Accelerator R&D for HEP:
The Next Decade and Beyond

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DPF-PHENO'2024 · May 14, 2024 · U. Pittsburgh & Carnegie Mellon U.

Acknowledgements

- Kathleen Amm
- Mei Bai
- Sergey Belomestnykh
- Steve Gourlay
- Michiko Minty
- Mark Palmer
- Sam Posen
- Pantaleo Raimondi
- Tor Raubenheimer
- Thomas Roser
- Diktys Stratakis
- Sasha Valishev
- Frank Zimmermann, et al.

Snowmass'21:

Accelerator Frontier WPs

Accelerator Frontier Report

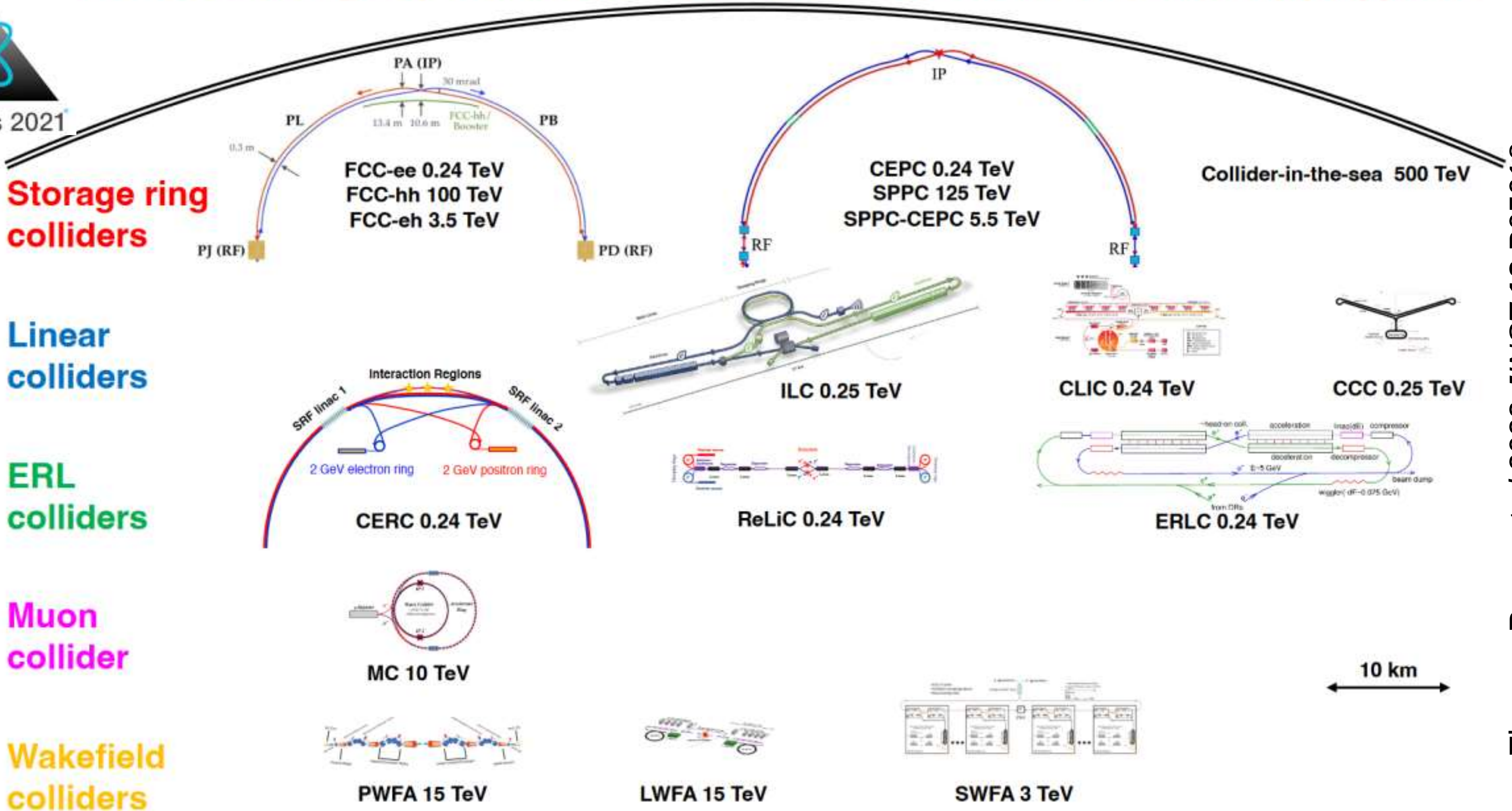
Snowmass'21 Summary Report

P5 Report

Future collider proposals: 0.125 – 500 TeV; e+e-, hh, eh, μμ, γγ, …

Snowmass 2021

- Storage ring colliders
- Linear colliders
- ERL colliders
- Muon collider
- Wakefield colliders



Thomas Roser *et al* 2023 *JINST* **18** P05018

P5 Recommendations

- **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.

P5 Area Recommendations

	Now (FY23 $)	P5 recomm.
General Accelerator R&D *	~50M$/yr	+10 M$/yr
Targeted Collider R&D	0 M$/yr	+35 M$/yr
FNAL Accel.Complex Plan	0 M$/yr	+10 M$/yr

~ 1B$ combined over the next decade

* Note: in addition, Accelerator Test Facilities are supported at ~40M$/yr – these are of great relevance for R&D and projects (eg tests and pre-project R&D)

Accelerator R&D in the US

General Accelerator R&D (GARD, OHEP program):

Supports ~30 university grants and 7 DOE national labs

- Advanced Accelerator Concepts
- Superconducting Magnets and Materials
- RF Accelerator Technology (NC and SC)
- Accelerator and Beam Physics
- Particle Sources and Targets

Of relevance are (smaller) programs/support from other offices: NP, BES, FES, ASCR, NSF…

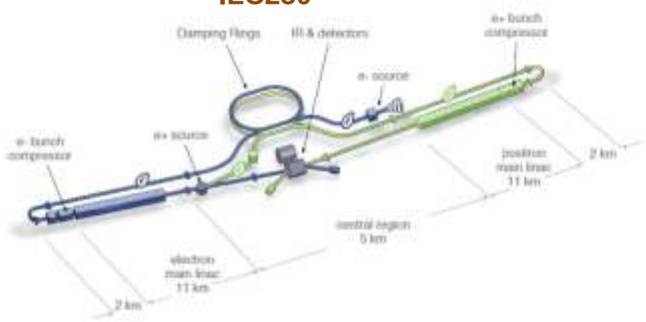
Very successful in the past: Nb3Sn magnets → LARP → HL-LHC, etc

