



# Accelerator R&D Synergies Across Higgs Factories and Other Colliders (C3, ILC, MuCol, EIC, CEPC)

**Vladimir SHILTSEV (Fermilab)**

FCC Workshop, BNL, April 24, 2023

# Content:

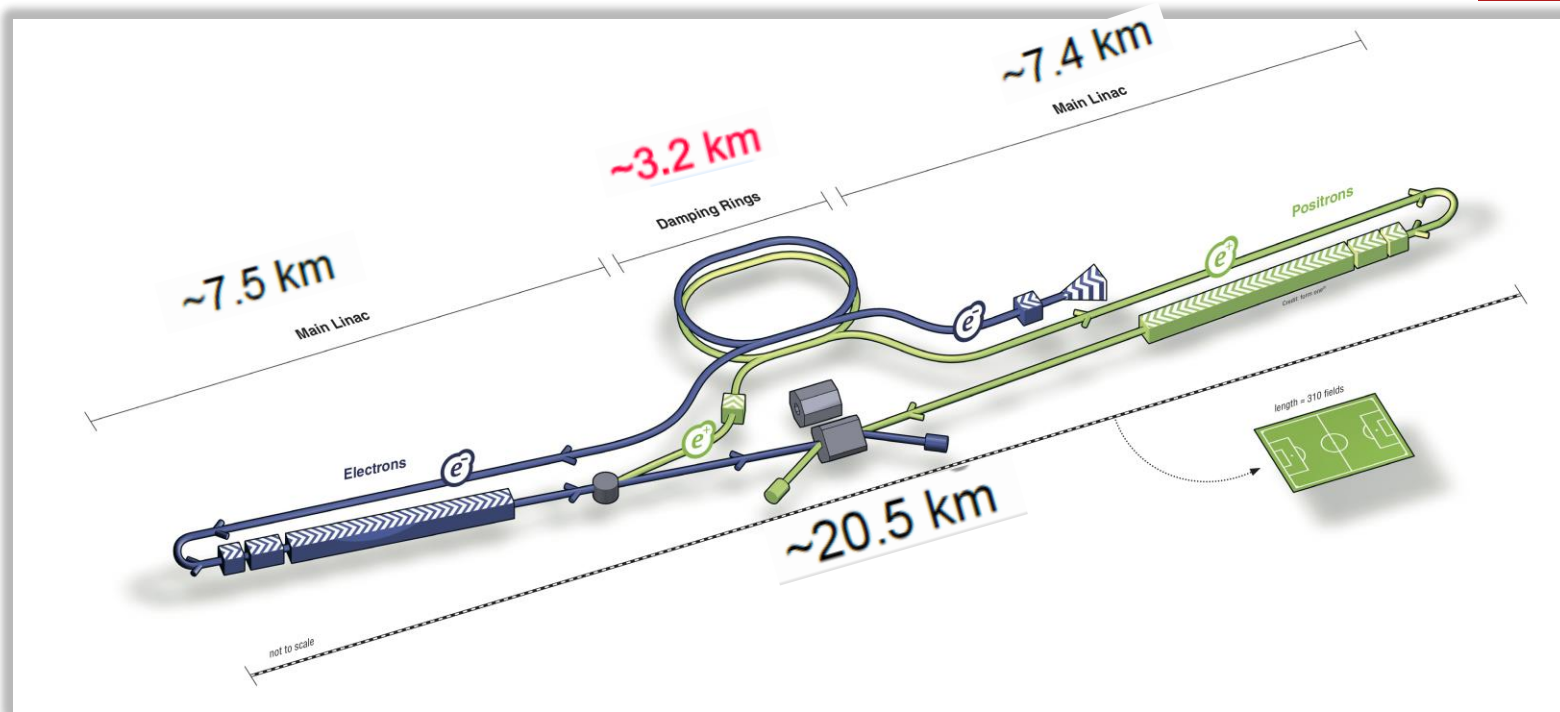
- Higgs factories proposals:
  - Traditional accelerator technologies (FCCee, CEPC, ILC, CLIC)
  - Semi-advanced accelerator technologies (C3, HELEN, MuCol, ERL,  $\gamma\gamma$ )
  - Advanced accelerator technologies (plasma and hybrid)
- Challenges and R&D:
  - General challenges (cost/power/timeline)
  - Specific challenges (R&D required)
- Synergies:
  - Design
  - Technology
  - With GARD, other colliders and non-HEP developments (EIC, FELs, etc)
- FCCee at the P5:
  - Our “message” on FCCee (key points)
  - **Integrated US Future Collider R&D Program**

# Approaches to Higgs Factories

# International Linear Collider

arXiv:1306.6328

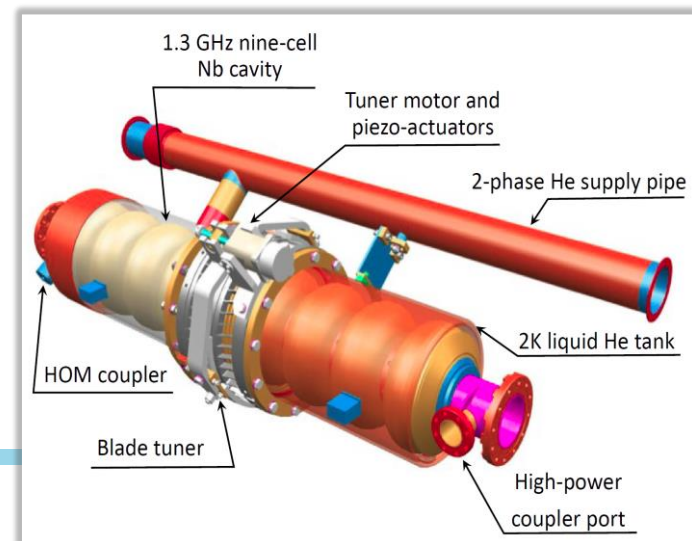
TDR



## Key facts:

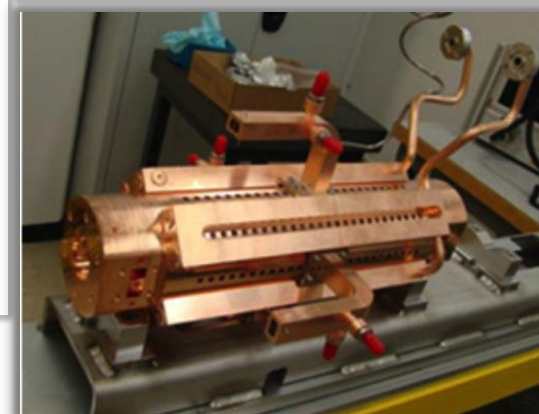
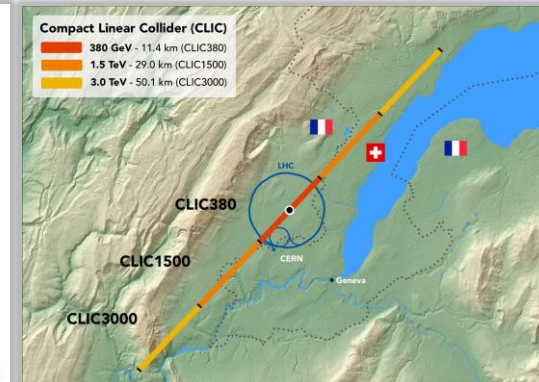
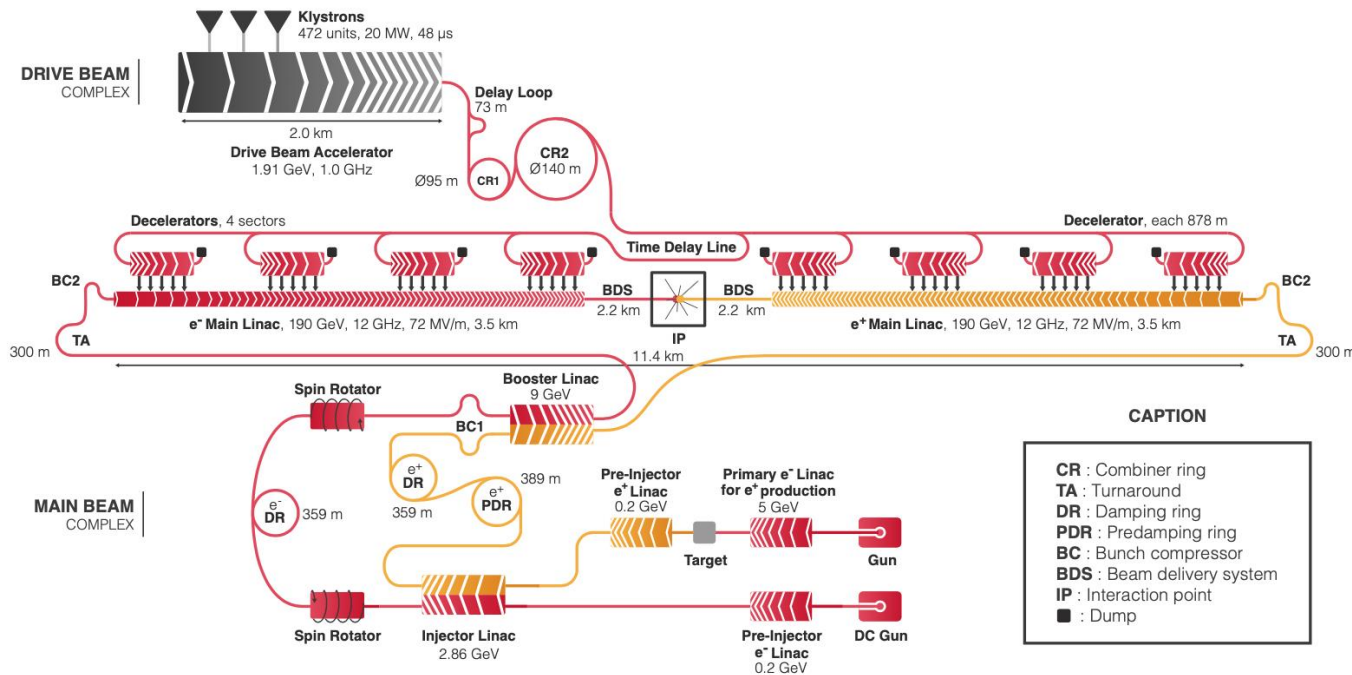
20 km, including 5 km of Final Focus  
SRF 1.3 GHz, 31.5 MV/m, 2 K  
130-110 MW site power @ 250 GeV c.m.e.  
Cost estimate 700 B JPY\*

\*  $\pm 25\%$  err,  
includes labor cost



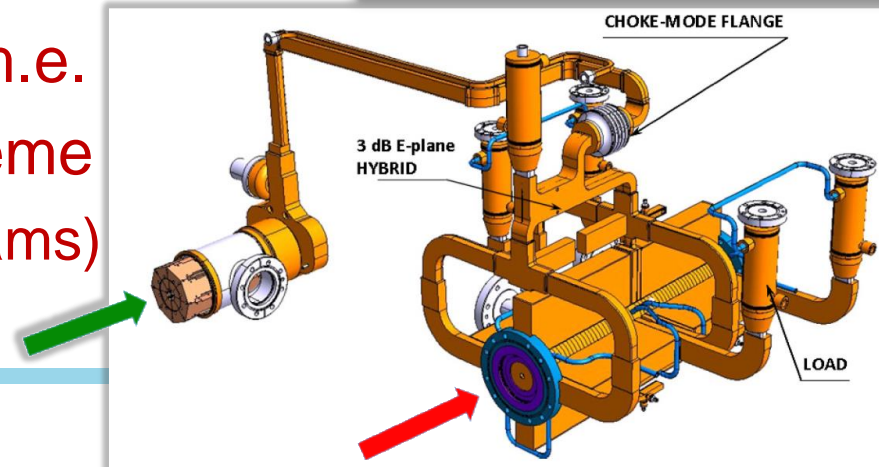
# Compact Linear Collider

arXiv:1209.2543 CDR



## Key facts:

11 km main linac @ 380 GeV c.m.e.  
NC RF 72 MV/m, two-beam scheme  
168 140 MW site power (~9MW beams)  
Cost est. 5.9 BCHF  $\pm$  25%



# Linear Colliders e+e- Higgs Factories

- *Advantages:*

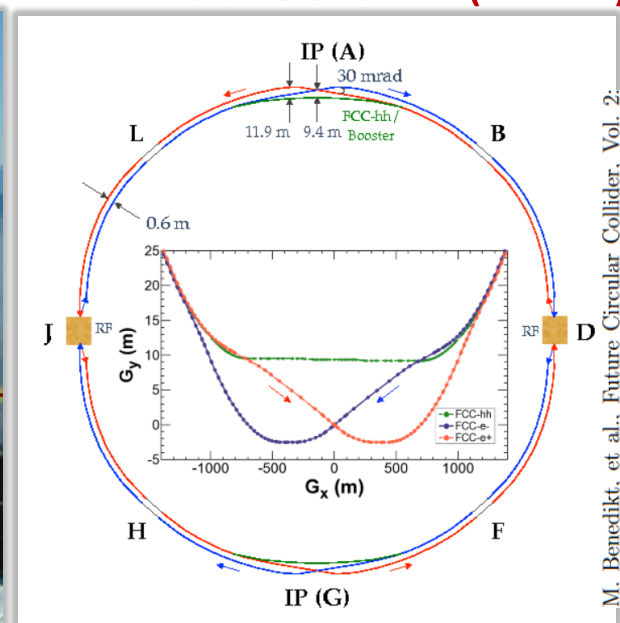
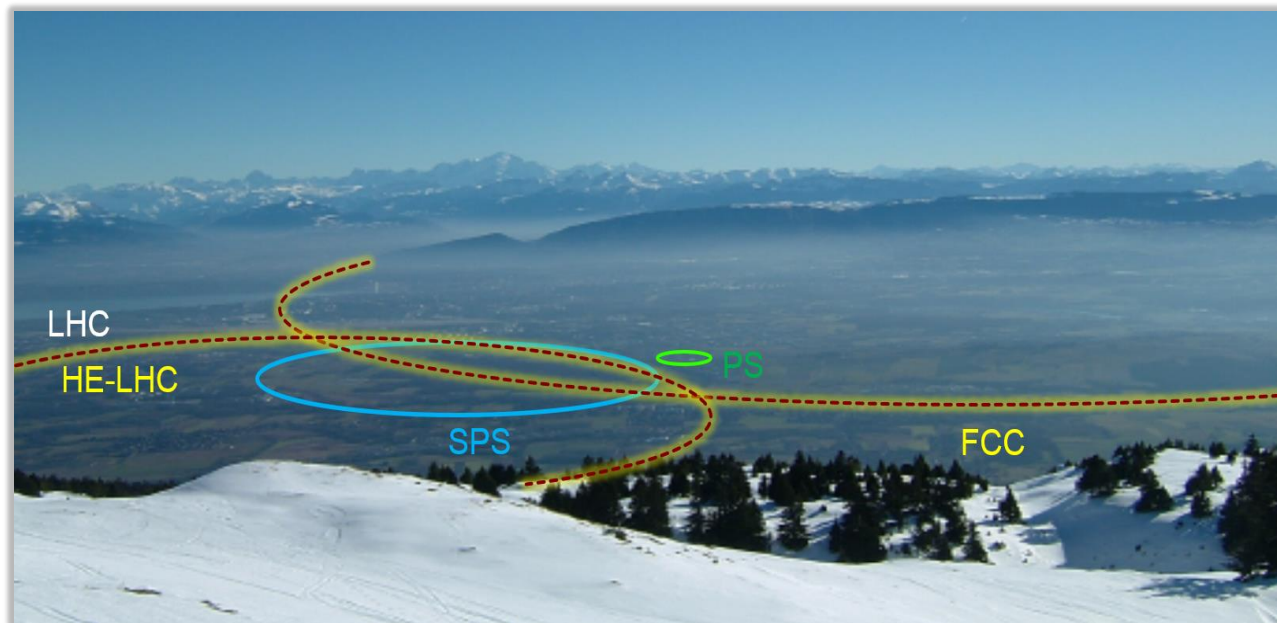
- Based on mature technology (Normal Conducting RF, SRF)
- Mature designs: ILC TDR, CLIC CDR and test facilities
- Polarization (ILC: 80%-30% ; CLIC 80% - 0%)
- Expandable to higher energies (ILC to 0.5 and 1 TeV, CLIC to 3 TeV)
- Well-organized international collaboration (LCC) → “we’re ready”
- Wall plug power ~110-140 MW (i.e.  $\leq$  LHC)

