Detector R&D in Support of the European Strategy for Particle Physics

P. Allport
(Birmingham)

LIP Lisboa 20/1/2022


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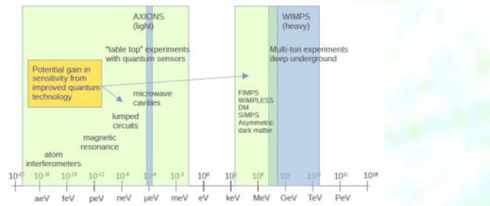
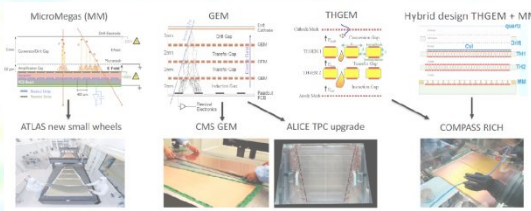
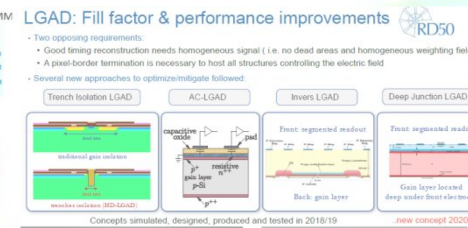
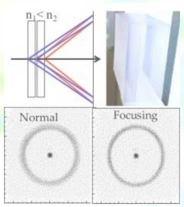
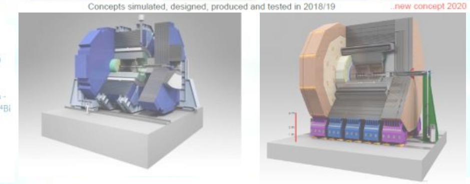


- **ECFA Detector R&D Roadmap**
  - **Motivation**
  - **Process**
  - **Key Observations**
  - **Recommendations**

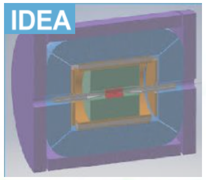


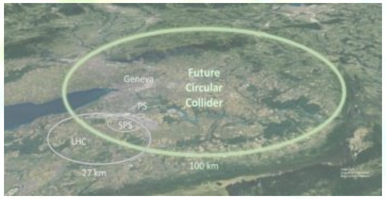


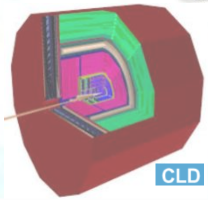


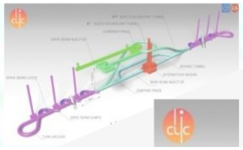


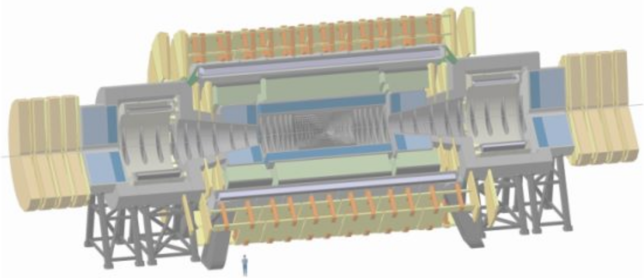
- **FCC-specific R&D**
  - **FCC-ee/eh/hh: Experiment Concepts**
  - **Vertex**
  - **Tracking**
  - **Calorimetry**
  - **PID, Photodetectors and Microelectronics**
  - **Muons, Magnets and Integration**











- **Conclusions and Observations**

ECFA Detector R&D Roadmap

The input to the process is the European Particle Physics Strategy Update as adopted by CERN Council on 19 June 2020.

"**Main report**: *"Recent initiatives with a view towards strategic R&D on detectors are being taken by CERN's EP department and by the ECFA detector R&D panel, supported by EU-funded programmes such as AIDA and ATTRACT. Coordination of R&D activities is critical to maximise the scientific outcomes of these activities and to make the most efficient use of resources; as such, there is a clear need to strengthen existing R&D collaborative structures, and to create new ones, to address future experimental challenges of the field beyond the HL-LHC. Organised by ECFA, a roadmap should be developed by the community to balance the detector R&D efforts in Europe, taking into account progress with emerging technologies in adjacent fields."*

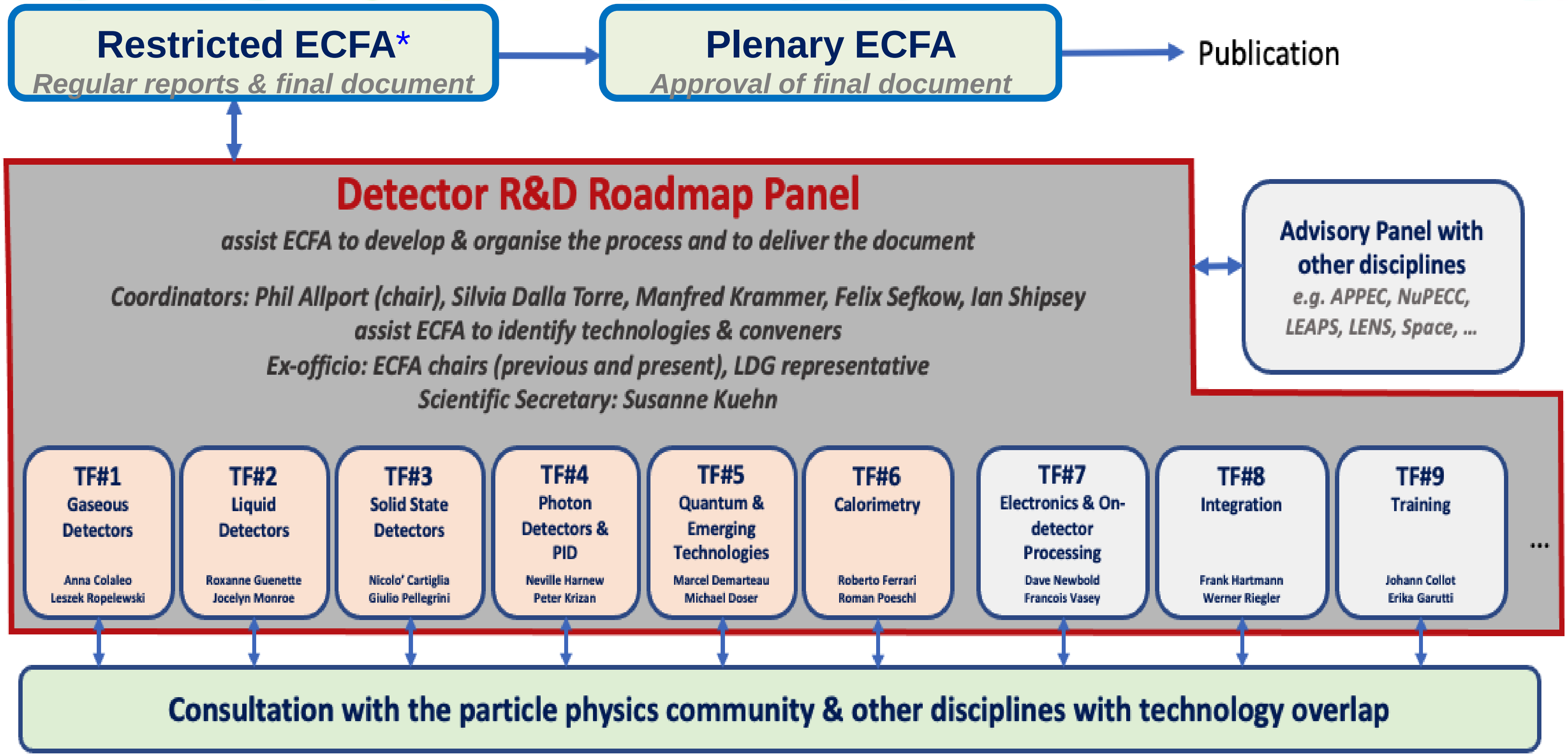
Deliberation document: *"Detector R&D programmes and associated infrastructures should be supported at CERN, national institutes, laboratories and universities. Synergies between the needs of different scientific fields and industry should be identified and exploited to boost efficiency in the development process and increase opportunities for more technology transfer benefiting society at large. Collaborative platforms and consortia must be adequately supported to provide coherence in these R&D activities. The community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels."*

Extracted from the documents of 2020 EPPSU, https://europeanstrategyupdate.web.cern.ch/

For previous presentations see Plenary ECFA: Jorgen D'Hondt (https://indico.cern.ch/event/933318/), Susanne Kuehn (https://indico.cern.ch/event/966397/) and Phil Allport (https://indico.desy.de/event/28202/)

More roadmap process details at: https://indico.cern.ch/e/ECFADetectorRDRoadmap

Detector R&D Roadmap Organisation

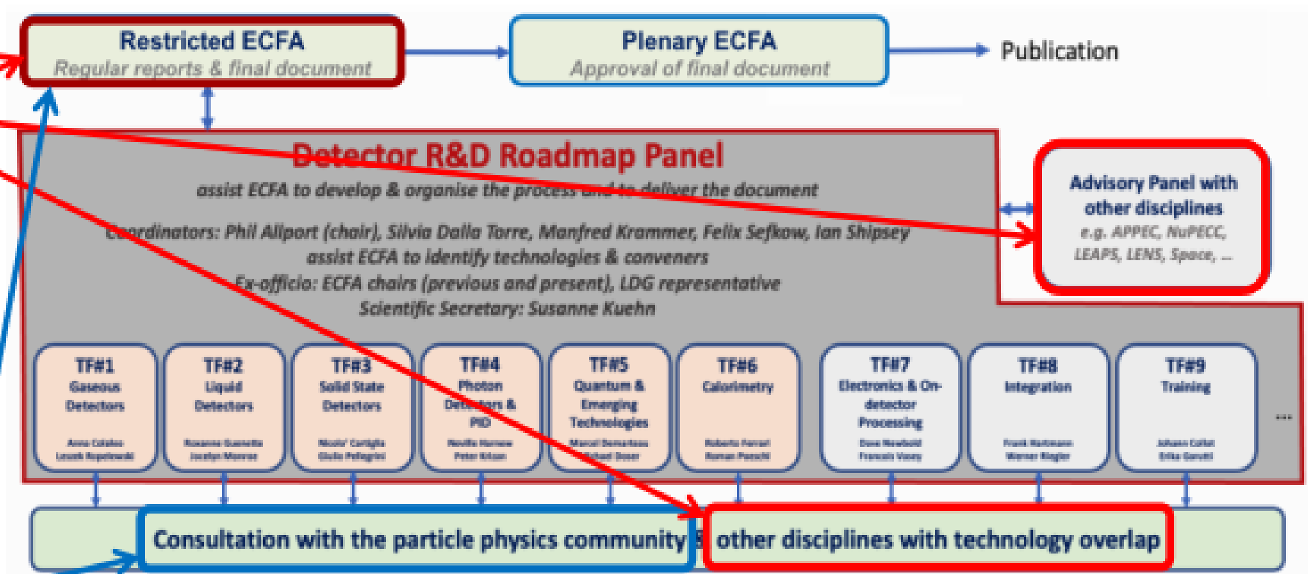


*community feedback via RECFA delegates and National Contacts

For Roadmap process web pages see https://indico.cern.ch/e/ECFADetectorRDRoadmap and introduction in the published document at http://cds.cern.ch/record/2784893/files/.

ECFA Detector R&D Roadmap

"Organised by ECFA, a roadmap should be developed by the community to balance the detector R&D efforts in Europe, taking into account progress with emerging technologies in adjacent fields" *



"The community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels" *

ECFA Detector R&D Roadmap Panel web pages at:
https://indico.cern.ch/e/ECFADetectorRDRoadmap

* 2020 European Particle Physics Strategy Update
https://europeanstrategyupdate.web.cern.ch/

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Broad Roadmap Topic Areas

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- Focus on the technical aspects of detector R&D requirements given the EPPSU deliberation document listed "*High-priority future initiatives*" and "*Other essential scientific activities for particle physics*" as input and organise material by Task Force.
- Task Forces start from **the future science programme** to identify main detector technology challenges to be met (both mandatory and highly desirable to optimise physics returns) and estimate the period over which the required detector R&D programmes may be expected to extend.
- Within each Task Force the aim is to propose a time ordered detector R&D programme in terms of **capabilities not currently achievable**.

Grouped targeted facilities/areas emerging from the EPPSU

- **Detector requirements for full exploitation of the HL-LHC (R&D still needed for LS3 upgrades and for experiment upgrades beyond then) including studies of flavour physics and quark-gluon plasma (where the latter topic also interfaces with nuclear physics).**
- **R&D for long baseline neutrino physics detectors (including aspects targeting astro-particle physics measurements) and supporting experiments such as those at the CERN Neutrino Platform.**
- **Technology developments needed for detectors at e^+e^- Higgs-EW-Top factories in all possible accelerator manifestations including instantaneous luminosities at 91.2GeV of up to $5\times10^{36}cm^{-2}s^{-1}$ and energies up to the TeV range.**
- **The long-term R&D programme for detectors at a future 100 TeV hadron collider with integrated luminosities targeted up to $30ab^{-1}$ and 1000 pile-up for 25ns BCO.**
- **Specific long-term detector technology R&D requirements of a muon collider operating at energies going up to 10 TeV and with a luminosity of the order of 10^{35} cm^{-2} s^{-1}.**

Broad Roadmap Topic Areas

Grouped targeted facilities/areas emerging from the EPPSU

- **Detector developments for accelerator-based studies of rare processes, DM candidates and high precision measurements (including strong interaction physics) at both storage rings and fixed target facilities, interfacing also with atomic and nuclear physics.**
- **R&D for optimal exploitation of dedicated collider experiments studying the partonic structure of the proton and nuclei as well as interface areas with nuclear physics.**
- **The very broad detector R&D areas for non-accelerator-based experiments, including dark matter searches (including axion searches), reactor neutrino experiments and rare decay processes, also considering neutrino observatories and other interface areas with astro-particle physics.**

- **Facilities needed for detector evaluation, including test-beams and different types of irradiation sources, along with the advanced instrumentation required for these.**
- **Infrastructures facilitating detector developments, including technological workshops and laboratories, as well as tools for the development of software and electronics.**
- **Networking structures in order to ensure collaborative environments, to help in the education and training, for cross-fertilization between different technological communities, and in view of relations with industry.**

- **Overlaps with neighbouring fields and key specifications required for exploitation in other application areas**
- **Opportunities for industrial partnership and technical developments needed for potential commercialisation**

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ECFA Detector R&D Roadmap Process

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Organisation

May 2020
EPPSU mandate to ECFA to develop a roadmap for detector R&D efforts in Europe

Sep 2020
Structure in place with **Detector R&D Roadmap Panel**

Dec 2020
Task Forces active

Website:
https://indico.cern.ch/e/ECFADetectorRDRoadmap

Expert & Community Consultation

Feb 2021
Collection of requirements of future facilities & projects

Feb/March 2021
Questionnaires of Task Forces to national contacts

Task Forces liaise with experts in
- ECFA countries
- adjacent disciplines
- industry

March-May 2021
Open Symposia

Drafting Roadmap & Feedback

May 2021
Task Forces collate input from symposia

25-28 May 2021 **Drafting sessions**
- opening session with all experts involved
- plenary & parallel sessions with Task Force members
- final session of Roadmap Panel

July 2021
Near final draft shared with RECFA*

30 July 2021
Presentation at Joint ECFA-EPS session

August 2021
Collect final community feedback*

October-December 2021
Detector R&D Roadmap Document circulated for approval to ECFA in Nov 2021 and presentation to Council in Dec 2021

Many more details at: https://indico.cern.ch/e/ECFADetectorRDRoadmap, Plenary ECFA presentation (https://indico.cern.ch/event/1085137/) and in published documents (http://cds.cern.ch/record/2784893/files/).

ECFA Detector R&D Roadmap Process

Many thanks to all the authors, the 12 expert Input Session speakers, ECFA National Contacts, respondents to the Task Force surveys, the 121 Symposia presenters, the 1359 Symposia attendees and the 44 APOD TF topic specific contacts.

Task Force convenors, Task Force expert members and Panel members of the ECFA Detector R&D Roadmap Process

Task Force 1 Gaseous Detectors: Anna Colaleo[1], Leszek Ropelewski[2] *(Conveners)* Klaus Dehmelt[3], Barbara Liberti[4], Maxim Titov[5], Joao Veloso[6] *(Expert Members)*

Task Force 2 Liquid Detectors: Roxanne Guenette[7], Jocelyn Monroe[8] *(Conveners)* Auke-Pieter Colijn[9], Antonio Ereditato[10,11], Ines Gil Botella[12], Manfred Lindner[13] *(Expert Members)*

Task Force 3 Solid State Detectors: Nicolo Cartiglia[14], Giulio Pellegrini[15] *(Conveners)* Daniela Bortoletto[16], Didier Contardo[17], Ingrid Gregor[18,19] Gregor Kramberger[20], Heinz Pernegger[2] *(Expert Members)*

Task Force 4 Particle Identification and Photon Detectors: Neville Harnew[16], Peter Krizan[20] *(Conveners)* Ichiro Adachi[21], Eugenio Nappi[1] Christian Joram[2], Christian Schultz-Coulon[22] *(Expert Members)*

Task Force 5 Quantum and Emerging Technologies: Marcel Demarteau[23], Michael Doser[2] *(Conveners)* Caterina Braggio[24], Andy Geraci[25], Peter Graham[26], Anna Grasselino[27], John March Russell[16], Stafford Withington[28] *(Expert Members)*

Task Force 6 Calorimetry: Roberto Ferrari[29], Roman Poeschl[30] *(Conveners)* Martin Aleksa[2], Dave Barney[2], Frank Simon[31], Tommaso Tabarelli de Fatis[32] *(Expert Members)*

Task Force 7 Electronics: Dave Newbold[33], Francois Vasey[2] *(Conveners)* Niko Neufeld[2], Valerio Re[29] Christophe de la Taille[34], Marc Weber[35] *(Expert Members)*

Task Force 8 Integration: Frank Hartmann[35], Werner Riegler[2] *(Conveners)* Corrado Gargiulo[2], Filippo Resnati[2], Herman Ten Kate[36], Bart Verlaat[2], Marcel Vos[37] *(Expert Members)*

Task Force 9 Training: Johann Collot[38], Erika Garutti[18,39] *(Conveners)* Richard Brenner[40], Niels van Bakel[9] Claire Gwenlan[16], Jeff Wiener[2], ex-officio Robert Appleby[41] *(Expert Members)*

ECFA — Two Days of Input Sessions

Input Session speakers provided detailed specifications and continued giving support for the process

… particularly for checking if there were any unmet detector R&D needs for the ESPP identified programme which may have been overlooked in the symposia programmes.

	Speaker	Presentation Topic
1	Chris Parkes	Detector R&D requirements for HL-LHC
2	Luciano Musa	Detector R&D requirements for strong interaction experiments at future colliders
3	Johannes Bernhard	Detector R&D requirements for strong interaction experiments at future colliders
4	Frank Simon	Detector R&D requirements for future linear high energy e+e- machines
5	Mogens Dam	Detector R&D requirements for future circular high energy e+e- machines
6	Martin Aleksa	Detector R&D requirements for future high-energy hadron colliders
7	Nadia Pastrone	Detector R&D requirements for muon colliders
8	Marzio Nessi	Detector R&D requirements for future short and long baseline neutrino experiments
9	Maarten De Jong	Detector R&D requirements for future astro-particle neutrino experiments
10	Laura Baudis	Detector R&D requirements for future dark matter experiments
11	Cristina Lazzeroni	Detector R&D requirements for future rare decay processes experiments
12	Alexandre Obertelli	Detector R&D requirements for future low energy experiments

19th November 2021

ECFA National Contacts

Country	Name
Austria	Manfred Jeitler
Belgium	Gilles De Lentdecker
Bulgaria	Venelin Koshuharov
Croatia	Tome Anticic
Cyprus	Panos Razis
Czech Republic	Tomáš Davídek
Denmark	Mogens Dam
Finland	Panja Lukka
France	Didier Contardo
Germany	Lutz Feld
Greece	Dimitris Loukas
Hungary	Dezso Varga
Italy	Nadia Pastrone
Israel	Erez Etzion
Netherlands	Niels van Bakel
Norway	Gerald Eigen
Poland	Marek Idzik
Portugal	Paulo Fonte
Romania	Mihai Petrovici
Serbia	Lidija Zivkovic
Slovakia	Pavol Strizenec
Slovenia	Gregor Kramberger
Spain	Mary-Cruz Fouz
Sweden	Christian Ohm
Swtizerland	Ben Kilminster
Turkey	Kerem Cankocak
United-Kingdom	Iacopo Vivarelli
Ukraine	Nikolai Shulga
CERN	Christian Joram

ECFA — Full-day Public Symposia

Two days of Input Sessions covered all the future facilities and topic areas identified in the EPPSU (see back-up).
Following these were nine technology focussed full-day public symposia as the main fora to collect community input.

Task Force	TF7	TF8	TF2	TF5	TF3	TF1	TF9	TF4	TF6
Dates	25/3/21	31/3/21	9/4/21	12/4/21	23/4/21	29/4/21	30/4/21	6/5/21	7/5/21
Unique users	369 + 123 (webcast)	154 + 17 (webcast)	197 + 5 (webcast)	220	504	339	105	207	201
Max. number of concurrent viewers	230 + 123 (webcast)	76 + 17 (webcast)	130 + 5 (webcast)	100	275	191	59	110	115

Common registration for the symposia had logged 1359 participants by the end of the last one.

Received extensive feedback during symposia and after by email.

Surveys were also employed to receive direct inputs from individuals and via RECFA delegates or their National Contacts.

APOD appointed experts consulted where needed by Task Force convenors for advice on developments in their disciplines.

May 2021
- 07 May ECFA Detector R&D Roadmap Symposium of Task Force 6 Calorimetry
- 06 May ECFA Detector R&D Roadmap Symposium of Task Force 4 Photon Detectors and Particle Identification Detectors

April 2021
- 30 Apr ECFA Detector R&D Roadmap Symposium of Task Force 9 Training
- 29 Apr ECFA Detector R&D Roadmap Symposium of Task Force 1 Gaseous Detectors
- 23 Apr ECFA Detector R&D Roadmap Symposium of Task Force 3 Solid State Detectors
- 12 Apr ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies
- 09 Apr ECFA Detector R&D Roadmap Symposium of Task Force 2 Liquid Detectors

March 2021
- 31 Mar ECFA Detector R&D Roadmap Symposium of Task Force 8 Integration
- 25 Mar ECFA Detector R&D Roadmap Symposium of Task Force 7 Electronics and On-detector Processing

19th November 2021

ECFA — Advisory Panel with Other Disciplines

Organisation name	Contact name
APPEC	Andreas Haungs (Chair)
NuPECC	Marek Lewitowicz (Chair)
LEAPS	Caterina Biscari (Chair)
LENS	Helmut Schober (Chair)
ESA	Guenther Hasinger (Director of Science) Franco Ongaro (Director of Technology, Engineering and Quality)

APPEC: Astro-Particle Physics European Consortium
ESA: European Space Agency
LEAPS: League of European Accelerator-based Photon Sources
LENS: League of advanced European Neutron Sources
NuPECC: Nuclear Physics European Collaboration Committee

Named contacts for each TF where appropriate

The Task Force Convenors join those listed below to compose the Detector R&D Roadmap Panel.