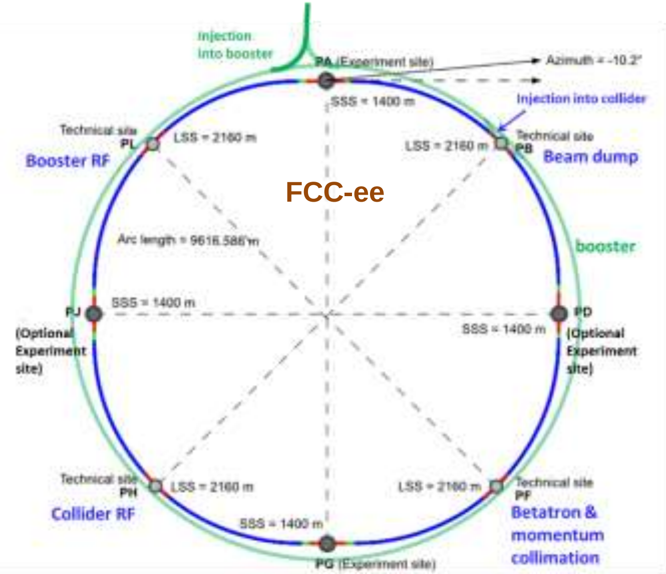
Targeted Accelerator R&D (to be org'd, see May'24 HEPAP mtg)

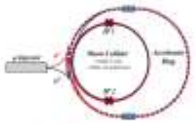
More focused; certain timeline… used to exist (ILC, LARP, MAP)

Scale & Timeline for HEP colliders

ILC250

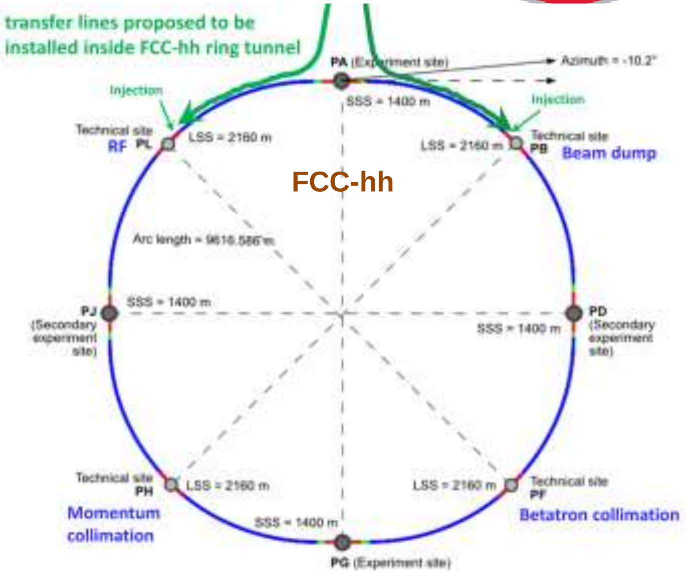






MC 10 TeV

10 km



CEPC
ILC

FCC-ee

Muon Collider

FCC-hh

2040

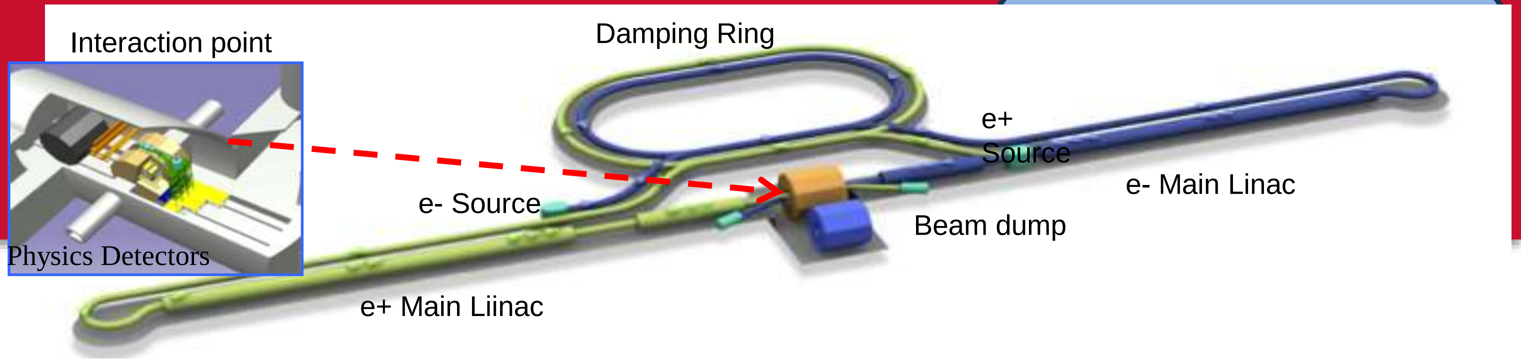
2050

2060

2070

Possible years to start collider operation – according to proponents

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) …still no host
- **Energy is upgradeable** with conventional Nb SRF technology to 500 GeV and to 1 TeV (45 MV/m, $Q_0 = 2\times10^{10}$) 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;** followed by a KEK test in 2021

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

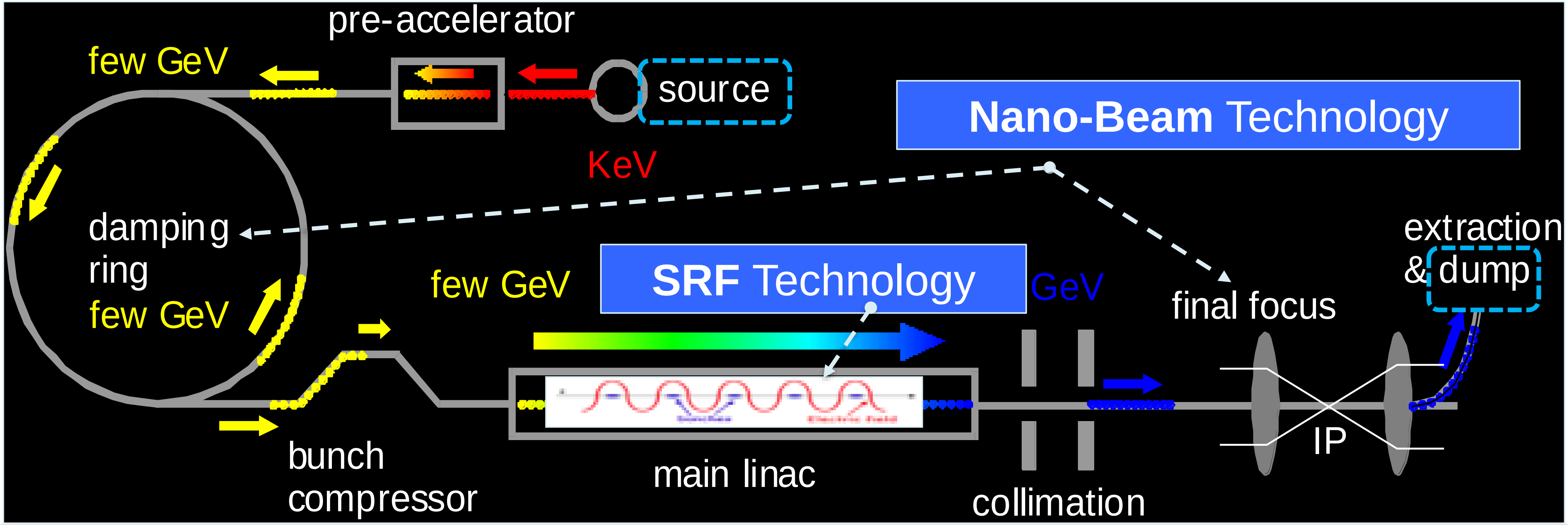
Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	Z pole	E / $\mathcal{L}$ Upgrades		
Centre of mass energy	$\sqrt{s}$	GeV	250	250	91.2	500	250	1000
Luminosity	$\mathcal{L}$	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	1.35	2.7	0.21/0.41	1.8/3.6	5.4	5.1
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)	80(30)	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 Remaining R&D Topics

