European R&D Roadmaps

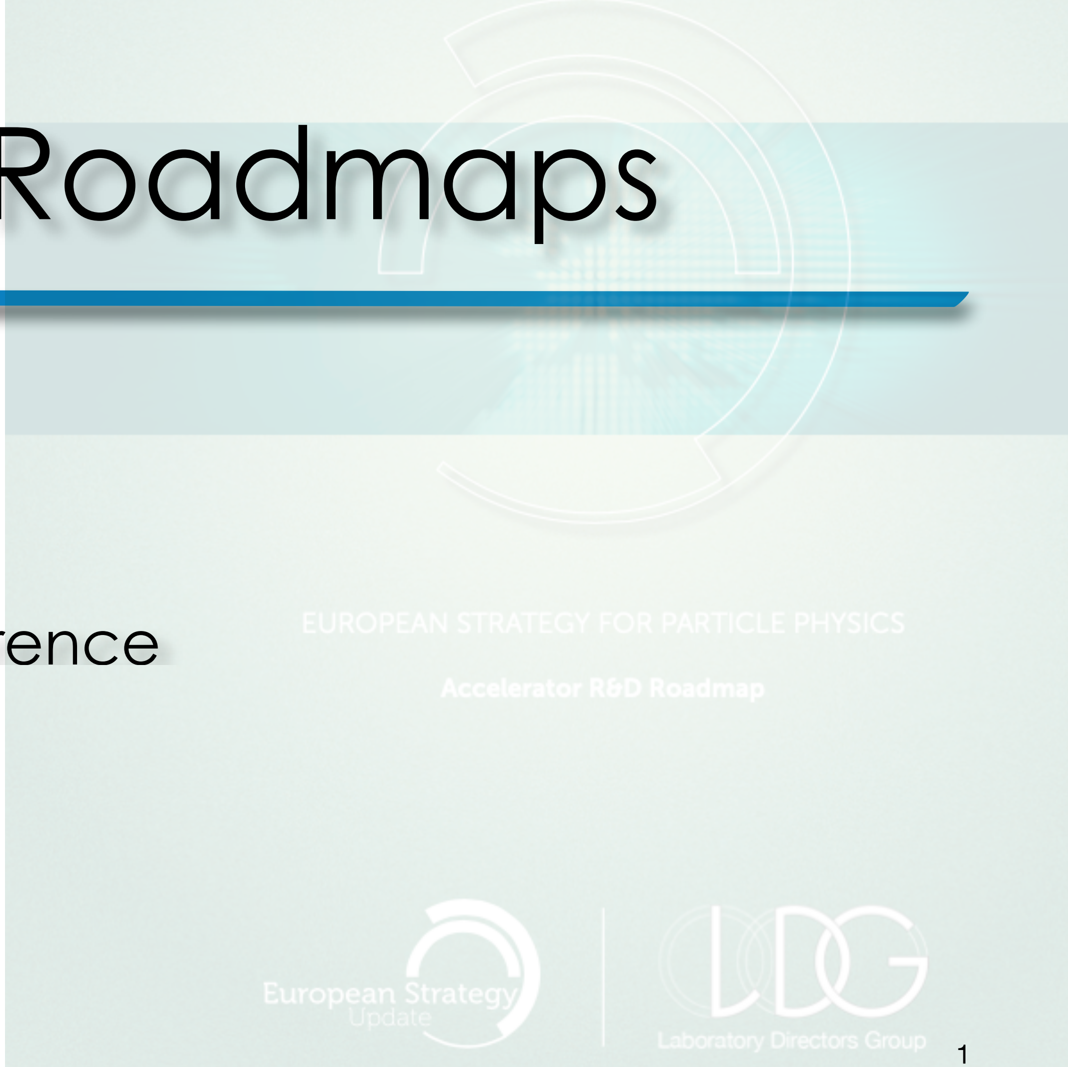
Iacopo Vivarelli
University of Sussex

IoP 2022 - Joint APP/HEPP Conference

See also:
P. Allport - Detector R&D Roadmap - Plenary ECFA
D. Newbold - Accelerator R&D Roadmap - Plenary ECFA
S. Kühn - Overview of detector R&D - Lepton-Photon 2021

THE 2021 ECFA DETECTOR
RESEARCH AND DEVELOPMENT ROADMAP

The European Committee for Future Accelerators
Detector R&D Roadmap Process Group



EUROPEAN STRATEGY FOR PARTICLE PHYSICS

Accelerator R&D Roadmap

The roadmapping exercise

- The physics case for new collider facilities is spelled out quite clearly:
  - Precision Higgs/EW/Top physics, dark matter, naturalness (hierarchy, but also strong CP phase) - and all this assuming no deviation from SM at (HL-)LHC.
- The role of **ECFA (European Committee for Future Accelerators)** and **LDG (Laboratory Directors Group)** is to bring the community to a decision about the "best" direction.

- However, "best" must take into account technology and resources availabilities, timelines, costs.
- Where does the community want the field to go? Discussed in the update to European strategy (2020).
- Do we need more information? How do we get there? The roadmapping exercise is about putting names on the roads, distances, and, in some case, costs.

The European Strategy Update

- The roadmapping exercise comes following explicit recommendations of the EPPSU. From the deliberation document:
  - "The European particle physics community must **intensify accelerator R&D** and sustain it with adequate resources. **A roadmap should prioritise the technology**, […]. **Deliverables for this decade should be defined in a timely fashion** […]"
  - "[…] **Detector R&D programmes** and associated infrastructures **should be supported** at CERN, national institutes, laboratories and universities. […] The community should define **a global detector R&D roadmap** that should be used to support proposals at the European and national levels."

Which roadmaps?

CERN-2022-001

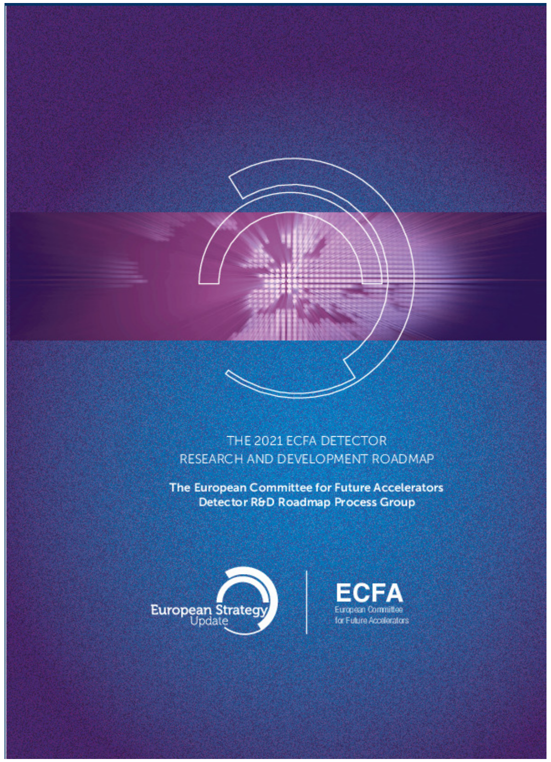
EUROPEAN STRATEGY FOR PARTICLE PHYSICS

Accelerator R&D Roadmap

European Strategy Update

LDG Laboratory Directors Group

European Strategy for Particle Physics - Accelerator R&D Roadmap



THE 2021 ECFA DETECTOR RESEARCH AND DEVELOPMENT ROADMAP

The European Committee for Future Accelerators Detector R&D Roadmap Process Group

European Strategy Update

ECFA European Committee for Future Accelerators

The 2021 ECFA Detector Research and Development Roadmap (+ Synopsis)

- Each document developed by a dedicated panel of experts
- Panel chairs: **D. Newbold (RAL)** for accelerators, **P. Allport (Birmingham)** for detectors.
  - More details about panel composition in the documents and here

A collective effort

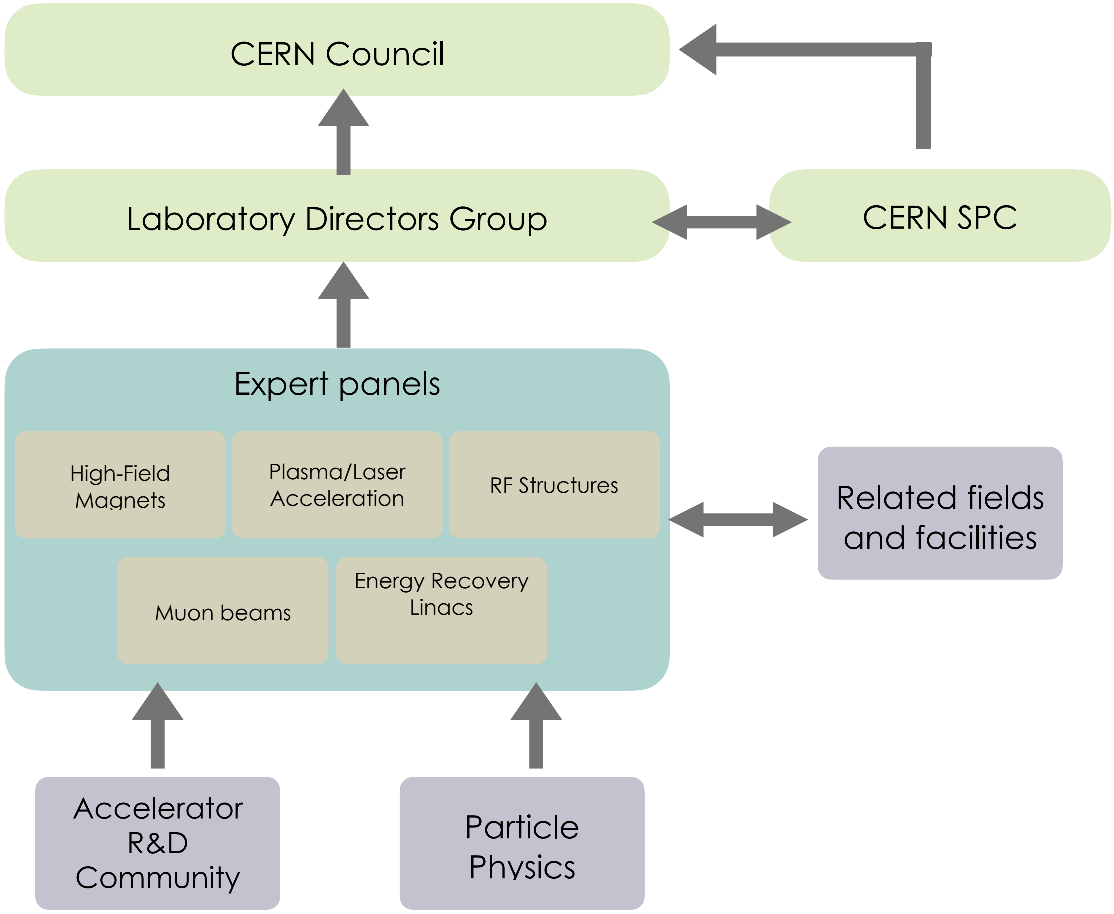
- Interaction with the community ensured by **the panel members** and **well-attended symposia** (+ consultation surveys for detectors)

Example: attendance to the detector panel symposia, spring 2021

	TF7	TF8	TF2	TF5	TF3	TF1	TF9	TF4	TF6
Unique users	369 + 123 webcast*	154 + 17 webcast*	197 + 5 webcast*	220	504	339	105	207	201
Max. number of concurrent views	230 + 123 webcast*	76 + 17 webcast*	130 + 5 webcast*	100	275	191	59	110	115

- In UK: interaction happening also through the **Particle Physics Technology Advisory Panel** (PPTAP - more details tomorrow)
  - Created to draft **UK response/policy document** while gathering input for the European process.
  - For detector roadmap, I.V. acted as national contact (gathering survey responses and comments on roadmap document drat).

Accelerator roadmap



CERN Council

Laboratory Directors Group

CERN SPC

Expert panels

High-Field Magnets

Plasma/Laser Acceleration

RF Structures

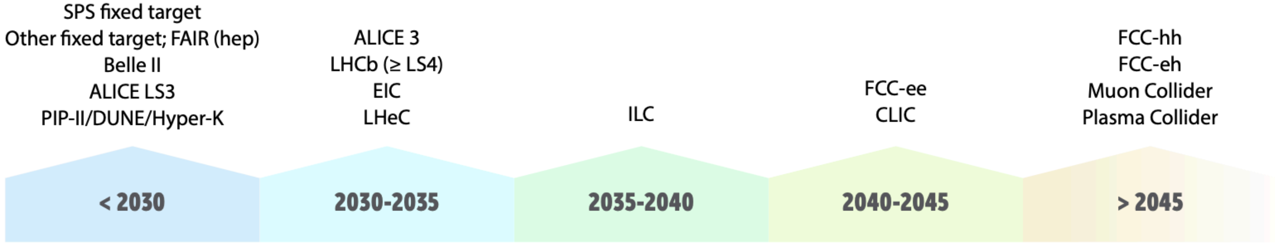
Muon beams

Energy Recovery Linacs

Related fields and facilities

Accelerator R&D Community

Particle Physics

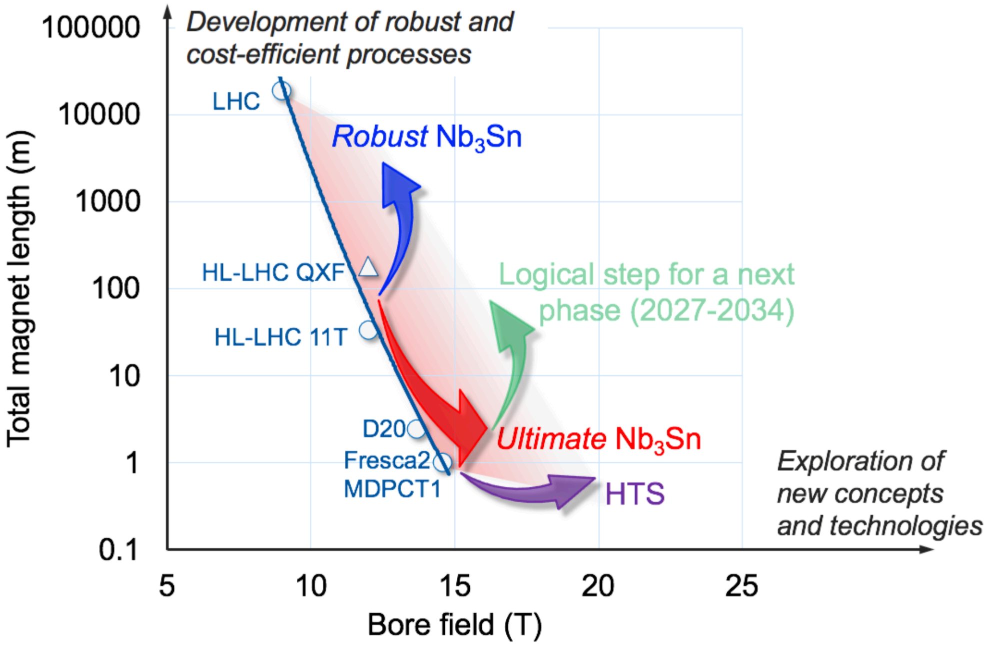


< 2030	2030-2035	2035-2040	2040-2045	> 2045
SPS fixed target Other fixed target; FAIR (hep) Belle II ALICE LS3 PIP-II/DUNE/Hyper-K	ALICE 3 LHCb (≥ LS4) EIC LHeC	ILC	FCC-ee CLIC	FCC-hh FCC-eh Muon Collider Plasma Collider

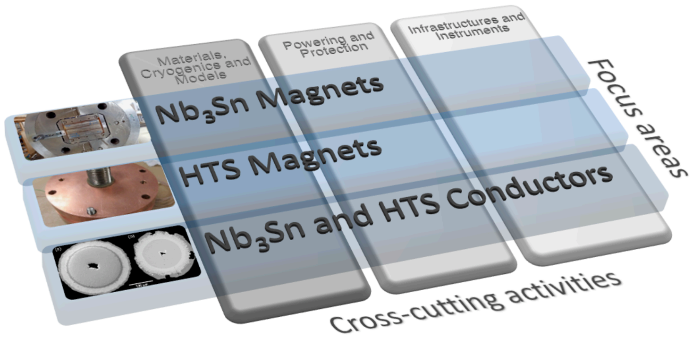
- Scope: define a programme to **enable a community decision** about next accelerator facility for next EPPSU.
- Questions to be answered:
  - What R&D is missing? Priorities?
  - Timeline and cost, alternative solutions and trade offs
  - Interdependencies and conflicts
  - Intermediate science output.
- Time-span: 5 to 10 years
- Planning:
  - Varying "readiness", from engineering to emerging technology

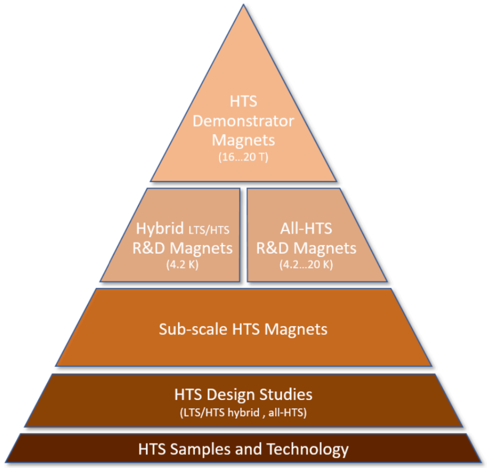
    Three baseline funding scenarios (Nominal, Aspirational, Minimal) considered.

High-Field magnets



- Magnetic field strength and target energy define the required field strength.
- High-energy frontiers requires **high-field (16 T and above)** magnets:
  - Nb_3Sn promising. Need to improve in **reliability**, **robustness**, **cost** while **improving performance**. R&D steps with quick intermediate turnaround demonstrators defined (for conductors and full magnets).
  - High-Temperature Superconductors can **increase field further**, but a longer way to go to achieve a full-scale system.




HTS Demonstrator Magnets (16...20 T)

Hybrid LTS/HTS R&D Magnets (4.2 K)

All-HTS R&D Magnets (4.2...20 K)

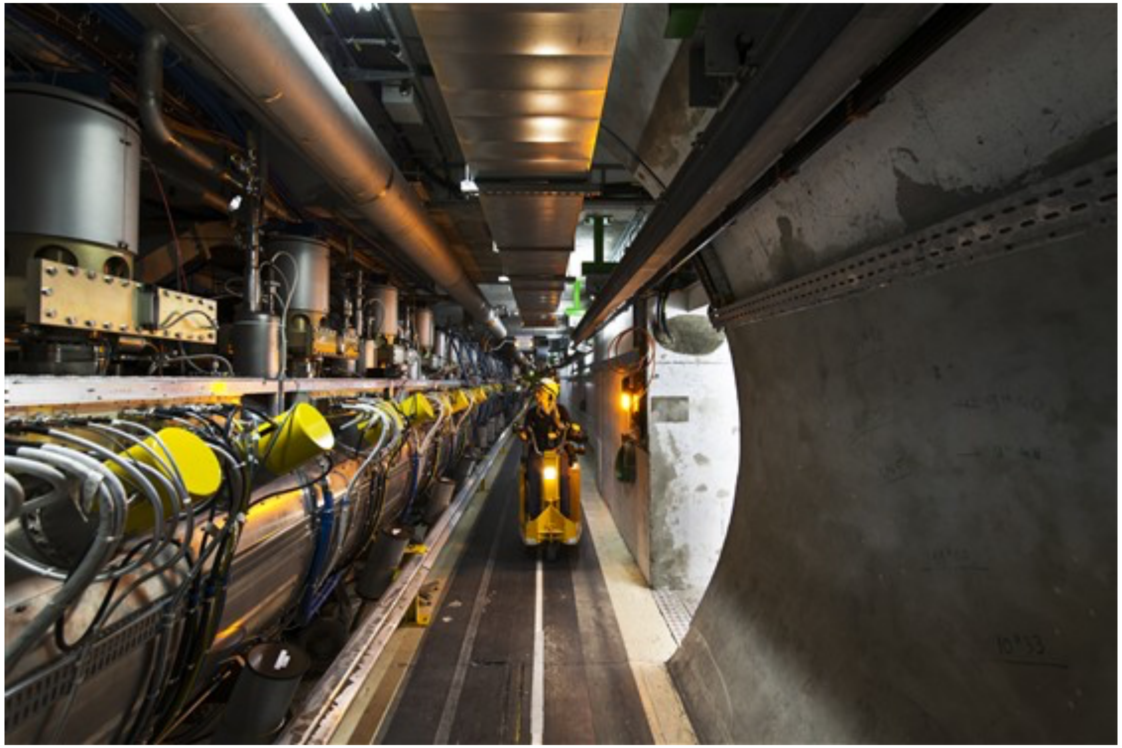
Sub-scale HTS Magnets

HTS Design Studies (LTS/HTS hybrid , all-HTS)

HTS Samples and Technology

RF Structures

- Radio-frequency cavities are the "accelerating" component of an accelerator.
- RF power **a significant fraction** of the wall-plug power cost of an accelerator
  - Emphasis on efficiency crucial for a "green" accelerator facility.
- Requirements vary depending on the facility one has in mind.

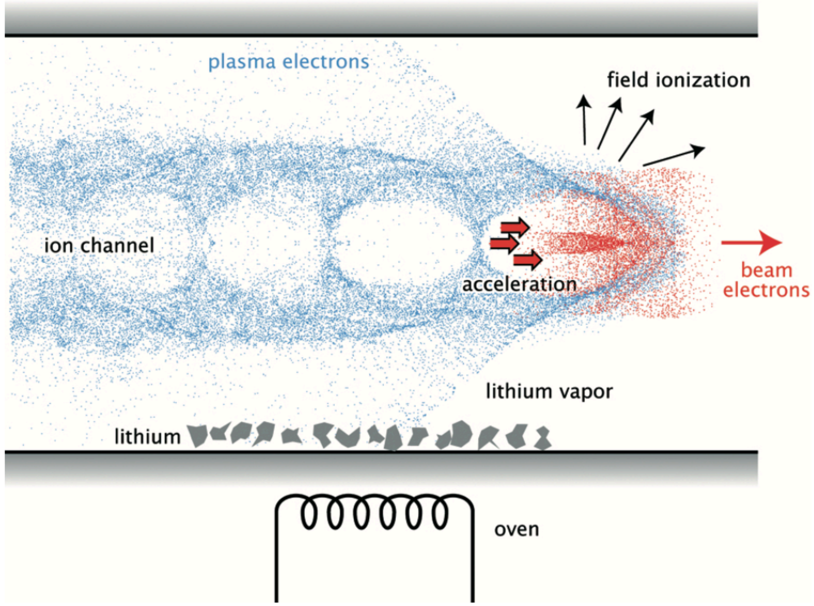


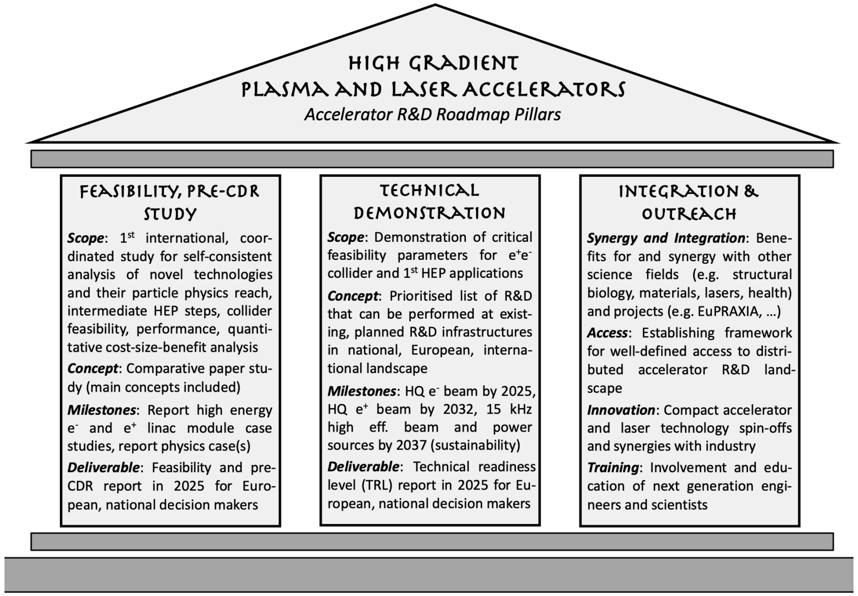
In general, main R&D aimed at:

- Maximising efficiency and optimisation of the system.
- Industrialisation for assembly and tuning.
- Diagnostic and feedback mechanism
- Development of new materials and structures

Plasma/Laser acceleration

- Very hot topic, with significant investment.
- However, **still in a development phase** from a particle physics perspective.
    - Potential: accelerations of **10s GeV/m** demonstrated (100-1000 better than RF).
    - Still to be demonstrated: **simultaneous achievement** of gradient, energy gain, charge, small energy spread, emittance, etc.
- Proposed R&D following three pillars of feasibility/pre-CDR, technical demonstration, integration and outreach.