- *Challenges:*

- LC luminosity  $<$  ring (e.g., FCC-ee), upgrades at the cost:
  - e.g. factor of 4 for ILC:  $\times 2 N_{\text{bunches}}$  and  $5 \text{ Hz} \rightarrow 10 \text{ Hz}$
- Luminosity risks
  - Emittances, vibrations, e+ production, polarization, etc
  - Limited LC experience (SLC), two-beam scheme (CLIC) is novel, klystron option as backup

# Circular e+e- Higgs Factories

FCC-ee CDR (2018)



M. Benedikt, et al., Future Circular Collider, Vol. 2:

## Key facts:

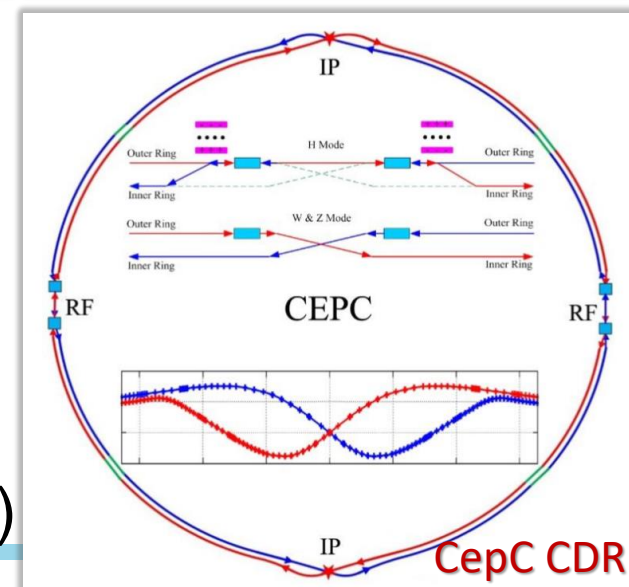
100 km tunnel, three rings (e-, e+, booster)

SRF power to beams 100 MW

Total site power <300MW

Cost est. FCCee 10.5 BCHF (+1.1BCHF for tt)

("< 6BCHF" cited in the CepC CDR)



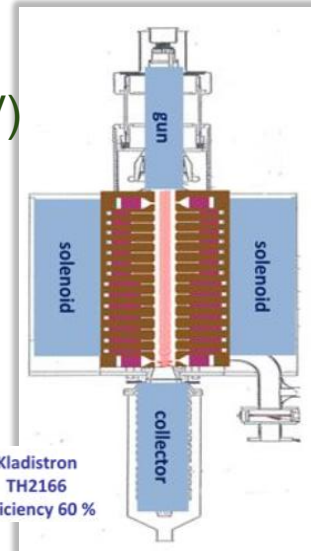
CepC CDR

arXiv:1809.00285

# e+e- Ring Higgs Factories

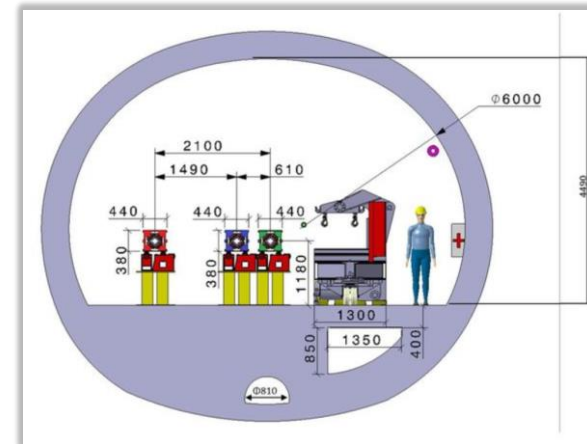
## • *Advantages:*

- Based on mature technology (**SRF**) and rich experience → lower risk
- High(er) luminosity and ratio **luminosity/cost**; upto 4 **IPs**, **EW factories**
- 100 km tunnel can be reused for a **pp collider** in the future
- Transverse polarization ( $\tau \sim 18$  min at  $tt$ ) for **E** calibration **O(100keV)**
- CDRs addressed key design points, mb ready for ca 2039 start
- Very strong and broad **Global FCC Collaboration**



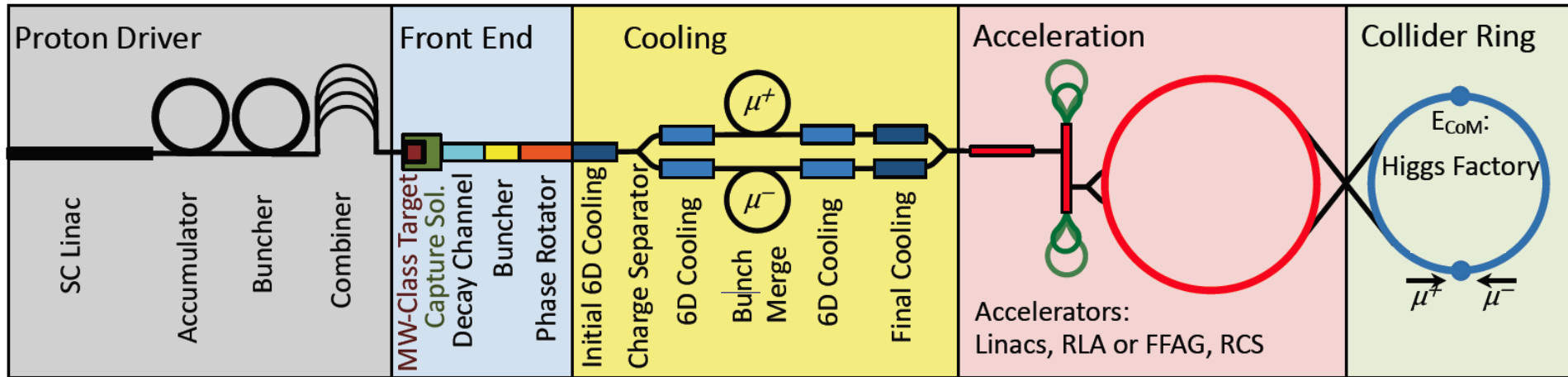
## Challenges (R&D needs):

- **High efficient RF sources:**
  - Klystron 400/800 MHz  $\eta$  from 65% to >85%
- **High efficiency SRF cavities:**
  - 20-25 MV/m and  $Q_0 \sim (3-6)e10$
- **Crab-waist collision scheme:**
  - *Super KEK-B* nanobeams experience will help
- **Energy Storage and Release R&D:**
  - Magnet energy re-use > 20,000 cycles
- **Efficient Use of Excavated Materials:**
  - 10 million cu.m. out of 100 km tunnel



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

V. Barger, et al, *Physics Reports* 286, 1-51 (1997)



## Key facts:

1/100 luminosity requirements (large cross-section in  $s$ -channel)

Half the energy  $2 \times 63 \text{ GeV}$   $\mu^+\mu^- \rightarrow H_0$

Small footprint ( $<6 \text{ km}$ ) and low cost

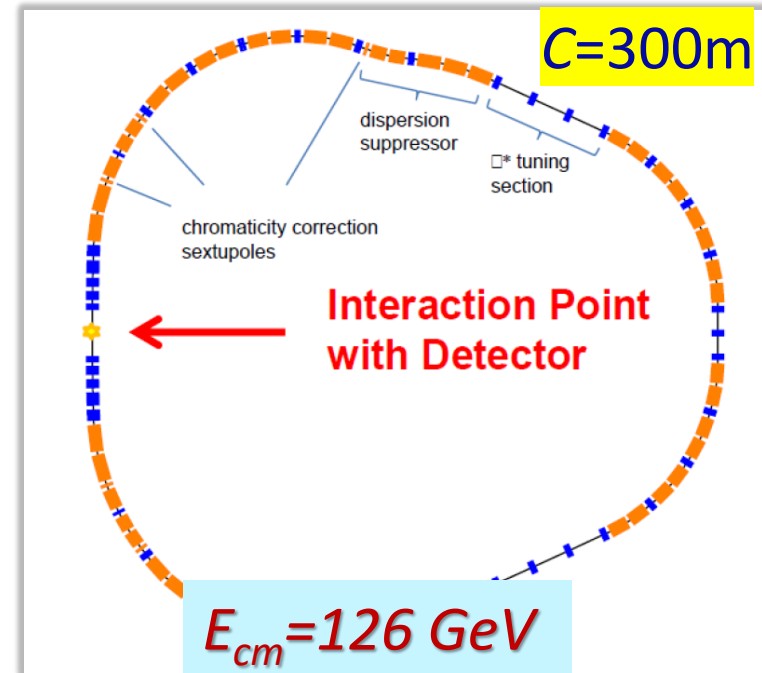
Small(est) energy spread  $\sim 3 \text{ MeV}$

Total site power  $\sim 200 \text{ MW}$

## Challenges (many...)

Muon production, cooling, acceleration

Pushing RF, magnets and targets limits



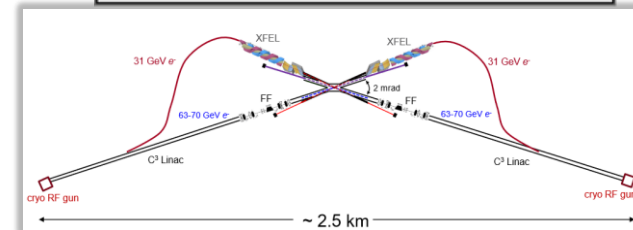
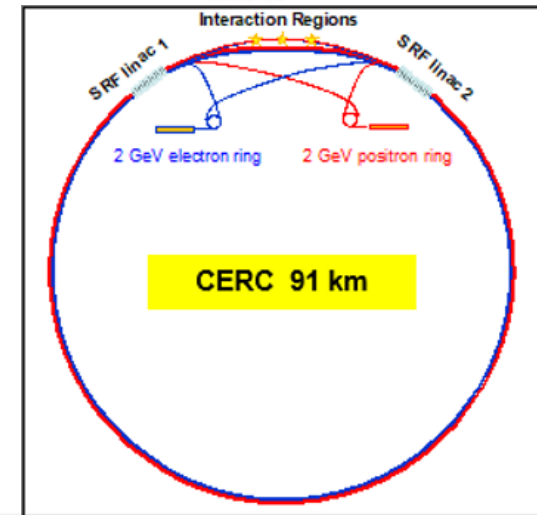
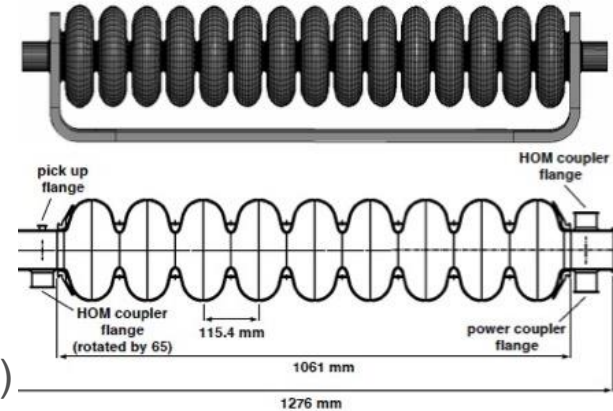
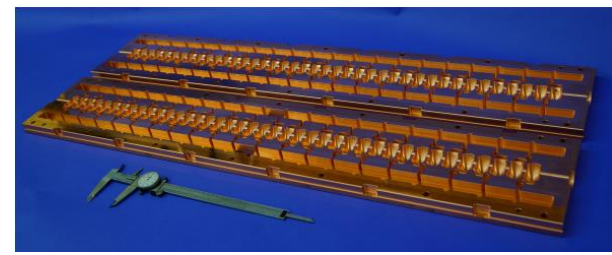
arXiv:1502.02042

Fermilab

04/24/2023

# HF: New Approaches

- C<sup>3</sup>: Cool Copper Collider
  - 72-150 MV/m, 5.7 GHz, 77K copper structures
    - Advance beyond NLC (65MV/m) and CLIC (100MV/m)
    - Needs R&D and viability demonstration
    - Needs complete and self-consistent design
- HELEN: High Energy LEptoN collider
  - 70 MV/m, 1.3 GHz, 2 K Nb structures (Nb<sub>3</sub>Sn?)
    - Advance beyond XFEL (28 MV/m) and ILC (31.5MV/m)
    - Needs R&D and viability demonstration
    - Needs complete and self-consistent design
- ERL based colliders
  - Circular or linear, energy recovery (SRF accel/decel)
    - Pushes existing SRF technologies to very high currents
    - Needs serious R&D and self-consistent design
- $\gamma\gamma$  colliders (eg two C3 linacs  $e^- \rightarrow \gamma$  at IP)
  - s-channel, only ~63 GeV beams, two XFELs, low L
    - Large  $dE/E$  cme spread
    - Needs serious R&D and self-consistent design



# Plasma Wakefield LCs

## Key facts:

High gradients 2-5 GeV/m  $\rightarrow$  small footprint (dominated by Final Focus)

Impressive proof-of-principle demos

In principle, feasible for  $e^+e^-$  collisions

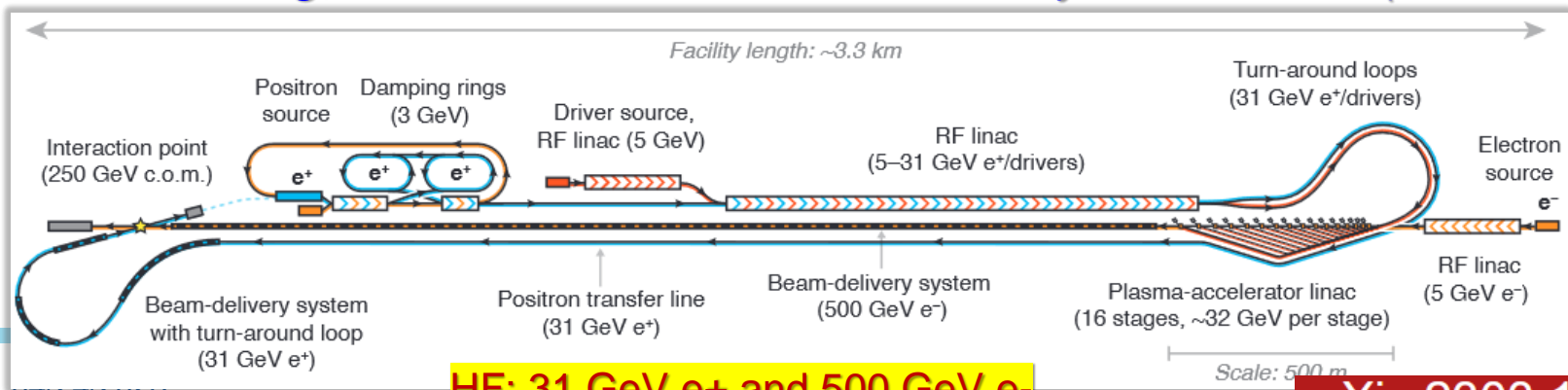
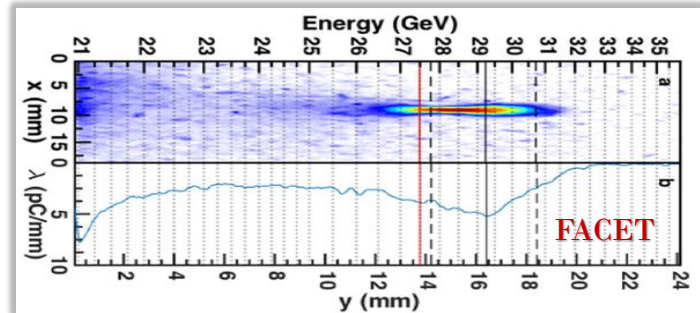
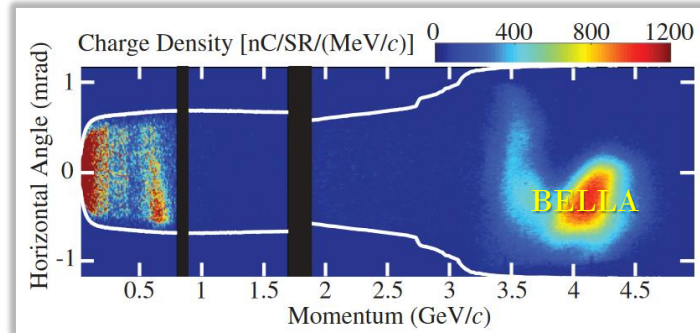
## Many challenges:

It'll take time to mature the technology

- Acceleration of positrons
- Staging and power efficiency
- Emittance control
- Beamstrahlung, etc etc etc

## Concepts are being proposed:

- Can not compete with ILC, FCC, etc
- Now mostly about 15 TeV  $e^+e^-$
- Recent hybrid scheme (B.Foster *et al*)



HF: 31 GeV  $e^+$  and 500 GeV  $e^-$


arXiv:2303.10150

# **Higgs Factories – Overview (ITF)**

## **...just a glance – Thomas Roser's talk will follow**

# Implementation Task Force on Higgs Factories

Table I - ITF Report – T.Roser, et al, [arXiv:2208.06030](https://arxiv.org/abs/2208.06030)

		CME (TeV)	Lumi per IP/ tot (10 <sup>34</sup> )	Years, pre- project R&D	Years to 1 <sup>st</sup> Physics	Cost Range (2021 B\$)	Electric Power (MW)
Circular $e^+e^-$	FCCee (4 IPs)	0.24	7.7/29	0-2	13-18	12-18	290
	CEPC (2 IPs)	0.24	8.3/17	0-2	13-18	12-18	340
	FermiHF	0.24	1.2	3-5	13-18	7-12	~200
Linear $e^+e^-$	ILC	0.25	2.7	0-2	<12	7-12	110
	CLIC	0.38	2.3	0-2	13-18	7-12	150
	C <sup>3</sup>	0.25	1.3	3-5	13-18	7-12	150
	HELEN	0.25	1.4	5-10	13-18	7-12	~110
ERL-based	CERC	0.24	78	5-10	19-24	12-30	90
	ReLiC (2 IPs)	0.24	165/330	5-10	>25	7-18	315
	ERLC	0.24	90	5-10	>25	12-18	250
s-chan	XCC- $\gamma\gamma$	0.125	0.1	5-10	19-24	4-7	90
	$\mu\mu$ -Higgs	0.13	0.01	>10 <sup>13</sup>	19-24	4-7	200

# Higgs Factories: Synergies

# There are NUMEROUS synergies! – e.g. ITF report:

## Technical risk registry

- Technical risk registry of accelerator components and systems for **future  $e^+e^-$  and ep colliders**: lighter colors indicate progressively higher TRLs (less risk), white is for either not significant or not applicable.