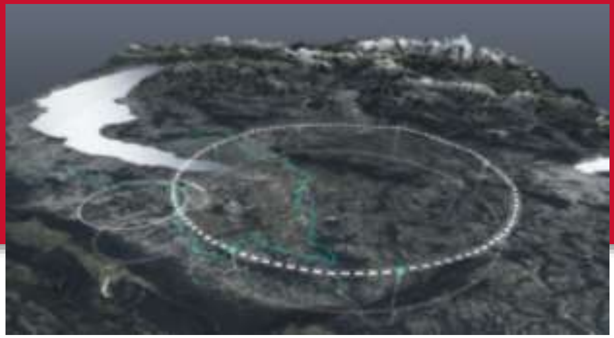
While the ILC is at TDR (“shovel-ready”) since 2013, some R&D is still ongoing to demonstrate beam parameters (nano-beams in ATF2 at KEK), further improve performance and demonstrate industrialization of the SRF linac, develop alternative concepts (e-linac-based positron source)

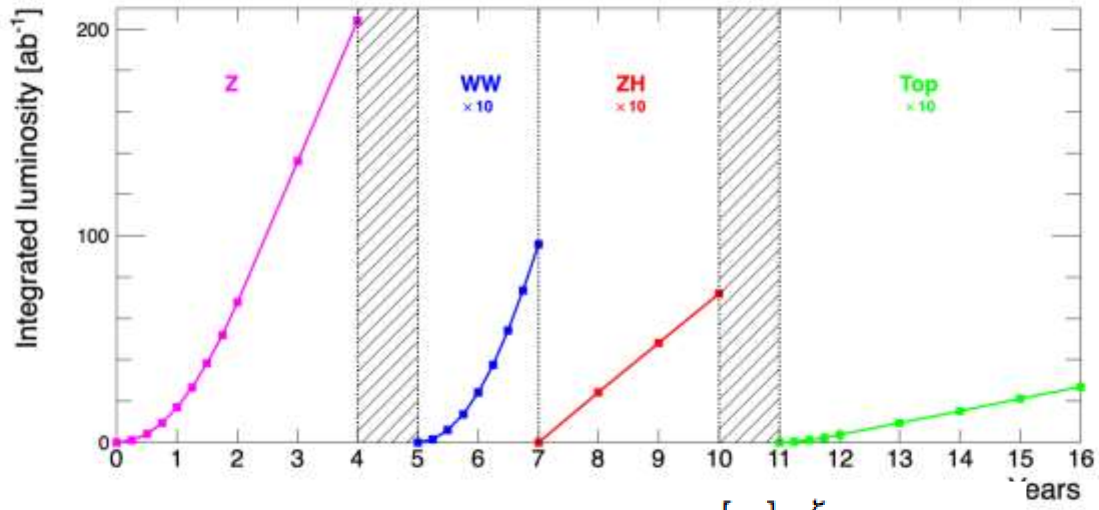
- SRF technology
- Nano-beam technology (damping ring and final focus)
- Positron source



FCC-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 100 MW of synchrotron radiation (2 beams)
- Two 90.7 km rings and booster in the same tunnel
- CDR (2018), Feasibility Study (2021- Mar'2025)
- Start operation in ~2045





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

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

US-FCC Plan (2023)

CERN Timeline*: approved 2028, start civil 2032, install'n 2041, beam 2045
US Timeline**: CD0 ~2029, CD1 2030/31, CD2 2033/34, CD4 2046/47

Proposed scope - RF Systems

1) 800 MHz SRF for Booster and Collider (28 CMs → 244 CMs)
2) 800 MHz RF power sources (klystrons >80% eff.)
3) RF for 6-20 GeV e+/e- injector linac (C3 tech.)

Proposed scope - Magnets Systems

1) IR magnets and cryostats (for 4 IRs)
2) Collider ring and Booster ring magnets (low field)
3) FCC-hh collider ring magnets (14-20 T)

Proposed scope – Optics/Design/Instr.

1) Interaction region design, and integrated machine design
2) Polarization (simul., wigglers, etc)
3) Beam Instrumentation (BPMs, feedback, etc)