HIGH GRADIENT
PLASMA AND LASER ACCELERATORS
Accelerator R&D Roadmap Pillars

FEASIBILITY, PRE-CDR STUDY

Scope: 1st international, coordinated study for self-consistent analysis of novel technologies and their particle physics reach, intermediate HEP steps, collider feasibility, performance, quantitative cost-size-benefit analysis

Concept: Comparative paper study (main concepts included)

Milestones: Report high energy e^- and e^+ linac module case studies, report physics case(s)

Deliverable: Feasibility and pre-CDR report in 2025 for European, national decision makers

TECHNICAL DEMONSTRATION

Scope: Demonstration of critical feasibility parameters for e^+e^- collider and 1st HEP applications

Concept: Prioritised list of R&D that can be performed at existing, planned R&D infrastructures in national, European, international landscape

Milestones: HQ e^- beam by 2025, HQ e^+ beam by 2032, 15 kHz high eff. beam and power sources by 2037 (sustainability)

Deliverable: Technical readiness level (TRL) report in 2025 for European, national decision makers

INTEGRATION & OUTREACH

Synergy and Integration: Benefits for and synergy with other science fields (e.g. structural biology, materials, lasers, health) and projects (e.g. EuPRAXIA, …)

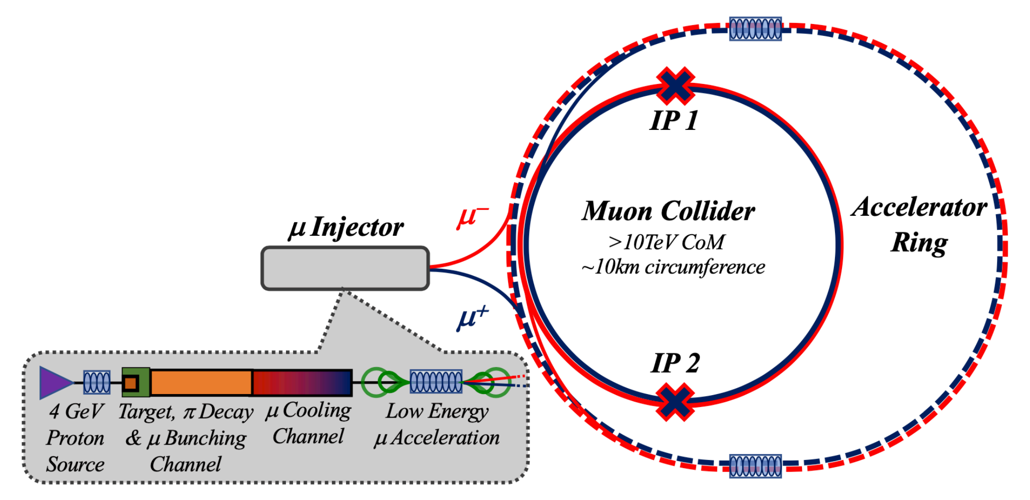
Access: Establishing framework for well-defined access to distributed accelerator R&D landscape

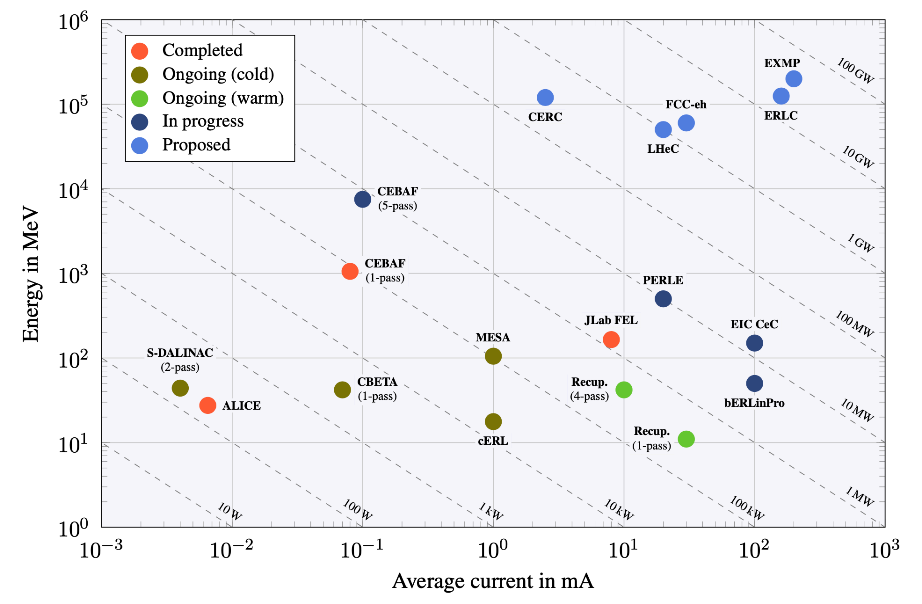
Innovation: Compact accelerator and laser technology spin-offs and synergies with industry

Training: Involvement and education of next generation engineers and scientists

Muon beams and ERL

- Muon colliders can deliver **high CM energy** with efficient use of power.
- However muons decay: challenges with **muon cooling** cells, **neutrino radiation**, **technology** for magnets (quick ramp-up) and RF (operations in high magnetic field and low temperature).
- Benchmark defined on a 10 TeV collider, possibly with an intermediate 3 TeV.



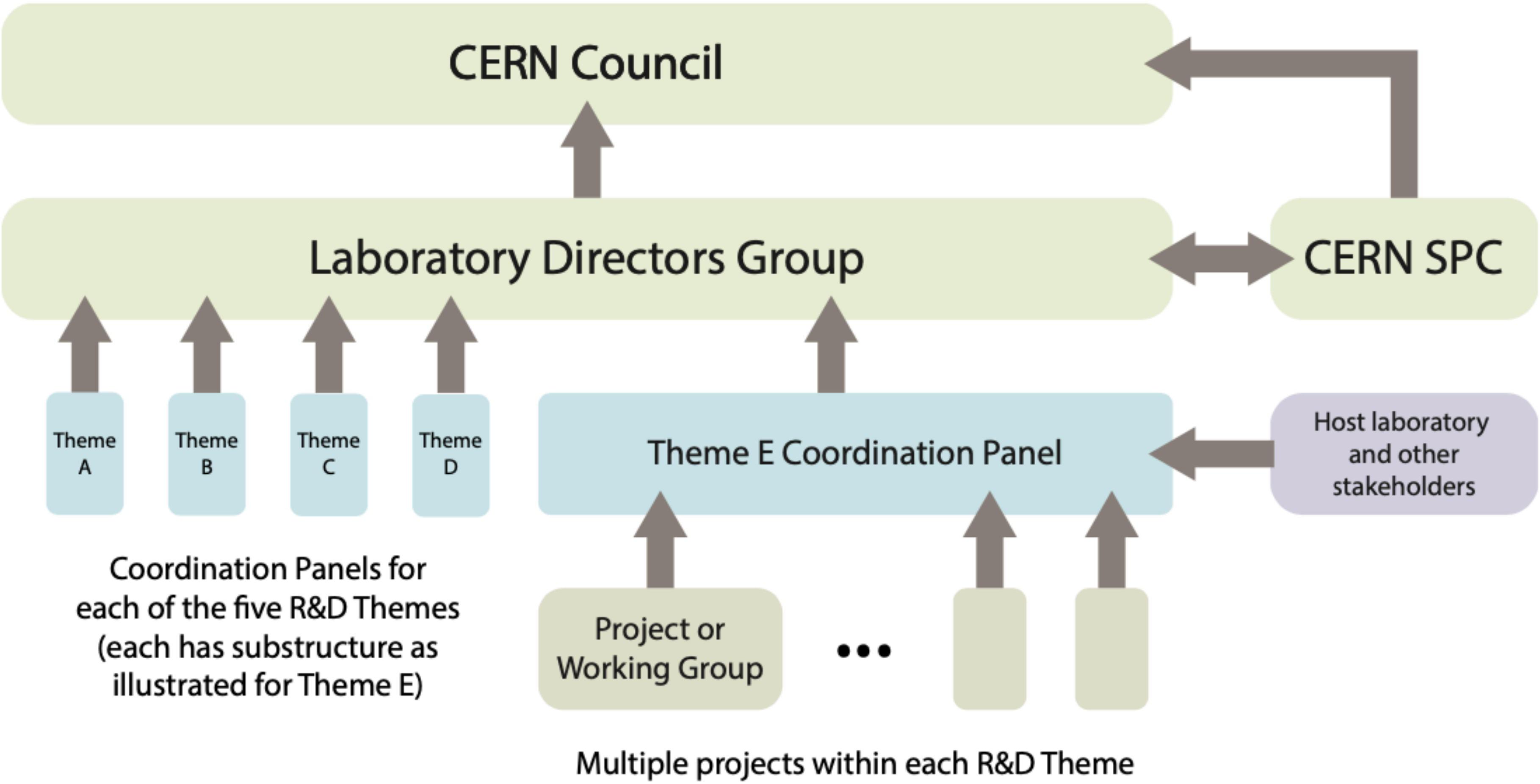


- In an ERL, the electron **energy is "recycled"** after the beam use.
- One can **achieve high beam power** with moderate RF power ⟹ promising way to "green" ee or eh machines.
  - Need to gain one or more orders of magnitude for the future needs.
- R&D largely done using existing facilities.

Accelerator Summary and Recommendations

- The document identifies a set of **common themes**, and gives **10 general recommendations**:
  - They recommend to maintain a **broad front of R&D**, with funding at least corresponding to the minimal scenario. There should be **room for novel developments** as well.
  - **Prompt scientific exploitation** should be emphasized where possible.
  - Environmental (but not only) sustainability should be a **primary consideration**.
  - **Links and collaborations** between **different European laboratories** and with **industry** are key: industrial norms should be adopted to widen the applicability of new developments
  - **Training and professional development** of accelerator physicists is a key factor in sustaining a vibrant and productive field.

Accelerator coordination structure



CERN Council

Laboratory Directors Group

CERN SPC

Theme A

Theme B

Theme C

Theme D

Theme E Coordination Panel

Host laboratory and other stakeholders

Coordination Panels for each of the five R&D Themes (each has substructure as illustrated for Theme E)

Project or Working Group

•••

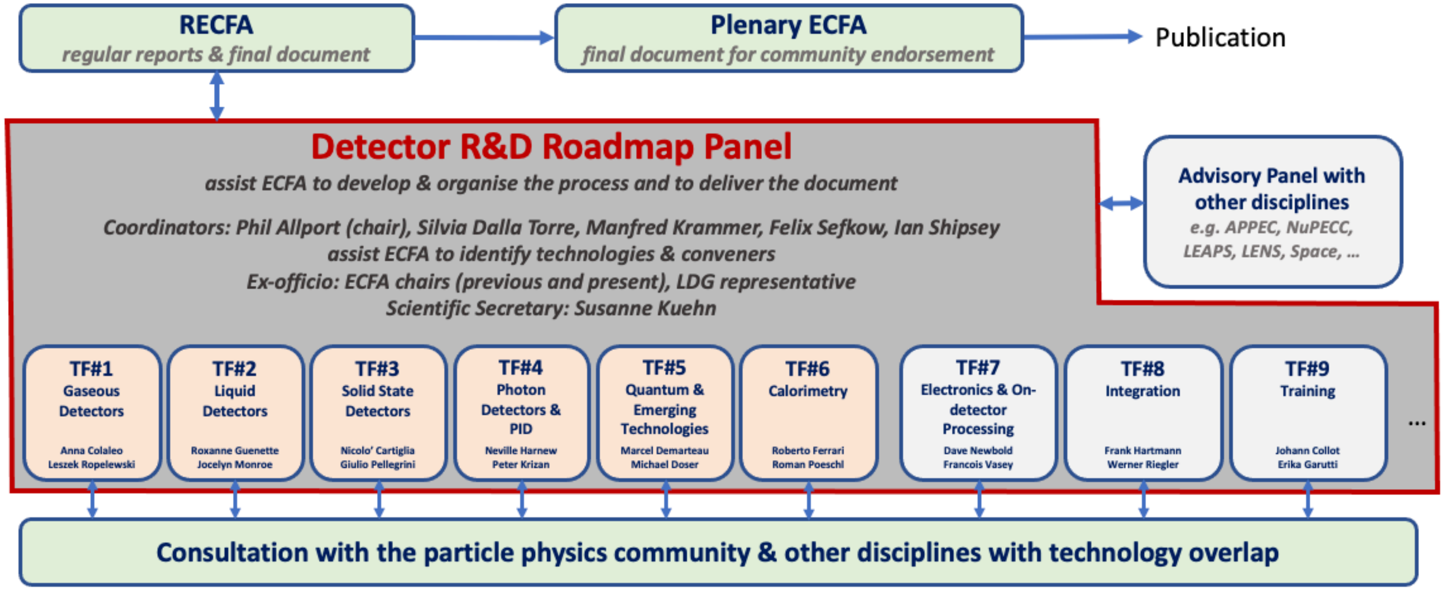
Multiple projects within each R&D Theme

Detector R&D roadmap

- Given the future physics programme, identify **the main technology R&D to be met so that detectors ar not the limiting factor for the timeline.**
- Detector context considered:

- Full exploitation of LHC
- Long baseline neutrinos
- Detectors for future Higgs-EW-Top factories (in all manifestations)
- Long term vision for 100 TeV hadron collider

- Future muon colliders
- Accelerator setup for rare decays/dark matter
- Experiments for precision QCD
- Non accelerator experiments (reactor neutrinos, double beta decay, dark matter)



RECFA
regular reports & final document

Plenary ECFA
final document for community endorsement

Publication

Detector R&D Roadmap Panel
assist ECFA to develop & organise the process and to deliver the document

Coordinators: Phil Allport (chair), Silvia Dalla Torre, Manfred Krammer, Felix Sefkow, Ian Shipsey
assist ECFA to identify technologies & conveners
Ex-officio: ECFA chairs (previous and present), LDG representative
Scientific Secretary: Susanne Kuehn

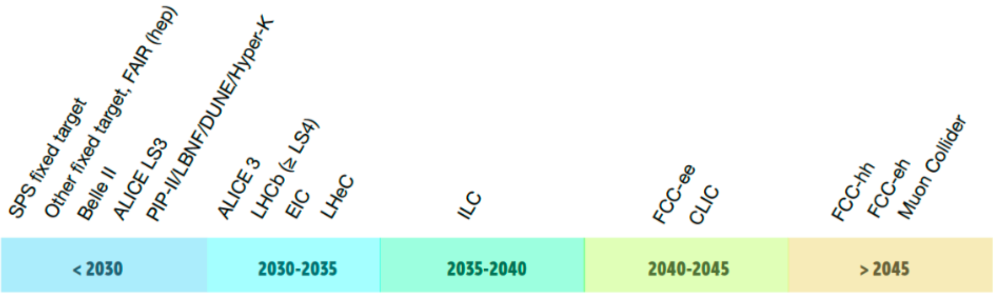
Advisory Panel with other disciplines
e.g. APPEC, NuPECC, LEAPS, LENS, Space, …

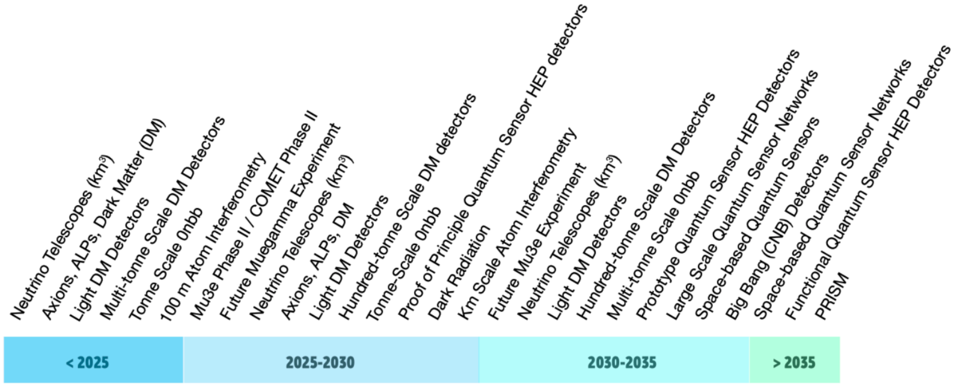
TF#1 Gaseous Detectors – Anna Colaleo, Leszek Ropelewski
TF#2 Liquid Detectors – Roxanne Guenette, Jocelyn Monroe
TF#3 Solid State Detectors – Nicolo' Cartiglia, Giulio Pellegrini
TF#4 Photon Detectors & PID – Neville Harnew, Peter Krizan
TF#5 Quantum & Emerging Technologies – Marcel Demarteau, Michael Doser
TF#6 Calorimetry – Roberto Ferrari, Roman Poeschl
TF#7 Electronics & On-detector Processing – Dave Newbold, Francois Vasey
TF#8 Integration – Frank Hartmann, Werner Riegler
TF#9 Training – Johann Collot, Erika Garutti
…

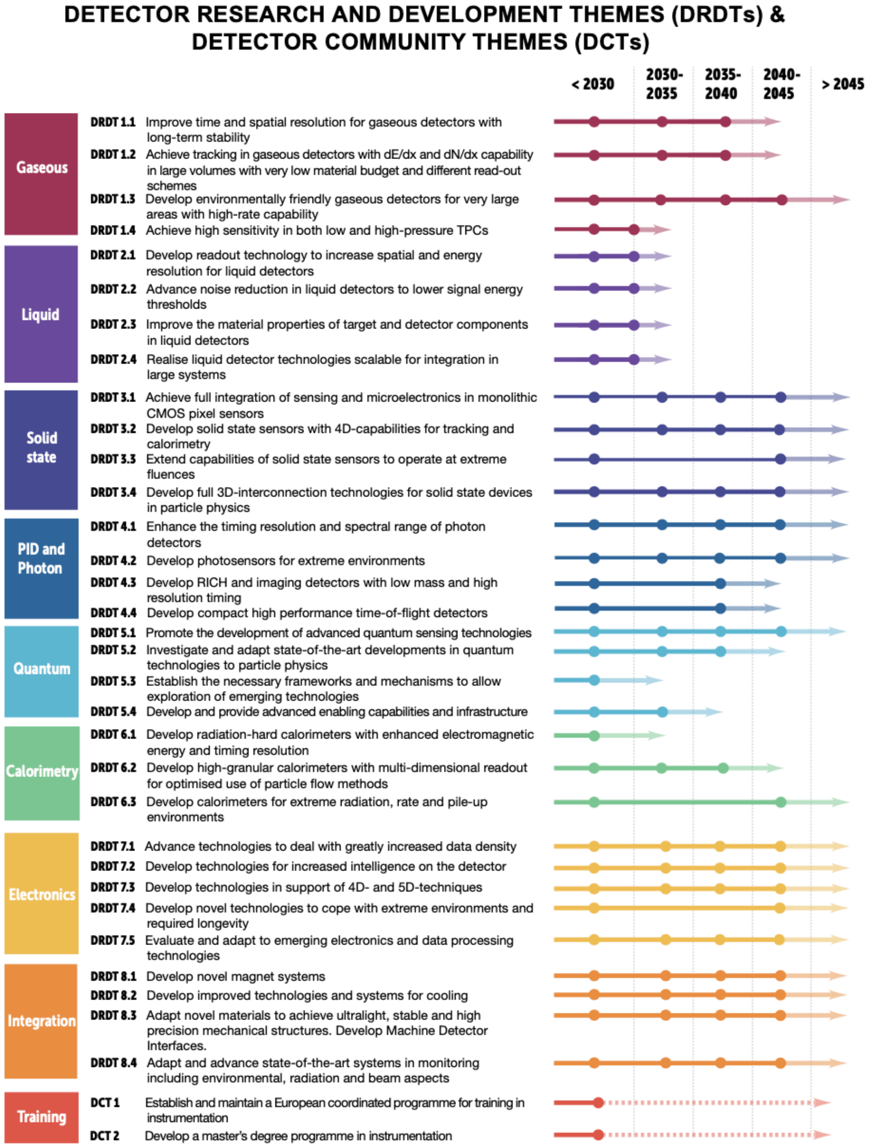
Consultation with the particle physics community & other disciplines with technology overlap

Structure of the document

- DRDTs define for each area the theme or R&D to be performed.






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

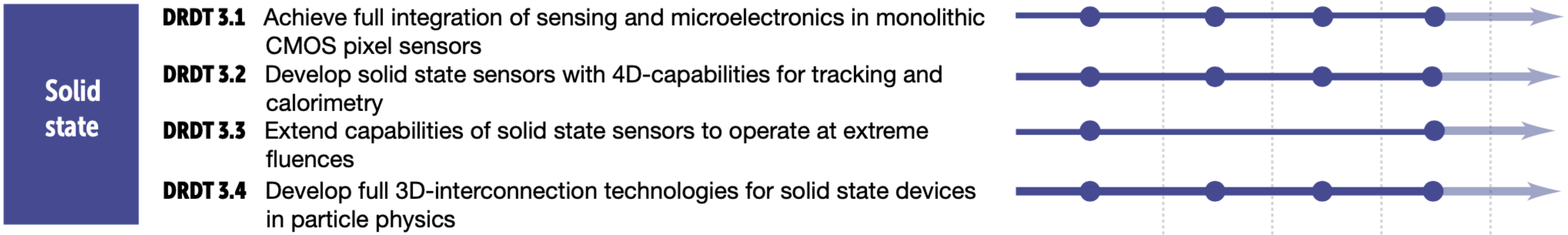
Gaseous	**DRDT 1.1**	Improve time and spatial resolution for gaseous detectors with long-term stability
	DRDT 1.2	Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes
	DRDT 1.3	Develop environmentally friendly gaseous detectors for very large areas with high-rate capability
	DRDT 1.4	Achieve high sensitivity in both low and high-pressure TPCs
Liquid	**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
Solid state	**DRDT 3.1**	Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors
	DRDT 3.2	Develop solid state sensors with 4D-capabilities for tracking and calorimetry
	DRDT 3.3	Extend capabilities of solid state sensors to operate at extreme fluences
	DRDT 3.4	Develop full 3D-interconnection technologies for solid state devices in particle physics
PID and Photon	**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	**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	**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
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	**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
Training	**DCT 1**	Establish and maintain a European coordinated programme for training in instrumentation
	DCT 2	Develop a master's degree programme in instrumentation

Structure of the document

- DRDTs define for each area the theme or R&D to be performed.

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

DRDT 1.1 Improve time and spatial resolution for gaseous detectors with long-term stability



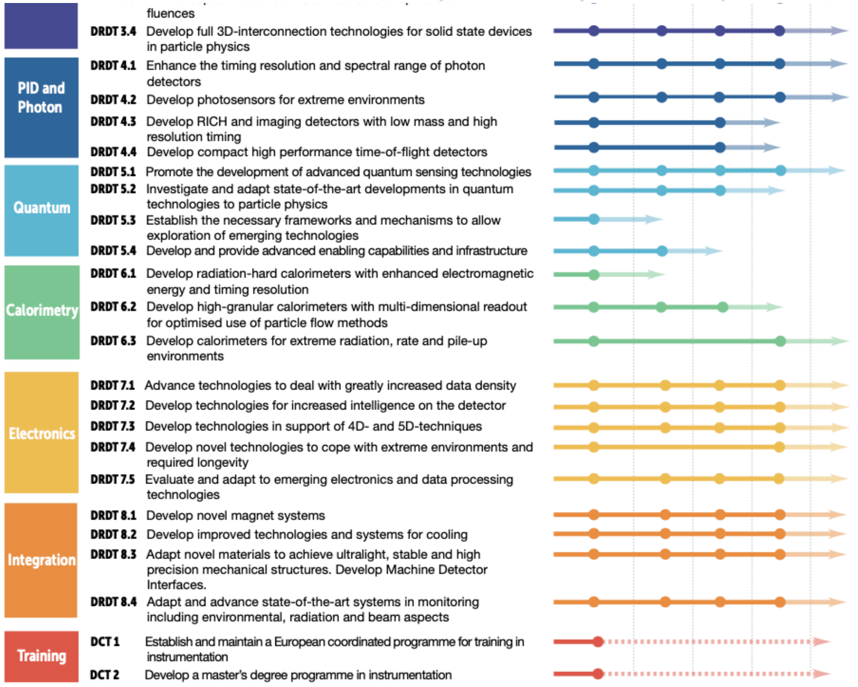
Solid state

DRDT 3.1 Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors

DRDT 3.2 Develop solid state sensors with 4D-capabilities for tracking and calorimetry

DRDT 3.3 Extend capabilities of solid state sensors to operate at extreme fluences

DRDT 3.4 Develop full 3D-interconnection technologies for solid state devices in particle physics



fluences

DRDT 3.4 Develop full 3D-interconnection technologies for solid state devices in particle physics

PID and Photon

DRDT 4.1 Enhance the timing resolution and spectral range of photon detectors

DRDT 4.2 Develop photosensors for extreme environments

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Quantum

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Calorimetry

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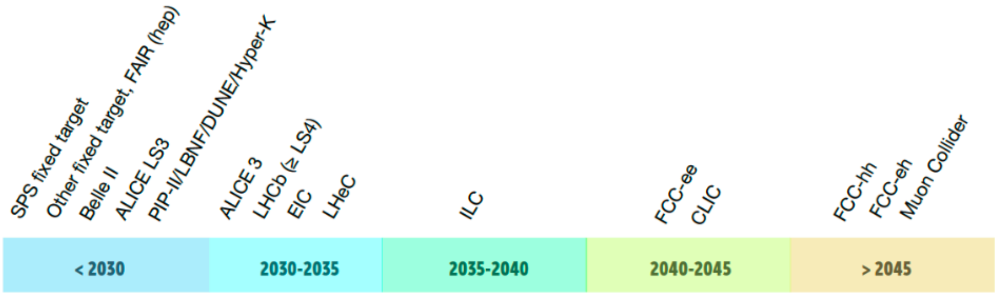
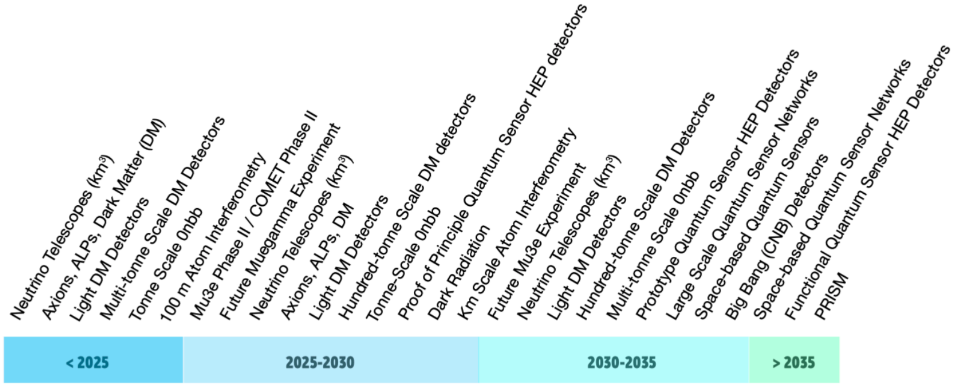
Training

DCT 1 Establish and maintain a European coordinated programme for training in instrumentation

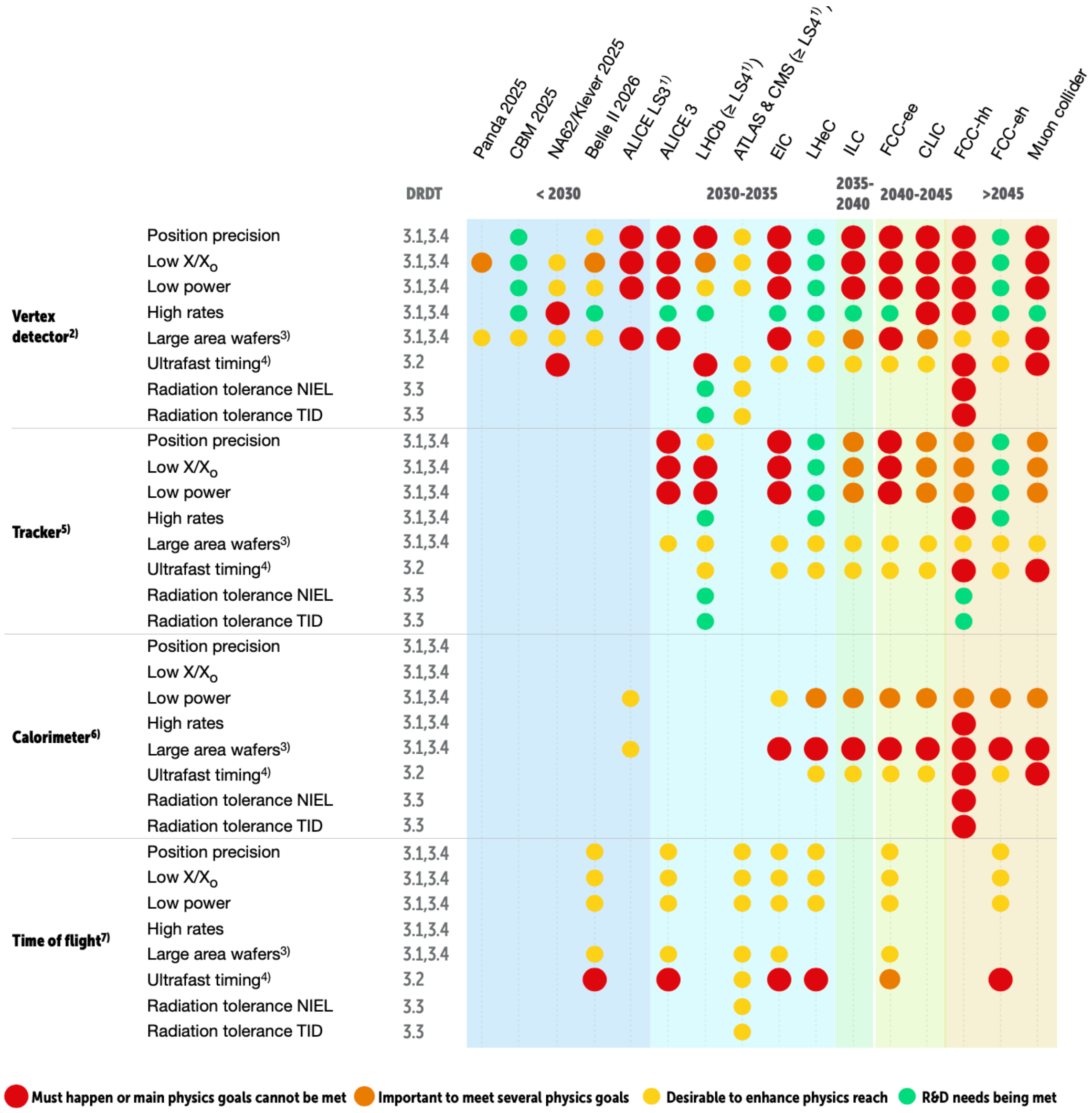
DCT 2 Develop a master's degree programme in instrumentation





Solid state detectors

- Some of the challenges to be met:
  - **Vertex detector** - high resolution ($\leq 3\ \mu$m), low mass ($X/X_0 < 0.05\,\%$, already for e^+e^- colliders), low power and high radiation hardness (up to ~10^{18} n_{eq}/cm^2 for hadron colliders).
  - **Trackers**: reliable affordable sensors - low power
  - **Calorimeters**: large-area, and affordable
  - **Time resolution of 10-100 ps** for PID/ToF
  - Integrated, etc.

