Caption

Snowmass'21 Accelerator Frontier

Snowmass 2021

Steve Gourlay, on behalf of the
Snowmass'21 Accelerator Frontier Conveners:
T. Raubenheimer, V. Shiltsev and S.G.

Accelerator Frontier

Caption

Steve Gourlay (LBNL -> FNAL)

Tor Raubenheimer (SLAC)

Vladimir Shiltsev (FNAL)

Description

The Accelerator Frontier activities included discussions on high-energy hadron and lepton colliders, high-intensity beams for neutrino research and for "Physics Beyond Colliders", accelerator technologies, science, education and outreach as well as the progress of core accelerator technology, including RF, magnets, targets and sources. Participants submitted Letters of Interest, contributed papers, took part in corresponding workshops and events, contributed to writing summaries and took part in general Snowmass'21 events.

Accelerator Frontier – Key Questions

Caption

1. What is needed to advance the physics?
2. What is currently available (state of the art) around the world?
3. What new accelerator facilities could be available on the next decade (or next next decade)?
4. What R&D would enable these future opportunities?
5. What are the time and cost scales of the R&D and associated test facilities as well as the time and cost scale of the facilities?

Accelerator Topical Groups and Conveners

Caption

Topical Group		Topical Group co-Conveners			
AF1	Beam Phys & Accel. Education	Z. Huang (Stanford)	M. Bei (GSI)	S. Lund (MSU)	
AF2	Accelerators for Neutrinos	J. Galambos (ORNL)	B. Zwaska (FNAL)	G. Arduini (CERN)	
AF3	Accelerators for EW/Higgs	F. Zimmermann (CERN)	Q. Qin (IHEP, Beijing)	G. Hoffstaetter (Cornell)	Angeles Faus-Golfe (IN2P2)
AF4	Multi-TeV Colliders	M. Palmer (BNL)	A. Valishev (FNAL)	N Pastrone (INFN, Torino)	J.Tang (IHEP, Beijing)
AF5	Accelerators for PBC and Rare Processes	E. Prebys (UC Davis)	M. Lamont (CERN)	R.Milner (MIT)	
AF6	Advanced Accelerator Concepts	C. Geddes (LBNL)	M. Hogan (SLAC)	P. Musumeci (UCLA)	R. Assmann (DESY)
AF7	Accelerator Technology R&D				
	Sub-group RF	E. Nanni (SLAC)	S. Belomestnykh (FNAL)	H. Weise (DESY)	
	Sub-Group Magnets	G. Sabbi (LBNL)	S. Zlobin (FNAL)	S. Izquierdo Bermudez (CERN)	
	Sub-Group Targets & Sources	C. Barbier (ORNL)	Y. Sun (ANL)	F. Pellemoine (FNAL)	

Plus, the **Accelerator Implementation Task Force** (ITF) to evaluate and compare various options
11 out of 30 are representatives of Asia and Europe; 7 women

Active participation by our Liaisons

- **AF to Theory Frontier - LianTao Wang (U Chicago)**
- **Rare Processes - Robert Bernstein (FNAL)**
- **Neutrino Frontier - Laura Fields (FNAL) and Alycia Marino (Colorado)**
- **Energy Frontier - Meenakshi Narain (Brown) and Dmitri Denisov (BNL)**
- **Instrumentation Frontier - Andy White (UTA)**
- **Computation Frontier - Jean-Luc Vay (LBNL)**
- **Community Engagement - Jeoren van Tilborg (LBNL)**
- **Snowmass Young - Edith Nissen (Jlab) and Nikita Kuklev (U.Chicago)**

Implementation Task Force (ITF)

Caption

- Charged with developing metrics and processes to facilitate comparisons between collider proposals.
  - Evaluated 32 collider proposals in terms of
    - Cost and schedule
    - Technical readiness, required R&D
    - Power requirements, complexity
    - Physics reach (impact), parameters
    - Called for R&D on energy efficiency

The full report is available on the arXiv:2208.06030v1

See talk by Thomas Roser at BNL Townhall

Thomas Roser (BNL, Chair)

Philippe Lebrun (CERN)

Steve Gourlay (LBNL)

Tor Raubenheimer (SLAC)

Katsunobu Oide (KEK)

Jim Strait (FNAL)

Sarah Cousineau (ORNL)

Marlene Turner (LBNL)

Spencer Gessner (SLAC)

Vladimir Shiltsev (FNAL)

Reinhard Brinkmann (DESY)

John Seeman (SLAC)

