European Roadmaps for Accelerator - R&D

Mike Lamont

UPHUK -8 5th September 2022

Acknowledgements: Dave Newbold, Lucio Rossi, Bernhard Auchmann

European Strategy for Particle Physics update 2020

… an **electron-positron Higgs factory is the highest-priority next collider** for the field, followed by a **hadron collider at the energy frontier** in the longer term

should investigate the technical and financial feasibility of a **future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage.**

The timely realisation of the **electron-positron International Linear Collider (ILC)** in Japan would be compatible with this strategy

Two possible energy-frontier colliders have been studied for implementation at CERN, namely **CLIC and FCC**...

In addition to the high field magnets the **accelerator R&D roadmap** could contain: **an international design study for a muon collider, as it represents a unique opportunity to achieve a multi-TeV energy domain** beyond the reach of e+e- colliders, and potentially within a more compact circular tunnel than for a hadron collider.

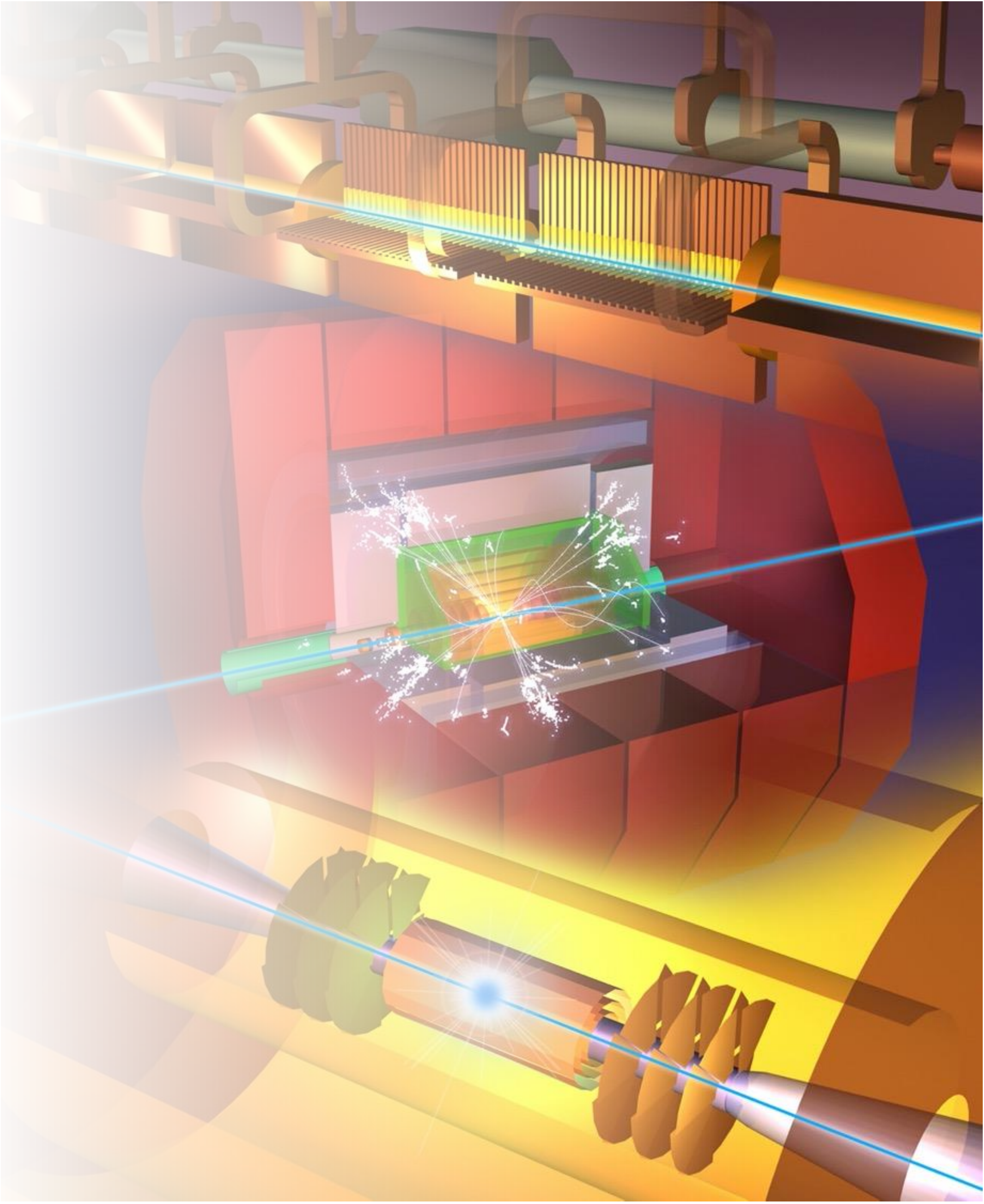
Future Collider options

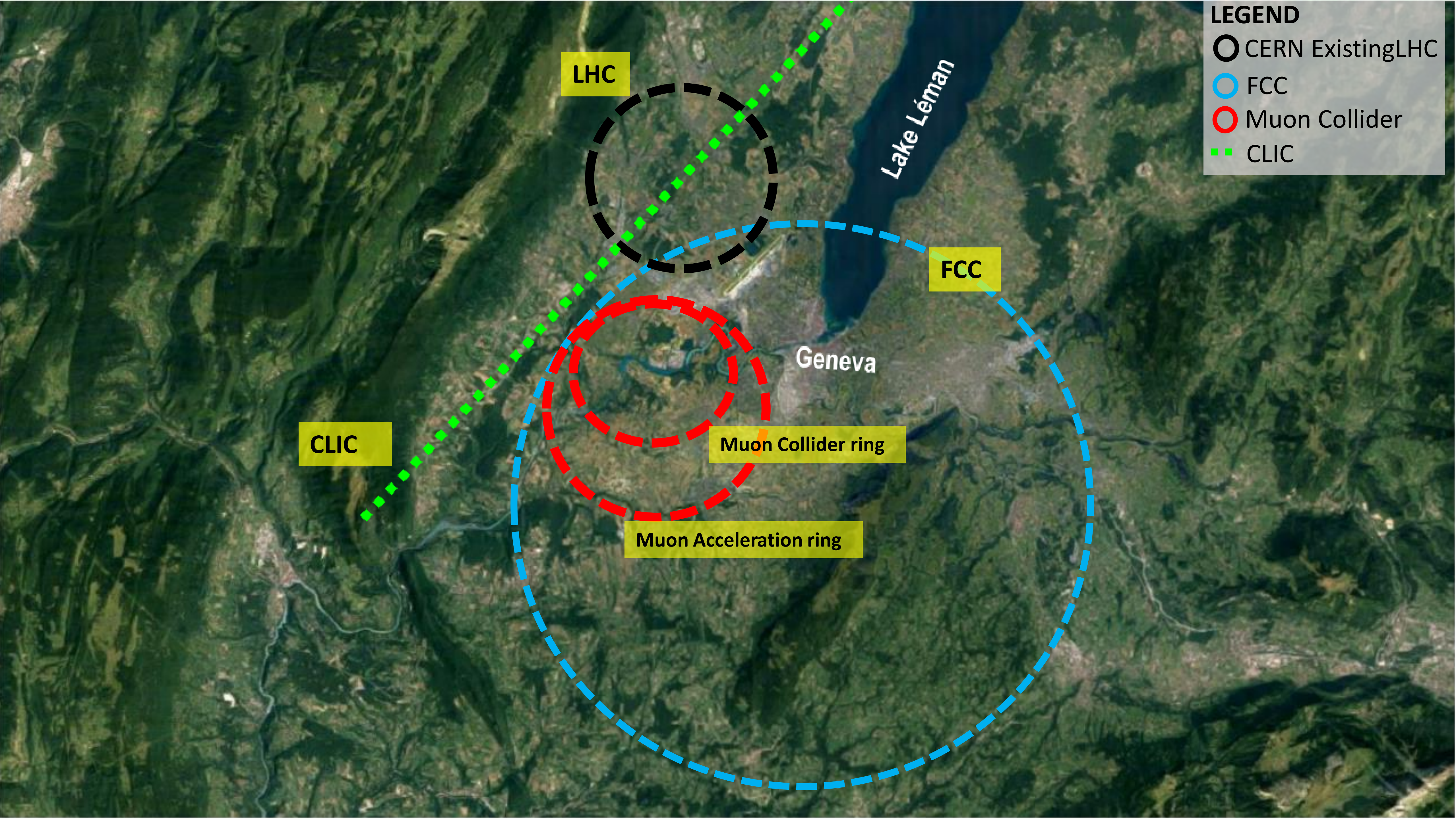
Higgs factory

- Plan A1: FCC-ee
- Plan A2: ILC
- Plan B: CLIC
- Plan C: CepC, C^3

Multi-TeV

- e+e- : CLIC, C^3
- muons: Muon Collider
- protons: FCC-hh, SppC

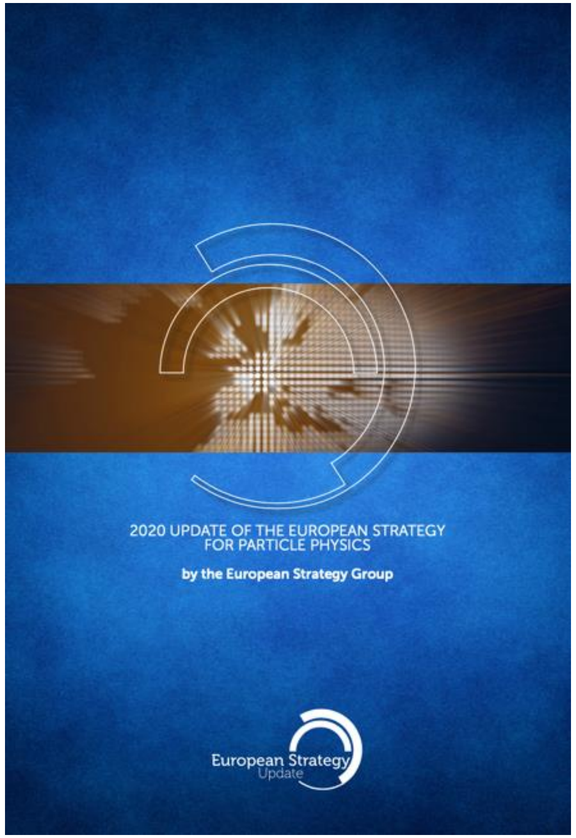



LEGEND
CERN ExistingLHC
FCC
Muon Collider
CLIC
LHC
Lake Léman
FCC
Geneva
CLIC
Muon Collider ring
Muon Acceleration ring

2020 Update of the European Strategy for Particle Physics

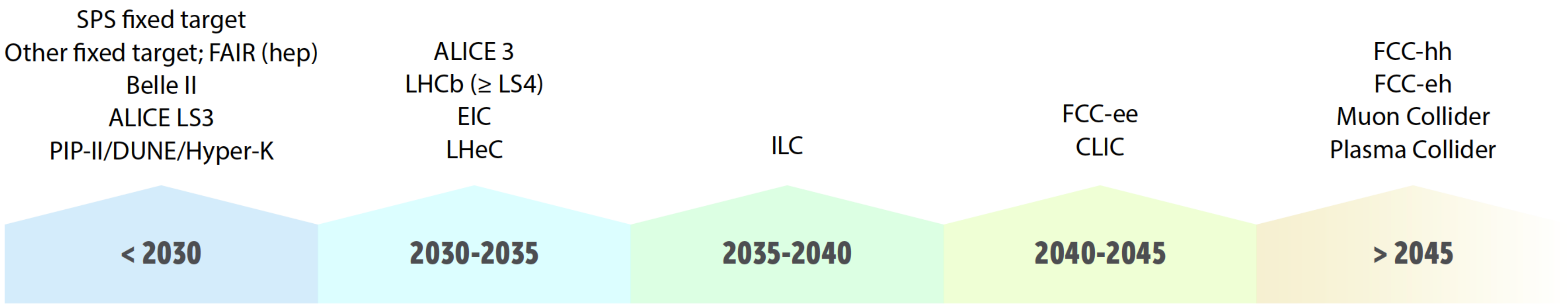
- ***"The technologies under consideration include high-field magnets, high-temperature superconductors***, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. The European particle physics community must intensify accelerator R&D and sustain it with adequate resources.