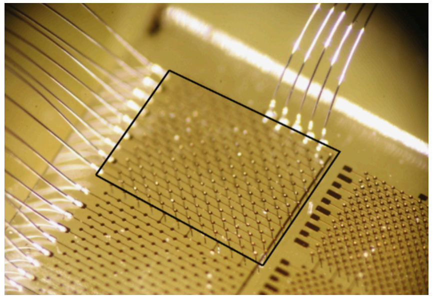


		DRDT	Panda 2025	CBM 2025	NA62/Klever 2025	Belle II 2026	ALICE LS3[1]	ALICE 3	LHCb (≥ LS4[1])	ATLAS & CMS (≥ LS4[1]) ,	EIC	LHeC	ILC	FCC-ee	CLIC	FCC-hh	FCC-eh	Muon collider
			< 2030					2030-2035					2035-2040	2040-2045		>2045		
Vertex detector[2]	Position precision	3.1,3.4		🟢		🟡	🔴	🔴	🔴	🟡	🔴	🟢	🔴	🔴	🔴	🔴	🟢	🔴
	Low X/X_0	3.1,3.4	🟠	🟢	🟡	🟠	🔴	🔴	🟠	🟡	🔴	🟢	🔴	🔴	🔴	🔴	🟢	🔴
	Low power	3.1,3.4		🟢	🟡	🟡	🔴	🔴	🟡	🟡	🔴	🟢	🔴	🔴	🔴	🔴	🟢	🔴
	High rates	3.1,3.4		🟢	🔴	🟢		🟢	🟢		🟢	🟢	🟢	🟢	🔴	🔴	🟢	🟢
	Large area wafers[3]	3.1,3.4	🟡	🟡	🟡	🟡	🔴	🔴			🔴	🟡	🟠	🔴	🟠	🟡	🟡	🔴
	Ultrafast timing[4]	3.2			🔴				🔴	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴
	Radiation tolerance NIEL	3.3							🟢	🟡						🔴		
	Radiation tolerance TID	3.3							🟢	🟡						🔴		
Tracker[5]	Position precision	3.1,3.4						🔴	🟡		🔴	🟢	🟠	🔴	🟠	🟠	🟢	🟠
	Low X/X_0	3.1,3.4						🔴	🔴		🔴	🟢	🟠	🔴	🟠	🟠	🟢	🟠
	Low power	3.1,3.4						🔴	🔴		🔴	🟢	🟠	🔴	🟠	🟠	🟢	🟠
	High rates	3.1,3.4							🟢			🟢				🔴	🟢	
	Large area wafers[3]	3.1,3.4						🟡	🟡		🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡
	Ultrafast timing[4]	3.2							🟡		🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴
	Radiation tolerance NIEL	3.3							🟢							🟢		
	Radiation tolerance TID	3.3							🟢							🟢		
Calorimeter[6]	Position precision	3.1,3.4																
	Low X/X_0	3.1,3.4																
	Low power	3.1,3.4					🟡				🟡	🟠	🟠	🟠	🟠	🟠	🟠	🟠
	High rates	3.1,3.4														🔴		
	Large area wafers[3]	3.1,3.4					🟡				🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴
	Ultrafast timing[4]	3.2										🟡	🟡	🟡	🟡	🔴	🟡	🔴
	Radiation tolerance NIEL	3.3														🔴		
	Radiation tolerance TID	3.3														🔴		
Time of flight[7]	Position precision	3.1,3.4				🟡		🟡		🟡	🟡	🟡		🟡			🟡	
	Low X/X_0	3.1,3.4				🟡		🟡		🟡	🟡	🟡		🟡			🟡	
	Low power	3.1,3.4				🟡		🟡		🟡	🟡	🟡		🟡			🟡	
	High rates	3.1,3.4																
	Large area wafers[3]	3.1,3.4				🟡		🟡		🟡	🟡			🟡				
	Ultrafast timing[4]	3.2				🔴		🔴		🟡	🔴	🔴		🟠			🔴	
	Radiation tolerance NIEL	3.3								🟡								
	Radiation tolerance TID	3.3								🟡								

🔴 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

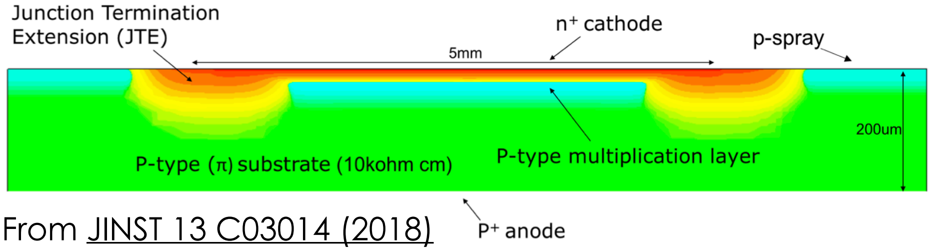
Solid state detectors - technologies

- CMOS MAPS provide **high spacial resolution** and **small material** (integrated circuitery)
- Used in a number of experiments - current time resolution ~ 100 ps, rad tolerance up to 1x10^{15} n_{eq}/cm^2 (Malta Monopix with modified TowerJazz (180 nm)
- Main R&D items:
  - Smaller pixel pitch
  - Stitching for large areas
  - Increased radiation hardness and reduced power consumption

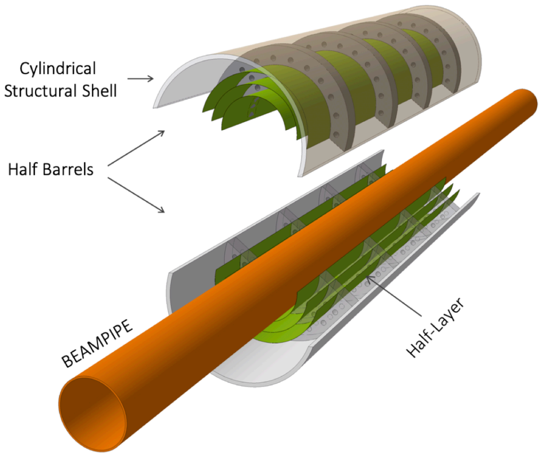


Diamond sensor bonding, taken from http://dx.doi.org/10.1016/j.nima.2015.03.033

- Thin and 3D silicon sensors operated at ~10^{16} n_{eq}/cm^2. Non-silicon sensors (diamond for example) target to achieve resistance to extreme fluences.



From JINST 13 C03014 (2018)

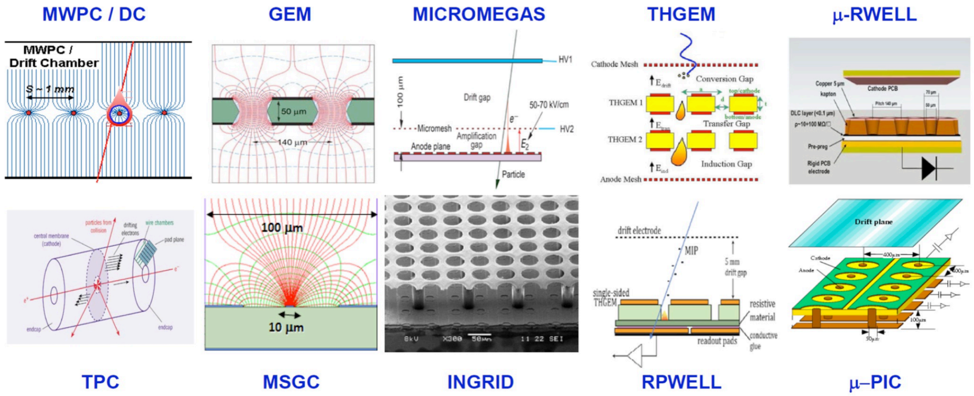


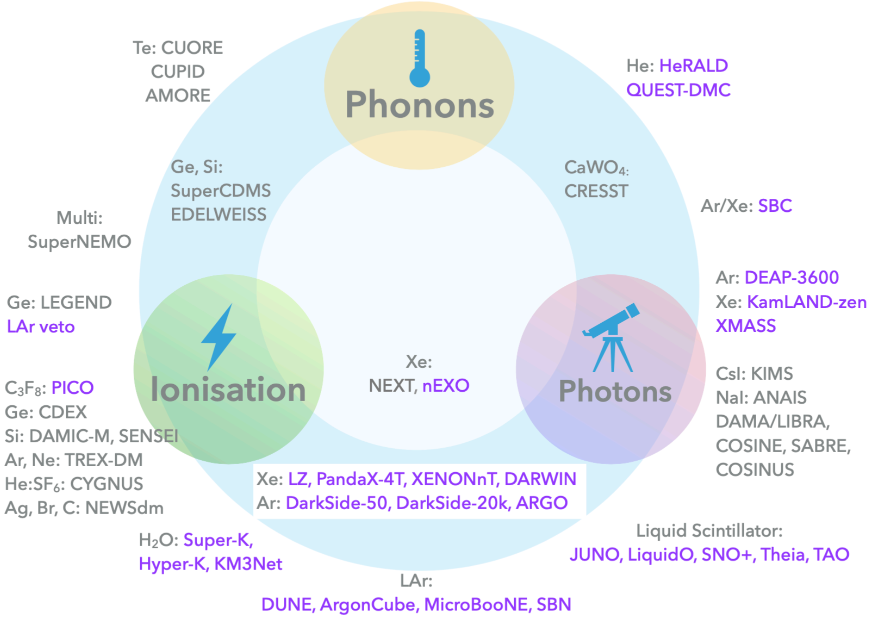
Bent sensor wafers for ALICE upgrade Taken from M.Mager, IAS Program on high energy physics

- 4D tracking (adding precise time information) a necessity in high-pileup configurations
- Low Gain Avalanche Detectors can achieve ~20 ps for 50 μm sensors for O(10 μm) resolution and 10^{15} n_{eq}/cm^2 radiation tolerance

Gas and liquid detectors

- Gaseous detectors ideal for **large-area coverage** with low material budget.
- Good timing performance ⟹ suited for TOF, etc.
- Micro Pattern Gas Detectors (in their different forms) widely used in LHC upgrades (ATLAS NSW, CMS GEM, etc.)
- Eco-gas **a priority** for future collider needs.





Phonons

Ionisation

Photons

Te: CUORE
CUPID
AMORE

He: HeRALD
QUEST-DMC

Ge, Si:
SuperCDMS
EDELWEISS

CaWO$_4$:
CRESST

Ar/Xe: SBC

Multi:
SuperNEMO

Ge: LEGEND
LAr veto

Ar: DEAP-3600
Xe: KamLAND-zen
XMASS

Xe:
NEXT, nEXO

C$_3$F$_8$: PICO
Ge: CDEX
Si: DAMIC-M, SENSEI
Ar, Ne: TREX-DM
He:SF$_6$: CYGNUS
Ag, Br, C: NEWSdm

CsI: KIMS
NaI: ANAIS
DAMA/LIBRA,
COSINE, SABRE,
COSINUS

Xe: LZ, PandaX-4T, XENONnT, DARWIN
Ar: DarkSide-50, DarkSide-20k, ARGO

H$_2$O: Super-K,
Hyper-K, KM3Net

Liquid Scintillator:
JUNO, LiquidO, SNO+, Theia, TAO

LAr:
DUNE, ArgonCube, MicroBooNE, SBN

- Liquid detectors: a rapid development field, shorter period of R&D outlined.
- Main liquid detector challenges:
  - Readout: spacial resolution, low-energy threshold.
  - Multi-ton, high-purity experiments (e.g. DM direct searches) target doping, purification, components radiopurity.

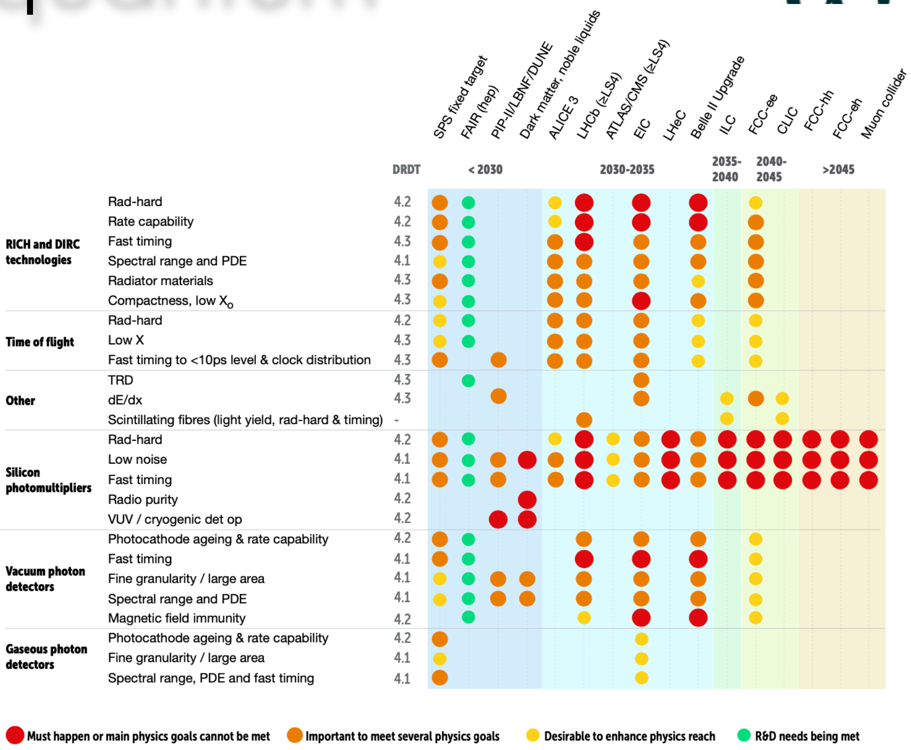
PID, photodetectors and quantum technologies

Particle identification used on a variety of different experiments (LHCb RICH upgrade is one example)

SiPM **flexible and cheap**. Will be used in **LB neutrino experiments** and **colliders** applications.

Main R&D items: extension of **efficiency to near UV**, reduction of **dark count**, increased **radiation hardness.**

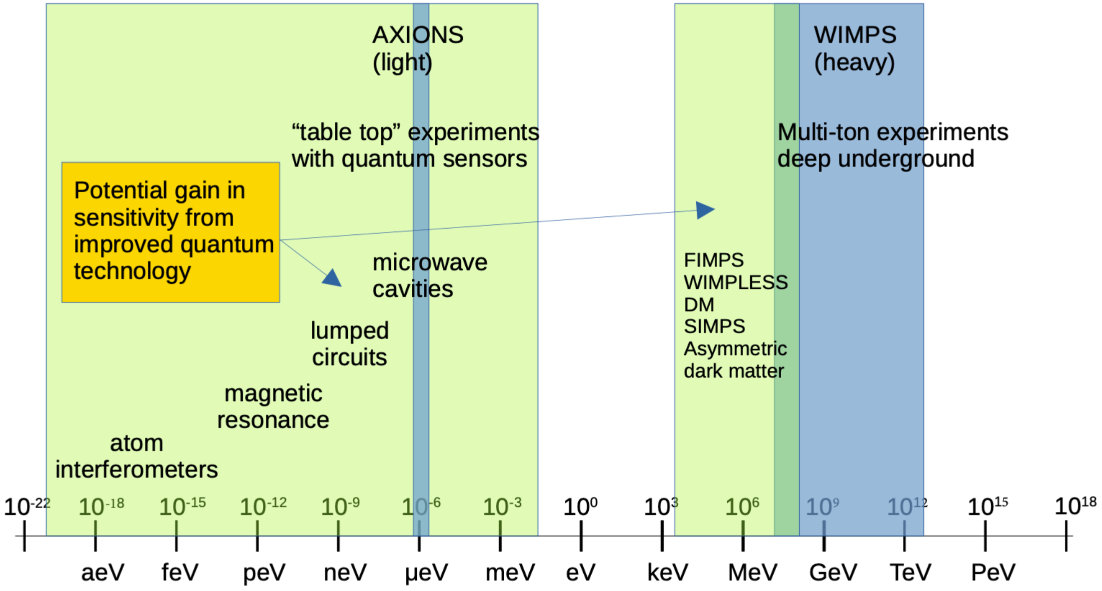
MCP-PMT and LAPPD good candidates for **large area coverage**, but at the moment expensive (also need to improve magnetic field tolerance)



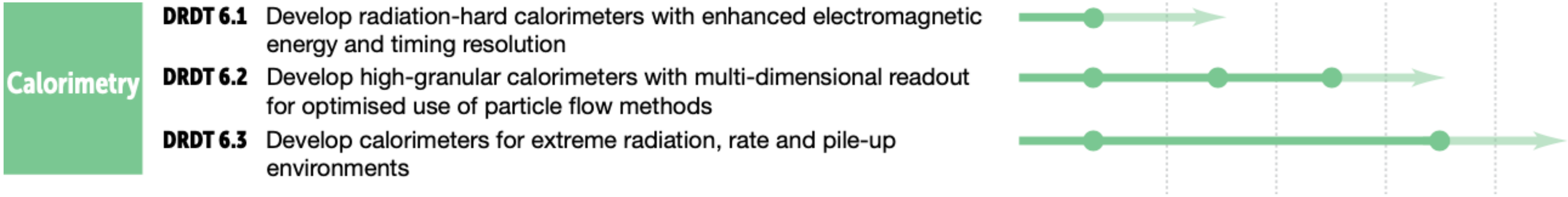
		DRDT	< 2030				2030-2035						2035-2040	2040-2045		>2045		
			SPS fixed target	FAIR (hep)	PIP-II/LBNF/DUNE	Dark matter, noble liquids	ALICE 3	LHCb (≥LS4)	ATLAS/CMS (≥LS4)	EIC	LHeC	Belle II Upgrade	ILC	FCC-ee	CLIC	FCC-hh	FCC-eh	Muon collider
RICH and DIRC technologies	Rad-hard	4.2	🟠	🟢			🟡	🔴		🔴		🔴		🟡				
	Rate capability	4.2	🟠	🟢			🟡	🔴		🔴		🔴		🟠				
	Fast timing	4.3	🟠	🟢			🟠	🔴		🟠		🟠		🟠				
	Spectral range and PDE	4.1	🟡	🟢			🟠	🟠		🟠		🟠		🟠				
	Radiator materials	4.3	🟠	🟢			🟠	🟠		🟠		🟡		🟠				
	Compactness, low X_o	4.3	🟡	🟢			🟠	🟠		🔴		🟠		🟠				
Time of flight	Rad-hard	4.2	🟡	🟢			🟠	🟠		🟠		🟡		🟡				
	Low X	4.3	🟡	🟢			🟠	🟠		🟠		🟡		🟡				
	Fast timing to <10ps level & clock distribution	4.3	🟠		🟠		🟠	🟠		🟠		🟡		🟡				
Other	TRD	4.3		🟢						🟠								
	dE/dx	4.3			🟠					🟠			🟡	🟠	🟡			
	Scintillating fibres (light yield, rad-hard & timing)	-						🟠					🟡		🟡			
Silicon photomultipliers	Rad-hard	4.2	🟠	🟢			🟡	🔴	🟡	🟠	🔴	🟠	🔴	🔴	🔴	🔴	🔴	🔴
	Low noise	4.1	🟠	🟢	🟠	🔴	🟠	🔴	🟡	🟠	🔴	🟠	🔴	🔴	🔴	🔴	🔴	🔴
	Fast timing	4.1	🟠	🟢	🟠		🟠	🔴	🟡	🟠	🔴	🟠	🔴	🔴	🔴	🔴	🔴	🔴
	Radio purity	4.2				🔴												
	VUV / cryogenic det op	4.2			🔴	🔴												
Vacuum photon detectors	Photocathode ageing & rate capability	4.2	🟠	🟢				🟠		🟠		🟠		🟡				
	Fast timing	4.1	🟠	🟢				🔴		🔴		🔴		🟡				
	Fine granularity / large area	4.1	🟡	🟢	🟠	🟠		🟠		🟠		🟠		🟡				
	Spectral range and PDE	4.1	🟡	🟢	🟠	🟠		🟠		🟠		🟠		🟡				
	Magnetic field immunity	4.2		🟢				🟡		🔴		🔴		🟡				
Gaseous photon detectors	Photocathode ageing & rate capability	4.2	🟠							🟡								
	Fine granularity / large area	4.1	🟡							🟡								
	Spectral range, PDE and fast timing	4.1	🟠							🟡								

🔴 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

- Quantum sensors promise to have significant impact on particle phsyics.
- Many different technologies being considered/developed (clocks, spin-based sensors, superconducting electronics, 3D microwave cavities,optomechanical sensors, interferometry)

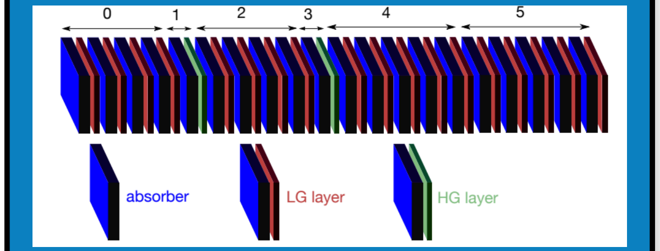


Calorimeters



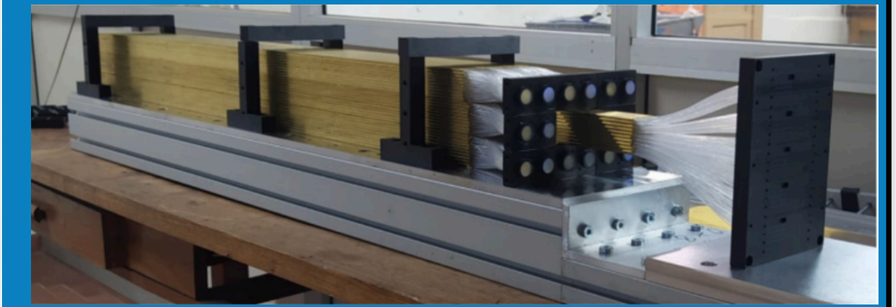
Calorimetry		
	DRDT 6.1	Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution
	DRDT 6.2	Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods
	DRDT 6.3	Develop calorimeters for extreme radiation, rate and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

DRDT 6.1 - example **MAPS based FOCAL EM calorimeter** R&D for ALICE forward calorimetry (SiW calorimeter - exploring hit counting)



DRDT 6.3 - connection with electronics and solid state detectors - design of a 4D calorimeter (including timing)

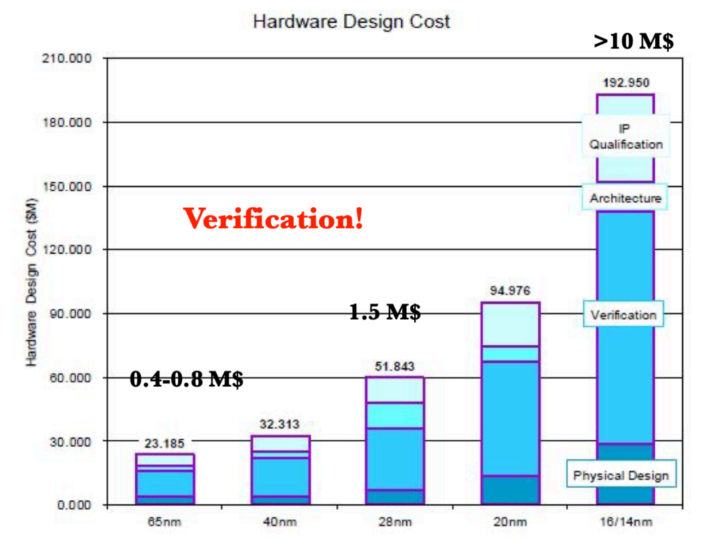
DRDT 6.2 - Different approaches (high-granularity Si or scintillator based, crystal- or fiber-based dual readout, LAr) - **largely complementary technologies** (with different R&D challenges)



Duaal readout EM prototype

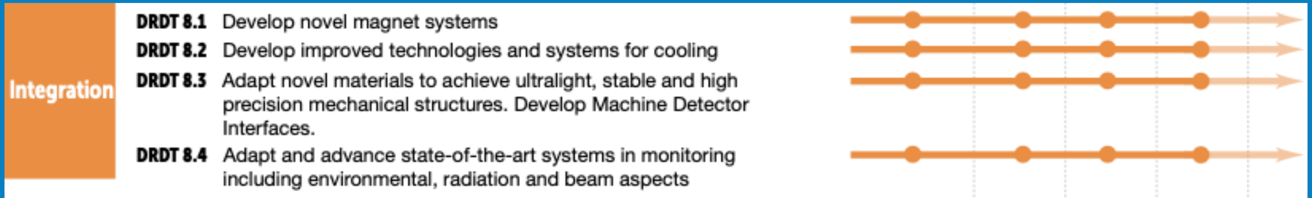
Electronics and integration

- Main challenges on electronics: high granularity and resolution, precision timing, etc. imply a cost in processing and eventually power → need latest advances in **high-speed links and microelectronics.**
- However very specific need for PP in terms of, e.g., radiation hardness.
- Call for a **change of approach** from the past with **increased coordination** around Europe



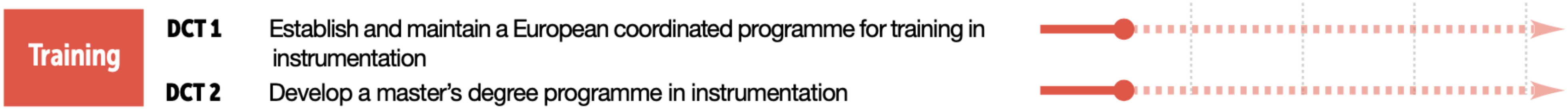
A. Rivetti, TF7 symposium

- Detector **magnetic system development**, including expert design and modelling software is a priority for almost all future experiments/facilities.
- Cooling technologies to **improve efficiency and reduce amount of material** (micro-channeling, improved air flows, etc.)
- Ultra low mass precision mechanics for machine/detector interface.



