Future Colliders from the Accelerator Perspective

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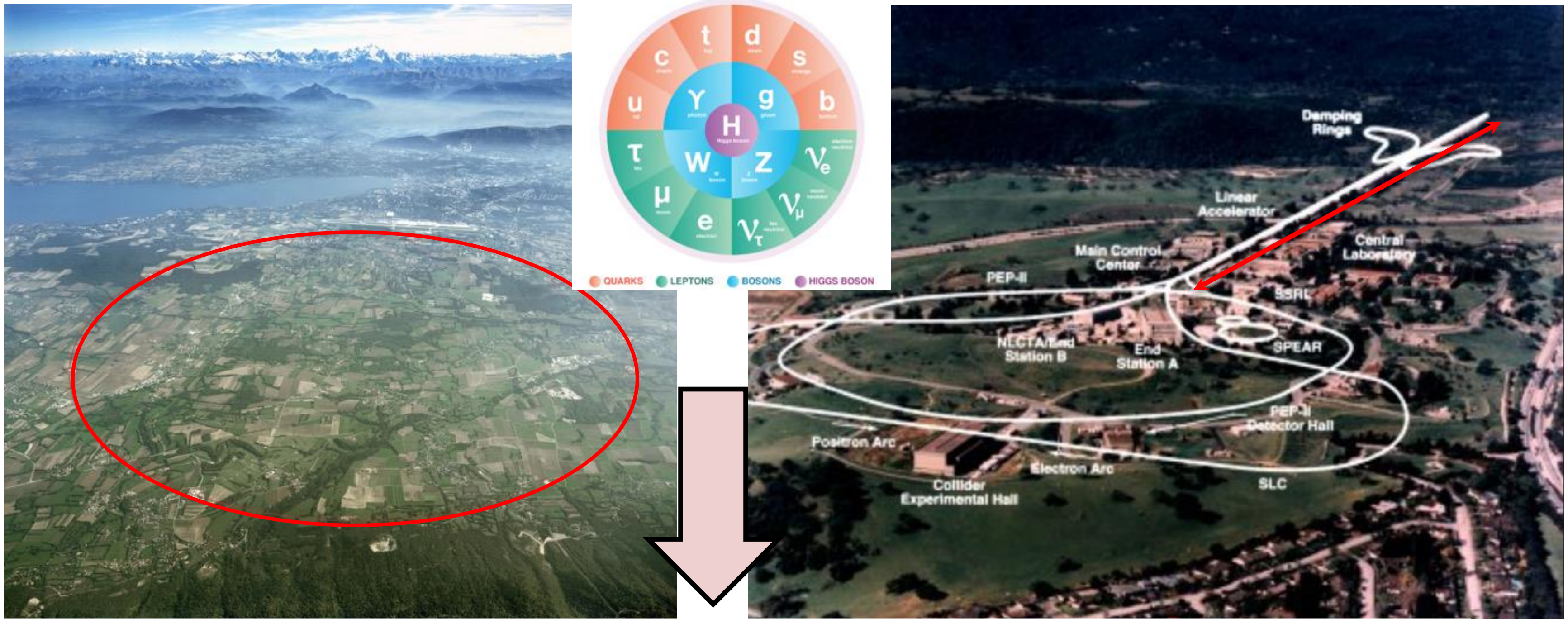
LHCP 2024
6/4/2024

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Accelerators Drive Discovery for High Energy Physics

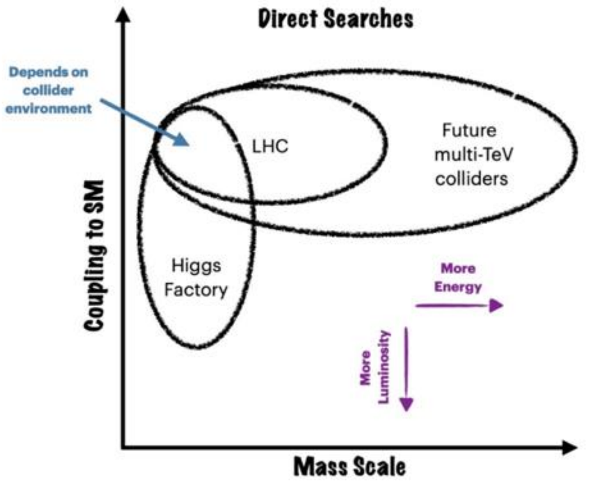
Experimental validation of the Standard Model of Particle Physics



What determines the performance of an accelerator? How do accelerators work across different scales in size and energy?

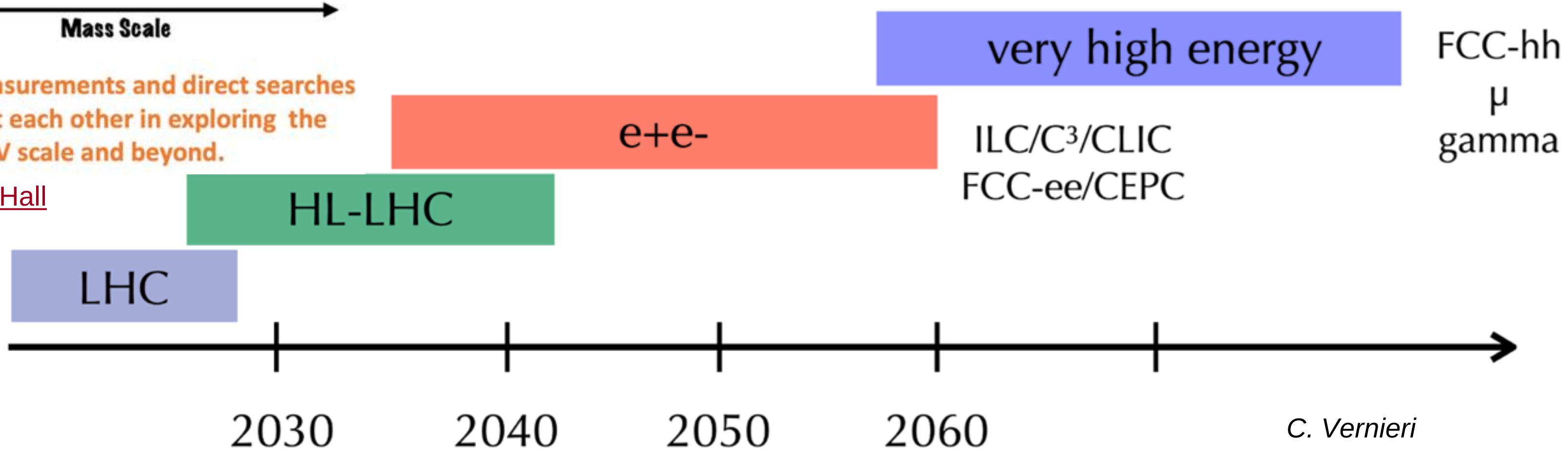
What’s Next for the Energy Frontier?

- Many options in consideration beyond HL-LHC
- Precision studies with Higgs Factories
- Discovery physics on the >TeV scale



Higgs coupling measurements and direct searches will complement each other in exploring the 1-10 TeV scale and beyond.

