On Assessment of Luminosity and Power Challenges of Future Higgs/EW factories

Vladimir Shiltsev (Fermilab)

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Higgs factory summary table ..from Snowmass ITF report[7]

- Main parameters of the submitted Higgs factory proposals.
- The cost range is for the single listed energy.
- The superscripts next to the name of the proposal in the first column indicate:
  - (1) Facility is optimized for 2 IPs. Total peak luminosity for multiple IPs is given in parenthesis;
  - (2) Energy calibration possible to 100 keV accuracy for MZ and 300 keV for MW ;
  - (3) Collisions with longitudinally polarized lepton beams have substantially higher

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
FCC-ee[1,2]	0.24 (0.09-0.37)	7.7 (28.9)	0-2	13-18	12-18	290
CEPC[1,2]	0.24 (0.09-0.37)	8.3 (16.6)	0-2	13-18	12-18	340
ILC[3] - Higgs factory	0.25 (0.09-1)	2.7	0-2	<12	7-12	140
CLIC[3] - Higgs factory	0.38 (0.09-1)	2.3	0-2	13-18	7-12	110
CCC[3] (Cool Copper Collider)	0.25 (0.25-0.55)	1.3	3-5	13-18	7-12	150
CERC[3] (Circular ERL Collider)	0.24 (0.09-0.6)	78	5-10	19-24	12-30	90
ReLiC[1,3] (Recycling Linear Collider)	0.24 (0.25-1)	165 (330)	5-10	>25	7-18	315
ERLC[3] (ERL linear collider)	0.24 (0.25-0.5)	90	5-10	>25	12-18	250
XCC (FEL-based $\gamma\gamma$ collider)	0.125 (0.125-0.14)	0.1	5-10	19-24	4-7	90
Muon Collider Higgs Factory[3]	0.13	0.01	>10	19-24	4-7	200

NB: luminosity and power consumption values as provided by proponents

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Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
High Energy LeptoN (HELEN) e^+e^- colider	0.25 (0.09-1)	1.4	5-10	13-18	7-12	~110
e^+e^- Circular Higgs Factory at FNAL	0.24 (0.09-0.24)	1.2	3-5	13-18	7-12	~200

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

Power and Luminosity Concerns

- **Common**
  - What are the power/energy consumption limits for future facilities - 200 MW? 1 TWh/yr?
  - Or primary concerns are electricity cost and CO_2 footprint?
  - Total(integrated) MW/TWh/yr of “per Higgs particle”?
  - (so far muted) machine commissioning time and availability
- **Q’s depending on approach:**
  - **Circular ee:** used to be considered “well understood”, but the Super-KEKB lumi progress shows that there are many “unknown unknowns” at the luminosity frontier
  - **Linear ee/$\gamma\gamma$:** past experience of the SLC is not fully assuring, present machines (XFEL, LSLS-II) are not colliders – different specs; future LC *P* and *L* exhibited big variations recently
  - **Circular and linear ERL-based:** how “real” are claimed benefits? What are the recirculation efficiency limits? Nowadays currents and powers are 3 order of magnitude off…

