ECFA
European Committee for Future Accelerators

Durham University

Hadron Colliders (including HL-LHC) - UK studies for EU strategy

UK studies for the European Particle Physics Strategy Update in Durham, 23rd - 26th September

Stephen Gibson

John Adams Institute for Accelerator Science

Royal Holloway, University of London

Overview

- *Scope: overview of landscape of hadron colliders, and smaller non-collider projects*
  - *Challenges of projects; highlight current and potential future, contributions*
- *High-Luminosity LHC upgrade*
  - *LHC status and timeline to High Luminosity era*
  - *HL-LHC-UK accelerator community contributions*
- *UK contributions to confirmed global projects*
- *Potential new hadron colliders at CERN*
  - *FCC-hh: technology challenges, resources and contributions*
  - *HE-LHC, LHeC & FCC-he*
- *Proton drivers for neutrino & muon beams*
- *Physics beyond colliders programme*
  - *Fixed target beamlines for NA61/SHINE & NA62/ Klever, SHiP*
  - *Forward Physics Facility*

Future colliders: how to beat the synchrotron limit?

Synchrotron radiation loss per turn

$$\Delta E_s = \frac{e^2}{3\epsilon_0} \times \frac{E^4}{(mc^2)^4} \times \frac{1}{R}$$

Increase m, same R:
reuse LEP tunnel with protons → **LHC, HL-LHC**

increase R (and B)

FCC-hh in 100 km tunnel requires **high-field magnets**

→ this talk

switch to higher lepton m

Challenge is to produce, capture and cool beams of short-lived muons

→ Chris's talk

set R to infinity: linear colliders

→ Phil's talk

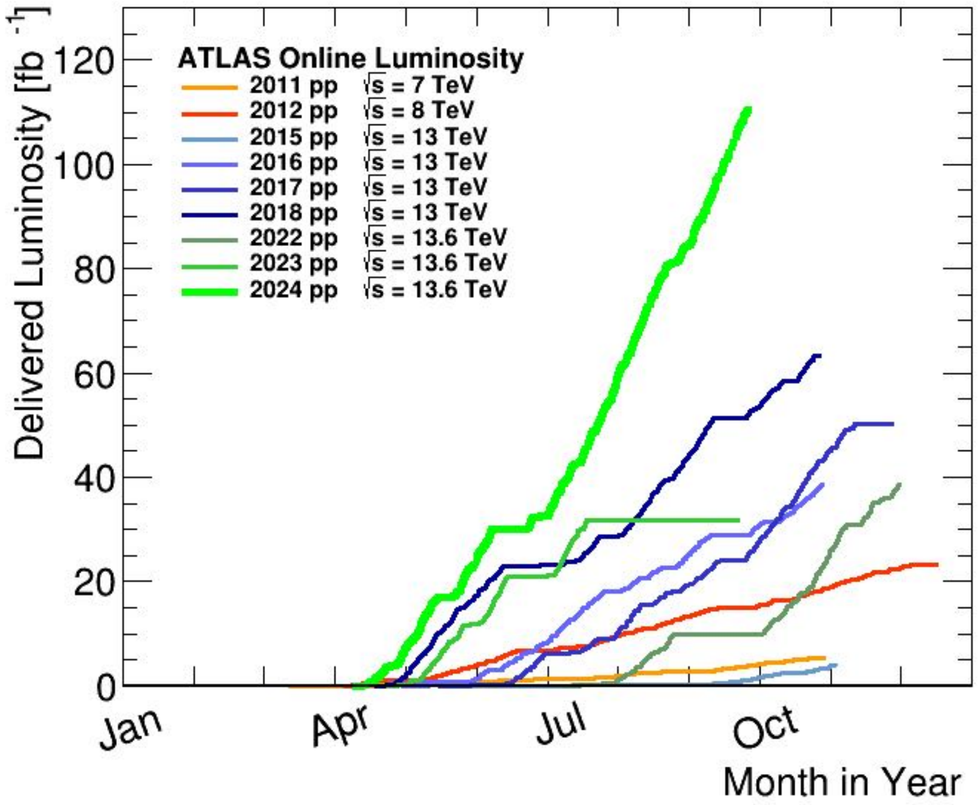
high gradients:

SCRF structures,
drive beams or advanced accelerator concepts;

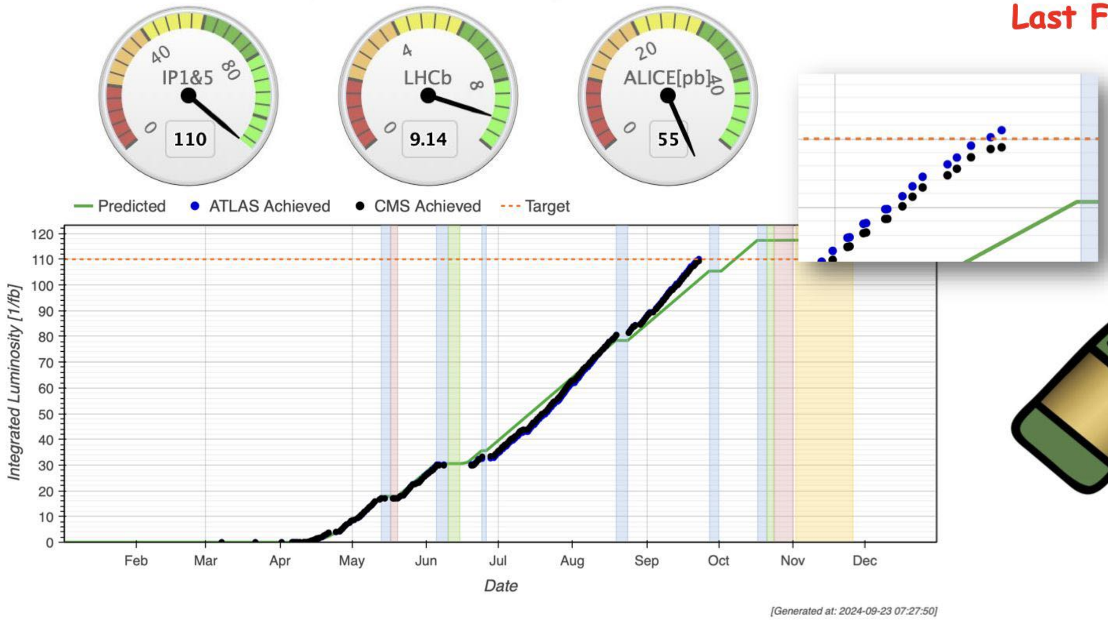
plasma wakefield / HALHF → Richard's talk

LHC performance and future

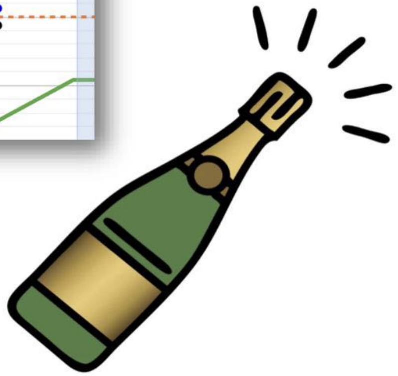
- ***LHC performance has exceeded yearly targets in quest to measure Higgs Boson couplings and search for exotic physics.***
- ***Recently reached 2024 target of 110 fb^{-1}, with 3 weeks to go:***



Yearly target (110 fb^{-1}) reached

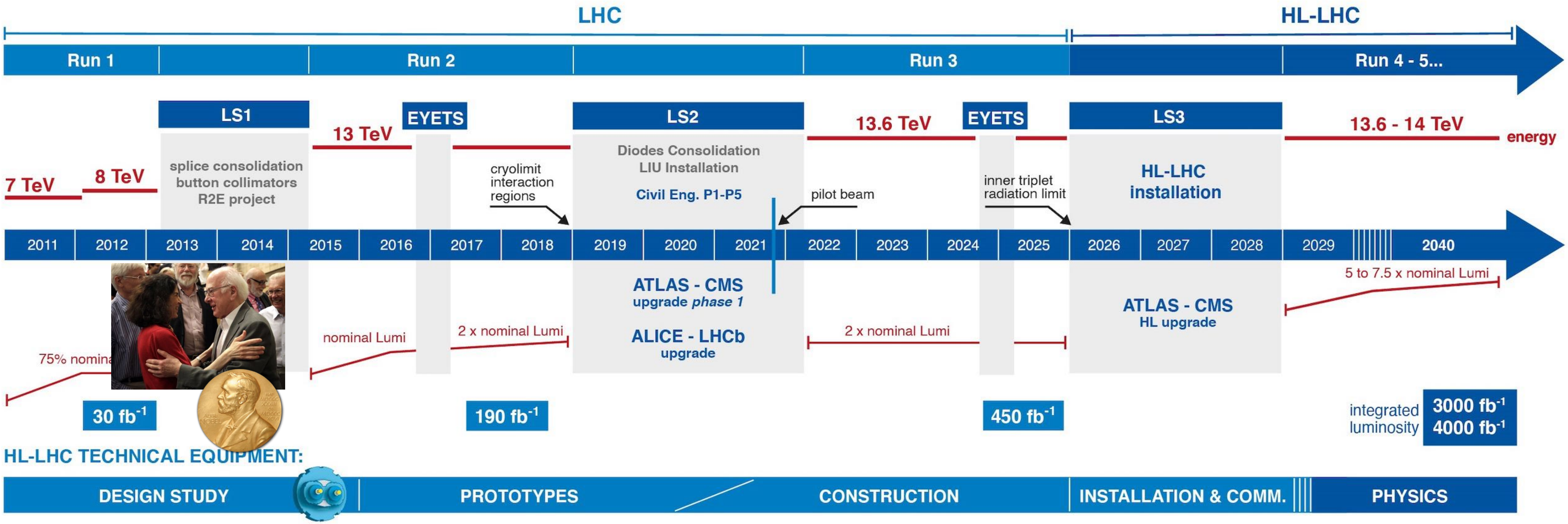


100 fb^{-1} celebration
Last Friday in CCC @5pm



Timeline to High Luminosity LHC era

- ***EU strategy 2020 1A:** The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics … The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.*



HL-LHC UK contribution:

FP7 Design Study	UK Phase I, £8M	UK Phase II, £26M	UK Phase III … ?

Potential Phase III for exploitation of UK investment

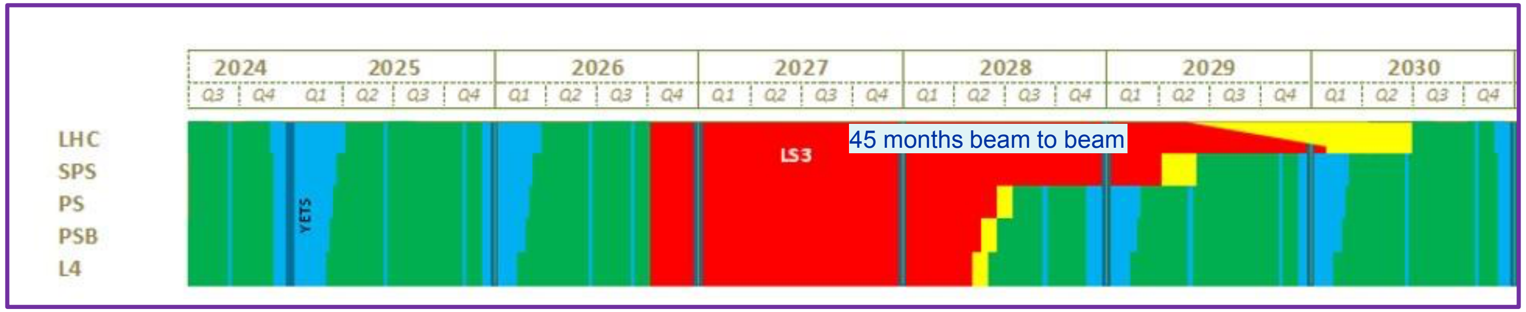
Long Shutdown 3 Readiness Review, Sept 2024

- ***LHC LS3 start date and duration recently reviewed by coordination team:***
  - ***Provisional +9 months schedule considered, with feasibility and acceptability evaluated.***
  - ***Ion run in Sept 2026, start LS3 in October 2026, beam back in July 2030: to be confirmed***

Reference schedule

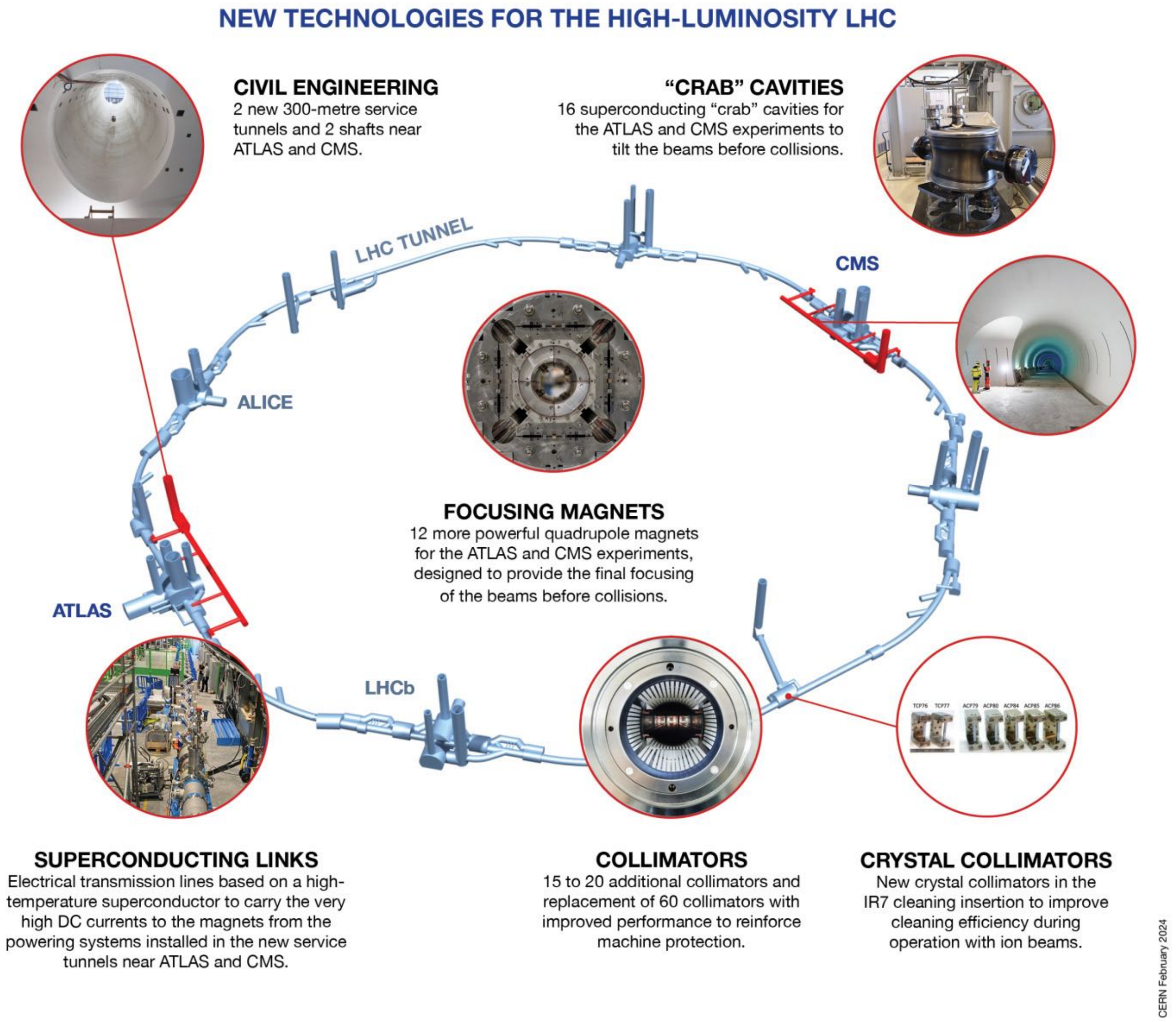
And a revised timeline being considered

Preliminary



J.-Ph. Tock

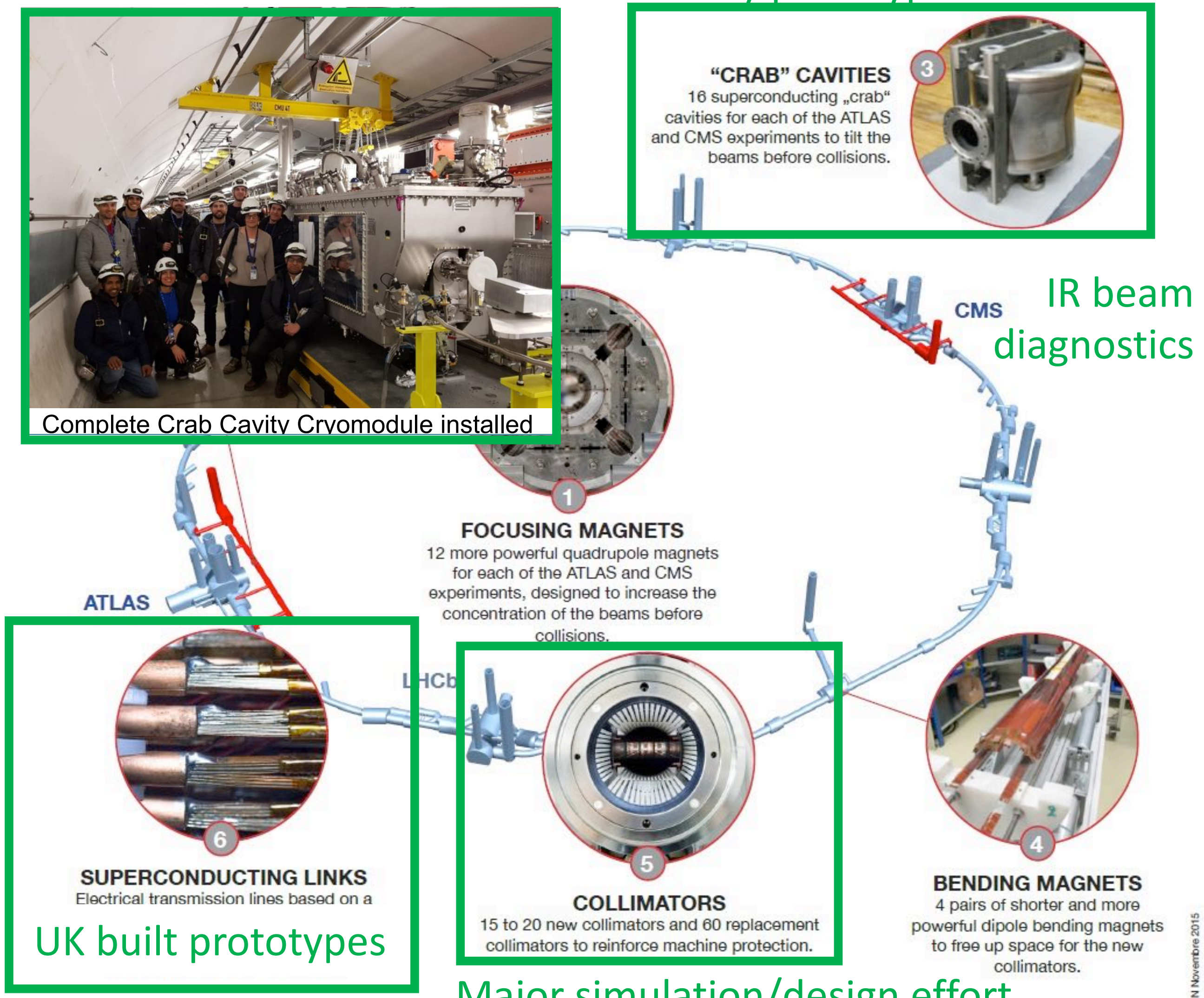
High Luminosity – how?



