Introduction to Snowmass21 Accelerator Frontier

Jingyu Tang (IHEP)
on behalf of the
Snowmass21 Accelerator Frontier Conveners

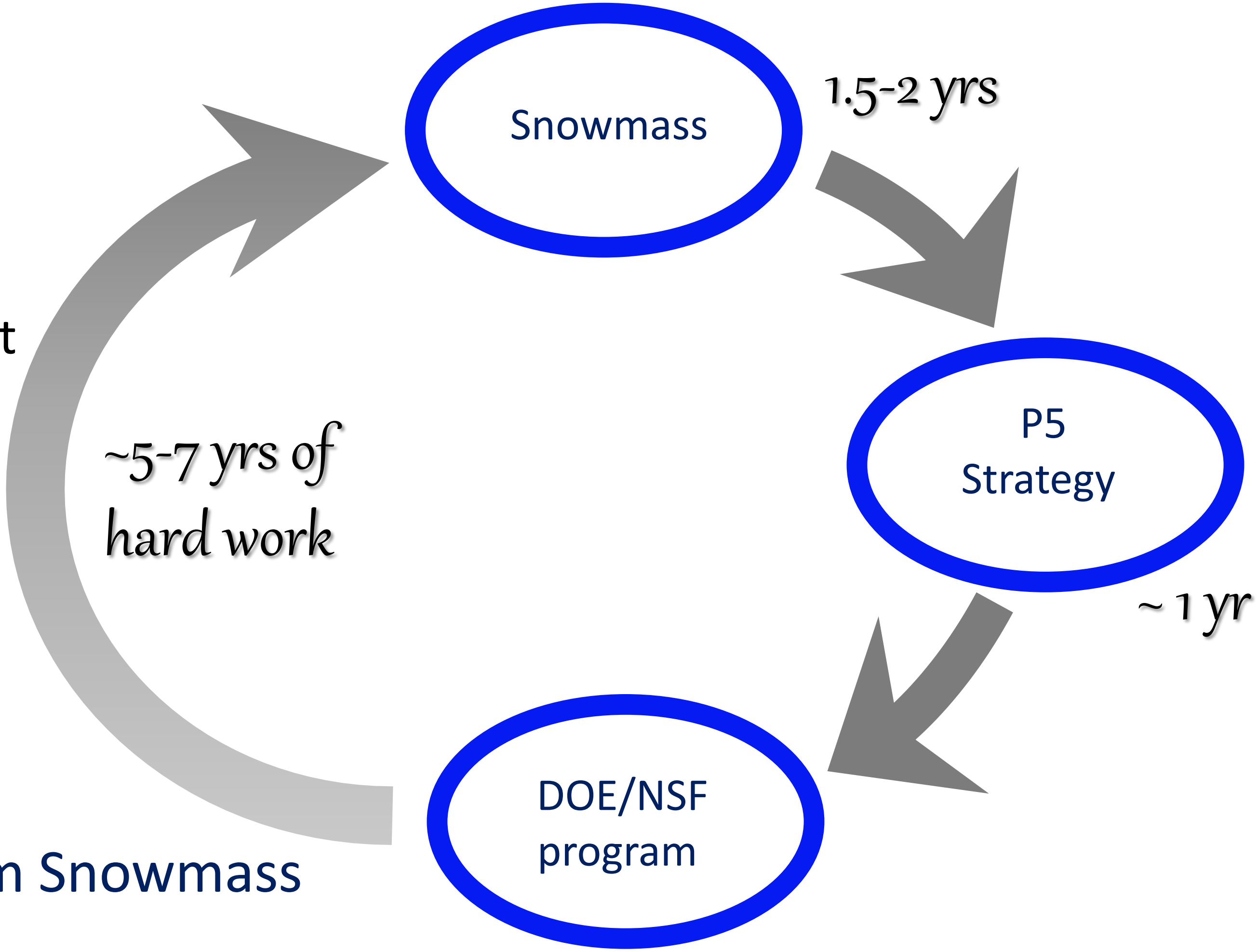
What is “Snowmass?”

Snowmass 2021

- Snowmass is a particle physics community study in US, with international participation
- https://www.snowmass21.org/

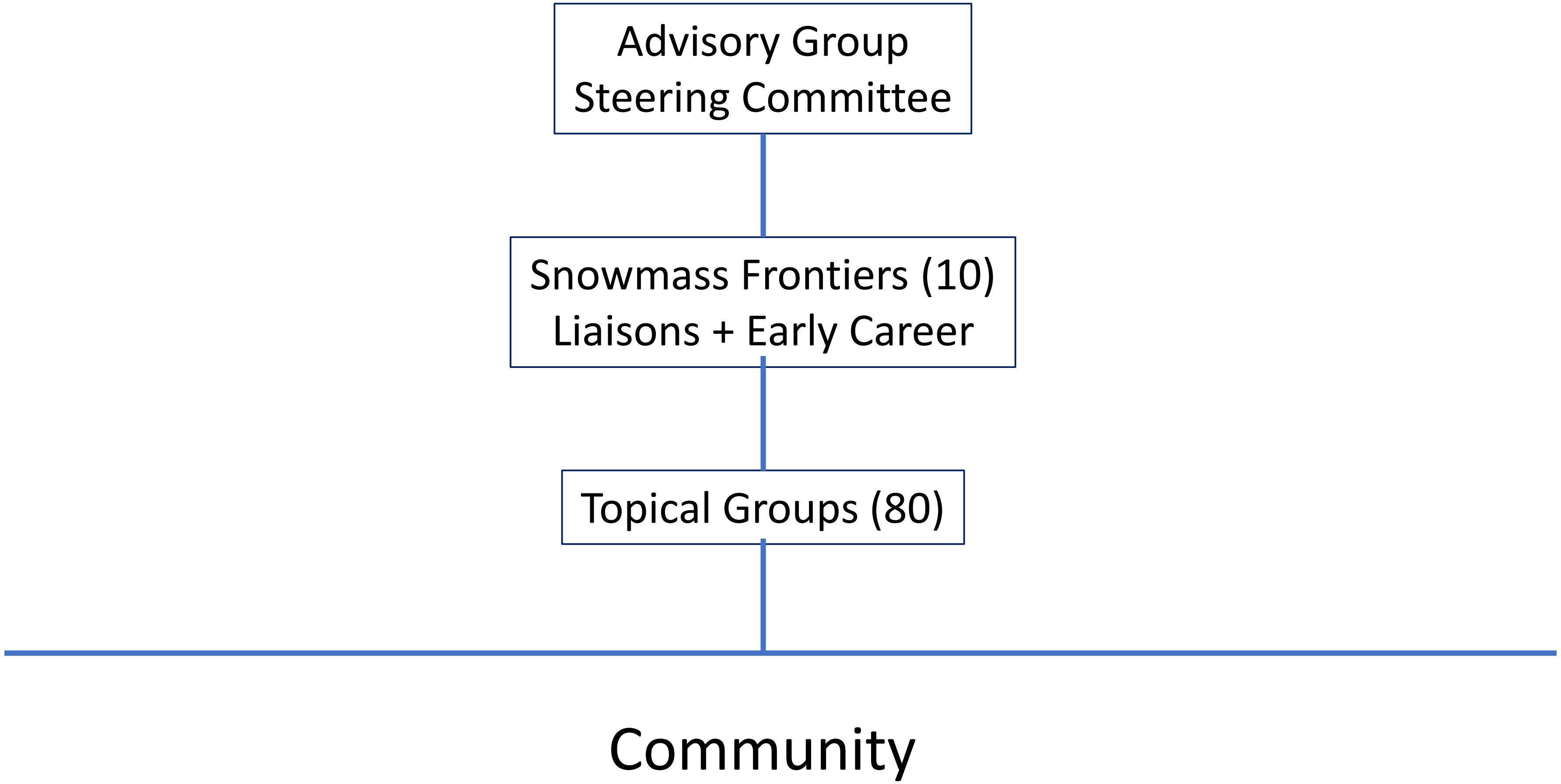
- Provides input to P5 (Particle Physics Project Prioritization Panel) that develops a strategy for the US HEP program

Organized by DPF Exec Committee
Representatives from DPB, DNP, DGRAV, DAP and the international community



No prioritizations from Snowmass

Snowmass Organization



Snowmass'21 Frontier Conveners

Energy Frontier


Meenakshi Narain (Brown U)


Laura Reina (FSU)


Alessandro Tricoli (BNL)

Frontiers in Neutrinos


Patrick Huber (Virginia Tech)


Kate Scholberg (Duke U.)


Elizabeth Worcester (BNL)

Frontiers in Rare & Precision


Marina Artuso (Syracuse U.)


Alexey Petrov (Wayne State U.)


