

ECFA Detector RoadMap

Alberto Cervelli

Assemblea di Sezione

What are ECFA Research and Development (DRD)

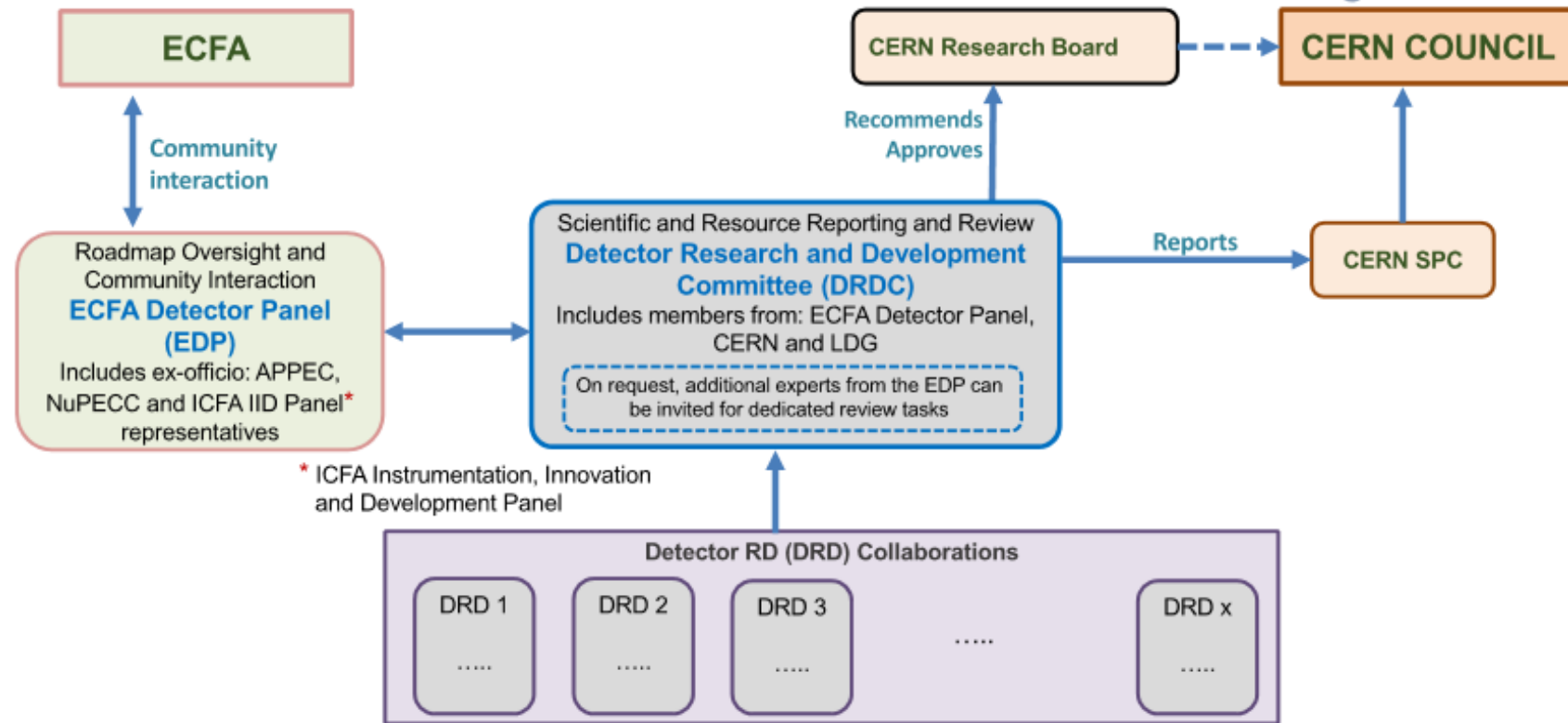
Organization involving European Union (ECFA) and hosted by CERN.

Goal: having a shared roadmap for future detector R&Ds

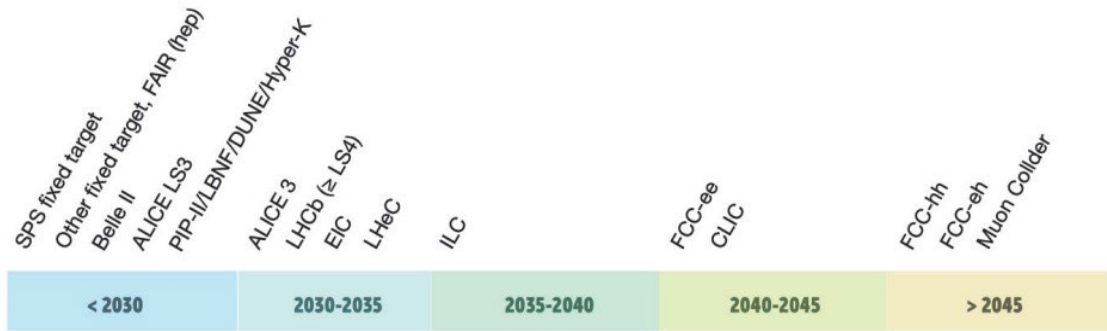
There is no financial autonomy for the Research and Development projects.

Past experiences (RD projects) worked in strong synergy with present and near-future experiments, allowing an easy flow of resources..

Today we do not have a strong push for upgrades which helped building a strong R&D program, however....



New Detectors for New Initiatives



Previous ECFA R&D projects (RD5*) strongly driven by LHC needs. Now there is no strong workhorse pushing for a focused R&D, however there are plenty of future projects brewing up both on accelerator and non-accelerator physics.

Different Physics goals call for different detectors, experience from current experiments can be brought to new projects and new fields.

