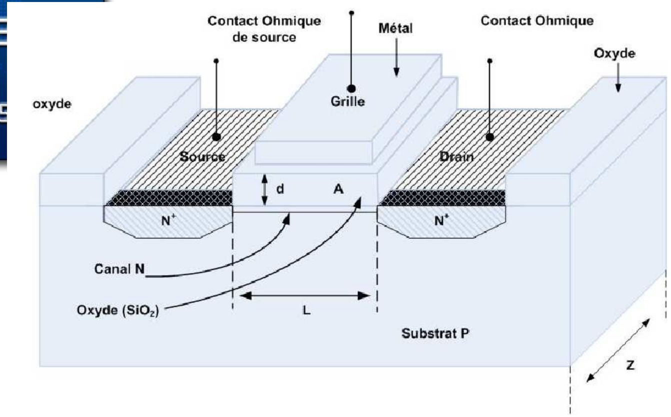
  ≡ Application-Specific Integrated Circuits

  - ASICs populate every day's life: e.g. credit cards, PC, cell-phones, cars, washing machines, ...

    ⇛ industrial mass production item

    (world revenue ∼ several 100 billions USD/year)

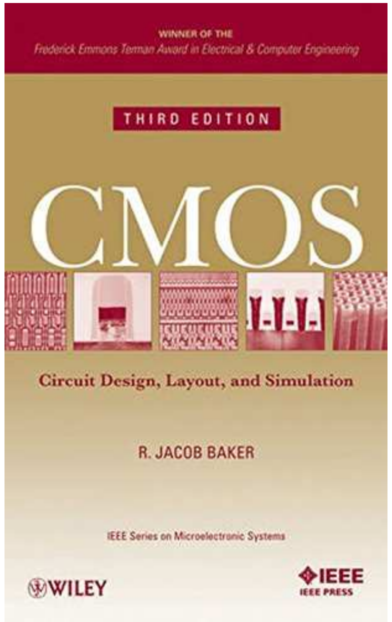
  - key element: MOSFET transistors & conductive traces printed in **Silicon** (usually)



Substrat type P pour MOSFET canal N
Substrat type N pour MOSFET canal P

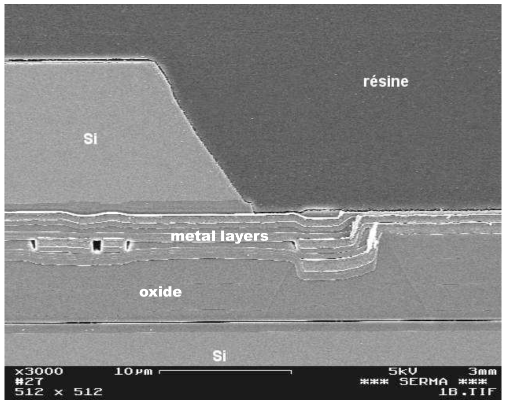
- **C.M.O.S. ≡ Complementary Metal Oxyde Semi-conductor**

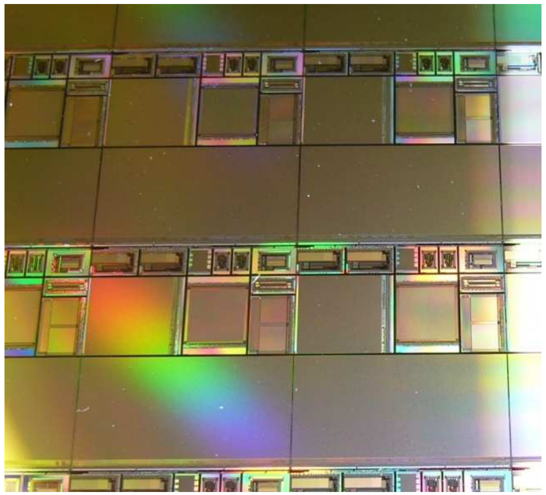
  - widespread technology for constructing integrated circuits used in microprocessors, microcontrollers, memories, etc.

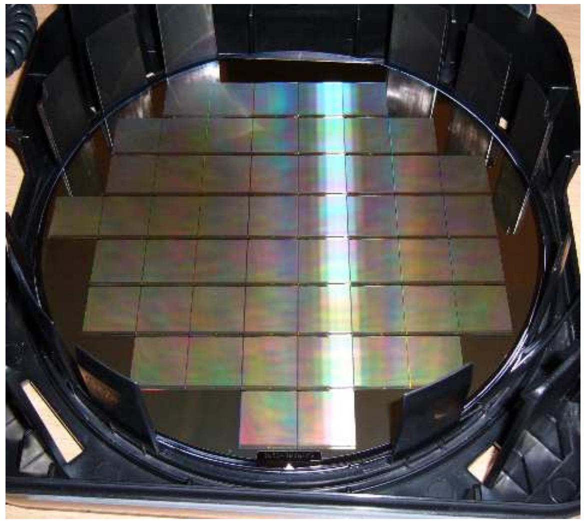


CMOS Technology

- **CMOS fabrication mode :**
  - μcircuit lithography on a substrate sliced from a crystal ingot (or *boule*)
  - proceeds through reticules (e.g. 21x23 or 25x32 mm^2) organised in wafers