Reina, P5 Town Hall

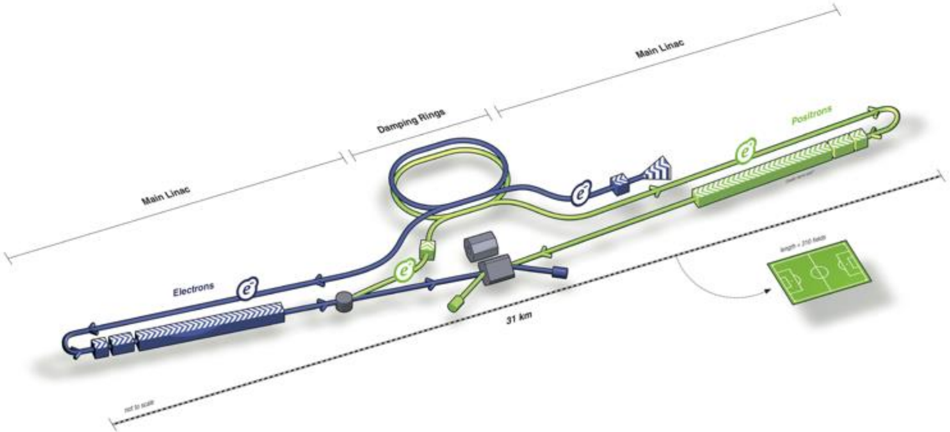


C. Vernieri

Linear vs. Circular

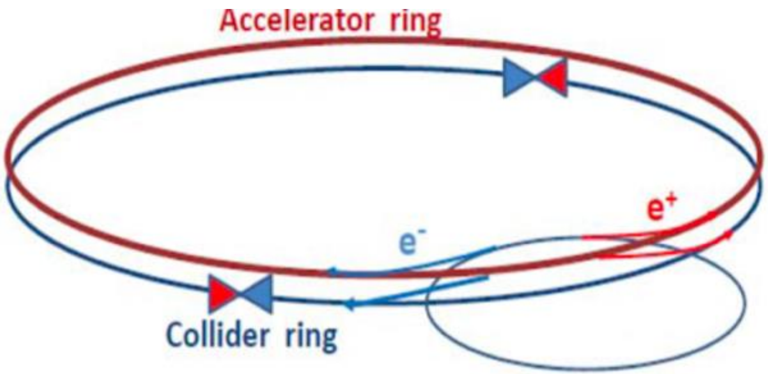
Linear e^+e^- colliders: ILC, C^3, CLIC

- Reach higher energies (~TeV), a
  can use polarized beams
- Relatively low radiation
- Collisions in bunch trains

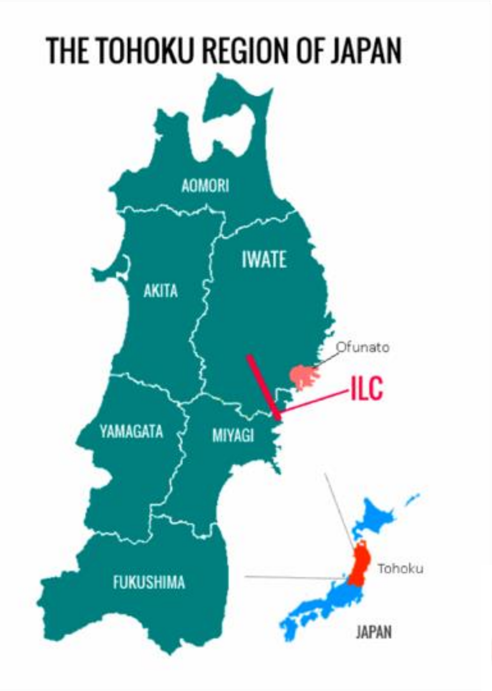


Circular e^+e^- colliders: FCC-ee, CEPC

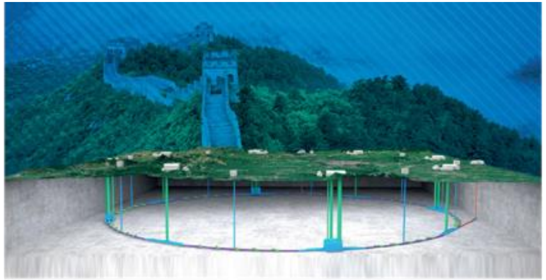
- Highest luminosity collider at Z/WW/ZH
- limited by synchrotron radiation above 350 – 400 GeV (~ γ^4/ρ^2)
- Beam continues to circulate after collision



Higgs Factory Proposals

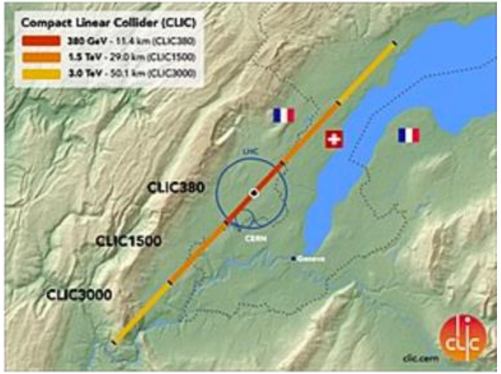


ILC
250/500 GeV

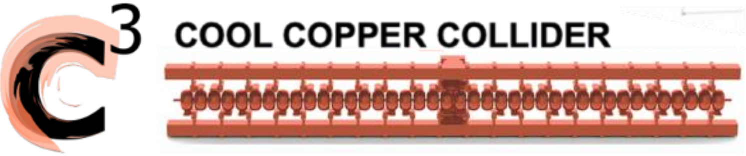


CEPC
240 GeV

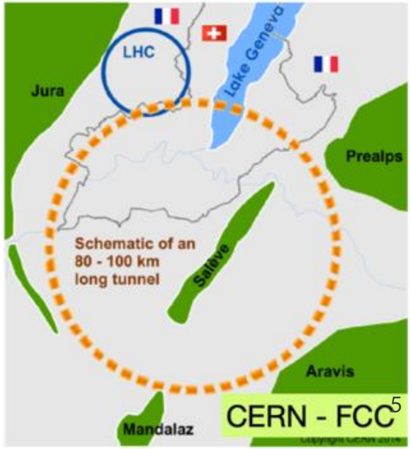
CLIC 380/1000/3000 GeV



FCC-ee
240/365 GeV

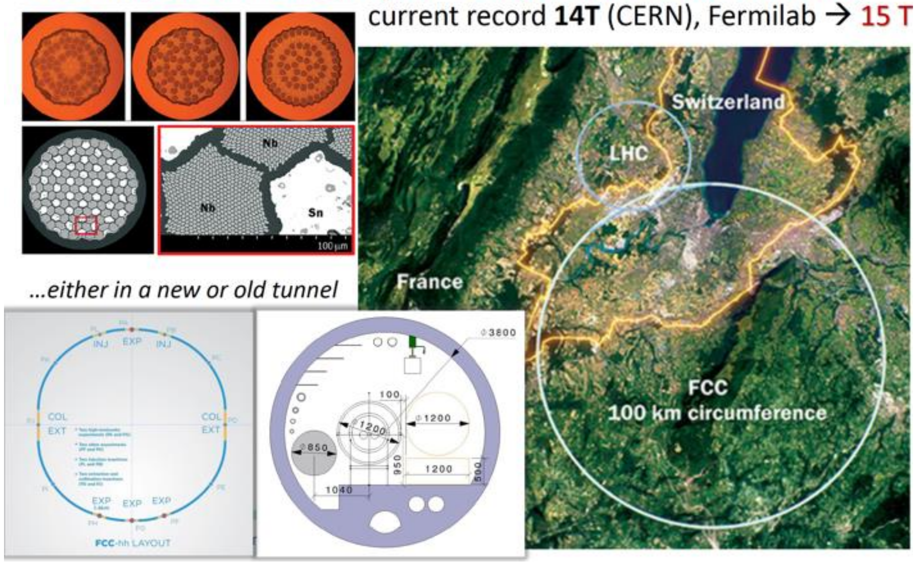


250/550 GeV
… > TeV



Future *Muon, Wakefield and hh* Colliders

New magnet technology Nb_3Sn – **16 T** (vs **8 T** in the LHC with NbTi)


