National Future Colliders R&D

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On behalf of

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U.S. National Accelerator R&D Program on Future Colliders

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P5 Townhall @ SLAC
May 3-5, 2023

Outline

- Introduction
- Why national future colliders R&D?
- The proposed future colliders R&D program
- Highlights of US engagement in global projects
- Future Collider Options for the US
- R&D plans, synergies
- Closing remarks

Introduction

- The United States has a rich history in particle accelerators and colliders, which enabled major discoveries in particle physics and establishing of the Standard Model.

- Future colliders are an essential component of strategic vision for Particle Physics beyond LHC/HL-LHC.
  - For precision studies of the Higgs; “Use the Higgs boson as a new tool for discovery”
  - For exploration of higher mass scales than will be accessible at the HL-LHC

- To ensure continued progress, U.S. leadership is critical
  - Future colliders need US expertise. US engagement should be early for maximum impact and leadership roles.
  - Develop compact, cost-effective options for hosting future colliders at home

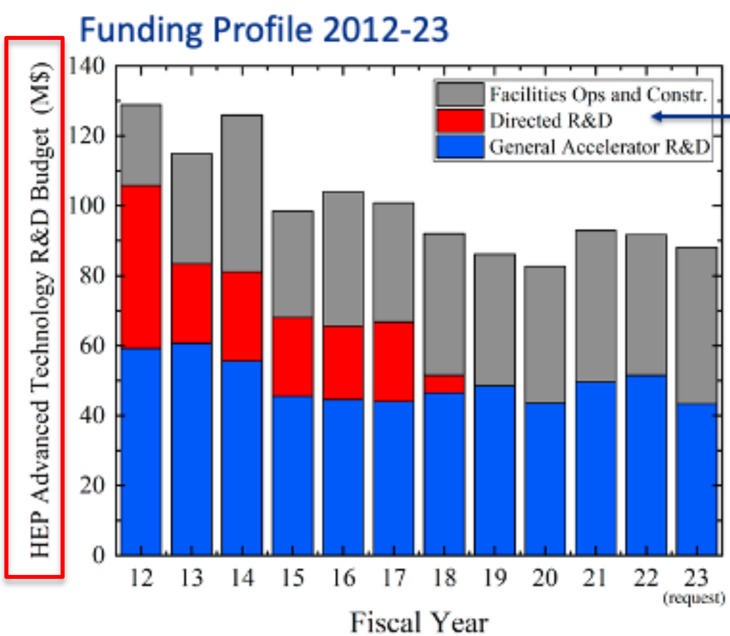
- The US HEP “Snowmass” and P5 process provide a timely opportunity to define and forge a bold new path forward.

Snowmass21 EF and AF Highlights

- The Snowmass Energy Frontier vision calls for
  - the U.S. to facilitate construction of a global e^+e^- Higgs Factory, as soon as possible
    - Prime (mature) candidates: FCC-ee, ILC, CLIC
    - New, novel concepts: C3, HELEN,..
  - vigorous R&D to develop designs for a high energy collider to access physics at ~10 TeV partonic scale and beyond
    - FCC-hh, Muon Collider,..
- The US energy frontier community also expressed
  - its ambition to bring back energy frontier collider physics to the US soil, while maintaining its international partnerships and obligations, and
  - its support for the U.S. initiative for the targeted development of future colliders and their detectors
- The accelerator frontier concluded that the US and global community have the expertise in a broad array of accelerator technologies needed to design and construct any of the near-term accelerator projects and that the planning of R&D should be aligned with the strategic planning for particle physics.
- The proposed national future colliders R&D program also garnered strong support from the community, after extensive discussions at a major session dedicated to the topic, at the 2022 Snowmass summer meeting in Seattle.

Why Future Collider R&D?

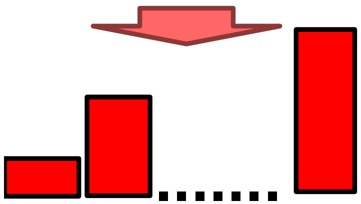
- The U.S. HEP accelerator R&D program has no support for targeted development of collider concepts for strategic planning
  - Compromises U.S. leadership role in collider design and development
  - Severely limits our ability for strategic planning of US based colliders
  - Limits U.S. leadership in particle physics
- An integrated national accelerator R&D program on future colliders is proposed to address this shortcoming in the U.S. accelerator R&D.



Completed:
US ILC
US LARP (LHC)
US MAP (Muon)

No support for directed R&D on future colliders since 2019
Total down from $130M to ~$90M

Proposed for 2024-30:
Future Colliders



Objective of the Proposed Program

- **The overarching objective: Address in an integrated fashion the technical challenges of promising future collider concepts, particularly those aspects of accelerator design, technology, and beam physics that are not covered by the existing General Accelerator R&D (GARD) program.**

- The goal is to advance design studies and technologies to help in the selection among the collider concepts by the next European strategy update and the next US community planning cycle
  - Help move towards realization of the next collider (e+e- Higgs factory) as soon as possible
  - Help to advance towards a collider at a higher energy scale to probe multi-TeV scale

Advancing Technology and Workforce Development

- The proposed accelerator R&D program will energize accelerator and particle physics communities, inspire (give hope to) and engage the early career community, and advance collider concepts and technologies to accelerate science.
- The R&D program will
  - enable substantial and synergistic U.S. engagement in ongoing global efforts
  - help develop Collider concepts and proposals for exciting and novel options feasible to be hosted in the US
- The program will also help attract new talent, develop, train and retain a skilled workforce in accelerator science and technology.
  - Each R&D project for a major collider concept requires 40 – 50 FTE/year.   It is critical to start workforce development ASAP.
- A significant investment commensurate with delivery of the above goals is required. There should be balanced investments between near-, medium-, long-term R&D.

