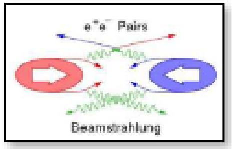
Projet de détecteur de vertex pour FCCee

Articulations

R&D TPSCo 65nm - DRD3 – FCCee – Stratégie in2p3/CEA

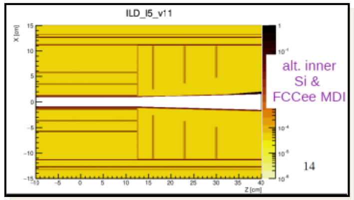
Synergies avec les autres projets

A.Besson, Université de Strasbourg



Requirements reminder

- Geometry
  - ✓ 5-6 layers in the inner radius (~< 6-10 cm) + disks
- Spatial resolution
  - ✓ (σ_{sp} ~3 µm) ⇨ Pitch ~14-17 µm (Binary output)
- Material budget
  - ✓ ~ 0.1-0.2 % X0 / layer
- Time resolution: O(100 ns)
  - ✓ BX time = 20 ns (Z); 1 µs (ZH); 3 µs (tt)
  - ✓ Integrate over O(10) BX is probably affordable
- Particle flux
  - ✓ Occupancy mainly coming from beam background
  - ✓ Dead time < per mil
  - ✓ Up to 100-400 MHz/cm^2 (with safety factors)
- Power (without Power pulsing)
  - ✓ ~< 50mW/cm^2 (assuming air flow cooling
  - ✓ ~< O(100 W) in total



Physics
⇨ Flavour tagging
⇨ Low pT tracks
⇨ Vertex/Jet charge determination

Material Budget
⇨ ~ 0.1-0.2 % X_0 / layer
⇨ < 1% X_0 for the whole VTX
~ 900 µm Si
+ ~0.14% X_0 for the beam pipe (ILC)
+ ~0.6 % X_0 for the beam pipe (FCC)

500 µm Be ~ 0.15 % X_0
100 µm Si ~ 0.1 % X_0

Radiation hardness
O(100kRad/yr) & O(10^{11})n_{eq}/yr

Cooling
Stiffness / Alignment

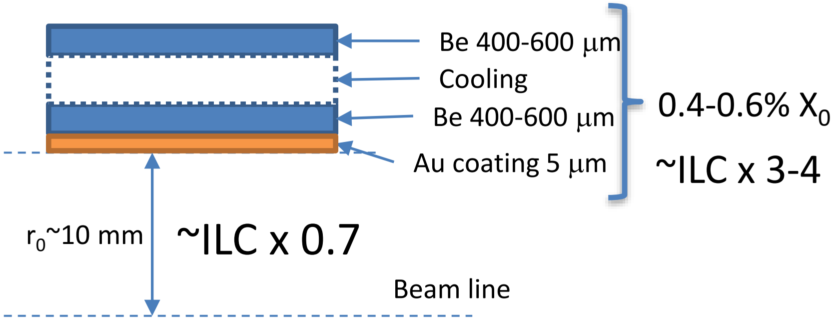
FCCee

$$\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2}\theta}$$

$$a \simeq 5\,\mu\text{m}; \quad b \simeq 15\,\mu\text{m}\,\text{GeV}$$

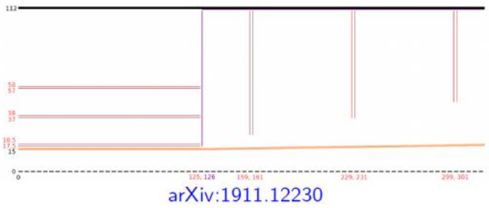
$$b \sim r_0 \sqrt{material}$$

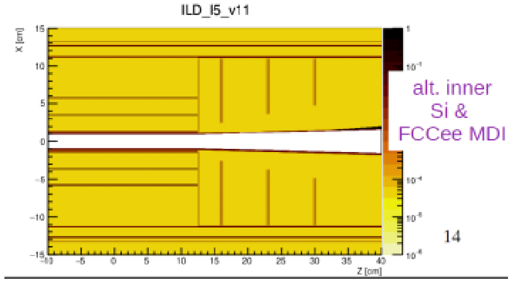
$$a \sim \sqrt{r_0}$$



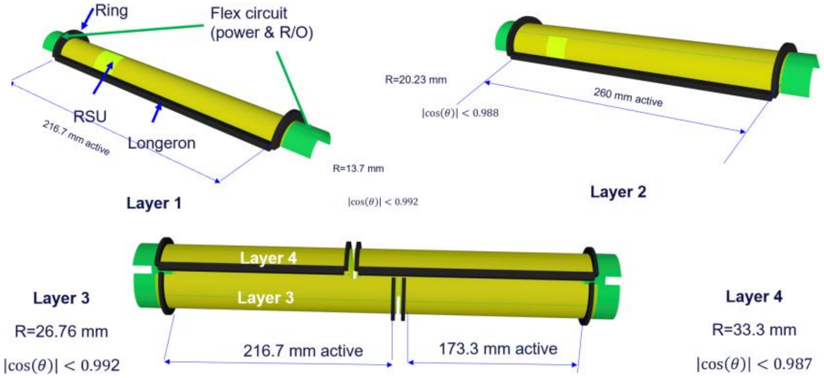
Design concepts

- À la CLD/ILD:
  - ✓ 3 double ladders + discs
  - ✓ Layer 1: $|z_{max}|$ ~ 12cm
  - ✓ R_{in} ~12 mm

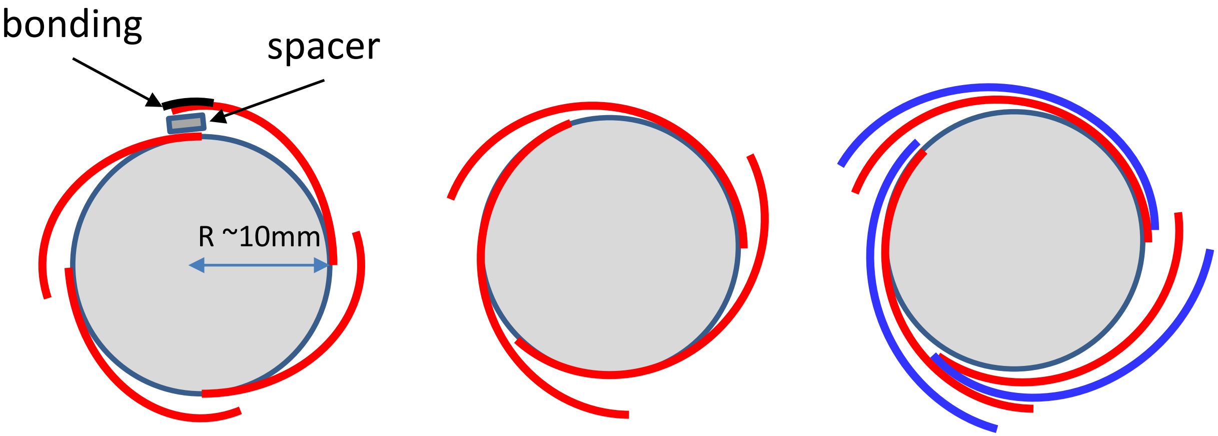

arXiv:1911.12230



- À la ALICE ITS-3
  - ✓ 3/4 layers with stitched half cylinders
  - ✓ Fill factor not 100% per layer
  - ✓ Stitching mandatory
    - Pitch ? Power ? Yield ? Fill factor ? Bent radius ?

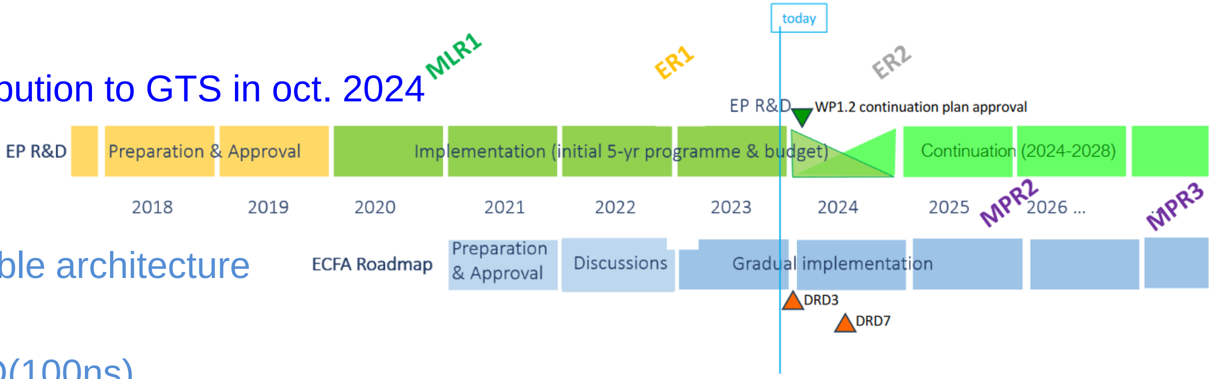


- Concept Schnecke
  - ✓ Stitching or not stitching
  - ✓ Full acceptance in ϕ / z
  - ✓ Double sided can considered
  - ✓ Competitive for mat. Budget.



Roadmap (to be discussed)

- Goal: reach the requirements before ~ 2030
- ESPPU: (2025-26)
  - ✓ In2p3/CEA: submit VTX contribution to GTS in oct. 2024
- DRD3/7 and submissions



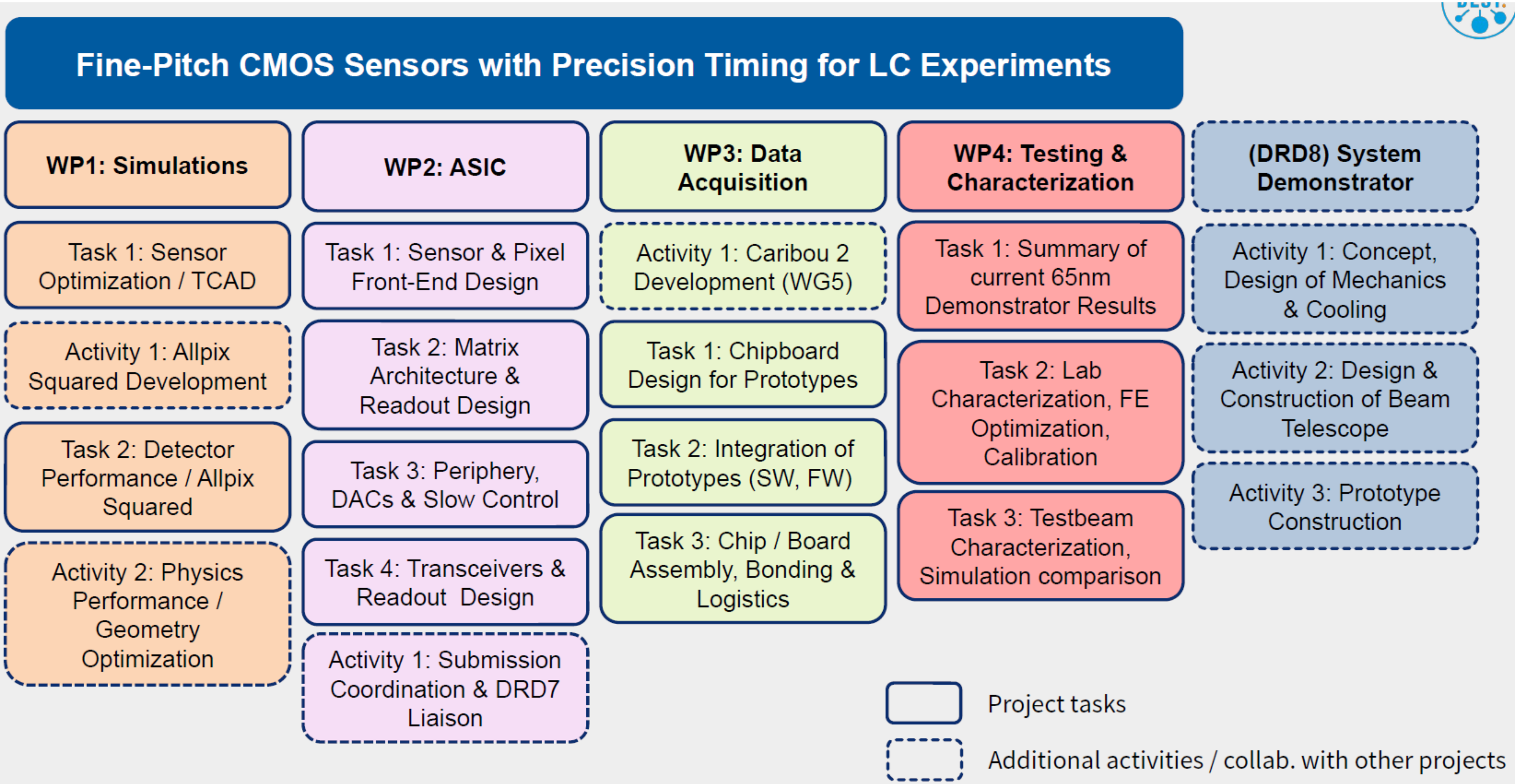
  - ✓ "Fine pitch" project
    - ▪ Determine the most suitable architecture
    - ▪ Target 3 µm resolution
    - ▪ Improve time resolution O(100ns)
    - ▪ Relax Power constraints
  - ✓ Step 1: explore architectures & spatial resolution (use previous MLR1/ER1/ER2 results)
  - ✓ Step 2: large size demonstrator usable for beam telescopes
- Strategy:
  - ✓ Maintain the know with short/mid term projects (MIMOSIS, OBELIX, MOSAIX, etc.)
  - ✓ Priority on the chip design (spatial resolution) but integration and simulations can not be neglected
- FCCee: EoI/LOI for detector concepts
  - ✓ Submit a realistic/robust vertex detector concept independent from the whole detector concepts
    - ▪ Backbone: chip design fulfilling the requirements based on an architecture developed @ C4PI.
    - ▪ Global design: versatile enough to cope with stitched / unstitched approaches.
    - ▪ Simulation ⇨ quantify precisely figures of merit (resolution down to tagging capabilities)
    - ▪ Integration ⇨ Bent sensors and ladders to demonstrate the feasibility of concept

Challenges & discussion

- FTE (in particular designers & integration)
  - ✓ C4PI resources
  - ✓ Tests FTE is demanding but easier to find
- French strategy with respect to other projects ? (Belle-2, ALICE 3, other LHC upgrades, etc.)
- Relationship with ALICE
  - ✓ Strong push from ALICE-3 @ CERN to find synergies with FCCee
  - ✓ How to find a way to not be absorbed by ALICE ?
- Relationship with other countries (Germany, Italy, etc.)
- DRD3
  - ✓ "Fine pitch" project on track and structured
  - ✓ Identified list of partners (IPHC, APC, DESY, CERN, Zurich, Prague, etc.)
- Outer tracker (larger pitch) synergies ?
  - ✓ Common architectures blocks ?
- Submission and funding strategy (MPR2 ~2026 ; MPR3 ~ 2027-2028)
  - ✓ Reticle: >6 cm^2 ; 650 000 keuros per Ing. Run; half of it payed by CERN
  - ✓ Master project GRAM / DEPHY ? Others ?
  - ✓ Spread the cost over years: 30-50 keuros / year ? + costs for tests, etc.
- Integration activities
  - ✓ Not independent from the design
  - ✓ Crucial to propose a global concept & for the visibility
  - ✓ Services, mechanics, Power/read-out/driving scheme, Cooling, interconnexion, alignment, acceptance, etc.
- Simulations & performances (Full simulation, tagging performances, charge transport, digitization, etc.)
  - ✓ Crucial for the visibility
  - ✓ Crucial to perform the right choices
  - ✓ Cf. PhD G. Sadowski ⇨ what's next ?