current record **14T** (CERN), Fermilab → 15 T

...either in a new or old tunnel

FCC-hh

Wakefield


The international journal of science / 22 July 2021

nature

COMPACT SOURCE

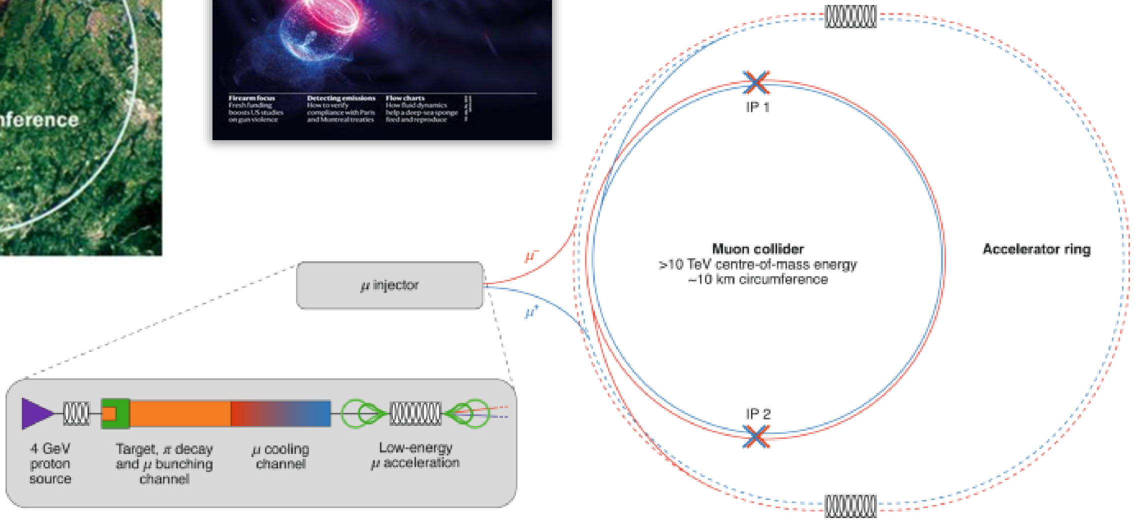
Plasma-based acceleration paves way to smaller free-electron lasers

Firearm focus
Fresh funding boosts US studies on gun violence

Detecting emissions
How to verify compliance with Paris and Montreal treaties

Flow charts
How fluid dynamics help a deep-sea sponge feed and reproduce

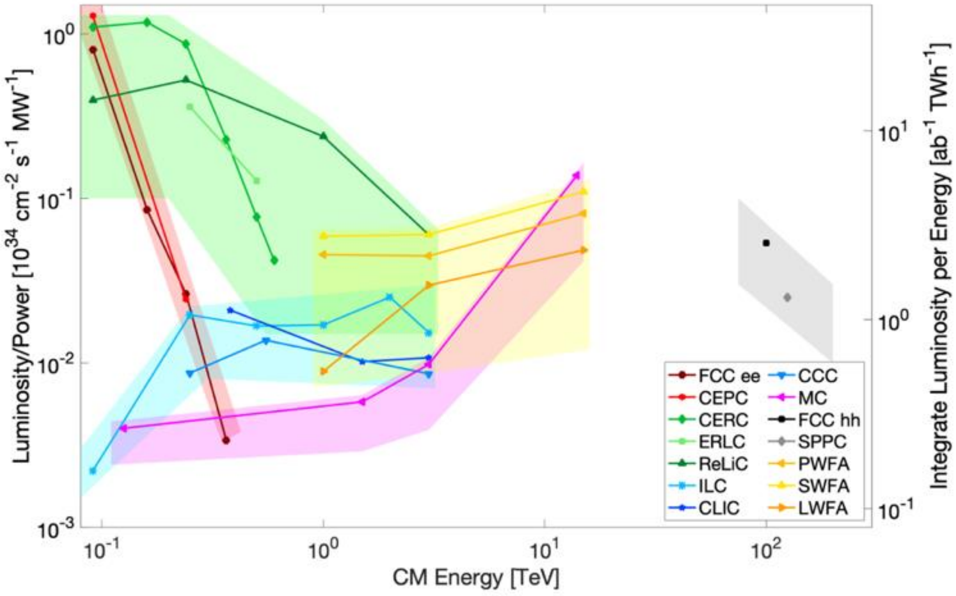
Muon Collider



Landscape of High Energy Colliders

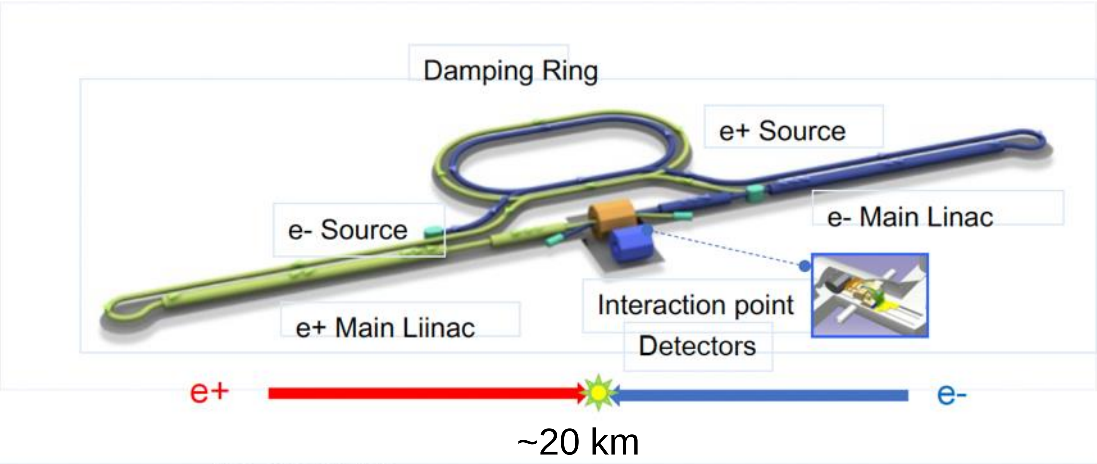
Snowmass Implementation Task Force comparisons of machine concepts

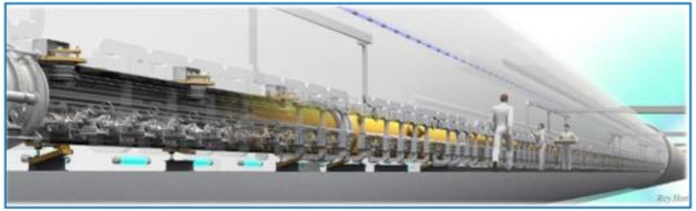
Future studies focusing on physics potential for operation ***AND*** construction