- **Lower beta* (~15 cm)**
  - New inner triplets - wide aperture Nb_3Sn
  - Large aperture NbTi separator magnets
  - Novel optics solutions
- **Crossing angle compensation**
  - Crab cavities
  - Long-range beam-beam compensation
- **Dealing with the regime**
  - Collision debris, high radiation
- **Beam from injectors**
  - Major upgrade of complex (LIU)
  - High bunch population, low emittance, 25 ns beam

Major UK contributions to design & build HL-LHC: UK phase I (2016-2020)

UK delivered crab cavity prototype to SPS



IR beam diagnostics

UK built prototypes

Major simulation/design effort

UK institutes on ***HL-LHC-UK***

£8M CERN-STFC investment in UK

HiLumi HL-LHC PROJECT

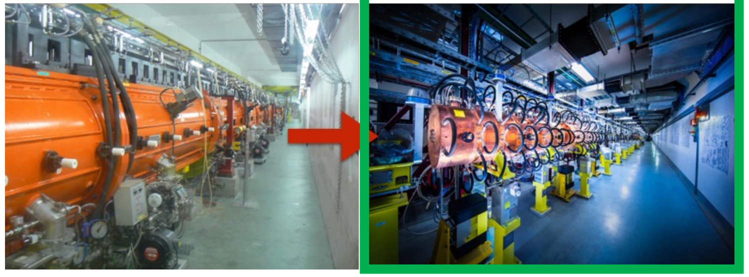
Manchester 1824 The University of Manchester · The Cockcroft Institute of Accelerator Science and Technology · Lancaster University · University of Liverpool · Science & Technology Facilities Council · Royal Holloway University of London · JAI John Adams Institute for Accelerator Science · University of Oxford (from 2020) · University of Southampton · University of Huddersfield · ASTeC

+ new injector diagnostics

LHC Injectors Upgrade

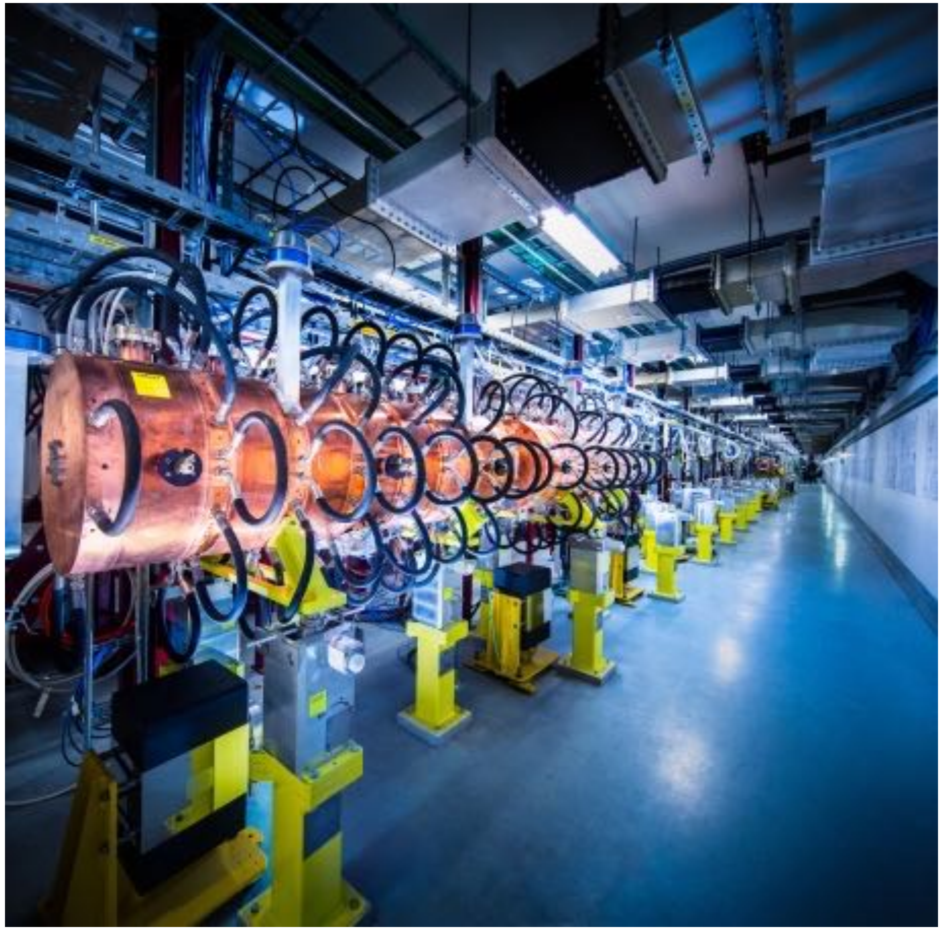
Linac2:
50 MeV protons

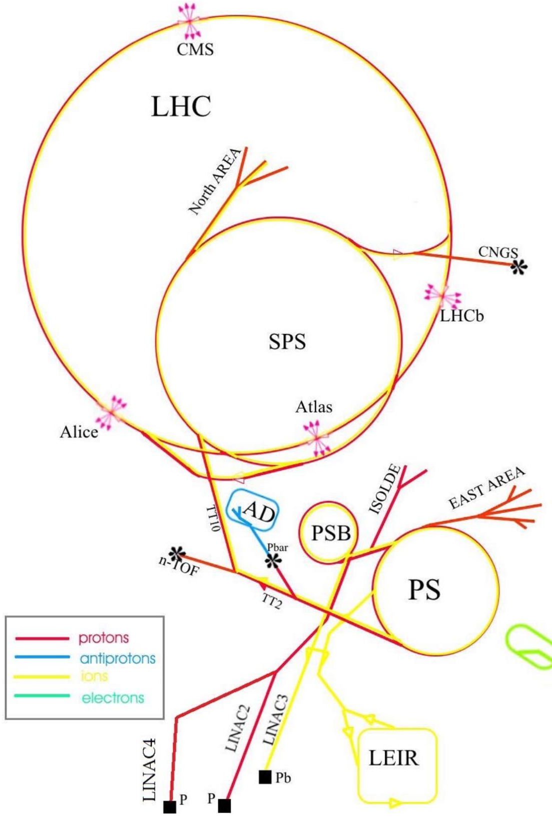
Linac4:
160 MeV H⁻ ions
http://home.cern/about/accelerators/linear-accelerator-4



CERN's Linac2 replaced by Linac4 as main injector

- ***Linac4 is the main injector for LHC since connection to PSB in LS2 2019/20***

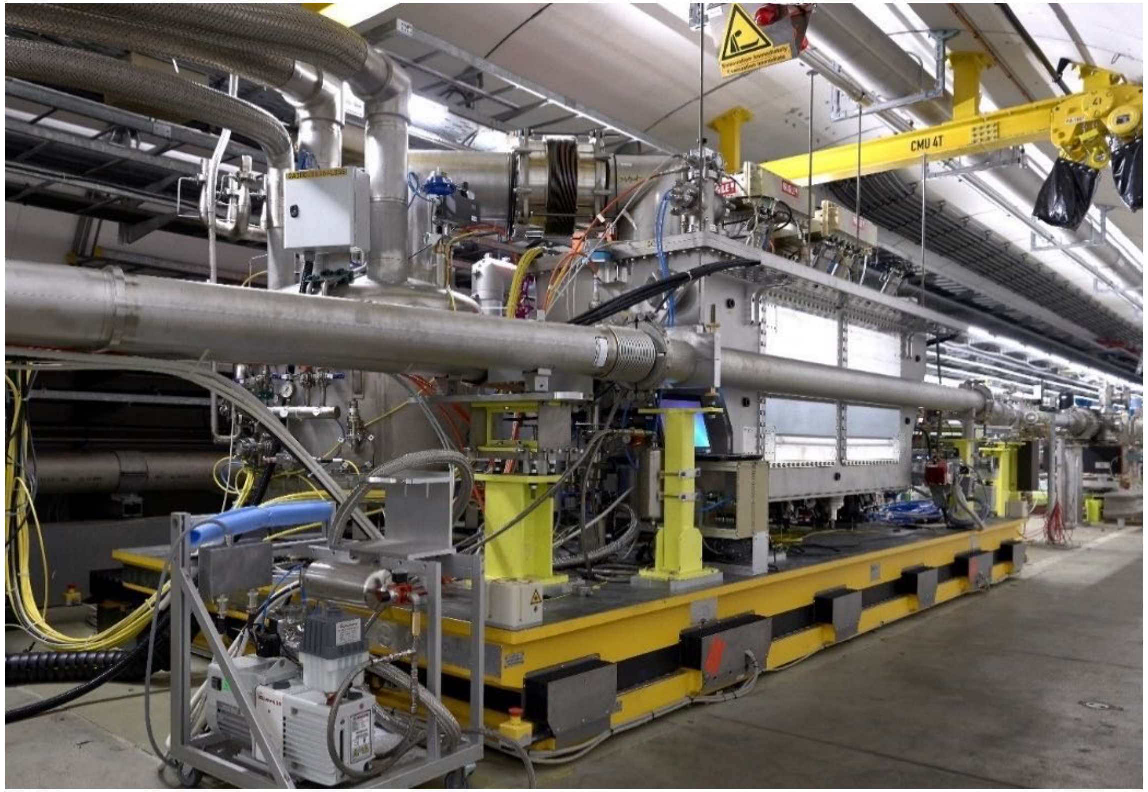




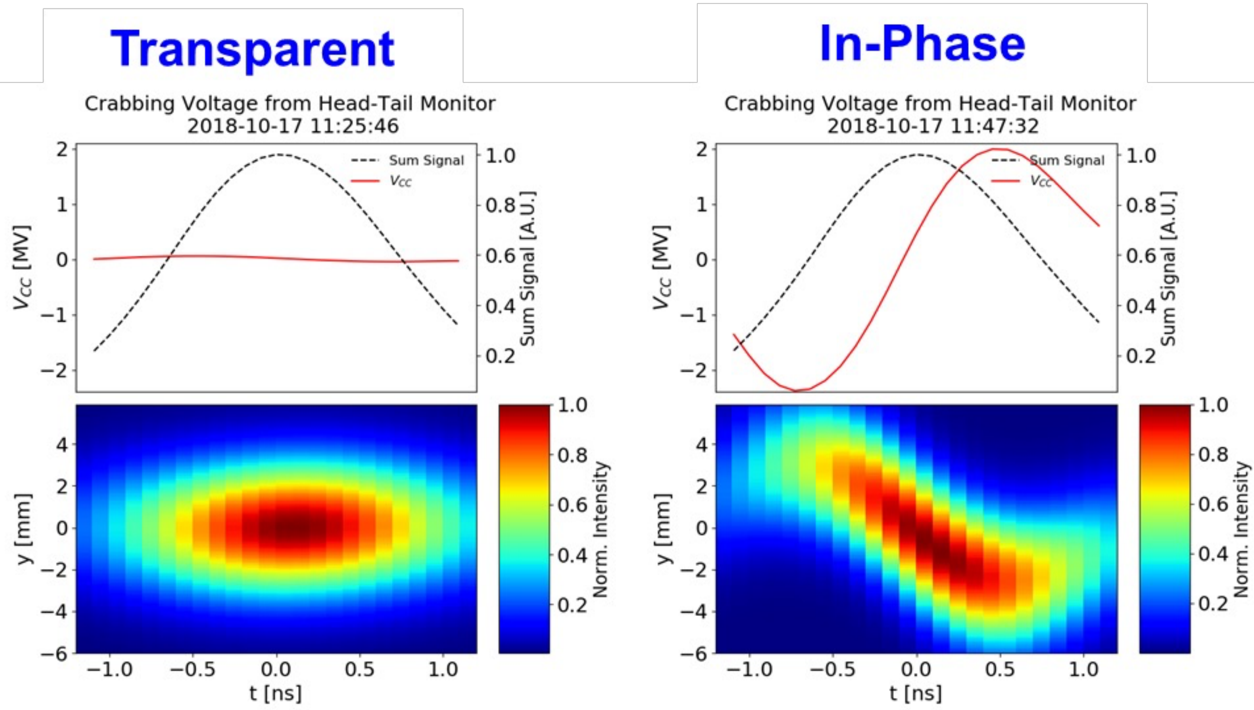
- *H^- ions boosted to 160 MeV*
  - *3 MeV, 352MHz Radio-Frequency Quadrupole (RFQ)*
  - *50 MeV drift tube linacs (DTLs)*
  - *100 MeV coupled-cavity drift tube linacs (CCDTLs)*
  - *160 MeV Pi-mode structures (PIMS)*
- *Commissioned 160 MeV in 2016.*
- *Multi-turn H- charge exchange injection to PSB enables a more brilliant beam for HL-LHC.*

Demonstration of crabbed-bunch rotation

- 2 DQW vertical crab cavities were installed in the SPS at the start of 2018, enabling first measurements of the proton-crab cavity interaction.



World's first crabbing of proton beam – 12:55 on May 23rd 2018. Shown right is crabbing reconstruction from the headtail monitor.



G. Burt et al

HL-LHC-UK Phase II (2020 – 2025/26)

https://stfc.ukri.org/news/project-to-upgrade-the-large-hadron-collider-now-underway/

Upgrade to Large Hadron Collider underway

HiLumi HL-LHC PROJECT

11 September 2020

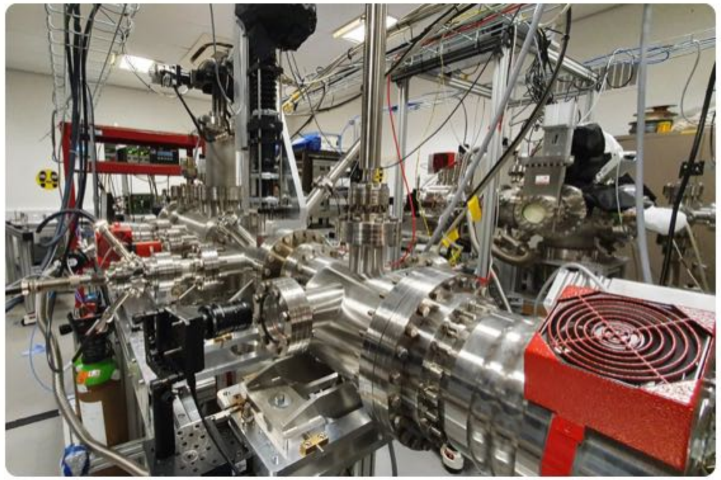
Scientists, engineers and technicians from the UK have embarked on a £26 million project to help upgrade the Large Hadron Collider (LHC) at CERN, on the French/Swiss border near Geneva.

The collaboration is between the Science and Technology Facilities Council (STFC), CERN, the Cockcroft Institute, the John Adams Institute, and eight UK universities. STFC is contributing £13.05 million.

Science Minister Amanda Solloway said:

"Ever since it first switched on in 2008, CERN's Large Hadron Collider has been working to answer some of the most fundamental questions of the universe.

