Snowmass'21

Accelerator Frontier:

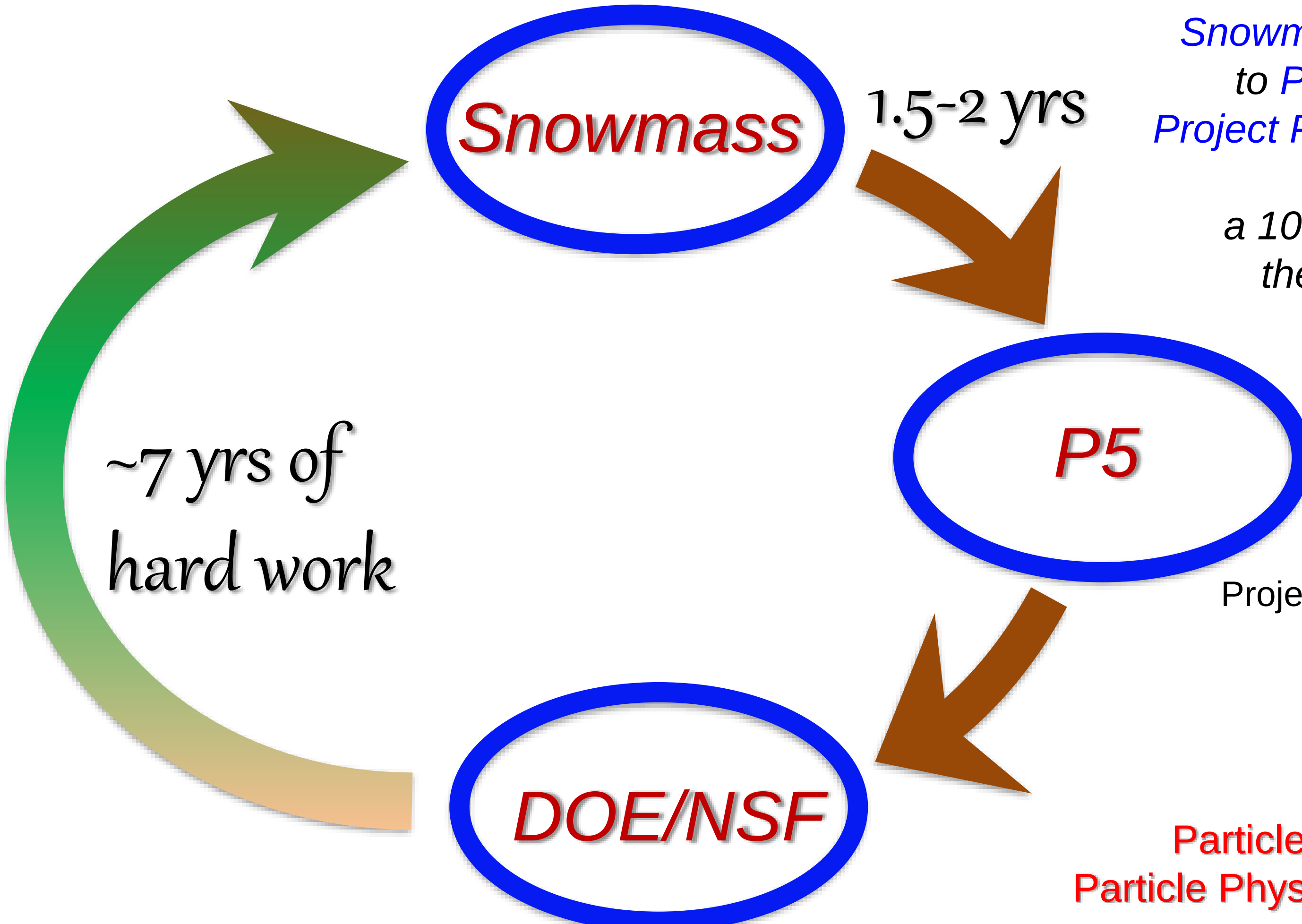
Summary of Discussions on Future HEP Facilities in the US

ICHEP'2022 – Bologna, Italy, July 8, 2022

Vladimir Shiltsev,
Stephen Gourlay, Tor Raubenheimer
(Snowmass'21 AF Conveners)

What is *Snowmass* :

"Snowmass is a particle physics community study"



Snowmass provides input to P5 (Particle Physics Project Prioritization Panel) which develops a 10-20 yrs strategy for the US HEP program

Particle Physics Project Prioritization Panel

Particle Physics is global
Particle Physics is not isolated

https://www.snowmass21.org/

Previous *Snowmass/P5* (2013/14)

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

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

Few Examples – Facilities/Programs

(under construction) AUP LHC Nb_3Sn IR quads for HI-LHC

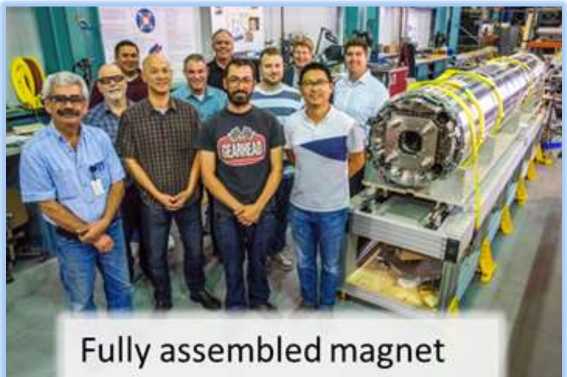
CD-3 project

be ready LS3

FNAL

BNL

LBNL



(construction started) PIP-II 800 MeV proton SRF linac @FNAL

Goal: 1.2MW for LBNF/DUNE

Beam to Booster in 2029

30% Int'l contrib.

