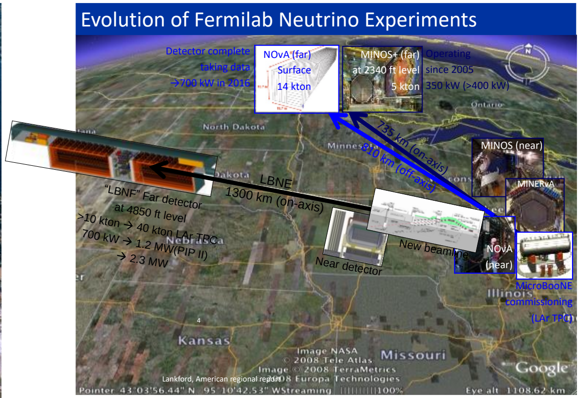
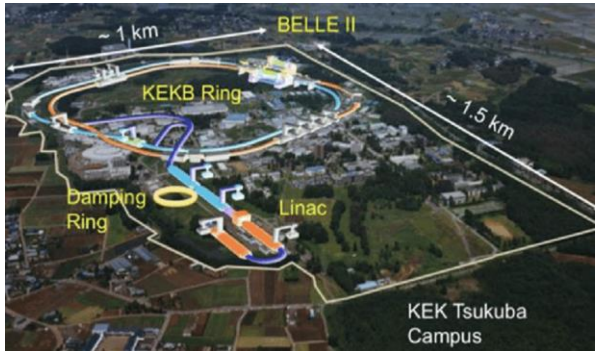
Higgs-factories ++
NorCC
- Workshop 2023 -

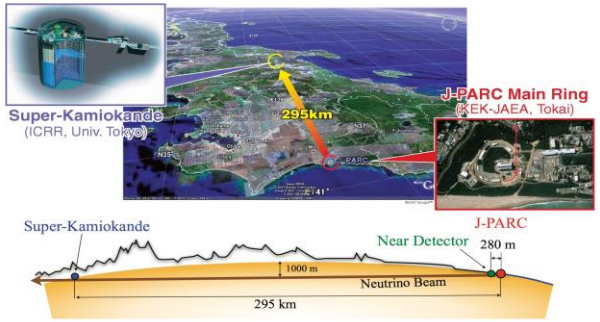
Steinar Stapnes

HVL 28.09.2023

Some of our existing tools

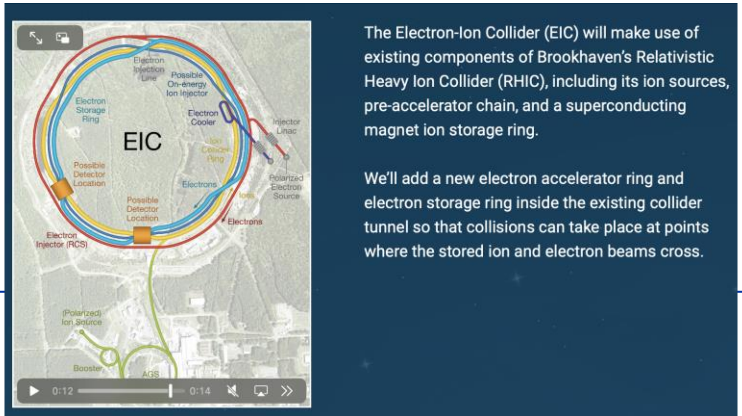






"The T2K Experiment", K. Abe, et al., Nucl. Instr. and Meth. A **659**, 106 (2011)

Colliders and proton drivers



Approved and becoming available in the next decade; EIC and GSI facility

The collider landscape
(agreed next goal – a Higgs factory)

From the established Higgs factory studies to new ideas:
FCC-ee, CEPC, ILC, CLIC …. C3 ….. HALVF, several conceptual energy recovery and plasma options

Proposal Name (c.m.e. in TeV)	Collider Design Status	Lowest TRL Category	Technical Validation Requirement	Cost Reduction Scope	Performance Achievability	Overall Risk Tier
FCCee-0.24	II					1
CEPC-0.24	II					1
ILC-0.25	I					1
CCC-0.25	III					2
CLIC-0.38	II					1
CERC-0.24	III					2
ReLiC-0.24	V					2
ERLC-0.24	V					2
XCC-0.125	IV					2
MC-0.13	III					3
ILC-3	IV					2
CCC-3	IV					2
CLIC-3	II					1
ReLiC-3	IV					3
MC-3	III					3
LWFA-LC 1-3	IV					4
PWFA-LC 1-3	IV					4
SWFA-LC 1-3	IV					4
MC 10-14	IV					3
LWFA-LC-15	V					4
PWFA-LC-15	V					4
SWFA-LC-15	V					4
FCChh-100	II					3
SPPC-125	III					3
Coll.Sea-500	V					4

+ more

Higgs-factory related R&D (examples):

- Efficient RF, luminosity, dealing with synchrotron radiation (circular machines)
- Beam-dynamics, beam–beam, lattices
- "Nanobeams" from start to end
  - Alignment, stability, damping, beam-instrumentation, vacuum and surface treatments, collimators, timing, etc
- Positron production
- Magnet stability and energy use

Timeline for R&D 5-15 years, to be implemented in Higgs factories

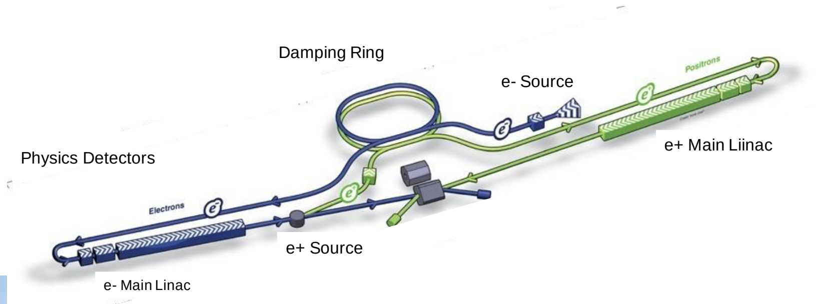
LDG acc. roadmap:
Relevant for Higgs factories but also to enable new accelerator concepts beyond the Higgs factories:

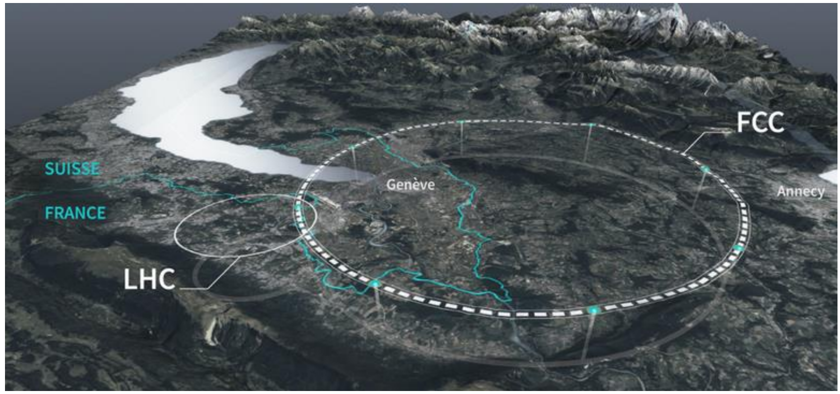
- RF and HF magnets
- Muon collider
- Energy Recovery
- Plasma

Timeline in some cases significantly longer than above

HF magnets enables FCC-hh and SppC
Muon collider project studies – enabled by RF and magnet studies
HALVF and other plasma concepts
Energy recovery based concepts
High(er) power proton-drivers

A Higgs factory



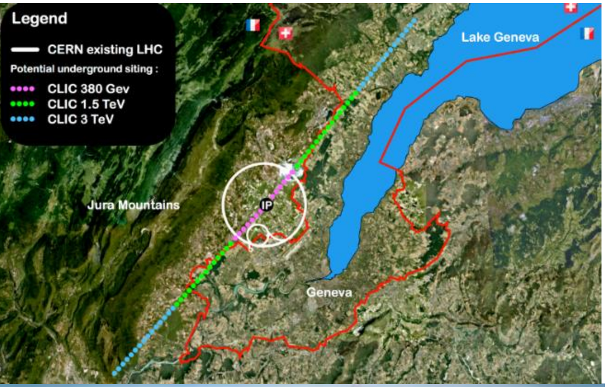


Need e+e- collisions at least at 250 GeV, four mature alternatives:

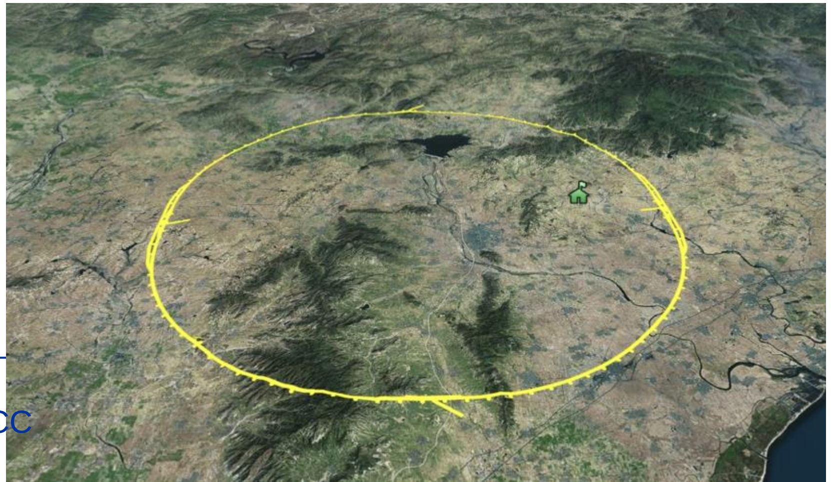
ILC in Japan (linear)
CLIC at CERN (linear)

FCC at CERN (ring)
CEPC in China (ring)

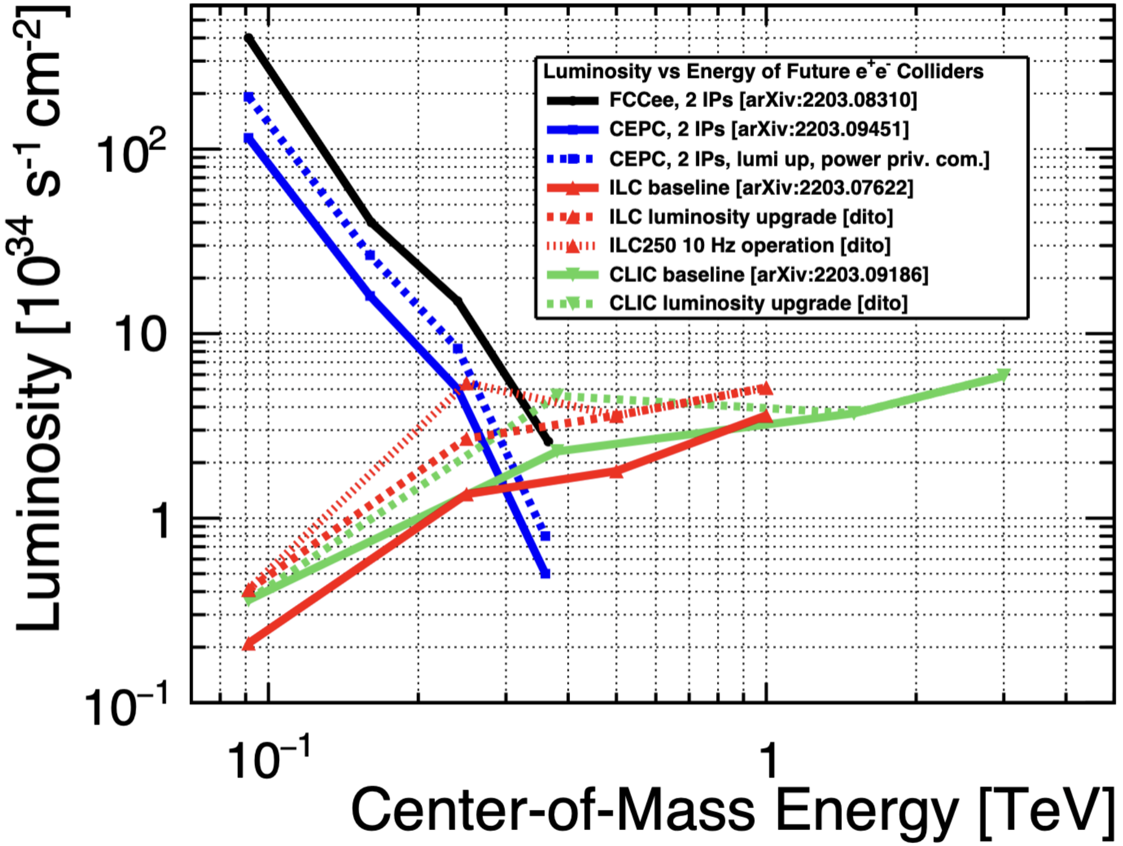
Linear colliders: 13 (Higgs) -> 50 (max) km for higher energies later



Rings ~100km, can be used for protons after



Some features



Per IP, from Snowmass

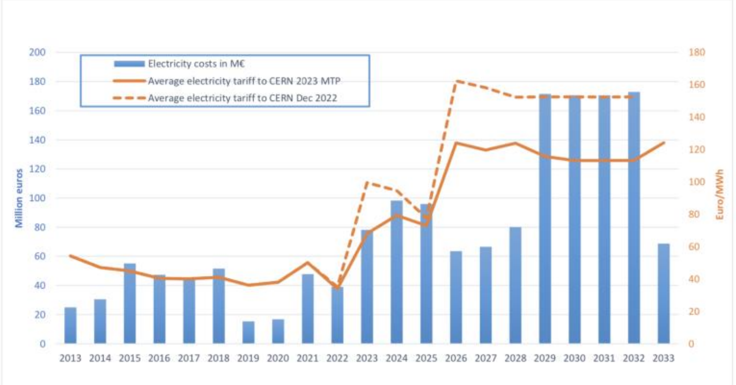
EPPS 2019:

- FCC-ee (~11-12 BCHF), FCC-hh (~+17-18 BCHF) – FCC-hh standalone (~24 BCHF)
- ILC 250 (~5 BCHF)
- CLIC 380 and CEPC (both ~6 BCHF)
- CLIC 3TeV (~+11 BCHF) if extended from 380 GeV, or standalone (~18 BCHF)
- ILC 1 TeV and luminosity increase (+ depends on SRF technology advances ..)
- Muons not estimated at that time

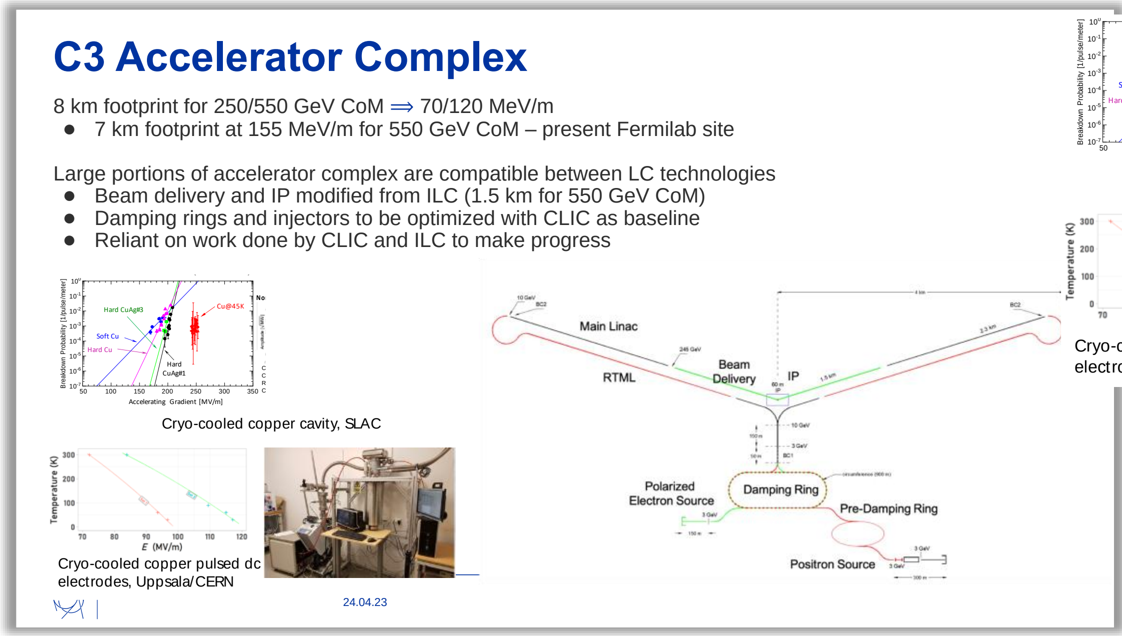
Material costs (value) estimated in a traditional way (ala LHC), prices in 2018 CHF

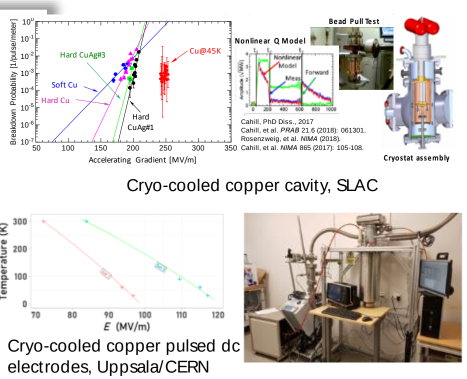
Proposal Name	Power Consumption	Size	Complexity	Radiation Mitigation
FCC-ee (0.24 TeV)	290	91 km	I	I
CEPC (0.24 TeV)	340	100 km	I	I
ILC (0.25 TeV)	140	20.5 km	I	I
CLIC (0.38 TeV)	110	11.4 km	II	I
ILC (3 TeV)	~400	59 km	II	II
CLIC (3 TeV)	~550	50.2 km	III	II

100 MW gives around 0.6 TWh annually



New ideas being developed

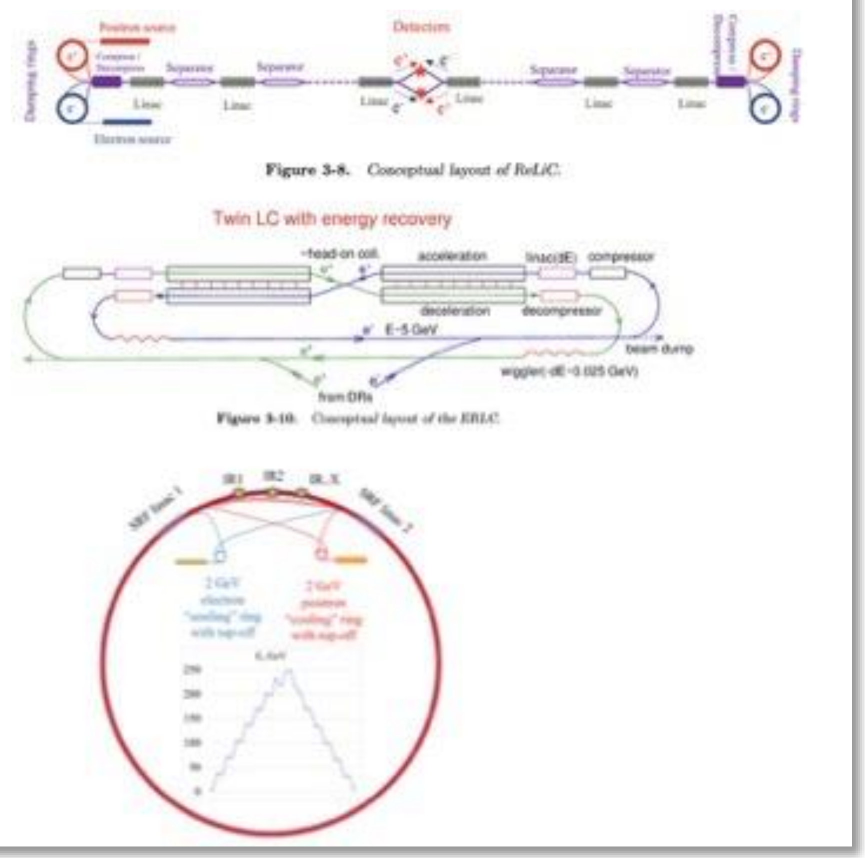




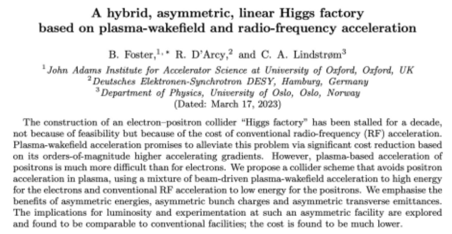
Cryo-cooled copper cavity, SLAC

Cryo-cooled copper pulsed dc electrodes, Uppsala/CERN

Various energy recovery based ideas



Smaller and cost-wise possibly ½ of a LC and ¼ of a CC


A hybrid, asymmetric, linear Higgs factory based on plasma-wakefield and radio-frequency acceleration

B. Foster,[1,*] R. D'Arcy,[2] and C. A. Lindstrøm[3]

[1] *John Adams Institute for Accelerator Science at University of Oxford, Oxford, UK*
[2] *Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany*
[3] *Department of Physics, University of Oslo, Oslo, Norway*
(Dated: March 17, 2023)

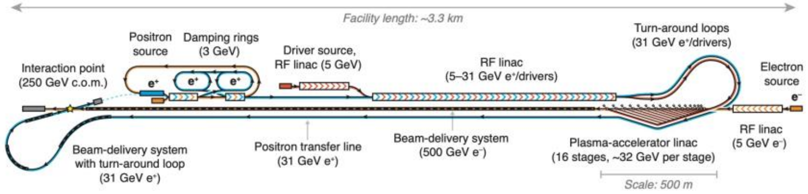
The construction of an electron–positron collider "Higgs factory" has been stalled for a decade, not because of feasibility but because of the cost of conventional radio-frequency (RF) acceleration. Plasma-wakefield acceleration promises to alleviate this problem via significant cost reduction based on its orders-of-magnitude higher accelerating gradients. However, plasma-based acceleration of positrons is much more difficult than for electrons. We propose a collider scheme that avoids positron acceleration in plasma, using a mixture of beam-driven plasma-wakefield acceleration to high energy for the electrons and conventional RF acceleration to low energy for the positrons. We emphasise the benefits of asymmetric energies, asymmetric bunch charges and asymmetric transverse emittances. The implications for luminosity and experimentation at such an asymmetric facility are explored and found to be comparable to conventional facilities; the cost is found to be much lower.

HALHF

https://arxiv.org/abs/2303.10150

Certainly very compact so embedded CO_2, likely very reduced costs compared to other Higgs-factories, not clear of power is different to any other LC.

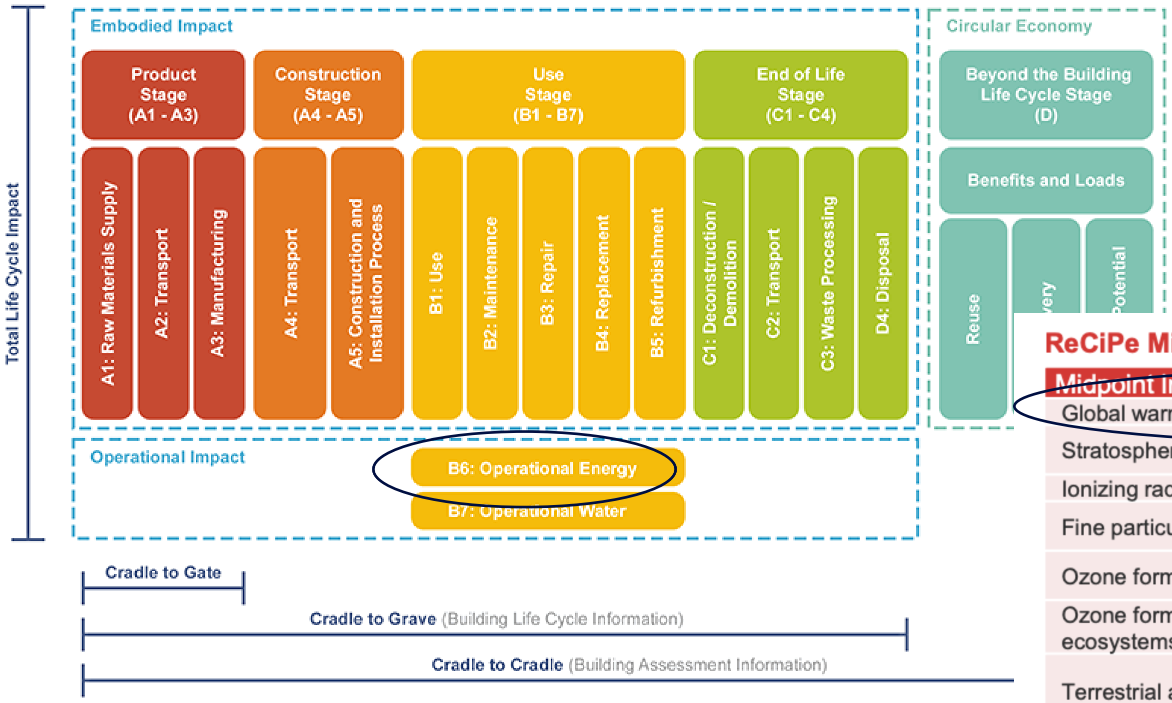
Technically still uncertain.