"I am delighted that the UK's science and research industry will play a central role in upgrading what is the world's largest and highest energy particle collider, enabling leading physicists to continue making monumental discoveries."



Gas jet beam profile monitor setup at the Cockcroft Institute.

Crab-Cavity Cryomodules delivered by UK team

HiLumi HL-LHC PROJECT

- ***Components***

Accelerating NEWS

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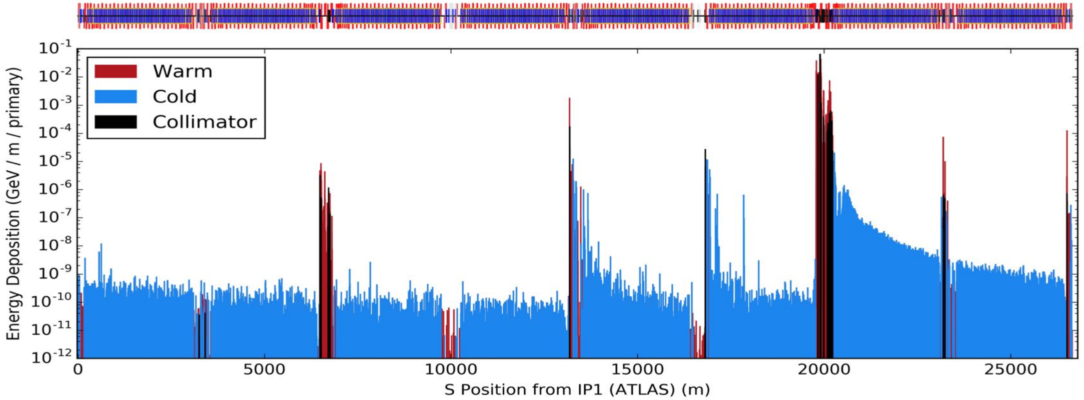
UK delivers first state-of-the-art cryomodule to CERN for the High-Luminosity LHC upgrade

The first pre-series cryomodule equipped with superconducting Radio Frequency Dipole (RFD) crab cavities was completed in October 2023 at Science and Technology Facilities Council (STFC)'s Daresbury Laboratory as a collaboration between HL-LHC-UK and CERN

The teams from STFC, Lancaster University, and CERN who worked on the technology. (Image credit: STFC Daresbury Laboratory)

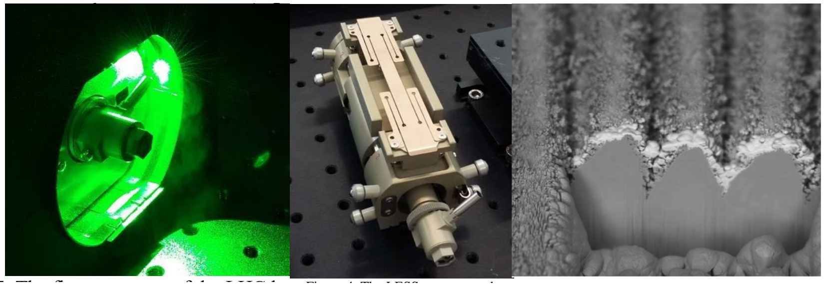
Further key HL-LHC-UK2 deliverables:

Collimation studies:

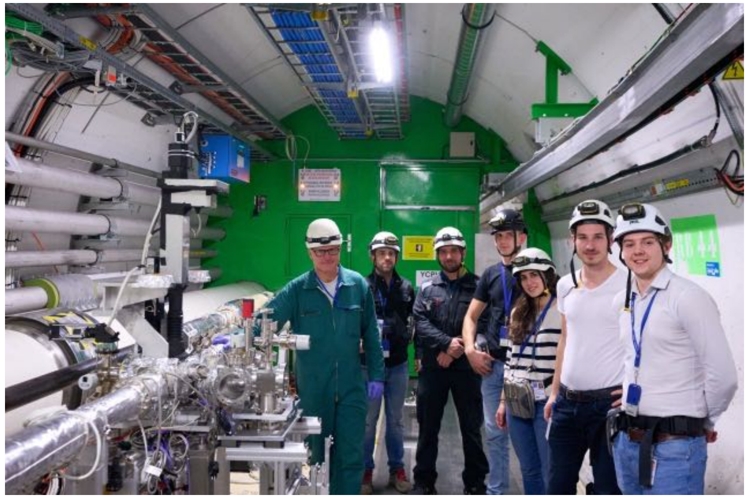


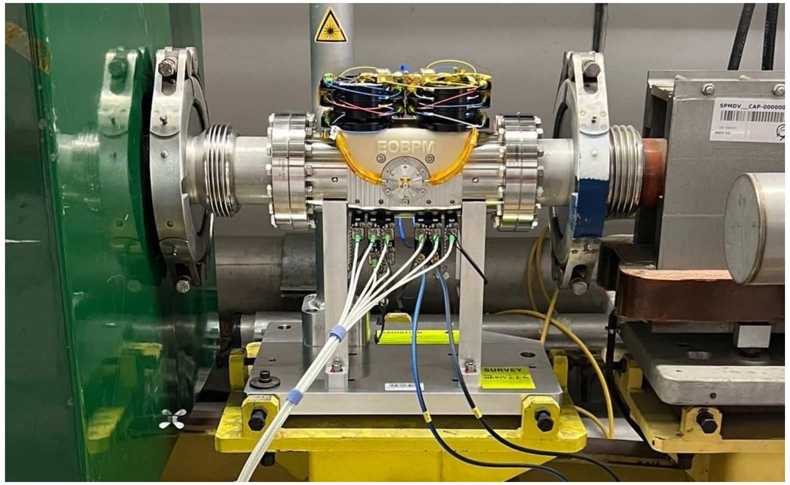
Cold powering with superconducting links

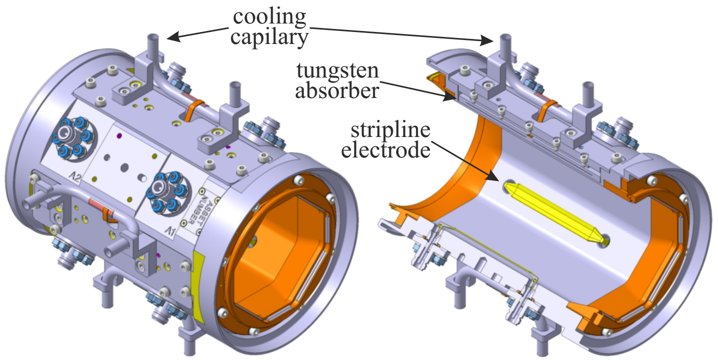
Laser engineered surfaces: to mitigate e-cloud



Novel Beam Diagnostics: Beam Gas Curtain; Electro-Optic BPM; Interaction Region BPMs







Work soon to start!

HL/LHC Activities

EYETS 24-25

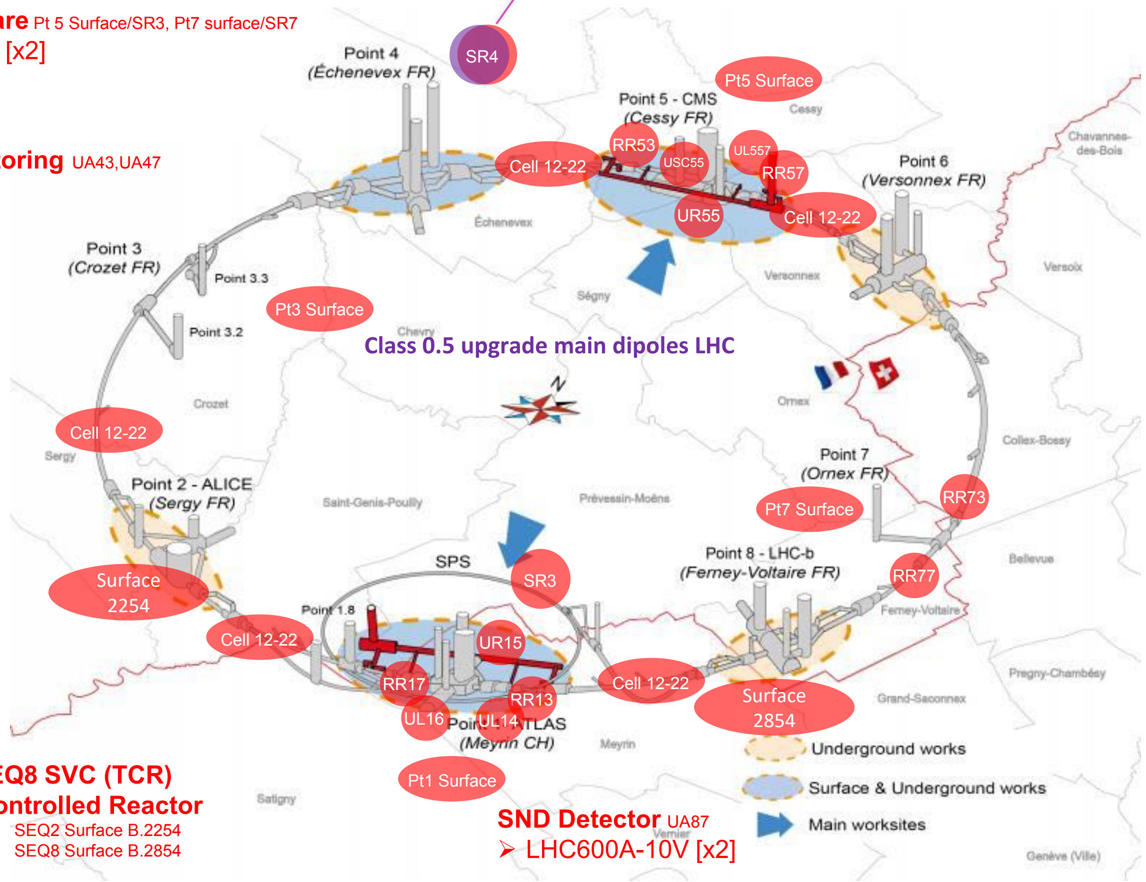
LS3

FGC4 Candidate

LHC RF Powering Cons B.SR4
- ➢ 18kV oil transformers replac. [x5]
- ➢ Step-up transformers, diode tanks, control Cons [x5]

LHC Cons - RD34 Spare Pt 5 Surface/SR3, Pt7 surface/SR7
- ➢ RPTG conv removal [x2]
- ➢ New SATURN [x2]

LHC Beam Gas Monitoring UA43,UA47
- ➢ New POLARIS [x4]



LHC Cons - SEQ2&SEQ8 SVC (TCR)
Control / Thyristor Controlled Reactor
SEQ2 Surface B.2254
SEQ8 Surface B.2854

SND Detector UA87
- ➢ LHC600A-10V [x2]

HL-LHC Harmonic Filters Powering
Surface Point 1 SEF1/B.9117
Surface Point5 SEF58/B.9500

LHC machine
- ➢ LHC±120A removal [x112] RRs, ULs, USC55
- ➢ RD2 removal [x4] RR13,RR17, RR53, RR57
- ➢ ITs removal [x12] Pt1 and Pt5
- ➢ LHC60A removal [x144] Cells 12-22
- ➢ LHC600A removal [x28] ULs, USC55
- ➢ RD1 removal [x2 SATURN, 2x RPTG] Pt1/SR1 and Pt5 Surface/SR5

HL-LHC - Interaction Point Upgrade IT UR15, UR55
- ➢ New HL-LHC±60A$_{35A}$ [x4]
- ➢ New HL-LHC±600A [x16]
- ➢ New HL-LHC±2kA [x32]
- ➢ New HL-LHC14kA[x8]
- ➢ New HL-LHC18kA [x4]

HL-LHC Long Straight Sections RRs, ULs, USC55
- ➢ New R2E HL-LHC±120A [x124]
- ➢ New R2E-HL-LHC±200A [x4]

HL-LHC Arcs Cells 12-22
- ➢ New R2E HL-LHC±60A [x144]

Core UK expertise in accelerators & enabling technology

The UK accelerator community has broad range of relevant expertise ready to deploy, including and not limited to:

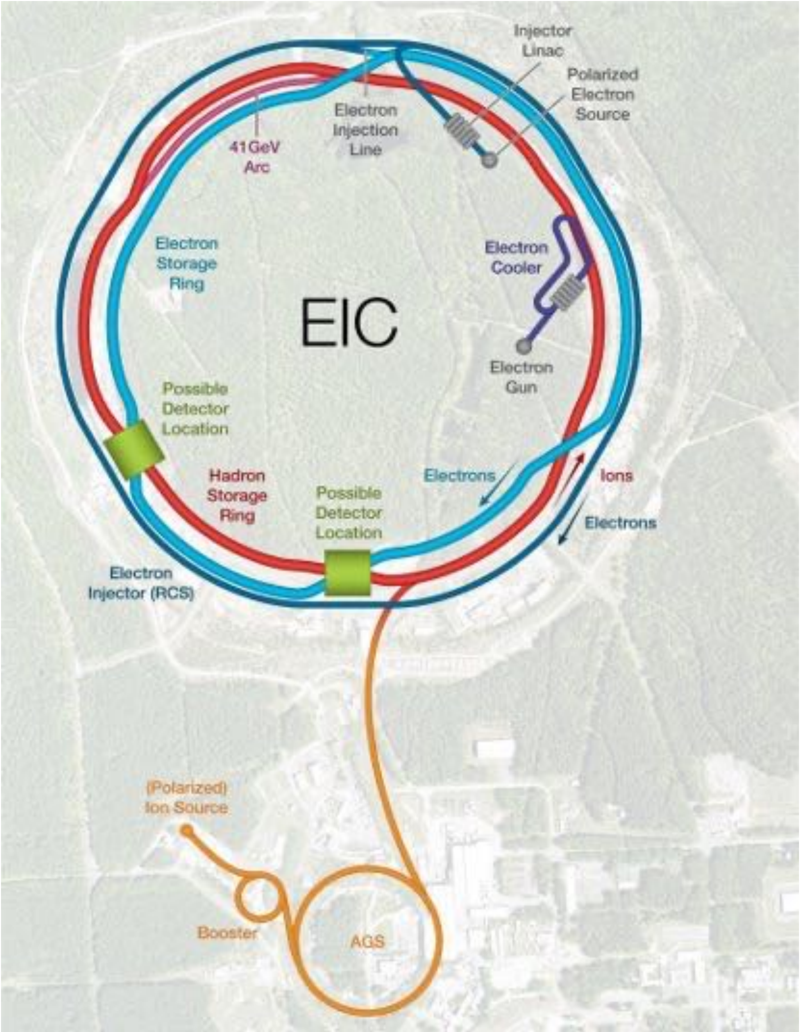
- *Beam dynamics simulations; optical lattice design & optimisation*
- *Novel collimation techniques: crystal, hollow electron lens.*
- *Machine detector interface & accelerator backgrounds*
- *Superconducting RF cavities, crab-cavities / cryomodules, high efficiency klystron development*
- *Beam diagnostics, including non-invasive profile & bunch instability monitoring*
- *Nanobeam control and fast feedback*
- *Cryogenic systems, cold powering.*
- *Vacuum systems & electron cloud mitigation*
- *Accelerator alignment systems*
- *Operational experience of low emittance electron storage rings & FEL test facilities…*

*ESPP2020 "Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. … **The European particle physics community must intensify accelerator R&D and sustain it with adequate resources**.*

Outside Europe: confirmed new Electron-Ion Collider

- *Design based on existing **RHIC complex at Brookhaven***
  - *RHIC is well maintained, operating at its peak*
  - *RHIC accelerator chain will provide EIC hadrons*
- *High luminosity interaction region(s)*
  - *L = 1034cm-2s-1*
- *Hadron Storage Ring (HSR: RHIC Rings) 40-275 GeV*
  - *Supplied by AGS and booster Injectors*
  - *Hadron cooling*
- *Electron Storage Ring(ESR) 5–18 GeV*
  - *Need to inject polarized bunches every second*
- *Rapid Cycling Synchrotron (RCS)*
  - *Designed to supply polarized bunches to the ESR every second*
- *Polarized e-source and pre-injector*

UK contribution: detector + accelerator funding announced, £59M

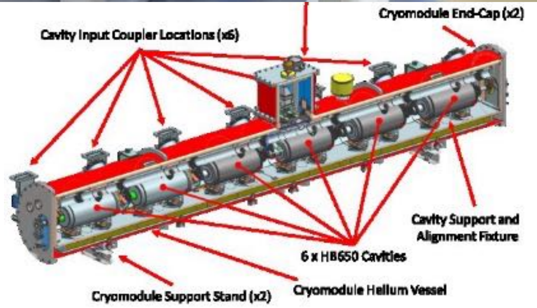


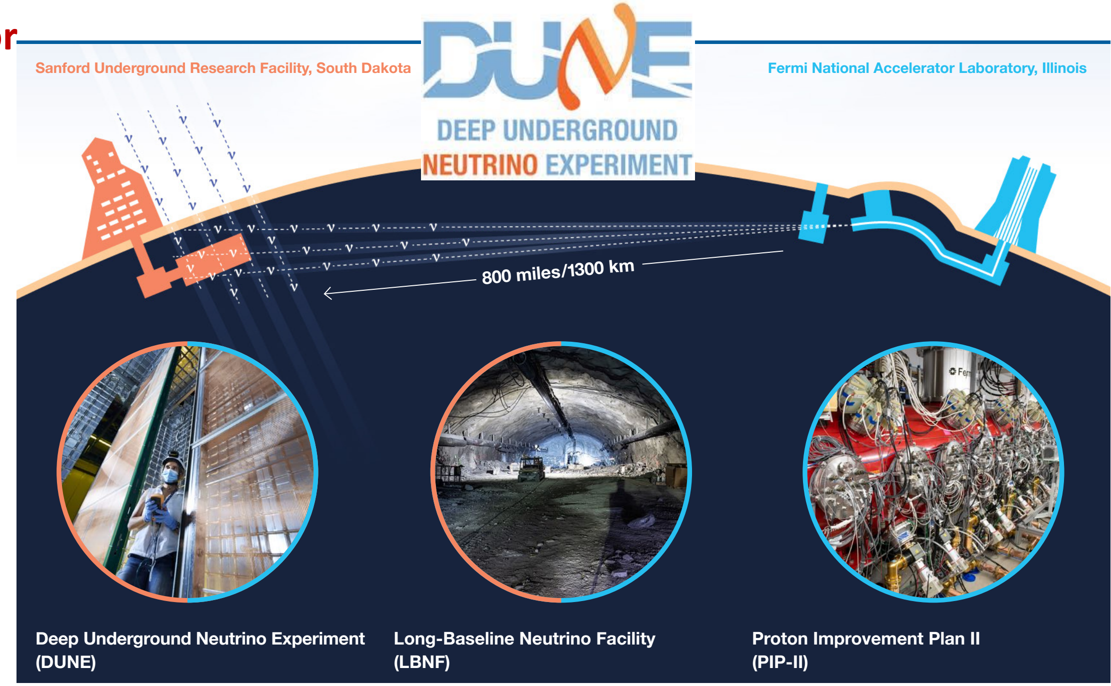
E_{cm} = 20 GeV -141 GeV
High luminosity goal: $L = 10^{34} cm^{-2} s^{-1}$

Outside Europe: PIP-2 for LBNF & DUNE

- ***UK's contributing SRF cryomodule expertise to the international Proton Improvement Plan II project***
  - *Successful shipment test of cryomodule between Fermilab & STFC Daresbury*
  - *STFC is investing £65 million as part of the $500 million international project*

PIP-II 650MHz cavity demonstrator





What’s the future of the Large Hadron Collider?