	FCCee/CEPC	ILC	HE ILC	CCC	HE CCC	CLIC	HE CLIC	CERC	ReLiC	HE ReLiC	ERLC	XCC	LHeC/FCCeh <sup>24</sup>
RF Systems													
Cryomodules													
HOM detuning/damp													
High energy ERL													
Positron source													
Arc&booster magnets													
Inj./extr. kickers													
Two-beam acceleration													
Damping rings													
Emitt. preservation													
IP spot size/stability													
High power XFEL													
$e^-$ bunch compression													
High brightness $e^-$ gun													
IR SR and asymm.quads													

Technical Risk Factor	Score	Color Code
TRL = 1,2	4	
TRL = 3,4	3	
TRL = 5,6	2	
TRL = 7,8	1	

(from T.Roser presentation at the BNL P5 Town Hall (April'23))

# Future Colliders R&D Program: Synergies

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

	Country	Facility	Experience
<i>SuperKEKB</i>	Japan	7+4 GeV $e^+e^-$ , 8e35	nano-beams scheme, IR/MDI
<i>HL-LHC</i>	CERN	x5 LHC luminosity	Nb <sub>3</sub> Sn IR magnets, crab cavities, MDI
<i>PIP-II</i>	USA	SRF linac to double # $\nu$ 's	CW SRF, ~2 MW targets, RF sources
<i>LCLS-II-HE</i>	USA	8 GeV CW SRF	efficient SRF, cryo
<i>EIC</i>	USA	20-140 GeV $ep/ei$	IR/MDI, magnets, polarization, cool
<i>NICA</i>	Russia	$ii/pp$ 11-27 GeV	e- & stoch cool, fast SC magnets
<i>ESS</i>	Sweden	5 MW pulsed SRF	SRF, cryo, targetry

# **Let's take a closer look at the FCC needs (part of the ongoing US-FCCee planning)**

# RF Systems - R&D, Design and Fabrication

1. **800 MHz SRF cavities** with  $Q_0 = (3 \rightarrow 6)e10$  at 25 MV/m; then 4-cavity **Cryomodules**

- 28 RF cryomodules are needed for the Higgs operation, plus 244 CMs (later) for Booster/Collider Rung at  $t\bar{t}$
- Synergy with: LCLS-II, PIP-II, HL-LHC crabs, ILC/HELEN, GARD RF, MuCollider RF, ...

2. High efficiency **power sources** for 800 MHz with  $\eta > 80\%$  :

- Synergy with: CLIC, GARD RF, MuColl RF, ESS, ...

3. High gradient 70 MV/m 150 MOhm/m **copper RF** for injector, **6-18 GeV RF** high gradient inj. Linac

- Synergy with: CLIC, GARD RF, C3, MuColl RF, ...

# Magnets/MDI - R&D, Design and Fabrication

1. IR magnets, cryostats, masks (for 4 IPs)
  - Synergy with: SuperKEKB, HL-LHC, EIC IR, ILC/HELEN, GARD magnets (MDP), MuCollider magnets, ...
2. FCCee collider ring magnets (low field, DC)
  - Synergy with: EIC ESR, ILC/HELEN/CLIC/C3 DRs, Synchrotron Radiation light sources (rings)...
3. Booster ring magnets (low field,  $\sim 1$ s ramp)
  - Synergy with: EIC ESR, Synchrotron Radiation light sources (boosters)...
4. Polarization wigglers (0.1-0.7 T)
  - Synergy with: XFELs and Synchrotron Radiation light sources, ILC/HELEN/CLIC/C3 DRs...
5. FCChh collider ring magnets ( $\sim 16$ T, DC)
  - Synergy with: HL-LHC, GARD magnets (MDP), MuCollider magnets, ...

# “Dynamics” - R&D, Design and Fabrication

## 1. Interaction region design, and integrated machine design

- Modeling/simulations: crab waist and beam-beam/beamstrahlung, DA, chromatic compensation and optics correction schemes
- Synergy with: SuperKEKB, HL-LHC, EIC IR, ILC/HELEN, GARD magnets (MDP), MuCollider magnets, ...

## 2. Losses, collimation and background

- Modeling/simul: halo formation, background in detectors, TMCI, efficient collimation system(elens/NLO/CS), detector background masking, **build collimation system for 4 IRs and rings**
- Synergy with: SuperKEKB, HL-LHC, EIC IR, ILC/HELEN, GARD magnets (MDP), MuCollider magnets, ...

## 3. Polarization (esp. at 45 GeV and 80 GeV beam energies):

- Modeling/simulations: 45-80 GeV energy calibration, error analysis, design and **build wigglers, polarimeters, polarized sources**
- Synergy with: SuperKEKB, HL-LHC, EIC IR, ILC/HELEN, GARD magnets (MDP), MuCollider magnets, ...

## 4. Instrumentation:

- Design and prototyping, then build, luminosity monitors , TMCI feedback systems emittance and halo monitors
- Synergy with: SuperKEKB, HL-LHC, EIC IR, ILC/HELEN, GARD magnets (MDP), MuCollider magnets, ...

# Our Message to P5 (US FCCee)

# Relevant US Expertise

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

**Challenge:** the FCCee pre-CD2 phase 2024-2033 requires up to ~40FTEs/yr (Sci, Eng, Tech), that is **60-100 qualified people** - some of them don't exist, many involved on other projects/ops... other initiatives need the same type of people (ACE, MuColl, C3, GARD) → need a community-wide assessment and planning of the **accelerator workforce development** (expect P5/EPP to comment)

# Moving Forward

- ❑ Assuming the approval of FCC in ~2028, we can expect DOE CD-0 in ~2029 and creation of the US FCC Project Office to follow (like for the LHC process).
  - ❑ CD-0 & CD-1 is within the 10-year window of consideration by this P5 committee.
- ❑ While a formal US FCC Project office can only be formed following CD-0 (which must wait for a formal approval of the FCC project), it is critical that the community comes together now to develop a strategic and coherent US program.
  - ❑ The formation of a US proto-collaboration **now** that can prioritize, scope and channel the U.S. efforts into a coherent effort on FCC-ee accelerators is necessary.
  - ❑ Funding for **targeted accelerator R&D at a range of upto \$12-20M per year** in the early phase and subsequently ramping up following the approval of FCC
  - ❑ Scale of the targeted R&D similar to the past US-LARP program.
- ❑ Early engagement and investments in accelerator/detector R&D is crucial to seed our role in the global initiatives and allow the U.S. to be in a position of strength and be significant stakeholders in future international projects.

# Summary –

- Higgs Factory is slated to be the next high priority Energy Frontier project following the completion of HL-LHC.
- FCCee is one of the most feasible HF options... it has challenges (power consumption, cost, etc) but the concept is based on well-understood accelerator technology and greatly benefit from synergies with existing and planned accelerators and ongoing technology developments.
- We seek the P5 approval and recommendation:

*Motivated by the strong scientific importance of FCC as a Higgs factory, and the initiatives at CERN to host it including the FCC feasibility study, the U.S. must promptly engage, at appropriate levels, in targeted accelerator and detector design and prepare the groundwork to projectize these efforts in anticipation of the FCC approval in 2028.*

# Back up slides

# ITF's Evaluations: Higgs Factories & Multi-TeV

ITF Report – T. Roser, et al, arXiv:2208.06030

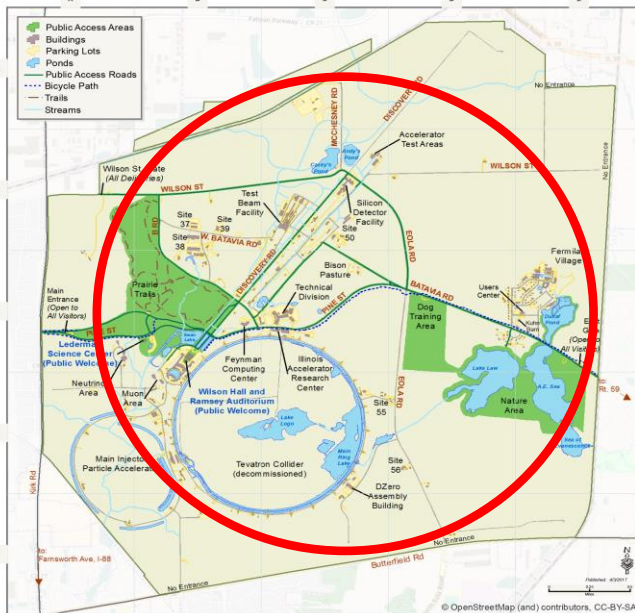
	CME (TeV)	Lumi per IP (10 <sup>34</sup> )	Years, pre- project R&D	Years to 1 <sup>st</sup> Physics	Cost Range (2021 B\$)	Electric Power (MW)
<b>FCCee-0.24</b>	0.24	8.5	0-2	13-18	12-18	290
<b>ILC-0.25</b>	0.25	2.7	0-2	<12	7-12	140
<b>CLIC-0.38</b>	0.38	2.3	0-2	13-18	7-12	110
<b>HELEN-0.25</b>	0.25	1.4	5-10	13-18	7-12	110
<b>CCC-0.25</b>	0.25	1.3	3-5	13-18	7-12	150
<b>CERC(ERL)</b>	0.24	78	5-10	19-24	12-30	90



# Future Colliders: Options for Fermilab Site

Snowmass Whitepaper, P.Bhat, et al, <https://arxiv.org/abs/2203.08088>

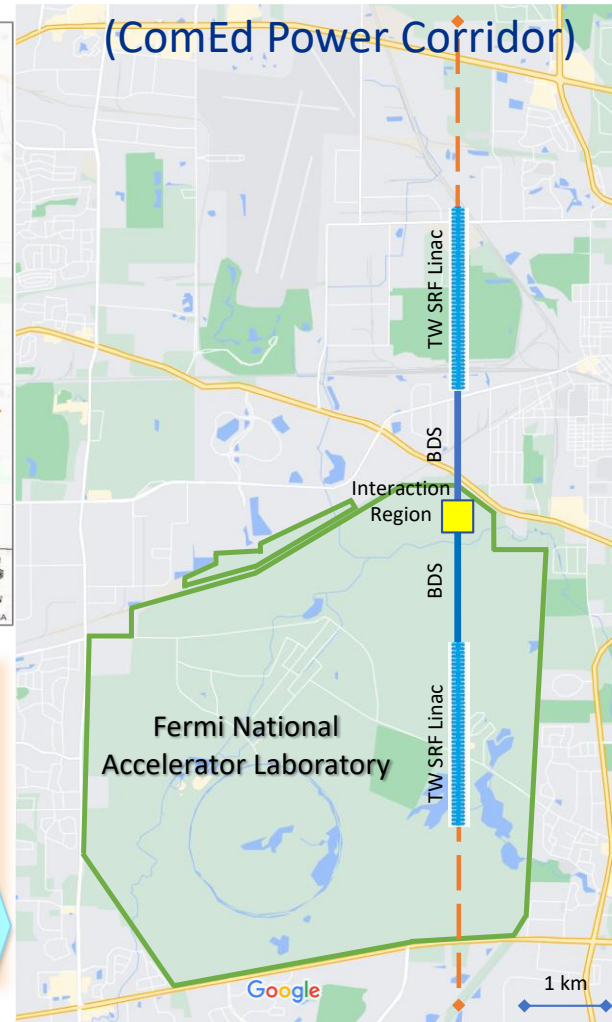
16 km Ring



7 km Linear



12 km Linear  
(ComEd Power Corridor)

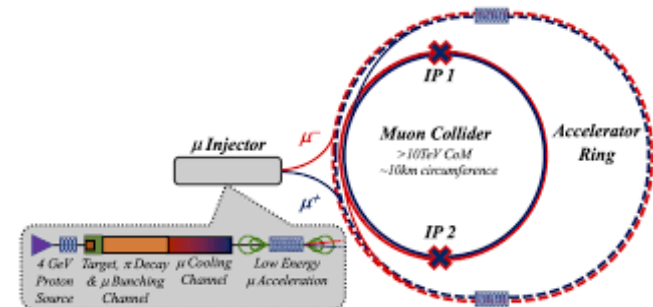
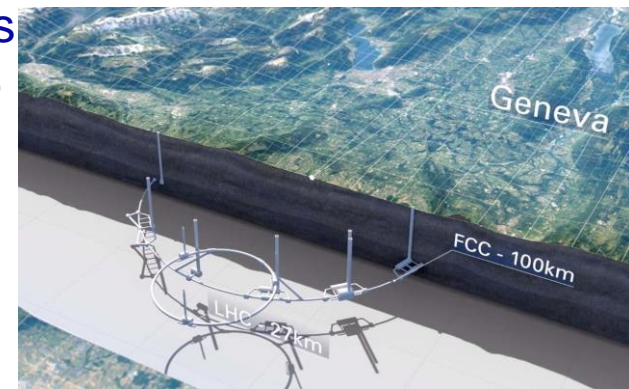
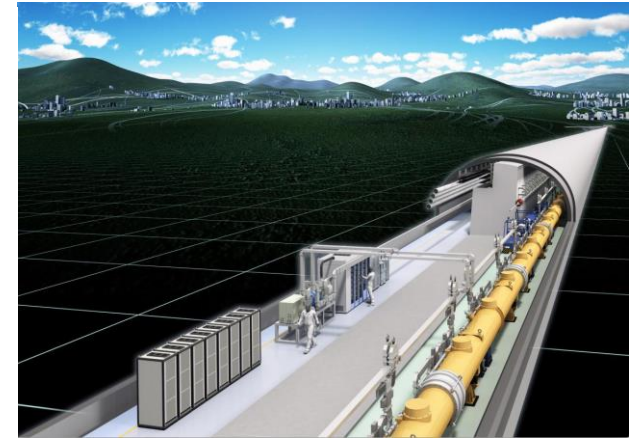