- ***A roadmap should prioritise the technology,*** taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. ***Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes."***



http://cds.cern.ch/record/2721370

Future Facilities Timeline



‘Chicken-and-egg’ problem

- Need the approximate dates of future facilities to define an R&D timeline
- Cannot predict dates of future facilities without knowing R&D needs

- Detector / accelerator roadmaps have used a common timeline
- Highly approximate, and not to be used out of context
- Dates represent the ‘earliest feasible date’, driven by both technical considerations and approval processes
- The goal on both sides is that R&D shall not be the rate-limiting step

CERN’s scientific priorities

Following the ESPP update

successful completion of the high-luminosity upgrade of the LHC machine and experiments, with a view to the full exploitation of the LHC physics potential;

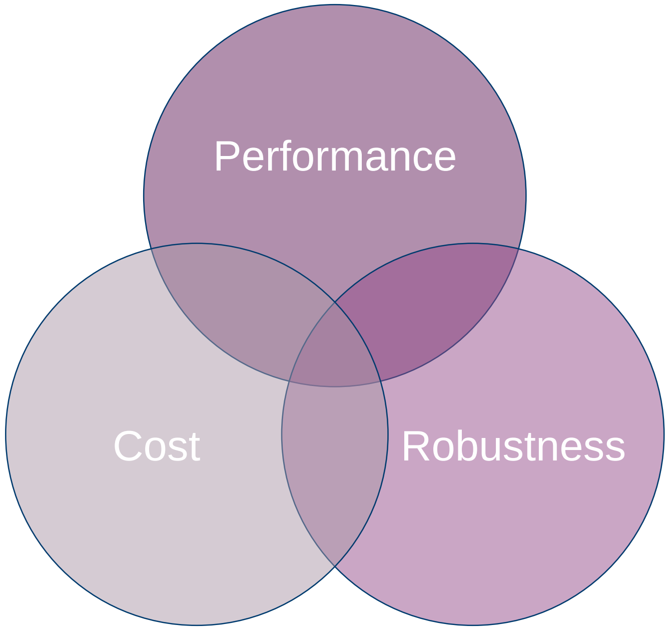
increased R&D efforts on advanced accelerator technologies, including high-field superconducting magnets, high-gradient accelerating structures, plasma wakefield acceleration, muon colliders, etc.;

investigation of the technical and financial feasibility of a future hadron collider at CERN, with a centre-of-mass energy of at least 100 TeV, and with an electron-positron Higgs and electroweak factory as a possible first stage;

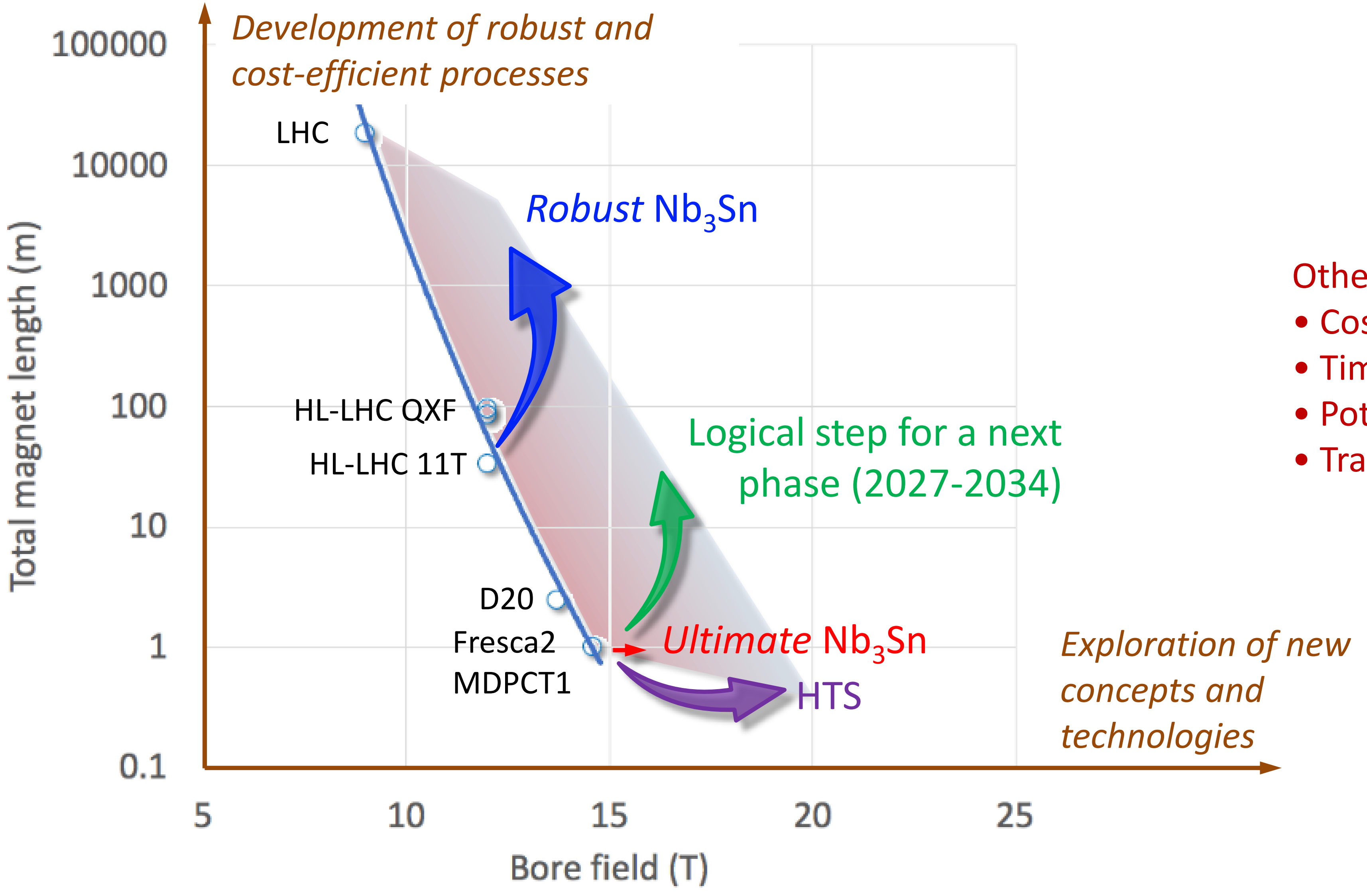
support to long-baseline neutrino experiments in Japan and the United States; and support to a diverse, high-impact scientific programme complementary to high-energy colliders.

HFM R&D Goals

1. **Demonstrate Nb_3Sn magnet technology for large scale deployment, pushing it to its limits in terms of maximum field and production scale.**
   a. The effort to quantify and demonstrate Nb_3Sn ultimate field comprises the development of conductor and magnet technology towards the ultimate Nb_3Sn performance.
   b. Develop Nb_3Sn magnet technology for collider-scale production, through robust design, industrial manufacturing and cost reduction.
2. **Demonstrate the suitability of HTS for accelerator magnets,** providing a proof-of-principle of HTS magnet technology beyond the reach of Nb_3Sn.



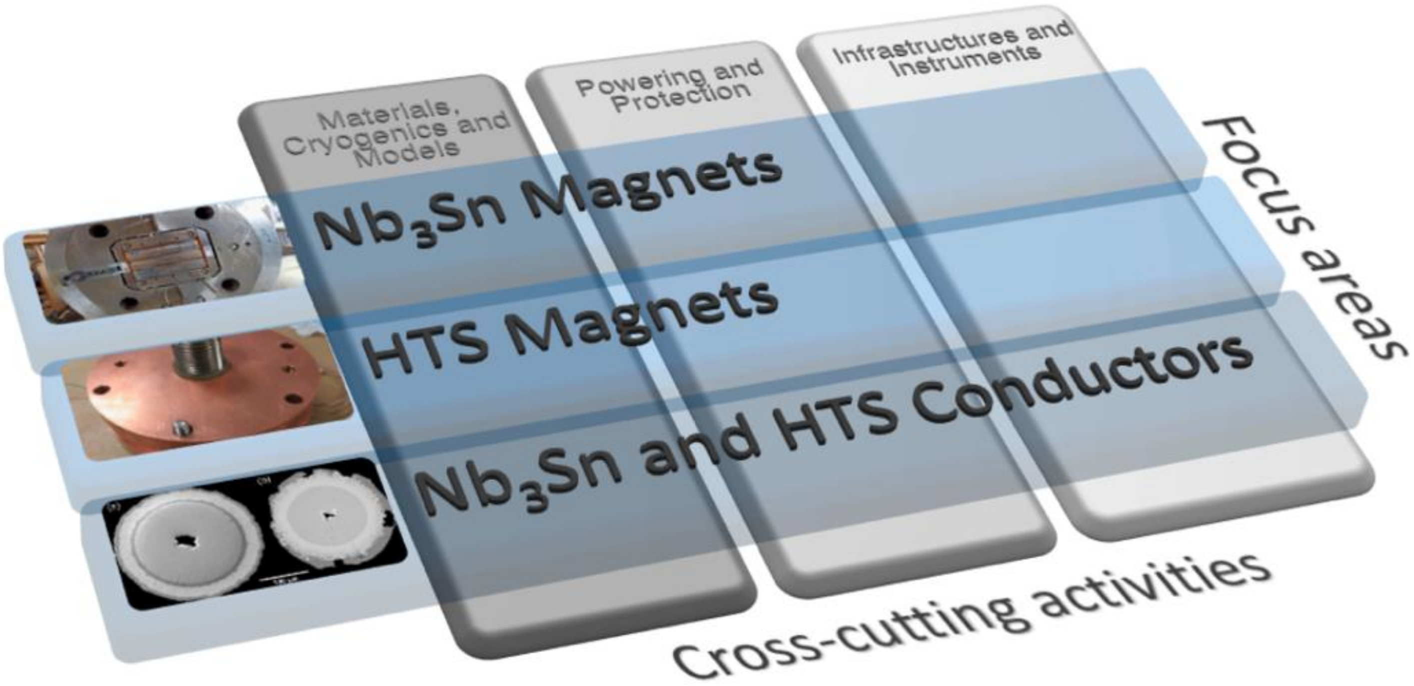
HFM strategy



Other key parameters:

- Cost of Magnets & R&D
- Timeline of a realistic development
- Potential for wider societal applications
- Training and education