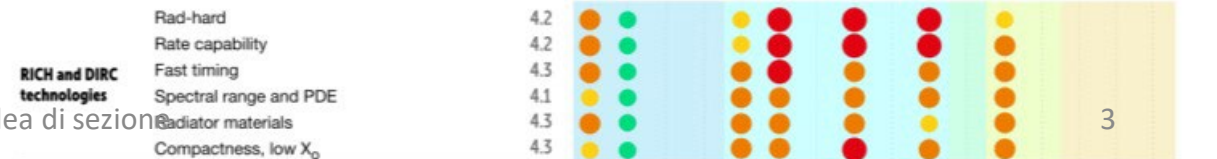


Different timelines for the new project will shape the R&D efforts in the coming years

“Technical” Start Date of Facility
 (This means, where the dates are not known, the earliest technically feasible start date is indicated - such that detector R&D readiness is not the delaying factor)

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Assemblea di sezione



What is in DRD projects

- DRD – 1 : Gas Detectors
- DRD – 2 : Liquid Detectors
- DRD – 3 : Solid State Detectors
- DRD – 4 : Particle Identification
- DRD – 5 : Quantum Technologies
- DRD – 6 : Calorimetry
- DRD – 7 : Electronics
- DRD – 8 : Integration

General Recommendations

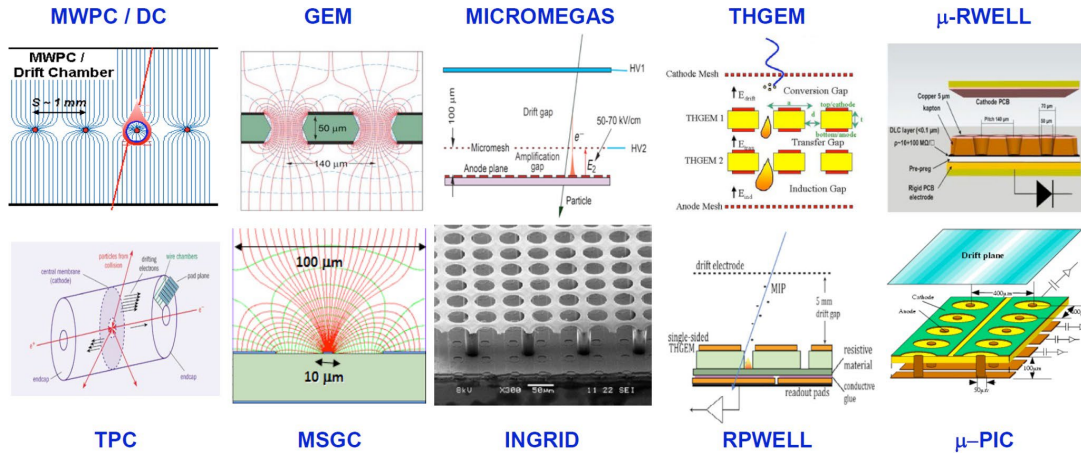
1. **Supporting R&D facilities** : coordinated infrastructure for Test-Beams, irradiation, large scale prototyping
2. **Engineering support for detector R&D**: electrical and mechanical engineering support for ever-growing integrated systems
3. **Specific software for instrumentation**: state-of-the-art R&D-specific software packages must be maintained and continuously updated
4. **International coordination and organisation of R&D activities**: connecting and involving all partners, there is a need to refresh the CERN RD programme structure and encourage new programmes for next generation detectors
5. **Distributed R&D activities with centralised facilities**: Establish in the relevant R&D areas a distributed yet connected and supportive tiered system for R&D efforts across Europe
6. **Establish long-term strategic funding programmes**: long-term strategic funding programmes to sustain both research and development of the multi-decade DRDTs
7. **“Blue-sky” R&D**: “Blue-sky” developments in particle physics have often been of broader application and had immense societal benefit.
8. **Attract, nurture, recognise and sustain the careers of R&D experts**: Training programs and an adequate number of positions with a sustained career in instrumentation R&D
9. **Industrial partnerships**
10. **Open Science**

Gas Detectors - DRD1

Best Choice for large detectors with low material budget:

→ Focus on speed: TOF systems

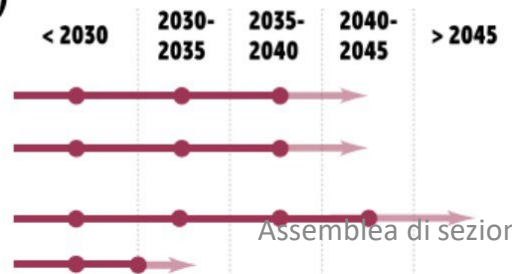
→ Focus on tracking: drift chambers, TPC



DETECTOR RESEARCH AND DEVELOPMENT THEMES (DRDTs) & DETECTOR COMMUNITY THEMES (DCTs)

Gaseous

- DRDT 1.1** Improve time and spatial resolution for gaseous detectors with long-term stability
- DRDT 1.2** Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes
- DRDT 1.3** Develop environmentally friendly gaseous detectors for very large areas with high-rate capability
- DRDT 1.4** Achieve high sensitivity in both low and high-pressure TPCs



Assemblea di sezione

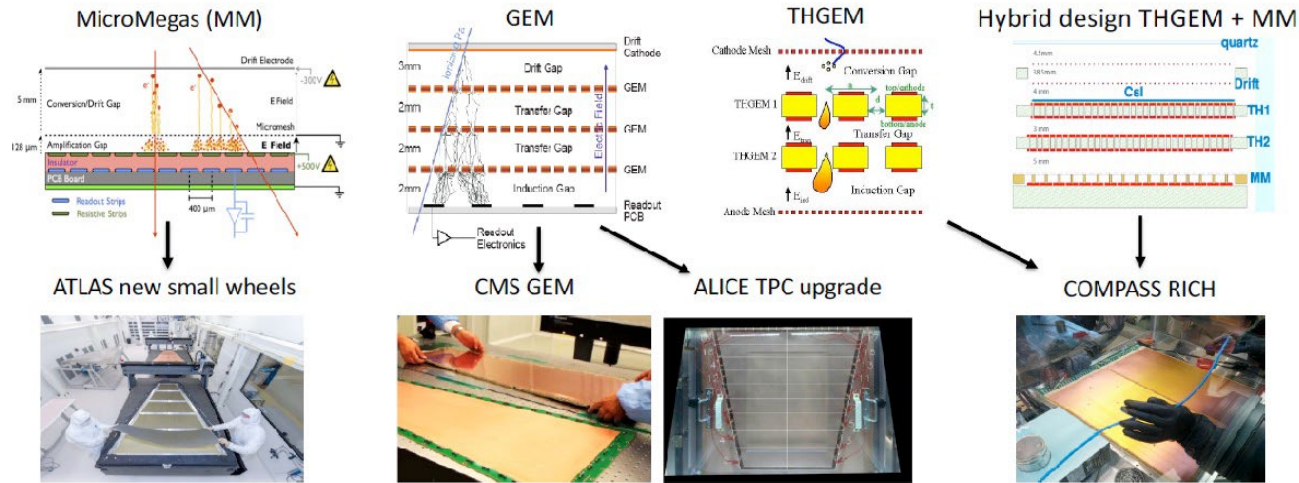
SPS fixed target (Aurifer, NA62+, NA63)
 FAIR (PANDA, CBM)
 Other fixed target (COMET, MUPE...)
 Neutrino near detectors (DUNE)
 Large ion dual-phase (DUNE)
 Light dark matter...²⁾
 LHCb (sLSc)
 ATLAS/CMS (sLSc)
 EIC
 LHeC
 R&D DM/Neutrino experiments³⁾
 R&D ion scale (nbb)
 ILC
 FCC-ee
 CLIC
 STCF
 FCC-hh
 FCC-eh
 Muon collider