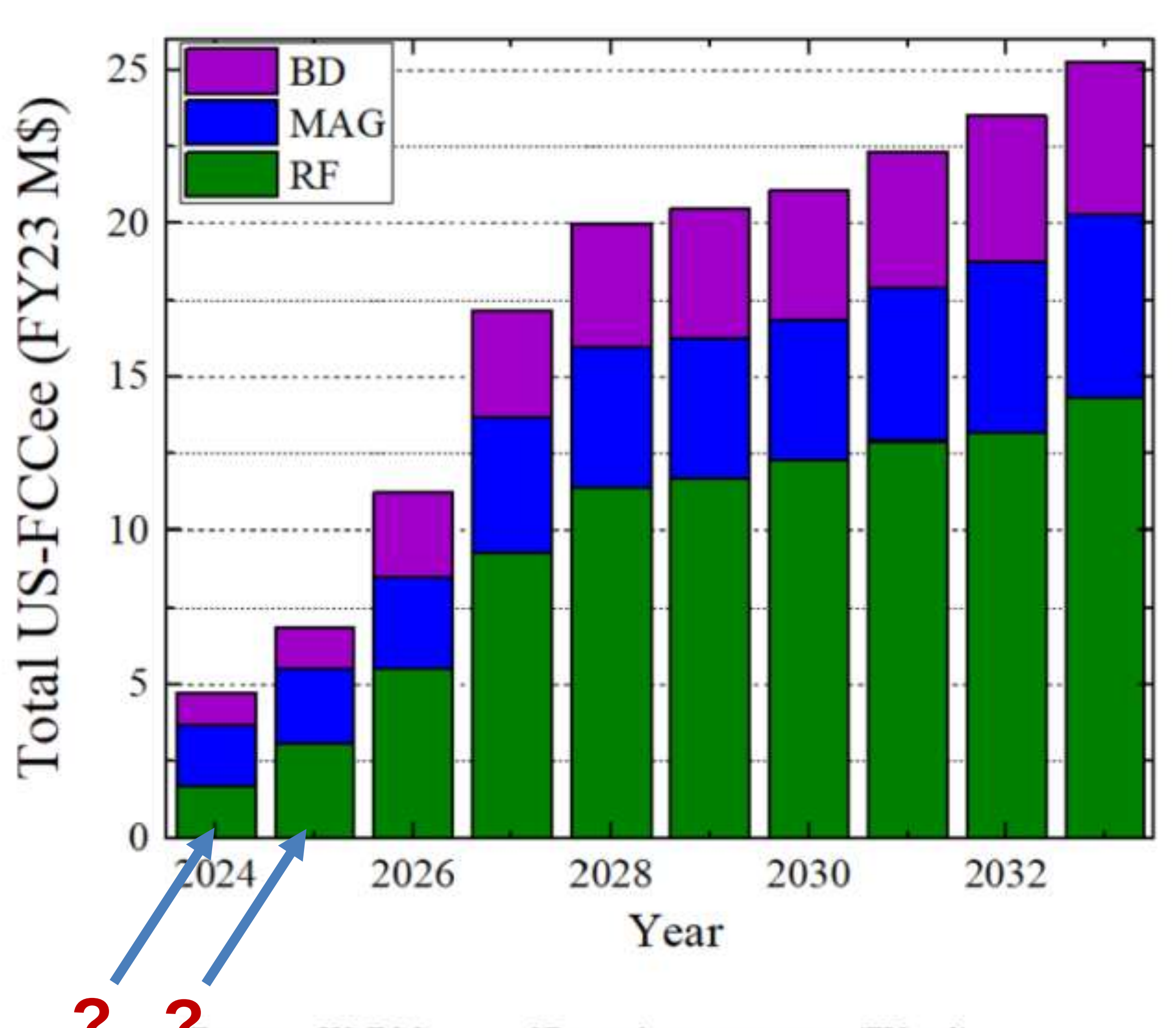
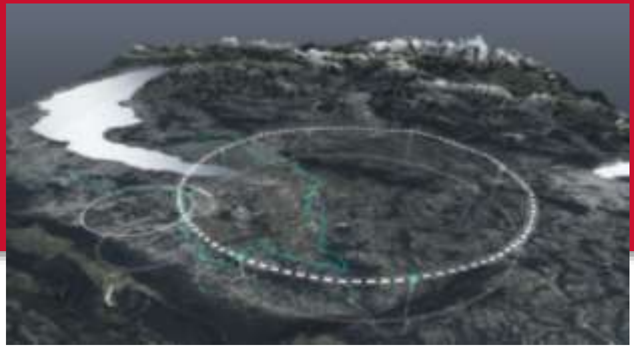


Figure 2: US FCC-ee pre-CD2 work cost estimates (FY23 $).

FCC-hh: Key Issues



- 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 give significantly more time for high-field magnet R&D aiming at highest possible energies
- Start operation in ~2070
- High-field superconducting magnets: 14 - 20 T: The magnet technology will determine the energy reach of the machine (current record 14.5T)
- Power load on cold vacuum chamber in arcs from synchrotron radiation: 4 MW ($\sim 10^3$ times higher than LHC) → cryogenics, vacuum
- Stored beam energy: ~ 9 GJ (~10 times of HL-LHC) → machine protection
- Pile-up in the detectors: ~1000 events/crossing
- R&D to reduce cost (ITF: 30-50 B$ no esc., no cont.) and energy consumption (4 TWh/year) → cryogenics, HTS, beam current, …
- Synergy with ***SppC in China***

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

Muon Collider

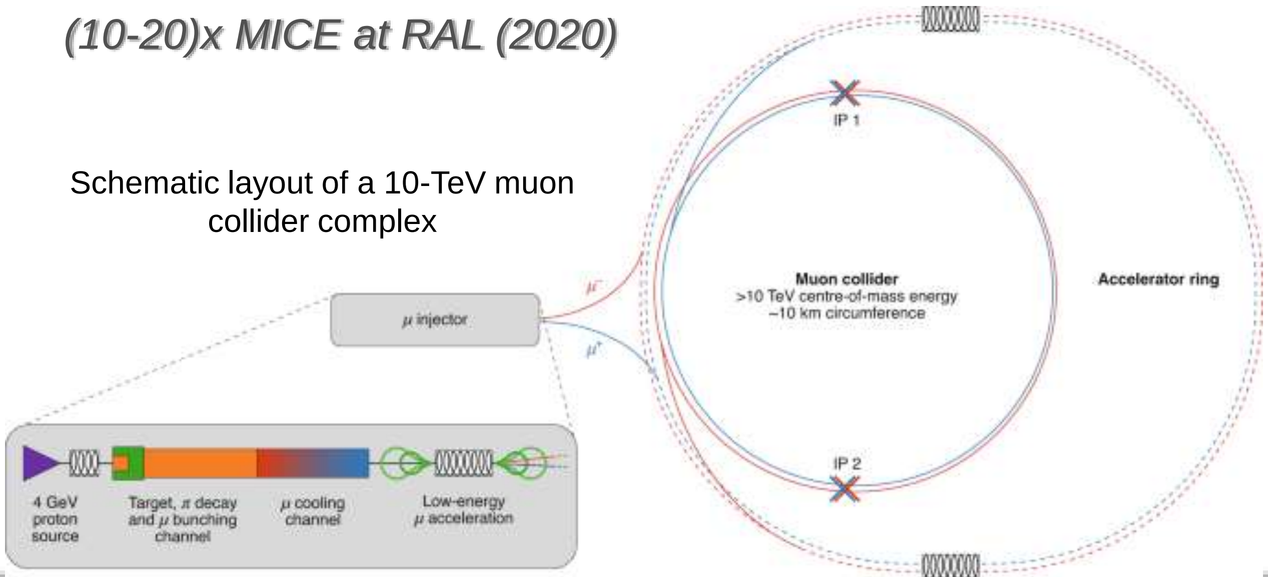
$$\mathcal{L} = \frac{N_+ N_- n_{eff} f_{rep}}{4\pi\sigma_x^*\sigma_y^*}$$

