Future Collider Options for US/Fermilab

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Introduction

- Future Colliders are an essential component of strategic vision for particle physics. Physics at the Energy Frontier is of paramount importance!

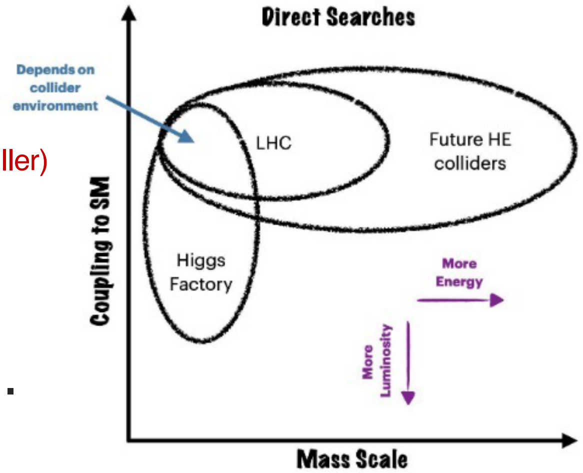
- The U.S. has a rich history in particle accelerators and colliders, which enabled major discoveries in particle physics and establishing of the Standard Model.

- To ensure continued progress, U.S. leadership is critical
  - Needs to be a key partner in developing next generation colliders abroad
  - Develop compact, cost-effective options for hosting future colliders at home

- The US HEP Community Study, "Snowmass", that was just completed on July 25th 2022, provided a timely opportunity to explore strategies for both.

The Global Energy Frontier Landscape

- July saw the 10th anniversary of the discovery of the Higgs boson, a particle like none other! A lot has been learned about the Higgs at the LHC, but it is still shrouded in mystery!
- LHC/HL-LHC will be our flagship collider facility
  - An impressive physics program for the next two decades
  - Opportunities for new physics discoveries and precision measurements of the SM
- Strong consensus in the global community that an e+e- Higgs Factory should be the next global collider, and that it should be realized as soon as possible.
  - Prime candidates: ILC, (CLIC), FCC-ee, CEPC
  - Promising, novel concepts: C3, HELEN, FNAL-SF (site-filler)



- Beyond a Higgs Factory, progress at the Energy Frontier would need a high energy collider to access physics at ~10 TeV scale.
  - FCC-hh, ~10 TeV Muon Collider, SppC, *VLHC*

See for example, https://arxiv.org/abs/1306.2369

- See Snowmass EF Summary:
https://indico.fnal.gov/event/22303/contributions/247435/attachments/158065/208160/Reina-Physics-Panel.pdf

Higgs Factory Options

- ILC: “shovel ready”, but no takers so far
  - Can be operational by ~2035, and run concurrently with LHC
  - But, the goal-post keeps getting moved for ILC in Japan
- CLIC: on the backburner for now
- FCC-ee: front-runner at CERN; feasibility studies underway
  - If yes, then operations by ~2048
- CepC: Projected for ~2035; Funding uncertain/unknown
- C3: new, promising, compact, need viability demo
  - Possible operation by late 2030s
- High Gradient SRF machines: need aggressive R&D
  - Maybe possible in 2040s
- Muon Collider HF: More challenging than higher energies; 2040s – 50s
- FNAL-SF-ee: Very preliminary studies; many constraints

Colliders for the 10-TeV scale

- FCC-hh: Prime candidate; very distant, beyond 2070
- SppC: to follow CepC, distant (2060s)
- Muon Collider (8-10 TeV and beyond)
  - Unique, challenging, need aggressive R&D and more demo
  - A great tool for both precision and energy-scale
  - Could be feasible in 2040s-50s with intense efforts
  - A good candidate for Fermilab
- VLHC: 40 TeV with 2T transmission magnets (233 km)
  - Could be a 100 km ring, say, in Chicagoland (~ FCC-hh)
- For farther future, Advanced Accelerator options would come into play.
- Intermediate Energy Options (~28 TeV Collisions):
  - HE-LHC (issues using LHC tunnel)
  - FNAL-SF-pp (proxy for HE-LHC): need aggressive magnet R&D (~25T)

Future Colliders Initiative at Fermilab

- A Future Colliders Group (FCG) was formed at Fermilab about a year ago with the following objectives:
  - Develop Fermilab's **engagement plans in future collider projects**, across aspects of accelerators, technology, particle physics and detectors
  - Provide a **forum to synergize efforts** on future colliders/accelerators across frontiers
  - **Develop a roadmap** for further (design) studies and R&D for future colliders
  - Work with US universities and other US national labs, and with international collaborators on pertinent issues and proposals
  - **In the past year, the focus was to produce robust input for Snowmass.**
- Recent Activities:
  - Snowmass Agora series on future colliders (5 events, Dec.'21- Apr. '22)
  - Organized mini-workshops (e.g., C^3)
  - Collaborated/co-authored several Future Colliders whitepapers for Snowmass
  - Produced a comprehensive summary of "Future Collider Options for the U.S." https://arxiv.org/abs/2203.08088/
  - Proposed a national R&D program

"U.S. National Accelerator R&D Program on Future Colliders" https://arxiv.org/abs/2207.06213

FUTURE COLLIDERS GROUP
(P. Bhat, Head)
(S. Jindariani, Deputy Head)

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(Z. Gecse)

Snowmass Agora on Future Colliders

- The Fermilab Future Colliders Group organized a series of Snowmass "Agora" on Future Colliders, in conjunction with Snowmass Accelerator and Energy Frontier conveners.
  - Org. Committee:
    - M. Narain, L. Reina, A. Tricoli, S. Gourlay, T. Raubenheimer, V. Shiltsev, P. Bhat, J. Butler
- Five Agora events held from Dec. 2021 to April 2022, once a month, on Wednesdays. Each 2.5 hrs; 4-5 talks, ~1 hr moderated Q&A, 30 min. informal post-Agora chat.

– **Linear e+e- colliders**	**Dec. 15, 2021**
– **Circular e+e- colliders**	**Jan. 19, 2022**
– **Muon colliders**	**Feb. 16, 2022**
– **Circular pp and ep**	**Mar. 16, 2022**
– **Advanced colliders**	**Apr. 13, 2022**

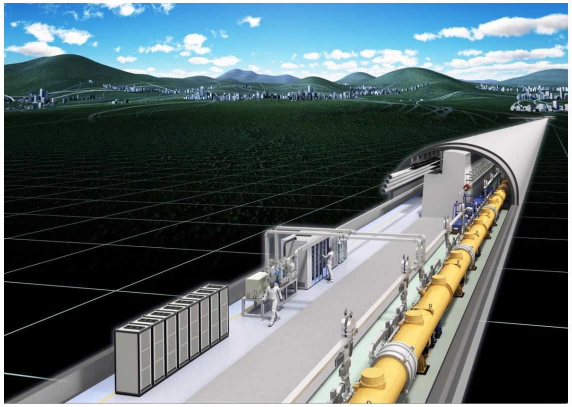
Aspects covered:

Physics reach
Challenges and R&D required
Synergy of project with global context
Synergy of project with local resources
Time frame (short-term R&D, long-term construction)
Costs projections: both R&D and construction costs

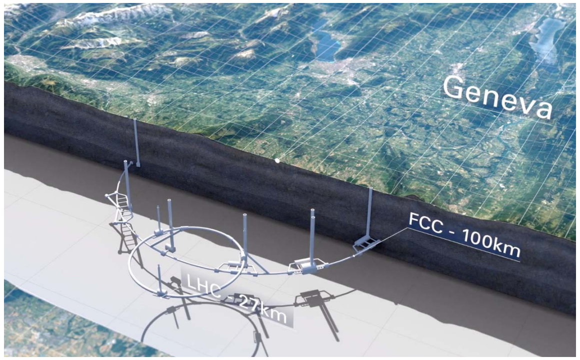
- Comparative physics potential of various machines
- Intense focus on proposed machines in various categories!
  - Technical readiness or maturity status, what specifications have been achieved, remaining challenges, timelines, cost, …
- Slides, videos, google doc with Q&A, summary from moderators available on the indico pages. https://indico.fnal.gov/e/snowmass-agora-n/ (n=1,..5)

U.S. Engagement in Global Projects

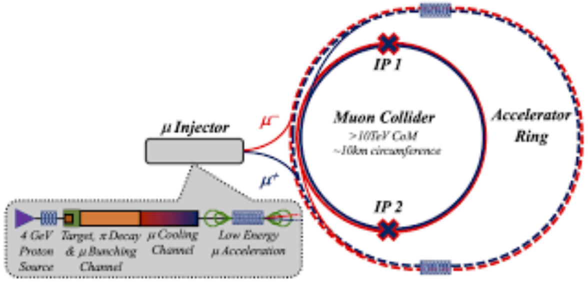
- The International Linear Collider
  - U.S. scientists engaged in efforts of the ILC-IDT (ILC International Development Team)
    - SRF R&D for ILC main linacs and ILC++
    - Polarized Positron Source and Damping Ring, ..



- Future Circular Colliders (FCC-ee/hh)
  - CERN conducting Technical and financial feasibility studies; results and CDR++ by ~2026
  - CERN/DOE agreement signed in Dec. 2020
    - Opportunities for engineering design studies, beam physics studies, High Q_0 SRF R&D, magnet R&D,..



- Muon Collider Collaboration
  - Intense work in progress in the International Muon collider Collaboration; US community engaged
    - Machine scenarios, beam induced background, neutrino radiation, demonstrator facility, detector/physics studies
    - Exploring formal U.S. engagement



Future Collider Options for Fermilab Site

- A comprehensive whitepaper outlines several options for e+e-, μ+ μ- and pp colliders at Fermilab.