	DRDT	< 2030	2030-2035	2035-2040	2040-2045	> 2045
Muon system	Rad-hard/longevity	1.1	●	●●	●	●●
	Time resolution	1.1	●	●	●	●
	Fine granularity	1.1	●	●	●	●
	Gas properties (eco-gas)	1.3	●	●	●	●
	Spatial resolution	1.1	●	●	●	●
Inner/central tracking with PID	Rad-hard/longevity	1.1	●●	●	●	●
	Low X ₀	1.2	●●	●	●	●
	IBF (TPC only)	1.2	●●	●	●	●
	Time resolution	1.1	●	●	●	●
	Rate capability	1.3	●	●	●	●
Preshower/Calorimeters	Rad-hard/longevity	1.1	●	●	●	●
	Low power	1.1	●	●	●	●
	Gas properties (eco-gas)	1.3	●	●	●	●
	Fast timing	1.1	●	●	●	●
	Fine granularity	1.1	●	●	●	●
Particle ID/TOF	Rad-hard (photocathode)	1.1	●●	●	●	●
	IBF (RICH only)	1.2	●●	●	●	●
	Precise timing	1.1	●	●	●	●
	Rate capability	1.3	●	●	●	●
	dE/dx	1.2	●	●	●	●
TPC for rare decays	Low power	1.4	●●	●	●	●
	Fine granularity	1.4	●●	●	●	●
	Large array/volume	1.4	●●	●	●	●
	Higher energy resolution	1.4	●●	●	●	●
	Lower energy threshold	1.4	●●	●	●	●

● 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

1) Large ton dual-phase (PandaX-4T, LZ, DarkSide-20k, Argo 200k, ARIADNE, ...)
 2) Light dark matter, solar axion, Cnbb, rare nuclei/sions and astro-particle reactions, Ba tagging
 3) R&D for 100-ton scale dual-phase DM/Neutrino experiments

Gas Detectors - DRD1



LHC upgrade led to a wide array of new developments for tracking, muon spectrometry and triggering

New development for TPC development (ALICE)

Timing with multi-gaps RPCs (ALICE)

Enabling technology for future detector Timing GEMs

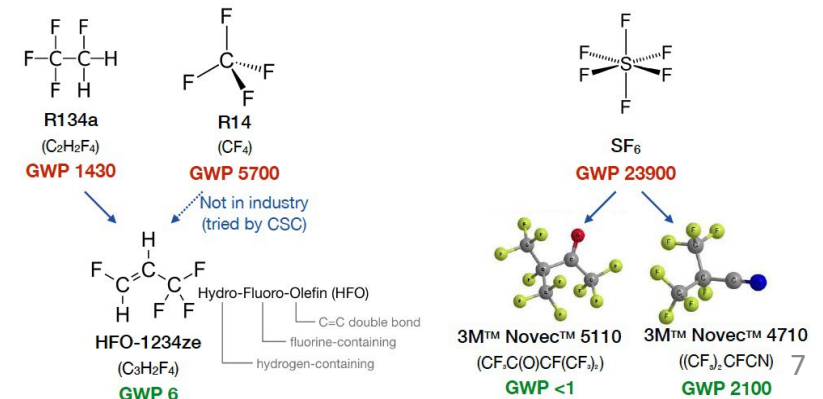
92% of emission at CERN related to large LHC experiments

Important R&D (ATLAS):
A lot of work especially in RPC community to search for alternative to C₂H₂F₄

Not an easy task to find new eco-friendly gas mixture for current detectors

Possible alternatives to GHG gases

New eco-friendly liquids/gases have been developed for industry as refrigerants and HV insulating medium... ionisation properties in particle detection not well known



Liquid Detectors - DRD2

Many detectors in advanced design phases will use liquid detectors, both in large- and small-scale experiments

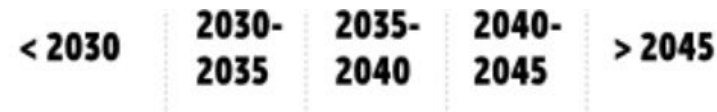
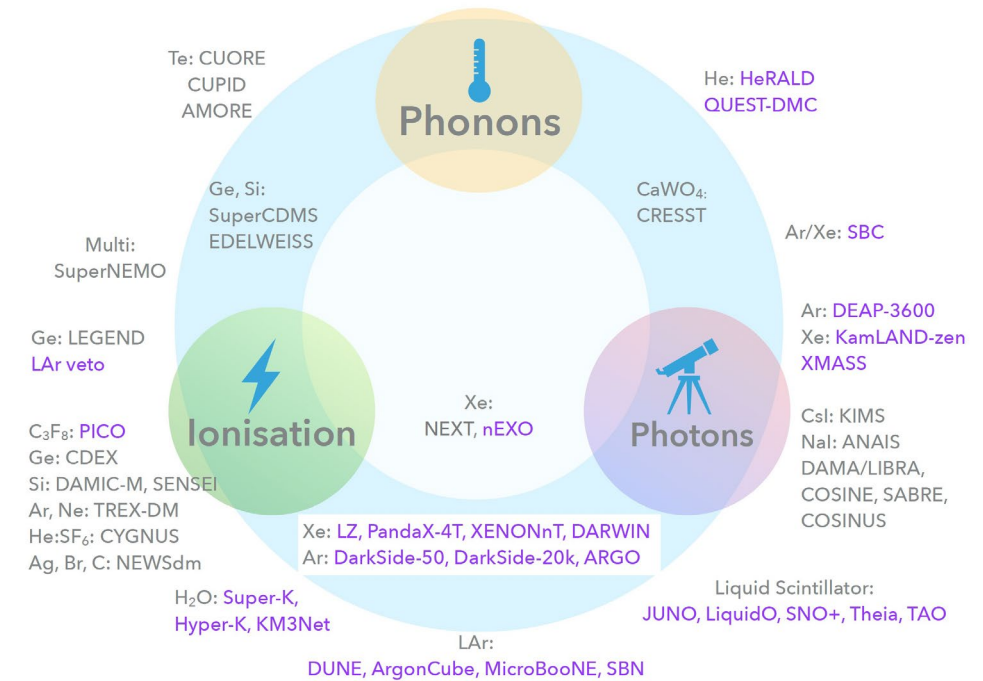
Underground Dark Matter Experiments – small and rare signals