(completed) ILC@Fermilab 1st 1.3GHz full CM with beam

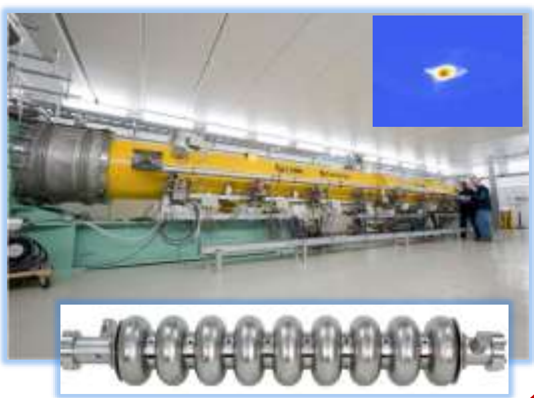
FAST facility

ILC type beam

31.5MeV/m

255 MeV/CM

= *G*, Q_0 specs



(ongoing) muon beams for g-2 and mu2e experiments

FNAL

8 GeV *p*'s → target → μ's

Run-I (2021) major muon *g-2* discovery

Few Examples – Accelerator R&D

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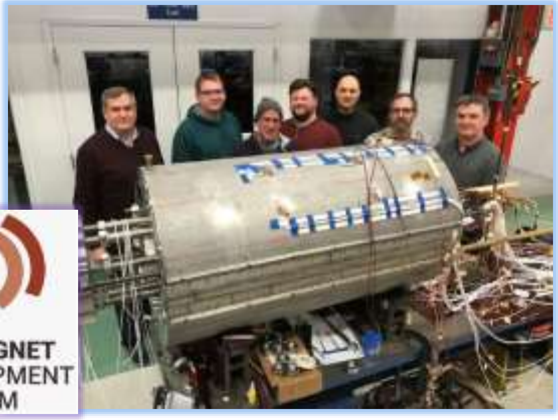
Record 14.5T Dipole (at FNAL, part of the US MDP)

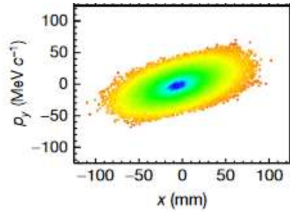
Nb3Sn conductor

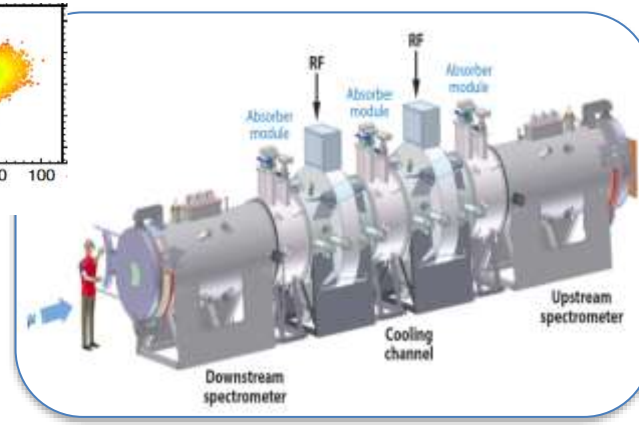
Stress control



U.S. MAGNET DEVELOPMENT PROGRAM

MAP/MICE: Ionization cooling of muons (140 MeV/*c*, RAL, UK)





MICE

~10% in one pass

FACET-II User facility (SLAC)

BELLA: PWFA records (LBNL)

Unique beam

10 GeV

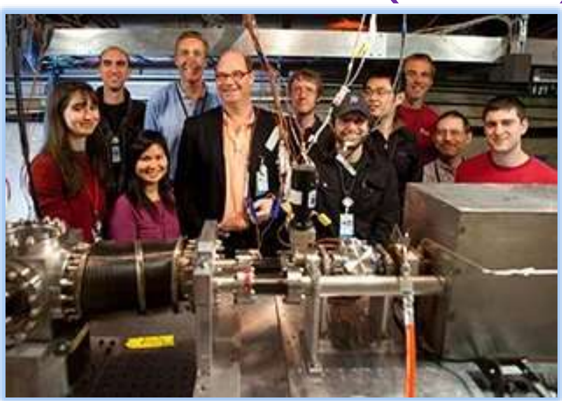
1 nC

1x1x1 μm

8 GeV/0.2m

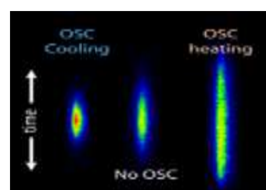
staging p.o.p

5+0.1 GeV



IOTA Ring/Optical Stochastic cooling *e*- (100 MeV, FNAL)

soon – experiments with *p*’s



THz bandwidth

(back to current) Snowmass'2021

Snowmass 2021

- Started in 2020→ ~1 yr COVID delay → finish 2022:
  - Community of ~3000 people, incl. international
  - Snowmass *CSS Workshop* in Seattle next week (please, join!) >600 people
  - Final report to P5, that starts in September'22 (for ~ a year)
- **10 "Frontiers": Energy, Theory, Cosmic, … Accelerator**

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?

Accelerator Frontier Conveners

Steve Gourlay
(LBNL)

Tor Raubenheimer
(SLAC)

Vladimir Shiltsev
(FNAL)

Topical Group		Topical Group co-Conveners			
AF01	Beam Phys & Accel. Education	Z. Huang (Stanford)	M. Bai (SLAC)	S. Lund (MSU)	
AF02	Accelerators for Neutrinos	J. Galambos (ORNL)	B. Zwaska (FNAL)	G. Arduini (CERN)	
AF03	Accelerators for EW/Higgs	F. Zimmermann (CERN)	Q. Qin (ESRF)	G.Hoffstaetter (Cornell) A.Faus-Golfe (IN2P3)	
AF04	Multi-TeV Colliders	M. Palmer (BNL)	A. Valishev (FNAL)	N. Pastrone (INFN)	J.Tang (IHEP)
AF05	Accelerators for PBC and Rare Processes	E. Prebys (UC Davis)	M. Lamont (CERN)	Richard Milner (MIT)	
AF06	Advanced Accelerator Concepts	C. Geddes (LBNL)	M. Hogan (SLAC)	P. Musumeci (UCLA)	R. Assmann (DESY)
AF07	Accelerator Technology R&D				
	Sub-Group RF	E. Nanni (LBNL)	H.Weise (DESY)	S. Belomestnykh (FNAL)	
	Sub-Group Magnets	G. Sabbi (LBNL)	S. Zlobin (FNAL)	S. Izquierdo Bermudez (CERN)	
	Sub-Group Targets/Sources	C. Barbier (ORNL)	Y. Sun (ANL)	Frederique Pellemoine (FNAL)	

Snowmass Activities: pre-Seattle

Proponents' Inputs	Letters-Of-Interest 257	White Papers 114
AF1: Beam Physics, Education & General	61	24
AF2: Accelerators for Neutrinos	18	9
AF3: Accelerators for EW/Higgs	32	11
AF4: Multi-TeV Colliders	56	10
AF5: Accelerators for PBC and Rare Proc.	37	7
AF6: Advanced Accelerator Concepts	71	10
AF7: Accelerator Technology R&D	137	43

PLUS:

- > 30 Topical Workshops
- 8 Cross-Frontier ***Agoras***
  - All types of colliders: ee, linear/circular, mumu, pp, advanced
  - Experiments and acceleratosr for rare processes physics
- Special cross-Frontier Groups (e.g., AF-EF-TF)
  - eeCollider Forum, Muon Collider Forum, Implementation Task Force

Accelerator Frontier Summary

- Now – *Draft Report Only*, will be finalized in Seattle
- AF Topical Group, ITF and Fora Summaries – mostly available
- Below, only few topics will be briefly covered:
  - Accelerators for Neutrinos
  - Accelerators for Rare Processes/DM Searches
  - Future Colliders
  - Key Accelerator R&D
- For each - key "messages" (vision):
  - Proposed directions ("what")
  - Timeline ("when") – e.g., by 2030, after 2030
  - Challenges ("what's needed")

1. Multi-MW ν Beams for DUNE

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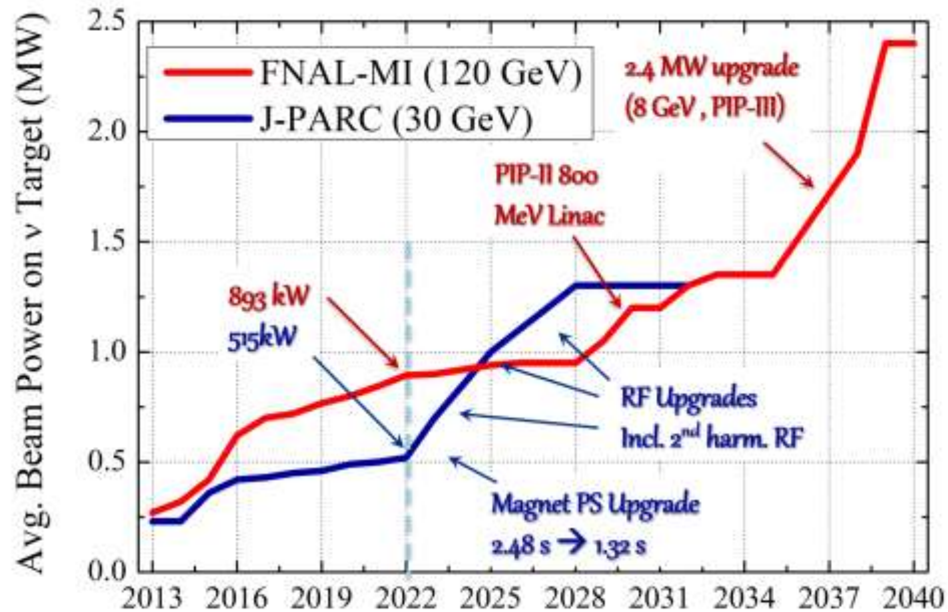
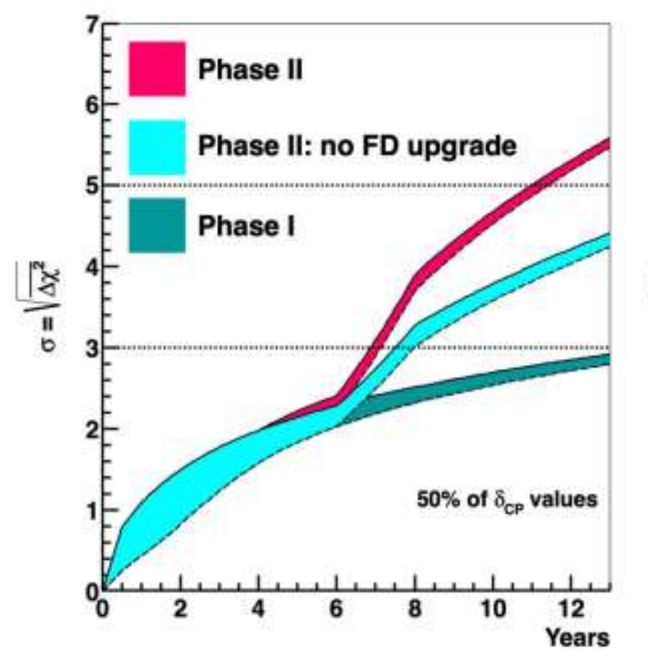
LBNF/DUNE Project – Phase I :

- By 2032: **1.2 MW** proton beam (120 GeV) on target + near ν-detector + 20 kton LAr ν-detector in Lead, SD
- Expected rate of "physics" outcome – up to ~3σ in δ_{CP}, in the first 6 years (also Δm^2_{32}, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$)
- To get to ~5σ will get too long, plus – competitor experiment Hyper-K in Japan



Proposed Plan - LBNF/DUNE Phase II :

- By 2038: ~2.4 MW proton beam (120 GeV) on target + new near ν-detector + extra 20 kton Lar ν-detector
- Expected to get to ~5σ in δ_{CP} in the following 6 years
- Accelerator options proposed/under active study now:
  - (understand max performance and limits with PIP-II linac)
  - New 8 GeV RCS [two options] with/w.o. new 1-3 GeV linac upgrade
  - New 8 GeV linac with or without new 8 GeV accumulator ring
  - In any case – need upgrade of MI RF power and new m-MW targets
  - See S.Nagaitsev talk earlier today
  - Fermilab has formed a special design group



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2. >20 Proposed Experiments For Rare Processes

(most via Snowmass Whitepapers)

DM searches, Axion searches, CLFV experiments, muons, light mesons, beam dump experiments… calls for corresponding beam facilities @ FNAL, SLAC, Jlab