Future Collider Options for the US

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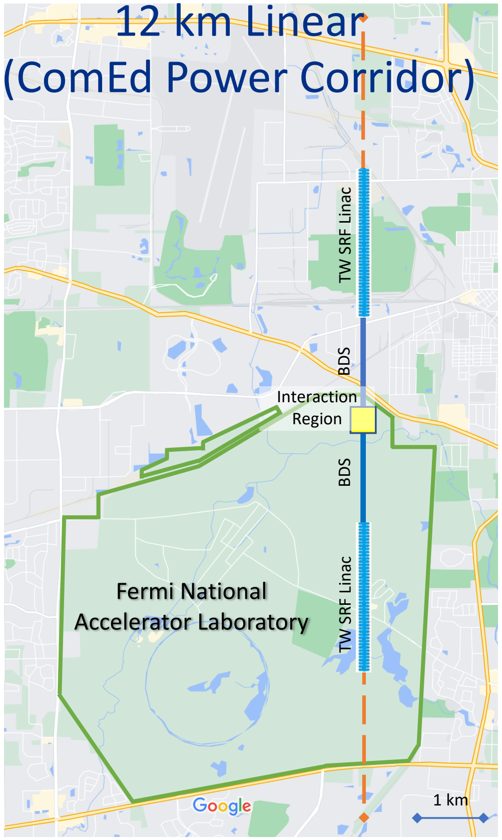
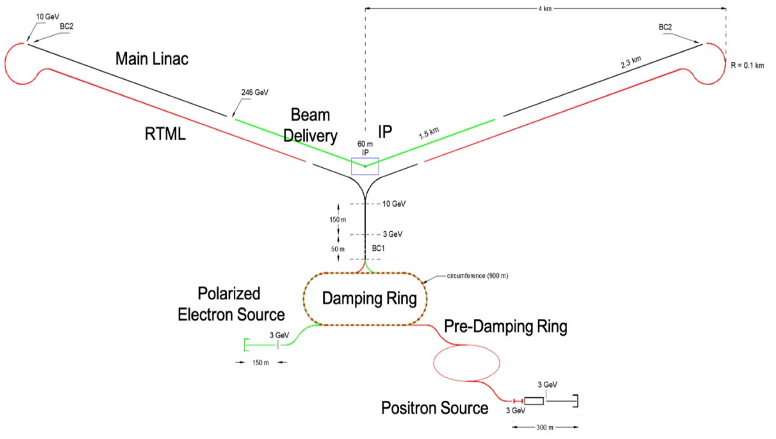
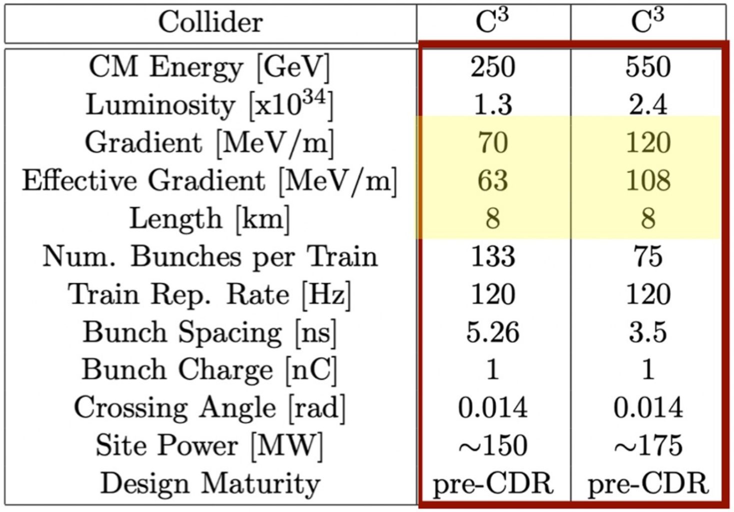


Higgs Factories

The Cool Copper Collider (CCC or C³)

- SLAC (E. Nanni, C. Vernieri, et al.) proposal for a normal conducting RF linear accelerator/collider operating at 77K.
  - Could reach gradient ~155 MV/m
  - 1-2e34 @250 GeV; using 70 -85 MV/m at FNAL
  - Scalable to 550 GeV at FNAL
    - RF upgrade and higher gradient (155 MV/m to fit 7 km footprint)
    - Can use lower gradient for footprint extending beyond site
    - Upgradeable to Multi-TeV if built off-site
- Benefits from other developed LC technologies
  - Beam Delivery system & IP modified from ILC
  - Damping rings and injectors to be optimized with CLIC as baseline
- Single cavity tests yield excellent results
- C³ collaboration proposing R&D stages and a 3- Cryomodule demonstrator facility
  - Collaborative R&D work between Labs, universities
  - Feasibility at Fermilab/FAST for R&D and demonstrator under study





Collider	C³	C³
CM Energy [GeV]	250	550
Luminosity [x10³⁴]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Crossing Angle [rad]	0.014	0.014
Site Power [MW]	~150	~175
Design Maturity	pre-CDR	pre-CDR

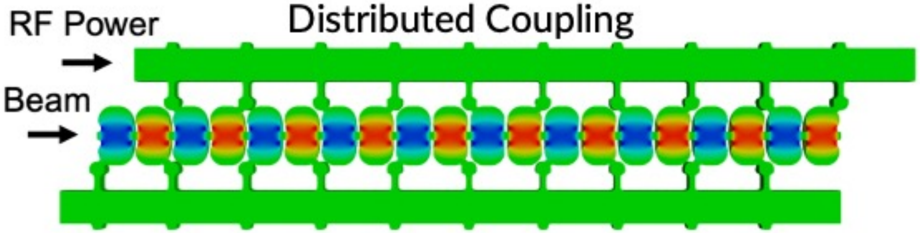
From E. Nanni

Key Technologies

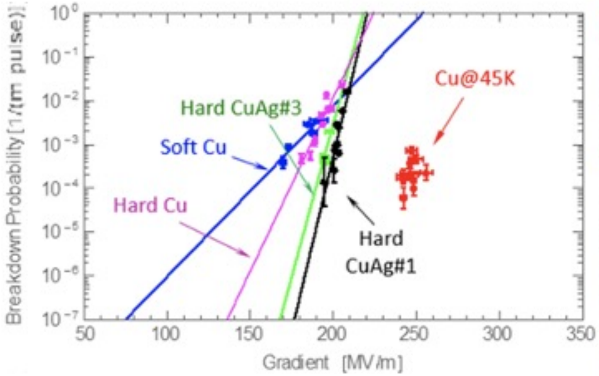
Present Focus is the Main Linac
In Future Expand to Rest of Complex

Maximize Structure Efficiency and Performance

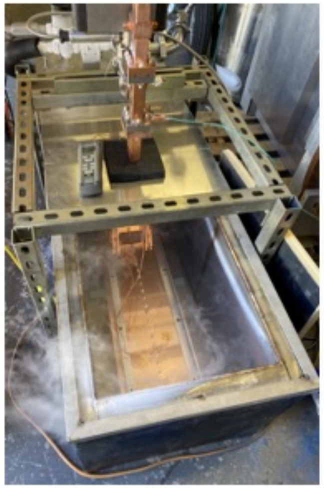
Distributed Coupling



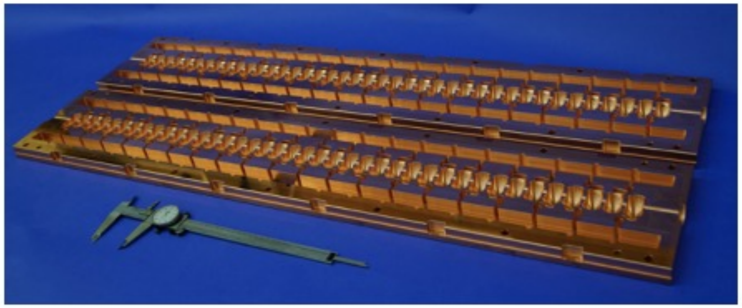
High Accelerating Gradients
Cryogenic Operation



C^3 Cryo Test



Modern Manufacturing
Prototype One Meter Structure

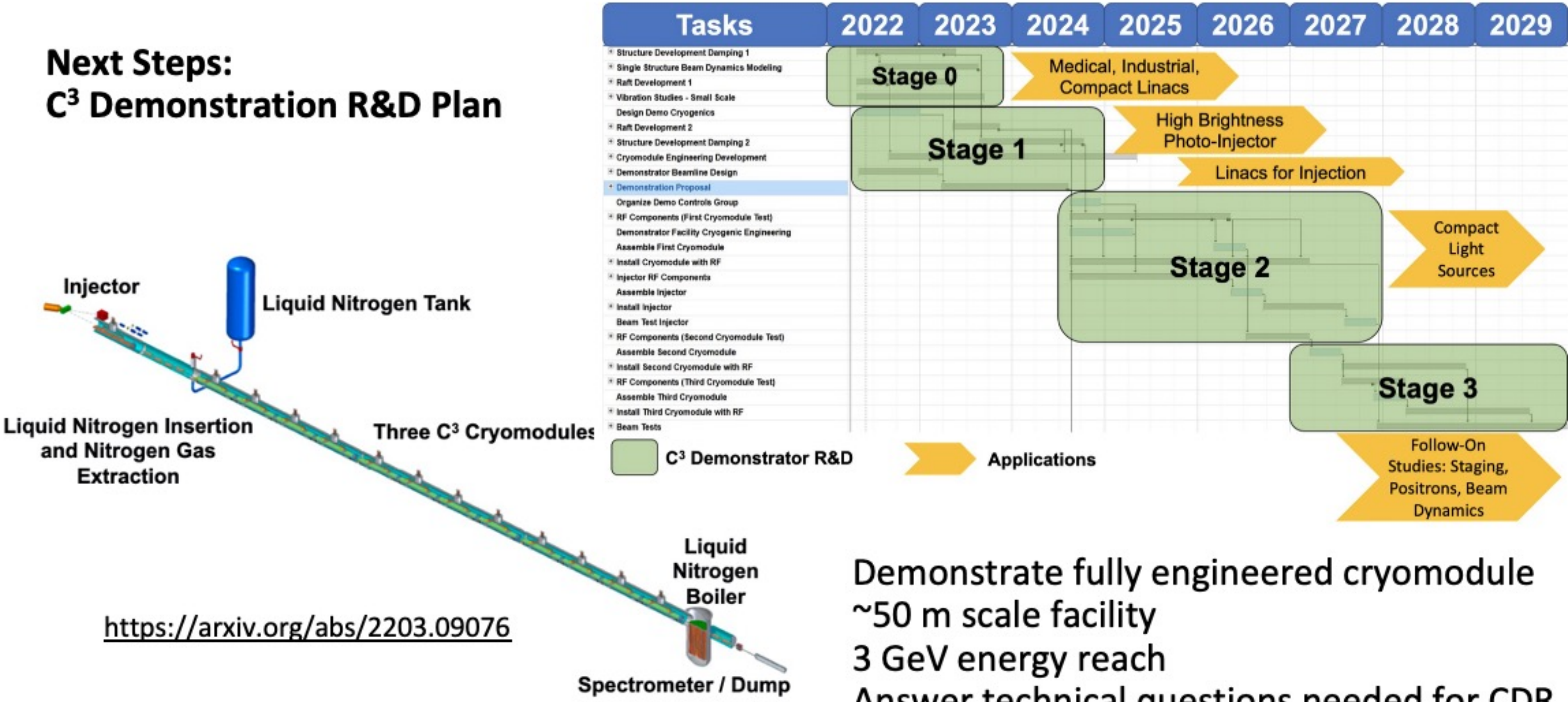


Integrated Damping
Slot Damping with NiChrome Coating

From E. Nanni

State of Proposal and R&D needs (5 years)

Next Steps:
C^3 Demonstration R&D Plan



https://arxiv.org/abs/2203.09076

Demonstrate fully engineered cryomodule
~50 m scale facility
3 GeV energy reach
Answer technical questions needed for CDR

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on the Future of Particle Physics (Snowmass 2021)

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Strategy for Understanding the Higgs Physics:
The Cool Copper Collider

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C³ Demonstration Research and Development Plan

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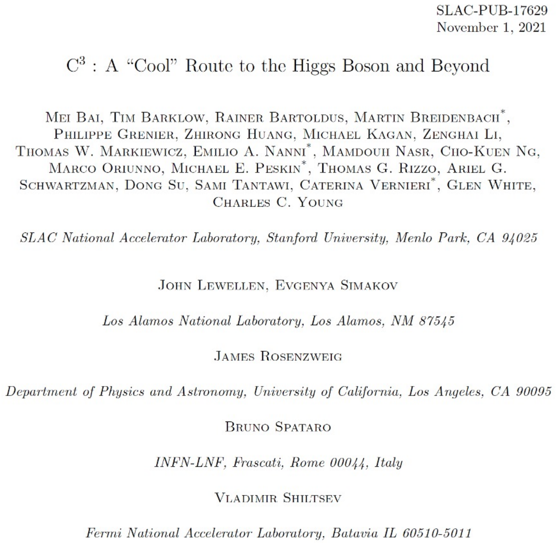