Back up

DRD3 WP1 project: Fine-pitch CMOS pixel sensors with precision timing for vertex detectors at future Lepton-Collider experiments



Fine-Pitch CMOS Sensors with Precision Timing for LC Experiments

WP1: Simulations

- Task 1: Sensor Optimization / TCAD
- Activity 1: Allpix Squared Development
- Task 2: Detector Performance / Allpix Squared
- Activity 2: Physics Performance / Geometry Optimization

WP2: ASIC

- Task 1: Sensor & Pixel Front-End Design
- Task 2: Matrix Architecture & Readout Design
- Task 3: Periphery, DACs & Slow Control
- Task 4: Transceivers & Readout Design
- Activity 1: Submission Coordination & DRD7 Liaison

WP3: Data Acquisition

- Activity 1: Caribou 2 Development (WG5)
- Task 1: Chipboard Design for Prototypes
- Task 2: Integration of Prototypes (SW, FW)
- Task 3: Chip / Board Assembly, Bonding & Logistics

WP4: Testing & Characterization

- Task 1: Summary of current 65nm Demonstrator Results
- Task 2: Lab Characterization, FE Optimization, Calibration
- Task 3: Testbeam Characterization, Simulation comparison

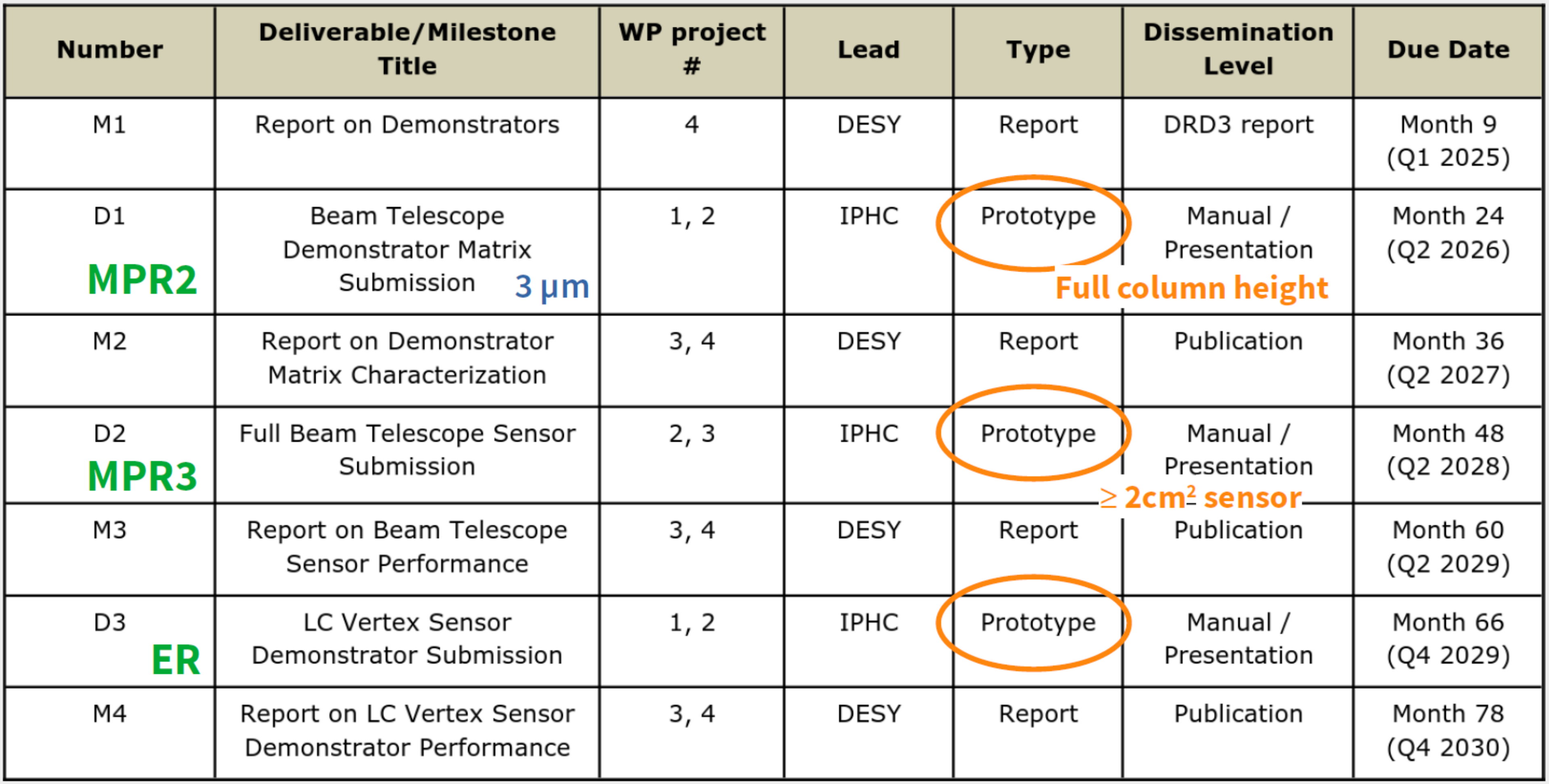
(DRD8) System Demonstrator

- Activity 1: Concept, Design of Mechanics & Cooling
- Activity 2: Design & Construction of Beam Telescope
- Activity 3: Prototype Construction

Project tasks

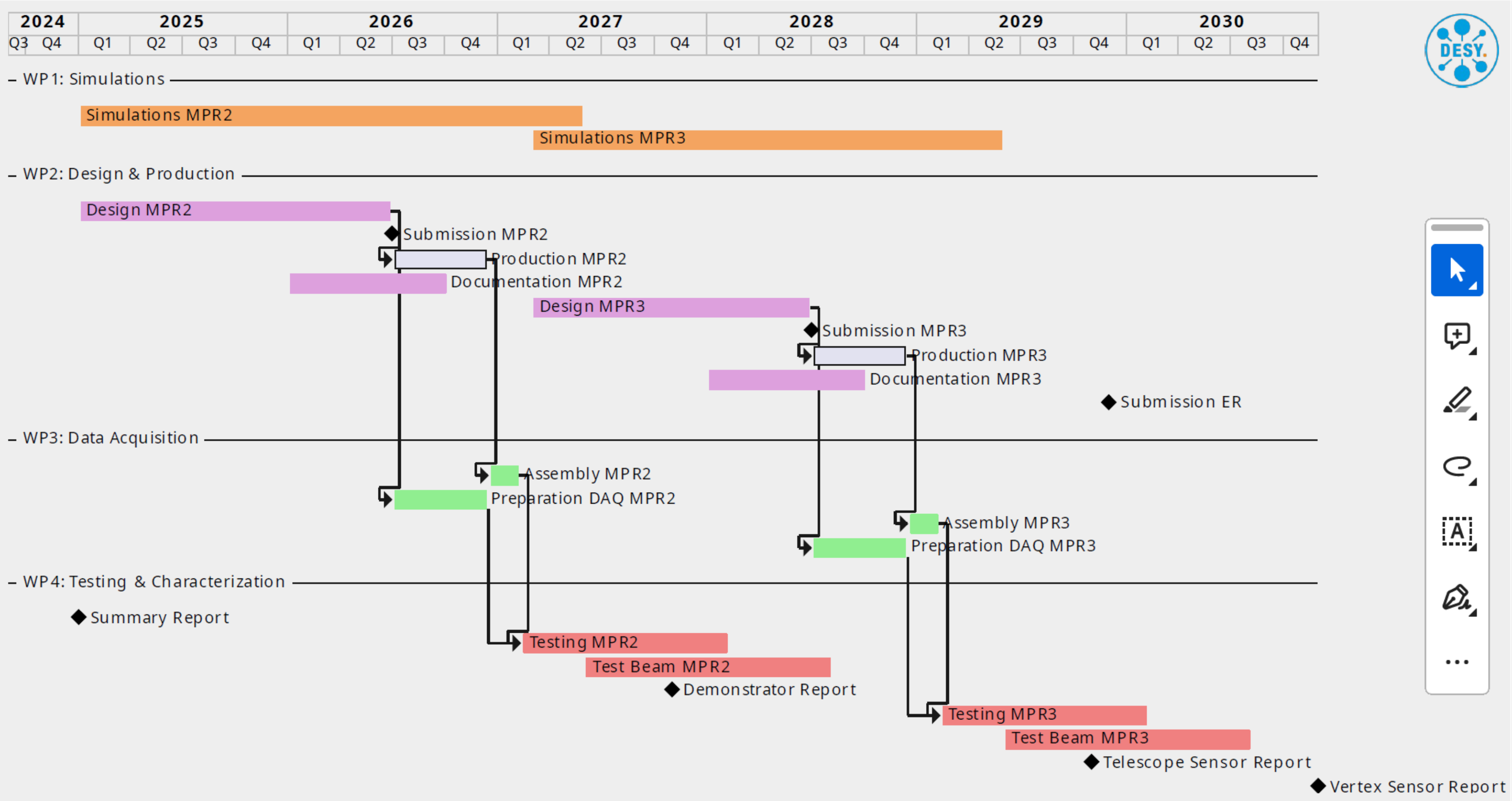
Additional activities / collab. with other projects