Integration	**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

Training

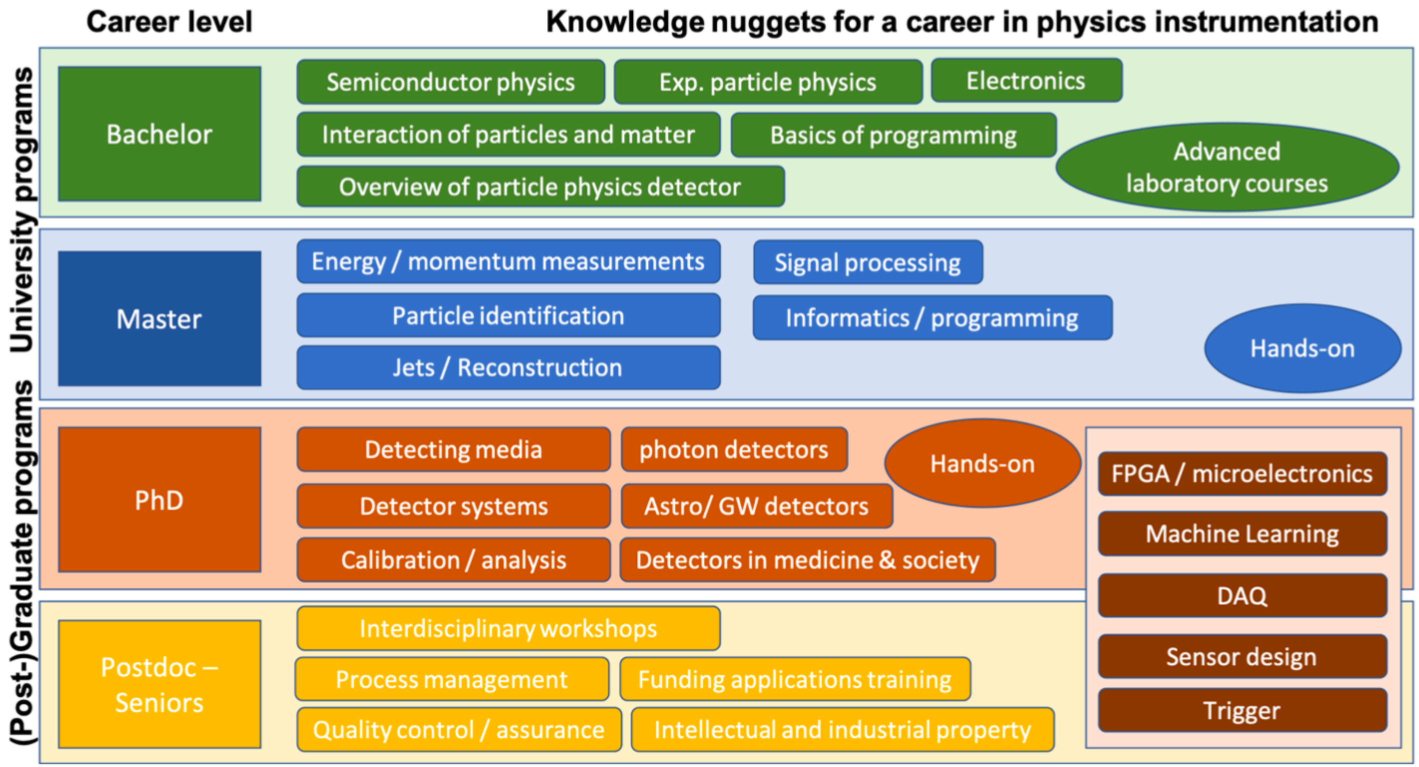


Training

DCT 1 Establish and maintain a European coordinated programme for training in instrumentation

DCT 2 Develop a master's degree programme in instrumentation

- Training for a career in physics instrumentation is a key element (especially given the timescale of the projects).
- Specific recommendation for the development of an education programme in instrumentation



Career level — **Knowledge nuggets for a career in physics instrumentation**

University programs

Bachelor
- Semiconductor physics
- Exp. particle physics
- Electronics
- Interaction of particles and matter
- Basics of programming
- Overview of particle physics detector
- Advanced laboratory courses

Master
- Energy / momentum measurements
- Signal processing
- Particle identification
- Informatics / programming
- Jets / Reconstruction
- Hands-on

(Post-)Graduate programs

PhD
- Detecting media
- photon detectors
- Hands-on
- Detector systems
- Astro/ GW detectors
- Calibration / analysis
- Detectors in medicine & society

Postdoc – Seniors
- Interdisciplinary workshops
- Process management
- Funding applications training
- Quality control / assurance
- Intellectual and industrial property

- FPGA / microelectronics
- Machine Learning
- DAQ
- Sensor design
- Trigger

Generic strategic recommendations

- The document gives **10 General Strategic Recommendations (GSR - see details in the backup)**:

GSR 1 - Supporting R&D facilities

GSR 2 - Engineering support for detector R&D

GSR 3 - Specific software for instrumentation

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

GSR 5 - Distributed R&D activities with centralised facilities

GSR 6 - Establish long-term strategic funding programmes

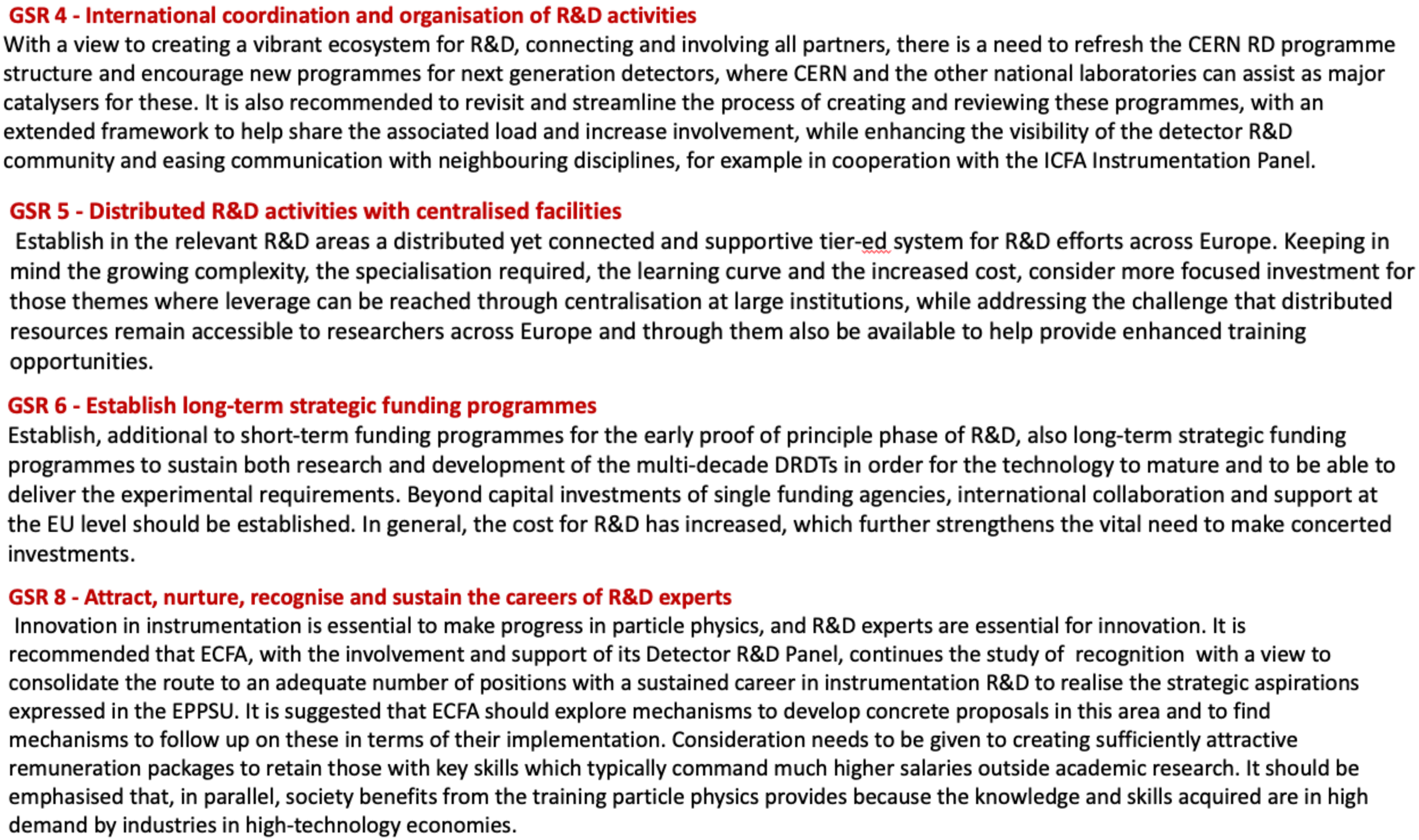
GSR 7 - Blue-sky R&D

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

GSR 9 - Industrial partnerships

GSR 10 - Open Science

General strategic recommendations



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.

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 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.

Summary

- The **scale and complexity** of the next big particle physics facility requires a **common ground for R&D** at European level.
- ECFA and LDG roadmaps have **defined the landscape of future R&D** in Europe:
  - To define short- and mid-term goals to **help decision making process** in the context of the European strategy.
  - To define a **broad and versatile R&D programme** that can meet the challenges (not only technological) of the next decades.
- The roadmaps emerge from **a thorough consultation process** with the community.
- The UK research landscape is **largely aligned** with the roadmaps (and in many cases it is one of the driving forces).
  - Dedicated discussion in town hall meeting tomorrow on UK internal process(es).

Backup

Accelerators - recommendations

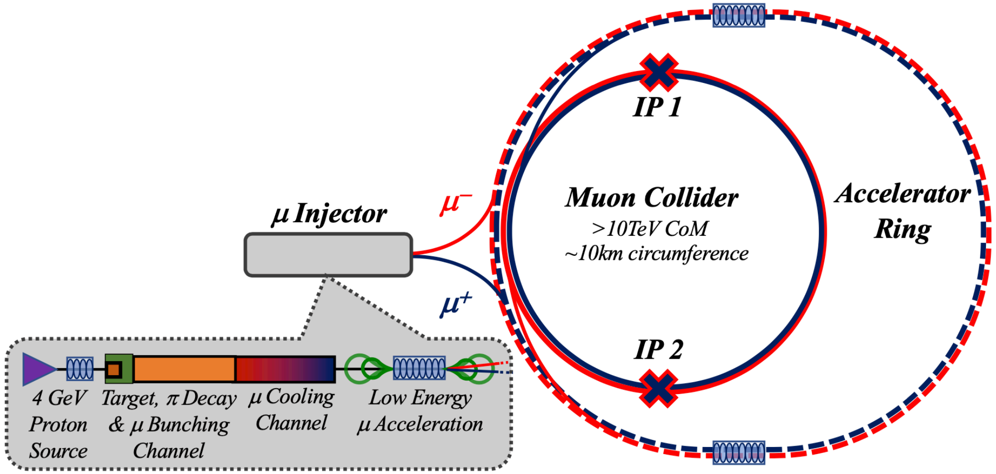
- [The Roadmap] should be accepted as the consensus view of the communities.
  - Further discussion, organisation, and prioritisation will be needed…
- Governance structures should oversee the ongoing R&D programmes, to ensure:
  - They are properly coordinated and balanced in their goals and execution
  - Their focus remains on implementation of the scientific goals of the European Strategy
  - Regular updates on progress are available to the community and to CERN Council.
- A broad front of R&D should be maintained, corresponding to at least the minimal [resource] scenario identified in each of the five areas.
- Provision must be left for the generation of novel developments
  - Revolutionary ideas have arisen via such routes in the past.
- Priority should be given to continuity of funding over the medium term, allowing the necessary investments in infrastructures and facilities
  - This is as important as the actual funding level.

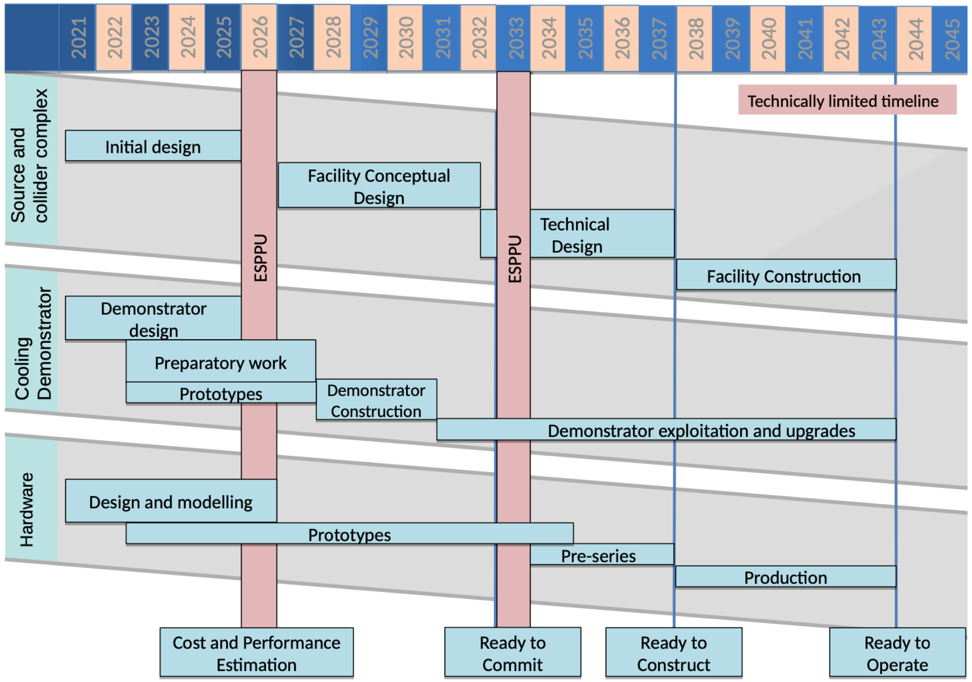
Accelerators - recommendations

- Environmental sustainability should be a primary consideration
  - Objective metrics should allow judgment of the cost and impact of future facilities over their entire life cycle.
- Emphasis should be placed on prompt scientific exploitation of R&D outputs
  - Careful appraisal of the potential of novel R&D [on] nearer-term major facilities
- Practical considerations of manufacturing, assembly, testing, and commissioning should factor into the design and parameters of future machines with the close engagement of industry
  - Industrial norms should be adopted, widening the applicability of new developments, and increasing the potential return on investment for industry
- Close cooperation between European and international laboratories is required
- Training and professional development of accelerator physicists is a key factor in sustaining a vibrant and productive field
  - Preferably in concert with corresponding initiatives for detector-focused particle physicists and computing specialists

Muon beams

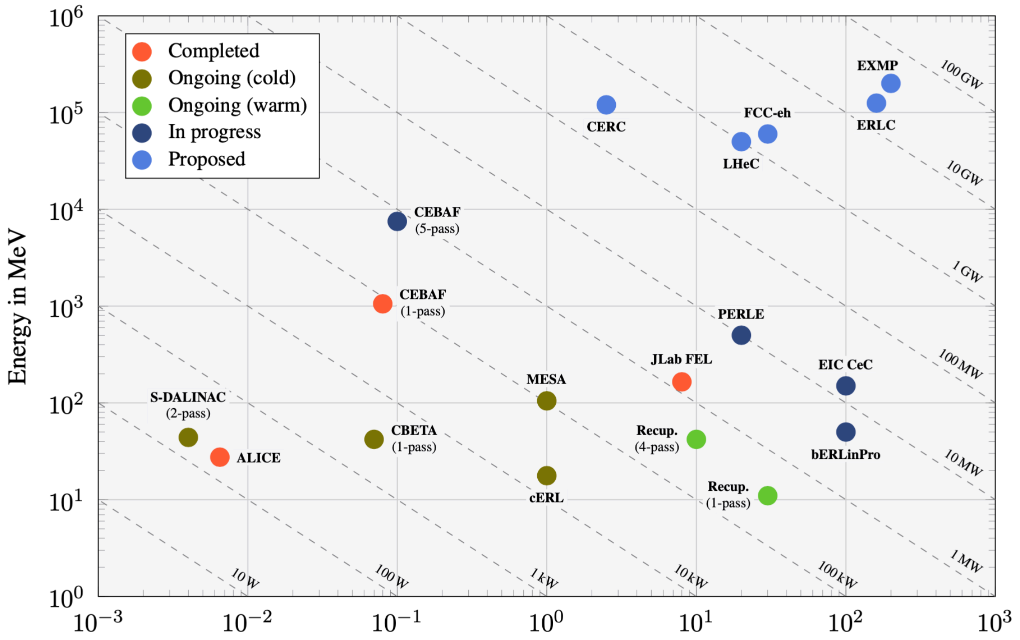
- Muon colliders are interesting because they can deliver high CM energy with efficient use of power.
- However muon decay: challenges with muon cooling cells, neutrino radiation,technology for magnets (quick ramp-up) and RF (operations in high magnetic field and low temperature).
- Benchmark defined on a 10 TeV collider, possibly with an intermediate 3 TeV.

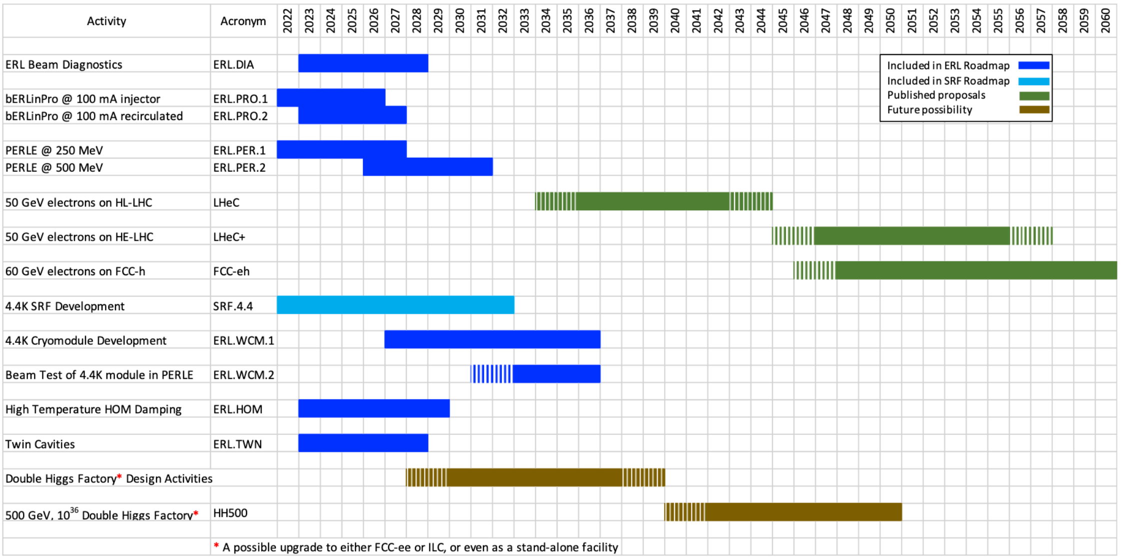




Energy Recovery Linacs

- In an ERL, the electron energy is “recycled” after the beam use.
- One can achieve high beam power with moderate RF power.
- Need to gain one or more order of magnitude (or more) for the future needs.
- R&D largely using existing facilities.

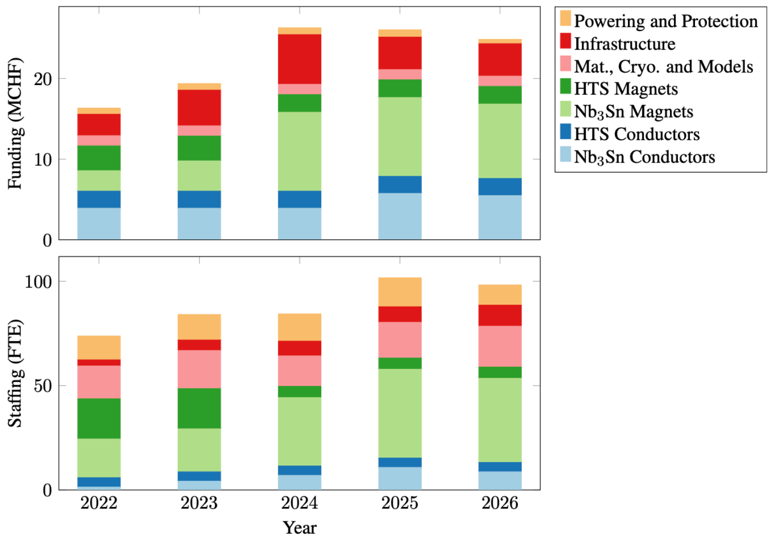


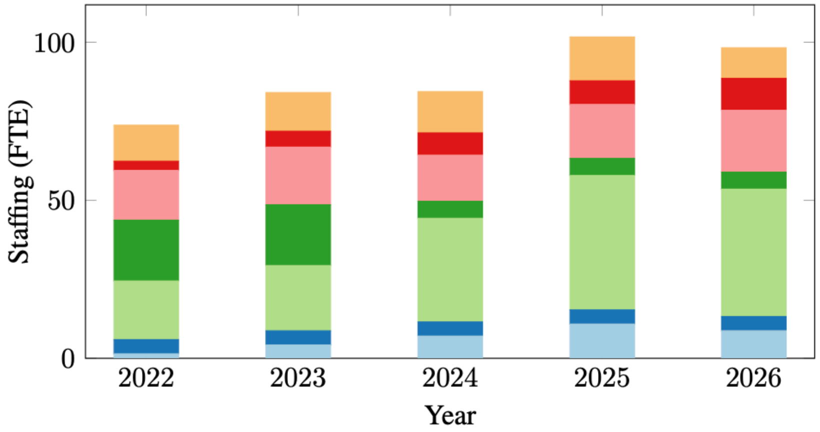


Activity	Acronym
ERL Beam Diagnostics	ERL.DIA
bERLinPro @ 100 mA injector	ERL.PRO.1
bERLinPro @ 100 mA recirculated	ERL.PRO.2
PERLE @ 250 MeV	ERL.PER.1
PERLE @ 500 MeV	ERL.PER.2
50 GeV electrons on HL-LHC	LHeC
50 GeV electrons on HE-LHC	LHeC+
60 GeV electrons on FCC-h	FCC-eh
4.4K SRF Development	SRF.4.4
4.4K Cryomodule Development	ERL.WCM.1
Beam Test of 4.4K module in PERLE	ERL.WCM.2
High Temperature HOM Damping	ERL.HOM
Twin Cavities	ERL.TWN
Double Higgs Factory* Design Activities	
500 GeV, 10^{36} Double Higgs Factory*	HH500

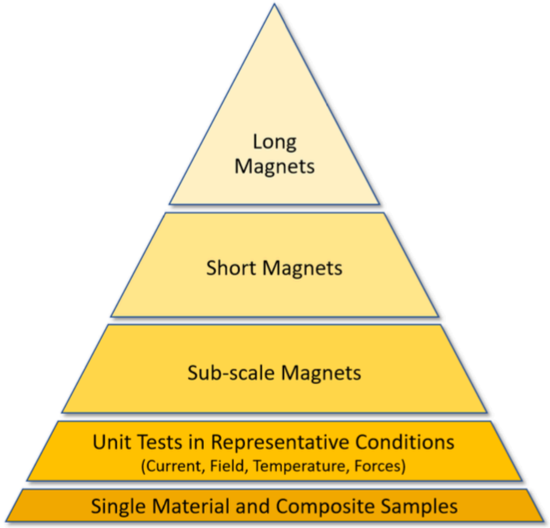
* A possible upgrade to either FCC-ee or ILC, or even as a stand-alone facility