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November 1, 2021

C³ : A "Cool" Route to the Higgs Boson and Beyond

Mei Bai, Tim Barklow, Rainer Bartoldus, Martin Breidenbach*, Philippe Grenier, Zhirong Huang, Michael Kagan, Zenghai Li, Thomas W. Markiewicz, Emilio A. Nanni*, Mamdouh Nasr, Cho-Kuen Ng, Marco Oriunno, Michael E. Peskin*, Thomas G. Rizzo, Ariel G. Schwartzman, Dong Su, Sami Tantawi, Caterina Vernieri*, Glen White, Charles C. Young

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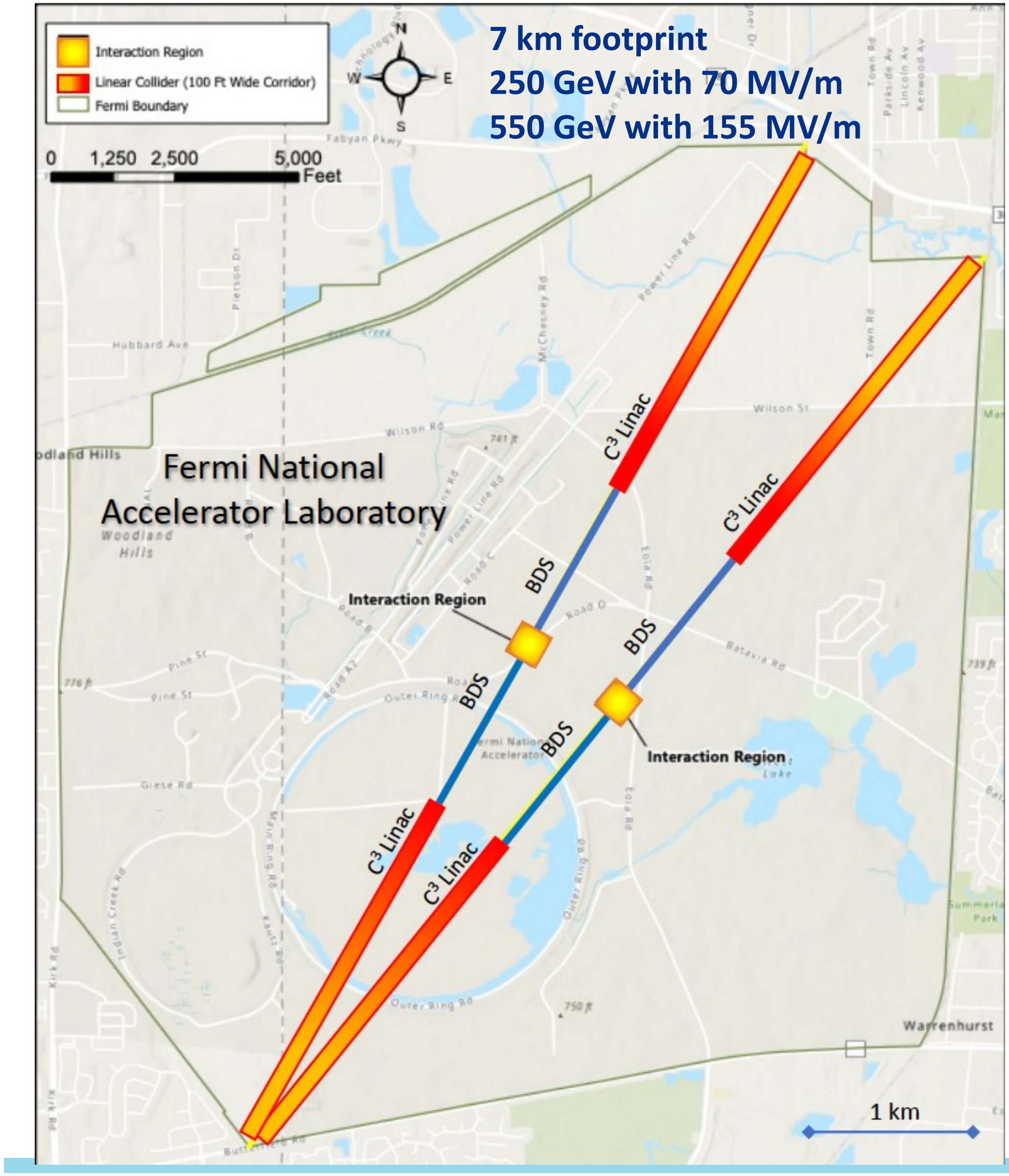
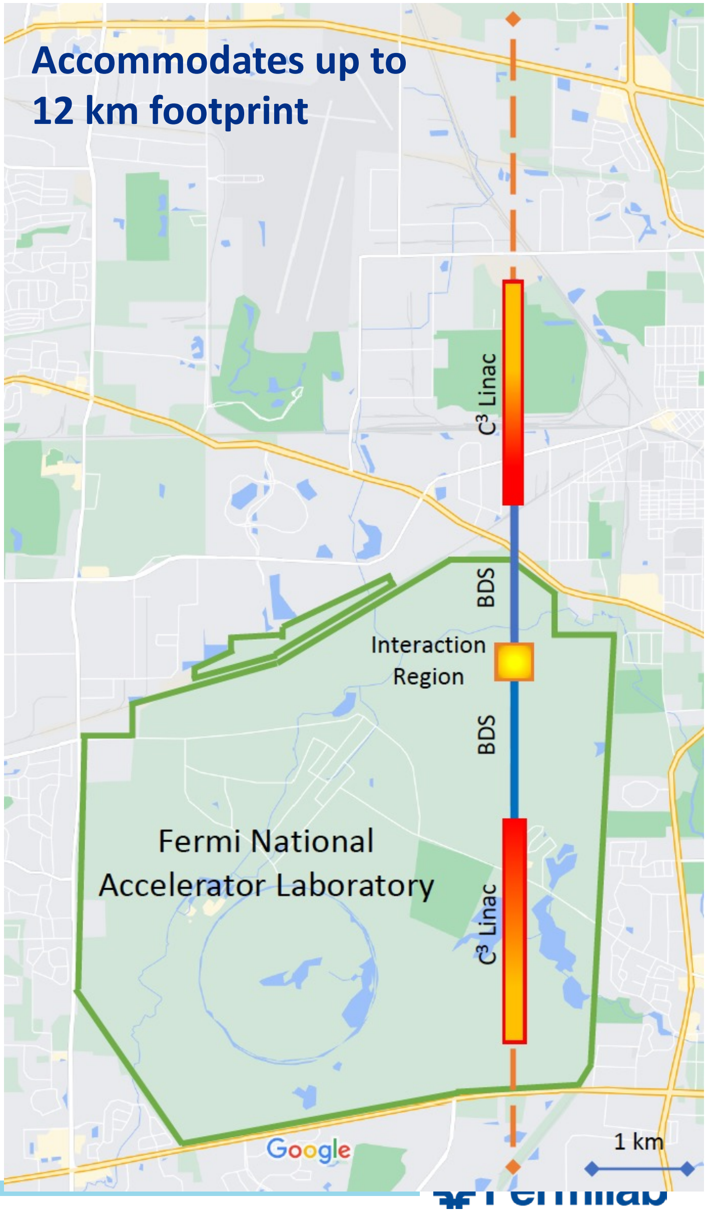
More Details Here (Follow, Endorse, Collaborate):
https://indico.slac.stanford.edu/event/7155/