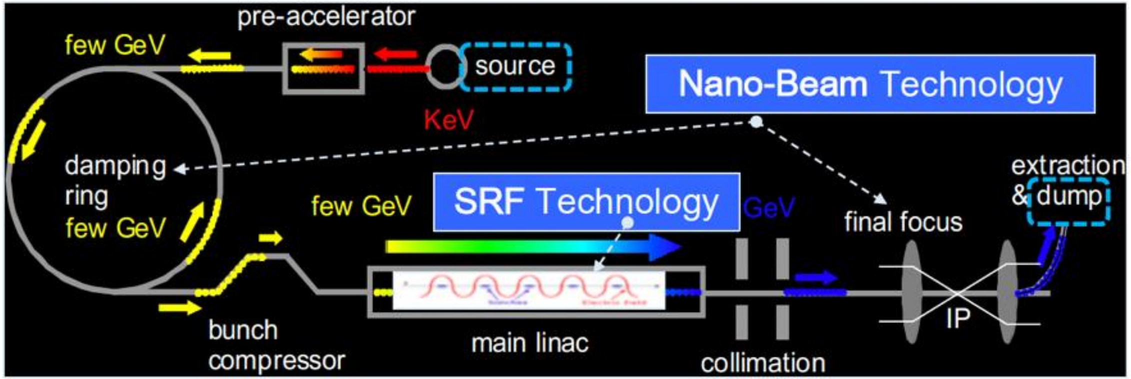


https://arxiv.org/pdf/2208.06030.pdf

ILC and the Accelerator Technology





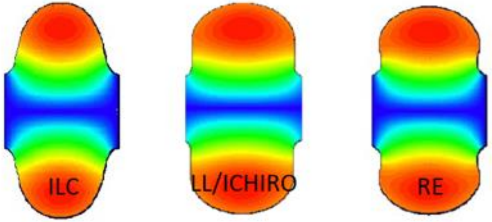


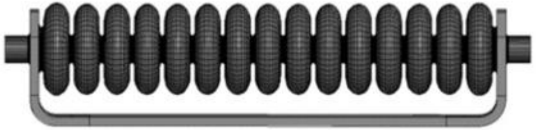
Parameters	Value
Beam Energy	125 + 125 GeV
Luminosity	1.35 / 2.7 x 10^{10} cm^2/s
Beam rep. rate	5 Hz
Pulse duration	0.73 / 0.961 ms
# bunch / pulse	1312 / 2625
Beam Current	5.8 / 8.8 mA
Beam size (y) at FF	**7.7** nm
SRF Field gradient	< 31.5 > MV/m (+/-20%) $Q_0 = 1x10^{10}$
#SRF 9-cell cavities (CM)	~ 8,000 (~ 900)
AC-plug Power	111 / 138 MW

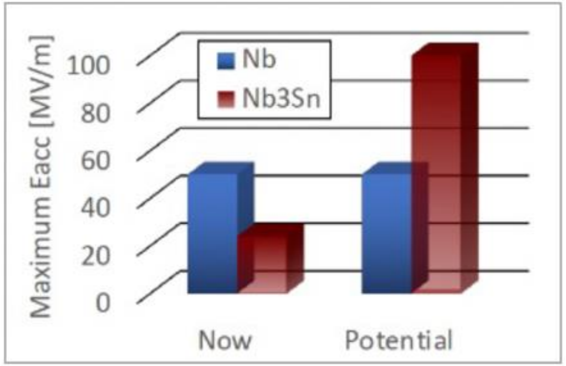
TDR was published in 2013.

SRF technology for ILC-250 beyond present limits

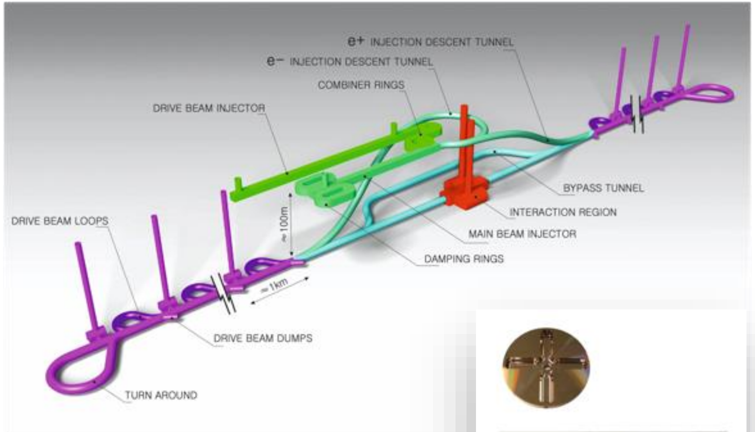
- Advanced shape standing wave SRF cavities – Low Loss (LL), ICHIRO,
- Reentrant (RE) – increase peak quench magnetic field by 10-20%, potentially bringing accelerating gradient limit to ≲ 60 MV/m
- Traveling wave (TW) SRF offers better cryogenic efficiency and higher accelerating gradient up to ~ 70 MV/m – possible application: ILC energy upgrade, HELEN collider, ACE at Fermilab
- Advanced SRF materials – Nb3Sn cavities can potentially reach ~ 90 MV/m







The Compact Linear Collider (CLIC)



Accelerating structure prototype for CLIC: 12 GHz (L~25 cm)

The CLIC accelerator studies are mature:

- Optimised design for cost and power
- Many tests in CTF3, FELs, light-sources and test-stands
- Technical developments of "all" key elements

- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20'500 structures at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged programme with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier)

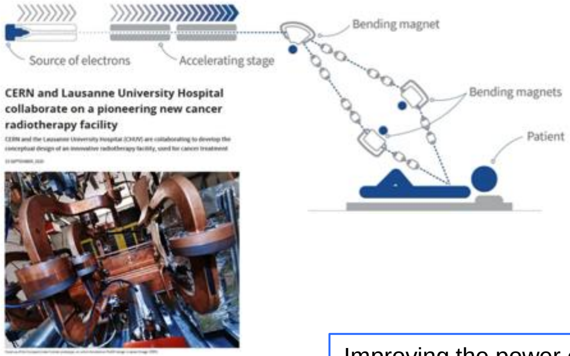
- CDR in 2012 with focus on 3 TeV. Updated project overview documents in 2018 (Project Implementation Plan) with focus 380 GeV for Higgs and top.

Recent talks (with more references): eeFACT1 and eeFACT2

On-going CLIC studies towards next ESPP update

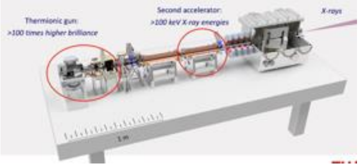
Project Readiness Report as a step toward a TDR
Assuming ESPP in ~ 2026, Project Approval ~ 2028, Project (tunnel) construction can start in ~ 2030.

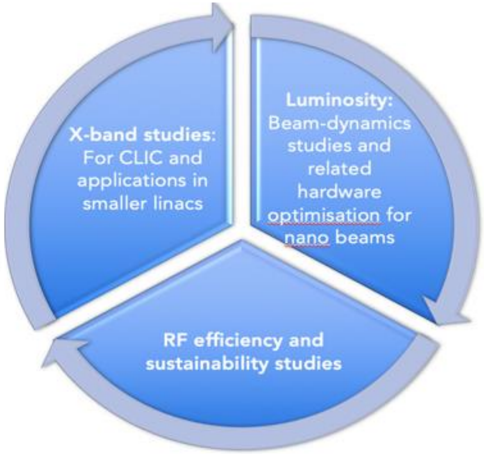
The X-band technology readiness for the 380 GeV CLIC initial phase - more and more driven by use in small compact accelerators



CERN and Lausanne University Hospital collaborate on a pioneering new cancer radiotherapy facility

CERN and the Lausanne University Hospital (CHUV) are collaborating to develop the conceptual design of an innovative radiotherapy facility, used for cancer treatment





X-band studies: For CLIC and applications in smaller linacs

Luminosity: Beam-dynamics studies and related hardware optimisation for nano beams

RF efficiency and sustainability studies

Optimizing the luminosity at 380 GeV – already implemented for Snowmass paper, further work to provide margins will continue.