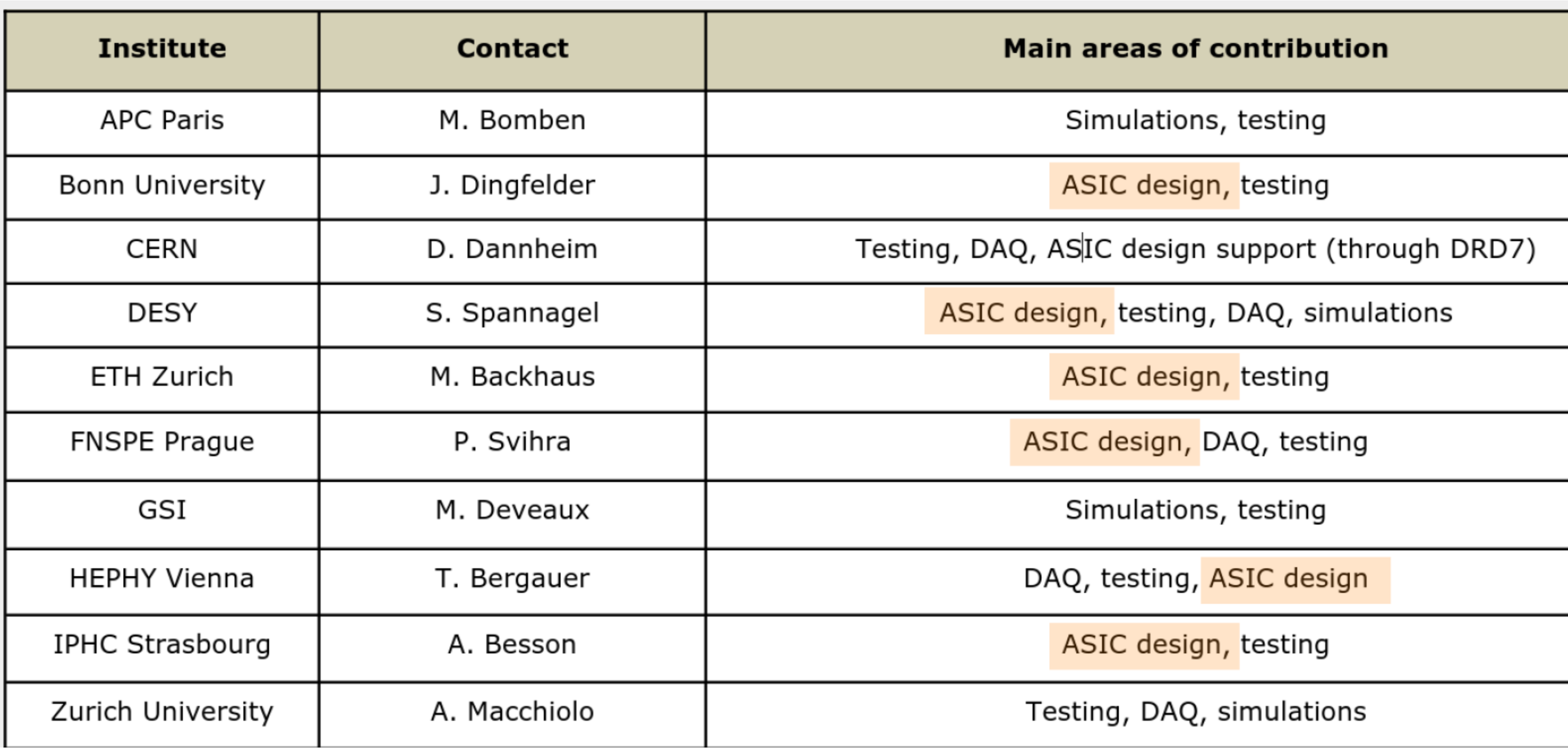
Milestones/deliverables



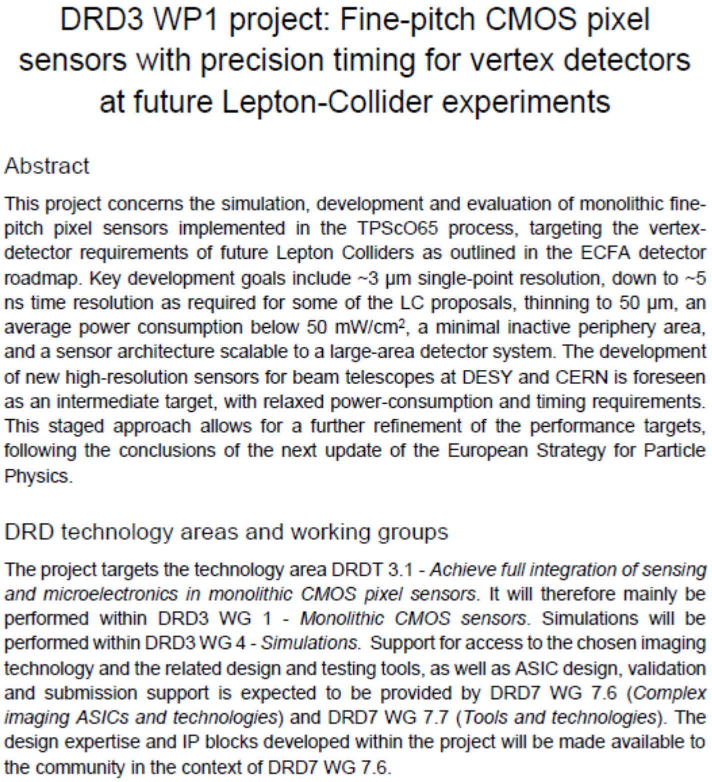
Number	Deliverable/Milestone Title	WP project #	Lead	Type	Dissemination Level	Due Date
M1	Report on Demonstrators	4	DESY	Report	DRD3 report	Month 9 (Q1 2025)
D1 **MPR2**	Beam Telescope Demonstrator Matrix Submission **3 µm**	1, 2	IPHC	Prototype	Manual / Presentation **Full column height**	Month 24 (Q2 2026)
M2	Report on Demonstrator Matrix Characterization	3, 4	DESY	Report	Publication	Month 36 (Q2 2027)
D2 **MPR3**	Full Beam Telescope Sensor Submission	2, 3	IPHC	Prototype	Manual / Presentation **$\geq 2cm^2$ sensor**	Month 48 (Q2 2028)
M3	Report on Beam Telescope Sensor Performance	3, 4	DESY	Report	Publication	Month 60 (Q2 2029)
D3 **ER**	LC Vertex Sensor Demonstrator Submission	1, 2	IPHC	Prototype	Manual / Presentation	Month 66 (Q4 2029)
M4	Report on LC Vertex Sensor Demonstrator Performance	3, 4	DESY	Report	Publication	Month 78 (Q4 2030)

Gantt plan


2024
2025
2026
2027
2028
2029
2030
Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4
DESY.
WP1: Simulations
Simulations MPR2
Simulations MPR3
WP2: Design & Production
Design MPR2
Submission MPR2
Production MPR2
Documentation MPR2
Design MPR3
Submission MPR3
Production MPR3
Documentation MPR3
Submission ER
WP3: Data Acquisition
Assembly MPR2
Preparation DAQ MPR2
Assembly MPR3
Preparation DAQ MPR3
WP4: Testing & Characterization
Summary Report
Testing MPR2
Test Beam MPR2
Demonstrator Report
Testing MPR3
Test Beam MPR3
Telescope Sensor Report
Vertex Sensor Report



Institute	Contact	Main areas of contribution
APC Paris	M. Bomben	Simulations, testing
Bonn University	J. Dingfelder	ASIC design, testing
CERN	D. Dannheim	Testing, DAQ, ASIC design support (through DRD7)
DESY	S. Spannagel	ASIC design, testing, DAQ, simulations
ETH Zurich	M. Backhaus	ASIC design, testing
FNSPE Prague	P. Svihra	ASIC design, DAQ, testing
GSI	M. Deveaux	Simulations, testing
HEPHY Vienna	T. Bergauer	DAQ, testing, ASIC design
IPHC Strasbourg	A. Besson	ASIC design, testing
Zurich University	A. Macchiolo	Testing, DAQ, simulations



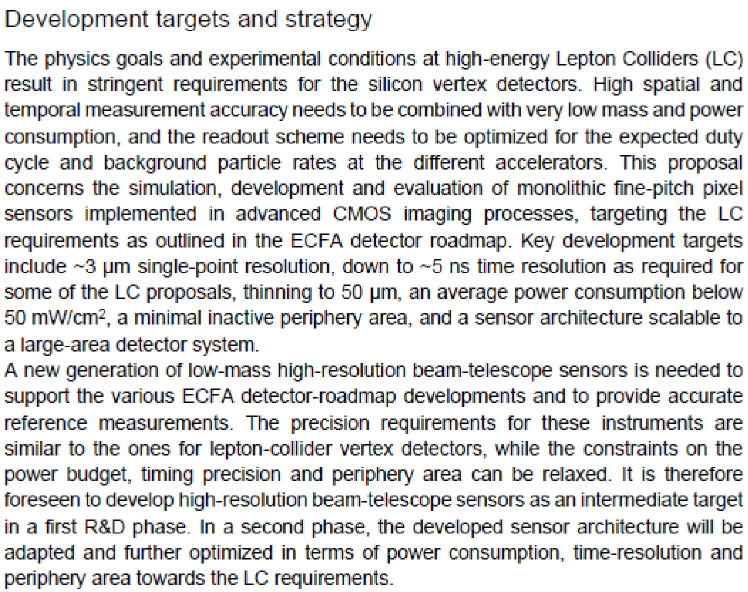
DRD3 WP1 project: Fine-pitch CMOS pixel sensors with precision timing for vertex detectors at future Lepton-Collider experiments

Abstract

This project concerns the simulation, development and evaluation of monolithic fine-pitch pixel sensors implemented in the TPScO65 process, targeting the vertex-detector requirements of future Lepton Colliders as outlined in the ECFA detector roadmap. Key development goals include ~3 µm single-point resolution, down to ~5 ns time resolution as required for some of the LC proposals, thinning to 50 µm, an average power consumption below 50 mW/cm^2, a minimal inactive periphery area, and a sensor architecture scalable to a large-area detector system. The development of new high-resolution sensors for beam telescopes at DESY and CERN is foreseen as an intermediate target, with relaxed power-consumption and timing requirements. This staged approach allows for a further refinement of the performance targets, following the conclusions of the next update of the European Strategy for Particle Physics.

DRD technology areas and working groups

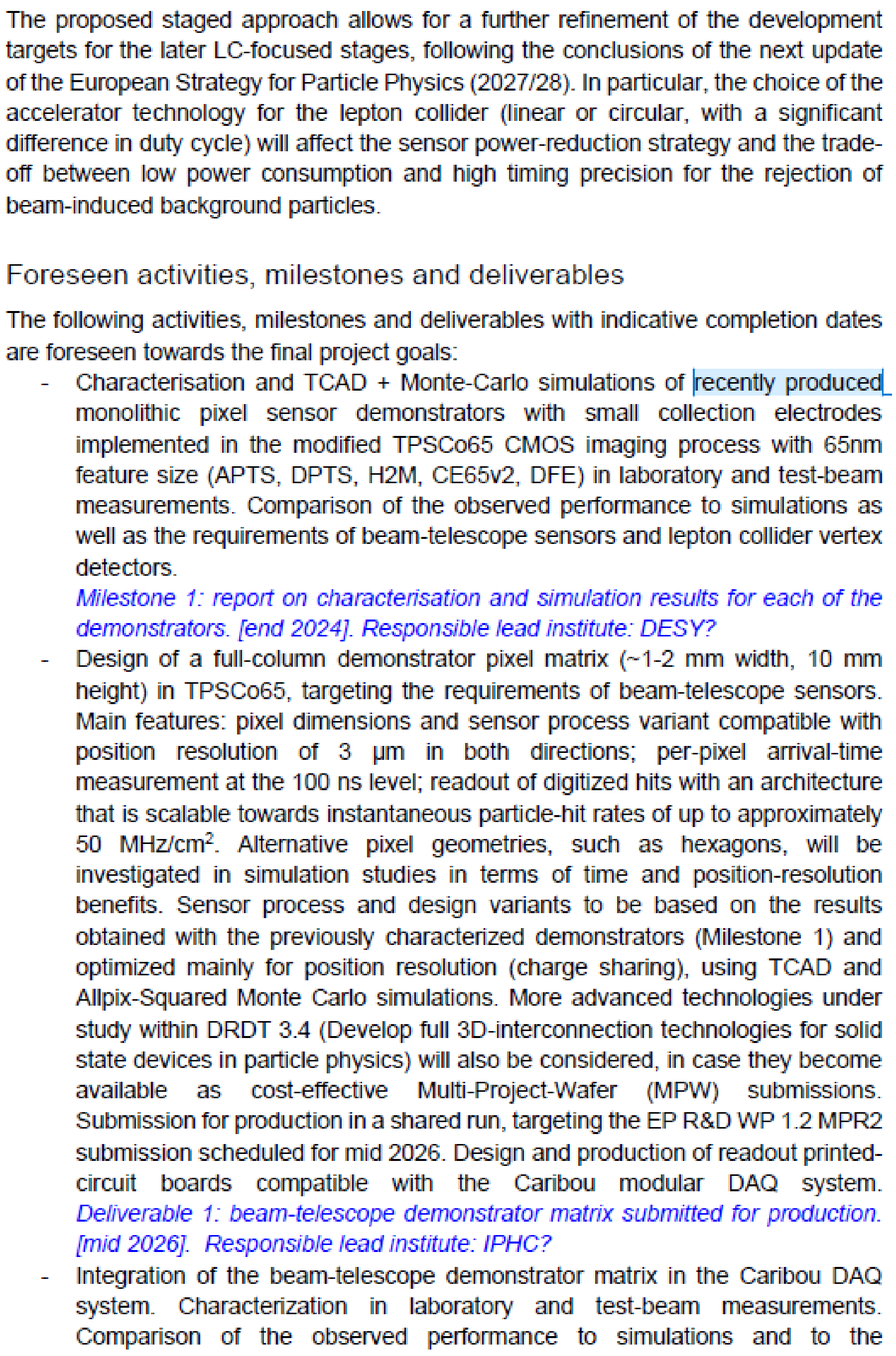
The project targets the technology area DRDT 3.1 - *Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors*. It will therefore mainly be performed within DRD3 WG 1 - *Monolithic CMOS sensors*. Simulations will be performed within DRD3 WG 4 - *Simulations*. Support for access to the chosen imaging technology and the related design and testing tools, as well as ASIC design, validation and submission support is expected to be provided by DRD7 WG 7.6 (*Complex imaging ASICs and technologies*) and DRD7 WG 7.7 (*Tools and technologies*). The design expertise and IP blocks developed within the project will be made available to the community in the context of DRD7 WG 7.6.



Development targets and strategy

The physics goals and experimental conditions at high-energy Lepton Colliders (LC) result in stringent requirements for the silicon vertex detectors. High spatial and temporal measurement accuracy needs to be combined with very low mass and power consumption, and the readout scheme needs to be optimized for the expected duty cycle and background particle rates at the different accelerators. This proposal concerns the simulation, development and evaluation of monolithic fine-pitch pixel sensors implemented in advanced CMOS imaging processes, targeting the LC requirements as outlined in the ECFA detector roadmap. Key development targets include ~3 µm single-point resolution, down to ~5 ns time resolution as required for some of the LC proposals, thinning to 50 µm, an average power consumption below 50 mW/cm^2, a minimal inactive periphery area, and a sensor architecture scalable to a large-area detector system.

A new generation of low-mass high-resolution beam-telescope sensors is needed to support the various ECFA detector-roadmap developments and to provide accurate reference measurements. The precision requirements for these instruments are similar to the ones for lepton-collider vertex detectors, while the constraints on the power budget, timing precision and periphery area can be relaxed. It is therefore foreseen to develop high-resolution beam-telescope sensors as an intermediate target in a first R&D phase. In a second phase, the developed sensor architecture will be adapted and further optimized in terms of power consumption, time-resolution and periphery area towards the LC requirements.

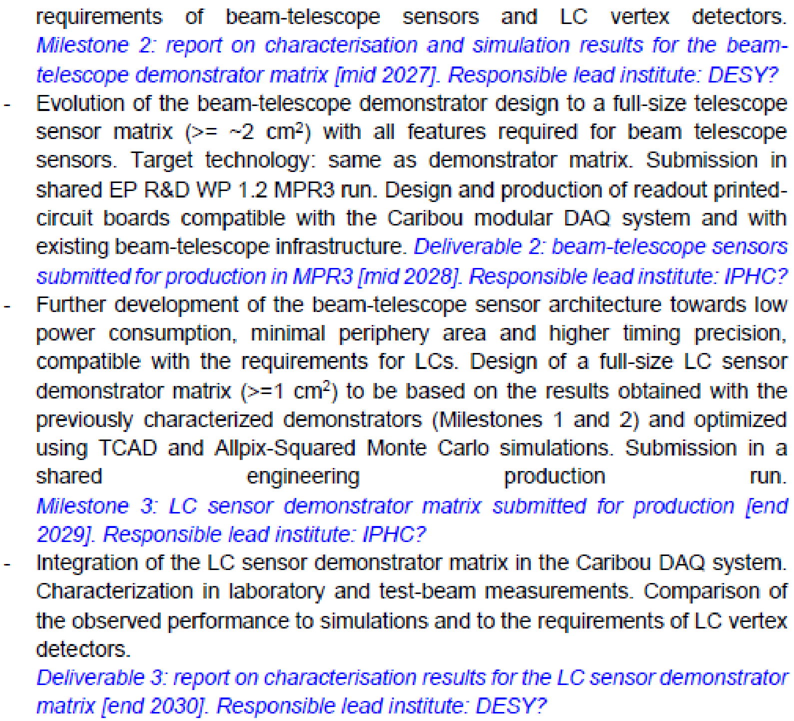


The proposed staged approach allows for a further refinement of the development targets for the later LC-focused stages, following the conclusions of the next update of the European Strategy for Particle Physics (2027/28). In particular, the choice of the accelerator technology for the lepton collider (linear or circular, with a significant difference in duty cycle) will affect the sensor power-reduction strategy and the trade-off between low power consumption and high timing precision for the rejection of beam-induced background particles.