Experiment	Experiment type	Primary beam particle	Beam Energy [GeV]	Beam power [kW]	Beam time structure
Proton Storage Ring: EDM and Axion Searches	Precision tests, Dark Matter	proton	0.7 GeV/c beam momentum	1e11 polarized protons per fill	Fill the ring every 1000s
Physics with Muonium	Precision tests	proton (producing surface muons)	0.8 GeV	1e13pml POT per second	CW
Nucleon Electromagnetic Form Factors from Lepton Scattering	Neutrino	electron or proton (producing muons)	0.85 GeV to 2 GeV	1 nA to 10 microA for electrons; 10^7 to 10^6 per second for muons	A continuous or pulsed structure (ideally with a duty factor of 1% or larger) should be sufficient
Rare Decays of Light Mesons (REDTOP)	Precision tests	proton	1.8-2.2 GeV (Run I), 0.8-0.92 (Run II), 1.7 (Run III)	0.03-0.05 (Run I), 200 (Runs II and III)	CW, slow extraction for Run I
Ultra-cold Neutron Source for Fundamental Physics Experiments, Including Neutron-Anti-Neutron Oscillations	Precision tests	proton	0.8-2	1,000	quasi-continuous
CLFV with Muon Decays	CLFV	proton	Not critical 0.8 to a few GeV	100 or more	continous beam on the timescale of the muon lifetime i.e. proton pulses separated by a microsecond or less. The more continuous the better
Mu2e II	CLFV	proton	1 to 3	100	pulse width 10s of ns or better separated by 200 to 2000 ns. Flexible time structure and minimal pulse-to-pulse variation
Fixed Target Searches for new physics with O(1 GeV) Proton Beam Dump	Dark Sector, Neutrino	proton	0.8 to 1.5 GeV	100 or more	<O(1 micro s) pulse width for neutrino measurements; <O(30 ns) pulse width for dark matter searches; 10^(-5) or better duty factor
PRISM-like Charged Lepton Flavor Violation	CLFV	proton	1-3 GeV	up to 2 MW	5ns pulses at a rep rate of about 1 kHz
Electron Missing Momentum (LDMX)	Dark Sector	electron	~3 GeV to ~20 GeV	O(1 electron per RF bucket at 53 MHz)	CW-ish
Electron Beam Dumps	Dark Sector	electron	few GeV	10^(20) electrons on target over the experiment al runtime	Pulsed beam (duty factor not specified)
Proton Irradiation Facility	R&D	proton	Energy is not very important	1e18 protons in a few hours	Pulsed beam (duty factor not specified)
SBN	Neutrino	proton	8	32	20Hz
Mu2e	CLFV	proton	8	8	<10^(-10) extinction
Fixed Target Searches for new physics with O(10 GeV) Proton Beam Dump	Dark Sector, Neutrino	proton	8	up to 115	Beam spills less than a few microsec with separation between spills greater than 50 microsec
Muon beam dump	Dark Sector	proton (producing muons)	3 GeV muons	3e14 muons in total on target for the whole run	CW
Muon Collider R&D and Neutrino Factory	R&D	proton	5 - 30GeV	1e12 to 1e13 protons per bunch	10 - 50 Hz rep rate and bunch length 1-3 ns
Muon Missing Momentum	Dark Sector	proton (producing muons)	few 10s of GeV	10^(10) muons per experimental runtime	Pulsed beam (duty factor not specified)
High Energy Proton Fixed Target	Dark Sector, Neutrino	proton	O(100 GeV)	1e12 POT/s therefore ~20 kW	CW via resonant extraction. "If we could up the duty factor that woul dbe even better"(?)
Test-Beam Facility	R&D	proton	120, lower energies would also be beneficial	10 to 100 kHz on the testing apparatus	Pulsed beam (duty factor not specified)
Tau Neutrinos	Neutrino	proton	120	1200 or higher	MI time structure

Electron beams:
~ GeV to multi-GeV

Proton beams:

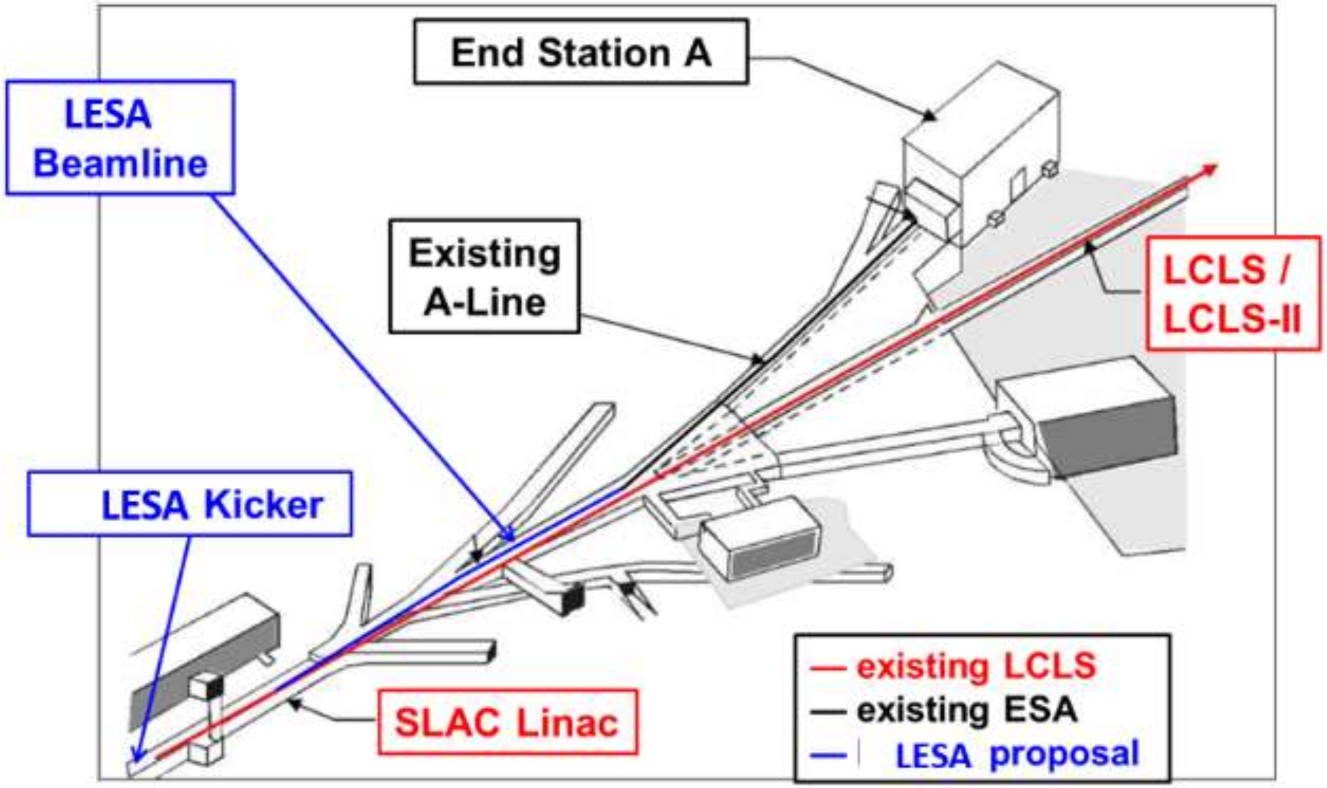
~2 GeV CW-capable beam

~2 GeV pulsed beam from storage ring ~1MW

~8 GeV pulsed beam ~1MW

120 GeV Slow extraction or LBNF beam

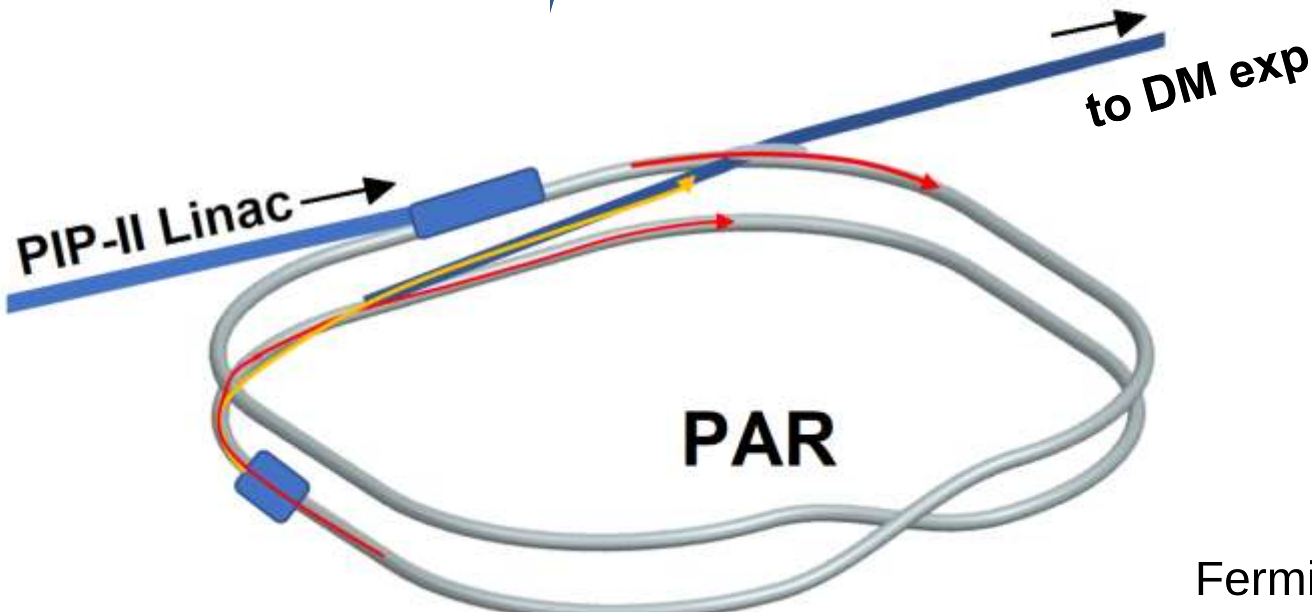
Started LESA Beamline for LDMX @ SLAC



Features:

- SLAC electron SRF linac *E*=4-8 GeV
- Low intensity, almost CW beamline, 1-500 *e-/us*
- Beam dump and LDMX experiment
- CD-process started

Proposed PIP-II Accumulator Ring (PAR)



Snowmass white papers PAR, PIP2-BD

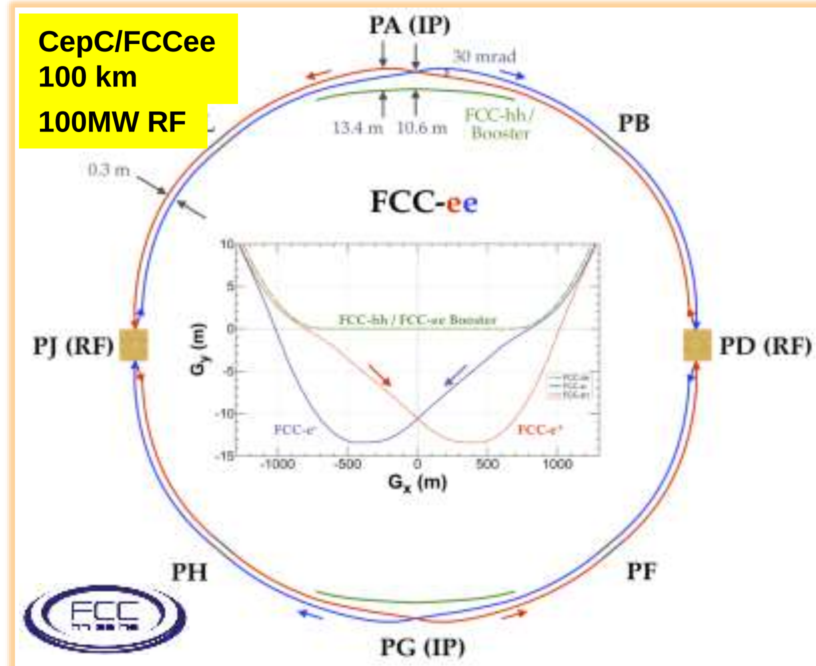
Fermilab

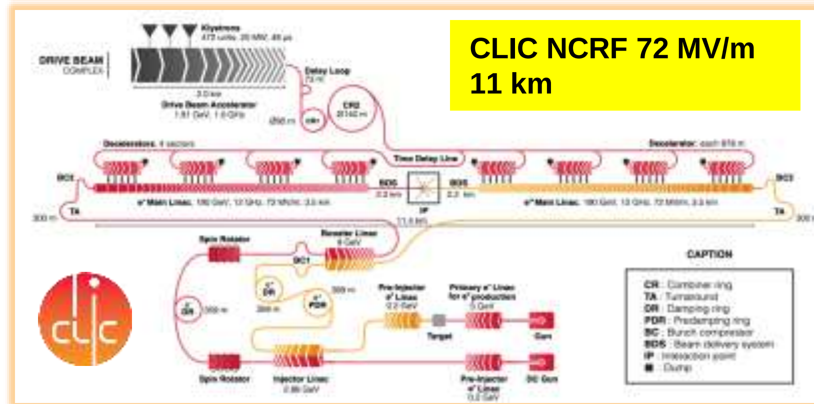
Features:

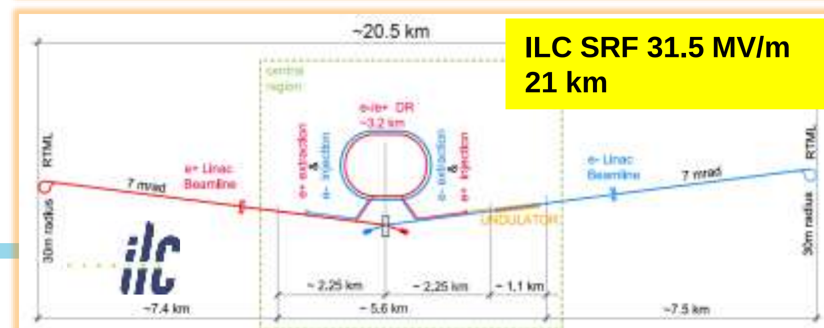
- Fixed *E*=0.8-1.0 GeV proton storage ring
- *C*=480m in the form of a *folded figure 8*
- Power 100 kW for Dark Sector program, 100Hz
- There is also compact version *C*=120 m