Luminosity margins and increases:

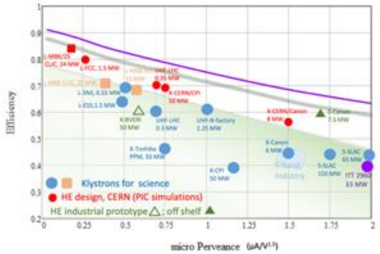
- Initial estimates of static and dynamic degradations from damping ring to IP gave: 1.5 x 10^{34} cm^{-2} s^{-1}
- Simulations taking into accord static and dynamic effects with corrective algorithms give 2.8 on average, and 90% of the machines above **2.3 x 10^{34} cm^{-2} s^{-1}** (this is the value currently used)

Improving the power efficiency for both the initial phase and at high energies, including more general sustainability studies

Power estimate bottom up (concentrating on 380 GeV systems)

- Very large reductions since the CDR, better estimates of nominal settings, much more optimised drive-beam complex and more efficient klystrons, injectors more optimized, main target damping ring RF significantly reduced, recent L-band klystron studies

Energy consumption ~0.6 TWh yearly, CERN is currently (when running) at 1.2 TWh (~90% in accelerators



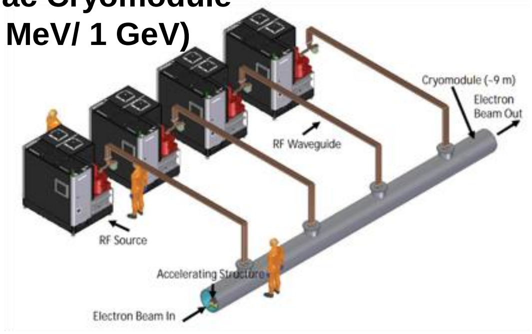
Accelerator Complex

8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m

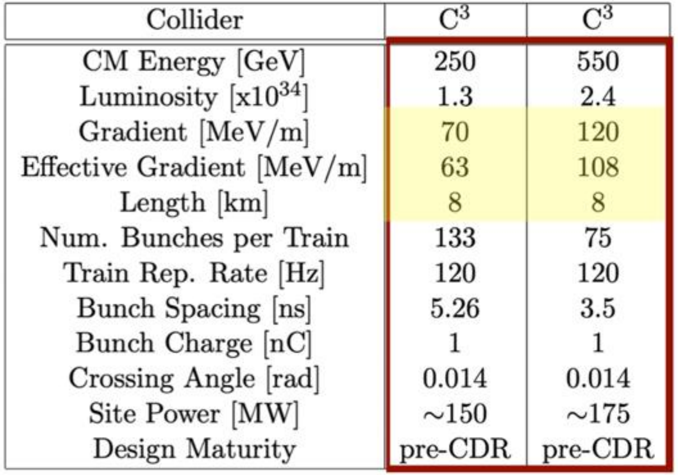
Large portions of accelerator complex compatible between LC technologies

- Beam delivery / IP modified from ILC (1.5 km for 550 GeV CoM), compatible w/ ILC-like detector
- Damping rings and injectors to be optimized with CLIC as baseline

C^3 Main Linac Cryomodule
9 m (600 MeV/ 1 GeV)

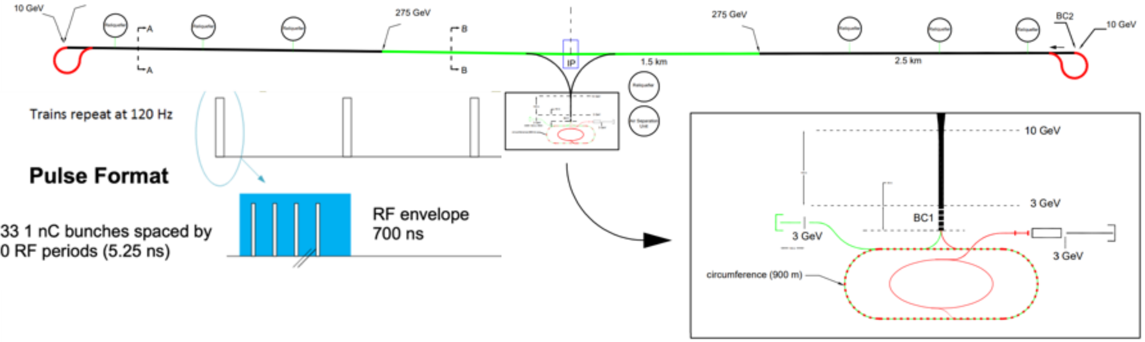


C^3 Parameters



Collider	C^3	C^3
CM Energy [GeV]	250	550
Luminosity [x10^{34}]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Crossing Angle [rad]	0.014	0.014
Site Power [MW]	~150	~175
Design Maturity	pre-CDR	pre-CDR

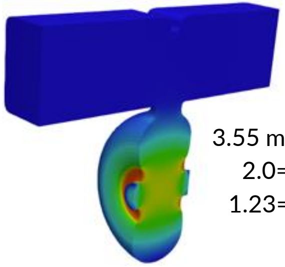
C^3 - 8 km Footprint for 250/550 GeV (to scale)



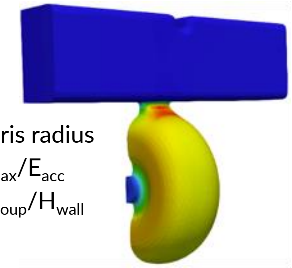
Alignment and Vibrations

System level optimization essential for achieving performance

RF Structure Optimization



3.55 mm iris radius
2.0=E_{max}/E_{acc}
1.23=H_{coup}/H_{wall}

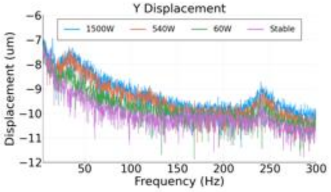


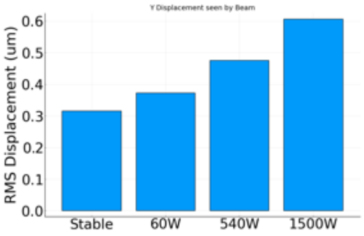
Electric Field

Magnetic Field

M. Shumail, Z. Li

Vibration Measurements and Analysis





RadiaBeam

Z. George, V. Borzenets, A. Dhar, D. Palmer

Two-Phase Fluid Simulations

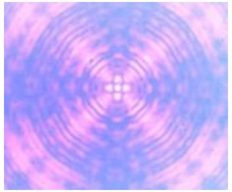
FAMU-FSU College of Engineering

K. Shoele

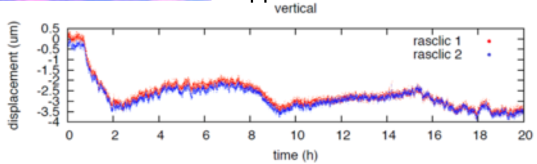
Precision Short and Long Range Alignment

H. Van Der Graaf

Nikhef

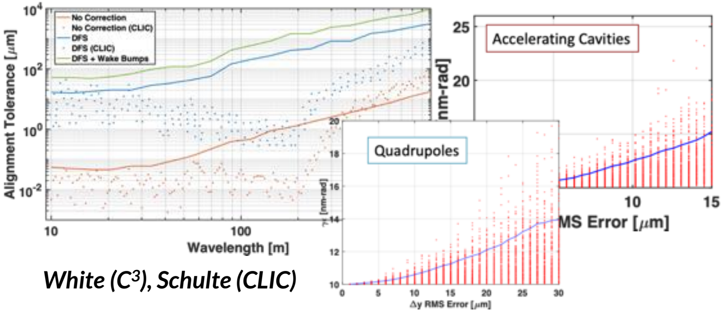


100 nm resolution
Approved effort to test cold



https://arxiv.org/pdf/2307.07981.pdf

Main Linac Beam Dynamics



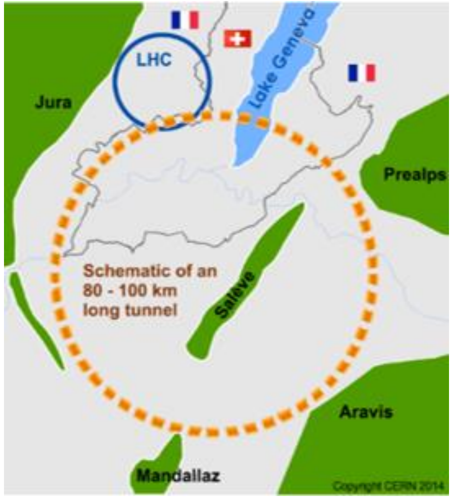
White (C^3), Schulte (CLIC)