Panel coordinators: Phil Allport[42] *(Chair)*, Silvia Dalla Torre[43], Manfred Krammer[2], Felix Sefkow[18], Ian Shipsey[16]

Ex-officio Panel members: Karl Jakobs[44] *(Current ECFA Chair)*, Jorgen D'Hondt[45] *(Previous ECFA Chair)*, Lenny Rivkin[46] *(LDG Representative)*

Scientific Secretary: Susanne Kuehn[2]

https://indico.cern.ch/e/ECFADetectorRDRoadmap

European Detector R&D Planning

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Birmingham Instrumentation Laboratory for Particle physics and Applications (BILPA)

The outcomes are summarised in a 250 page main document and an 8 page synopsis for less specialist readers. A key guiding policy has been trying to ensure that:

Detector R&D readiness should not be the determining factor in the future of particle physics

http://cds.cern.ch/record/2784893/files/

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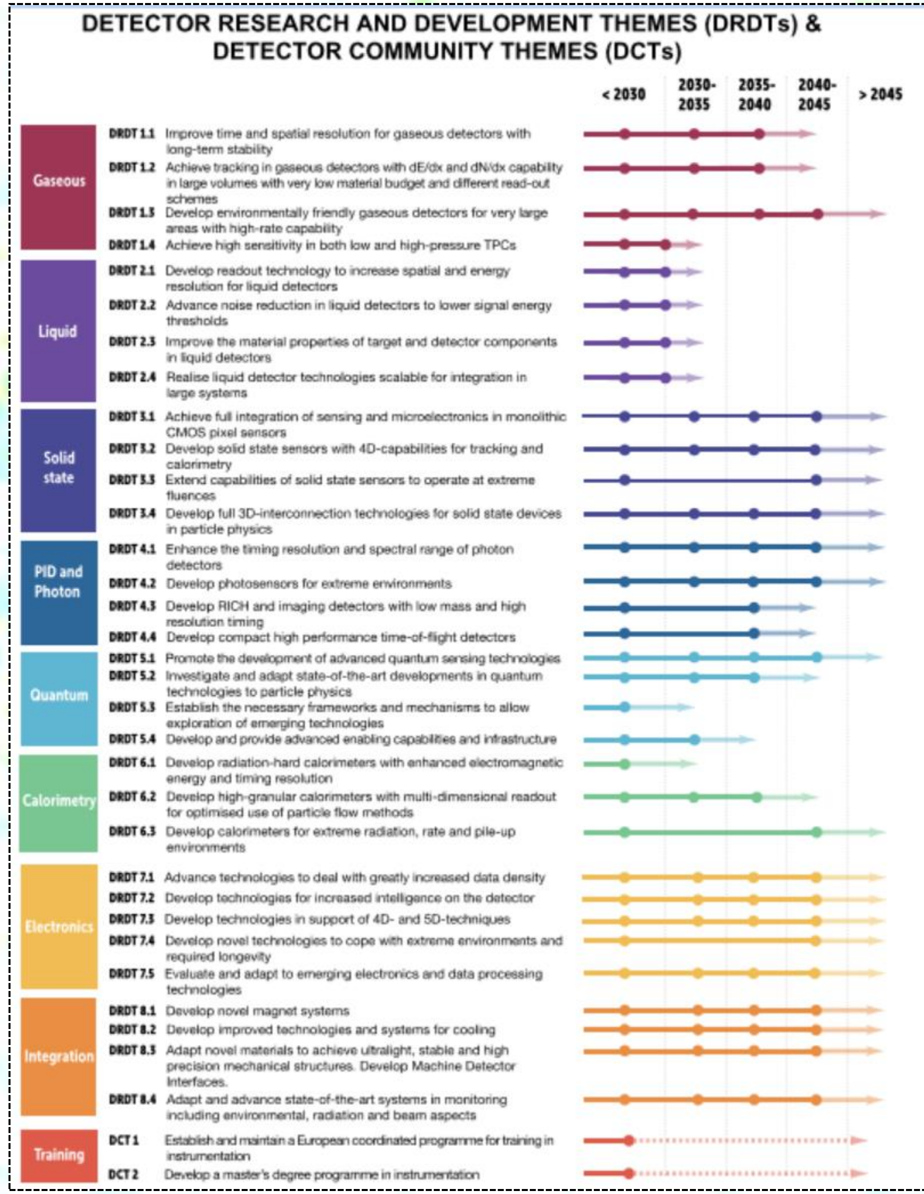
https://indico.cern.ch/event/949705/contributions/4575435/attachments/2372982/4052970/DetectorRDOverview_LP2022_SKuehn.pdf



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ECFA Detector R&D Roadmap

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Plenary ECFA presentation at https://indico.cern.ch/event/1085137/contributions/4562906/attachments/2349055/4006852/Plenary%20ECFA%20Detector%20R%26D%20Roadmap.pptx

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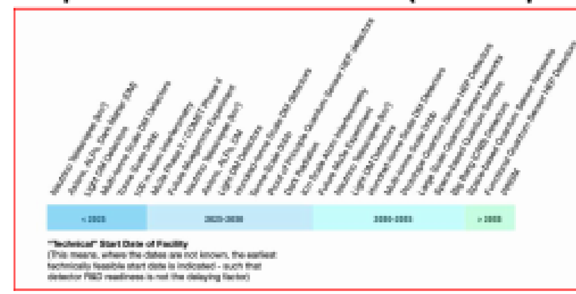
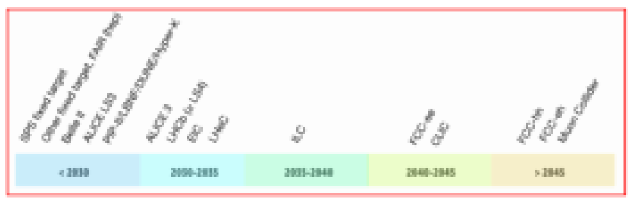
Detector R&D Roadmap

The dates used in these diagrams have a deliberately low precision, and are intended to represent the earliest 'feasible start date' (where a schedule is not already defined), taking into account the necessary steps of approval, development and construction for machine and civil engineering. They do not constitute any form of plan or recommendation, and indeed several options presented are mutually exclusive.

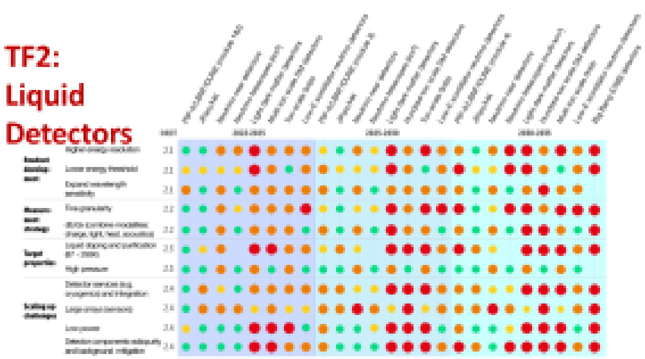
Furthermore, the projects mentioned here are usually limited to those mentioned in the EPPSU, although it should be noted that detector R&D for other possible future facilities is usually aligned with that for programmes already listed.

Example non-accelerator dates (not complete)

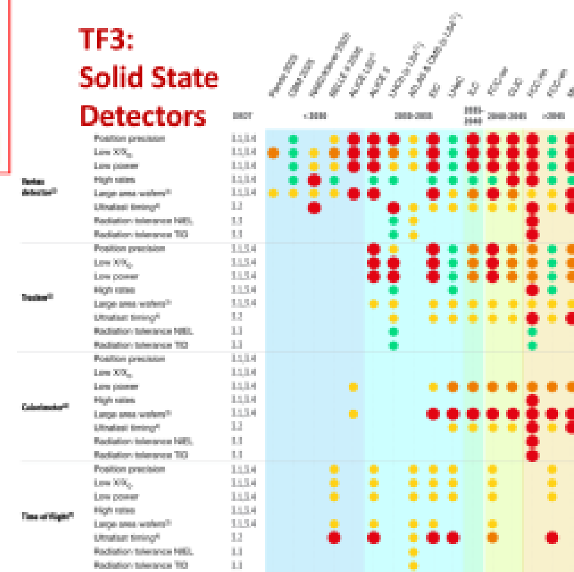




TF2: Liquid Detectors



TF3: Solid State Detectors



Must happen or main physics goals cannot be met
Important to meet several physics goals
Desirable to enhance physics reach
R&D needs being met

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ECFA Detector R&D Roadmap

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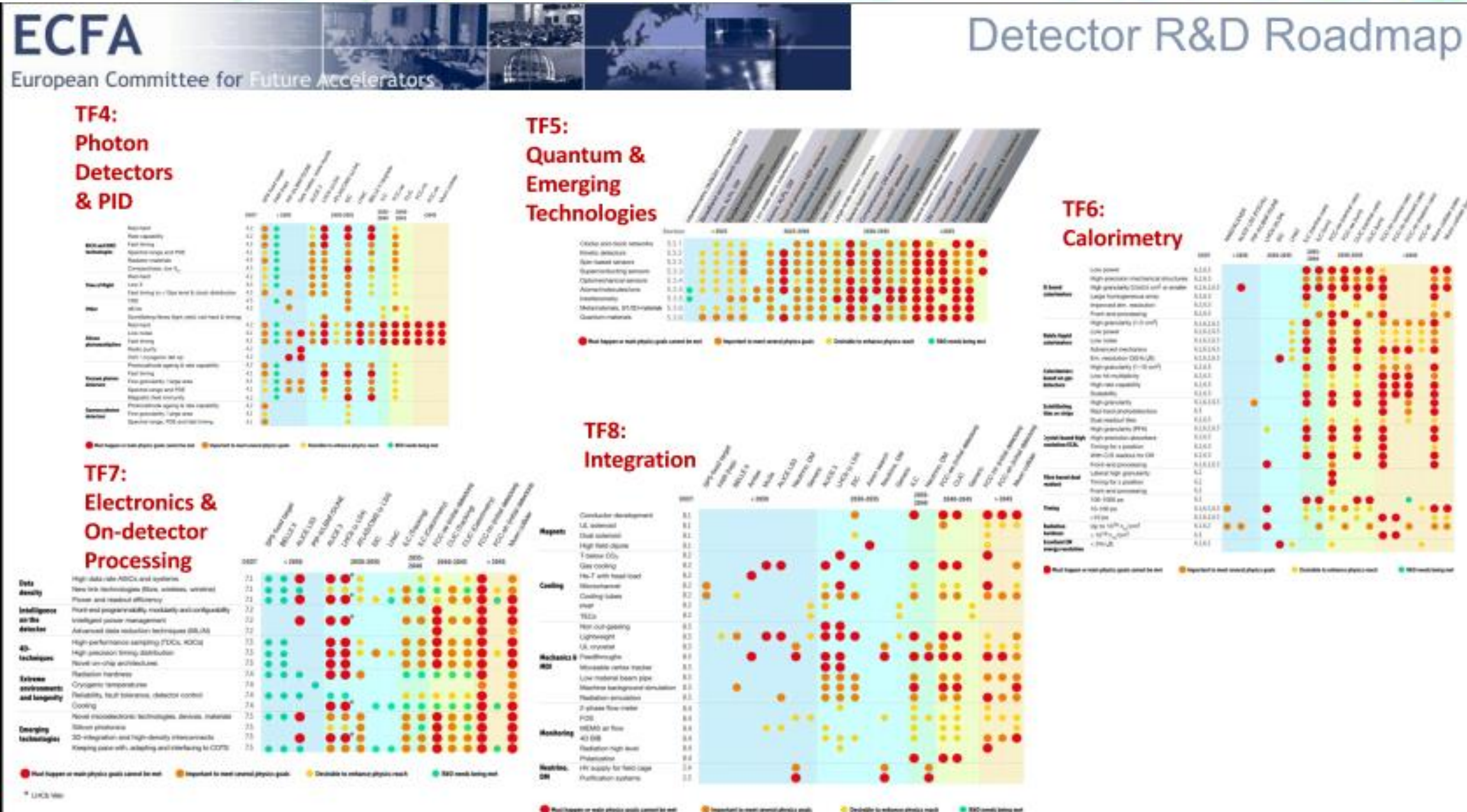
Plenary ECFA presentation at https://indico.cern.ch/event/1085137/contributions/4562906/attachments/2349055/4006852/Plenary%20ECFA%20Detector%20R%26D%20Roadmap.pptx



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Detector R&D Roadmap

GSR 1 - Supporting R&D facilities

It is recommended that the structures to provide Europe-wide coordinated infrastructure in the areas of: test beams, large scale generic prototyping and irradiation be consolidated and enhanced to meet the needs of next generation experiments with adequate centralised investment to avoid less cost-effective, more widely distributed, solutions, and to maintain a network structure for existing distributed facilities, e.g. for irradiation

GSR 2 - Engineering support for detector R&D

In response to ever more integrated detector concepts, requiring holistic design approaches and large component counts, the R&D should be supported with adequate mechanical and electronics engineering resources, to bring in expertise in state-of-the-art microelectronics as well as advanced materials and manufacturing techniques, to tackle generic integration challenges, and to maintain scalability of production and quality control from the earliest stages.

GSR 3 - Specific software for instrumentation

Across DRDTs and through adequate capital investments, the availability to the community of state-of-the-art R&D-specific software packages must be maintained and continuously updated. The expert development of these packages - for core software frameworks, but also for commonly used simulation and reconstruction tools - should continue to be highly recognised and valued and the community effort to support these needs to be organised at a European level.

GSR 4 - International coordination and organisation of R&D activities

With a view to creating a vibrant ecosystem for R&D, connecting and involving all partners, there is a need to refresh the CERN RD programme structure and encourage new programmes for next generation detectors, where CERN and the other national laboratories can assist as major catalysers for these. It is also recommended to revisit and streamline the process of creating and reviewing these programmes, with an extended framework to help share the associated load and increase involvement, while enhancing the visibility of the detector R&D community and easing communication with neighbouring disciplines, for example in cooperation with the ICFA Instrumentation Panel.

ECFA Detector R&D Roadmap

Plenary ECFA presentation at https://indico.cern.ch/event/1085137/contributions/4562906/attachments/2349055/4006852/Plenary%20ECFA%20Detector%20R%26D%20Roadmap.pptx

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Detector R&D Roadmap

GSR 5 - Distributed R&D activities with centralised facilities

Establish in the relevant R&D areas a distributed yet connected and supportive tier-ed system for R&D efforts across Europe. Keeping in mind the growing complexity, the specialisation required, the learning curve and the increased cost, consider more focused investment for those themes where leverage can be reached through centralisation at large institutions, while addressing the challenge that distributed resources remain accessible to researchers across Europe and through them also be available to help provide enhanced training opportunities.

GSR 6 - Establish long-term strategic funding programmes

Establish, additional to short-term funding programmes for the early proof of principle phase of R&D, also long-term strategic funding programmes to sustain both research and development of the multi-decade DRDTs in order for the technology to mature and to be able to deliver the experimental requirements. Beyond capital investments of single funding agencies, international collaboration and support at the EU level should be established. In general, the cost for R&D has increased, which further strengthens the vital need to make concerted investments.

GSR 7 – "Blue-sky" R&D

It is essential that adequate resources be provided to support more speculative R&D which can be riskier in terms of immediate benefits but can bring significant and potentially transformational returns if successful both to particle physics: unlocking new physics may only be possible by unlocking novel technologies in instrumentation, and to society. Innovative instrumentation research is one of the defining characteristics of the field of particle physics. "Blue-sky" developments in particle physics have often been of broader application and had immense societal benefit. Examples include: the development of the World Wide Web, Magnetic Resonance Imaging, Positron Emission Tomography and X-ray imaging for photon science.

ECFA Detector R&D Roadmap

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Detector R&D Roadmap

GSR 8 - Attract, nurture, recognise and sustain the careers of R&D experts

Innovation in instrumentation is essential to make progress in particle physics, and R&D experts are essential for innovation. It is recommended that ECFA, with the involvement and support of its Detector R&D Panel, continues the study of recognition with a view to consolidate the route to an adequate number of positions with a sustained career in instrumentation R&D to realise the strategic aspirations expressed in the EPPSU. It is suggested that ECFA should explore mechanisms to develop concrete proposals in this area and to find mechanisms to follow up on these in terms of their implementation. Consideration needs to be given to creating sufficiently attractive remuneration packages to retain those with key skills which typically command much higher salaries outside academic research. It should be emphasised that, in parallel, society benefits from the training particle physics provides because the knowledge and skills acquired are in high demand by industries in high-technology economies.

GSR 9 - Industrial partnerships

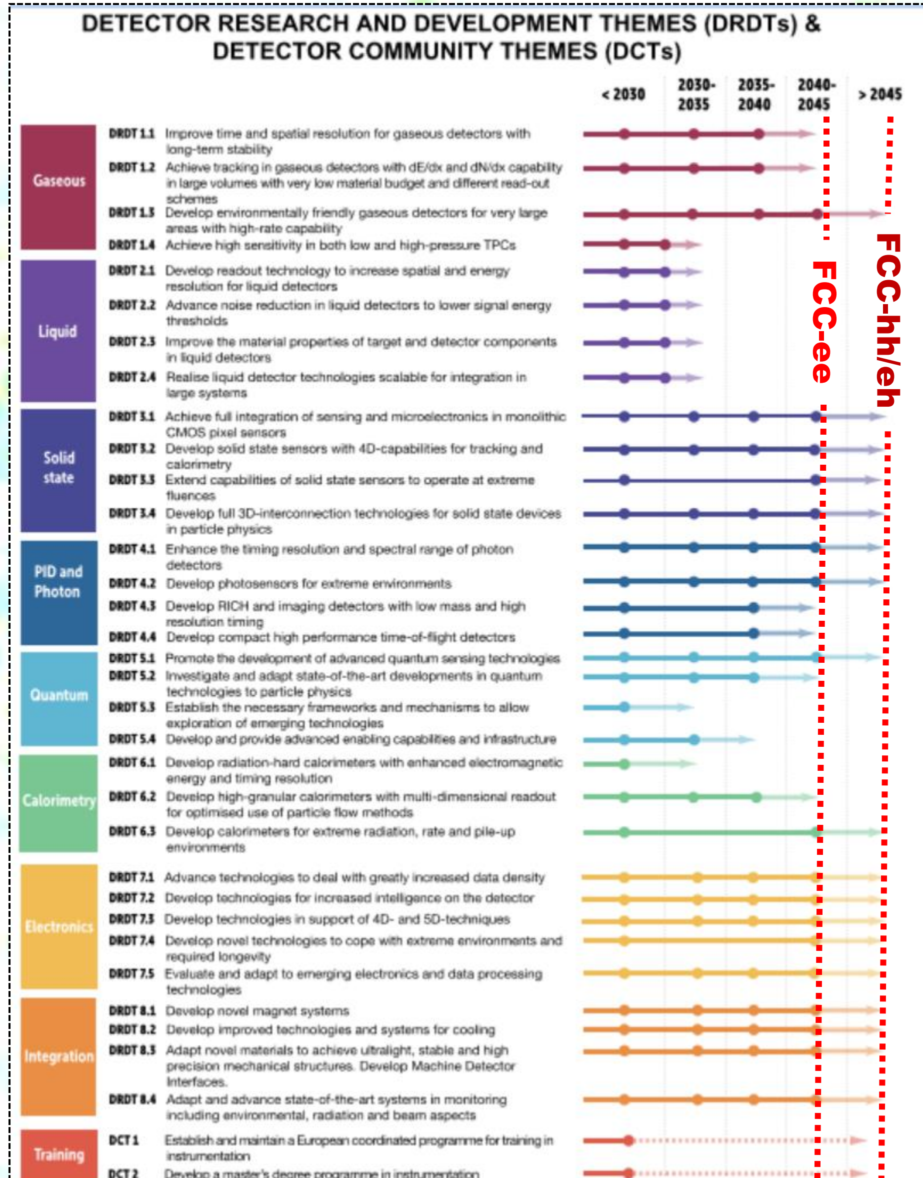
It is recommended to identify promising areas for close collaboration between academic and industrial partners, to create international frameworks for exchange on academic and industrial trends, drivers and needs, and to establish strategic and resources-loaded cooperation schemes on a European scale to intensify the collaboration with industry, in particular for developments in solid state sensors and micro-electronics.

GSR 10 – Open Science

It is recommended that the concept of Open Science be explicitly supported in the context of instrumentation, taking account of the constraints of commercial confidentiality where these apply due to partnerships with industry. Specifically, for publicly-funded research the default, wherever possible, should be open access publication of results and it is proposed that the Sponsoring Consortium for Open Access Publishing in Particle Physics ($SCOAP^3$) should explore ensuring similar access is available to instrumentation journals (including for conference proceedings) as to other particle physics publications.

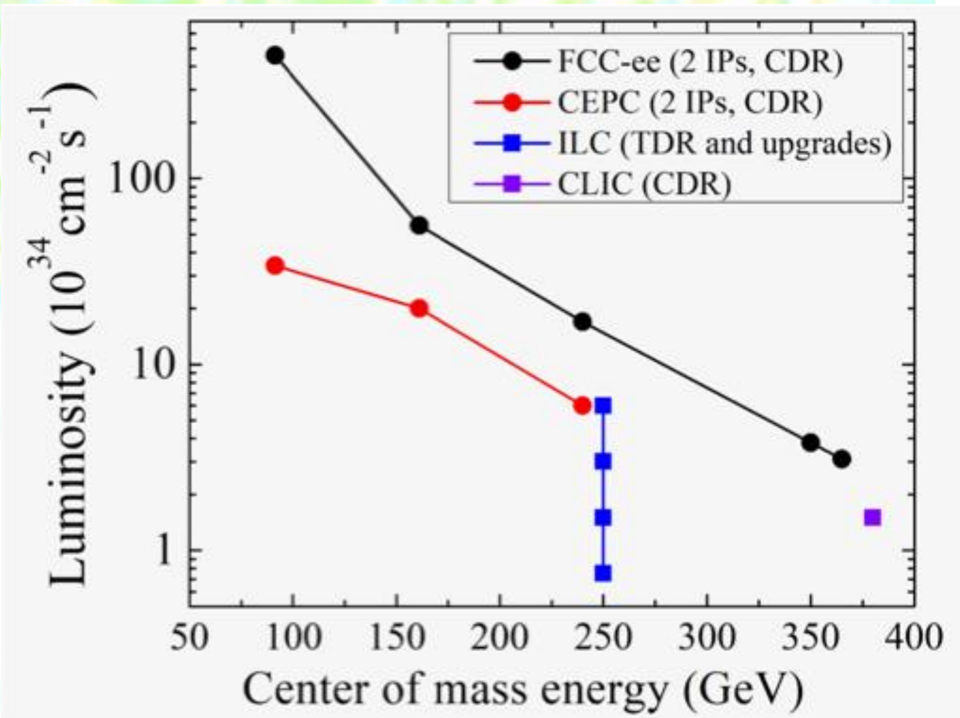
ECFA Detector R&D Roadmap: FCC

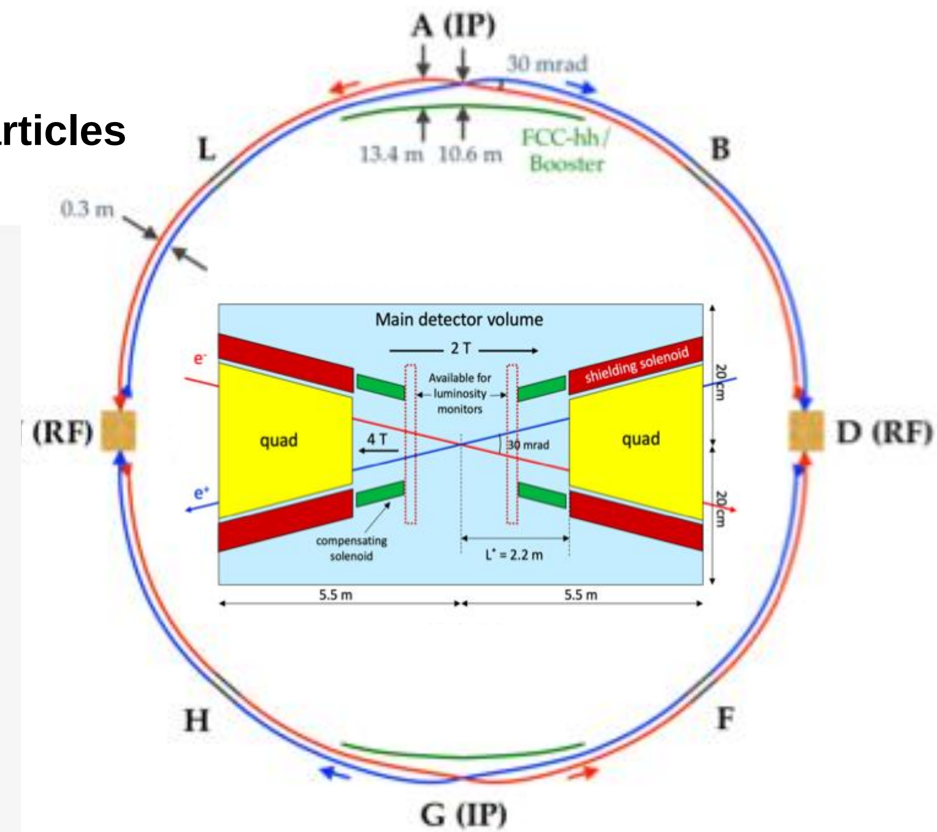
https://indico.cern.ch/event/949705/contributions/4575435/attachments/2372982/4052970/DetectorRDOverview_LP2022_SKuehn.pdf



FCC-ee

- **Two (possibly four) interaction regions.** (https://fcc-cdr.web.cern.ch/#FCCEE)
- **Higgs Factory programme: 1.2M $e^+e^- \to HZ$; 75k $W^+W^- \to H$; senstivity $H \to HH$; $e^+e^- \to H$**
- **EW: 5×10^{12} Z ; 10^8 W^+W^- ; 10^6 $t\bar{t}$ (Indirect sensitivity to new physics up to $\Lambda \gtrsim 70$ TeV)**
- **Flavour: 10^{12} $b\bar{b}$, $c\bar{c}$; 1.7×10^{11} $\tau^+\tau^-$**
- **Discovery potential for feebly interacting particles**



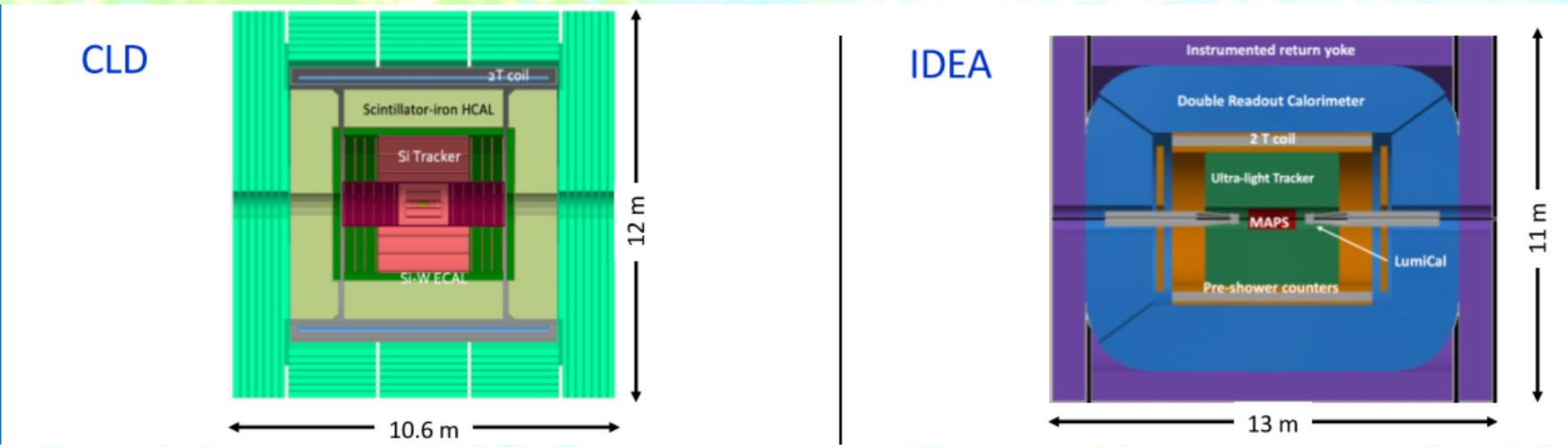


See Mogens Dams (19/2/21)
https://indico.cern.ch/event/994685/

FCC-ee

Some specifications to control systematic errors at $\boxed{10^{-5}\text{ level}}$.

