Future Colliders: Accelerator

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8/22/2024

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- Exploring the Energy Frontier
- Major Systems and Components of Accelerator Facilities
  - Particle Sources
  - Energy Gain
  - Steering
- Future Colliders
  - Linear
  - Circular

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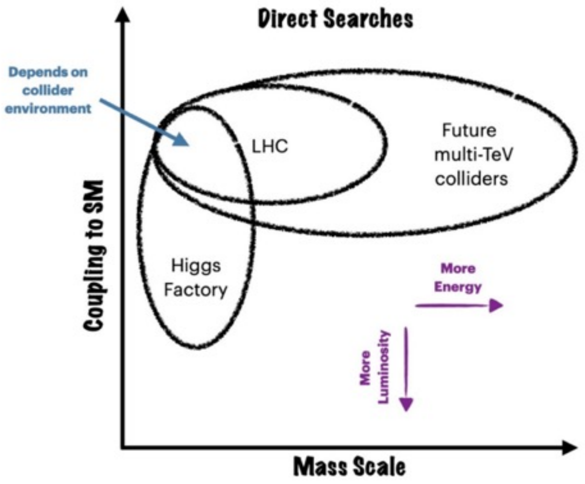
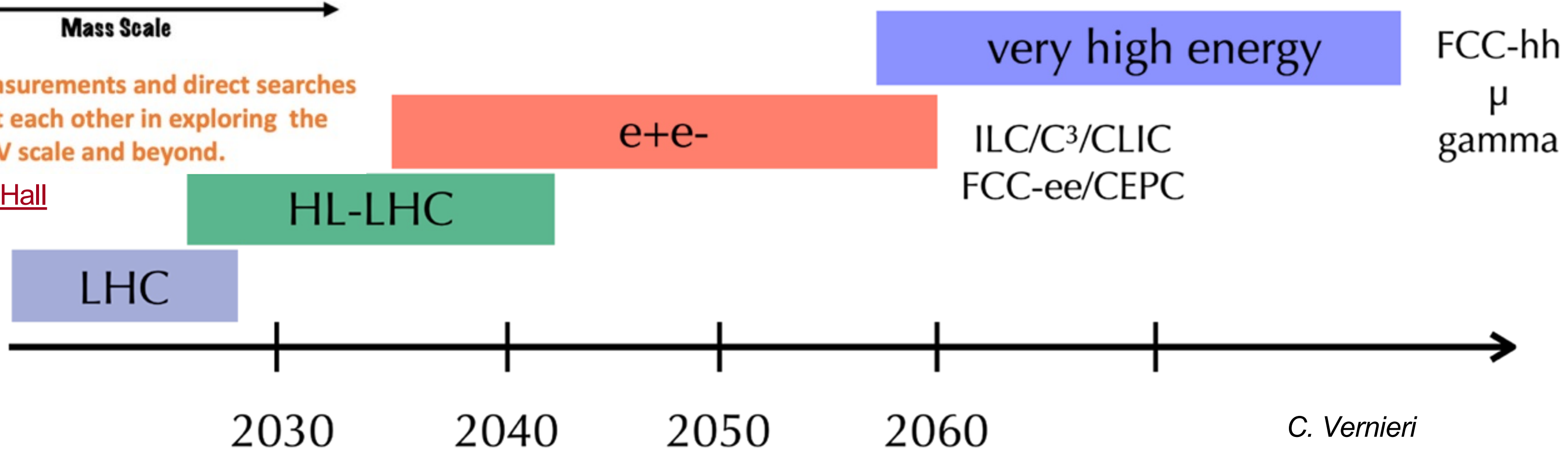
What's Next for the Energy Frontier?



- 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

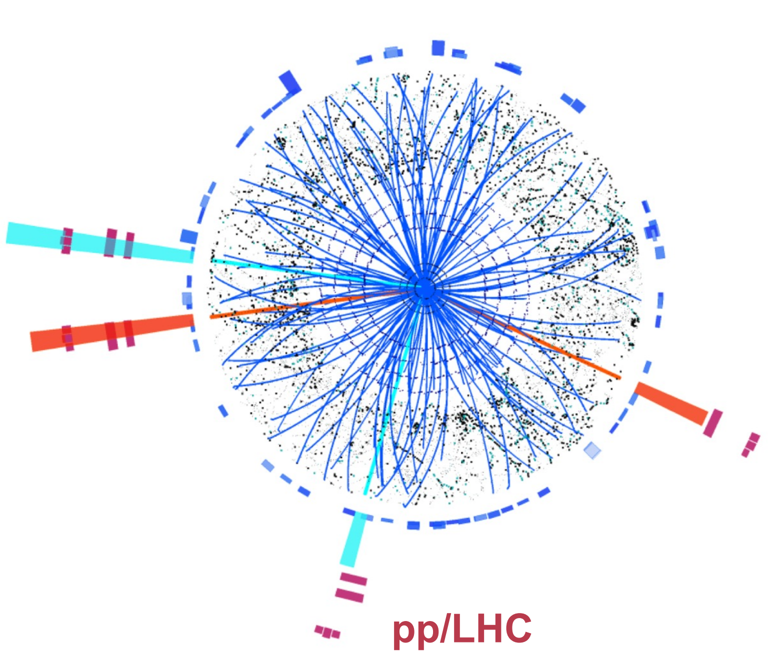


C. Vernieri

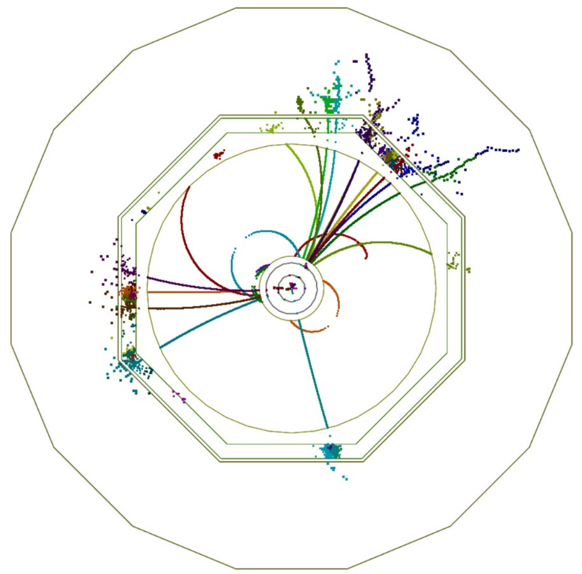
Why e^+e^-?

Initial state well defined & polarization $\Longrightarrow$ High-precision measurements

Higgs bosons appear in 1 in 100 events $\Longrightarrow$ Clean environment and trigger-less readout



pp/LHC



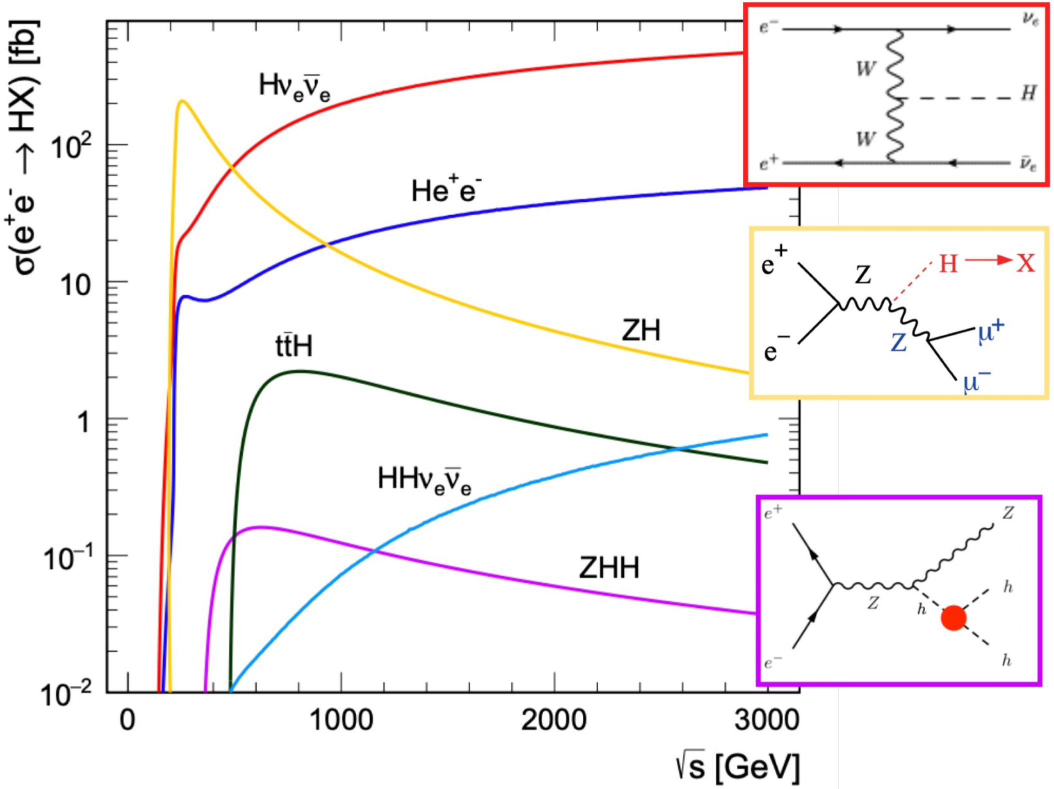
e^+e^-

Higgs Production at e^+e^-

ZH is dominant at **250 GeV**

Above **500 GeV**

- Hvv dominates
- ttH opens up
- HH production accessible with ZHH



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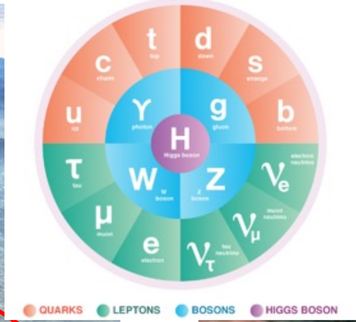
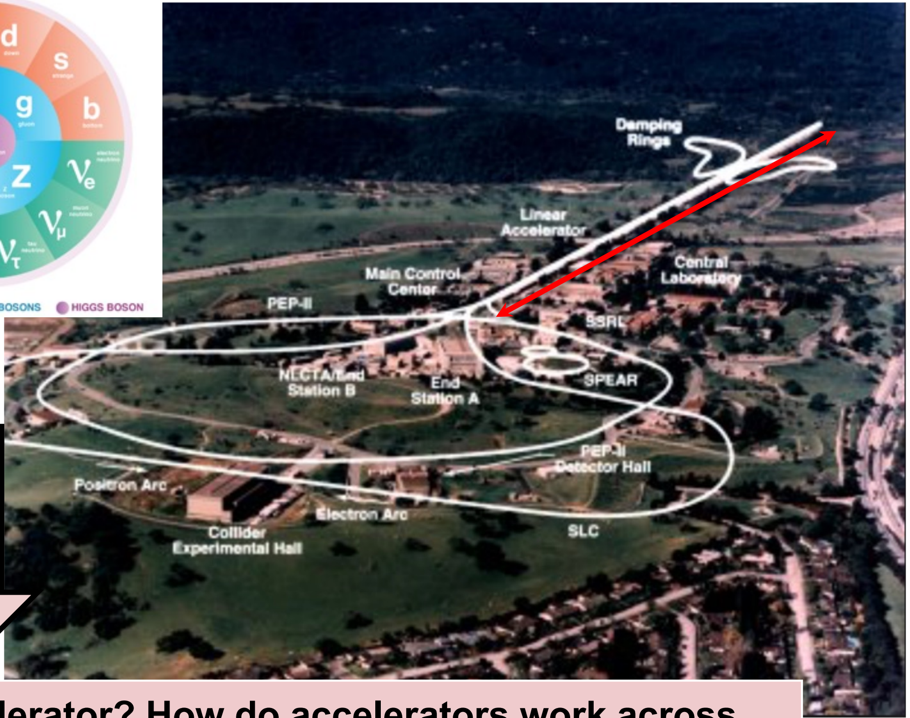
Accelerators Drive Discovery for High Energy Physics

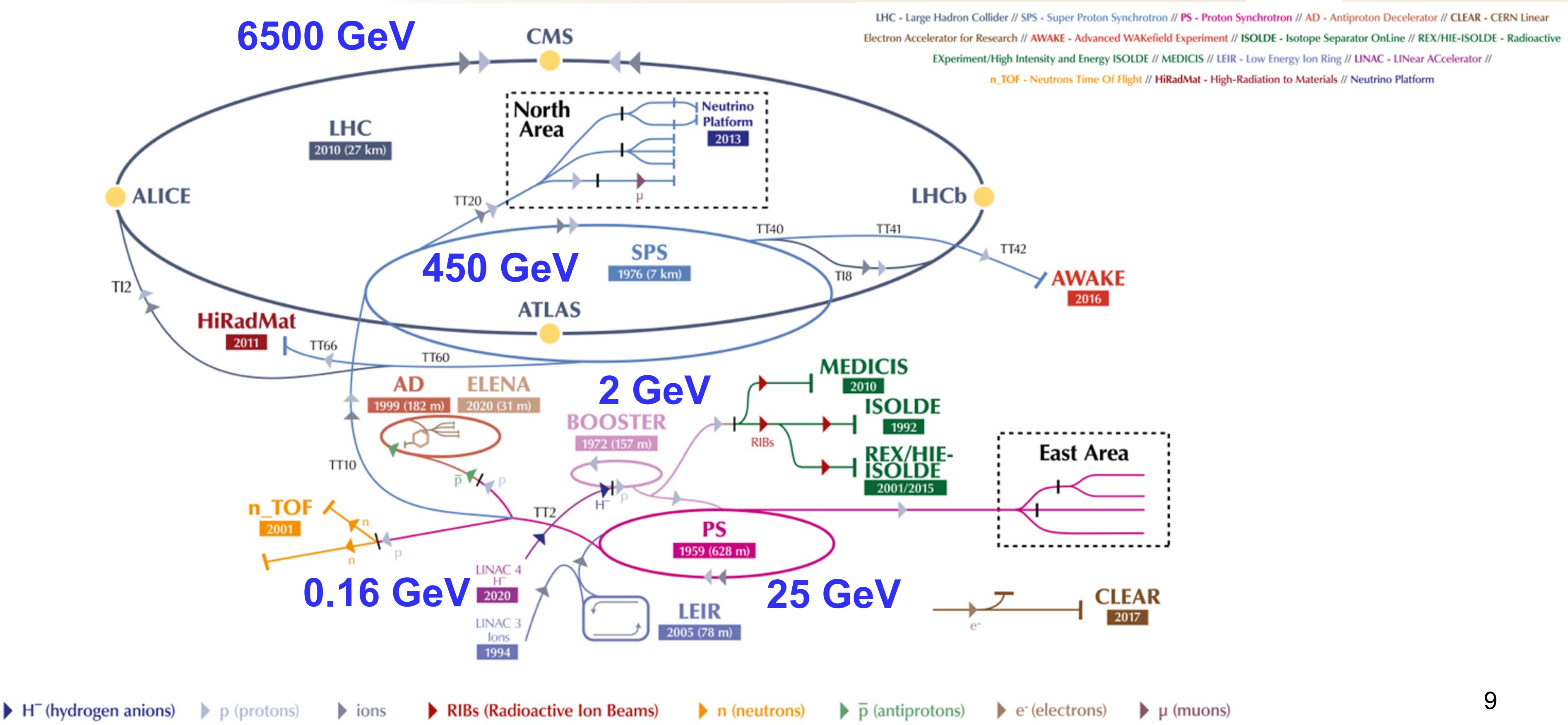
Experimental validation of the Standard Model of Particle Physics





