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Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

[Accelerator] R&D for future colliders

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APS April meeting

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Sacramento & Virtual

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Introduction

- In this talk I will discuss accelerator R&D topics critical for future colliders through the prism of recent P5 report
- These colliders include circular and linear e^+e^- Higgs factories, and longer-term options such as muon and hadron high energy colliders
- As it is impossible to cover all possible R&D topics, I will discuss only the several key topics
- I will start with P5 recommendations for future colliders, followed by a brief description of those colliders
- Then the talk will cover R&D topics: beam optics & MDI, muon production, ionization muon cooling, high-filed superconducting magnets, and radio frequency technology
- The choice of topics reflects my preference and in some cases ignorance, which I think is inevitable when one tries to cover such a broad subject ☺

Acknowledgments

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and many others who directly or indirectly helped me to prepare this presentation

From Snowmass to P5

New LC proposals: C^3, HELEN

ERL-based

"I always tend to assume there's an infinite amount of money out there."
*"There might as well be, "Arsibalt said, "but most of it gets spent on [...], sugar water and bombs. **There is only so much that can be scraped together for particle accelerators**."*
– Neal Stephenson

- **Recommendation 2c:** An **off-shore Higgs factory**, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of **FCC-ee** and **ILC** meet our scientific requirements. **The US should actively engage in feasibility and design studies**. […]
- **Recommendation 4a:** Support **vigorous R&D toward a cost-effective 10 TeV pCM collider** based on **proton**, **muon**, or **possible wakefield technologies**, including an evaluation of options for US siting of such a machine, with a goal of being ready to build **major test facilities and demonstrator facilities within the next 10 years** […]
- Wakefield concepts for a collider are in the early stages of development. A critical next step is the delivery of an end-to-end design concept, including cost scales, with self-consistent parameters throughout. This will provide an important yardstick against which to measure progress with this emerging technology path.

ILC, CLIC
FCC-ee / CEPC
FCC-hh / SppC

Roads don't necessarily have to go somewhere, they just have to have somewhere to start.
- Terry Pratchett

P5:
d down to a few options

ere you started
ever leaving.
erry Pratchett

gain
- Yogi Berra

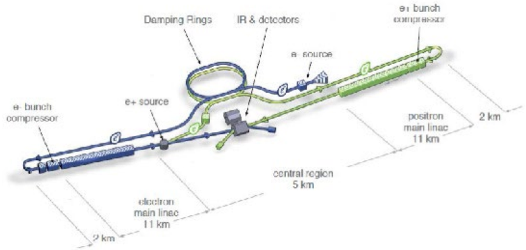
Off-shore Higgs factory
ILC or FCC-ee
10 TeV pCM collider
FCC-hh or Muon Collider

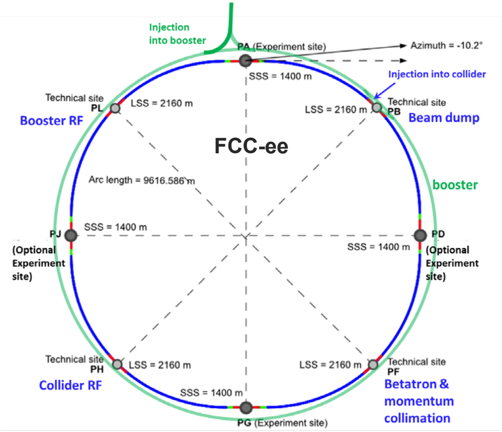
and possibly a linear collider based on advanced wakefield technology

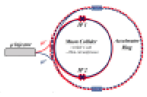
In the following I will consider only "conventional" colliders (ILC, FCC-ee & -hh) and muon collider

Scale and timeline for HEP colliders

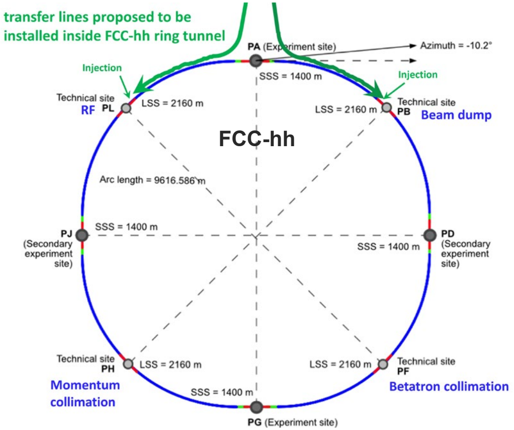
ILC250







MC 10 TeV



ILC	FCC-ee Muon Collider		FCC-hh
2040	2050	2060	2070

Possible years to start collider operation

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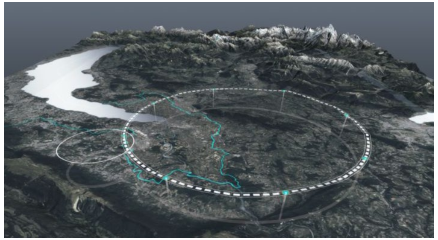
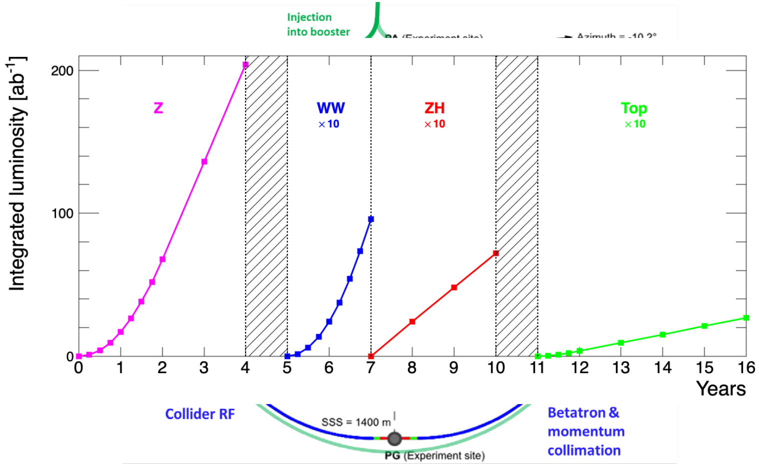
FCC-ee



- Stage 1 of the Future Circular Collider (FCC): an e^+e^- Higgs factory, electroweak & top factory operating at highest luminosities ($Z, W, H, t\bar{t}$)
- Limited by 50 MW of synchrotron radiation per beam
- Two 90.7 km rings and booster in the same tunnel
- CDR (2018), Feasibility Study (2021-2025)
- Start operation in ~2045

$$L[\text{cm}^{-2}s^{-1}] = 2.45 \cdot 10^{33} \cdot P_{SR}[\text{MW}] \cdot \frac{\rho[\text{m}] \cdot \xi_y}{E^3_{beam}[\text{GeV}] \cdot \beta^*_y[\text{m}]} \cdot R_{HG}$$