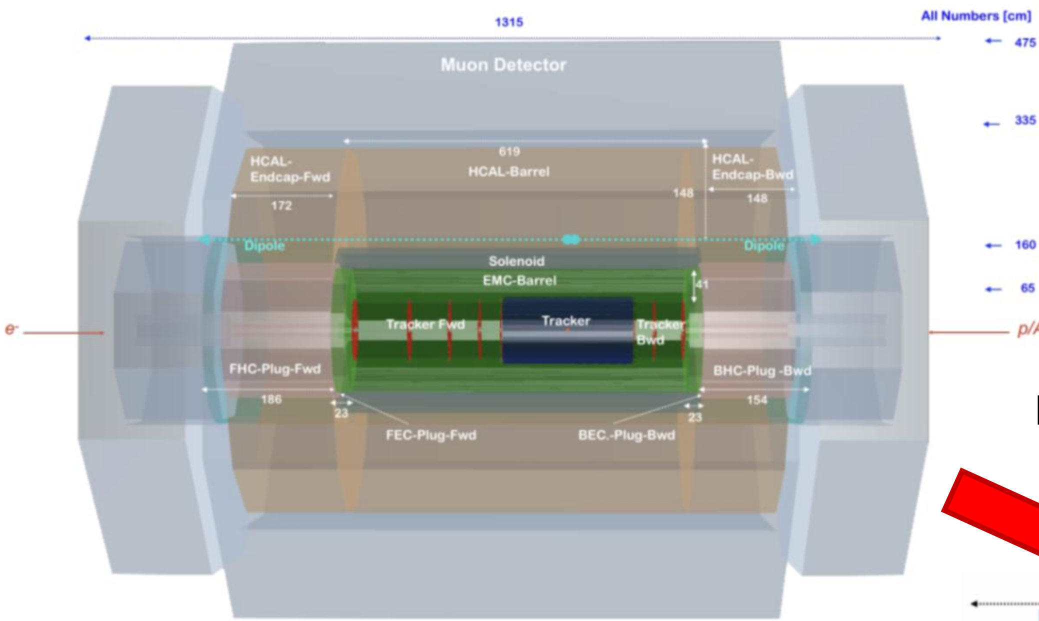
- $\sigma_{p_T}/p_T^2 \approx 2 \times 10^{-5}$GeV^{-1} **EM resolution ~ few %/$\sqrt{E}$; jet energy $\leq 30\%/\sqrt{E}$; B-field stable 10^{-6} (and < 2T) ; luminosity $\sim 10^{-4}$; beam energy spread – di-muons $\sigma_\theta < 0.1$ mrad ; 0.2μm secondary vertex flight path resolution.**
- **PID: K/π separation ($\frac{dE}{dx}$ or $\frac{dN}{dx}$, ToF, RICH) and π^0/γ discrimination; "tracking" calorimetry.**
- **Two main detector concepts CLIC-Like Detector (CLD) and Innovative Detector for Electron-positron Accelerator (IDEA)**

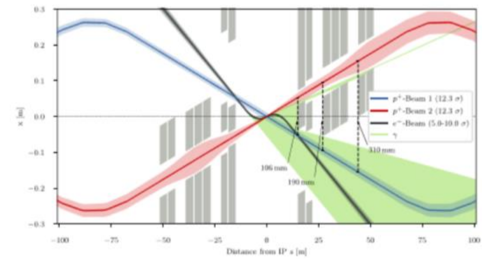


https://arxiv.org/abs/1911.12230, https://arxiv.org/abs/1905.02520 https://pos.sissa.it/390/

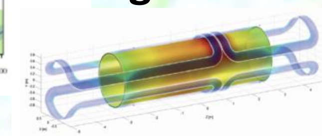
Mogens Dams (19/2/21) https://indico.cern.ch/event/994685/

FCC-eh





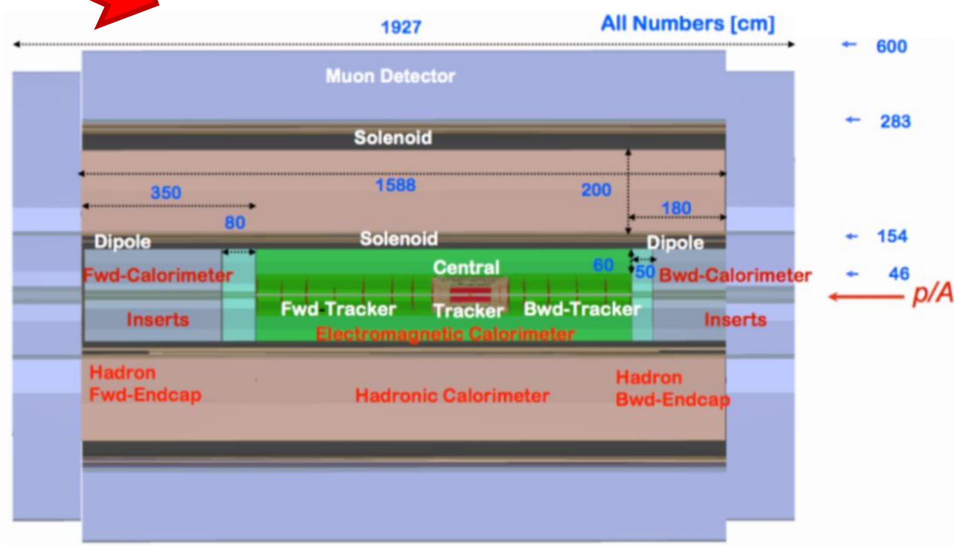
Complex magnet configuration

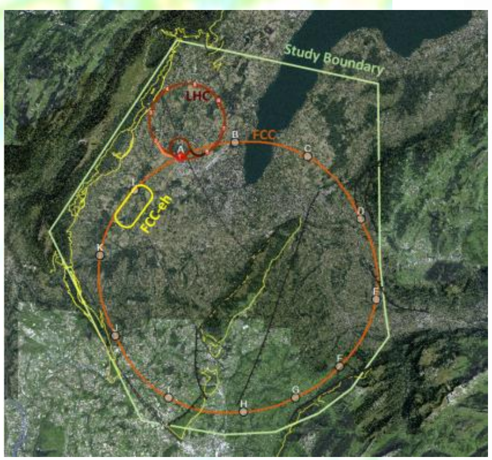


Solenoid Detector Magnet (3.5T)
Dual dipole magnets (0.15 – 0.3 T) throughout detector region (|z| < 14m) to guide and bend electron beam

For FCC-eh scaled up version of proposed LHeC detector

https://arxiv.org/abs/2007.14491





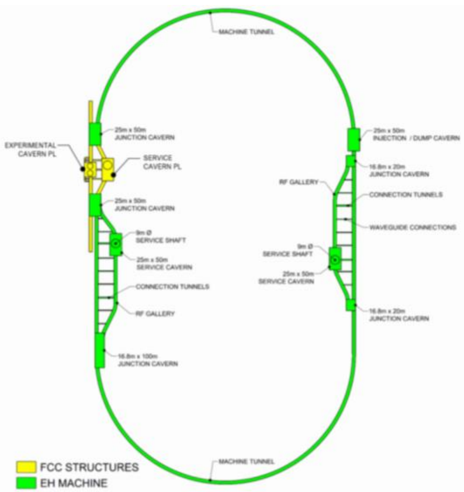


Figure 10.57: Schematic layout showing the proposed underground structures for FCC-eh

See also Luciano Musa (19/2/21)
https://indico.cern.ch/event/994685/

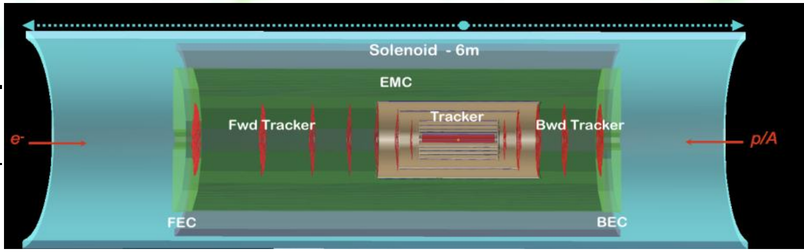
FCC-eh

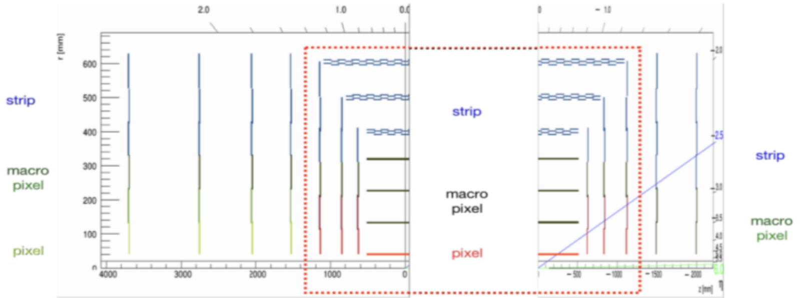
CERN-ACC-Note-2020-0002

https://arxiv.org/abs/2007.14491

Parameter	Unit	LHeC	FCC-eh (E_p=20 TeV)	FCC-eh (E_p=50 TeV)
Ion energy E_{Pb}	PeV	0.574	1.64	4.1
Ion energy/nucleon E_{Pb}/A	TeV	2.76	7.88	19.7
Electron beam energy E_e	GeV	50	60	60
Electron-nucleon CMS $\sqrt{s_{eN}}$	TeV	0.74	1.4	2.2
Bunch spacing	ns	50	100	100
Number of bunches		1200	2072	2072
Ions per bunch	10^8	1.8	1.8	1.8
Normalised emittance ϵ_n	μm	1.5	1.5	1.5
Electrons per bunch	10^9	6.2	6.2	6.2
Electron current	mA	20	20	20
IP beta function β_A^*	cm	10	10	15
e-N Luminosity	$10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	7	14	35

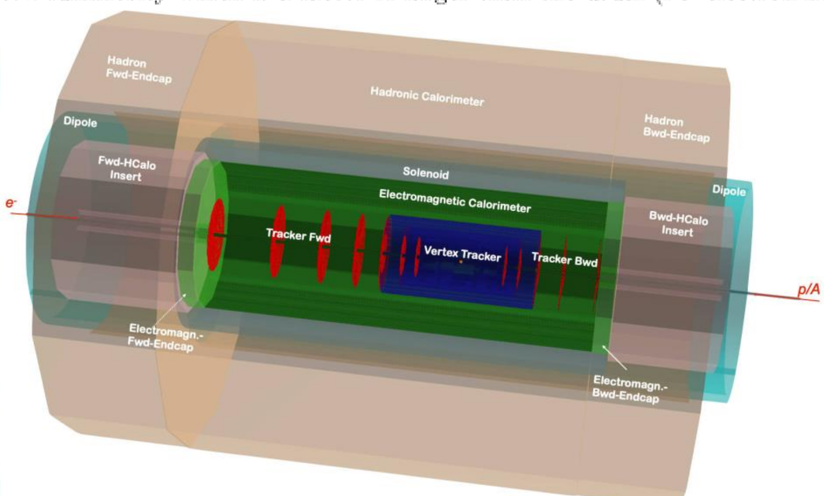
Table 2.4: Baseline parameters of future electron-ion collider configurations based on the electron ERL, in concurrent eA and AA operation mode with the LHC and the two versions of a future hadron collider at CERN. Following established convention in this field, the luminosity quoted, at the start of a fill, is the *electron-nucleon* luminosity which is a factor A larger than the usual (i.e. electron-nucleus) luminosity.





Barrel & ECAP Layers/Wheels

Retain 1° tracking resolution for electrons and charged particles in jets to $|\eta| \leq 5$.



Calo (lowE-FCCeh)	EMC	HCAL		
	Barrel	Ecap Fwd	Barrel	Ecap Bwd
Readout, Absorber	Sci,Pb	Sci,Fe	Sci,Fe	Sci,Fe
Layers	49	91	68	78
Integral Absorber Thickness [cm]	36.6	206.0	184.0	178.0
$\eta_{\max}$, $\eta_{\min}$	2.8, −2.5	2.0, 0.8	1.6, −1.4	−0.7, −1.8
$\sigma_E/E = a/\sqrt{E} \oplus b$ [%]	12.6/1.1	38.9/3.3	42.4/4.2	40.6/3.5
Λ_I / X_0	$X_0 = 66.2$	$\Lambda_I = 12.7$	$\Lambda_I = 11.3$	$\Lambda_I = 11.0$
Total area Sci [m^2]	2915	4554	12298	3903

Calo (lowE-FCCeh)	FHC Plug Fwd	FEC Plug Fwd	BEC Plug Bwd	BHC Plug Bwd
Readout, Absorber	Si,W	Si,W	Si,Pb	Si,Cu
Layers	296	49	59	238
Integral Absorber Thickness [cm]	256.9	29.6	27.9	220.8
$\eta_{\max}$, $\eta_{\min}$	5.8, 1.8	5.4, 1.8	−1.5, −5.2	−1.5, −5.6
$\sigma_E/E = a/\sqrt{E} \oplus b$ [%]	61.9/0.5	26.5/0.4	24.7/0.4	46.7/4.4
Λ_I / X_0	$\Lambda_I = 15.5$	$X_0 = 84.7$	$X_0 = 50.2$	$\Lambda_I = 14.7$
Total area Si [m^2]	2479	364	438	1994

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FCC-hh

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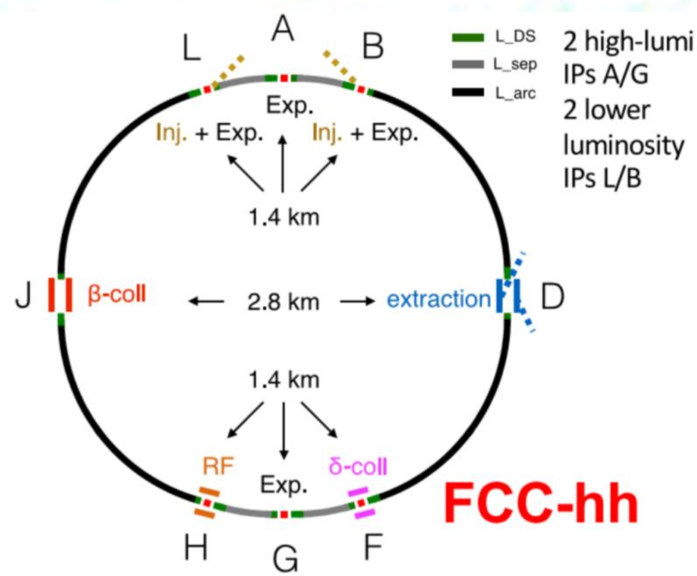
See Martin Aleksa (19/2/21) https://indico.cern.ch/event/994685/

(https://fcc-cdr.web.cern.ch/#FCCHH)



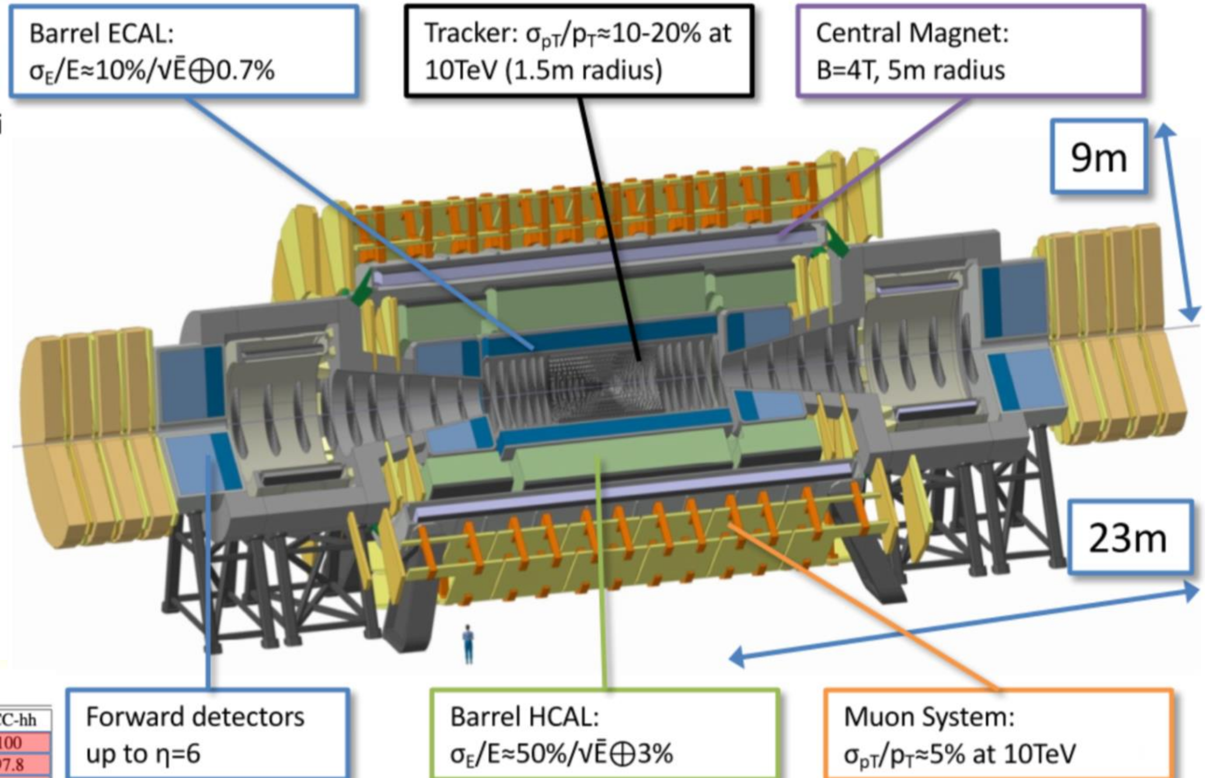


Table 7.1: Key numbers relating the detector challenges at the different accelerators.

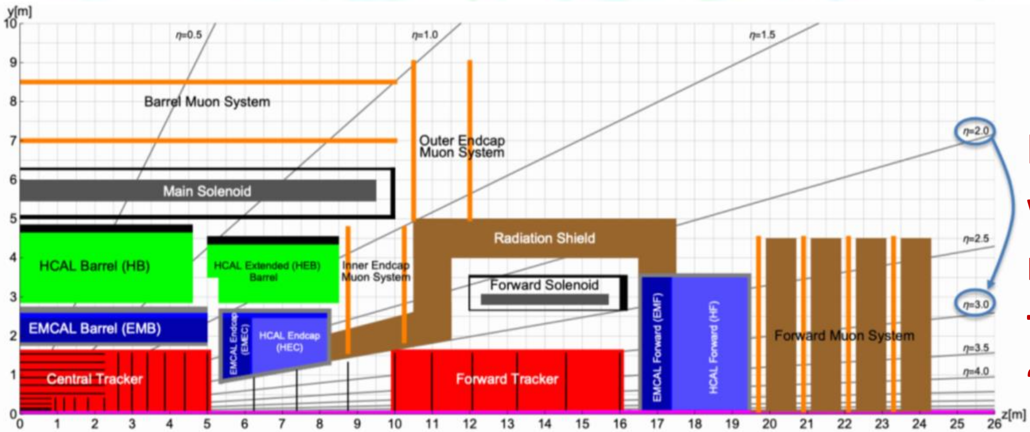
Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
Circumference	km	26.7	26.7	26.7	97.8
Peak $\mathcal{L}$, nominal (ultimate)	$10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1 (2)	5 (7.5)	16	30
Bunch spacing	ns	25	25	25	25
Number of bunches		2808	2760	2808	10600
Goal $\int\mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel} [331]	mb	80	80	86	103
σ_{tot} [331]	mb	108	108	120	150
BC rate	MHz	31.6	31.0	31.6	32.5
Peak pp collision rate	GHz	0.8	4	14	31
Peak av. PU events/BC, nominal (ultimate)		25 (50)	130 (200)	435	950
Rms luminous region σ_z	mm	45	57	57	49
Line PU density	mm^{-1}	0.2	1.0	3.2	8.1
Time PU density	ps^{-1}	0.1	0.29	0.97	2.43
$dN_{ch}/d\eta\|_{\eta=0}$ [331]		6.0	6.0	7.2	10.2
Charged tracks per collision N_{ch} [331]		70	70	85	122
Rate of charged tracks	GHz	59	297	1234	3942
$<p_T>$ [331]	GeV/c	0.56	0.56	0.6	0.7
Bending radius for $<p_T>$ at B=4 T	cm	47	47	49	59

Table 7.1: Key numbers relating the detector challenges at the different accelerators.

Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
Total number of pp collisions	10^{16}	2.6	26	91	324
Charged part. flux at 2.5 cm, est.(FLUKA)	$\mathrm{GHz\,cm}^{-2}$	0.1	0.7	2.7	8.4 (10)
1 MeV-neq fluence at 2.5 cm, est.(FLUKA)	$10^{16}\,\mathrm{cm}^{-2}$	0.4	3.9	16.8	84.3 (60)
Total ionising dose at 2.5 cm, est.(FLUKA)	MGy	1.3	13	54	270 (300)
$dE/d\eta\|_{\eta=5}$ [331]	GeV	316	316	427	765
$dP/d\eta\|_{\eta=5}$	kW	0.04	0.2	1.0	4.0
90% $b\bar{b}$ $p_T^b > 30$ GeV/c [332]	$\|\eta\|<$	3	3	3.3	4.5
VBF jet peak [332]	$\|\eta\|$	3.4	3.4	3.7	4.4
90% VBF jets [332]	$\|\eta\|<$	4.5	4.5	5.0	6.0
90% $H \to 4l$ [332]	$\|\eta\|<$	3.8	3.8	4.1	4.8

FCC-hh

See Martin Aleksa (19/2/21) https://indico.cern.ch/event/994685/



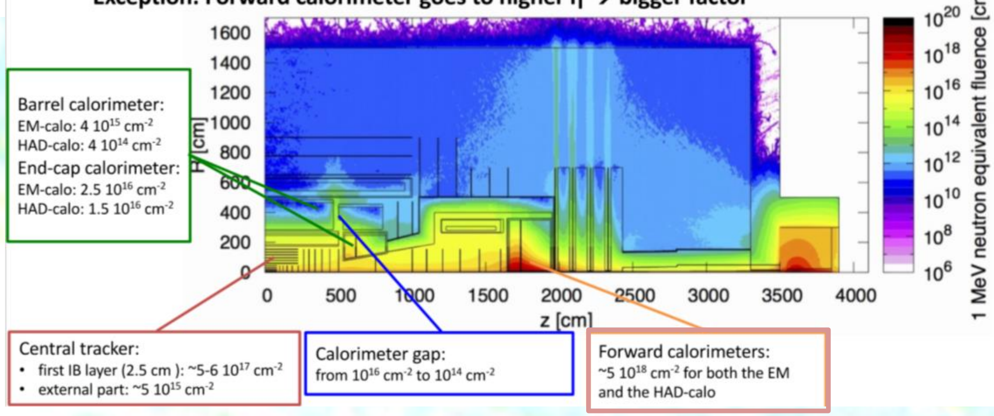
Forward solenoid adds about 1 unit of η with full lever-arm

Forward solenoid requires additional radiation shield to connect endcap and forward calorimeter

Largest challenge is that radiation levels go well beyond what any currently available microelectronics can survive ($\lesssim$ MGy) and few sensor technologies can cope beyond ~$10^{16} n_{eq}/cm^2$ (HL-LHC vertex layers)

Generally ~10-30 times worse than HL-LHC

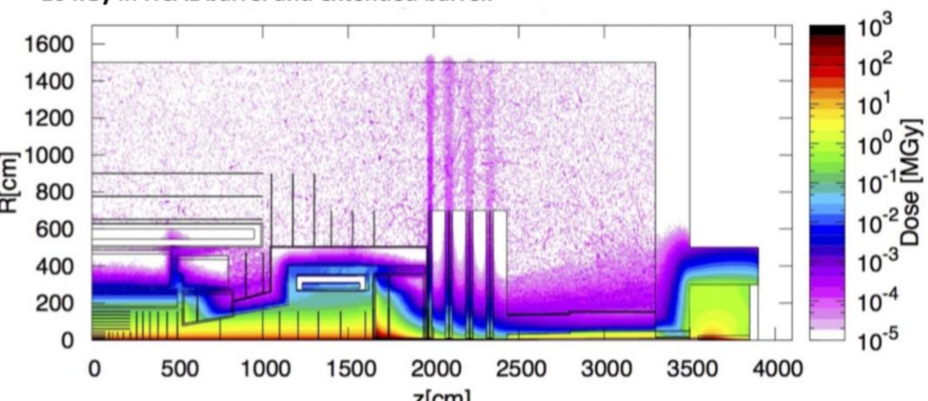
Exception: Forward calorimeter goes to higher η → bigger factor



Aim of FCC-hh CDR was to prove that with known detector techniques the primary physics goals could be met (see https://fcc-cdr.web.cern.ch/#FCCHH)

Dose of 300 MGy (30 Grad) in the first tracker layers.

< 10 kGy in HCAL barrel and extended barrel.



However, these radiation levels mean <u>no actual technologies currently exist to instrument much of the detector volume</u>

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We've been here before ….

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Detector R&D

- From 1986, vigorous CERN programme with 40 MCHF funding from Italian government (Zichichi's LAA Project)
- CERN Detector R&D Committee set up mid 1990. By March 1992: 35 proposals, 24 approved – involving 800 people in 170 institutes

Detector Research and Development Committee (DRDC), 1990 - 1995

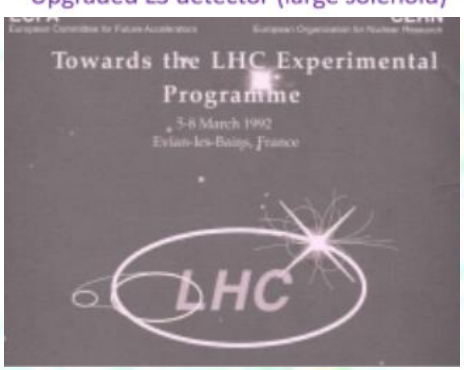
The Detector Research and Development Committee (DRDC) was set up in July 1990. It received proposals for detector R&D involving people from Member States, other countries, and CERN itself. The committee operated in the same way as the other experimental committees of CERN, and forwarded its recommendations to the Research Board for final decision. It held its last meeting in January 1995. Its role was taken over by the LHC Committee (LHCC).

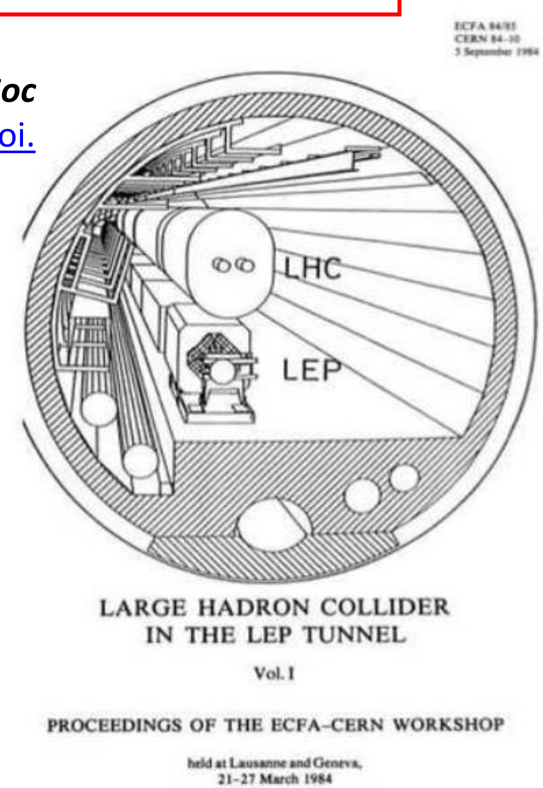
"Genesis of the LHC"
C. Llewellyn Smith, *Phil Tran Roy Soc A373:20140037* (2016) http://dx.doi.org/10.1098/rsta.2014.0037

- 1987 La Thuile Workshop
- 1989 Barcelona Workshop
- 1990 Aachen Workshop
- **1992 ECFA*-CERN** Evian Worksop:**

Expressions of Interest presented:

ASCOT (central solenoid + outer toroid)
EAGLE (central solenoid + outer toroid)
CMS (large solenoid)
Upgraded L3 detector (large solenoid)





First pages of the Proceedings of the LHC workshops held in Lausanne, 1984, and Aachen, 1990 [ECFA-CERN 1984] [Jarlskog, Rein 1990]. Note the early design of the machine layout in the LEP tunnel, with the LHC and the LEP rings together. Coexistence of the two machines was considered up to 1995, when it was dismissed by Chris Llewellyn Smith at the Lepton-Photon Conference in Beijing.

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US and EU International R&D Programmes

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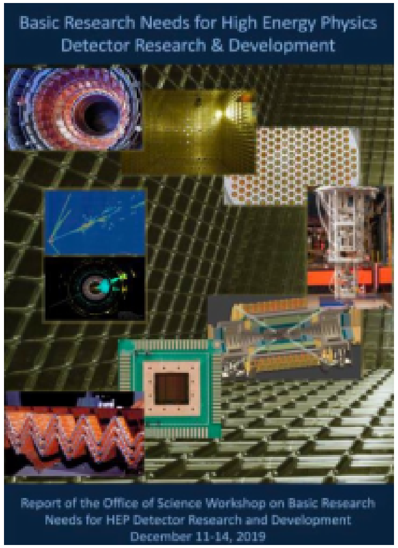
DOE-BRN Report published (Sep. 2020) https://science.osti.gov/hep/Community-Resources/Reports



Snowmass Instrumentation Frontier: The Snowmass Process is organized by the DPF of the American Physical Society: **https://snowmass21.org**

- Identify and document a vision for the future of particle physics (PP) in the US in a global context
- Communicate opportunities for discovery in PP to broader community and to the (US) government.
- Aim for Snowmass Book and online archive by end of 2022
- https://snowmass21.org/instrumentation/start Conveners: P. Barbeau, P. Merkel, J. Zhang

Snowmass Report « Community-Driven »:

- **Snowmass Summary for Public**
  - 2 pages
- **Snowmass Summary Report**
  - ~50 pages
    - Executive Summary: ~10 pages
    - Introduction
    - 10 Frontier Executive Summaries
    - Executive Summaries of Multi-Frontier Topics
    - Conclusion
- **Snowmass Book**
  - ~500 pages
    - Snowmass Summary Report (~50 pages)
    - Frontier Summaries (~400 pages with 10 Frontiers)
    - Multi-Frontier Topic Summaries (~50 pages)
- **Topical Group Reports**
    - Topical Group Reports: short reports
- **Reports of Multi-Frontier Topics**
    - Multi-Frontier Topics spanning multiple Frontiers.
    - Each Multi-Frontier Topic Summary: ~10 page
    - References

IF Frontier Summary: 40 pages

(Written by TG members including early careers)

(Written by the community including early careers)

New AIDAinnovaCall / Objectives:

- Support research **infrastructure** networks developing and implementing a **common strategy/ roadmap** including technological development required for improving their services through **partnership with industry**
- Support **incremental innovation** and cooperation with industry
- Complementarity to ATTRACT
- Increased focus on industrial partners
- No Transnational Access Proposed
- Funding 10 M€ for 4 years

Some targeted applications:

- Higgs Factories
- ATLAS, CMS LS4, ALICE, LHCb LS3 pre-TDR
- Accelerator-based neutrino experiments

Higgs Factory Detector R&D

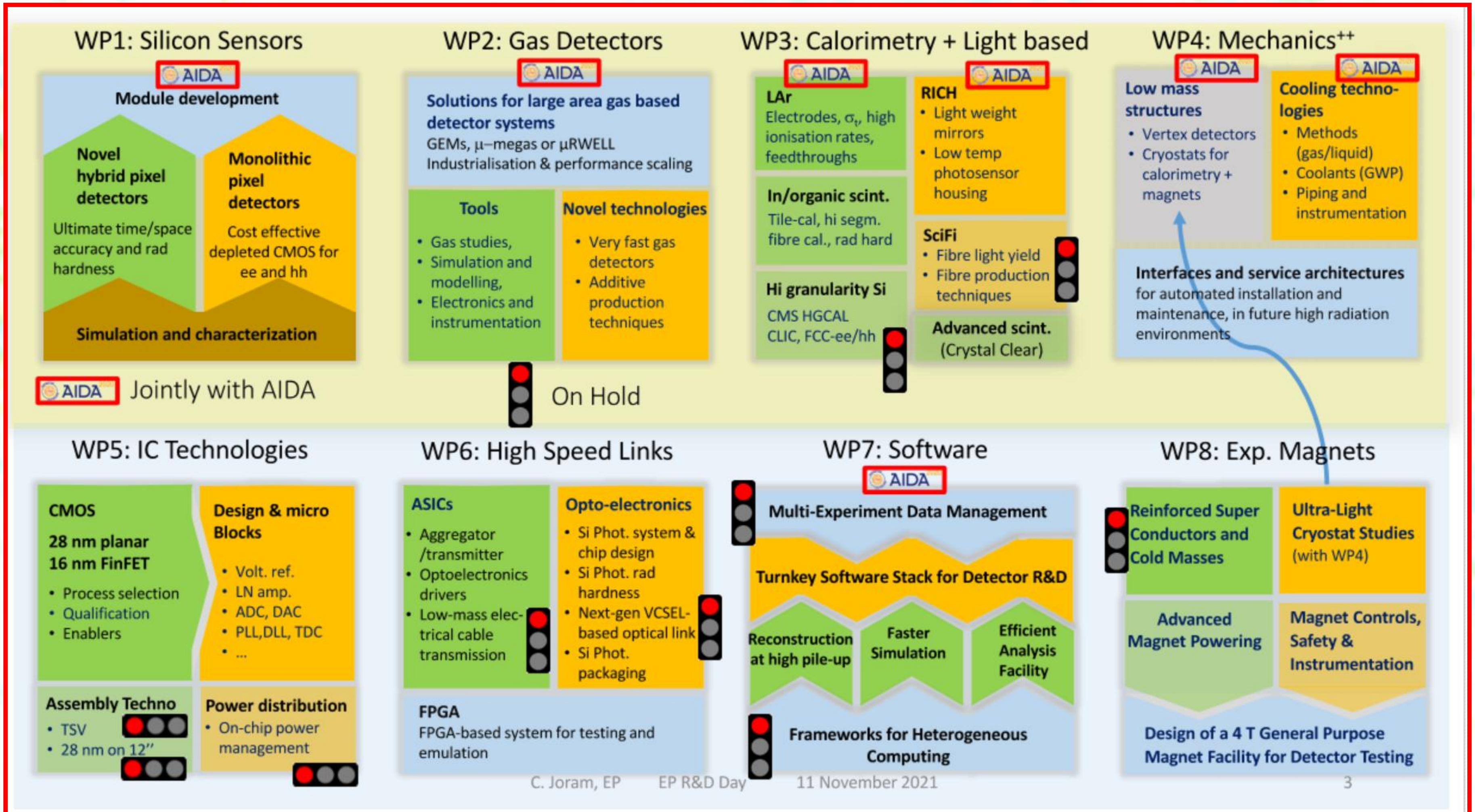
AIDA innova

Detector Technology	Linear & Circular Colliders common R&D	Differences
All	test infrastructure prototype electronics software for reconstruction and optimisation	readout rates power and cooling requirements
Silicon Vertex and Track Detectors	highest granularity and resolution, timing ultra-thin sensors and interconnects simulation and design tools low-mass support structures cooling micro-structures	emphasis on timing (background) and position resolution
Gaseous Trackers and Muon Chambers	ultra-light structures for large volumes industrialisation for large area instrumentation eco-friendly gases	DC and TPC presently considered only at some colliders
Calorimeters and Particle ID	highly compact structures and interfaces advanced photo-sensors and optical materials ps timing sensors and electronics	emphasis on granularity and stability DR and LAr pesresently only considered for circular

CERN EP R&D

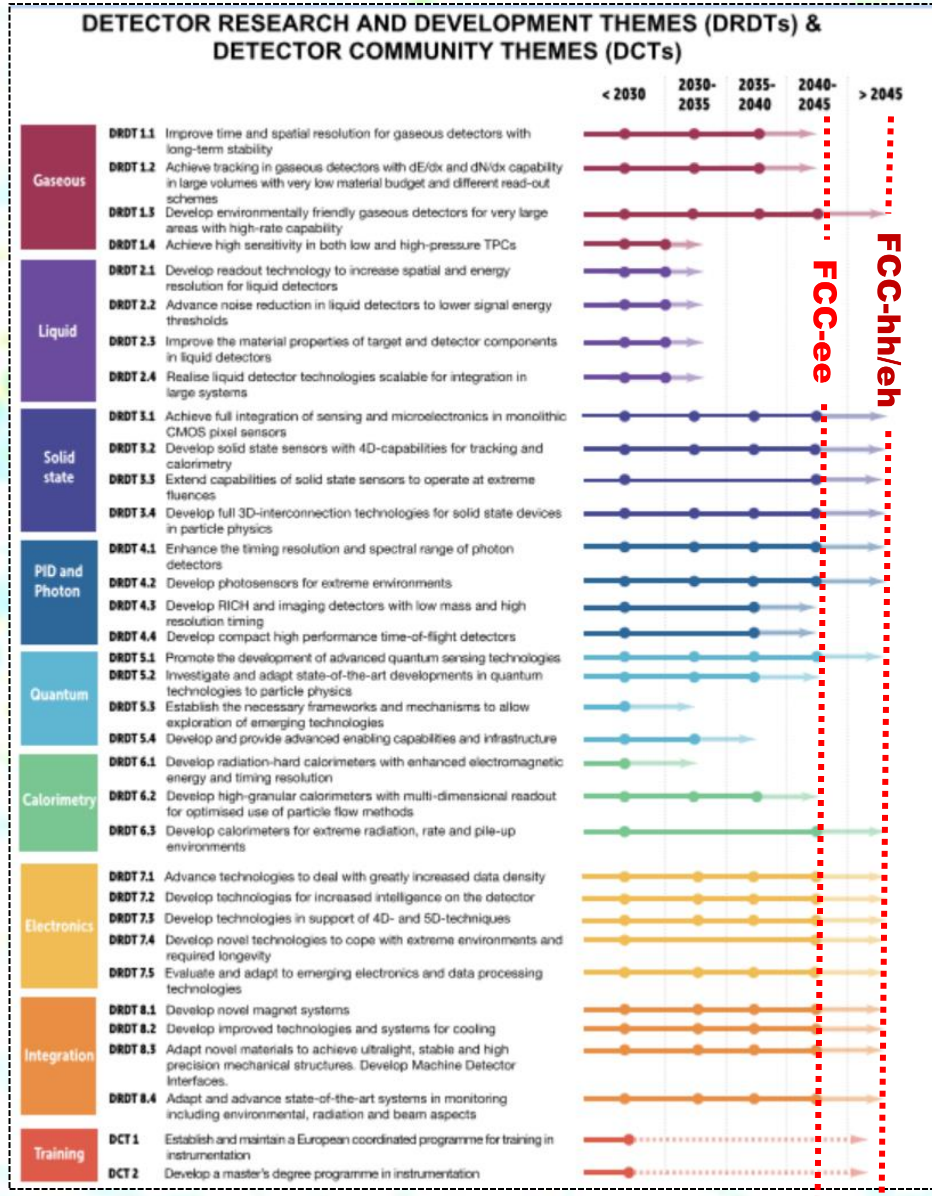
- Following tradition of **DRDC** (LHC Phase-0), White Paper R&D (LHC Phase-I)
- Target **beyond approved LHC upgrades**: e.g. FCC-ee/eh/hh
- Strong links/overlap with RD50, RD51, RD18 and AIDAinnova
- See materials at https://ep-rnd.web.cern.ch/.

R&D on EXPERIMENTAL TECHNOLOGIES



ECFA Detector R&D Roadmap: FCC

https://indico.cern.ch/event/949705/contributions/4575435/attachments/2372982/4052970/DetectorRDOverview_LP2022_SKuehn.pdf



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Vertex Detectors

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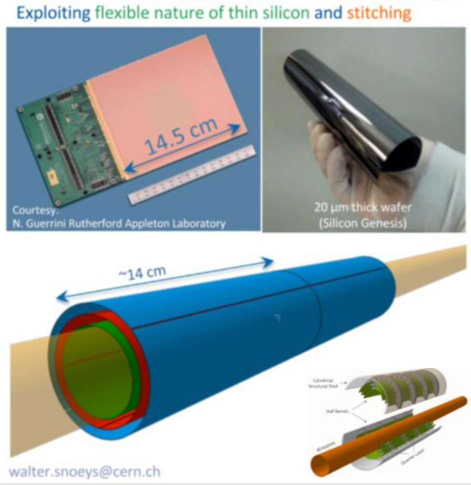
Detectors for FCC-ee draw heavily on those for LCs but without power cycling as an aid to reducing cooling requirements.

Target per layer spatial resolution of ≤ 3μm and X/X_0 ≤ 0.05% *cf* ALICE3 using CMOS pixel sensors.

→ Key is low power.

Parameter	ALPIDE (existing)	Wafer-scale sensor (this proposal)
Technology node	180 nm	65 nm
Silicon thickness	50 μm	20-40 μm
Pixel size	27 x 29 μm	O(10 x 10 μm)
Chip dimensions	1.5 x 3.0 cm	scalable up to 28 x 10 cm
Front-end pulse duration	~ 5 μs	~ 200 ns
Time resolution	~ 1 μs	< 100 ns (option: <10ns)
Max particle fluence	100 MHz/cm^2	100 MHz/cm^2
Max particle readout rate	10 MHz/cm^2	100 MHz/cm^2
Power Consumption	40 mW/cm^2	< 20 mW/cm^2 (pixel matrix)
Detection efficiency	> 99%	> 99%
Fake hit rate	< 10^{-7} event/pixel	< 10^{-7} event/pixel
NIEL radiation tolerance	~3 x 10^{13} 1 MeV n$_{eq}$/cm^2	10^{14} 1 MeV n$_{eq}$/cm^2
TID radiation tolerance	3 MRad	10 MRad



For FCC-hh the challenge is extreme radiation levels both 300MGy for micro-electronics and integrated fluence for the sensors of 8×10^{17}n$_{eq}$/cm^2 → both represent enormous challenges.

In addition fast timing is desirable: ≤ 50ps targeted for LHCb LS4 simultaneous with ≤ 10μm and X/X_0 ≤ 1%. • FCC-hh targets ≤ 20ps, ≤7μm and X/X_0 ≤ 1% but at the above fluence.

Hybrid technologies with thin, 3D-structures (columns/trenches) silicon and/or high bandgap materials (*eg* diamond) are mostly considered for really high radiation environments.

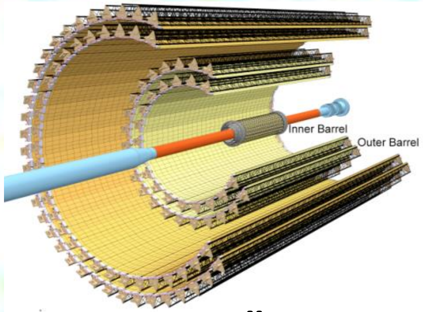
Ultra-fast silicon detectors (UFSDs) with various Low-Gain Avalanche Detector developments to reduce/remove inter-pixel (JTE) structures – trench isolation; AC LGADs; inverse LGADs.

The dream remains a truly monolithic solution with all the above properties.

Tracking Detectors

For e^+e^- experiment trackers, gaseous large volume detectors are attractive such as TPCs with Micro-Patter Gas Detector (MPGD) or even direct pixelated readout or, given for FCC-ee the constraints of high (70kHz) physics rates with continuous collision rates (no gating) $\rightarrow$ highly transparent drift detector: (90% He – 10% iC_4H_{10}) , $X/X_0 \leq$ 1.6% (radius 0.35 – 2.00) thin tungsten wires and dE/dx or dN/dx (cluster counting) particle identification (PID)

CLD: silicon $X/X_0 \leq$ 1% per layer (3 inner + 3 outer barrels and 7 + 4 disks). Attractive to consider CMOS sensors *cf* ALICE ITS ($10m^2$, $\sim 10^{10}$ channels).



Note B field limited to 2T due to 30mrad beam crossing of e^+e^- beams,

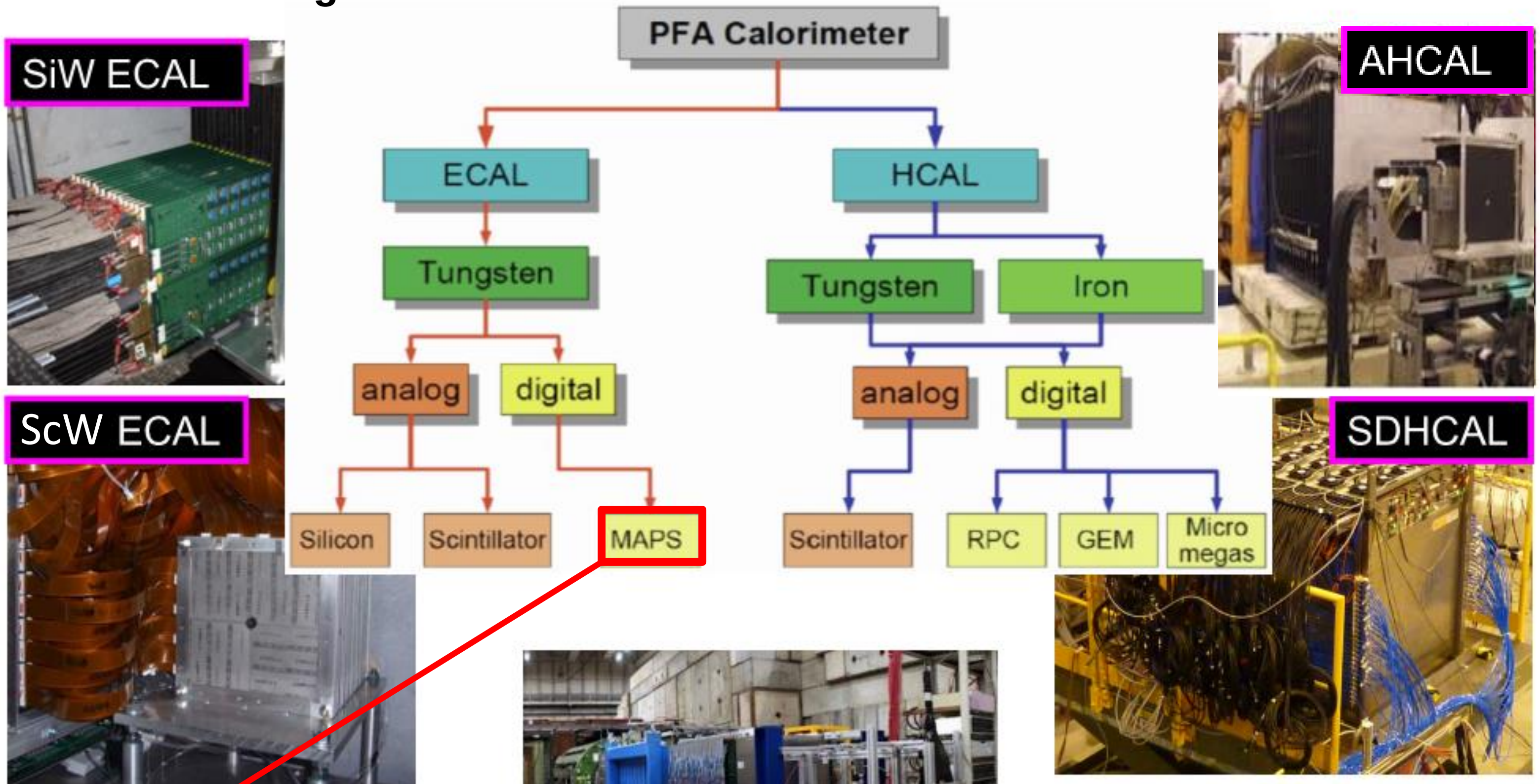
Also, even with gaseous large volume tracker (IDEA), still anticipate a “silicon wrapper”.