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

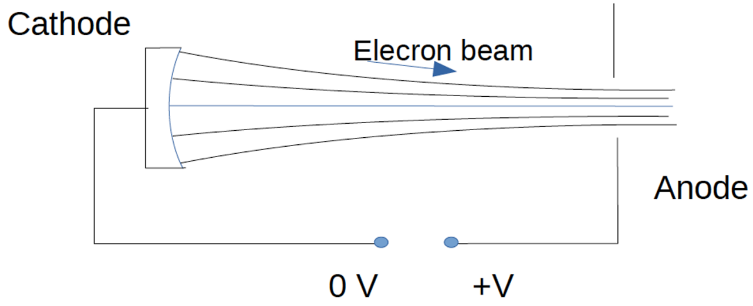
CERN Accelerator Complex



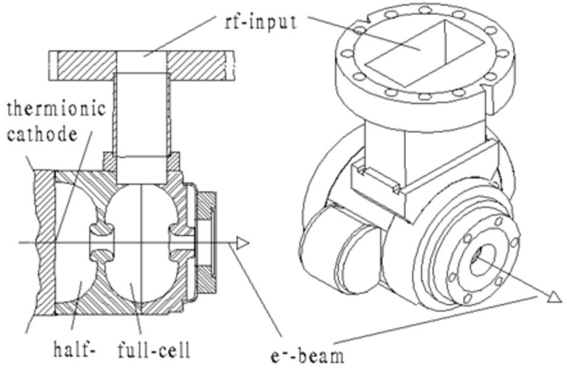
Particle (Electron) Sources

- Electrons emitted by providing enough free energy to overcome binding energy
- Thermionic, field and/or photo emission
- Need electric fields to accelerate particles away from the surface

DC Gun



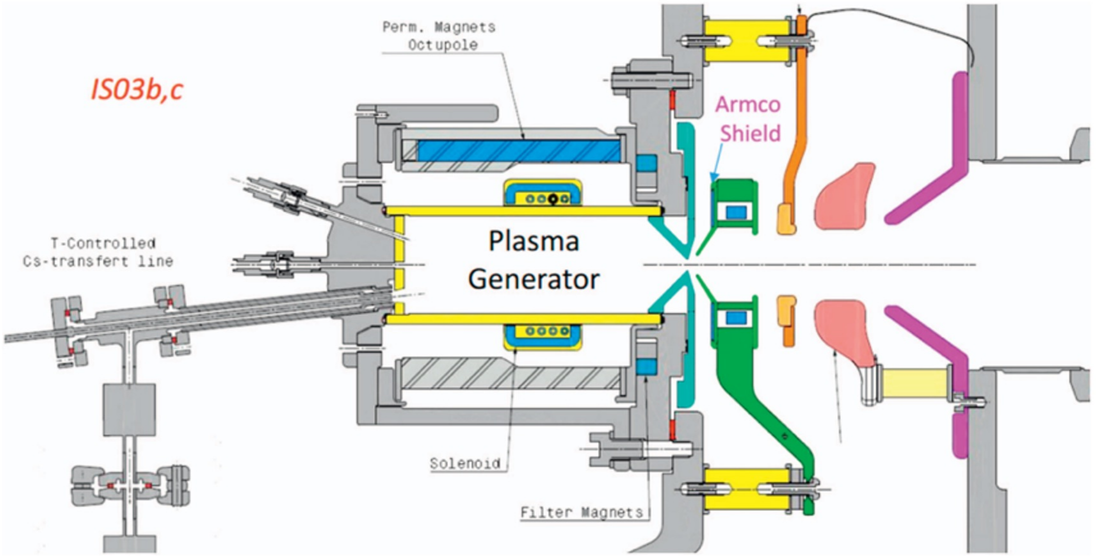
RF Gun



Particle (Ion) Sources

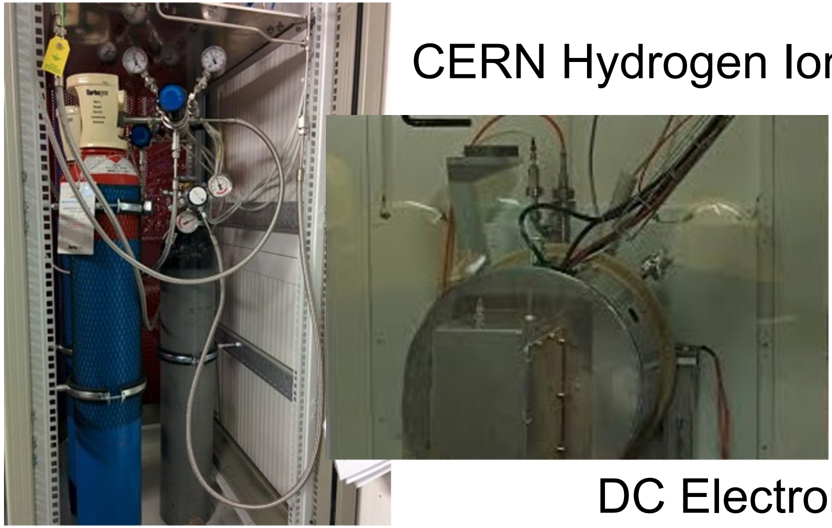
- Ionize gas and accelerate
- Set desired ionization by stripping or adding electrons
- Select ionization with magnets

Schematic of CERN's LINAC4 source



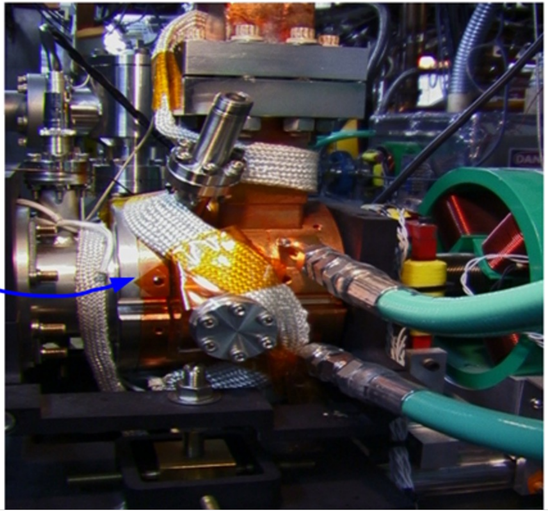
Real Particle Sources

CERN Hydrogen Ion Source



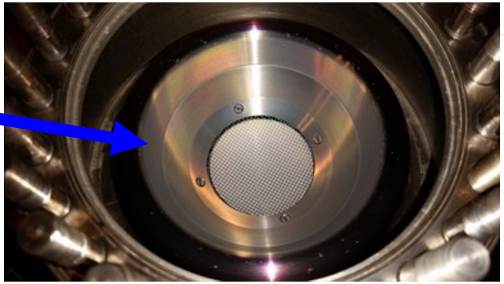
RF Electron Gun

cathode somewhere inside



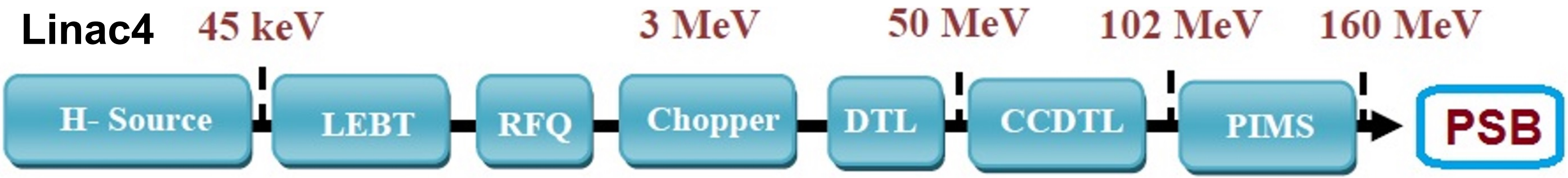
cooling hose that you see on most accelerator components

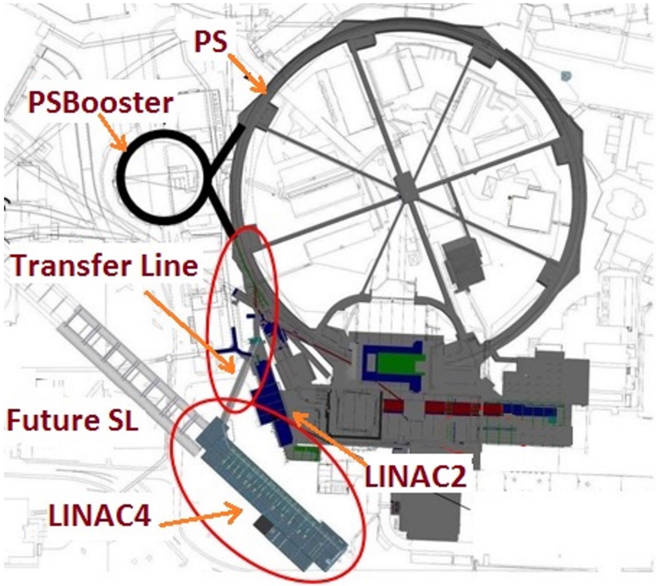
DC Electron Gun

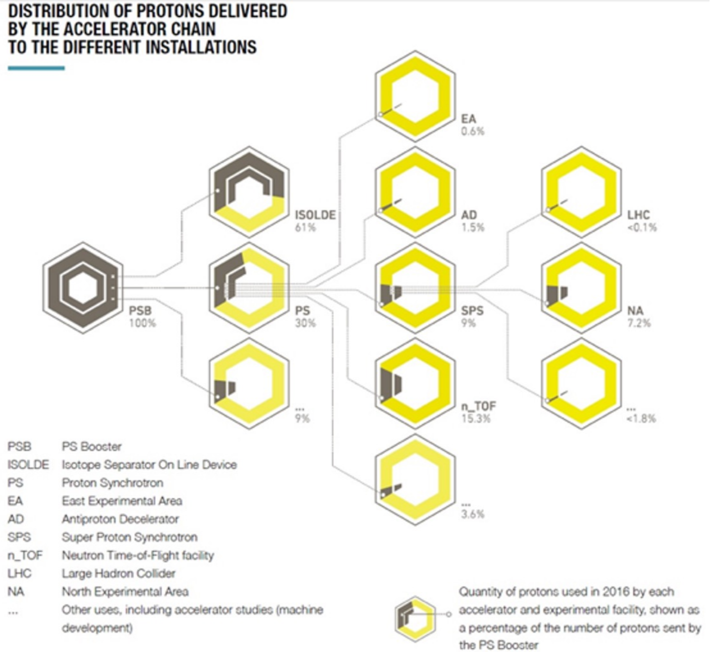


Emitter heated to 1000 ^{o}C

Particle Source for LHC

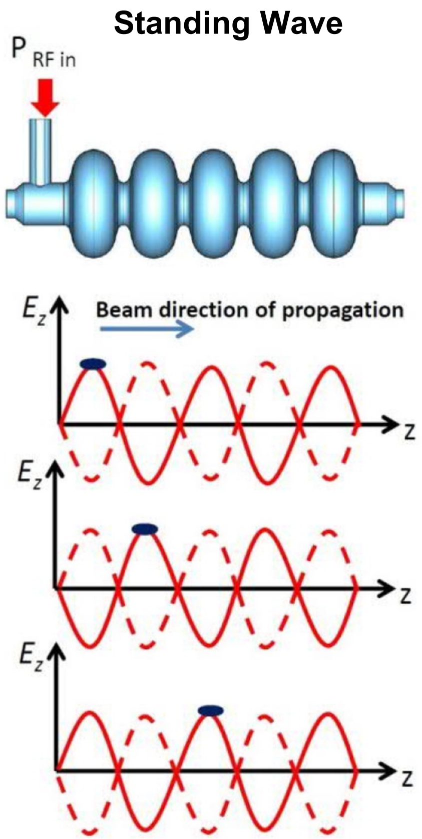


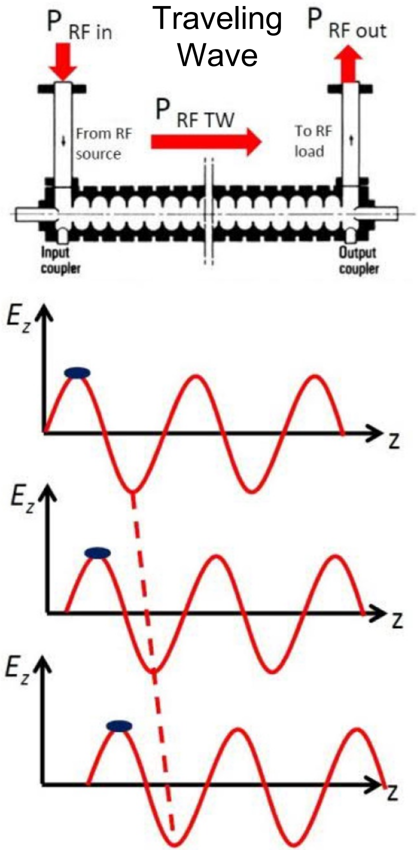




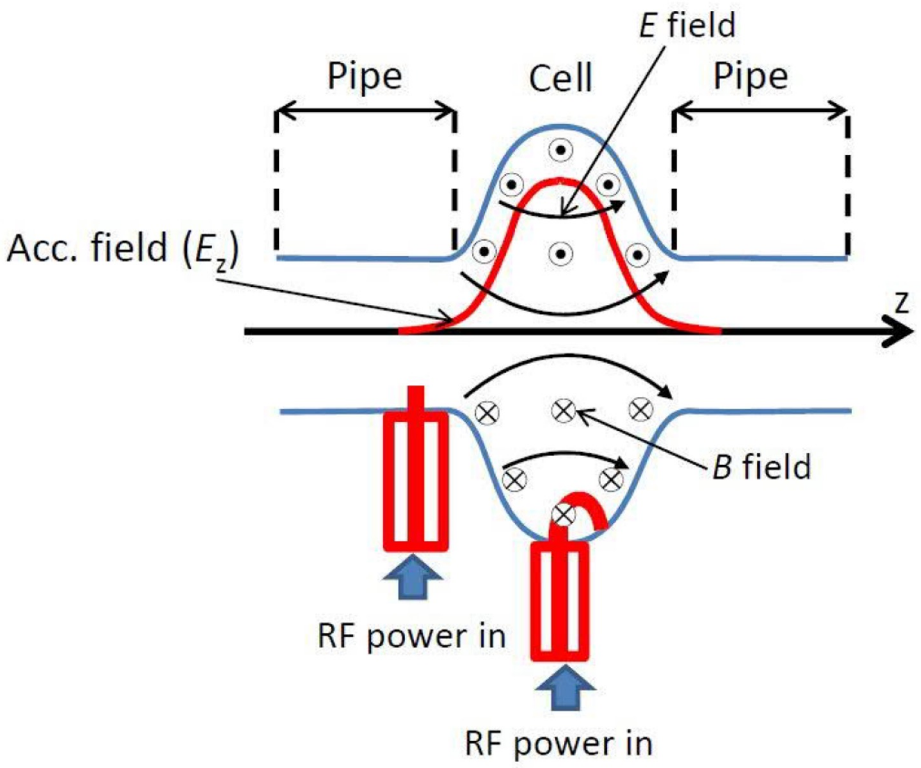
Electromagnetic Fields Used to Accelerate Particles

- Phase of electromagnetic wave needs to be controlled to match the particles velocity
- Standing Wave - fields in cavity alternate polarity in cavities and oscillate
- Traveling Wave – fields propagate with a phase velocity that matches particle velocity





Axial Electric Field Increases Kinetic Energy

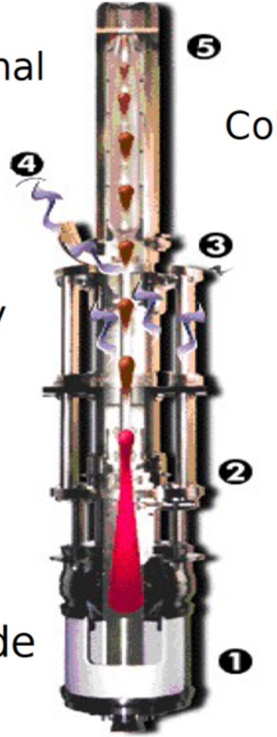


$$E_z(z,t) = E_{RF}(z)\cos\Big(\underbrace{2\pi f_{RF}}_{\omega_{RF}} t + \varphi\Big) = \mathrm{Real}\left[\tilde{E}_z(z)e^{j\omega_{RF}t}\right]$$

$$V_{acc} = \left| \int_{cavity} \tilde{E}_z(z) e^{j\omega_{RF}\frac{z}{v}} dz \right|$$