Foreseen activities, milestones and deliverables

The following activities, milestones and deliverables with indicative completion dates are foreseen towards the final project goals:

- Characterisation and TCAD + Monte-Carlo simulations of recently produced monolithic pixel sensor demonstrators with small collection electrodes implemented in the modified TPSCo65 CMOS imaging process with 65nm feature size (APTS, DPTS, H2M, CE65v2, DFE) in laboratory and test-beam measurements. Comparison of the observed performance to simulations as well as the requirements of beam-telescope sensors and lepton collider vertex detectors.
  Milestone 1: report on characterisation and simulation results for each of the demonstrators. [end 2024]. Responsible lead institute: DESY?
- Design of a full-column demonstrator pixel matrix (~1-2 mm width, 10 mm height) in TPSCo65, targeting the requirements of beam-telescope sensors. Main features: pixel dimensions and sensor process variant compatible with position resolution of 3 µm in both directions; per-pixel arrival-time measurement at the 100 ns level; readout of digitized hits with an architecture that is scalable towards instantaneous particle-hit rates of up to approximately 50 MHz/cm^2. Alternative pixel geometries, such as hexagons, will be investigated in simulation studies in terms of time and position-resolution benefits. Sensor process and design variants to be based on the results obtained with the previously characterized demonstrators (Milestone 1) and optimized mainly for position resolution (charge sharing), using TCAD and Allpix-Squared Monte Carlo simulations. More advanced technologies under study within DRDT 3.4 (Develop full 3D-interconnection technologies for solid state devices in particle physics) will also be considered, in case they become available as cost-effective Multi-Project-Wafer (MPW) submissions. Submission for production in a shared run, targeting the EP R&D WP 1.2 MPR2 submission scheduled for mid 2026. Design and production of readout printed-circuit boards compatible with the Caribou modular DAQ system. *Deliverable 1: beam-telescope demonstrator matrix submitted for production. [mid 2026]. Responsible lead institute: IPHC?*
- Integration of the beam-telescope demonstrator matrix in the Caribou DAQ system. Characterization in laboratory and test-beam measurements. Comparison of the observed performance to simulations and to the

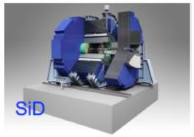


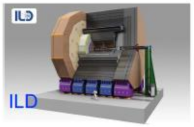
requirements of beam-telescope sensors and LC vertex detectors. *Milestone 2: report on characterisation and simulation results for the beam-telescope demonstrator matrix [mid 2027]. Responsible lead institute: DESY?*

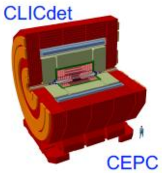
- Evolution of the beam-telescope demonstrator design to a full-size telescope sensor matrix (>= ~2 cm^2) with all features required for beam telescope sensors. Target technology: same as demonstrator matrix. Submission in shared EP R&D WP 1.2 MPR3 run. Design and production of readout printed-circuit boards compatible with the Caribou modular DAQ system and with existing beam-telescope infrastructure. *Deliverable 2: beam-telescope sensors submitted for production in MPR3 [mid 2028]. Responsible lead institute: IPHC?*
- Further development of the beam-telescope sensor architecture towards low power consumption, minimal periphery area and higher timing precision, compatible with the requirements for LCs. Design of a full-size LC sensor demonstrator matrix (>=1 cm^2) to be based on the results obtained with the previously characterized demonstrators (Milestones 1 and 2) and optimized using TCAD and Allpix-Squared Monte Carlo simulations. Submission in a shared engineering production run. *Milestone 3: LC sensor demonstrator matrix submitted for production [end 2029]. Responsible lead institute: IPHC?*
- Integration of the LC sensor demonstrator matrix in the Caribou DAQ system. Characterization in laboratory and test-beam measurements. Comparison of the observed performance to simulations and to the requirements of LC vertex detectors.
  Deliverable 3: report on characterisation results for the LC sensor demonstrator matrix [end 2030]. Responsible lead institute: DESY?

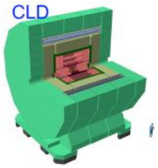
Tracking/vertexing detectors in future e^+e^- colliders

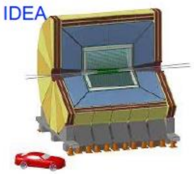
Collider	ILC		CLIC	FCCee			CEPC	
Bunch separation (ns)	330/550		0.5	20/990/3000			25/680	
Power Pulsing	yes		yes	no			no	
beamstrahlung	high		high	low			low	
Detector concept	SiD	ILD	CLICdet	CLD	IDEA	Lar	Baseline	IDEA
B Field (T)	5	3.5	4	2	2	2	3	2
Vertex	Si-Pixel	Si-Pixel	Si-Pixel	Si-Pixel	Si-Pixel	Si-Pixel	Si-Pixel	Si-Pixel
Vertex Rmin (mm)	16	16	31	~12	~12	~12	16	16
Tracker	Si-strips	TPC	Si-Pixel	Si-Pixel (+RICH ?)	DC/Si-strips	DC/Si-strips or Si-Pixels	TPC or Strips	DC/Si-strips
Tracker Rmax (m)	1.25	1.8	1.5	2.2	2.0	2.0	1.8	2.1
Disks layers	4 + 4	2 + 5	6 + 7	3 + 7	3 (150 mrad)		2+6	

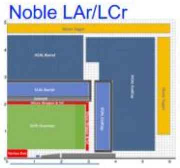


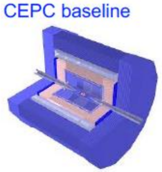


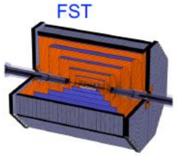








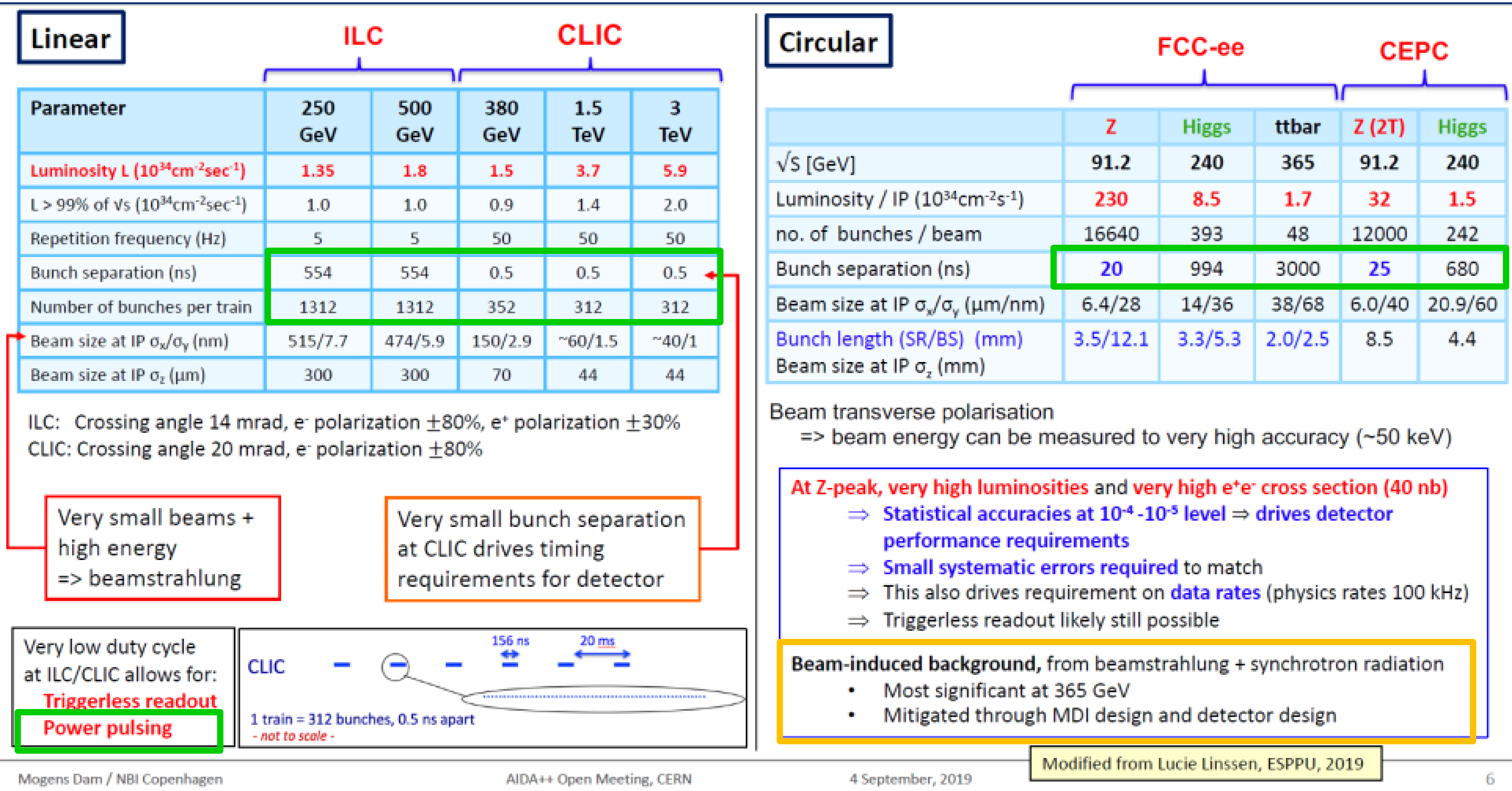




(From D. Dannheim)

Large similarities between the concepts but also significant differences

General considerations on future e+e- colliders



Linear

	ILC		CLIC		
Parameter	**250 GeV**	**500 GeV**	**380 GeV**	**1.5 TeV**	**3 TeV**
Luminosity L ($10^{34}cm^{-2}sec^{-1}$)	**1.35**	**1.8**	**1.5**	**3.7**	**5.9**
L > 99% of √s ($10^{34}cm^{-2}sec^{-1}$)	1.0	1.0	0.9	1.4	2.0
Repetition frequency (Hz)	5	5	50	50	50
Bunch separation (ns)	554	554	0.5	0.5	0.5
Number of bunches per train	1312	1312	352	312	312
Beam size at IP σ_x/σ_y (nm)	515/7.7	474/5.9	150/2.9	~60/1.5	~40/1
Beam size at IP σ_z (μm)	300	300	70	44	44

ILC: Crossing angle 14 mrad, e- polarization ±80%, e+ polarization ±30%
CLIC: Crossing angle 20 mrad, e- polarization ±80%

Very small beams + high energy => beamstrahlung

Very small bunch separation at CLIC drives timing requirements for detector

Very low duty cycle at ILC/CLIC allows for:
Triggerless readout
Power pulsing

CLIC
156 ns
20 ms
1 train = 312 bunches, 0.5 ns apart
- not to scale -

Circular

	FCC-ee			CEPC	
	Z	**Higgs**	**ttbar**	**Z (2T)**	**Higgs**
√s [GeV]	**91.2**	**240**	**365**	**91.2**	**240**
Luminosity / IP ($10^{34}cm^{-2}s^{-1}$)	**230**	**8.5**	**1.7**	**32**	**1.5**
no. of bunches / beam	16640	393	48	12000	242
Bunch separation (ns)	20	994	3000	25	680
Beam size at IP σ_x/σ_y (μm/nm)	6.4/28	14/36	38/68	6.0/40	20.9/60
Bunch length (SR/BS) (mm) Beam size at IP σ_z (mm)	3.5/12.1	3.3/5.3	2.0/2.5	8.5	4.4

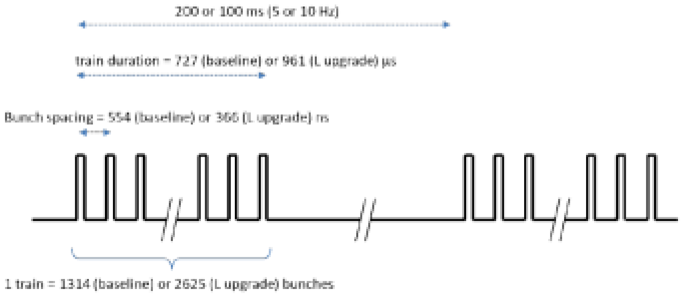
Beam transverse polarisation
=> beam energy can be measured to very high accuracy (~50 keV)

At Z-peak, very high luminosities and **very high e+e- cross section (40 nb)**
⇒ **Statistical accuracies at 10^{-4}-10^{-5} level ⇒ drives detector performance requirements**
⇒ **Small systematic errors required** to match
⇒ This also drives requirement on **data rates** (physics rates 100 kHz)
⇒ Triggerless readout likely still possible

Beam-induced background, from beamstrahlung + synchrotron radiation
- Most significant at 365 GeV
- Mitigated through MDI design and detector design

Mogens Dam / NBI Copenhagen   AIDA++ Open Meeting, CERN   4 September, 2019   Modified from Lucie Linssen, ESPPU, 2019   6

(slide from Mogens Dam/Lucie Linssen)

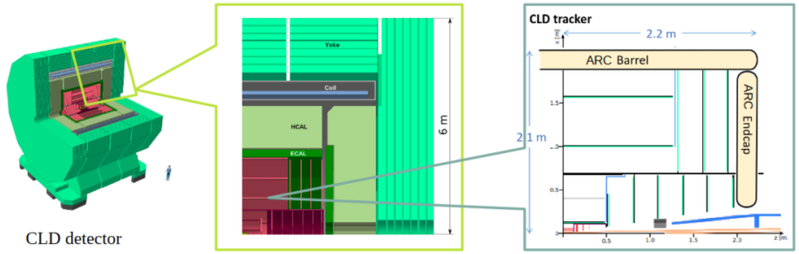


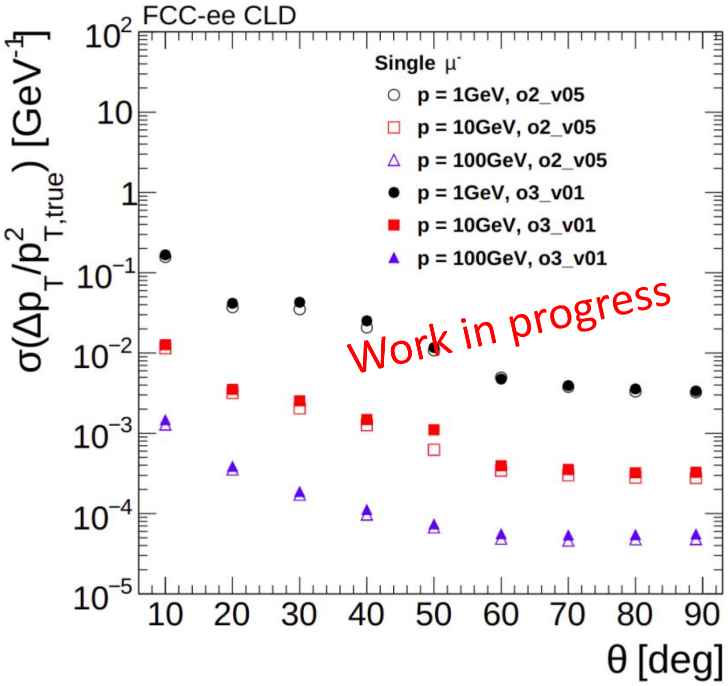
+ new concepts (C^3, etc.)

