Snowmass 2021

Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

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

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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)

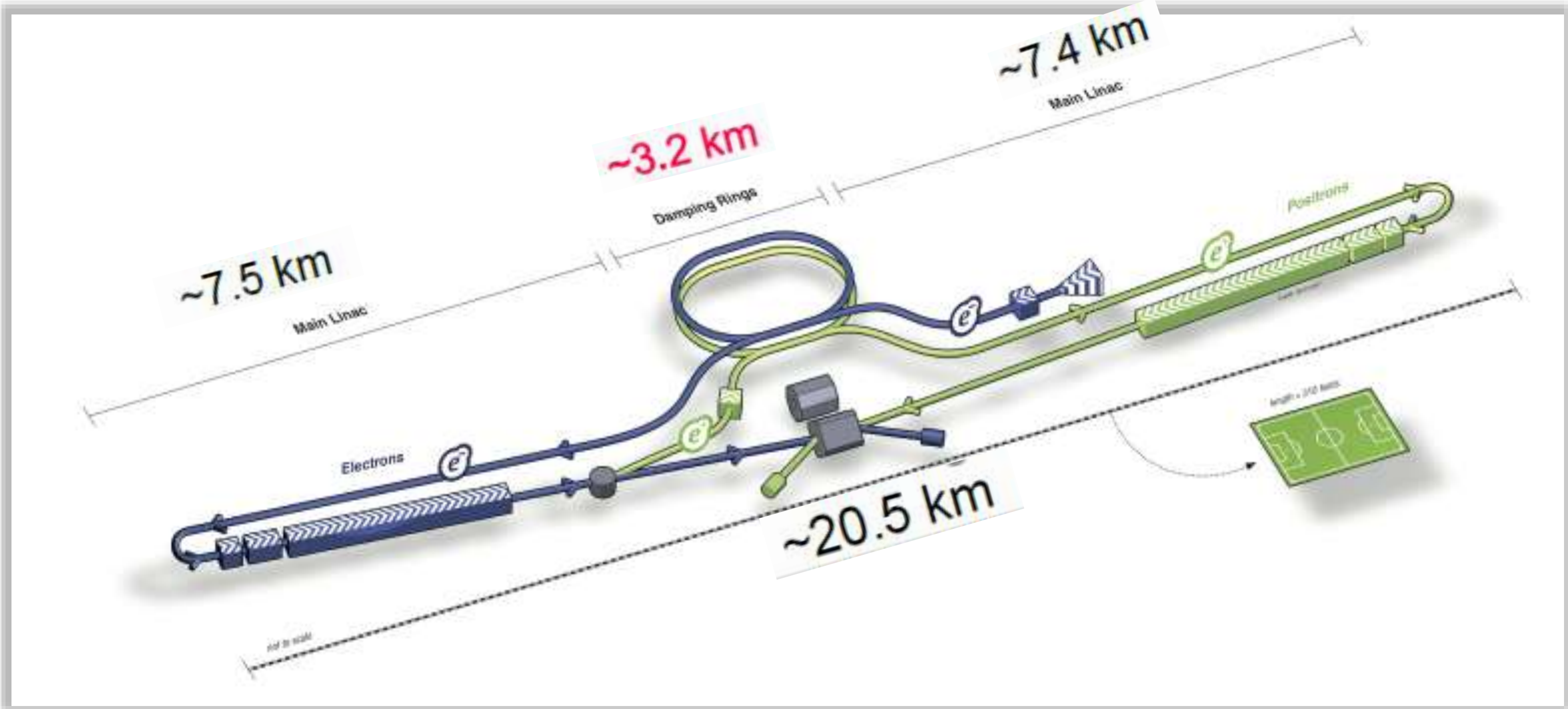
- FCCee at the P5:
  - Our "message" on FCCee (key points)
  - **Integrated US Future Collider R&D Program**

Approaches to Higgs Factories

International Linear Collider

arXiv:1306.6328

TDR



Key facts:

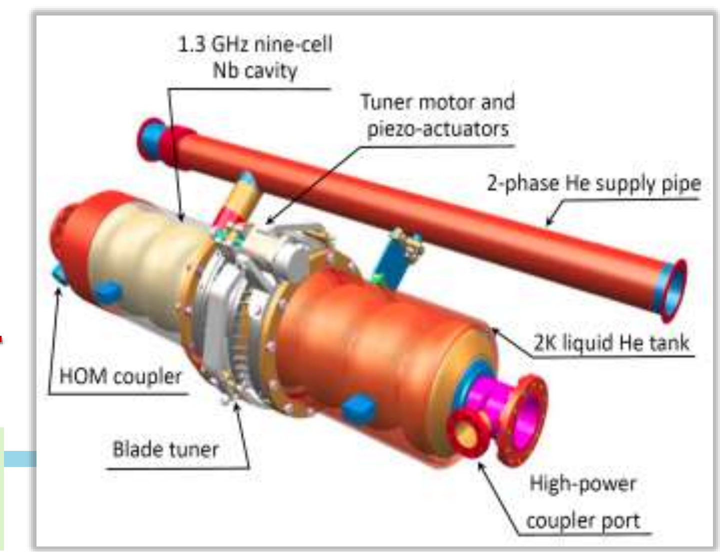
20 km, including 5 km of Final Focus

SRF 1.3 GHz, 31.5 MV/m, 2 K

~~130~~ 110 MW site power @ 250 GeV c.m.e.