R&D for multi-ton scale noble liquids:

Target doping and purification

Detector components radiopurity and background mitigation

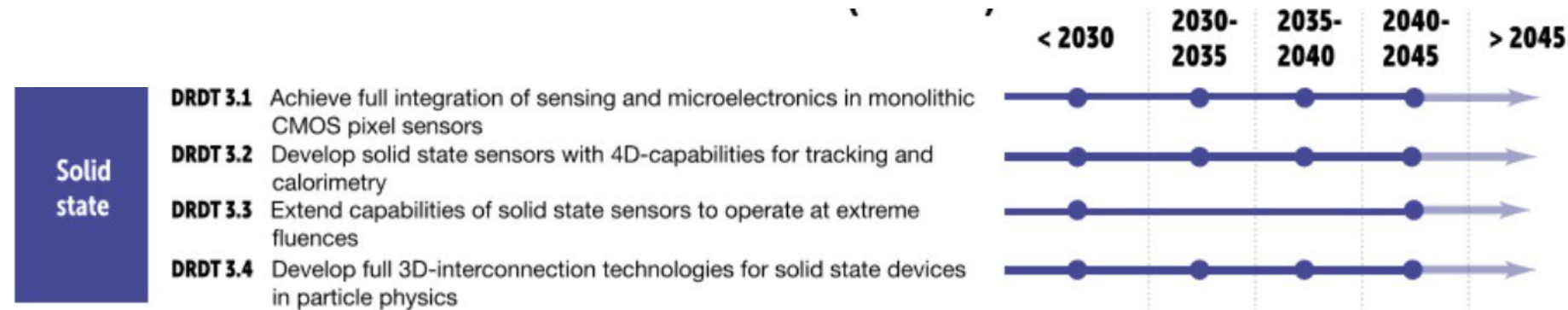
New readout technologies for liquid detectors



- DRDT 2.1** Develop readout technology to increase spatial and energy resolution for liquid detectors
- DRDT 2.2** Advance noise reduction in liquid detectors to lower signal energy thresholds
- DRDT 2.3** Improve the material properties of target and detector components in liquid detectors
- DRDT 2.4** Realise liquid detector technologies scalable for integration in large systems

R&D central for new experiments, difficult to foresee the timeline for a longer term

Solid State Detectors - DRD3



Fun Fact: **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**

Solid state detector now used more and more in Calorimetry and TOF detectors

Main Challenges for Future R&D:

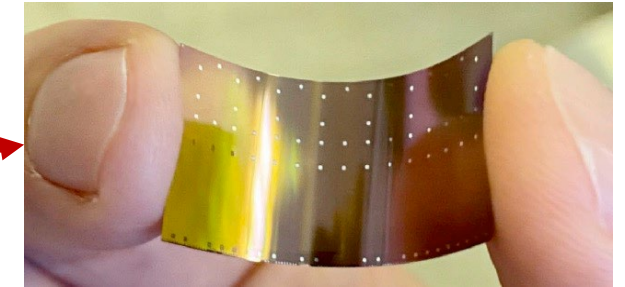
- **Vertex detectors with low material budget** (Target per layer spatial resolution of $\leq 3 \mu\text{m}$ and thickness $\leq 0.05\% X_0$) (FCC-ee)
- **affordable sensors** with low mass, high resolution, **low power** (FCC-hh, large area detectors)
- **Large area and granular devices for calorimeters**
- Detectors with **ultra-fast timing** ($O(10-100 \text{ ps})$) for PID, TOF

Solid State Detectors - DRD3 - Tracking

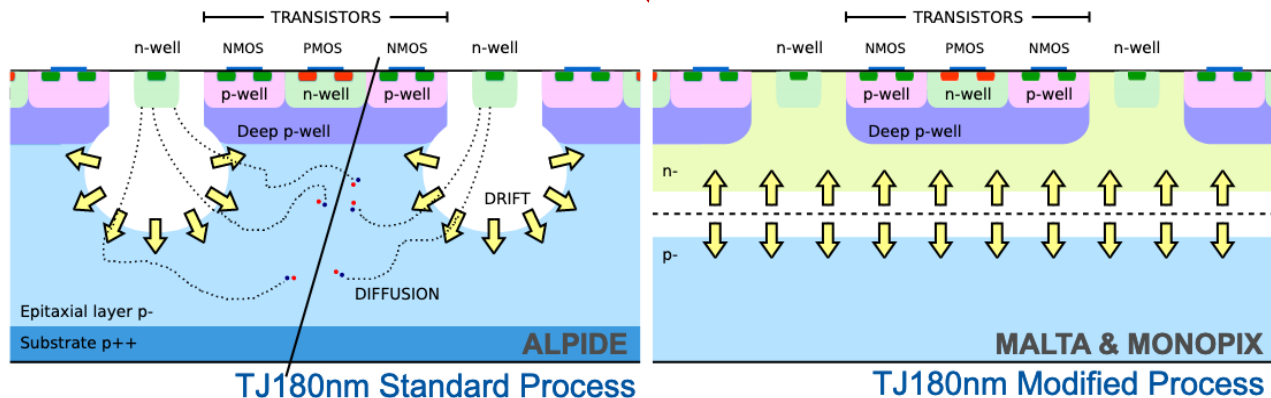
2 (+1) Great development paths for different physics goals:
 → radiation hard detectors with high spatial resolution (FCC-hh)

→ Monolithic CMOS for low material budget and large area detector

→ Radiation hard monolithic detectors



Three fully cylindrical, wafer-sized layers based on curved ultra-thin sensors (20-40 μm), air flow cooling
 Very low mass, < 0.02-0.04% per layer