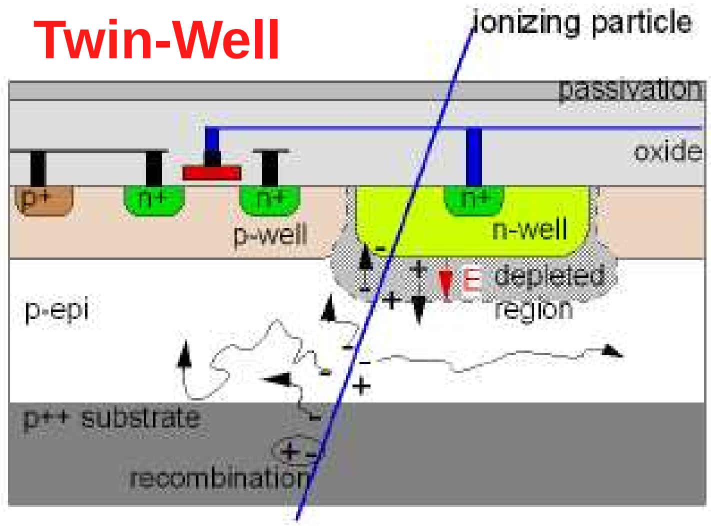




CMOS Pixel Sensors: Main Features

- **Prominent features of CMOS pixel sensors :**
  - high granularity $\Rrightarrow$ excellent (micronic) spatial resolution
  - signal generated in (very) thin (15-40 μm) epitaxial layer
    - $\hookrightarrow$ resistivity may be $\gg$ 1 k$\Omega \cdot cm$
  - signal processing μ-circuits integrated on sensor substrate
    - $\Rrightarrow$ impact on downstream electronics and syst. integration ($\Rrightarrow$ cost)

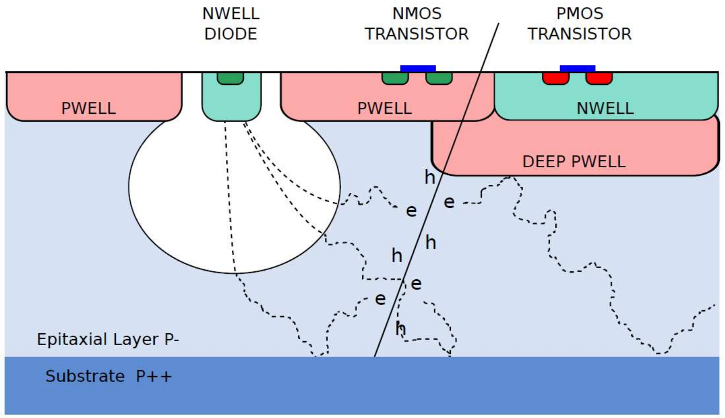
Twin-Well



- **CMOS pixel sensor technology has the highest potential :**

$\Rrightarrow$ R&D largely consists in trying to exploit potential at best with accessible industrial processes

$\hookrightarrow$ manufacturing param. not optimised for particle detection: wafer/EPI characteristics, feature size, N(ML), ...