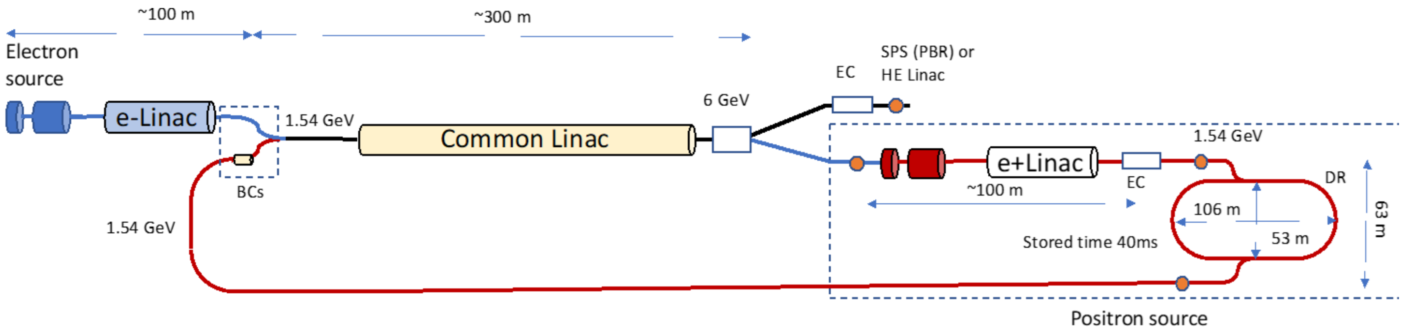


Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11

* Site **AC power** is 290 MW at CM energy 240 GeV

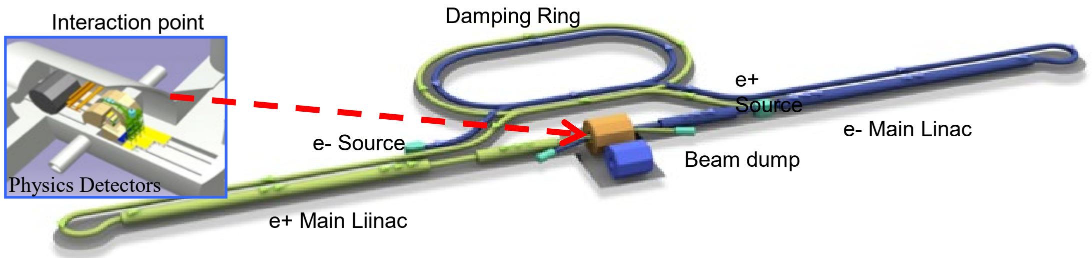
FCC-ee key R&D topics

- RF system R&D: SRF at 400 MHz and 800 MHz, high-efficiency klystron R&D, Nb_3Sn SRF – to improve overall RF system efficiency. RF & cryogenics dominate the overall AC power consumption of the machine
- MDI and final focus magnets, alignment, wakes
- Collider and booster beam optics
- Polarization studies and hardware design
- New e^+e^- injector, possibly using cold copper technology (similar to C[3], compact & high gradient)
- Synergy with CEPC in China



P. Craievich, I. Chaikovska, A. Grudiev, C. Milardi, et al

ILC



- International Linear Collider (ILC) is an e^+e^- machine based on superconducting RF linac technology
- Accelerating gradient 31.5 MV/m (ave.) at $Q_0 = 10^{10}$
- ~8,000 9-cell cavities in ~900 cryomodules
- "Shovel-ready" design: TDR (2013)
- Energy is upgradeable with conventional Nb SRF technology to 500 GeV and to 1 TeV (45 MV/m, $Q_0 = 2 \times 10^{10}$) or with advanced SRF (traveling wave or Nb_3Sn)
- The first SRF cryomodule (full ILC specifications) operation with beam was demonstrated at FAST (Fermilab) in 2018

$$L = \frac{P_{beam}}{E_{c.m.}} \cdot \frac{N_e}{4\pi\sigma_x^*\sigma_y^*} \cdot H_D$$

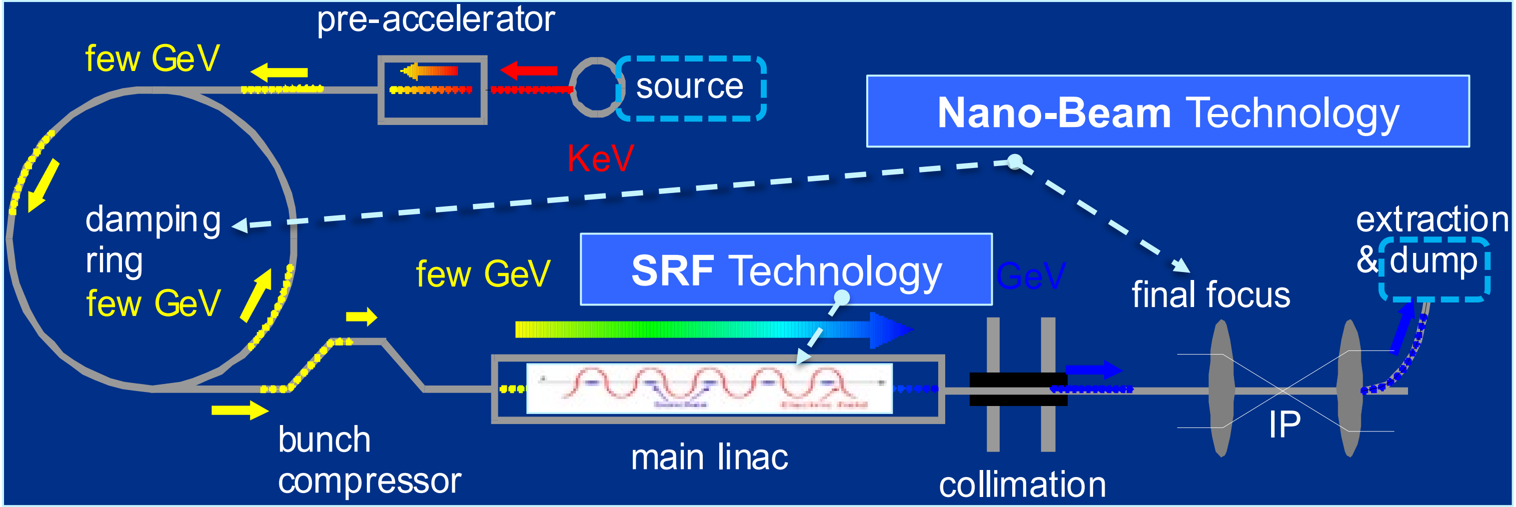
Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	Z pole	E / $\mathcal{L}$ Upgrades		
Centre of mass energy	$\sqrt{s}$	GeV	250	250	91.2	500	250	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.21/0.41	1.8/3.6	5.4	5.1
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)	80(30)	80(30)	80(30)	80(20)
Repetition frequency	f_{rep}	Hz	5	5	3.7	5	10	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312/2625	1312/2625	2625	2450
Bunch population	N_e	10^{10}	2	2	2	2	2	1.74
Linac bunch interval	Δt_b	ns	554	366	554/366	554/366	366	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8	5.8/8.8	5.8/8.8	8.8	7.6
Beam pulse duration	t_{pulse}	μs	727	961	727/961	727/961	961	897
Accelerating gradient	G	MV/m	31.5	31.5	31.5	31.5	31.5	45
Average beam power	P_{ave}	MW	5.3	10.5	1.42/2.84*)	10.5/21	21	27.2
RMS bunch length	σ_z^*	mm	0.3	0.3	0.41	0.3	0.3	0.225
Norm. hor. emitt. at IP	$\gamma\epsilon_x$	μm	5	5	5	5	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35	30
RMS hor. beam size at IP	σ_x^*	nm	516	516	1120	474	516	335
RMS vert. beam size at IP	σ_y^*	nm	7.7	7.7	14.6	5.9	7.7	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	99 %	58.3 %	73 %	44.5 %
Beamstrahlung energy loss	δ_{BS}		2.6 %	2.6 %	0.16 %	4.5 %	2.6 %	10.5 %
Site AC power *	P_{site}	MW	111	138	94/115	173/215	198	300
Site length	L_{site}	km	20.5	20.5	20.5	31	31	40