Scope of the Proposed R&D Program

- Sharply focused on future colliders
  - Address challenges for next future colliders (i.e., Higgs factories) and for further future collider concepts for ~10 TeV-scale machines
- Spans accelerator design, technology and full concept development
  - Supports critical R&D for a concept
  - Enables full development of collider concepts
- Complements the existing HEP GARD program
- Multifaceted but selective, and synergistic
  - Support multiple approaches but be selective among R&D topics in a way that leads to converging on viable option(s)
  - Cost-effective, opportunity for technical benefits, innovation
- **Priorities guided by P5 recommendations**

R&D Organization and Coordination

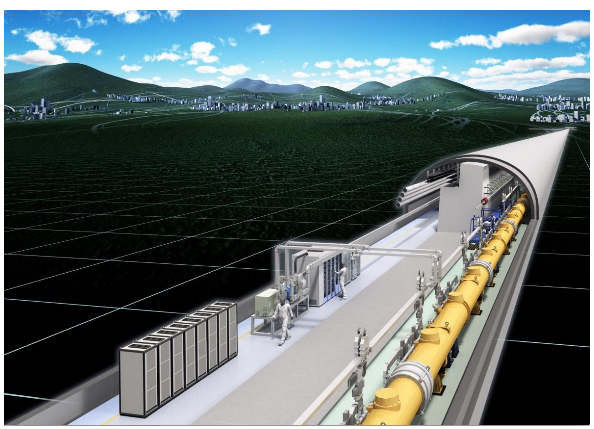
- Organization:
  - Coherent national program
    - Key: Advance developments and preparedness for future colliders
    - Program's portfolio of activities centrally selected, coordinated
    - **Guided by P5 priorities** and an Advisory Committee/Board
    - Funding allocations through internal proposals/review process by the Program
  - Collaborative effort of U.S. national labs and universities; under DOE OHEP
- Coordination:
  - Centrally coordinated and funded
    - Management hosted at a national lab
  - Coordinated with global design studies and R&D
    - Avoid duplication of efforts, engage in complementary R&D
  - Periodic assessment
    - Of coherence of activities, specifications
- Once the next collider choice is made, it is expected that
  - a collider-specific directed R&D project is created, and
  - the scope of the integrated program can be reevaluated.

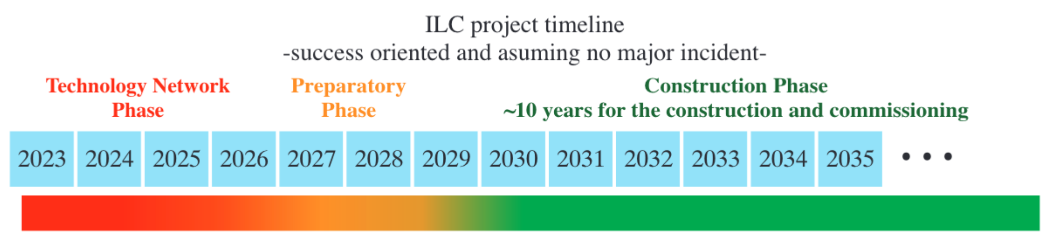
Status and Highlights of U.S. Engagement in Global Projects

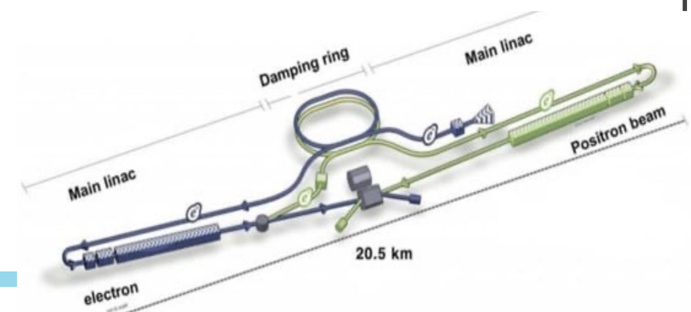
The International Linear Collider (ILC)

See talks by Nakada, Belomestnykh, Michizono

- “Shovel ready”, but no one to host, yet
  - Could be operational by ~2040, if started within the next ~5 years
- The US, having led the global design effort, is an integral part of the ILC-International Development Team (IDT) and potentially a part of the ILC Technology Network (ITN), if recommended by P5.
- U.S. scientists are engaged in efforts of the ILC-IDT on the accelerator and detector design and R&D
  - SRF R&D for ILC main linacs, crab cavities, Sources: polarized e- & e+, conventional e+, damping rings and kickers, beam delivery system and beam physics