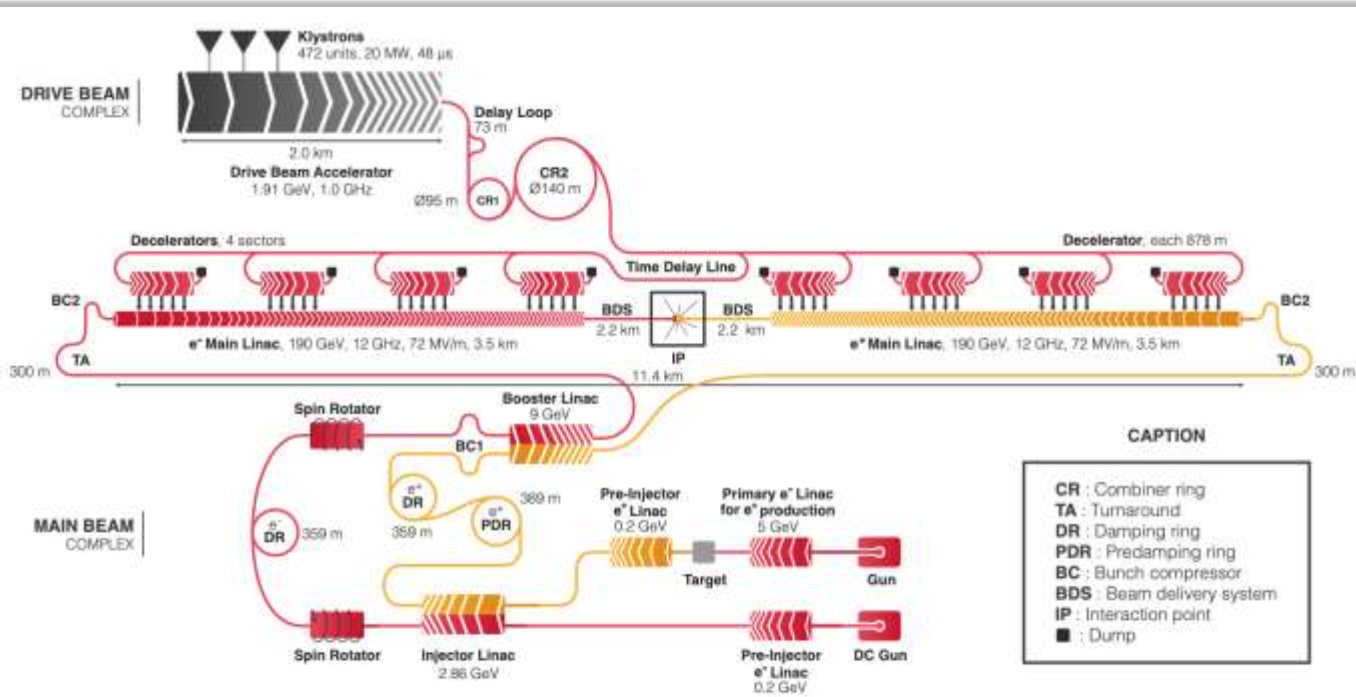
Cost estimate 700 B JPY*

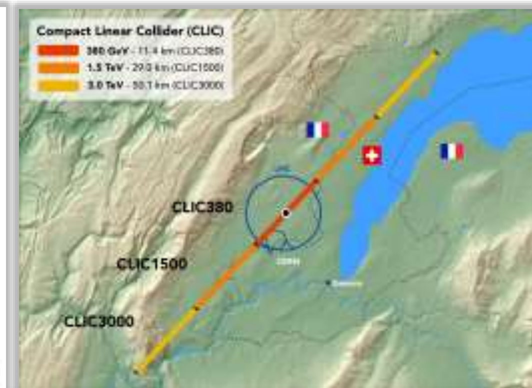
** ± 25% err, includes labor cost*



Compact LInear Collider

arXiv:1209.2543 CDR





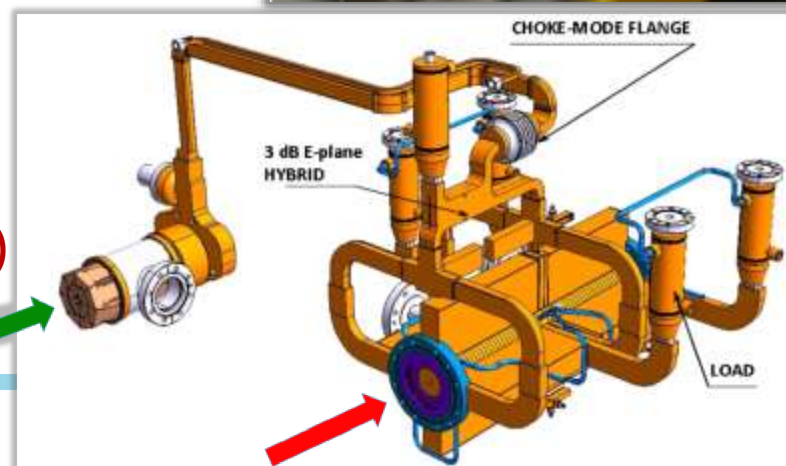
Key facts:

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 ± 25%

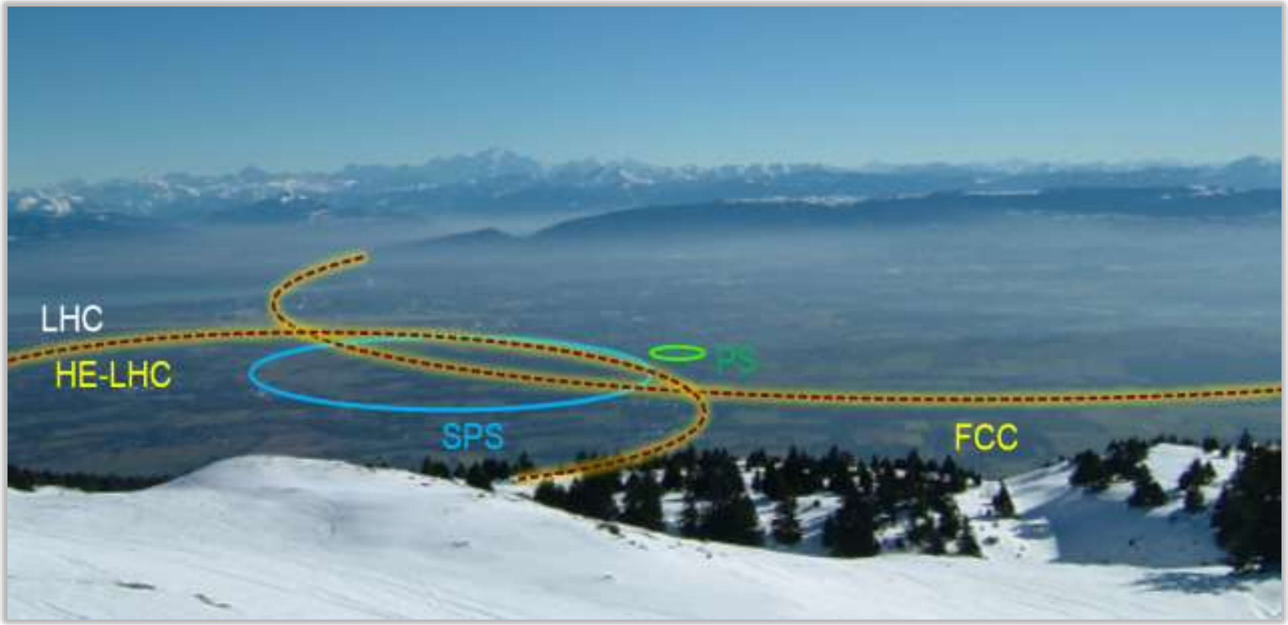


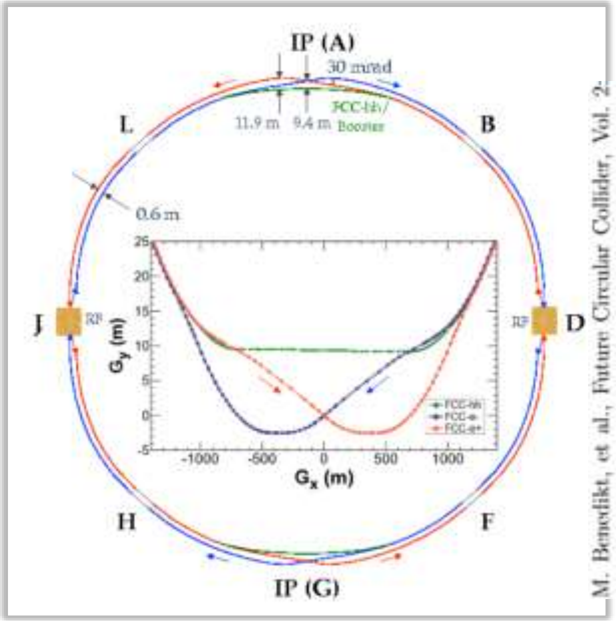
Linear Colliders *e+e-* Higgs Factories

- ***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. <= LHC)
- ***Challenges:***
  - LC luminosity < ring (e.g., FCC-ee), upgrades at the cost:
    - e.g. factor of 4 for ILC: *x2* $N_{bunches}$ and *5 Hz → 10 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)





Key facts:

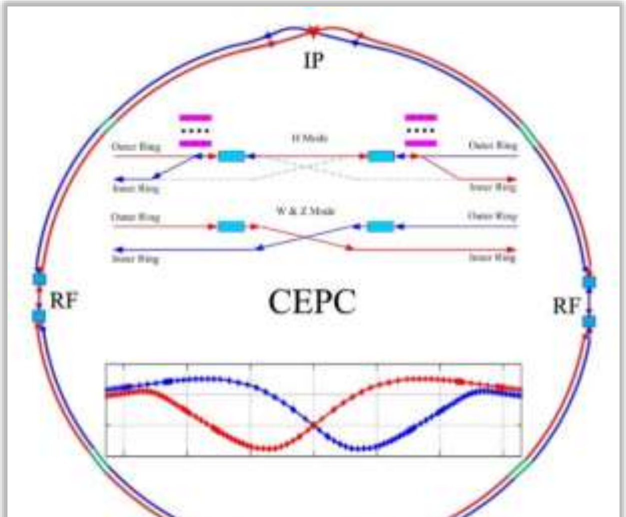
100 km tunnel, three rings (*e*-, *e*+, booster)

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*)

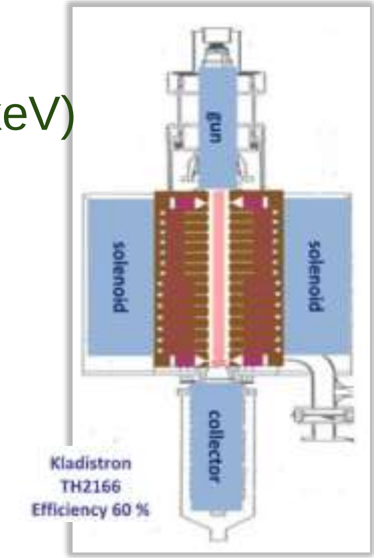


CepC CDR

arXiv:1809.00285

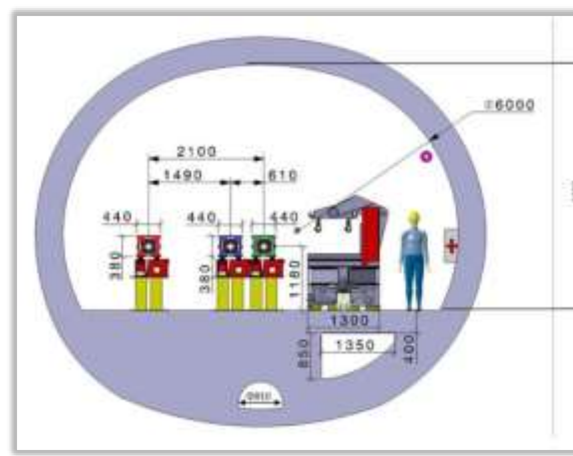
e+e- Ring Higgs Factories

- ***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 (τ~ 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*