Context for R&D – and collaborations – I

Optimize with respect to:

- Energy reach, luminosities, experimental conditions
- Facility size and schedule
- Costs and Power
- Environmental Impact and Sustainability (we are learning what this means)



ReCiPe Midpoint (H) 2016 Impact Categories

Midpoint Impact Categories	Abbr.	Unit
Global warming	GWP	kg CO_2 eq
Stratospheric ozone depletion	ODP	kg CFC-11 eq
Ionizing radiation	IRP	kBq Co-60 eq
Fine particulate matter formation	PMFP	kg PM2.5 eq
Ozone formation, Human health	HOFP	kg NOx eq
Ozone formation, Terrestrial ecosystems	EOFP	kg NOx eq
Terrestrial acidification	TAP	kg SO_2 eq
Freshwater eutrophication	FEP	kg P eq
Marine eutrophication	MEP	kg N eq
Terrestrial ecotoxicity	TETP	kg 1,4-DCB
Freshwater ecotoxicity	FETP	kg 1,4-DCB
Marine ecotoxicity	METP	kg 1,4-DCB
Human carcinogenic toxicity	HTPc	kg 1,4-DCB
Human non-carcinogenic toxicity	HTPnc	kg 1,4-DCB
Land use	LOP	m^2a crop eq
Mineral resource scarcity	SOP	kg Cu eq
Fossil resource scarcity	FFP	kg oil eq
Water consumption	WCP	m^3

Reference: ReCiPe Midpoint (H) 2016

"Not enough to look at operation power and guess the CO2 from this power in ~2050 in your favourite country"

Keep in mind: This is not only more constraints but also a new opportunity for R&D, new ideas, collaboration

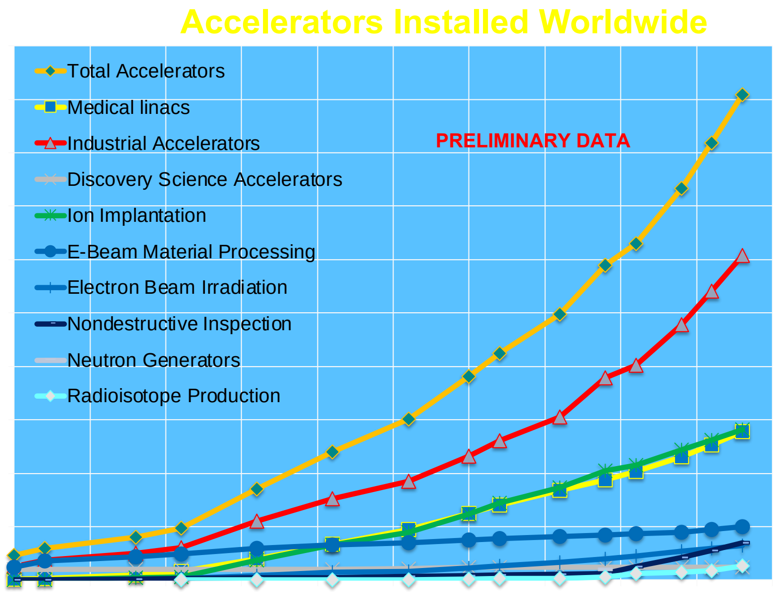
Context for R&D – and collaborations - II

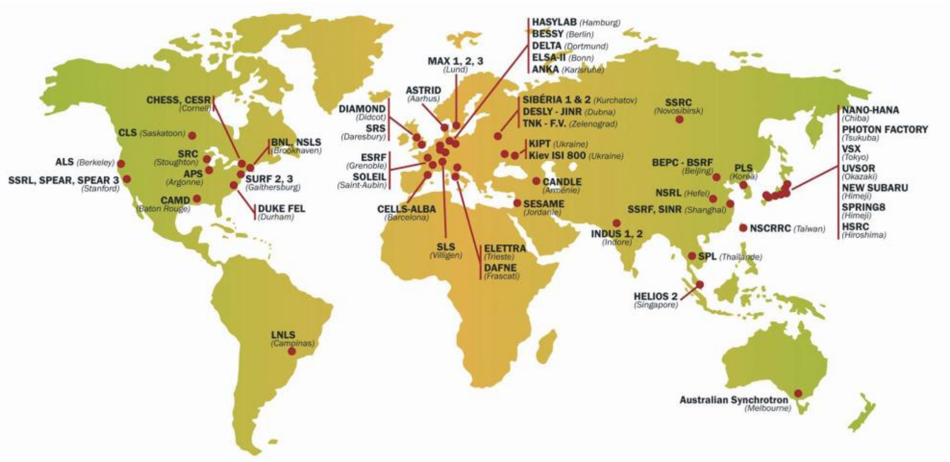
Landscape of accelerators

- The large markets are medical and industrial small accelerators (dominated by electron linacs and ion implantation)
- Material and life-sciences: Synchrotron-sources (new or upgrades) and FELs, ESS (0.5 - 2B projects)
- Research in particle and nuclear physics, LHC and HL, EiC, Neutrino "Factories", Future colliders …

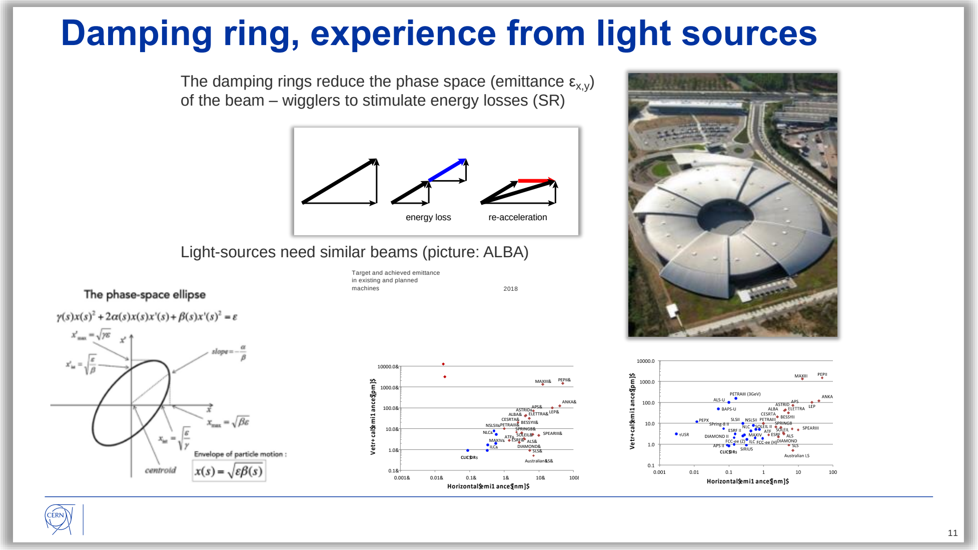
Whenever possible we benefit strongly from aligning to overall accelerator landscape – connected industry, connected laboratories

In some cases we can link to use of "our" key technologies in other fields, e.g. energy sector with HF magnets a very good example (fusion, power generators, etc)



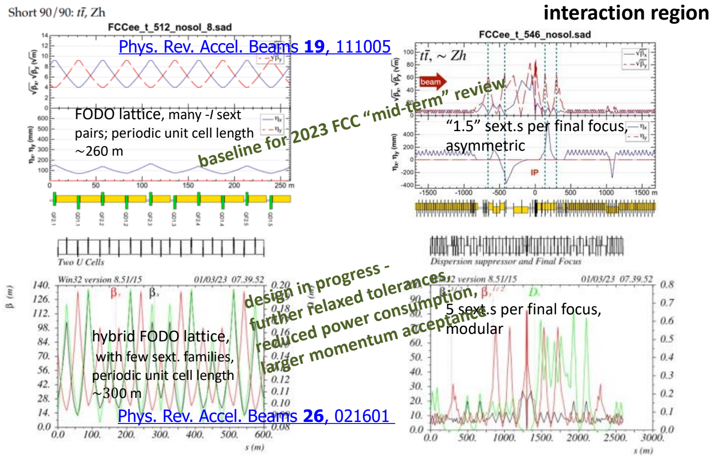


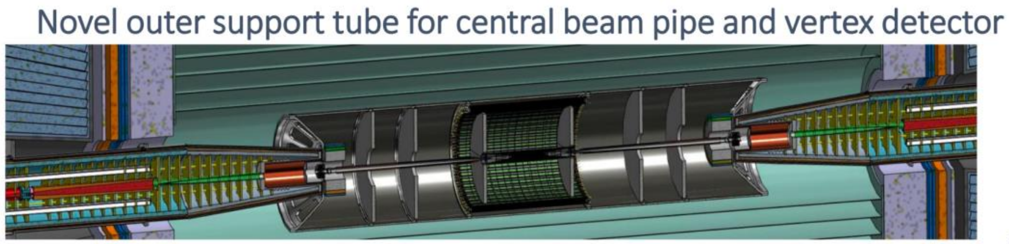
Several large electron linac and ring projects outside particle physics

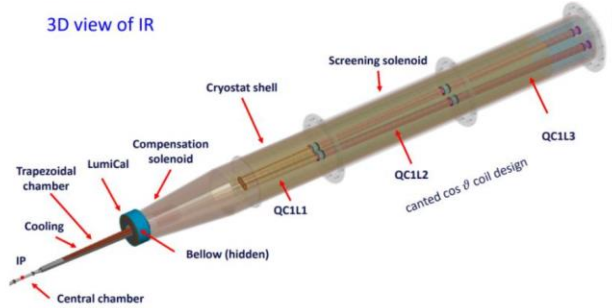


Electron accelerators providing a lot of technical expertise, industry support – but not colliders

Examples for FCC

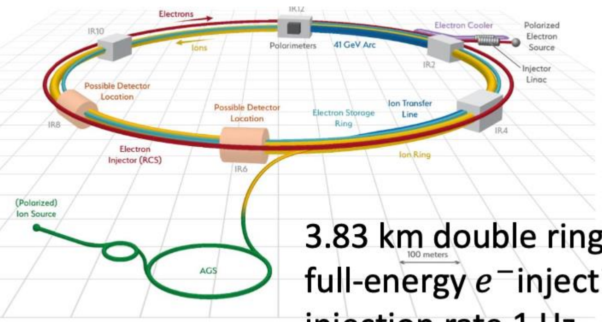






FCC-ee MDI examples, also studies of ID heat load distribution and beamstrahlung dump

US EIC Electron Storage Ring similar to FCC-ee
with beam parameters almost identical, but twice the maximum electron beam current, or half the bunch spacing, and lower beam energy.



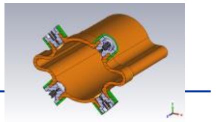
3.83 km double ring, full-energy e^- injection injection rate 1 Hz, every 2 min into same bucket

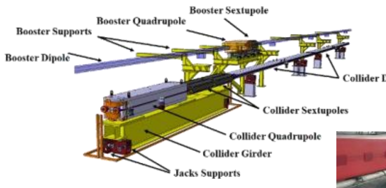
>10 areas of common interest identified by the FCC and EIC design teams, addressed through joint EIC-FCC working groups, still evolving.

Length	Mech. align.	Comment
6 m	20 - 50 um	Pre-align on girder
50 m	200 um	Structured laser tracker or analogous
200 m	500 um	Structured laser tracker or analogous
1000 m	2 mm	Smoothed alignment from local and surface
10000 m	5 mm	Surface alignment → tunnel

Planning to start from 'realistic' mechanical alignment and iterate with Beam-Based Alignment techniques to achieve ~10 um effective alignment.

Beam Position Measurement (BPM) – e.g ~1000/arc
Beam Loss Measurement (BLM)
Beam Size Measurement
Bunch Length Measurement
Polarisation and energy calibration
Beamstrahlung photons
….





From FCC week: Summaries of Benedikt, Raubenheimer, Zimmermann and Lefevre

The European ITN activities – July 2023

European ITN studies are distributed on five main activity areas:

A1 with three SC RF related tasks
- SRF: Cavities and Cryo Module
- Crab-cavities

- In addition Main Linac elements: ML quads and cold BPMs

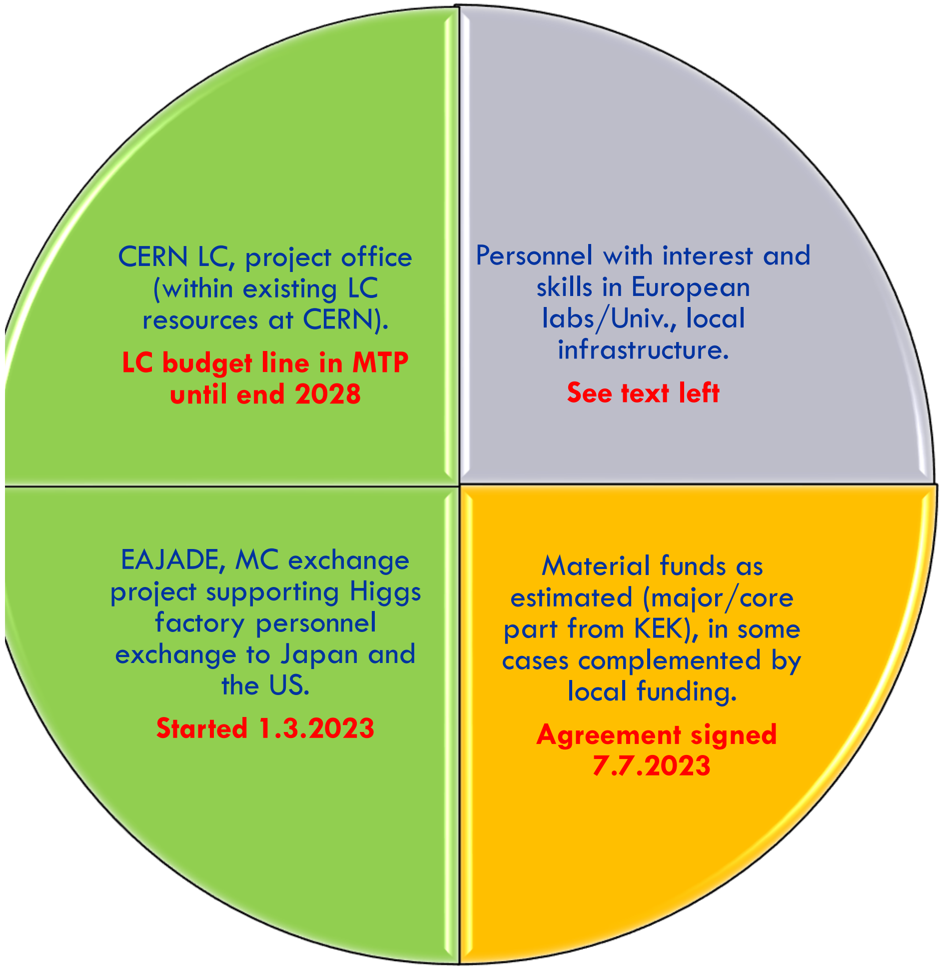
A2 Sources
- Pulsed magnet
- Wheel/target

A3 Damping Ring including kickers
- Low Emittance Ring lab(s)