$n_{eff} \approx 150\bar{B} \approx$ 1600 turns

- Muon collider combines precision and energy reach needed to test the deepest questions of particle physics
- x(4-7) smaller footprint than *pp*-collider for the same pCM energy
- Muons are 207 times heavier than electrons and are not limited by synchrotron radiation and beamstrahlung → energy efficiency
- BUT muons decay (2.2 µs lifetime at rest), hence many issues →
- 4-6 years to design of demonstration facility → muon beam R&D

(10-20)x MICE at RAL (2020)

Schematic layout of a 10-TeV muon collider complex



Tentative parameters based on U.S. Muon Accelerator Program 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

- The muon collider concept was developed by NF 1990s-2000s and by the U.S. MAP (2011-2016)
- In 2022 International Muon Collider Collaboration was formed, hosted by CERN
- *Aug.2024:* inaugural US-MCC Meeting (at Fermilab) *

$\mu\mu$Collider Challenges and R&D Topics

P5 priority: by ~2028 prepare a CDR of the 10 TeV+ pCM Collider and TDR of a Demonstrator Facility!

R&D focus on:

Feasibility of Energy Reach

- Fast magnets for the accelerator rings (~few ms, ~20 km)
- Economical high-gradient pulsed SRF (~few ms, ~20-40 GeV)
- Collider ring 12-16 T superconducting magnets (DC, ~10 km)

Feasibility of Luminosity Goals

- Proton driver: 1-4 MW at 5-20 GeV; accumulate bunches with up to 10^{14} particle, compress to few ns; deliver at 5-10 Hz rate
- Targets and cooling: DPAs, ~15 T SC solenoid with ~2 m aperture; high-gradient NC RF in 2-14 T SC solenoids of the ionization cooling channel (these are also prerequisites for the Demonstrator Facility – see next slides)
- Challenging MDI to suppress breakdown originating from muon decays; neutrino flux dilution scheme

Feasibility of Construction Cost

- Fast magnets for the accelerator rings (~few ms, ~20 km)
- Civil construction (~40 km)
- Economical high-gradient pulsed SRF (~few ms, ~20-40 GeV)
- Collider ring 12-16 T superconducting magnets (DC, ~10 km)
- Power infrastructure (~360 MW)

Cost is set by the scale (***energy, length, power***) and technology

~50±10 %

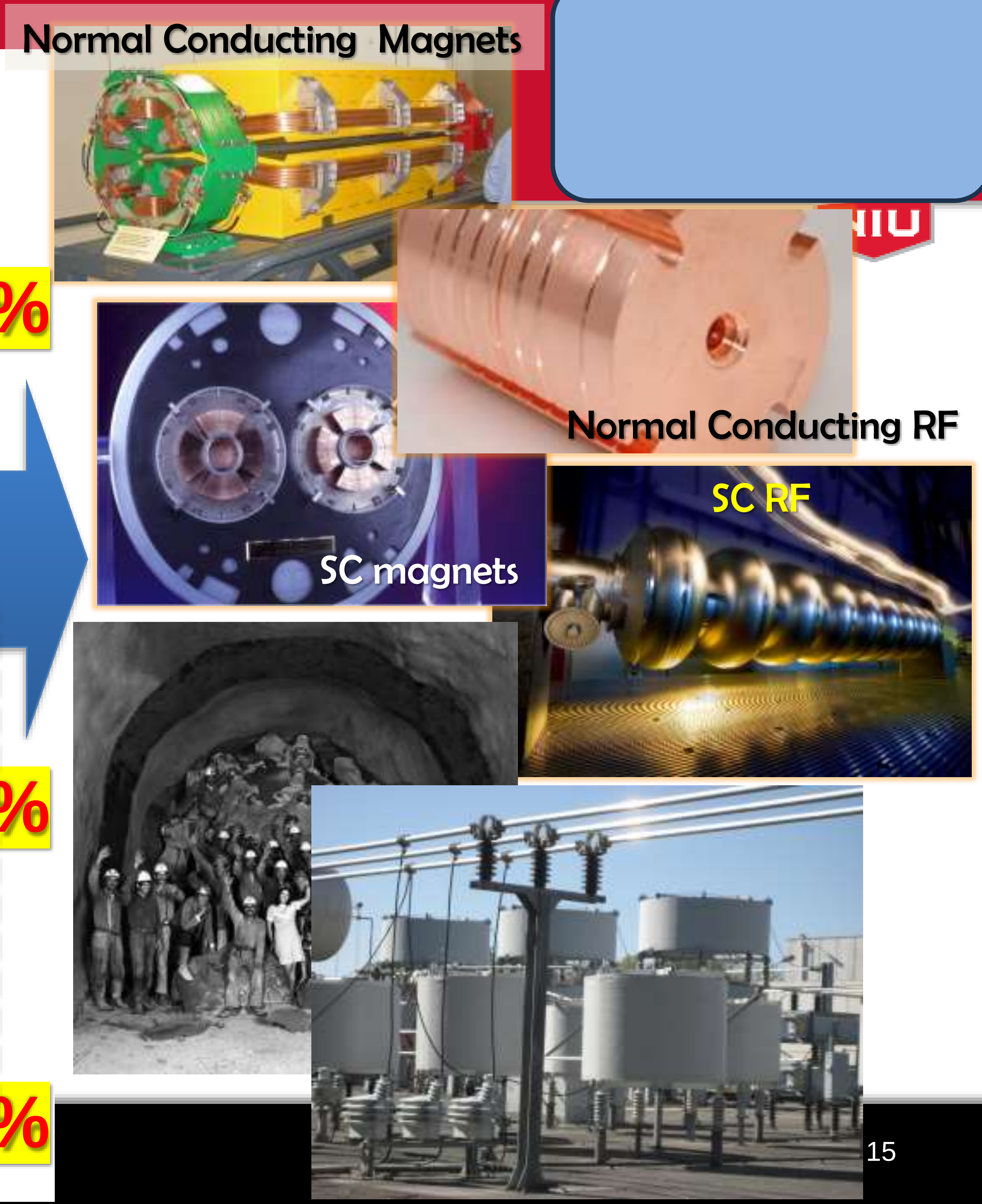
– *Accelerator technology* (magnets NC and SC, RF and SCRF, vacuum, etc)

– *Civil construction technology*

~35±15 %

– *Electric power production, delivery and distribution technology*

~15±10 %



Muons Give Us A Unique Chance!