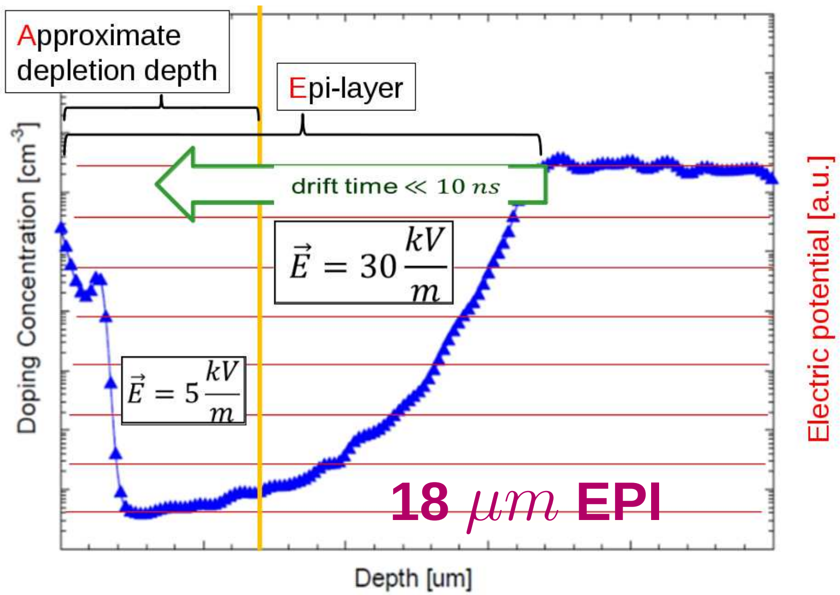


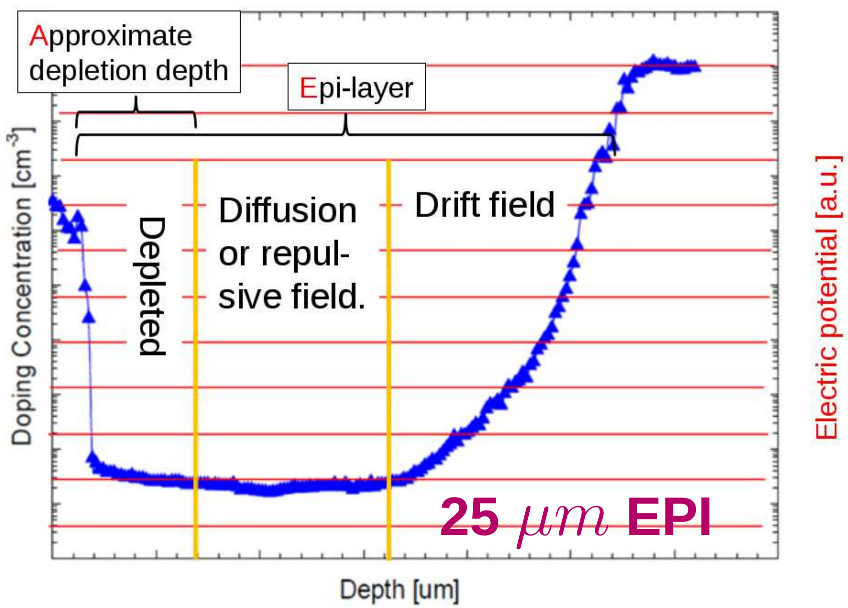
Quadruple-Well

- **Read-out architectures :**
  - 1st generation : rolling shutter (synchronous) with analog pixel output (end-of-column discriminators)
  - 2nd generation : rolling shutter (synchronous) with in-pixel discrimination
  - 3rd generation : data driven (asynchronous) with in-pixel discrimination
  - ...

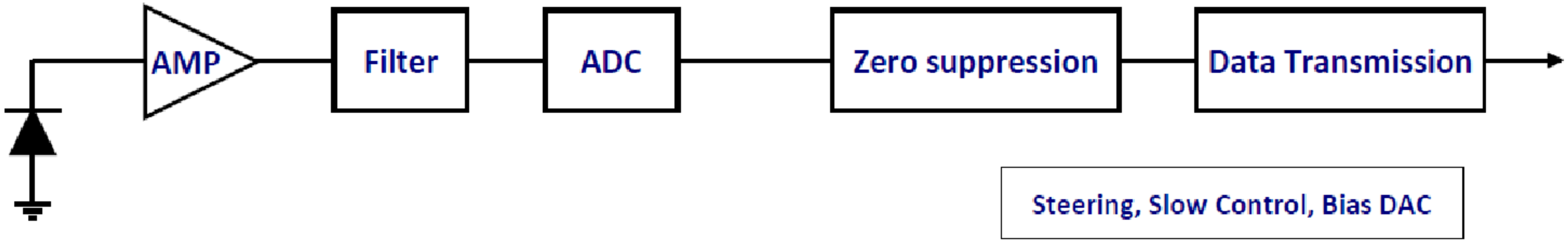
Role of the Epitaxial Layer $\equiv$ Detection Element

- **Main influences :**
  - $Q_{signal} \sim$ EPI thickness and doping profile
  - ϵ_{det} depends on depletion depth vs EPI thickness
  - NI radiation tolerance depends on depletion depth vs EPI thickness
  - Cluster multiplicity and σ_{sp} depend on pixel pitch / EPI thickness
- **Case dependent optimisation mandatory :**
  - Deep depletion $\Rrightarrow$ higher SNR (seed pixel) $\Rrightarrow$ improved ϵ_{det} but degraded spatial resolution ....
  - Spatial resolution depends on Nb of bits encoding charge vs pixel pitch ...
  - Density of in-pixel circuitry depends on CMOS process options : feature size, Nb(ML), twin/quadruple-well, ...





Main Components of the Signal Processing Chain



- **Typical components of read-out chain :**
  - **AMP :** In-pixel low noise pre-amplifier
  - **Filter :** In-pixel filter
  - **ADC :** Analog-to-Digital Conversion : 1-bit $\equiv$ discriminator

    $\hookrightarrow$ may be implemented at column or pixel level
  - **Zero suppression :** Only hit pixel information is retained and transfered

    $\hookrightarrow$ implemented at sensor periphery (usual) or inside pixel array
  - **Data transmission :** O(Gbits/s) link implemented on sensor periphery

- **Read-Out alternatives :**
  - **Synchronous :** rolling shutter architecture
  - **Asynchronous :** data driven architecture

- **Main features of sensor design and test $\Rrightarrow$ talks by Ch. Hu-Guo and G. Claus**