J. Andrea, G. Sadowski (PhD), Z El Bitar

An example of Full sim performances in CLD

- CLD_01_v04 = former geometry
- CLD_02_v05 = new beam pipe radius & material budget
  - ✓ 5 μm Au + 2 x 350 μm layers of BeAl + liquid parafin ~ 0.6 % X_0 ⇨ mat. Budget +33%
  - ✓ Inner radius: 15 mm ⇨ 10mm
- CLD_03_v01 = Adding a RICH
  - ✓ + Array of RICH Cells (ARC)





D0 resolution – single μ^- – CLD_o1_v04

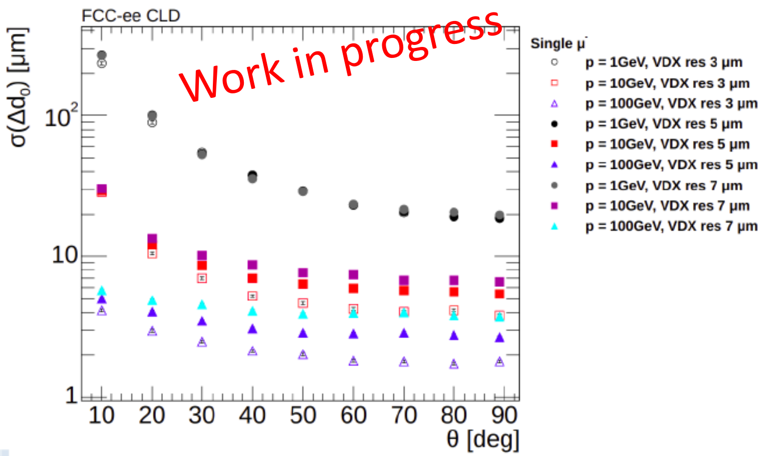


Figure: D0 resolution (10k events)

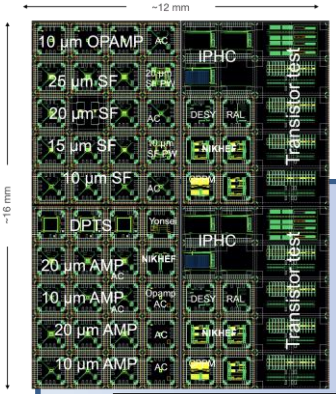
- Need to reassess the performances plots optimization for FCCee with respect to ILC context.
- Comparing resolutions between detector concepts has to be taken with caution (Different level of realism and conservatism on the technologie future performances)

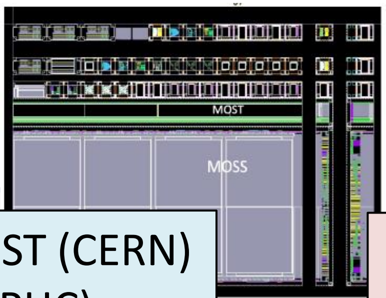
CMOS technology: moving from 180 nm to 65 nm

Technology	TowerJazz 180 nm	TPSCo 65 nm
Available since	2013 (mature technology)	2020 (access through CERN)
Large surface projects	• ALPIDE for ALICE ITS-2 • MIMOSIS for CBM-MVD • OBELIX for Belle-II upgrade	• MOSAIX for ALICE ITS-3 • DRD3/7 R&D ?
Price	affordable	More expensive
Wafer	• 8 inches (20 cm)	• Larger: 12 inches (30cm) ⇨ stitching + bent sensors
Epitaxial layer thickness	• 18/25/30/40/50 µm	• 10
Process options	• « standard » • « modified », « gap »	• « standard » • « modified », « gap »
Technology	• Feature size (180 nm) • V (1.8V) • 6 Metal Layers	• Feature size (65nm) • Lower V (1.2 V) • 7 Metal layers ⇨Pitch reduction, power saving, more functionnalites, etc.

⇨ Strong motivations to switch to a smaller feature size to increase the performances space

TPSCo 65nm Submissions





- ➢ MOSS/MOST (CERN)
- ➢ CE65_v2 (IPHC)
- ➢ Etc.

- ➢ MOSAIX (CERN)
- ➢ SPARCS ? (IPHC)
- ➢ Etc.

ALICE ITS-3

MLR1 (2020) → ER1 (2022) → ER2 (2024) → ER3 (2025?)

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029

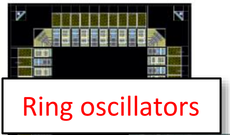
ER1 (2022) → MPR2 (2025-26) → MPR3 (2027-28)

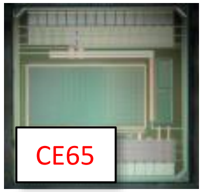
- ➢ CE65_v1 (IPHC)
- ➢ DPTS (CERN)
- ➢ APTS (CERN)
- ➢ TANGERINE (DESY)
- ➢ Ring oscillators (CPPM)
- ➢ Etc.

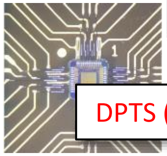
- ➢ Fine pitch demonstrator
- ➢ Architectures exploration

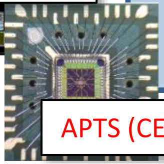
- ➢ Fine pitch telescope
- ➢ Fast timing ?
- ➢ Power optimization ?

Generic R&D via DRD3/7

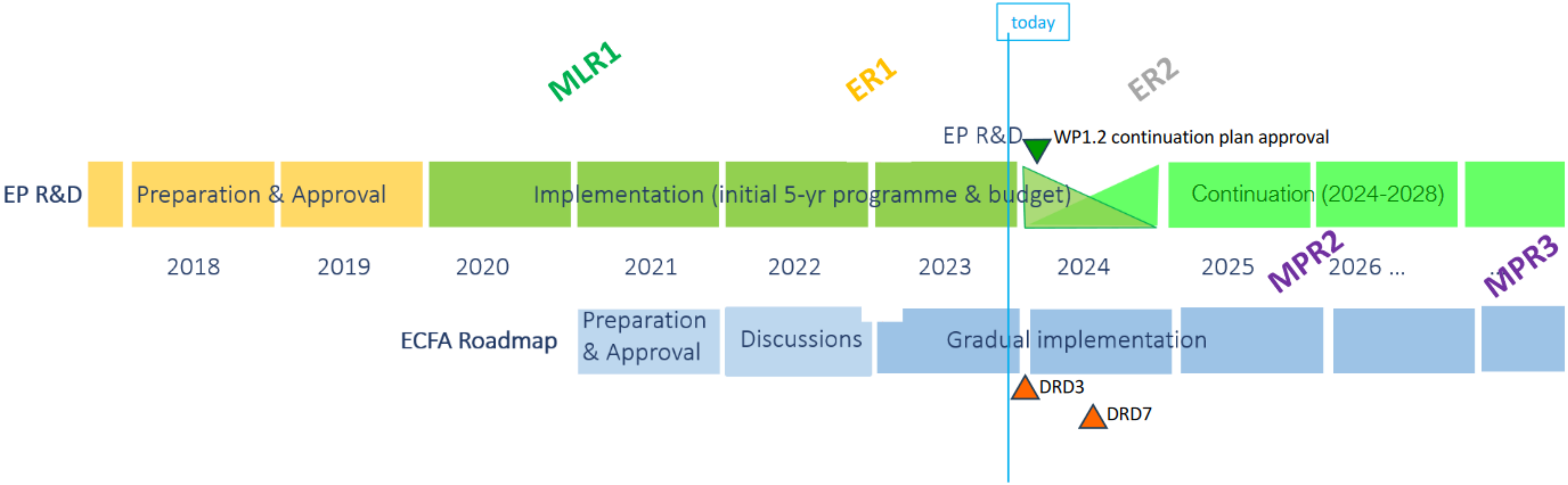

Ring oscillators


CE65


DPTS (CERN)

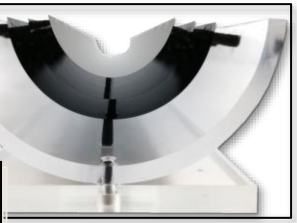

APTS (CERN)

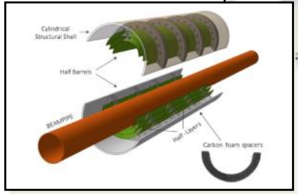
CERN WP 1.2



https://indico.cern.ch/event/1339888/

How to adapt ITS-3 approach to FCCee ?

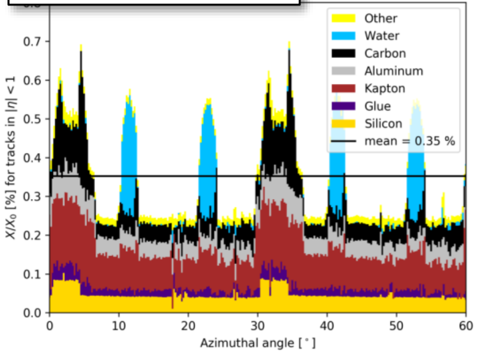


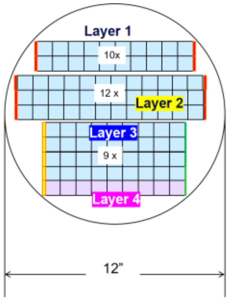


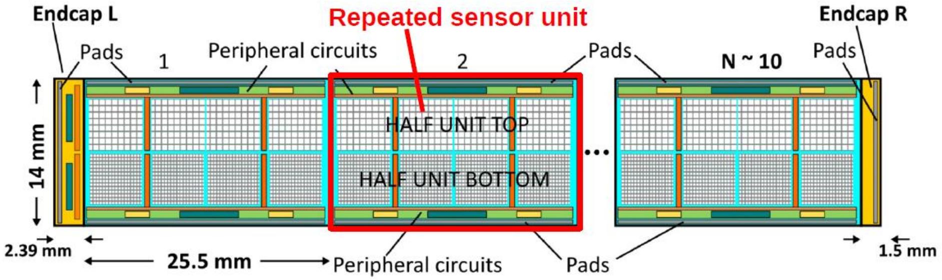
- ALICE-ITS3/CERN drives the R&D on stitching + bent sensors:
  - ✓ Sensor part ~15% of total material budget
  - ✓ Sensors thinned down to 50 μm or less ?
    - ▪ Tests performed by ALICE (cf. ITS3-TDR)
  - ✓ Minimizing overlapping regions,
  - ✓ minimizing minimal radius around the beam pipe
- Challenges and caveats (for e^+e^- colliders)
  - ✓ Mechanics ? Bonding ? Air cooling only ?
  - ✓ Power dissipation map could be a challenge
  - ✓ Design: Minimizing peripheral circuits (Fill factor ~90%)
  - ✓ Bent sensor performances ? Yield ? Radiation hardness ?
  - ⇨ design rules constraints the minimal pitch (~22 μm) ?
  - ✓ ITS-3 do not have disk (chip periphery adds Z position constraint)
  - ✓ Approach validated in a limited radius range (R> 18mm) ?
    - ▪ Trials performed by ALICE down to R = 10mm (thickness 30-50 μm)

Figure 4.42: Setup for the bending strength measurements.

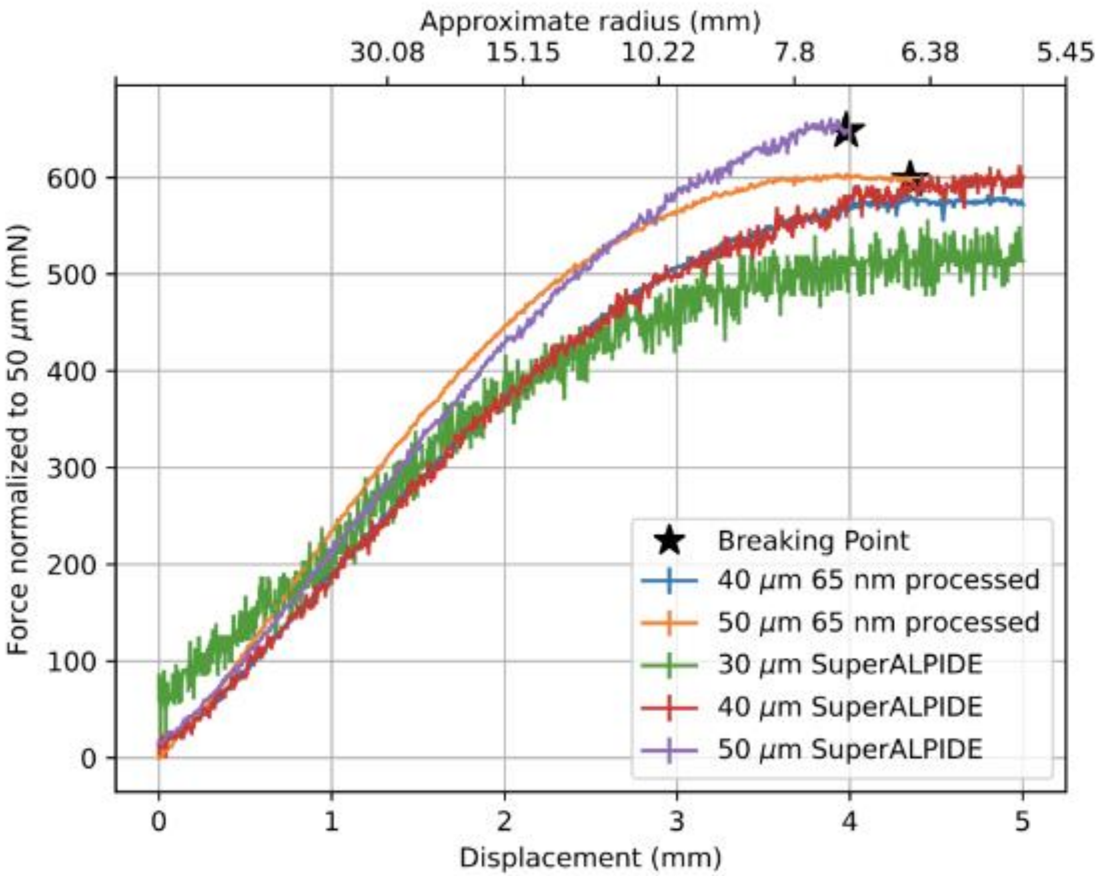
ALICE ITS2
Material budget







Bent sensor tests for different thicknesses/radii



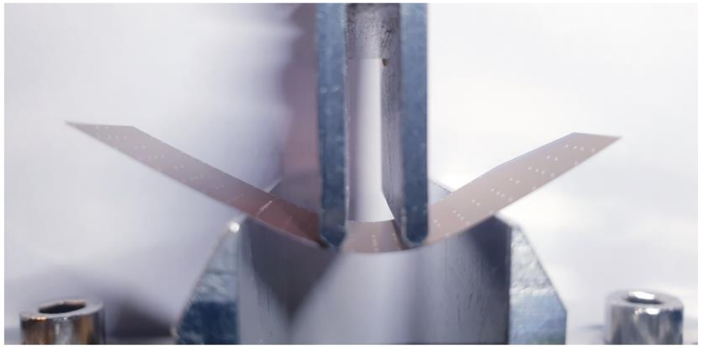
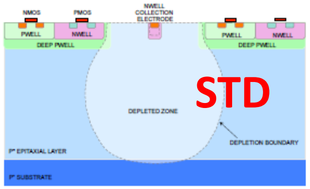
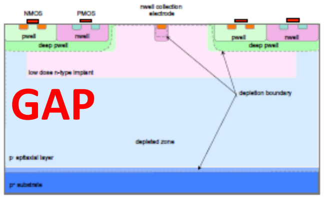