(due to that factor of ~7 in "equivalent pCM")

- The smallest footprint for "traditional core technologies"
  - less total cost for technology and tunnels

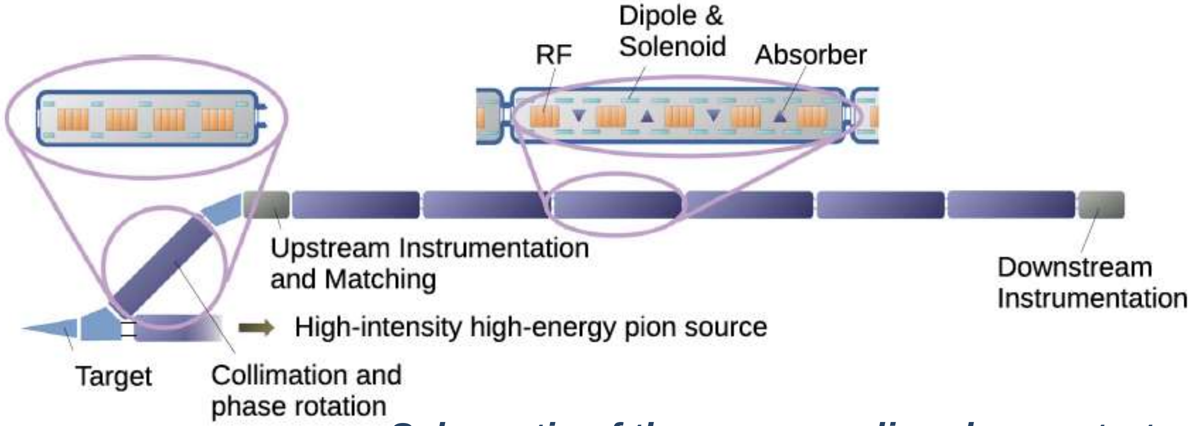
(due to absence of synchrotron radiation → multi-turn acceleration in rings, rather than one-time in linear colliders)

- The lowest power consumption:
  - *per* ab^{-1} and *total* among 10+ TeV pCM colliders
- All in all – "lowest cost + feasible/traditional technologies + fastest"
  - Snowmass'21 ITF estimates *">10 yrs of pre-project R&D*" and "*19-24 yrs to 1st physics*" after the start of the program (not started yet)
  - ***"just do it!"* = CDR → the Demonstrator → TDR → Construction)**

Ionization Cooling Demonstrator

https://doi.org/10.1140/epjc/s10052-023-11889-x

- MC ionization cooling channel consists of ~800 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 (D=1 m) to 20+ T (D=0.05 m)
- RF cavities (300-800 MHz) must operate in multi-Tesla fields
- Wedge-shaped absorbers must and large muon beam intensities



Schematic of the muon cooling demonstrator

	Muon energy, MeV	Total length, m	Total # of cells	B_max, T	6D emm. reduction	Beam loss, %
Full scale MC	200	~980	~820	2-14	x $1/10^5$	~70%
Demonstrator	200	48	24	0.5-7	x 1/2	4-6%

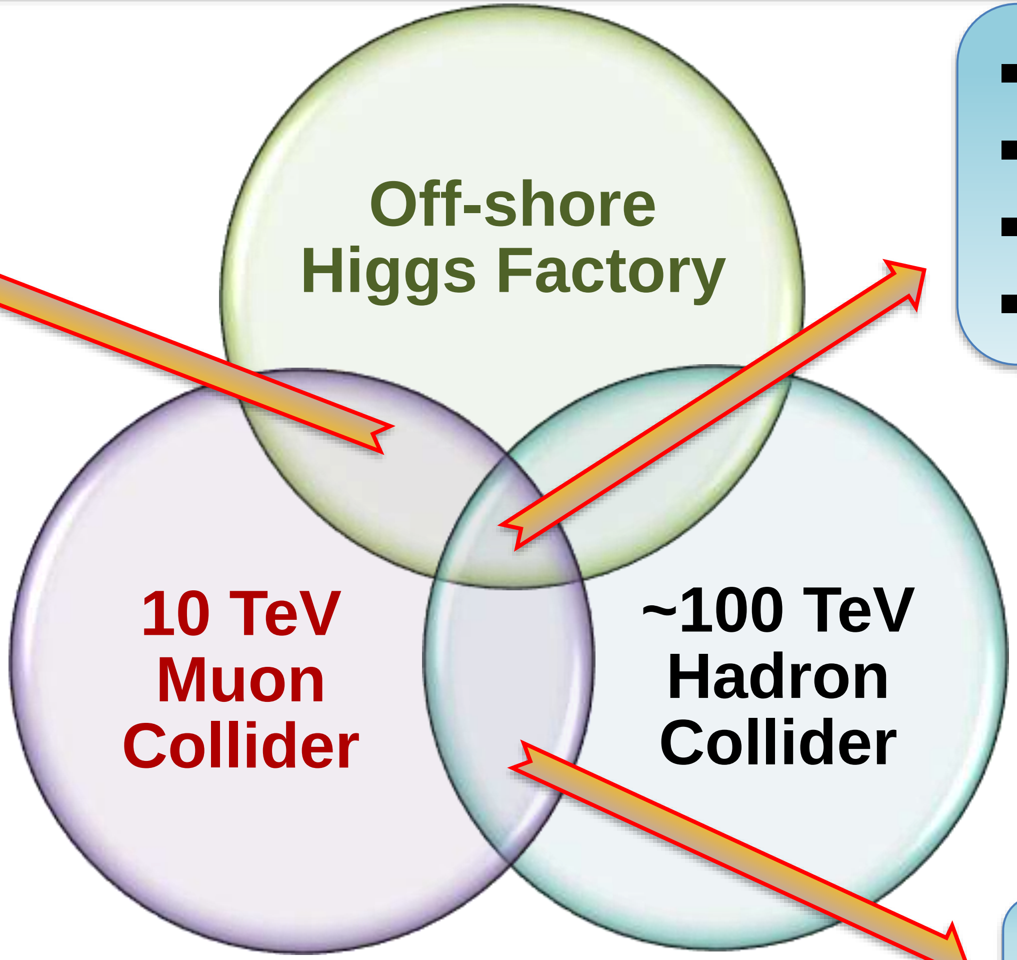
■ Timeline: 2029-2034 ■ Location: Fermilab or CERN ■ Cost: 200-300 M$