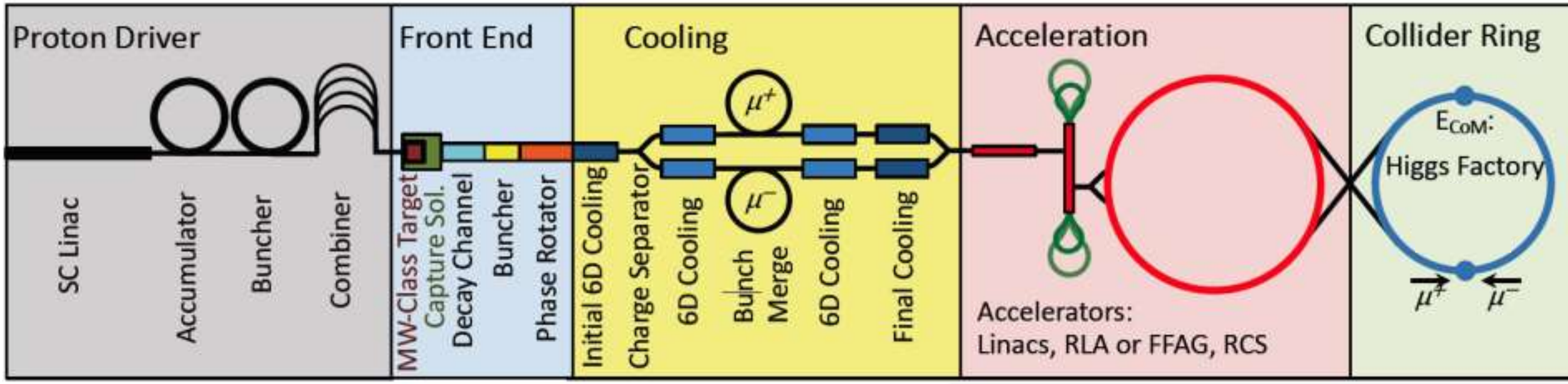
Challenges (R&D needs):

- High efficient RF sources:
  - Klystron 400/800 MHz η from 65% to >85%
- High efficiency SRF cavities:
  - 20-25 MV/m and Q_0 ~(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



μ+μ- 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 x 63 GeV $\mu+\mu- \rightarrow H_0$

Small footprint (<6 km) and low cost

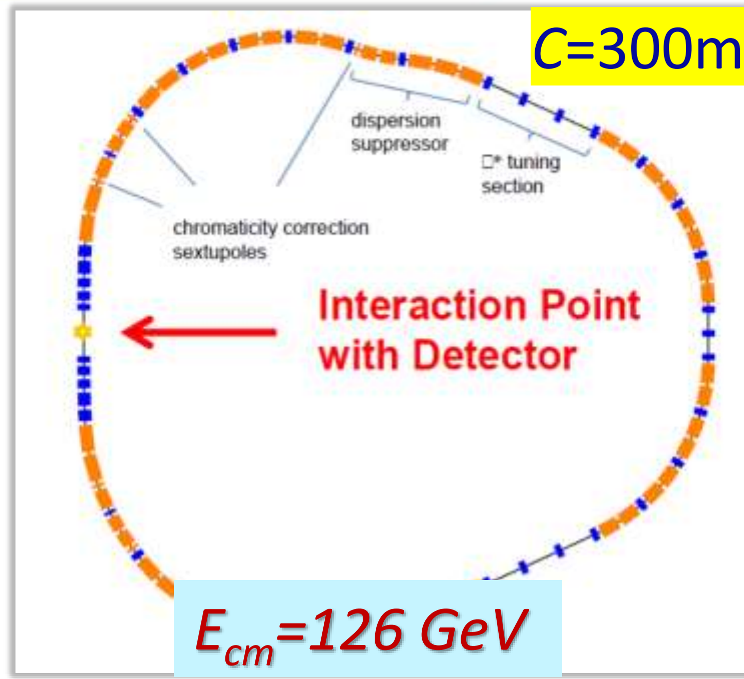
Small(est) energy spread ~3 MeV

Total site power ~200MW

Challenges (many…)