Limits on *Luminosity*

- General Equation

$$L = f_0 n_b N^2 / 4\pi\sigma^2$$

  - *sheer beam power*

$$\boxed{P_b = f_0 n_b N \gamma m c^2}$$

  - *Rings SR power*

$$L \propto (\xi/\beta^*)(P_{SR}/2\pi R)(R^2/\gamma^3))$$

  - *LC power, BS, jitter*

$$L \propto (P/E)(N_\gamma/\sigma_y)$$

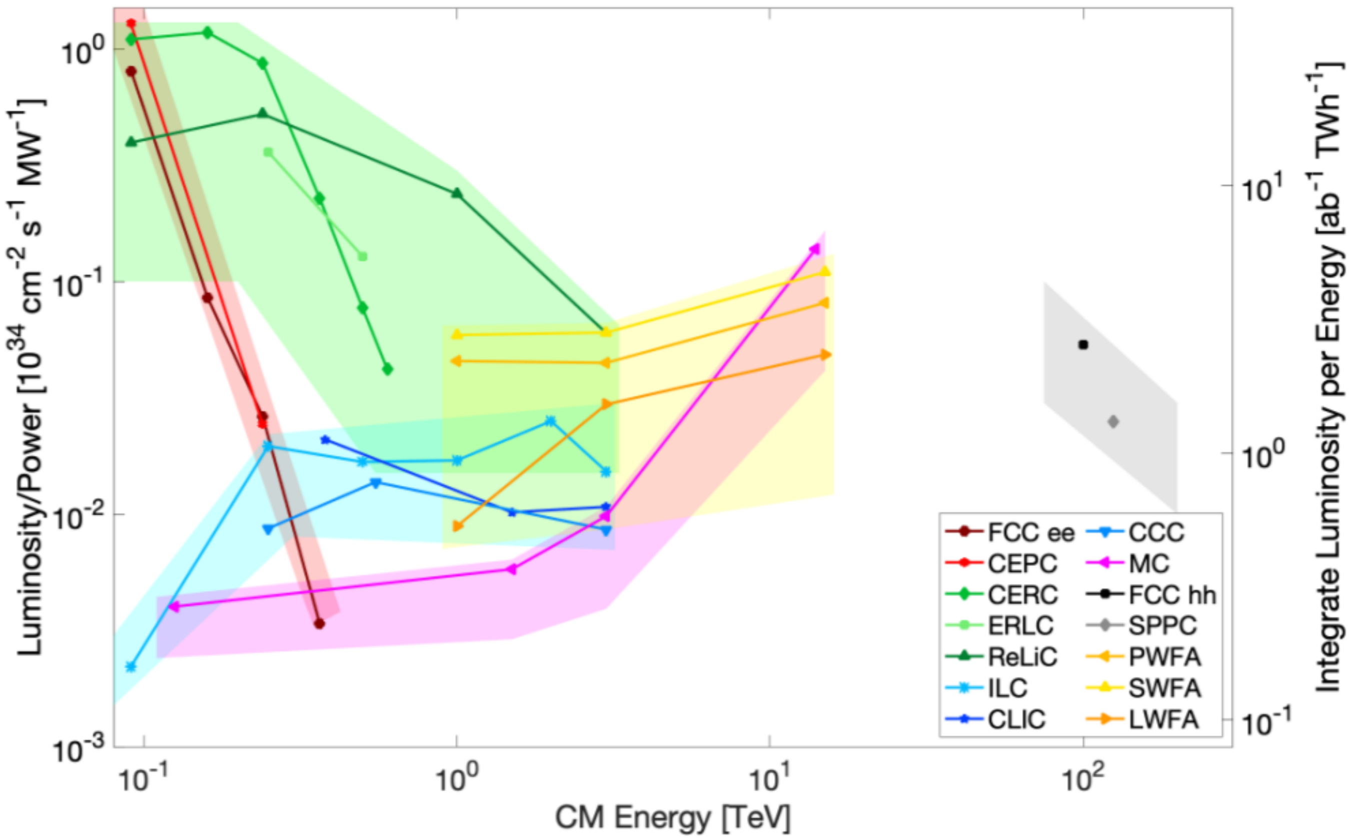
  - *ERL lumi*

$$\boldsymbol{L = L_{\text{ring or LC}} \cdot R_{\text{gain factor}}}$$

Luminosity per Power

Circular *ee*	ERL based *ee*	Linear *ee*	Muon coll	Wakefield	Hadron *pp*

- Figure-of-merit Peak Luminosity (per IP) per Input Power and Integrated Luminosity per TWh.
- Integrated luminosity assumes 10^7 seconds per year.
- The luminosity is per IP.
- Data points are provided to the ITF by proponents of the respective machines.
- The bands around the data points reflect approximate power consumption uncertainty for the different collider concepts.



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

Remaining topic to be addressed by the accelerator community is evaluation of possible ranges in both luminosity and power consumption values.

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"Ranges of Certainty"

- **Factor 1 - Power**
  - If the facility power $\boldsymbol{P_{tot}}$ is limited, what is beam/SR power $\boldsymbol{P_b}$ available?
  - What is the range of certainty $\boldsymbol{x} = \boldsymbol{P_p} / \boldsymbol{P_{tot}}$
- **Other factors:**
  - **Circular ee:** *beam-beam / beta** - how stretched are those? What can be done?
  - **Linear ee/γγ:** N_γ*/sigma_y* - how stretched are those? What can be done?
  - **Circular and linear ERL-based:** is there good understanding of the gain due to energy recovery $\boldsymbol{R}_{\text{gain factor}}$?

HEP Community Inquiry

"Kind of a charge" (request) from the Snowmass:
"…take a look at the luminosity and power consumption projections for various ee-Factories and provide "expert comparative evaluation" for them. Such "independent" evaluation would be very helpful."