* **AC** plug-**power** may be further **reduced** (10 ~ 20 %), if the RF **(Klystron)** and SRF/Cryogenics (Q-value) **Efficiency** may be **improved**.

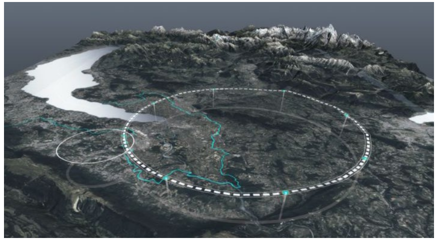
ILC key R&D topics

While the ILC is at TDR ("shovel-ready") since 2013, some R&D is still ongoing to demonstrate beam parameters (nano-beams in ATF2 at KEK), further improve performance and demonstrate industrialization of the SRF linac, develop alternative concepts (e-linac-based positron source)

- SRF technology
- Nano-beam technology (damping ring and final focus)
- Positron source



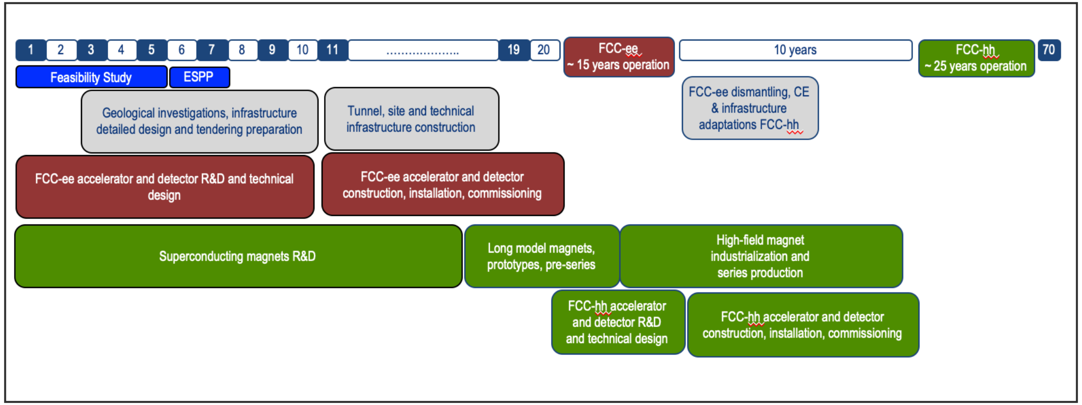
FCC-hh



- Stage 2 of the Future Circular Collider: ~100 TeV, a natural continuation at energy frontier with pp collisions and eh option
- With FCC-hh after FCC-ee there will be significantly more time for high-field magnet R&D aiming at highest possible energies
- Start operation in ~2070

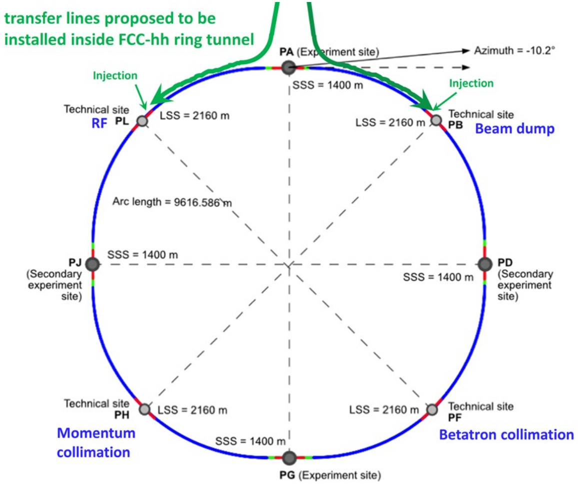
parameter	FCC-hh
collision energy cms [TeV]	81 - 115
dipole field [T]	14 - 20
circumference [km]	90.7
arc length [km]	76.9
beam current [A]	0.5
bunch intensity [10^{11}]	1
bunch spacing [ns]	25
synchr. rad. power / ring [kW]	1020 - 4250
SR power / length [W/m/ap.]	13 - 54
long. emit. damping time [h]	0.77 – 0.26
peak luminosity [10^{34} cm^{-2}s^{-1}]	~30
events/bunch crossing	~1000
stored energy/beam [GJ]	6.1 - 8.9
Integrated luminosity/main IP [fb^{-1}]	20000

* Estimated operating **AC power** is ~560 MW



FCC-hh key challenges and R&D topics

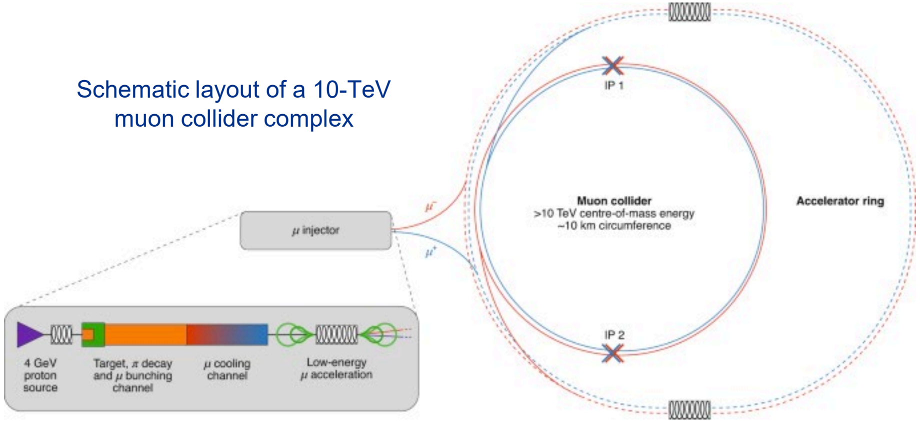
- High-field superconducting magnets: 14 - 20 T. The magnet technology will determine the energy reach of the machine
- Power load on cold vacuum chamber in arcs from synchrotron radiation: 4 MW ($\sim 10^3$ time higher than LHC) → cryogenics, vacuum
- Stored beam energy: ~ 9 GJ (~10 times of HL-LHC) → machine protection
- Pile-up in the detectors: ~1000 events/xing
- R&D to reduce energy consumption (4 TWh/year) → cryogenics, HTS, beam current, …
- Synergy with SppC in China