Figure 4.41: Setup for the bending strength measurements.

ALICE ITS-3 TDR: Bent layers at R ~12 mm seems doable

TPSCo 65 nm & spatial resolution



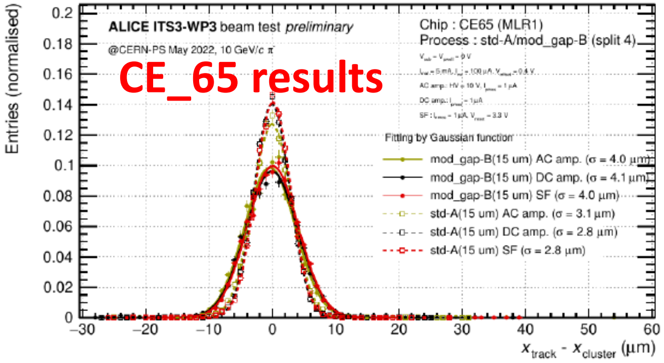


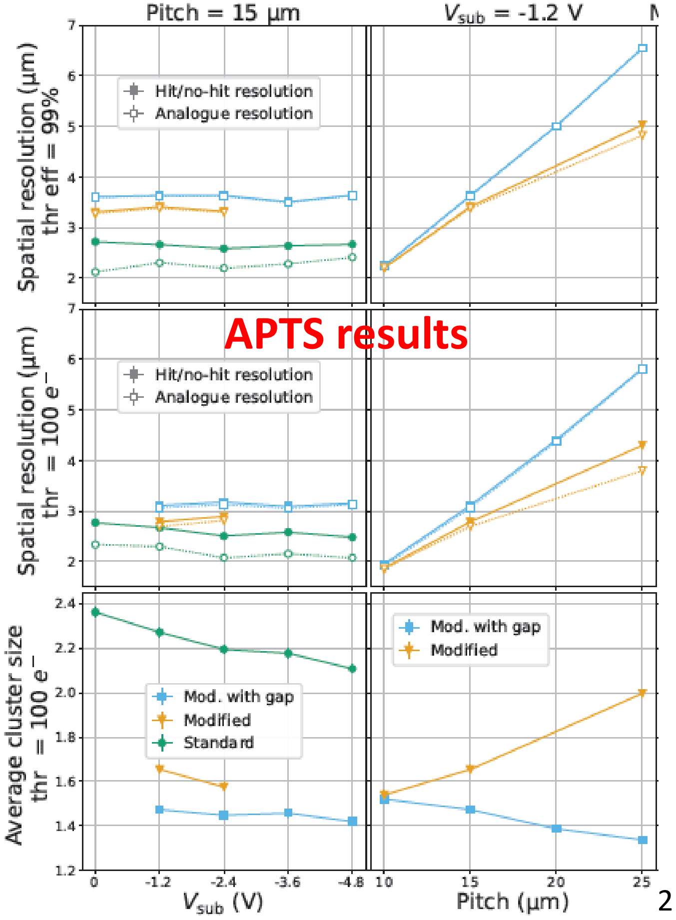
CE_65 results

PCB	Geo	Process	Pitch(um)	HV(V)	Sp. Res.(um) (telescope resolution subtracted)
10	SQ	GAP	22.5	10	~5.1
02	SQ	GAP	18	10	~4.1
19	SQ	GAP	15	10	~3.2
18	SQ	STD	22.5	10	~2.4
23	SQ	STD	18	10	~1.8
06	SQ	STD	15	10	~1.3

Telescope resolution: **~2.1um** (Calculated from https://mmager.web.cern.ch/telescope/tracking.html)

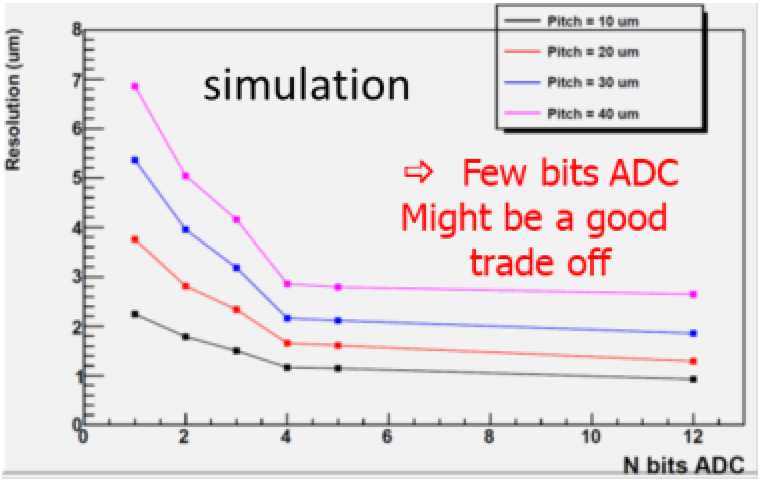
- 3 µm resolution with Analog output
  - ✓ STD ⇨ pitch ~ 25 µm
  - ✓ GAP ⇨ pitch ~ 14 µm
- 3 µm resolution with Binary ouput
  - ✓ STD ⇨ pitch ~ 17 µm
  - ✓ GAP ⇨ pitch ~ 14 µm
- Few bits ADC valuable with presence of charge sharing
  - ✓ On going studies





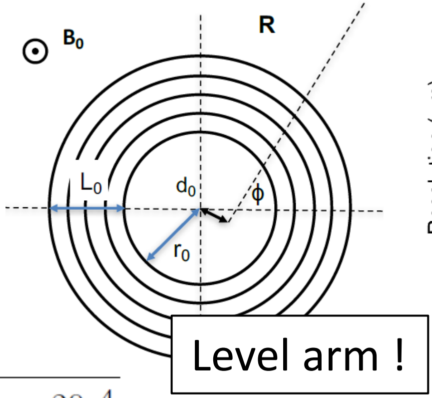
Spatial resolution in Higgs factories

- Typical targets:
  - ✓ σ_{sp}~3 µm for the vertex layers
  - ✓ σ_{sp}~5-10 µm for the outer tracker layers
- Resolution in each layer depends on
  - ✓ Pitch
    - In conflict with the functionnalities inside the pixel
    - Favored by small feature size technology
  - ✓ Charge deposition
    - Sensitive layer thickness
  - ✓ Charge sharing (SNR vs resolution)
    - Depletion:
    - Staggered pixels
  - ✓ Charge encoding
    - Binary output / ADC / Tot / etc.



⇨ Few bits ADC Might be a good trade off

$$\boxed{{\sigma_{d0}}^2 = a^2 + \left(\frac{b}{p.\,sin^{3/2}\theta}\right)^2}$$

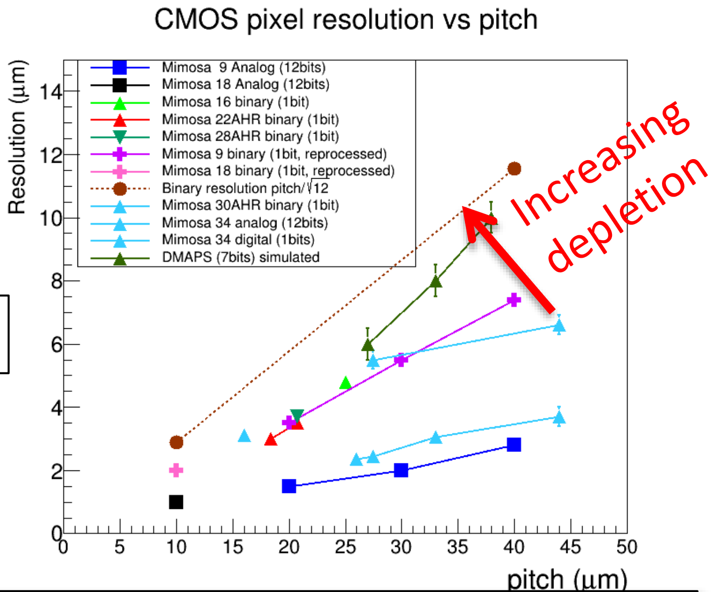


Level arm !

$$\Delta d_0|_{res.} \approx \frac{3\sigma_{r\phi}}{\sqrt{N+5}}\sqrt{1+\frac{8r_0}{L_0}+\frac{28r_0^2}{L_0^2}+\frac{40r_0^3}{L_0^3}+\frac{20r_0^4}{L_0^4}}$$

$$\Delta d_0|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{\beta p_T} r_0 \sqrt{\frac{d}{X_0\sin\theta}}\sqrt{1+\frac{1}{2}\left(\frac{r_0}{L_0}\right)+\frac{N}{4}\left(\frac{r_0}{L_0}\right)^2}$$

d = layer thickness, N = # layers



CMOS pixel resolution vs pitch

Increasing depletion

⇨ σ_{sp} ~ 3 µm ⇦⇨ pitch ~ 15-20 µm

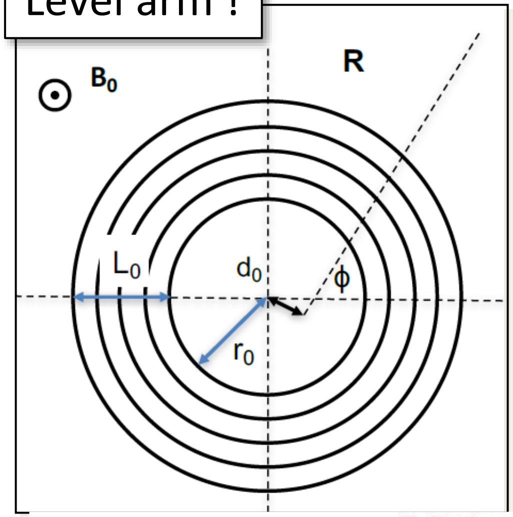
(assuming binary output, ~20 µm epi.thickness & large depletion in 180nm tech.)

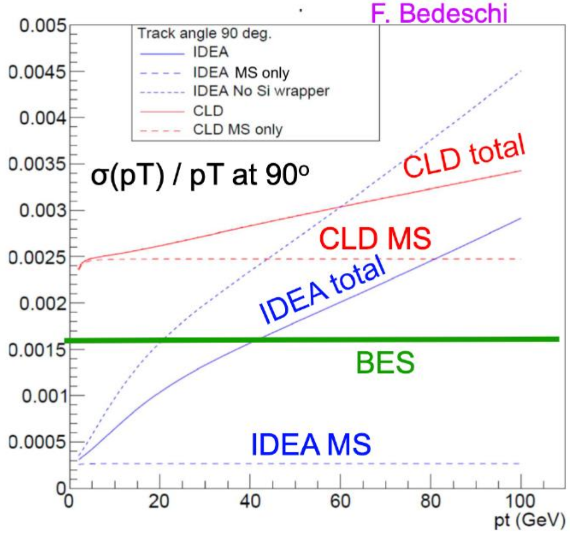
Tracker requirements

Expected performances

$$\frac{\sigma_{p_T}}{p_T^2} \sim 2 \times 10^{-5} GeV^{-1}$$

Level arm !





Physics
- ⇨ Momentμm resolution
- ⇨ Tracking efficiency
- ⇨ Track separation, low p fake tracks
- ⇨ Etc.

- Level arm also plays a crucial role for the VTX

- Material budget vs intrinsic resolution
  - ✓ Typically σ_{sp} ~5-10 μm/layer ; material ~1-2% X_0/layer ; Power ~< 100 mW/cm^2
  - ✓ Low momentμm vs high momentμm ⇦ physics input
- 2 main options:
  - ✓ All silicon (CLD, CLICdet, SiD)
    - Few high resolution layers
    - Possibly timing capabilities
  - ✓ Silicon + Gazeous detector
    - TPC (ILD) / Drift Chamber (IDEA) / RICH (CLD ?)
    - dEdx/dNdx capabilities,
    - More hits, overall less materials
    - TPC: Ion back flow issue for circular colliders
- PID Strategy to be included (RICH, timing, dEdx, etc.)