A4 ATF activities for final focus and nanobeams
- **On-going run**

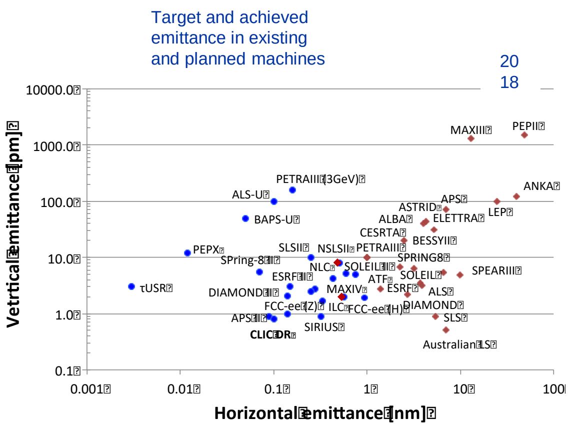
A5 Implementation including Project Office
- Dump, CE, Cryo – earlier efforts at CERN, possible visitor from KEK to CERN for dump later this year
- Sustainability, Life Cycle Assessment

- EAJADE started (EU funding)



EAJADE: Information at LINK

Low emittance generation and preservation in CLIC

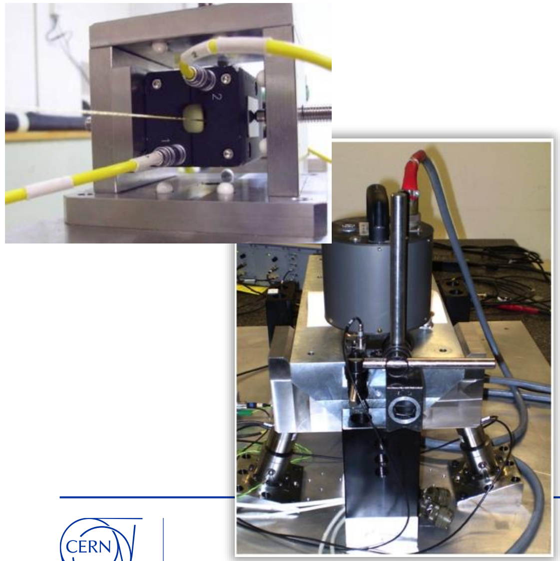


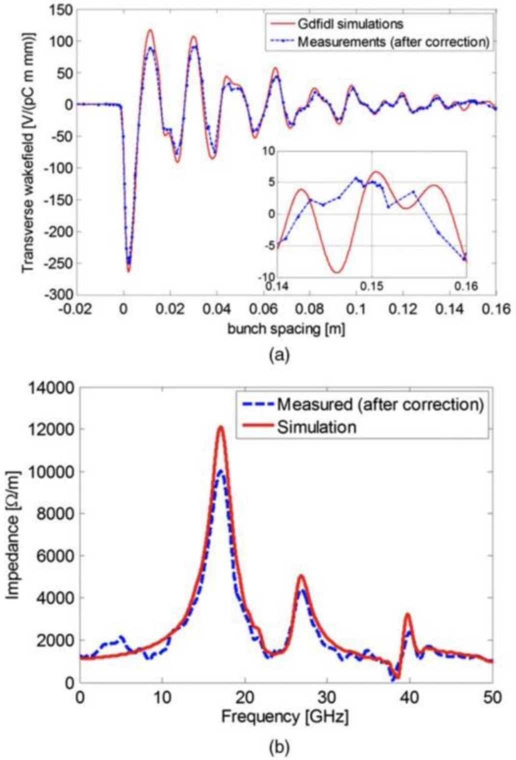
Low emittance damping rings

Preserve by

- Extraction kicker - prototyped
- Align components (10 μm over 200 m)
- Control/damp vibrations (from ground to accelerator)
- Instrumentation performance and module studies
- Beam based measurements
  – allow to steer beam and optimize positions
- Effect and mitigation of stray fields
- Algorithms for measurements, beam and component optimization, feedbacks

- Experimental tests in existing accelerators of equipment and algorithms (FACET at Stanford, ATF2 at KEK, CTF3, Light-sources)





Wake-field measurements in FACET

(a) Wakefield plots compared with numerical simulations.
(b) Spectrum of measured data versus numerical simulation.

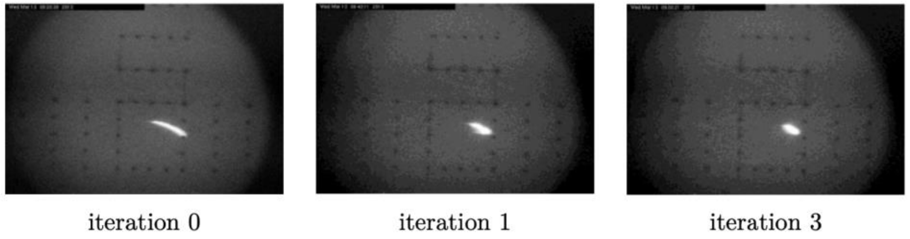
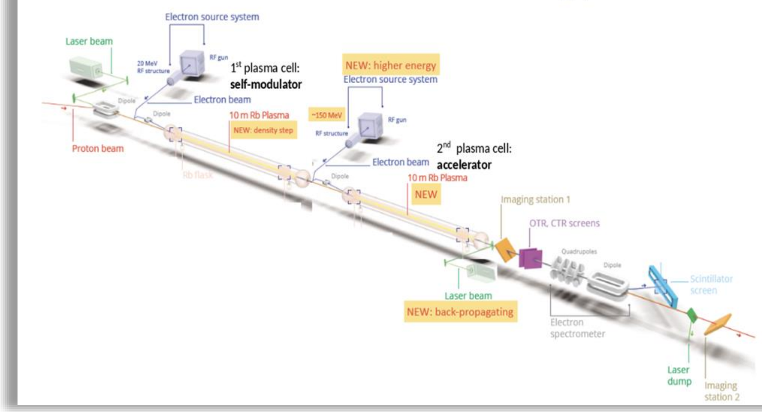
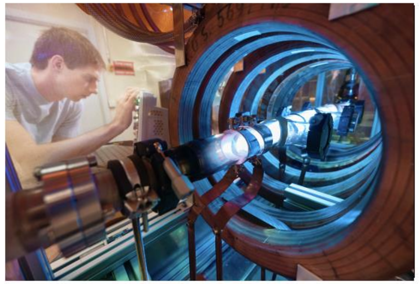


Figure 8.10: Phosphorous beam profile monitor measurements at the end of the FACET linac, before the dispersion correction, after one iteration step, and after three iteration steps. Iteration zero is before the correction.

AWAKE: Proton-beam-driven facilitates long plasma cells and reduces/removes need for staging.



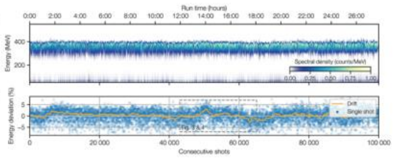


Plasma source 10m long, 4cm diameter, density $10^{14} – 10^{15} cm^{-3}$

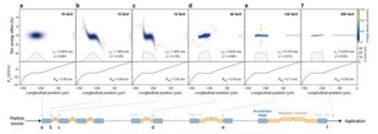
AWAKE talk yesterday (LINK)

Innovations required: **Plasma-accelerator R&D**

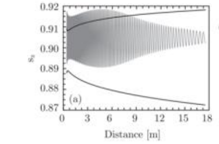
> Toward high energy:
>> Compact staging optics with quality preservation
>> Multi-stage driver distribution
> Toward high beam quality:
>> Transverse and longitudinal stability
>> Emittance and energy-spread preservation
>> Spin-polarization preservation



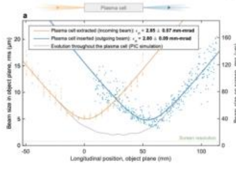
From: Maier et al., Phys. Rev. X 10, 031039 (2020).



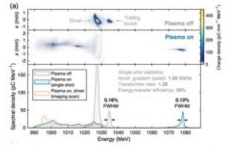
From: Lindstrøm (arXiv: 2104.14460).



From: Vieira et al. PR-STAB 14, 071303 (2011)



From: Lindstrøm et al. (submitted)



From: Lindstrøm et al., PRL 126, 014801 (2021)

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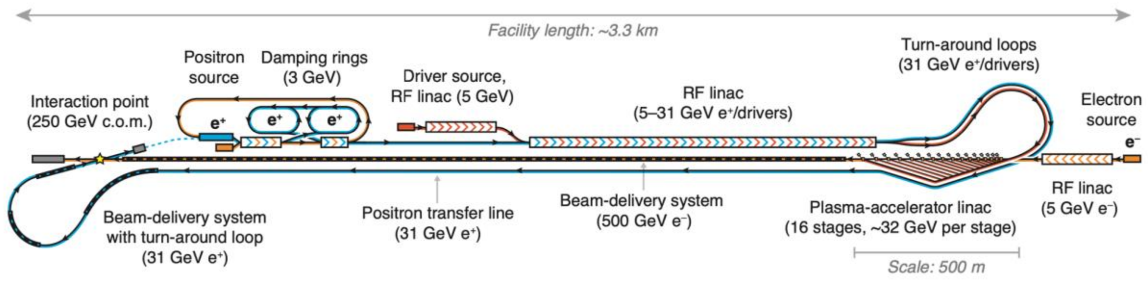
Schematic layout of HALHF



Source: **Foster, D'Arcy & Lindstrøm**, preprint at arXiv:2303.10150 (2023)

> Overall length: ~3.3 km ⇒ **fits in ~any major particle-physics lab**
>> Length dominated by e⁻ beam-delivery system

Smaller and possibly ½ of a LC and ¼ of a CC

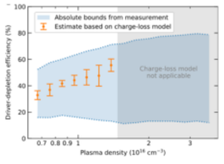
Innovations required: **Plasma-accelerator R&D**

> Toward high energy:
>> Compact staging optics with quality preservation
>> Multi-stage driver distribution
> Toward high beam quality:
>> Transverse and longitudinal stability
>> Emittance and energy-spread preservation
>> Spin-polarization preservation
> Toward high beam power:
>> High-overall efficiency (wall-plug to beam)
>> Repetition rate
>> Plasma-cell cooling

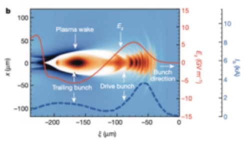
Depletion efficiency

(Must be achieved simultaneously)

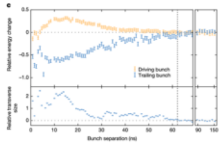
Extraction efficiency



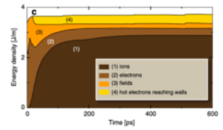
From: Peña et al. (arXiv:2305.09581)



From: Litos et al., Nature 515, 92 (2014).



From: D'Arcy et al., Nature 603, 58 (2022).



From: Zgadzaj et al., Nat. Commun. 11, 4753 (2020)

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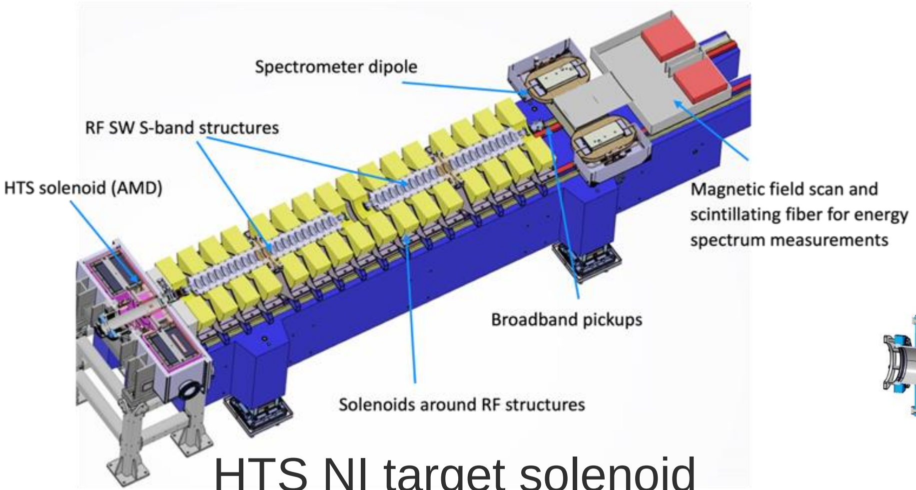
"All" Higgs factories have a positron programme

- a couple of R&D examples -

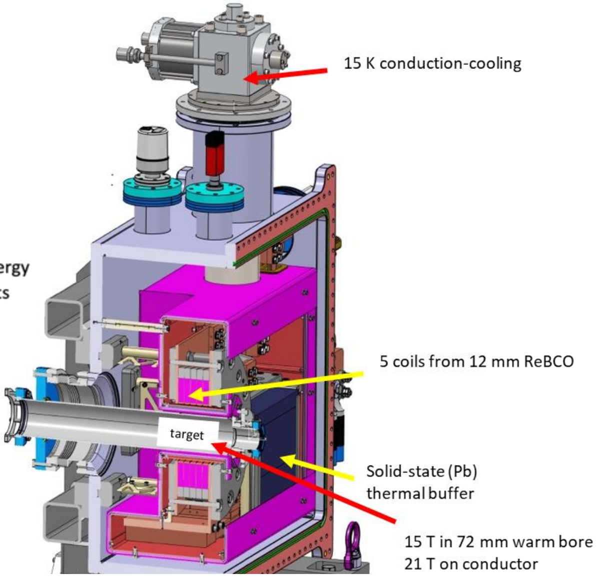
Positrons for FCC (LINK)