Telescope → 3 μm track resolution achieved

Up to 97% efficiency after fluence of 10^{15} n_{eq}/cm²

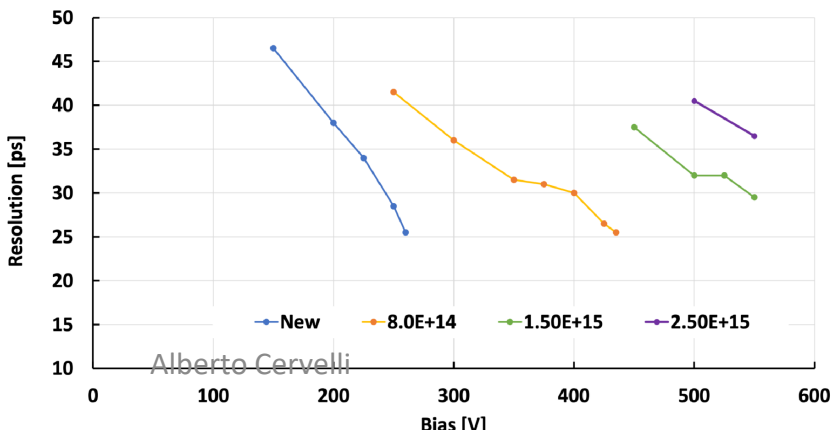
Solid State Detectors - DRD3 – Timing

4D tracking is getting more and more reliable: first large area detector should be ready in the near future

LGAD produced by FBK (and other producers).

Crucial for high pile-up environments, such as FCC-hh and future hadronic facilities

FBK 45-micron UFSD3.2 W13

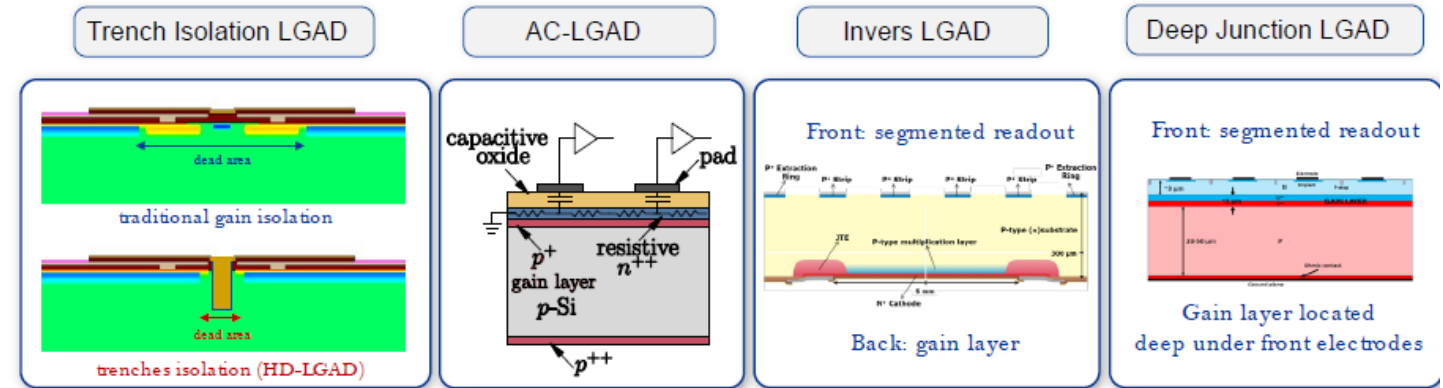


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LGAD: Fill factor & performance improvements



- Two opposing requirements:
 - Good timing reconstruction needs homogeneous signal (i.e. no dead areas and homogeneous weighting field)
 - A pixel-border termination is necessary to host all structures controlling the electric field
- Several new approaches to optimize/mitigate followed:



Concepts simulated, designed, produced and tested in 2018/19

..new concept 2020

Development stemming from RD50 (involvement from Bologna - ALICE)

Future goals:
 Improve timing, fill factor, radiation hardness, charge drift simulation and knowledge

Particle Identification - DRD4

PID methods: dE/dx, TOF, Cherenkov light detection

→ Challenges for **SiPMs**: high dark count rate and moderate radiation hardness prevented their use in RICH detectors where single photon detector required at low noise

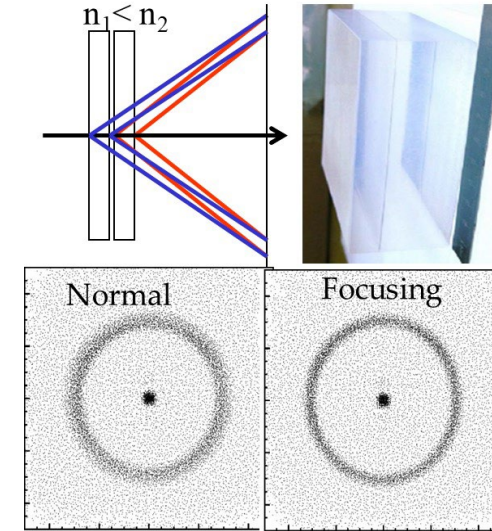
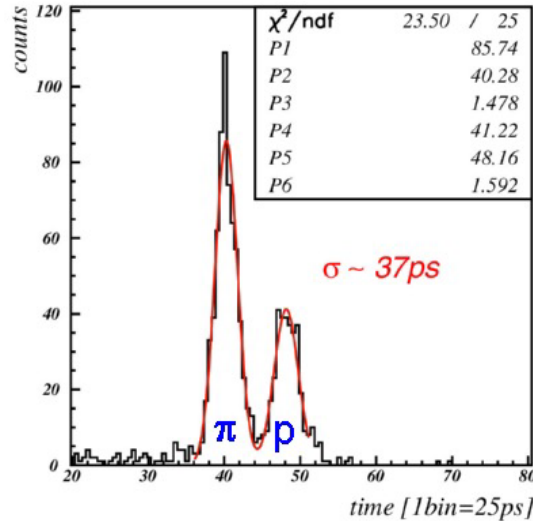
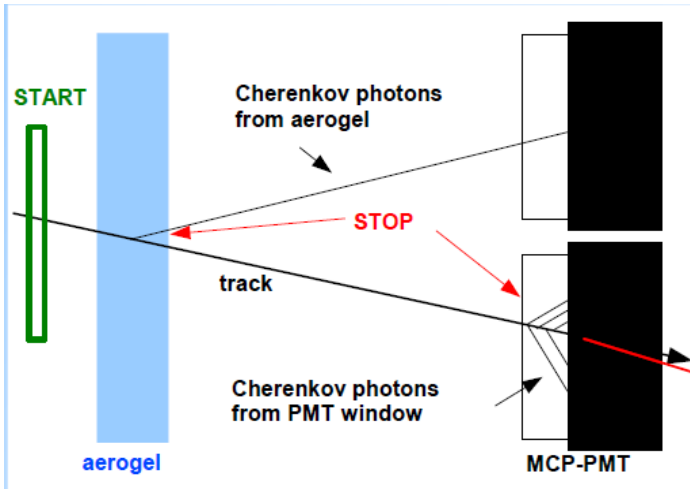
→ Challenges for **MCP-PMTs** reduce price and sensitivity to B fields, similarly **Large-Area Picosecond Timing Detectors** (LAPPD) promising, but need higher granularity and pixellation