R&D Focus Areas and Cross-Cutting Activities

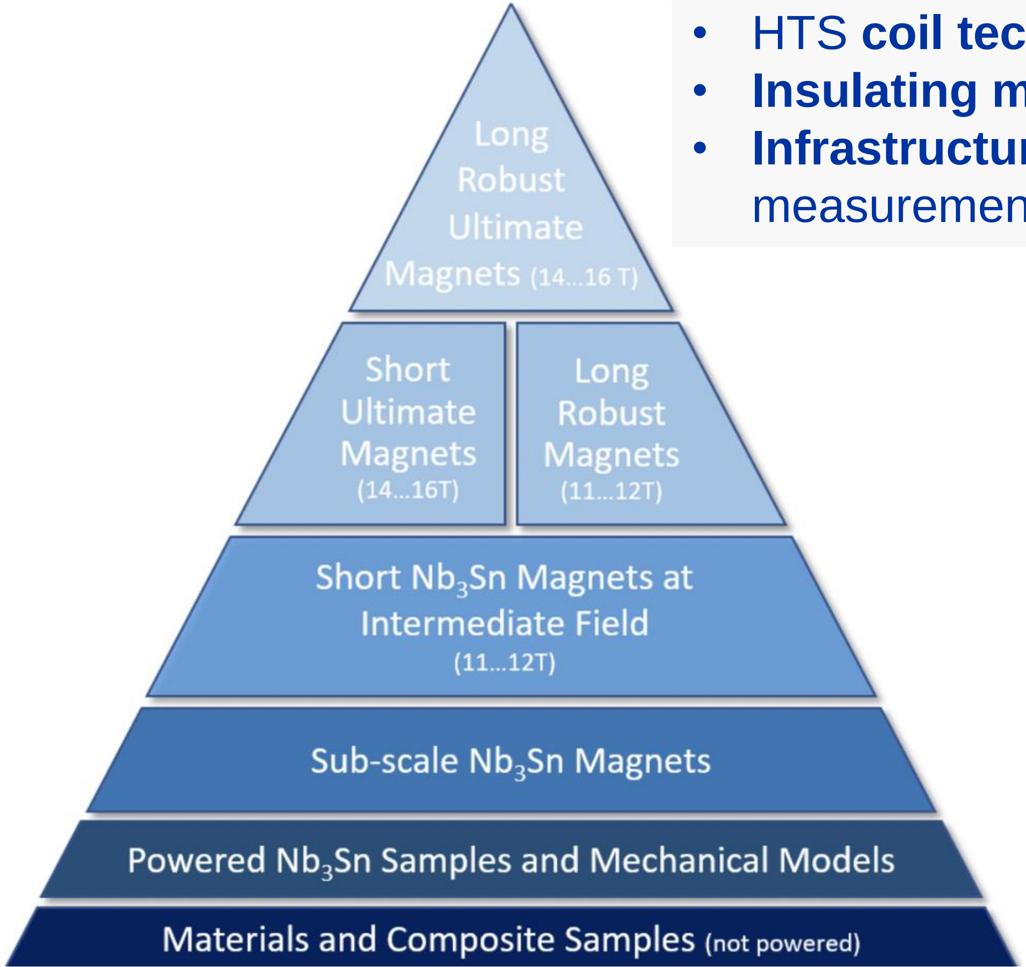


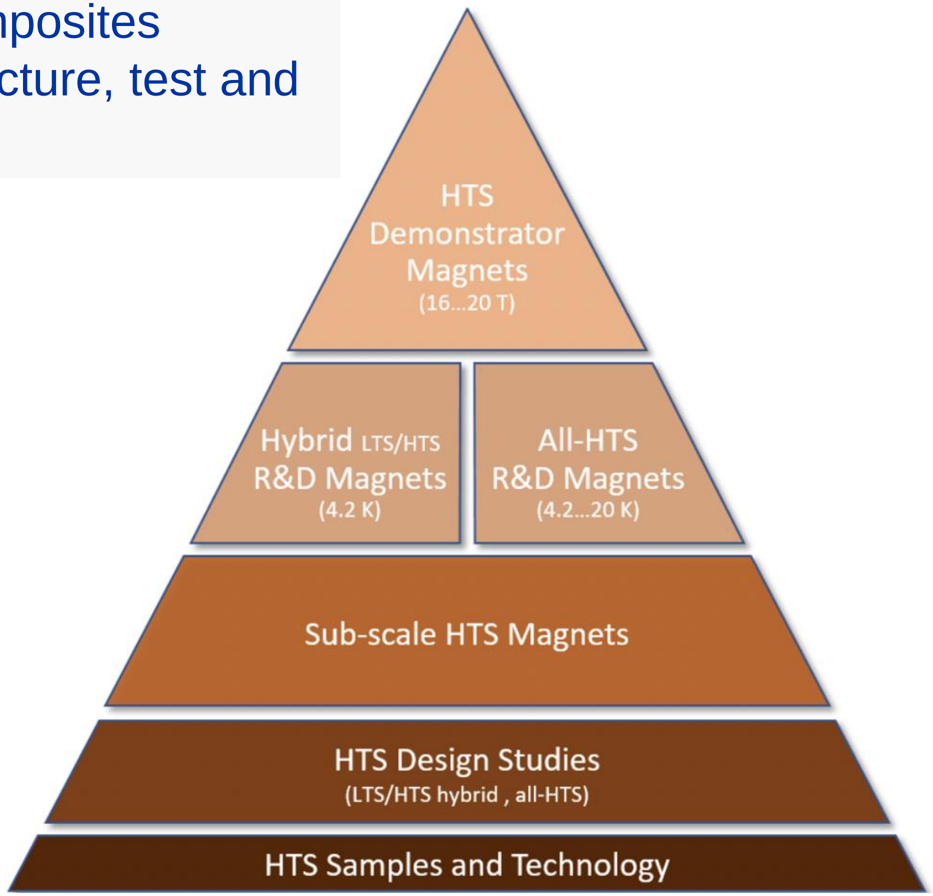
“The R&D programme must be holistic in nature: a compatible selection of electromagnetic, mechanical and thermal design approaches, conductors, materials, and manufacturing processes and methods needs to be integrated seamlessly with instrumentation and protection into a specific magnet solution responding to the required specification.“

- **Conversely, work across R&D areas must be closely coordinated.**

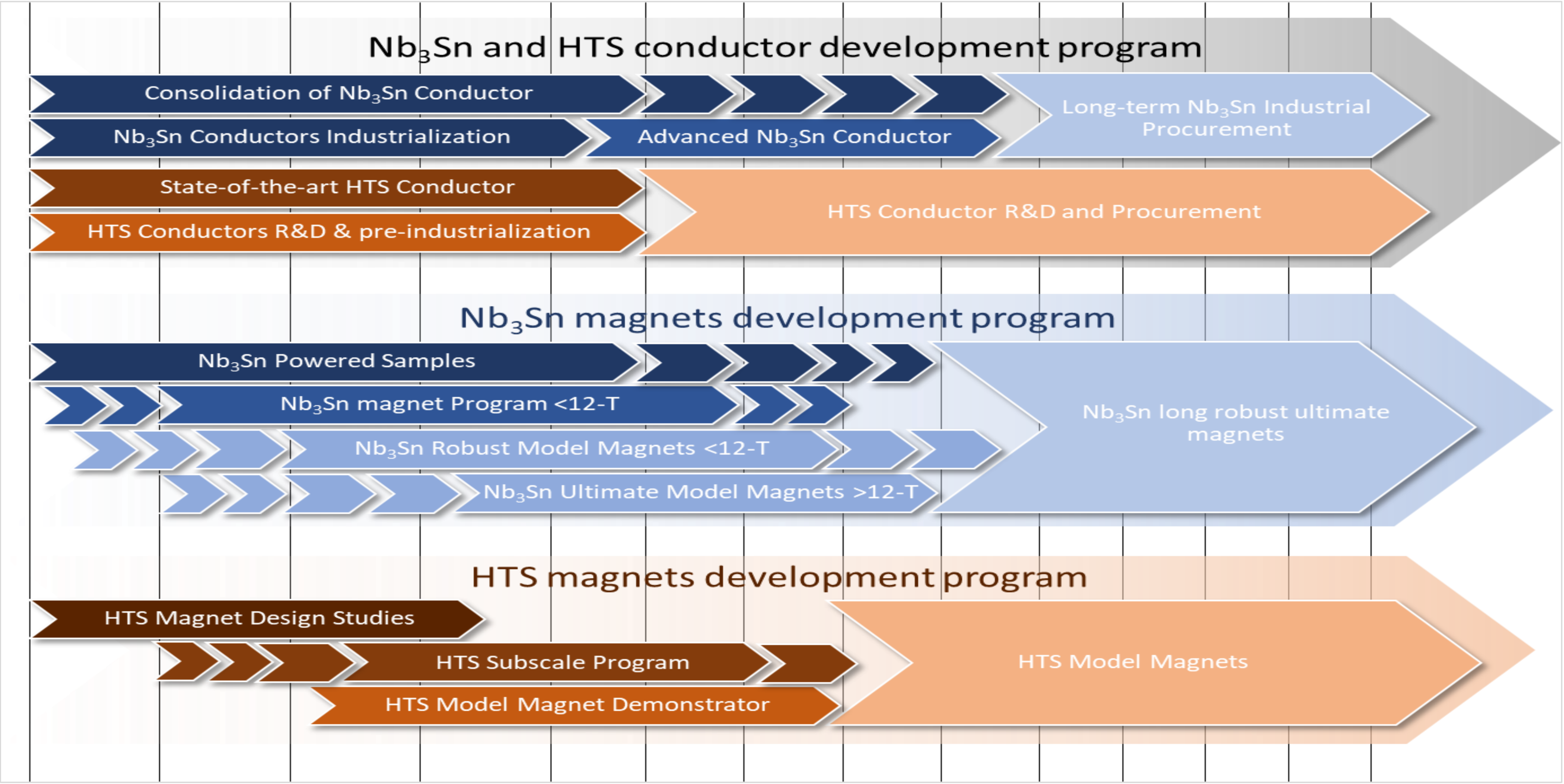
HFM - Overall vision

- Nb_3Sn **conductor** R&D
- Nb_3Sn **magnet technology** R&D
- Nb_3Sn **accelerator magnet** development
- HTS **material and conductor** R&D
- HTS **coil technology and accelerator magnet** R&D
- **Insulating materials**, polymers and composites
- **Infrastructure** for development, manufacture, test and measurement