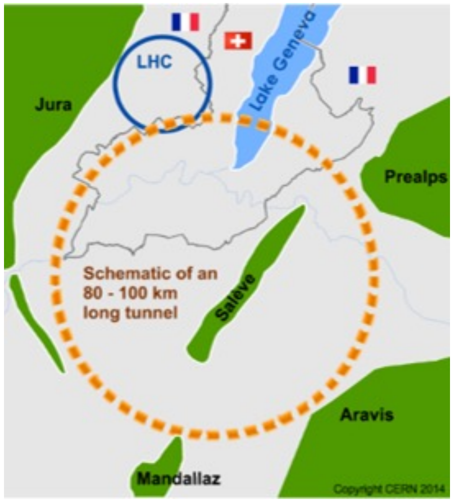




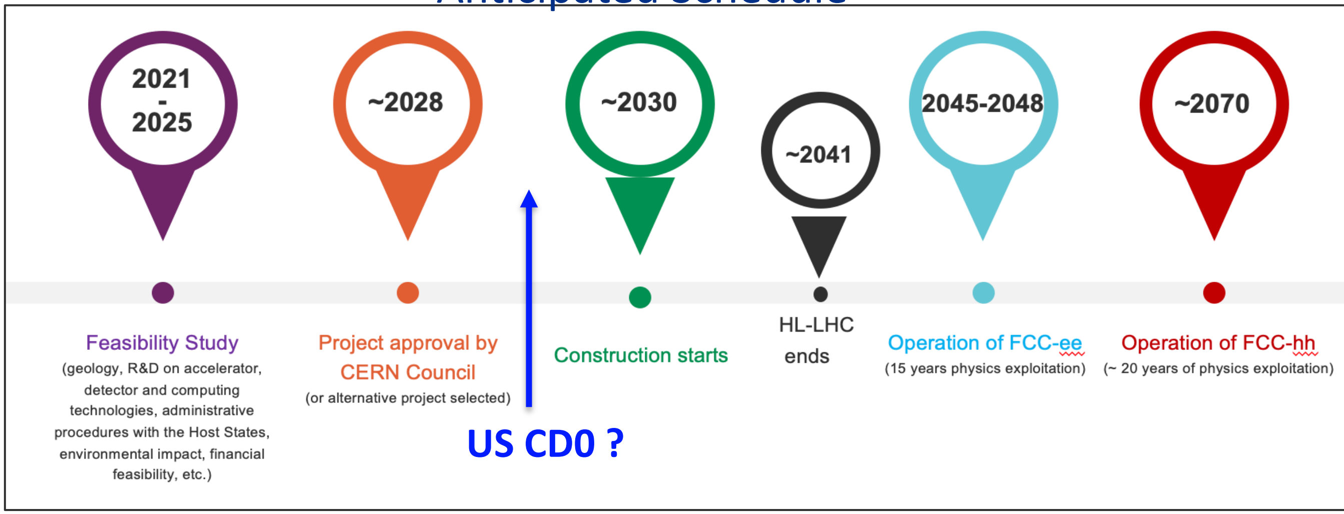


Future Circular Collider (FCC)

See talks by Zimmermann, Shiltsev



Anticipated Schedule



- Dec. 2020 ← CERN-DOE agreement signed
- US represented in FCC organization
  - Lia Merminga (Steering Committee), Andy Lankford (CB Vice-Chair), Tor Raubenheimer (co-lead for accelerator)
  - US-FCC Planning Panel has been formed just recently
- Plan for US-CD0 in 2029, assuming project approval in 2028
- Opportunities/interests for US efforts
  - High Q_0 SRF (400/800 MHz) R&D, NCRF (C^3-type cavities), SC IR magnets R&D, MDI, polarization, Beam Instrumentation, beam physics, (FCC-hh magnets)

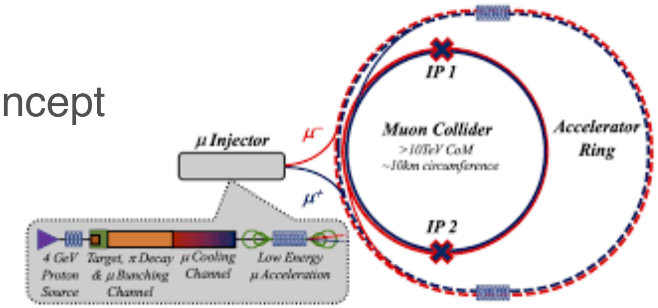
Relevant US expertise

	ANL	BNL	FNAL	LANL	LBNL	JLab	SLAC	Universities
SRF cavities/CMs			■			■	■	Cornell, ODU ...
RF sources/modul.	■						■	IIT, Stanford
Copper RF linac	■			■			■	NIU, IIT
IR magnets		■	■		■			FSU, MIT, TAMU
Booster/MR magnets	■	■	■		■			
Beam Optics	■	■	■	■	■	■	■	Cornell, ...
Collimation		■	■				■	
Polarization		■	■			■		Cornell, UNM, ...
Instrumentation	■	■	■		■	■	■	many
Infrastructure	■	■	■	■	■	■	■	

First US-FCC workshop @ BNL held Apr. 24-26, 2023
https://indico.cern.ch/event/1244371/

International Muon Collider Collaboration (IMCC)

- The IMCC, established by European Lab Directors' Group (LDG), hosted at CERN, is charged to carry out a study of the Muon Collider concept.
- The IMCC goal:
  - Develop a baseline project for a proton driver-based concept
  - Focus on 10 TeV collider with 3 TeV as an early option
  - Use output of US Muon Accelerator Program (MAP) as starting point
  - Study report to be delivered by the time of the next ESPP update to inform decisions on CERN's future machine