Muon collider

- Muon collider combines precision and energy reach needed to test the deepest questions of particle physics
- Smaller footprint than proton-proton-collider for the same pCM energy
- Muons are 207 times heavier than electrons and are not limited by synchrotron radiation
- BUT muons decay (2.2 μs lifetime at rest), hence must be accelerated rapidly
- 5-7 years of R&D to prepare a concept of demonstration facility

Schematic layout of a 10-TeV muon collider complex



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Tentative parameters based on U.S. Muon Accelerator Program (MAP) studies

Parameter	Unit	Higgs Factory	3 TeV	10 TeV
COM Beam Energy	TeV	0.126	3	10
Collider Ring Circumference	km	0.3	4.5	10
Interaction Regions		1	2	2
Est. Integ. Luminosity	ab$^-$1/year	0.002	0.4	4
Peak Luminosity	10^{34} cm^{-2} s^{-1}	0.01	1.8	20
Repetition rate	Hz	15	5	5
Time between collisions	μs	1	15	33
Bunch length, rms	mm	63	5	1.5
IP beam size σ^*, rms	μm	75	3	0.9
Emittance (trans), rms	mm-mrad	200	25	25
β function at IP	cm	1.7	0.5	0.15
RF Frequency	MHz	325/1300	325/1300	325/1300
Bunches per beam		1	1	1
Plug power	MW	~ 200	~ 230	~ 300
Muons per bunch	10^{12}	4	2.2	1.8
Average field in ring	T	4.4	7	10.5

$$\mathcal{L} = \frac{N_+ N_- n_{eff} f_{rep}}{4\pi\sigma_x^* \sigma_y^*}$$

$n_{eff} \approx 150\bar{B}$ is an *effective* number of turns

- The muon collider concept was developed by U.S. Muon Accelerator Program (2011-2016)
- In 2022 International Muon Collider Collaboration (IMCC) was formed, hosted by CERN

International MUON Collider Collaboration

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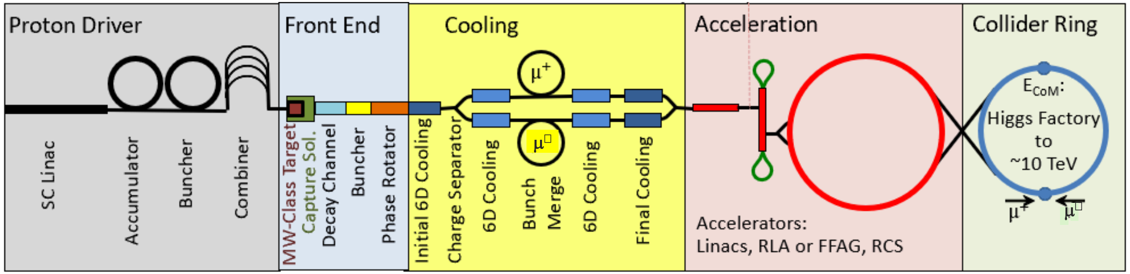
Don't believe in miracles – depend on them.
- Laurence J. Peter

Muon collider key challenges and R&D topics

Challenges at each step of the muon collider chain of accelerators

- Proton driver: 1-4 MW beam power at 5-20 GeV; accumulate bunches with up to 10^{14} particle, compress to ns duration; deliver at 5-10 Hz rate
- Target must withstand beam power, will be immersed in a ~15 T SC solenoid with ~2 m aperture; muons to be captured for cooling
- Ionization cooling
- Muon acceleration: need to accelerate muon as fast as possible to reduce the loss of muons due to decay
- Collider ring: challenging MDI to suppress breakdown originating from muon decays
- Large variety of challenging magnets
- NC RF in high magnetic field
- SRF for fast acceleration

Muon collider concept from MAP studies



MW-scale proton driver

muon production target

Capture 200 MeV bunches

Ionization cooling channel to reduce 6D emittance

Acceleration to TeV scale energy

Collider ring for counter-propagating muons

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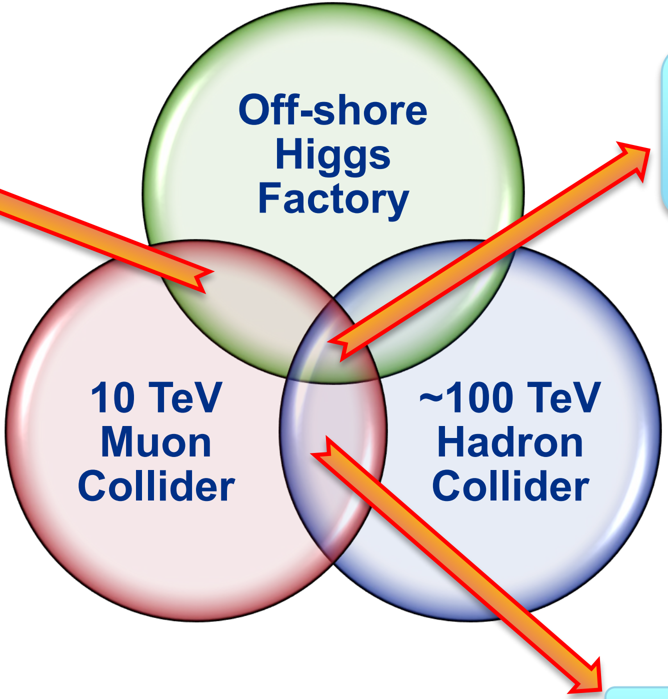
R&D synergies for future HEP colliders

- *RF power efficiency*
- *SRF system*



- *Beam optics*
- *Collective effects*
- *MDI*
- *Machine efficiency*

Examples of synergies with U.S. projects and accelerators:

- ***EIC*** *(a NP machine in the DOE lingo): MDI, SRF, beam polarization, collective effects…*
- ***PIP-II****: SRF, proton driver*
- ***LCLS-II****: SRF*
- ***LBNF****: targetry*
- ***SNS****: proton driver*

FCC-ee and –hh have many synergies with similar projects in China: CEPC and SppC

- *High-field SC magnets*

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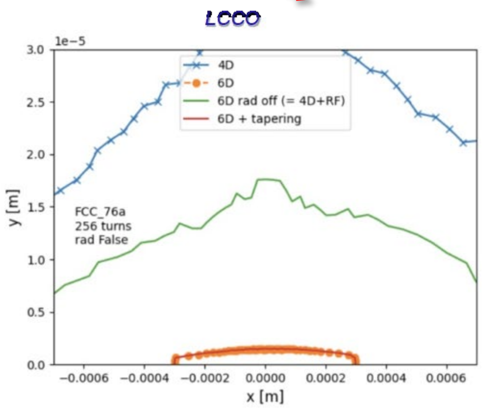
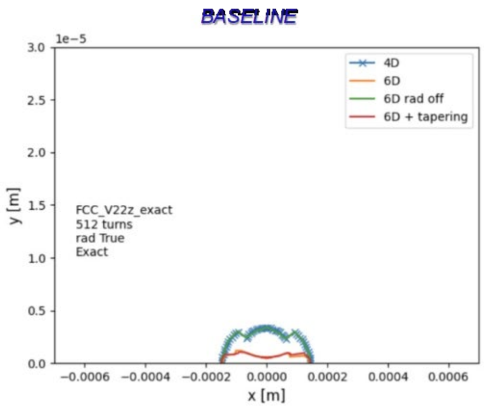
Beam optics, collective effects, machine design: new FCC-ee lattice