Future Collider Proposals:
8 Higgs/EW factories

Name	Details
CepC	e+e-, $\sqrt{s} = 0.24$ TeV, L= 3.0 $\times 10^{34}$
CLIC (Higgs factory)	e+e-, $\sqrt{s} = 0.38$ TeV, L= 1.5 $\times 10^{34}$
ERL ee collider	e+e-, $\sqrt{s} = 0.24$ TeV, L= 73 $\times 10^{34}$
FCC-ee	e+e-, $\sqrt{s} = 0.24$ TeV, L= 17 $\times 10^{34}$
gamma gamma	X-ray FEL-based $\gamma\gamma$ collider
ILC (Higgs factory)	e+e-, $\sqrt{s} = 0.25$ TeV, L= 1.4 $\times 10^{34}$
LHeC	ep, $\sqrt{s} = 1.3$ TeV, L= 0.1 $\times 10^{34}$
MC (Higgs factory)	$\mu\mu$, $\sqrt{s} = 0.13$ TeV, L= 0.01 $\times 10^{34}$

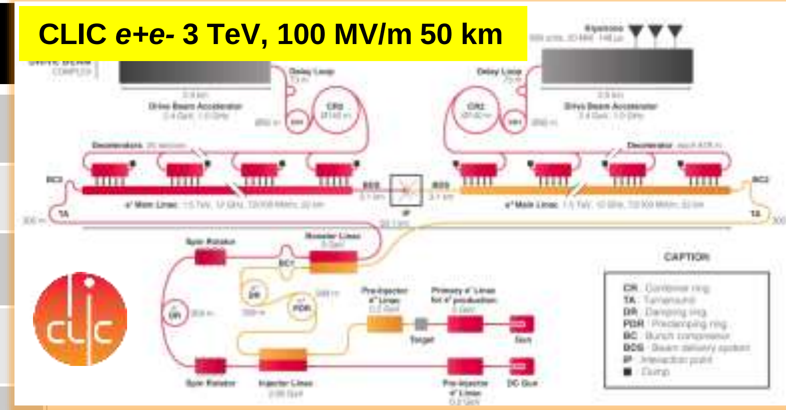


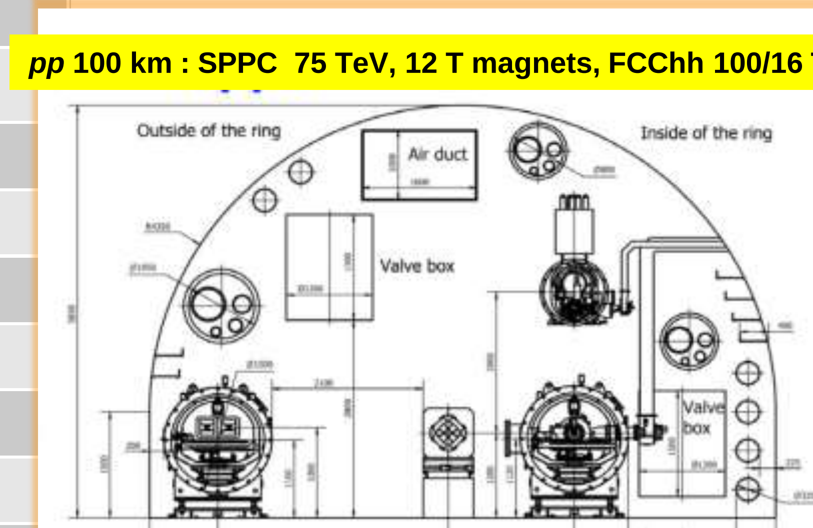


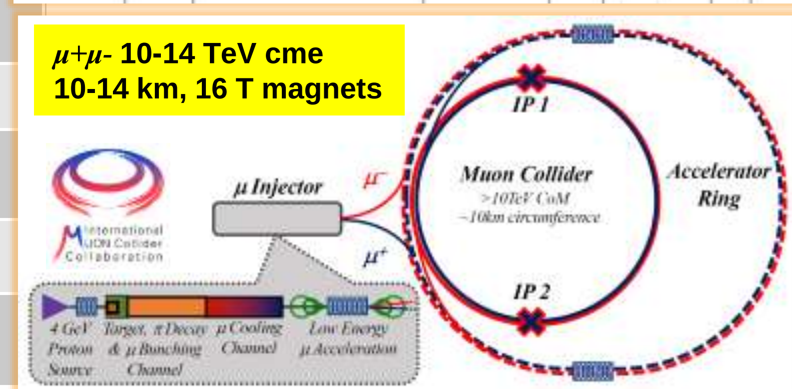


17 (!) High Energy Collider Concepts/Proposals

Name	Details
Cryo-Cooled Copper linac	e+e-, $\sqrt{s} = 2$ TeV, L= 4.5 $\times 10^{34}$
High Energy CLIC	e+e-, $\sqrt{s} = 1.5 - 3$ TeV, L= 5.9 $\times 10^{34}$
High Energy ILC	e+e-, $\sqrt{s} = 1 - 3$ TeV
FCC-hh	pp, $\sqrt{s} = 100$ TeV, L= 30 $\times 10^{34}$
SPPC	pp, $\sqrt{s} = 75/150$ TeV, L= 10 $\times 10^{34}$
Collider-in-Sea	pp, $\sqrt{s} = 500$ TeV, L= 50 $\times 10^{34}$
LHeC	ep, $\sqrt{s} = 1.3$ TeV, L= 1 $\times 10^{34}$
FCC-eh	ep, $\sqrt{s} = 3.5$ TeV, L= 1 $\times 10^{34}$
CEPC-SPPpC-eh	ep, $\sqrt{s} = 6$ TeV, L= 4.5 $\times 10^{33}$
VHE-ep	ep, $\sqrt{s} = 9$ TeV
MC – Proton Driver 1	$\mu\mu$, $\sqrt{s} = 1.5$ TeV, L= 1 $\times 10^{34}$
MC – Proton Driver 2	$\mu\mu$, $\sqrt{s} = 3$ TeV, L= 2 $\times 10^{34}$
MC – Proton Driver 3	$\mu\mu$, $\sqrt{s} = 10 - 14$ TeV, L= 20 $\times 10^{34}$
MC – Positron Driver	$\mu\mu$, $\sqrt{s} = 10 - 14$ TeV, L= 20 $\times 10^{34}$
LWFA-LC (e+e- and $\gamma\gamma$)	Laser driven; e+e-, $\sqrt{s} = 1 - 30$ TeV
PWFA-LC (e+e- and $\gamma\gamma$)	Beam driven; e+e-, $\sqrt{s} = 1 - 30$ TeV
SWFA-LC	Structure wakefields; e+e-, $\sqrt{s} = 1 - 30$ TeV