- US community is engaged with IMCC
  - A few universities have Memorandum of Cooperation; Others, National Labs, would like formal engagement
  - Several US scientists in coordinating roles
  - Ongoing studies of machine scenarios, beam induced background, neutrino radiation, demonstrator facility, detector/physics simulation studies

Examples of other R&D:
- 15T SC dipoles (jointly with MDP)
- High power test of HG SRF
- Design/test of High power targetry
- Design of muon cooling demo
- Accelerator/collider design

Developing
Collider Options for the US

Future Collider Options for the US

Future Collider Options for the US

arXiv:2203.08088

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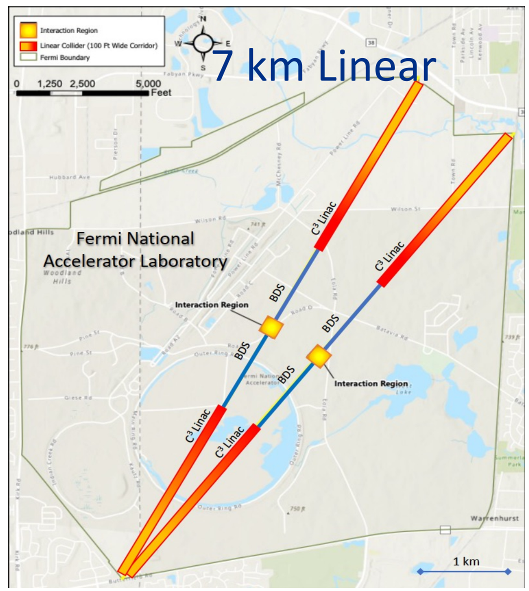
$\mu^+\mu^-$ 6-10 TeV

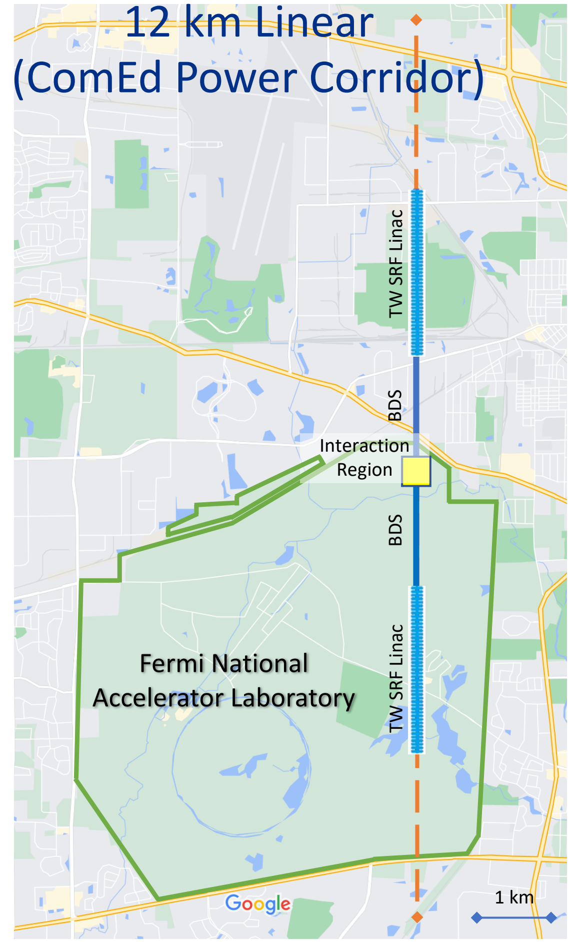
e^+e^- 240 GeV

pp 25-26 TeV



e^+e^- 250 GeV

(C3, HELEN)



e^+e^- 250 - ≥550 GeV

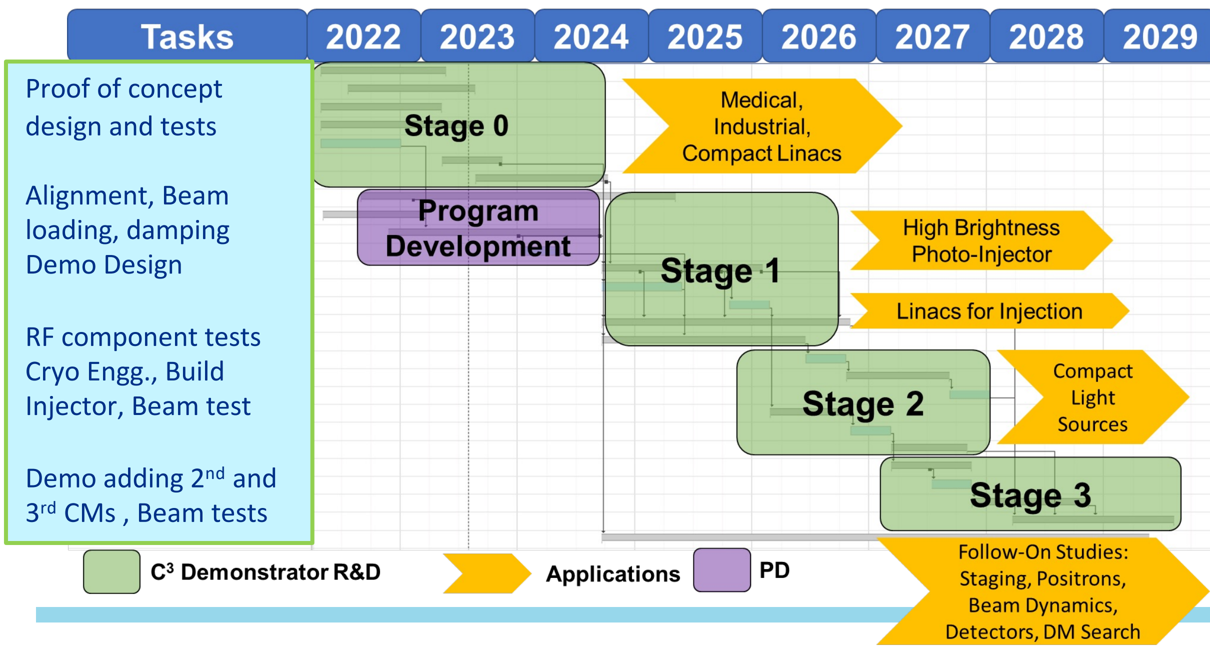
(C3, HELEN,...)