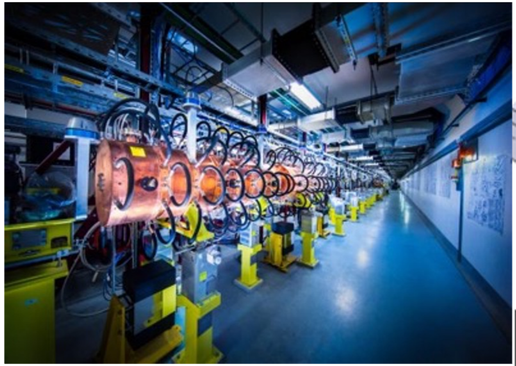
RF Sources Power the Accelerator

RF Source (Klystron)

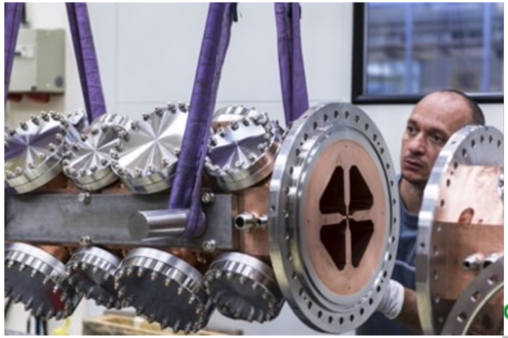


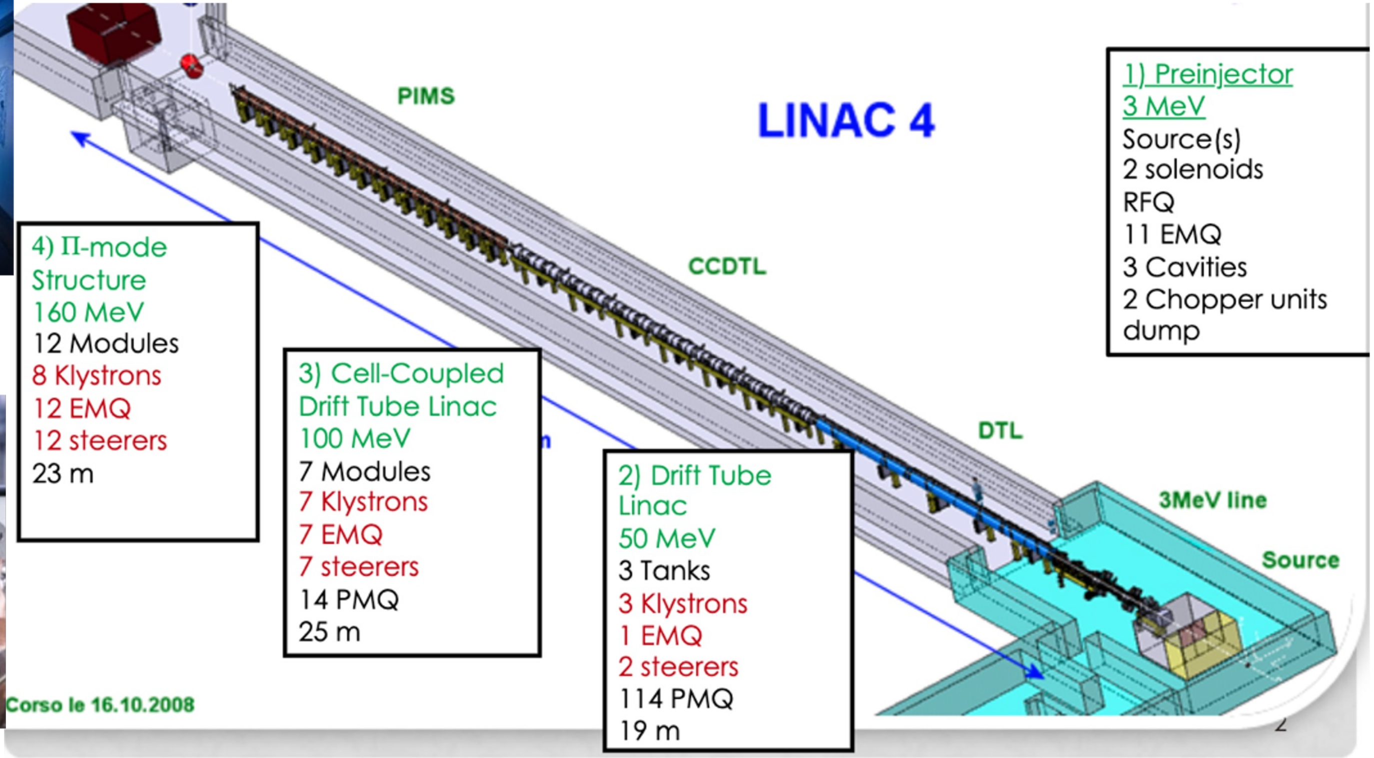
400 MHz, 500 kW LHC Klystron

The Proton Source: Linear Accelerator 4 (Linac4)



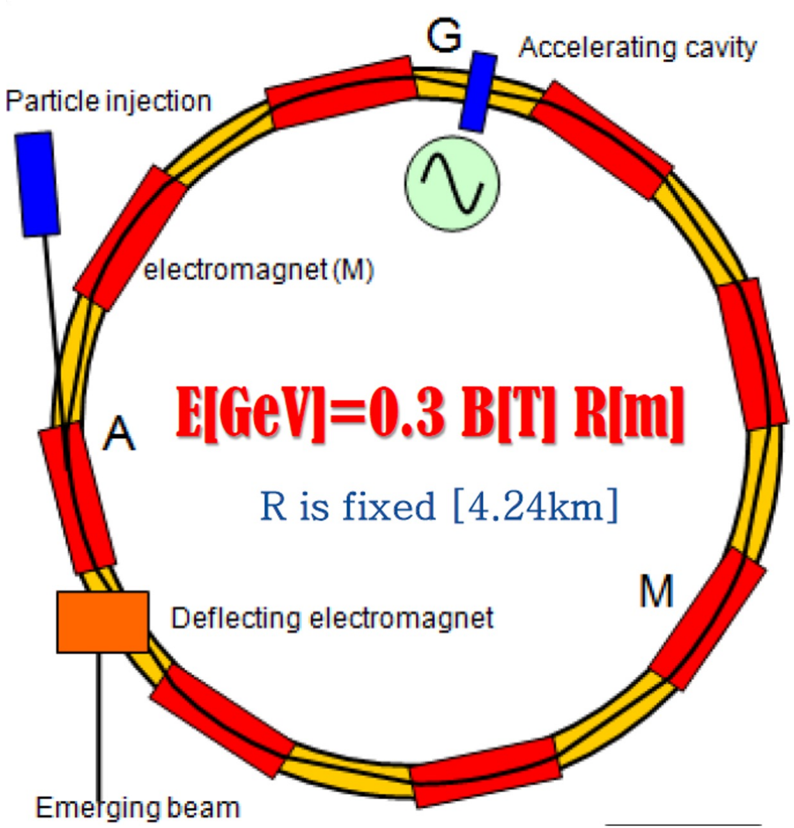
Linac4 Radio Frequency Quadrupole





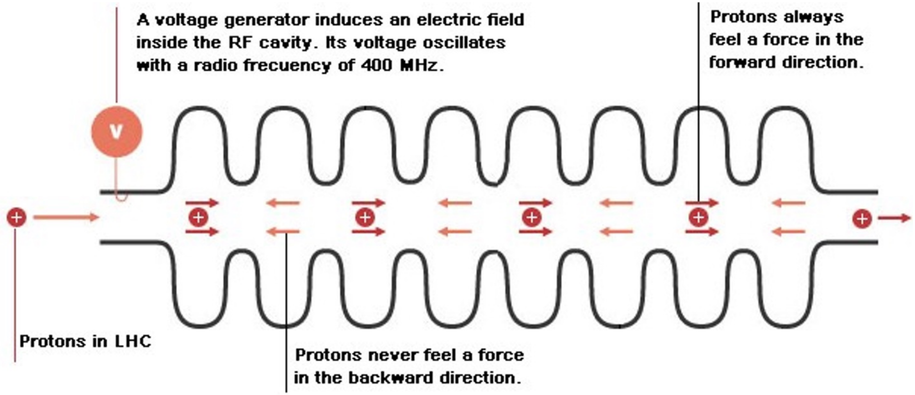
LHC Synchrotron

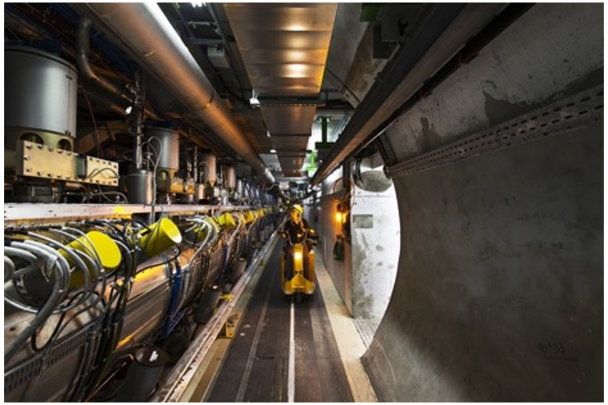
- Synchrotron recirculates a beam providing additional energy with each pass
- The magnetic field is increased with increasing beam energy



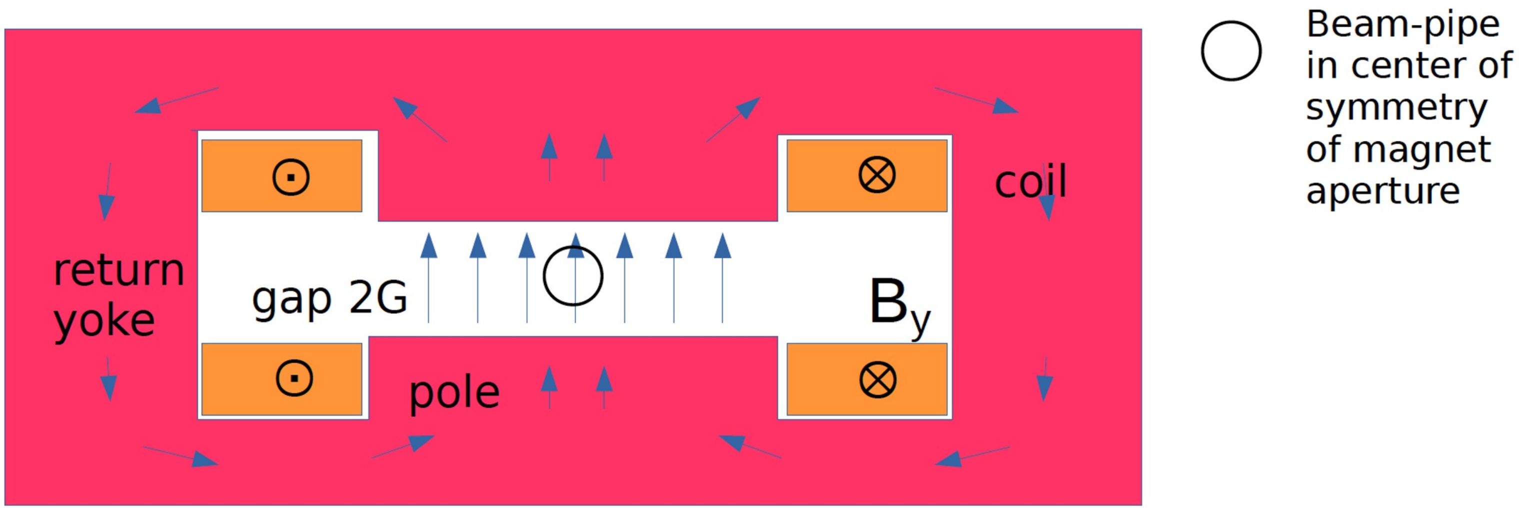
LHC Cryomodule

The LHC uses eight cavities per beam, each delivering 2 MV (an accelerating field of 5 MV/m) at 400 MHz. The cavities operate at 4.5 K — the LHC magnets use superfluid helium at 1.9 K.





Magnets Guide and Transport the Beam

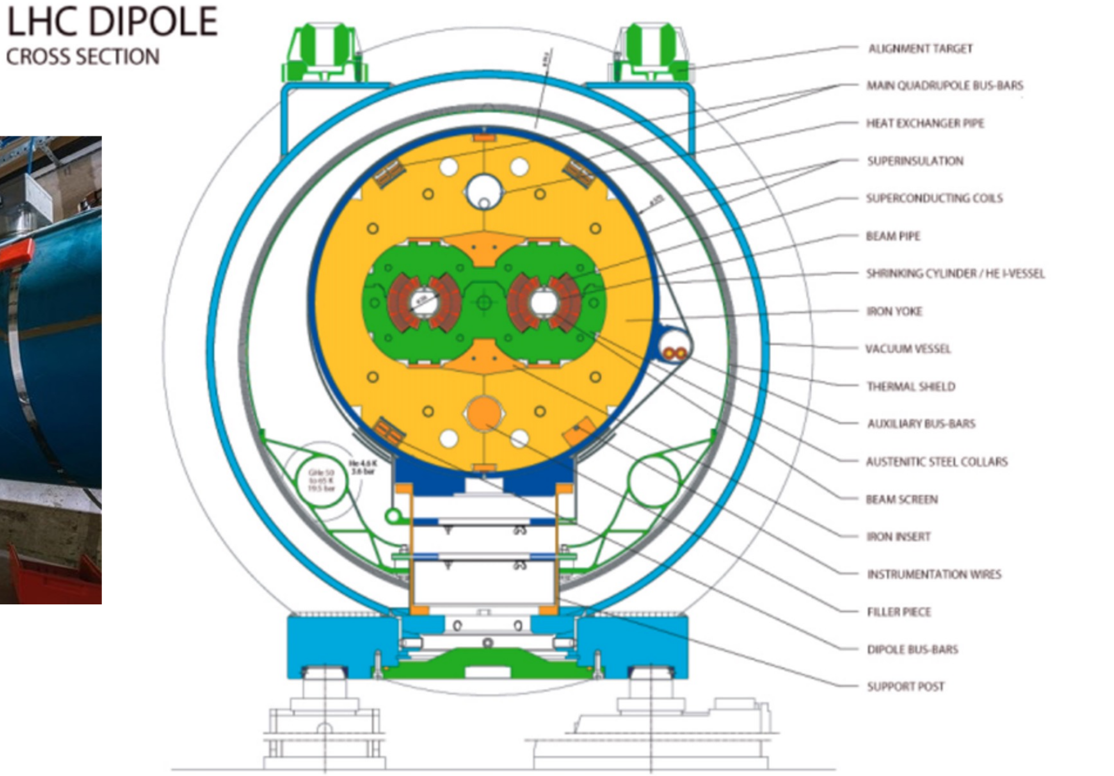


$$B_y[T] = \frac{0.4\,\pi}{10^4} \frac{I[A-turn]}{G[cm]}$$

$$\frac{1}{\rho[m]} = 0.3\,\frac{B_y[T]}{\beta E[GeV]}$$

LHC Superconducting Magnets

LHC Dipole in Tunnel

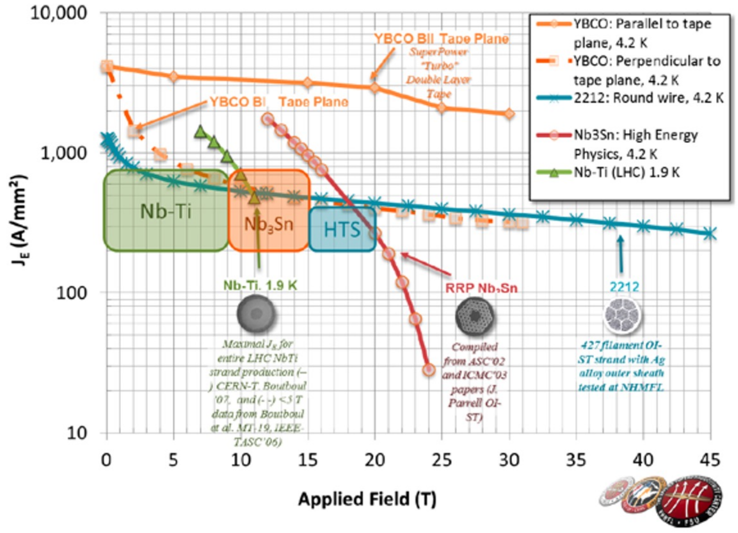


8.3 T

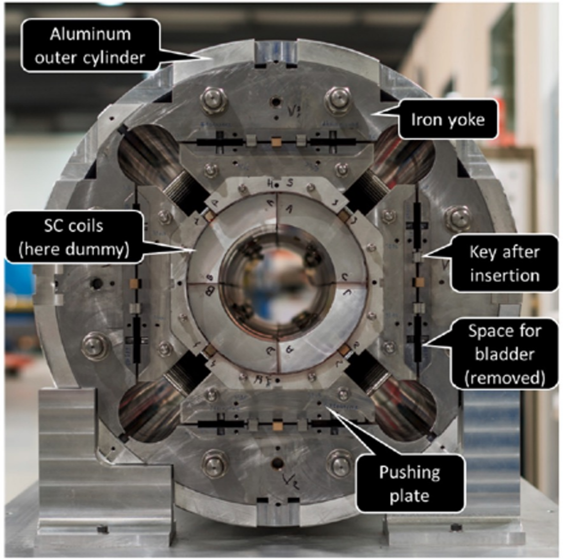
Path Forward for Superconducting Magnets