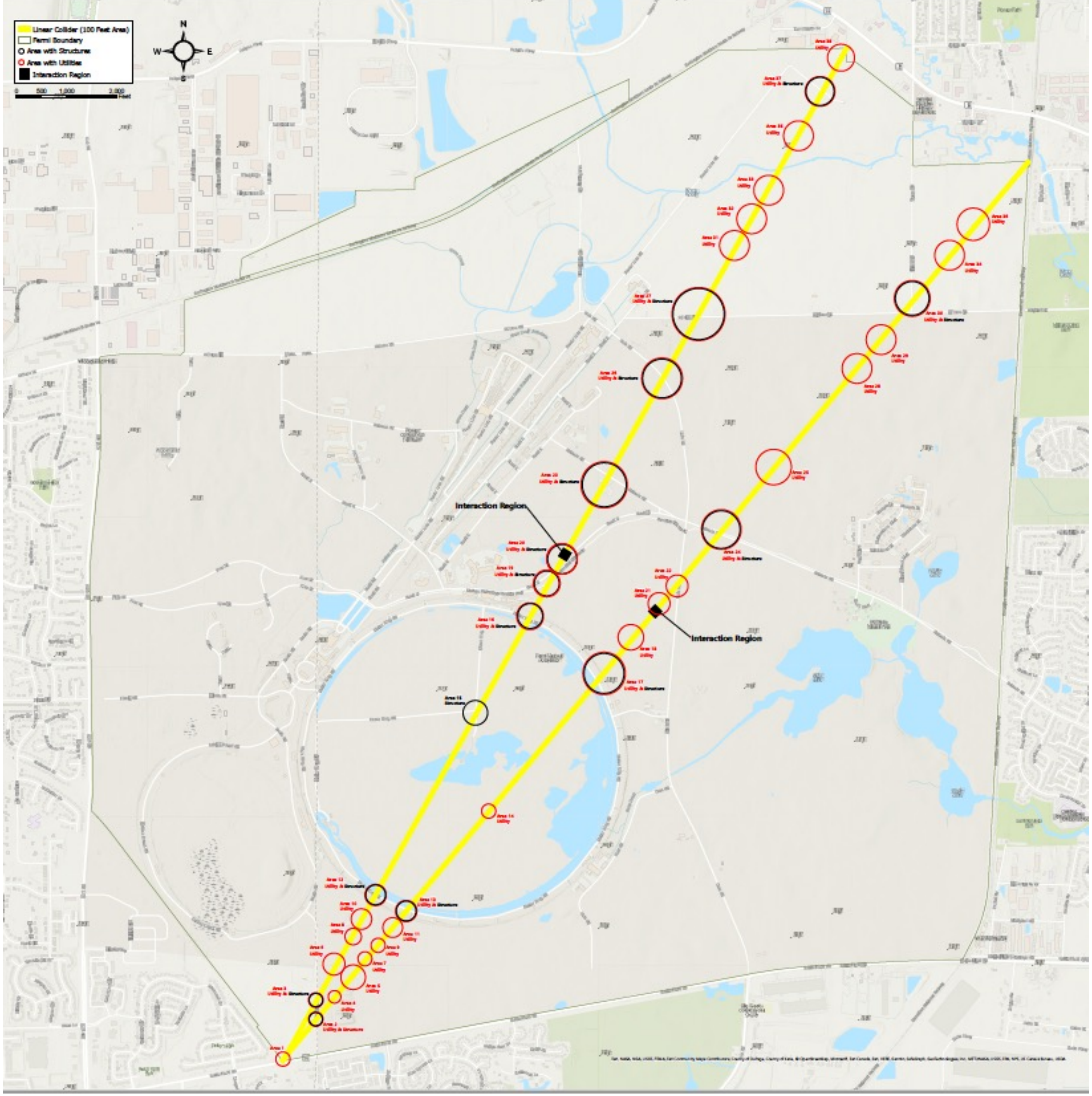
C^3 Siting Options at Fermilab



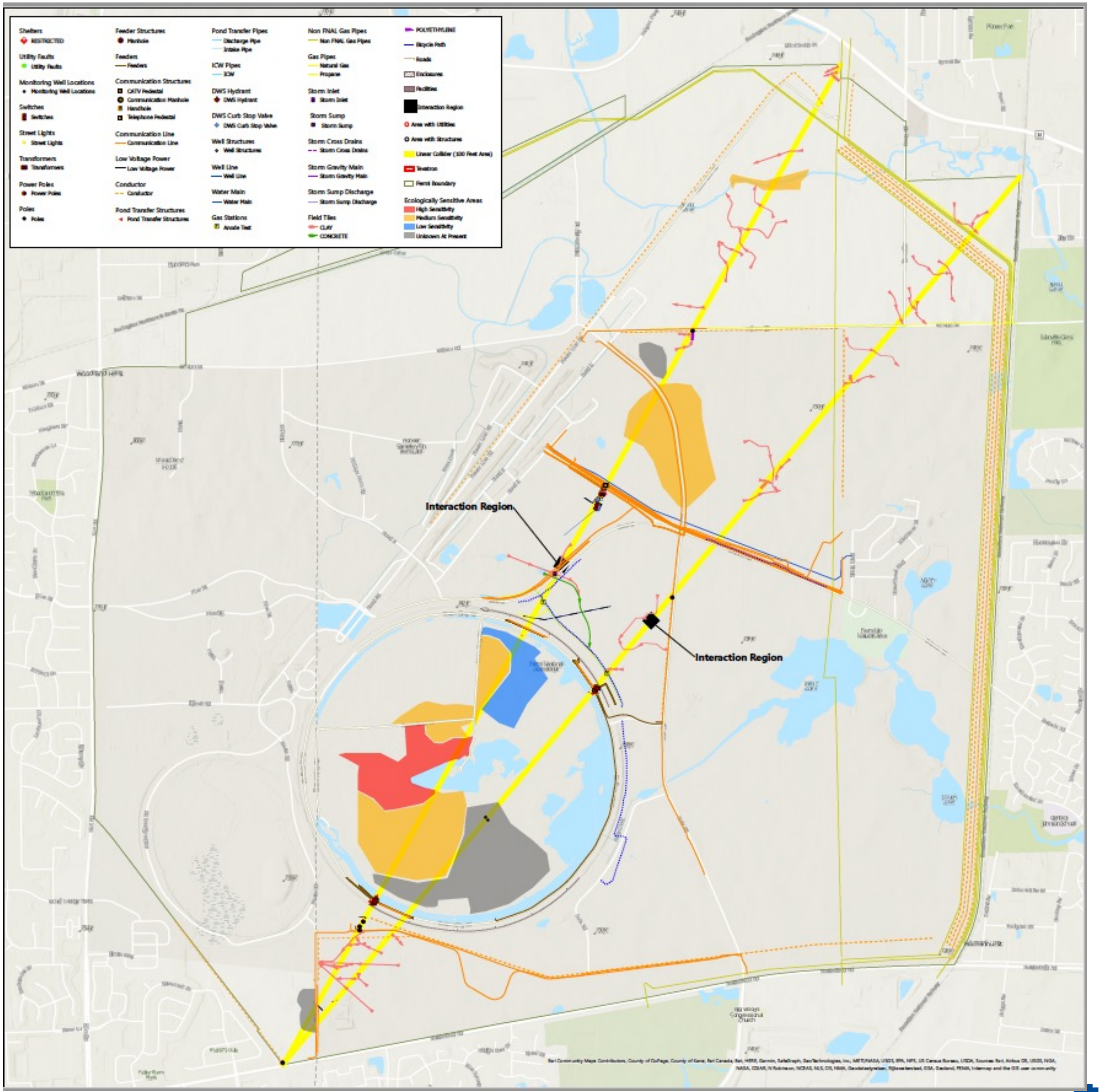
7 km footprint
250 GeV with 70 MV/m
550 GeV with 155 MV/m



Accommodates up to
12 km footprint



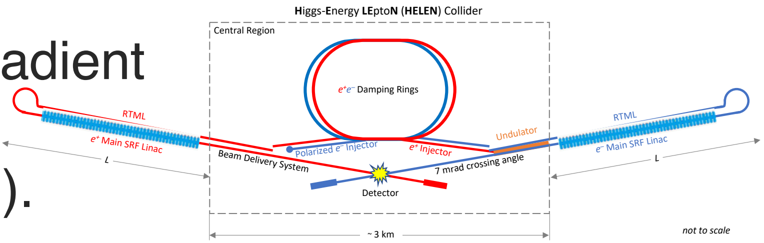
Fermilab FESS studying proposed siting



Fermilab
FESS

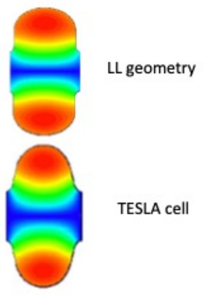
Higgs Energy LEptoN (HELEN) Collider

- HELEN is a linear collider based on high gradient SRF (in the range of 55 MV/m to 90 MV/m; standing wave or travelling wave structures).

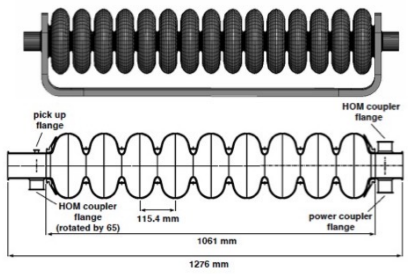


- There has been steady progress in SRF technology with gradients up to 50 MV/m demonstrated while ILC design is 31.5 MV/m.
- Further improvements in gradients can be expected with aggressive R&D.
- Three options considered
  - **Advanced geometry standing wave (SW) structure operating at 55 MV/m.** Advanced cavity shape and new treatment recipes should allow reaching accelerating gradients of ~60 MV/m. This would be essentially the ILC with different SRF cavities operating at a higher gradient.
  - **Baseline option: TW structure operating at 70 MV/m. The traveling wave option assumes an accelerating gradient of 70 MV/m.**
  - **Nb_3Sn structure operating at 90 MV/m.**

Parameter	Advanced SW	Traveling wave	Nb_3Sn
Accelerating gradient (MV/m)	55	70	90
Fill factor	0.711	0.804	0.711
Real estate (effective) gradient (MV/m)	39.1	55.6	64.0
Cavity Q (10^{10})	1.0 (2 K)	0.69 (2 K)	1.0 (4.5 K)
Active cavity length (m)	1.038	2.37	1.038
Cavity R/Q (Ohm)	1158	4890	1158
Geometry factor G (Ohm)	279	186	279
B_{pk}/E_{acc} mT/(MV/m)	3.71	2.89	3.71
E_{pk}/E_{acc}	1.98	1.73	1.98
Number of cavities	4380	1527	2677
Number of cryomodules	505	382	309
Collider length (km)	9.4	7.5	6.9
AC power for main linacs (MW)	49	39	58
Total collider AC power (MW)	121	110	129