The Cool Copper Collider

The C³ R&D and Demonstrator

See talk by Nanni

- A novel concept for a collider with normal conducting RF cavities operating at 77K. Attractive as it affords high gradients ~ 70 - 155 MV/m.
- C³ benefits from other developed LC technologies such as ILC, CLIC
- C³ NCRF technology can have HEP applications beyond the collider. e.g., for FCC-ee injector, e- driven e+ source for ILC, muon collider cooling channel and acceleration in RCS; and many non-HEP applications including medical and FELs, x-ray sources.



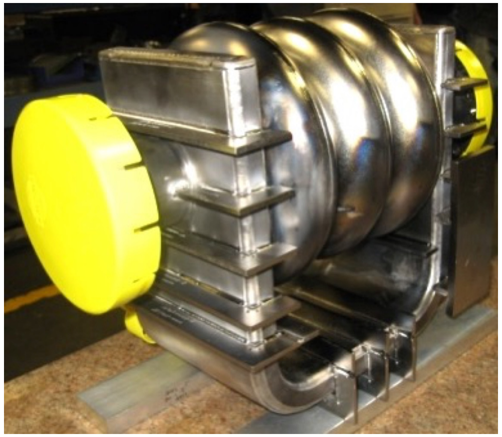
C³ demonstrator R&D needed before a CDR:

- 3 fully engineered cryomodules; ~50 m facility, 3 GeV energy
- Organized in 3 stages; success of each stage leading to applications

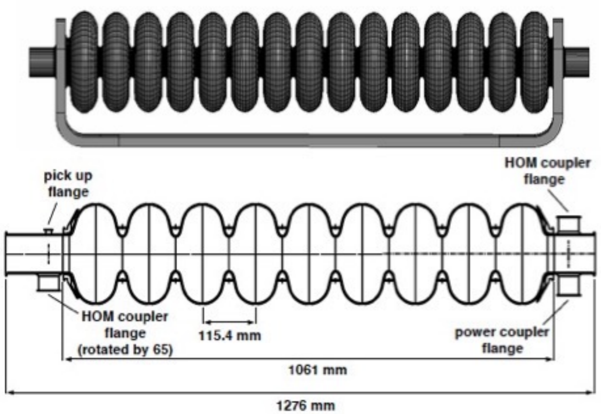
Higgs Energy LEptoN (HELEN) Collider

- HELEN is a linear collider concept based on high gradient SRF
  - 55 MV/m to 90 MV/m; standing wave or travelling wave structures.
- Travelling wave (TW) structures offer some advantages over the traditional standing wave SRF structures:
  - Substantially lower peak surface magnetic field → higher ultimate limit on the accelerating gradient, up to ~70 MV/m.
  - Substantially higher (factor of 2) R/Q → better cryogenic efficiency.
- The proposed SRF R&D program would focus on advancing the TW SRF technology to demonstrate its feasibility
  - Testing and improving performance of the 3-cell cavity at Fermilab (fabricated under an SBIR project)
  - Design and test proof-of-principle fully dressed TW cavity.
  - Design and build a prototype TW SRF cryomodule. Potentially test with beam, e.g., at FAST (Fermilab).

Travelling Wave SRF R&D



Fabricated 3-cell TW cavity

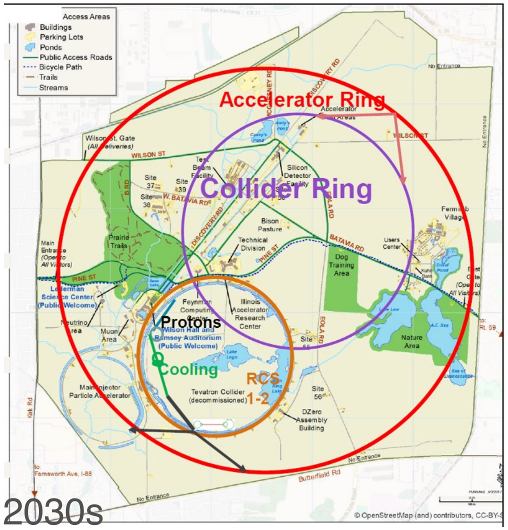


The TW structure with a 105° phase advance per cell (top) compared to the one-meter standing-wave TESLA structure (bottom)