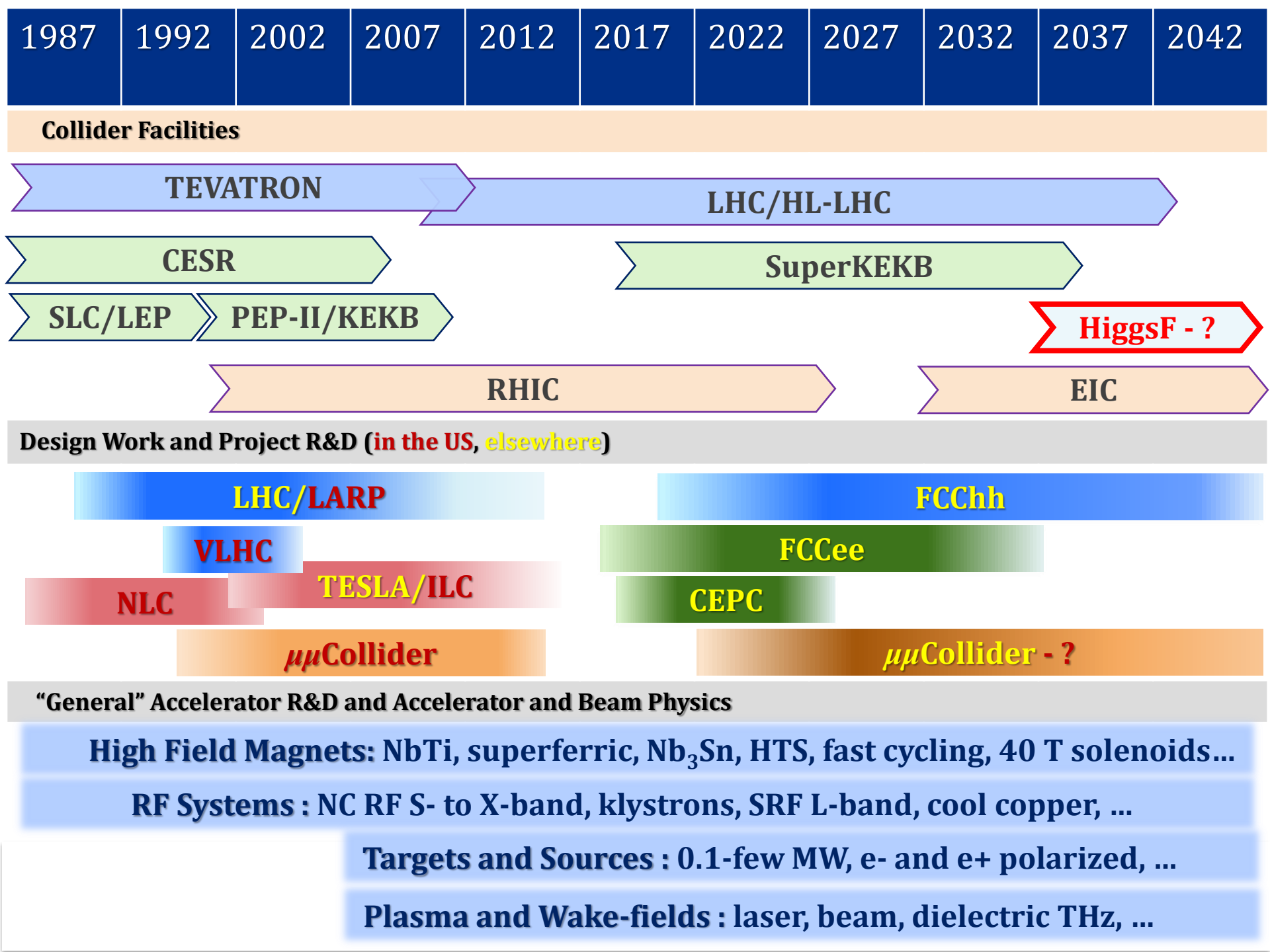
**240 GeV cme e+e- ring**  
**6-10 TeV cme muon collider**  
**24 TeV pp collider**

**250 GeV cme e+e- linear**  
**C<sup>3</sup> and HELEN colliders**  
**upto ~550 GeV if outside**

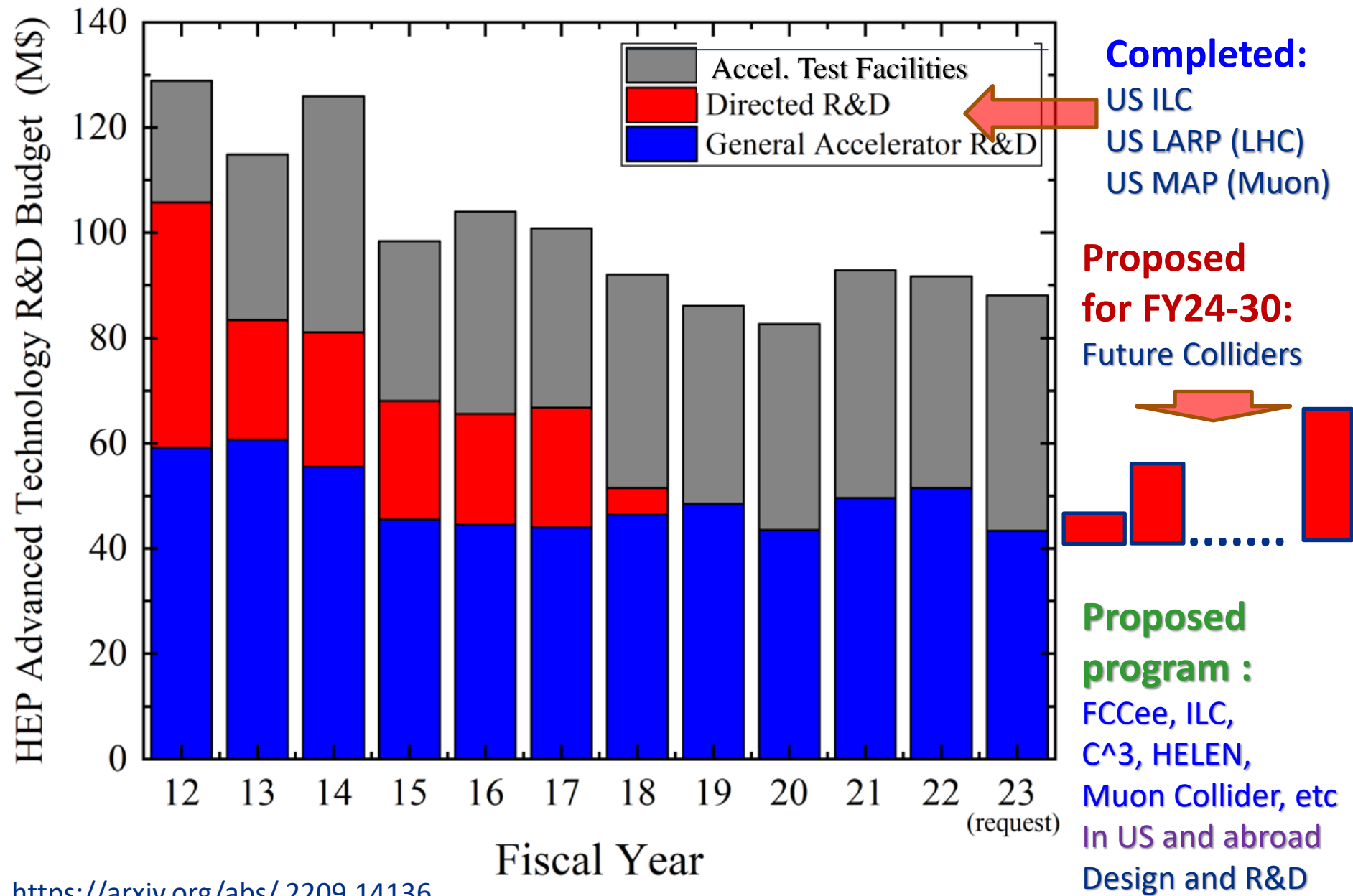
# U.S. Engagement in Global Projects

- International Linear Collider (ILC)
  - U.S. scientists engaged in efforts of the GDE, TDR, and ILC-IDT (ILC International Development Team)
    - SRF R&D for ILC main linacs, other areas
    - Polarized positron source and damping ring, ...
- Future Circular Colliders (FCC)
  - CERN conducting FCCee and magnets studies plus financial feasibility; Feasibility Study Report in 2025
  - 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 (IMCC)
  - 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
  - US community ready to engage - exploring formal U.S. engagement (3 Universities are in, talks w. DOE)





# Gap in R&D Towards Future Colliders



# A National Future Collider R&D Program

Supported by the *Snowmass'21* AF

P.Bhat, et al, <https://arxiv.org/abs/2207.06213>  
S.Gourlay, et al, <https://arxiv.org/abs/2209.14136>

- 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 Higgs/EW factories and 10+ TeV scale collider concepts by the next European strategy update and the **next US community planning cycle**. The program will:
  - develop collider concepts and proposals for options feasible to be hosted in the U.S. (e.g., **CCC, HELEN, Muon Collider**, etc)
  - enable synergistic U.S. engagement in ongoing global efforts (e.g., **FCC, ILC, IMCC**)

# Future Colliders R&D Program: Scope

- Sharply focused on **future colliders**
- Spans **accelerator design, technology and full concept** development
- Complements the existing HEP GARD program (see next slide)
- Multifaceted but **selective, and synergistic**
- **Integrates** all critical R&D for a concept
- Priorities **guided by P5**

# Future Colliders R&D Program

P.Bhat, et al, <https://arxiv.org/abs/2207.06213>

- **Organization:**
  - Coherent national program
  - Collaborative effort of U.S. national labs and universities
- **Coordination:**
  - Centrally coordinated and funded
  - Coordinated with global design studies and R&D
  - Periodic assessment
- **Support:**
  - An impactful program might require an average annual investment of \$25M (minimum) or more between now and the next Snowmass/P5 cycle.
- **Important:** this program will also ensure the critical recruitment, development, and retention of a skilled workforce in accelerator science and technology

# Future Colliders R&D Program: Synergies

- Present GARD thrusts (and **synergies**):
  - Accelerator and Beam Physics
    - Integrated machine design, codes, instrumentation and controls, beam facilities
  - Superconducting magnets and materials (MDP)
    - High-field SC magnets, advanced SC materials, test facilities, ...
  - RF Acceleration Technology
    - High performance NC and RF cavities, RF sources, test facilities, ...
  - Particle Sources and Targets
    - Multi-MW targets, positron sources, test facilities ...
  - Advanced Acceleration Methods
    - Wakefield modeling & simulation tools
- Non-HEP synergies (see **Sarah C. talk**):
  - Technologies and expertise from BES, NP, ARDAP, NSF...
- International partners (see **Lenny R. talk**):
  - Coordination with future collider activities abroad is a must !
  - Tons of expertise and support for FCCee, ILC, MuColl, technologies...

# Back up slides

# FCC : from F.Gianotti slides in Seattle

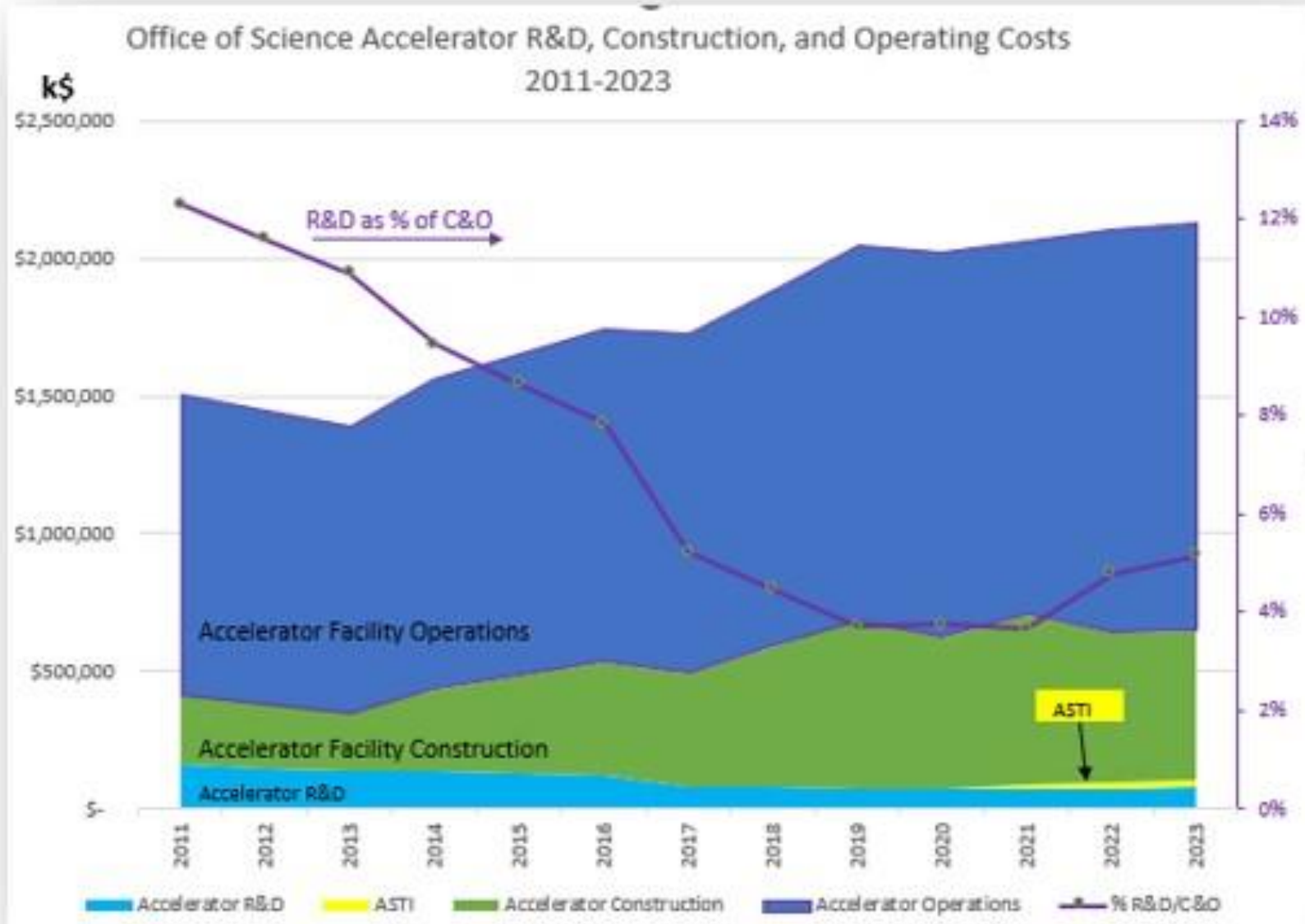


## FCC Feasibility Study 2021-2025: main objectives

- ❑ Demonstration of the [geological, technical, environmental and administrative feasibility of the tunnel and surface areas](#) and optimisation of [placement and layout of the ring](#) and related infrastructure
- ❑ Pursuit, [together with the Host States, of the preparatory administrative processes required for a potential project approval](#) to identify and remove any showstopper
- ❑ [Optimisation of the design of FCC-ee and FCC-hh colliders and their injector chains, supported by R&D to develop the needed key technologies](#)
- ❑ Elaboration of a [sustainable operational model for the machine and experiments in terms of human and financial resource needs, as well as environmental aspects and energy efficiency](#)
- ❑ Development of a [consolidated cost estimate](#), as well as the [funding and organisational models](#) needed to enable the project's technical design completion, implementation and operation (emphasis on FCC-ee)
- ❑ [Identification of substantial resources from outside CERN's budget](#) for the implementation of the first stage project (tunnel and FCC-ee)
- ❑ [Consolidation of the physics case and detector concepts \(in particular FCC-ee detector requirements and technologies\)](#)
  - ❑ FCC Collaboration: 147 Institutes (12 from US) from 34 countries
  - ❑ Plenty of opportunities for interesting work (new detector concepts, accelerator technologies, environmental impact and sustainability, etc.)  
→ more collaborators from the US would be very much welcome!