Drasal, Riegler, https://doi.org/10.1016/j.nima.2018.08.078

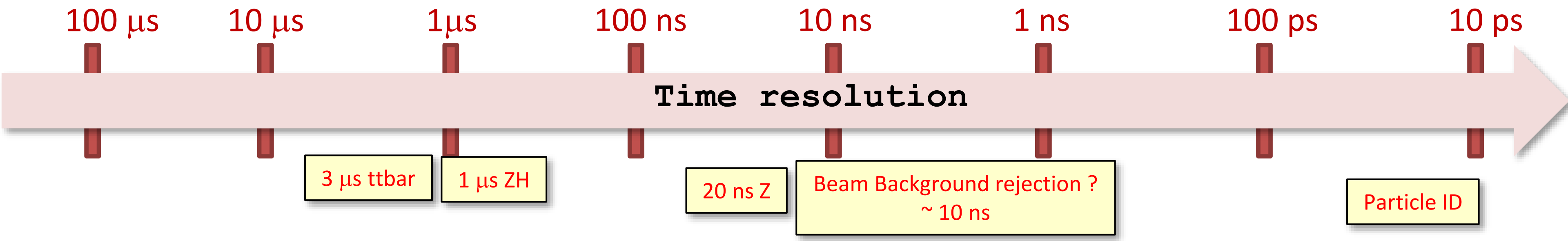
$$d_{tot}/X_0 = (N+1)d/X_0.$$

d = layer thickness, N = # layers

$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\, B_0 L_0}\sqrt{\frac{d_{tot}}{X_0 \sin\theta}} \qquad \frac{\Delta p_T}{p_T}\Big|_{res.} \approx \frac{12\,\sigma_{r\phi}\, p_T}{0.3\, B_0 L_0^2}\sqrt{\frac{5}{N+5}}$$

m.s. term dominates for pT ~< O(100) GeV/c

Timing & 4-D tracking



100 μs 10 μs 1μs 100 ns 10 ns 1 ns 100 ps 10 ps

Time resolution

3 μs ttbar

1 μs ZH

20 ns Z

Beam Background rejection ?
~ 10 ns

Particle ID

- Time resolution Δt
  - ✓ Bunch separation (3 μs / 1 μs / 20 ns @ FCCee)
  - ✓ Background rejection ? (1-10 ns range)
  - ✓ Particle ID (10-100 ps)
- Usual drawbacks to go faster
  - ✓ Power consμmption
  - ✓ Active Cooling & geometrical acceptance due to services
  - ✓ In pixel circuitry ⇨ larger pixels (or multipixels)
  - ✓ Fill factor, dead time
  - ✓ PID Restricted to low momentμm particles (~< few GeV/c)
- Still
  - ✓ Forward region not covered by a central gazeous detector (TPC)
  - ✓ Added value for intermediate radii (e.g. LLPs ?)
- Specialized layers
  - ✓ Doesn’t compromise the other requirements (material budget and granularity)
    - Probably not in the most inner layers

Particle ID and time resolution DRD4 & 1/3

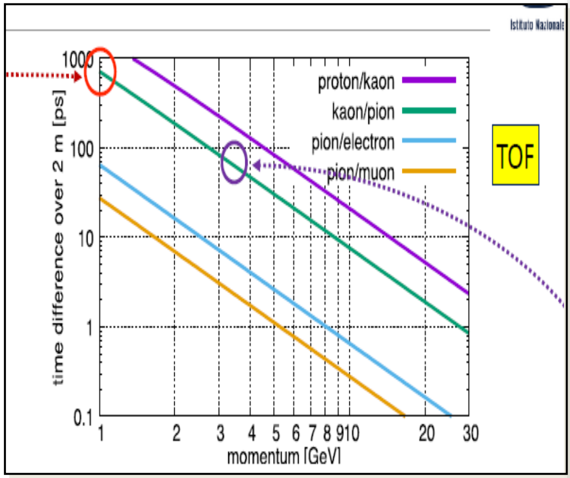
More details here: https://indico.cern.ch/event/1202105/contributions/5402790/attachments/2662086/4612032/FCC-DRD4.pdf

- Goal:
  - ✓ K/π, π/e$^-$ separation, etc. ⇨ Interest to push beyond 10 ps resolution
  - ✓ Even more important for the physics program @ Z peak

Fast timing (<100 ps)
Solid state (pixelated) detector (DRD3)

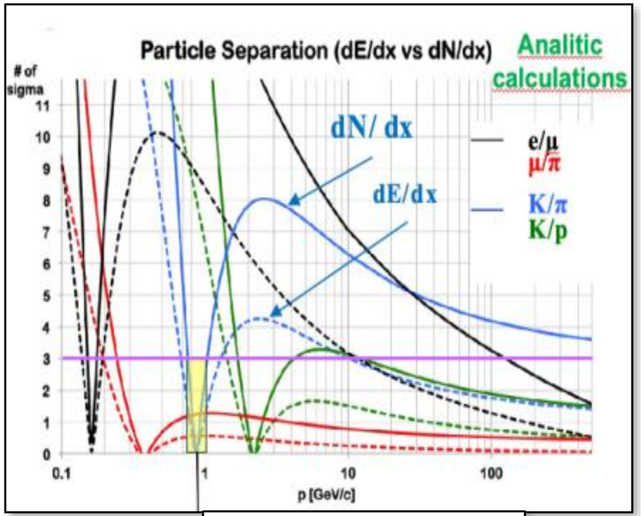
dE/dx + dN/dx
Mainly gazeous detector, e.g. TPC, DC, RICH (DRD1)

Time difference (ps)



Time of Flight

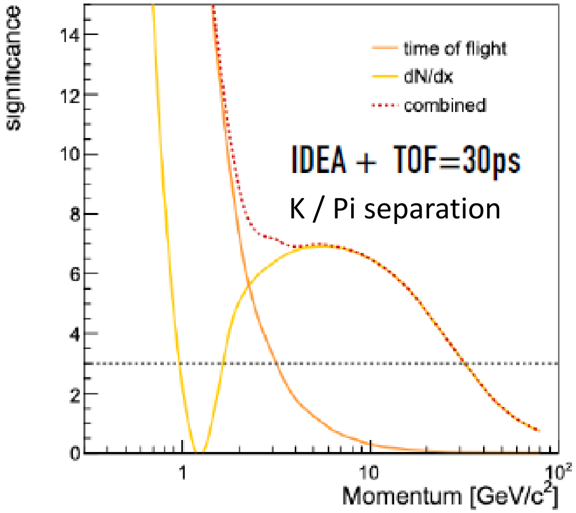
Separation Power (significance)



dE/dx – dN/dx

Separation Power

Bedeschi et al Eur. Phys. J. C 82, 646



Combined measurement

Momentum (GeV/c)

Particle ID and time resolution DRD4 & 1/3

TF#1	TF#2	TF#3	TF#4	TF#5	TF#6
Gaseous Detectors	Liquid Detectors	Solid State Detectors	Photon Detectors & PID	Quantum & Emerging Technologies	Calorimetry
Anna Colaleo Leszek Ropelewski	Roxanne Guenette Jocelyn Monroe	Nicolo' Cartiglia Giulio Pellegrini	Neville Harnew Peter Krizan	Marcel Demarteau Michael Doser	Roberto Ferrari Roman Poeschl

More details here: https://indico.cern.ch/event/1202105/contributions/5402790/attachments/2662086/4612032/FCC-DRD4.pdf

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dE/dx + dN/dx
Mainly gazeous detector, e.g. TPC, DC, RICH (DRD1)

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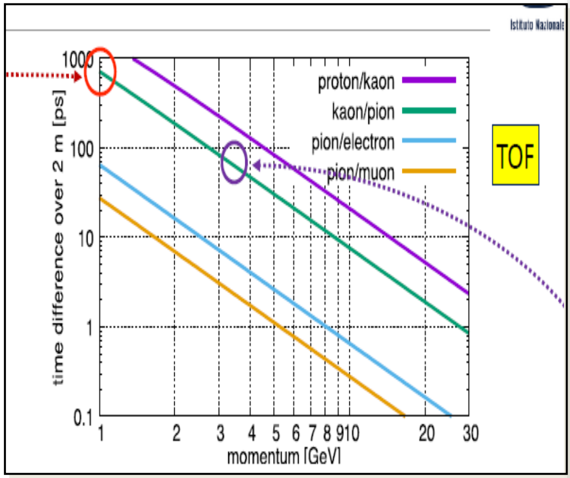
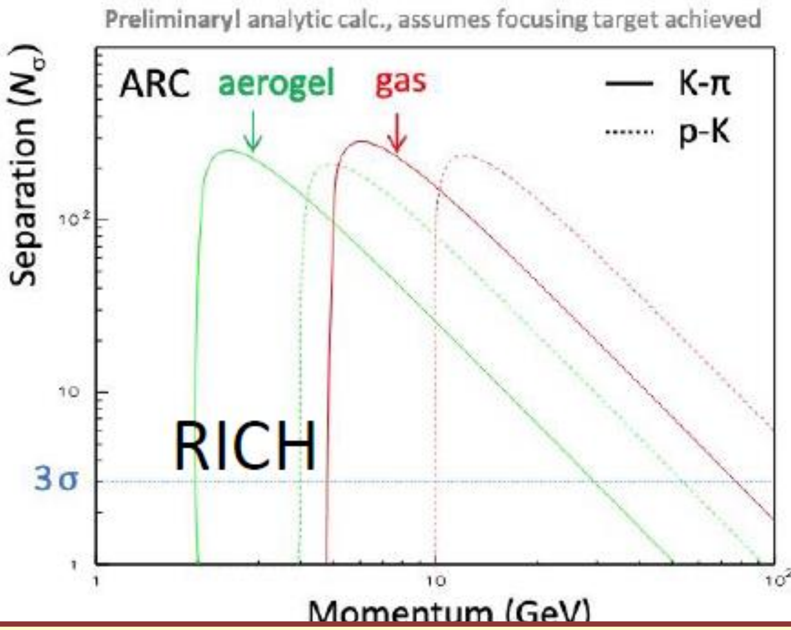
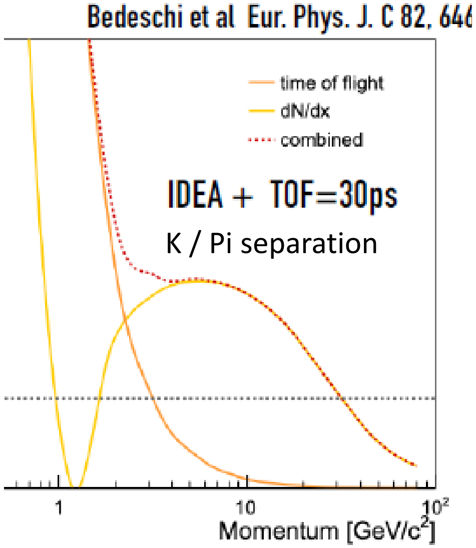


Time of Flight

Separation Power



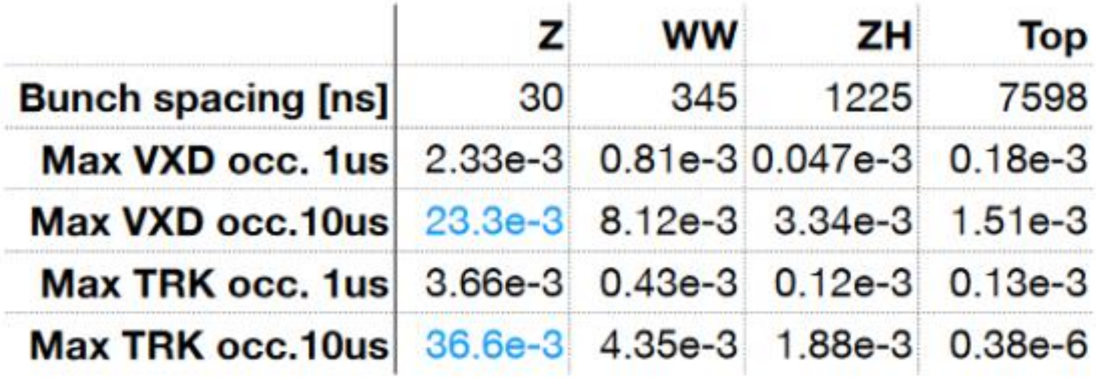


…bined measurement

Particle ID has to be integrated in the VTX/TRK concept

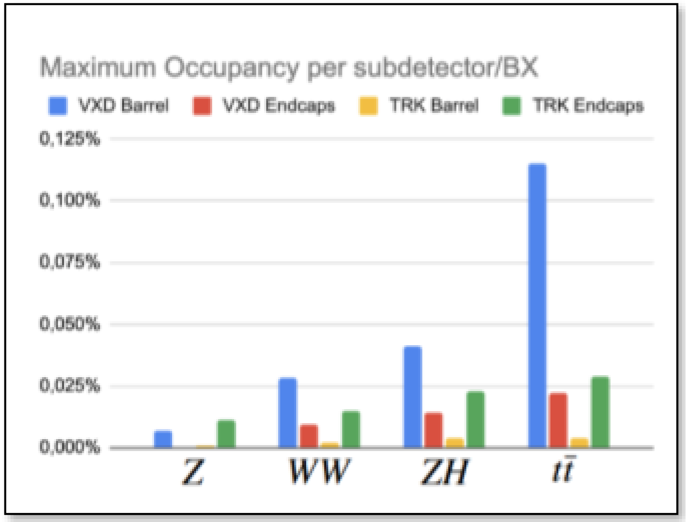
)

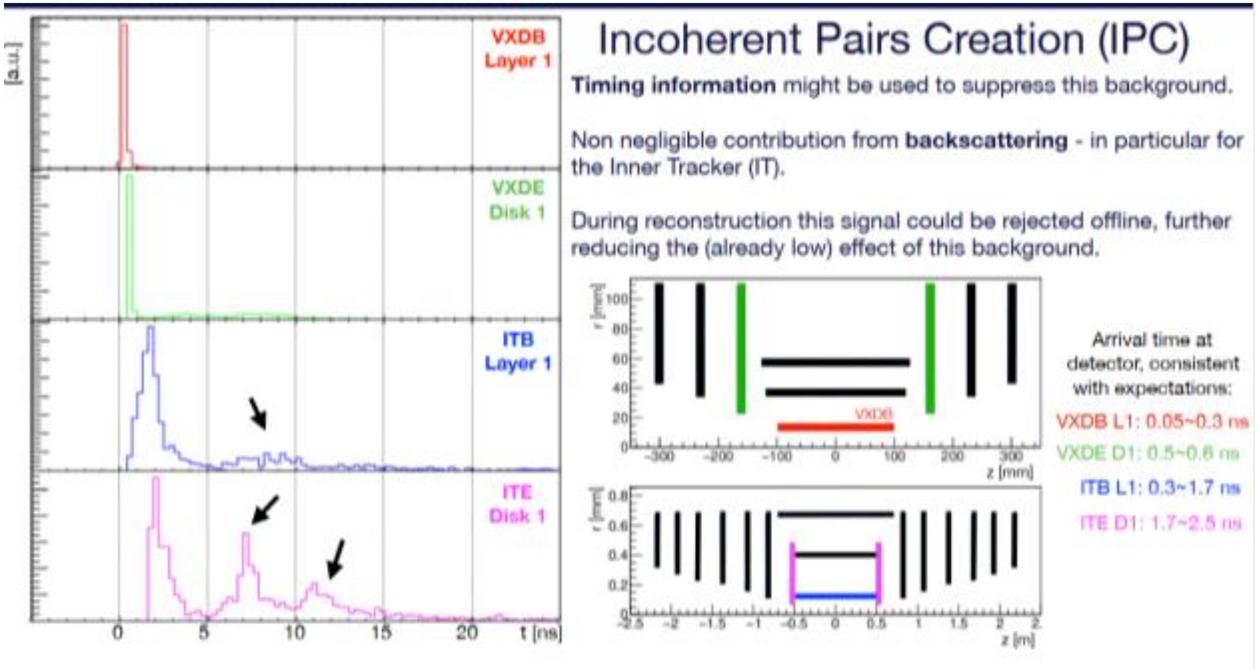
Example of study in CLD



	Z	WW	ZH	Top
Bunch spacing [ns]	30	345	1225	7598
Max VXD occ. 1us	2.33e-3	0.81e-3	0.047e-3	0.18e-3
Max VXD occ.10us	23.3e-3	8.12e-3	3.34e-3	1.51e-3
Max TRK occ. 1us	3.66e-3	0.43e-3	0.12e-3	0.13e-3
Max TRK occ.10us	36.6e-3	4.35e-3	1.88e-3	0.38e-6

US FCC workshop 25/04/2023 Ciarma





Incoherent Pairs Creation (IPC)

Timing information might be used to suppress this background.