Overall Functionnality Distribution: Example of MIMOSA-26

CMOS 0.35 µm OPTO technology

Chip size : 13.7 x 21.5 mm²

- Pixel array: 576 x 1152, pitch: 18.4 µm
- Active area: ~10.6 x 21.2 mm²
- In each pixel:
  - Amplification
  - CDS (Correlated Double Sampling)

- Testability: several test points implemented all along readout path
  - Pixels out (analogue)
  - Discriminators
  - Zero suppression
  - Data transmission

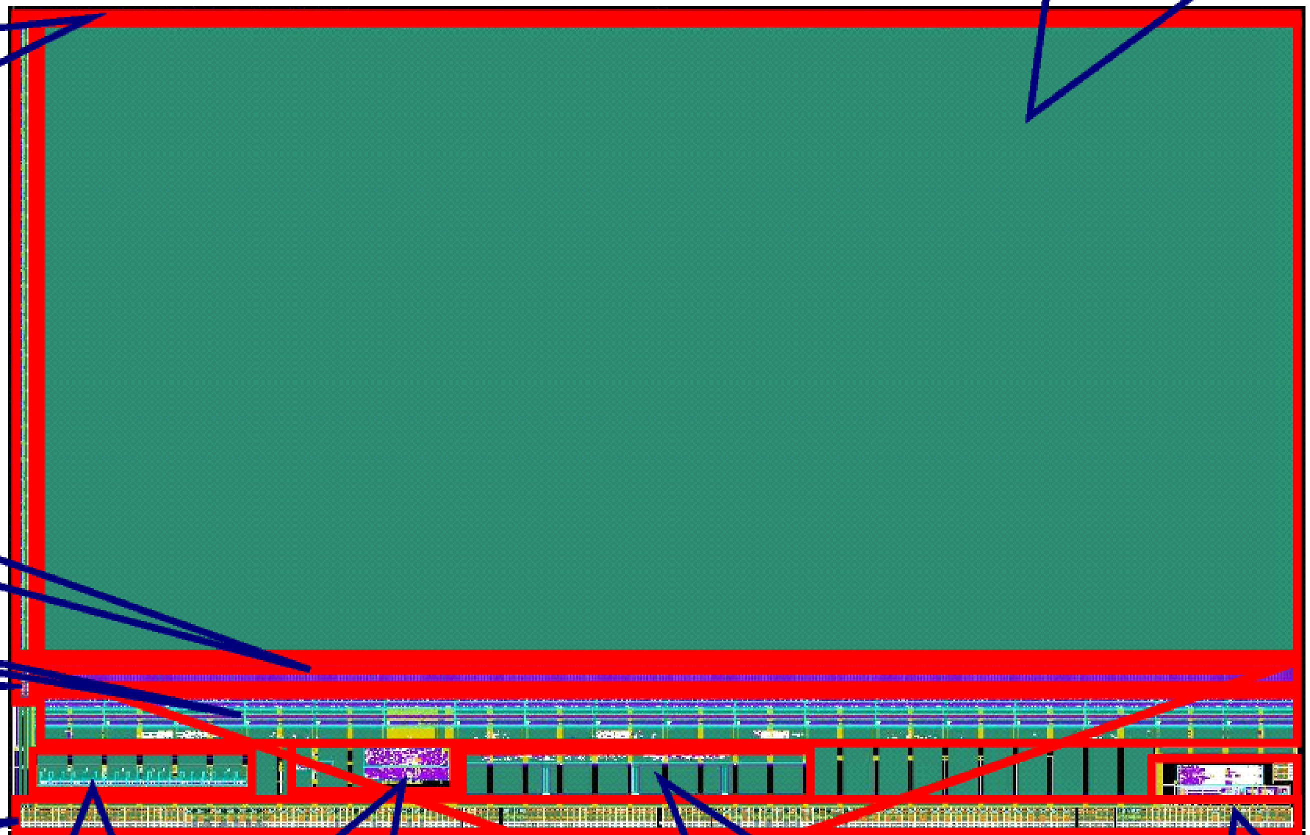
- Row sequencer
- Width: ~350 µm

- 1152 column-level discriminators
  - offset compensated high gain preamplifier followed by latch