- Magnet performance will determine energy reach of future colliders
- FCC-hh baseline at 16 T
- HL-LHC will also benefit from higher fields

Superconducting Wire Performance



HL-LHC Nb3Sn IT Quad



Existing quads
- 70 mm aperture
- 200 T/m gradient

Proposed for upgrade
- At least 120 mm aperture (now 150 mm)
- 200 T/m gradient
- Field 70% higher at pole face

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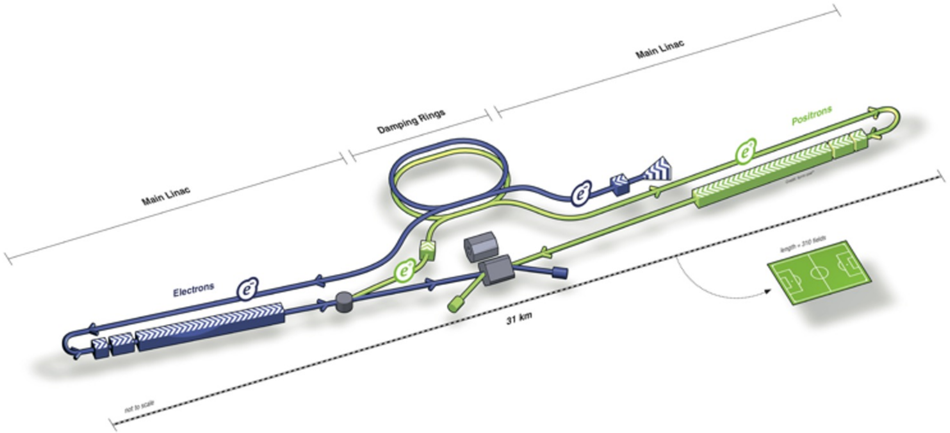
Linear vs. Circular

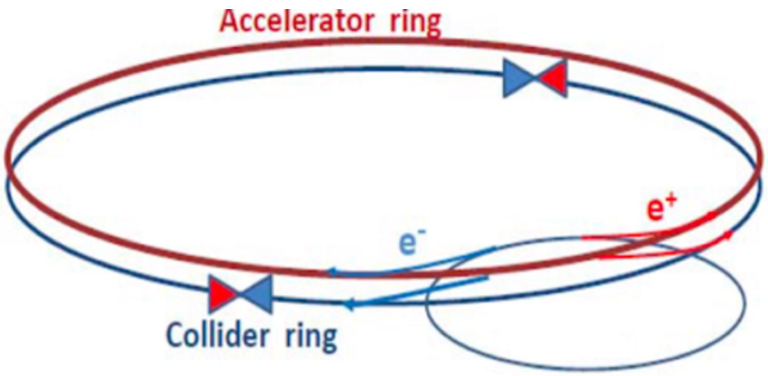
Linear e^+e^- colliders: ILC, C^3, CLIC

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



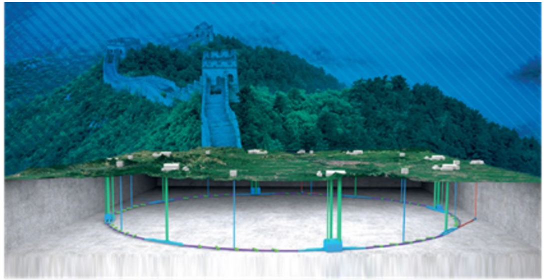
Circular e^+e^- colliders: FCC-ee, CEPC

- Highest luminosity collider at Z/WW/ZH
- limited by synchrotron radiation above 350 – 400 GeV ($\sim \gamma^4 / \rho^2$)
- Beam continues to circulate after collision



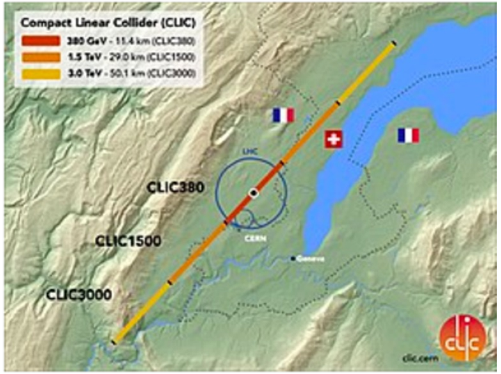
Higgs Factory Proposals

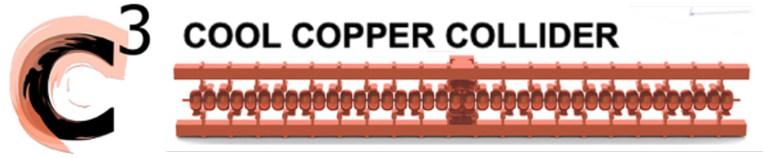
ILC
250/500 GeV



CEPC
240 GeV

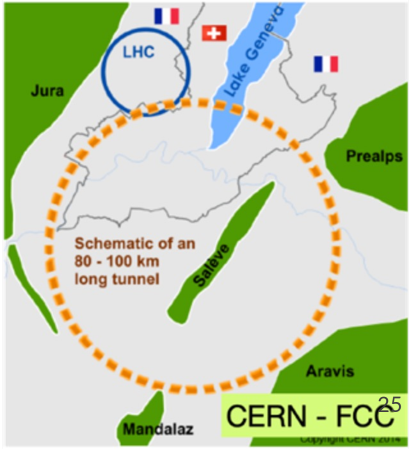
CLIC 380/1000/3000 GeV





250/550 GeV
… > TeV

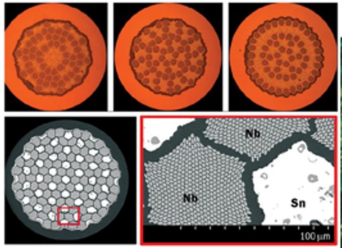
FCC-ee
240/365 GeV

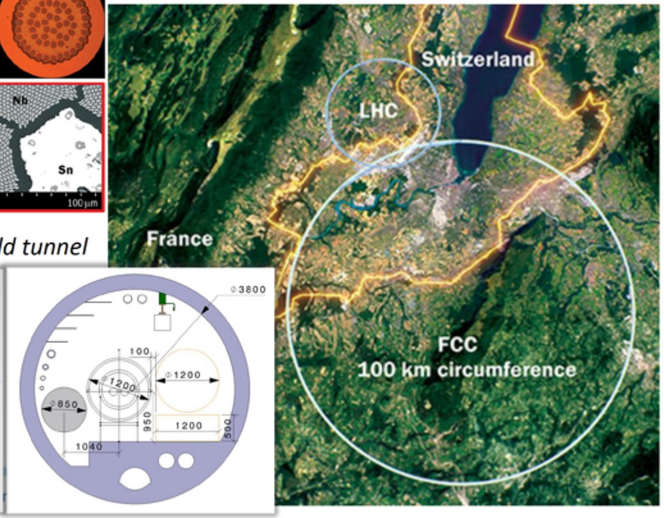


Future *Muon, Wakefield and hh* Colliders

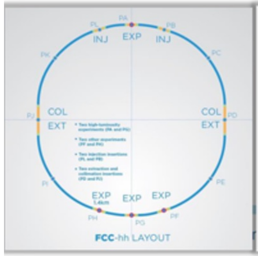
New magnet technology Nb_3Sn – **16 T** (vs 8 T in the LHC with NbTi)

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





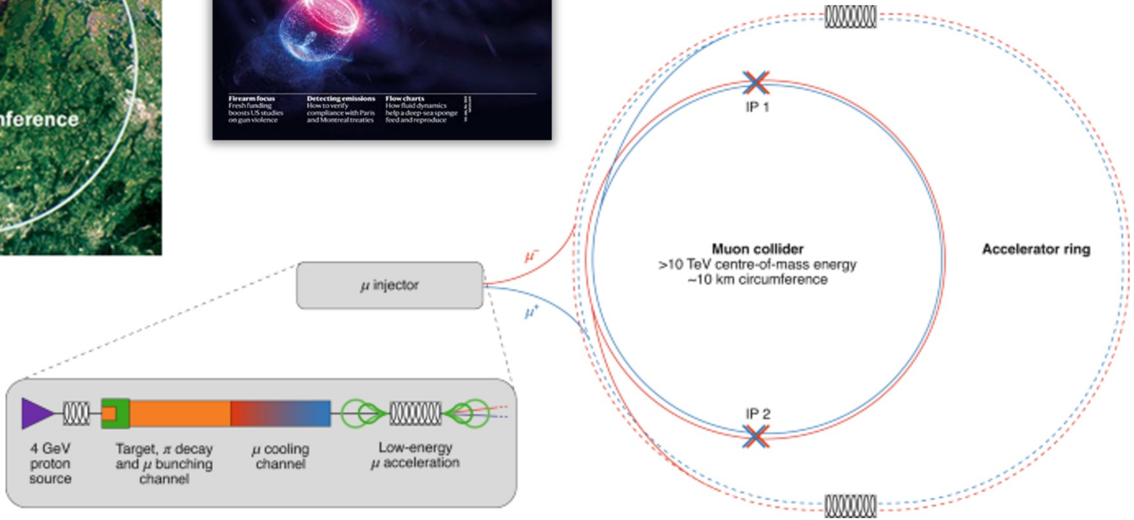
...either in a new or old tunnel



FCC-hh

Wakefield

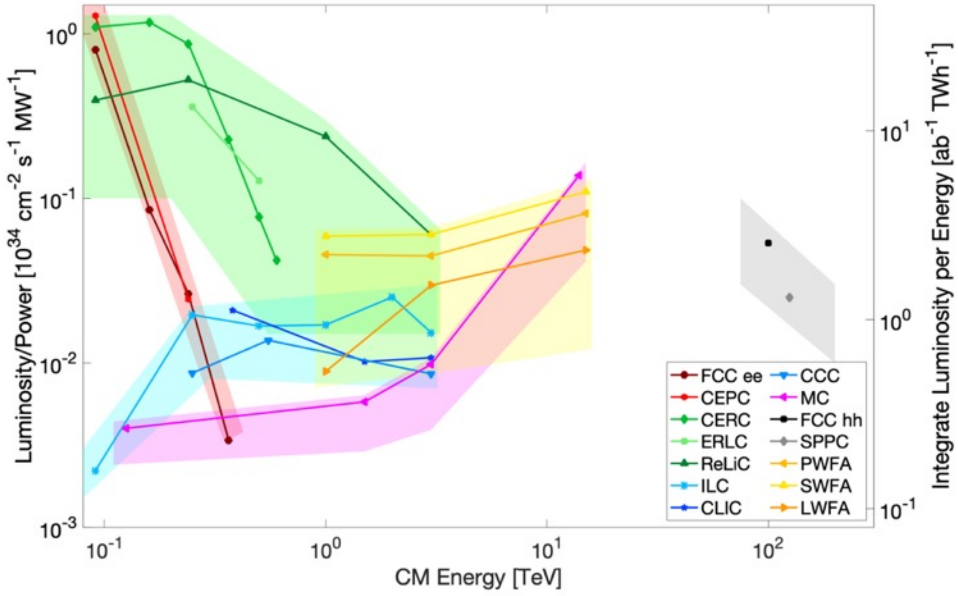
Muon Collider



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

Pushing the Limits of the Energy Frontier

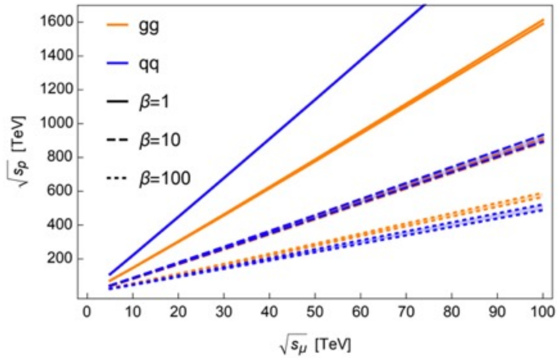
Sustainability Plays an Increasingly Critical Role as CoM Approaches and Exceeds 10 TeV

- Heavy species needed to extend the efficiency of circular colliders to high energy
- Muons provide an alternative to hadrons and perform significantly better than electrons for synchrotron radiation
  - ~106 MeV muon mass
  - Synchrotron Radiation $\propto \frac{E^4}{\rho^2 m^4}$
  - Exceptional efficiency at ~10 TeV
  - Compelling physics reach
  - Clean(ish) environment

Can ask what collider energy yield same total σ when using "Parton Luminosity"

e.g. this case $2 \to 2$ process w/ $\beta \equiv \hat{\sigma}_p / \hat{\sigma}_\mu$

Meade, P5 Town Hall



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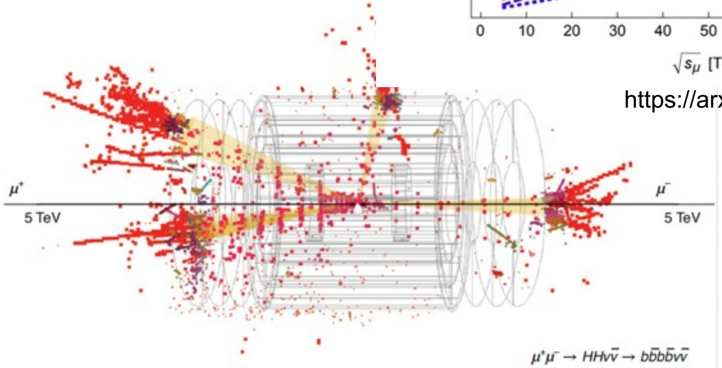