FCC-eh and FCC-hh consider silicon tracking assuming, conservatively, hybrid (either macro-pixel + strip) solutions, but CMOS monolithic active pixel sensor (MAPS) options of strong interest. FCC-hh radiation tolerance an issue even at $r > 30\text{cm}$, requiring $\sim 10^{16} n_{eq}/cm^2$, 10 MGy survival which can be achieved with HL-LHC hybrid pixels but needs work for MAPS designs, *esp* with small collection electrodes (which offer lower power and higher speed).

4D tracking (with <25ps timing via LGAD or other technology) as opposed to just timing layers (such as LHC high granularity timing detectors) hugely benefits pile-up suppression at FCC-hh.

Calorimetry

Options for e^+e^- for include: dual-readout (IDEA: f_{EM} from absorber with combined scintillator parallel plates and Čerenkov PMMA fibres); high granularity LAr/LKr; finely segmented crystals or Particle Flow (CLD) based on a "tracking calorimeter" concept with very fine sense element segmentation.

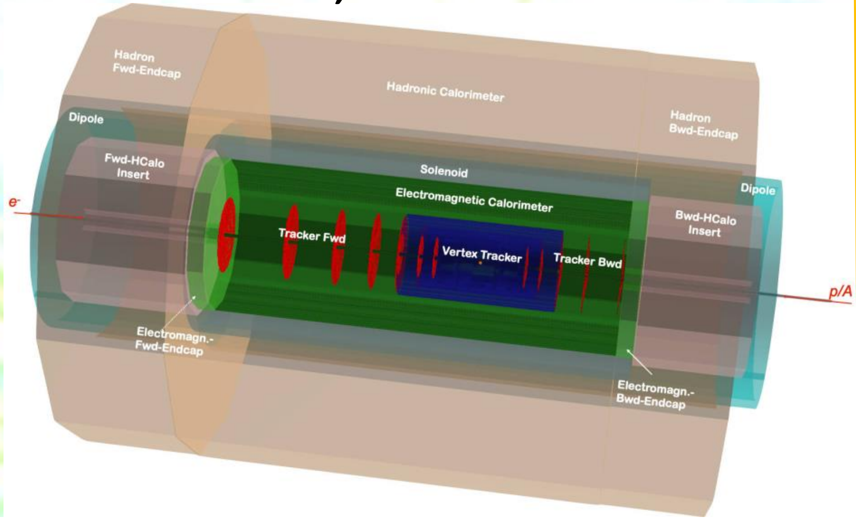


(see for example 9th October 2020 EP Detector Seminar https://indico.cern.ch/event/960851/)

With thanks for help to Roman Pöschl, Fabrizio Salvatore and Nige Watson

Calorimetry

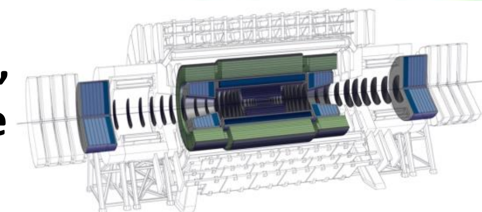
eh: combination of scintillator and absorber and silicon with W, Pb and Cu for forward

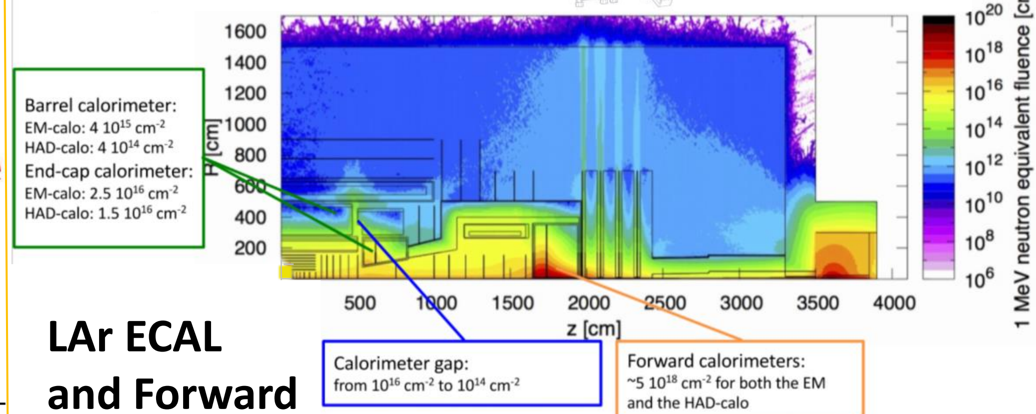


Calo (lowE-FCCeh)	EMC	HCAL		
	Barrel	Ecap Fwd	Barrel	Ecap Bwd
Readout, Absorber	Sci,Pb	Sci,Fe	Sci,Fe	Sci,Fe
Layers	49	91	68	78
Integral Absorber Thickness [cm]	36.6	206.0	184.0	178.0
η_{max}, η_{min}	2.8, −2.5	2.0, 0.8	1.6, −1.4	−0.7, −1.8
$\sigma_E/E = a/\sqrt{E} \oplus b$ [%]	12.6/1.1	38.9/3.3	42.4/4.2	40.6/3.5
Λ_I / X_0	$X_0 = 66.2$	$\Lambda_I = 12.7$	$\Lambda_I = 11.3$	$\Lambda_I = 11.0$
Total area Sci [m^2]	2915	4554	12298	3903

Calo (lowE-FCCeh)	FHC	FEC	BEC	BHC
	Plug Fwd	Plug Fwd	Plug Bwd	Plug Bwd
Readout, Absorber	Si,W	Si,W	Si,Pb	Si,Cu
Layers	296	49	59	238
Integral Absorber Thickness [cm]	256.9	29.6	27.9	220.8
η_{max}, η_{min}	5.8, 1.8	5.4, 1.8	−1.5, −5.2	−1.5, −5.6
$\sigma_E/E = a/\sqrt{E} \oplus b$ [%]	61.9/0.5	26.5/0.4	24.7/0.4	46.7/4.4
Λ_I / X_0	$\Lambda_I = 15.5$	$X_0 = 84.7$	$X_0 = 50.2$	$\Lambda_I = 14.7$
Total area Si [m^2]	2479	364	438	1994

hh: issues include unprecedented doses, massive size and huge particle flux

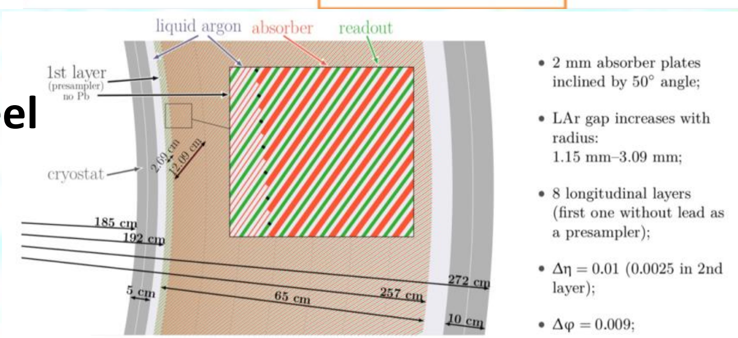




LAr ECAL and Forward $\leq 10\%/\sqrt{E}$

Sci tiles + steel barrel HCAL $\sim 40\%/\sqrt{E}$

(*cf* ATLAS)



SiW/Pb ECAL (*cf* CMS HGCal) and digital ECAL with CMOS studied as futuristic barrel option with enhanced PF capabilities (see M. Aleksa et al. *arXiv:1912.0996*).

PID, Photodetectors and Microelectronics

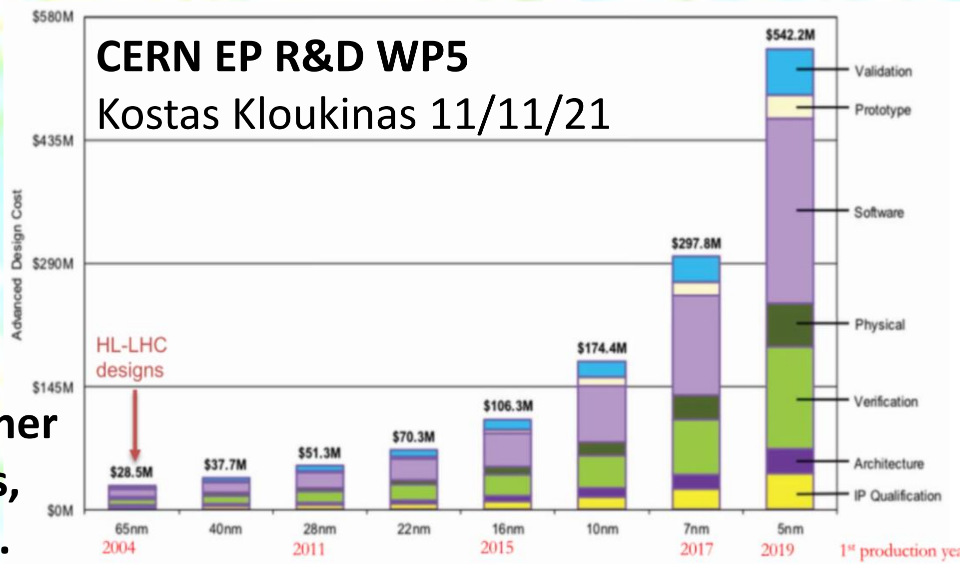
Although not in the layouts shown, additional dedicated compact PID concepts highly desirable (eg Detection of Internally Reflected Čerenkov light, Time of Flight, …)

Note: precision timing (ToF; 4D tracking), ultra-high granularity and improved signal resolution all come at a cost in terms of data handling, processing, complexity and power.

These inevitably require exploiting the latest advances in commercial photodetectors, microelectronics and high-speed links.

However, increasing sophistication, entry cost and complexity demand radically different approaches to those historically adopted by the HEP community.

The need for bespoke solutions for even modest radiation or magnetic fields is a further problem as these are not commercial drivers, with HEP at best a niche low volume market.



Chip Design and Manufacturing Cost under Different Process Nodes: Data Source from IBS*

Much of the ECFA Detector R&D Roadmap is dedicated to discussion of the need for better organisation and coordination across Europe to cope with these considerable challenges.

Combining signatures from different devices and improved online intelligence, along with many aspects of data analysis, can also benefit greatly from cutting edge AI developments.

Muons, Magnets and Integration

- **Upgrades to a number of systems used at the LHC for tracking, muon spectroscopy and triggering have taken advantage of the renaissance in gaseous detectors (*esp* MPGDs)**
- **Gaseous detectors remain the most-cost effective route to instrumenting very large areas where rates are still low compared with central tracking and offer very competitive timing through Multi-gap Resistive Plate Chambers (MRPCs) and Fast Timing MPGS (FTMs).**
- **However challenges remain in terms of pushing spatial and temporal resolution without compromising long-term stability and adopting more eco-friendly gas mixtures.**
- **Investigation of novel superconductors for magnet systems as well as support of expert design capabilities and modelling software for future experiments is vital.**
- **Cooling technologies for cryogenics and low-mass heat removal from on-detector electronics and semiconductor sensors require dedicated generic R&D activities.**
- **Ultra low mass, stable, precision mechanics and machine detector interface design are major topics, particularly to realise the physics goals of FCC-ee and FCC-eh.**
- **Novel materials and enhanced radiation testing capabilities will be vital for FCC-hh.**
- **Evaluation infrastructures, teat-beams, access to advanced engineering tools and personnel, retention and training of detector experts and much more are detailed in the ECFA Detector R&D Roadmap as mandatory to the success or the FCC programme as well as the long-term health of experimental particle physics as a whole.**

Conclusions and Observations

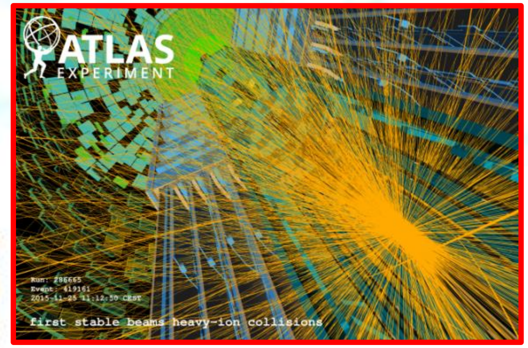
- Major R&D funding for the LHC detector R&D programme was in place from 1986.
- The ECFA Detector R&D Roadmap starts from the principle of needing to identify the mission critical detector R&D for all the future programmes considered as viable options in the 2020 Update to the European Strategy for Particle Physics.
- Mission critical for different facilities means different things:
  - For FCC-hh, at the energy frontier, it may mean finding technologies that function adequately for long enough given the extreme conditions and requirements.
  - For FCC-ee/eh, at the luminosity frontier, the issue is not to be systematics limited by the detector performance such that the unprecedented statistical precision is wasted.
- The FCC programme as envisaged in the updated European Strategy for Particle Physics represents an exciting but very challenging future for particle physics in Europe.
- Without the required investment in detector R&D the opportunities this offers will be squandered – installing a LEP experiment at the FCC-ee would be as pointless as installing a LHC experiment at the FCC-hh.

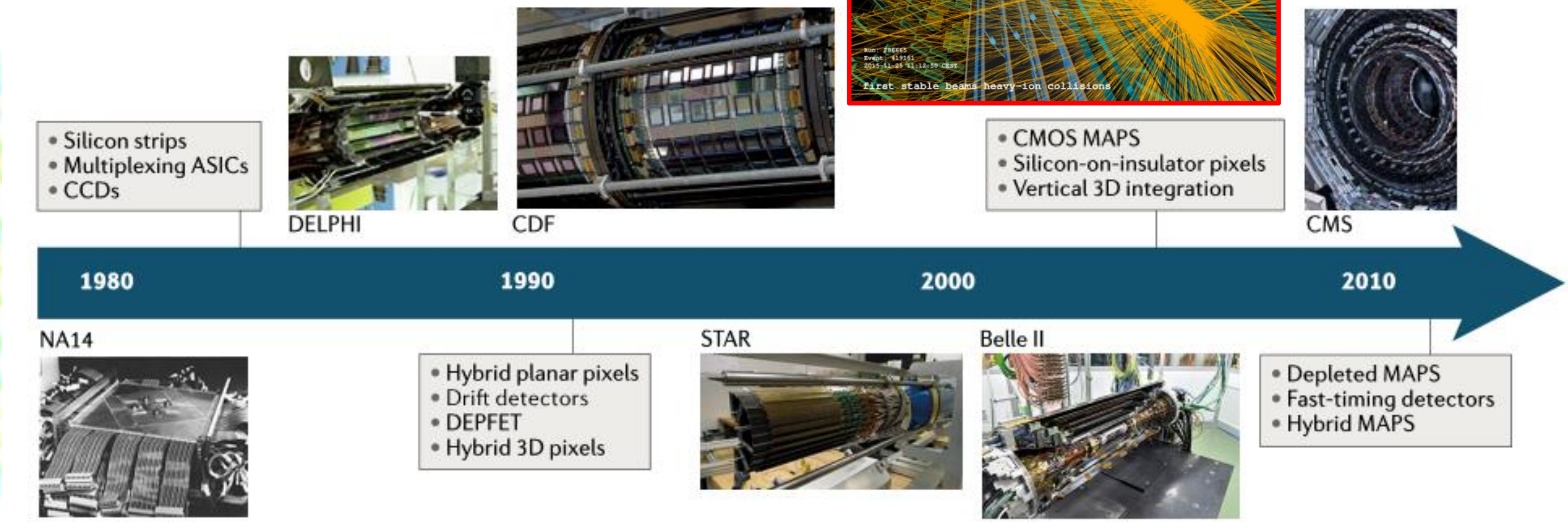
→ **Lead times of at least 20 years should be anticipated for the more demanding technology aspects and in some cases (eg sensors or microelectronics for FCC-hh) it is not even currently clear what would be the best direction to go in to meet the most extreme radiation-hardness specifications.**

BACK-UP

Silicon Sensor Technology Developments

Many different silicon detector technologies for particle tracking have been developed over the last four decades.



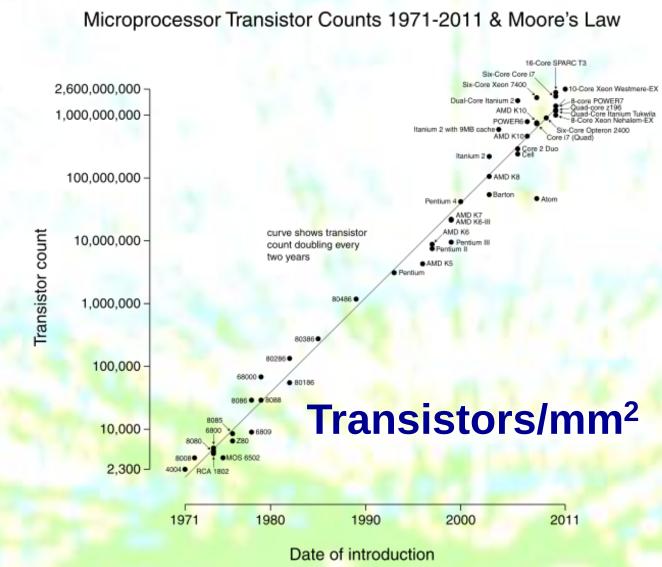


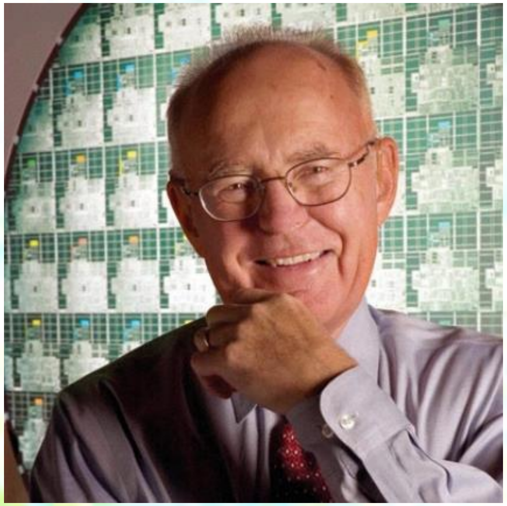
Applications of silicon strip and pixel-based particle tracking detectors - Nature Reviews Physics - https://doi.org/10.1038/s42254-019-0081-z Allport2019ER

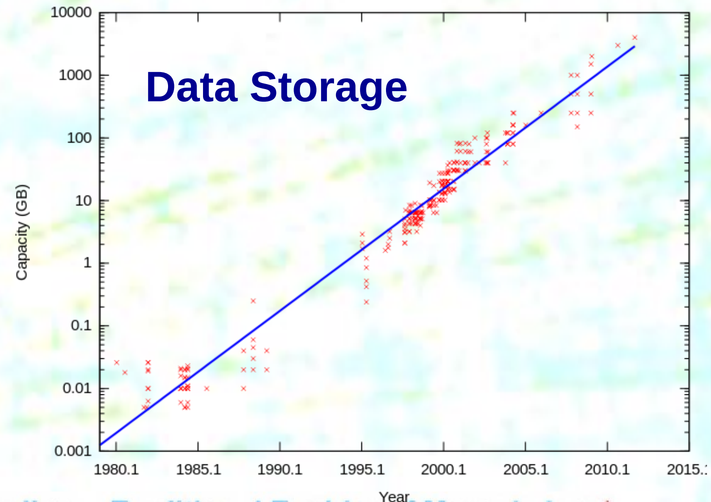
What is remarkable is that every decade the instrumented areas have increased by a factor of 10 while the numbers of channels in the largest arrays have increased by a factor of 100.

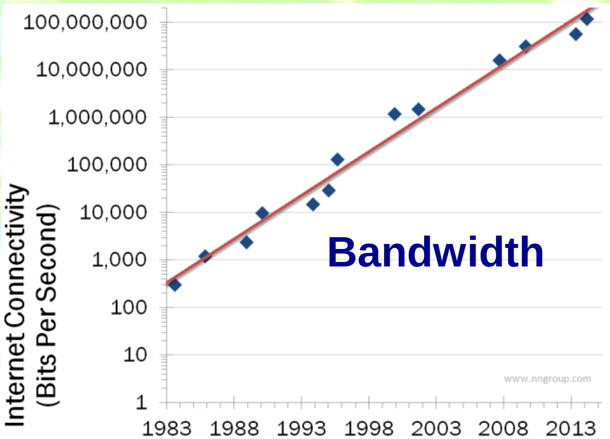
This despite other specifications for readout speed, spatial resolution, reduced multiple scattering (minimal total material including cooling and services) and radiation hardness also becoming much more demanding