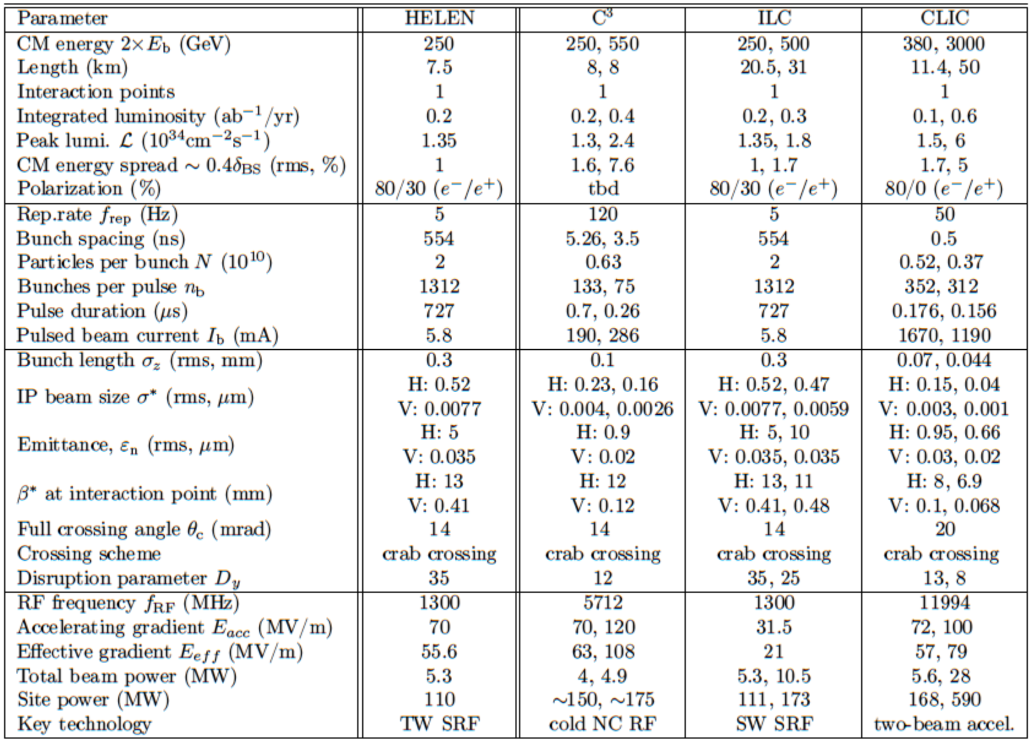


Comparison of SW SRF cavity shapes

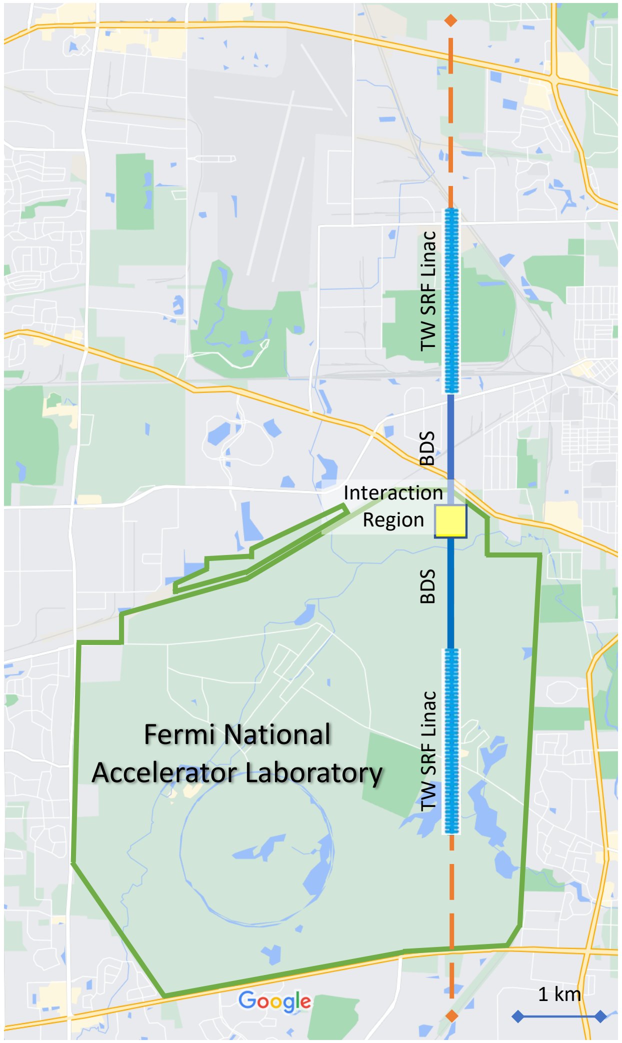


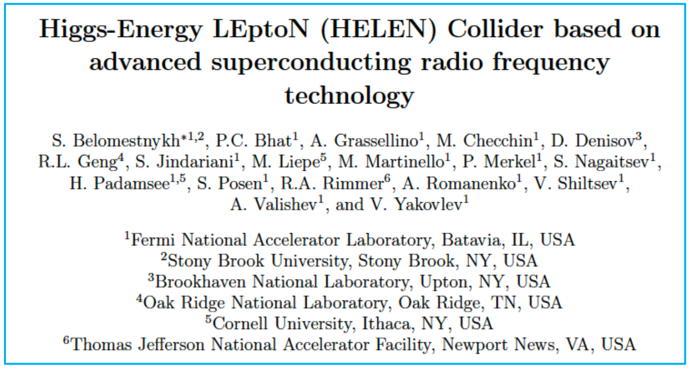
The TW structure with a 105° phase advance per cell compared to the one-meter standing-wave TESLA structure

HELEN Higgs Facotry



Parameter	HELEN	C^3	ILC	CLIC
CM energy $2\times E_b$ (GeV)	250	250, 550	250, 500	380, 3000
Length (km)	7.5	8, 8	20.5, 31	11.4, 50
Interaction points	1	1	1	1
Integrated luminosity (ab^{-1}/yr)	0.2	0.2, 0.4	0.2, 0.3	0.1, 0.6
Peak lumi. $\mathcal{L}$ (10^{34}cm^{-2}s^{-1})	1.35	1.3, 2.4	1.35, 1.8	1.5, 6
CM energy spread $\sim 0.4\delta_{BS}$ (rms, %)	1	1.6, 7.6	1, 1.7	1.7, 5
Polarization (%)	80/30 (e^-/e^+)	tbd	80/30 (e^-/e^+)	80/0 (e^-/e^+)
Rep.rate f_{rep} (Hz)	5	120	5	50
Bunch spacing (ns)	554	5.26, 3.5	554	0.5
Particles per bunch N (10^{10})	2	0.63	2	0.52, 0.37
Bunches per pulse n_b	1312	133, 75	1312	352, 312
Pulse duration (μs)	727	0.7, 0.26	727	0.176, 0.156
Pulsed beam current I_b (mA)	5.8	190, 286	5.8	1670, 1190
Bunch length σ_z (rms, mm)	0.3	0.1	0.3	0.07, 0.044
IP beam size σ^* (rms, μm)	H: 0.52 V: 0.0077	H: 0.23, 0.16 V: 0.004, 0.0026	H: 0.52, 0.47 V: 0.0077, 0.0059	H: 0.15, 0.04 V: 0.003, 0.001
Emittance, ε_n (rms, μm)	H: 5 V: 0.035	H: 0.9 V: 0.02	H: 5, 10 V: 0.035, 0.035	H: 0.95, 0.66 V: 0.03, 0.02
β^* at interaction point (mm)	H: 13 V: 0.41	H: 12 V: 0.12	H: 13, 11 V: 0.41, 0.48	H: 8, 6.9 V: 0.1, 0.068
Full crossing angle θ_c (mrad)	14	14	14	20
Crossing scheme	crab crossing	crab crossing	crab crossing	crab crossing
Disruption parameter D_y	35	12	35, 25	13, 8
RF frequency f_{RF} (MHz)	1300	5712	1300	11994
Accelerating gradient E_{acc} (MV/m)	70	70, 120	31.5	72, 100
Effective gradient E_{eff} (MV/m)	55.6	63, 108	21	57, 79
Total beam power (MW)	5.3	4, 4.9	5.3, 10.5	5.6, 28
Site power (MW)	110	~150, ~175	111, 173	168, 590
Key technology	TW SRF	cold NC RF	SW SRF	two-beam accel.





Higgs-Energy LEptoN (HELEN) Collider based on advanced superconducting radio frequency technology

S. Belomestnykh*[1,2], P.C. Bhat[1], A. Grassellino[1], M. Checchin[1], D. Denisov[3], R.L. Geng[4], S. Jindariani[1], M. Liepe[5], M. Martinello[1], P. Merkel[1], S. Nagaitsev[1], H. Padamsee[1,5], S. Posen[1], R.A. Rimmer[6], A. Romanenko[1], V. Shiltsev[1], A. Valishev[1], and V. Yakovlev[1]

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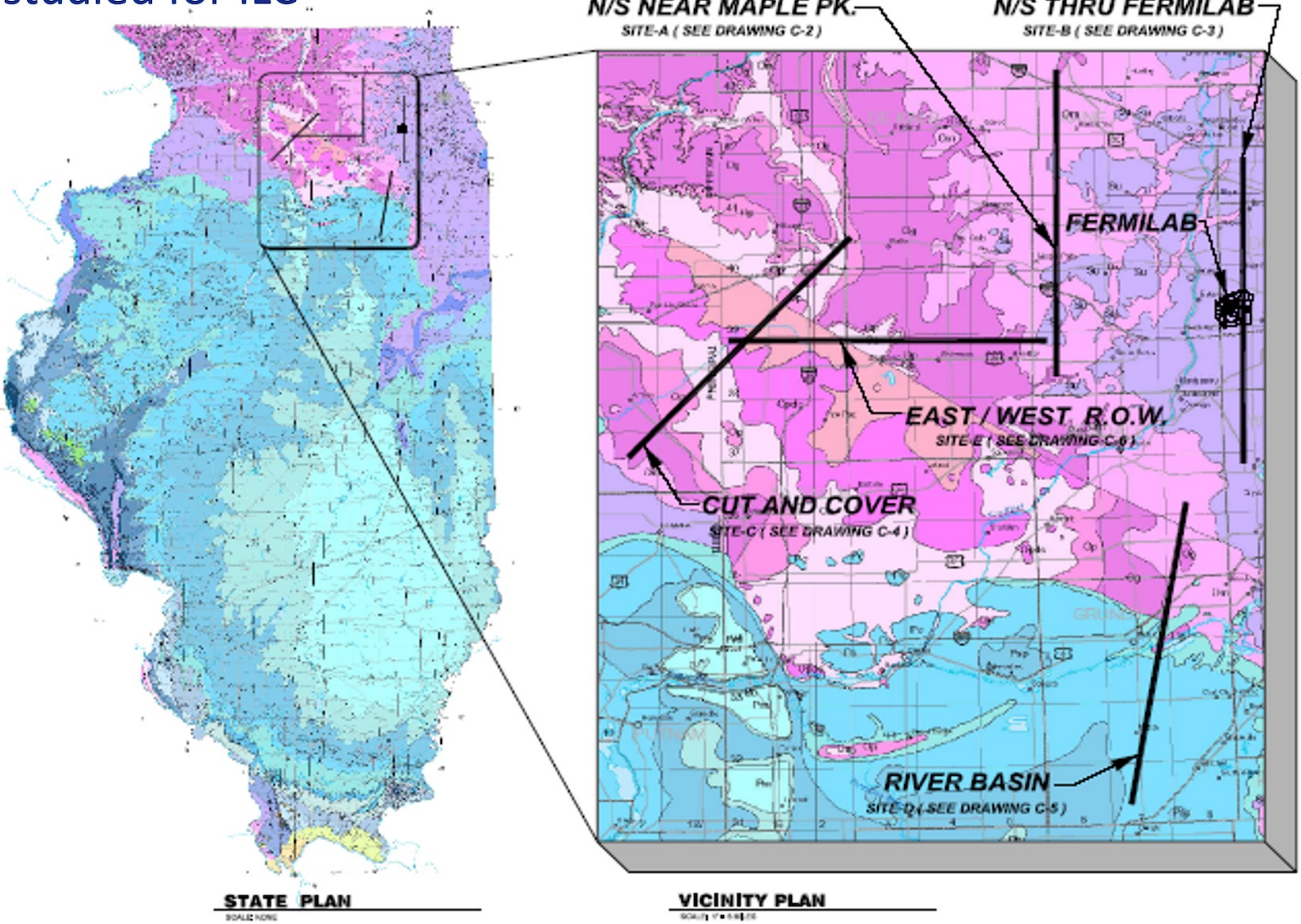
[5]Cornell University, Ithaca, NY, USA
[6]Thomas Jefferson National Accelerator Facility, Newport News, VA, USA

ILC Site options in the US/Fermilab

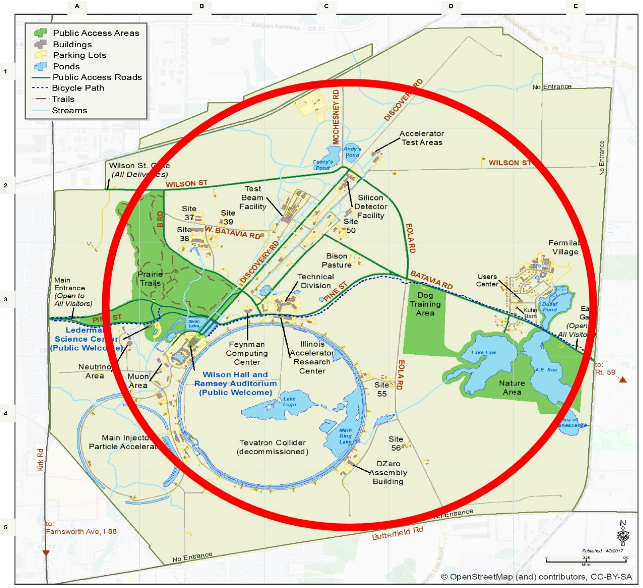
Sites studied for ILC



Circular Fermilab Site Filler e+e-

FNAL-SF-ee

- Design Strategy
  - Circular FNAL site filler ; 16 km ring
  - Limit synchrotron radiation power to 2x50 MW
  - One IP; few bunches with high bunch current
    - minimize beam-beam tune shift
    - Reduce chromaticity