ITF Summary

Caption

- Focus on colliders
- Reviewed concepts to allow comparison but did not prioritize
- Did not review luminosity and power consumption (proponent input)
- ITF recommends (AF supports) – that R&D to reduce the cost and energy consumption of future collider projects be given high priority
- Suggests that evaluations could be updated on a regular basis

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
CERC[3] (Circular ERL Collider)	0.24 (0.09-0.6)	78	5-10	19-24	12-30	90
ReLiC[1,3] (Recycling Linear Collider)	0.24 (0.25-1)	165 (330)	5-10	>25	7-18	315
ERLC[3] (ERL linear collider)	0.24 (0.25-0.5)	90	5-10	>25	12-18	250
XCC (FEL-based $\gamma\gamma$ collider)	0.125 (0.125-0.14)	0.1	5-10	19-24	4-7	90
Muon Collider Higgs Factory[3]	0.13	0.01	>10	19-24	4-7	200

Cross-Frontier and Community Engagement

Caption

- Accelerator/Energy/Theory with input from IF, RPF and NF

  Joint workshops (many)

  The Agoras (Hosted by Future Colliders Initiative at Fermilab)

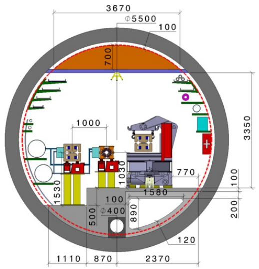
  Linear e+e- colliders

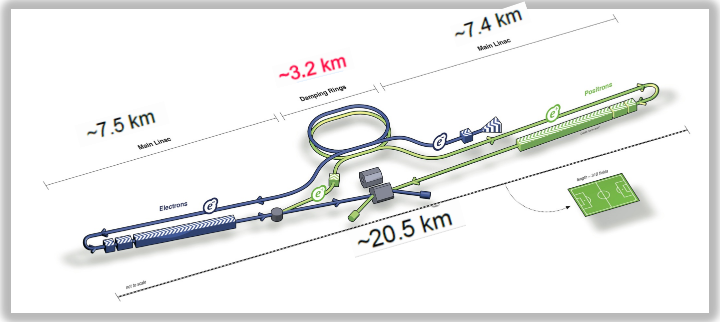
  Circular e+e- colliders

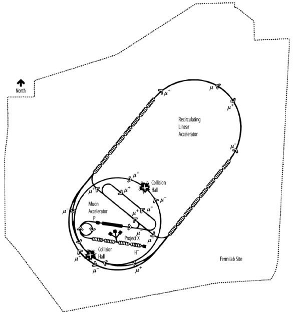
  Muon colliders

  Circular pp and ep

  Advanced colliders



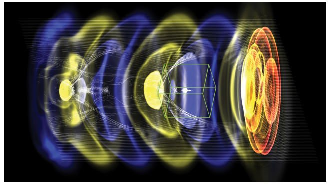




EF conveners: Meenakshi Narain, Laura Reina, Alessandro Tricoli,

AF conveners: Steve Gourlay, Tor Raubenheimer, Vladimir Shiltsev

Fermilab Future Colliders group: Pushpa Bhat, Joel Butler



Community Forums – broaden communication

Caption

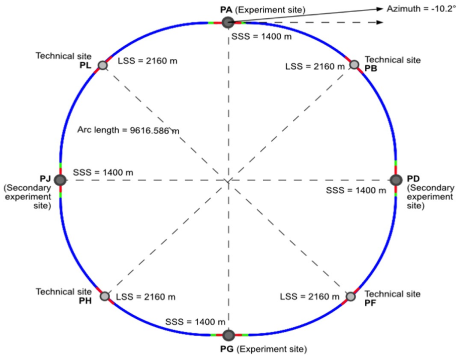
- **e+e- Forum**

  EF convenors: Maria Chamizo Liatas (BNL), Sridhara Dasu (Wisconsin)

  AF convenors: Emilio A. Nanni (SLAC), John Power (ANL)

  IF convenors: Ulrich Heintz (Brown), Stephen Wagner (Colorado)

  Joint EF-AF-IF Initiative



- **Muon Collider Forum**

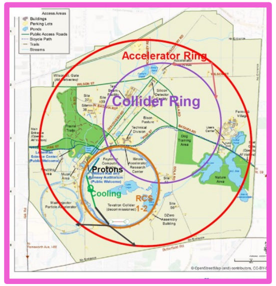
  AF: Derun Li (LBNL), Diktys Stratakis (FNAL)