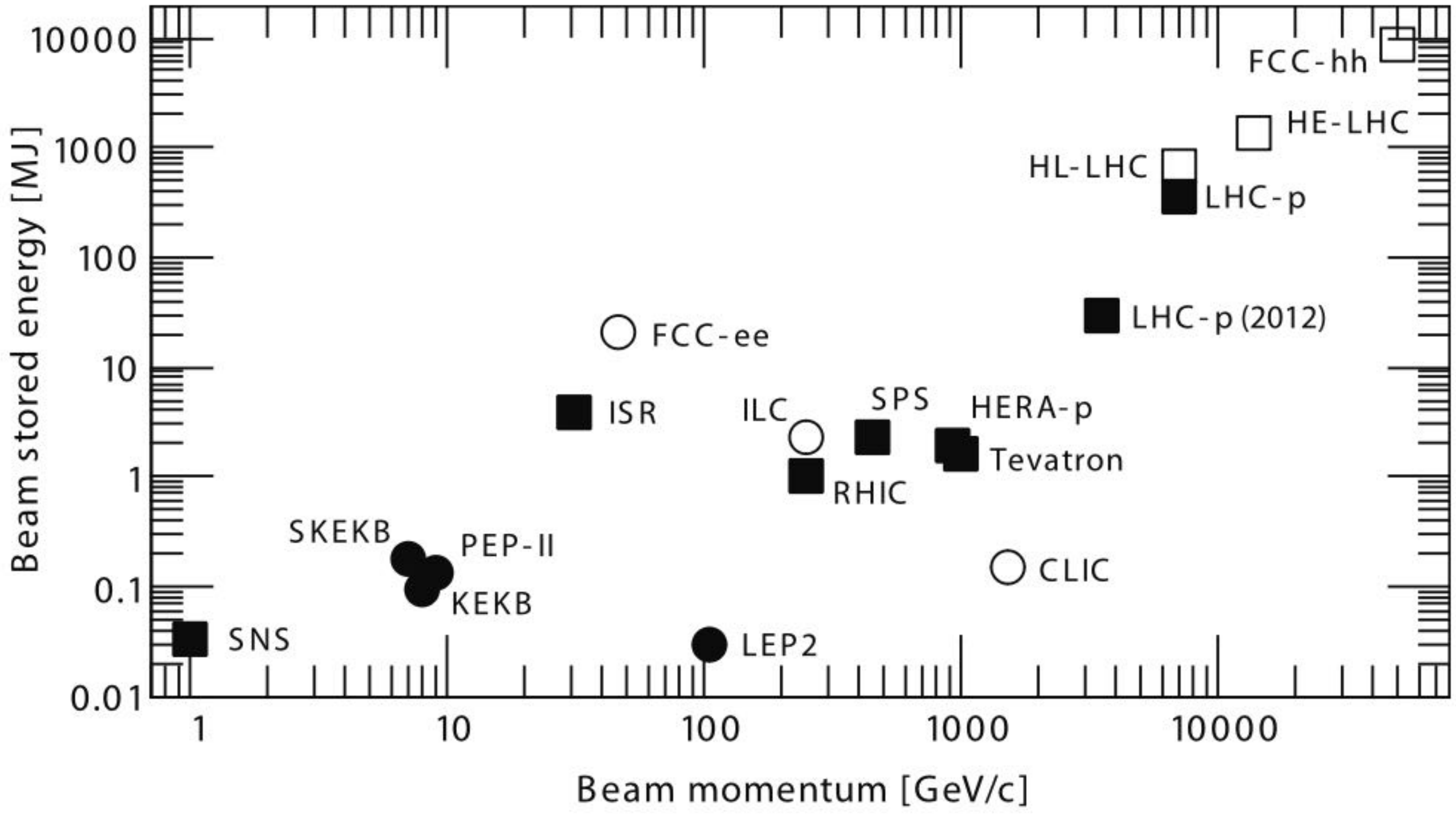
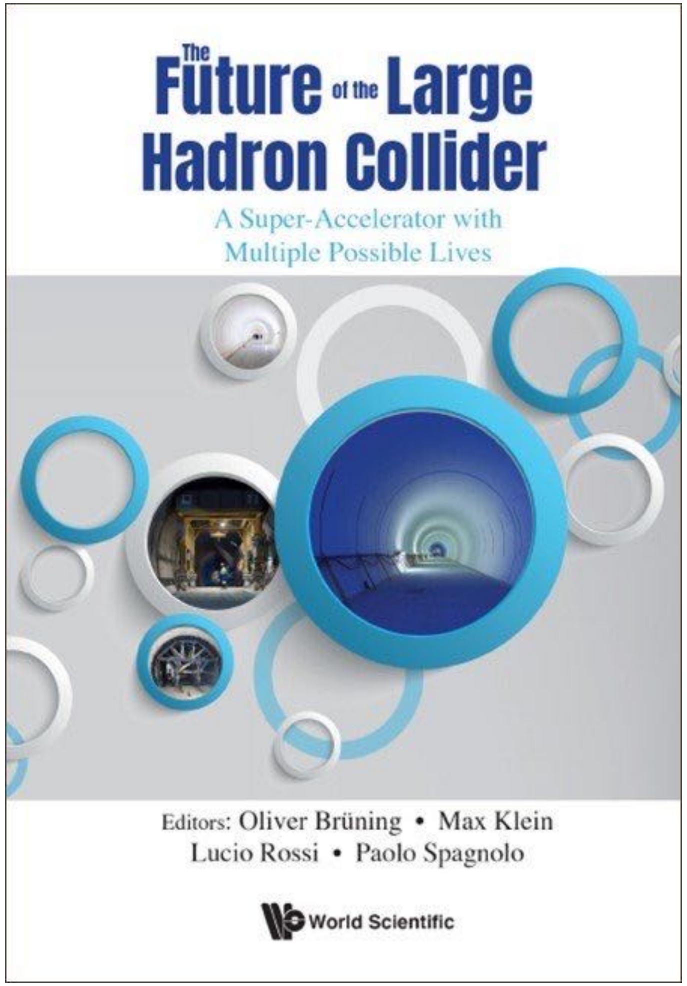


Fig. 1. Livingston-like plot of the stored beam energies for hadron (squares) and lepton (circles) accelerators. Filled symbols are used for past or operating machine and empty symbols indicate future accelerators. *Courtesy R. Aßmann.*

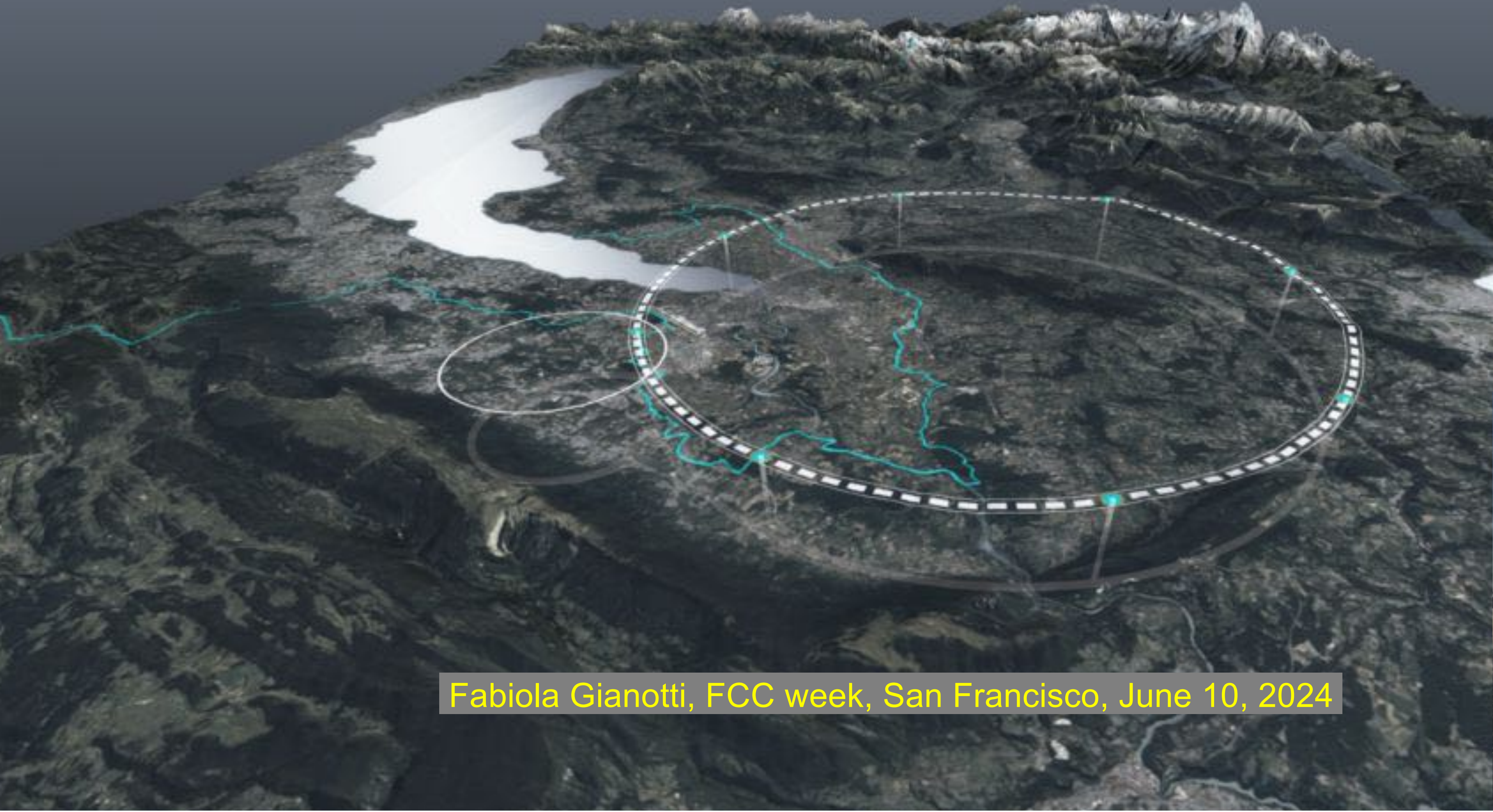


‘My Lords, can my noble friend tell us what a large hadron collider is, and whether a smaller one might not do?’ — LORD ELTON*

*speaking in the House of Lords debate on the LHC, Hansard, 18th July 1994.

The full transcript:
http://hansard.millbanksystems.com/lords/1994/jul/18/large-hadron-collider

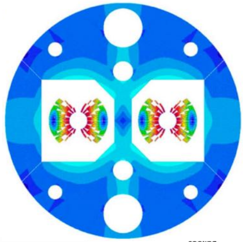
Future Circular Collider : CERN plans

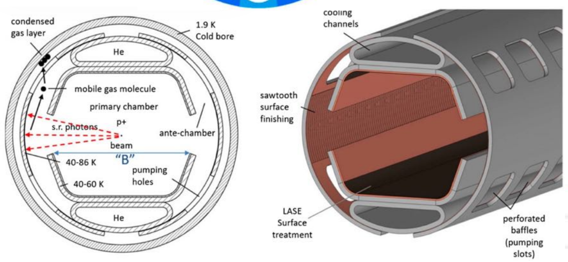


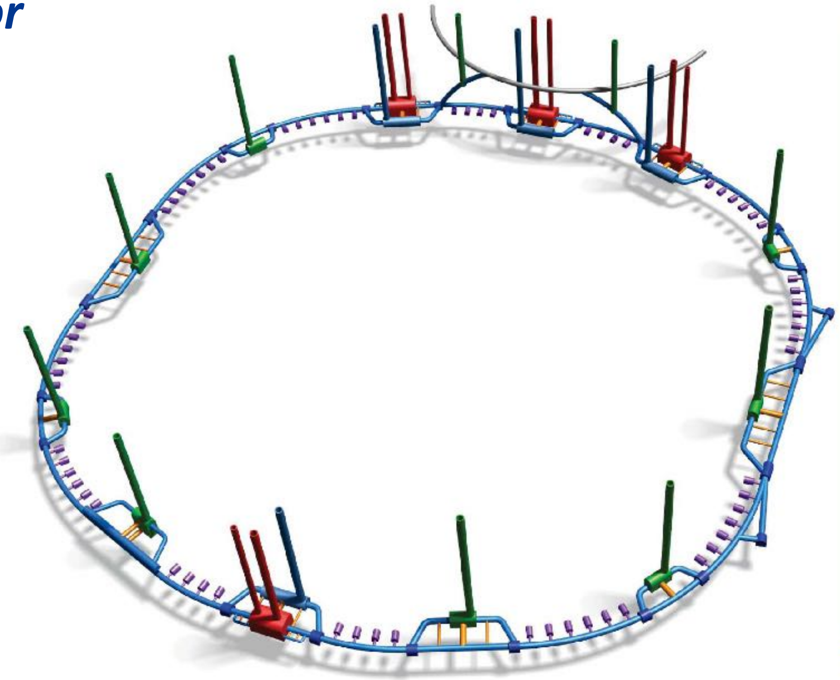
Fabiola Gianotti, FCC week, San Francisco, June 10, 2024

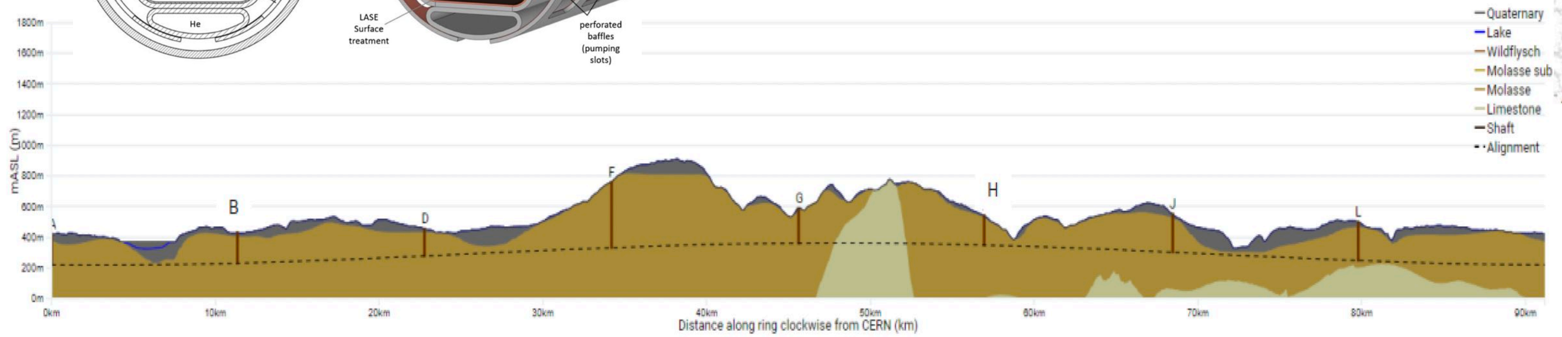
FCC-hh - Future Circular Collider hadron-hadron