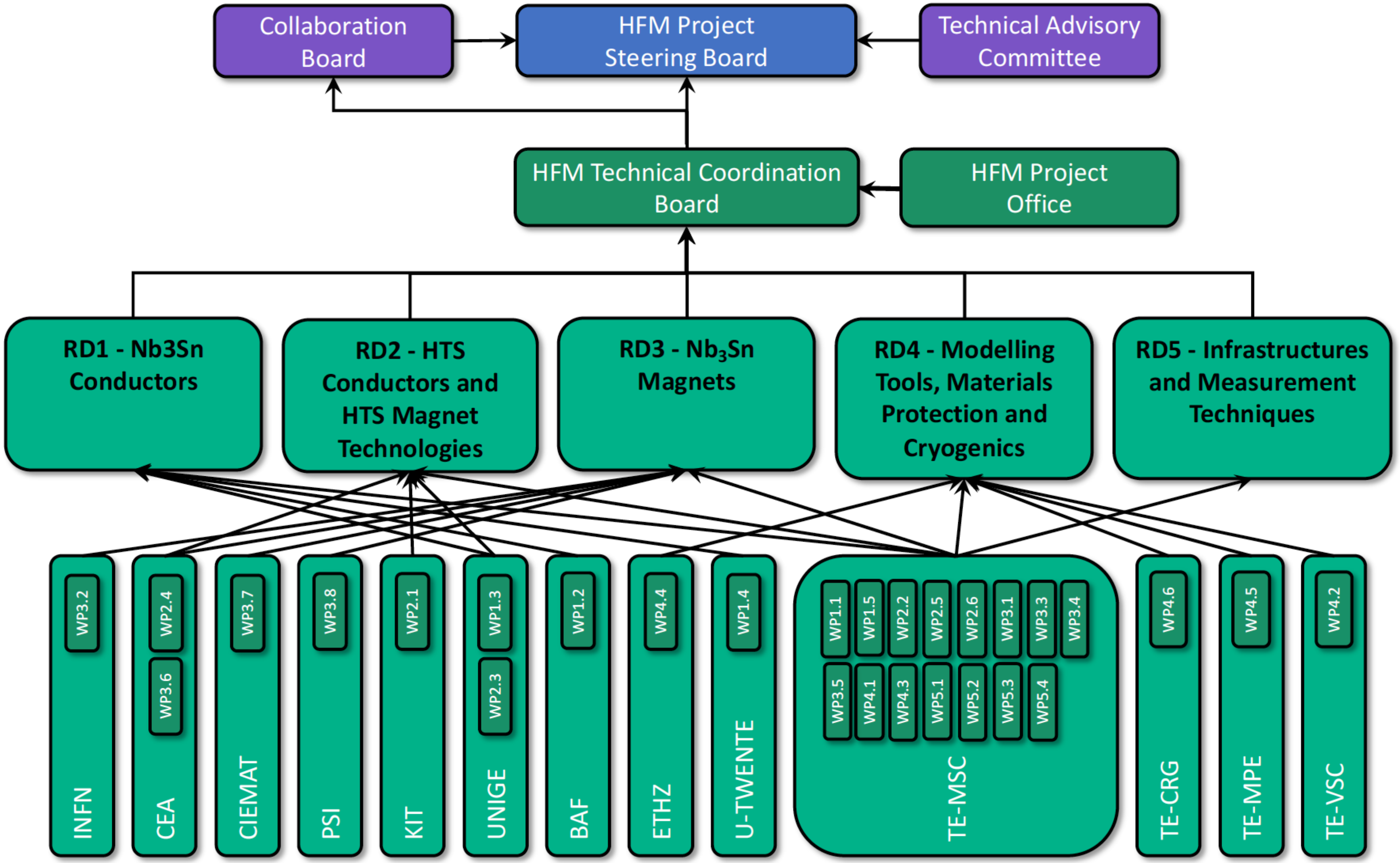


HFM

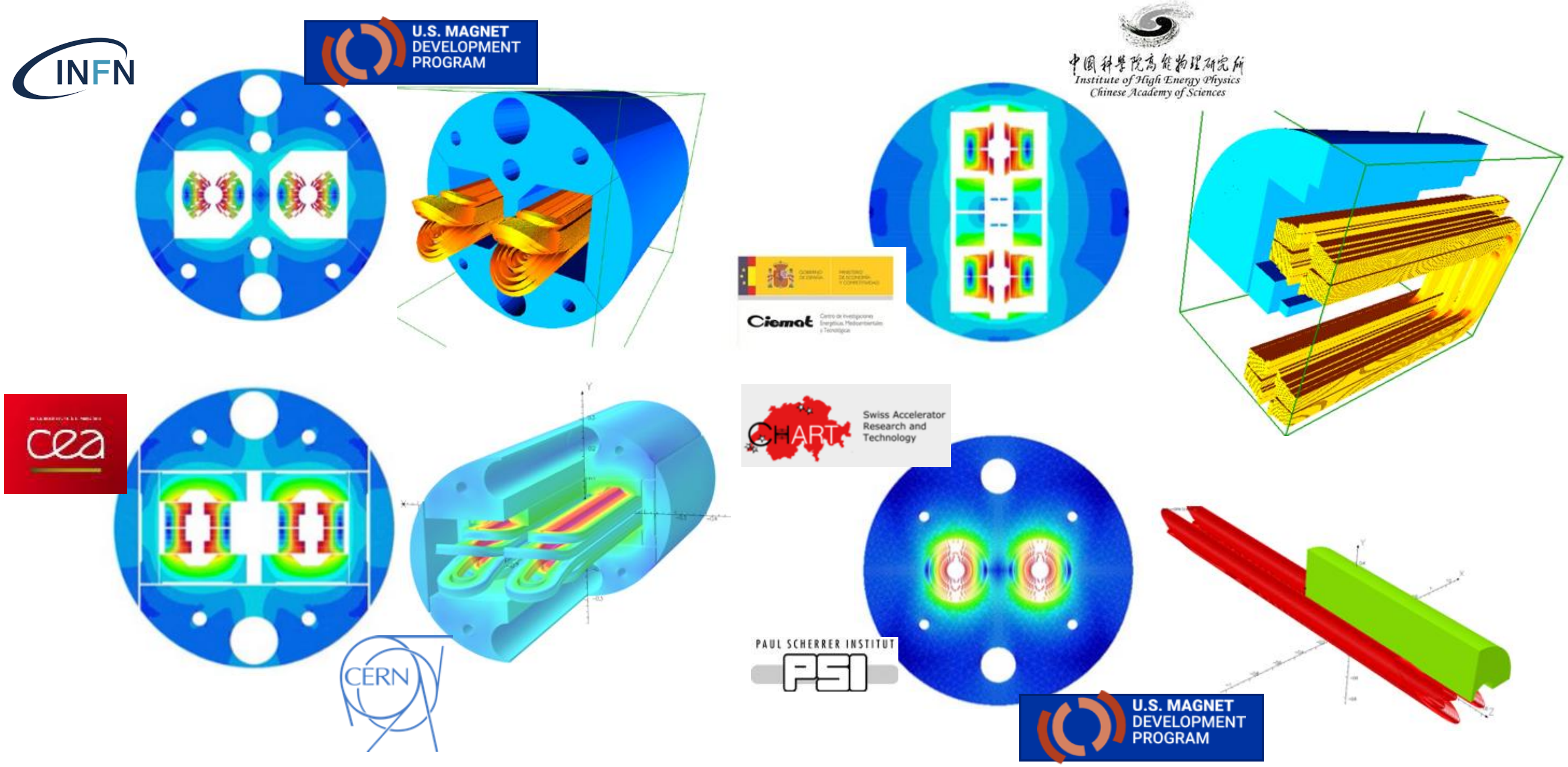


Nb3Sn and HTS conductor development program
Consolidation of Nb3Sn Conductor
Nb3Sn Conductors Industrialization
Advanced Nb3Sn Conductor
Long-term Nb3Sn Industrial Procurement
State-of-the-art HTS Conductor
HTS Conductors R&D & pre-industrialization
HTS Conductor R&D and Procurement
Nb3Sn magnets development program
Nb3Sn Powered Samples
Nb3Sn magnet Program <12-T
Nb3Sn Robust Model Magnets <12-T
Nb3Sn Ultimate Model Magnets >12-T
Nb3Sn long robust ultimate magnets
HTS magnets development program
HTS Magnet Design Studies
HTS Subscale Program
HTS Model Magnet Demonstrator
HTS Model Magnets

In practice… implementation of HFM Roadmap

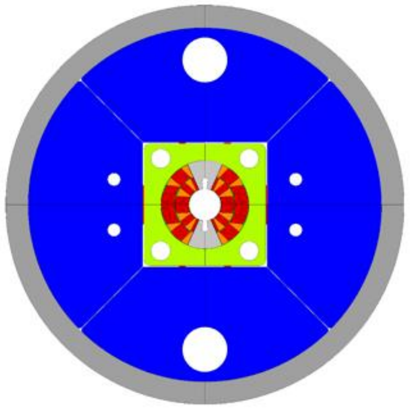


FCC-hh high field dipole R&D: world effort



OD = 600 mm, L = 2 m, 50 mm aperture, **B = 16 T**

FALCON DIPOLE



INFN CERN

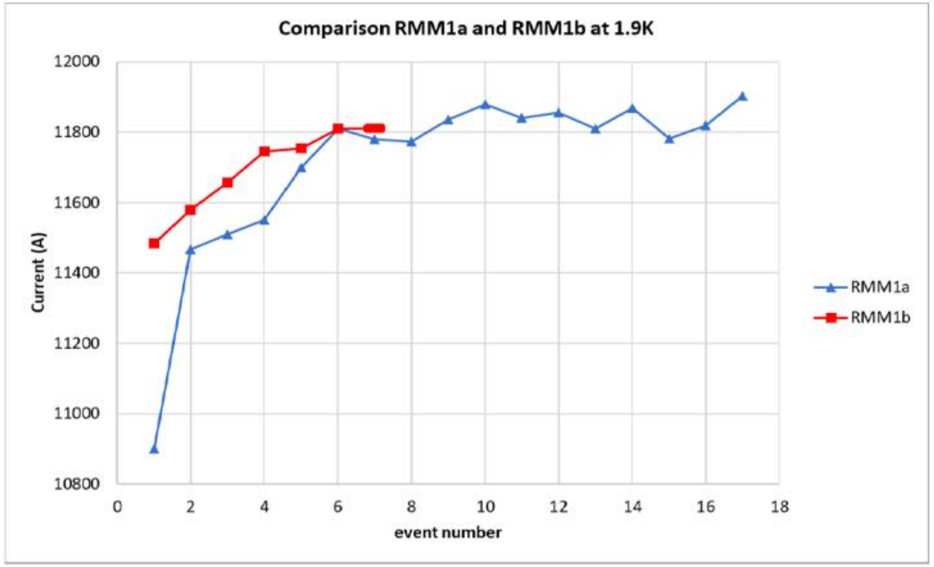
50 mm aperture

B = 12 T

Robust design & procedures

CERN, CEA, INFN-GE-MI, ...

2 weeks ago at CERN

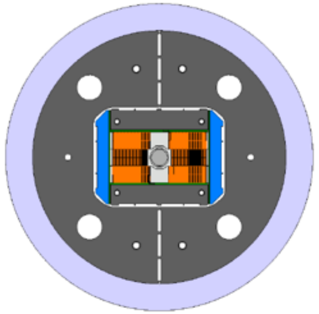


RMM

Racetrack Model Magnet

16 T in a 50 mm cavity

- Demonstrate field on the aperture
- Mechanics (including inner coil support)



The RMM1b quench training at a higher value than for RMM1a, but after 5 quenches reached about the same level.

3 powering ramps were done, all reaching the present target of 11.81 kA (16.5 T conductor peak field)

Part 1 of the test program is now completed

The quench signatures seem rather similar to that of RMM1a except that the mechanical vibrations on the rods disappeared.

RF

Huge amount going on out there both SRF and RT

Strongly application driven (ILC, CLIC, FCC-ee, LCLS-II, PIP2, ESS, ERL…)

Aim is to help exploit synergies, focus attention etc. and report up…

End	Description	MCHF	FTE.y	CERN	Saclay & CNRS	DESY	Uppsala	INFN	UK/STFC	UK/Cockcroft
2026	Superconducting RF: bulk Nb	4	75	2	1	1	U	2	U	2
2026	Superconducting RF: field emission	4	40	2	2	1		U	2	
2026	Superconducting RF: thin film	15	100	1	2	2			2	2
2026	Superconducting RF: infrastructure	5	15	1	2	2	U		U	U
2026	Superconducting RF: power couplers	4	16	1	2	2			U	
2026	Normal conducting RF: general NC studies	0	27	1				1	2	1
2026	Normal conducting RF: NC manufacturing techniques	2.5	30	1				1	2	2
2026	Normal conducting RF: mm wave & high frequency	0	5			1				4
2026	High-power RF: high-efficiency klystron & solid state	5.5	20	1	2			2		2
2026	High-power RF: mm-wave & gyro devices	0	5							1
2026	High-power RF: reduced RF power needs tuners	0.4	6	1						1
2026	AI and machine learning	0.6	26			1			2	1
2026	NC RF test stands	5.3	40	1				1	U	U
2026	Test stand: new materials	0.7	16	1			2			2
2026	Test stand: cavities in strong magentic fields (aspirational)	3	20		1					1
2026	Test stand: SRF Horizontal cryostat	0.9	10		1		1			

1	Heavy involvement
2	Light involvement
U	User - less R&D

SRF Technology: vast experience, diffuse know-how

Progress (1988~)
- TRISTAN
- LEP-II
- HERA
- CEBAF
- CESR
- KEKB
- BES
- cERL

In Operation: → # cavities
- **SNS: 1 GeV**
- **CEBAF 12 GeV → 80**
- **ISAC-II, ARIEL**
- **Super-KEKB**
- **Eu-XFEL → 800**
- **FRIB → 340**

Under Construction:
- **LCLS=II → 300**
- **PIP-II → 115**
- **ESS→ 150**
- **Shine → 600**

To be realized:
- HL-LHC-Crab → 20
- EIC
- **ILC-250 → 8,000**
- FCC
- CEPC/SPPS

1980

2000

2020

The success of the EU-XFEL at Desy is instrumental for all

Courtesy A. Yamamoto

> **2,000** SRF cavities realized, in last 10 years !

Recent trends

- Nitrogen doping of Nb cavities at 800 ℃ (e.g. Grassellino, FNAL)
- Effective magnetic flux expulsion by fast/high thermal gradient
- Cooldown to achieve record low residual resistances
- Coating of Nb with a thin layer of Nb_3Sn (allows operation at larger T, improved cryogenic efficiency, e.g. Posen, Cornell)
- Use of large grain Nb (e.g. JLAB)

} Bulk Nb

- Coating of Cu cavities with Nb by HiPIMS (High Power Impulse Magnetron Sputtering, e.g. Calatroni, CERN)

} Thin film coating on copper

- High-efficiency klystron
- Solid state amplifiers

- Design optimization, fabrication and operation of high power couplers of CW operation (e.g. Montesinos, CERN)

E.g. SRF at CERN

Well defined, not discussed here

Projects & operation

Operation:

LHC, HIE-ISOLDE, SPS crab cavity test stand, SRF infrastructure

Projects:

HL-LHC (until 2027)
LHC dressed spares (until 2022)
requested: 5th HIE-ISOLDE CM
requested: SRF building

Funding: ***infrastructure operation*** is underfunded and typically topped up by other RF OP codes or by SRF R&D budget (~10%).
HL activities in principle covered by HL.
Unexpected problems (leaks, multiple re-tests, etc) are not fully covered.

Targeted R&D

LHC - related
FCC
Collaborations (PERLE, Soleil, EIC..)
Muon Collider
RF separated beams
Axions
...

Funding: Mostly funded by study-specific funding, partly funded by SRF R&D budget (~15%, specifically LHC).

Fundamental R&D and infrastructure

4 main areas:

i) substrate fabrication for coated cavities (mostly with MME)
ii) coatings with various methods and various superconductors (with VSC).
iii) procedures: for increased performance
iv) test environment, infrastructure,
v) cold testing

Funding: Bulk (~75%) of SRF R&D budget goes in this area, some specific items funded by FCC.

These 2 areas suffer from manpower shortage, as priority is always given to OP and Projects.