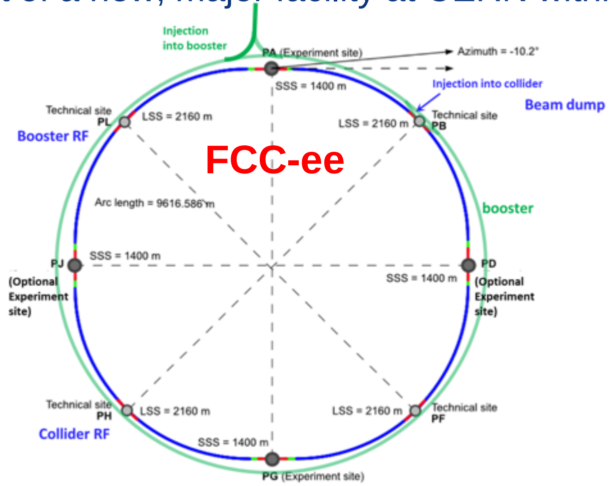
Alignment Parameters	Units	Value
Raft Components	µm	5
Short Range (~10m)	µm	30
Long Range (>200m)	µm	1000
Structure Vert. Vibration	µm	9
Quad Vert. Vibration	nm	15
BPM Resolution	µm	0.1
BPM-Quad Alignment	µm	2

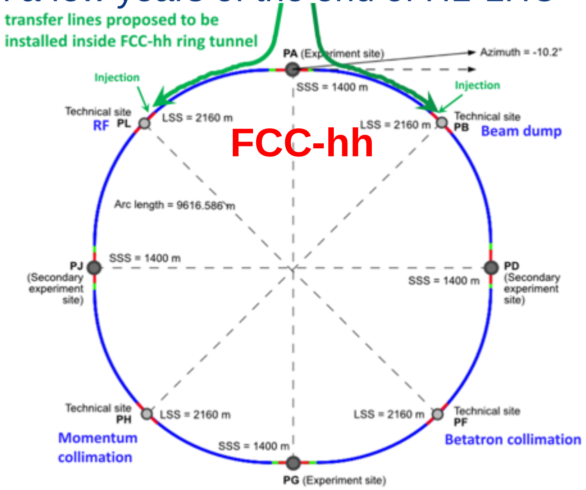
FCC integrated program

comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, w pp & AA collisions; also eh option**
- highly synergetic and complementary programme boosting the physics reach of both colliders (e.g. model-independent measurements of the Higgs couplings at FCC-hh thanks to input from FCC-ee; and FCC-hh as “energy upgrade” of FCC-ee)
- common civil engineering and technical infrastructures, building on and reusing CERN’s existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC







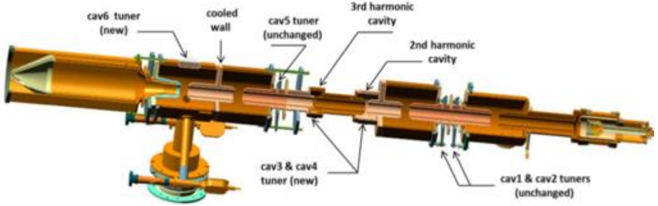
2020 - 2040 **2045 - 2060** **2070 - 2095**

a similar two-stage project CEPC/SPPC is under study in China

FCC-ee accelerator R&D - examples

efficient RF power sources (400 & 800 MHz)

I. Syratchev

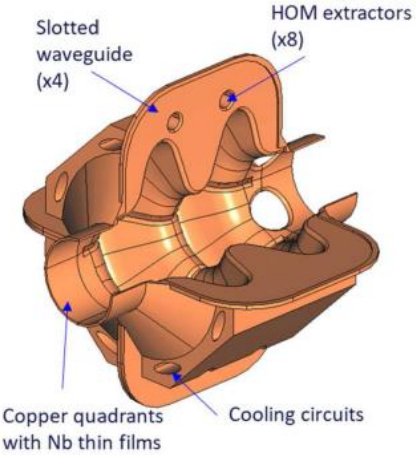


high efficiency klystrons
& scalable solid-state amplifiers

FPC & HOM coupler, cryomodule, thin-film coatings

efficient SC cavities

400 MHz 1- & 2-cell Nb/Cu, 4.5 K



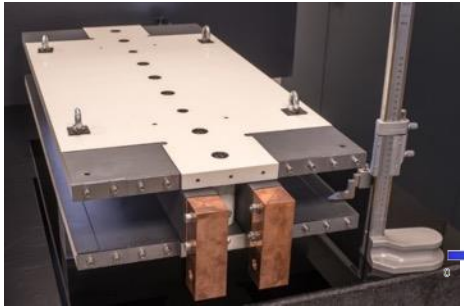
Slotted Waveguide Elliptical cavity (SWELL) for high beam current & for high gradient, seamless by nature – links to past work at ANL (Liu & Nassiri, PRAB 13, 012001)

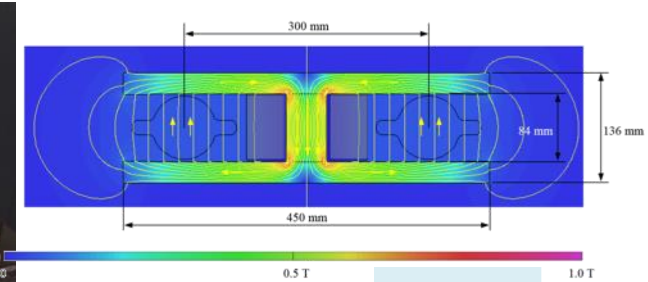
I. Syratchev

under study: **CCT HTS quad's & sext's for arcs**

reduce energy consumption by O(50 MW)

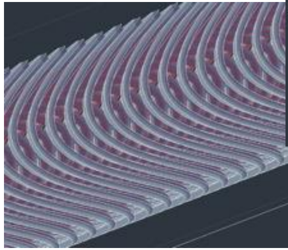
energy **efficient** twin aperture **arc dipoles**

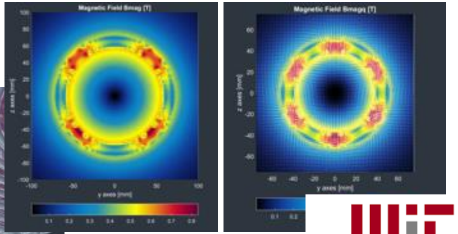




A. Milanese

PAUL SCHERRER INSTITUT PSI

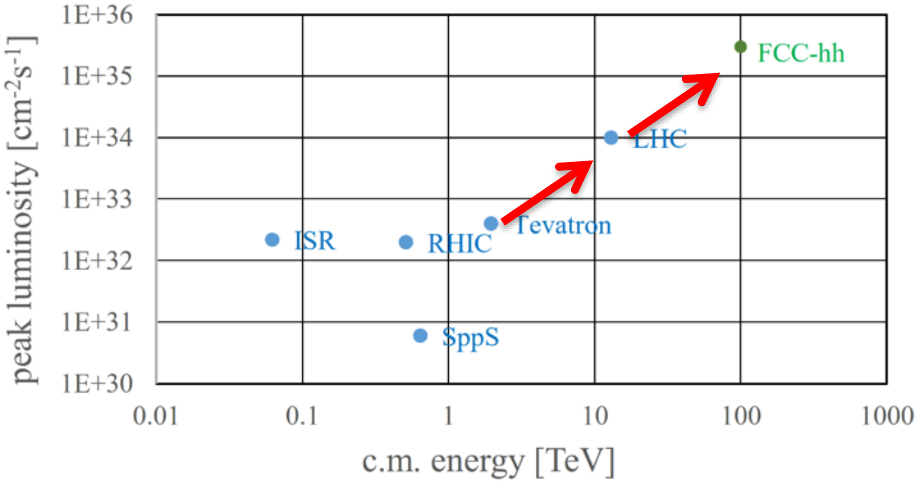




M. Koratzinos, B. Auchmann

Massachusetts Institute of Technology

Stage 2: FCC-hh: highest collision energies



~order of magnitude performance increase in both energy & luminosity wrt LHC

~100 TeV cm collision energy
(vs 14 TeV for LHC)