Consider FCC-ee as an example

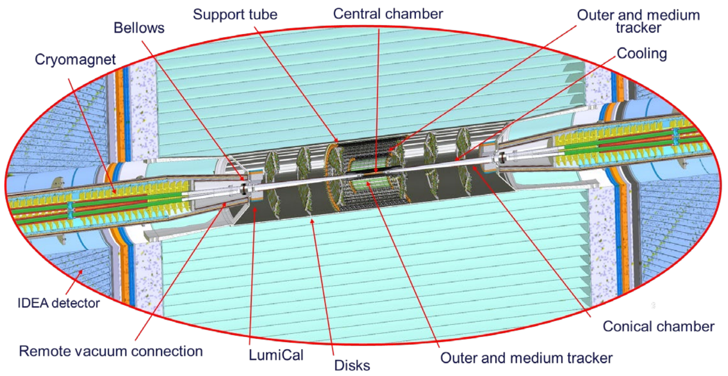
- The baseline beam optics of FCC-ee was established several years ago, then was adjusted to the new circumference and further improved recently
- At the same time, significant work on an alternative lattice resulted in the LCCO (Local Chromatic Correction Optics, P. Raimondi) with
  - Larger dynamic aperture with fewer magnets
  - Significant reduction of quadrupole and sextupole magnets' length and strength
  - Simplified powering scheme
  - Lower energy loss due to SR (12%)
  - Reduced power consumption
  - Increased momentum acceptance
  - Relaxed tolerances
- Work in progress

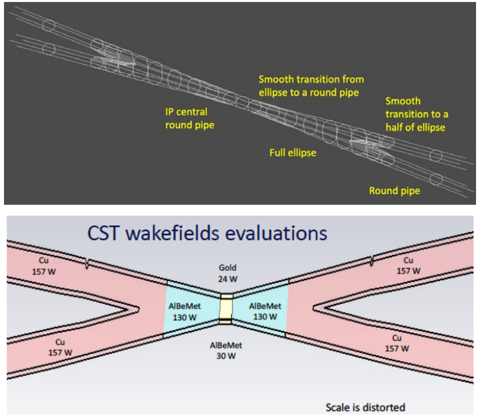


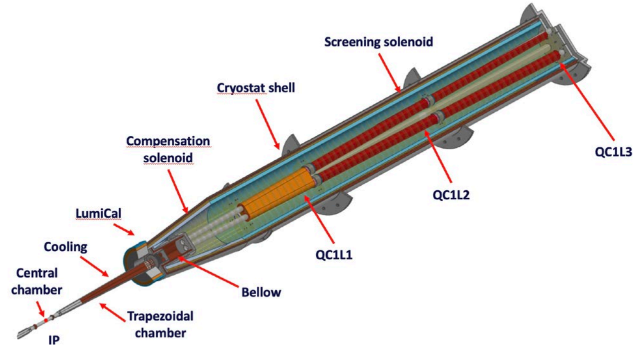


Beam optics, collective effects, machine design: FCC-ee IR

- Interaction region (IR), where accelerator and detector are connected (machine-detector interface, MDI), is a very complicated region in any collider
- In FCC-ee the same IR will serve all energies, must have a flexible design with a detector field of 2 T. Very high luminosity of $\sim 10^{36} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ at Z pole requires crab-waist scheme, nano-beams, and large crossing angle of 100 mrad. At $t\bar{t}$ the IR must deal with synchrotron radiation (SR): critical energy below 100 keV constrains final focus optics, requires asymmetric bending.
- Two anti-solenoid inside the detector are needed to compensate the detector field
- Special considerations (low material budget for central vacuum chamber alignment and stabilization) to accommodate luminosity monitor at Z to achieve 10^{-4} with low-angle Bhabhas
- Beam pipe optimization to minimize beam impedance, SR masks, design BPMs, HOM absorbing bellows, cooling scheme, …







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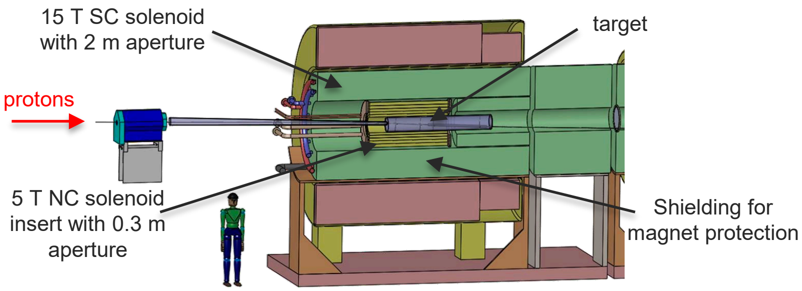
High power proton driver and target for muon collider

- MAP baseline design (based on simulations) calls for $\sim 10^{14}$ protons/bunch with 1-3 ns bunch length
- MW-class target, an interface between the proton driver and front-end channel, must produce copious amounts of muons and be tolerant to MW beams
- Front end captures pions/muons
- μ/p efficiency is 10-15% for each sign
- Thermal shock is a key parameter for survivability of high-power target
- Graphite, liq. lead and tungsten powder are currently considered, studies look promising
- Need: simulations, irradiation materials studies, pion yield measurements

Need to design a target capable of withstanding such an exceptionally high thermal shock

	Neutron spallation source (ESS, SNS, CSNS)	Accelerator neutrino beam (T2K, CNGS, NuMI, SBN, LBNF)	Muon collider (MAP, IMCC design)
Proton beam energy	Low (1-3 GeV)	Wide range (8-400 GeV)	Medium (5-20 GeV)
Proton beam bunch length	Short (105-700 ns)	Long (4.2-10.5 μs)	**Extremely short (1-3 ns)**
Proton beam intensity per bunch	Medium $(10^{13} - 1.5 \times 10^{14})$	Medium $(4.8 \times 10^{13} - 3.2 \times 10^{14})$	**High** $(10^{14} - 10^{15})$
Repetition rate	High (14-60 Hz)	Low (0.4-2 Hz)	Medium (5-15 Hz)
Target material	Liq. Hg, W, Liq. Li, etc.	graphite	TBD