SRF R&D Activities

Cavity 1.3 GHz
Bulk-machined (Cu-OFE)

Significant progress Nb/Cu cavities

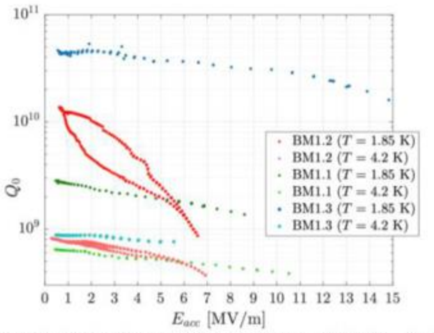
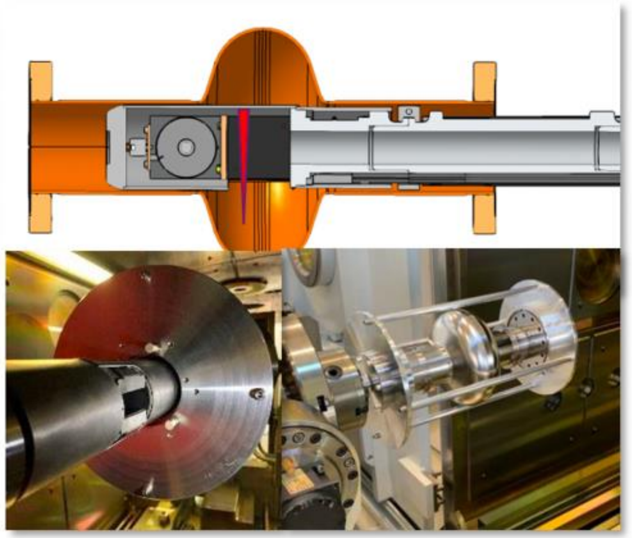


Figure 3: Quality factor (Q_0) vs accelerating field (E_{acc}) of the tested BM1 coatings at normal and superfluid LHe.

Electron Beam deflector: welding from the inside !

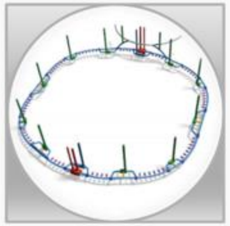


1.3 GHz Nb cavity for KEK

1.3 GHz Cu cavity for CERN

Additive manufacturing of niobium

FCC: RF R&D program



Coordination, parameters and design

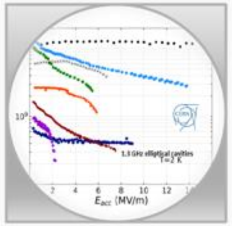
Coordination and review
Challenge the operational scenarios (timeline, cost,..)

Cavity Studies & Beam Dynamics

- Determine the cavity design for each FCC machines.
- Validate the HOM damping schemes
- Carry out the beam-cavity interactions studies
- Evaluate the cavity control system (LLRF) challenges

Cavity Engineering & Fabrication

- Push the limits of fabrication technologies: seamless, internal welding, precision machining, 3D printing (?)
- Built a cavity for Z machine



SRF & Substrate Preparation

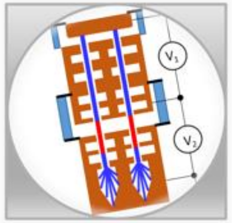
- Establish the limits of surface preparation and Nb coatings
- Optimize HIPIMS coatings using 1.3 GHz seamless cavities
- Pursue exploration of A15
- Prepare and validate a cavity for Z machine

Cryomodule Development

- Develop a test bed for new cavity, FPC and CM technologies
- re-assess generic CM challenges: thermal performances, magnetic shielding, cavity & FPC support,…
- study HOM power extraction schemes for Z machine
- define feasibility of 2K and 4.5 K operation (SWELL)
- built a CM mockup to validate cavity for Z machine

FPC & HOM Couplers

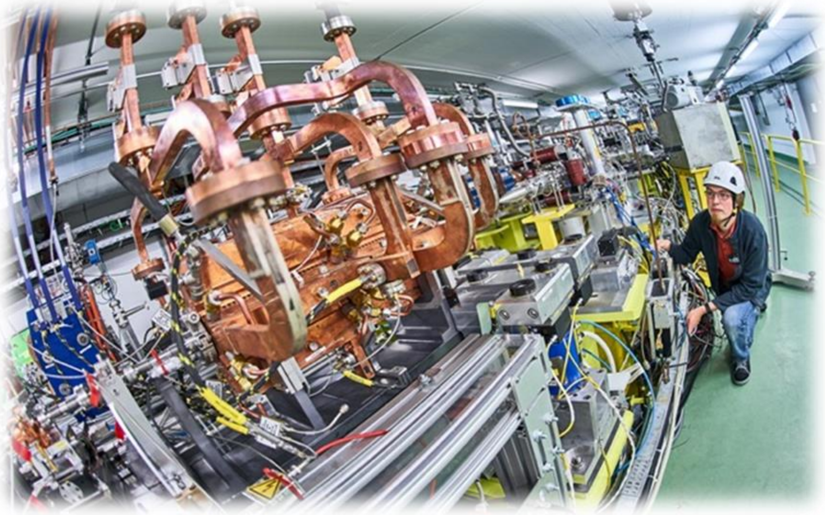
- Push the limits of FPC performances
- Towards 1 MW (baseline)
- Towards large adaptability (SWELL, baseline)
- HOMC mechanical design & production



High power RF Systems

- Challenge RF power systems and power distribution schemes
- Demonstrate HE two stage technology (baseline)
- Evaluate alternative technologies (SWELL, baseline)

CLIC – X-band



- **Optimise and develop the X-band core-technology** by exploiting the existing experimental facilities, the High Gradient test stands, for testing and verifications of prototypes made within the collaboration;
- Maintain linear collider and linac design capabilities;
- Continue **High Efficiency klystron** optimisation in a coordinated effort with other studies and projects at CERN with similar needs;
- **Continue high gradient studies, using the CLEAR facility**, including among others wakefields, instrumentation for nano-beams, medical accelerators based on the technology;
- Follow up with collaborators the **many smaller projects outside CERN where X-band technology is used** – for medical, industrial and research linacs, providing very relevant effort/studies for CLIC, including industrial capability build up;

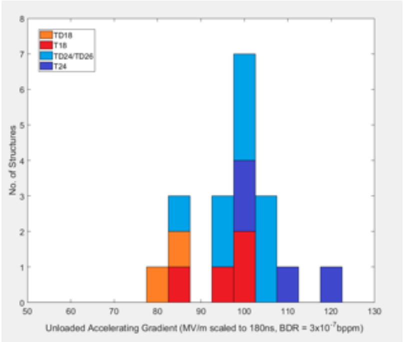
NC Linac Technology status

Courtesy: W. Wuensch, S. Stapnes, A. Yamamoto

Components:

Laboratory with commercial

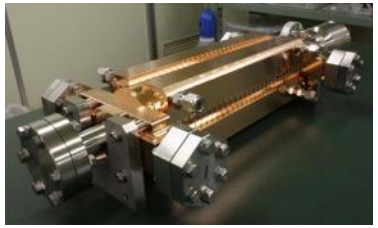
- Accelerating structures
- pulse compressors
- alignment
- Stabilization, etc.



~ 100 (+/-20) MV/m

Full commercial supply

- X-band klystrons
- solid state modulator,

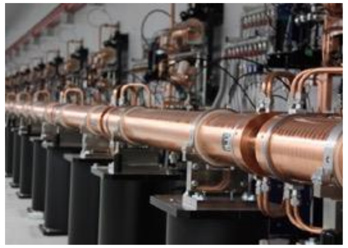


Systems Facilities:
(100 MeV-range)

- XBoxes at CERN
- (NEXTEF KEK)
- Frascati
- NLCTA SLAC
- Linearizers at Electra, PSI, Shanghai and Daresbury
- Test stand at Tsinghua
- Deflectors at SLAC, Shanghai, PSI and Trieste
- NLCTA
- SmartLight
- FLASH

C-band (6 GHz),
low-emittance
GeV-range facilities
Operational:

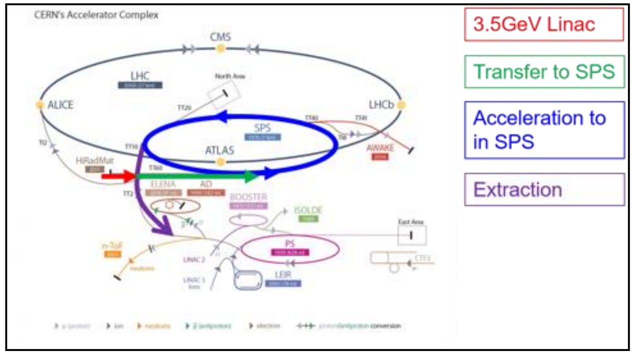
- **SACLA**
- **SwissXFEL (8 GeV)**



X-band (12 GHz)
GeV-range facilities
Planning:

- **Eu-Praxia**
- **e-SPS**
- **CompactLight (EU DS for X-band FEL→ EuPraxia → Flash Therapy)**

CLIC



Roadmap Plan - Overview

- Superconducting RF
  - High quality factor bulk niobium
  - Field emission reduction
  - Thin superconducting films
  - SRF couplers
- Normal-conducting RF
  - Design, modelling and simulations
  - Manufacturing technology
  - mm-wave and higher frequencies
- Powering and LLRF
  - High-efficiency sources
  - mm-wave and gyro devices
  - Power need reduction
  - LLRF
  - Applications of AI / ML

Tasks	Begin	End	Description
RF.SRF.BKNb	2022	2026	Superconducting RF: bulk Nb
RF.SRF.FE	2022	2026	Superconducting RF: field emission
RF.SRF.ThF	2022	2026	Superconducting RF: thin film
RF.SRF.INF	2022	2026	Superconducting RF: infrastructure
RF.SRF.FPC	2022	2026	Superconducting RF: power couplers
RF.SRF			**Total of superconducting RF**
RF.NC.GEN	2022	2026	Normal conducting RF: general NC studies
RF.NC.MAN	2022	2026	Normal conducting RF: NC manufacturing techniques
RF.NC.HF	2022	2026	Normal conducting RF: mm wave & high frequency
			Total of normal conducting RF
RF.HP.HE	2022	2026	High-power RF: high-efficiency klystron & solid state
RF.HP.HF	2022	2026	High-power RF: mm-wave & gyro devices
RF.HP.TUN	2022	2026	High-power RF: reduced RF power needs (tuners)
RF.HP.AI	2022	2026	AI and machine learning
			Total of high-power RF
RF.TS.NCRF	2022	2026	NC RF test stands
RF.TS.MAT	2022	2026	Test stand: new materials
RF.TS.BEAM	2022	2026	Beam test
RF.TS.SRF	2022	2026	Test stand: SRF Horizontal cryostat
			Total for test stand