  EF: Kevin Black (Wisconsin), Sergo Jindariani (FNAL)

  TF: Patrick Meade (Stony Brook), Fabio Maltoni (Louvain)

  Joint EF-AF-TF Initiative

  Aspirations for energy frontier facility in the US



Based on results of the successful US-Muon Accelerator Program (MAP) that ended in 2016 and bold CERN-led initiative in Europe

Foundation for Accelerator Frontier

Caption

- Major developments since the last Snowmass/HEPAP P5 in 2013-2014

  Start of PIP-II – (international)

  Construction of LBNF/DUNE – (international/CERN)

  HL-LHC - (international/CERN)

  Emergence of a number of projects focused on EW/Higgs physics

  - FCC-ee @ CERN
  - CepC in China
  - C^3 and HELEN in the US

  Reduction of linear collider activities (ILC in Japan and CLIC at CERN)

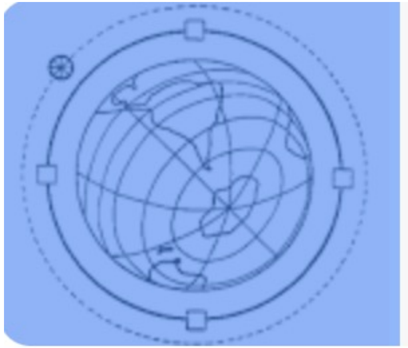
  The end of the Muon Accelerator Program (MAP) in the US

  The start of International Muon Collider Collaboration (IMCC) in the EU

  Lots of planning exercises

  - GARD and Accelerator R&D Roadmaps
  - EU Strategy for Particle Physics
  - EuPRAXIA . . . .
  - EU Accelerator Roadmaps

HEP has evolved into a truly global enterprise



FNAL Accelerator Complex Evolution (ACE)
Update since AF Summary Report

Caption

ACE Workshop January
https://indico.fnal.gov/event/57326/

- PIP-II construction and commissioning (2020's)
- Proposed ACE (2030's)

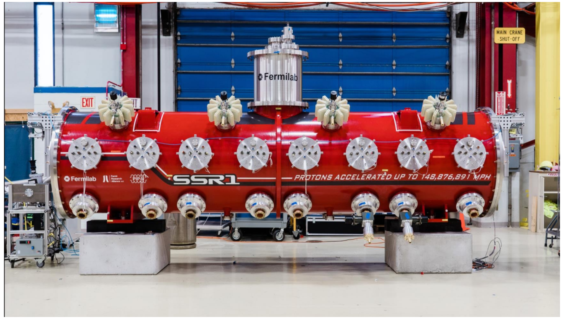
See talks by
Mary Convery
Diktys Stratakis

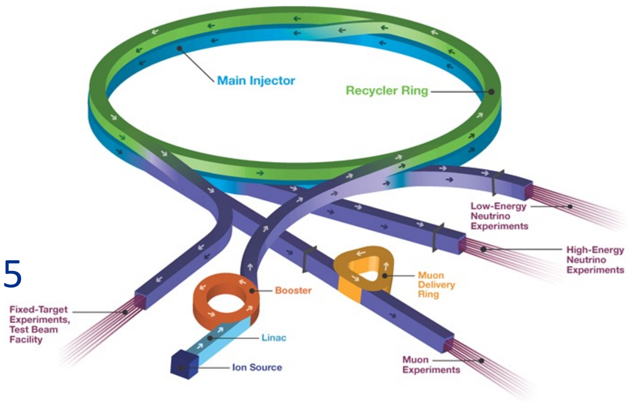
Part 1: > 1.2 MW proton beam

Part 2: Booster Replacement Project (late 30's) for reliable 2.4 MW to DUNE with capability and capacity to support new experiments and accelerator advancements

Considerations

Competition with Hyper-K / J-PARC – short timeline
MI upgrade (RF and Magnets)
Multi-MW Targets
Performance (beam losses for various reasons)
Muon collider compatibility





Options to be discussed at the ACE Science Workshop June 14 -15

Previous Snowmass/P5 (2013/14)

Caption

- Major accelerator-related recommendations:
  - Contribute to LHC and HL-LHC ✓
  - Engage in the ILC in Japan, contribute if it goes ?
  - Build >1 MW proton source PIP-II for ν LBNF/DUNE In Process
  - Provide beams for g-2 and mu2e experiments ✓ and In Process
  - Reassess Muon Accelerator Program and MICE ✓