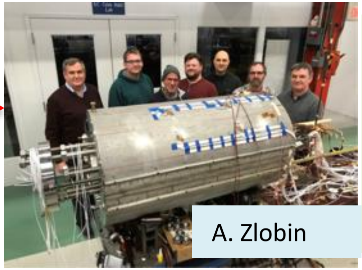
20 ab^{-1} per experiment over 25 years
of operation (vs 3 ab^{-1} for LHC)

similar performance increase as from Tevatron to LHC

key technology: high-field magnets

from
LHC technology
8.3 T NbTi dipole

via
HL-LHC technology
12 T Nb_3Sn quadrupole



A. Zlobin

FNAL dipole demonstrator
4-layer cosϑ
14.5 T Nb_3Sn
in 2019

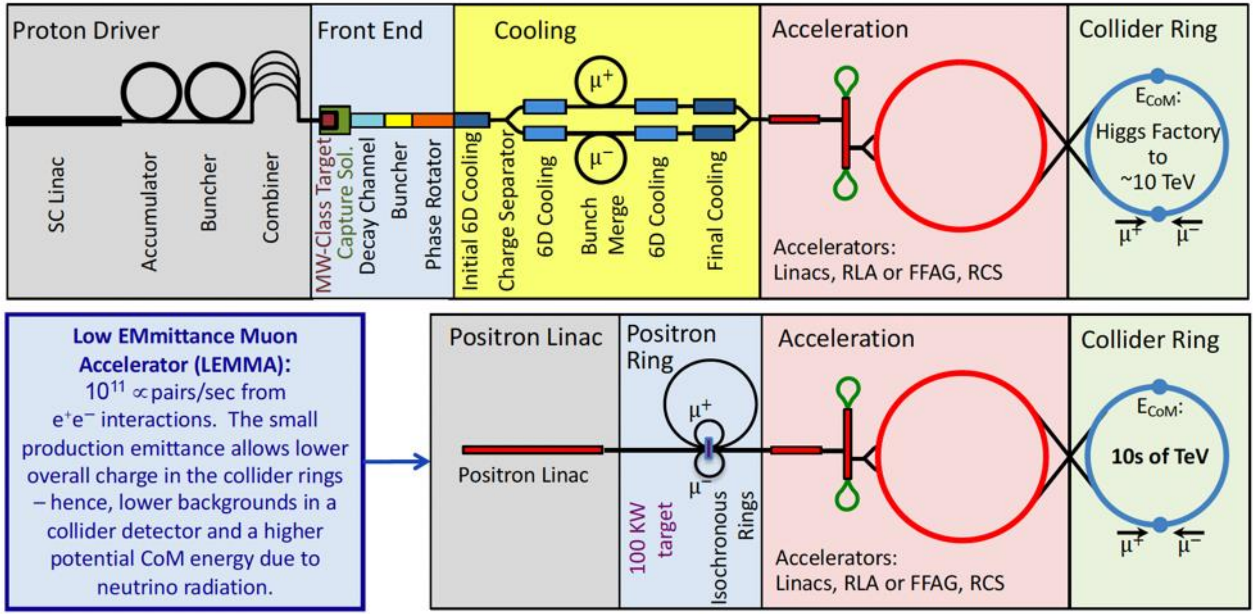
HTS technology

Hybrid
Nb-Ti/HTS

Muon Collider Concept

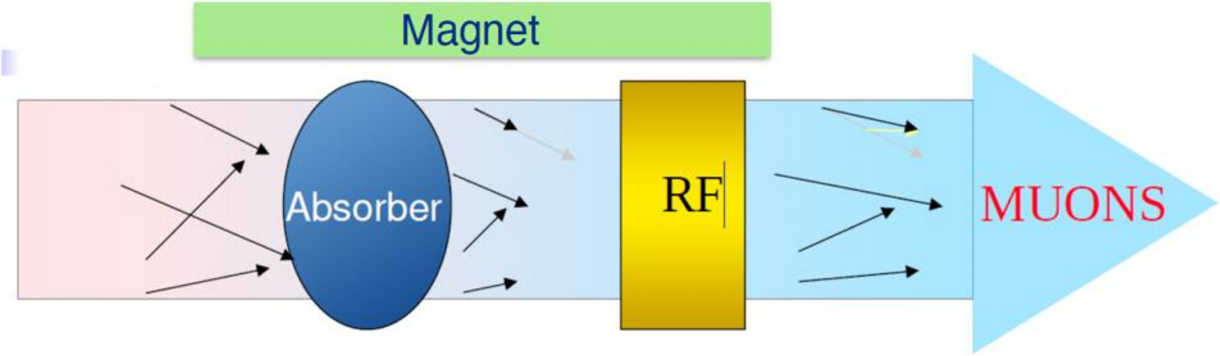
- Leading concept for Muon Collider is a proton driven target for muon production followed by 6D cooling to reduce the beam emittance
- Alternative concept – positron driven muon production

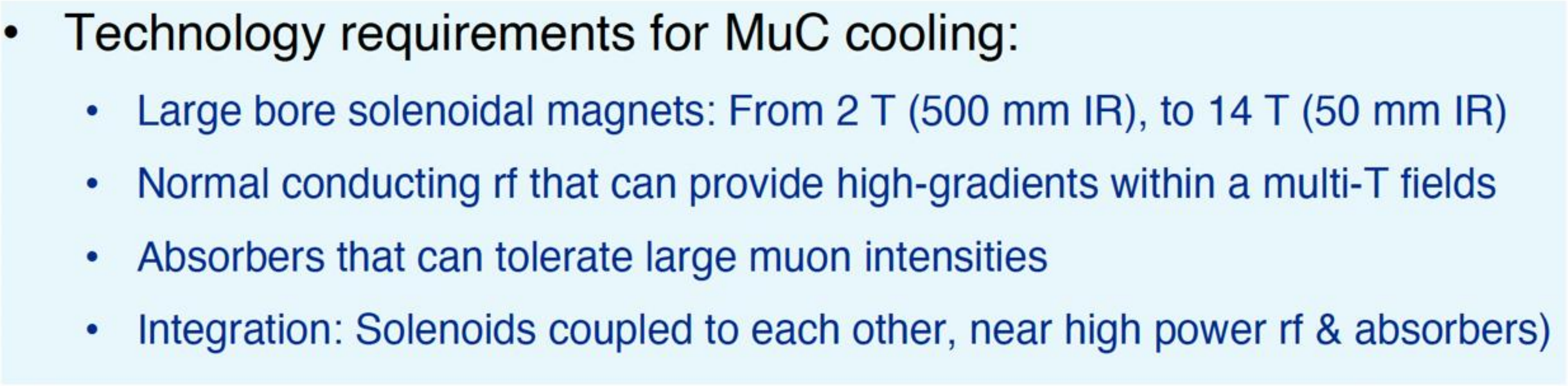
- Challenges:
  - Muon cooling for proton driven source
  - High flux positron source


ArXiv: 1808.01858

Low EMmittance Muon Accelerator (LEMMA):
$10^{11} \propto$ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.