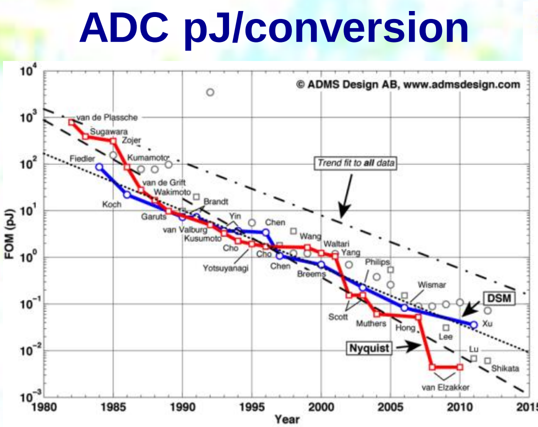
Historical Microelectronics Evolution

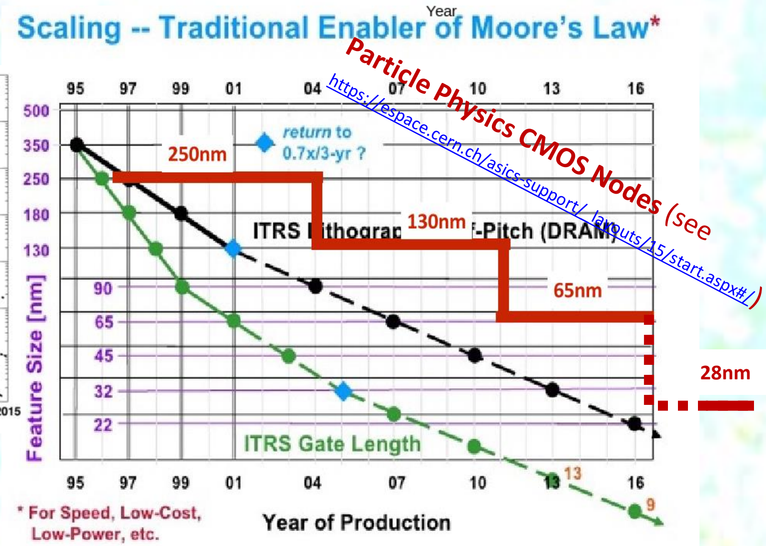










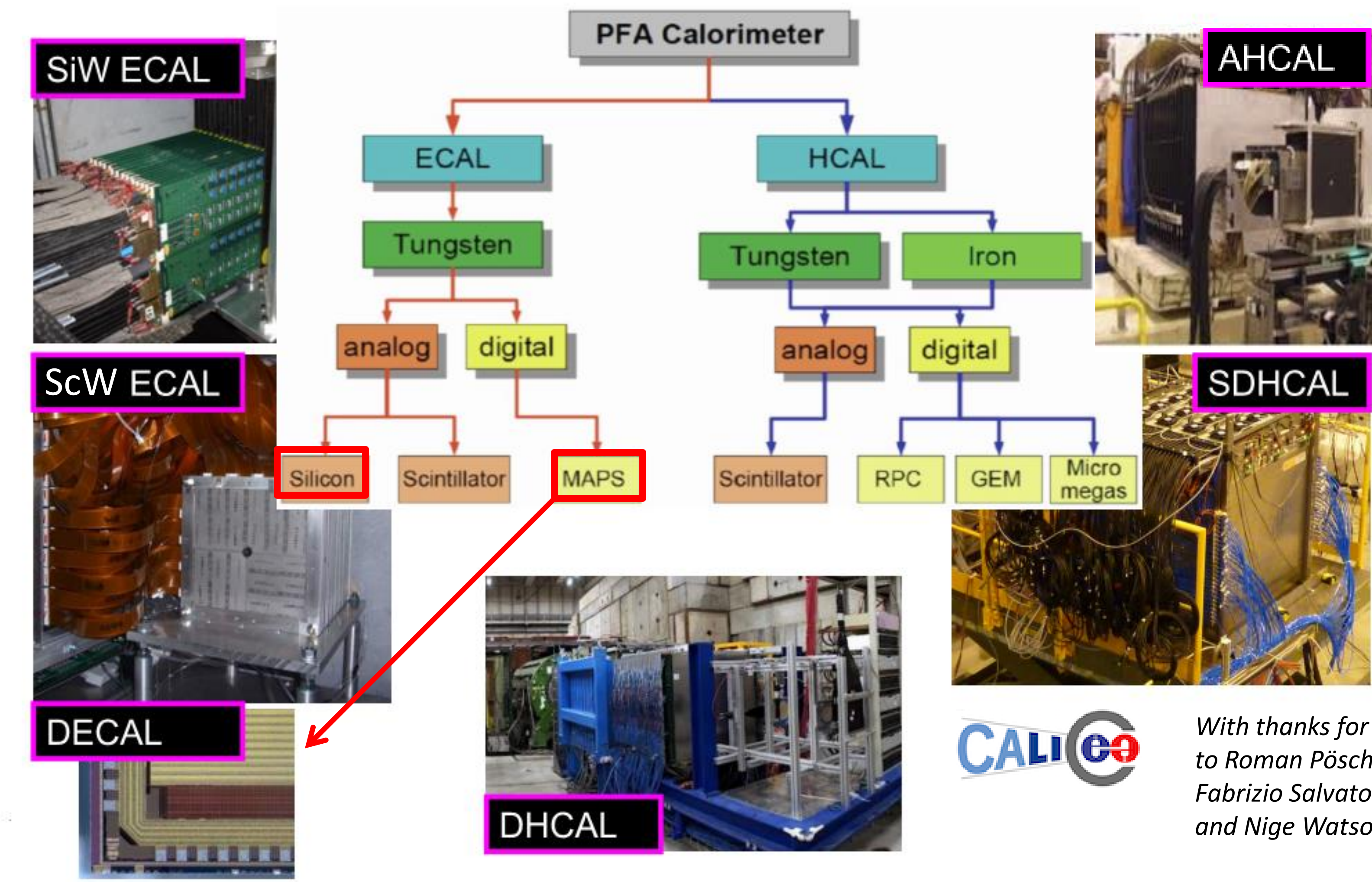


F Faccio: https://indico.cern.ch/event/468486

Microelectronics doubling times were < 2 years but now slowing.
However, CMOS nodes used by particle physics lag significantly behind.
Sensor technology feature size lags even further behind – just starting with TPSCo 65nm CMOS Imaging Sensor

Compact Calorimetry: CALICE

- **The concept of SiW calorimetry has long been under consideration as a possible option within the CALICE collaboration as offering unprecedented granularity for PFA and is the focus of extensive prototyping and test beam activities**



With thanks for help to Roman Pöschl, Fabrizio Salvatore and Nige Watson

CALICE: SiW EM Calorimetry

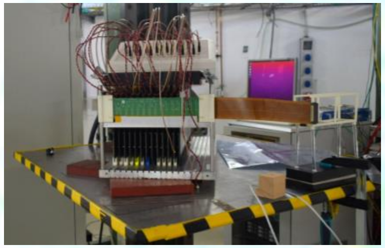
Milestone	Date	Object	Details	REM
1st ASIC proto	**2007**	SK1 on FEV4	36 ch, 5 SCA	proto, lim @ 2000 mips
1st ASIC	2009	SK2	64ch, 15 SCA	3000 mips
1st prototype of a PCB	**2010**	FEV7	8 SK2	COB
1st working PCB	2011	FEV8	16 SK2 (1024 ch)	CIP (QGFP)
1st working ASU in BT	**2012**	FEV8	4 SK2 readout (256ch)	best S/N ~ 14 (HG), no PP retriggers 50–75%
1st run in PP	2013	FEV8-CIP		BGA, PP
1st full ASU	**2015**	FEV10	4 units on test board 1024 channel	S/N ~ 17–18 (High Gain) retrigger ~ 50%
1st SLABs	2016	FEV11	7 units	
pre-calo	**2017**	FEV 11	7 units	S/N ~ 20 (12)$_{\text{Trig.}}$ 6–8 % masked
1st technological ECAL	2018	SLABvFEV11 & FEV13 SK2a+ Compact stack Long Slab	SK2 & SK2a (⊃timing) 8 ASUs	Improved S/N Timing...
1st working COB	2019	FEV-COB	2×1/4 ASUs	

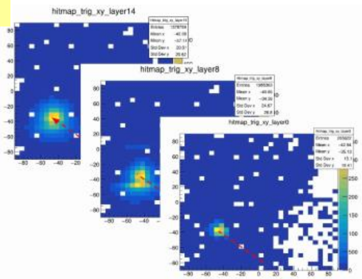
CALICE SiW ECAL Test Beam

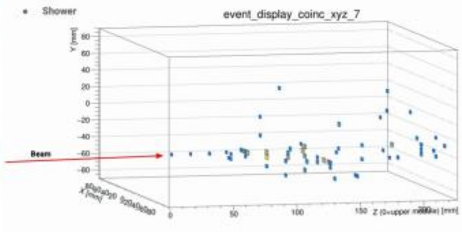
- **culmination of 10 years of prototyping**
- **Integrated front-end and digital electronics**
- **15 layers with 15360 channels**
- **2.1 mm (x11) and 4.2 mm (x3) tungsten**

DESY Test Beam November 2021

https://aitanatop.ific.uv.es/aitanatop/siwecal-tb2021/

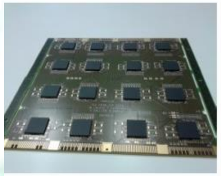




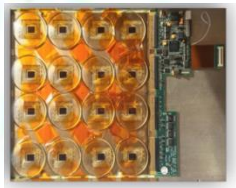


Different generations of Active Sensor Units and FE PCBs (FEV)

FEV10-12

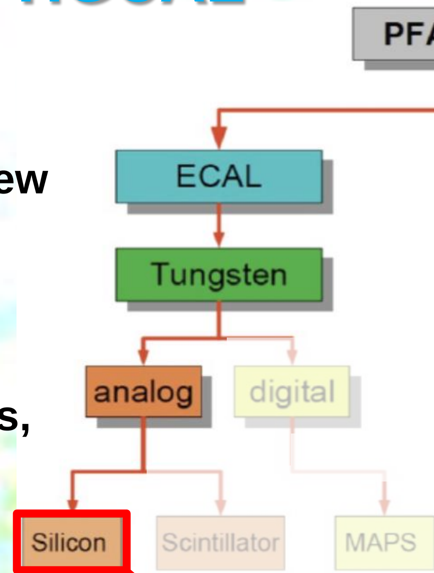


FEV_COB

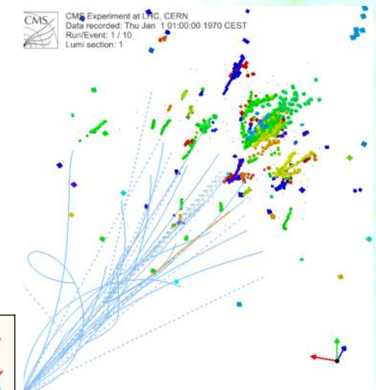


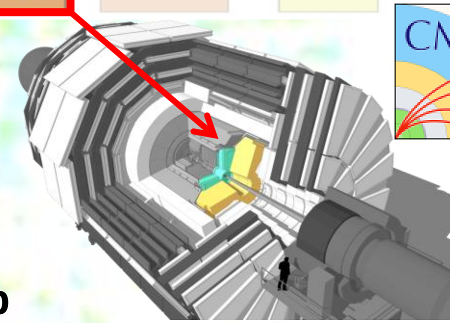
FEV13

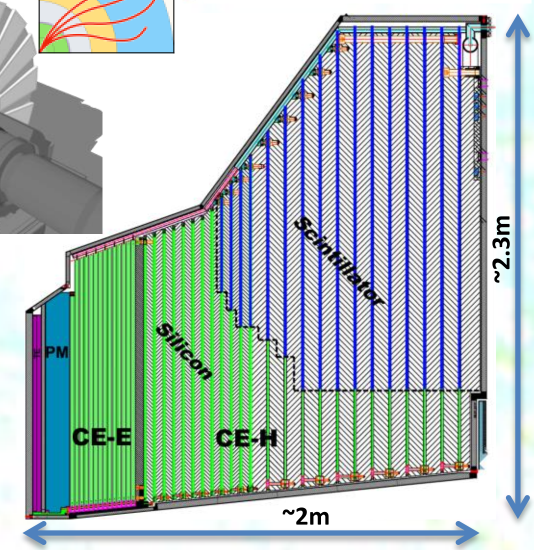
CMS HGCAL



- Some of the R&D being discussed here grew out of ideas within CALICE, but initially with a view to FCC-hh, inspired also by developments within CMS for Phase-II
- Given the very high radiation environments, CMS is building the High Granularity Calorimeter (HGCAL) as the upgrade path for their forward calorimetry at HL-LHC
- The HGCAL will have ~600m^2 of silicon sensors (~500m^2 of scintillators) with 6M Si channels, 0.5 or 1.1 cm cell size and overall ~27000 silicon modules
- The ECAL has 28 layers with Si + Cu/CuW/Pb absorbers giving 26 X_0 and ~1.7λ
- Silicon module costs ~4$ / cm^2

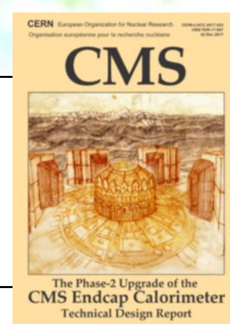






CE-E: 1.7λ Cu/CuW/Pb absorbers

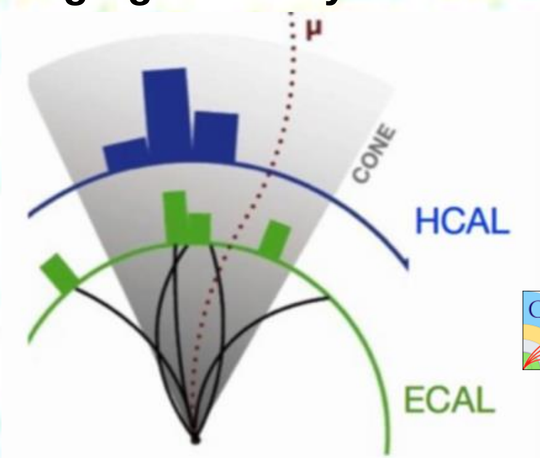
1.3, 1.4	Silicon sensors and modules	26 514
	GRAND TOTAL	67 153



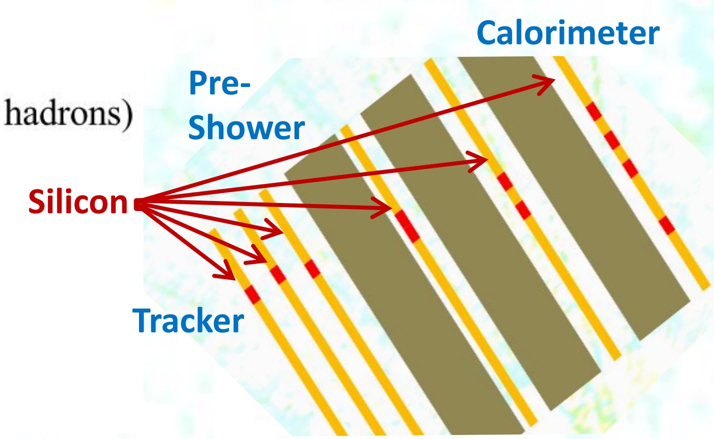
D. Barney, https://indico.cern.ch/event/718124/

Particle Flow Considerations

- In addition to vertexing, silicon detectors are widely assumed to be an important option for outer tracking either for a fully silicon "compact" tracker (often with high field) or outside a gaseous tracking volume (as "silicon wrapper" see for example Attilio Andreazza: https://indico.cern.ch/event/838435/contributions/3672992/attachments/1970363/3277344/LargeSiliconSystems_v2.pdf at 3rd FCC Workshop).
- Silicon detectors also technology of choice where high radiation, high speed or high granularity requirements; either in collider or fixed target experiments.
- The PFA concept requires excellent extrapolation of charged tracks into the calorimeter layers as well as high spatial resolution on EM showers (including resolving photons from high energy π^0 decays) and the start of hadron showers.
- Silicon layers (with tungsten or lead absorber) are also a leading candidate for such high granularity calorimeters, at least as far as the technology can be cost effective.



"Typical" jet:
~62% charged particles (mainly hadrons)
~27% photons
~10% neutral hadrons
~1% neutrinos



Birmingham Instrumentation Laboratory for Particle physics and Applications
BILPA

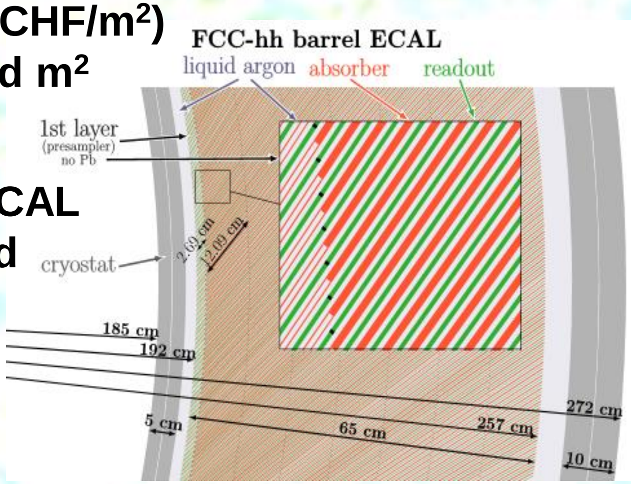
SiW ECAL CMOS MAPS Motivation

UNIVERSITY OF BIRMINGHAM

- **Current hybrid strip and pixel costs are still a major consideration (ATLAS Upgrade costs from Attilio Andreazza "*Large Silicon Systems*" at 3rd FCC Workshop, CERN January 2020, *referenced above*)**

	Strip	Pixels
Area	165 m^2	13 m^2
Power density	43 mW/cm^2	700 mW/cm^2
Module cost (TDR)	36900 kCHF	25067 kCHF
	224 $kCHF/m^2$	1900 $kCHF/m^2$

- **Even CMS HGCAL silicon module costs ~4CHF/cm^2 (40$kCHF/m^2$) would still need to come down further for many thousand m^2 (» $10^7 cm^2$) array to become affordable**



11th FCC - ee Workshop — M. Aleksa

➢ ***NB* partially mitigated by cost savings from reducing ECAL thickness (eg for FCC-hh) to < 20cm and removing need for cryostat with respect to LAr. (Depending in inner radius, could reduces total cost of HCAL, magnet system and muon spectrometer by up to factor of 2)**

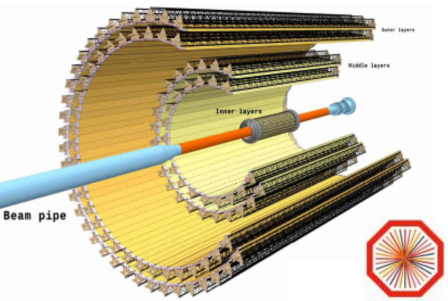
- **Excellent PFA capabilities but difficult to match LAr for cost, radiation-hardness and EM energy resolution**

- **For a hybrid silicon system (such as the CMS HGCAL), at some stage the price of polished high- ρ wafers could set a lower limit to what overall costs might be possible with separate thick depleted silicon substrate (although other options may exist)**

- **For both vertexing and outer tracking, thinking for silicon technology at future colliders is moving towards the use of CMOS Monolithic Active Pixel Sensors**

SiW ECAL CMOS MAPS Motivation

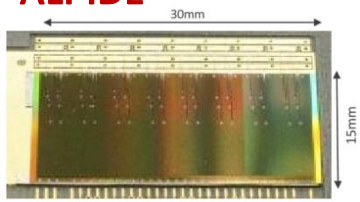
- **Currently, CMOS Imaging Sensors represent a ~20B$ business internationally (https://www.marketsandmarkets.com/Market-Reports/cmos-image-sensor-market-252212367.html) and market expected to continue growing rapidly driving down prices for such detectors**
- **Although existing CMOS sensor array (such as for ALICE ITS Monolithic Active Pixel Sensor) cost estimates can typically be ~5-10 times* those for CMS HGCAL, expect prices could be significantly lower for much larger orders and as a function of time, while integration of electronics within the sensor also reduces cost of full system**
- **Prototypes (see later) demonstrate concept of digital ECAL with same CMOS fabrication line that CERN and collaborators have shown, with appropriate design and processing, is now delivering radiation hardness to > $10^{15} n_{eq}/cm^2$**



ALICE

7 layers, 12.5 Gpixels covering **10 m²**
with 5 μm position resolution
Closer: Inner layer radius 39 mm -> 22 mm
Thinner: X/X_0 1.14% -> 0.3 % (inner layers)
Pixel size: 50 x 425 μm² -> 27 x 29 μm²

ALPIDE



***ALICE-TDR-017 (~10^{10} Channels 10m²)**
CMOS costs ~200kCHF/m² also suggested: Attilio Andreazza (private communication)

Table 9.1: Cost estimate

Item	Cost (kCHF)
Total	**12 039**
Pixel Chip	**5000**
CMOS wafers	3500
Thinning & dicing	1000
Series test	500

SiW ECAL CMOS MAPS Motivation

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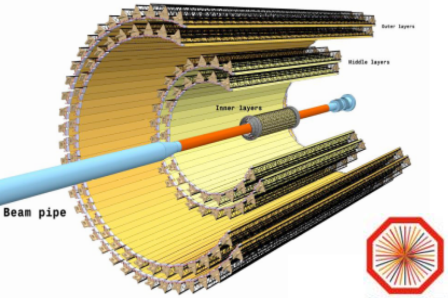

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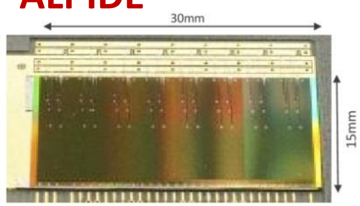

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The Digital EM Calorimeter Concept

Birmingham Instrumentation Laboratory for Particle physics and Applications
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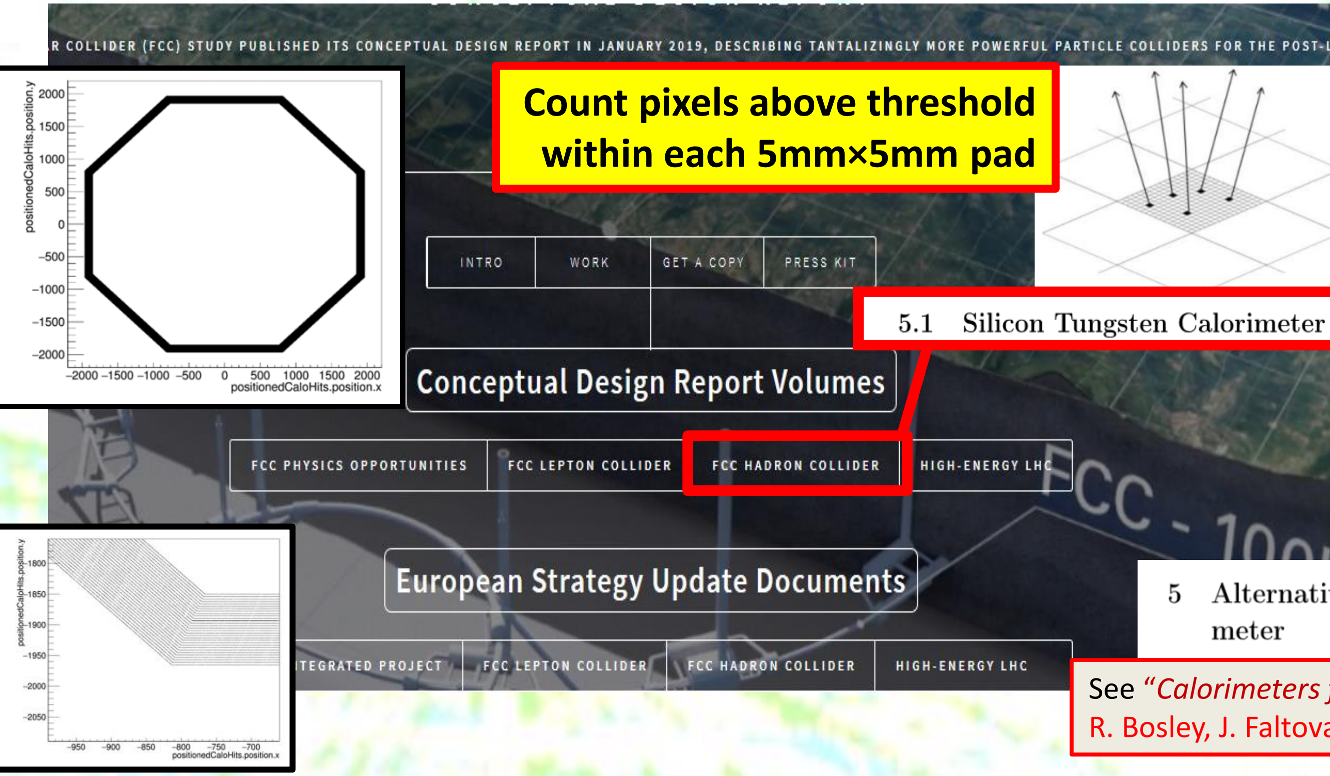
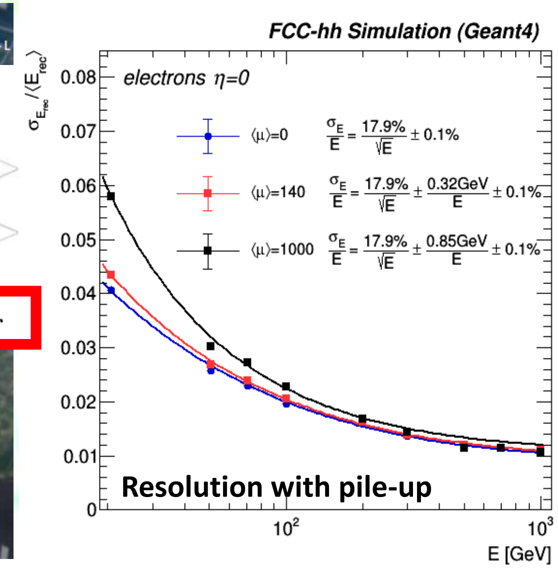




5 Alternative Technology for the EM Barrel Calorimeter

FCC Week (1/6/17) T. Price

See *"Calorimeters for the FCC"*, M. Aleksa , P. Allport, R. Bosley, J. Faltova et al. , CERN-FCC-PHYS-2019-0003

Idea initially in context of CALICE but then adapted to FCC-hh environment.