- A follow-up 2015 Accelerator R&D subpanel recommended several thrusts :
  - Beam Physics (incl. IOTA and PIP-III)
  - Sources and Targets (incl. multi-MW)
  - RF (high-Q, high-G, low cost)
  - Magnets and materials (16 T, low cost)
  - Advanced acceleration (towards wakefield colliders)

Moving ahead

Caption

AF provided input to the community/P5 on future facilities

Proposed Accelerator Initiatives/Projects

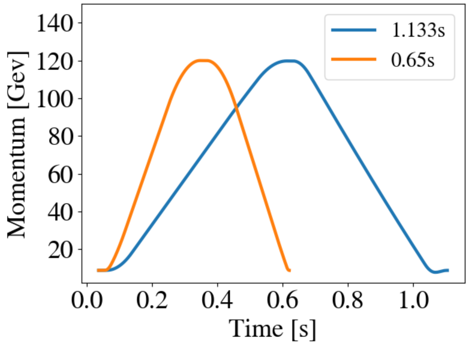
Caption

- **For Neutrino Physics:** PIP-II followed by
  0.65s cycle → 2.2MW; ASAP(ca 2031)
  Followed by the Booster replacement

- **For Rare Processes (DM, CLFV, etc):**
  0.8 GeV PAR (Accumulator Ring) ~100kW
  AMF (Advanced Muon Facility) two rings

- **For Energy Frontier (colliders) – design and R&D:**

  e^+e^- Higgs Factories: FCCee at CERN, C^3, ILC/HELEN, CepC
  Muon Colliders (6-10-14 TeV c.m.e.)
  pp colliders: FCChh at CERN (100 TeV), SppC
  In collaboration with international partners
  In coordination with corresponding physics/detector teams



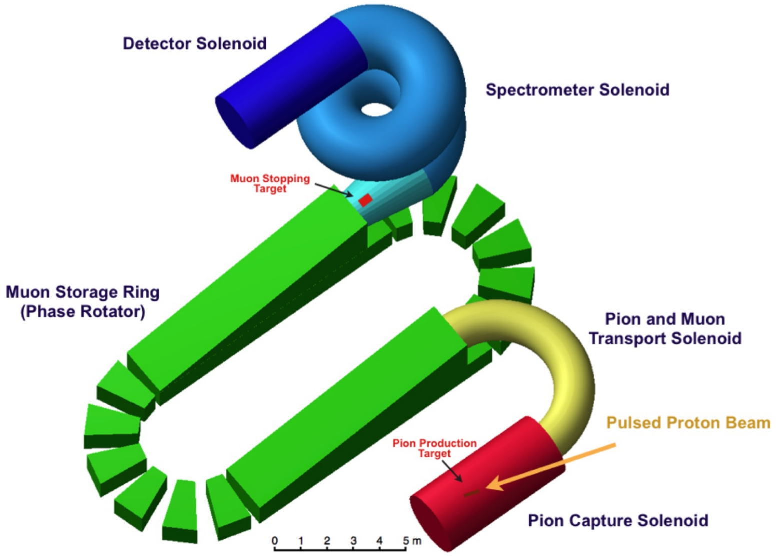
Increase Main Injector Ramp Rate

NEEDS P5 APPROVAL

Accelerators for Rare Processes

Caption

- Searches for DM, axions, EDMs, CLFV experiments, muons, light mesons, beam dump experiments . . .
- Several new beam facilities requested (FNAL, SLAC, JLab, SNS)



2 GeV Facility for Muon CLFV

e-beams
GeV to multi-GeV
p-beams
2 GeV CW
2 GeV pulsed from storage ring (1 MW)
8 GeV pulsed (1 MW)
120 GeV slow extraction for LBNF

Many existing and planned facilities can be utilized

arXiv:2209.06289 arXiv:2203.08278

Colliders

Caption

Note:

There are too many concepts to cover here in any detail

Brief technical descriptions in RMP and PDG:

V. Shiltsev, F. Zimmermann, RMP 93, 015006 (2021);

https://pdg.lbl.gov/2021/reviews/rpp2021-rev-accel-phys-colliders.pdf

Detail evaluations and discussions in the Accelerator Topical Group Reports AF3, AF4, AF6 and AF7, and the ITF report:

available at https://snowmass21.org/accelerator/

Colliders – AF alignment with EF

Caption

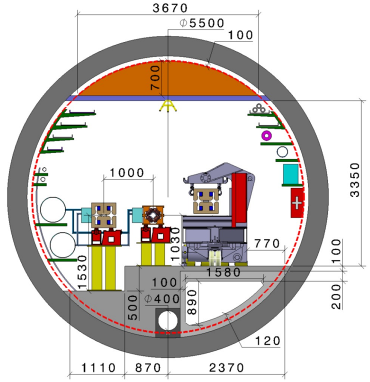
- Five-year period starting in 2025
  - Prioritize HL-LHC physics program
  - Establish a targeted e^+e^- Higgs factory detector R&D program for US participation in a global collider
  - Develop an initial design for a first stage TeV-scale MuC in the US (pre-CDR)
  - Support critical detector R&D towards EF multi-TeV colliders
- Five-year period starting in 2030
  - Continue strong support of HL-LHC program
  - Support construction of an e^+e^- Higgs Factory
  - Demonstrate principal risk mitigation and deliver CDR for a first-stage TeV-scale MuC
- After 2035
  - Evaluate continuing HL-LHC physics program to the conclusion of archival measurements
  - Begin and support the physics program of the Higgs Factories
  - Demonstrate readiness to construct and deliver a TDR for a first-stage TeV-scale MuC
  - Ramp up funding support for detector R&D for EF multi-TeV colliders

Input from the Forums

Caption

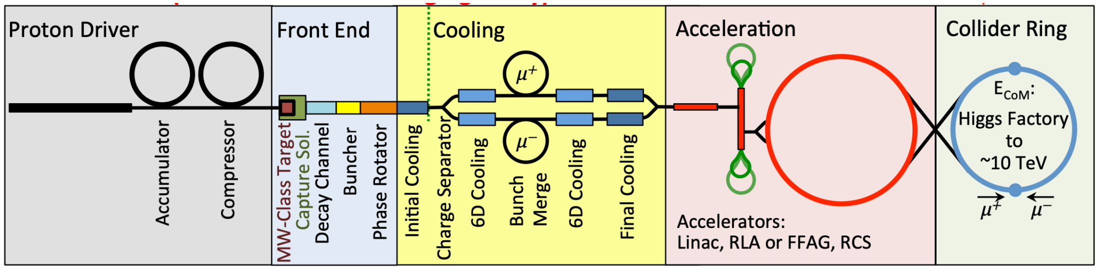
- e^+e^- Collider Forum w/ EF and IF

  FCCee and CepC more luminosity but $$
  ILC and C^3 faster and less costly
  US to contribute to any committed Higgs Factory
  (~10 TeV) colliders: Wakefield – R&D focused on collider specs



- $\mu^+\mu^-$ Collider Forum w/ EF and TF

  6 - 10 TeV cme - ideal
  No showstoppers, best ab^{-1}/TWh, $
  Need engineering and targeted R&D
  Develop pre-CDR/RDR by 2030
  Establish US MC organization
  Join International Muon Collider Collaboration (CERN)



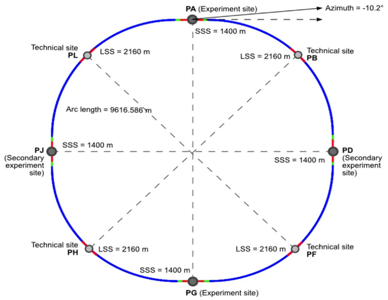
Higgs factory Proposals (High level of maturity)

Caption

- FCC-ee (CepC) Vladimir's Talk

  Supported by CERN (+)

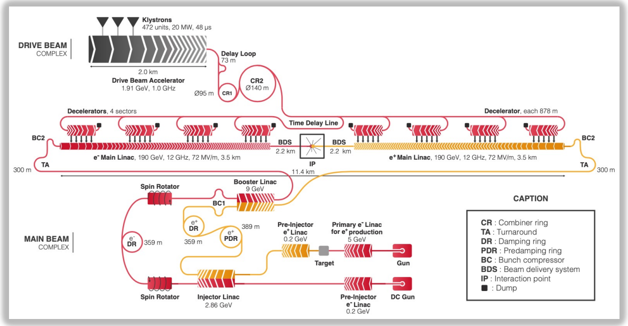
  Large footprint, power consumption (-)



- CLIC

  Lower power needs, smaller footprint (+)

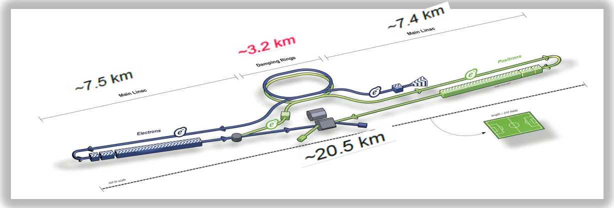
  2-beam, tolerances (-)