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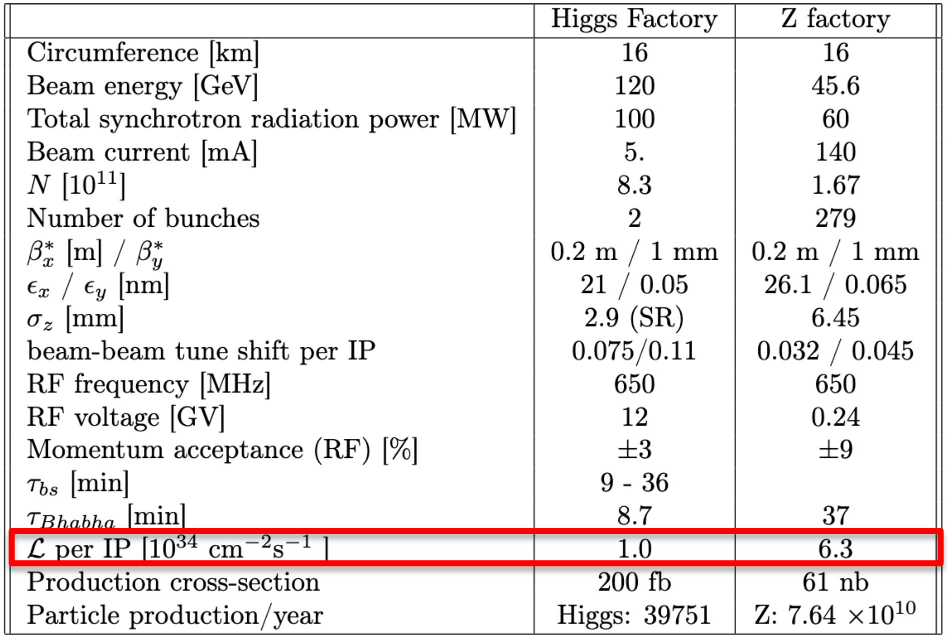


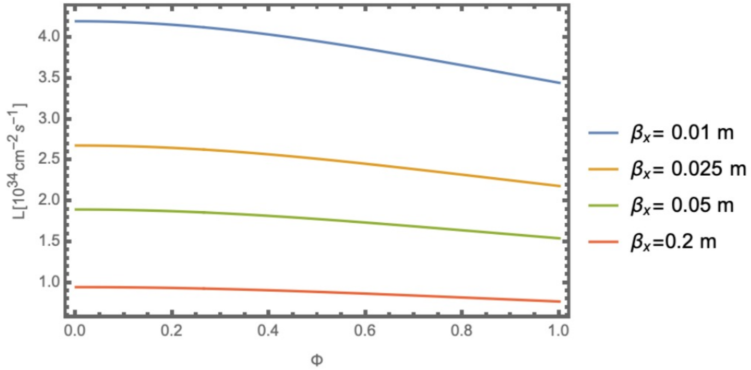
	Higgs Factory	Z factory
Circumference [km]	16	16
Beam energy [GeV]	120	45.6
Total synchrotron radiation power [MW]	100	60
Beam current [mA]	5.	140
N $[10^{11}]$	8.3	1.67
Number of bunches	2	279
β_x^* [m] / β_y^*	0.2 m / 1 mm	0.2 m / 1 mm
ϵ_x / ϵ_y [nm]	21 / 0.05	26.1 / 0.065
σ_z [mm]	2.9 (SR)	6.45
beam-beam tune shift per IP	0.075/0.11	0.032 / 0.045
RF frequency [MHz]	650	650
RF voltage [GV]	12	0.24
Momentum acceptance (RF) [%]	±3	±9
τ_{bs} [min]	9 - 36	
τ_{Bhabha} [min]	8.7	37
$\mathcal{L}$ per IP $[10^{34}\ \mathrm{cm^{-2}s^{-1}}]$	1.0	6.3
Production cross-section	200 fb	61 nb
Particle production/year	Higgs: 39751	Z: 7.64 $\times 10^{10}$

Recent Updates on FNAL-SF-ee

- Introduce crossing angle
- $\beta_x^* \sim 10$ mm, $\beta_y^* = 0.0005$ m
- $\phi < 2$
- $\xi_y \sim 0.14$

➔ $L \sim 4 \times 10^{34}$ cm^{-2} s^{-1}

at $\sqrt{s}$=240 GeV (HF)



- **Challenges:**
  - IR optics with small β_y^*, control non-linear chromaticity, sufficient dynamic aperture, energy acceptance
  - Top-up injection needed due to low beam lifetime (successful at PEP and KEKB)
  - Synchrotron radiation effects
  - Vacuum system to deal with SR
  - RF systems: high efficiency, frequency choices, positioning along the ring
  - Vert. emittance: minimize growth

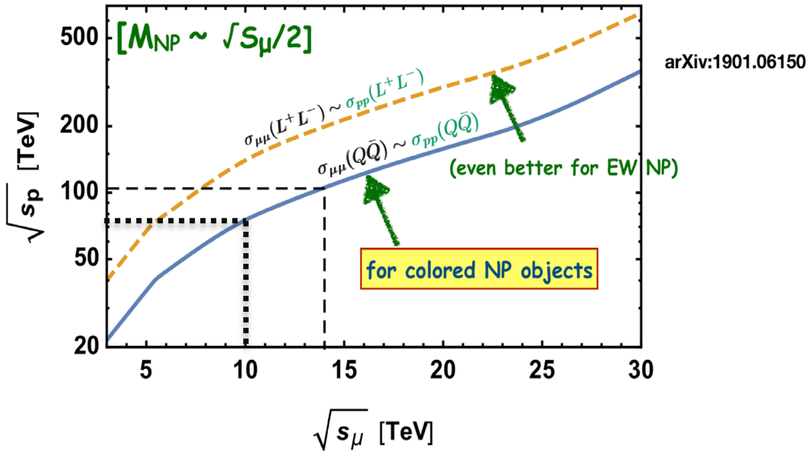
  …

Multi-TeV Colliders

Muon Collider

- There has been an explosion of interest recently in the collider community!
- A Compact collider for multi-TeV scale
- A precision and discovery machine!
  - Excellent precision for Higgs coupling measurements
  - Great direct reach for new physics
    - 10 TeV $\mu^+\mu^-$ ≅ 70 TeV pp
    - 10 TeV $\mu^+\mu^-$ ≅ 150 TeV pp for EW
- Technologically challenging, exciting, with unique opportunities for innovation
- Can be staged with physics at each stage:
  - Demonstrator facility, Higgs Factory, (nuSTORM), Multi-TeV Collider
- Intense ongoing work in the new International Muon Collider Collaboration and Snowmass Muon Collider Forum

Equivalent reach in pp after rescaling for



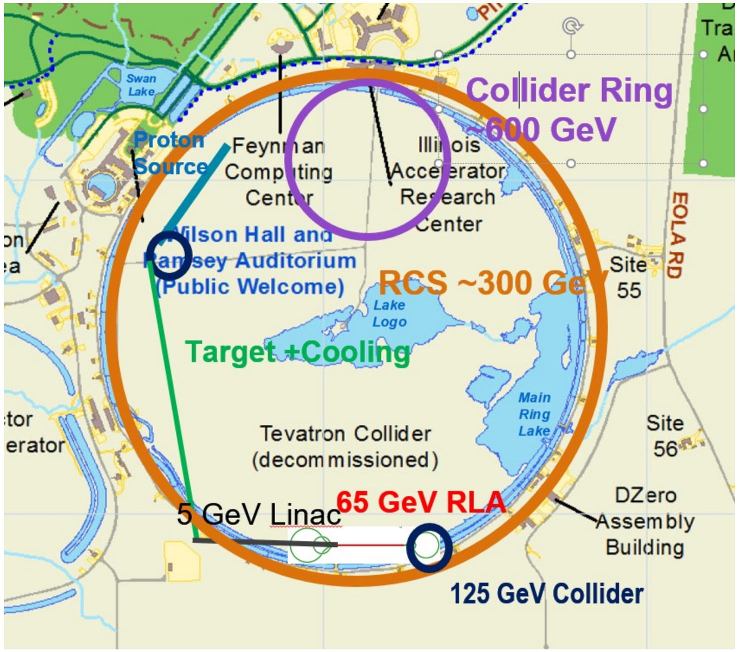
125 GeV to 8 TeV (10 TeV?)
Muon collider can fit on Fermilab site

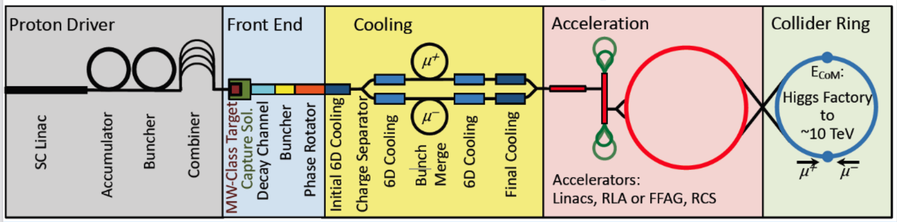
Machine scenarios, beam-induced background, neutrino radiation, detector/physics simulations

Muon Collider at Fermilab

Site Filler (10 TeV collider)

125 GeV and 600 GeV staging options





Muon Collider (Contd.)

RAST, Vol 10, No. 01, pp. 189-214 (2019)

+ D. Neuffer

Muon Collider Parameters. √s = 0.126 - 6 TeV						
Parameter	Units		Higgs 0.126 TeV	Top 0.35 TeV	3 TeV Collider	6 TeV Collider
Circumference	km		0.3	0.7	4.5	6
Ring Depth	m		135	135	135	540
Avg. Luminosity	$10^{34} cm^{-2} s^{-1}$		0.008	0.6	4.4	12
# of IPs			1	1	2	2
$b^*_{x,y}$	cm		1.7	0.5	0.3 - 3	0.25
# of Muons/bunch	$10^{12.}$		4	3	2	2
Trans. Emittance, e_T	p-mm-rad		0.2	0.05	0.025	0.025
Long emittance, e_L	p-mm-rad		1.5	10	70	70
Bunch Length	cm		6.3	0.5	0.5	0.2
Proton driver power	MW		4	4	4	1.6
Wall Plug Power	MW		200	203	230	270
# of Higgs/10^7 s			13,500	60,000	200,000	820,000
Max Mag. Field	T		8	8	10	16
RF	MV		6000	10000	15000	30000

Planned development of Fermilab accelerator complex for LBNF/DUNE will provide a robust infrastructure for a future muon collider

- Multi-MW proton beam with PIP-II linac and Booster replacement

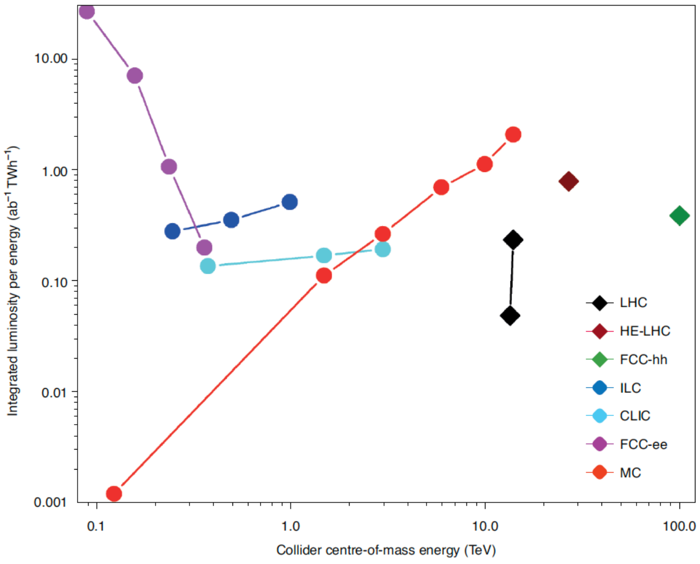
Synergy with neutrino program via nuSTORM in the initial phase, and with precision physics program