R&D Synergies for Future HEP Colliders

- ***RF power efficiency***
- ***SRF systems***

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*



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

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

- ***High-field SC magnets***

Hard "Simple" Question

- Why does it ("*your accelerator R&D*") take so long?
  - 1990's: SLAC linac had 17 MV/m → Now: XFEL has ~25 MV/m (ILC 31.5 MV/m)
  - Muon collider R&D since 1990s → Now: still no CDR
  - 2000s: LHC 8 T NbTi SC magnets → Now: still no 16 T magnets
  - 2006: 1 GeV plasma acceleration stage → Now : sill no demo of multistage
- No "simple" answer …combination of:
  - Our modern-day technologies are too far from *industrial applications*
  - Chasing "*pCM dreams*": 100 GeV → 1 TeV → 10 TeV → 100 TeV → PeV ??
    - Higher energy, higher luminosity, larger [size, cost, power, complexity] → more [$$, people, time] for R&D
  - Always – *limited budget*… more and more often - *inadequate expertise*:
    - bigger scale + "brain drain" to other fields + beam physics abandoned at Universities (in the US)

US Accelerator S&T Workforce:

- **DOE Office of Sciences, P5, EPP2024 recognize diminishing expertise in accelerators (design, projects and operation) in the US and increased demand:**
  - **DESPITE – several recent initiatives:** Particle Accelerators for Science and Society and Workforce Training (2021); RENEW: Reaching a New Energy Sciences Workforce (2023); FAIR: Funding for Accelerated, Inclusive Research (2023); MIni-Workshop on Accelerator Scientist / Engineer Workforce of National Labs (2024)
  - **DESPITE – there are several select institutes :** Center for Advanced Studies of Accelerators, CASA (JLab/ODU); Cornell Laboratory for Accelerator-based ScienceS and Education, CLASSE, and the Center for Bright Beams (NSF); Center for Accelerator Science and Education, CASE, at Stony Brook University (HEP); MSU cryo-initiative – collaboration between FRIB and MSU College of Engineering (NP); Virginia Innovative Traineeships in Accelerators, VITA (DOE)
- **YET – the AS&T workforce situation is actually worsening**
  - Barely enough to keep up with current projects and operations (NP, BES, HEP, …)
  - Plus, the level of expertise required for the future HEP facilities/colliders is much higher

The US HEP Community Must Act!

- **Next big HEP facilities (Higgs Factories, 10+ TeV pCM colliders, etc) will not be "off-the-shelf" particle accelerators,** they require numerous innovative breakthroughs over a range of beam physics topics and accelerator technologies – **over the next *O*(20 years)**
- **That requires the leading US universities to get intellectually involved:**
  - **E.g. out of ~70 Universities represented at this meeting, only 6 have some elements of accelerator R&D (besides major National labs)**
  - **Need more accelerator/beam physics faculty!**

$$\min N_{AST\ faculty} \geq \left[\frac{N_{part.phys.faculty}}{4}\right]$$

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.
- Situation with the **accelerator science and technology workforce** is very worrisome, there are concerns whether the required challenging R&D for HEP colliders can be finished successfully in a reasonable time. Besides the $$ (OHEP prerogative), serious **intellectual involvement of universities** is critical.

Thank you for your attention!

Questions?

Back Up Slides… Not Covered:

- Plasma and other advanced methods. Are they really helpful for HEP?
- *What about China? The CEPC can get approval next year or about.*
- Connections to other fields using accelerators? There's a lot with NP (EIC), FES (magnetic confinement setups), and BES (light sources and spallation neutron sources).
- *How much AST research $$ available now?*


U.S. DEPARTMENT OF ENERGY | Office of Science

Department of Energy Announces $16 Million for Traineeships in Accelerator Science & Engineering

Research projects will partner students with DOE national labs to help students develop hands-on research experience

Today, the **U.S. Department of Energy (DOE)** announced $16 million in funding for four projects providing classroom training and research opportunities to train the next generation of accelerator scientists and engineers needed to deliver scientific discoveries.

These synergies once again emphasize importance of *"General Accelerator R&D"*

High Power Targetry R&D


Metal rod exploded by beam impact

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

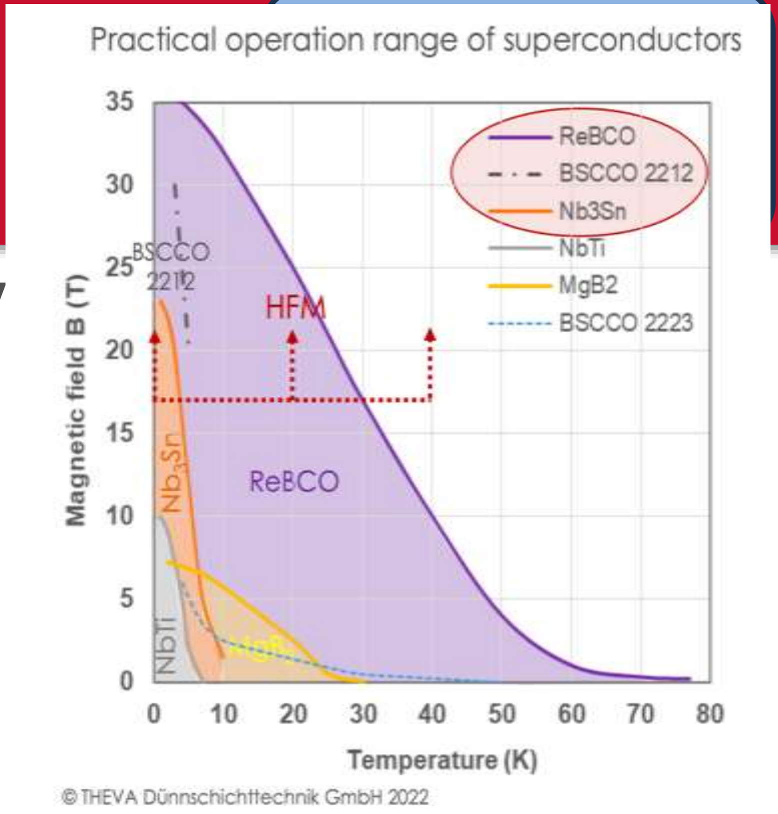
- Multi-MW targets are needed for neutron spallation sources, accelerator neutrino beam facilities and muon colliders
- Currently: 1-1.5 MW targets exist (FNAL, SNS, …)
- Huge challenges above that level:
  - DPAs
  - Thermal shock

Need to be explored:

- New materials (graphite, liquid lead, tungsten powder)
- New forms: wheels, rolling balls, fibers, etc
- Similar issues with horns, baffles, windows, etc
- Modeling and simulation tools
- Dedicated facilities for irradiation studies, pion yield measurements, target survivability/lifetime

	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

Magnet Technology R&D



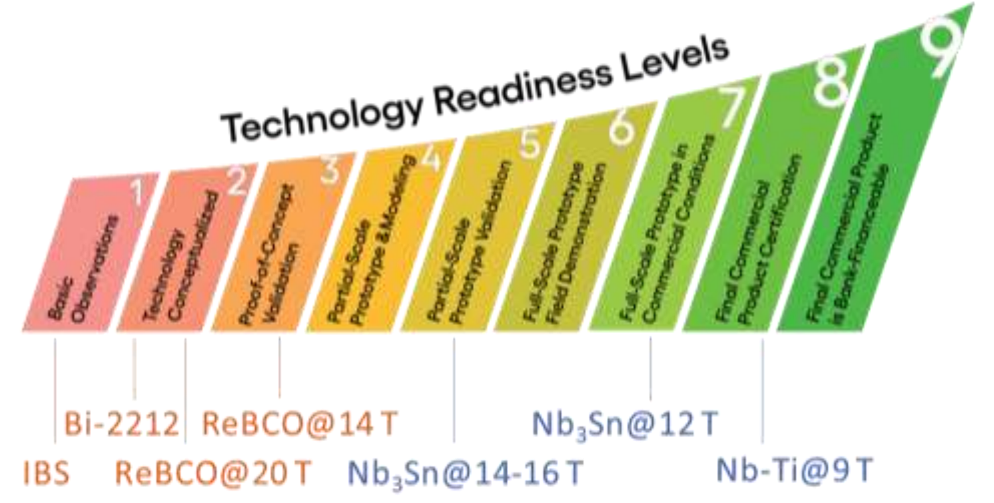
FCC-hh & muon collider require beyond state-of-the-art magnet technology

- 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

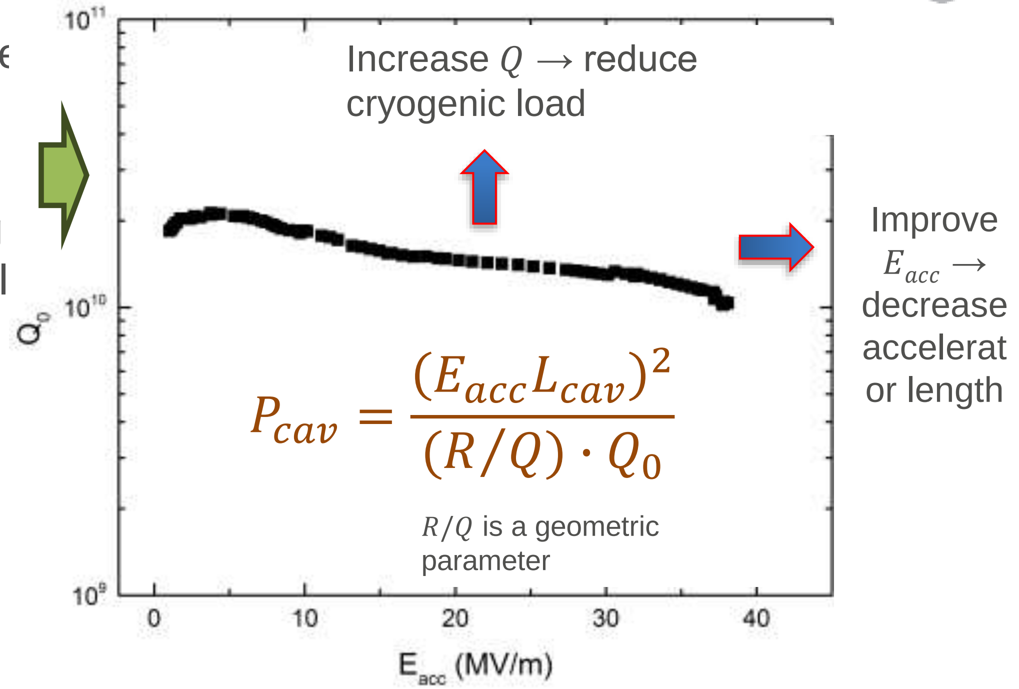


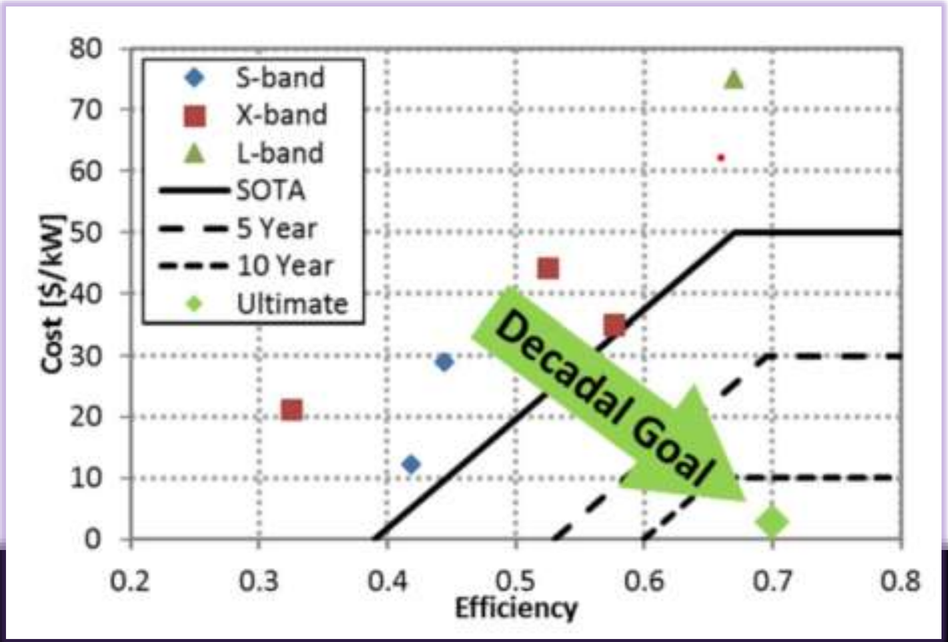
RF Technology R&D Thrusts

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 – incl. C3 technology and operating RF in high magnetic fields as part of the muon ionization cooling channel
- High-efficiency RF sources (FCC-ee, ILC) to reduce overall AC power consumption of the machine

Typical ILC cavity at T = 2 K





From the decadal NC conducting RF structure and RF source 10-year roadmap (2017):
RF source cost including modulators in $ per peak KW vs. efficiency for mature RF source technologies.