- ILC

  Shovel ready, polarization (+) Sergey's Talk

  Large footprint, no decision from Japan (-)

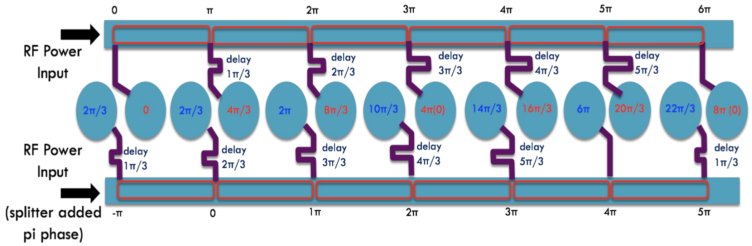


LC-Higgs Factories on FNAL site (new development)

Caption

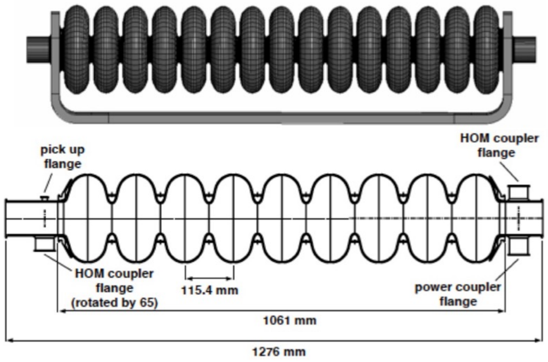
- Must fit ~ 7km including beam delivery system
- Requires RF gradients of at least 70 MV/m
- Compact -> lower cost compared to ILC, CLIC
- Two options

Cool Copper Collider (C^3) – 5.7 GHz @ 77K



Emilio's Talk

Higgs-Energy LEptoN (HELEN) – Traveling wave ILC, 1.3GHZ @ 2K



Sergey's Talk

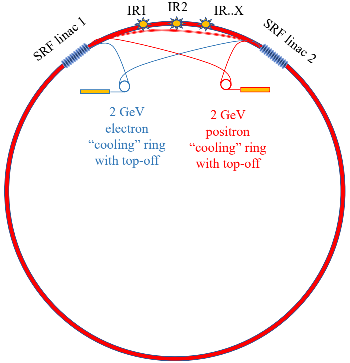
More aggressive Higgs Factory alternatives

Caption

- Energy Recovery based on e^+e^- colliders (circular or linear)

  High luminosity per MW power consumption (+)

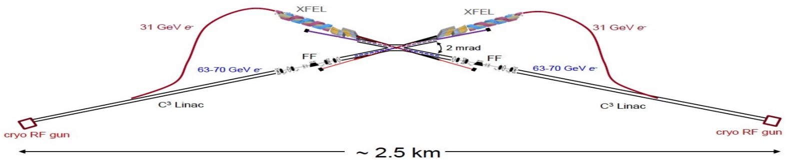
  Not yet mature (orders of magnitude in current, Q_0), long, expensive (-)



- Gamma-gamma linear colliders

  Need only ½ of the energy, short, potentially less expensive, no e^+ (+)

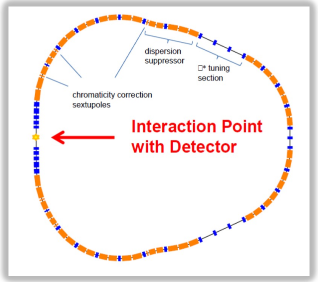
  Need two beyond-state-of-the-art FELs to generate gammas's in collisions with e^- (-)



- Muon collider Higgs factory

  Need only ½ the energy (65+65 = 130 GeV), very compact, less expensive +)

  Long development time, low luminosity but high X-section (-)



3-10 TeV/parton cme (most discussed)

Caption

- CLIC-3 TeV

  Established CDR, demo facilities (+)

  Large footprint, $$$ huge power consumption (-)

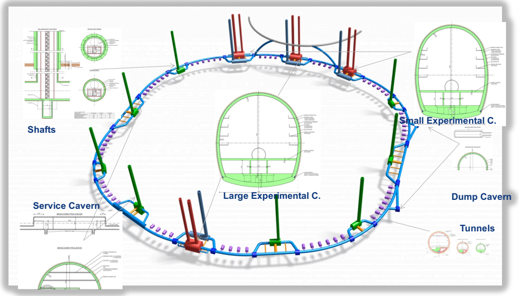
- FCC-hh 100/ TeV (100km tunnel)