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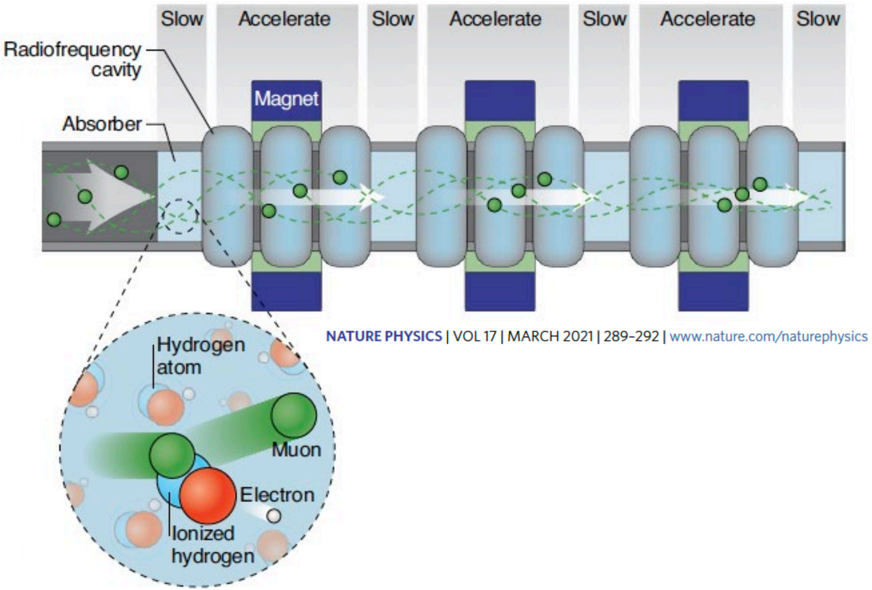
Ionization cooling

- Ionization cooling channel consists of 1,000+ muon cooling cells
- The cooling of muons requires very compact assembly of normal conducting RF cavities, superconducting solenoids, and either liquid hydrogen or LiH absorbers
- Large bore solenoids: from 2 T (1 m aperture) to 20+ T (0.05 m aperture)
- RF cavities (300-800 MHz) must operate in milti-tesla fields
- Absorbers (wedge-shaped) must tolerate large muon beam intensities
- Need to develop an end-to-end design with realistic cooling lattice that meets muon collider luminosity requirements
- Conceptual design of a demo facility



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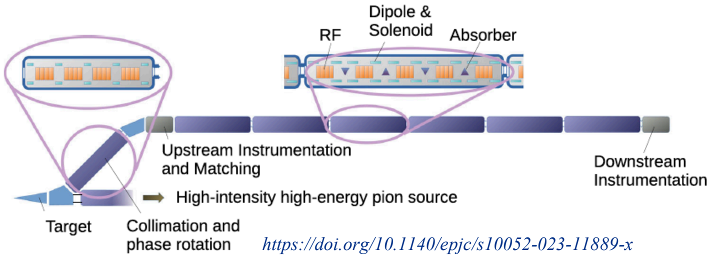
Schematic of the muon cooling demonstrator



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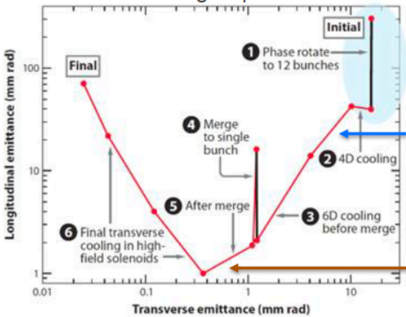
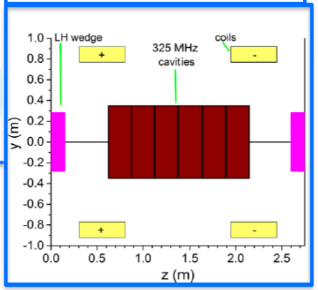
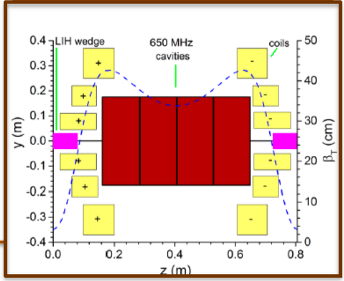
MuC cooling requirement



Early cell ("easy") – 2T peak



Late cell ("hard") – 14 T peak



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Magnet technology R&D

FCC-hh and muon collider require beyond state-of-the-art magnet technology

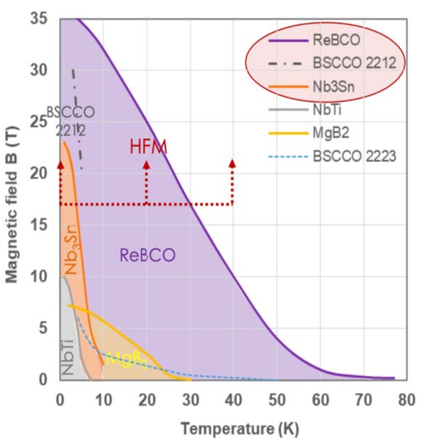
- High field dipoles – up to 17 T (and perhaps 20 – 24 T)
- Large aperture with fields up to 13 T (or more)
- (Very) fast ramping magnets
- Large aperture, high field solenoids (> 30 T)
- Large aperture interaction region quadrupoles

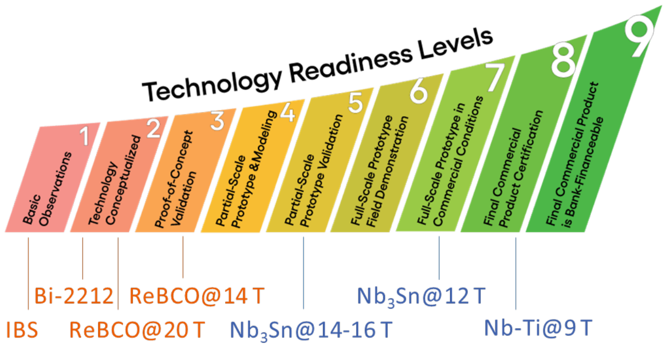
- High radiation environment
  - Radiation Damage
  - Heat deposition
- Manage stress

Conductor ultimately determines magnet performance

- Six different technological superconductors
- Low Temperature Superconductors (LTS)
  - NbTi, **Nb_3Sn**, MgB_2
- High Temperature Superconductors (HTS), also high field
  - $Bi_2Sr_2CaCu_2O_8$ (**Bi-2212** or BSCCO), $Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi-2223), rare-earth Ba_2Cu3O_7 (**ReBCO**)
- Plus, a new family of iron-based superconductors (IBS), not yet commercially available

Practical operation range of superconductors





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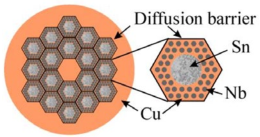
Potential conductor choices

Nb_3Sn has been around for many years



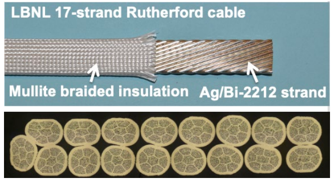
- After ~ half a century(almost) used for accelerator magnet – HiLumi LHC
- Max practical field ~ 14-15 T at 4.2 / 1.8 K
- Still possible improvements – J_c, high C_p
  - Work on increasing heat capacity of strands
  - Artificial Pinning Centers (X. Xu et al, MDP/FNAL)
- Demonstrate technology for large-scale accelerator deployment
  - Substantial CERN program to develop industrial capacity