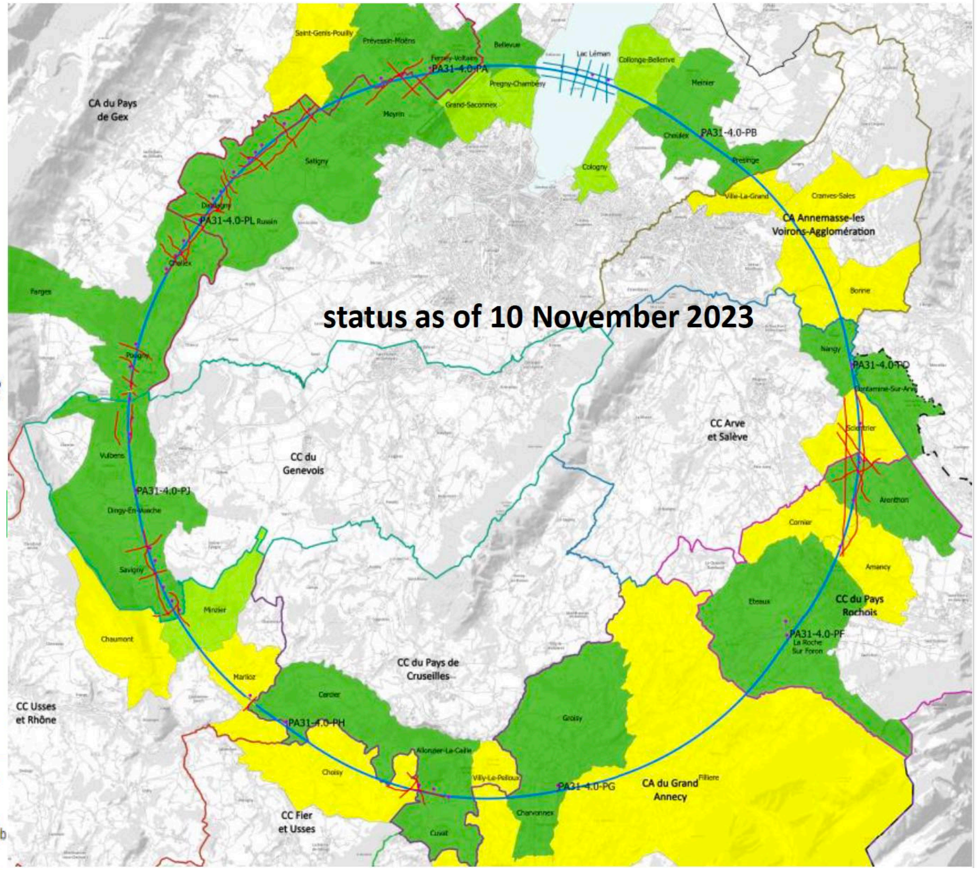
- ***81 - 115 TeV pp collider with 90.7 km ring***
- ***Re-use LHC as 3 TeV injector***
- ***14 - 20 T** magnets*
- ***4 MW** synch. rad. power*
- ***9 GJ** stored energy / beam*











Meetings with municipalities concerned in France (31) and Switzerland (10)

- Individual meeting
- Individual meeting planned
- Collective meeting

FCC-hh main parameters for pp and physics potential

F. Gianotti
FCC Week 2024

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	81 - 115	14	
dipole field [T]	14 (Nb_3Sn) - 20 (HTS)	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10^{11}]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

If FCC-hh after FCC-ee: significantly more time for high-field magnet R&D aim at highest possible energie (HTS) and lowest electricity consumption

Formidable challenges:
- ❑ high-field superconducting magnets: 14 - 20 T
- ❑ power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- ❑ stored beam energy: up to 9 GJ → machine protection
- ❑ pile-up in the detectors: ~1000 events/xing
- ❑ energy consumption: 4 TWh/year → R&D on cryo, HTS, beam current, …

Formidable physics reach, including:
- ❑ Direct discovery potential up to ~ 40 TeV
- ❑ Measurement of Higgs self to ~ 5% and ttH to ~
- ❑ High-precision and model-indep (with FCC-ee inp measurements of rare Higgs decays ($\gamma\gamma$, $Z\gamma$, μμ
- ❑ Final word about WIMP dark matter
- ❑ Insight into EW phase transition in early universe

Magnet limitations

- Limits: Critical current, Critical B field, Critical temperature
  - remember: typically coil-dominated magnets
- Materials: NbTi (LHC current), Nb_3Sn (HL-LHC, FCC-hh)
  - Nb_3Sn supports ~2x maximum B, but more costly
  - HTS is even more expensive than Nb_3Sn
- Mechanical: length of magnet, stress, stored energy
  - quite a difference between a 1m and 14m magnet
  - superconductors are often extremely brittle
- For FCC-hh we need a leap in maximum current and active R&D is well underway for this
  - material chemistry for maximum current

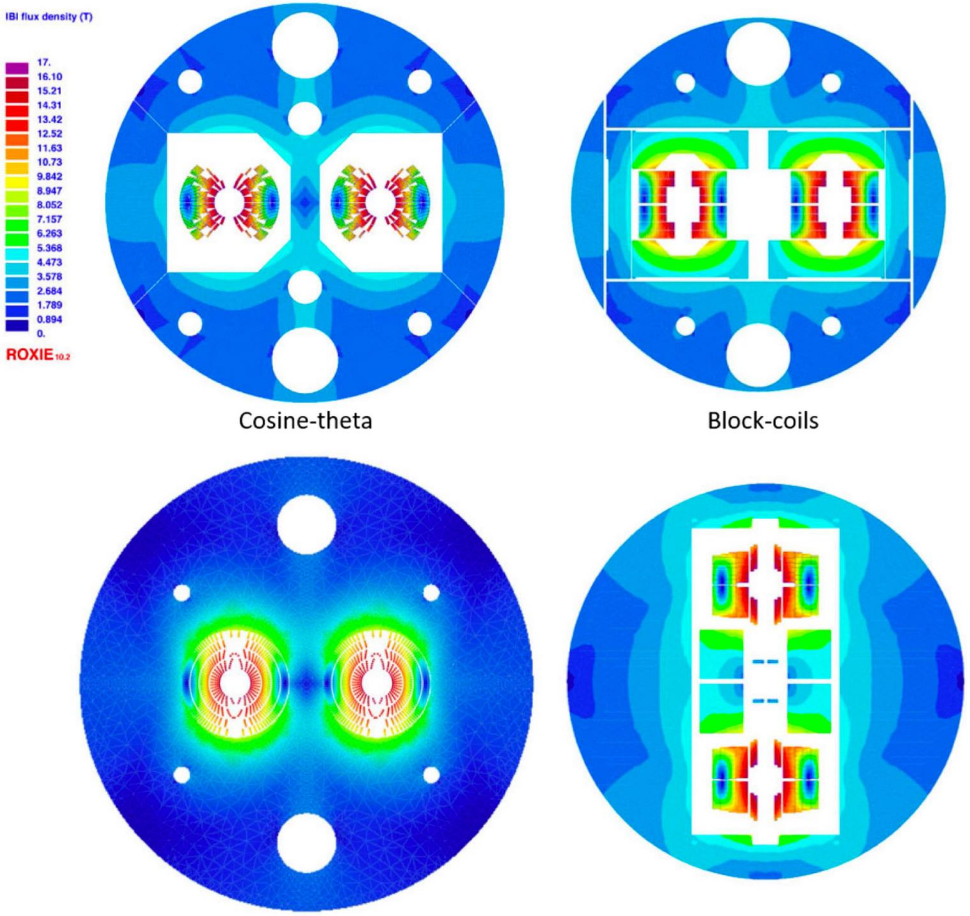


Fig. 3.7. Electromagnetic cross sections of the 16 T dipole design variants.

variety of FCC-hh dipole designs

R&D on HTS high-field magnets

- **High Temperature Superconductors**: an **enabling technology** for high field (≥ 15 T) magnets - a **sustainable opportunity** for future accelerator technology
- **Focus** of the LDG Accelerator R&D Roadmap is presently on **REBCO**, but alternative options are also considered (**IBS** as in China)
- To exploit the potential, a rigorous **R&D program** is required
- **R&D on conductor** is essential for subsequent successful implementation in HTS magnets. This requires:
  - reaching **controlled**, **homogeneous** and **reproducible properties** on industrially available conductor;
  - achieving **long** (~ 1 km) **lengths** of industrially available conductor;
  - **innovation** via development of **high-current cables**;
  - validation of the technology via **a parallel programme** of small **demonstrator coils**; this is needed to provide feedback to conductor R&D and to support/launch magnet design and development

Michael Benedikt and Frank Zimmermann, CERN

Development of new, challenging technologies needed

F. Gianotti
FCC Week 2024

Formidable technical challenges → vigorous R&D efforts in many areas required for both FCC-ee and FCC-hh
Emphasis also on sustainability and on minimising environmental impact

Examples of areas where vigorous R&D work is needed

High-field superconducting magnets with empahsis on HTS (for both FCC-hh and FCC-ee)

SRF cavities with increased gradient performance and energy efficiency

High-power RF sources (klystrons, solid state amplifiers) aiming at improving efficiency by up to 40% compared to current technology

New materials for collimators, masks and dumps, with low impedance and high thermal shock resistance

Surface treatment and coating techniques for vacuum components

Optimised cooling architectures to maxime waste heat reuse (including heat storage system)

New cryogenic fluids and thermodynamic processes to improve energy efficiency of cooling plants

Fertilisation of tunnel excavation material for agricultural use

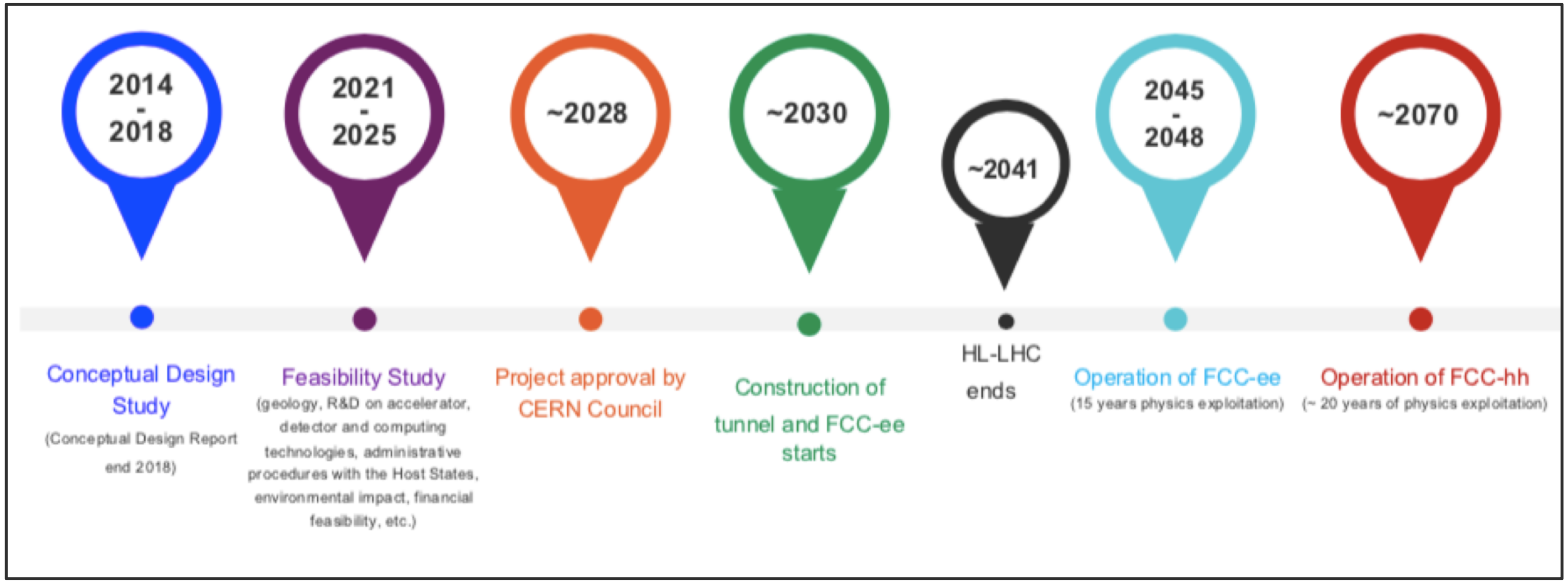
Robotics and AI-based operation algorithms

Detector technologies coping with machine luminosities and radiation levels, and with performance matching expected stat. uncertainties

Note: huge potential applications to society: medicine, fusion, large tunnel infrastructures, electricity transmission, industry, etc.

FCC timeline

F. Gianotti
FCC Week 2024



1st stage collider FCC-ee:
electron-positron collisions 90-360 GeV: electroweak and Higgs factory
2nd stage collider FCC-hh:
proton-proton collisions at ~ 100 TeV

"Realistic" schedule taking into account:
- ❑ past experience in building colliders at CERN
- ❑ the various steps of approval process: ESPP update, CERN Council decision
- ❑ HL-LHC will run until ~ 2041

→ ANY future collider at CERN cannot start physics operation before ~ 2045 (but construction will proceed in parallel to HL-LHC operation)

Other Options at CERN?

High Energy LHC: what could be achieved with new dipole magnets in LHC tunnel?

- ***27 TeV collider, 15 ab^{-1} data over 20 years operation***
- ***16 T** dipole magnets, Nb_3Sn*
- ***101 kW** synch. rad. power*
  - *Use beam-screen design of FCC-hh*
- ***1.3 GJ** stored energy / beam*
  - *Upgrade LHC collimation system*
- *(33 TeV with 20 T, HTS magnets)*
- *CDR in 2019*

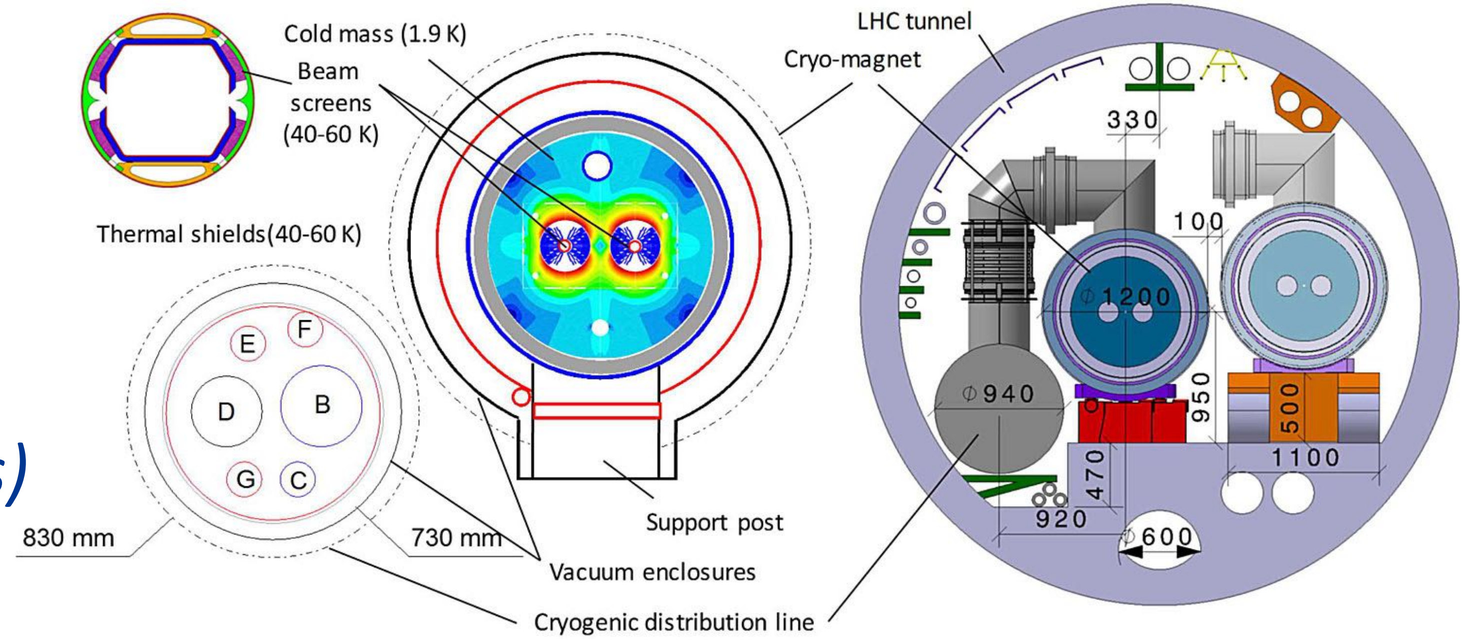


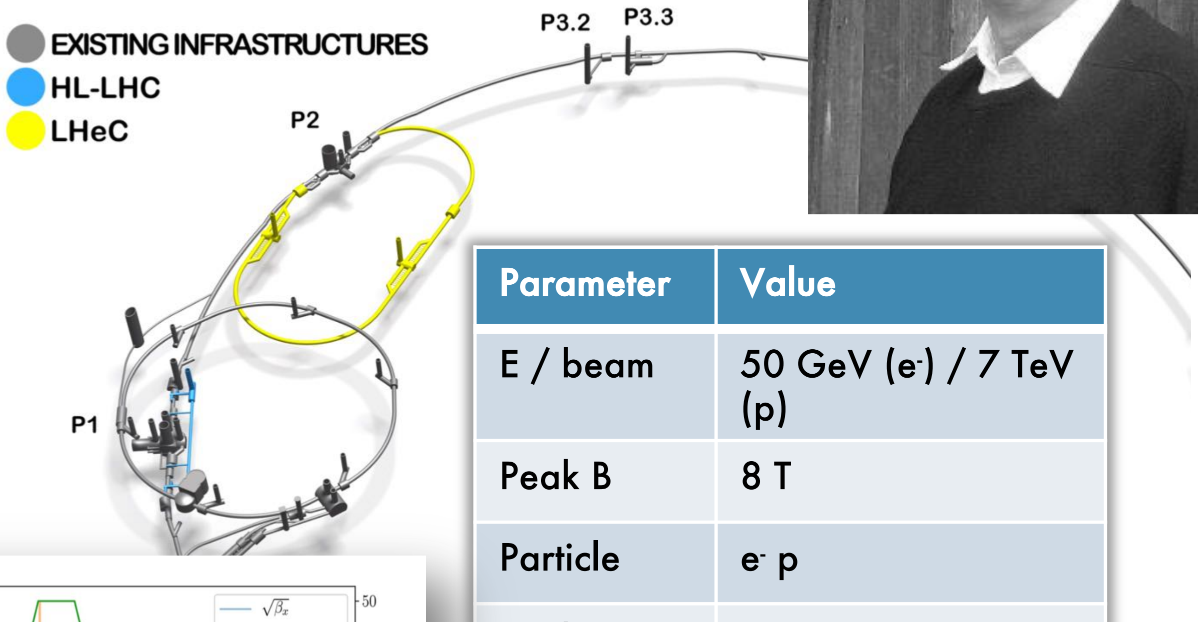
Fig. 4. Cross section of the LHC tunnel and main HE-LHC cryogenic components.