Bob Bernstein (FNAL)

Cosmic Frontier


Aaron Chou (Fermilab)


Marcelle Soares-Santos (U.Michigan)


Tim Tait (UC Irvine)

Theory Frontier


Nathaniel Craig (UCSB)


Csaba Csaki (Cornell)


Aida El-Khadra (UIUC)

Accelerator Frontier


Steve Gourlay (LBNL)


Tor Raubenheimer (SLAC)


Vladimir Shiltsev (FNAL)

Instrumentation Frontier


Phil Barbeau (Duke)


Petra Merkel (FNAL)


Jinlong Zhang (ANL)

Computational Frontier


Steven Gottlieb (Indiana U.)


Ben Nachman (LBNL)


Daniel Elvira (FNAL)

Underground Facilities and Infrastructure Frontier


Laura Baudis (U. Zurich)


Jeter Hall (SNOLAB)


Kevin Lesko (LBNL)


John Orrell (PNNL)

Community Engagement Frontier


Kétévi Assamagan (BNL)


Breese Quinn (Mississippi)

Accelerator Frontier

- **Co-Conveners**

- Steve Gourlay (LBNL, Retired)
- Tor Raubenheimer (SLAC)
- Vladimir Shiltsev (FNAL)



Description

The Accelerator Frontier activities include discussions on high-energy hadron and lepton colliders, high-intensity beams for neutrino research and for the "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 will submit Letters of Intent, contributed papers, take part in corresponding workshops and events, contribute to writing summaries and take part in the general Snowmass'21 events

Accelerator Frontier Topical Groups and Contributed White Papers (so far)

Topical Working Groups

• AF1: Beam Physics and Accelerator Education	6
• AF2: Accelerators for Neutrinos	10
• AF3: Accelerators for EW/Higgs	10
• AF4: Multi-TeV Colliders	10
• AF5: Accelerators for PBC and Rare Proc.	4
• AF6: Advanced Accelerator Concepts	9
• AF7: Accelerator Technology R&D	
• Magnets	18
• RF	16
• Targets and Sources	4

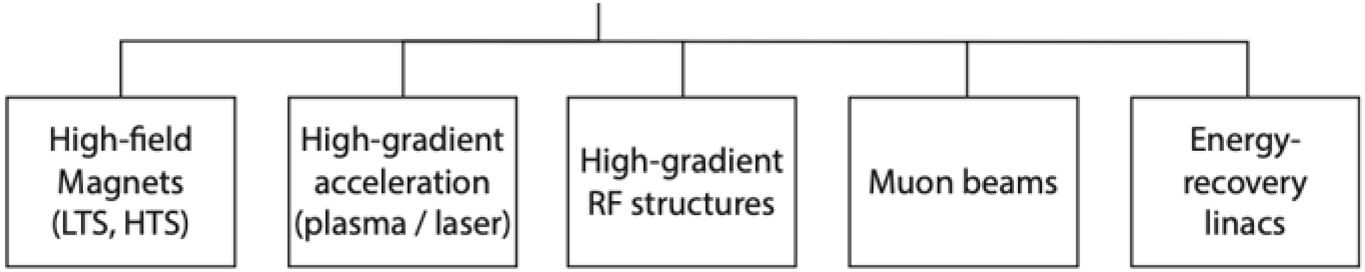
Snowmass Accelerator Frontier Key Questions

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?

European Planning Influences Snowmass Topics

- European Strategy for Particle Physics (ESPP) describes strategy for particle physics in Europe and their contributions world-wide (June 19, 2020)
- European National Laboratories Directors Group (LDG) – July 2 (Chaired by Lenny Rivkin)
  - Immediate outcome → Accelerator R&D Task Forces reporting to Lab Directors Group (LDG) and CERN Council
- Address the question of what are the most promising Accelerator R&D activities for HEP

5 Targetted Accelerator R&D Expert Panels



Snowmass AF participants are active on all the LDG panels

Cross-Frontier and Community Engagement

- Accelerator/Energy/Theory
  - 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** (April 13)
      - 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

- e^+e^- Forum
  - EF convenors: Laura Reina, Meenakshi Narain, Alessandro Tricoli
  - AF convenors: Stephen Gourlay, Tor Raubenheimer, Vladimir Shiltsev
  - IF convenors: Jinlong Zhang, Petra Merkel, Phillip Barbeau
- Muon Collider Forum
  - Accelerator Frontier: Derun Li, and Diktys Stratakis
    Energy Frontier: Kevin Black, and Sergo Jindariani
    Theory Frontier: Patrick Meade, and Fabio Maltoni
  - Joint EF-AF-TF-IF Initiative
  - Aspirations for energy frontier facility in the US

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

Steps Toward a Muon Collider in Europe

- EU Strategy –International Design Study
- High-priority future initiatives . . . In addition to the high field magnets the accelerator R&D Roadmap could contain:
- . . . An international design study for a muon collider, as it represents a unique opportunity to achieve a *multi-TeV energy domain beyond the reach of e^+e^- colliders*, and potentially within a *more compact circular tunnel* than for a hadron collider. The biggest challenge remains to produce an intense beam of cooled muons, but *novel ideas are being explored*;

  - LDG agrees to start building the collaboration for an international muon collider design study
  - Daniel Schulte as interim project leader – with N. Pastrone and L. Rivkin
  - Kick-off meeting held – July 3
  - > 250 participants – https://indico.cern.ch/event/930508/

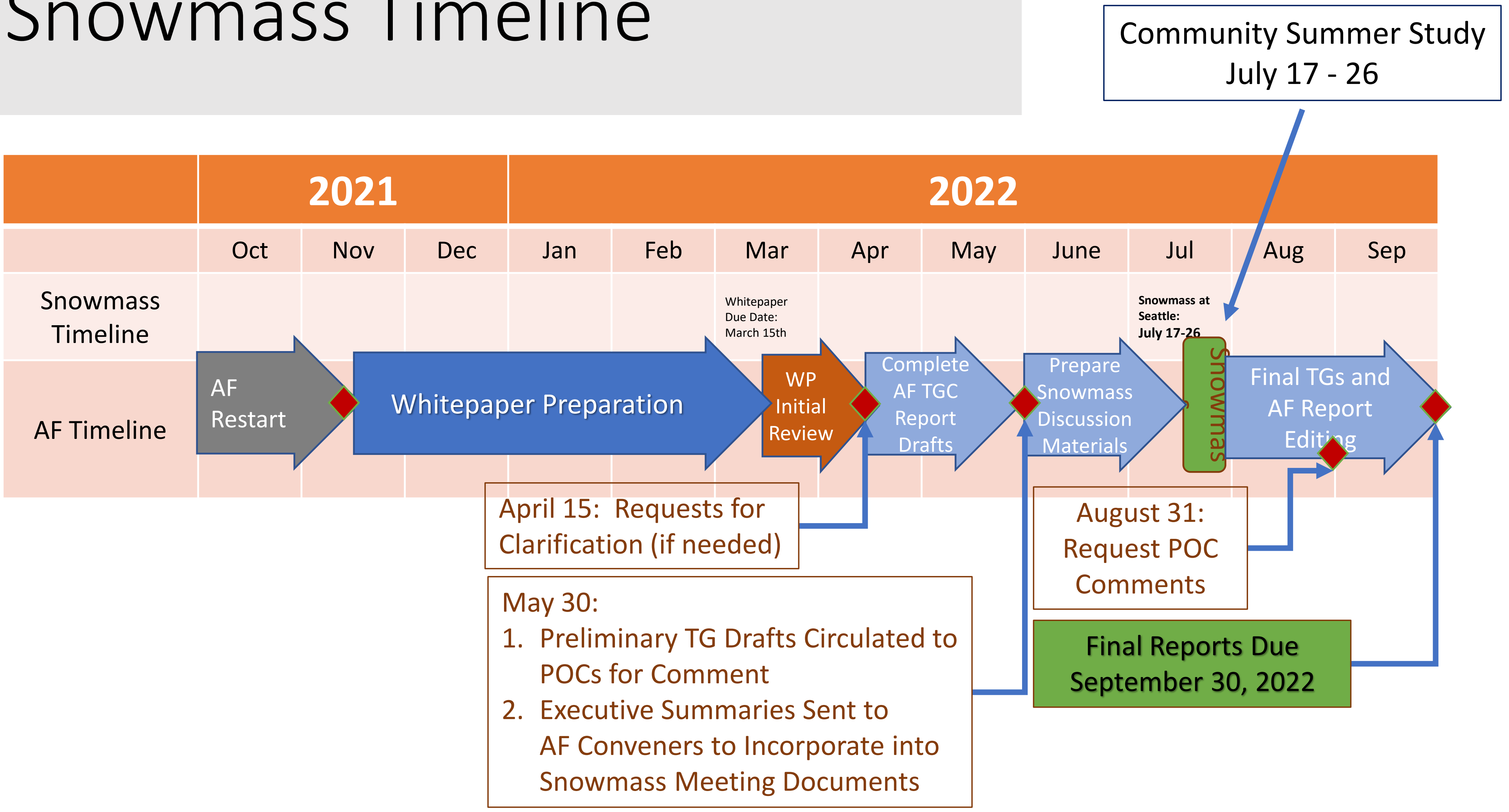
Another task of AF: Analyzing and comparing facility proposals