  Re-use FCC-ee tunnel, high luminosity, LHC experience (+)

  20(?) years for magnet development 16T (-)

  For 100 TeV -> 17.8T for 91km tunnel (--)

  Recently backed down to a more practical 14T/ 80 TeV (+)

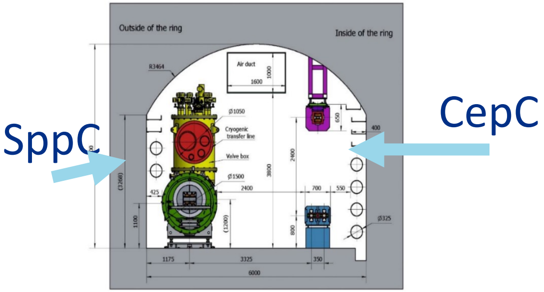


- SppC-125 TeV

  Re-use CepC tunnel, ep 0.12+62.5 TeV (+)

  20T magnets (--)

  Intermediate stage at 75 TeV with 12T magnets using Iron-based SC) (-/+)



- Muon Collider

  Potentially lowest cost, best luminosity/TWh (+)

  6D Cooling “R”, “D” on many subsystems (-)

6 – 10 TeV Muon Collider on FNAL site

Caption

- First design concept of up to 10 TeV collider developed
- Operation at 125 GeV, 1 and 3 TeV could be intermediate stages
- Capitalizes on existing FNAL facilities and expertise

PIP-II and upgrades
Tevatron tunnel
Facilities for cooling, target, SRF and magnet R&D

World-class intellectual leadership in these areas

A variety of other options

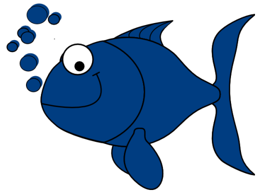
Caption

- Circular or linear colliders pushing the limits

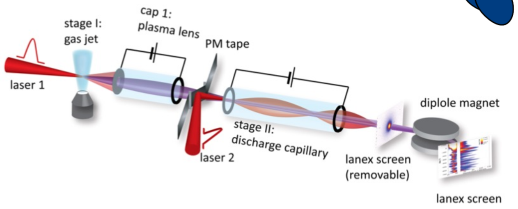
  ILC-3 TeV, ERL-based Linear colliders (3 TeV), 2100 km "Collider in the Sea"

  "Just" scale-up technology (+)

  Enormous power consumption, large footprint, expensive (--)



  Wakefield acceleration (Laser, proton, structure)



  Linear ee/gamma-gamma colliders

  Most compact, perhaps cost efficient, multi-Tev collisions (+)

  More R&D needed:

  e^+ acceleration, staging, beam quality, power efficiency . . . (-)

- Additions to existing machines

  ep/eh colliders (LHeC, FCC-eh, epChina

  Very cost effective, feasible, nice additions to proton machines (+)

  High current 50 GeV ERL technology needs demonstration (3 orders of magnitude in power) (-)

Caption

Accelerator Frontier Messages

Future Facilities

Caption

- 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 HEP accelerator projects.

"Tell us what you want, and we will build it"

But tell us NOW. It will take time.

Quads for LHC upgrade took 2 – 3 decades.

AF Recommendation

"Planning of accelerator development and research should be aligned with the strategic planning for particle physics and *should be part of the P5 prioritization process*."