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Particle Identification - DRD4

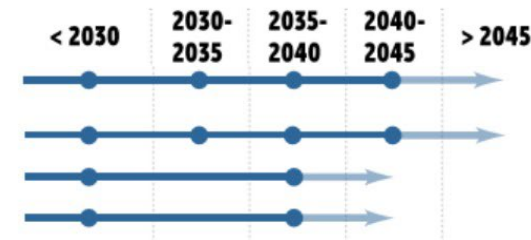


RICHes with proximity focusing: thin radiator (liquid, solid, aerogel) and **low momenta**

Time-Of-Flight (TOF) detectors: use prompt Cherenkov light, **fast gas detector**

RICHes with focalisation: extended radiator (gas), **high momenta**

- DRDT 4.1** Enhance the timing resolution and spectral range of photon detectors
- DRDT 4.2** Develop photosensors for extreme environments
- DRDT 4.3** Develop RICH and imaging detectors with low mass and high resolution timing
- DRDT 4.4** Develop compact high performance time-of-flight detectors

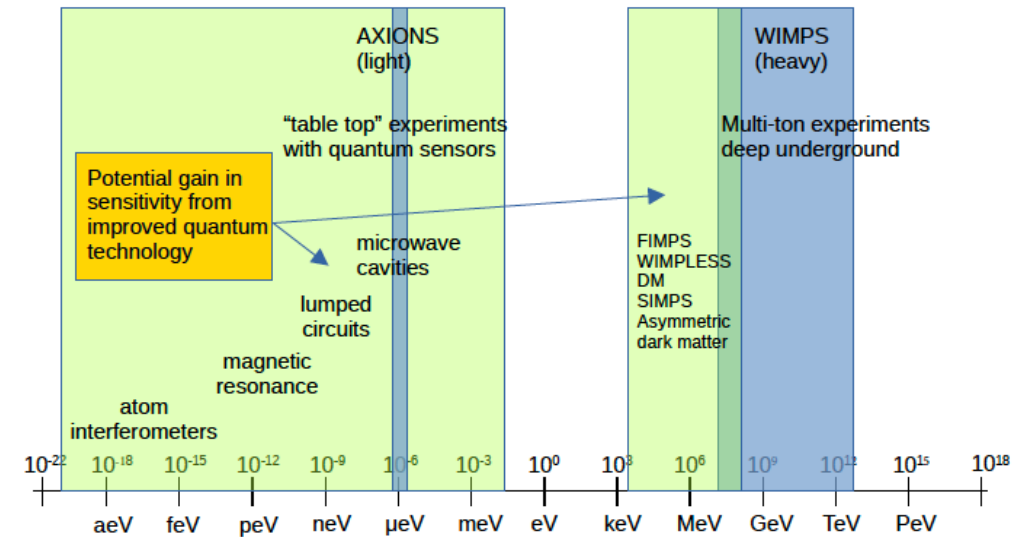


Quantum Technologies -DRD5

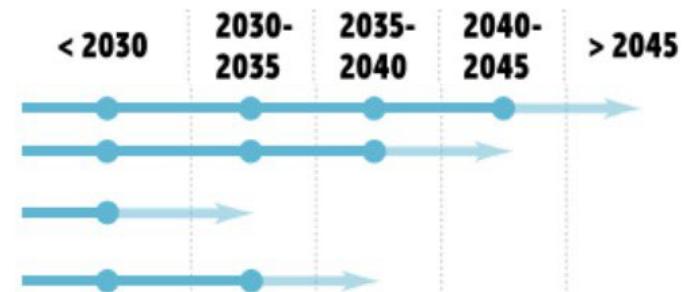
Rapidly emerging area of technology development to study fundamental physics

Use quantum systems to improve measurement sensitivity holds great promise

Many different sensor and technologies being investigated: clocks and clock networks, kinetic detectors, spin-based, superconducting, optomechanical sensors, atoms/molecules/ions, interferometry, ...



- | | | |
|----------------|-----------------|---|
| Quantum | DRDT 5.1 | Promote the development of advanced quantum sensing technologies |
| | DRDT 5.2 | Investigate and adapt state-of-the-art developments in quantum technologies to particle physics |
| | DRDT 5.3 | Establish the necessary frameworks and mechanisms to allow exploration of emerging technologies |
| | DRDT 5.4 | Develop and provide advanced enabling capabilities and infrastructure |