- We added another working group to handle this task

The "Implementation Task Force" (ITF)

- Developed a parameter spreadsheet and solicited community input
- Collected spreadsheets for 24! major proposals, some with multiple parameter sheets. (multiple energy operation, staging, upgrades . .)
  - Higgs factories concepts
  - High energy lepton colliders concepts
  - High energy hadron and lepton/hadron collider concepts

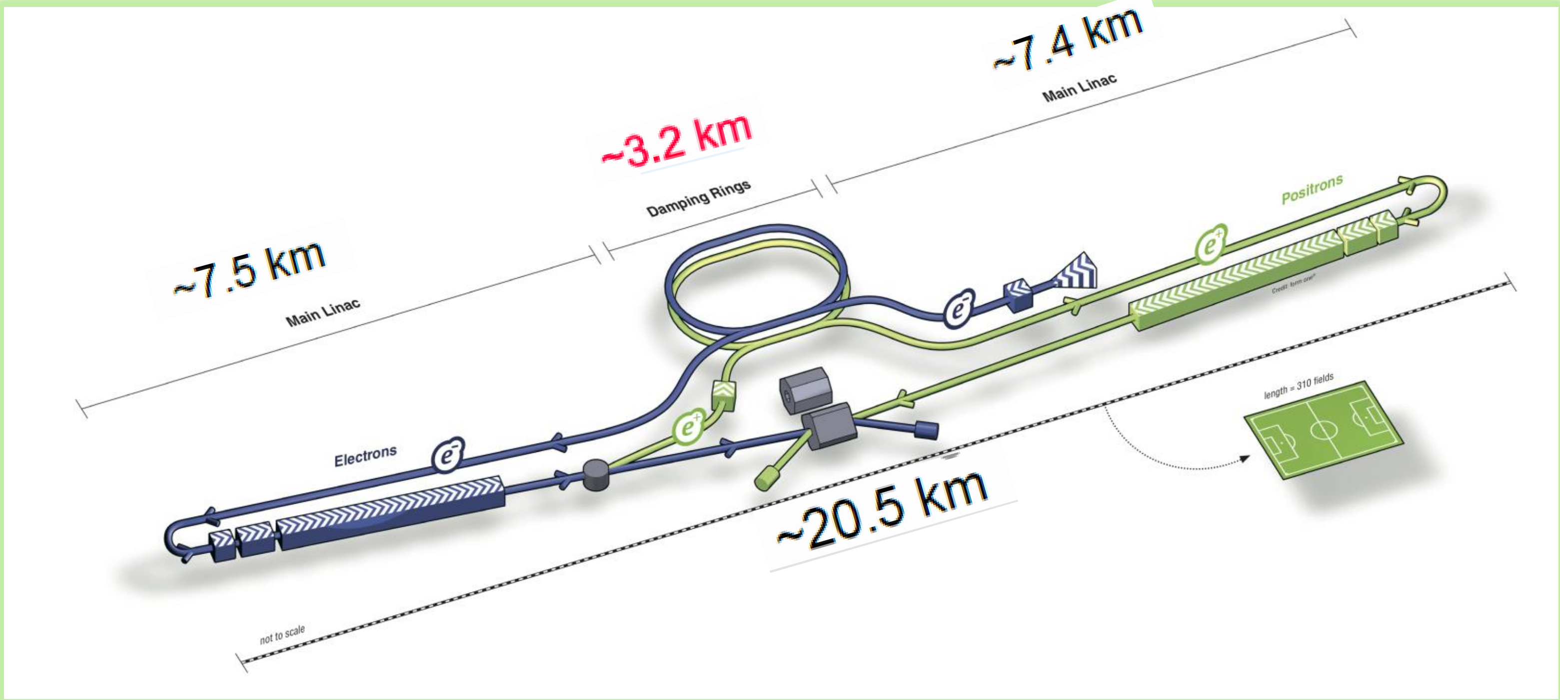
Snowmass Timeline



Higgs factories, high energy lepton and $\gamma\gamma$ colliders

ILC

International Linear Collider



- Key features/challenges
  - Superconducting RF
  - 2K cryo
  - Positron source
  - Luminosity
- Overall Technical Maturity – nearly shovel ready
  - More work on cost reduction
  - International cooperation agreement

Beam Energy	GeV	125
RF Gradient	MV/m	31.5
# IPs	N	1
Site Power	MW	130
Length/Circum.	km	20

”The International Linear Collider”, arXiv:2203.07622 [physics.acc-ph]

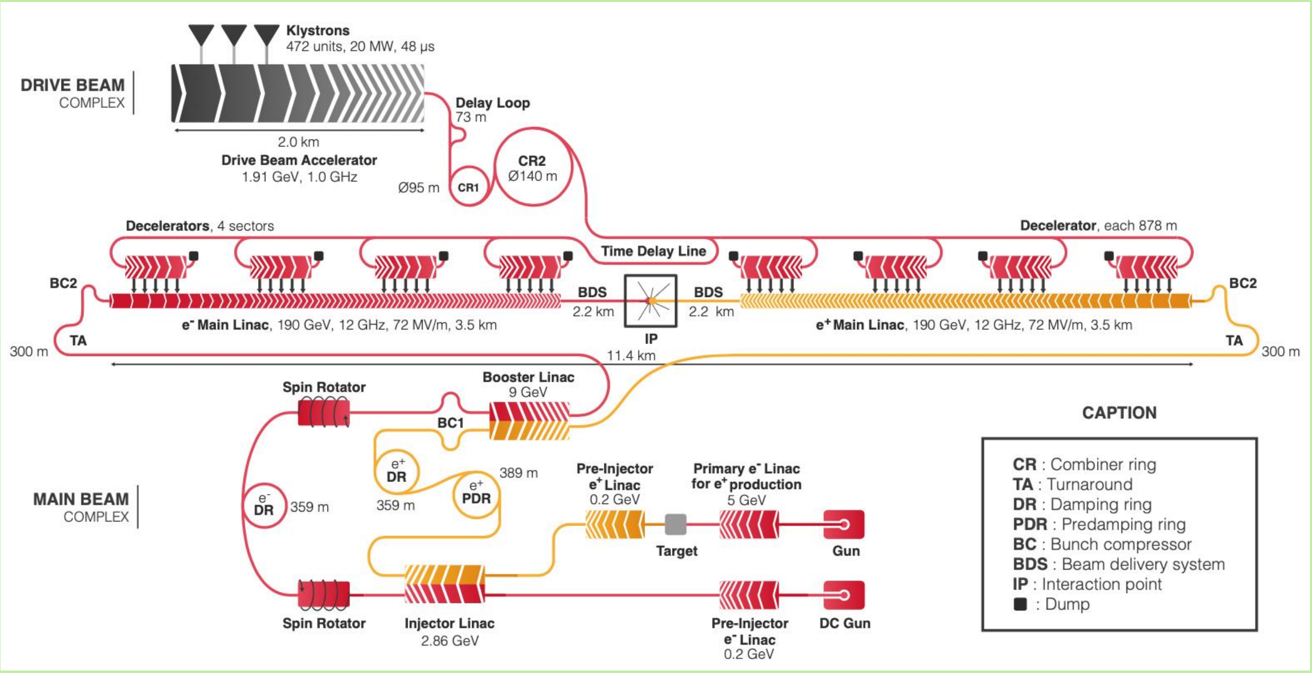
CERN

CLIC

Compact LInear Collider

- Key features/challenges
  - Two-beam acceleration scheme
    - Normal conducting RF 100 MV/m
    - High current low-energy drive beam decelerated to power low current high-energy main beam
  - Higher energy reach than ILC
  - And as the name states – “Compact”
- Overall Technical Maturity – CDR

”The CLIC project”, arXiv:2203.09186 [physics.acc-ph]



arXiv preprint arXiv:1812.0798

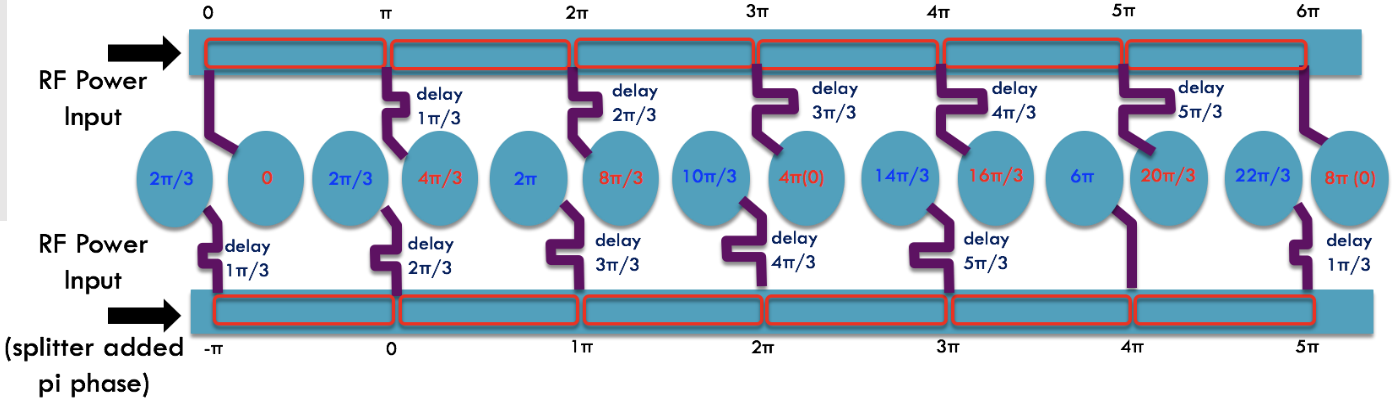
arXiv:1209.2543

Beam Energy	GeV	190
RF Gradient	MV/m	72
# IPs	N	1
Site Power	MW	168
Length/Circum.	km	11