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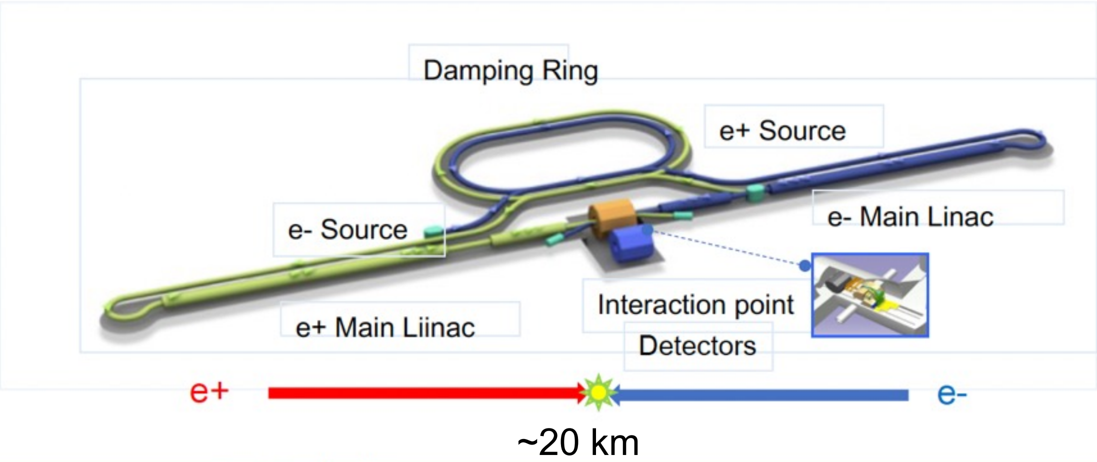
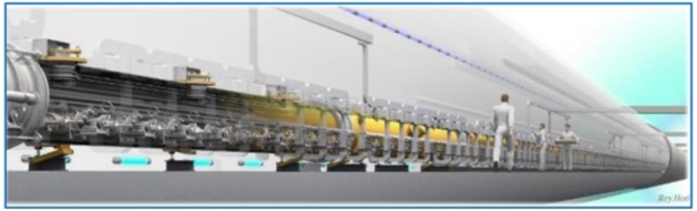
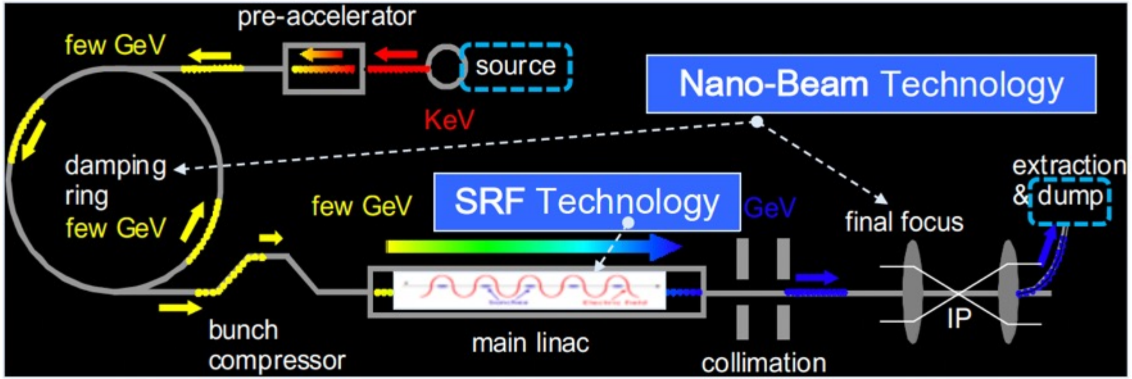
ILC and the Accelerator Technology





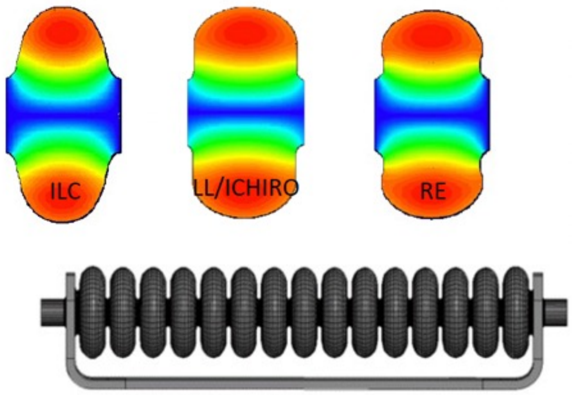


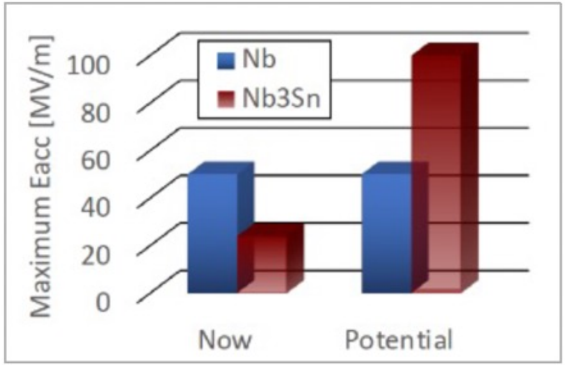
Parameters	Value
Beam Energy	125 + 125 GeV
Luminosity	1.35 / 2.7 x 10^{10} cm^2/s
Beam rep. rate	5 Hz
Pulse duration	0.73 / 0.961 ms
# bunch / pulse	1312 / 2625
Beam Current	5.8 / 8.8 mA
Beam size (y) at FF	7.7 nm
SRF Field gradient	< 31.5 > MV/m (+/-20%) Q_0 = 1x10^{10}
#SRF 9-cell cavities (CM)	~ 8,000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

TDR was published in 2013.

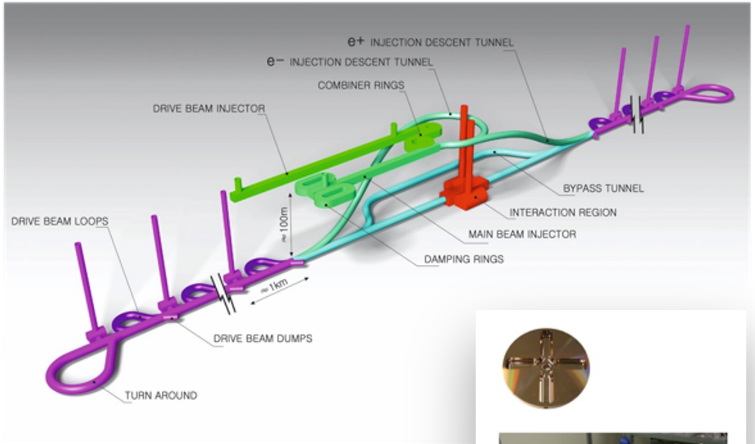
SRF technology for ILC-250 beyond present limits

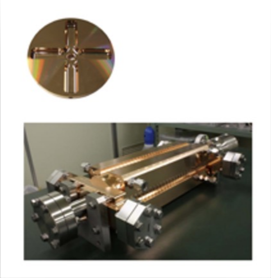
- Advanced shape standing wave SRF cavities – Low Loss (LL), ICHIRO,
- Reentrant (RE) – increase peak quench magnetic field by 10-20%, potentially bringing accelerating gradient limit to ≲ 60 MV/m
- Traveling wave (TW) SRF offers better cryogenic efficiency and higher accelerating gradient up to ~ 70 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)

- **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

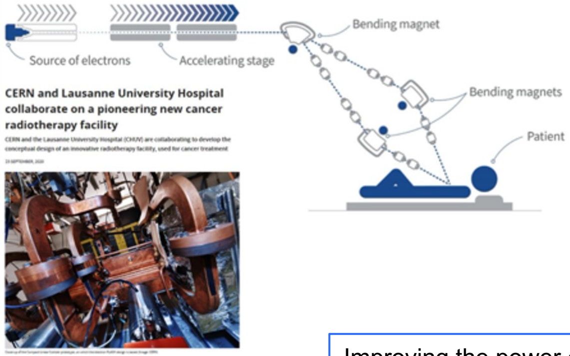
The CLIC accelerator studies are mature:

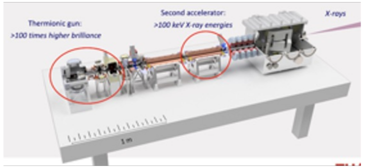
- Optimised design for cost and power
- Many tests in CTF3, FELs, light-sources and test-stands
- Technical developments of "all" key elements

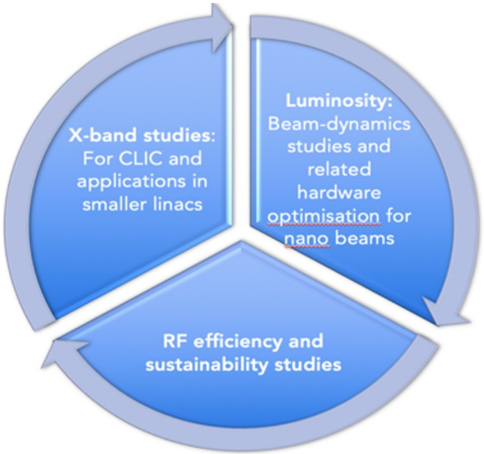
On-going CLIC studies towards next ESPP update

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







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

Luminosity margins and increases:

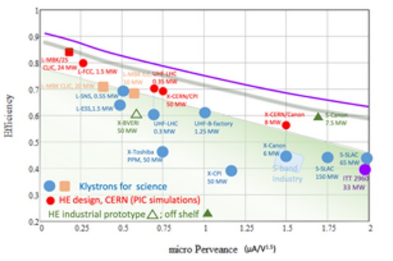
- Initial estimates of static and dynamic degradations from damping ring to IP gave: 1.5 x 10^{34} cm^{-2} s^{-1}
- Simulations taking into accord static and dynamic effects with corrective algorithms give 2.8 on average, and 90% of the machines above **2.3 x 10^{34} cm^{-2} s^{-1}** (this is the value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



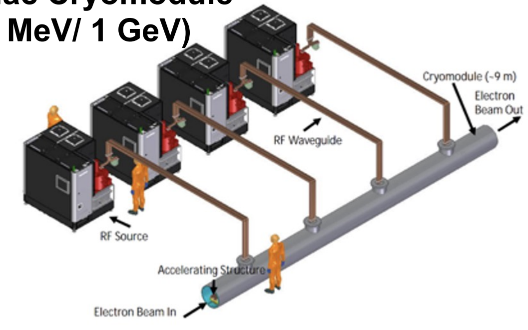
Accelerator Complex

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

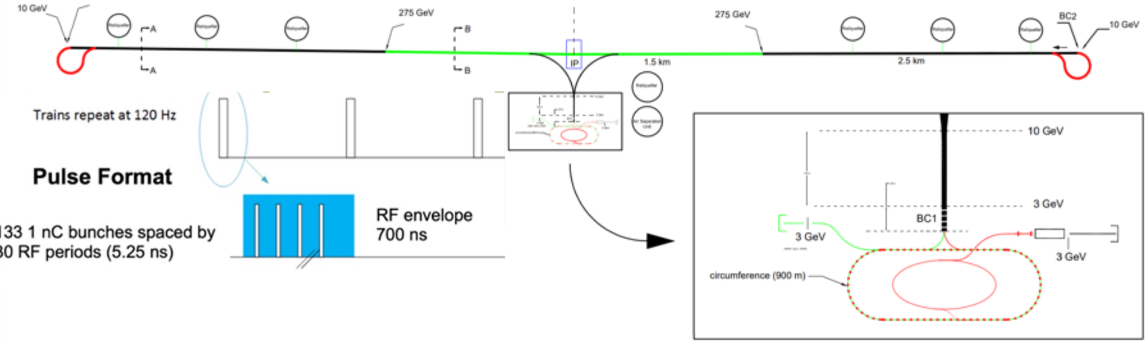
C^3 Main Linac Cryomodule
9 m (600 MeV/ 1 GeV)



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

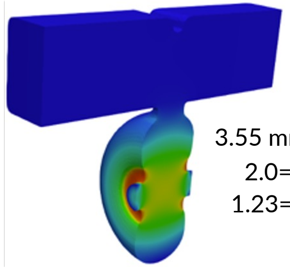
C^3 - 8 km Footprint for 250/550 GeV (to scale)



Alignment and Vibrations

System level optimization essential for achieving performance

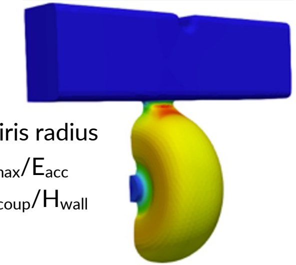
RF Structure Optimization



3.55 mm iris radius

$2.0 = E_{max}/E_{acc}$

$1.23 = H_{coup}/H_{wall}$

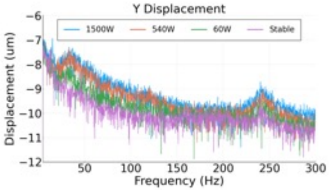


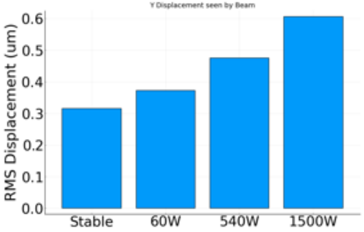
Electric Field

Magnetic Field

M. Shumail, Z. Li

Vibration Measurements and Analysis





RadiaBeam

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

Two-Phase Fluid Simulations

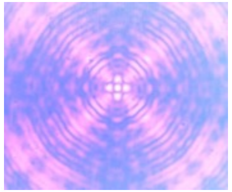
FAMU-FSU College of Engineering

K. Shoele

Precision Short and Long Range Alignment

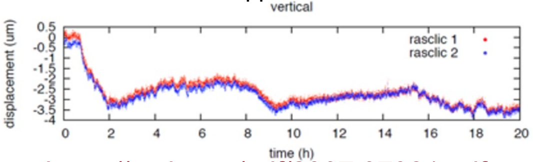
H. Van Der Graaf

Nikhef



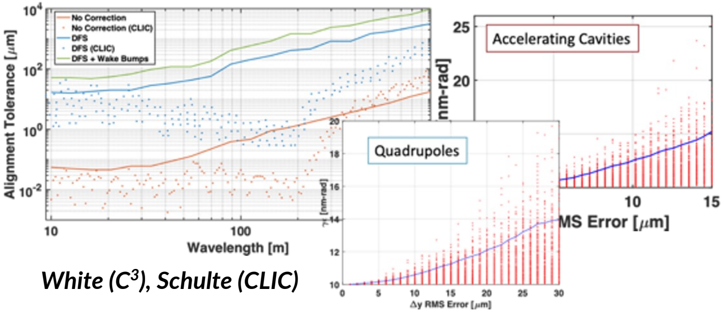
100 nm resolution

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

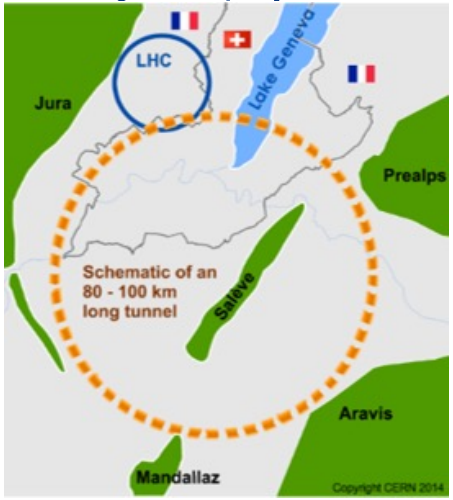
Outline

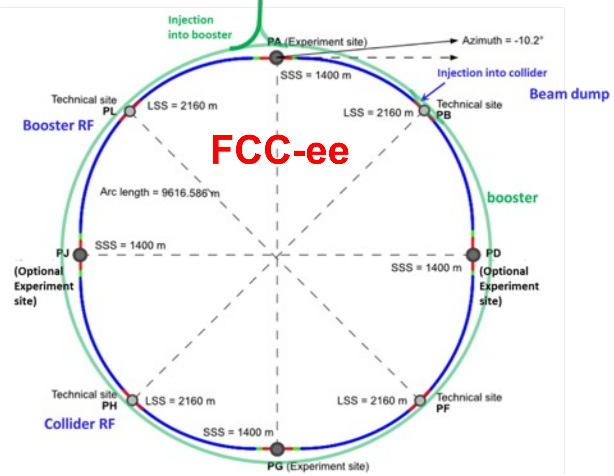
- Exploring the Energy Frontier
- Major Systems and Components of Accelerator Facilities
  - Particle Sources
  - Energy Gain
  - Steering
- Future Colliders
  - Linear
  - Circular