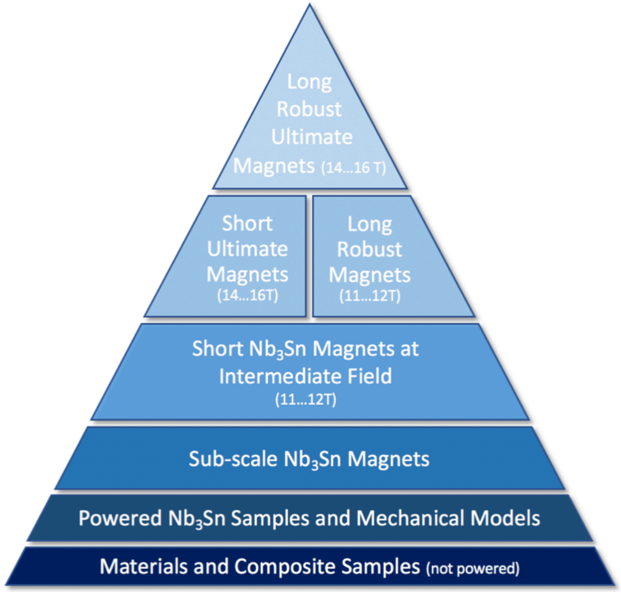
Overview of estimated costs

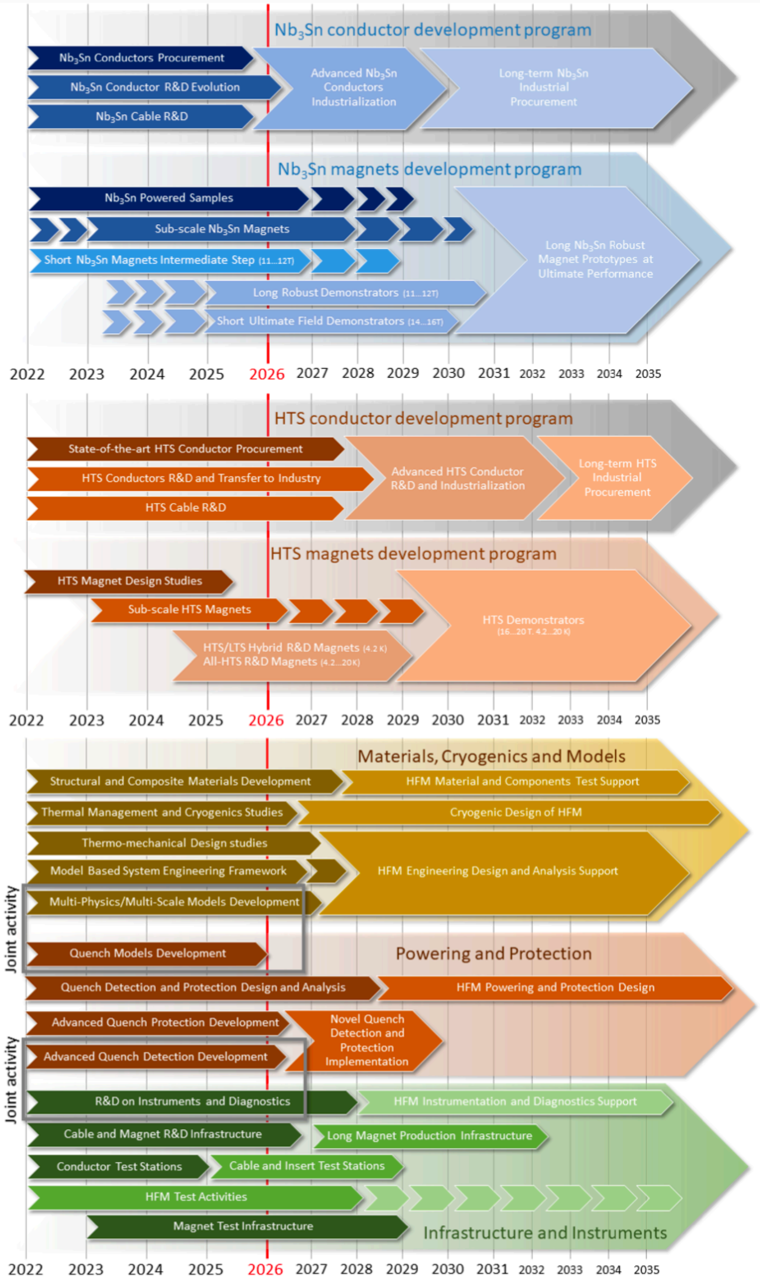




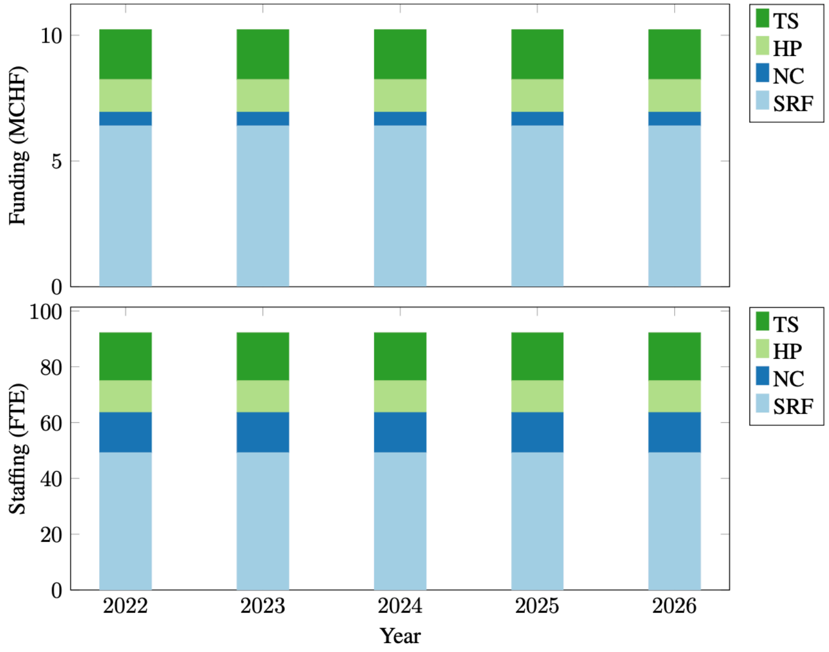
Tasks	Begin	End	Description	Nom. 5 y		Nom. 7 y		Asp. 7 y		Min. 7 y	
				M	P	M	P	M	P	M	P
MAG.LTSC.SOAP	2022	2025	Nb$_3$Sn conductors procurement	12.7	14.0	12.7	14.0	12.7	14.0	6.3	7.0
MAG.LTSC.COND	2022	2026	Nb$_3$Sn conductors R&D evolution	11.0	17.5	11.0	17.5	49.5	62.5	11.0	17.5
MAG.LTSC.CABL	2022	2025	Nb$_3$Sn cable R&D	2.2	10.5	2.2	10.5	2.2	10.5	2.2	10.5
MAG.LTSC.ADVP	2022	2031	Advances Nb$_3$Sn conductors Industrialisation	0.0	0.0	7.2	7.0	7.2	7.0	3.6	3.5
MAG.LTSC			**Total of Nb$_3$Sn conductor**	25.9	42.0	33.0	49.0	71.5	94.0	23.1	38.5
MAG.HTSC.SOAP	2022	2027	State-of-the-art HTS Conductor procurement	3.9	10.0	5.5	14.0	5.5	14.0	2.8	7.0
MAG.HTSC.COND	2022	2028	HTS conductors R&D and transfer to industry	5.5	7.0	5.5	7.0	5.5	7.0	0.0	0.0
MAG.HTSC.CABL	2022	2027	HTS cable R&D	3.9	10.5	3.9	10.5	3.9	10.5	1.1	5.0
MAG.HTSC			**Total of HTS conductor**	13.3	27.5	14.9	31.5	14.9	31.5	3.9	12.0
MAG.LTSM.SMPL	2022	2027	Nb$_3$Sn powered samples	1.6	25.0	2.2	35.0	2.2	35.0	1.1	17.0
MAG.LTSM.SUBS	2022	2028	Sub-scale Nb$_3$Sn magnets	7.1	35.0	9.9	49.0	9.9	49.0	5.0	25.0
MAG.LTSM.SD12	2022	2028	Short Nb$_3$Sn magnets intermediate step (11–12 T)	7.3	30.3	7.3	30.3	7.3	30.3	3.7	16.7
MAG.LTSM.LD12	2024	2031	Long robust demonstrators (11–12 T)	8.4	34.7	14.7	60.7	33.4	86.7	7.3	33.3
MAG.LTSM.SD16	2024	2031	Short ultimate field demonstrators (14–16 T)	11.0	40.0	15.4	56.0	15.4	56.0	7.7	28.0
MAG.LTSM			**Total of Nb$_3$Sn magnets**	35.4	165.0	49.5	231.0	68.2	257.0	24.8	120.0
MAG.HTSM.DSGN	2022	2025	HTS magnet design studies	4.4	32.5	4.4	32.5	4.4	32.5	2.2	16.5
MAG.HTSM.SUBS	2022	2027	Sub-scale HTS magnets	4.4	15.0	4.4	15.0	4.4	15.0	2.2	7.5
MAG.HTSM.SRDM	2024	2029	HTS/LTS hybrid (4.2 K) and all-HTS (4.2–20 K) R&D magnets	3.3	0.0	6.6	12.0	25.3	52.0	3.3	6.0
MAG.HTSM			**Total of HTS magnets**	12.1	47.5	15.4	59.5	34.1	99.5	7.7	30.0
MAG.MCM.MTRL	2022	2031	Structural and composite materials Development and characterisation	4.4	32.0	6.6	41.0	6.6	41.0	3.3	20.0
MAG.MCM.CRYO	2022	2028	Thermal management Cryogenics studies	2.2	37.0	2.2	37.0	2.2	37.0	1.1	18.0
MAG.MCM.THME	2022	2027	Thermo-mechanical design studies	0.0	11.0	0.0	12.3	0.0	12.3	0.0	6.7
MAG.MCM.MBSE	2022	2024	MBSE framework development	0.0	11.0	0.0	12.3	0.0	12.3	0.0	6.7
MAG.MCM.MDLS	2022	2027	Multi-physics and multi-scales models development	0.0	11.0	0.0	12.3	0.0	12.3	0.0	6.7
MAG.MCM			**Total of materials, cryogenics and models**	6.6	102.0	8.8	115.0	8.8	115.0	4.4	58.0
MAG.IETI.INST	2022	2028	Instrumentation diagnostics R&D	2.2	10.0	2.2	10.0	2.2	10.0	2.2	10.0
MAG.IETI.PINF	2022	2027	Cabling and magnet production R&D infrastructure	7.0	10.5	12.5	16.5	12.5	16.5	12.5	16.5
MAG.IETI.TCON	2022	2025	Conductor test stations (LTS and HTS)	3.9	6.5	3.9	6.5	3.9	6.5	3.9	6.5
MAG.IETI.TINS	2025	2029	Cables and insert test stations	0.0	1.5	5.5	4.0	5.5	4.0	5.5	4.0
MAG.IETI.TMAG	2023	2029	Magnet test infrastructure	2.2	4.0	4.4	14.0	15.4	24.0	4.4	14.0
MAG.IETI			**Total of infrastructures and instruments**	15.3	32.5	28.5	51.0	39.5	61.0	28.5	51.0
MAG.PETP.MDLS	2022	2026	Quench models development	0.0	4.0	0.0	5.0	0.0	5.0	0.0	5.0
MAG.PETP.DSGN	2022	2028	Quench detection Protection design and analysis	1.1	18.0	1.1	20.0	1.1	20.0	1.1	10.0
MAG.PETP.INST	2022	2026	Advanced quench Detection methods development	1.7	12.0	1.7	15.0	1.7	15.0	1.7	7.0
MAG.PETP.PROT	2022	2026	Advanced quench protection Strategies and methods development	1.7	28.0	1.7	30.0	1.7	30.0	1.7	15.0
MAG.PETP			**Total of powering and protection**	4.4	62.0	4.4	70.0	4.4	70.0	4.4	37.0
			Total	**112.9**	**478.5**	**154.4**	**607.0**	**241.3**	**728.0**	**96.7**	**346.5**


Long Magnets
Short Magnets
Sub-scale Magnets
Unit Tests in Representative Conditions
(Current, Field, Temperature, Forces)
Single Material and Composite Samples


Long Robust Ultimate Magnets (14...16 T)
Short Ultimate Magnets (14...16T)
Long Robust Magnets (11...12T)
Short Nb_3Sn Magnets at Intermediate Field (11...12T)
Sub-scale Nb_3Sn Magnets
Powered Nb_3Sn Samples and Mechanical Models
Materials and Composite Samples (not powered)

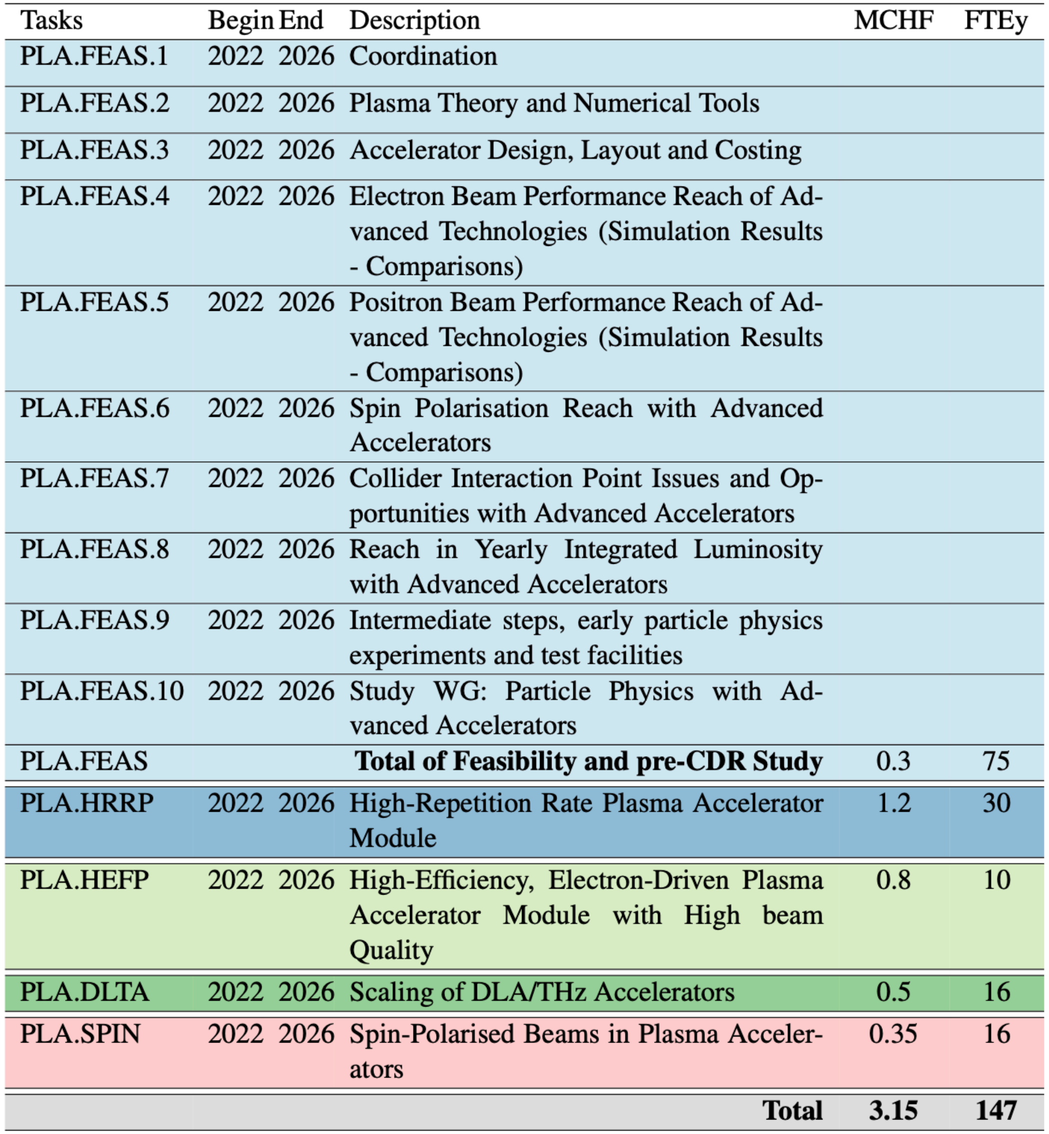

Nb_3Sn conductor development program
Nb_3Sn Conductors Procurement
Nb_3Sn Conductor R&D Evolution
Nb_3Sn Cable R&D
Advanced Nb_3Sn Conductors Industrialization
Long-term Nb_3Sn Industrial Procurement
Nb_3Sn magnets development program
Nb_3Sn Powered Samples
Sub-scale Nb_3Sn Magnets
Short Nb_3Sn Magnets Intermediate Step (11...12T)
Long Robust Demonstrators (11...12T)
Short Ultimate Field Demonstrators (14...16T)
Long Nb_3Sn Robust Magnet Prototypes at Ultimate Performance
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
HTS conductor development program
State-of-the-art HTS Conductor Procurement
HTS Conductors R&D and Transfer to Industry
HTS Cable R&D
Advanced HTS Conductor R&D and Industrialization
Long-term HTS Industrial Procurement
HTS magnets development program
HTS Magnet Design Studies
Sub-scale HTS Magnets
HTS/LTS Hybrid R&D Magnets (4.2 K)
All-HTS R&D Magnets (4.2...20K)
HTS Demonstrators
(16...20 T, 4.2...20 K)
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
Materials, Cryogenics and Models
Structural and Composite Materials Development
HFM Material and Components Test Support
Thermal Management and Cryogenics Studies
Cryogenic Design of HFM
Thermo-mechanical Design studies
Model Based System Engineering Framework
HFM Engineering Design and Analysis Support
Joint activity
Multi-Physics/Multi-Scale Models Development
Quench Models Development
Powering and Protection
Quench Detection and Protection Design and Analysis
HFM Powering and Protection Design
Advanced Quench Protection Development
Novel Quench Detection and Protection Implementation
Joint activity
Advanced Quench Detection Development
R&D on Instruments and Diagnostics
HFM Instrumentation and Diagnostics Support
Cable and Magnet R&D Infrastructure
Long Magnet Production Infrastructure
Conductor Test Stations
Cable and Insert Test Stations
HFM Test Activities
Magnet Test Infrastructure
Infrastructure and Instruments
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035

RF resource

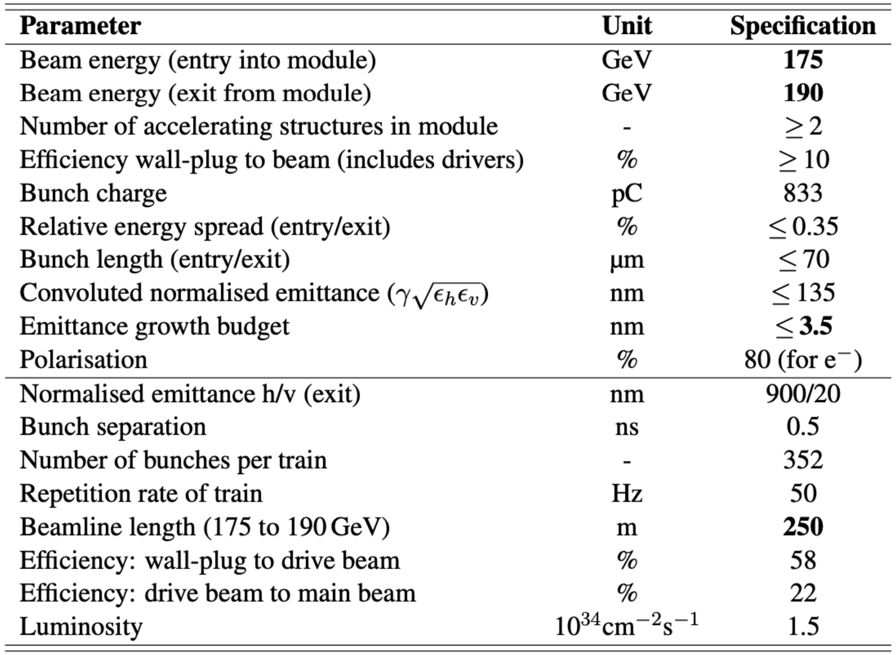


Tasks	Begin	End	Description	MCHF	FTEy
RF.SRF.BKNb	2022	2026	Superconducting RF: bulk Nb	4	75
RF.SRF.FE	2022	2026	Superconducting RF: field emission	4	40
RF.SRF.ThF	2022	2026	Superconducting RF: thin film	15	100
RF.SRF.INF	2022	2026	Superconducting RF: infrastructure	5	15
RF.SRF.FPC	2022	2026	Superconducting RF: power couplers	4	16
RF.SRF			**Total of superconducting RF**	32	246
RF.NC.GEN	2022	2026	Normal conducting RF: general NC studies	0	27
RF.NC.MAN	2022	2026	Normal conducting RF: NC manufacturing techniques	2.5	30
RF.NC.HF	2022	2026	Normal conducting RF: mm wave & high frequency	0.2	15
RF.NC			**Total of normal conducting RF**	2.7	72
RF.HP.HE	2022	2026	High-power RF: high-efficiency klystron & solid state	5.5	20
RF.HP.HF	2022	2026	High-power RF: mm-wave & gyro devices	0	5
RF.HP.TUN	2022	2026	High-power RF: reduced RF power needs (tuners)	0.4	6
RF.HP.AI	2022	2026	AI and machine learning	0.6	26
RF.HP			**Total of high-power RF**	6.5	57
RF.TS.NCRF	2022	2026	NC RF test stands	5.3	40
RF.TS.MAT	2022	2026	Test stand: new materials	0.7	16
RF.TS.BEAM	2022	2026	Beam test	3	20
RF.TS.SRF	2022	2026	Test stand: SRF Horizontal cryostat	0.9	10
RF.TS			**Total for test stand**	9.9	86
			Total	**51.1**	**461**

Laser/Plasma acceleration

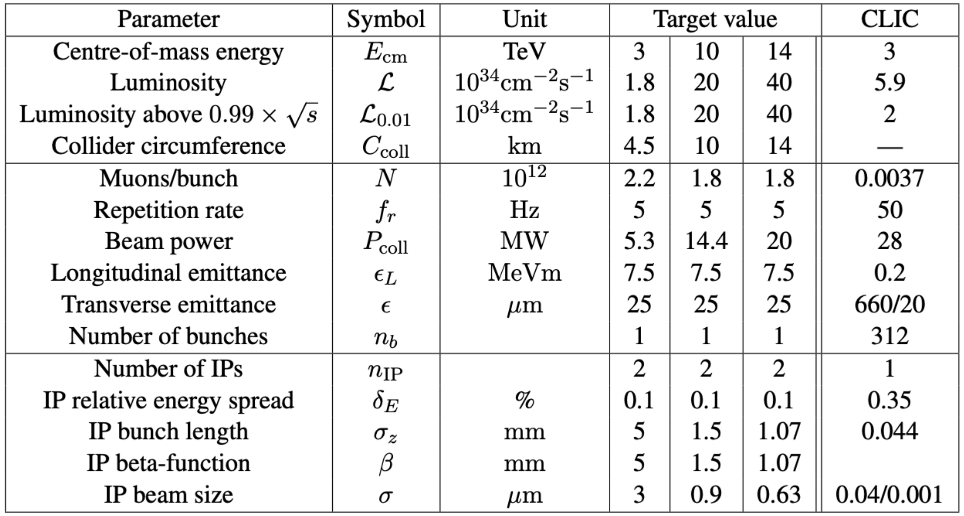


Tasks	Begin	End	Description	MCHF	FTEy
PLA.FEAS.1	2022	2026	Coordination		
PLA.FEAS.2	2022	2026	Plasma Theory and Numerical Tools		
PLA.FEAS.3	2022	2026	Accelerator Design, Layout and Costing		
PLA.FEAS.4	2022	2026	Electron Beam Performance Reach of Advanced Technologies (Simulation Results - Comparisons)		
PLA.FEAS.5	2022	2026	Positron Beam Performance Reach of Advanced Technologies (Simulation Results - Comparisons)		
PLA.FEAS.6	2022	2026	Spin Polarisation Reach with Advanced Accelerators		
PLA.FEAS.7	2022	2026	Collider Interaction Point Issues and Opportunities with Advanced Accelerators		
PLA.FEAS.8	2022	2026	Reach in Yearly Integrated Luminosity with Advanced Accelerators		
PLA.FEAS.9	2022	2026	Intermediate steps, early particle physics experiments and test facilities		
PLA.FEAS.10	2022	2026	Study WG: Particle Physics with Advanced Accelerators		
PLA.FEAS			**Total of Feasibility and pre-CDR Study**	0.3	75
PLA.HRRP	2022	2026	High-Repetition Rate Plasma Accelerator Module	1.2	30
PLA.HEFP	2022	2026	High-Efficiency, Electron-Driven Plasma Accelerator Module with High beam Quality	0.8	10
PLA.DLTA	2022	2026	Scaling of DLA/THz Accelerators	0.5	16
PLA.SPIN	2022	2026	Spin-Polarised Beams in Plasma Accelerators	0.35	16
			Total	**3.15**	**147**

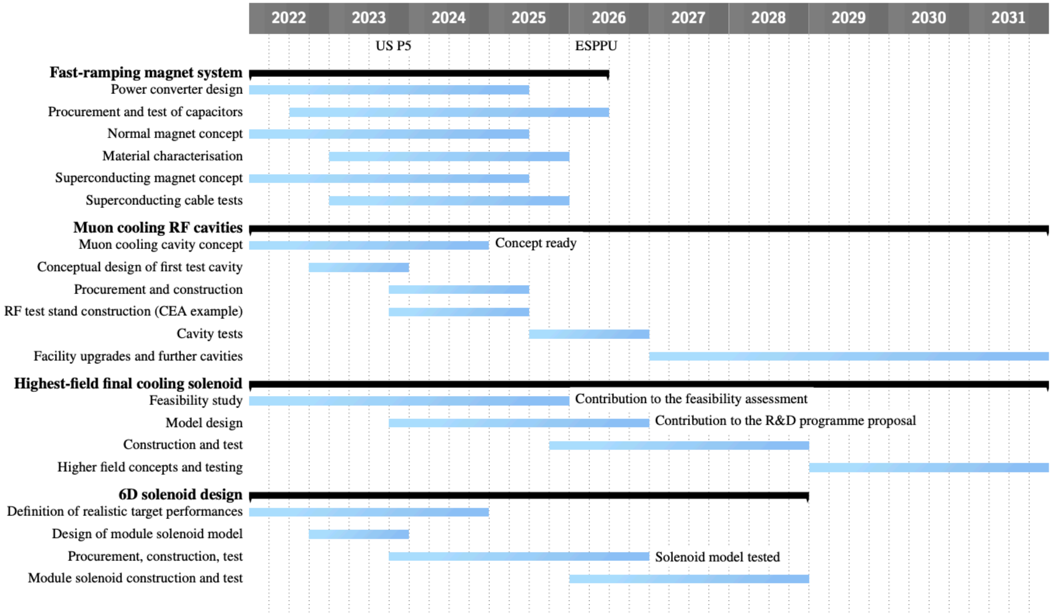


Parameter	**Unit**	**Specification**
Beam energy (entry into module)	GeV	**175**
Beam energy (exit from module)	GeV	**190**
Number of accelerating structures in module	-	≥ 2
Efficiency wall-plug to beam (includes drivers)	%	≥ 10
Bunch charge	pC	833
Relative energy spread (entry/exit)	%	≤ 0.35
Bunch length (entry/exit)	µm	≤ 70
Convoluted normalised emittance ($\gamma\sqrt{\epsilon_h\epsilon_v}$)	nm	≤ 135
Emittance growth budget	nm	$\leq$ **3.5**
Polarisation	%	80 (for e^-)
Normalised emittance h/v (exit)	nm	900/20
Bunch separation	ns	0.5
Number of bunches per train	-	352
Repetition rate of train	Hz	50
Beamline length (175 to 190 GeV)	m	**250**
Efficiency: wall-plug to drive beam	%	58
Efficiency: drive beam to main beam	%	22
Luminosity	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.5

Muon collider



Parameter	Symbol	Unit	Target value			CLIC
Centre-of-mass energy	E_{cm}	TeV	3	10	14	3
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.8	20	40	5.9
Luminosity above $0.99 \times \sqrt{s}$	$\mathcal{L}_{0.01}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.8	20	40	2
Collider circumference	C_{coll}	km	4.5	10	14	—
Muons/bunch	N	10^{12}	2.2	1.8	1.8	0.0037
Repetition rate	f_r	Hz	5	5	5	50
Beam power	P_{coll}	MW	5.3	14.4	20	28
Longitudinal emittance	ϵ_L	MeVm	7.5	7.5	7.5	0.2
Transverse emittance	ϵ	μm	25	25	25	660/20
Number of bunches	n_b		1	1	1	312
Number of IPs	n_{IP}		2	2	2	1
IP relative energy spread	δ_E	%	0.1	0.1	0.1	0.35
IP bunch length	σ_z	mm	5	1.5	1.07	0.044
IP beta-function	β	mm	5	1.5	1.07	
IP beam size	σ	μm	3	0.9	0.63	0.04/0.001



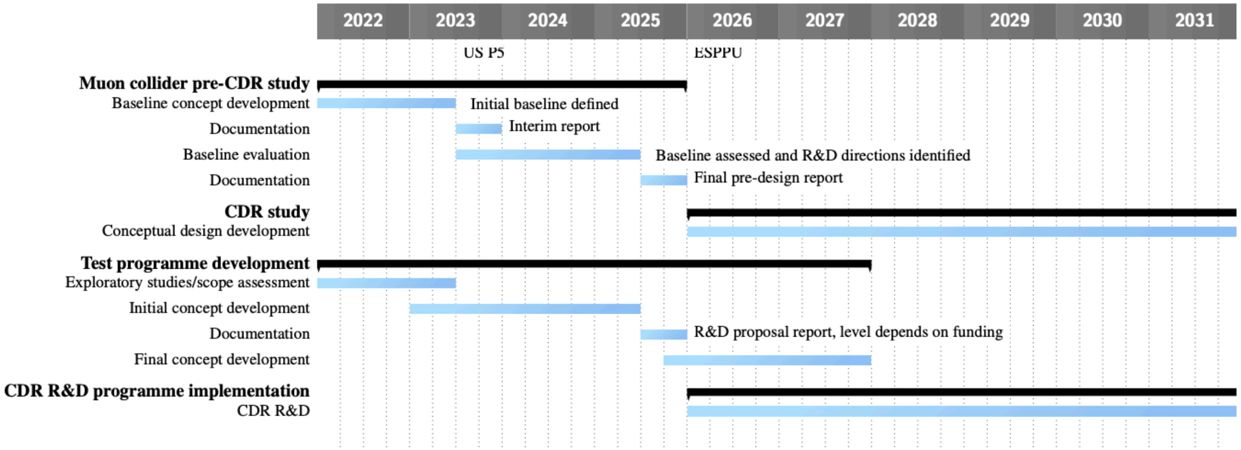


Fig. 5.4: Overall timeline for the R&D programme.