Muon Collider

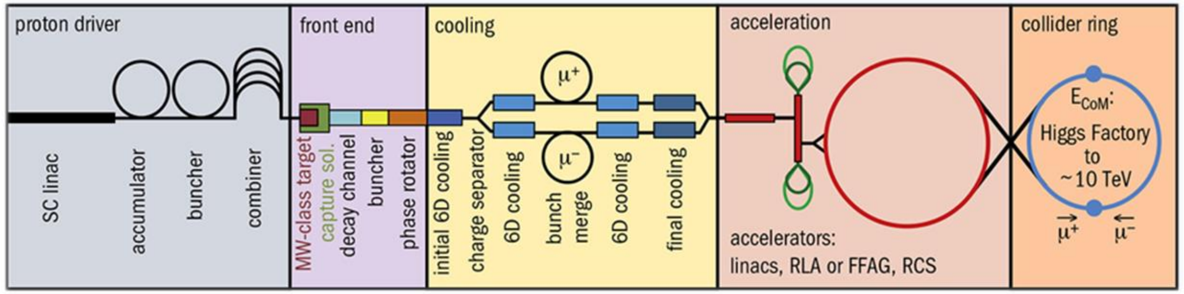
International Design Study

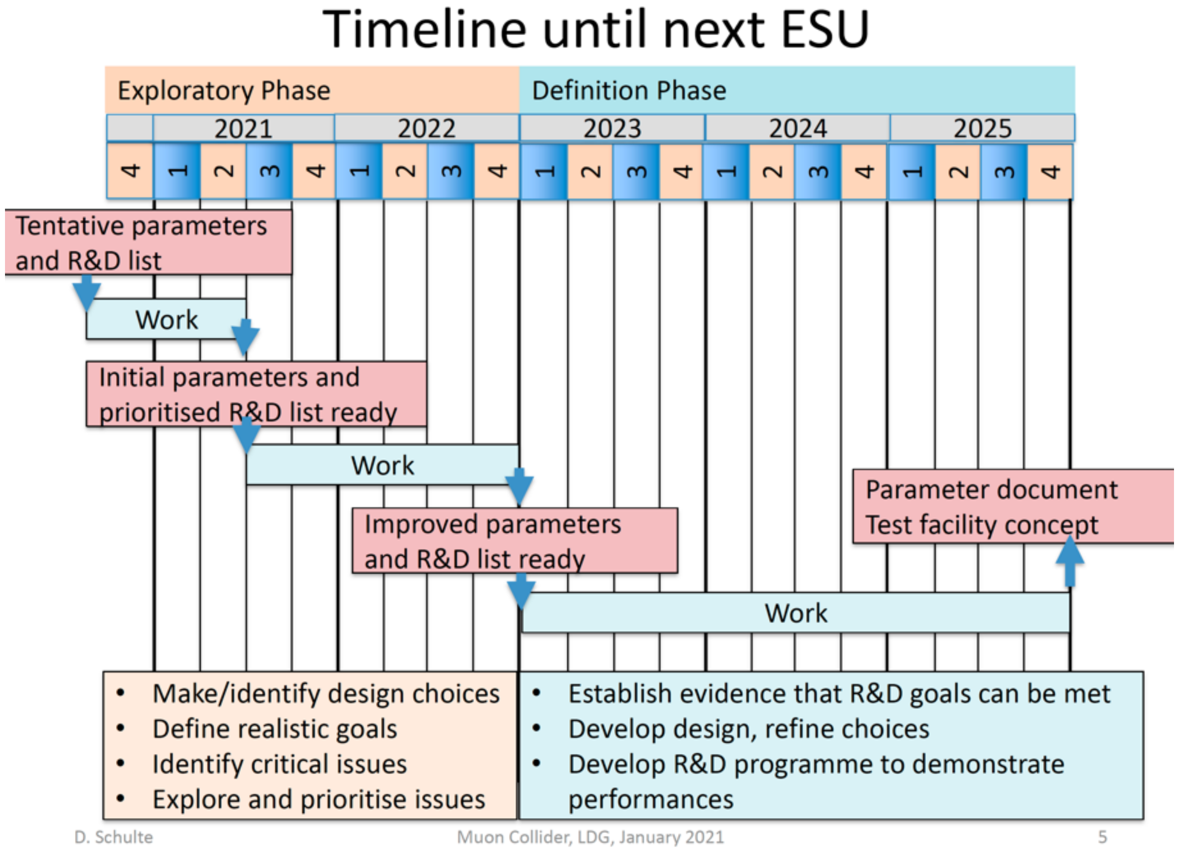
Main foreseen R&D lines:

- **High field superconducting magnets**
  - Collider ring, interaction region, muon cooling, target area, …
- **Fast-ramping magnets and efficient energy recovery**
  - RT or HTS magnets in accelerator, recovery of magnetic energy
- **Superconducting RF**
  - Efficient acceleration with high gradients
- **Normal conducting RF**
  - Very high fields in muon cooling system to minimize muon loss
- **Target area with high proton beam power**
  - Stress in target, radiation in magnets and RF components
- **Re-optimization of muon cooling system**

It is, and will be, intensely collaborative!

See Christian Carli – up next





Shrinking the Size of Particle Physics Facility

RF Accelerators

> 30,000 operational – many serve for Health

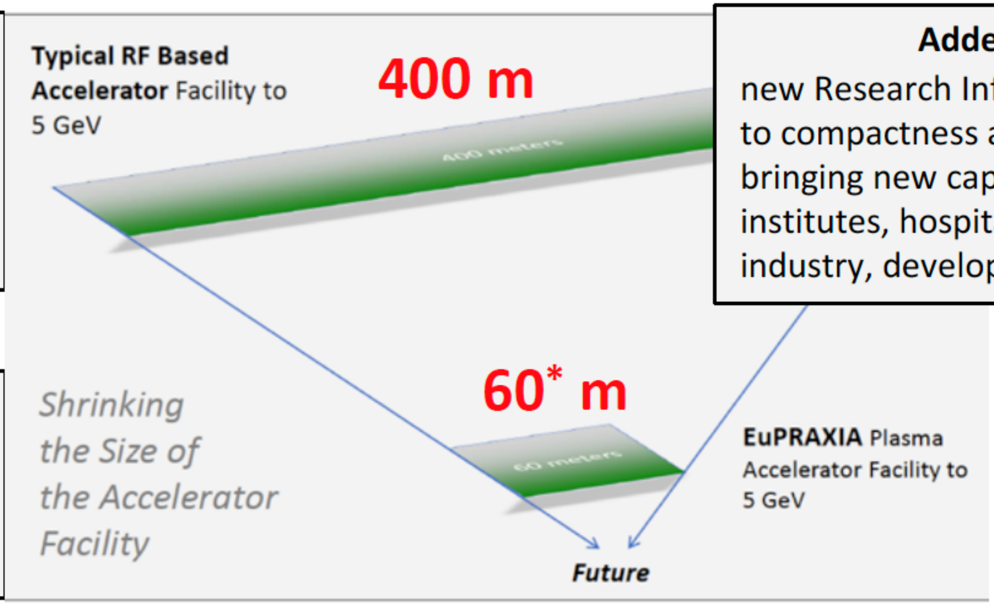
30 million Volt per meter

RF: 90 years of success story for society

Plasma Accelerators

first user facility to be realized

100,000 million Volt per meter



Added value

new Research Infrastructures due to compactness and cost-efficiency bringing new capabilities to science, institutes, hospitals, universities, industry, developing countries.

5 GeV example

realistic design including all required infrastructure for powering, shielding, …

Can we shrink the Linear Collider, provide e^- and e^+ beams in the **TeV** energy regime and produce **> 10^{34} cm^{-2} s^{-1}** luminosity?

R. Assmann, E. Gschwendtner

Fig. 4.3: A plasma cell is shown here in comparison to the super-conducting accelerator FLASH at DESY. *Image credit: DESY, H. Mueller-Elsner*

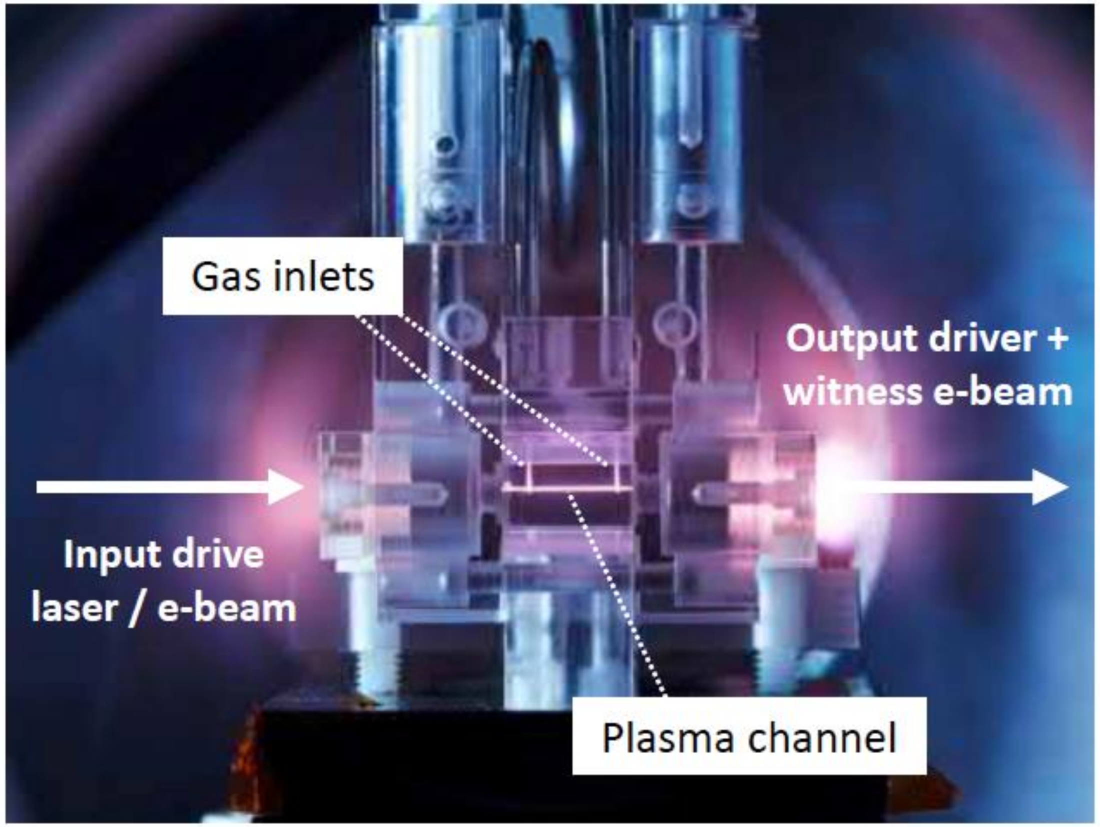
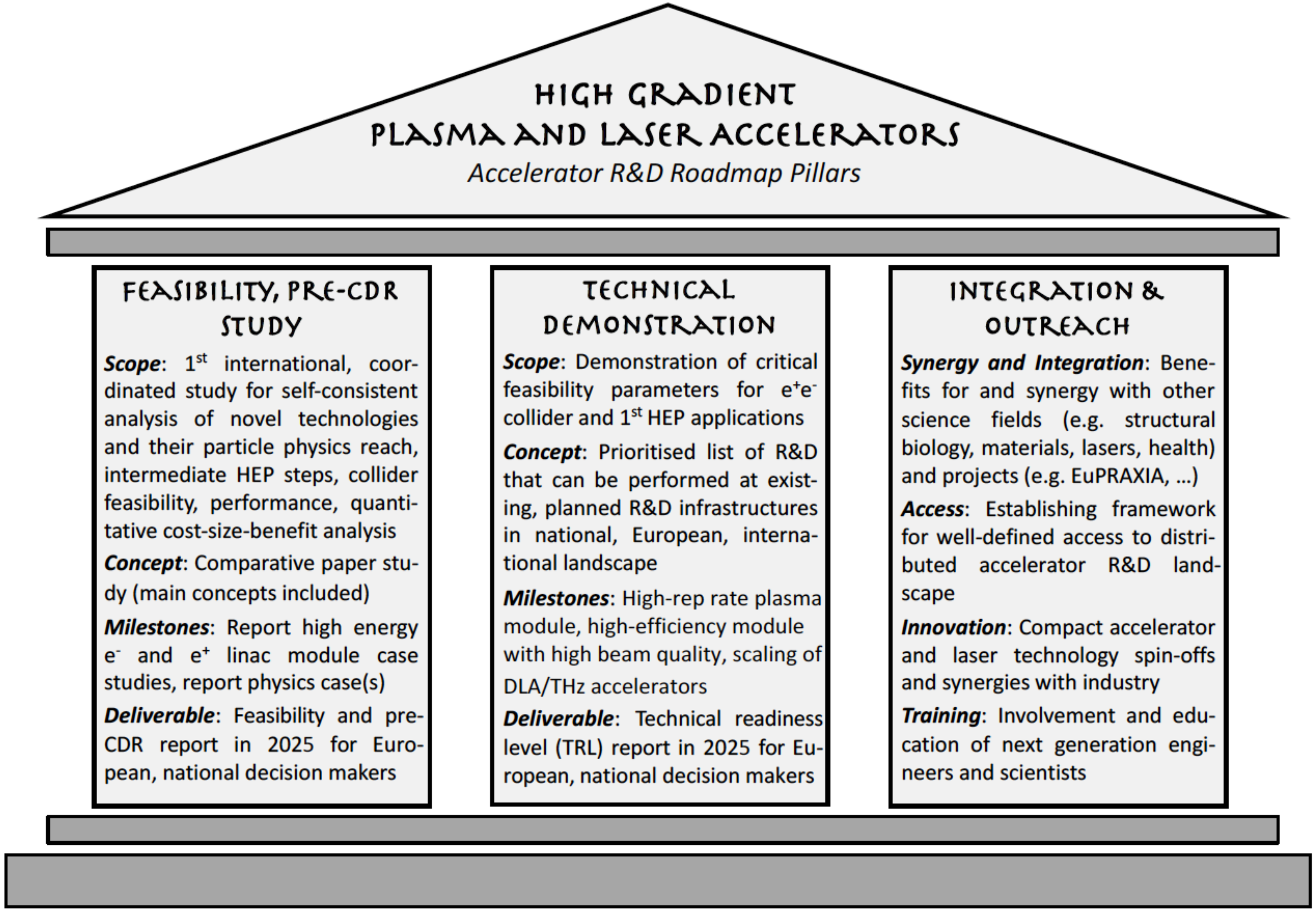


Fig. 4.5: Building blocks of a plasma wakefield accelerator: this setup, only a few centimeters in size, is used to generate a plasma channel. *Image: DESY, H. Mueller-Elsner*

High Gradient Plasma and laser Accelerators



Goal is to complement large ‘external’ investment in plasmas

Ensure that the HEP-specific aspects are fully covered

Drive for plausible case for large-scale project at next ESPPU

Long term plans

2025 - Feasibility and pre-CDR Report on Advanced Accelerators for Particle Physics. This includes an assessment of Technical Readiness Levels (TRL), taking into account results from technical milestones until 2025.