- Zero suppression logic

- Reference Voltages Buffering for 1152 discriminators

- I/O Pads
  Power supply Pads
  Circuit control Pads
  LVDS Tx & Rx



- Current Ref.
- Bias DACs

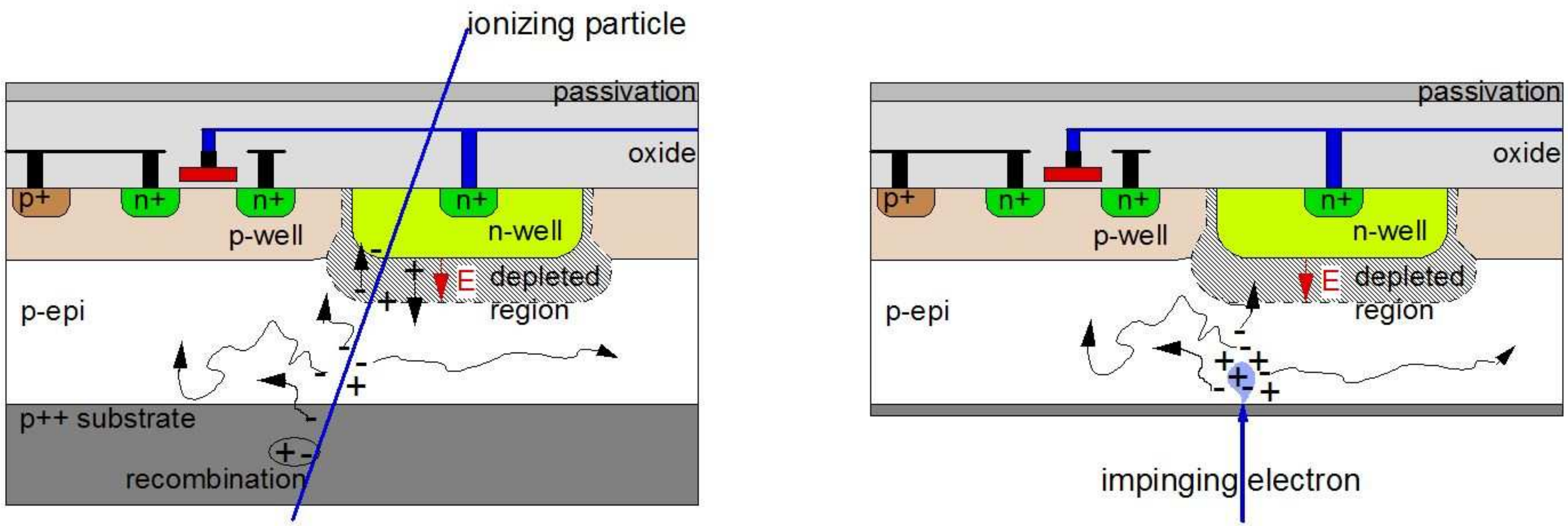
- Readout controller
- JTAG controller

- Memory management
- Memory IP blocks

- PLL, 8b/10b optional

Spectrum of Applications of CPS

- **2 categories of particle detection:**
  - **Minimum ionising particle detection:** traversing the sensor
  - **X-Ray & β imaging:** absorbed in the epitaxial layer (backside illumination)



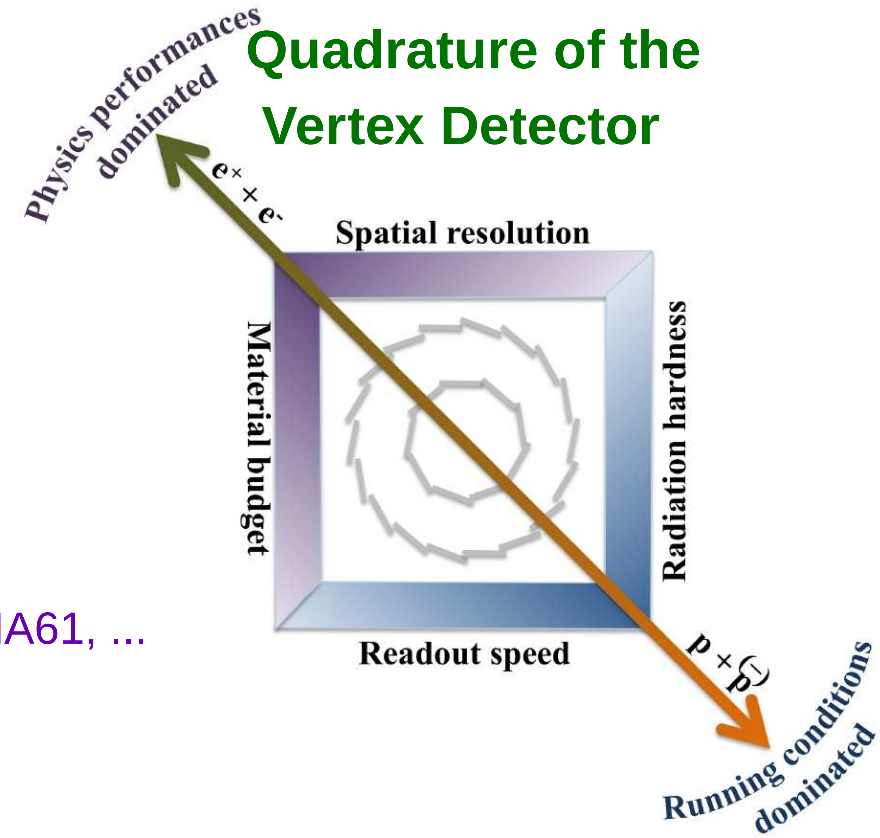
- **2 categories of applications:**
  - **Minimum ionising particle detection:** vertex detectors, trackers, beam telescopes, ... $\Rrightarrow$ **talk of A. Besson**
  - **X-Ray & β imaging:** hadrontherapy, dosimetry, neuroscience, mat. science, industry, ... $\Rrightarrow$ **talk of J. Baudot**