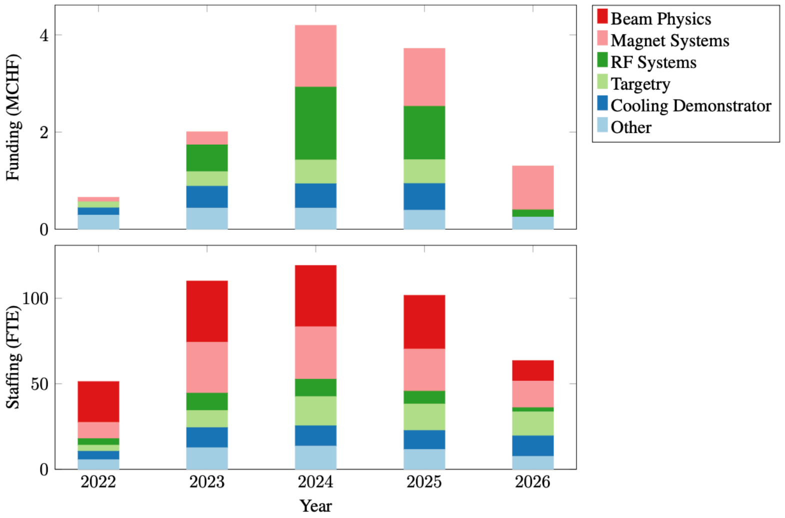


Fig. 5.7: Muon resource requirement profile in the aspirational programme.

Energy Recovery Linacs

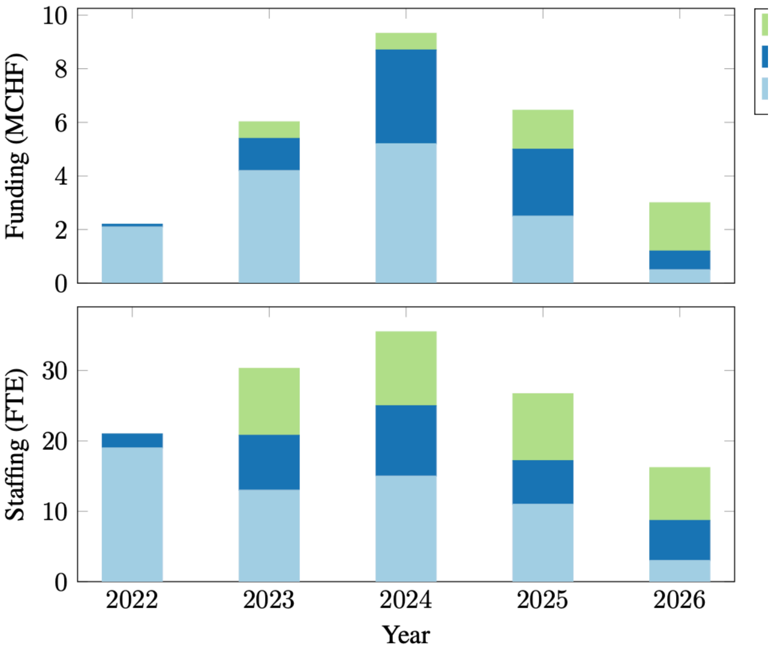
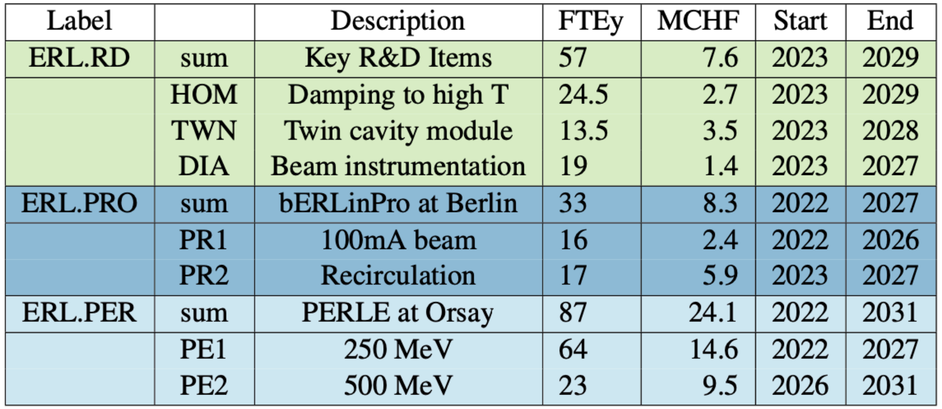
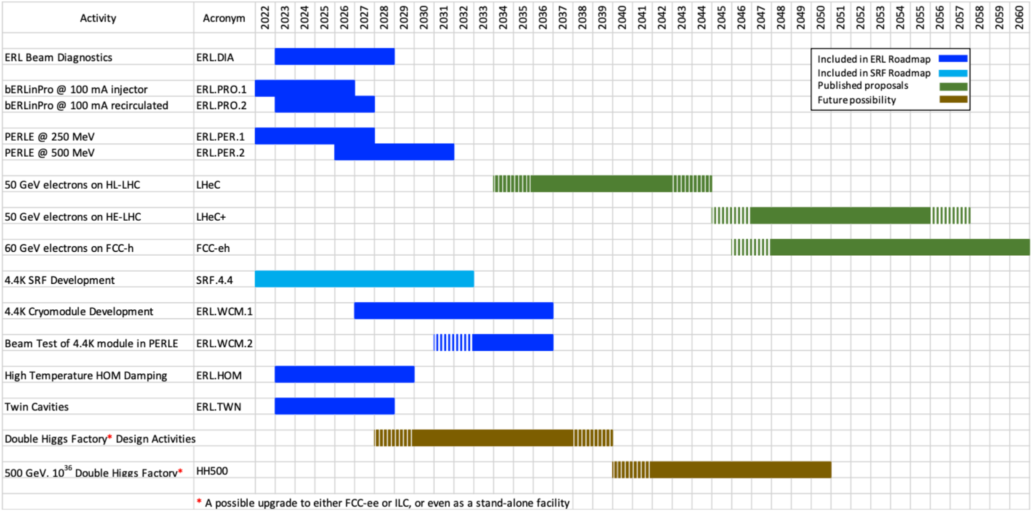


Table 6.5: Total effort for the R&D program on energy recovery linacs as presented in this roadmap, providing the total number of FTE years and MCHF for the duration as indicated. More detailed information is provided with the charts for all topics as presented above. The table does not include in-kind and infrastructure contributions nor further investments in ongoing facilities.



Label		Description	FTEy	MCHF	Start	End
ERL.RD	sum	Key R&D Items	57	7.6	2023	2029
	HOM	Damping to high T	24.5	2.7	2023	2029
	TWN	Twin cavity module	13.5	3.5	2023	2028
	DIA	Beam instrumentation	19	1.4	2023	2027
ERL.PRO	sum	bERLinPro at Berlin	33	8.3	2022	2027
	PR1	100mA beam	16	2.4	2022	2026
	PR2	Recirculation	17	5.9	2023	2027
ERL.PER	sum	PERLE at Orsay	87	24.1	2022	2031
	PE1	250 MeV	64	14.6	2022	2027
	PE2	500 MeV	23	9.5	2026	2031



Activity	Acronym
ERL Beam Diagnostics	ERL.DIA
bERLinPro @ 100 mA injector	ERL.PRO.1
bERLinPro @ 100 mA recirculated	ERL.PRO.2
PERLE @ 250 MeV	ERL.PER.1
PERLE @ 500 MeV	ERL.PER.2
50 GeV electrons on HL-LHC	LHeC
50 GeV electrons on HE-LHC	LHeC+
60 GeV electrons on FCC-h	FCC-eh
4.4K SRF Development	SRF.4.4
4.4K Cryomodule Development	ERL.WCM.1
Beam Test of 4.4K module in PERLE	ERL.WCM.2
High Temperature HOM Damping	ERL.HOM
Twin Cavities	ERL.TWN
Double Higgs Factory* Design Activities	
500 GeV, 10^{36} Double Higgs Factory*	HH500

* A possible upgrade to either FCC-ee or ILC, or even as a stand-alone facility

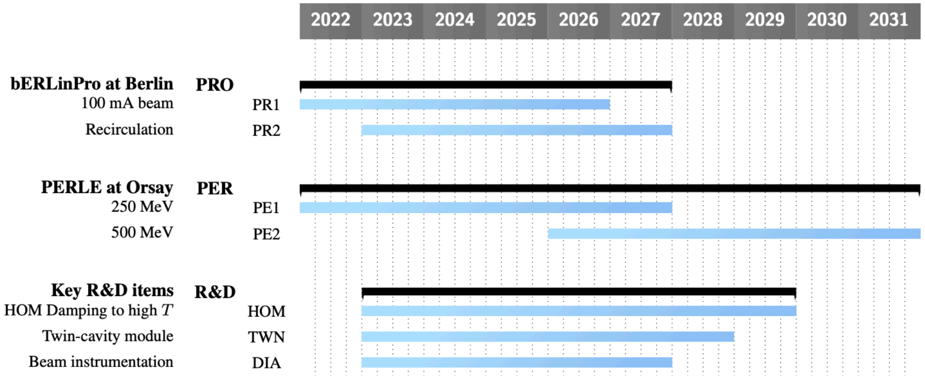
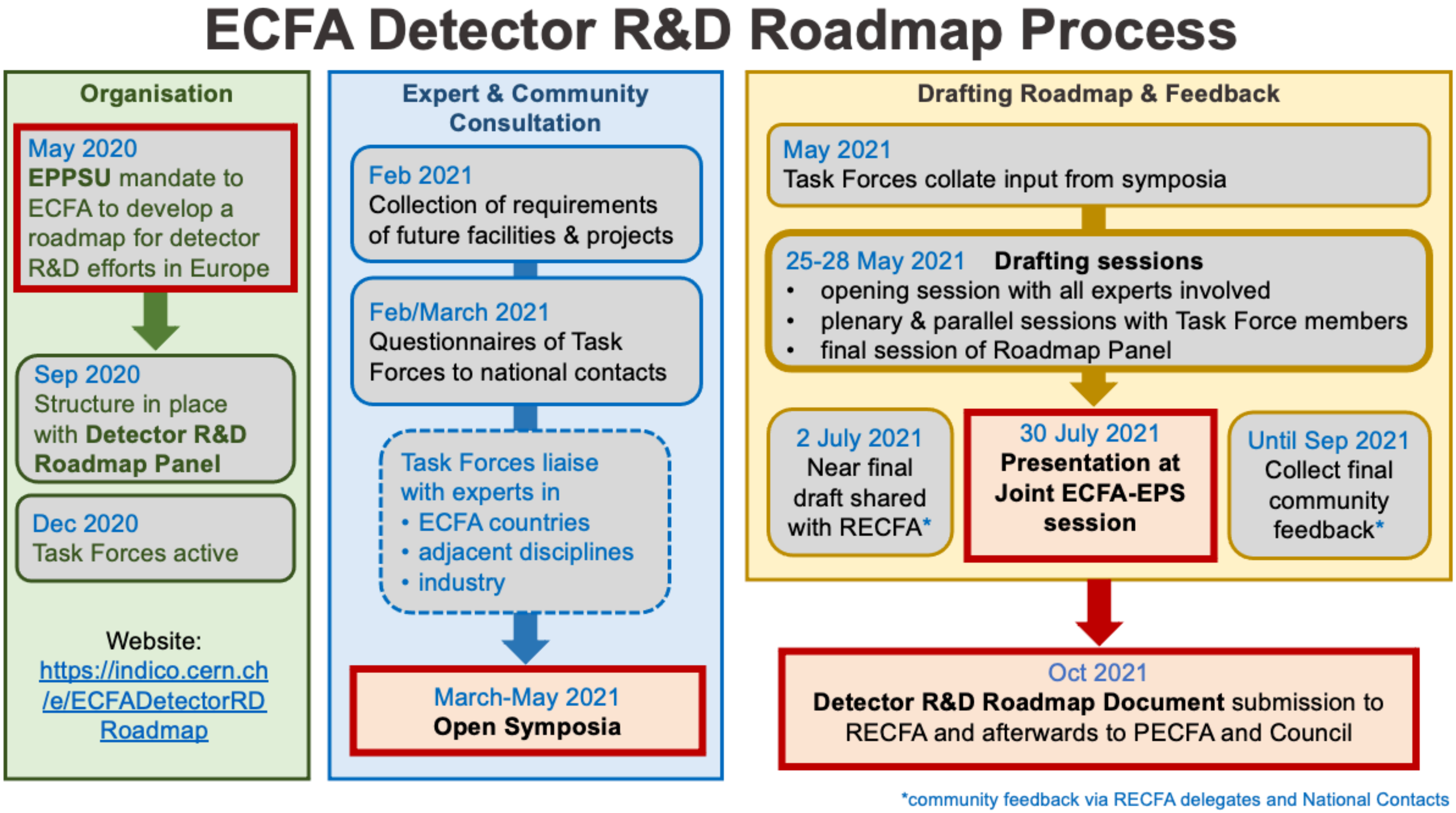


Fig. 6.4: Time lines of the key ERL roadmap themes.

Community consultation



ECFA Detector R&D Roadmap Process

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

2 July 2021
Near final draft shared with RECFA*

30 July 2021
Presentation at Joint ECFA-EPS session

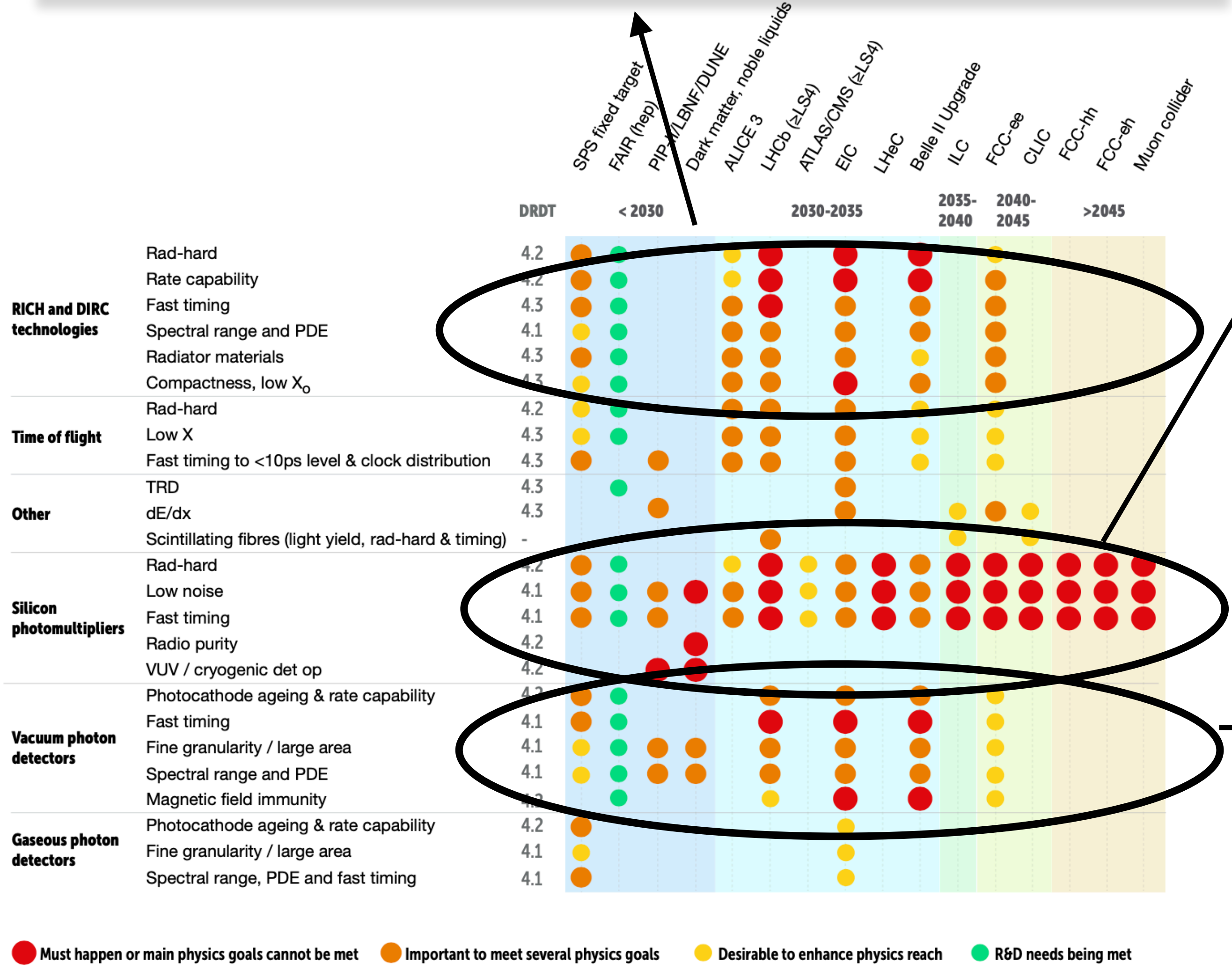
Until Sep 2021
Collect final community feedback*

Oct 2021
Detector R&D Roadmap Document submission to RECFA and afterwards to PECFA and Council

*community feedback via RECFA delegates and National Contacts

Photon sensors - Particle Identification

Particle identification touches upon a number of different detectors used on a variety of different experiments (LHCb upgrade is one example)



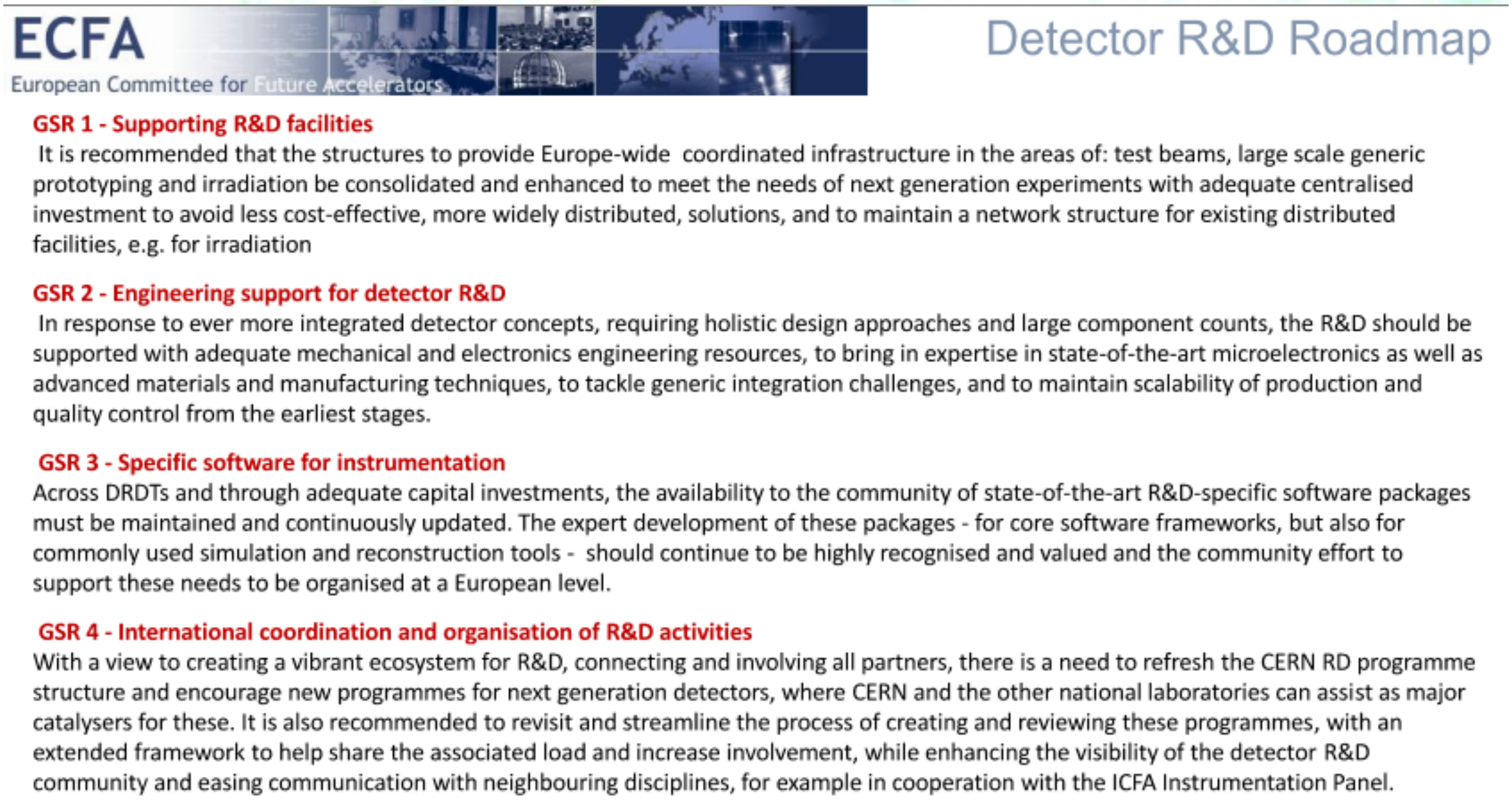
			< 2030				2030-2035						2035-2040	2040-2045		>2045		
		DRDT	SPS fixed target	FAIR (hep)	PIP-II/LBNF/DUNE	Dark matter, noble liquids	ALICE 3	LHCb (≥LS4)	ATLAS/CMS (≥LS4)	EIC	LHeC	Belle II Upgrade	ILC	FCC-ee	CLIC	FCC-hh	FCC-eh	Muon collider
RICH and DIRC technologies	Rad-hard	4.2	🟠	🟢			🟡	🔴		🔴		🔴		🟡				
	Rate capability	4.2	🟠	🟢			🟡	🔴		🔴		🔴		🟠				
	Fast timing	4.3	🟠	🟢			🟠	🔴		🟠		🟠		🟠				
	Spectral range and PDE	4.1	🟡	🟢			🟠	🟠		🟠		🟠		🟠				
	Radiator materials	4.3	🟠	🟢			🟠	🟠		🟠		🟡		🟠				
	Compactness, low X_0	4.3	🟡	🟢			🟠	🟠		🔴		🟠		🟠				
Time of flight	Rad-hard	4.2	🟡	🟢			🟠	🟠		🟠		🟡		🟡				
	Low X	4.3	🟡	🟢			🟠	🟠		🟠		🟡		🟡				
	Fast timing to <10ps level & clock distribution	4.3	🟠		🟠		🟠	🟠		🟠		🟡		🟡				
Other	TRD	4.3		🟢						🟠								
	dE/dx	4.3			🟠					🟠			🟡	🟠	🟡			
	Scintillating fibres (light yield, rad-hard & timing)	-						🟠					🟡		🟡			
Silicon photomultipliers	Rad-hard	4.2	🟠	🟢			🟡	🔴	🟡	🟠	🔴	🟠	🔴	🔴	🔴	🔴	🔴	🔴
	Low noise	4.1	🟠	🟢	🟠	🔴	🟠	🔴	🟡	🟠	🔴	🟠	🔴	🔴	🔴	🔴	🔴	🔴
	Fast timing	4.1	🟠	🟢	🟠		🟠	🔴	🟡	🟠	🔴	🟠	🔴	🔴	🔴	🔴	🔴	🔴
	Radio purity	4.2				🔴												
	VUV / cryogenic det op	4.2			🔴	🔴												
Vacuum photon detectors	Photocathode ageing & rate capability	4.2	🟠	🟢				🟠		🟠		🟠		🟡				
	Fast timing	4.1	🟠	🟢				🔴		🔴		🔴		🟡				
	Fine granularity / large area	4.1	🟡	🟢	🟠	🟠		🟠		🟠		🟠		🟡				
	Spectral range and PDE	4.1	🟡	🟢	🟠	🟠		🟠		🟠		🟠		🟡				
	Magnetic field immunity	4.2		🟢				🟡		🔴		🔴		🟡				
Gaseous photon detectors	Photocathode ageing & rate capability	4.2	🟠							🟡								
	Fine granularity / large area	4.1	🟡							🟡								
	Spectral range, PDE and fast timing	4.1	🟠							🟡								

🔴 **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**

SiPM a flexible and cheap photon detector needed in LB neutrino experiments as well as colliders applications.