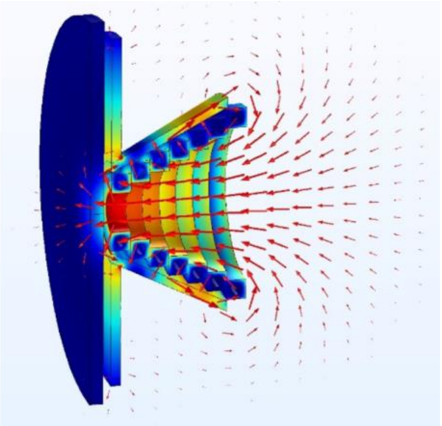
ILC concept and R&D, presentations in the parallel sessions here (LINK1 – more general than ILC), (LINK2 directly on ILC programme)

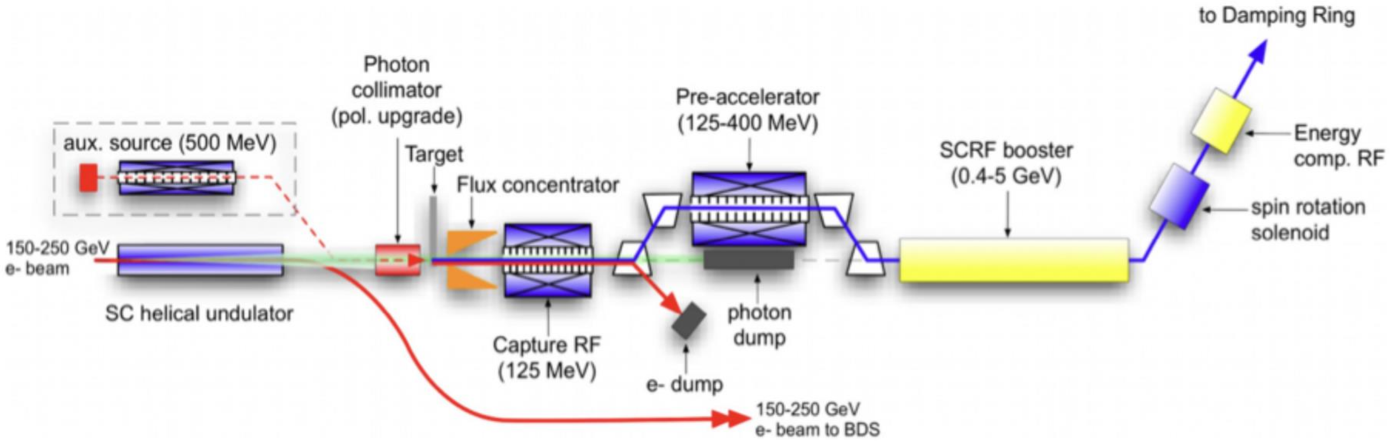
"Positron production experiment" at PSI's SwissFEL, beam tests from 2025/26



HTS NI target solenoid



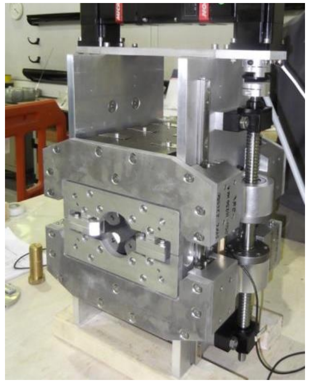




Low power magnets – in linear and circular Higgs – factories (and synchrotron source) - examples

ZEPTO (Zero Power Tuneable Optics) project is a collaboration between CERN and STFC Daresbury Laboratory to save power and costs by switching from resistive electromagnets to permanent magnets.

For CLIC the dominant power is in the drive-beam quadrupoles, successfully prototyped and tested as permanent (two different strengths) magnets, and also dipoles (in drivebeam turn arounds)

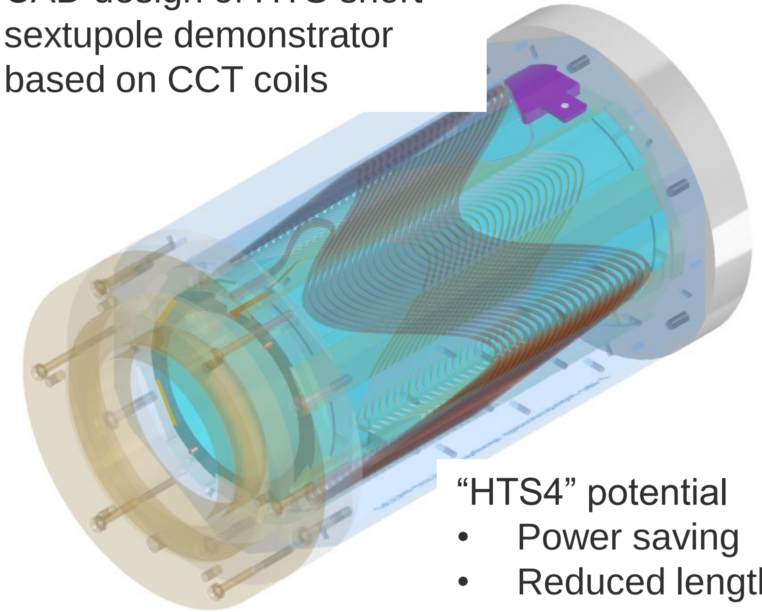
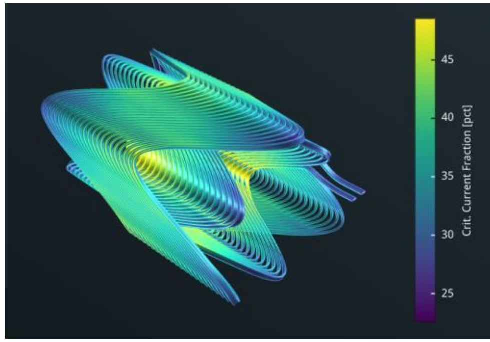

Longitudinal gradient dipole magnet for the CLIC DR (CIEMAT)

doi:10.18429/JACoW-IPAC2018-MOPML048

“HTS4” project within CHART collaboration

- Nested SC sextupole and quadrupole.
- HTS conductors operating at around 40K.
- Cryo-cooler supplied cryostat
- Produce a ~1m prototype by 2026

CAD design of HTS short sextupole demonstrator based on CCT coils

“HTS4” potential

- Power saving
- Reduced length and increased dipole filling factor
- Optics flexibility

From FCC-week (LINK)

NorCC

Many opportunities:

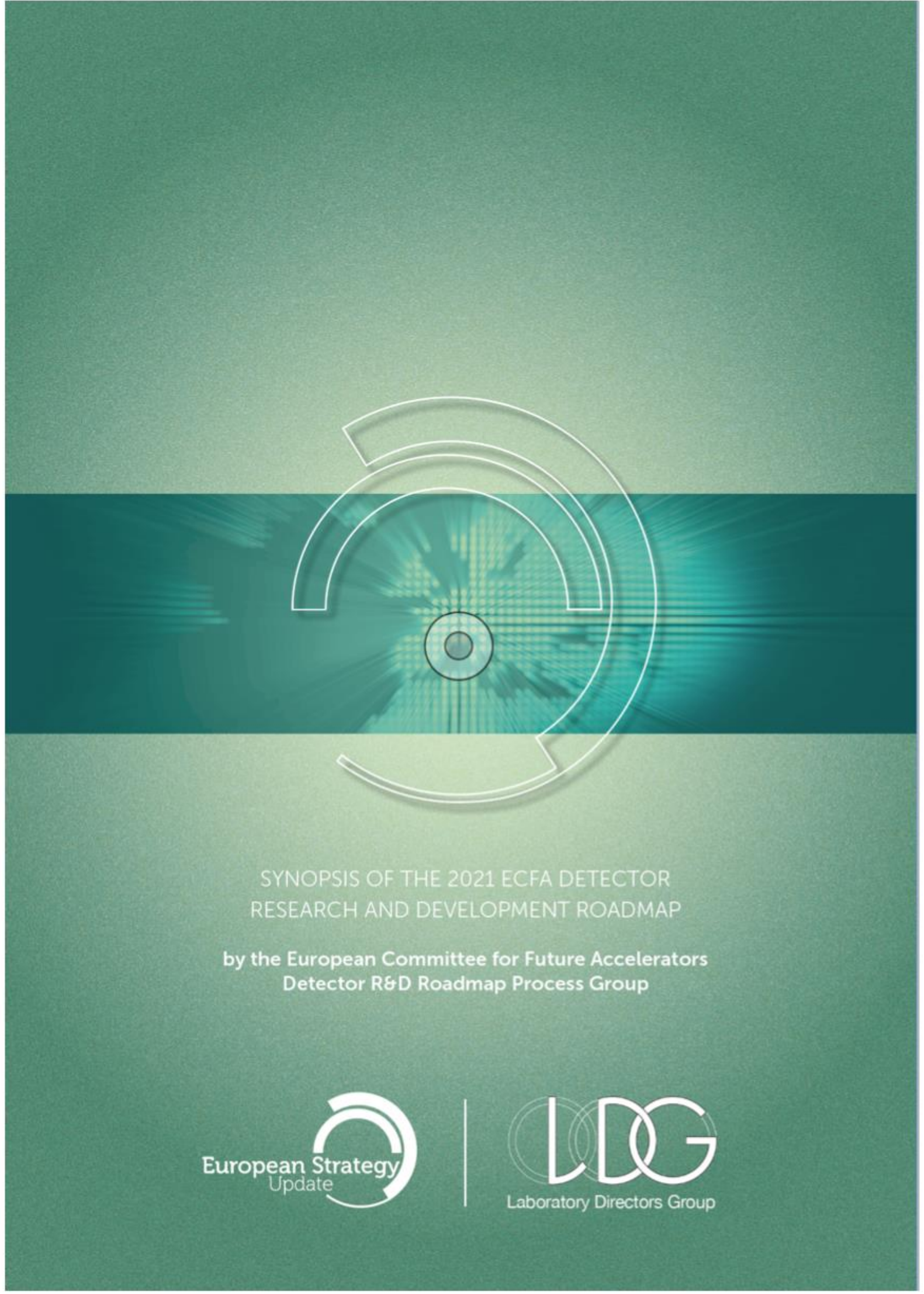
The plasma studies have become more relevant for a possible Higgs factory with the HALHF idea.

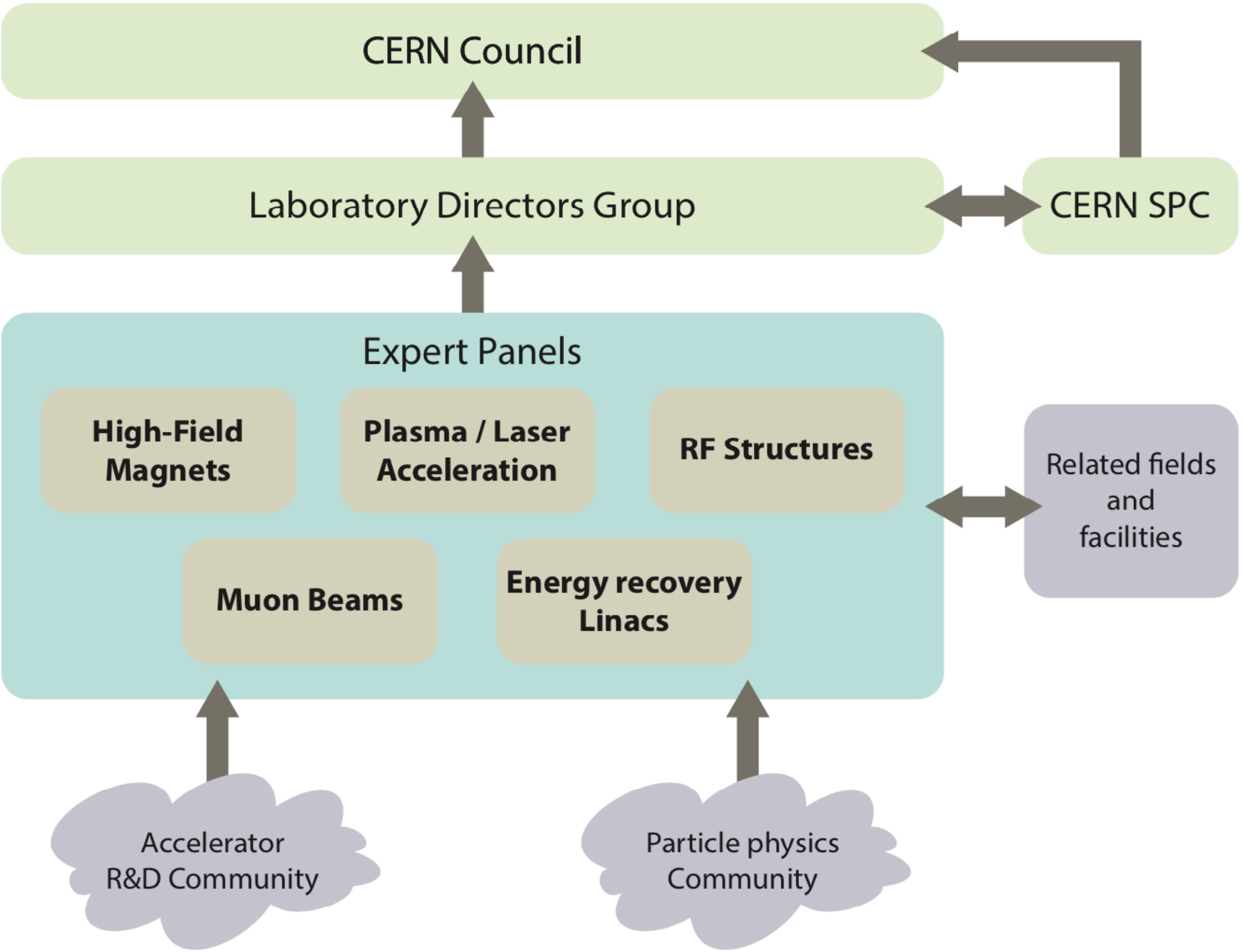
The CLIC/CLEAR experience links very naturally to smaller compact machines as an R&D area (usually for other fields), and links also to HALHF and possibly muons.