Colliders

Caption

- US National Collider R&D Initiative

See talk by Pushpa Bhat

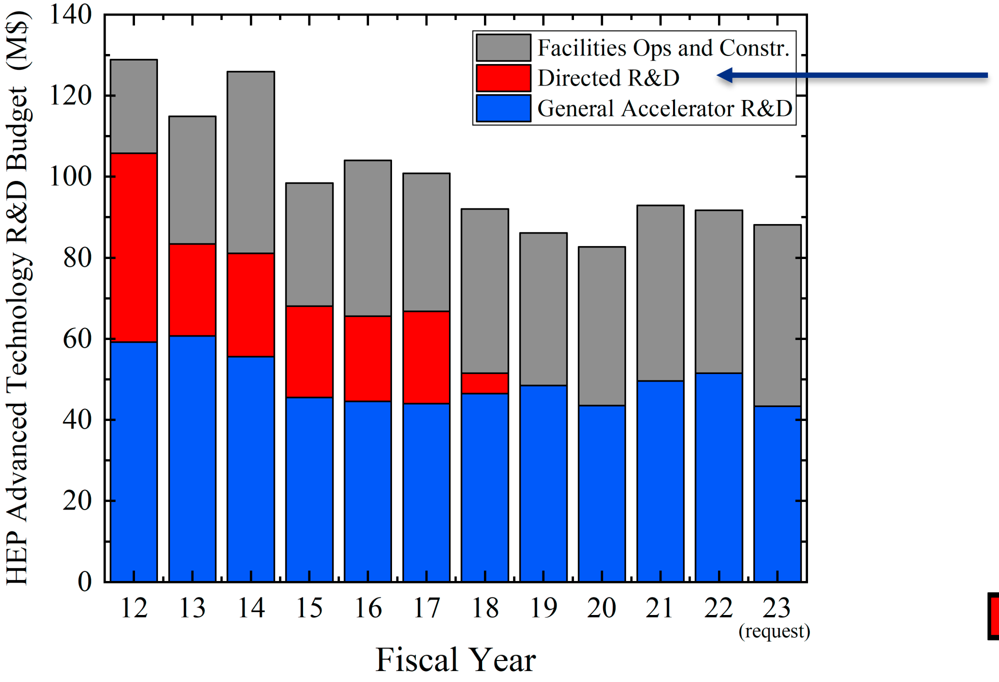
Establish a targeted OHEP program

Integrated approach to cover international efforts (FCC, ILC, IMCC . . .) and development toward feasible US options (C^3, HELEN, 6 - 10 TeV MC, . . .)

Address in an integrated fashion the technical challenges of promising future collider concepts that are not covered by the existing General Accelerator R&D (GARD) program

US Accelerator R&D Funding History

Caption

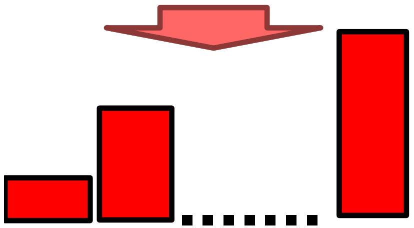


US ILC
US LARP (LHC)
US MAP (Muon)

Completed

Proposed for FY24 ->

Future Colliders



Accelerator R&D

Caption

- We have an ongoing R&D program aimed at fundamental beam physics and long-term accelerator concepts and technologies

Office of High Energy Physics (OHEP), General Accelerator R&D (GARD) program

Accelerator and Beam Physics (ABP)

RF Acceleration Technology (Normal and Superconducting)

Particle Sources and Targets

Advanced Accelerator Concepts (AAC)

Superconducting Magnets and Materials (SCM)

Mei’s Talk

- All these areas have broad applicability to future accelerators with ideas from universities and labs

- R&D is key to facilities for neutrinos, rare processes and colliders

Accelerator R&D for the next decade

Caption

Multi-MW targets

- 2.4 MW for PIP-II
- 1 – 4 MW for Muon Collider

Magnets for Colliders and RCS

- 14 – 16 T dipoles
- 40T+ solenoids
- 1000 T/s rapid cycling

U.S. MAGNET DEVELOPMENT PROGRAM

Soren's Talk

Wakefields

Spencer's Talk

- Collider-quality beams
- Efficient drivers and staging
- Close coordination with International programs

SC/NC RF

- 70 – 120 MV/m C^3
- 70 MV/m TW SRF
- New materials, high Q_0
- Efficient RF sources

Accelerator and Beam Physics

High intensity/brightness beam acceleration and control

High performance computer modeling and AI/ML approaches

Design integration and optimization, including energy efficiency

Workforce

Caption

- Strengthen and expand education/training programs

  Support for university-based research, including grants to involve professors in DOE lab facilities and projects
  Strengthen USPAS
  Encourage labs to accept more traineeship students including international
- Outreach

  Enhance recruiting, promote colloquia at universities
- DEI

  Enhance support for national undergrad recruiting class to draw women and URM talent

Thanks to everyone for all the hard work!

Caption

- Accelerator Frontier Working Group Conveners
- Liaisons (EF, IF, NF, TF, CEF, CF)
- Sergei Nagaitsev, DPB
- Implementation Task Force
- e^+e^- collider forum
- Muon collider forum
- Fermilab Collider Group
- Convenors of the Collider and RPF Agoras
- Our many international partners
- And in particular . . .

The accelerator community for their enthusiastic participation

Snowmass 2021