Motivation for Developing CMOS Sensors

- **CPS development triggered by need of**
  very high granularity & low material budget

- **Applications exhibit much milder running conditions than pp/LHC**

$\Rrightarrow$ **Relaxed speed & radiation tolerance specifications**



- **Increasing panel of existing, foreseen or potential application domains :**
  - **Heavy Ion Collisions :** STAR-PXL, ALICE-ITS, CBM-MVD, NA61, ...
  - **e^+e^- collisions :** ILC, CEPC, BES-3, ...
  - **Non-collider experiments :** FIRST, NA63, Mu3e, PANDA, ...
  - **High precision beam telescopes** adapted to medium/low energy electron beams :
    $\hookrightarrow$ few μm resolution achievable on DUT with EUDET-BT (DESY), **BTF-BT (Frascati)**, ...
  - **Numerous spin-offs in a vaste variety of domains:**
    $\hookrightarrow$ Scientific: experiments at light sources and in neuroscience, medical imaging
    Societal needs: hadrontherapy, industrial control systems, ...

CPS Development Strategy: Surf on wave of reachable requirements

Synergy Among Projects

Ultimate objective: ILC, with staged performances

CPS applied to other experiments with intermediate requirements

EUDET 2006/2010

Beam Telescope

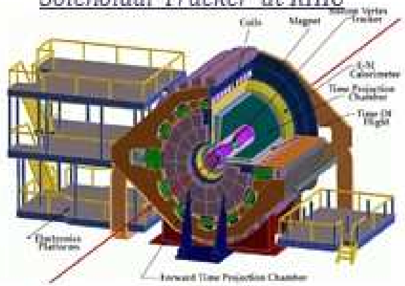
ILC ~2030

International Linear Collider

- ❑ **Tracking of Charged Particles**
  - Subatomic physics
  - Beam instrumentation
  - Hadron therapy
- ❑ **Imaging**
  - B-rays, low energy e$^-$
  - X-rays
  - Dosimetry
  - Hybrid photo-detector
  - Bio-inspired vision