Possible to take on studies related to FCC, Muons (with RF links to CLIC and proton driver links to ESS, and possibly HTS magnets) and even ILC if there is a funding opportunity

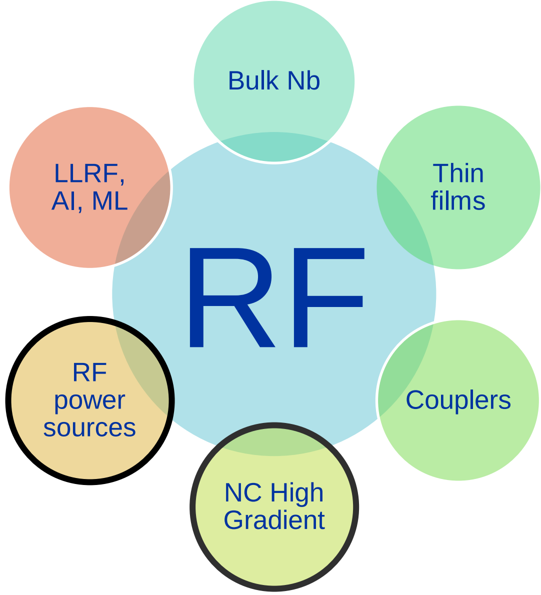
A possible link between HTS magnets (mostly solenoids for muons) and our energy sector (windmill generators and fusion). HTS magnets also relevant for FCC-hh - but dipoles so less industry relevant for us

https://cds.cern.ch/record/2800190/files/146-138-PB.pdf



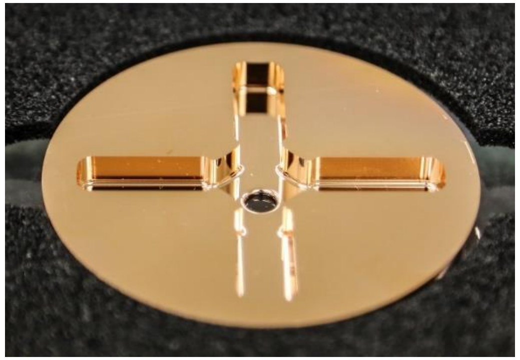


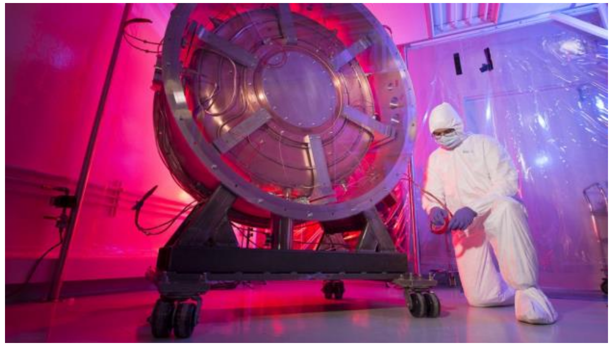
RF – accelerating the beams



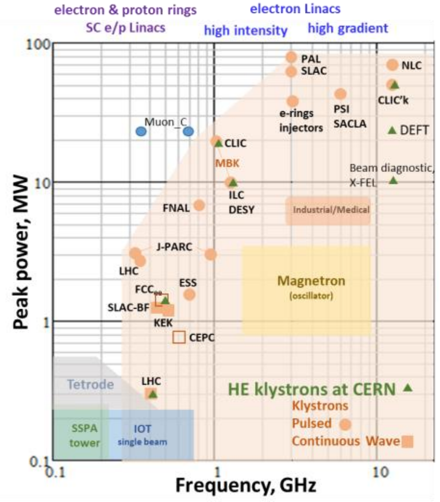
HG design, materials and processes, cold operation (C3), in magnetic field (MC), efficiency and costs – wide application outside research

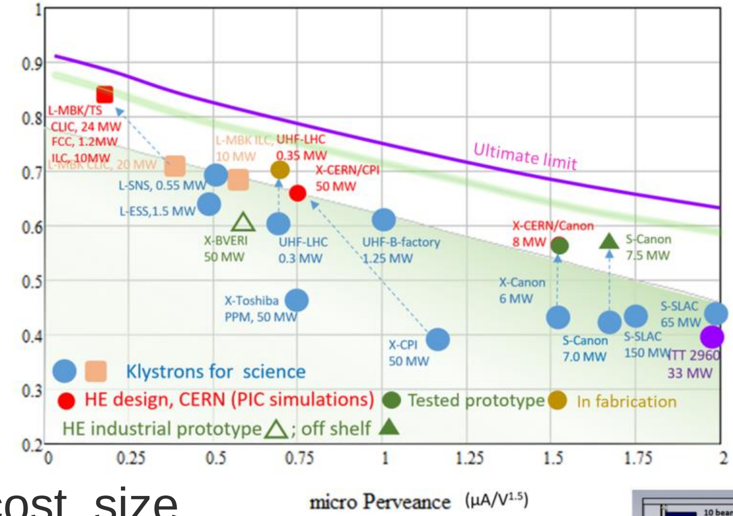
CLIC



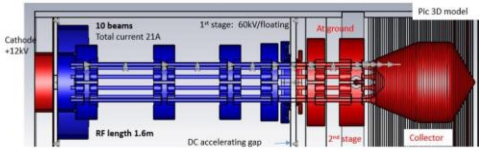


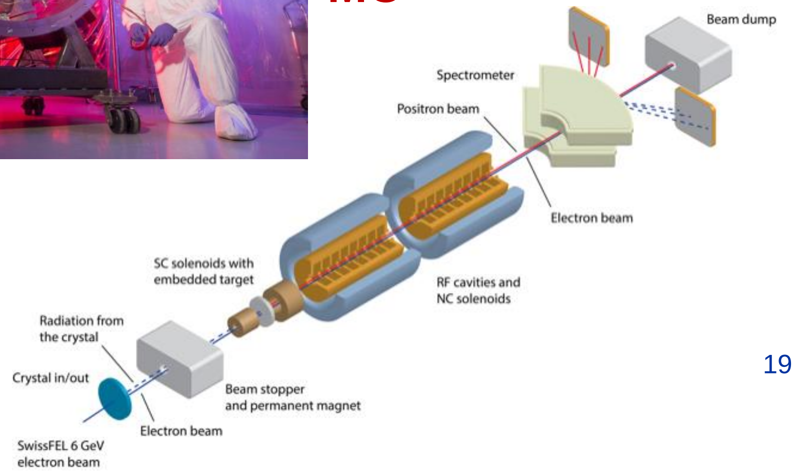
MC





Efficiency, power, cost, size, klystrons but also other devices (SSPA)

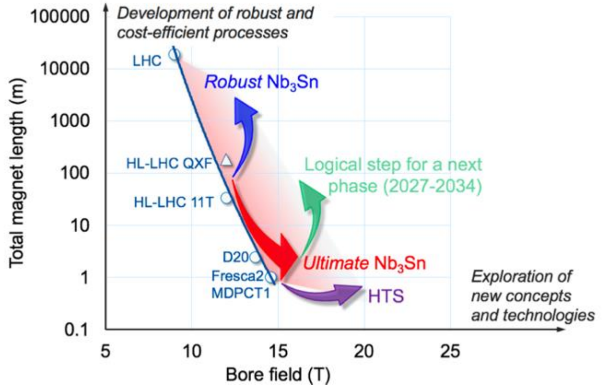


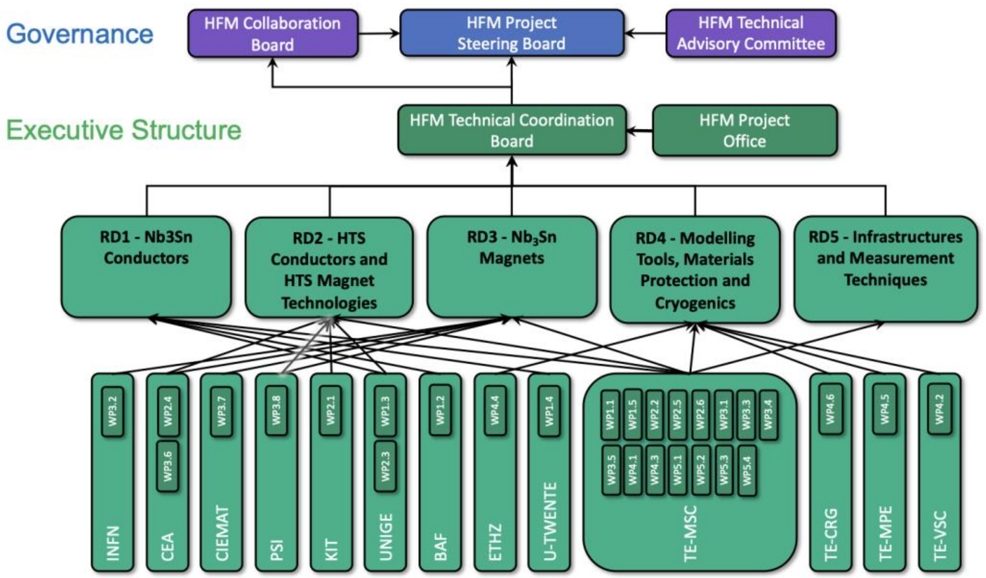


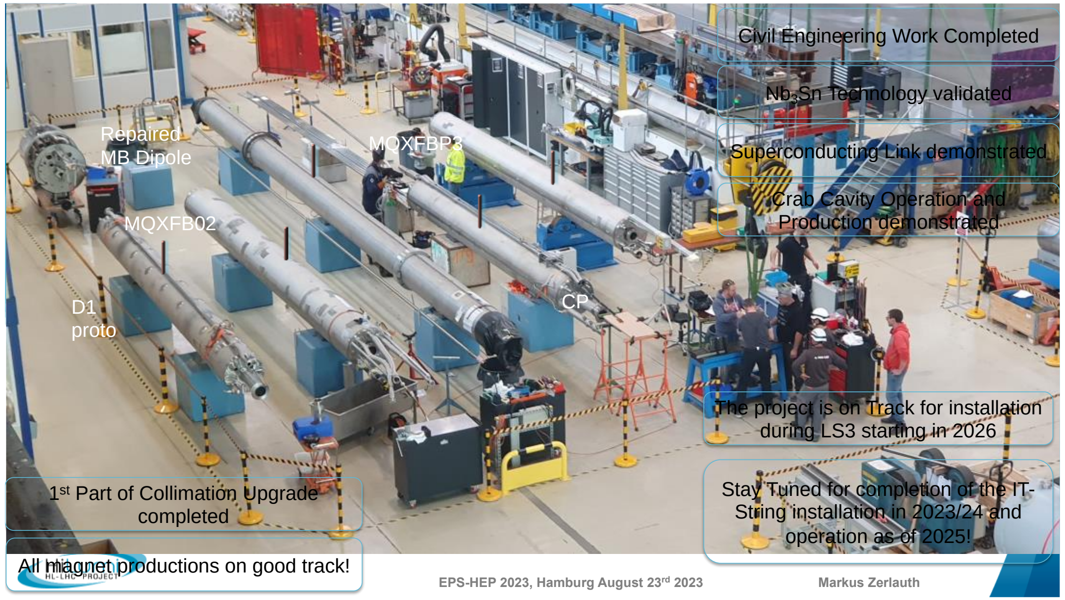
Injectors – here FCC

High Field Magnets (HFM)

1. Demonstrate Nb3Sn magnet technology for large scale deployment, pushing it to its limits in terms of maximum field and production scale.
   - The effort to quantify and demonstrate Nb3Sn ultimate field comprises the development of conductor and magnet technology towards the ultimate Nb3Sn performance.
   - Develop Nb3Sn 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 Nb3Sn.