Parameter Sets for the International MC Collaboration

- Performance Aims:
  - Achieve the target integrated luminosity in ~5 years of running

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Energy Efficiency



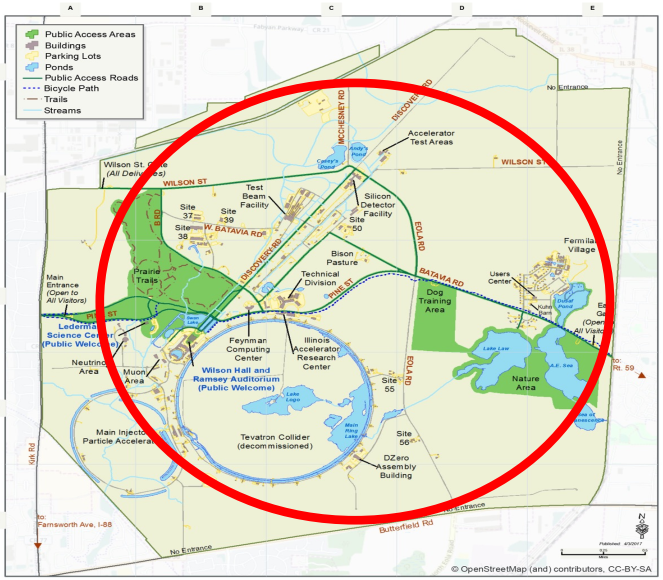
Parameter	Unit	3 TeV	10 TeV	14 TeV
L	$10^{34}\,\text{cm}^{-2}\text{s}^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	μm	25	25	25
$\sigma_{x,y}$	μm	3.0	0.9	0.63

Compare: 28 MW for 3 TeV CLIC

A Compact Hadron Collider

- Prime candidates for Hadron Colliders beyond HL-LHC are the FCC-hh (physics in 2070s) and SPPC (projected 2060s)
- A Compact Hadron Collider at Fermilab
  - Site Filler (16 km ring, 24-28 TeV); need > 24 T LTS/HTS or IBS magnets
  - **Intermediate step to FCC and test bed for high field magnet use**

- Planned development of the complex provide a robust injector infrastructure.
- The new machine can be an injector to a future VLHC (100 km or 233 km pp collider.)
- Cheaper, high-field magnets critical.



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A Compact Hadron Collider

FNAL-SF numbers T. Sen

parameter	FNAL SF	HE-LHC	FCC-hh	
collision energy cms [TeV]	24	27	100	
dipole field [T]	24.4	16	16	
circumference [km]	16	26.7	97.8	
beam current [A]	0.41	1.12	0.5	
bunch intensity [10^{11}]	1.05	2.2	1 (0.2)	1
bunch spacing [ns]	25	25	25 (5)	25
IP $b^*_{x,y}$ [m]	0.5, 0.5	0.45	1.1	0.3
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	15	5	30
peak #events/bunch crossing	135	800	170	1020
stored energy/beam [GJ]	0.26		8.4	
synchrotron rad. [W/m/beam]	3.9	3.74	30	
transv. emit. damping time [h]	1.8		1.1	
initial proton burn off time [h]	3.5	3.0	17.0	3.4

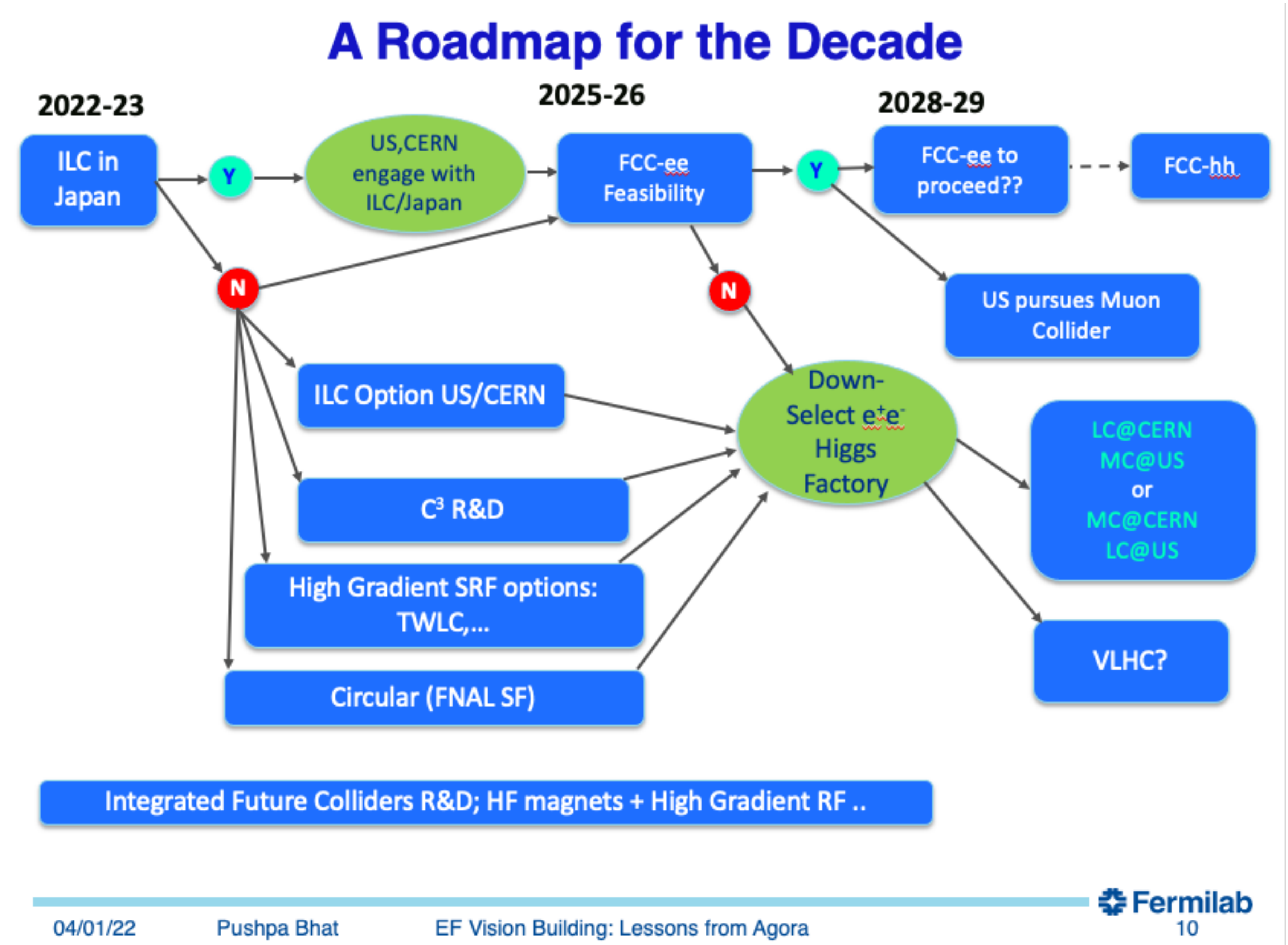
pp Collider Challenges

- High field dipole magnets
  - Requires fields above 20 T and also high field quality
- Interaction region magnets
  - Must withstand debris power from pp interactions
- Machine protection
  - Very high beam energy and magnetic energy, improved & sophisticated collimation required
- High synchrotron radiation
  - Impact on components, cryogenic system, radiation hard electronics ….
- Beam dynamics issues
  - Electron cloud effects, beam-beam interactions (head-on and long-range) & compensation, instabilities, crab cavity operation, ….
- Cost: ??

Key Challenge:

High Field Magnet Technology

- Current record for Nb3Sn Magnet:
  - 16.5 T on conductor, 14.5 T magnet w/ 60 mm aperture
  - Attempts at 17-18 T ongoing
- Hybrid w/ HTS insert R&D
  - Results in the next couple of years
  - 20-25 T demo in the next 10 years
- US Magnet Development Program
  - Advance technology, improve performance, reduce cost
- IBS magnet research promising for >20T but early days
  - Need aggressive R&D
  - Might provide cheap and robust HF magnet option



A Roadmap for the Decade

2022-23

2025-26

2028-29

ILC in Japan

Y

US,CERN engage with ILC/Japan

FCC-ee Feasibility

Y

FCC-ee to proceed??

FCC-hh

N

N

US pursues Muon Collider

ILC Option US/CERN

Down-Select e^+e^- Higgs Factory

LC@CERN
MC@US
or
MC@CERN
LC@US

C^3 R&D

High Gradient SRF options: TWLC,...

VLHC?

Circular (FNAL SF)

Integrated Future Colliders R&D; HF magnets + High Gradient RF ..

04/01/22 Pushpa Bhat EF Vision Building: Lessons from Agora

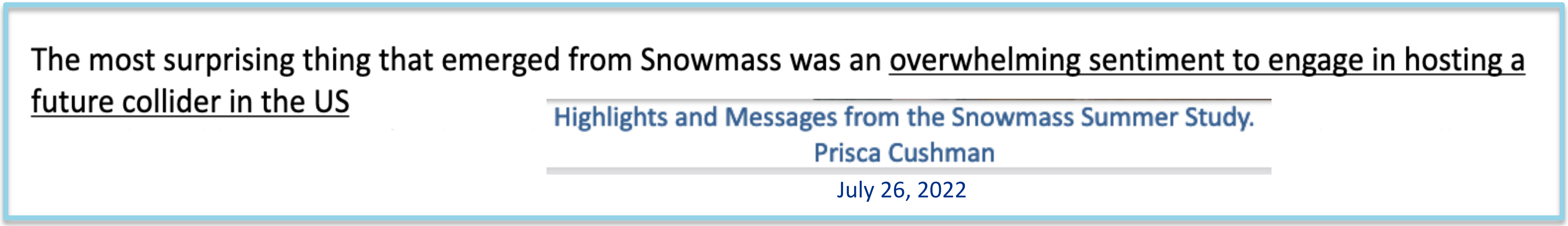
Fermilab
10

A National Accelerator R&D Initiative on Future Colliders

- The U.S. HEP accelerator R&D program currently has no support for development of collider concepts for strategic planning.
  - **Compromises U.S. leadership**
- An integrated national R&D program on future colliders is proposed to address this shortcoming in the U.S. accelerator R&D.
- **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 inform decisions in down-selecting 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 as soon as possible (e+e- Higgs Factory)**
  - **help to subsequently advance towards a collider at a higher energy scale (to probe Multi-TeV scale)**