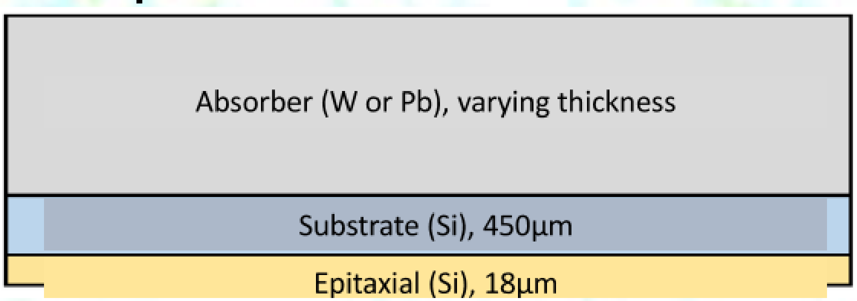
Simulated 4 different geometries:

30 Layers, 3.5mm W (30 × 1.0 X_0)

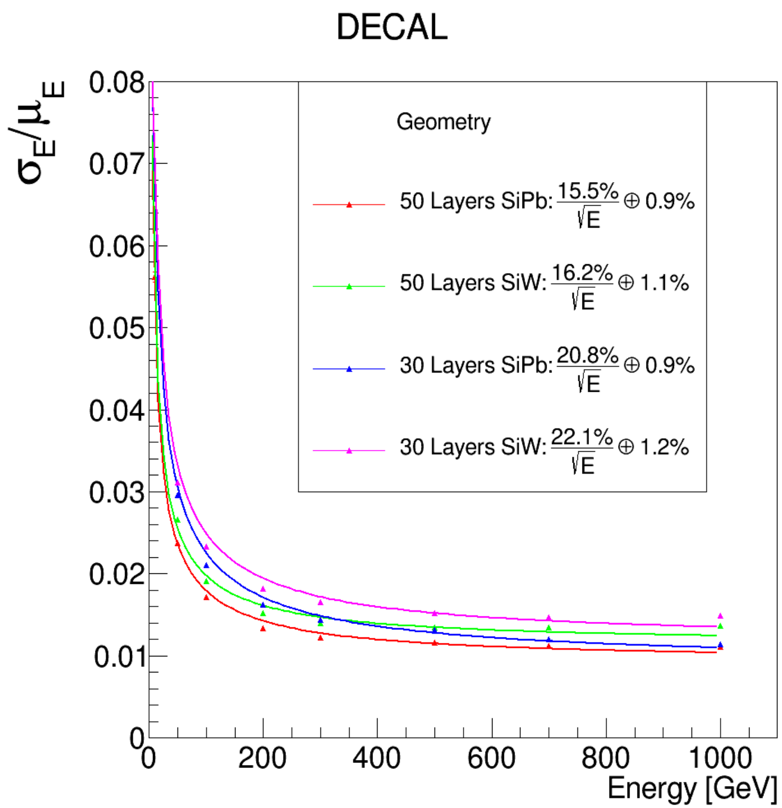
5.6mm Pb

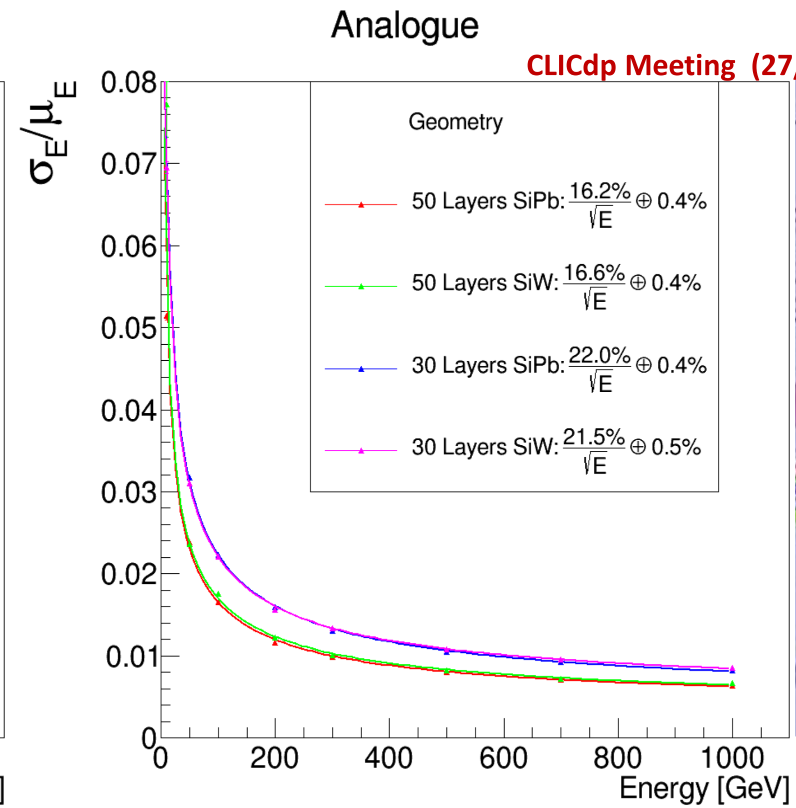
50 Layers, 2.1mm W (50 × 0.6 X_0)

3.4mm Pb

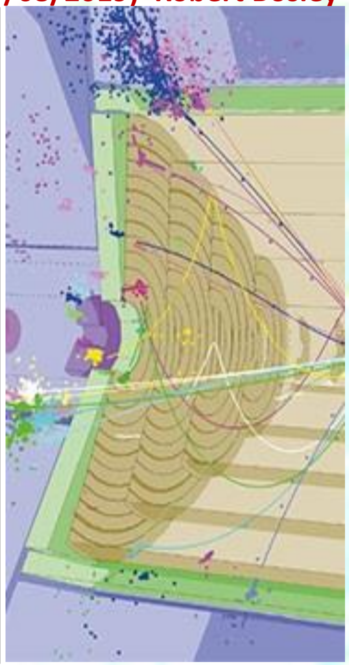


Silicon Calorimetry





CLICdp Meeting (27/08/2019) Robert Bosley



- **For single electrons, similar performance of Digital ECAL (with realistic channel threshold per pixel of 480e*) and Analogue ECAL (with perfect performance and full substrate signal per pad) up to around 300GeV (4T field without pile-up)**
- **Above this energy, saturation (more than one hit per $50\mu m \times 50\mu m$ pixel) starts to impact performance of digital compared with analogue ECAL**

***6 $\times$ σ assuming noise of $\sigma = 80e$**

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ALICE FoCal MAPS R&D

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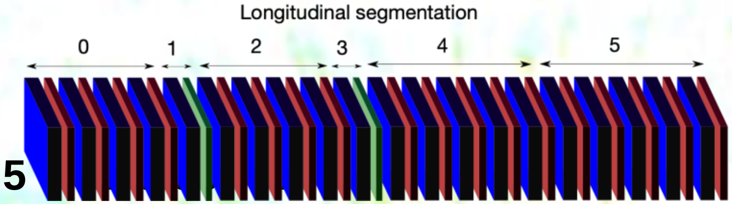
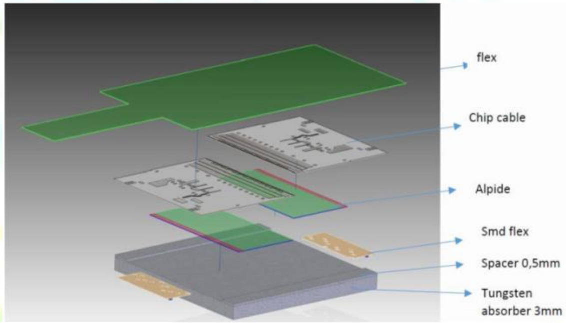
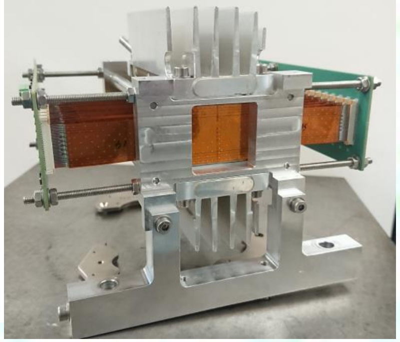
T. Peitzmann: "*R&D for the ALICE-FoCal Detector Proposal -Towards Truly High-Granularity Calorimeters*"; CERN Detector Seminar 25/10/19

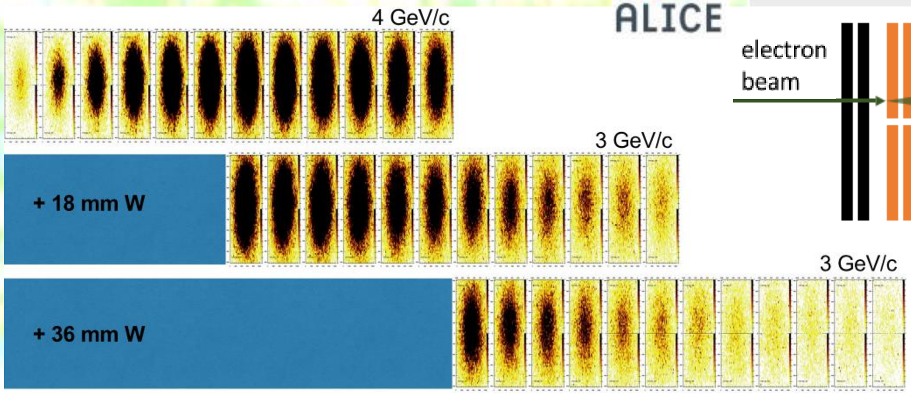
H. Yokoyama: "*Test beam performance of a digital pixel calorimeter*", T. Rogoschinski: "*Simulation of a SiW pixel calorimeter*": TIPP 26/5/21

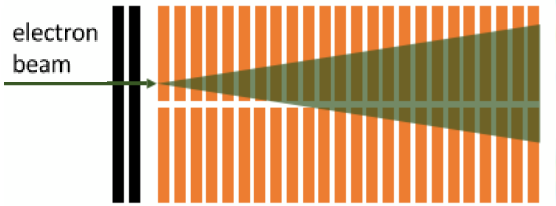


ALPIDE CMOS sensor based
3cm×3cm area 24 layer stack

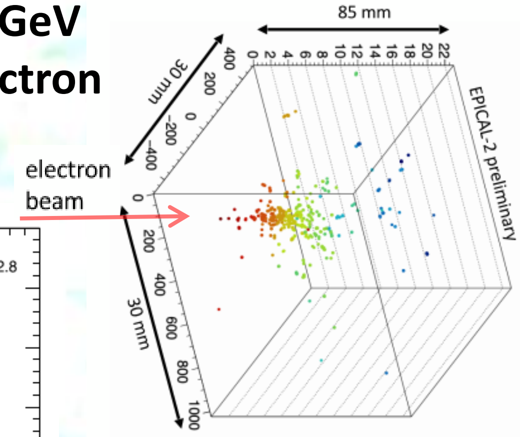


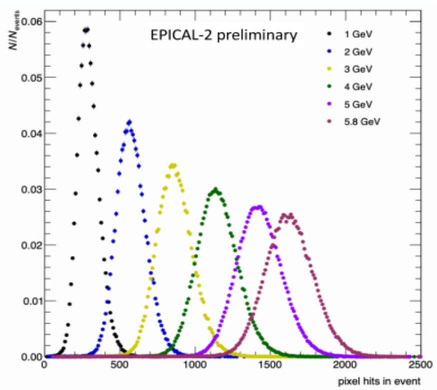


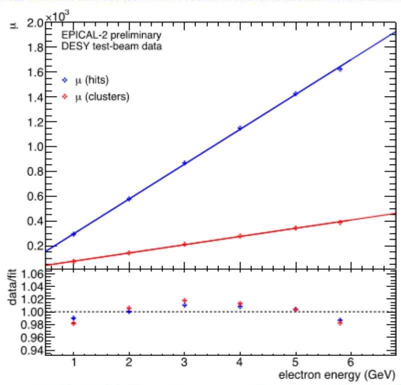


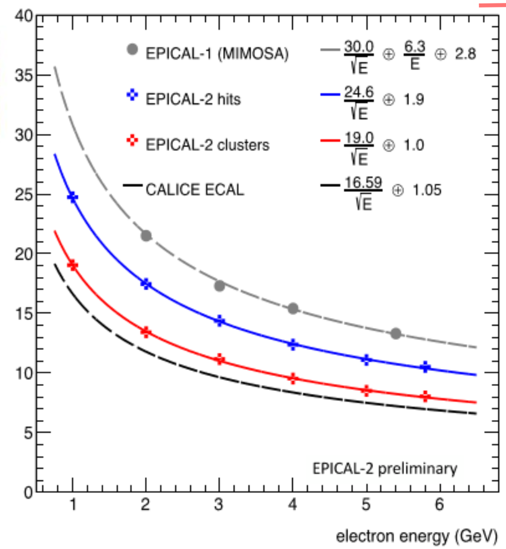


5 GeV Electron

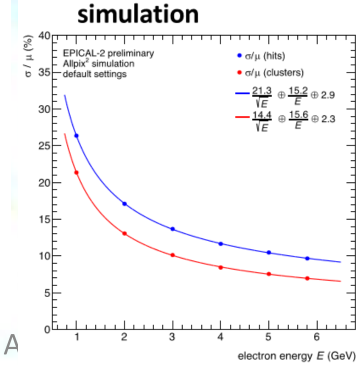








simulation



Small Diode CMOS Prototyping

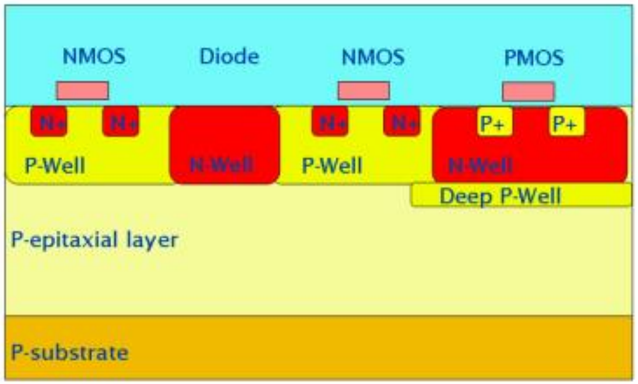
Birmingham Instrumentation Laboratory for Particle physics and Applications BILPA

UNIVERSITY OF BIRMINGHAM

Developments with STFC CMOS Sensor Design Group (CSDG) in technology also used for ALPIDE and MALTA developments by CERN

Walter Snoeys FCC workshop CERN, Jan 14, 2020

The INMAPS process: quadruple well for full CMOS in the pixel



STFC development, in collaboration with TowerJazz

Additional deep P-well implant allows complex in-pixel CMOS and 100 % fill-factor

New generation of CMOS sensors for scientific applications (TowerJazz CIS 180nm)

Also 5Gb/s transmitter in development

Sensors 2008 (8) 5336, DOI:10.3390/s8095336

https://iopscience.iop.org/article/10.1088/1748-0221/7/08/C08001/meta

https://iopscience.iop.org/article/10.1088/1748-0221/14/01/C01006/meta

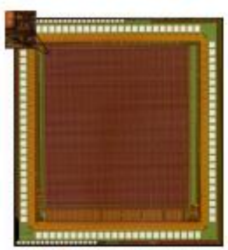
http://pimms.chem.ox.ac.uk/publications.php ...

courtesy of N. Guerrini, STFC

TPAC
ILC ECAL (CALICE)

50μm pixel

DECAL
Calorimetry

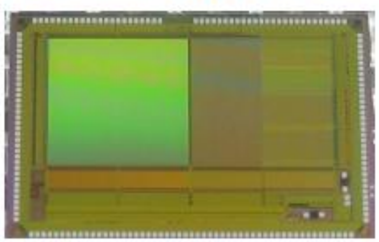


50μm pixel

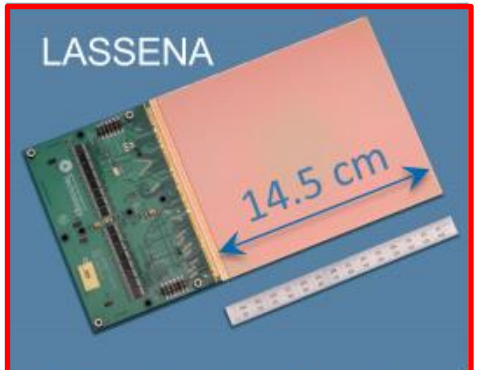
PIMMS
TOF mass spectroscopy

70μm pixel

CHERWELL
Calorimetry/Tracking



48 μm x 96 μm pixel



50μm pixel, waferscale

Also used for the ALPIDE (27 μm x 29 μm pixel) and MIMOSIS (CBM)

walter.snoeys@cern.ch

9

Applications of Large Format Sensors

Birmingham Instrumentation Laboratory for Particle physics and Applications (BILPA)

UNIVERSITY OF BIRMINGHAM

Developments with STFC CMOS Sensor Design Group (CSDG) in technology also used for ALPIDE and MALTA developments by CERN

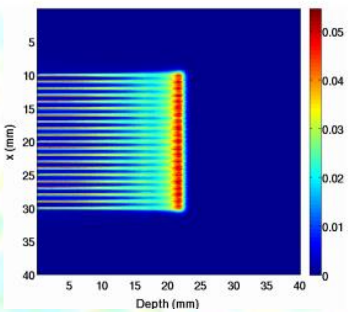
CSDG have also developed many applications of large format sensors for space, electron microscopy, x-ray detection and medical imaging.

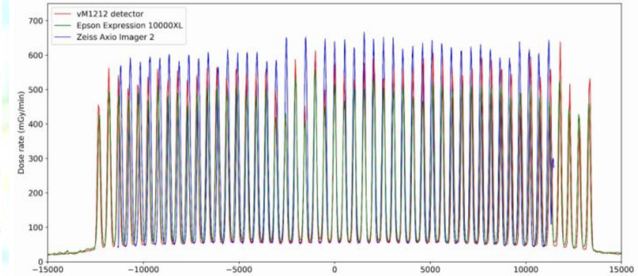
In radiotherapy, FLASH (2-40 Gy in less than 500ms) and Mini-beam or Micro-beam (sub mm) treatments currently very exciting as found to greatly improved sparing of healthy tissue (both x-ray and hadrons)

One recent example using the LASSENA senor shows resolution (contrast) better than film with fast (34fps) real time image

Needs further development
For use at hadron facilities

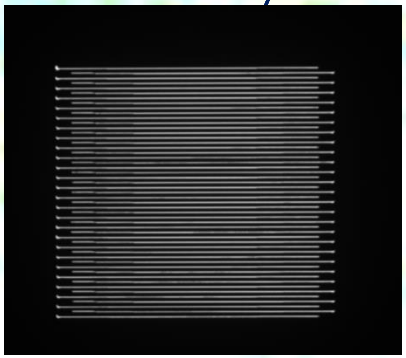
"Evaluation of a pixelated large format CMOS sensor for x-ray microbeam radiotherapy" Medical Physics, 2020

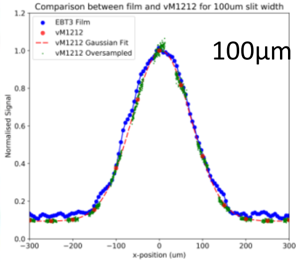




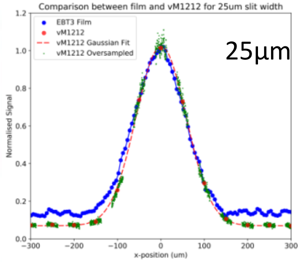
S. Flynn, T Price. (NPL and UoB)
225 kV, 1.65 Gy/min, Helmholtz Research Centre in Munich
https://doi.org/10.1002/mp.13971

Microbeam slit system

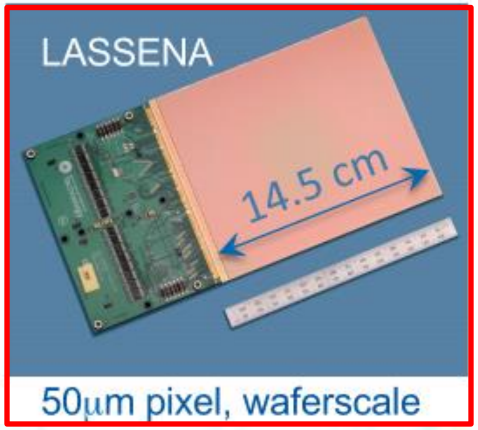




100μm



25μm



Small collection electrode development

- The small collection electrode design has a very small detector capacitance that allows to design a compact, low power FE → small pixels and low material
  - <5fC for small electrode vs. a few hundred fC for large electrode

Estimated power consumption of ITk full scale 2x2 cm^2 DMAPS

	MALTA	TJ-MONOPIX	LF-MONOPIX
Architecture	TJ Asynch.	TJ Synch.	LF Synch.
Coll. Elect.	Small	Small	Large
Pixel size	$36.4 \times 36.4\,\mu m^2$	$36.4 \times 40\,\mu m^2$	$50 \times 150\,\mu m^2$
Number of pixels	512×512	512×512	400×132
Matrix Analog Power	238 mW ($\sim 0.9\,\mu W$/pixel)	238 mW ($\sim 0.9\,\mu W$/pixel)	1000 mW ($\sim 18\,\mu W$/pixel)
Matrix Digital Power	12 mW ($\sim 0.05\,\mu W$/pixel)	240 mW ($\sim 0.9\,\mu W$/pixel)	80 mW ($\sim 1.5\,\mu W$/pixel)
Periphery Digital Power	267 mW	225 mW	225 mW
Total Expected Power	514 mW	703 mW	1305 mW

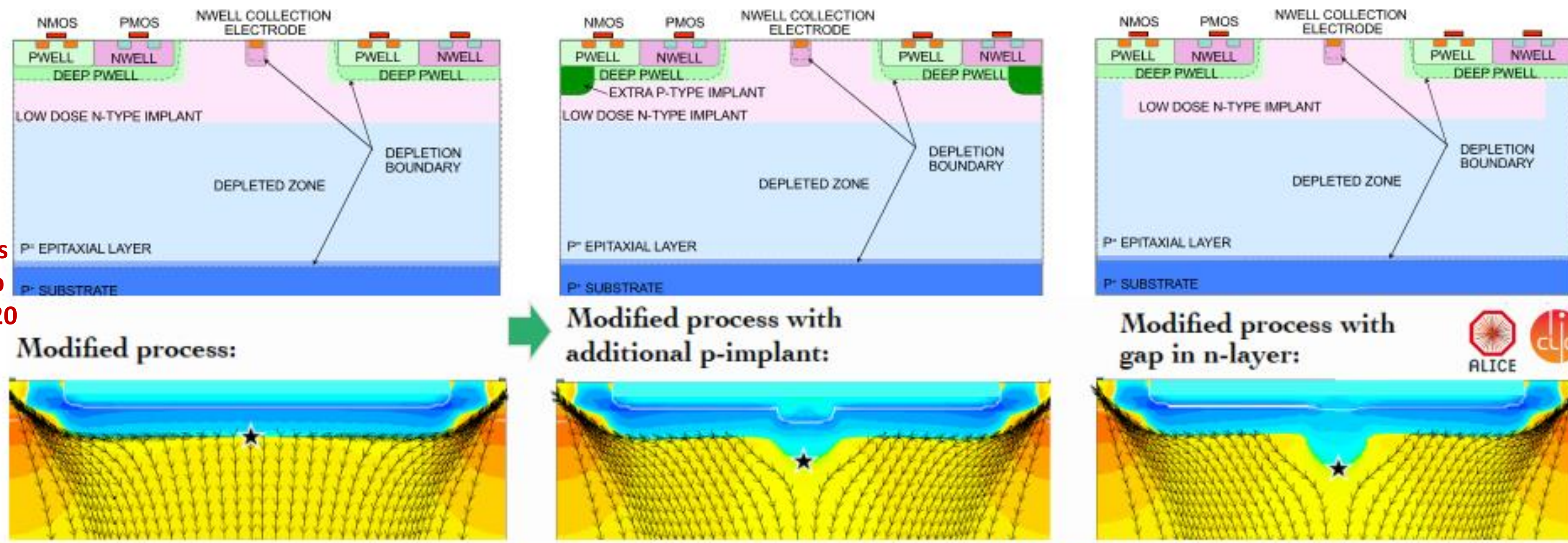
https://doi.org/10.1088/1748-0221/14/06/C06019

- Radiation-hardness is challenging, significant effort to develop process modifications (CERN/TJ collaboration)
- Different readout architectures explored for low power readout at high rate
  - MALTA: novel asynchronous architecture
  - TJ-MONOPIX: synchronous column drain architecture

CERN TJ Developments

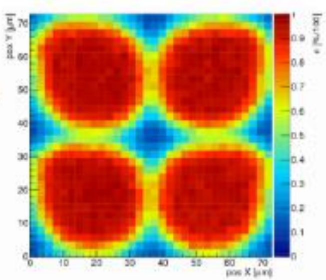
- **From ALPIDE, CERN has further developed the radiation hardness of the TJ process**

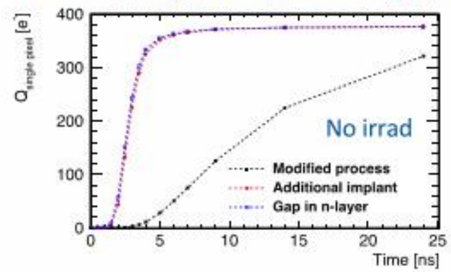
Walter Snoeys
FCC workshop
CERN, Jan 2020



Extra p-type implant or gap in the n-layer for improved lateral field

Efficiency drop at pixel edges after irradiation for 36.4 x 36.4 μm² pixel needs improvement
E. Schioppa et al, VCI 2019

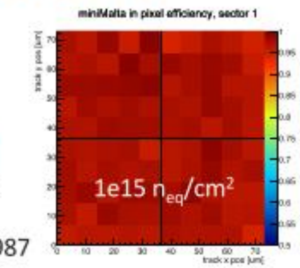




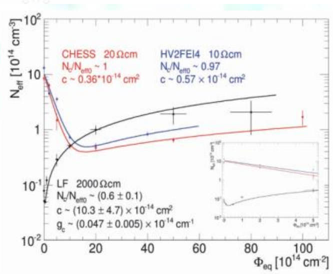
3D TCAD simulation
M. Munker et al. PIXEL2018

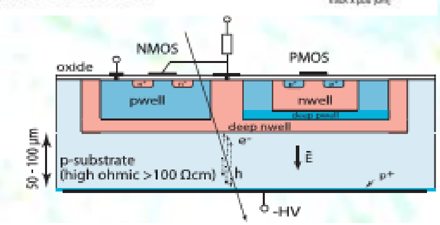
Significant improvement verified
Also encouraging results with Cz
H. Pernegger et al., Hiroshima 2019

M. Dyndal et al., arXiv:1909.11987



- **Similar results with other processes and designs**
- **Excellent for fast, full signal collection, as well as radiation hardness suitable for hadron colliders**

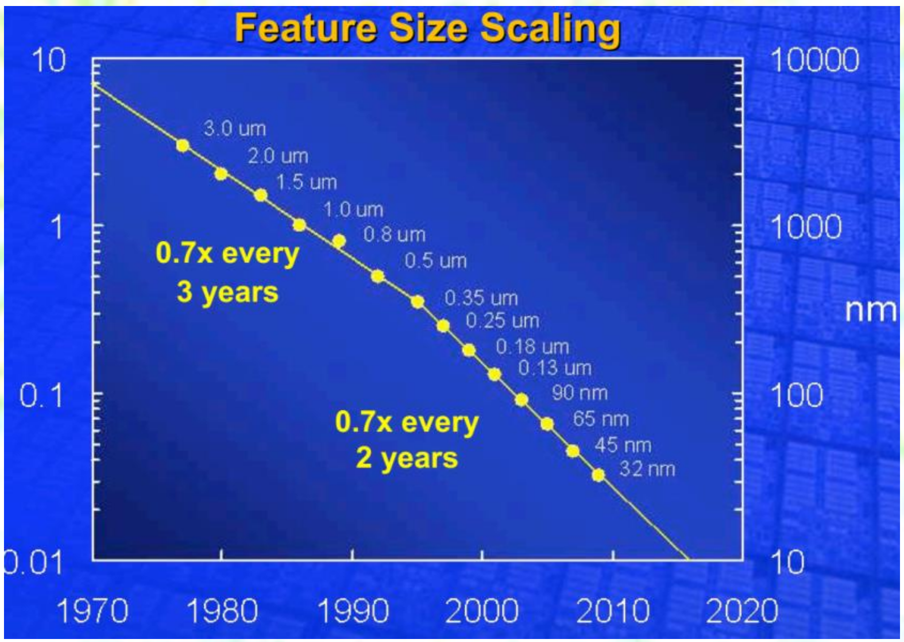




Garcia-Sciveres, M. & Wermes, N. A review of advances in pixel detectors for experiments with high rate and radiation. *Rep. Prog. Phys.* **81**, 066101 (2018).