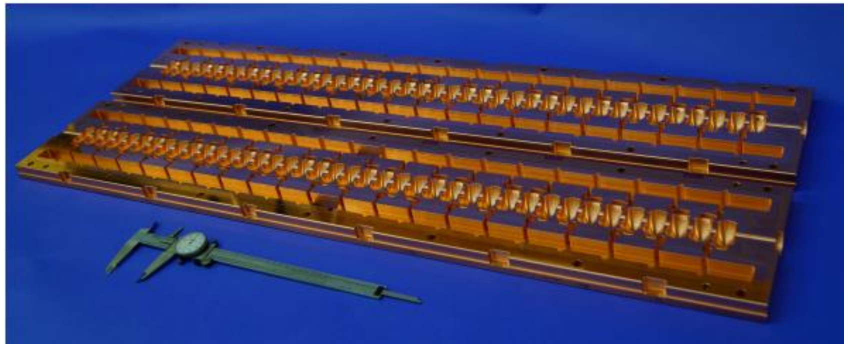
SLAC

C^3

Cool Copper Collider



- Key features/challenges
  - Cold (77K) Normal Conducting RF (70 MeV/m)
    - Increased material strength – higher gradient
    - Higher conductivity – reduced RF
  - Cryo is relatively simple
  - Focus is on major cost reduction
  - Up to 550 GeV with 155 MeV/m
- GeV-scale demo facility - TDR



E. Nanni, SLAC

Beam Energy	GeV	125
RF Gradient	MV/m	70
# IPs	N	1
Site Power	MW	150
Length/Circum.	km	8

“C3: A 'Cool' Route to the Higgs Boson and Beyond”, arXiv:2110.15800 [hep-ex]

”Strategy for Understanding the Higgs Physics: The Cool Copper Collider”, arXiv:2203.07646 [hep-ex]

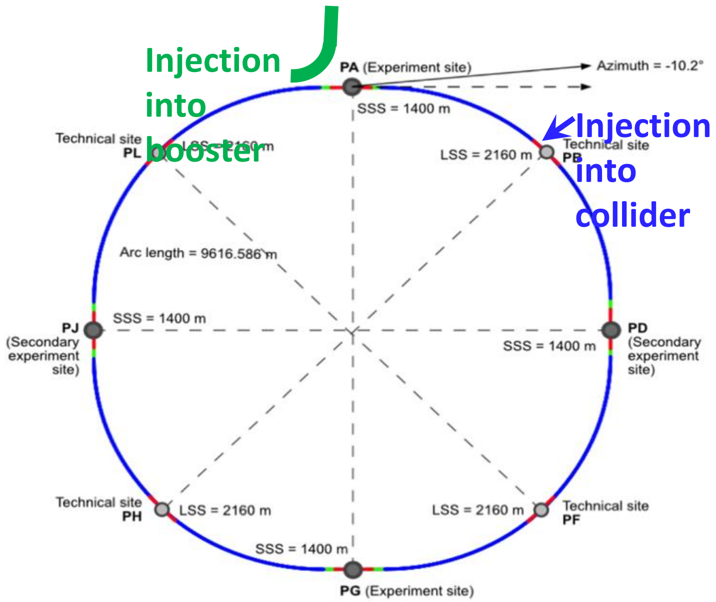
C^3 Demonstration Research and Development Plan”, arXiv:2203.09076 [physics.acc-ph]

FCC-ee

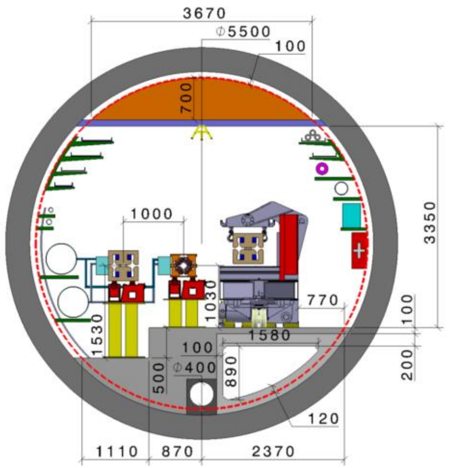
Future Circular Collider – e^+e^-

- Key features/challenges
  - Step toward high energy hadron collider
  - Range of physics from Z^0 to tt-bar
  - 100 MW SynchRad power loss
  - Beam lifetime limited by beam-beam to 18 min
    - Requires large acceptance optics
    - Full energy top-off

- Overall Technical Maturity - Shovel ready



CERN



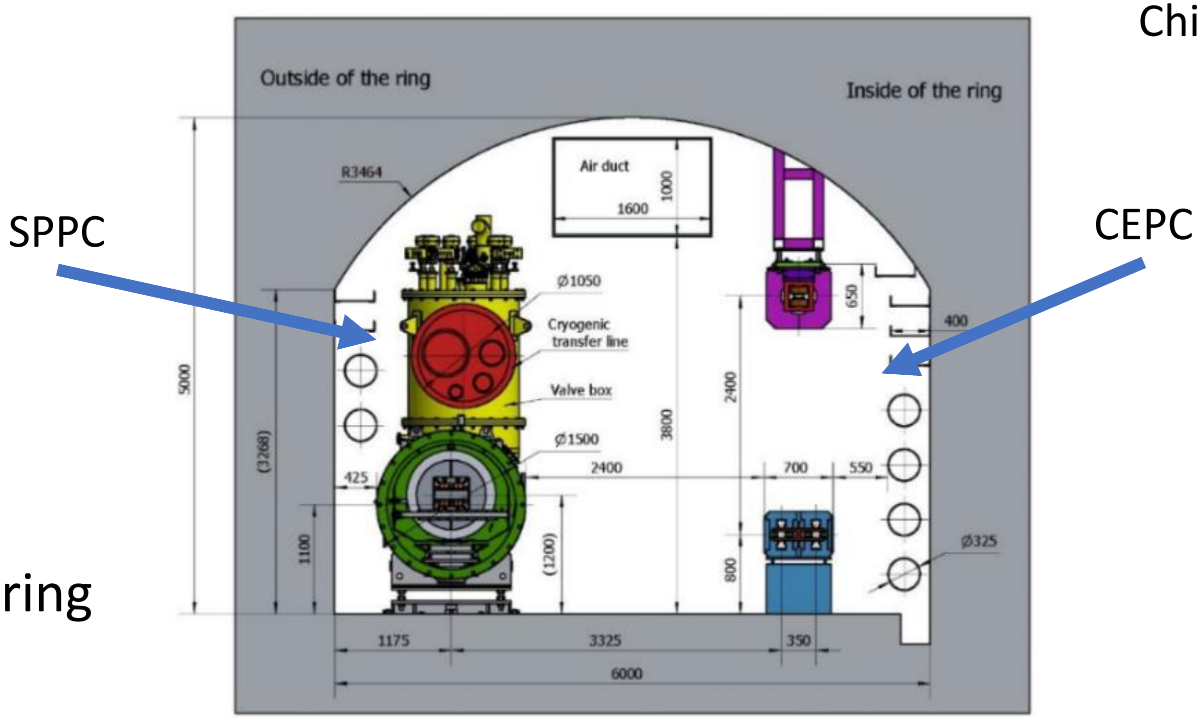
Beam Energy	GeV	45 - 183
RF Gradient	MV/m	1.3 - 19.8
# IPs	N	2 - 4
Site Power	MW	~ 300
Length/Circum.	km	100

"The Future Circular Collider: a Summary for the US 2021 Snowmass Process", arXiv:2203.06520 [hep-ex]

CEPC

Circular electron positron Collider

China



- Key features/challenges
  - Staged scheme similar as FCC
  - Range of physics from Z^0 to H
  - 30 MW/beam SR power loss in collider ring
    - Beam lifetime (0.2 – 3 hr)
    - Full energy top-off
    - Higher luminosity requires faster ramping

- Overall Technical Maturity - Shovel ready
- Timeline – TDR 2022. Start of construction 2028
- Multiple sites in China under study