21

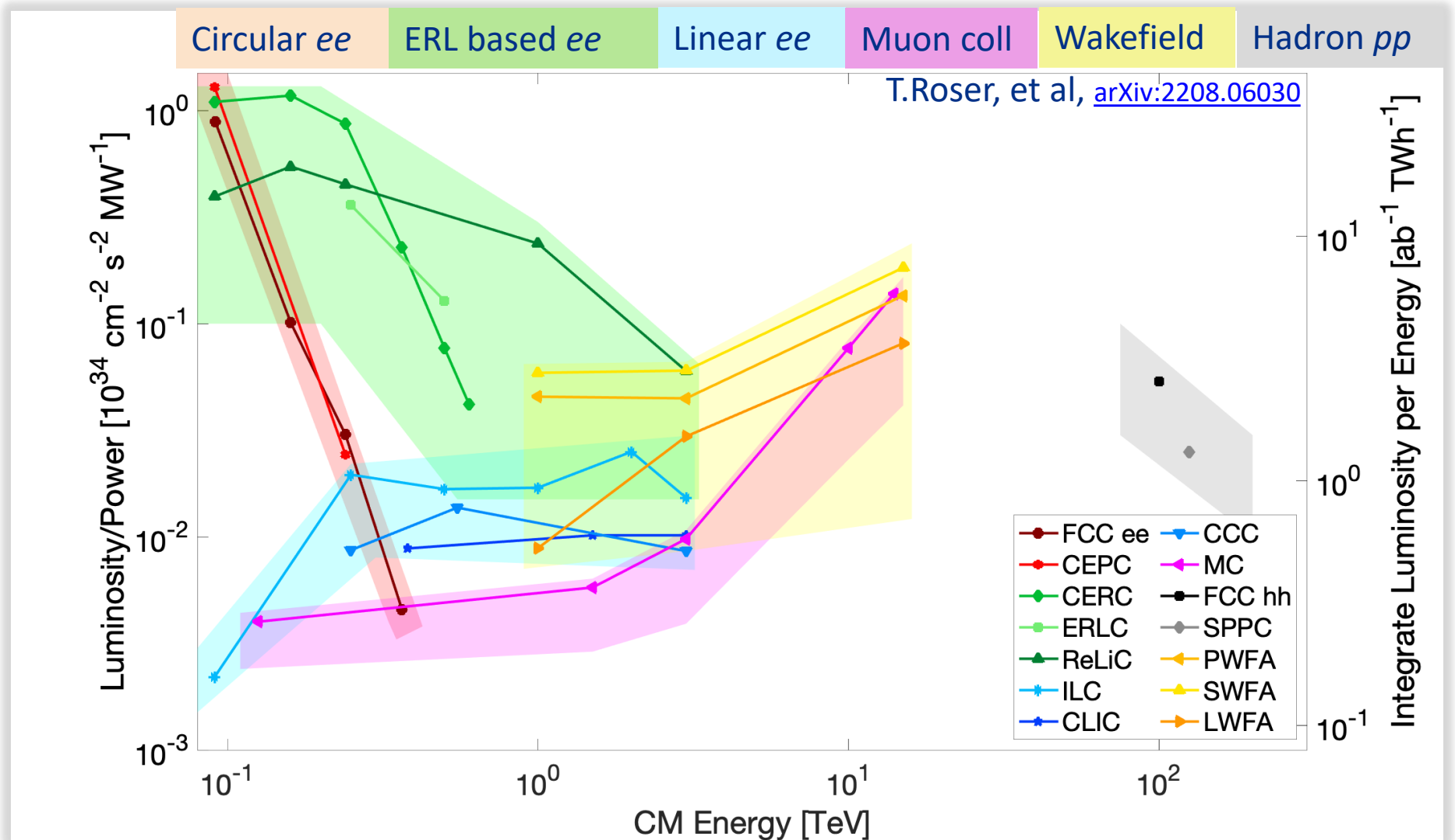
# Integrated US DOE Office of Science Accelerator Expenditures *(annual, 2011-2022 actuals, and 2023 request)*



VS

E.Colby (DOE), NAPAC 2022

# Luminosity per MW of electric Power



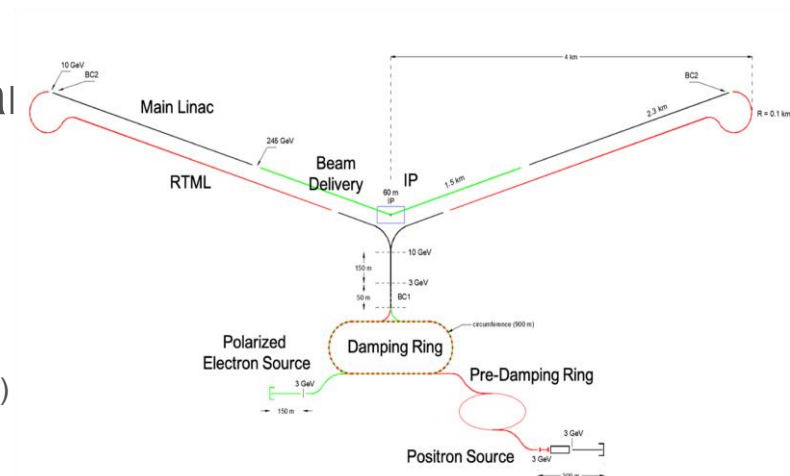
Luminosity is per IP, Integrated luminosity assumes 1e7 seconds/yr. *Luminosity and power consumption values have not been reviewed by ITF - we used proponents' numbers.* Color bands reflect approximate uncertainty for different collider concepts.

# Higgs Factories

# The Cool Copper Collider (CCC or C<sup>3</sup>)



- SLAC (E. Nanni, C. Vernieri, et al.) proposal for a normal conducting RF linear accelerator/collider operating at 77K.
  - Could reach gradient  $\sim 155$  MV/m
  - $1\text{-}2\text{e}34$  @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
- C<sup>3</sup> 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



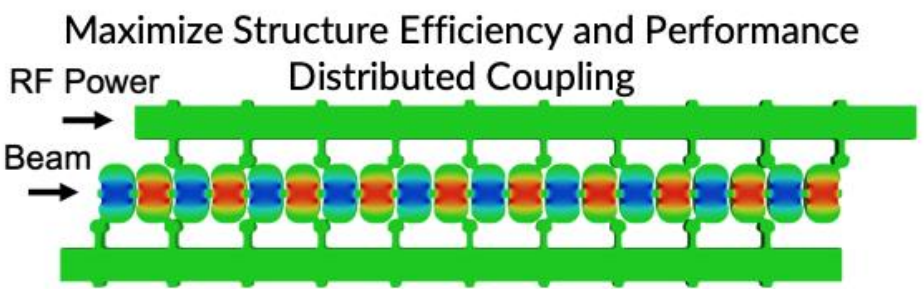
Collider	C <sup>3</sup>	C <sup>3</sup>
CM Energy [GeV]	250	550
Luminosity [ $\times 10^{34}$ ]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Crossing Angle [rad]	0.014	0.014
Site Power [MW]	$\sim 150$	$\sim 175$
Design Maturity	pre-CDR	pre-CDR

From E. Nanni

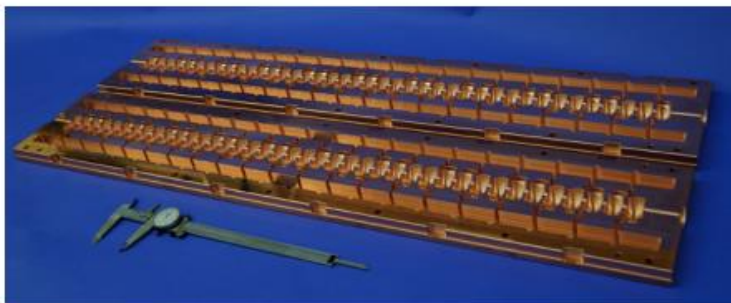


# Key Technologies

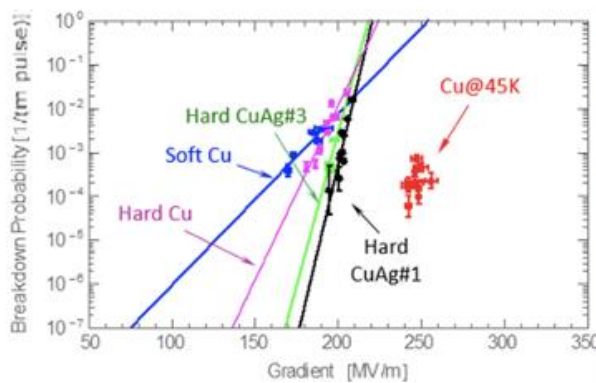
Present Focus is the Main Linac  
In Future Expand to Rest of Complex



Modern Manufacturing  
Prototype One Meter Structure



High Accelerating Gradients  
Cryogenic Operation



C<sup>3</sup> Cryo Test



Integrated Damping  
Slot Damping with NiChrome Coating

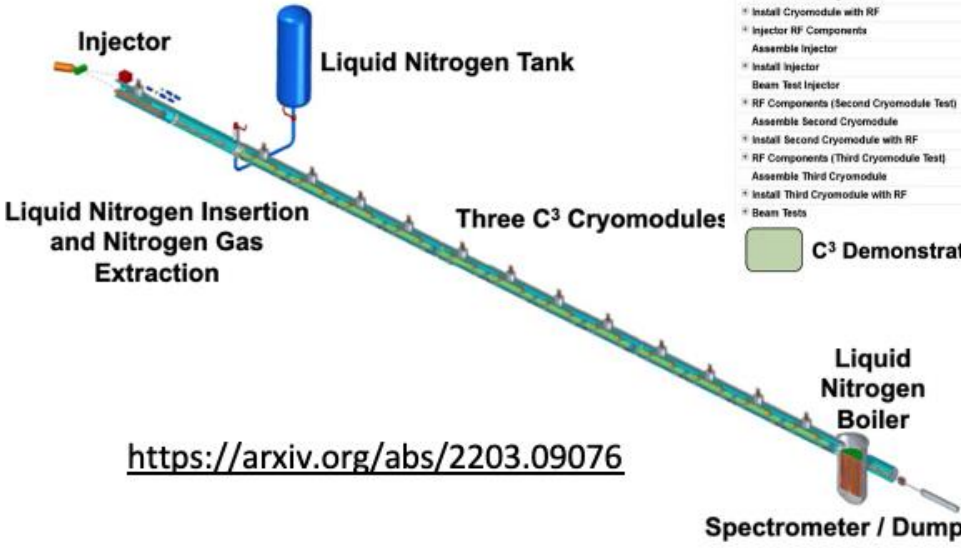


From E. Nanni

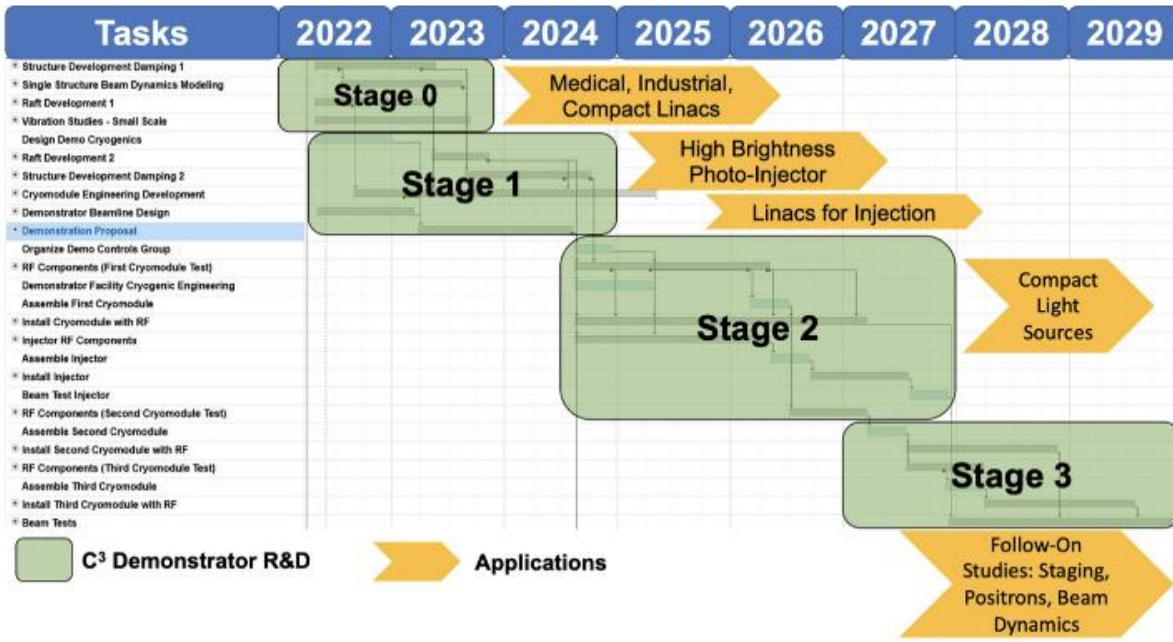
# State of Proposal and R&D needs (5 years)



## Next Steps: C<sup>3</sup> Demonstration R&D Plan

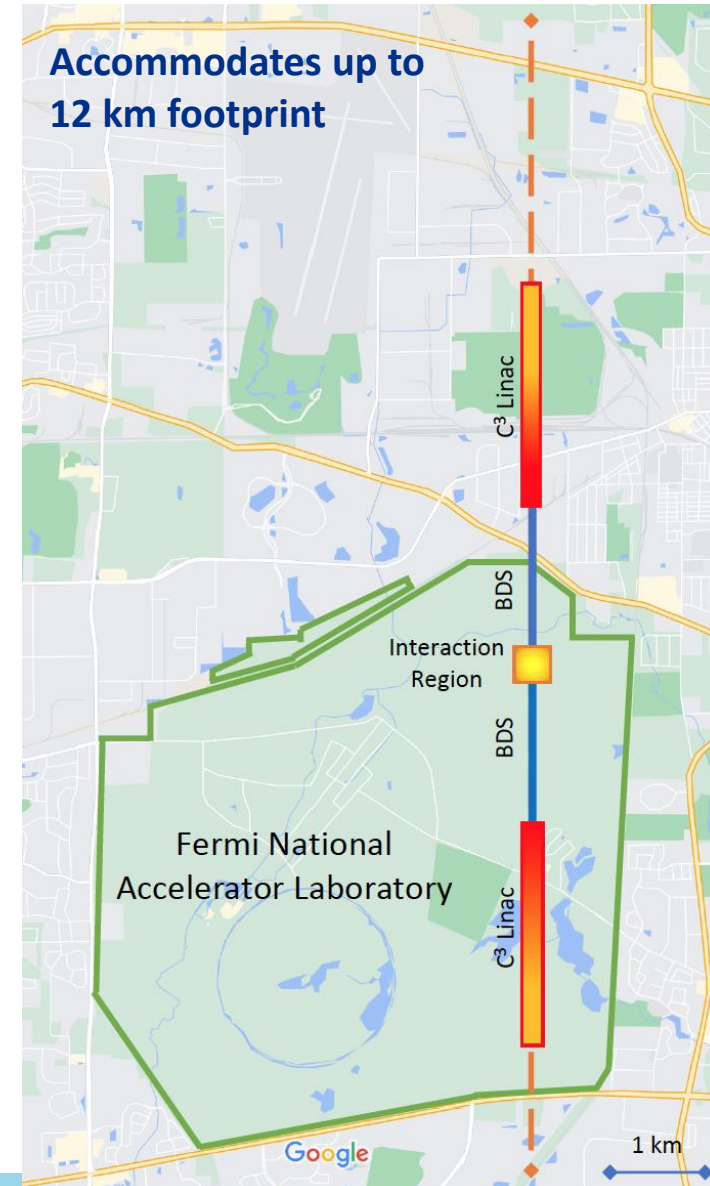
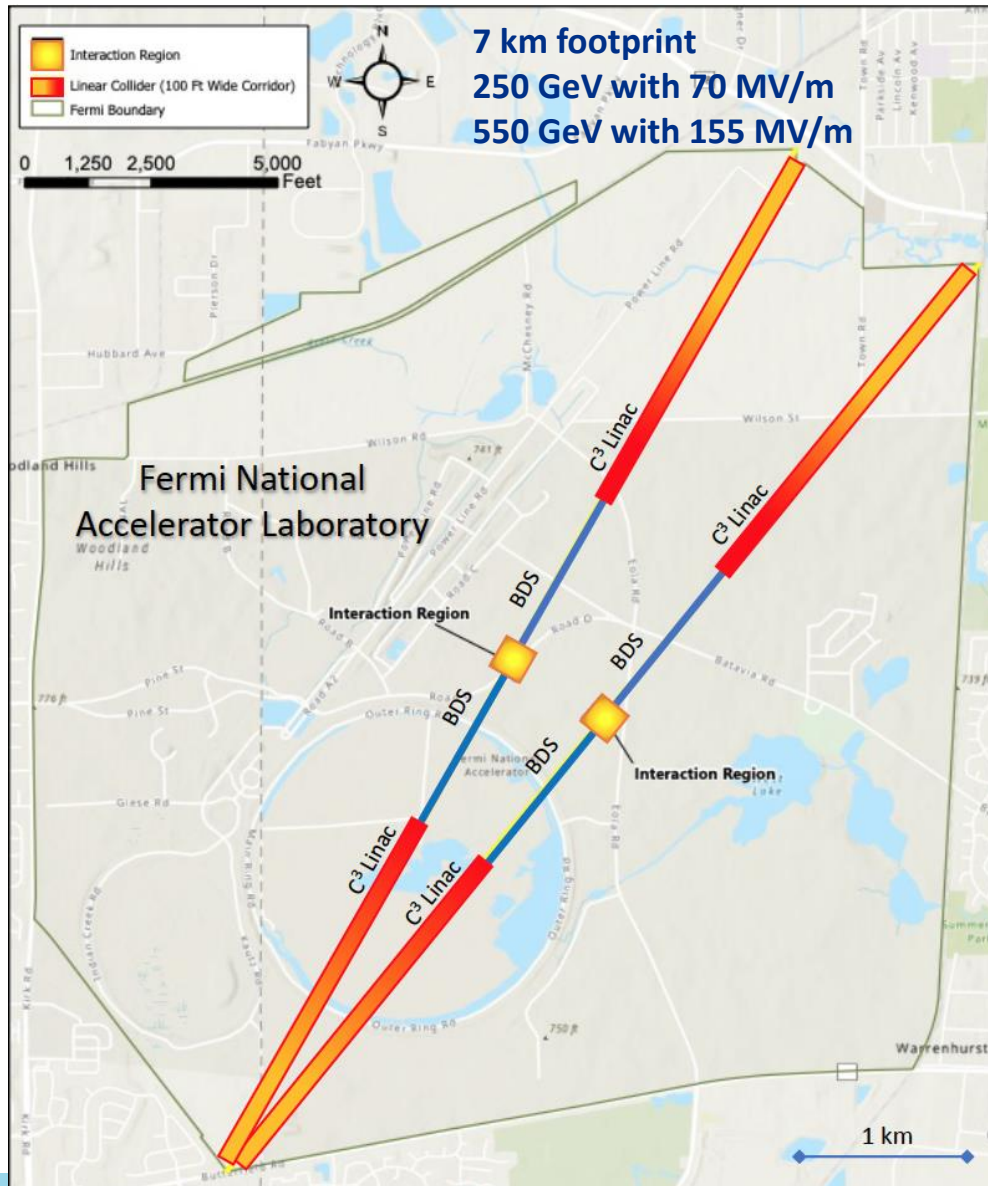