Muon Collider in the US

See talk by Stratakis

- The prospects for a Muon Collider has enchanted and inspired a significant fraction of the US collider community!
  - A Compact collider for multi-TeV scale; power efficient
  - A precision and discovery machine!
  - Can be staged with physics at each stage
  - Demonstrator facility; sub-TeV, 3 TeV, 6-10 TeV
- Focus on 6-10 TeV collider to fit Fermilab site
- R&D Plans for 2023-2030
  - Work with IMCC on the study of a proton driver-based concept
  - Accelerator design, technology R&D, component R&D/tests
  - Produce a Reference Design for a 6-10 TeV collider by 2030
  - Produce a Technical Design for a Demonstrator to be hosted in the 2030s
- US Coordination group has been formed
  - Chairs: S. Jindariani, D. Stratakis, S. Dasu



A 6-10 TeV Muon collider can fit on Fermilab site

A Muon Collider is highly compatible with Fermilab accelerator complex. With ACE, the complex can provide a great platform for Muon Collider component R&D and the demonstrator project, and provide the foundation to host the collider. Has synergy with potential future Fermilab physics program with neutrinos, muons, an advanced muon facility, dark matter searches, ..

Exploiting Synergies in R&D

- The collider R&D program will exploit synergies between collider concepts and technologies.
- Given the existing talent/skills pool (which maybe limited) for the R&D, it is necessary to share it across projects to make progress.
- Following critical areas have a lot of synergies across colliders considered

	Colliders
– RF System	
• High gradient, high efficiency SRF cavities	ILC, HELEN, MuC, FCC-ee
• High gradient NCRF	CLIC, C3, MuC, FCC-ee
• High efficiency power sources	All
– Magnets	
• Large bore solenoids	MuC
• Low field magnets	FCC-ee
• High Field Magnets (~16T)	MuC, FCC-hh (MDP)
• IR magnets	All
• Fast ramping magnets	MuC, FCC-ee

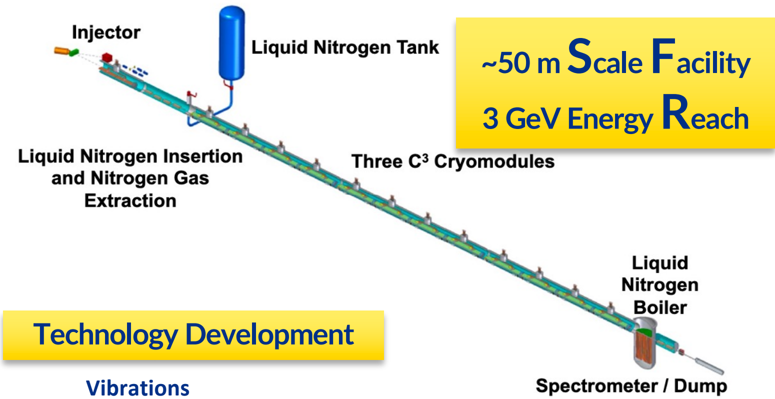
See talk by Prestemon

- Accelerator/Collider Design
  - Parametric studies, beam dynamics, hardware specs, beam control and instrumentation
  - Synergy for e+e- Higgs factories: Injectors, Positron source, Beam polarization, Beam Delivery System (BDS), Interaction Region (IR), Machine Detector Interface

C³ and Muon Collider R&D plans call for demonstrators

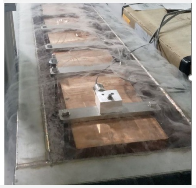
C³ Demonstration R&D Plan (2024-30)

- **Demonstrate operation of fully engineered and operational cryomodule**
- Demonstrate operation with full cryogenic flow
- Multi-bunch photo injector - high charge bunch to induce wakes, tunable delay witness bunch to measure wakes
- Demonstrate fully operational gradient 120 MeV/m (and higher > 155 MeV/m)
- **Fully damped-detuned accelerating structure**



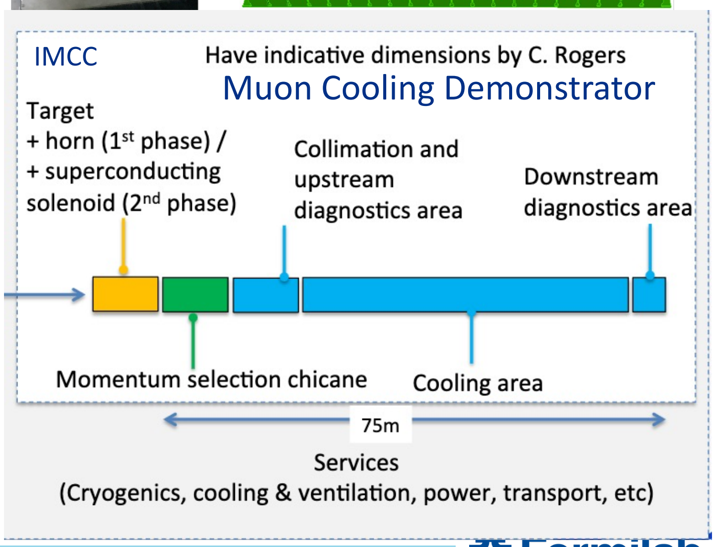
Technology Development

Vibrations



Muon Collider Demonstrator R&D (2031-40?)