(New!) LC-Higgs Factories on FNAL Site

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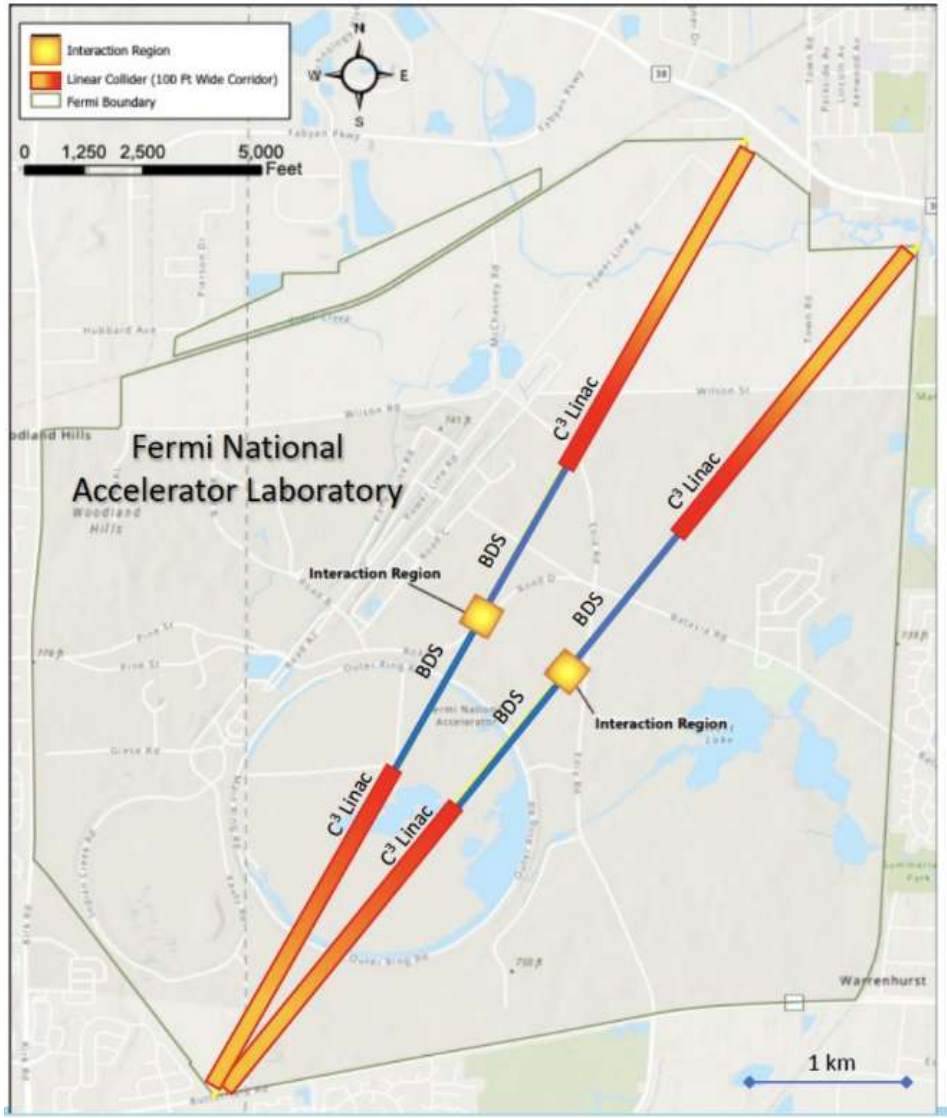
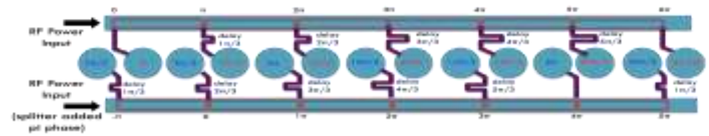


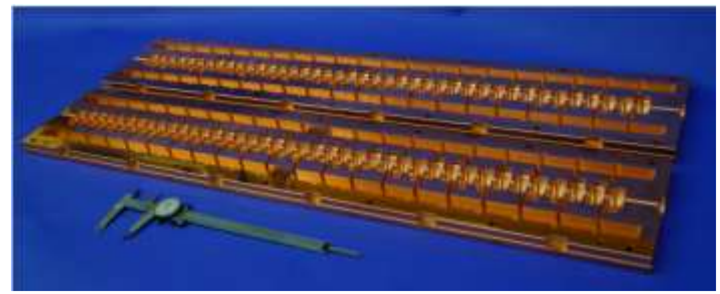
Must fit ~7 km incl BDS

Requires gradients of at least 72MV/m

Compact → lower cost (wrt ILC/CLIC)

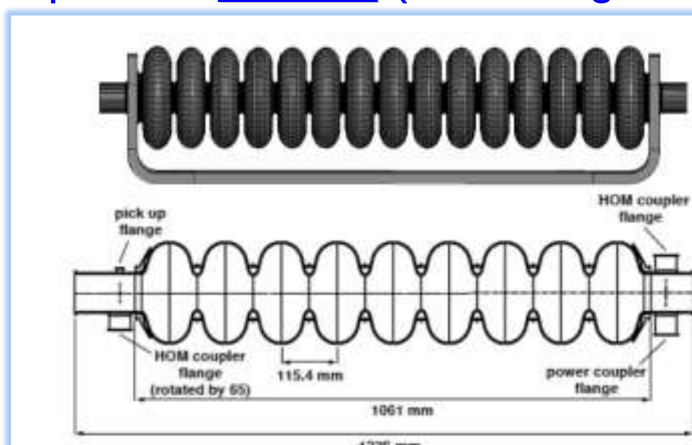
Option 1: Cool Copper Collider (C^3)





5.7GHz
77K

Option 1: *HELEN* (Travelling Wave ILC)