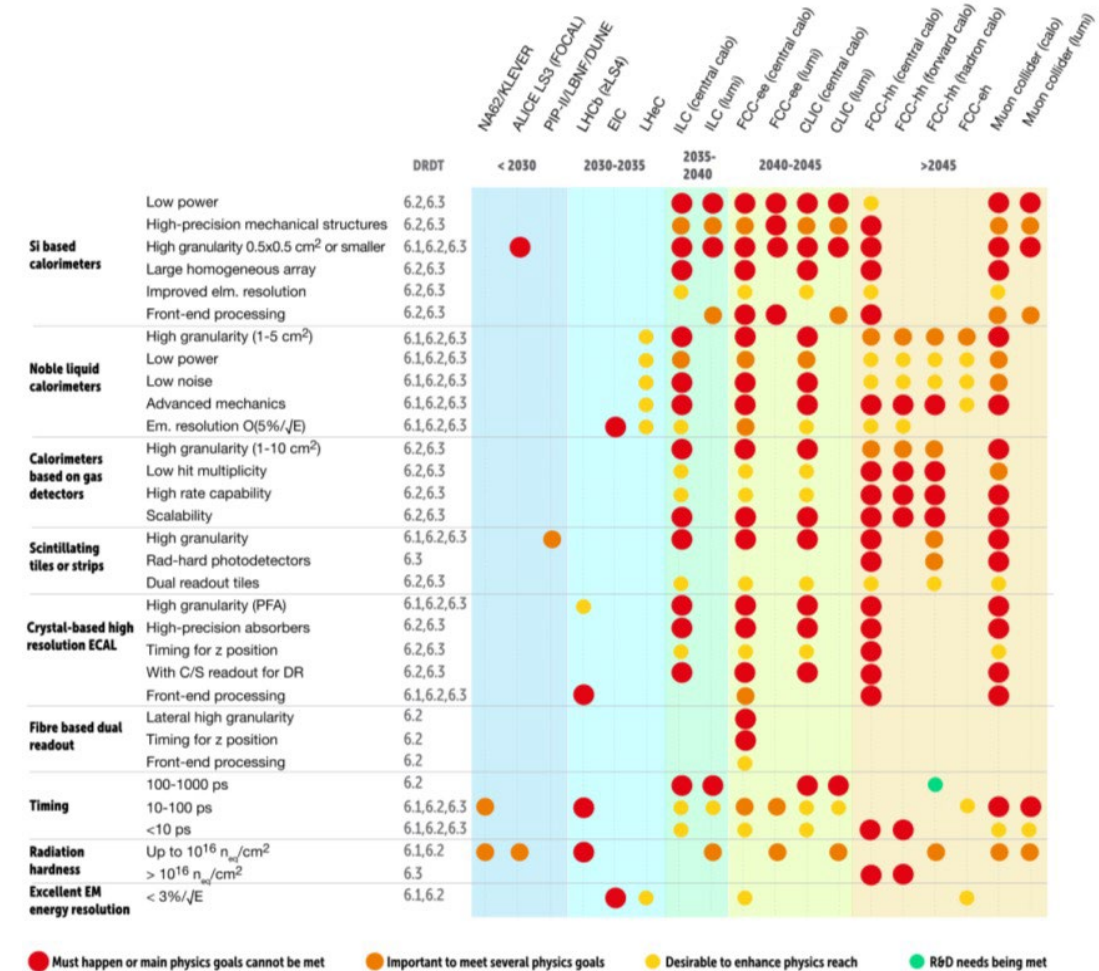
Calorimetry - DRD6

The enhanced electromagnetic energy and timing resolution most relevant in next decade for upgrades of ALICE and LHCb.

Particle Flow based on high granularity calorimeters:

- Dual-readout (e.g. DREAM/RD52 Collaboration, FCC-ee IDEA)
- High granularity LAr/LKr: LAr proven technique but high granularity challenging
- Finely segmented crystals
- Particle Flow based “tracking calorimeter” concept with very fine sense element segmentation

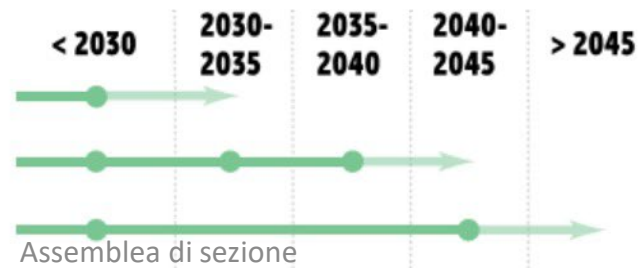
Extreme radiation hardness and pile-up rejection (FCC-hh)



Calorimetry

- DRDT 6.1** Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution
- DRDT 6.2** Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods
- DRDT 6.3** Develop calorimeters for extreme radiation, rate and pile-up environments

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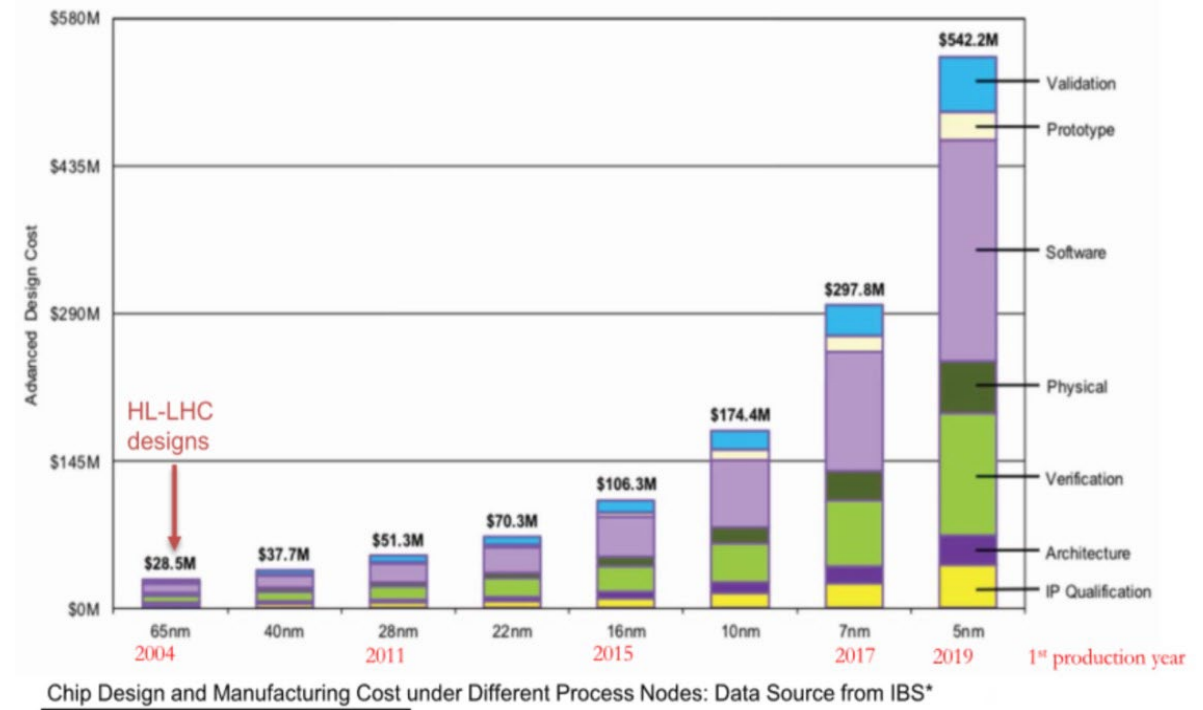
Electronics - DRD7