Muon production, cooling, acceleration

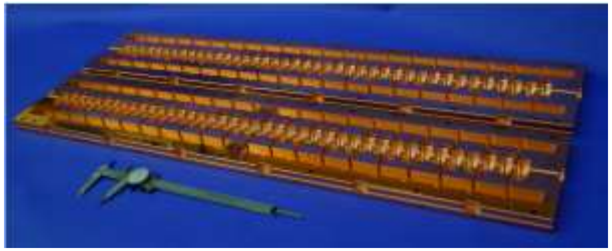
Pushing RF, magnets and targets limits

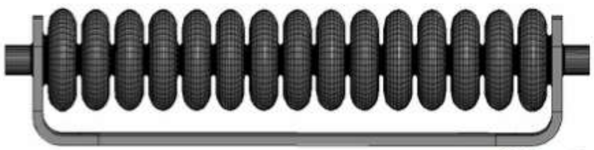


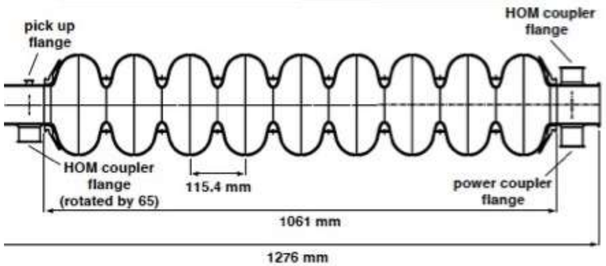
arXiv:1502.02042

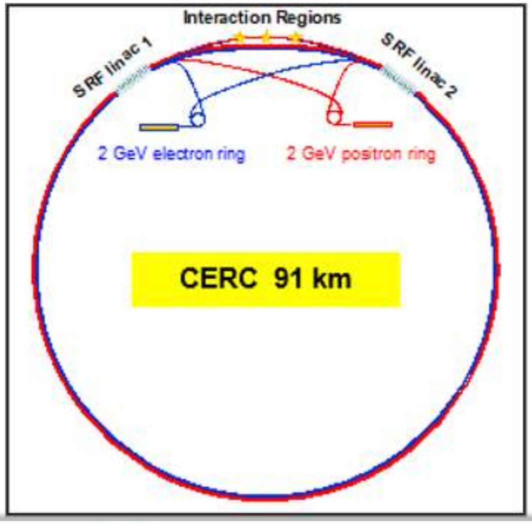
HF: New Approaches

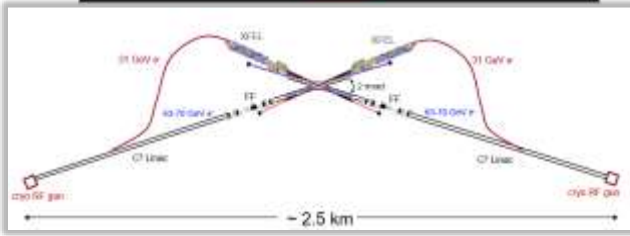
- C^3: Cool Copper Collider
  - 72-150 MV/m, 5.7 GHz, 77K copper structures
    - Advance beyond NLC (65MV/m) and CLIC (100MV/m)
    - Needs R&D and viability demonstration
    - Needs complete and self-consistent design
- HELEN: High Energy LEptoN collider
  - 70 MV/m, 1.3 GHz, 2 K Nb structures (Nb3Sn?)
    - 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- → γ 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