- Fermilab is a possible site for the demonstrator
- TDR for the demonstrator to be produced by 2030
- Modular approach, add as demo progresses
- Component materials R&D to demonstrate radiation and shock resistance
- High field magnet tests with muon production, cooling, acceleration
- High gradient, NC RF cavities in cooling channel and SRF for acceleration
- **Demonstrate a fully integrated module as an engieeering prototype**



Closing Remarks

- In order to position the U.S. as a leading partner in future HEP facilities hosted abroad and to develop the concepts, technology and capacity to host a future collider in the U.S., the proposed U.S. national accelerator R&D program focused on future colliders is essential.

- The first recommendation of the P5 2014 was, “Pursue the most important opportunities wherever they are, and host unique, world-class facilities that engage the global scientific community.”
  - It is in that spirit that the U.S. Future Colliders R&D program is proposed.

- We ask P5 to recommend
  - Creation of an integrated U.S. national R&D program, with new investment, directed towards engagement in future collider projects abroad as well as developing concepts for future colliders to be considered for hosting in the US.

Extra Slides

Future Colliders R&D Program: Synergies

- OHEP General Accelerator R&D Program (GARD)
  - Labs and Universities, test facilities and research
  - About 95M$ total (FY 2022)
- Present GARD thrusts (and synergies):
  - Advanced Acceleration Methods (33%)
    - Wakefield modeling & simulation tools
  - Superconducting magnets and materials (22%)
    - High-field SC magnets, advanced SC materials, test facilities, …
  - RF Acceleration Technology (18%)
    - High performance SRF and NC cavities/CMs, RF sources, test facilities, …
  - Accelerator and Beam Physics (18%)
    - Integrated machine design, codes, instrumentation and controls, beam facilities
  - Particle Sources and Targets (2%)
    - Multi-MW targets, positron sources, test facilities …
- Non-HEP synergies, International partners

AF Implementation Task Force

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
FCC-ee[1,2]	0.24 (0.09-0.37)	7.7 (28.9)	0-2	13-18	12-18	290
CEPC[1,2]	0.24 (0.09-0.37)	8.3 (16.6)	0-2	13-18	12-18	340
ILC[3] - Higgs factory	0.25 (0.09-1)	2.7	0-2	$<$12	7-12	140
CLIC[3] - Higgs factory	0.38 (0.09-1)	2.3	0-2	13-18	7-12	110
CCC[3] (Cool Copper Collider)	0.25 (0.25-0.55)	1.3	3-5	13-18	7-12	150
High Energy ILC	3 (1-3)	6.1	5-10	19-24	18-30	$\sim$400
High Energy CLIC	3 (1.5-3)	5.9	3-5	19-24	18-30	$\sim$550
High Energy CCC	3 (1-3)	6.0	3-5	19-24	12-18	$\sim$700

AF Implementation Task Force (cont.)

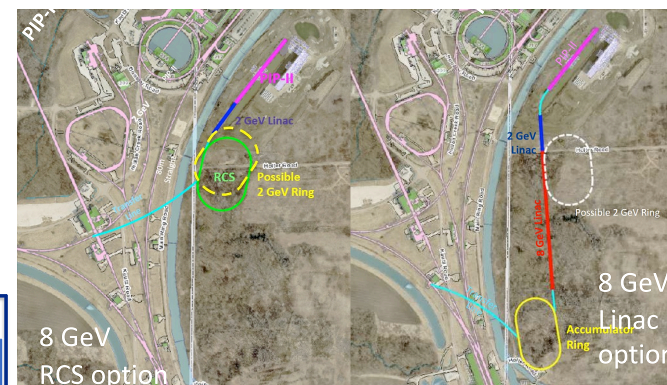
Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
Muon Collider	10 (1.5-14)	20 (40)	>10	>25	12-18	~300
FCC-hh	100	30 (60)	>10	>25	30-50	~560
SPPS	125 (75-125)	13 (26)	>10	>25	30-80	~400

Fermilab ACE and the Muon Collider

- A Muon Collider is highly compatible with the Fermilab accelerator complex. With ACE, the complex provides a great platform for Muon Collider component R&D and for the demonstrator project.
- The idea of a Muon Collider at Fermilab is not a new idea! Explored in late 90s and 2000s, leading to US-MAP in 2011-14.
- The R&D and demonstrator facility have synergies with a number of proposed future experiments at Fermilab
  - Short and long baseline neutrino program; Charged lepton flavor violation; Dark matter searches,…

See talks by Stratakis, Convery

Fermilab Accelerator Complex with the new PIP-II Linac (under construction)



Plans for Fermilab Accelerator Complex Evolution (ACE)

Muon Collider Proton Driver Parameters	
Energy	5-15 GeV
Rep. rate	5-10 Hz
Ave. Beam Power	1-4 MW
Proton structure	1-3 ns bunch with ~10^{14}

Synergies with ACE program			
ACE	Target	SRF	Proton Driver
Main injector upgrade	YES		
Booster replacement	YES	YES	YES