Main challenges:

- precision timing (ToF; 4D tracking),
- High granularity and resolution imply a cost in terms of data handling, processing, complexity and power.
- Low consumption electronics → no need for cooling

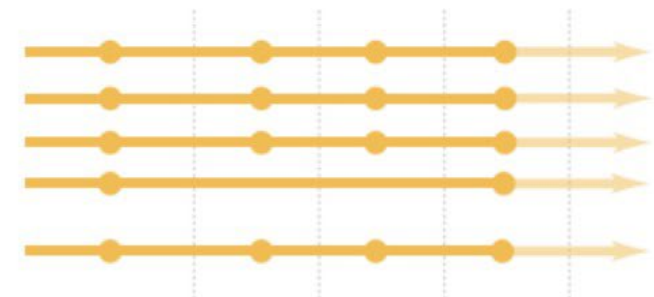
Need latest advances in commercial microelectronics and high-speed links

specific needs for HEP in e.g. radiation hardness or operation in magnetic fields with HEP at best a niche low volume market
 → Long time to develop radiation



Electronics

- DRDT 7.1** Advance technologies to deal with greatly increased data density
- DRDT 7.2** Develop technologies for increased intelligence on the detector
- DRDT 7.3** Develop technologies in support of 4D- and 5D-techniques
- DRDT 7.4** Develop novel technologies to cope with extreme environments and required longevity
- DRDT 7.5** Evaluate and adapt to emerging electronics and data processing technologies



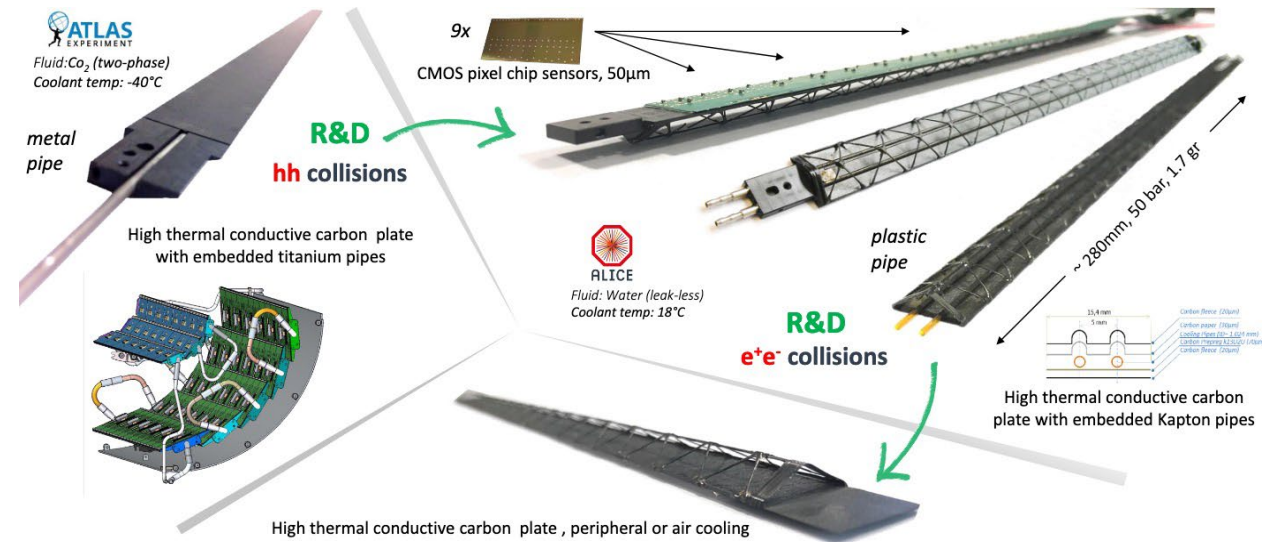
Integration – DRD 8 [Includes Luminometry]

Investigation of novel superconductors for magnet systems as well as support of expert design capabilities and modelling software for future experiments is vital.

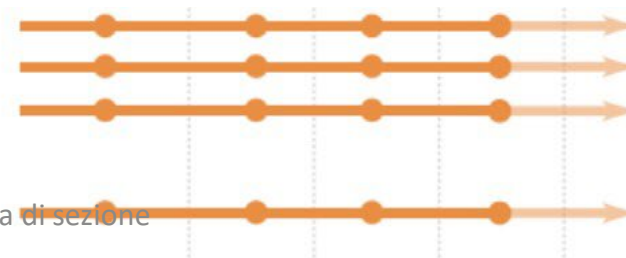
Cooling technologies for cryogenics and low-mass heat removal from on-detector electronics and semiconductor sensors require dedicated R&D activities.

Integration Ultra low mass, stable, precision mechanics and machine detector interface design are major topics

Monitoring for environmental radiation and beam aspects



- DRDT 8.1** Develop novel magnet systems
- DRDT 8.2** Develop improved technologies and systems for cooling
- DRDT 8.3** Adapt novel materials to achieve ultralight, stable and high precision mechanical structures. Develop Machine Detector Interfaces.
- DRDT 8.4** Adapt and advance state-of-the-art systems in monitoring including environmental, radiation and beam aspects



Opportunities

- Many R&D projects are already ongoing in Bologna! We should join the new R&D projects bringing our own expertise while seeking for synergies and collaborations with other groups working on similar developments
- Lots of different areas of expertise are already available, together with a great amount of infrastructures and instrumentation.
- The Technical and Technological areas of Bologna are already involved and well prepared for new and difficult challenges.
- Despite not having a focused project for this R&D efforts, the development of new detectors is crucial for any new project, and so we need to jump on this opportunity in order to be in the best shape to have leading roles in the future

Conclusions

- Bologna is involved in several R&D developments already. These activities should be reflected also in the new DRDs.
- The new DRDs might provide synergies and collaborations with other groups.
- We should participate to the formation of DRD groups and shape them such that they reflect our ongoing interests
- INFN has ongoing activities in basically all the DRD groups and in the general recommendations. It is therefore important to properly coordinate the various contributions to make sure that INFN' strong role in detector R&D is recognised.