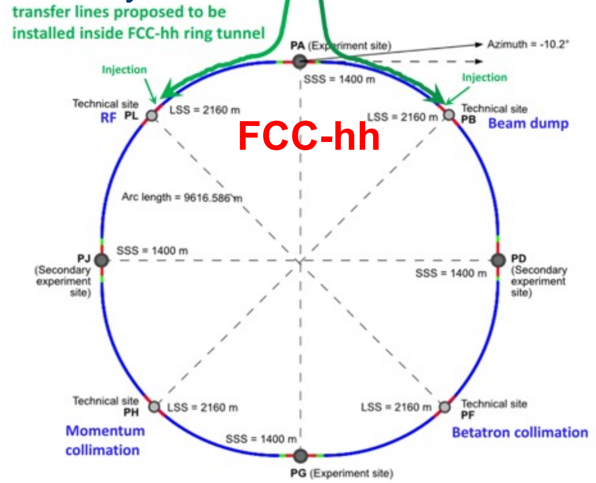
FCC integrated program

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







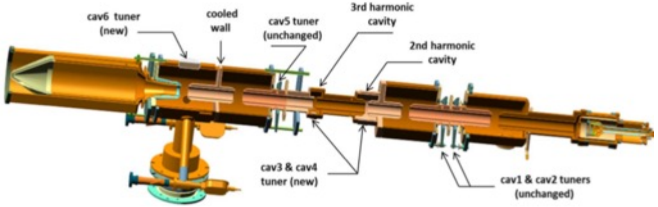
2020 - 2040 | 2045 - 2060 | 2070 - 2095

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

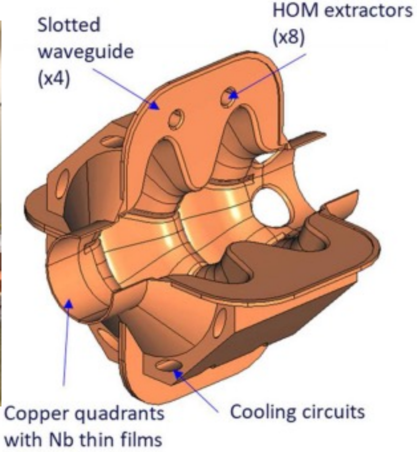


high efficiency klystrons
& scalable solid-state amplifiers

FPC & HOM coupler, cryomodule, thin-film coatings

efficient SC cavities

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



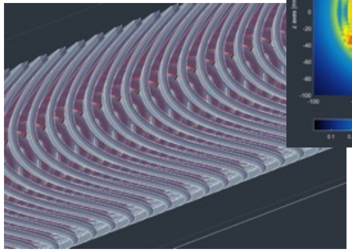
Slotted Waveguide Elliptical cavity (SWELL) for high beam current & for high gradient, seamless by nature – links to past work at ANL (Liu & Nassiri, PRAB 13, 012001)

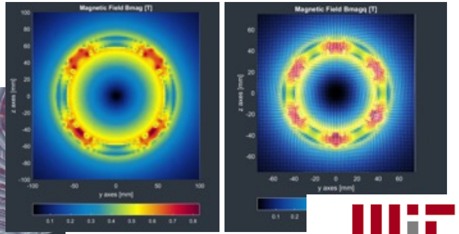
I. Syratchev

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

reduce energy consumption by O(50 MW)

PAUL SCHERRER INSTITUT PSI

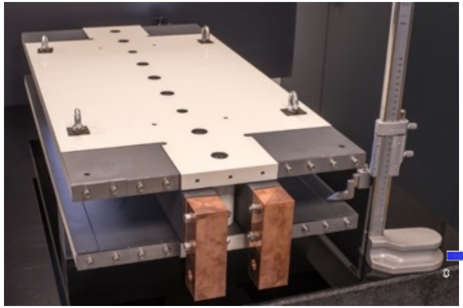


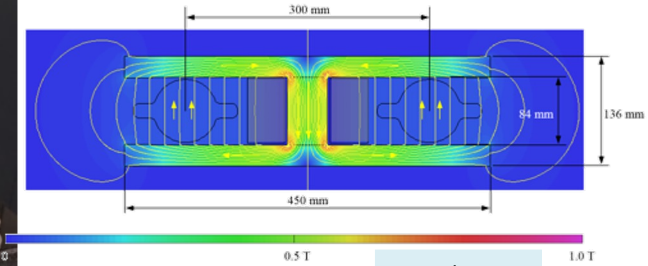


M. Koratzinos, B. Auchmann

Massachusetts Institute of Technology

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

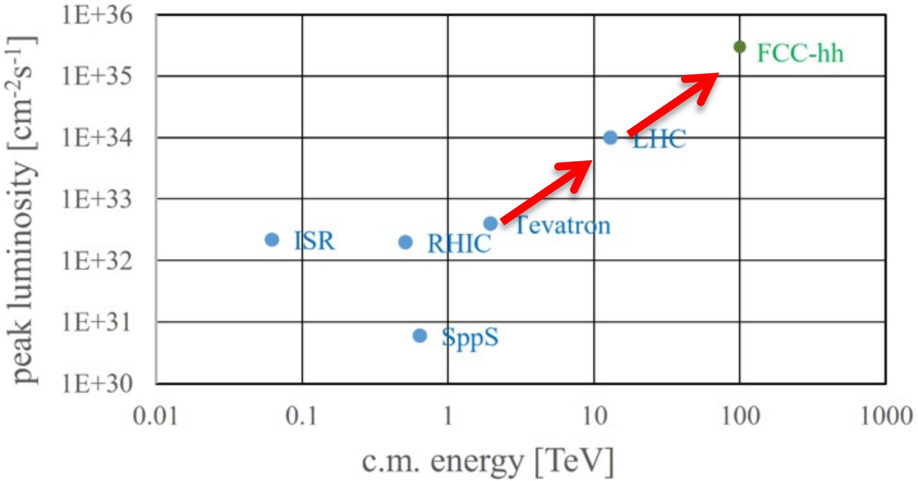




A. Milanese

FUTURE CIRCULAR COLLIDER

Stage 2: FCC-hh: highest collision energies



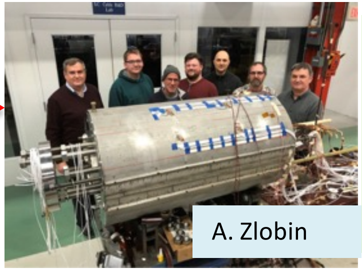
- ~order of magnitude performance increase in both energy & luminosity wrt LHC
- ~100 TeV cm collision energy (vs 14 TeV for LHC)
- 20 ab^{-1} per experiment over 25 years of operation (vs 3 ab^{-1} for LHC)

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



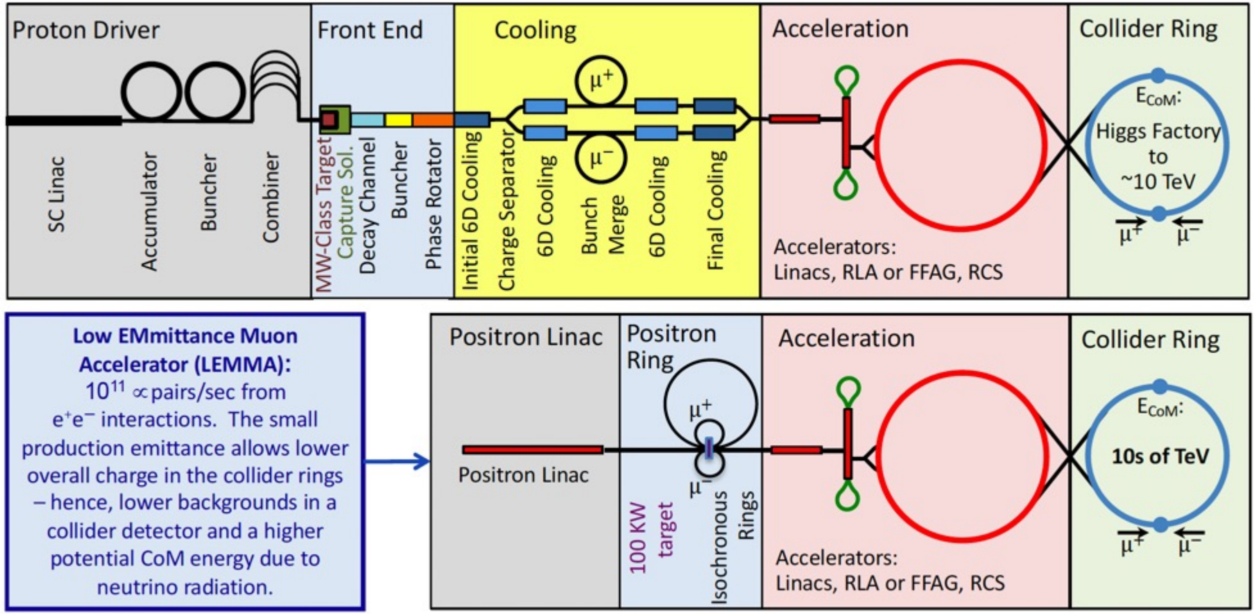
FNAL dipole demonstrator 4-layer cosϑ 14.5 T Nb_3Sn in 2019	**HTS technology** **Hybrid Nb-Ti/HTS**

Muon Collider Concept

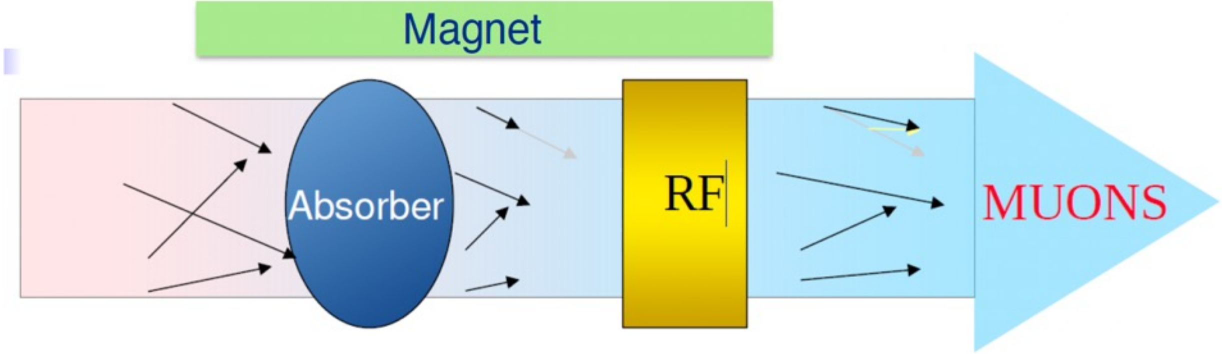
- Leading concept for Muon Collider is a proton driven target for muon production followed by 6D cooling to reduce the beam emittance
- Alternative concept – positron driven muon production

ArXiv: 1808.01858

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



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)

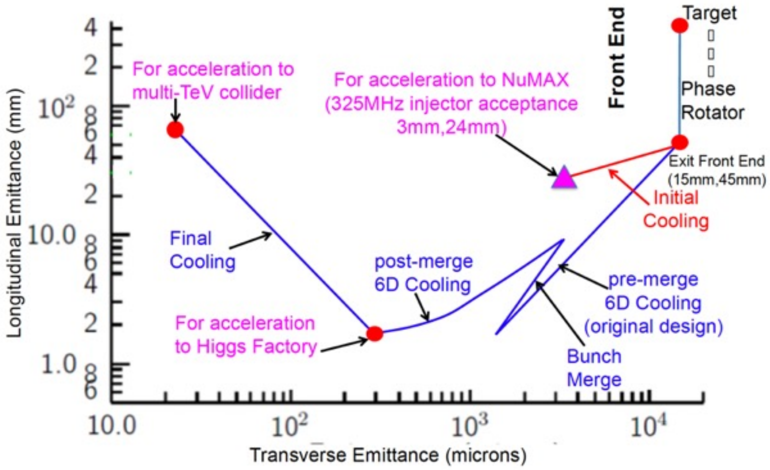
Target Parameters for Muon Collider from Snowmass 2021

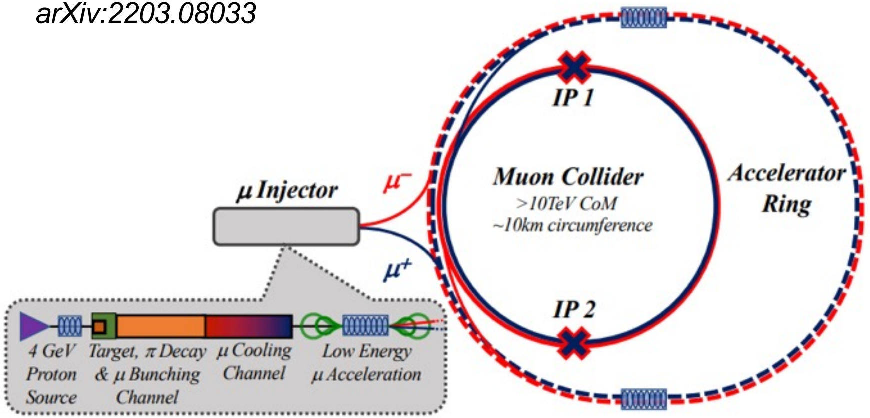
Accelerator R&D areas:

- 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

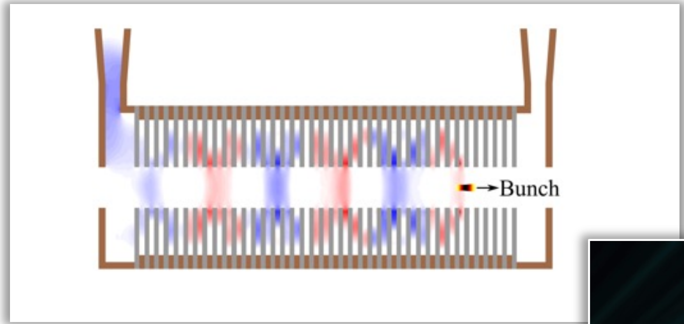
arXiv:2203.08033





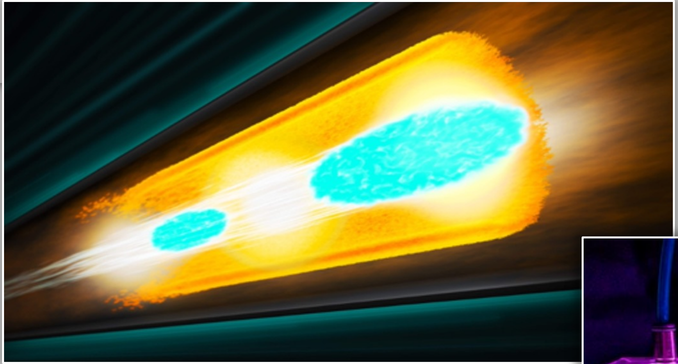
Wakefield Accelerator Technologies

Structure Wakefield Accelerators @

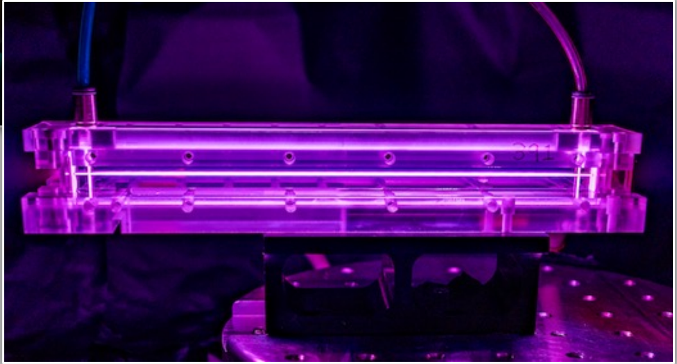


Argonne, SLAC, and LBNL are the stewards of SWFA, PWFA, and LWFA technology in the US, with university participation.

Beam Driven Plasma @ SLAC



Laser Driven Plasma @ BERKELEY LAB



Key advantages:

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

The Next Steps

Challenges

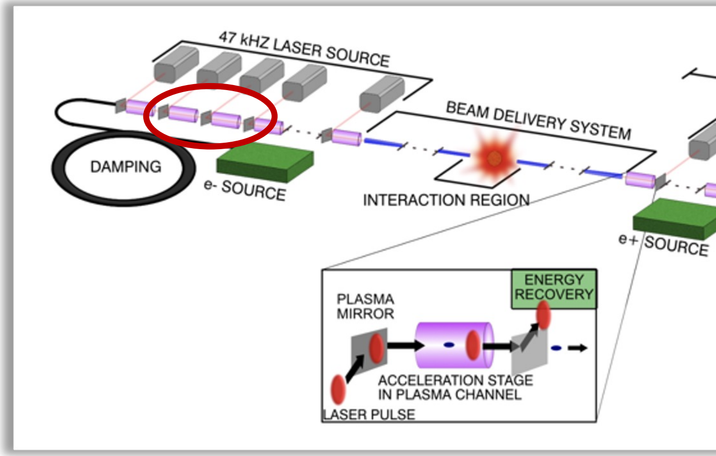
Staging

Repetition Rate

Positron Acc.

Energy Recovery

Beam Delivery Syst.



Laser-Plasma Linear Collider
arXiv 2203.08366

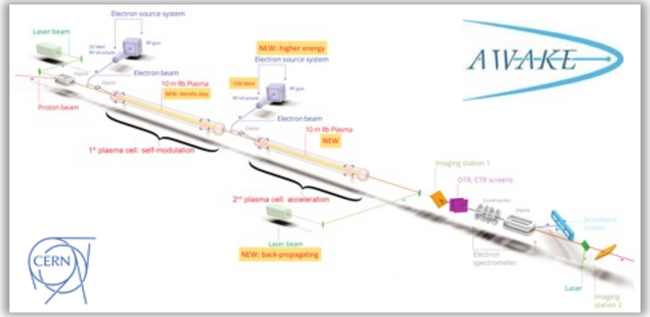
Some of the next steps in the R&D path are achievable at existing facilities, while others are not.