2027 – Definition of physics case and selection of technology base for a Conceptual Design Report (CDR), in accordance with guidance from the European Strategy. An update on the timeline will be provided appropriate to particle physics requirements and realistically achievable goals.

2031 – Publication of a CDR for a Plasma-Based Particle Physics collider.

2032 – Start of Technical Design Report (TDR), prototyping and preparation phase. Eventual start of a dedicated test facility (to be defined in the pre-CDR report).

2039 – Decision on construction, taking into account the results of the advanced accelerator R&D and the international landscape of colliders.

2040 – Start of advanced collider construction.

Beyond 2050 – It is expected that a plasma-based collider can only become available for particle physics experiments beyond 2050, given the required feasibility and R&D work described in this report

Task breakdown
Minimal scheme

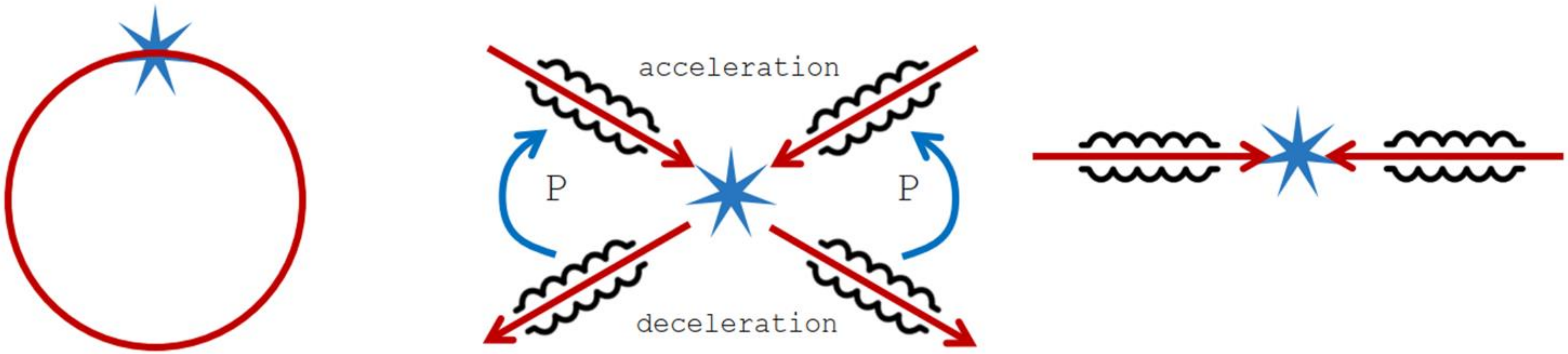
WP	Task	Short Description	Invest Personnel
COOR		Coordination Plasma and Laser Accelerators for Particle Physics	—
FEAS		Feasibility and pre-CDR Study on Plasma and Laser Accelerators for Particle Physics	300 kCHF 75 FTEy
	FEAS.1	Coordination	
	FEAS.2	Plasma Theory and Numerical Tools	
	FEAS.3	Accelerator Design, Layout and Costing	
	FEAS.4	Electron Beam Performance Reach of Advanced Technologies (Simulation Results - Comparisons)	
	FEAS.5	Positron Beam Performance Reach of Advanced Technologies (Simulation Results - Comparisons)	
	FEAS.6	Spin Polarization Reach with Advanced Accelerators	
	FEAS.7	Collider Interaction Point Issues and Opportunities with Advanced Accelerators	
	FEAS.8	Reach in Yearly Integrated Luminosity with Advanced Accelerators	
	FEAS.9	Intermediate steps, early particle physics experiments and test facilities	
	FEAS.10	Study WG: Particle Physics with Advanced Accelerators	
HRRP		Experimental demonstration: High-Repetition Rate Plasma Accelerator Module	1200 kCHF 30 FTEy
HEFP		Experimental demonstration: High-Efficiency, Electron-Driven Plasma Accelerator Module with High beam Quality	800 kCHF 10 FTEy
DLTA		Experimental demonstration: Scaling of DLA/THz Accelerators	500 kCHF 16 FTEy
SPIN		Experimental demonstration: Spin-Polarised Beams in Plasma Accelerators	350 kCHF 16 FTEy
LIAI		Liaison to Ongoing Advanced Accelerator Projects, Facilities, Other Science Fields	—

Energy Recovery Linacs (ERL)

Ring Collider
beams circulate

ERL
power re-cirulated

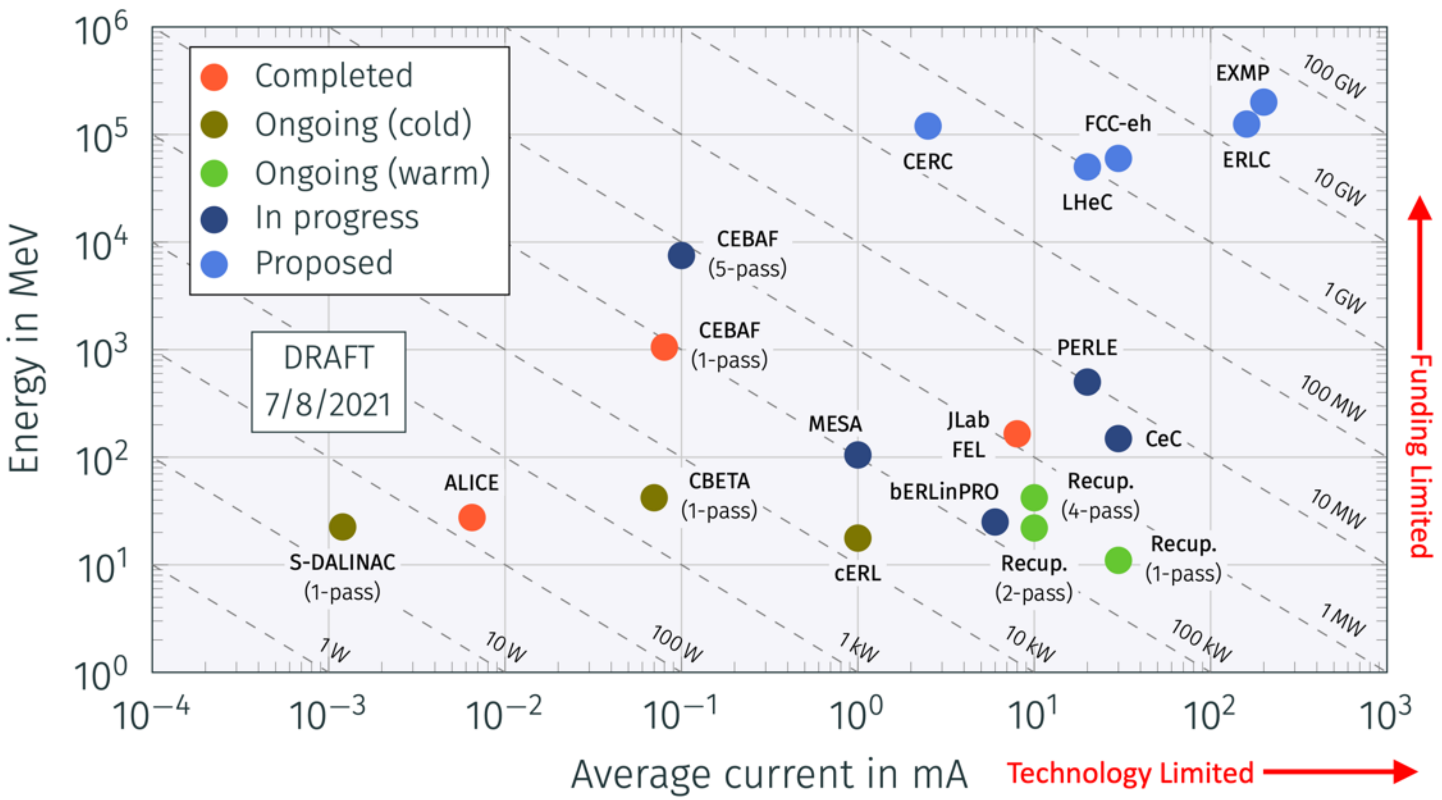
Linear Collider
beams collide once



- beam used once
- but power recirculated
- ambitious collision parameters lead to low beam intensity

→ **overall low energy consumption, but higher initial investments**

ERL Objectives

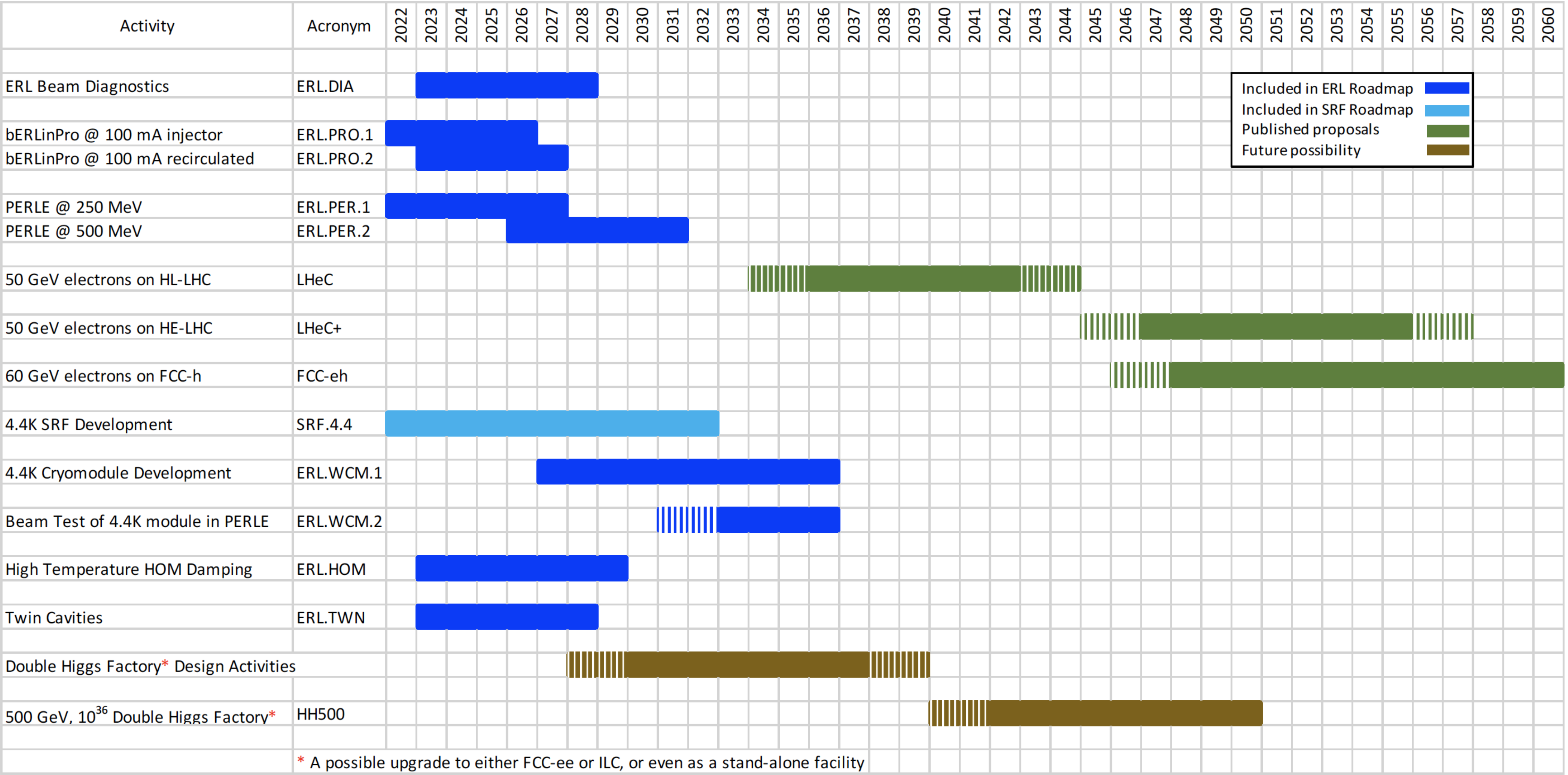


3 part programme

- Support and exploit ongoing facility programmes (worldwide)
- Focussed technical R&D into key technologies
- Development or upgrade European facilities for mid-2020s

Relevant to both absolute performance and sustainability of future machines

ERL Plan


Activity
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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
Included in ERL Roadmap
Included in SRF Roadmap
Published proposals
Future possibility
* A possible upgrade to either FCC-ee or ILC, or even as a stand-alone facility

Technology R&D

Two main areas: electron guns and SRF

Electron Guns – options include thermionic, CW DC, NCRF and SRF

- Examples exist of all of these gun types, mostly at lower performance
- Need to down-select two and build prototypes at full specifications
- Example: PERLE electron gun must deliver 20 mA (same as LHeC)
  - Easy for unpolarized electrons, harder for polarized electrons

SRF – ERLs have some specific features that require additional R&D to that of SRF accelerators

- Higher Order Modes are extremely important, requires careful mode analysis and heavy damping
- Fast Reactive Tuner (FRT) technology can drastically reduce RF power requirements
- Example: PERLE cryomodules must support 120 mA (3-pass accelerating, 3-pass decelerating)

Other technology areas: arcs, beam dynamics, beam loss, separate recovery transport . . . .