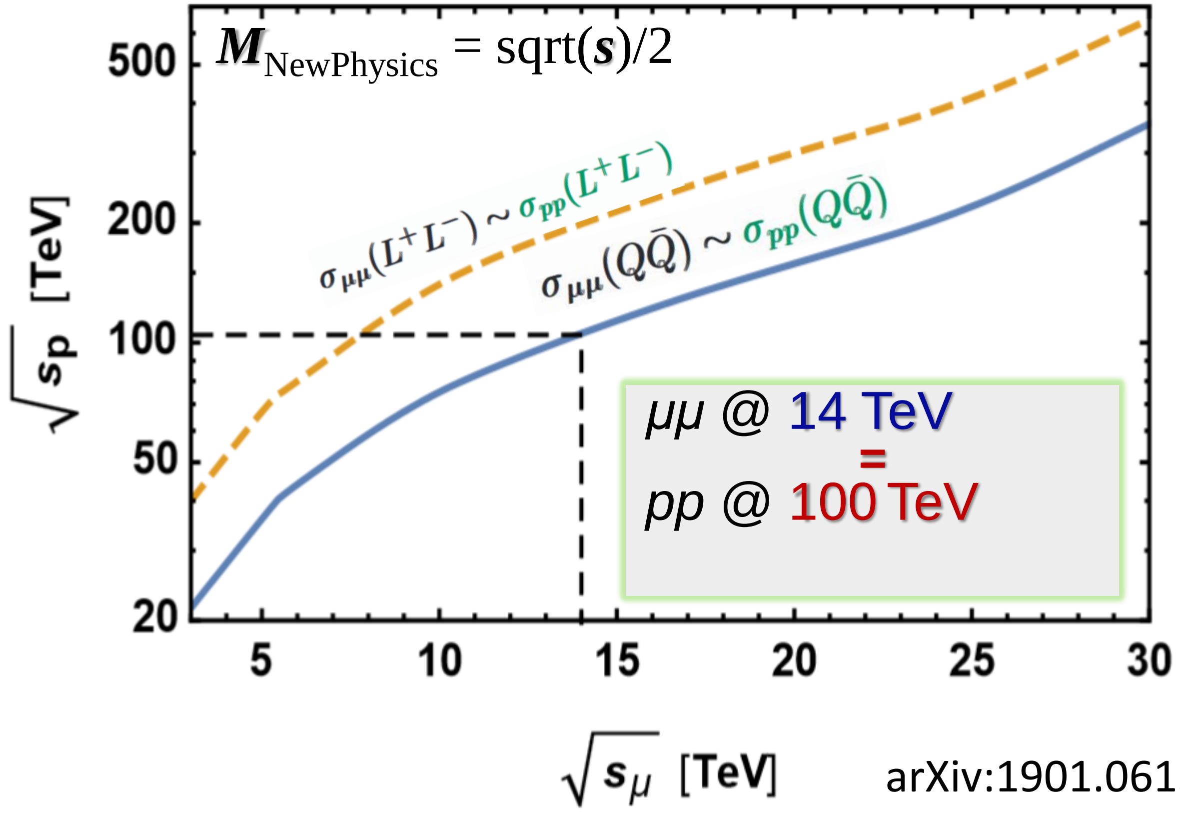
Beam Energy	GeV	45.5 - 120
RF Gradient	MV/m	4 - 40
# IPs	N	2 - 4
Site Power	MW	~ 300
Length/Circum.	km	100

”Circular Electron Positron Collider (CEPC)“, arXiv:2203.09451 [physics.acc-ph]

$\mu^+\mu^-$ Collider

International

- Key features
  - Lower (X100 luminosity requirement)
  - Small energy spread
  - Large bore, high field dipoles
  - Energy reach X7 over pp
  - Luminosity/power ratio best among lepton colliders
  - Relatively small footprint
  - Precision and exploratory physics
- Overall Technical Maturity - Conceptual



arXiv:1901.06150v1

Parameter	Units	Higgs	Multi-TeV		
CoM Energy	TeV	0.126	1.5	3	6
Circumference	km	0.3	2.5	4.5	6
# IPs	N	1	2	2	2
Wall Plug	MW	200	216	230	270

Proton Driver Based Option

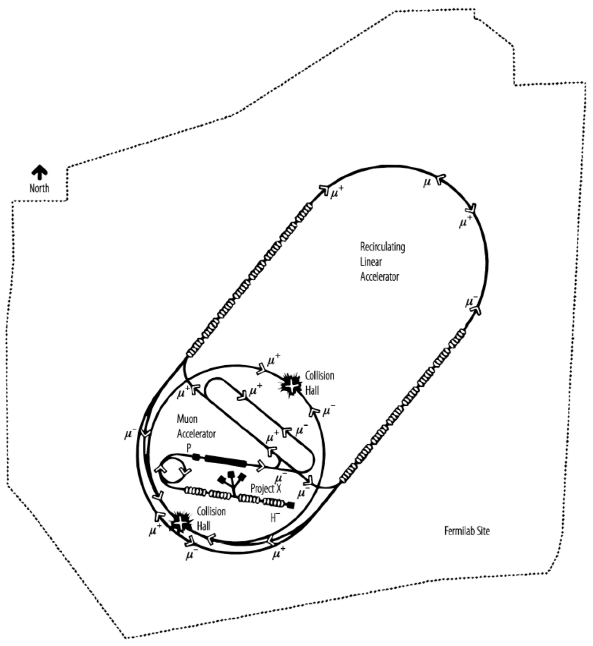
Did not fare well in the last Snowmass

However . . .

"A Muon Collider Facility for Physics Discovery", arXiv:2203.08033 [physics.acc-ph]

$\mu^+\mu^-$ Collider - Significant R&D progress since last Snowmass

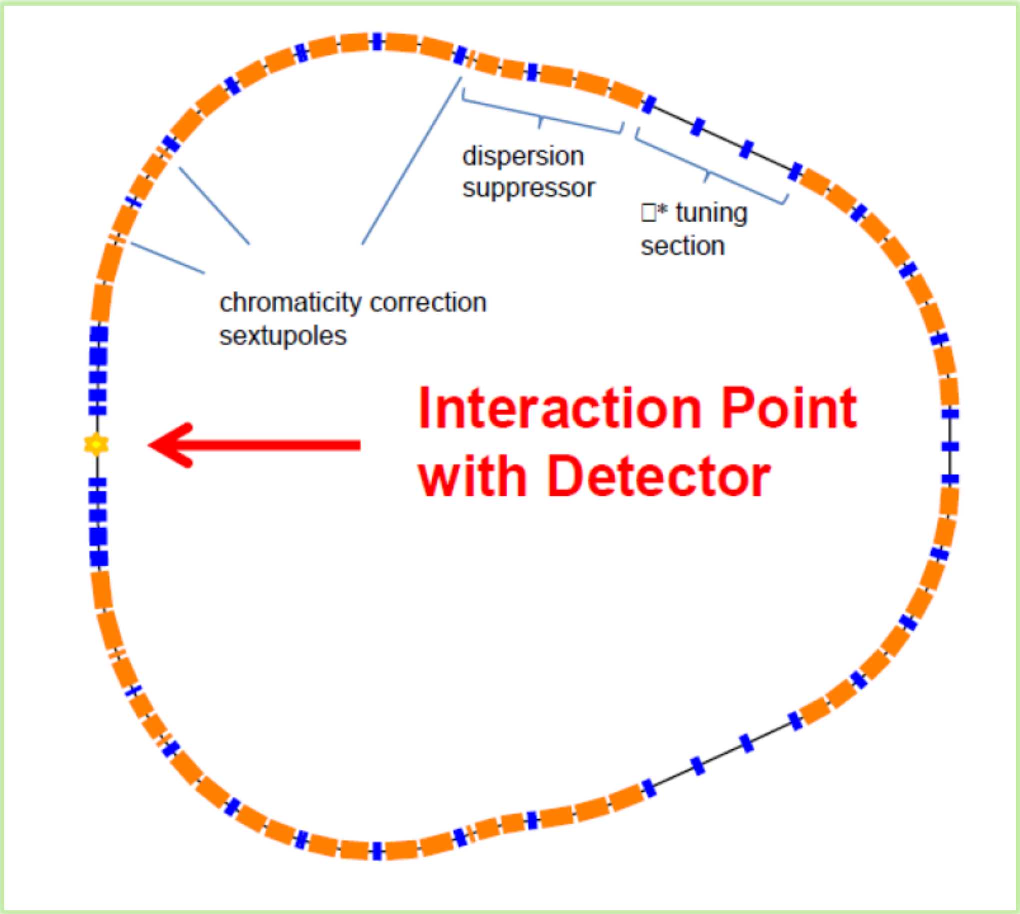
- Muon Accelerator Program (MAP)
  - Operation of RF in high magnetic fields (MuCool, FNAL)
  - Cooling - Recent demo (MICE)
- R&D path
  - Test facility to demonstrate significant x-verse and longitudinal cooling – muon bunches
  - Very high field solenoids – 32T already demonstrated
  - Fast acceleration schemes
  - High field and fast ramping dipoles – large bore, high rad load at the mid-plane