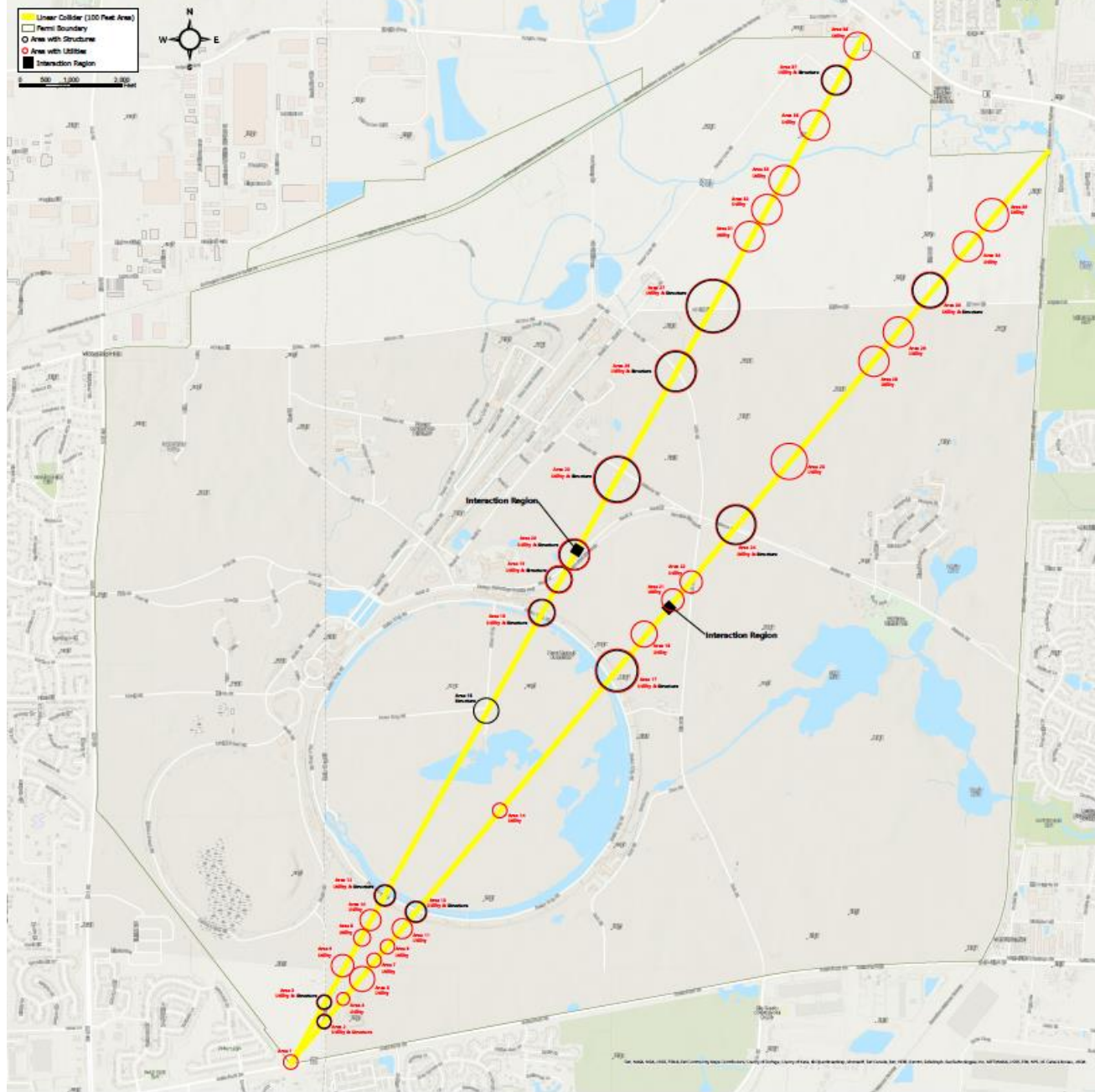
<https://arxiv.org/abs/2203.09076>



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

# C<sup>3</sup> Siting Options at Fermilab





Fermilab  
FESS  
studying  
proposed  
siting

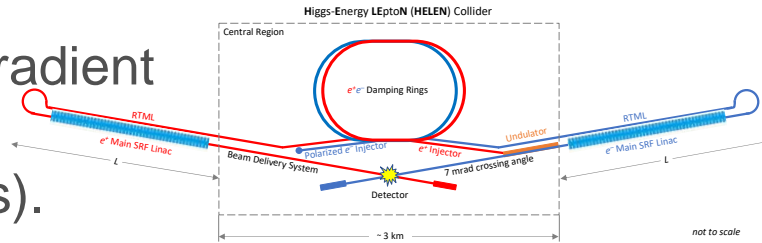


# Higgs Energy LEptoN (HELEN) Collider

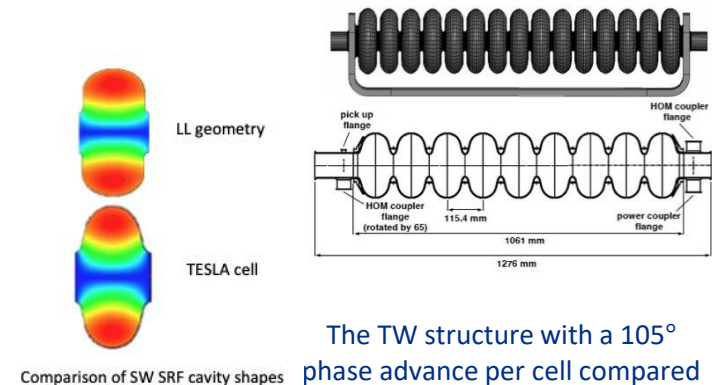
- HELEN is a linear collider based on high gradient SRF (in the range of 55 MV/m to 90 MV/m; standing wave or travelling wave structures).

- 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  $\sim 60$  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<sub>3</sub>Sn structure operating at 90 MV/m.



Parameter	Advanced SW	Traveling wave	Nb <sub>3</sub> Sn
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 <sup>3</sup>	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 ( $\text{ab}^{-1}/\text{yr}$ )	0.2	0.2, 0.4	0.2, 0.3	0.1, 0.6
Peak lumi. $\mathcal{L}$ ( $10^{34} \text{cm}^{-2} \text{s}^{-1}$ )	1.35	1.3, 2.4	1.35, 1.8	1.5, 6
CM energy spread $\sim 0.4\delta_{\text{BS}}$ (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 $f_{\text{rep}}$ (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 ( $\mu\text{s}$ )	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 $\sigma_z$ (rms, mm)	0.3	0.1	0.3	0.07, 0.044
IP beam size $\sigma^*$ (rms, $\mu\text{m}$ )	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, $\epsilon_n$ (rms, $\mu\text{m}$ )	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
$\beta^*$ 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 $\theta_c$ (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 $f_{\text{RF}}$ (MHz)	1300	5712	1300	11994
Accelerating gradient $E_{\text{acc}}$ (MV/m)	70	70, 120	31.5	72, 100
Effective gradient $E_{\text{eff}}$ (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	$\sim 150$ , $\sim 175$	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<sup>\*1,2</sup>, P.C. Bhat<sup>1</sup>, A. Grassellino<sup>1</sup>, M. Checchin<sup>1</sup>, D. Denisov<sup>3</sup>, R.L. Geng<sup>4</sup>, S. Jindariani<sup>1</sup>, M. Liepe<sup>5</sup>, M. Martinello<sup>1</sup>, P. Merkel<sup>1</sup>, S. Nagaitsev<sup>1</sup>, H. Padamsee<sup>1,5</sup>, S. Posen<sup>1</sup>, R.A. Rimmer<sup>6</sup>, A. Romanenko<sup>1</sup>, V. Shiltsev<sup>1</sup>, A. Valishev<sup>1</sup>, and V. Yakovlev<sup>1</sup>

<sup>1</sup>Fermi National Accelerator Laboratory, Batavia, IL, USA

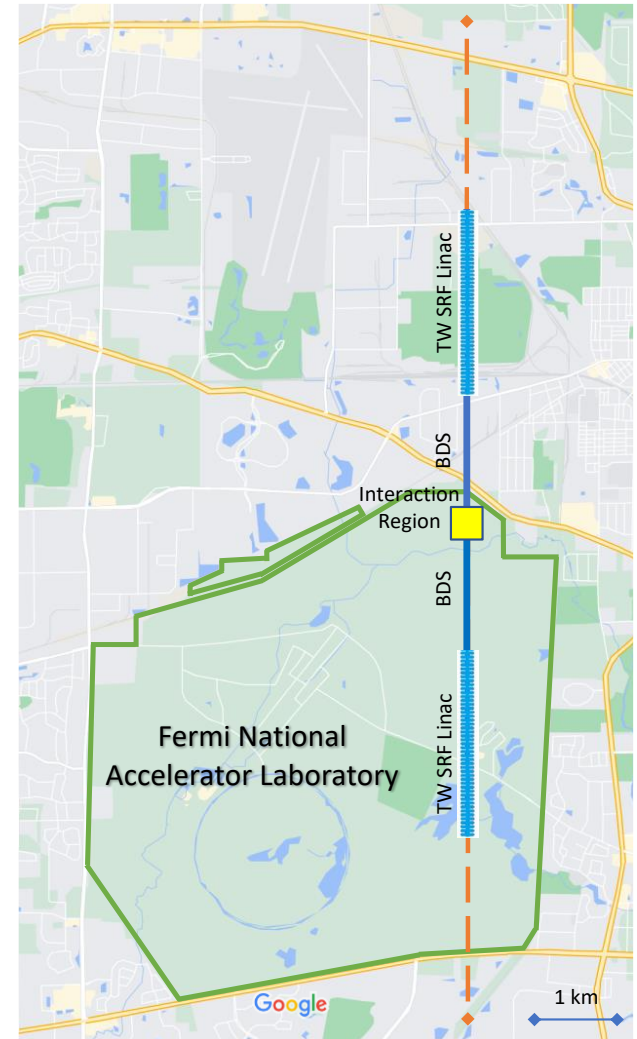
<sup>2</sup>Stony Brook University, Stony Brook, NY, USA

<sup>3</sup>Brookhaven National Laboratory, Upton, NY, USA

<sup>4</sup>Oak Ridge National Laboratory, Oak Ridge, TN, USA

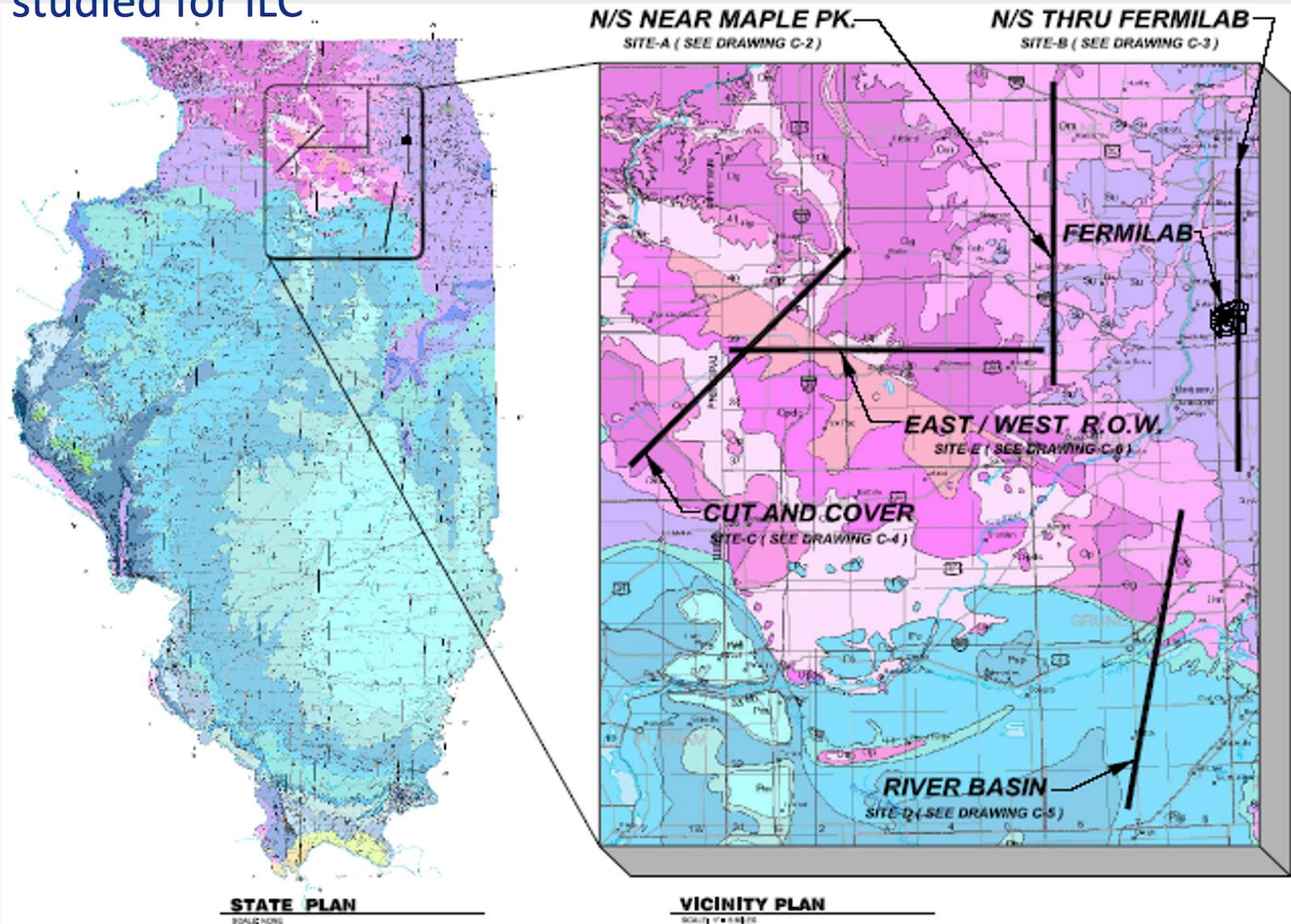
<sup>5</sup>Cornell University, Ithaca, NY, USA

<sup>6</sup>Thomas Jefferson National Accelerator Facility, Newport News, VA, USA