European Efforts

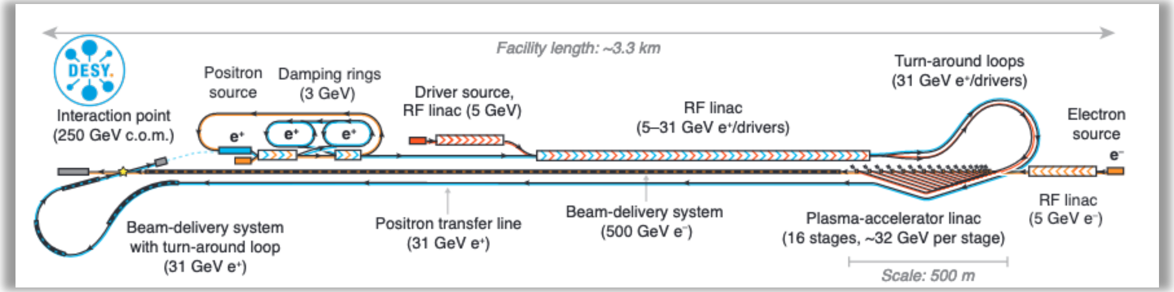
Europe is moving ahead with major Wakefield Accelerator projects, such as AWAKE at CERN, and EuPRAXIA User Facility at INFN, which is on ESFRI Roadmap.

New ideas like Hybrid PWFA Boosted Higgs Factory will be covered in an Integrated Design Study.

Support from P5 is critical for keeping pace with our European Partners!



AWAKE: Proton-driven PWFA for experiment at CERN aims to generate O(100) GeV electrons for Dark Sector searches.



Plasma Collider Boosted Higgs Factory, B. Foster et al. arXiv:2303.10150

EuPRAXIA Plasma Accelerator User Facility at INFN

Conclusions

SLAC

- 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?

Acknowledgements & References

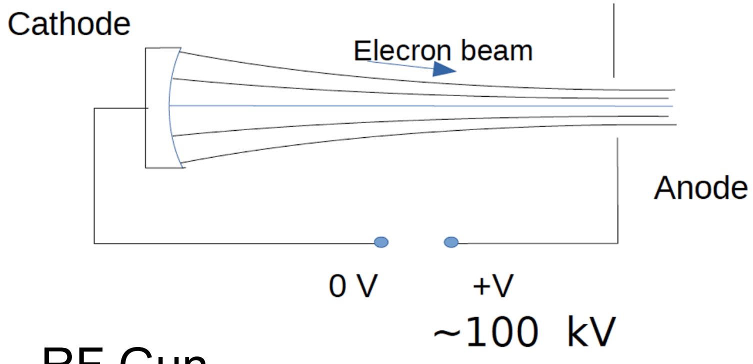
- Eric Prebys & Vladimir Shiltsev CMS Data School Talks from 2022/2020
- Michael Fazio

- US Particle Accelerator School
  - https://uspas.fnal.gov/index.shtml
  - https://people.nscl.msu.edu/~lund/uspas/ap_2021/
  - https://sites.google.com/view/uspas-2020-winter-fundamentals/course-syllabus
- Alesini, David. "Linear Accelerator Technology." *CERN Yellow Reports: School Proceedings* 1 (2018): 79-79.
- Kain arXiv:1608.02449v1 Beam Dynamics and Beam Losses – Circular Machines
- P5 Proponents for Colliders – SLAC Town Hall
- Many more references on slides and in speaker notes

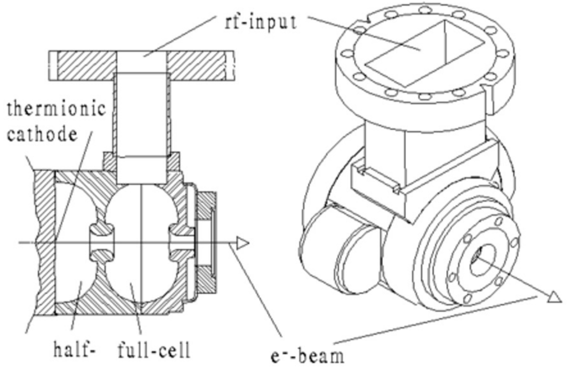
Particle (Electron) Sources

- Electrons emitted by providing enough free energy to overcome binding energy
- Thermionic, field and/or photo emission
- Need electric fields to accelerate particles away from the surface

DC Gun



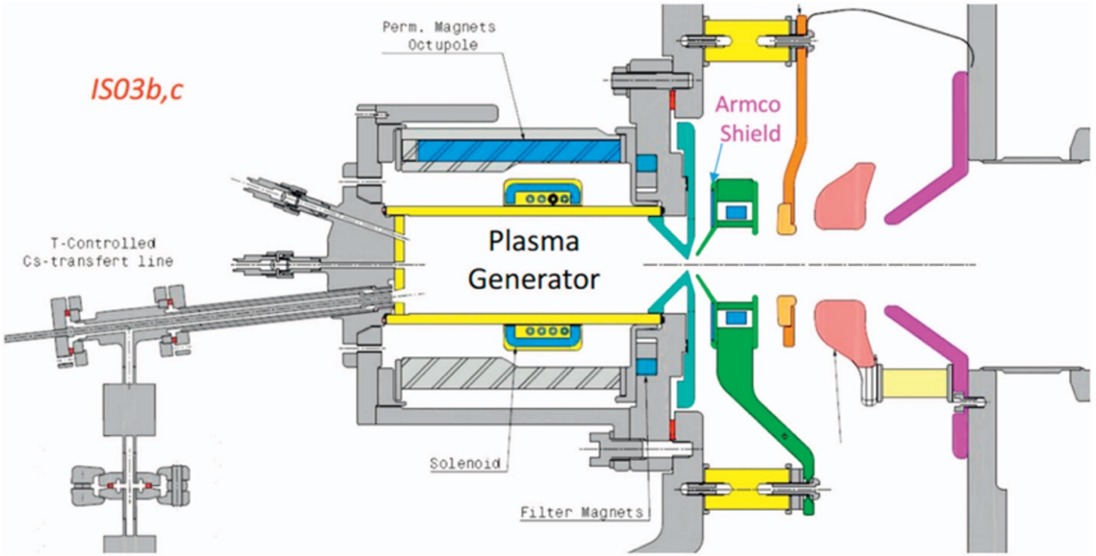
RF Gun



Particle (Ion) Sources

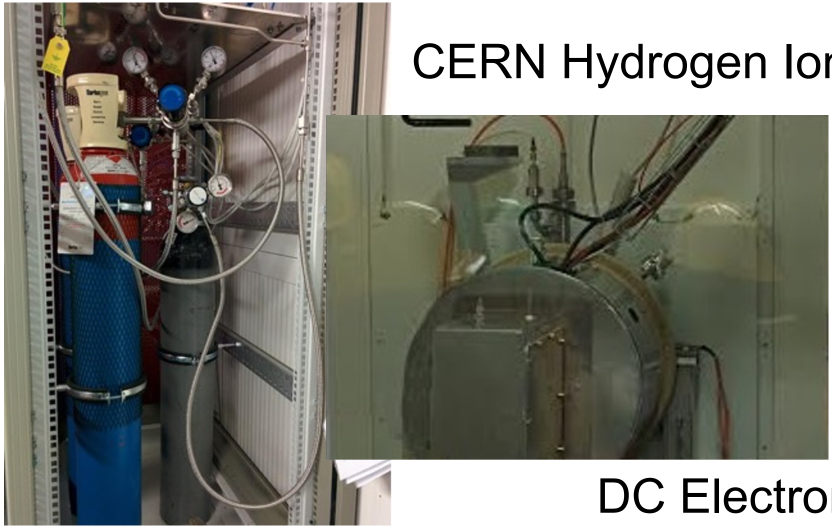
- Ionize gas and accelerate
- Set desired ionization by stripping or adding electrons
- Select ionization with magnets

Schematic of CERN's LINAC4 source



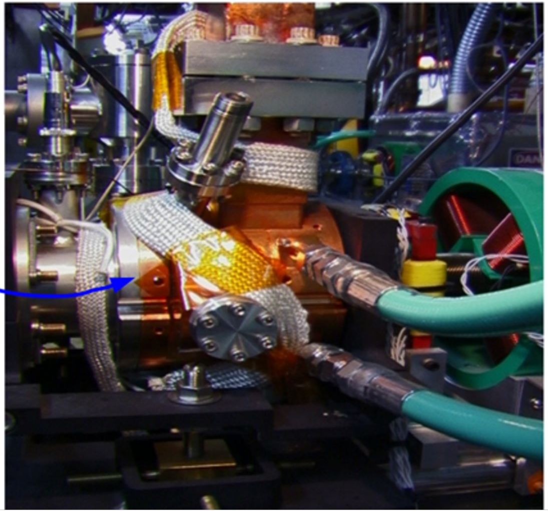
Real Particle Sources

CERN Hydrogen Ion Source



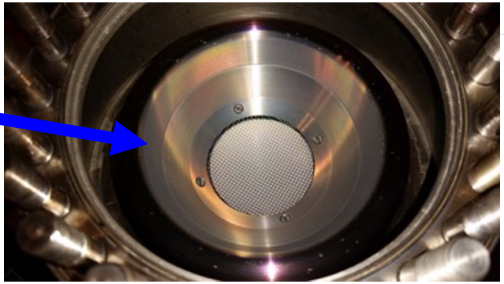
RF Electron Gun

cathode somewhere inside



cooling hose that you see on most accelerator components

DC Electron Gun

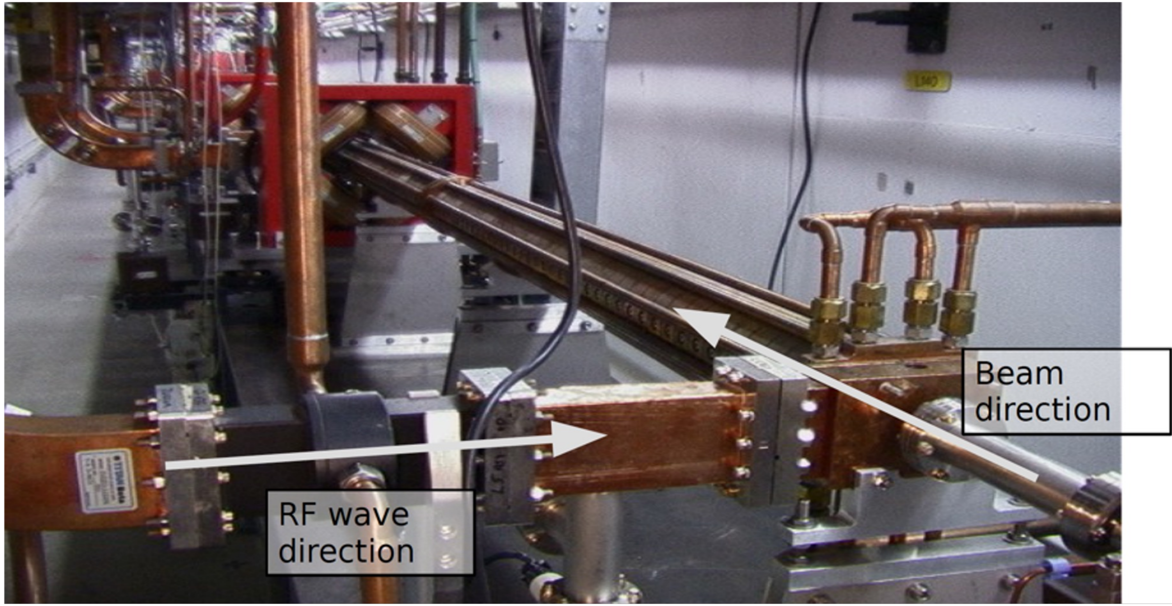


Emitter heated to 1000 ^{o}C

RF Linear Accelerator Increases Beam Energy

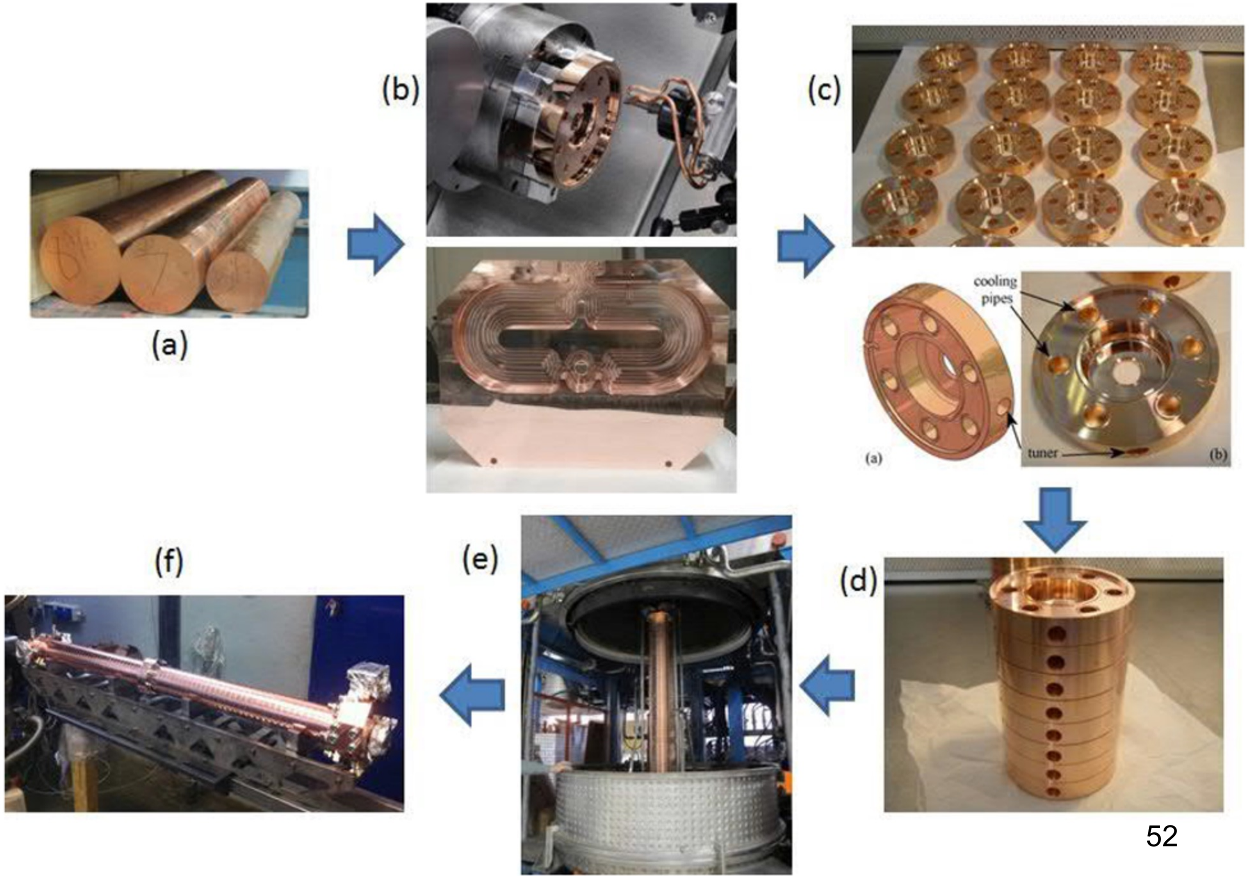
- Electromagnetic wave accelerates particles to higher energy
- Linear accelerator is common for injection into a circular machine
- Higher beam quality; used to bunch, focus and compress beam