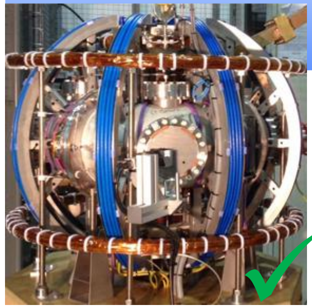


HTS for fusion

Development Roadmap

Tokamak Energy

2014



ST25

ST25 Achievements
- ST Concept
- Plasma heating and current drive development

2015

ST25-HTS

ST25-HTS Achievements
- First HTS TF coils
- H plasma held for 29 hours

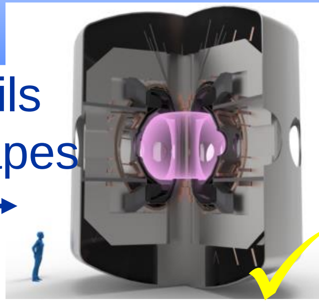
2016 – on-going

ST40

ST40 Achievements
- Highest field ST worldwide at 2.1 T on-axis.
- 100M °C D-H plasma temperature
- On-going development programme

- TF and PF REBCO Coils
- Stacks of tapes

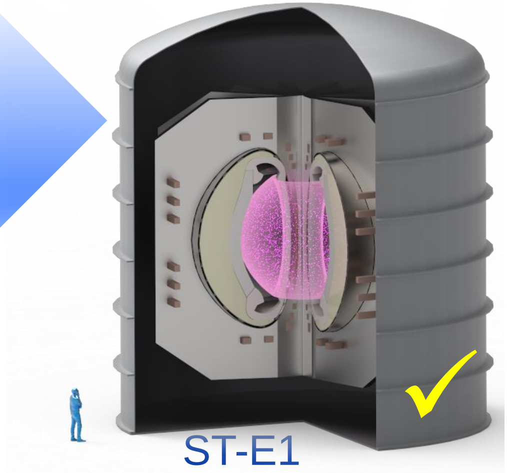
Build completion 2026



ST80-HTS

ST80-HTS Objectives
- Demonstrate long pulse operation
- Control and protection of mid-scale HTS magnets

Early 2030s



ST-E1

ST-E1 Objectives
- Up to 200MW of net electrical power
- Prototype energy generating ST
- Full scale HTS magnets
- Demonstrate plasma control and fault condition recovery at scale

Up to 20 T in the TF coils (~ 30 kA)

2018

QA NI coils

QA NI Coils Achievements
- Tape QA
- Defect tolerant coils
- Robust jointing & ETI plates
- Modular magnet build

2019

Demo3

Demo3 Achievements
- First, conduction-cooled all REBCO magnet to exceed 22T (field on tape) at 20K

2020

Demo2

Demo2 Achievements
- PI development
- Validation of bespoke transient modelling tools (Racoon)
- Quench resistant
- Magnet dynamics very closely correlated to model predictions

2020 -2022

AMR WP4

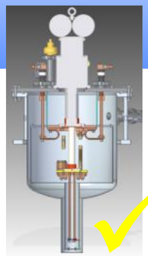
AMR Achievements
- Demonstrated cryogenic PSU technology
- Developed EFC coil design code
- Coil scale-up study
- Coil Cryogenic Compression System designed and built
- Quench modelling code developed and validated

2019 - 2023

Demo4

Demo4 Objectives
- Demonstrate PI for TF coils
- Operation of balanced set of TF coils
- Explore transient control and losses in PF coils
- Explore PF field shine on TF coils
- Quench protection and energy dumping trials

2023



Gamma

Gamma Objectives
- Irradiate small test coils wound from selected REBCO tapes
- Co60 irradiation up to 10MGy dose.
- Coils are cooled to 20K and energised to Ic
- Ic degradation measured in real time

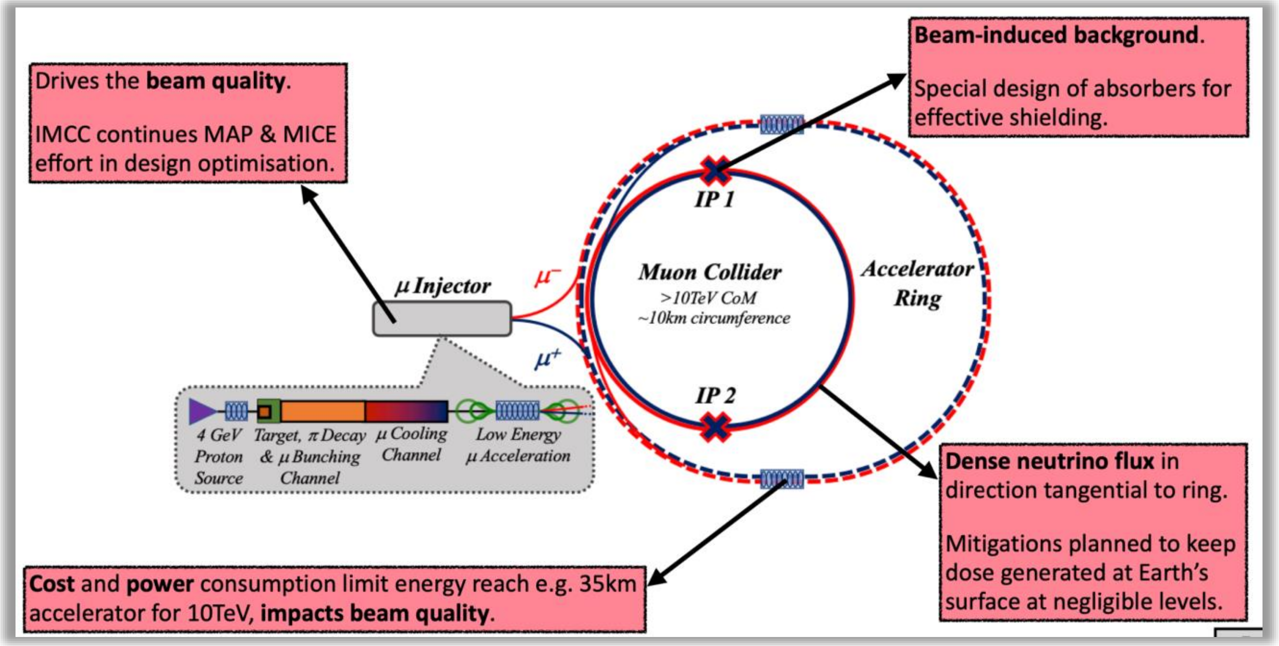
2022 - 2026

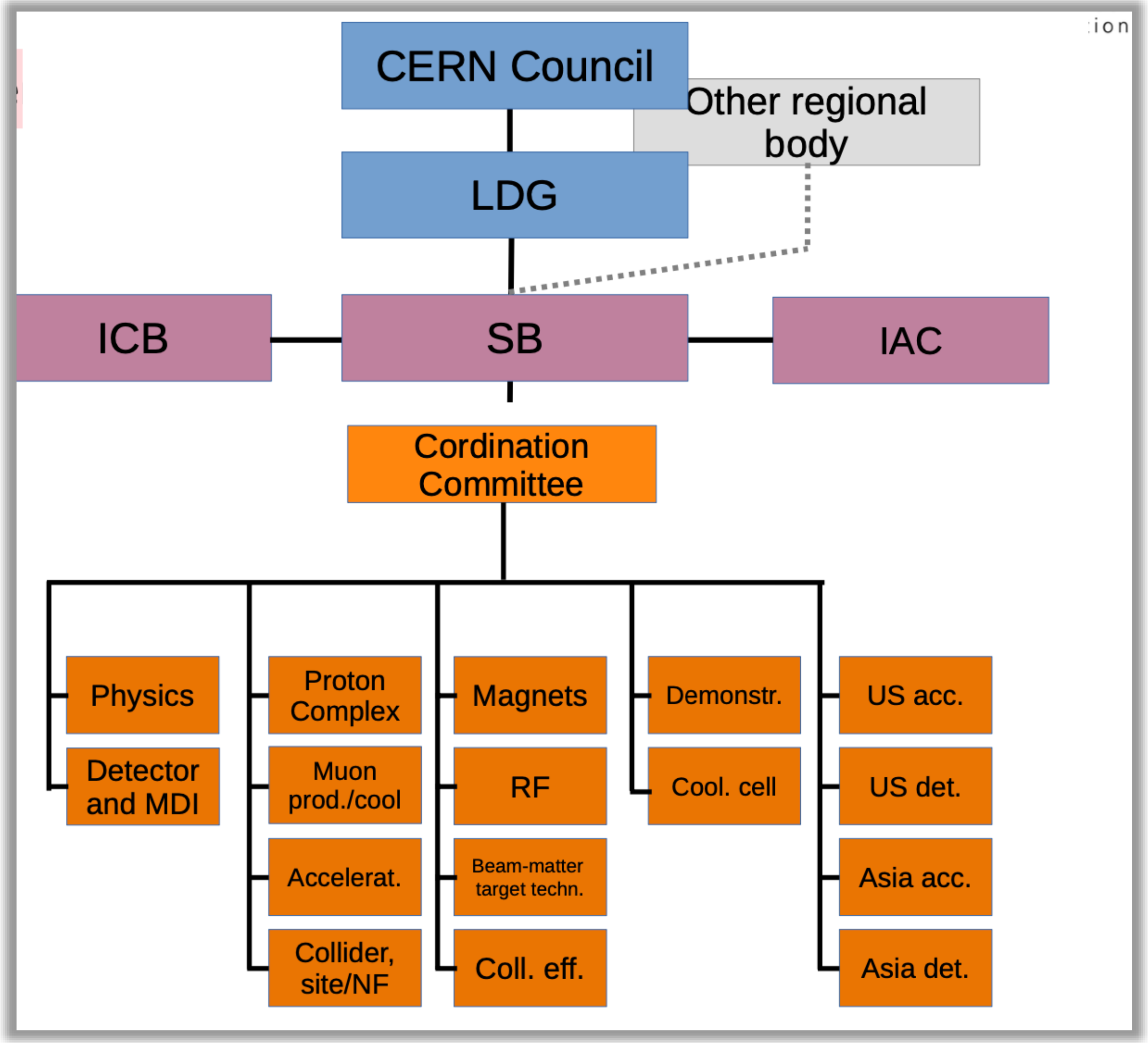
BB01

BB01 Objectives
- Developing prototype coils for ST80
- Developing coil manufacturing processes and tooling
- Developing magnet assembly processes and tooling

Rod Bateman, presented at HiTAT Workshop – March 2023

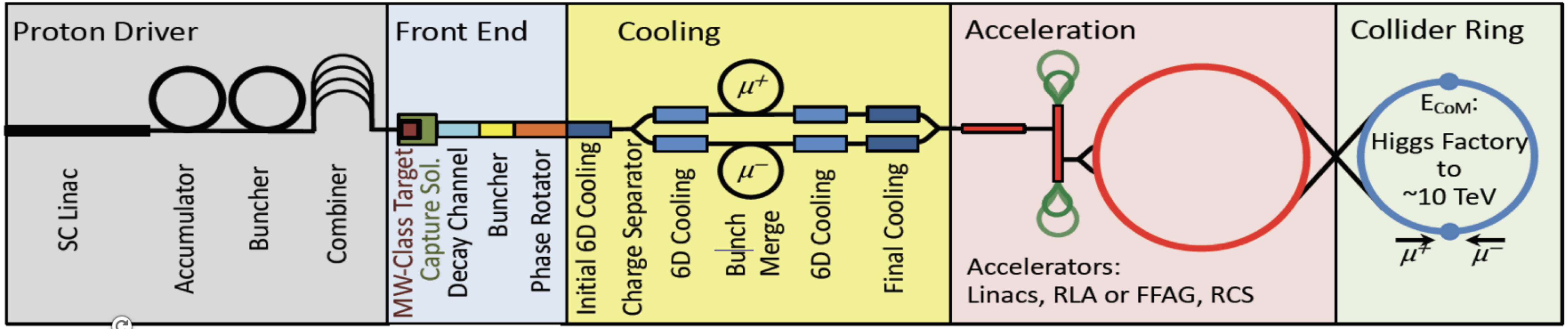
Muon collider study and the International Muon Collider Collaboration



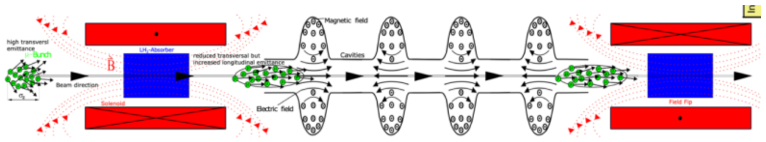


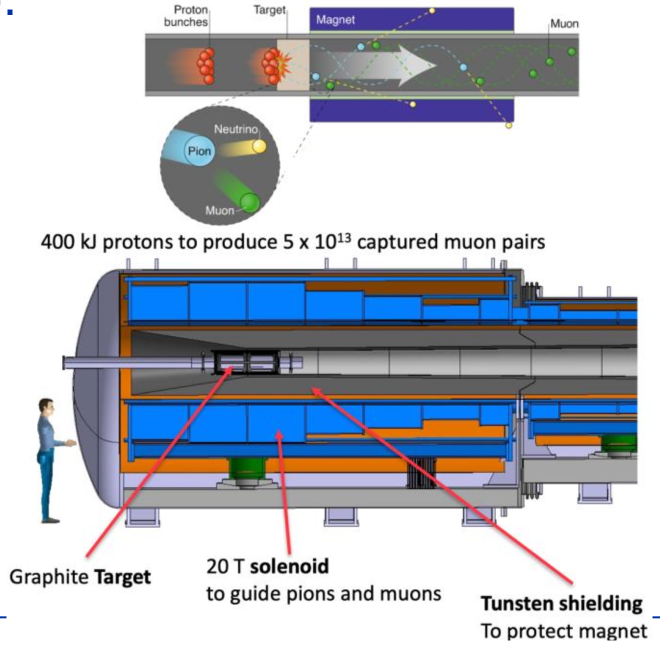
From LDG talks and talk yesterday (K.Skoufaris):LINK

Status of the International Muon Collider Complex Study at 10 TeV	*KYRIACOS SKOUFARIS*	
Hörsaal H, Historic main building		09:35 - 09:55
Machine-Detector interface for multi-TeV Muon Collider	*Donatella Lucchesi*	
Hörsaal H, Historic main building		09:55 - 10:10