# ILC Site options in the US/Fermilab

## Sites studied for ILC

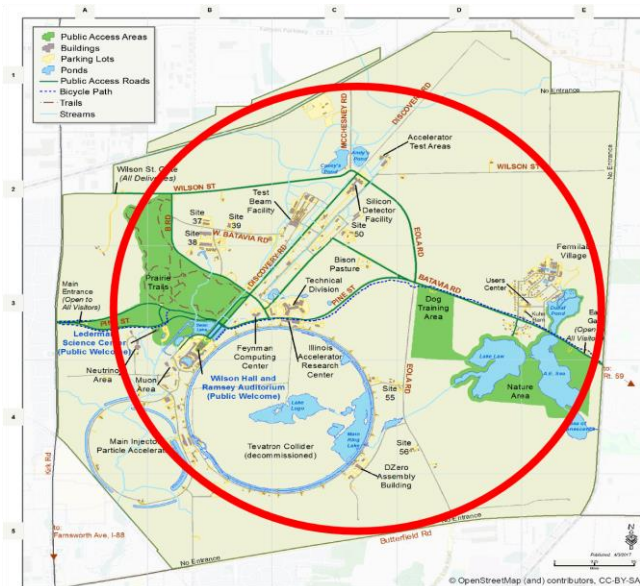


# Circular Fermilab Site Filler e+e-

- 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

FNAL-SF-ee



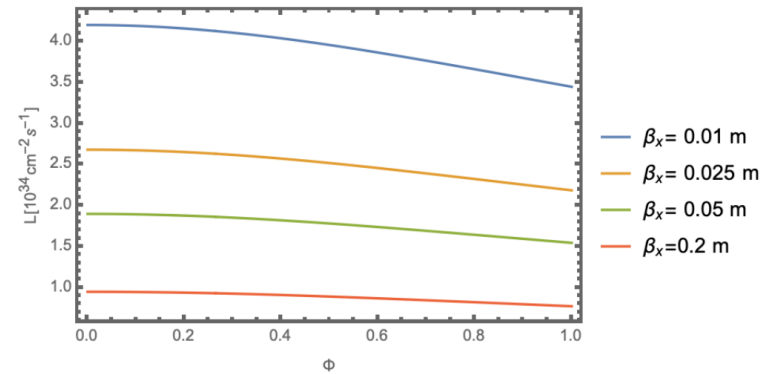
	Higgs Factory	Z factory
Circumference [km]	16	16
Beam energy [GeV]	120	45.6
Total synchrotron radiation power [MW]	100	60
Beam current [mA]	5.	140
$N [10^{11}]$	8.3	1.67
Number of bunches	2	279
$\beta_x^* [\text{m}] / \beta_y^*$	0.2 m / 1 mm	0.2 m / 1 mm
$\epsilon_x / \epsilon_y [\text{nm}]$	21 / 0.05	26.1 / 0.065
$\sigma_z [\text{mm}]$	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) [%]	$\pm 3$	$\pm 9$
$\tau_{bs} [\text{min}]$	9 - 36	
$\tau_{Bhabha} [\text{min}]$	8.7	37
$\mathcal{L}$ per IP [ $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ]	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
- $\beta_x^* \sim 10 \text{ mm}$ ,  $\beta_y^* = 0.0005 \text{ m}$
- $\phi < 2$
- $\xi_y \sim 0.14$

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

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



## ■ Challenges:

- IR optics with small  $\beta_{y^*}$ , 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

...

# Muon Collider (Contd.)

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

+ D. Neuffer

Muon Collider Parameters. $\sqrt{s} = 0.126 - 6 \text{ TeV}$						
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	$10^{34} \text{cm}^{-2} \text{s}^{-1}$		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/ $10^7 \text{ s}$			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

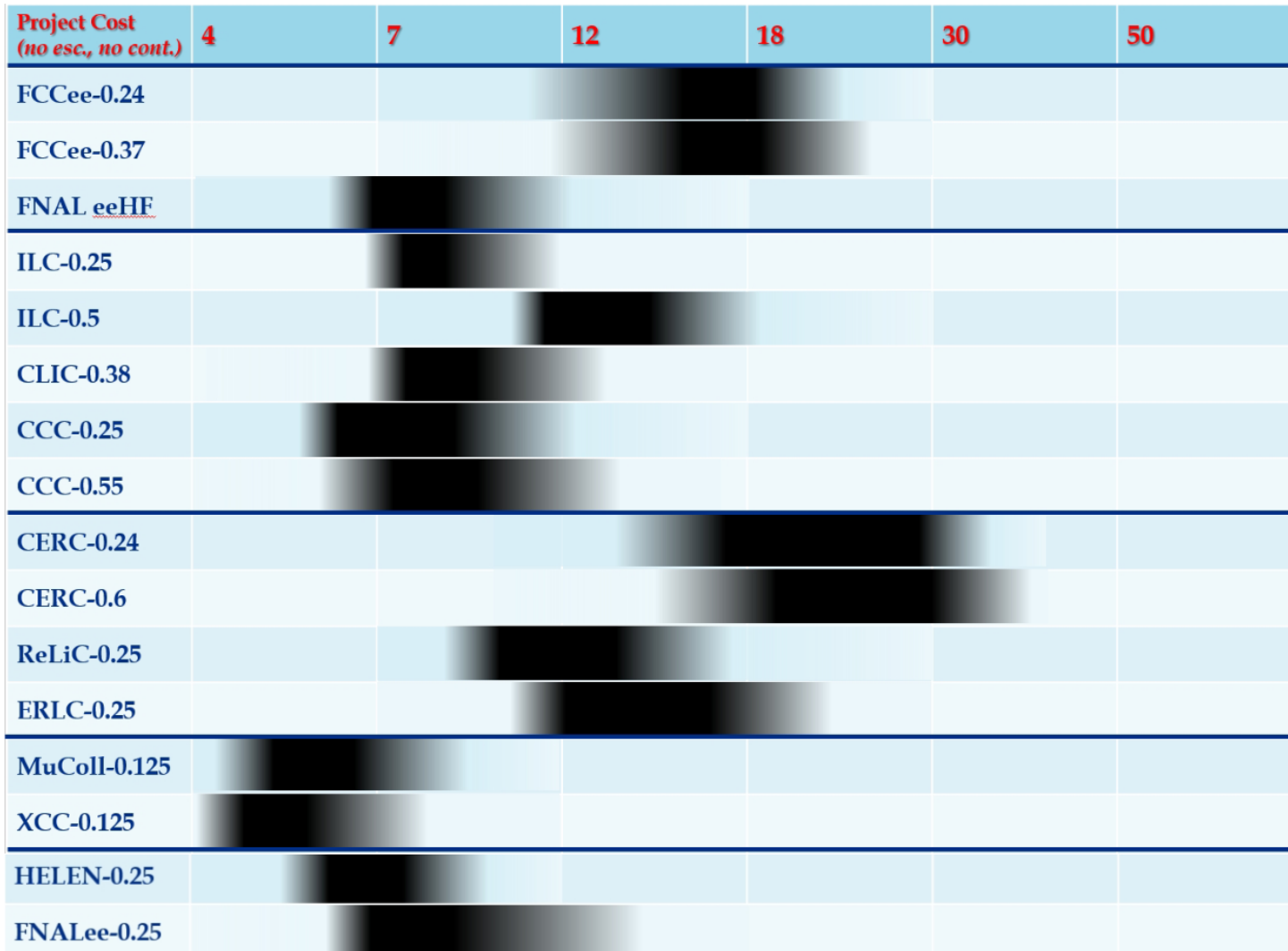
- Multi-MW proton beam with PIP-II linac and Booster replacement

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

# ITF on the scale of R&D

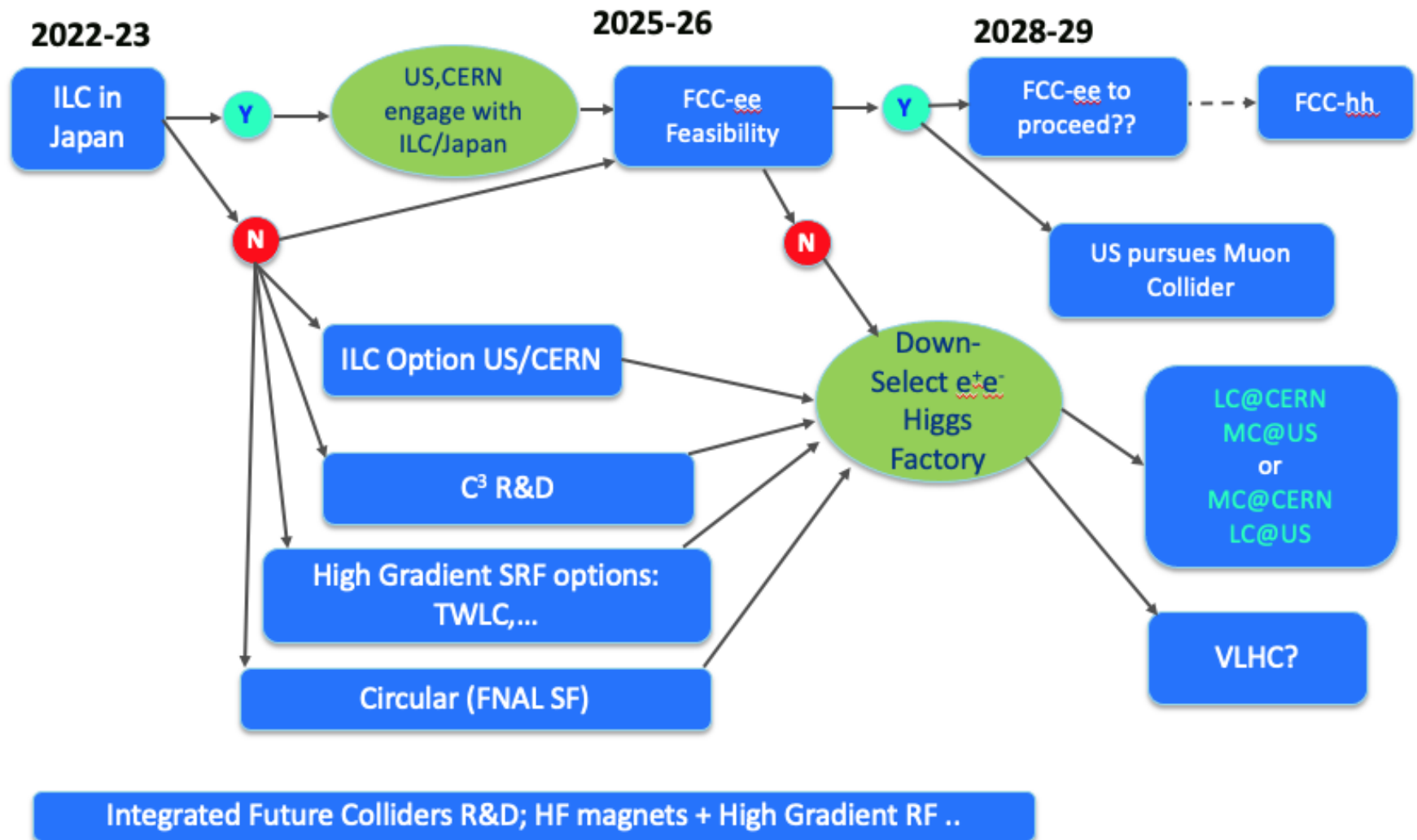
R&D Program Facility Name	Benefiting Concept	Duration (Years)	Integrated Cost (M\$)	Funding Source	Key Topics Rationale
<b>Linear <math>e^+e^-</math> colliders</b>					
NLC/NLCTA/FFTB	NLC/C <sup>3</sup>	14	120	OHEP	NC RF gradient, final focus
TESLA/TTF	ILC	~10	150	DESY/Collab	SCRF CMs and beam ops
ILC in US/FAST	ILC	6	250	OHEP	SCRF CMs and beam ops
ILC in Japan/KEK	ILC	10	100	KEK	SCRF CMs and beam ops
ATF/AFT2	ILC	15	100	KEK/Intl	LC DR and final focus
CLIC/CTF/CTF3	CLIC	25	500	CERN/Intl	2-beam scheme and driver
General RF R&D	All LCs	8	160	GARD	see RF Roadmap; incl facilities
ILC in Japan/KEK	ILC	5	50	KEK	next 5 yr request
High- $G$ RF & Syst.	CLIC/SRF	5	150	LDG/CERN	NC/SC RF and klystrons
C <sup>3</sup> input	C <sup>3</sup>	8	200	tbd	72-120 MV/m CMs, design
HELEN input	HELEN	n/a	200	tbd	pre-TDR, TW SRF tech
ILC-HE input	ILC-HE	20	100	tbd	10 CMs 70MV/m $Q=2e10$
ILC-HighLumi input	ILC-HL	10	75	tbd	31.5 MV/m at $Q=2e10$
<b>Circular/ERL <math>ee/eh</math> colliders</b>					
CBB	LCs	6	25	NSF	high-brightness sources
CBETA	ERLCs	5	25	NY State	multi-turn SRF ERL demo
ERLs/PERLE	ERLCs	5	80*	LDG/CERN	NC/SC RF, klystrons
FNALee input	FNALee	n/a	100	tbd	design and demo efforts
LHeC/FCCeh input	eh-coll.	n/a	100	tbd	demo facility, design
CEPC input	CEPC	6	154	tbd	SRF, magn. cell, plasma inj.
ReLiC input	ReLiC	10	70	tbd	demo $Q=1e10$ at 20 MV/m
XCC input	XCC	7	200	tbd	demo and design efforts
CERC input	CERC	8	70	tbd	demo high- $E$ ERL at CEBAF
<b>Muon colliders</b>					
NFMCC	MC	12	50	OHEP	design study, prototyping
US MAP	MC	7	60	OHEP	IDS study, components
MICE	MC	12	60	UK/Collab	4D cooling cell demo
IMCC/pre-6D demo	MC-HE	5	70	LDG/CERN	pre-CDR work, components
IMCC/6D cool.	MC-HE	7	150	CERN/Collab	6D cooling facility and R&D
<b>Circular <math>hh</math> colliders</b>					
LHC Magnet R&D	LHC	12	140	CERN	8T NbTi LHC magnets
US LARP	LHC	15	170	OHEP	more LHC luminosity faster
SC Magnets General	$pp, \mu\mu$	10	120	GARD	HF-magnets and materials
US MDP	$pp, \mu\mu$	5	40	GARD	see HFM Roadmap
HFM Program	FCChh	7	170	LDG/CERN	16 T magnets for FCChh
FNALpp input	FNALpp	n/a	100	tbd	25T magnets demo
FCChh input	FCChh	20	500	tbd	large demo, R&D and design
Coll.Sea input	CollSea	16	400	tbd	300m magnets underwater
<b>AAC colliders</b>					
SWFA/AWA	SWFA-LC	8	40	GARD	2-beam accel in THz structures
LWFA/BELLA	LWFA-LC	8	80	GARD	laser-plasma WFA R&D
LWFA/DESY	LWFA-LC	10	30	DESY	laser-plasma WFA R&D
PWFA/FACET-I,II	PWFA-LC	13	135	GARD	2-beam PWFA, facility
AWAKE	PWFA-LC	8	40	CERN/Collab	proton-plasma PWFA, facility
EUPRAXIA	LWFA-LC	10	570	EUR/Collab.	high quality/eff. LWFA R&D
LWFA/DESY	LWFA-LC	10	80	DESY	laser WFA R&D
SWFA input	SWFA-LC	8	100	tbd	0.5 & 3GeV demo facilities
LWFA input	LWFA-LC	15	130	tbd	2nd BL, $e^+$ , kBELLA project
PWFA input	PWFA-LC	10	100	tbd	demo and design effort

# Higgs Factories Costs: Nuances

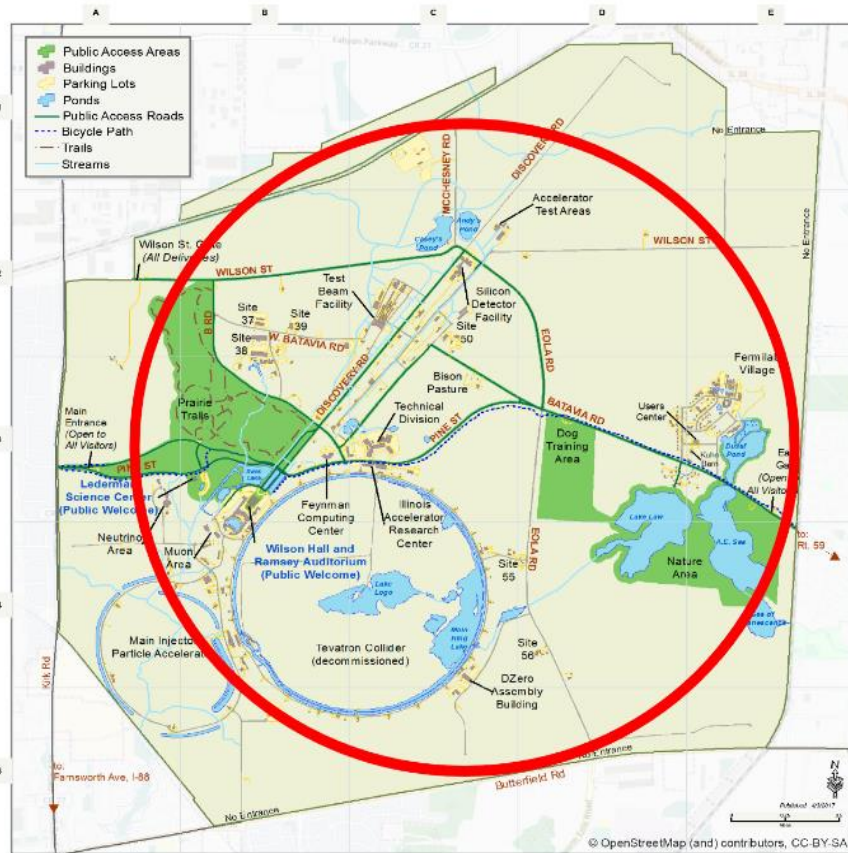


30-parameter ITF cost model. Horizontal scale is approximately logarithmic for the project total cost in 2021 B\$ without contingency and escalation. Black horizontal bars with smeared ends indicate the cost estimate range for each machine.