Main R&D items:
- extension of efficiency to near UV
- Reduction of dark count,
- Increased radiation hard

MCP-PMT and LAPPD are good candidates for large area coverage, but at the moment expensive (and not necessarily tolerant to high magnetic fields)



ECFA

European Committee for Future Accelerators

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.

Detector R&D Roadmap

GSR 5 - Distributed R&D activities with centralised facilities

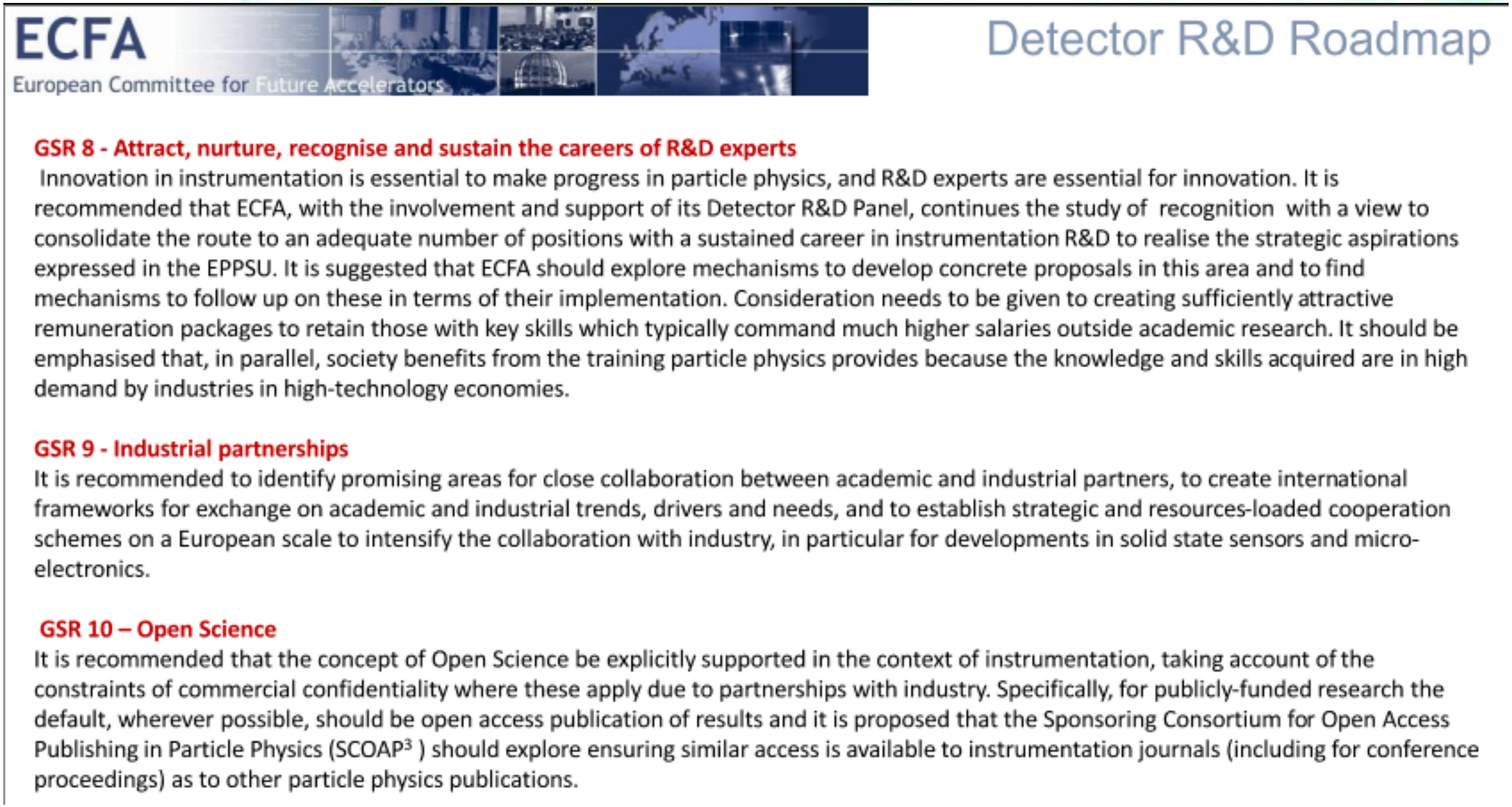
Establish in the relevant R&D areas a distributed yet connected and supportive tier-ed system for R&D efforts across Europe. Keeping in mind the growing complexity, the specialisation required, the learning curve and the increased cost, consider more focused investment for those themes where leverage 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

European Committee for Future Accelerators

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

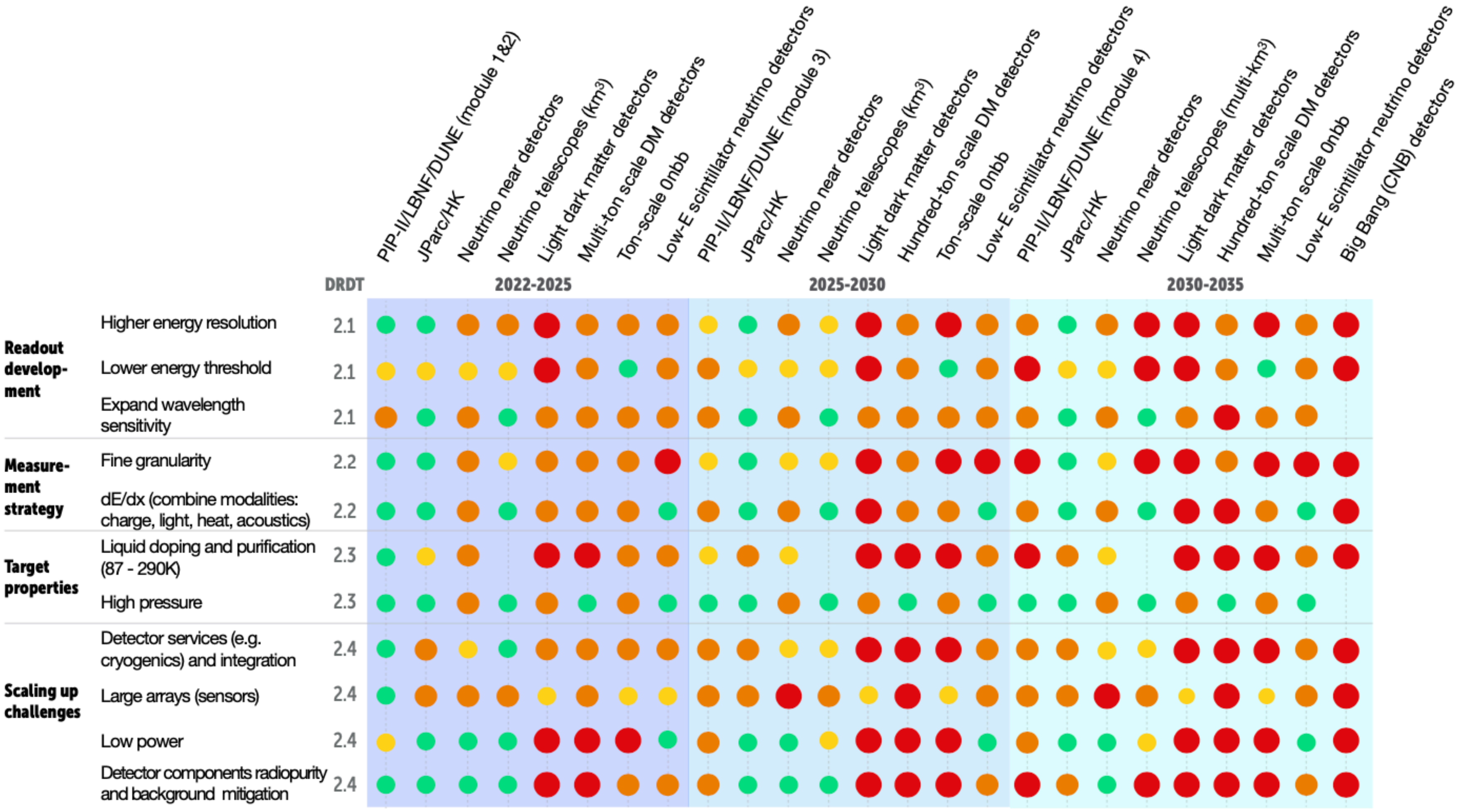
It is recommended that the concept of Open Science be explicitly supported in the context of instrumentation, taking account of the constraints of commercial confidentiality where these apply due to partnerships with industry. Specifically, for publicly-funded research the default, wherever possible, 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.

Gaseous detectors

		DRDT	< 2030						2030-2035						2035-2040	2040-2045			>2045		
			SPS fixed target (Amber, NA62+, NA60)	FAIR (PANDA, CBM)	Other fixed target (COMET, MU2E,...)	Neutrino near detectors (DUNE)	Large ton dual-phase[1)]	Light dark matter...[2)]	LHCb (≥LS4)	ATLAS/CMS (≥LS4)	EIC	LHeC	R&D DM/neutrino experiments[3)]	R&D ton scale 0nbb	ILC	FCC-ee	CLIC	STCF	FCC-hh	FCC-eh	Muon collider
Muon system **Proposed technologies:** RPC, Multi-GEM, resistive GEM, Micromegas, micropixel Micromegas, μRwell, μPIC ...	Rad-hard/longevity	1.1		🟢					🔴	🔴		🔴			🟢	🟢	🟢		🔴	🟢	🟡
	Time resolution	1.1							🟡	🟡		🟡			🟢	🟡	🟢		🟡	🟡	🟠
	Fine granularity	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟡	🟢		🔴	🟡	🔴
	Gas properties (eco-gas)	1.3								🟠						🔴			🔴	🔴	🔴
	Spatial resolution	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🟠	🟠	🟠
	Rate capability	1.3	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🔴	🟢	🟡
Inner/central tracking with PID **Proposed technologies:** TPC+(multi-GEM, Micromegas, Gridpix), drift chambers, cylindrical layers of MPGD, straw chambers	Rad-hard/longevity	1.1	🟠	🟠	🟠						🟡				🟢		🟢				
	Low X_o	1.2	🟠	🟠	🟠						🟠				🟠	🔴	🟠	🔴			
	IBF (TPC only)	1.2	🟠	🟠											🔴	🔴	🔴	🔴			
	Time resolution	1.1	🟡		🟡						🟠				🟢	🟡	🟢	🟡			
	Rate capability	1.3	🟠		🟠						🟠				🟢	🟡	🟢	🟡			
	dE/dx	1.2	🟠								🟠				🟠	🟠	🟠	🟠			
	Fine granularity	1.1	🟠		🟠						🟠				🟠	🟠	🟠	🟠			
Preshower/ Calorimeters **Proposed technologies:** RPC, MRPC, Micromegas and GEM, μRwell, InGrid (integrated Micromegas grid with pixel readout), Pico-sec, FTM	Rad-hard/longevity	1.1													🟡	🟡	🟡		🔴	🔴	🔴
	Low power	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Gas properties (eco-gas)	1.3													🔴	🔴	🔴		🔴	🔴	🔴
	Fast timing	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Fine granularity	1.1													🟠	🟠	🟠		🟠	🟠	🟠
	Rate capability	1.3													🟠	🟠	🟠		🔴	🔴	🟠
	Large array/integration	1.3													🔴	🔴	🔴		🔴	🔴	🔴
Particle ID/TOF **Proposed technologies:** RICH+MPGD, TRD+MPGD, TOF: MRPC, Picosec, FTM	Rad-hard (photocathode)	1.1	🟠	🟠							🟡										
	IBF (RICH only)	1.2	🟠	🟠							🟠										
	Precise timing	1.1	🟡	🔴							🔴										
	Rate capability	1.3		🟢							🟠										
	dE/dx	1.2		🟢																	
	Fine granularity	1.1		🟠							🟠										
TPC for rare decays **Proposed technologies:** TPC+MPGD operation (from very low to very high pressure)	Low power	1.4				🔴	🔴						🔴								
	Fine granularity	1.4				🟢	🟠	🟠					🟠	🟠							
	Large array/volume	1.4				🟡	🟠	🟡					🔴	🔴							
	Higher energy resolution	1.4				🟢	🔴	🔴					🔴	🔴							
	Lower energy threshold	1.4				🔴	🟠	🔴					🟠	🔴							
	Optical readout	1.4				🟡	🟠	🟠					🟠	🟠							
	Gas pressure stability	1.4				🟢		🔴						🔴							
	Radiopurity	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**

Liquid detectors



		DRDT	2022-2025							
			PIP-II/LBNF/DUNE (module 1&2)	JParc/HK	Neutrino near detectors	Neutrino telescopes (km^3)	Light dark matter detectors	Multi-ton scale DM detectors	Ton-scale 0nbb	Low-E scintillator neutrino detectors
Readout development	Higher energy resolution	2.1	🟢	🟢	🟠	🟠	🔴	🟠	🟠	🟠
	Lower energy threshold	2.1	🟡	🟡	🟡	🟡	🔴	🟠	🟢	🟠
	Expand wavelength sensitivity	2.1	🟠	🟢	🟠	🟢	🟠	🟠	🟠	🟠
Measurement strategy	Fine granularity	2.2	🟢	🟢	🟠	🟡	🟠	🟠	🟠	🔴
	dE/dx (combine modalities: charge, light, heat, acoustics)	2.2	🟢	🟢	🟠	🟢	🟠	🟠	🟠	🟢
Target properties	Liquid doping and purification (87 - 290K)	2.3	🟢	🟡	🟠		🔴	🔴	🟠	🟠
	High pressure	2.3	🟢	🟢	🟠	🟢	🟠	🟢	🟠	🟢
Scaling up challenges	Detector services (e.g. cryogenics) and integration	2.4	🟢	🟠	🟡	🟢	🟠	🟠	🟠	🟠
	Large arrays (sensors)	2.4	🟢	🟠	🟠	🟠	🟡	🟠	🟡	🟡
	Low power	2.4	🟡	🟢	🟢	🟢	🔴	🔴	🔴	🟢
	Detector components radiopurity and background mitigation	2.4	🟢	🟢	🟢	🟢	🔴	🔴	🟠	🟠

		DRDT	2025-2030							
			PIP-II/LBNF/DUNE (module 3)	JParc/HK	Neutrino near detectors	Neutrino telescopes (km^3)	Light dark matter detectors	Hundred-ton scale DM detectors	Ton-scale 0nbb	Low-E scintillator neutrino detectors
Readout development	Higher energy resolution	2.1	🟡	🟢	🟠	🟡	🔴	🟠	🔴	🟠
	Lower energy threshold	2.1	🟠	🟡	🟡	🟡	🔴	🟠	🟢	🟠
	Expand wavelength sensitivity	2.1	🟠	🟢	🟠	🟢	🟠	🟠	🟠	🟠
Measurement strategy	Fine granularity	2.2	🟡	🟢	🟡	🟡	🔴	🟠	🔴	🔴
	dE/dx (combine modalities: charge, light, heat, acoustics)	2.2	🟠	🟢	🟠	🟢	🔴	🟠	🟠	🟢
Target properties	Liquid doping and purification (87 - 290K)	2.3	🟡	🟠	🟡		🔴	🔴	🔴	🟠
	High pressure	2.3	🟢	🟢	🟠	🟢	🟠	🟢	🟠	🟢
Scaling up challenges	Detector services (e.g. cryogenics) and integration	2.4	🟠	🟠	🟡	🟡	🔴	🔴	🔴	🟠
	Large arrays (sensors)	2.4	🟠	🟠	🔴	🟠	🟡	🔴	🟡	🟠
	Low power	2.4	🟠	🟢	🟢	🟡	🔴	🔴	🔴	🟢
	Detector components radiopurity and background mitigation	2.4	🟠	🟢	🟢	🟢	🔴	🔴	🔴	🟠

		DRDT	2030-2035								
			PIP-II/LBNF/DUNE (module 4)	JParc/HK	Neutrino near detectors	Neutrino telescopes (multi-km^3)	Light dark matter detectors	Hundred-ton scale DM detectors	Multi-ton scale 0nbb	Low-E scintillator neutrino detectors	Big Bang (CNB) detectors
Readout development	Higher energy resolution	2.1	🟠	🟢	🟠	🔴	🔴	🟠	🔴	🟠	🔴
	Lower energy threshold	2.1	🔴	🟡	🟡	🔴	🔴	🟠	🟢	🟠	🔴
	Expand wavelength sensitivity	2.1	🟠	🟢	🟠	🟢	🟠	🔴	🟠	🟠	
Measurement strategy	Fine granularity	2.2	🔴	🟢	🟡	🔴	🔴	🟠	🔴	🔴	🔴
	dE/dx (combine modalities: charge, light, heat, acoustics)	2.2	🟠	🟢	🟠	🟢	🔴	🔴	🟠	🟢	🔴
Target properties	Liquid doping and purification (87 - 290K)	2.3	🔴	🟠	🟡		🔴	🔴	🔴	🟠	🔴
	High pressure	2.3	🟢	🟢	🟠	🟢	🟠	🟢	🟠	🟢	
Scaling up challenges	Detector services (e.g. cryogenics) and integration	2.4	🟠	🟠	🟡	🟡	🔴	🔴	🔴	🟠	🔴
	Large arrays (sensors)	2.4	🟠	🟠	🔴	🟠	🟡	🔴	🟡	🟠	🔴
	Low power	2.4	🟠	🟢	🟢	🟡	🔴	🔴	🔴	🟢	🔴
	Detector components radiopurity and background mitigation	2.4	🔴	🟠	🟢	🔴	🔴	🔴	🔴	🟠	🔴

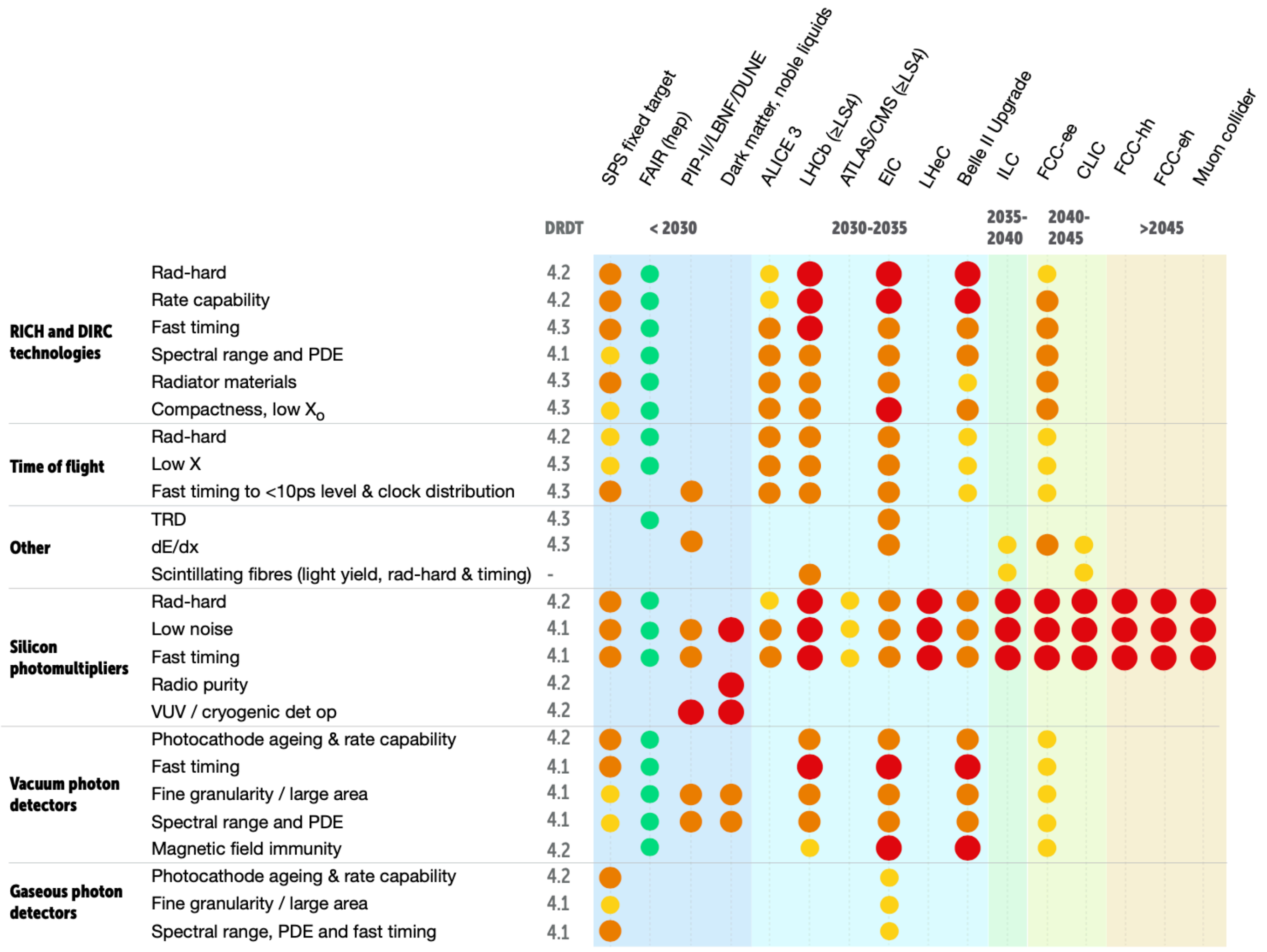
🔴 **Must happen or main physics goals cannot be met**

🟠 **Important to meet several physics goals**

🟡 **Desirable to enhance physics reach**

🟢 **R&D needs being met**

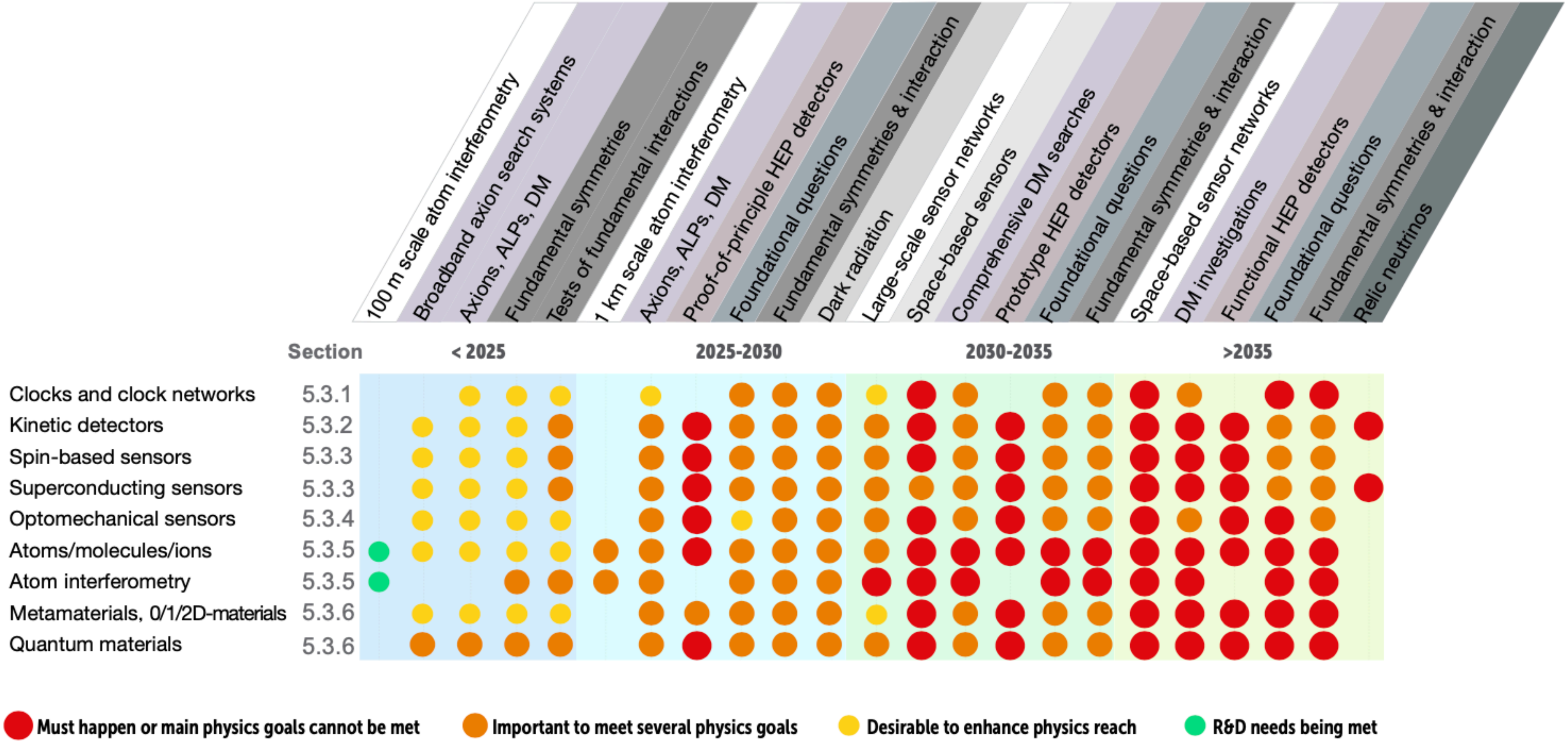
Photodetectors and PID



		DRDT	< 2030				2030-2035						2035-2040	2040-2045		>2045		
			SPS fixed target	FAIR (hep)	PIP-II/LBNF/DUNE	Dark matter, noble liquids	ALICE 3	LHCb (≥LS4)	ATLAS/CMS (≥LS4)	EIC	LHeC	Belle II Upgrade	ILC	FCC-ee	CLIC	FCC-hh	FCC-eh	Muon collider
RICH and DIRC technologies	Rad-hard	4.2	🟠	🟢			🟡	🔴		🔴		🔴		🟡				
	Rate capability	4.2	🟠	🟢			🟡	🔴		🔴		🔴		🟠				
	Fast timing	4.3	🟠	🟢			🟠	🔴		🟠		🟠		🟠				
	Spectral range and PDE	4.1	🟡	🟢			🟠	🟠		🟠		🟠		🟠				
	Radiator materials	4.3	🟠	🟢			🟠	🟠		🟠		🟡		🟠				
	Compactness, low X_o	4.3	🟡	🟢			🟠	🟠		🔴		🟠		🟠				
Time of flight	Rad-hard	4.2	🟡	🟢			🟠	🟠		🟠		🟡		🟡				
	Low X	4.3	🟡	🟢			🟠	🟠		🟠		🟡		🟡				
	Fast timing to <10ps level & clock distribution	4.3	🟠		🟠		🟠	🟠		🟠		🟡		🟡				
Other	TRD	4.3		🟢						🟠								
	dE/dx	4.3			🟠					🟠			🟡	🟠	🟡			
	Scintillating fibres (light yield, rad-hard & timing)	-						🟠					🟡		🟡			
Silicon photomultipliers	Rad-hard	4.2	🟠	🟢			🟡	🔴	🟡	🟠	🔴	🟠	🔴	🔴	🔴	🔴	🔴	🔴
	Low noise	4.1	🟠	🟢	🟠	🔴	🟠	🔴	🟡	🟠	🔴	🟠	🔴	🔴	🔴	🔴	🔴	🔴
	Fast timing	4.1	🟠	🟢	🟠		🟠	🔴	🟡	🟠	🔴	🟠	🔴	🔴	🔴	🔴	🔴	🔴
	Radio purity	4.2				🔴												
	VUV / cryogenic det op	4.2			🔴	🔴												
Vacuum photon detectors	Photocathode ageing & rate capability	4.2	🟠	🟢				🟠		🟠		🟠		🟡				
	Fast timing	4.1	🟠	🟢				🔴		🔴		🔴		🟡				
	Fine granularity / large area	4.1	🟡	🟢	🟠	🟠		🟠		🟠		🟠		🟡				
	Spectral range and PDE	4.1	🟡	🟢	🟠	🟠		🟠		🟠		🟠		🟡				
	Magnetic field immunity	4.2		🟢				🟡		🔴		🔴		🟡				
Gaseous photon detectors	Photocathode ageing & rate capability	4.2	🟠							🟡								
	Fine granularity / large area	4.1	🟡							🟡								
	Spectral range, PDE and fast timing	4.1	🟠							🟡								