High intensity proton drivers (FNAL, CERN, ESS, JPARC).
SC RF





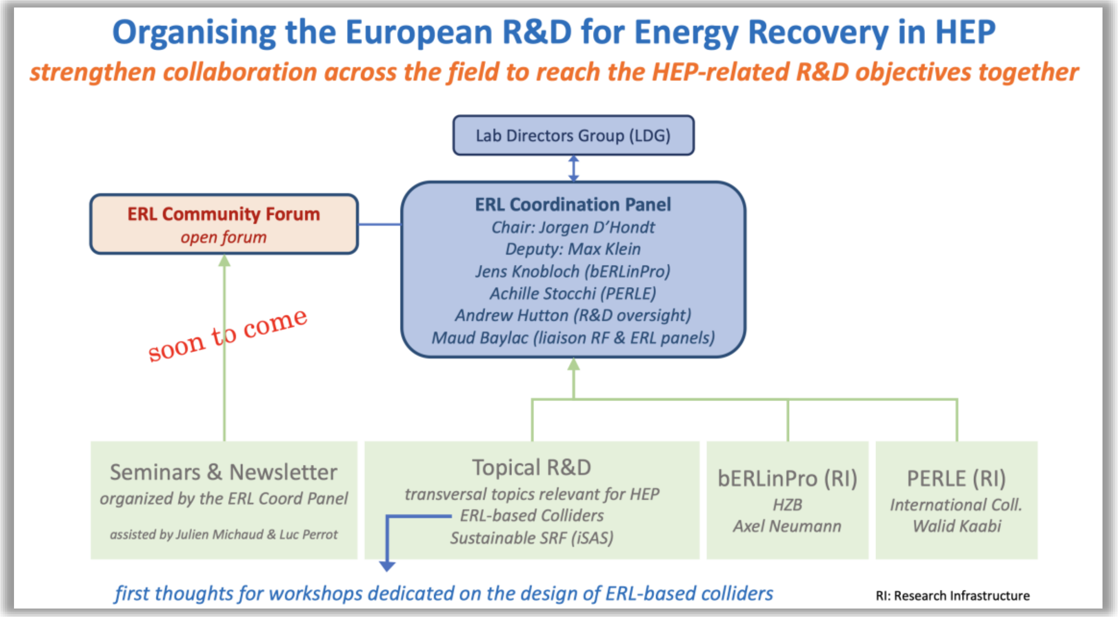
NC RF in high magnetic field, HF solenoids, windows/absorbers -> cooling cell integration and studies

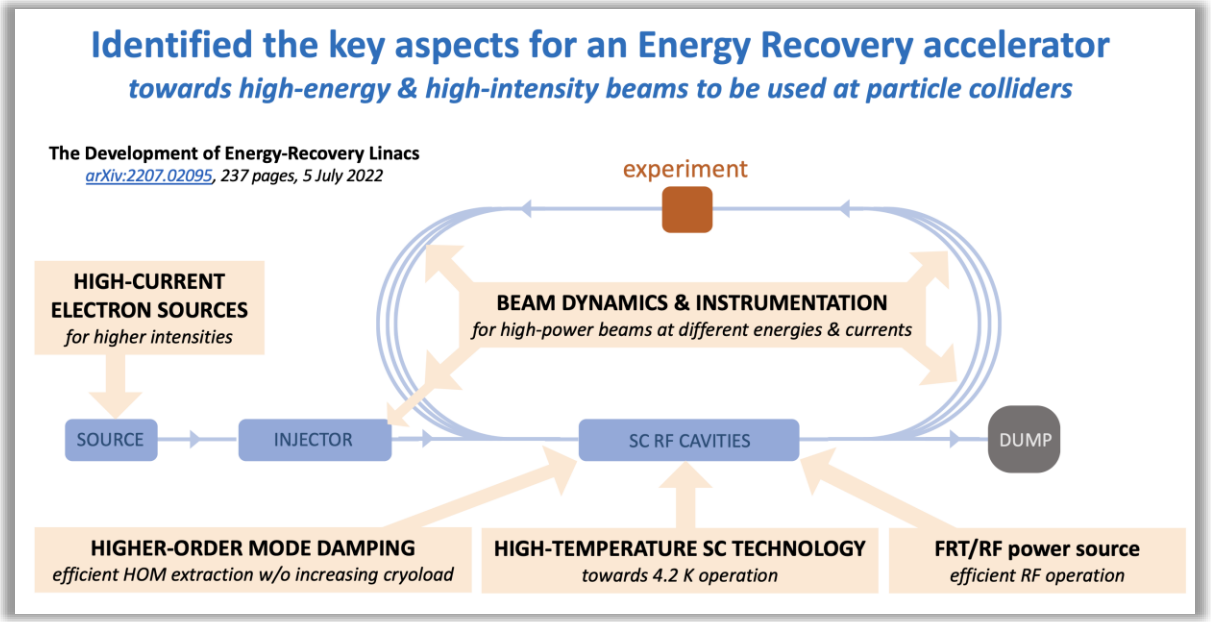
Fast ramping magnets and power management, SCRF

HF magnets (dipoles), detector interface, movements system to reduce neutrino background

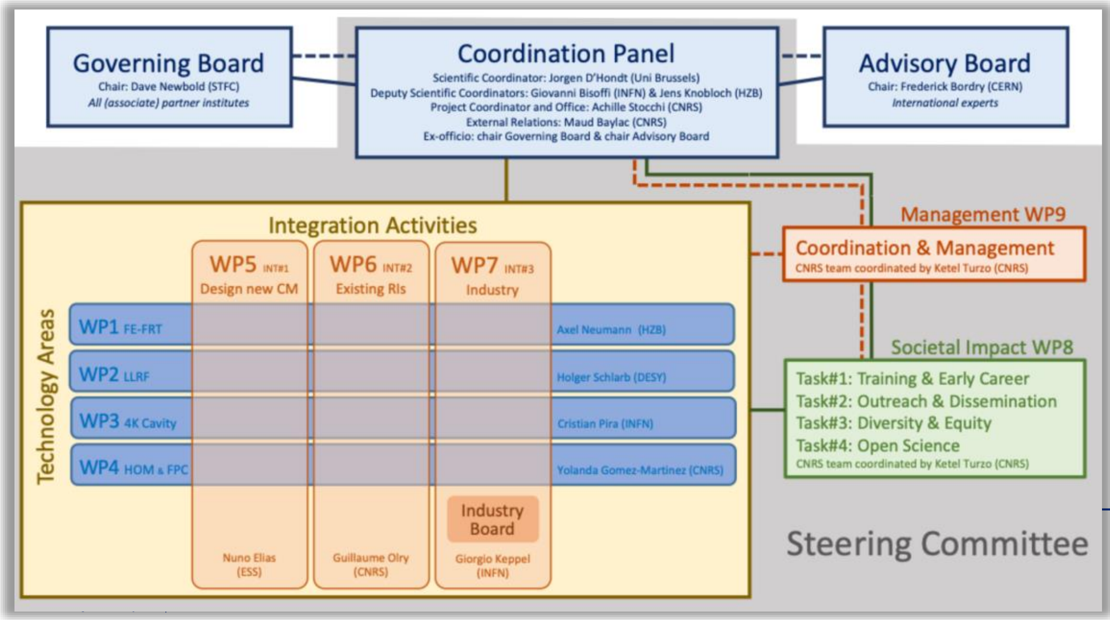
Many of the magnet studies can be addressed by the HTS study mentioned earlier (solenoids and dipoles)

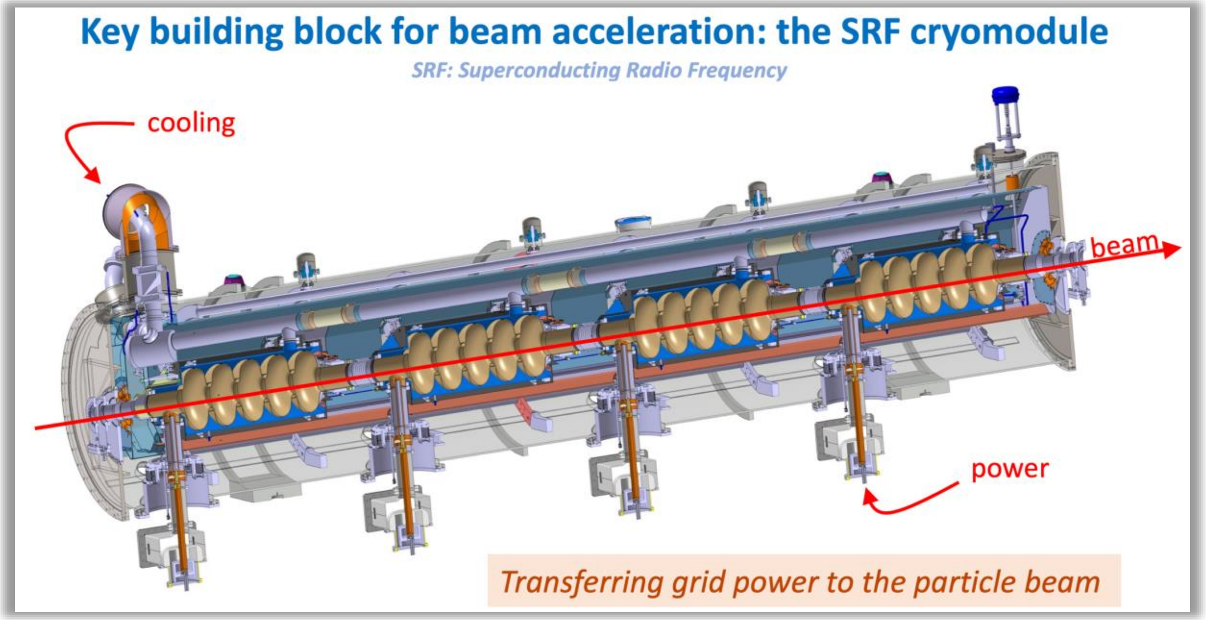
Target, HF solenoid





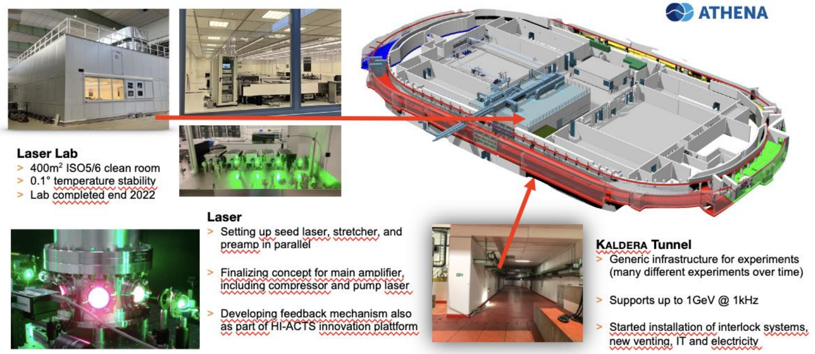
Important development: Approved EU project in June, start early 2024.
iSAS: Innovate for Sustainable Accelerating Systems



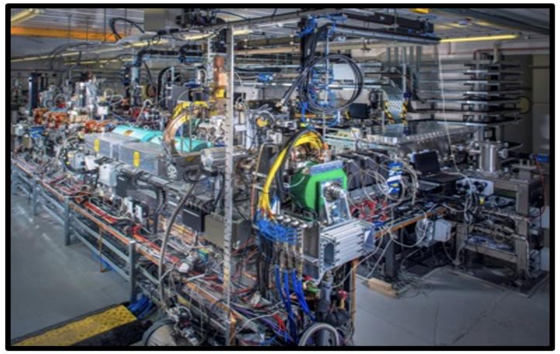


Plasma

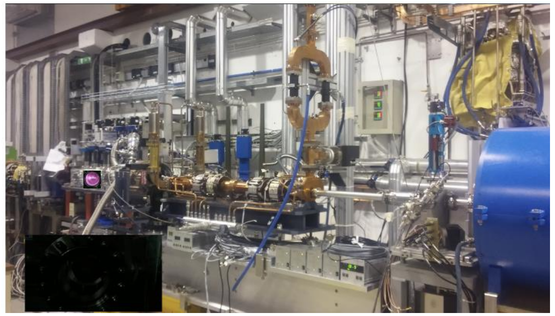
WP No.	Workpackage
1.1	Overall collider concepts (Higgs Factory)
1.2	Beam driven electron linac – integrated simulations
1.3	Laser driven electron linac
1.4	Positron acceleration
1.5	Spin preservation
1.6	Final focus system
1.7	Sustainability analysis
2.1	High-repetition rate laser-driven plasma module (coordination)
2.2	High rep-rate laser drivers
2.3	High rep-rate targetry
2.4	LPA-experimental facility design (EPAC, CALA, ELI)
3.1	Electron-beam driven PWFA – experiment (FLASHForward/CLARA)
3.2	Proton-driven PWFA (at AWAKE)
4.1	Early High energy physics experiments

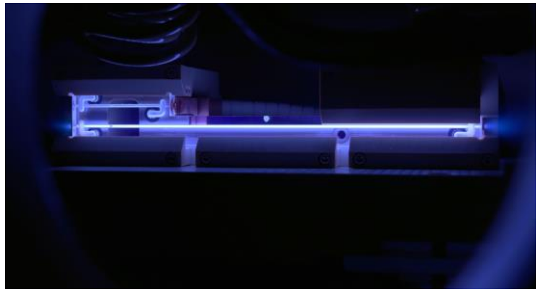


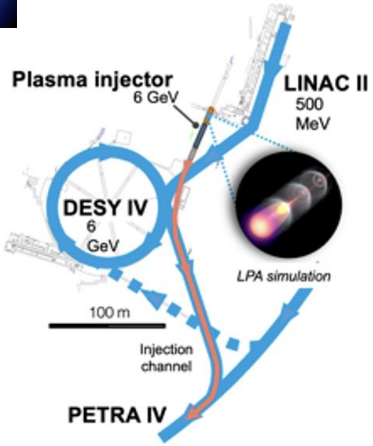
CLARA beamline



INFN PWFA chamber







Supported by the EUPRAXIA preparatory phase project: (LINK)

The AWAKE Run 2 programme and beyond *Matthew Wing*
Hörsaal H, Historic main building 16:30 - 16:50

LhARA, the Laser-hybrid Accelerator for Radiobiological Applications *Kenneth Long*
Hörsaal H, Historic main building 16:50 - 17:05

A hybrid, asymmetric, linear Higgs factory based on plasma-wakefield and radio-frequency acceleration
Prof. Brian Foster

Status of the PWFA experiment FLASHForward *Mr Stephan Wesch*
Hörsaal H, Historic main building 17:20 - 17:35