Electrons at APS

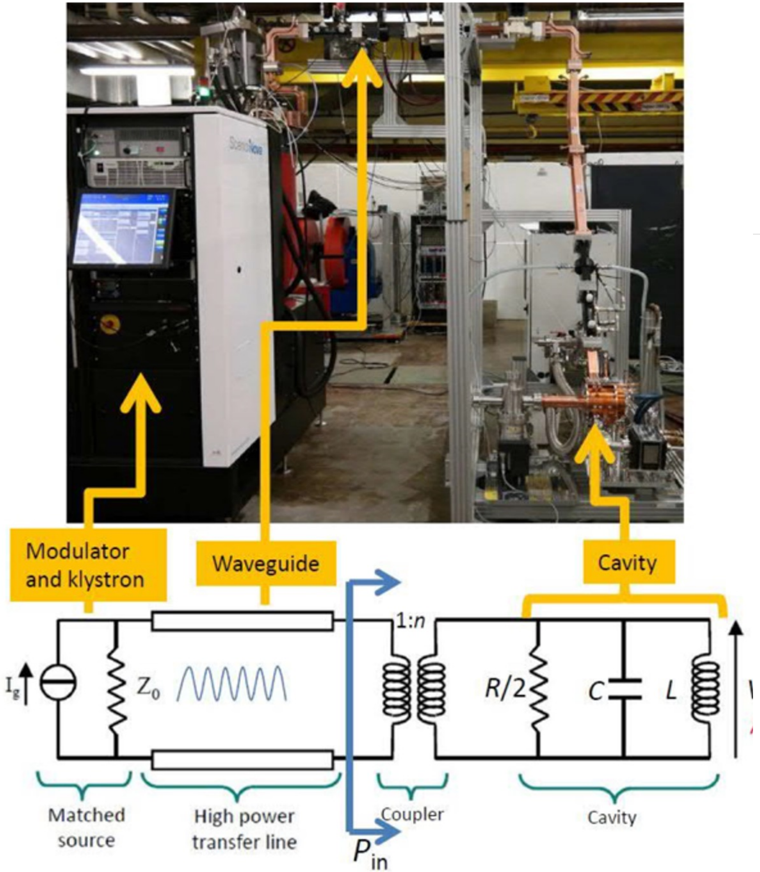


Fabrication of RF Accelerators

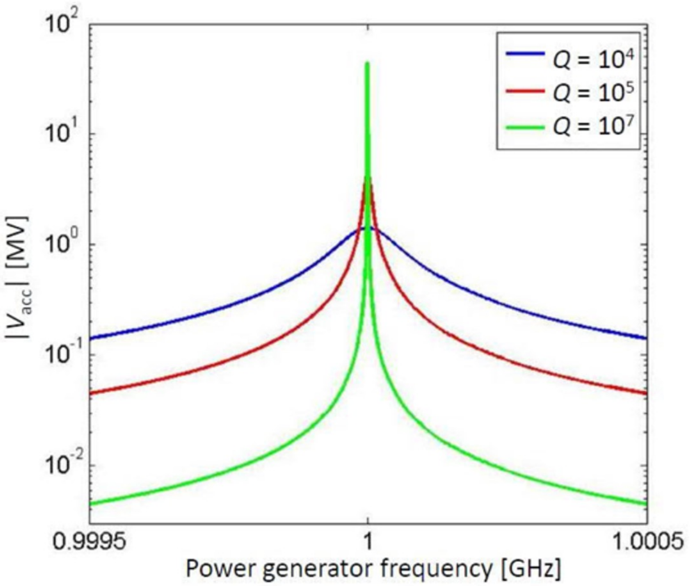
(a) OFHC forged copper; (b) realization of cells by lathes; (c) single cells machined and ready to be stacked; (d) cells piled up before brazing; (e) the structure in a vacuum or hydrogen furnace; (f) the brazed structure.



Circuit Model for Powering Accelerators

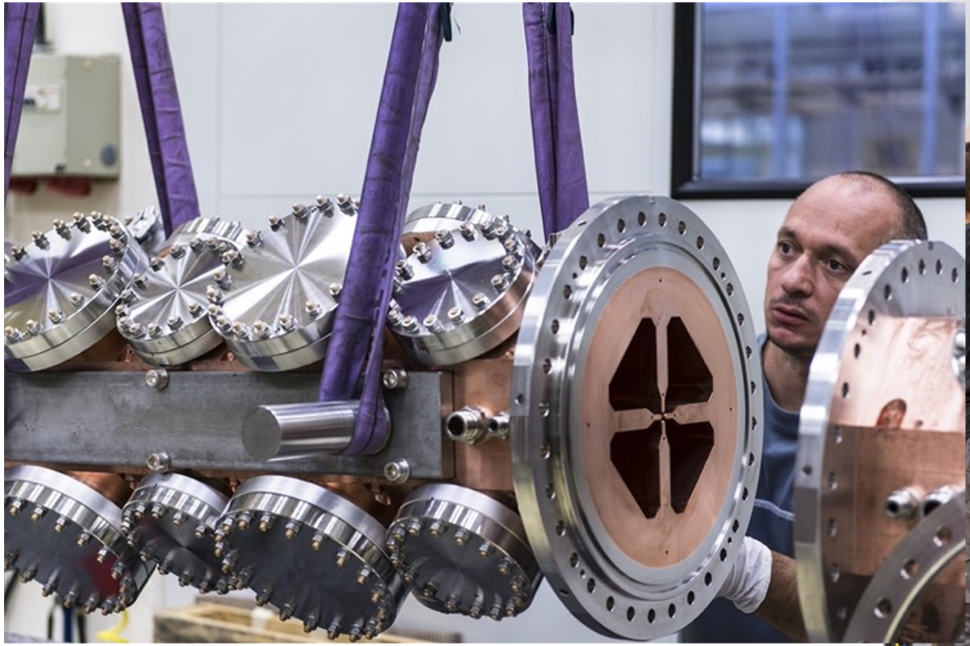


- High quality factor increases energy gain for fixed power



RF Cavities in Linac4

Linac4 Radio Frequency Quadrupole



Linac4 Drift Tube Linac

Superconducting Magnets

1232 bending magnets 15m
NbTi cables, 13 кA@1.9 K 10 GJ

4.5T

Tevatron,
6 m, 76 mm
774 dipoles

4.5 K He, NbTi
+ warm iron
small He-plant

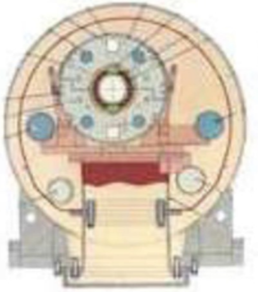
5.3T

HERA,
9 m, 75 mm
416 dipoles

NbTi cable
cold iron
Al collar

3.5T

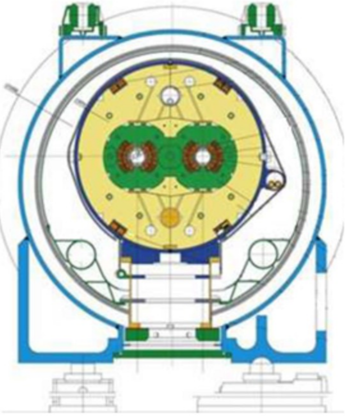
RHIC,
9 m, 80 mm
264 dipoles



NbTi cable
simple &
cheap

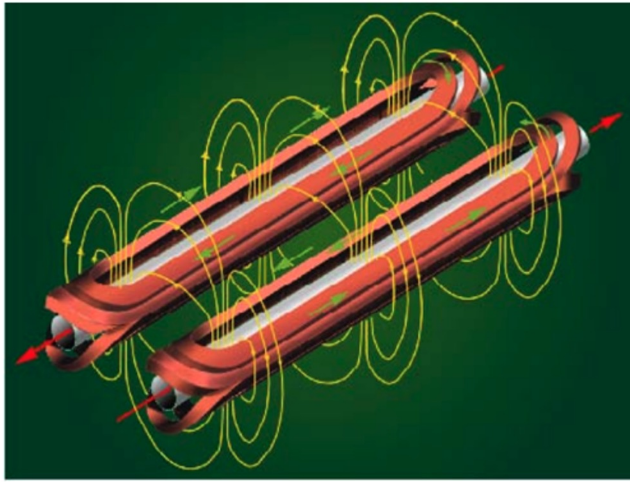
8.3T

LHC,
15 m, 56 mm
1276 dipoles



NbTi cable
2K He
two bores

Dipole Field Produced by SC Tape



The Next Steps: Staging

A proof-of-principle demonstration of staging was performed at LBNL in 2016.

BELLA is well-positioned to demonstrate GeV-scale staging with the existing facility.

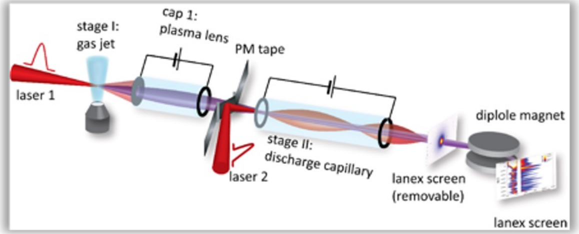
AWA plans a 0.5-GeV demo followed by a 3-GeV fully-featured module.

Ask to P5: Upgrade AWA facility for 0.5 GeV demonstrator.

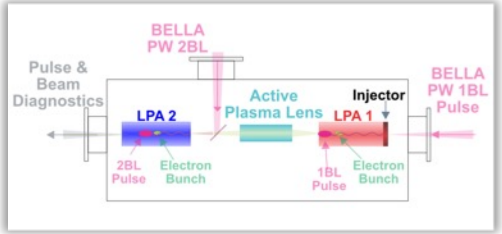
FACET-II can study beam transport in and out of a single stage.

Future Request: Facility for demonstrating two or more PWFA stages.

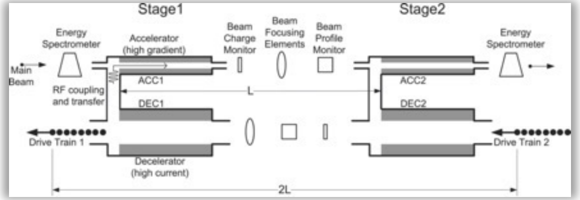
Note to P5: PWFA Staging experiment may be possible at C^3 Demo facility.



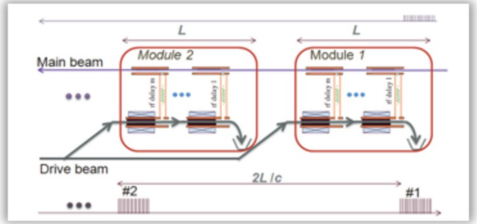
100 MeV-scale of LWFA Accelerators
S. Steinke et al. Nature (2016)



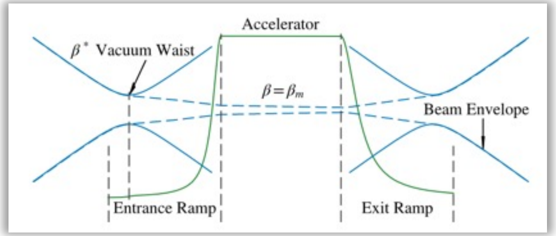
GeV-scale staging schematic



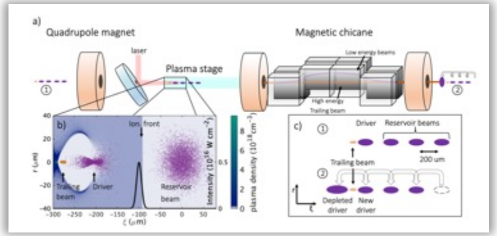
SWFA Staging Experiment
C. Jing et al NIM A (2018)



SWFA 0.5 GeV Staging Demo
C. Jing and G. Ha, JINST (2022)



Beam matching with plasma ramps
R. Ariniello et al. PRAB (2019)



Laser-gated multistage plasma accelerator
A. Knetsch et al. arXiv:2210.02263

FCC-ee SRF system

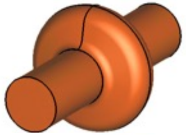
FUTURE CIRCULAR COLLIDER

Universität Rostock · INFN LNL Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Legnaro · Jefferson Lab · Fermilab

F. Peauger, O. Brunner

Z

1-cell 400 MHz, Nb/Cu



low R/Q, HOM damping, powered by 1 MW RF coupler and high efficiency klystron

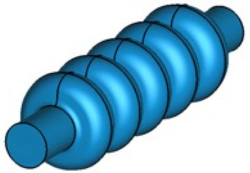
W, H

2-cell 400 MHz, Nb/Cu

moderate gradient and HOM damping requirements; 500 kW / cavity, allowing reuse of klystrons already installed for Z

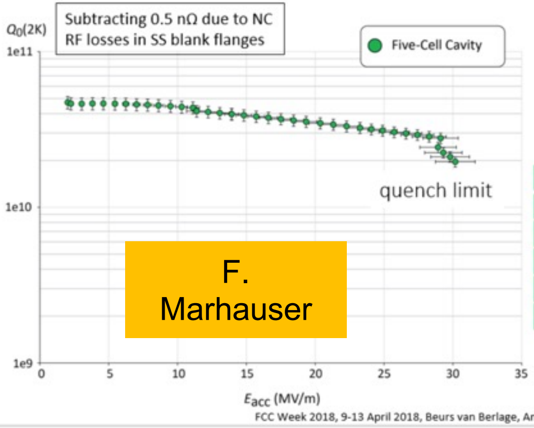
ttbar, booster

5-cell 800 MHz, bulk Nb



high RF voltage and limited footprint thanks to multicell cavities and higher RF frequency; 200 kW/ cavity

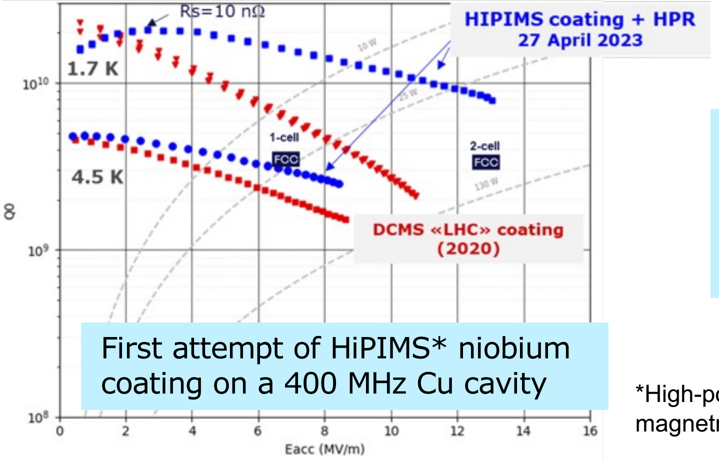
5-cell cavity development (2018), successful collaboration with JLAB



F. Marhauser

Main post-processing steps

	Unit	CRN5
Bulk BCP	µm	216
High-T heat treatment	°C, hrs.	800, 3
Final EP	µm	30
HPR cycles		4
Low-T bake-out	°C, hrs.	120, 12



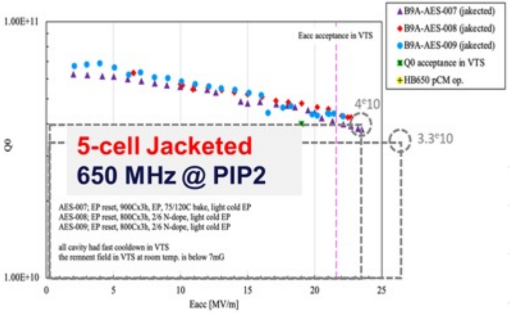
HIPIMS coating + HPR 27 April 2023

DCMS «LHC» coating (2020)

First attempt of HiPIMS* niobium coating on a 400 MHz Cu cavity

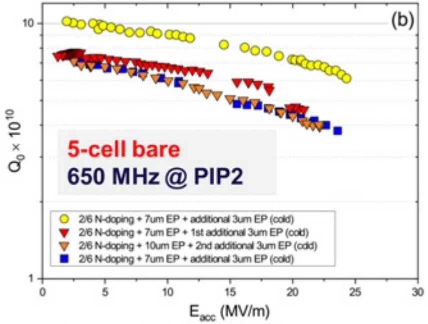
*High-power impulse magnetron sputtering

Promising R&D towards ultra-high Q_0. Collaboration with FNAL



5-cell Jacketed 650 MHz @ PIP2

Q0 = 3.5e10 @ 25 MV/m with 2/6 N-doping or midT bake + EP



5-cell bare 650 MHz @ PIP2

Q0 = 6e10 @ 25 MV/m with 2/6 N-doping + EP + cold EP