Eur. Phys. J. Special Topics 228, 1109–1382 (2019)
https://doi.org/10.1140/epjst/e2019-900088-6

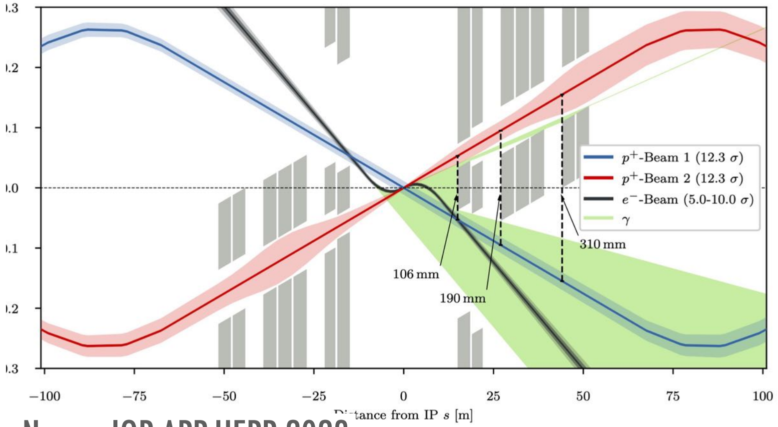
LHeC

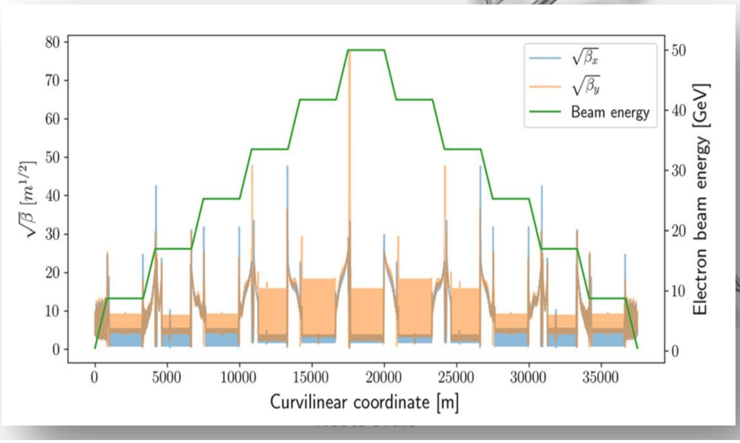
- 50 GeV e⁻ with LHC 7 TeV p
  - ~1.1 TeV c.o.m.
- Small addition to the CERN complex
- Use energy-recovery linac to achieve luminosity within power budget
  - allow larger e⁻ beam size
  - after crossing e⁻ beam gives up energy
  - new e⁻ gain energy (efficiently!)

Max Klein, led the LHeC study, 2008 to 2022



Parameter	Value
E / beam	50 GeV (e⁻) / 7 TeV (p)
Peak B	8 T
Particle	e⁻ p
Peak Lumi.	1 x 10^{34} $cm^{-2}s^{-1}$
Int. Lumi.	Est. 50 fb^{-1} / year

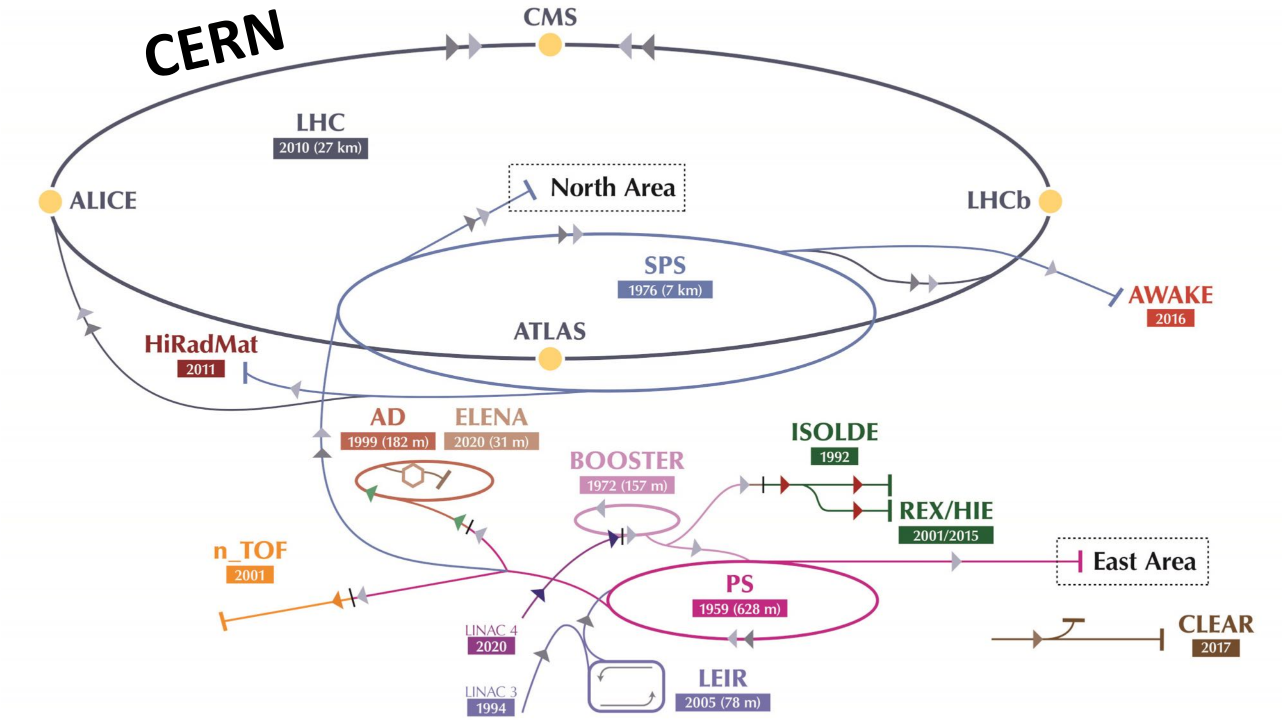


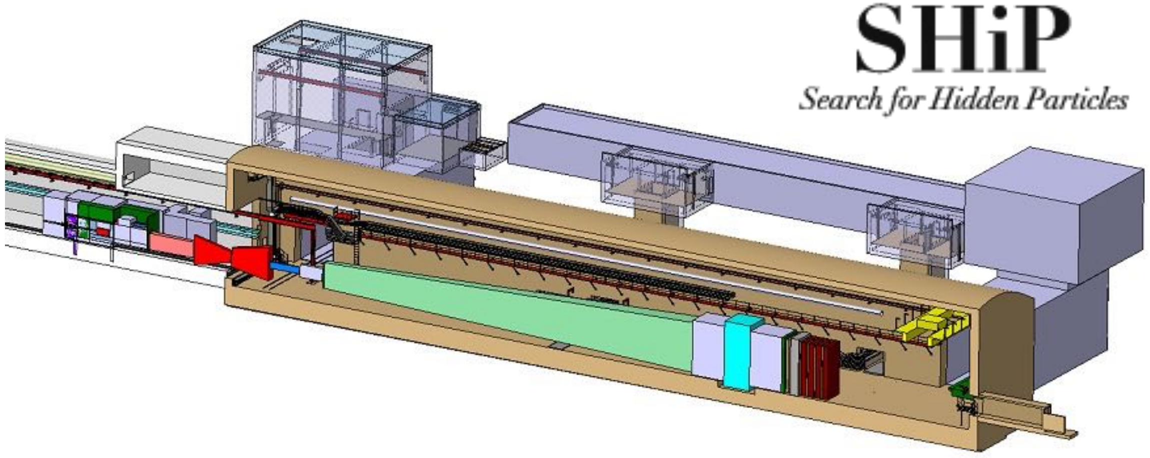


Laurie Nevay, IOP APP-HEPP 2023

Non-collider projects that use proton drivers at CERN:

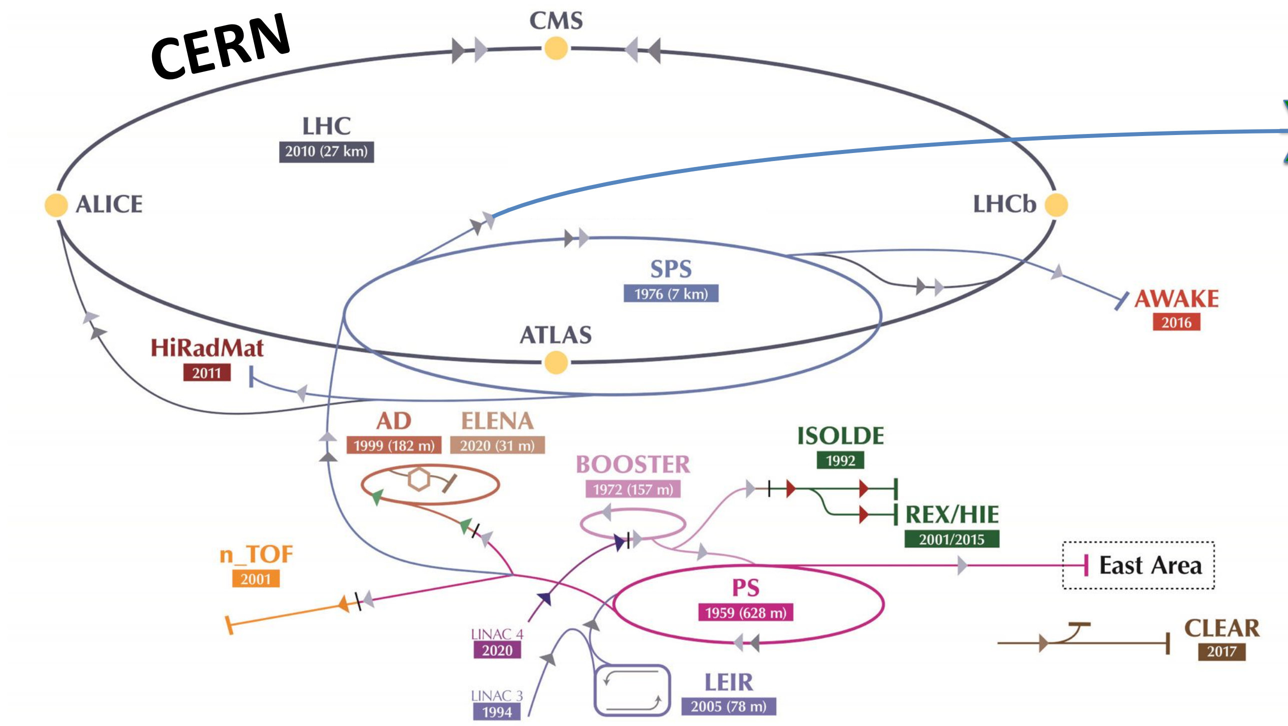
- ***Several smaller projects that build on CERN's existing infrastructure:***
- ***New fixed target PP experiments with high intensity beams; such as hidden sector searches at SHiP: 400 MeV protons driver for production of charm mesons and photons:***
- ***Physics beyond colliders and neutrino programme***

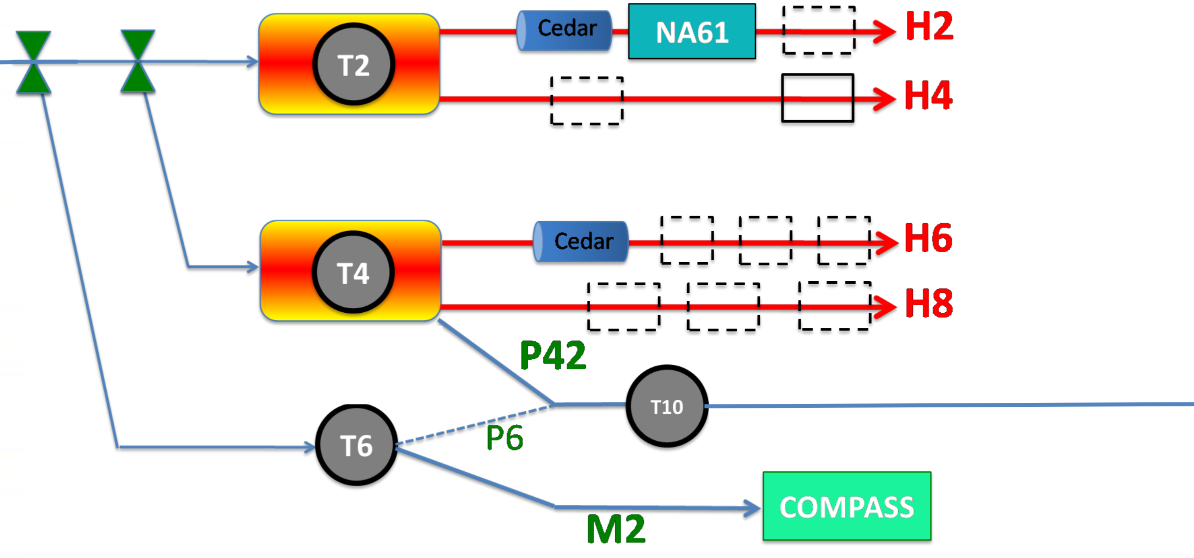




CERN's future fixed-target beamlines

F. Stummer, & L. Nevay
ROYAL HOLLOWAY UNIVERSITY OF LONDON





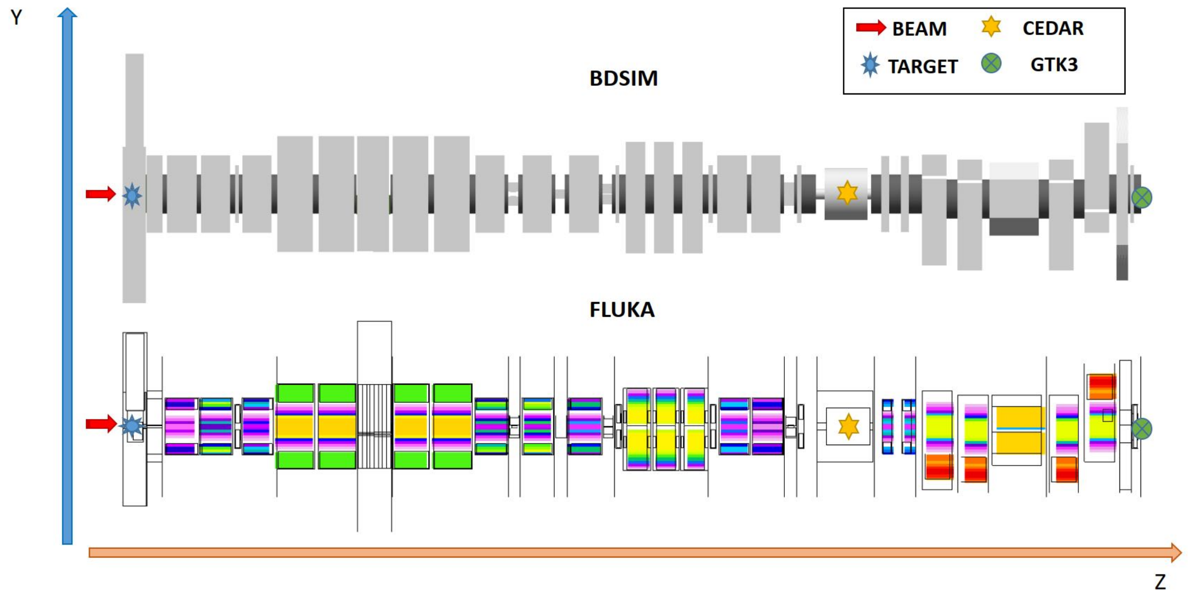
K12 beamline

HIKE
High Intensity Kaon Experiments

G.L. D'Alessandro,
F. Stummer, + C. Mussolini (Ox)