🔴 **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**

Quantum and emerging technologies



		100 m scale atom interferometry	Broadband axion search systems	Axions, ALPs, DM	Fundamental symmetries	Tests of fundamental interactions	1 km scale atom interferometry	Axions, ALPs, DM	Proof-of-principle HEP detectors	Foundational questions	Fundamental symmetries & interaction	Dark radiation	Large-scale sensor networks	Space-based sensors	Comprehensive DM searches	Prototype HEP detectors	Foundational questions	Fundamental symmetries & interaction	Space-based sensor networks	DM investigations	Functional HEP detectors	Foundational questions	Fundamental symmetries & interaction	Relic neutrinos
	Section	< 2025					2025-2030						2030-2035						>2035					
Clocks and clock networks	5.3.1			🟡	🟡	🟡		🟡		🟠	🟠	🟠	🟡	🔴	🟠		🟠	🟠	🔴	🟠		🔴	🔴	
Kinetic detectors	5.3.2		🟡	🟡	🟡	🟠		🟠	🔴	🟠	🟠	🟠	🟠	🔴	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🟠	🟠	🔴
Spin-based sensors	5.3.3		🟡	🟡	🟡	🟠		🟠	🔴	🟠	🟠	🟠	🟠	🔴	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🟠	🟠	
Superconducting sensors	5.3.3		🟡	🟡	🟡	🟠		🟠	🔴	🟠	🟠	🟠	🟠	🟠	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🟠	🟠	🔴
Optomechanical sensors	5.3.4		🟡	🟡	🟡	🟡		🟠	🔴	🟡	🟠	🟠	🟠	🔴	🟠	🔴	🟠	🟠	🔴	🟠	🔴	🔴	🟠	
Atoms/molecules/ions	5.3.5	🟢	🟡	🟡	🟡	🟡	🟠	🟠	🔴	🟠	🟠	🟠	🟠	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	
Atom interferometry	5.3.5	🟢			🟠	🟠	🟠	🟠		🟠	🟠	🟠	🔴	🔴	🔴		🔴	🔴	🔴	🔴		🔴	🔴	
Metamaterials, 0/1/2D-materials	5.3.6		🟡	🟡	🟡	🟡		🟠	🟠	🟠	🟠	🟠	🟡	🔴	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🔴	🔴	
Quantum materials	5.3.6		🟠	🟠	🟠	🟠		🟠	🔴	🟠	🟠	🟠	🟠	🔴	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🔴	🔴	

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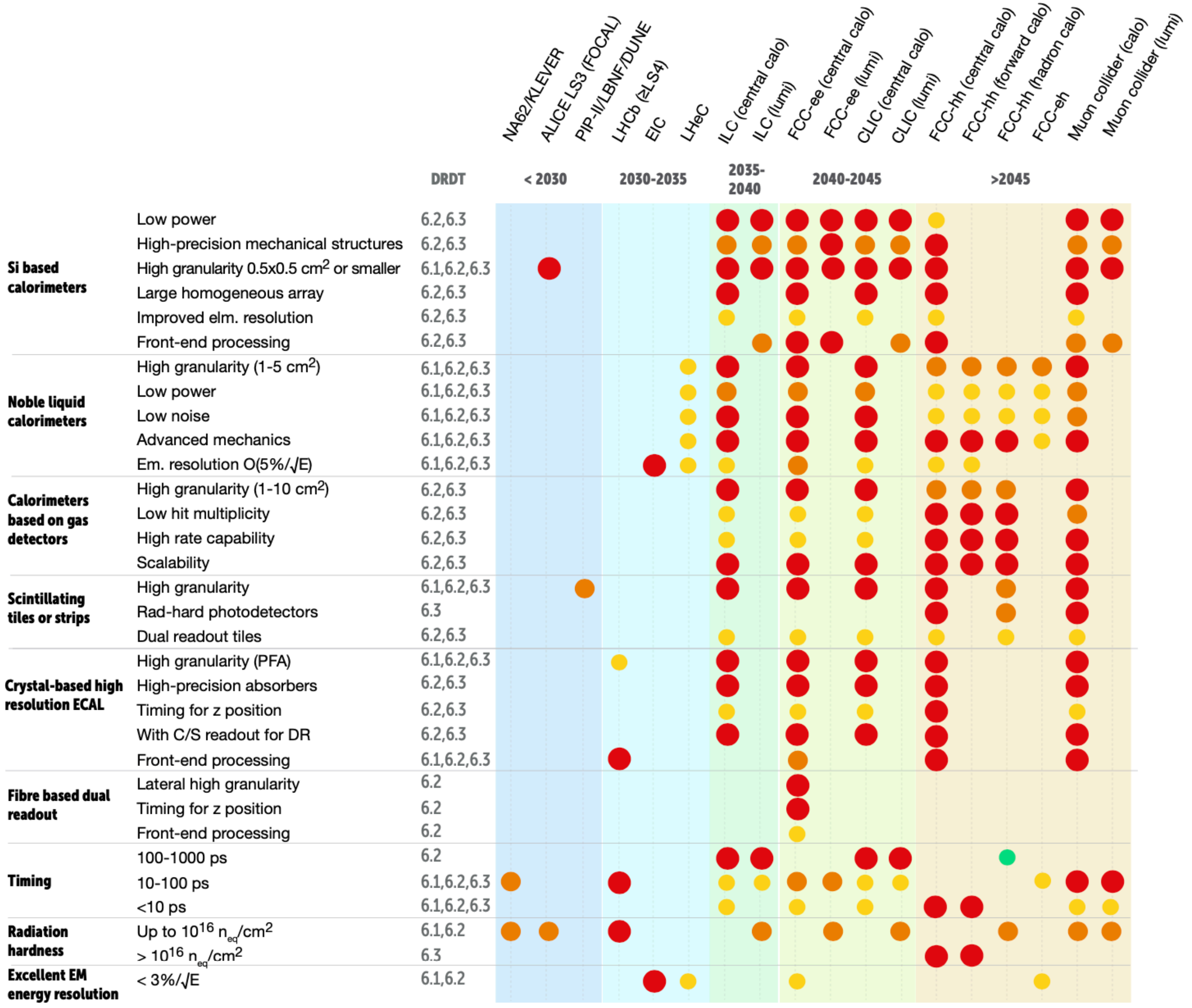
Calorimeters



			< 2030			2030-2035			2035-2040		2040-2045				>2045					
		DRDT	NA62/KLEVER	ALICE LS3 (FOCAL)	PIP-II/LBNF/DUNE	LHCb (≥LS4)	EIC	LHeC	ILC (central calo)	ILC (lumi)	FCC-ee (central calo)	FCC-ee (lumi)	CLIC (central calo)	CLIC (lumi)	FCC-hh (central calo)	FCC-hh (forward calo)	FCC-hh (hadron calo)	FCC-eh	Muon collider (calo)	Muon collider (lumi)
Si based calorimeters	Low power	6.2,6.3							🔴	🔴	🔴	🔴	🔴	🔴	🟡				🔴	🔴
	High-precision mechanical structures	6.2,6.3							🟠	🟠	🟠	🔴	🟠	🟠	🔴				🟠	🟠
	High granularity 0.5x0.5 cm^2 or smaller	6.1,6.2,6.3		🔴					🔴	🔴	🔴	🔴	🔴	🔴	🔴				🔴	🔴
	Large homogeneous array	6.2,6.3							🔴		🔴		🔴		🔴				🔴	
	Improved elm. resolution	6.2,6.3							🟡		🟡		🟡		🟡				🟡	
	Front-end processing	6.2,6.3								🟠	🔴	🔴		🟠	🔴				🟠	🟠
Noble liquid calorimeters	High granularity (1-5 cm^2)	6.1,6.2,6.3						🟡	🔴		🔴		🔴		🟠	🟠	🟠	🟠	🔴	
	Low power	6.1,6.2,6.3						🟡	🟠		🟠		🟠		🟡	🟡	🟡	🟡	🟠	
	Low noise	6.1,6.2,6.3						🟡	🔴		🔴		🔴		🟡	🟡	🟡	🟡	🟠	
	Advanced mechanics	6.1,6.2,6.3						🟡	🔴		🔴		🔴		🔴	🔴	🔴	🟡	🔴	
	Em. resolution O(5%/√E)	6.1,6.2,6.3					🔴	🟡	🟡		🟠		🟡		🟡	🟡				
Calorimeters based on gas detectors	High granularity (1-10 cm^2)	6.2,6.3							🔴		🔴		🔴		🟠	🟠	🟠		🔴	
	Low hit multiplicity	6.2,6.3							🟡		🟡		🟡		🔴	🔴	🔴		🟠	
	High rate capability	6.2,6.3							🟡		🟡		🟡		🔴	🔴	🔴		🔴	
	Scalability	6.2,6.3							🔴		🔴		🔴		🔴	🔴	🔴		🔴	
Scintillating tiles or strips	High granularity	6.1,6.2,6.3			🟠				🔴		🔴		🔴		🔴		🟠		🔴	
	Rad-hard photodetectors	6.3													🔴		🟠		🔴	
	Dual readout tiles	6.2,6.3							🟡		🟡		🟡		🟡		🟡		🟡	
Crystal-based high resolution ECAL	High granularity (PFA)	6.1,6.2,6.3				🟡			🔴		🔴		🔴		🔴				🔴	
	High-precision absorbers	6.2,6.3							🔴		🔴		🔴		🔴				🔴	
	Timing for z position	6.2,6.3							🟡		🟡		🟡		🔴				🟡	
	With C/S readout for DR	6.2,6.3							🔴		🔴		🔴		🔴				🔴	
	Front-end processing	6.1,6.2,6.3				🔴					🟠				🔴				🔴	
Fibre based dual readout	Lateral high granularity	6.2									🔴									
	Timing for z position	6.2									🔴									
	Front-end processing	6.2									🟡									
Timing	100-1000 ps	6.2							🔴	🔴			🔴	🔴			🟢			
	10-100 ps	6.1,6.2,6.3	🟠			🔴			🟡	🟡	🟠	🟠	🟡	🟡				🟡	🔴	🔴
	<10 ps	6.1,6.2,6.3							🟡		🟡		🟡		🔴	🔴			🟡	🟡
Radiation hardness	Up to 10^{16} n_{eq}/cm^2	6.1,6.2	🟠	🟠		🔴				🟠		🟠		🟠			🟠		🟠	🟠
	> 10^{16} n_{eq}/cm^2	6.3													🔴	🔴				
Excellent EM energy resolution	< 3%/√E	6.1,6.2					🔴	🟡			🟡							🟡		

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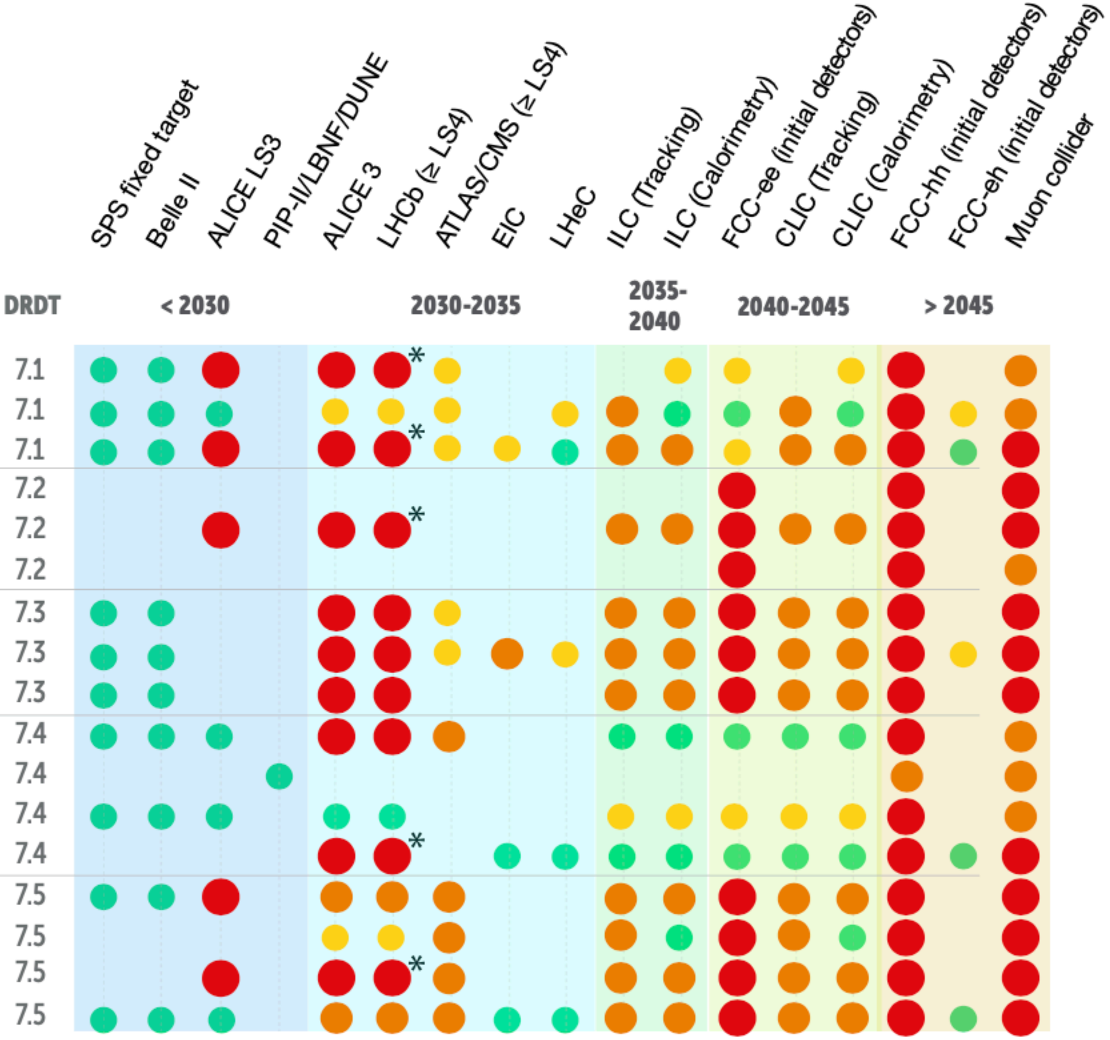
Electronics and Data Processing



		DRDT	< 2030				2030-2035					2035-2040		2040-2045			> 2045		
			SPS fixed target	Belle II	ALICE LS3	PIP-II/LBNF/DUNE	ALICE 3	LHCb (≥ LS4)	ATLAS/CMS (≥ LS4)	EIC	LHeC	ILC (Tracking)	ILC (Calorimetry)	FCC-ee (initial detectors)	CLIC (Tracking)	CLIC (Calorimetry)	FCC-hh (initial detectors)	FCC-eh (initial detectors)	Muon collider
Data density	High data rate ASICs and systems	7.1	🟢	🟢	🔴		🔴	🔴*	🟡				🟡	🟡		🟡	🔴		🟠
	New link technologies (fibre, wireless, wireline)	7.1	🟢	🟢	🟢		🟡	🟡	🟡		🟡	🟠	🟢	🟢	🟠	🟢	🔴	🟡	🟠
	Power and readout efficiency	7.1	🟢	🟢	🔴		🔴	🔴*	🟡	🟡	🟢	🟠	🟠	🟡	🟠	🟠	🔴	🟢	🔴
Intelligence on the detector	Front-end programmability, modularity and configurability	7.2												🔴			🔴		🔴
	Intelligent power management	7.2			🔴		🔴	🔴*				🟠	🟠	🔴	🟠	🟠	🔴		🔴
	Advanced data reduction techniques (ML/AI)	7.2												🔴			🔴		🟠
4D-techniques	High-performance sampling (TDCs, ADCs)	7.3	🟢	🟢			🔴	🔴	🟡			🟠	🟠	🔴	🟠	🟠	🔴		🔴
	High precision timing distribution	7.3	🟢	🟢			🔴	🔴	🟡	🟠	🟡	🟠	🟠	🔴	🟠	🟠	🔴	🟡	🔴
	Novel on-chip architectures	7.3	🟢	🟢			🔴	🔴				🟠	🟠	🔴	🟠	🟠	🔴		🔴
Extreme environments and longevity	Radiation hardness	7.4	🟢	🟢	🟢		🔴	🔴	🟠			🟢	🟢	🟢	🟢	🟢	🔴		🟠
	Cryogenic temperatures	7.4				🟢											🟠		🟠
	Reliability, fault tolerance, detector control	7.4	🟢	🟢	🟢		🟢	🟢				🟡	🟡	🟡	🟡	🟡	🔴		🟠
	Cooling	7.4					🔴	🔴*		🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🔴
Emerging technologies	Novel microelectronic technologies, devices, materials	7.5	🟢	🟢	🔴		🟠	🟠	🟠			🟠	🟠	🔴	🟠	🟠	🔴		🔴
	Silicon photonics	7.5					🟡	🟡	🟠			🟠	🟢	🔴	🟠	🟢	🔴		🔴
	3D-integration and high-density interconnects	7.5			🔴		🔴	🔴*	🟠			🟠	🟠	🔴	🟠	🟠	🔴		🔴
	Keeping pace with, adapting and interfacing to COTS	7.5	🟢	🟢	🟢		🟠	🟠	🟠	🟢	🟢	🟠	🟠	🔴	🟠	🟠	🔴	🟢	🔴

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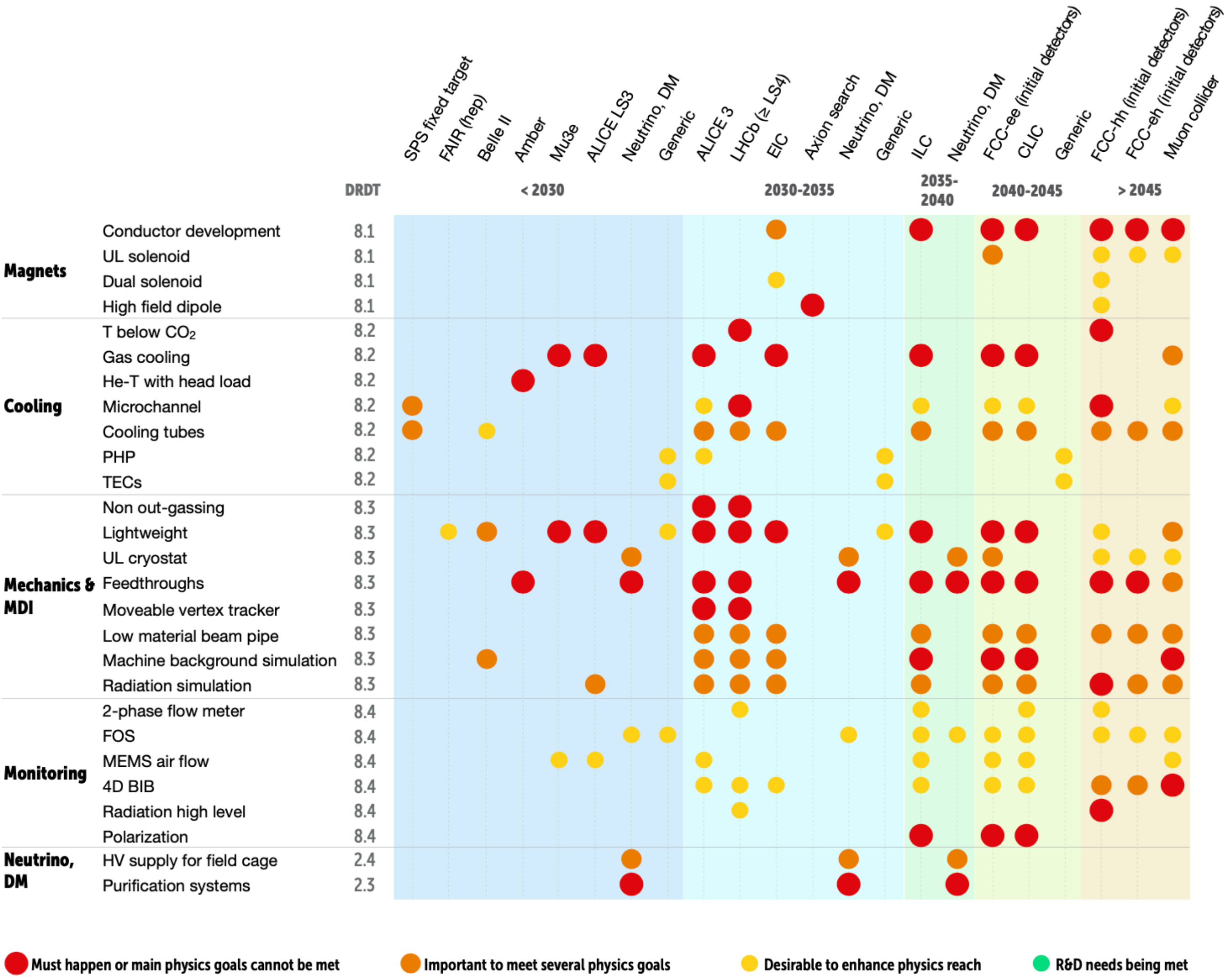
Integration



		DRDT	< 2030								2030-2035						2035-2040		2040-2045			> 2045		
			SPS fixed target	FAIR (hep)	Belle II	Amber	Mu3e	ALICE LS3	Neutrino, DM	Generic	ALICE 3	LHCb (≥ LS4)	EIC	Axion search	Neutrino, DM	Generic	ILC	Neutrino, DM	FCC-ee (initial detectors)	CLIC	Generic	FCC-hh (initial detectors)	FCC-eh (initial detectors)	Muon collider
Magnets	Conductor development	8.1											🟠				🔴		🔴	🔴		🔴	🔴	🔴
	UL solenoid	8.1																	🟠			🟡	🟡	🟡
	Dual solenoid	8.1											🟡									🟡		
	High field dipole	8.1												🔴								🟡		
Cooling	T below CO_2	8.2										🔴										🔴		
	Gas cooling	8.2					🔴	🔴			🔴		🔴				🔴		🔴	🔴				🟠
	He-T with head load	8.2				🔴																		
	Microchannel	8.2	🟠								🟡	🔴					🟡		🟡	🟡		🔴		🟡
	Cooling tubes	8.2	🟠		🟡						🟠	🟠	🟠				🟠		🟠	🟠		🟠	🟠	🟠
	PHP	8.2								🟡	🟡					🟡					🟡			
	TECs	8.2								🟡						🟡					🟡			
Mechanics & MDI	Non out-gassing	8.3									🔴	🔴												
	Lightweight	8.3		🟡	🟠		🔴	🔴		🟡	🔴	🔴	🔴			🟡	🔴		🔴	🔴		🟡		🟠
	UL cryostat	8.3							🟠						🟠			🟠	🟠			🟡	🟡	🟡
	Feedthroughs	8.3				🔴			🔴		🔴	🔴			🔴		🔴	🔴	🔴	🔴		🔴	🔴	🟠
	Moveable vertex tracker	8.3									🔴	🔴												
	Low material beam pipe	8.3									🟠	🟠	🟠				🟠		🟠	🟠		🟠	🟠	🟠
	Machine background simulation	8.3			🟠						🟠	🟠	🟠				🔴		🔴	🔴				🔴
	Radiation simulation	8.3						🟠			🟠	🟠	🟠				🟠		🟠	🟠		🔴	🟠	🟠
Monitoring	2-phase flow meter	8.4										🟡					🟡			🟡		🟡		
	FOS	8.4							🟡	🟡					🟡		🟡	🟡	🟡	🟡		🟡	🟡	🟡
	MEMS air flow	8.4					🟡	🟡			🟡						🟡		🟡	🟡				🟡
	4D BIB	8.4									🟡	🟡	🟡				🟡		🟡	🟡		🟠	🟠	🔴
	Radiation high level	8.4										🟡										🔴		
	Polarization	8.4															🔴		🔴	🔴				
Neutrino, DM	HV supply for field cage	2.4							🟠						🟠			🟠						
	Purification systems	2.3							🔴						🔴			🔴						

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