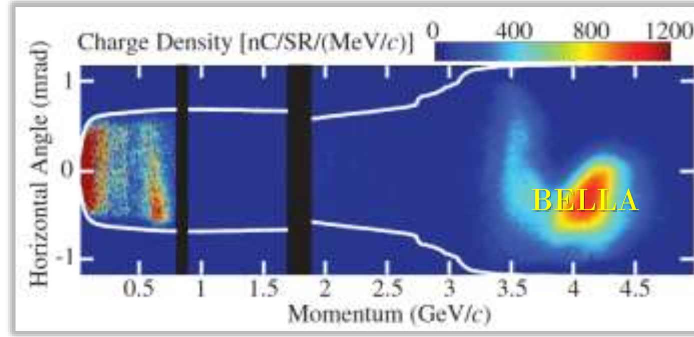








Plasma Wakefield LCs

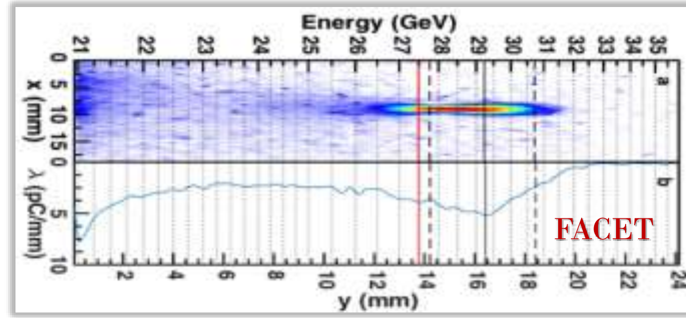


Key facts:

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

Impressive proof-of-principle demos

In principle, feasible for *e+e-* collisions



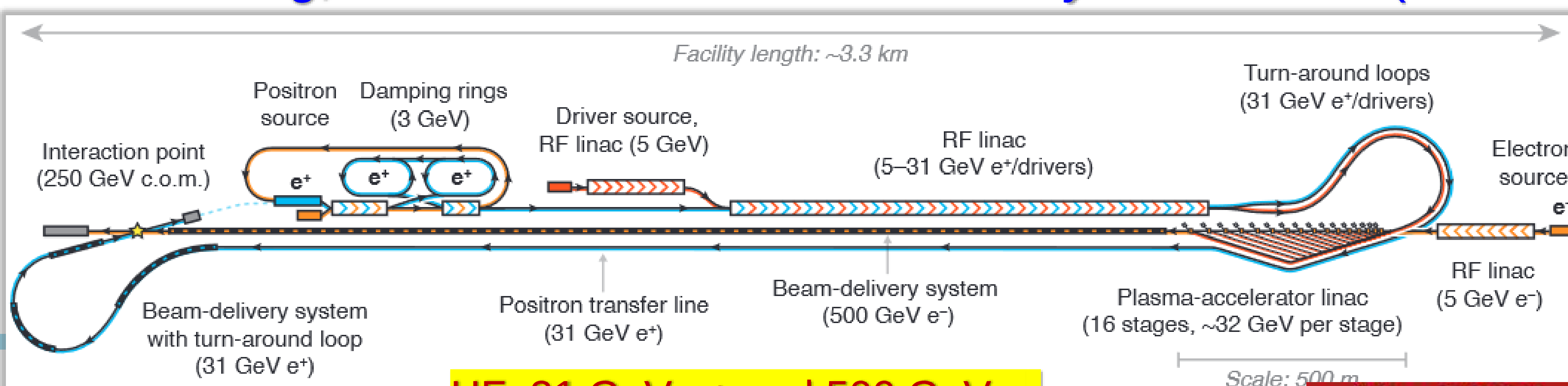
Many challenges:

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

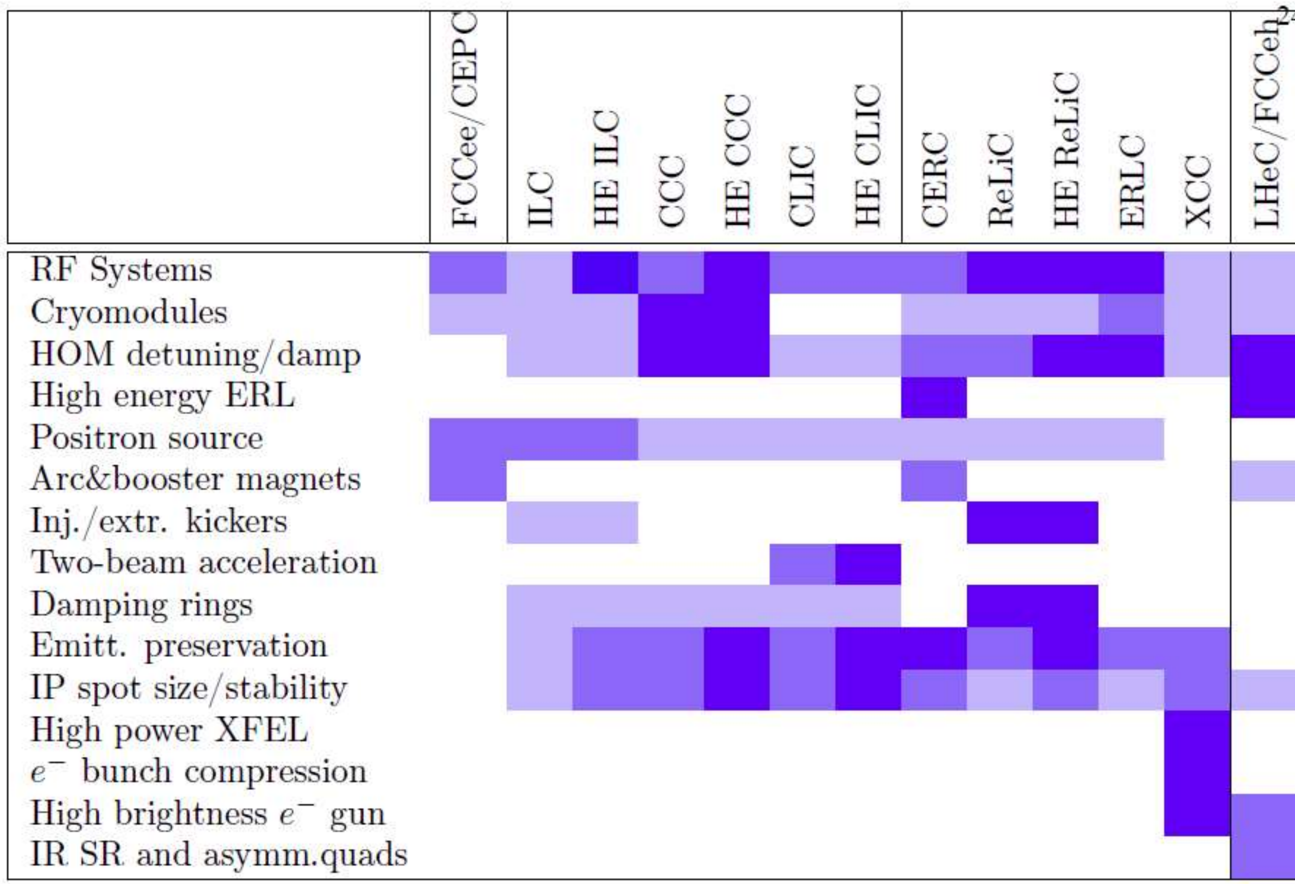
	Snowmass 2021	CME (TeV)	Lumi per IP/ tot (10^34)	Years, pre-project R&D	Years to 1st Physics	Cost Range (2021 B$)	Electric Power (MW)
Circular *e+e-*	FCCee (4 IPs)	0.24	7.7/29	0-2	13-18	12-18	290
	CEPC (2 IPs)	0.24	8.3/17	0-2	13-18	12-18	340
	FermiHF	0.24	1.2	3-5	13-18	7-12	~200
Linear *e+e-*	ILC	0.25	2.7	0-2	<12	7-12	110
	CLIC	0.38	2.3	0-2	13-18	7-12	150
	C^3	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-γγ	0.125	0.1	5-10	19-24	4-7	90
	μμ-Higgs	0.13	0.01	>10	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.



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
SuperKEKB	Japan	7+4 Gev *e+e-*, 8e35	nano-beams scheme, IR/MDI
HL-LHC	CERN	x5 LHC luminosity	Nb_3Sn IR magnets, crab cavities, MDI
PIP-II	USA	SRF linac to double # ν's	CW SRF, ~2 MW targets, RF sources
LCLS-II-HE	USA	8 GeV CW SRF	efficient SRF, cryo
EIC	USA	20-140 GeV *ep/ei*	IR/MDI, magnets, polarization, cool
NICA	Russia	*ii/pp* 11-27 GeV	e- & stoch cool, fast SC magnets
ESS	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 Q0 = (3→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 *ttbar*
   - 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, ~1s 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 (~16T, 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.*