Muon Cooling



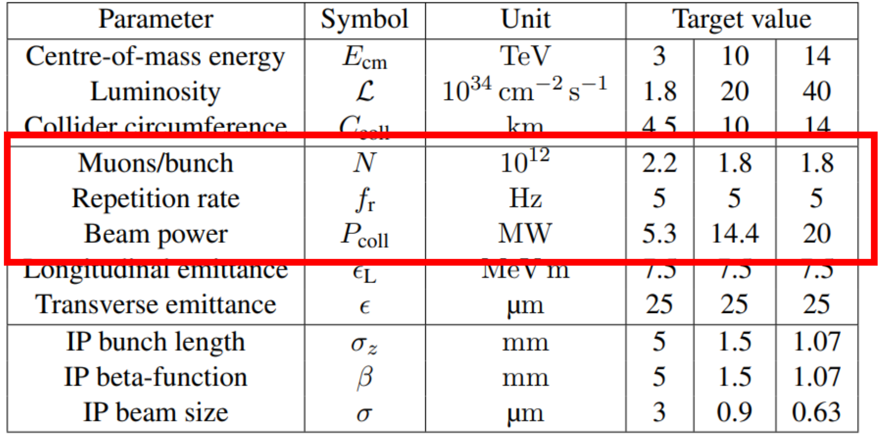


- Technology requirements for MuC cooling:
    - Large bore solenoidal magnets: From 2 T (500 mm IR), to 14 T (50 mm IR)
    - Normal conducting rf that can provide high-gradients within a multi-T fields
    - Absorbers that can tolerate large muon intensities
    - Integration: Solenoids coupled to each other, near high power rf & absorbers)

Target Parameters for Muon Collider from Snowmass 2021

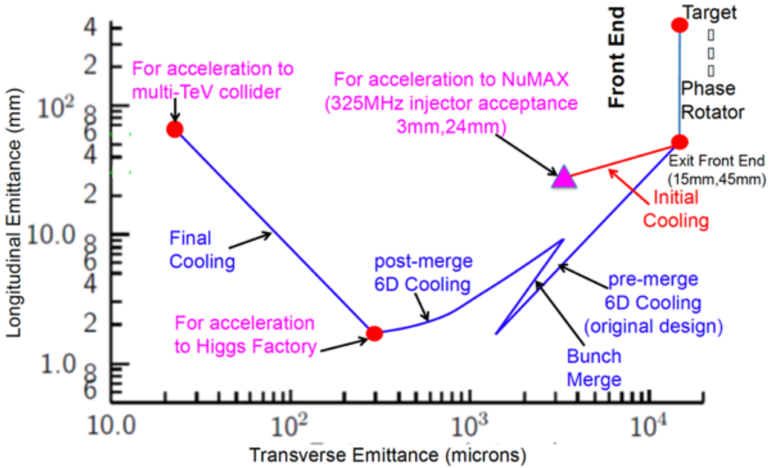
Accelerator R&D areas:

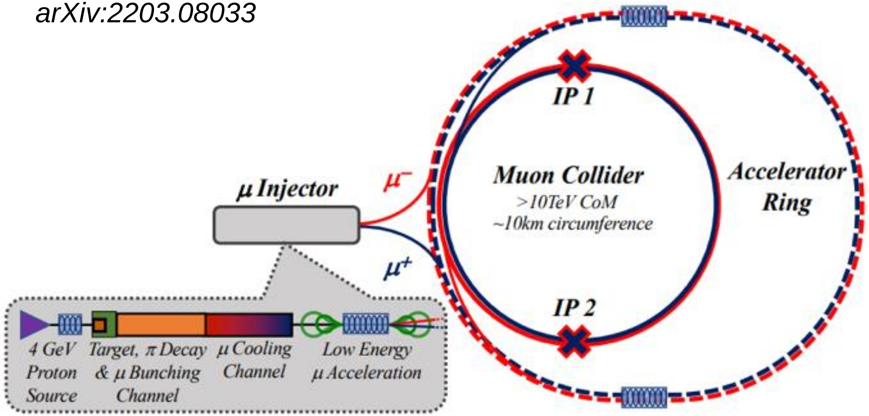
- High power proton driver
- Short lifetime of muons in injector (~microsec)
- **Cooling to reduce emittance**
- **Injection and acceleration**
- Mitigating radiation



Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathcal{L}$	$10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1.8	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Muons/bunch	N	10^{12}	2.2	1.8	1.8
Repetition rate	f_{r}	Hz	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	20
Longitudinal emittance	ϵ_{L}	MeV m	7.5	7.5	7.5
Transverse emittance	ϵ	µm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.07
IP beta-function	β	mm	5	1.5	1.07
IP beam size	σ	µm	3	0.9	0.63

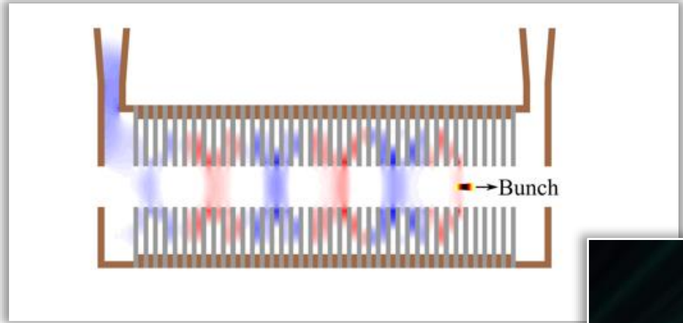
arXiv:2203.08033





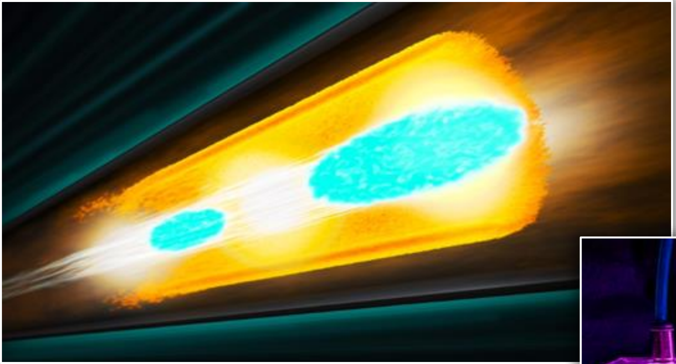
Wakefield Accelerator Technologies

Structure Wakefield Accelerators @

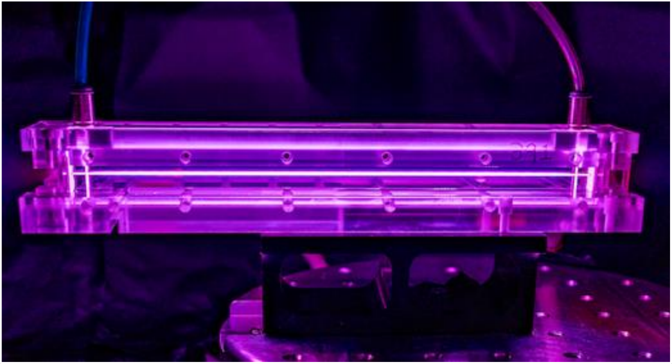


Argonne, SLAC, and LBNL are the stewards of SWFA, PWFA, and LWFA technology in the US, with university participation.

Beam Driven Plasma @ SLAC



Laser Driven Plasma @ BERKELEY LAB



Key advantages:

Ultra-large gradients (1-100 GeV/m)
Ultra-short bunches (suppress beamstrahlung)

Conclusions

- Accelerators are powerful tools for scientific discovery
- A great variety of parameters are achievable – species, power, wavelength, repetition rate
- Technology is evolving rapidly to enable new capabilities
- Ultimately accelerator technology will set the limits of collider performance
- Exciting time with great options for the community

Questions?