1.3GHz
2 K

FNAL Citing – *O*(10 TeV) Muon Collider

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- First design concept of up to 10 TeV collider developed
- Operation at 125 GeV, 1 and 3 TeV can be envisioned as intermediate stages
- Capitalize on existing facilities and expertise:
  - PIP-II and upgrades,

Muon Colliders Forum:

a) aim for 10 TeV cme

b) DOE support+join IMCC (CERN-led Int'l Muon Collider Collaboration)

c) Carry out R&D and deliver pre-CDR ca 2030

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Implementation Task Force

- The Accelerator **Implementation Task Force (ITF)** is charged with developing metrics and processes to facilitate a comparison between collider projects.
- 10 int'l experts, 2 *Snowmass Young's*, 3 liaisons to Energy & Theory Frontiers
- ITF addressed (four subgroups):
  - Physics reach (impact), beam parameters
  - Size, complexity, power, environment
  - Technical risk, technical readiness, validation and R&D required
  - Cost and schedule


Thomas Roser (BNL, Chair)


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Steve Gourlay (LBNL)


Tor Raubenheimer (SLAC)


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From the ITF Report Draft: Tables 1-3, 5

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	CME (TeV)	Lumi per IP (10^34)	Years, pre-project R&D	Years to 1st physics	Cost range (2021 B$)	Electric Power (MW)
FCCee-0.24	0.24	8.5	0-2	13-18	12-18	280
ILC-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC-0.38	0.38	2.3	0-2	13-18	7-12	110
HELEN-0.25	0.25	1.4	5-10	13-18	7-12	110
CCC-0.25	0.25	1.3	3-5	13-18	7-12	150
MC-Higgs	0.13	0.01	>10	19-24	4-7	~200
CLIC-3	3	5.9	3-5	19-24	18-30	~550
ILC-3	3	6.1	5-10	19-24	18-30	~400
MC-3	3	2.3	>10	19-24	7-12	~230
MC-FNAL	6-10	20	>10	19-24	12-18	O(300)
MC-10	10-14	20	>10	>25	12-18	O(300)
FCChh-100	100	30	>10	>25	30-50	~560

Future Colliders R&D Program - Initiative

Snowmass 2021

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

June 30, 2022

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

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A.J. Lankford[8,†], S. Nagaitsev[1,2,†], E.A. Nanni[4], M.A. Palmer[3], T. Raubenheimer[4],
V. Shiltsev[1], A. Valishev[1], F. Zimmermann[7]

We propose that the U.S. establish a national integrated R&D program on future colliders in the DOE Office of High Energy Physics (OHEP) and charge the program

- to carry-out technology R&D and accelerator design for future collider concepts,
- to enable synergistic engagement in projects proposed abroad (e.g. FCC, ILC, CLIC, IMCC),
- to develop design reports on collider options, by the time of the next Snowmass and P5 (2029–2030), particularly for options that are feasible to be hosted in the U.S.,
- to develop R&D plans for the decade beyond 2030.

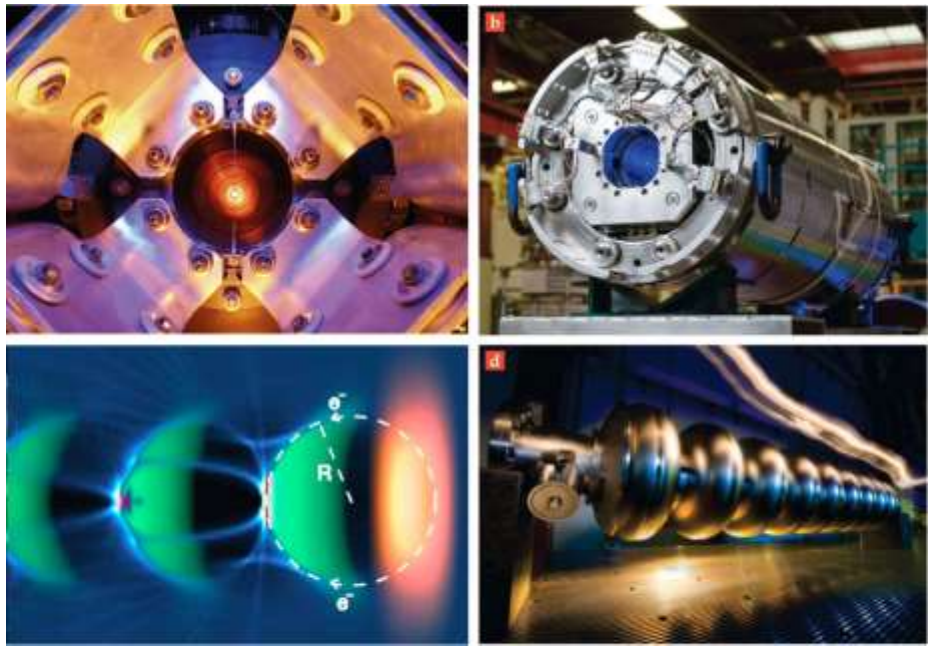
Multi-MW targets:

- 2.4MW PIP-III
- 4-8 MW for muon collider

Magnets for colliders and RCSs:

- 16T dipoles
- 30T solenoids
- 1000 T/s fast cycling ones

coordinate with US MDP



Advanced:

- collider quality beams
- efficient drivers
- close coordination with Int'l (Euro Roadmap, EUPRAXIA,..)

SC/NC RF:

- 72-120 MV/m C[3]
- 72 MV/m TW SRF
- new materials, high Q_0
- efficient power sources

Thanks for your attention!

- ICHEP'22 presentations on AF/related topics **Thursday, July 7**:
  - A.Faus-Golfe (AF3) on CLIC and ILC
  - N.Pastrone (AF4) on energy frontier colliders
  - S.Nagaitsev on multi-MW proton beams at FNAL
  - D.Druitti and R.Reimann on the muon g-2 ring
  - V.Pronskykh on the mu2e target
  - S.Nagaitsev on the optical stochastic cooling
  - D.Calzolari on MDI of multi-TeV muon collider
- Later in this session:
  - D.Schulte on the energy frontier muon colliders
  - P.Burrows – on ILC and CLIC

- Special thanks to
  - My co-conveners S.Gourlay and T.Raubenheimer
  - T.Roser (ITF chair) and P.Bhat (FNAL collider group leader)
  - Accelerator Frontier Topical Group conveners and liaisons to EF, NF and TF
- In preparation of the ***Snowmass in Seattle***, tons of material available at:

https://snowmass21.org/accelerator/start