More Observations on CMOS Costs

- Getting prices for commercial CMOS Imaging Sensors (CIS) not so easy, but entry costs (NRE, design, etc) are progressively higher with smaller feature size, so R&D prototyping expenses make it highly advantageous to have more common developments.
- Cost per transistor, rather than cost per area, tends to be what Moore's law scaling drives down most quickly (but we do not need *cutting edge*).

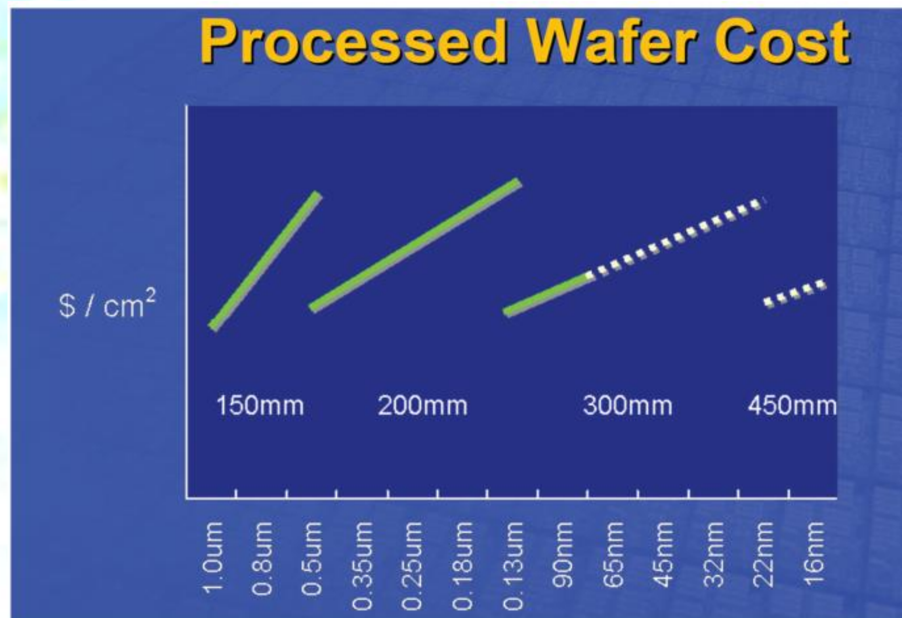


(Clearly for our purposes, we care about larger area, as well as greater functionality, unlike the main commercial drivers)

Measuring Moore's Law:
Evidence from Price, Cost, and Quality Indexes[1]

https://www.nber.org/chapters/c13897

Kenneth Flamm



Source: Holt (2005).

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Historical Development of Silicon Sensor Arrays

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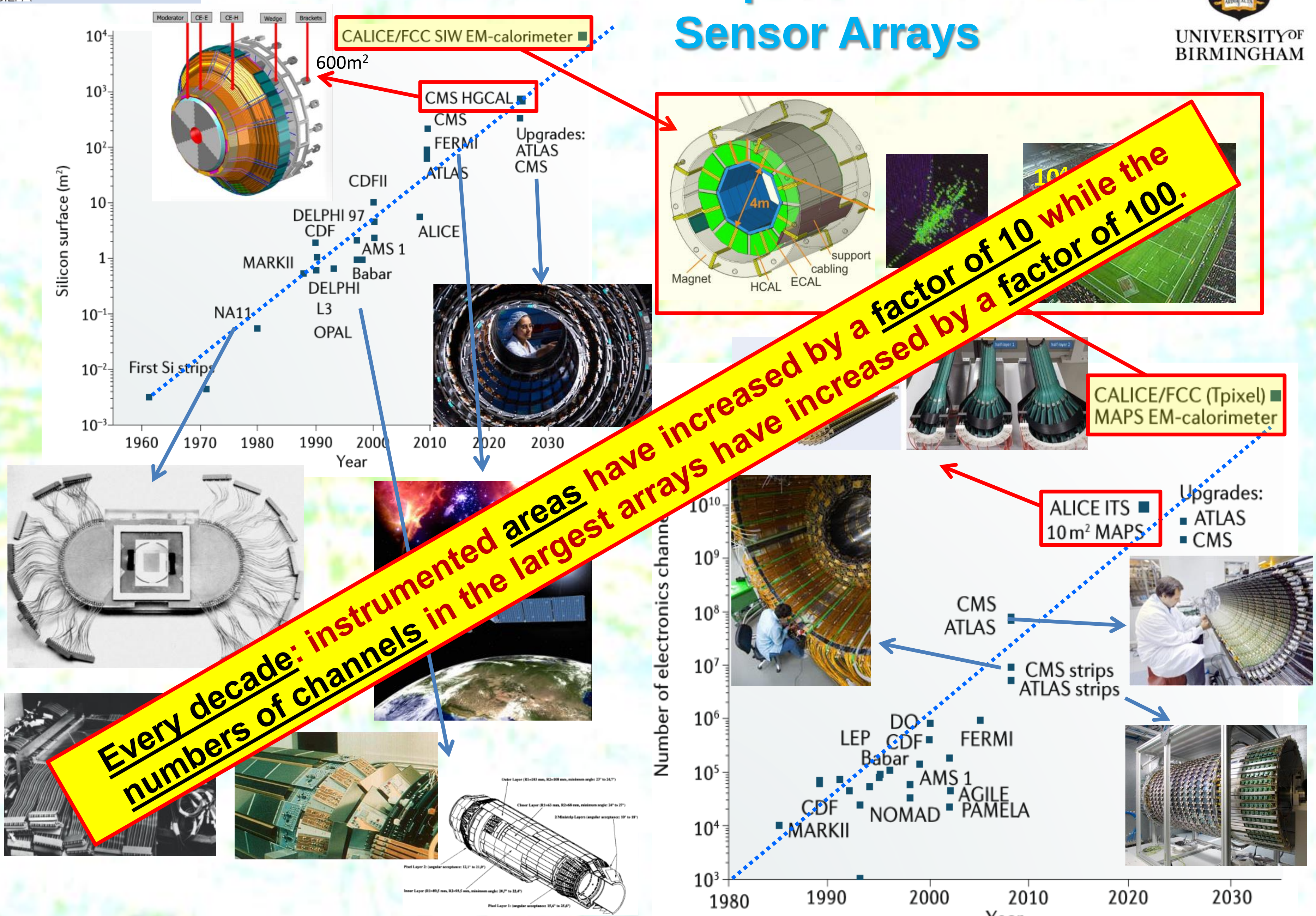
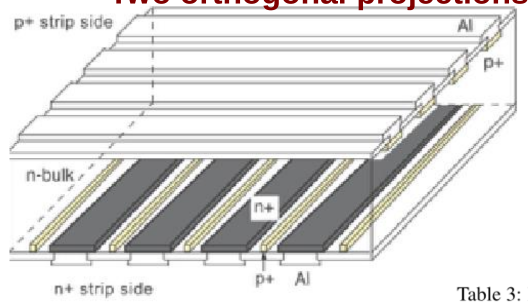


Historical Development of Silicon Sensor Arrays

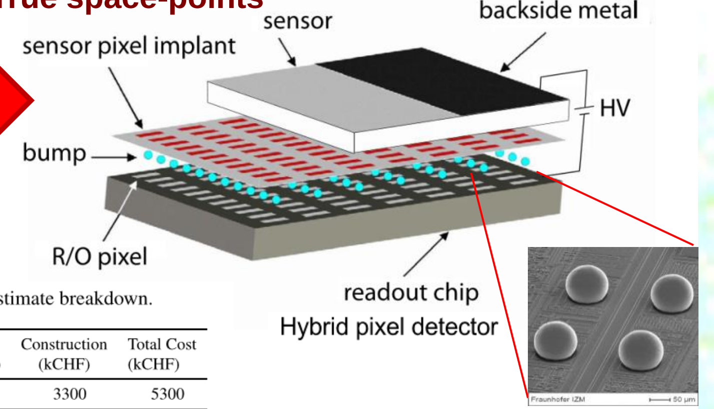
The highest channel count arrays are based on pixelated detectors. For **hybrid pixel sensors** connection to the electronics requires flip-chip technologies.

Two orthogonal projections

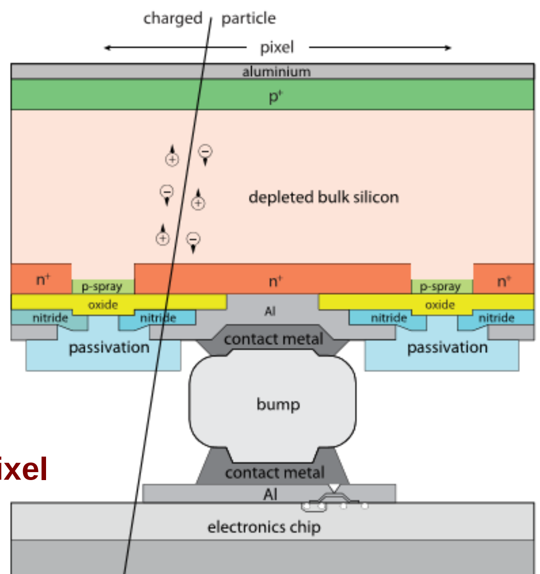


Double sided strip sensor

True space-points



Hybrid pixel detector

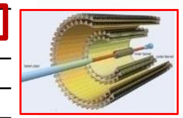


Hybrid Pixel Readout ASICs

Monolithic Active Pixel Detectors

Table 3: Project cost estimate breakdown.

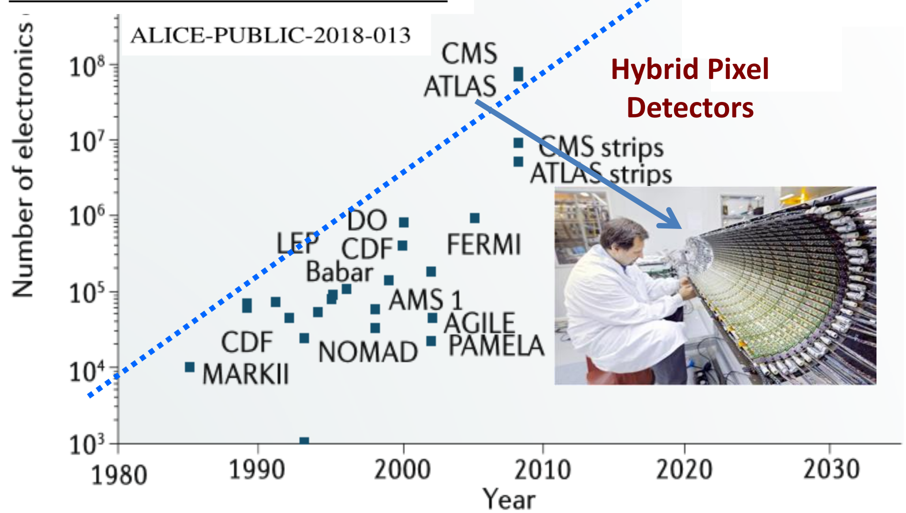
Item	R&D (kCHF)	Construction (kCHF)	Total Cost (kCHF)
Total	2000	3300	5300
Beampipe	600	900	1500
Pixel CMOS Sensors	700	700	1400
Sensor test	100	150	250
Thinning & dicing	200	300	500
Hybrid printed circuit	100	100	200
Mechanics	150	350	500
Assembly & test	50	200	250
Installation tooling	0	200	200
Air cooling	100	150	250
Services	0	100	100
Patch panels	0	150	150



CALICE/FCC (Tpixel)
MAPS EM-calorimeter

ALICE ITS
10 m² MAPS

Upgrades:
ATLAS
CMS

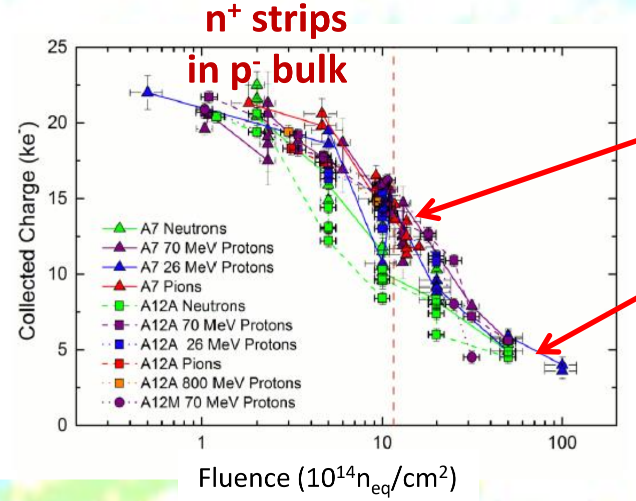


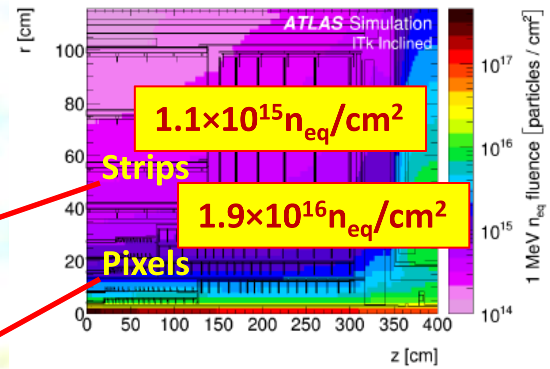
Hybrid Pixel Detectors

Minimum feature size	250nm	130nm	65nm
Example Read-out Hybrid Pixel Chips	ATLAS FE-I3 CMS Medipix	NA62 TDCPix ATLAS IBL FE-I4 LHCb VeloPix Medipix3RX TimePix3	CLICpix RD53A TimePix4
Typical hit data storage density capabilities	<1Gb/s/cm²	~5Gbp/s/cm²	40Gb/s/cm²
Output Bandwidth	40-160 Mb/s	0.3-1.2 Gb/s	2-20 Gb/s

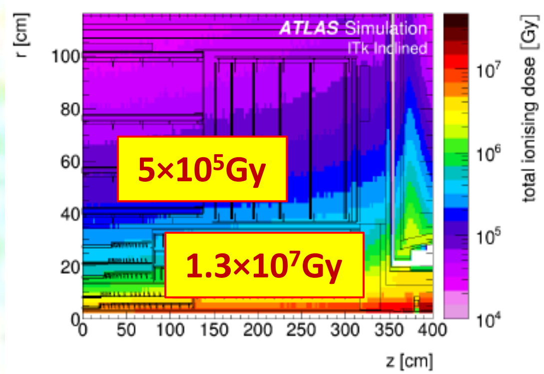
Radiation Effects: Sensors and Electronics

- Hybrid silicon detectors (pixels/strips) **signal** output drops with irradiation to very high doses





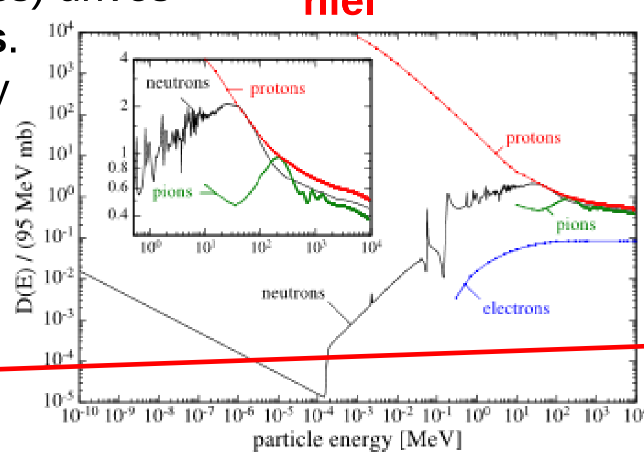
Example of radiation expected at High Luminosity LHC (HL-LHC) (Typically apply 1.5 safety factor)



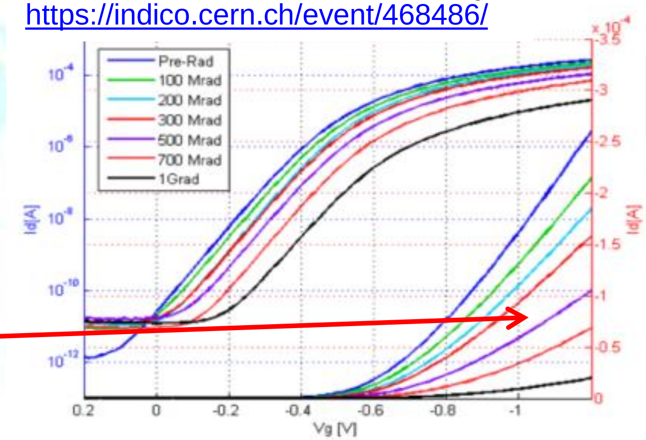
For Monolithic CMOS sensors initially target ~$10^{15}n_{eq}/cm^2$

- **Bulk damage** (measured in units of 1MeV equivalent neutrons/cm^2 (assuming scaling with **n**on-**i**onising **e**nergy **l**oss) drives the deterioration of **sensors.**
- For **microelectronics** worry about **t**otal **i**onising **d**ose.
- (65nm CMOS - **RD53**) can start to see significant deterioration above **500Mrad (5MGy)** ◊Many different effects◊

niel

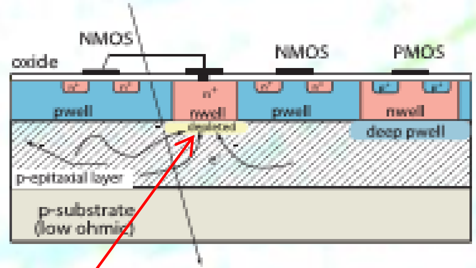


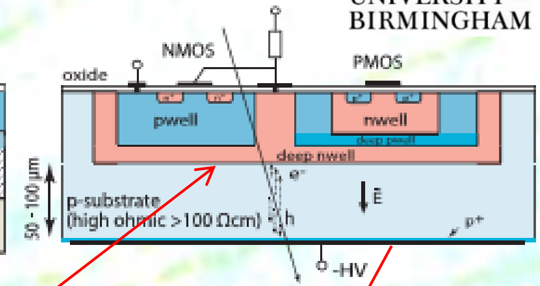
Federico Faccio: PMOS turn-on V_g
https://indico.cern.ch/event/468486/

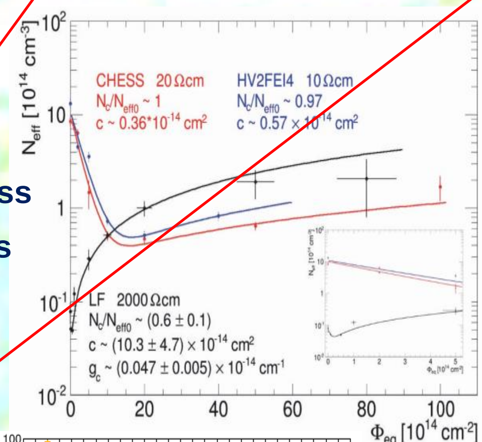


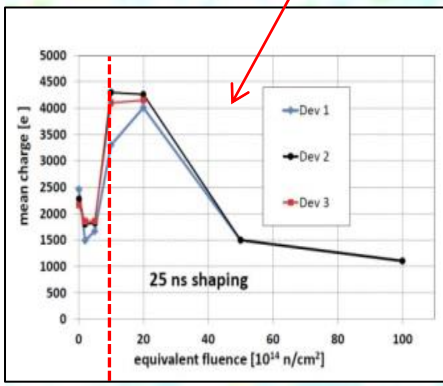
MAPS: HV/HR-CMOS Detectors

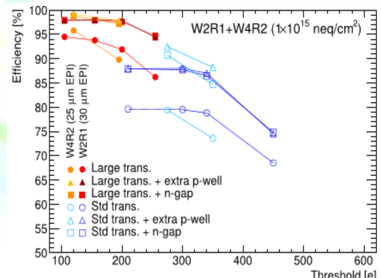
- **Commercial CMOS Image Sensors offer possible dramatic decrease in costs (Monolithic Active Pixel Sensors)**
- **MAPS can deliver very low power consumption at low R/O speeds, possibly <100mW/cm^2 i.e. simple water cooling**
  - **Ultra low material budget (cf ALICE ITS upgrade: <0.5% for inner layers, <1% for outer layers)**
  - **But these devices limited in speed and radiation hardness**
  - **Current and near future MAPS for heavy ion experiments**
    - **integration time up to 4μs (noise, electron diffusion)**
    - **radiation resistance up to few 10^{13} $n_{eq}cm^{-2}$**
- **Major developments in HV/HR-CMOS → deep depletion region with charge collection by drift not diffusion → huge improvements in collection speed and radiation hardness**
- **Can usually either have small collecting node (and therefore faster and low noise) but shallow charge collection or deplete from the deep n-well with larger signal produced in up to 100μm of silicon but higher capacitance (→more noise & slower)**

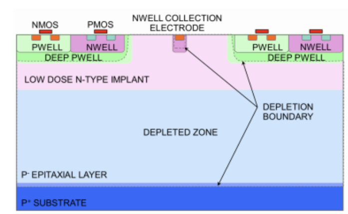








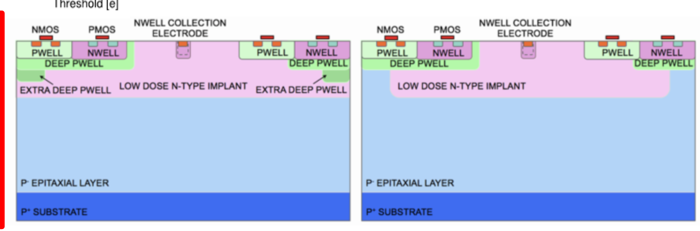




(a) The standard MALTA substrate

Modified process with junction in substrate

See presentation https://indico.cern.ch/event/803258/contributions/3582758/ by Heinz Pernegger



(b) The extra deep p-well (left) and n- gap (right) substrates