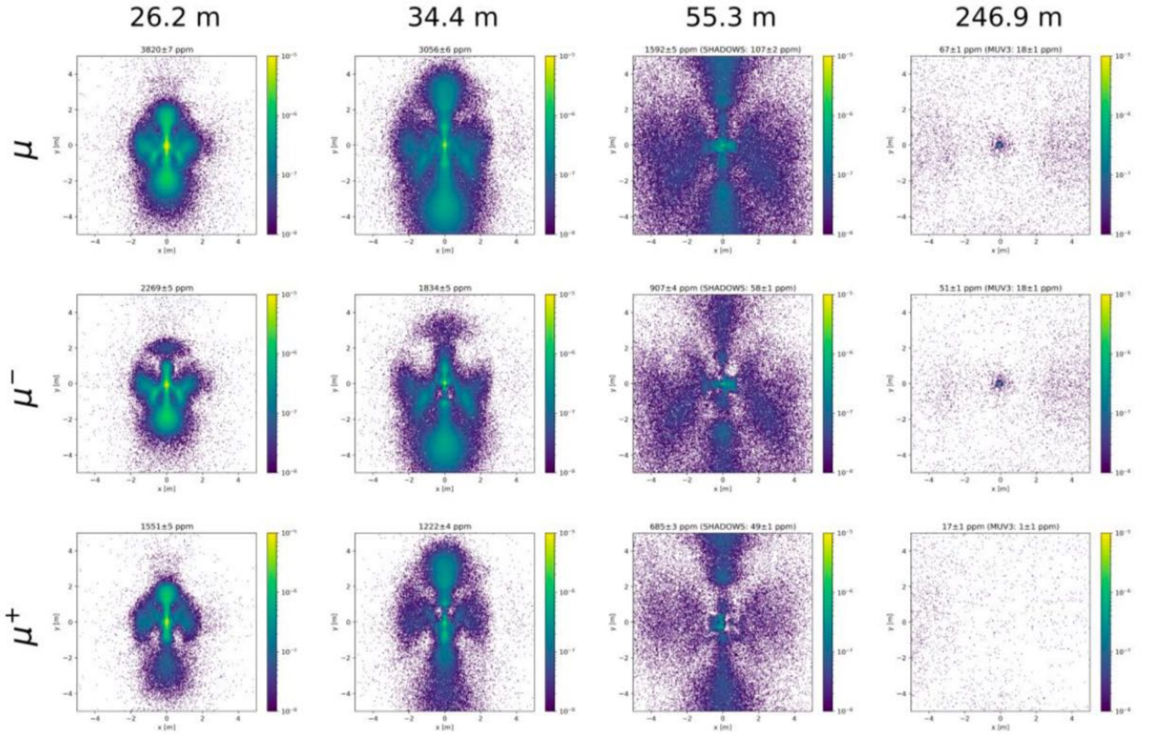
NA62 / KLEVER

- NA62 at CERN to study rare charged Kaon decay
- Highly detailed model built by Gian Luigi D'Alessandro et al,
- Model now integral part of MC chain for experiment



https://doi.org/10.1088/1748-0221/12/05/P05025

muon distribution at various planes



2021 IPAC: WEPAB185, WEPAB186, THPAB214
2021 CERN seminar: https://indico.cern.ch/event/1091199/
2022 NIM B: https://doi.org/10.1016/j.nimb.2021.11.021

A new low energy beamline for NA61/SHINE

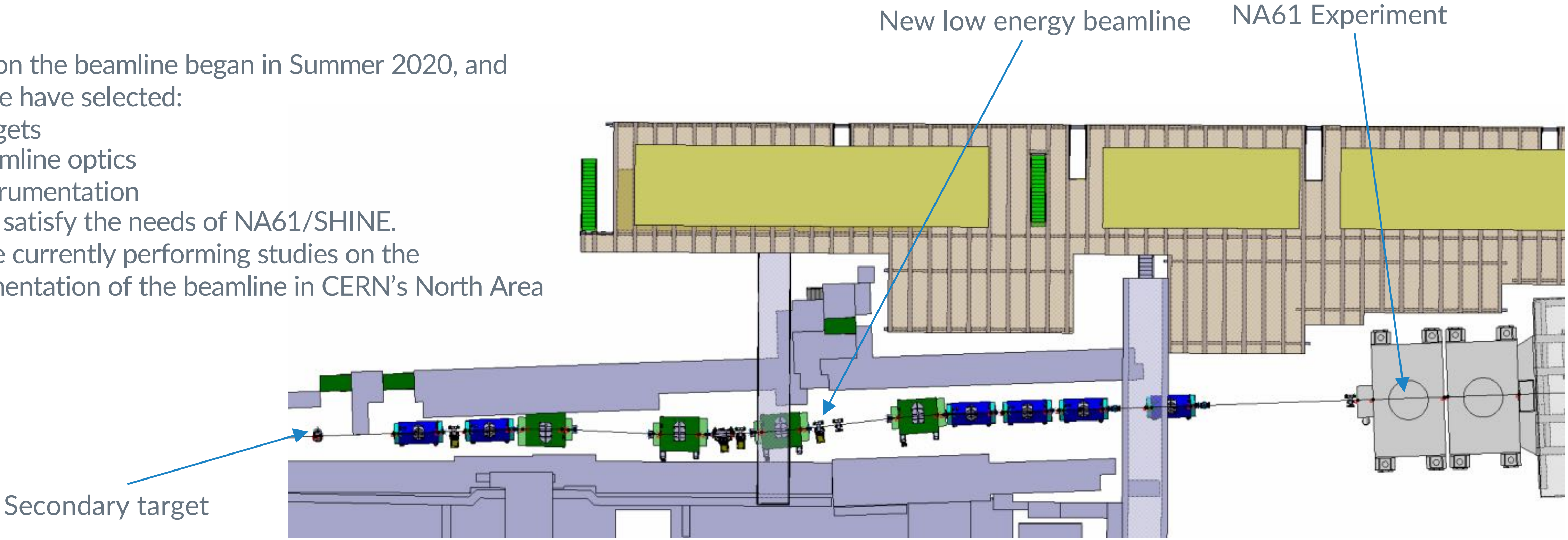
C. A. Mussolini,
N. Charitonidis

There is a lack of particle production data in the 1 – 13 GeV/c momentum range, results obtained by NA61/SHINE using this beamline could prove to be of great use in reducing the systematic uncertainties of many experiments [1]

Work on the beamline began in Summer 2020, and now we have selected:

- Targets
- Beamline optics
- Instrumentation

Which satisfy the needs of NA61/SHINE.
We are currently performing studies on the implementation of the beamline in CERN's North Area



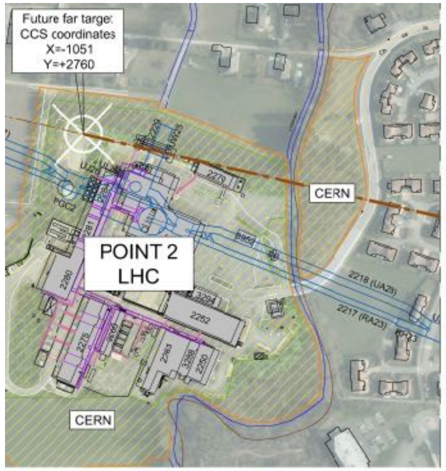
[1] "NA61/SHINE at Low Energy" workshop, December 2020

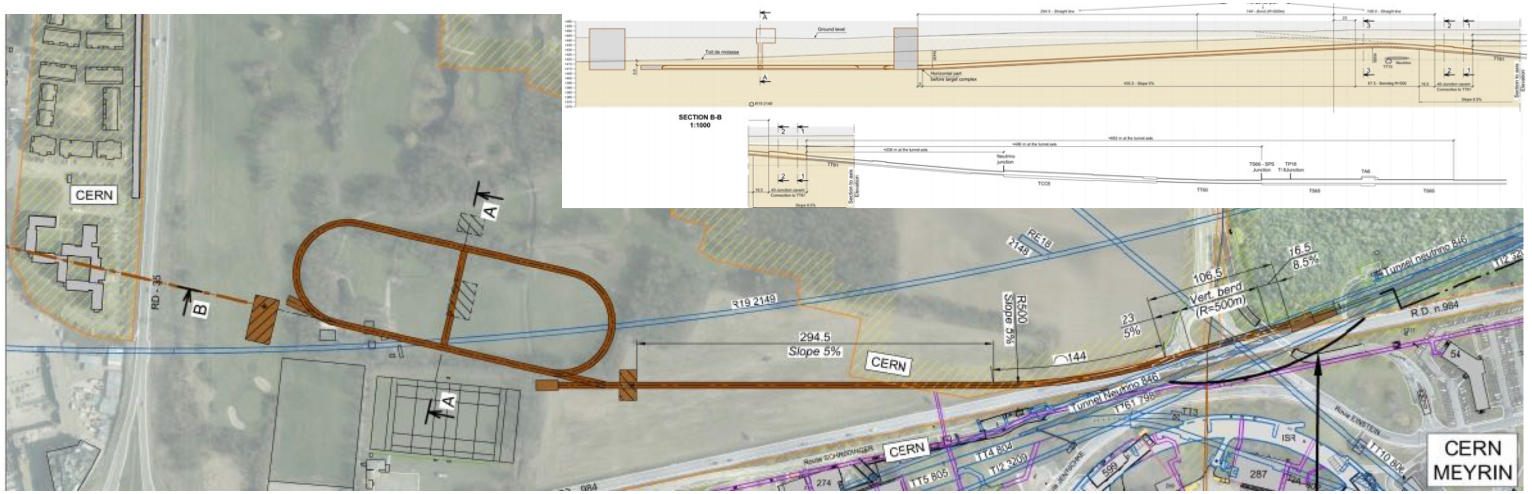
nuStorm overview

Ken Long
Imperial College London

CERN-PBC-2019-003

Extraction from SPS through existing tunnel
Siting of storage ring:
Allows measurements to be made 'on or off axis'
Preserves sterile-neutrino search option

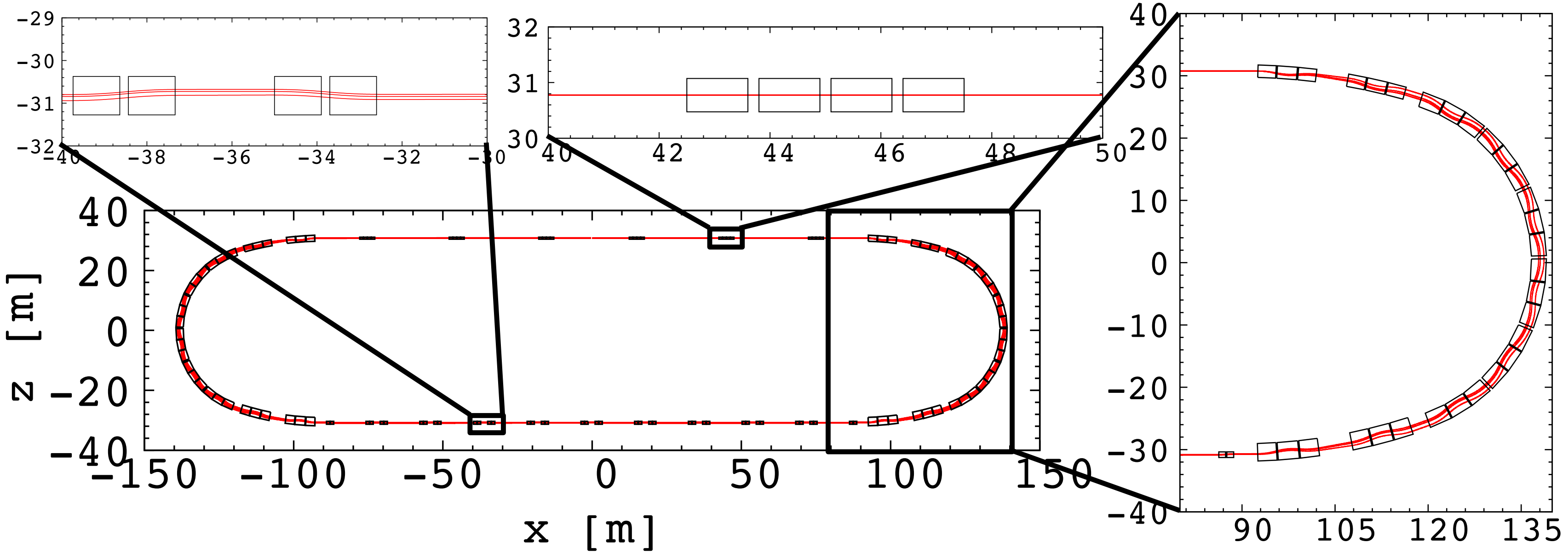




New design for decay ring:

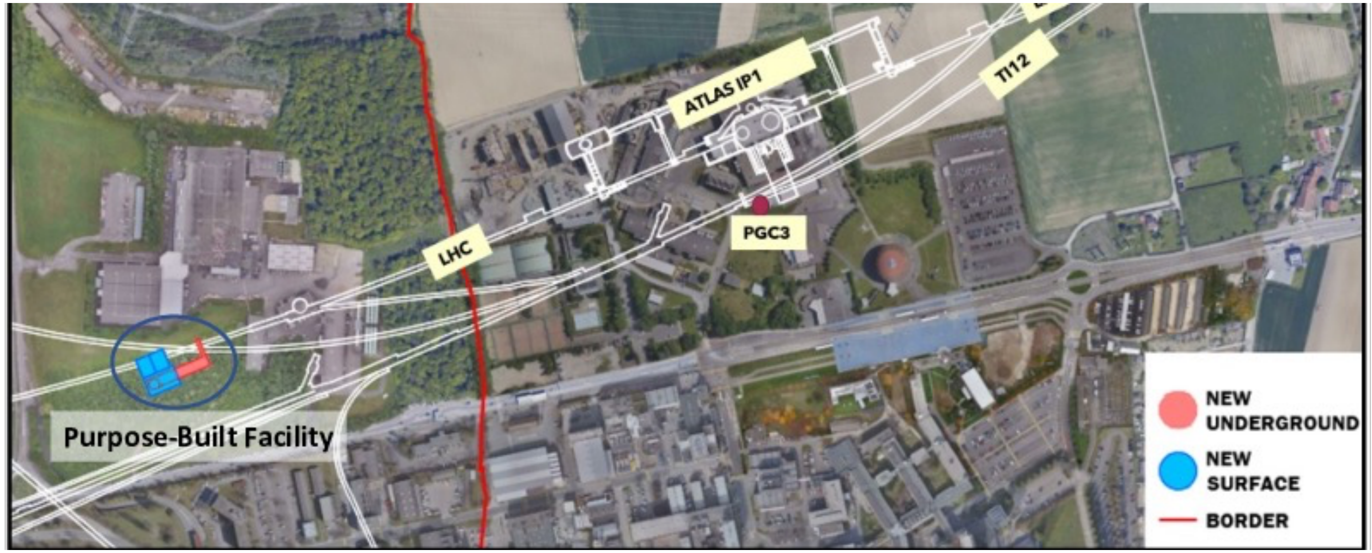
- Central momentum between 1 GeV/c and 6 GeV/c;
- Momentum acceptance of up to ±16%

→ See Chris's muon talk



Proposed Forward Physics Facility (FPF)

- ***Physics reach would benefit from larger detectors than can fit in the existing infrastructure.***
- ***Dedicated forward physics facility***
  - *New cavern behind UJ18*
  - *Proposal at Snowmass 2022, recent Update of Facility Technical Studies for the FPF, CERN-PBC-Notes-2024-004*
  - *+ plans for FPF@FCC:* arXiv:2409.02163v1