# A Roadmap for the Decade



# 250 GeV cme Fermilab Site-Fillers



16-km collider e+e- ring

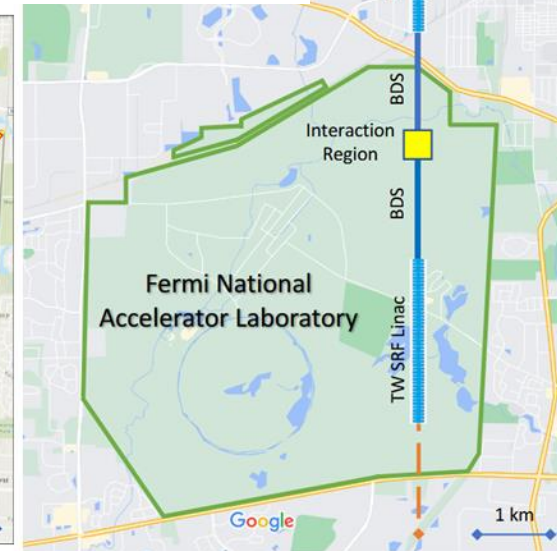
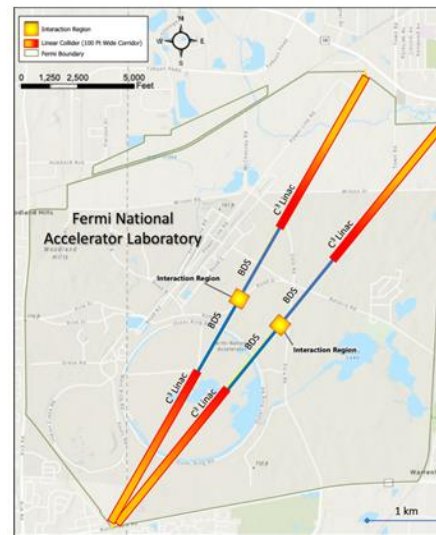
<https://arxiv.org/abs/2203.08088>

**CCC**

(cool copper collider)

**HELEN**

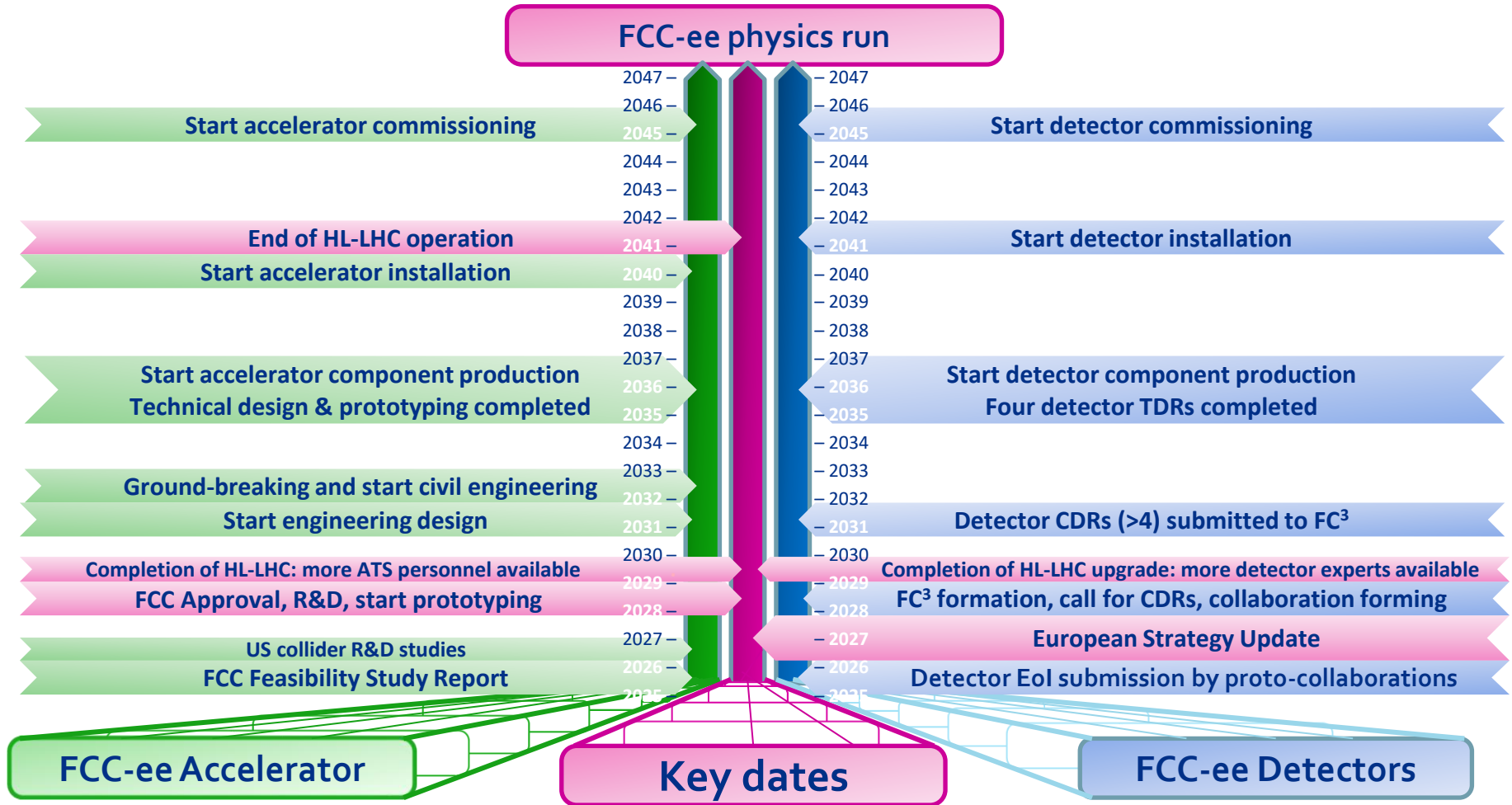
(TW SRF collider)



cool- or SC-RF e+e- linear colliders  
7-km for 250 GeV, 12-km 0.5+ TeV

<https://arxiv.org/abs/2203.08211>

<https://arxiv.org/abs/2110.15800>



US DOE project key dates might differ somewhat from the FCC project milestones shown above.  
 Possibly: CD0 ~2029, CD1 ~2030/31, CD2 ~2033/34, scope-specific CD3a ~2032-34, full CD3 2036/37, CD4~2046/47.

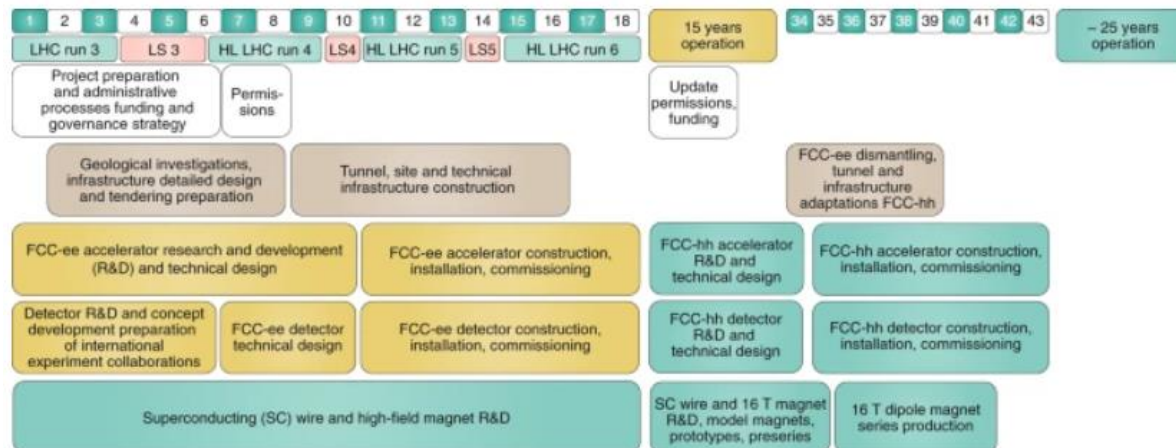
# Extra Slides

# 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.**



# Objective of the Proposed Program

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

## Accelerator and Beam Physics – Grand Challenges

The primary scientific mission of the ABP thrust is to address and resolve the Accelerator and Beam Physics Grand Challenges.

**Grand challenge #1 (beam intensity):** How do we increase beam intensities by orders of magnitude?

**Grand challenge #2 (beam quality):** How do we increase beam phase-space density by orders of magnitude, towards quantum degeneracy limit?

**Grand challenge #3 (beam control):** How do we control the beam distribution down to the level of individual particles?

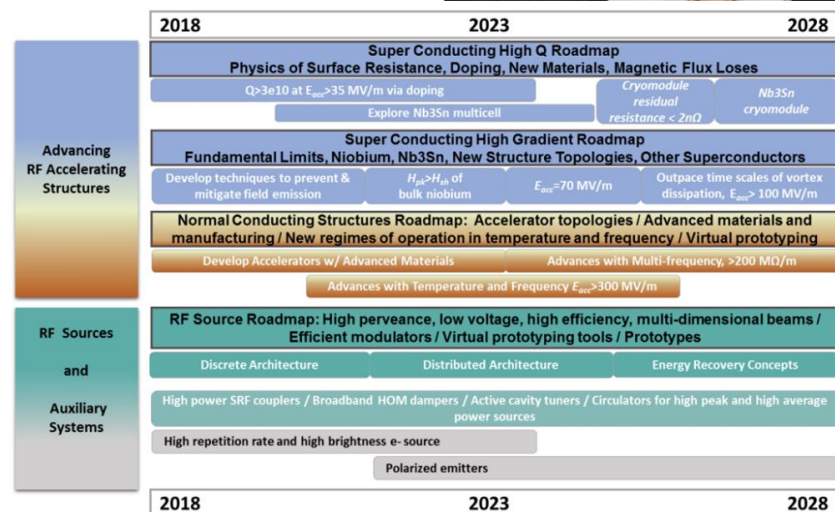
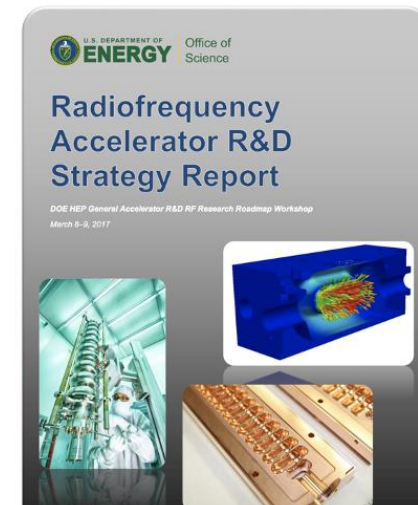
**Grand Challenge #4 (beam prediction):** How do we develop predictive “virtual particle accelerators”?

Link to Grand Challenges ([a more detailed description](https://arxiv.org/abs/2101.04107)):

<https://arxiv.org/abs/2101.04107>

## RF Accelerator Technology in GARD Program

- **Two main components:**
  - Advancement of RF structures
  - Advancement of the RF sources powering and auxiliary systems surrounding the structures
- The **overarching goal** is to dramatically improve performance and reduce cost
- Several thrusts with their own ten-year roadmaps and milestones addressing **HEP mid- and long-term R&D needs** that support the P5 strategy:
  - SRF (High Q and High gradient)
  - Normal conducting RF structures
  - Advanced RF sources
  - Auxiliary systems
- Additional considerations: Synergies, Facilities, Modeling and Simulations, Workforce



# MDP – an established GARD program to advance magnet technology for HEP colliders

## • Vision

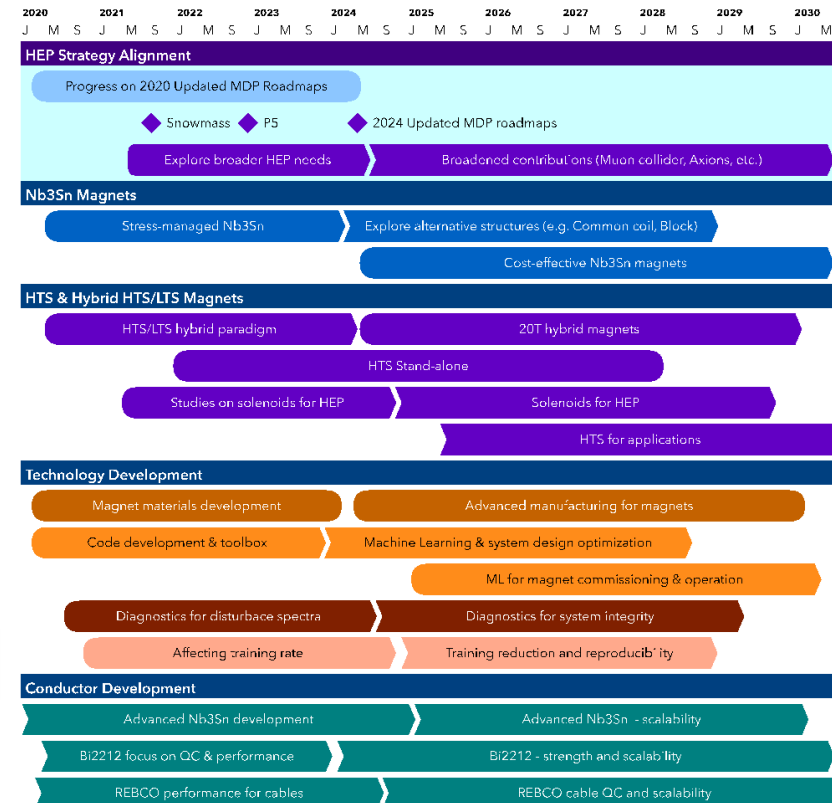
- Leadership in high-field accelerator magnet technology for colliders;
- Develop and integrate magnet research teams
- Identify and nurture cross-cutting / synergistic activities with other programs
- Motivate and grow a new generation of magnet experts for future facilities

## • Overarching goals:

- *Explore the performance limits of Nb3Sn accelerator magnets*
- *Develop and demonstrate an HTS accelerator magnet technology*
- *Investigate fundamental aspects of magnet design and technology*
- *Pursue Nb<sub>3</sub>Sn and HTS conductor R&D*

• MDP provides critical developments for many of the HEP science applications advocated at Snowmass  
04/24/2023 Vladimir Shiltsev - HEP

- Leverages synergies with broader DOE-SC (FES and industry)
- Close collaboration with international partners



# Advanced Accelerator Collider Study Needs

- Next steps: formalize and extend verification of parameter sets, towards an integrated collider study
  - Integrate collider community expertise
- Address AAC regimes and systems, incl.:
  - Wakefield structures with strong focusing
  - Jitter, tolerances, active alignment
  - Efficient, emittance preserving staging
  - Beam delivery and IP for intense beams
  - Luminosity spectrum and detector interface for round beam  $\sigma(10 \text{ TeV})$
  - $e^+e^-$ ,  $gg$  physics guidance
  - Potential re-use of nearer-term LC infrastructure (e.g. ILC, C3) or to provide sources, components...
- Our hope is that an R&D on Collider Development program can provide mechanism for sustained effort coordinated with International community & other technologies ILC, C<sup>3</sup>, muons etc.