ERLs - Sustainability

Any future particle accelerator facility is expected to be sustainable!

The accelerator community often conceives very large and energy-hungry machines, but we have an obligation to significantly improve energy efficiency to receive support from society

Methods to improve energy efficiency are already a part of any strategy towards future accelerator facilities

ERLs are an innovative, high luminosity, green accelerator concept, for HEP, NP and industrial applications with far reaching impacts for science and society

Dumping the beam at injection energy is environmentally friendly

ERLs are one of the key technologies for a sustainable HEP future

This message courtesy the ERL community

Sustainability, societal impact – in general

Environmental sustainability should be/has become a primary consideration

Objective metrics should allow judgment of the cost and impact of future facilities over their entire life cycle.

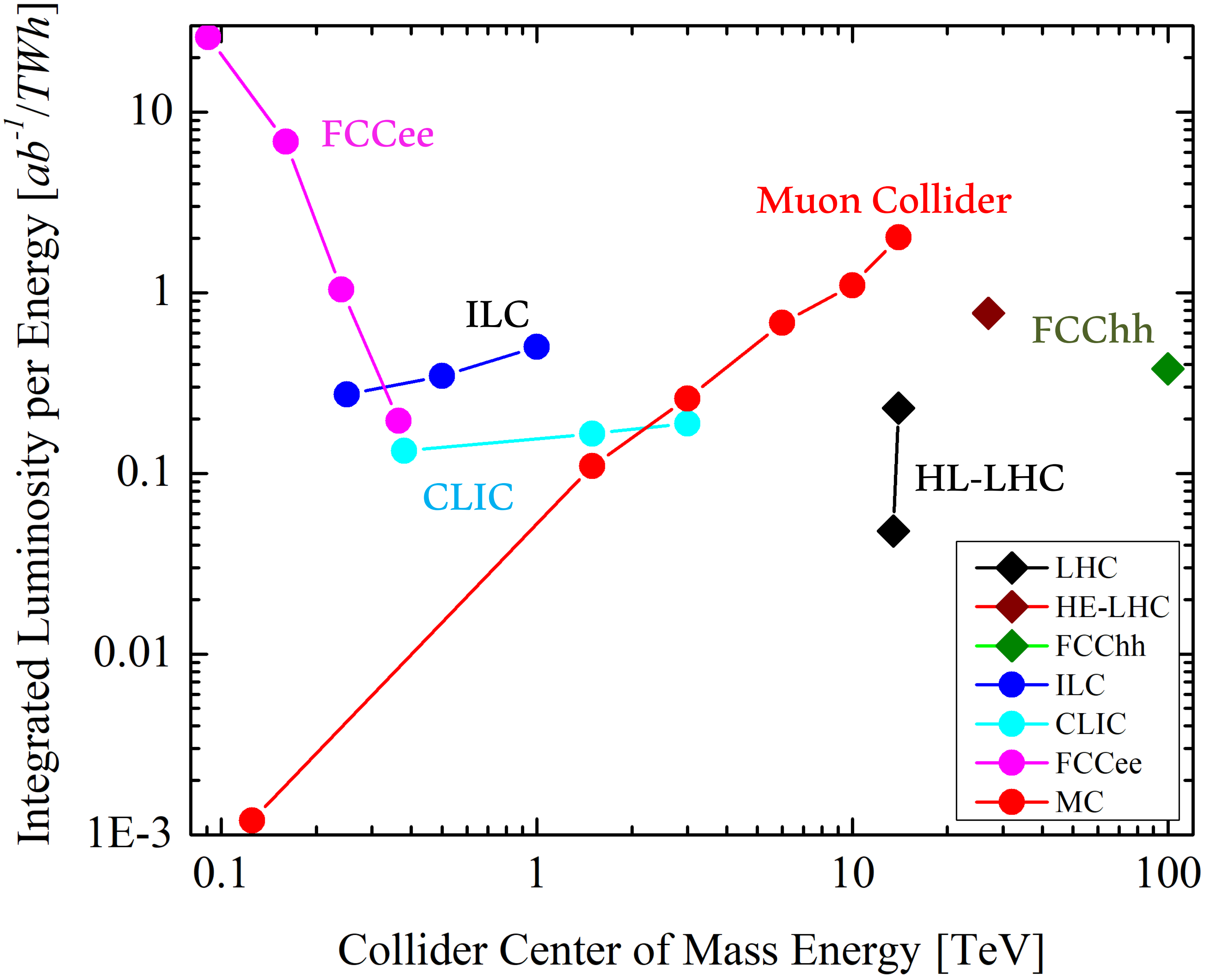
Emphasis should be placed on **prompt scientific exploitation** of R&D outputs

Practical considerations of manufacturing, assembly, testing, and commissioning should factor into the design and parameters of future machines with the close **engagement of 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

Energy Efficiency of Future Colliders



arXiv:2007.15684

Accelerators and Sustainability

Future machines – full lifecycle

- Construction to dismantling
- Technology: SRF, klystrons, magnets (SC, HTS, permanent)
- Design: optics, FFA, ERLs
- Technical infrastructure: efficiency, heat recovery

Innovative technology

- Power/energy distribution (HTS, smart grids, hydrogen…)
- Energy storage (SC magnets, hydrogen…)

Support to alternatives

- Fusion – ITER
- ADS, thorium – MYRHHA

Exploitation/energy use

- Energy Management Panel (heat recovery, targeted consolidation (magnets, RF, power converters), greenhouse gases, HVAC efficiency)
- CERN to adopt ISO 50001 - efficient energy management standards

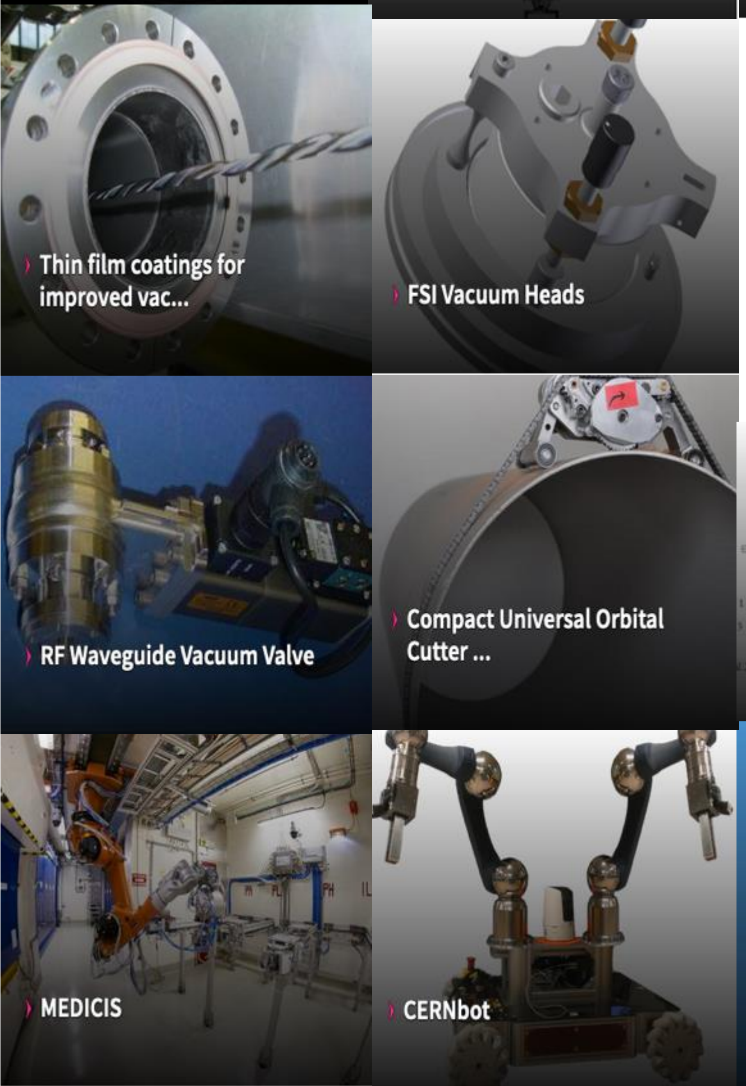
Climate research

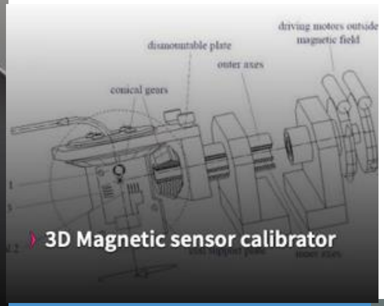
- CLOUD

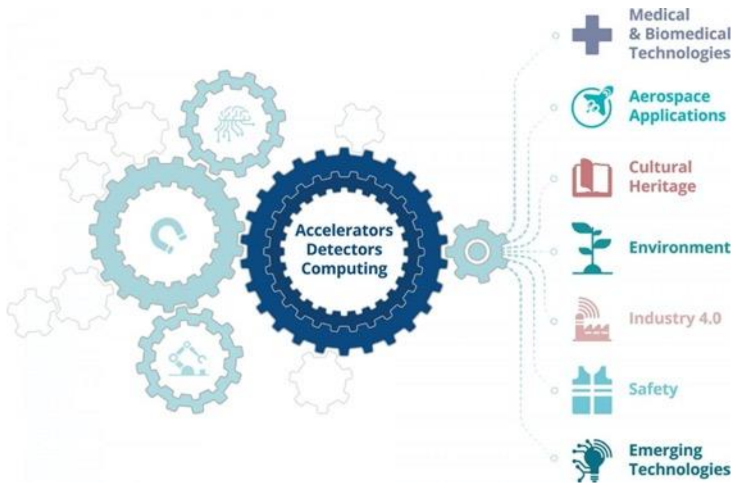
Procurement

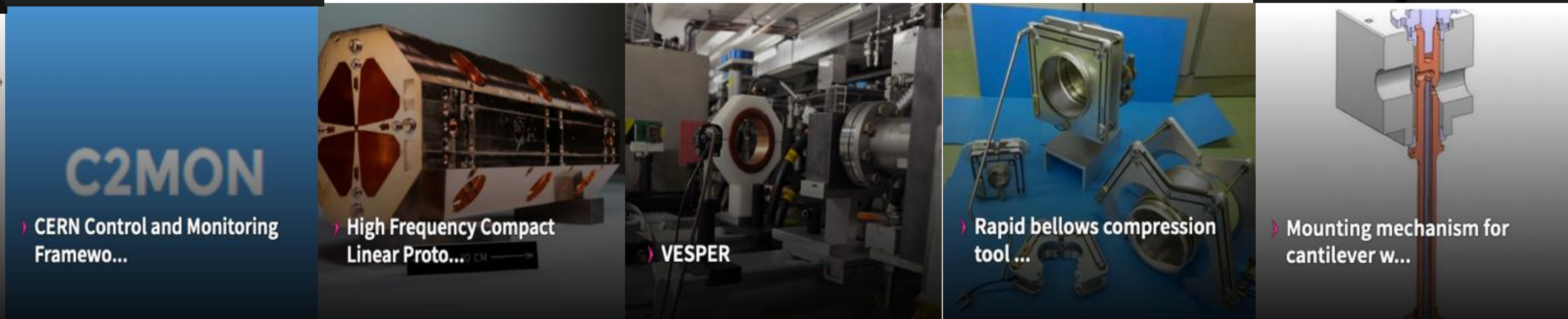
- Energy use considered in system design, specifications, arbitration

Knowledge Transfer









Conclusions

ESPP has bequeathed a challenging charge with the aim of providing a technological base for possible future developments in the field

Development of the Roadmap – has been an interesting, not obvious process

Implementation, funding, working together is going to required the strengthening of existing collaborative links… ongoing

But the initiative does provide an opportunity, visible and important focus for funding agencies, a formal reporting line to CERN Council and member state representatives.

We must recognize the increasing importance of sustainability and societal impact and look for these to become a core component of future developments