Fermilab Site

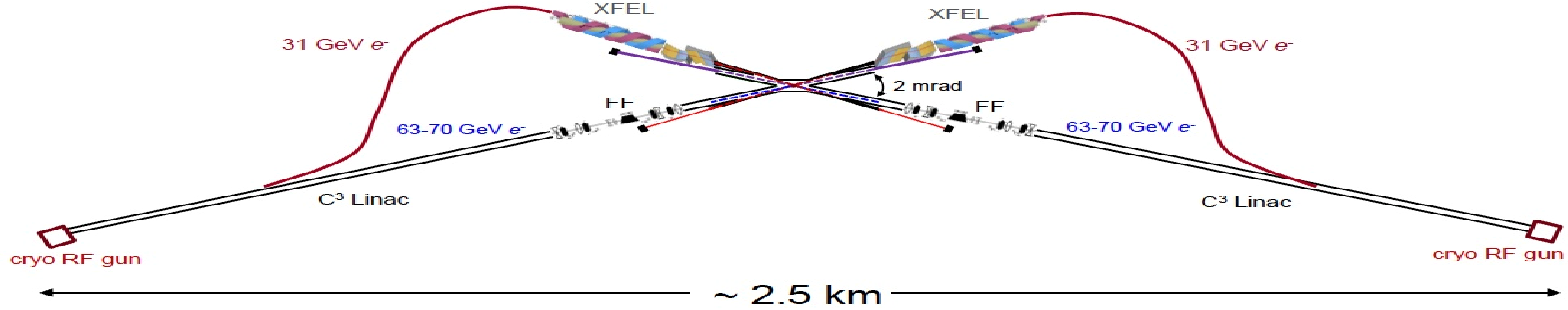
$\mu^+\mu^-$ Higgs Factory

- Half the energy 2 X 63 GeV for $\mu^+\mu^- \rightarrow H_0$
- Small footprint (lower cost)
- Simplest implementation of a muon collider but significant R&D still required



arXiv:2003.09084v1
arXiv:1502.02042

XCC – X-ray FEL-based $\gamma\gamma$ Collider Higgs Factory



- Could obtain $\gamma\gamma$ and γe^- collisions with luminosity and energy comparable to e^+e^-
- C^3 RF technology
- No beamstrahlung effect
- No need for positron production (a challenge with any e^+e^- collider)
- Energy is half of m_H for $\gamma\gamma$ -> Higgs
- Requires development of high power XFEL and ultra-high brightness polarized electron source

Beam Energy	GeV	62.5
# IPs	N	1
Site Power	MW	< 30
Length/Circum.	km	2.5

”XCC: An X-ray FEL-based $\gamma\gamma$ Collider Higgs Factory“, arXiv:2203.08484 [hep-ex]

RLAs and ERLs

Recirculating Linear Accelerators and Energy Recovery Linacs

- RLA
  - Uses same RF accelerating structures multiple times for the same beam
  - Arcs are less costly than RF
  - Much better beam quality compared with storage rings
  - Allows use of energy recovery
- ERL
  - Proposed by Tigner > 2 decades ago
  - Decelerates "used" beam back through accelerating structure out of phase
  - SRF technology mature enough now to make it feasible

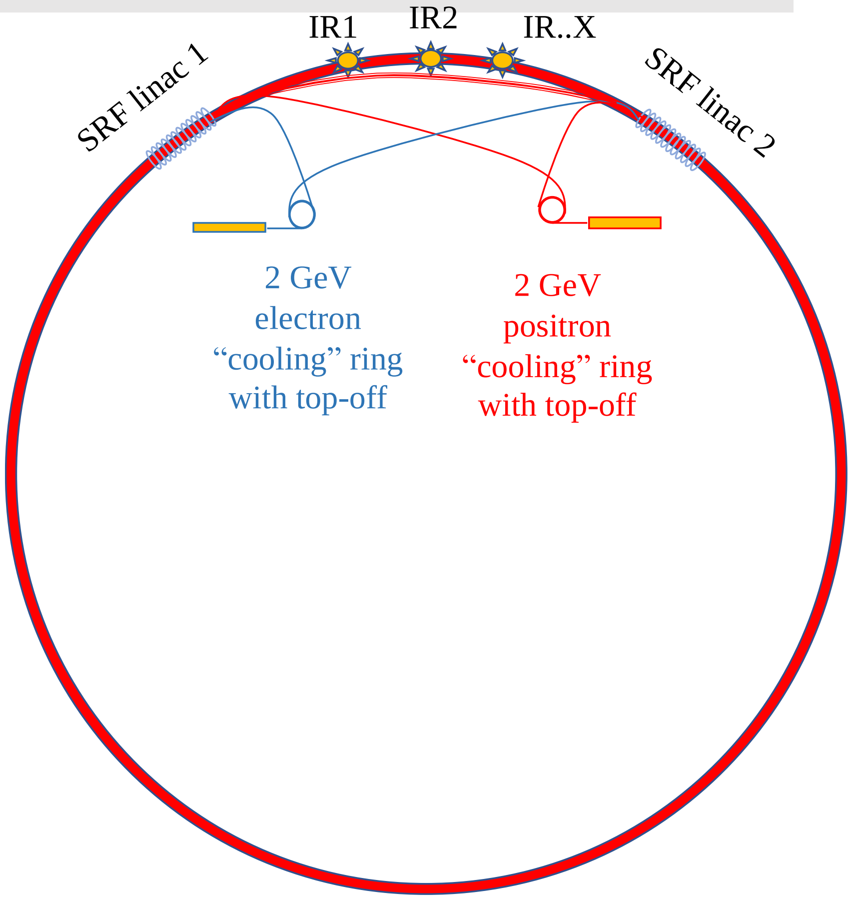
V. Shiltsev, F. Zimmermann
arXiv:2003.09084v1

RLA/ERL-based Higgs and $\gamma\gamma$ Colliders

Collider using Energy-Recovery Linacs - CERC

- Option for FCC-ee
  - Much smaller emittance (X100) than FCC-ee ring option
  - Significant fraction of the energy recovered
  - Still some challenges to preserve emittance over long arcs
  - Polarized beams
  - Energies up to 600 GeV

Beam Energy	GeV	120
# IPs	N	2+
Site Power	MW	90
Length/Circum.	km	100

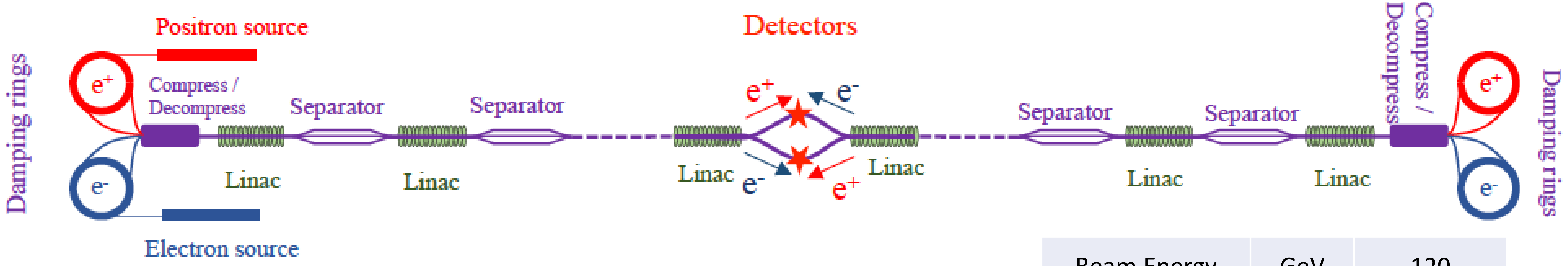


"CERC - Circular e+e- Collider using Energy-Recovery Linac", arXiv:2203.07358 [physics.acc-ph]

RLA/ERL-based Higgs and $\gamma\gamma$ Colliders

Linear Energy Recovery Linac Collider - ReLiC

Two large linear colliders



Beam Energy	GeV	120
# IPs	N	2
Site Power	MW	300
Length/Circum.	km	20

”The ReLiC: Recycling Linear e+e– Collider”, arXiv:2203.06476 [hep-ex]

Fermilab “site-fillers”

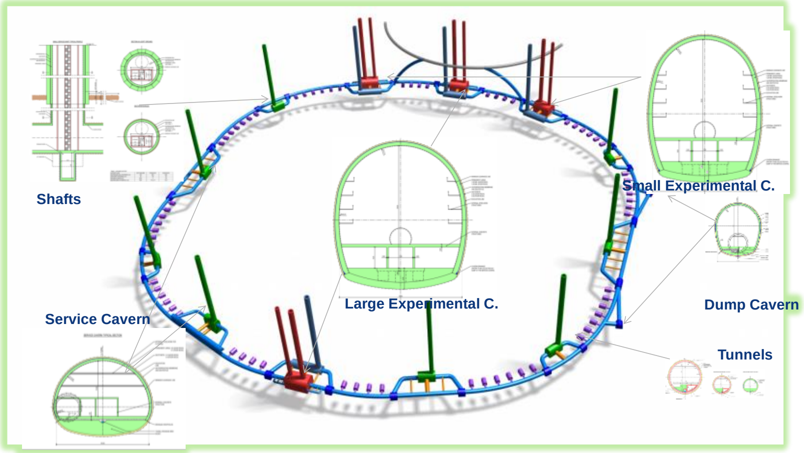
- Snowmass is seen as an opportunity to consider possible options that could be built in the US (in particular, the Fermilab site)
  - 7 km C^3 (250 GeV up to 550 GeV)
  - Linear, high gradient RF colliders; standing wave, travelling wave structures (250 – 500 GeV) [HELEN]
  - 16 km circumference circular e^+e^- collider (90 – 240 GeV)
  - Proton-proton collider at 24 – 27 TeV (23 – 27 T dipoles)
  - A staged muon collider from Higgs at 125 GeV up to 8 – 10 TeV.