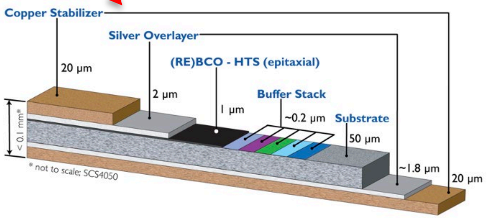
Bi-2212 has clear niche applications

- Several desirable properties: the only HTS available in the form of multifilamentary round wires, can be used to make Rutherford cable → high field quality
- High J_c only at low temperature, no good for 20 K operation
- Expensive (75% silver) and cost reduction path not so clear
- Powder supply chain? – only 2 manufacturers worldwide

ReBCO

- Fusion can drive capacity and has substantially lowered cost of some architectures.
- Excellent $J_c(B)$ performance at elevated temperatures
- Available as flexible tape – not good for field quality?
- Prohibitively expensive, but can the cost be driven down?
- R&D to improve performance – and make into a magnet conductor





Fe-based could be game-changer

- Active R&D in China
- Worth pursuing in the U.S.?
- Potentially lower cost but performance not there yet

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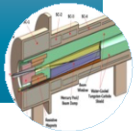
Magnet technology R&D for muon collider

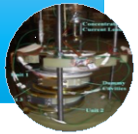
- Characteristics:
  - High field (15-20T)
  - Large bore (meter-scale)
  - Intense radiation environment – NC or HTS insert coil

Capture Solenoid for Simultaneous mu+ & mu- Beams



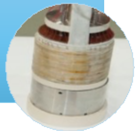
- Characteristics:
  - Solenoid-based cooling channel (LH_2/LiH absorbers)
  - RF cavities integral to focusing channel
  - Fields ranging from LTS to HTS conductor regime

Muon Ionization 6-Dimensional Cooling Channel



- Characteristics:
  - Emittance exchange channel for TeV-scale colliders – trade increased longitudinal beam emittance for smaller transverse emittance
  - Goal: 40-60 T HTS solenoids with d ~ 50mm

Muon Ionization Final Cooling Channel

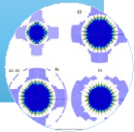


- Characteristics:
  - Present baseline based on the use of Rapid Cycling Synchrotrons
  - Requires magnets capable of ~400Hz operation with B>1.5T
  - Novel magnets, suitable modeling, efficient power system

Acceleration to the TeV Energy Scale for Muon Colliders

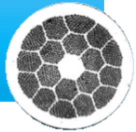
- Characteristics:
  - Decaying muon beams mean that luminosity is inversely proportional to circumference
  - 10T dipole ⇨ 15-20T dipoles improves luminosity
  - Radiation environment
  - Challenging IR magnets

Muon Collider Magnet Needs



- Characteristics:
  - A MC (w/decaying beams) obtains the greatest performance enhancement of any HEP collider from HTS magnet technology
  - High quality HTS cables and magnets must be a priority

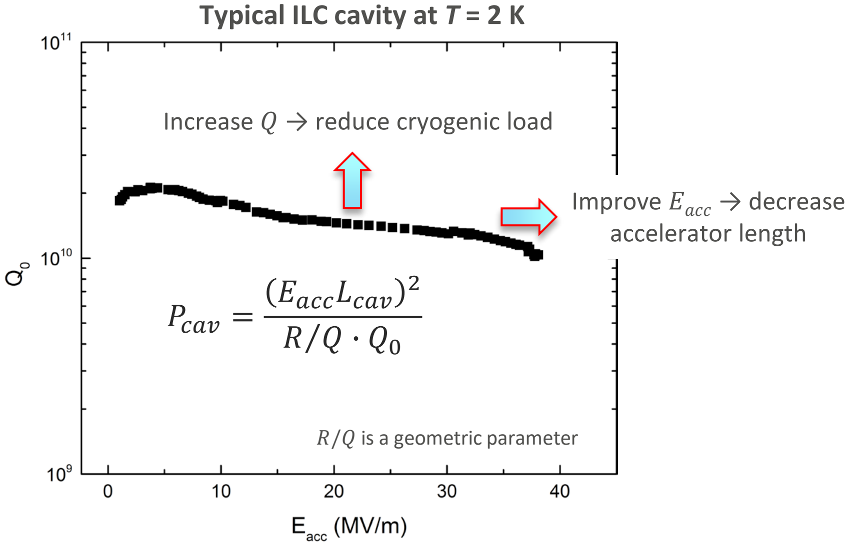
HTS Magnet Development



Radio frequency technology R&D thrusts

Three RF technology R&D thrusts

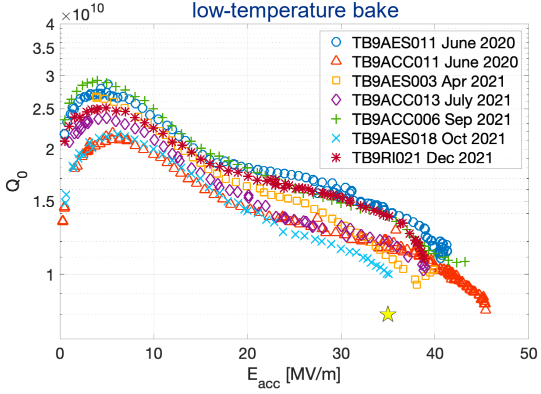
- Superconducting RF (SRF) technology will be used in all colliders that we discuss in this presentation. FCC-ee, ILC, and muon collider will have very large installations. Improving SRF cavity performance is critical.
- High-gradient normal conducting RF operating in high magnetic fields (Muon collider) as part of the ionization cooling
- High-efficiency RF sources (FCC-ee, ILC) to reduce overall AC power consumption of the machine



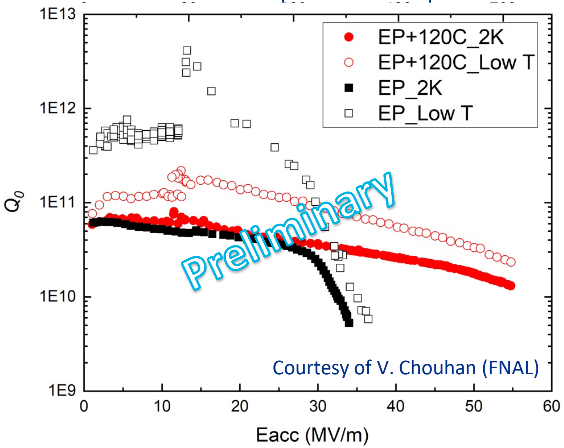
SRF R&D

- Improving the performance of bulk niobium cavities is achieved via surface treatment (only ~100 nm thick surface layer determines the performance)
  - Higher quality factor cavities to reduce cryogenic load (all). Goals for FCC-ee: $Q_0 = 3\ \times 10^{10}$ at $E_{acc} = 25$ MV/m for Booster initially, then $Q_0 = 6\ \times 10^{10}$ at $E_{acc} = 25$ MV/m for Booster and collider for $t\bar{t}$ operation. Goal for ILC: improveQ_0 to $> 2\ \times 10^{10}$ at $E_{acc} = 31.5$ MV/m for cost reduction and energy upgrade.
  - Improve accelerating gradient (ILC, Muon collider) via surface treatment and novel cavity geometries (traveling wave SRF for ILC energy upgrade)
- Nb/Cu R&D for 400 MHz FCC-ee SRF
- Develop designs with well-suppress higher order modes for high intensity operation (FCC-ee, Muon collider)
- Develop alternative SRF superconductors – e.g., Nb_3Sn – for operations at higher temperatures and accelerating gradients (FCC-ee, ILC energy upgrade, Muon collider)
- Understand operation of SRF cavities in the vicinity of strong magnetic fields during muon acceleration and develop mitigation measures (Muon collider). Goals: $E_{acc} = 20$ MV/m at 325 MHz, 25 MV/m at 650 MHz, 38 MV/m at 1300 MHz
- Synergies with EIC, PIP-II, LCLS-II, CEPC, ...