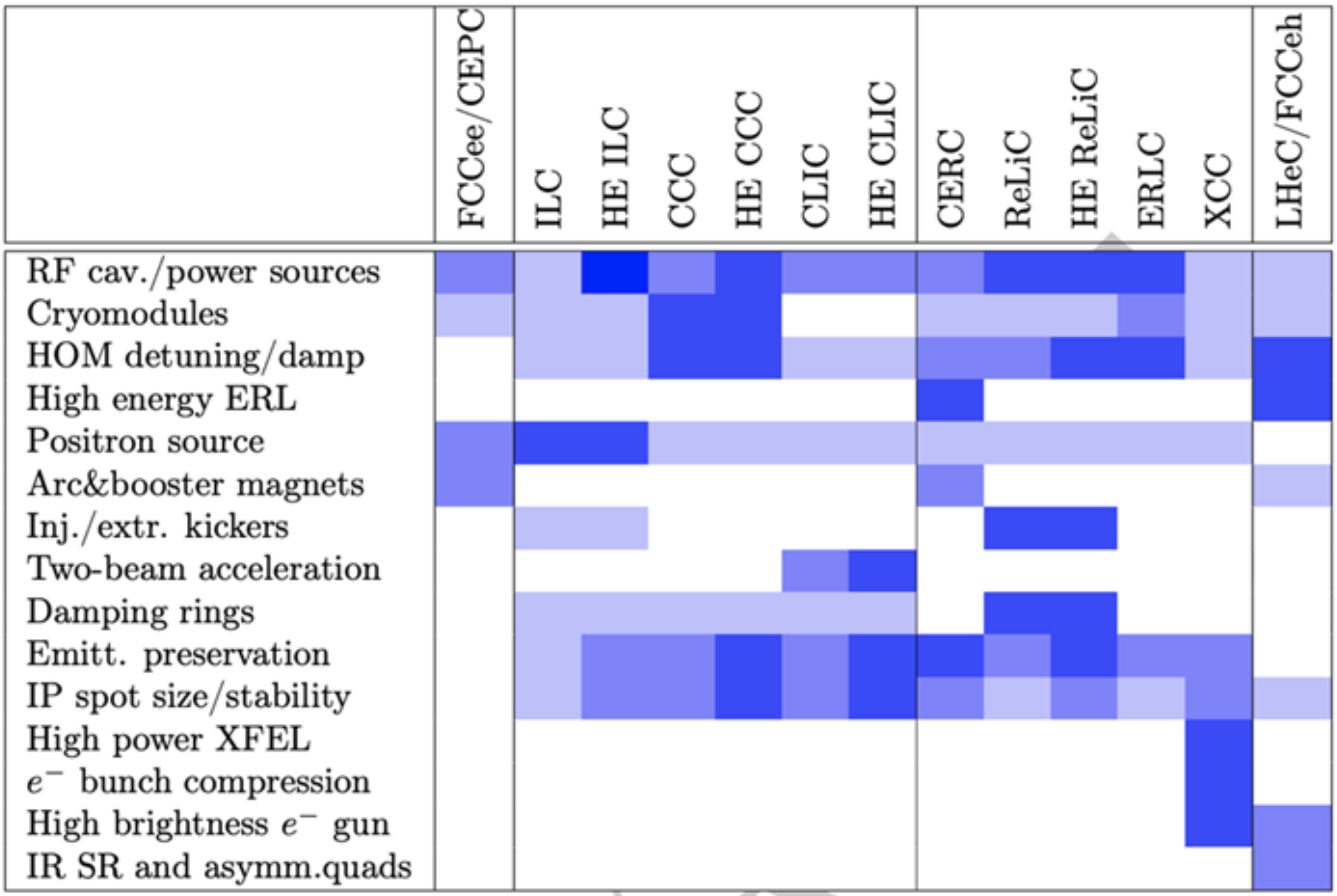
Booster Replacement Scenarios

- Initial scenarios under explorations included cases where available 8 GeV power is in 1-2 MW range
- Exact parameters still to be defined, including input from the upcoming ACE physics workshops

	Nominal	New RCS Scenarios			8 GeV Linac Scenarios		
Parameter		**v1**	**v2**	**v3**	**v1**	**v2**	**v3**
Linac Energy	0.8 GeV	2 GeV	2 GeV	2 GeV	8 GeV	8 GeV	8 GeV
Linac Current	2 mA	2 mA	2 mA	5 mA	2.7 mA	5 mA	5 mA
Rep. Rate	20 Hz	10 Hz	20 Hz	20 Hz	10 Hz	10 Hz	20 Hz
8 GeV Beam Power	160 kW	320 kW	960 kW	960 kW	320 kW	760 kW	1600 kW

Parameter	PIU scenarios	MuC-PD scenarios
Energy	8 GeV	8-16 GeV
Rep. rate	10-20 Hz	5-20 Hz
Avg. beam power	0.3-1.6 MW	1-4 MW
Proton structure	25-40 e12 over 2 μs ring	40-120 e12 in four 1-3 ns bunches

Synergies for Higgs Factories. (From ITF report)



Muon Collider Challenges, R&D Needs

- Multi-MW proton source as a driver for muon production
  - Fermilab ACE can provide MW-scale proton beam
- High power (multi-MW) target (HPT); target in high field solenoid
  - Synergy with multi-MW target R&D for LBNF/DUNE
  - Synergy for target in solenoid with Mu2e (and upgrades) and Advanced Muon Facility (AMF) proposal
  - Muon Collider targetry included in GARD (HPT Roadmap)
- Magnets: Large aperture solenoids (cooling, capture), fast ramping magnets (accelerator), High field magnets (accelerator, collider)
- Muon Cooling Study/Simulations
  - Absorber materials, High gradient NC RF in high fields
  - Realistic end-to-end design in next 5 years
- Muon Cooling Demonstrator
  - TDR by 2030 for a 6D cooling demonstrator with realistic lattice design
- IR design, MDI, etc.
- Neutrino flux mitigation

Design studies and some of the component R&D can begin now