Non negligible contribution from **backscattering** - in particular for the Inner Tracker (IT).

During reconstruction this signal could be rejected offline, further reducing the (already low) effect of this background.

Arrival time at detector, consistent with expectations:

VXDB L1: 0.05~0.3 ns

VXDE D1: 0.5~0.6 ns

ITB L1: 0.3~1.7 ns

ITE D1: 1.7~2.5 ns

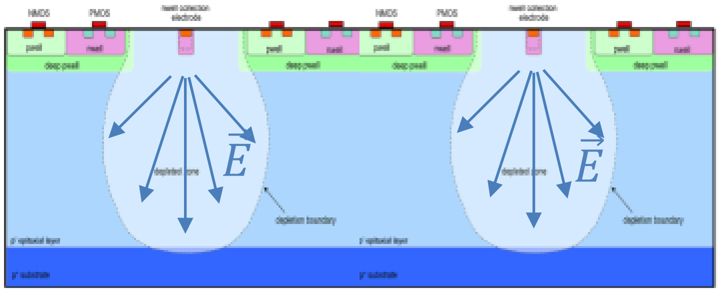
BX rate might be an issue at the Z-pole

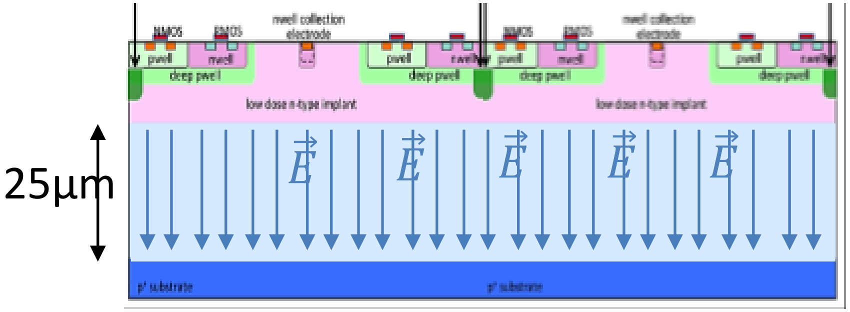
Timing resolution range to reject background ~ 1 ns

Example: MIMOSIS (CBM-MVD) & Decision on options for sensing elements

Process modification: Standard? P-stop? N-Gap?

25 or 50 µm epi?



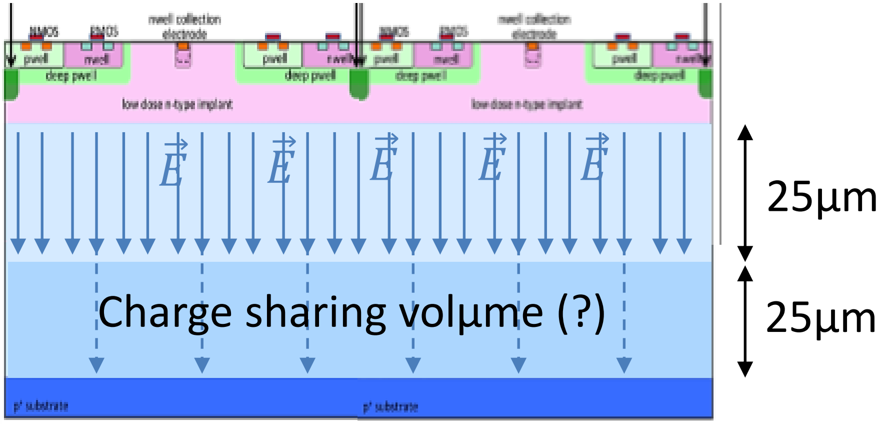


$\sigma = 4 - 5\ \mu\text{m}$
$> 3 \times 10^{13} n_{eq}/cm^2$

Spatial resolution
Rad. hardness

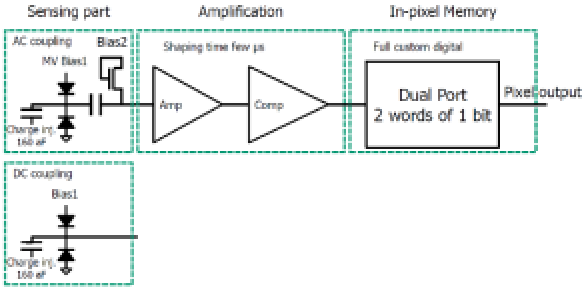
$\sigma = 5 - 7\ \mu\text{m}$
$> 30 \times 10^{13} n_{eq}/cm^2$

Process options inherited from ALPIDE



- Better spatial res. at given rad. tolerance?
- Higher S/N => Robustness to external noise?
- Nuclear fragment ID by dE/dx?

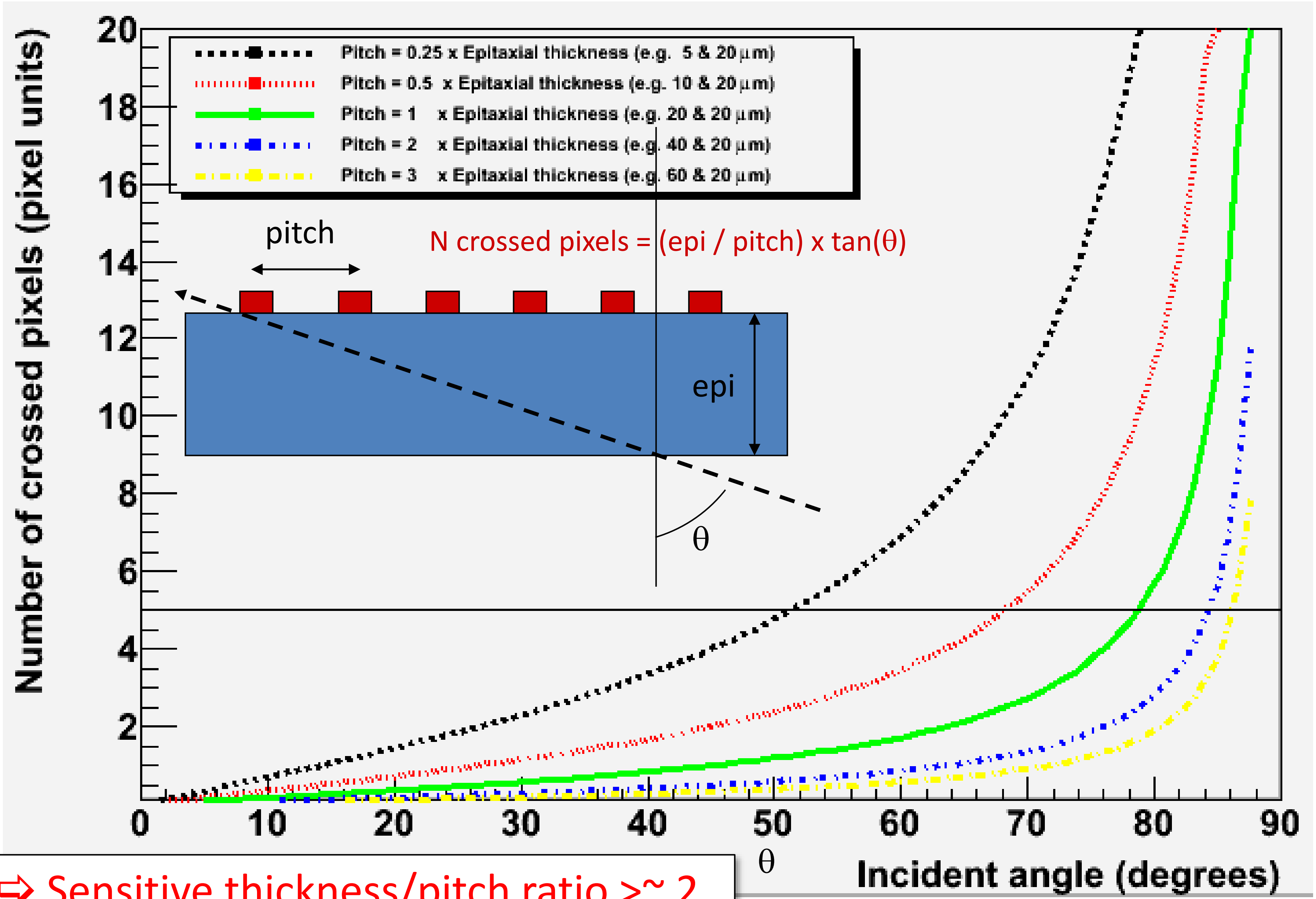
AC? DC? pixel



- DC pixel – limited rad. hardness.
- AC Pixel – more biasing lines.

W. Snoeys et al., NIM-A Vol.871 (2017) 90–96.
Munker, Vertex 2018, Status of silicon detector R&D at CLIC

Elongated clusters: low pT tagging

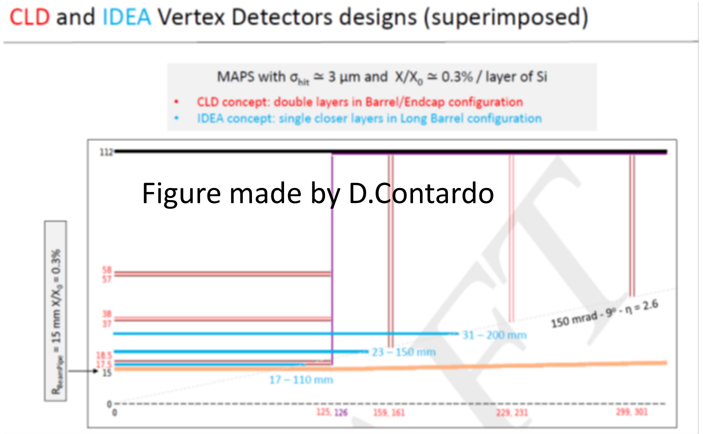


N crossed pixels = (epi / pitch) x tan(θ)

⇨ Sensitive thickness/pitch ratio >~ 2

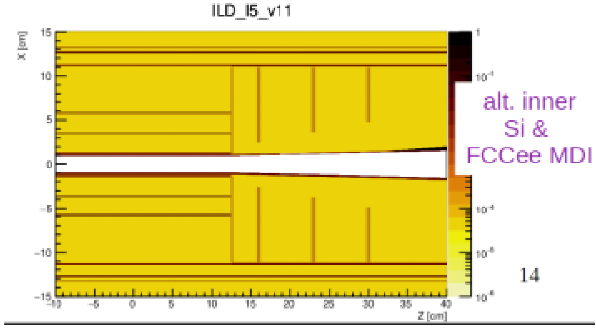
Vertex detector proposal @ ILD for FCCee

- Technology: CMOS pixel sensor as a baseline
  - ✓ (probably the generation after TPSCo 65nm)
- MDI constraints (implemented by D. Jeans in the simulation)
  - ✓ Inner layer as close as possible to the beam pipe: Rmin ~12 mm
- Geometry partly determined by the main tracker
  - ✓ Adaptable to any detector concept
- Requirements
  - ✓ Minimized material budget (~< 0.15% X_0 per layer)
    - Beam pipe radius/mat. budget fixes the requirement
  - ✓ Spatial resolution ~3 μm / layer
  - ✓ Time resolution: ~ 500 ns
  - ✓ Moderate Power dissipation (~< 50 mW/cm^2) allowing for air flow cooling
  - ✓ 5-6 layers in the inner radius (~< 6-10 cm)
    - Robustness / standalone tracking (≠ IDEA choice)
    - Double sided option still considered but not easily compatible with a stitched approach
    - « long barrel » preferable ⇨ minimize the distance between IP and the first hit
    - Low momentμm tracking capabilities
    - Track seeding @ different radii : e.g. FIPs, highly ionizining particles, LLPs, etc.
  - ✓ « merge » VTX and SIT ?
    - Same technology ? ⇨ Power dissipation optimization
  - ✓ Other pixel layers close to the main tracker
  - ✓ Stitched sensor: very promising approach by ALICE ITS-3
    - At least in the z dimension
    - Bent sensor considered (caveat: acceptance)
- Timing measurement capabilities (< 100 ps)
    - Either in a specialized/dedicated layer
    - Or preferably included in the same technology if R&D allows it


CLD and IDEA Vertex Detectors designs (superimposed)

MAPS with $\sigma_{hit} \simeq 3$ μm and $X/X_0 \simeq 0.3\%$ / layer of Si
- CLD concept: double layers in Barrel/Endcap configuration
- IDEA concept: single closer layers in Long Barrel configuration

Figure made by D.Contardo



D.Jeans