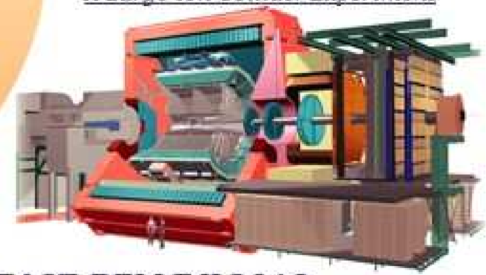
STAR 2013

Solenoidal Tracker at RHIC



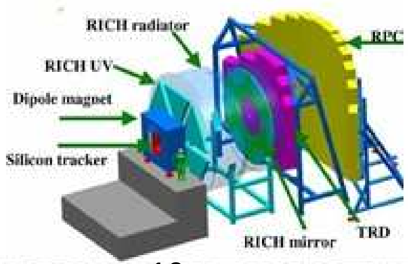
ALICE 2018

A Large Ion Collider Experiment



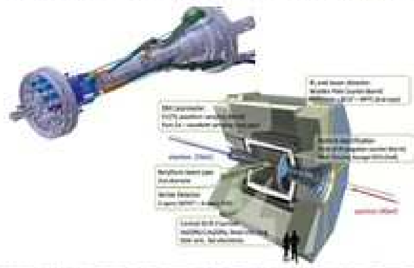
CBM >2020

Compressed Baryonic Matter

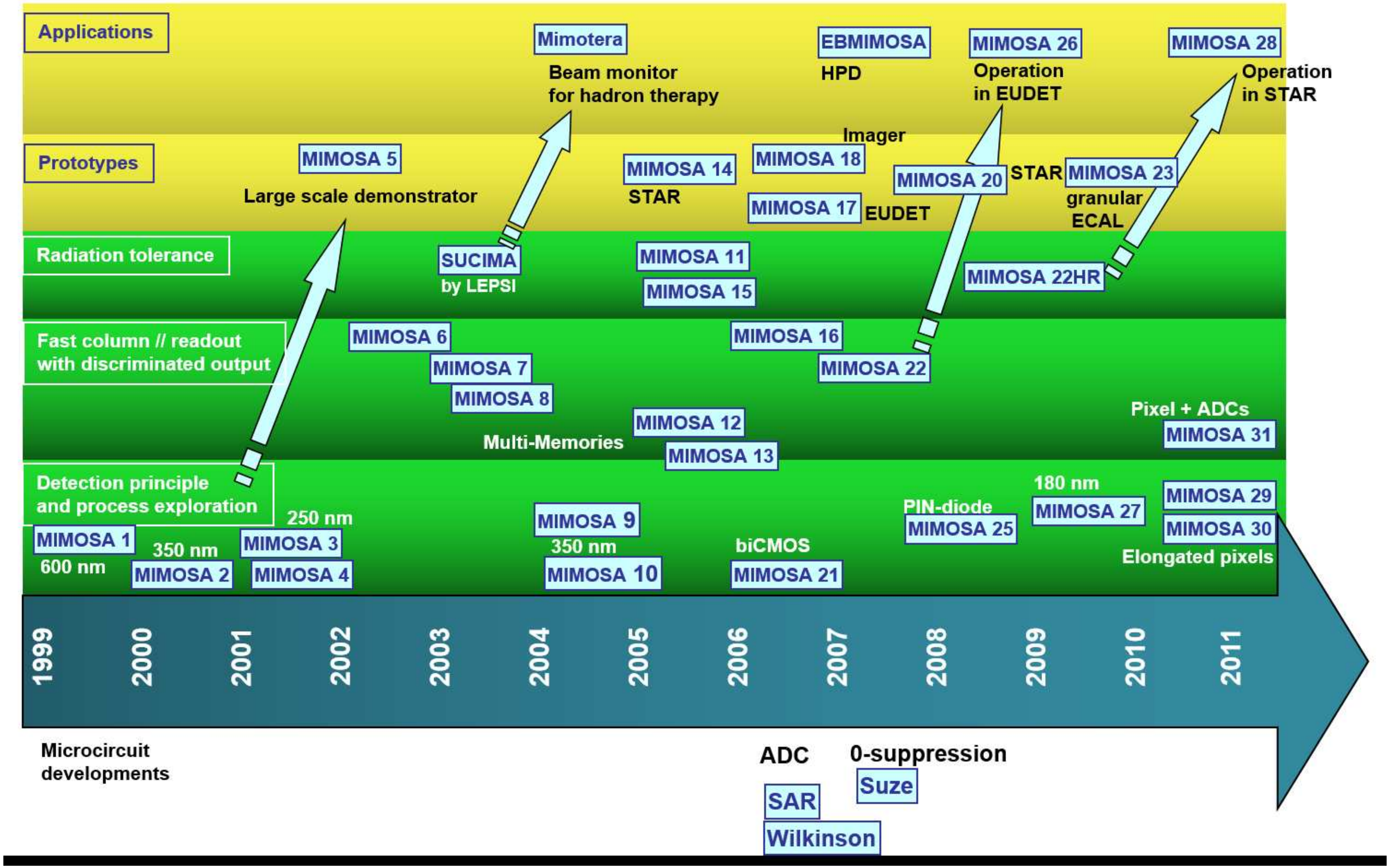


BEAST-BELLE II 2018

Beam Exorcism for A STable BELLE Experiment



Example of Twin-Well Process: Sensors & Application Domains



Location of Devices based on CPS from PICSEL

Sensor Realisation: Tasks Involving PICSEL Physicists (1/3)

- **YEAR 1: Prototyping separately the basic elements of the sensors**
  - identifying the adequacy of CPS for a specific application & potential spin-offs
  - simulating various tracking system options to derive the expected added value of CPS
    as a function of their characteristics (e.g. single point versus read-out speed vs material budget)
  - designs of: charge collection system, proto. exploring pixel array characteristics
  - defintion of main characteristics of the read-out circuitry w.r.t. hit density & data flow

- **YEAR 2: Tests of 1st prototypes (SP1) and design of 2nd set of prototypes (SP2)**

- **SP1:** **Task 1** $\equiv$ electronic performance evaluation (in-pixel noise, pixel-to-pixel dispersions)

  Task 2 $\equiv$ charge collection characterisation with radioactive sources

  Task 3 $\equiv$ chip irradiations $\Rrightarrow$ consecutive damage tests $\Rrightarrow$ result extraction

  Task 4 + 5 $\equiv$ detection perfo. evaluation with radioactive sources in lab. & with particle beams

  Task 6 $\equiv$ communication of test results to collaborators

- **SP2:** **Task 7** $\equiv$ choice of charge sensing parameters and pixel geometry for the next prototyping step

  Task 8 $\equiv$ definition of chips required for further specific investigations of in-pixel circuitry

  Task 9 $\equiv$ general discussion on the chips composing the next prototyping step

Sensor Realisation: Tasks Involving PICSEL Physicists (2/3)

- **YEAR 3: Tests of 2nd step prototypes (SP2) and design of 3rd set of prototypes (SP3)**
  - **SP2:** **Tasks:** 1, 2, 3, 4 + 5, 6
  - **SP3:** **Tasks:** 7, 8

    Task 10 $\equiv$ discussion on optimisation of conflicting parameters

    Tasks: 9

- **YEAR 4: Tests of 3rd step prototypes (SP3) and design of 1st full scale prototype (FP1)**
  - **SP3:** **Tasks:** 1, 2, 3, 4 + 5, 6
  - **FP1:** **Tasks:** 7, 8, 10, 9