”Future Collider Options for the US“, arXiv:2203.08088 [hep-ex]

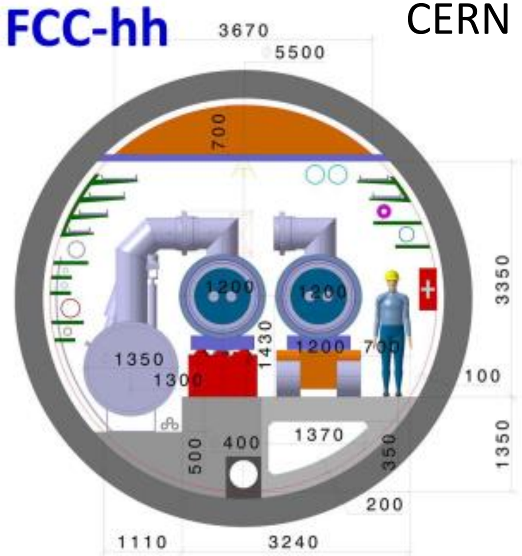
Hadron Colliders

FCC - hh

Future Circular Collider – proton proton



CERN



- Key features/challenges
  - 100 TeV CoM
  - Luminosity of ~10^{35} $cm^{-2}s^{-1}$
  - 16 T Superconducting Dipoles
  - Large synchrotron radiation heat load
  - Wall plug power ~ 500MW
  - Cost!
- Overall Technical Maturity - Significant R&D (15 – 20 years)

Beam Energy	TeV	50
RF Gradient	MV/m	N/A
# IPs	N	2
Site Power	MW	~ 560
Length/Circum.	km	100

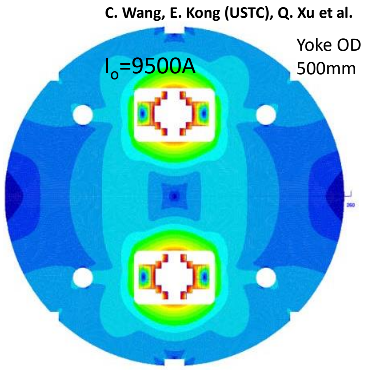
"Future Circular Hadron Collider FCC-hh: Overview and Status", arXiv:2203.07804 [physics.acc-ph]

FCC-hh CDR/ fcc-cdr.web.cern.ch

China

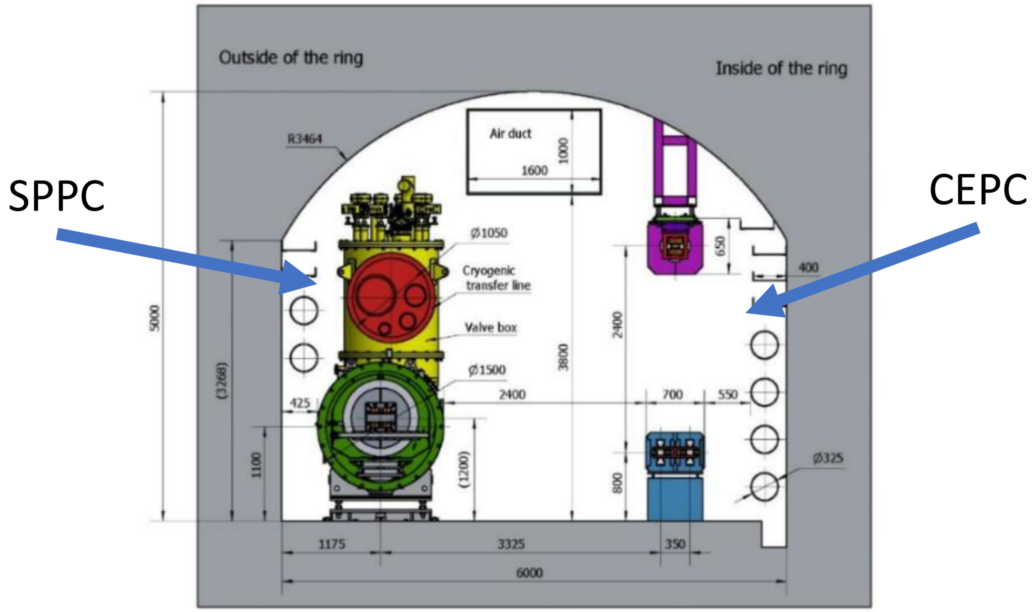
SPPC

Super proton proton Collider



- Key features/challenges
  - Tunnel accommodates both CEPC and SPPC
  - 125 TeV CoM
  - 20-T Fe-based superconductor
- Overall Technical Maturity – Significant R&D, especially magnet technology
- *e-p* collision could reach 6.7 TeV (by 62.5 TeV *p* X 180 GeV *e*)

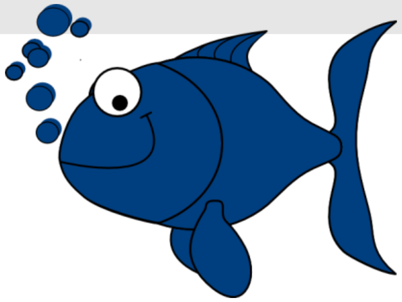
”SPPC”, [arXiv:2203.07987 [hep-ex]](arXiv:2203.07987)



Beam Energy	TeV	62.5
Dipole Field	T	20
# IPs	N	2
Site Power	MW	500
Length/Circum.	km	100

arXiv:1809.00285

McIntyre “Collider Under the Sea”



- Key features/challenges
  - Visionary concept
  - Ultimate hadron collider
  - Circular pipeline supported in neutral buoyancy in the Gulf of Mexico
  - Low-cost magnets (but lots of them)

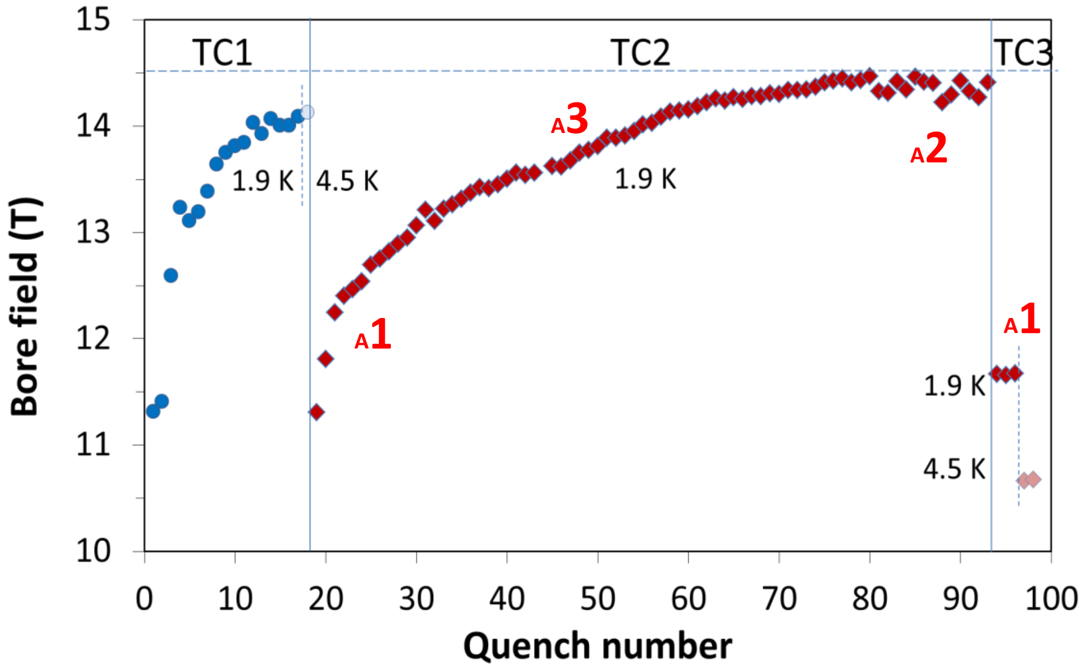
Beam Energy	TeV	500
Dipole Field	T	4
# IPs	N	2
Site Power	MW	200
Length/Circum.	km	2100

https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF4_AF0_Peter_McIntyre-239.pdf