9-cell 1300 MHz SRF cavities after 2-step low-temperature bake



Single-cell HB650 (PIP-II shape) 650 MHz cavity after modified EP recipe and low-temperature bake



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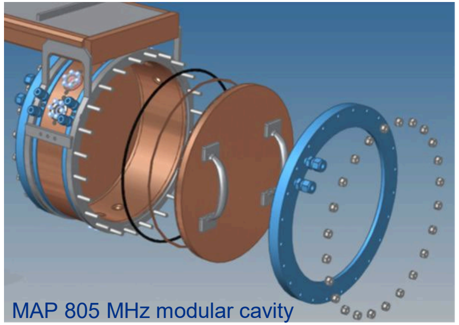
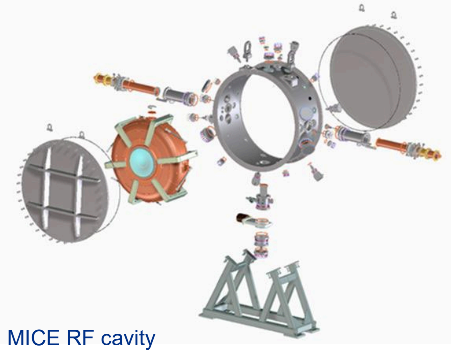
NCRF cavities in high magnetic fields

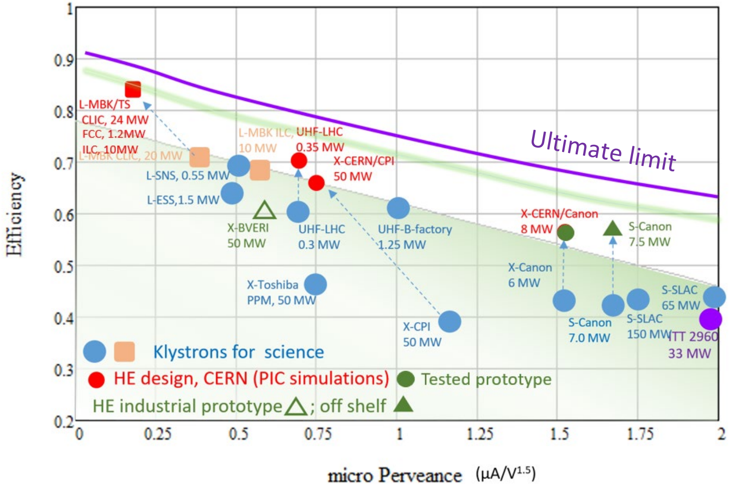
- Muon ionization cooling channel required 300-800 MHz RF cavities to operate in high magnetic fields from 2 to 20+ T
- A variety of parameters along the cooling channel: accelerating gradient, frequency, magnetic field, beam window thickness, etc.
- High-power, short-pulse RF power sources
- Considerable cavity R&Ds have been carried out in MAP and pre-MAP era to understand the RF breakdown in strong B field and how to mitigate it
- For the field gradient demonstration: an 805 MHz MAP vacuum modular cavity and an 805 MHz high pressure hydrogen-filled cavity have achieved ~50 MV/m in a 3 T B field
- The MICE 201 MHz cavity is a fully operational single cell cavity that has achieved the design gradient (~11 MV/m) in a ~0.2 T B field
- Much more needs to be learned about RF break down. Both simulations and experimental studies in a dedicated test facility are needed to explore different materials (e.g., aluminum, CuAg and other copper alloys, Be-coated copper,…) and magnetic field configurations.
- Cold copper technology might be a good choice, synergy with C^3 R&D


MAP 805 MHz modular cavity


MICE RF cavity

High-efficiency RF sources

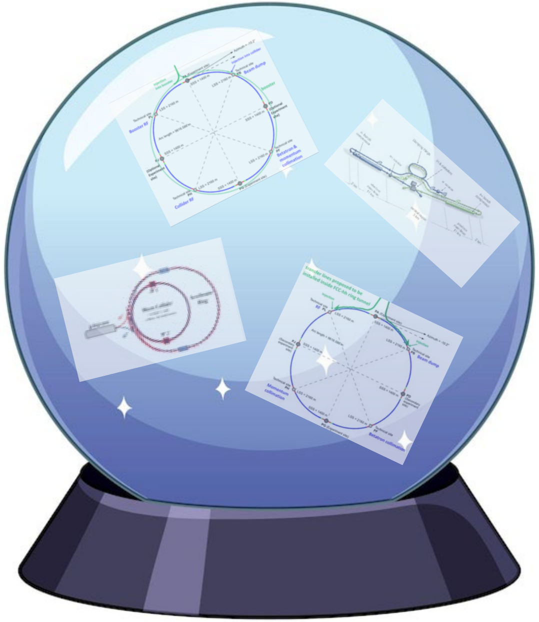
- High-efficiency klystrons are needed to reduce overall AC power consumption of the machine
- CERN-led HEIKA collaboration is targeting to improve efficiency and performance of klystrons for various applications
- Example: the klystron efficiency upgrade from existing 65% to 80% would potentially save ~1 TWh in 10 years of FCC-ee operation
- Several options of klystron design improvements are explored, some in collaboration with industry
- An off-the-shelf Canon klystron was retrofitted and tested, showing significant improvement



8-10 MW	E37113 at factory	HEX COM_M (CERN/Canon)
Voltage, kV	154	154
Current, A	94	94
Frequency, GHz	11.994	11.994
Peak power, MW	6.2	8.1
Sat. gain, dB	49	48
Efficiency, %	42	56.4
Life time, hours	30 000	30 000
Solenoidal magnetic field, T	0.35	0.42
RF circuit length, m	**0.127**	**0.127**

Summary

- P5 recommended to actively engage in feasibility and design studies of two off-shore Higgs factories, ILC and FCC-ee
- Also, P5 recommended to support vigorous R&D toward a cost-effective 10 TeV pCM collider based on proton, muon, or possible wakefield technologies
- The collider designs are at different stages of maturity, but all require quite extensive R&D efforts covering a wide range of challenging topics from beam optics to MDI to beam polarization to positron production to muons ionization cooling high-field SC magnet and RF technologies…
- Any future collider will require very high AC power to operate, special attention should be given to R&D topics that would improve efficiency of various systems
- There are synergies between the colliders and with other projects and accelerators
- In this presentation I gave you just a snapshot of some R&D topics for future collider
- A lot of fun to be had when we begin R&D in earnest!
- BUT →



We need funding, Uncle Sam!

Thank you!