- **YEAR 5: Tests of 1st full scale prototype (FP1) and design of 2nd full scale prototype (FP2)**
  - **FP1:** **Tasks:** 1, 2, 3, 4 + 5, 6
  - **FP2:** **Tasks:** 7, 8, 10, 9

Sensor Realisation: Tasks Involving PICSEL Physicists (3/3)

- **YEAR 6: Tests of 2nd full scale prototype (FP2)**
  and preparation of the pre-production (FP3)

  - **FP2:**
    - check of electronic performance (in-pixel noise, pixel-to-pixel dispersions)
    - check of charge collection performance with radioactive sources
    - residual chip irradiations and consecutive damage tests and verification
    - verification of detection performance with radioactive sources in the laboratory
    - final detection performance evaluation with particle beams
    - communication of test and assessment results to collaborators

  - **FP3:**
    - discussion on optimisation of conflicting parameters, if any
    - general discussion on the design of the pre-production sensor

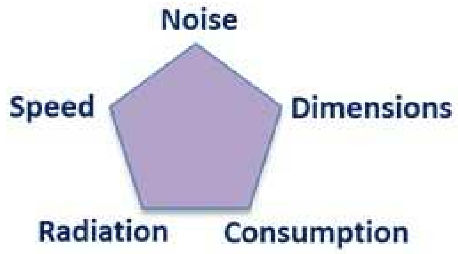
PICSEL Team vs CPS R&D: Key Aspects of Efficient Operation (1/2)

- **PICSEL team ≡ 3 particle physicists:**

  Jérôme BAUDOT (Unistra, BELLE-2), Auguste BESSON (Unistra, ILC), Marc WINTER (CNRS, ILC & CBM)

- **Realising a CPS for identified applications relies on an entanglement of expertises and tasks shared by physicists, electronicians and designers during several years**

- **PICSEL physicists intervene at all stages of the development:**
  - R&D level: choice of CMOS process and options
  - definition of requirements with their trade-offs
  - establishing a development strategy
  - design optimisation
  - laboratory tests
  - detection performance assessment (before / after irradiation)
  - interaction with collaborators and end-users
  - search for spin-offs and synergies
  - search for funding
  - etc.



↪ **Key aspects of the track record:**
- **tight daily interconnection between physicists, designers & test engineers**
- **autonomy for seeking devt goals/support without involvement beyond CPS devt**
- **persistent support of IN2P3 for CPS development for an ILC experiment**
- **extended network of collaborators and potential CPS ”end-users”**

PICSEL Team vs CPS R&D: Key Aspects of Efficient Operation (2/2)

- **Connection with engineers:** very close, face to face, intricated sharing of tasks & resources
  $\Rrightarrow$ encompass all aspects of a sensor realisation and impact its design optimisation

- **Activities:** CPS development as a main activity,
  combined with leading roles in a short term (e.g. CBM) and a long term (ILC) project
  $\Rrightarrow$ knowledgeable (experts) in CPS technology at large and within specific collaborations

- **Network:** widespread and diversified, encompassing various domains of CPS applications
  $\Rrightarrow$ belong to international CPS R&D task force, be an actor of spin-off applications
  and access complementary ressource opportunities

- **Financial resources:** recurrent funding for CPS R&D from funding agency,
  complemented with specific project oriented time limited funding

- **Involvement in projects:** not restricted to IN2P3 projects, nor to scientific feedback

- **Human resources:**

  core of instrumentation oriented staff physicists + few project oriented part-time staff membres

  complemented with post-docs predominantly involved in instrumentation related activities

PICSEL Team vs CPS R&D: Intricated Questions to Science Council

- The operation of the PICSEL team is specifically oriented towards exploiting the potential of the expertise and means available at IPHC for CPS development :

  Is this operation mode justified and appropriate ?

- The development of CPS is the main motivation of the PICSEL team existence:

  Is the potential of the technology justifying such an investment ?

- PICSEL Team composition:

  Jérôme BAUDOT (Unistra, BELLE-2), Auguste BESSON (Unistra, ILC), Marc WINTER (CNRS, ILC & CBM)

  $\Rrightarrow$ **Critical manpower situation**

Introduction to Next PICSEL Talks

- **Projects based on minimum ionising particle detection:**
  - Achievements (MIMOSA-26 for EUDET-BT & PLUME, MIMOSA-28 for STAR-PXL, ...),
    current mainstream (CBM), long term (ILC, generic R&D with CERN serving ALICE)
  - Illustration of relevance of CPS for subatomic physics, with outlook of their potential
- **CPS design and characterisation activities:**
  - CPS microcircuit design and test organisation, panel of complementary expertise, R&D issues
  - Illustration of realisation complexity, level of know-how and task force in CPS design and test
- **Projects involving X-Ray or β imaging devices :**
  - X-Ray and β-imaging realisations, connection to m.i.p. detection CPS development
  - illustration of impact of CPS on spin-off domains, of PICSEL team network and know-how