Accelerator Technologies and Advanced Accelerators

Recent Progress in High Field Accelerator Magnets

- MDP 15T project (see A. Zlobin talk at MT27)
  - MDPCT achieved 14.5 T at 1.9K
  - Degradation on subsequent thermal cycle



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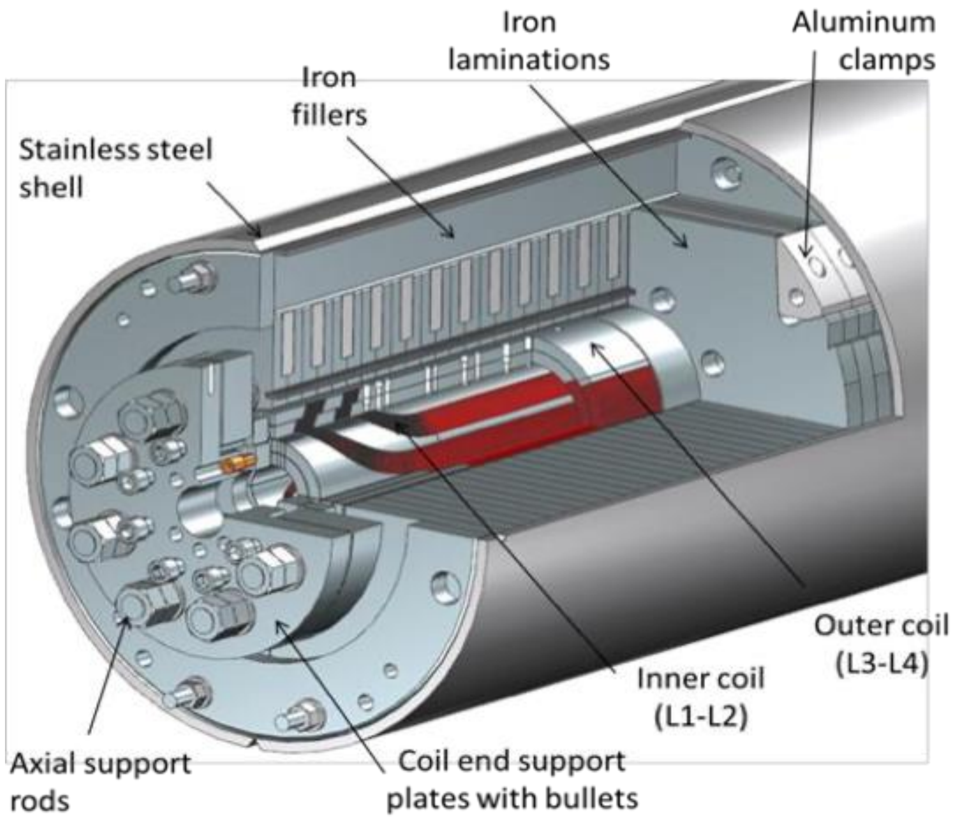
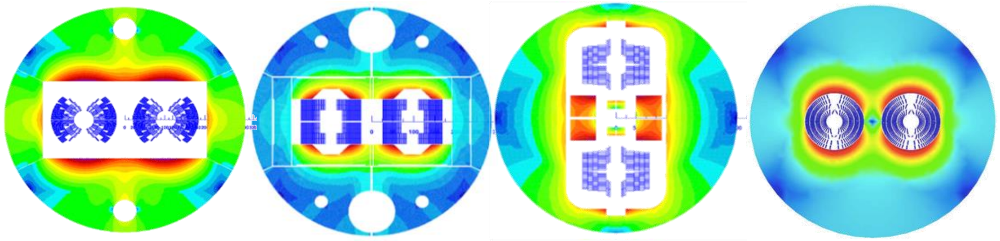


Courtesy, A. Zlobin, FNAL

Multiple options in conductor and magnets

- EU High Field Magnet Program (HFM)
  - Demonstrate Nb_3Sn full potential (16T)
  - Robust, industrial manufacturing and cost reduction (12T)
  - Demonstrate suitability of HTS for accelerator magnet applications (>20T)

INFN CEA Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas PAUL SCHERRER INSTITUT PSI



EU scoping study (16T) - Courtesy Luca Bottura, CERN

"High Field Magnet Development for HEP in Europe : A Proposal from LDG HFM Expert Panel", [arXiv:2203.08054 [physics.acc-ph]]

CEPC

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

- Iron-based Superconductor
- 12 – 24T

- Nb_3Sn: performance limits, reduce margin, minimize training
- HTS: >5T, >16T in background field
- Technology development: fundamental design, cost reduction
- Nb_3Sn/HTS – improve performance and reduce cost

U.S. MAGNET DEVELOPMENT PROGRAM

"A Strategic Approach to Advance Magnet Technology for Next Generation Colliders", [arXiv:2203.13985 [physics.acc-ph]]

RF

- Significant progress in RF technology development since last Snowmass
  - Up to 100 MV/m gradients achieved in the CLIC 12 GHz structures
  - 150 MV/m gradients in the first test of short 11.4 GHz NC structures cooled to 77K at SLAC
  - The full ILC specification of 31.5 MV/m has been demonstrated at the FNAL FAST facility (broemm
  - Working toward 50 MV/m gradients at 1.3 GHz
  - Work on efficiency, cost reduction of power sources

”Advanced RF Sources R&D for Economical Future Colliders”, arXiv:2203.15984 [physics.acc-ph]

”High Efficiency, Low Cost, RF Sources for Accelerators and Colliders”, arXiv:2203.12043 [physics.acc-ph]

”Nb3Sn Superconducting Radiofrequency Cavities: a Maturing Technology for Particle Accelerators and Detectors”, arXiv:2203.06752 [physics.acc-ph]

Targets and Sources

- High power targets are needed for future accelerators
  - New materials
  - New concepts
  - Numerical approaches to target design
  - Rad hard instrumentation
  - Development of irradiation methods for high power targets and irradiation facilities
  - High intensity positron sources are needed – perhaps advanced accelerator concepts?

This is a new General Acc. R&D area that came out of the last Snowmass/P5

”Irradiation Facilities and Irradiation Methods for High Power Target“, arXiv:2203.08239 [physics.acc-ph]

”Modeling Needs for High Power Target”, arXiv:2203.04714 [physics.acc-ph]

”Radiation hardened beam instrumentations for multi-Mega-Watt beam facilities”, arXiv:2203.06024 [physics.acc-ph]

”Novel Materials and Concepts for Next-Generation High Power Target Applications”, arXiv:2203.08357 [physics.acc-ph]

Plasma and Dielectric Wakefield Collider Concepts

Main advantages are very high gradient ~ 100 GeV/m and compact

- Laser-plasma
  - Achieved 8 GeV e^- over 20 cm – BErkeley Lab Laser Accelerator (BELLA) @ LBNL
- e^- beam-based
  - 9 GeV e^- over 1.3m – Facility for Advanced Accelerator Experimental Tests (FACET) @ SLAC
- Proton beam-based
  - 2 GeV over 10m – Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE) @ CERN
- Dielectric WakeField Accelerator (DWFA)
  - Similar concept to CLIC two-beam accelerator using dielectric structures
  - Activities at SLAC and ANL

”Continuous and Coordinated Efforts of Structure Wakefield Acceleration (SWFA) Development for an Energy Frontier Machine”, arXiv:2203.08275 [physics.acc-ph]

”Linear collider based on laser-plasma accelerators”, arXiv:2203.08366 [physics.acc-ph]

”AWAKE, Plasma Wakefield Acceleration of Electron Bunches for Near and Long Term Particle Physics Applications”, arXiv:2203.09198 [physics.acc-ph]

Plasma and Dielectric Wakefield Collider Concepts

- Challenges identified in AAC Roadmap https://www.osti.gov/servlets/purl/1358081
  - ***Staging:*** Higher energy (Multi-GeV) staging of electron acceleration, with independent drive beams, equal energy, and 90% beam capture.
  - ***Emittance:*** Understanding mechanisms for emittance growth and developing methods for achieving emittances compatible with colliders.
  - ***Higher energy electron acceleration stage:*** Completion of a single electron acceleration stage at higher energy.
  - ***Positron acceleration:*** Demonstration and understanding of positron acceleration.
  - ***Collider parameter set:*** Continuous, joint development of a comprehensive and realistic operational parameter set for a multi- TeV collider, to guide operating specifications for AAC.

Facility planning is still in the early stages – Need more R&D!

Summary

- Significant progress in accelerator science and technology since the last Snowmass
- Advances in
  - RF, magnets, sources, targets and advanced acceleration techniques
  - Beam physics and modeling
- Existing platforms for advancement
  - LHC upgrade, Super KEKB, PIP-II, ESS, EIC and FAIR
- P5 has a big challenge – but with strong support of the international accelerator and physics community there is an exciting future to look forward to

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