Closing Remarks

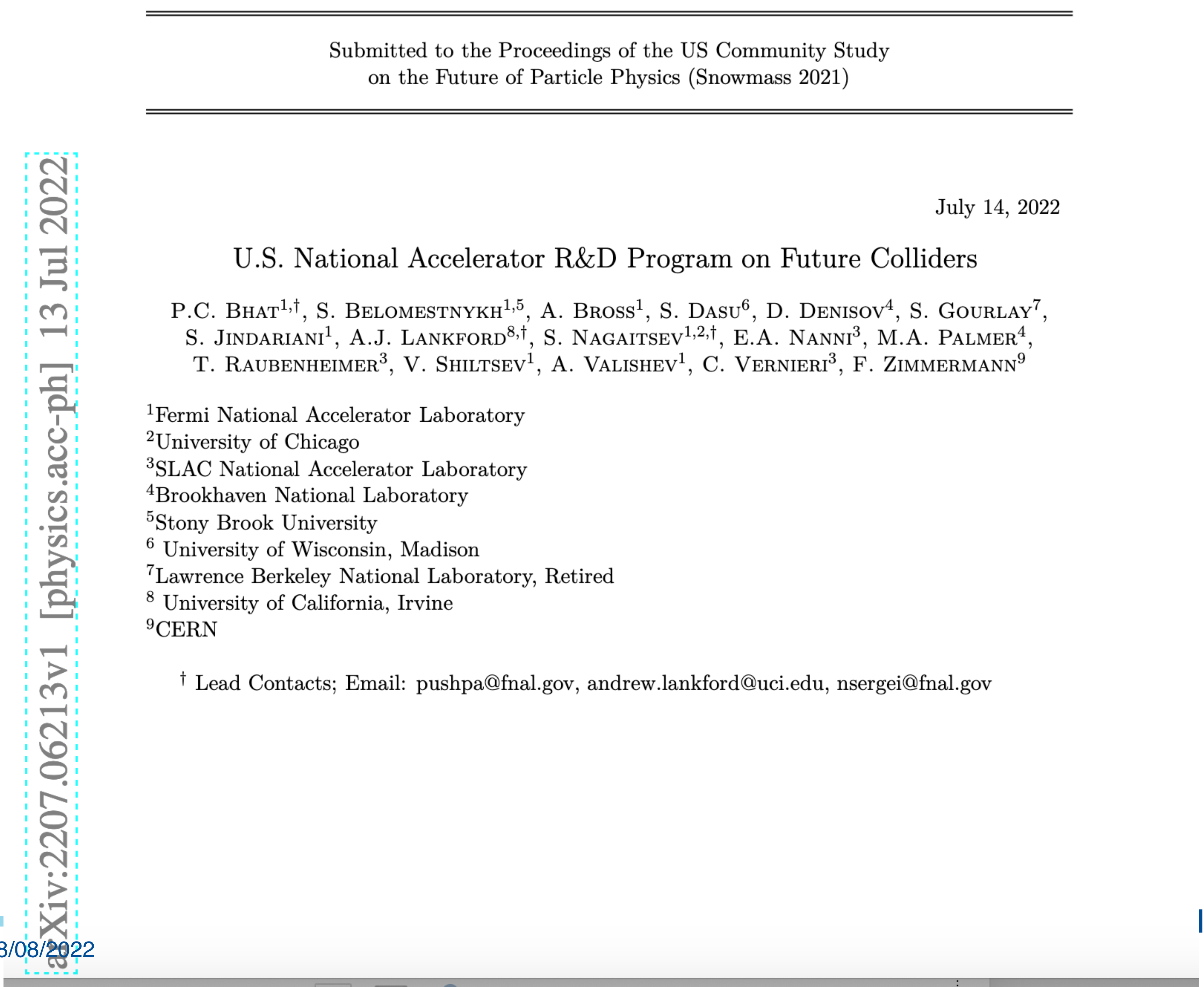
- Snowmass energy frontier discussions focused on the need to:
  - Realize an e+e- Higgs Factory as soon as possible
  - Work towards an energy frontier collider to access the ~10 TeV scale
- To help realize this vision, a ***national accelerator R&D program on future colliders*** has been proposed
  - Would enable concerted efforts for U.S. engagement in FCC, ILC and IMCC
  - Would allow exploration of collider concepts suitable for future siting in the U.S.
- Exploration of relatively compact colliders that might be realized on modest time scales and costs in the U.S. should prove beneficial to the field (and have spin-offs)!



The most surprising thing that emerged from Snowmass was an <u>overwhelming sentiment to engage in hosting a future collider in the US</u>

Highlights and Messages from the Snowmass Summer Study.
Prisca Cushman
July 26, 2022

Extra Slides



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

July 14, 2022

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

P.C. Bhat[1,†], S. Belomestnykh[1,5], A. Bross[1], S. Dasu[6], D. Denisov[4], S. Gourlay[7], S. Jindariani[1], A.J. Lankford[8,†], S. Nagaitsev[1,2,†], E.A. Nanni[3], M.A. Palmer[4], T. Raubenheimer[3], V. Shiltsev[1], A. Valishev[1], C. Vernieri[3], F. Zimmermann[9]

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[4]Brookhaven National Laboratory
[5]Stony Brook University
[6] University of Wisconsin, Madison
[7]Lawrence Berkeley National Laboratory, Retired
[8] University of California, Irvine
[9]CERN

[†] Lead Contacts; Email: pushpa@fnal.gov, andrew.lankford@uci.edu, nsergei@fnal.gov

Scope of the Proposed Program

- Scope:
  - Sharply focused on future colliders
    - Address challenges for next colliders (e.g., Higgs factories) and for collider concepts for ~10 TeV-scale machines
  - Spans accelerator design, technology and full concept development
  - 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
  - Integrates all critical R&D for a concept
    - Enable full development of collider concepts
  - Priorities guided by P5

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 and an Advisory Committee/Board
  - Collaborative effort of U.S. national labs and universities
    - Funding allocations through proposals/review process
- 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

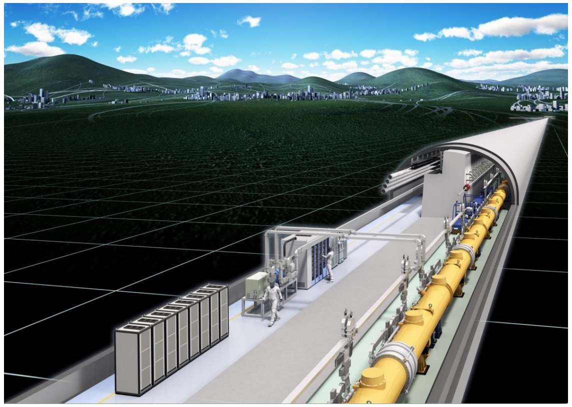
Summary

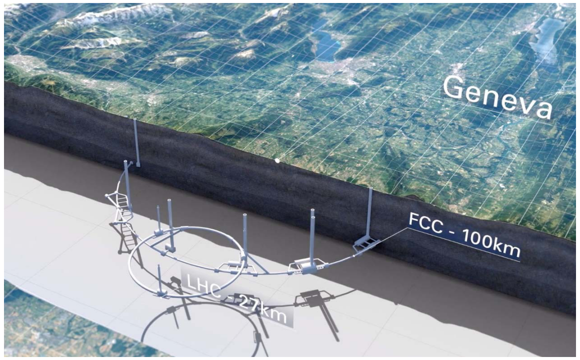
- In order to position the U.S. as a key player in future HEP facilities, whether hosted abroad or in the U.S., the proposed U.S. national accelerator R&D program focused on future colliders is essential.
- The potential scope of the program, and how it could be organized and coordinated are outlined.

https://arxiv.org/pdf/2207.06213.pdf

Engagement in Global Projects

- The International Linear Collider
  - Fermilab scientists engaged in efforts of the ILC-IDT (ILC International Development Team)
    - SRF R&D for ILC main linacs and ILC++
    - Polarized Positron Source and Damping Ring
    - Physics, detectors are of great interest
- Future Circular Colliders (FCC-ee/hh)
  - CERN conducting Technical and financial feasibility studies; results and CDR++ by ~2026
  - CERN/DOE agreement signed in Dec. 2020
    - Opportunities for engineering design studies, beam physics studies, High Q_0 SRF R&D, magnet R&D,..
    - Physics studies for Snowmass; EF work on detector, FastML technologies relevant
- Muon Collider Collaboration
  - Intense work in progress in the International Muon collider Collaboration, Snowmass Muon Collider Forum
    - Machine scenarios, beam induced background, neutrino radiation, demonstrator facility, detector/physics studies





Future Circular Colliders @CERN

- As per the 2020 European Strategy update, the FCC Study is now focused on investigating the technical and financial feasibility of a ~100 TeV pp collider at CERN in a 100 km ring, with an e+e- Higgs and electroweak factory as a first stage
  - FCC(ee) followed by FCC(hh)
- Highest priority studies:

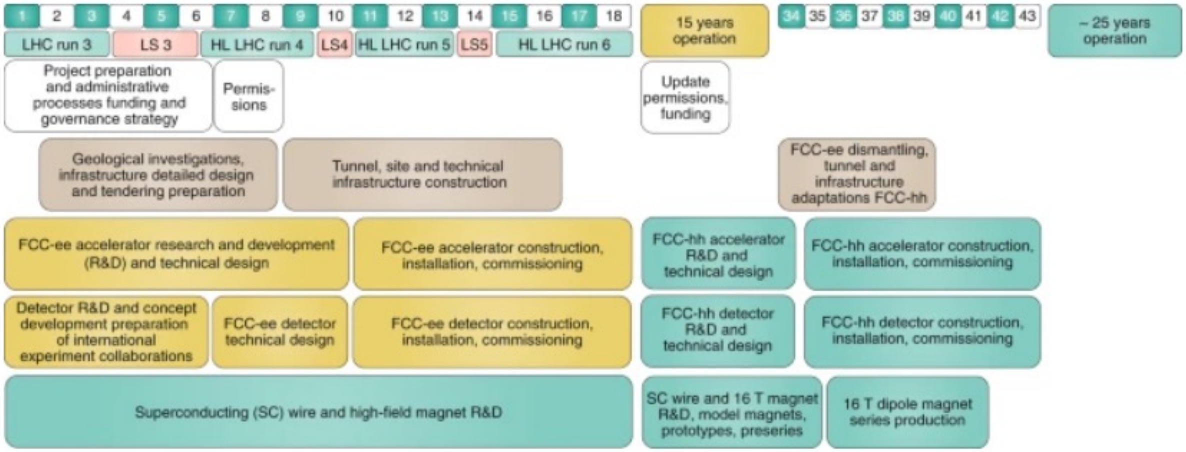
❑ tunnel: high-risk zones, surface areas, administrative processes, environment

❑ machines: R&D (e.g. superconducting RF for FCC-ee; magnets for FCC-hh); design

→ Goal is CDR++ with results of feasibility studies by ~ 2026.

~ 70 years timeframe

Fig. 1: Technical schedule of the FCC integrated project.



P5 (2013) Recommendations

- Recommendation 1: Pursue the most important opportunities wherever they are, and host unique, world-class facilities that engage the global scientific community.

ILC:

- Recommendation 11: Motivated by the strong scientific importance of the ILC and the recent initiative in Japan to host it, the U.S. should engage in modest and appropriate levels of ILC accelerator and detector design in areas where the U.S. can contribute critical expertise. Consider higher levels of collaboration if ILC proceeds.

FCC:

- Recommendation 24: Participate in global conceptual design studies and critical path R&D for future very high-energy proton-proton colliders. Continue to play a leadership role in superconducting magnet technology focused on the dual goals of increasing performance and decreasing costs.