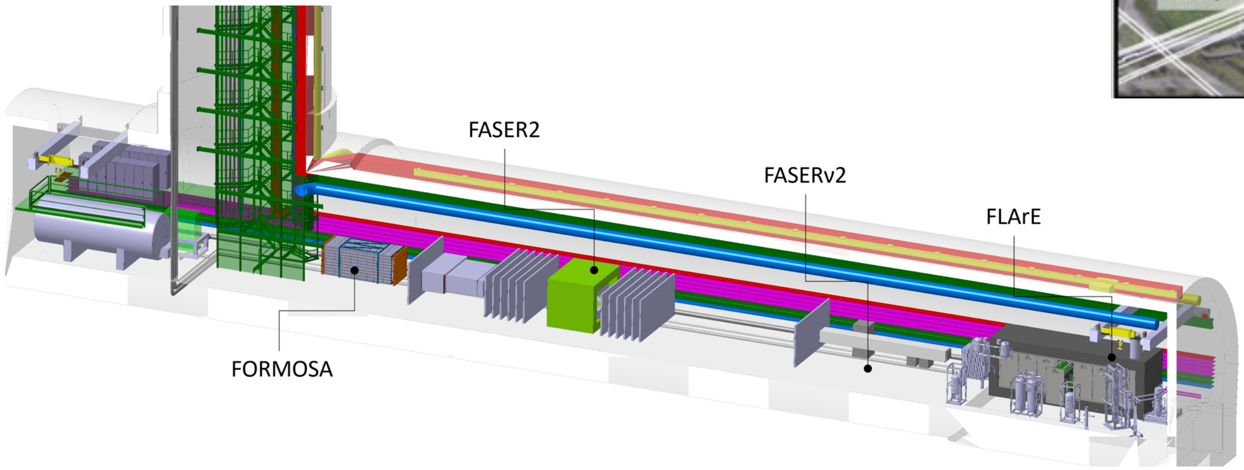
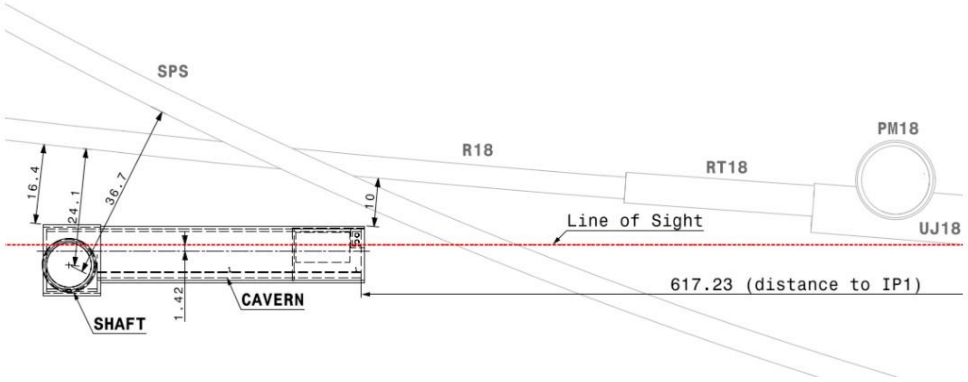
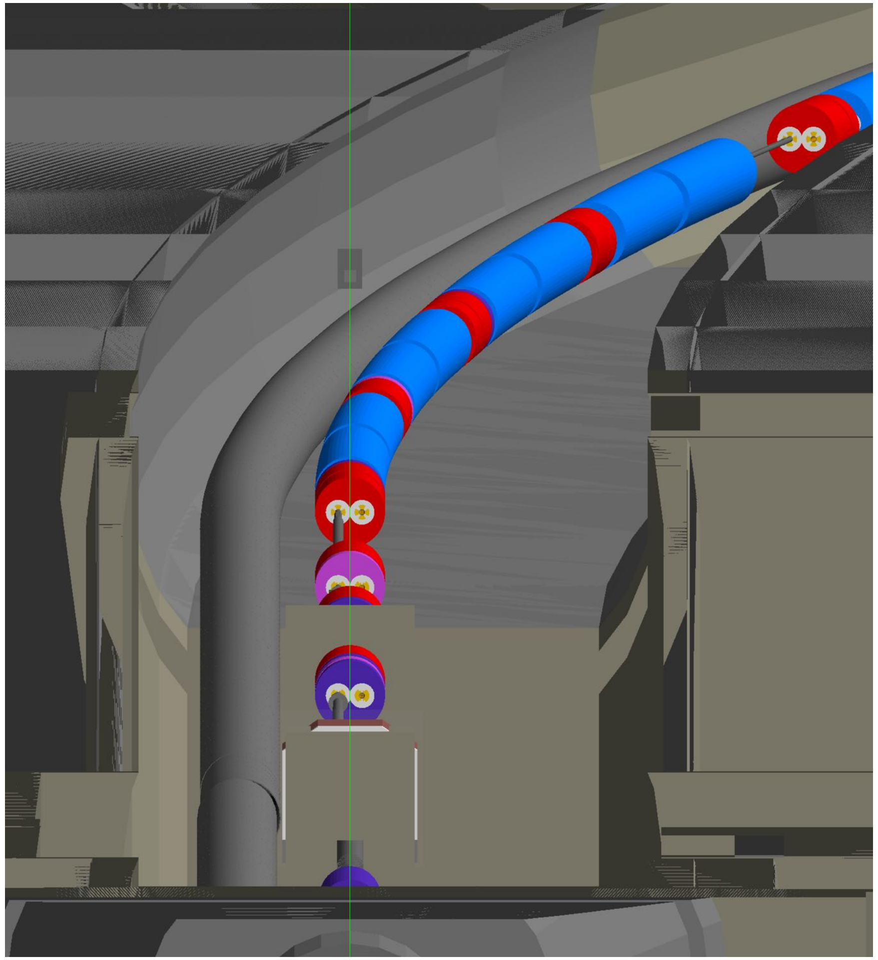


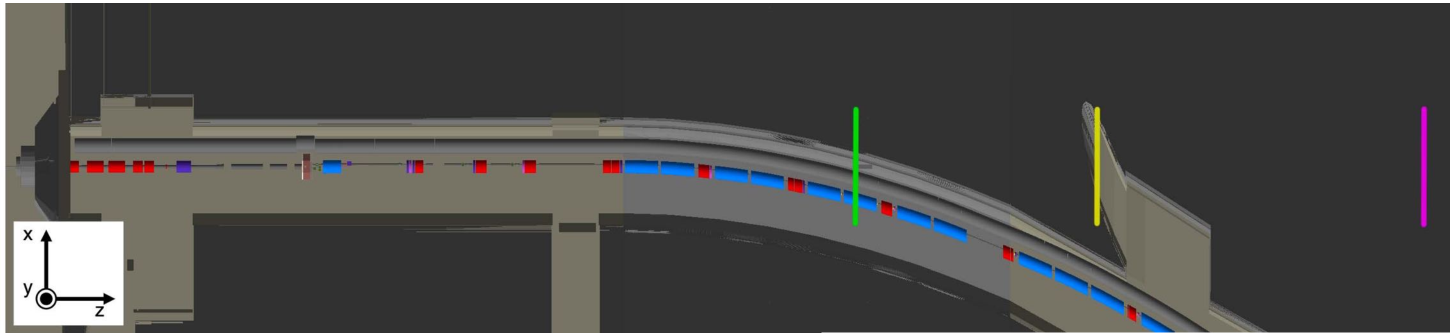
Figure 7: Baseline layout of detectors in the FPF cavern.

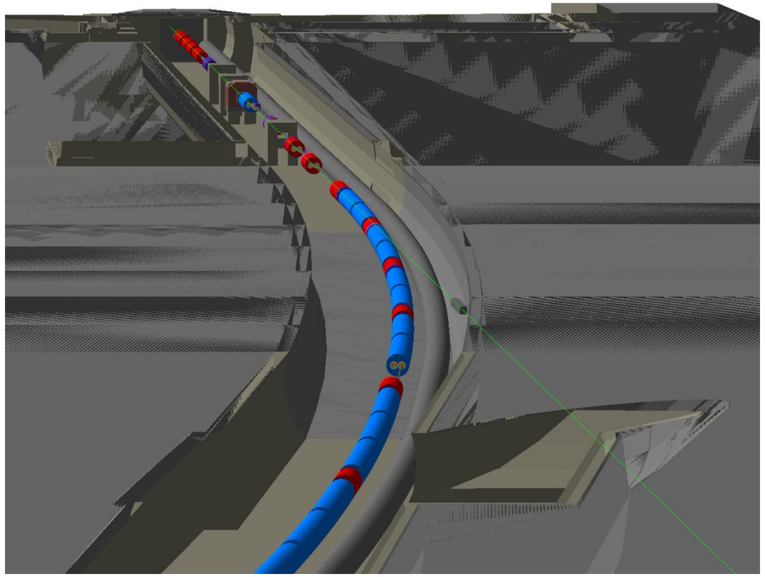


Model in BDSIM



beam line view from IP1 towards FPF





Accelerator models developed for HL-LHC applied to studies for FASER & FPF

Geometry composited using [pyg4ometry](https://doi.org/10.1016/j.cpc.2021.108228)
Comp. Physics Com. 272, March 2022, 108228.
https://doi.org/10.1016/j.cpc.2021.108228

Summary

- *Near term priority: LHC Run III & construction, commissioning and exploitation of HL-LHC.*
  - *UK accelerator community contributions through HL-LHC-UK Phase I & II projects.*
- *UK expertise active in build of electron-ion collider and PIP-II upgrade for LBNF/DUNE.*
- *Which hadron collider in the long term? Depends on **IPPP**; **I**nnovation, **P**hysics, **P**rice & **P**olitics:*
  - *FCC-hh: driven by R&D timeline for Nb_3Sn / HTS magnets (FCC-ee -> see Phil's talk!)*
  - *Other options: HE-LHC, LHeC, FCC-he, + SppC*
- *UK well placed to lead aspects of nuStorm/Muon Collider, building on historic efforts.*
- *Physics Beyond Colliders: a rich and growing programme with many non-collider PP experiments to exploit CERN's accelerator infrastructure + new forward physics facility.*

Thank you!

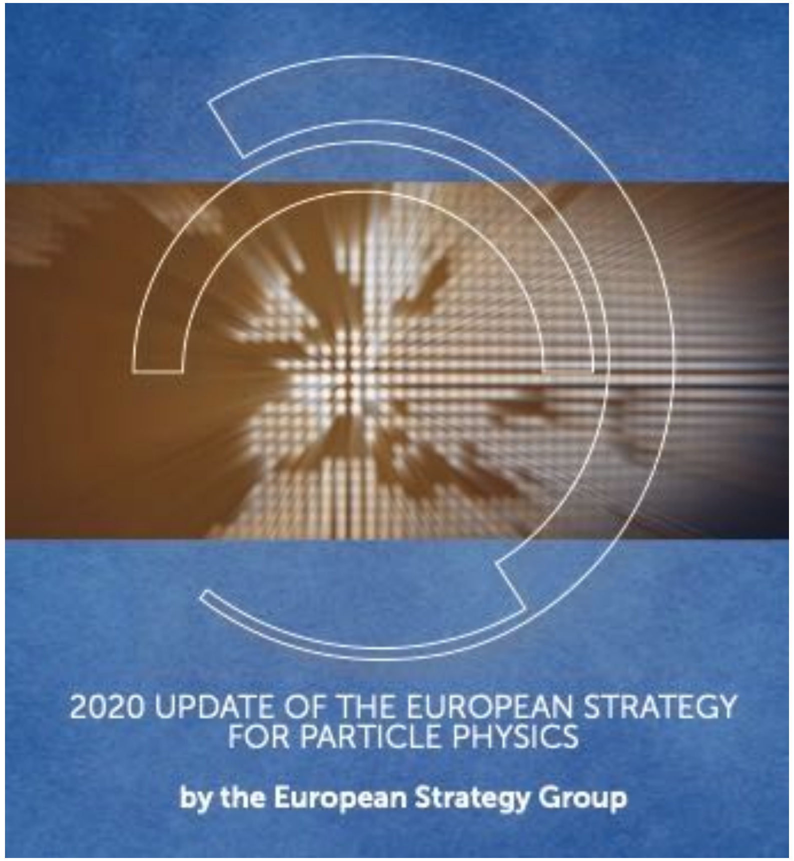
Back up

The Collider Landscape

	2020	2025	2030	2035	2040	2045
RHIC	*AA, pA, pp*					
EIC	TDR	Construction		20 GeV → 140 GeV		
LHeC	TDR	Construction		1.3 TeV		
(HL)-LHC		14 TeV 3 ab^{-1}				
CEPC	TDR	Construction	240 GeV	Z W		
ILC	Pre-constr'n	Construction		250 GeV		500 GeV
CLIC	TDR, pre-constr'n		Construction	380 GeV		1.5 TeV
FCC-*ee*	TDR, pre-construction		Construction		Z W	240 GeV → 350 GeV
HE-LHC		R&D, TDR, prototyping, pre-construction		Construction		27 TeV
FCC-*hh*		R&D, TDR, prototyping, pre-construction		Construction		100 TeV
Muon Collider		R&D, tests, TDR, prototyping, pre-construction		Construction		3 → 14 TeV
Plasma Coll.			R&D, feasibility studies, tests, TDR, prototyping, pre-construction		Construction	3 TeV

High-priority future initiatives

- ***Five technologies pillars were identified in the 2020 EU strategy and by CERN Council / SPC / LDG.***



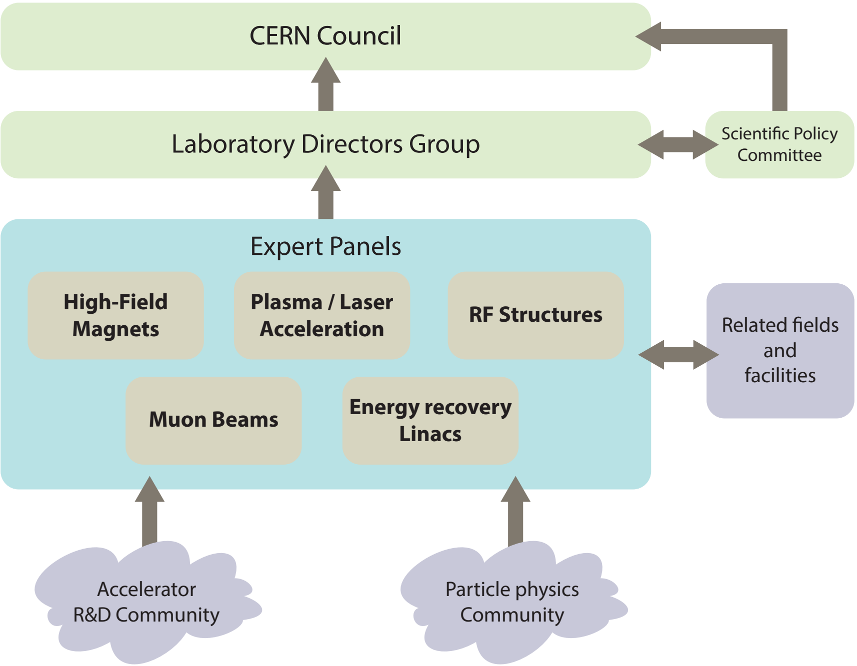
B. Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma 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.***

- *9th July 2021:* ***Symposium on the Accelerator R&D Roadmap for the HEP community***
  - *https://indico.cern.ch/event/1053889/*

- ***High-field magnets***
- ***High-gradient plasma / laser acceleration***
- ***High-gradient RF structures***
- ***Muon beams***
- ***Energy-recovery linacs***

Accelerator R&D Roadmap, published January 2022

arXiv:2201.07895 CERN-2022-001



- ***UK contributing to all five technology pillars***

European Strategy for Particle Physics - Accelerator R&D Roadmap

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Introduction and Conclusion

Author: D. Newbold[h,*]

High-field magnets

Panel members: P. Védrine[b,†] (Chair), L. García-Tabarés[k] (Co-Chair), B. Auchmann[g], A. Ballarino[a], B. Baudouy[b], L. Bottura[a], P. Fazilleau[b], M. Noe[o], S. Prestemon[p], E. Rochepault[b], L. Rossi[q], C. Senatore[r], B. Shepherd[s]

High-gradient RF structures and systems

Panel members: S. Bousson[c,‡] (Chair), H. Weise[e] (Co-Chair), G. Burt[d], G. Devanz[b], A. Gallo[f], F. Gerigk[a], A. Grudiev[a], D. Longuevergne[c], T. Proslier[b], R. Ruber[t]

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High-gradient plasma and laser accelerators

Panel members: R. Assmann[e,f,+] (Chair), E. Gschwendtner[a] (Co-Chair), K. Cassou[c], S. Corde[z], L. Corner[i], B. Cros[aa], M. Ferrario[f], S. Hooker[bb], R. Ischebeck[g], A. Latina[a], O. Lundh[cc], P. Muggli[dd], P. Nghiem[b], J. Osterhoff[e], T. Raubenheimer[w,ee], A. Specka[ff], J. Vieira[gg], M. Wing[hh]

Associated members: C. Geddes[p], M. Hogan[w], W. Lu[v], P. Musumeci[ii]

Bright muon beams and muon colliders

Panel members: D. Schulte[a,△] (Chair), M. Palmer[jj] (Co-Chair), T. Arndt[o], A. Chancé[b], J.-P. Delahaye[a], A. Faus-Golfe[c], S. Gilardoni[a], P. Lebrun[a], K. Long[h,kk], E. Métral[a], N. Pastrone[ll], L. Quettier[b], T. Raubenheimer[w,ee], C. Rogers[h], M. Seidel[g,mm], D. Stratakis[nn], A. Yamamoto[y]

Associated members: A. Grudiev[a], R. Losito[a], D. Lucchesi[oo,pp]

Energy-recovery linacs

Panel members: M. Klein[i,▽] (Chair), A. Hutton[x] (Co-Chair), D. Angal-Kalinin[qq], K. Aulenbacher[rr], A. Bogacz[x], G. Hoffstaetter[ss,jj], E. Jensen[a], W. Kaabi[c], D. Kayran[jj], J. Knobloch[tt,uu], B. Kuske[uu], F. Marhauser[x], N. Pietralla[vv], O. Tanaka[y], C. Vaccarezza[f], N. Vinokurov[ww], P. Williams[qq], F. Zimmermann[a]

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Sub-Panel on CERC and ERLC: A. Hutton[x] (Chair), C. Adolphsen[w], O. Brüning[a], R. Brinkmann[e], M. Klein[i], S. Nagaitsev[nn], P. Williams[qq], A. Yamamoto[y], K. Yokoya[y], F. Zimmermann[a]

The FCC-ee R&D programme

Authors: M. Benedikt[a,◁], A. Blondel[yy,r,▷], O. Brunner[a], P. Janot[a], E. Jensen[a], M. Koratzinos[zz], R. Losito[a], K. Oide[y], T. Raubenheimer[w,ee], F. Zimmermann[a,**]

ILC-specific R&D programme

Authors: S. Michizono[y,††], T. Nakada[mm], S. Stapnes[a]

CLIC-specific R&D programme

Authors: P. N. Burrows[bb], A. Faus-Golfe[c,‡‡], D. Schulte[a], S. Stapnes[a]

Sustainability considerations

Authors: T. Roser[jj,++], M. Seidel[g,mm,△△]

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CI/Daresbury
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