Outcomes of these discussions at the eeFACT'22 can (still) be captured in the *Snowmass Topical Group AF3 "Higgs/EW factories"* report:

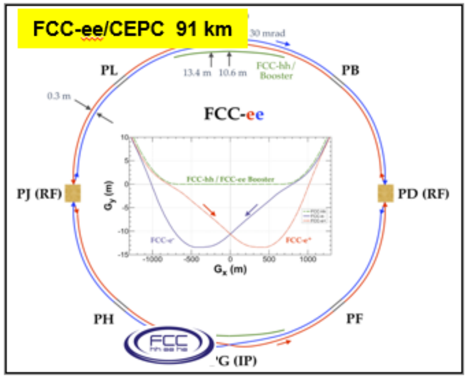
- A.Faus-Golfe, G.Hoffstadter, Q.Qin, F.Zimmermann
- v.1 https://arxiv.org/abs/2209.05827 → v.2

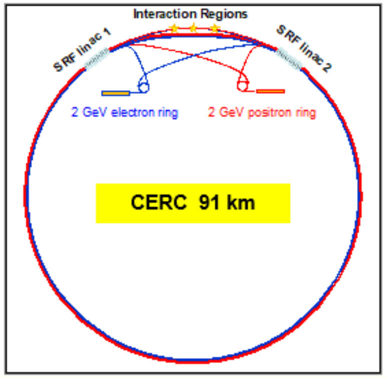
Back up slides

Proposals – Higgs/EW Physics

Higgs factory concepts (10)

Name	CM energy range
FCC-ee	e+e-, $\sqrt{s} = 0.09 - 0.37$ TeV
CEPC	e+e-, $\sqrt{s} = 0.09 - 0.37$ TeV
ILC (Higgs factory)	e+e-, $\sqrt{s} = 0.09 - 1$ TeV
CLIC (Higgs factory)	e+e-, $\sqrt{s} = 0.09 - 1$ TeV
CCC (Cool Copper Collider)	e+e-, $\sqrt{s} = 0.25 - 0.55$ TeV
CERC (Circular ERL collider)	e+e-, $\sqrt{s} = 0.09 - 0.60$ TeV
ReLiC (Recycling Linear Collider)	e+e-, $\sqrt{s} = 0.25 - 1$ TeV
ERLC (ERL Linear Collider)	e+e-, $\sqrt{s} = 0.25 - 0.50$ TeV
XCC (FEL-based $\gamma\gamma$ collider)	ee ($\gamma\gamma$), $\sqrt{s} = 0.125 - 0.14$ TeV
MC (Higgs factory)	$\mu+\mu-$, $\sqrt{s} = 0.13$ TeV





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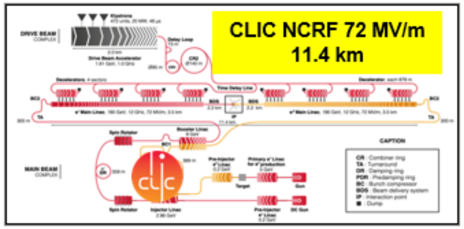

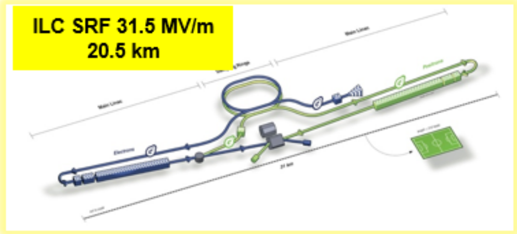

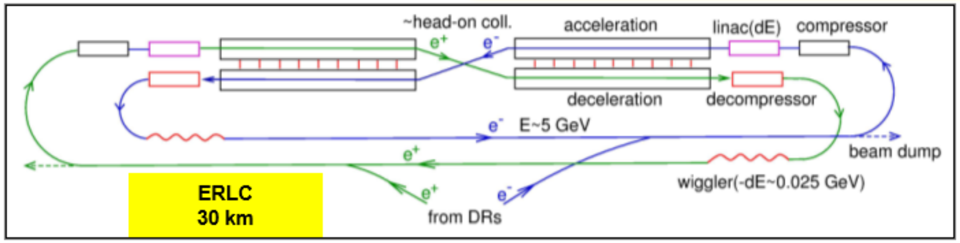

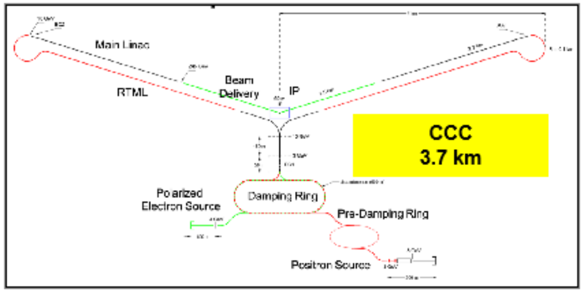

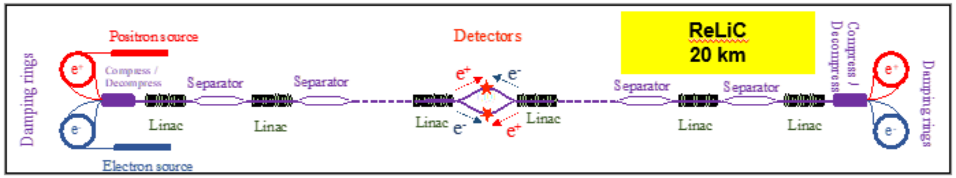

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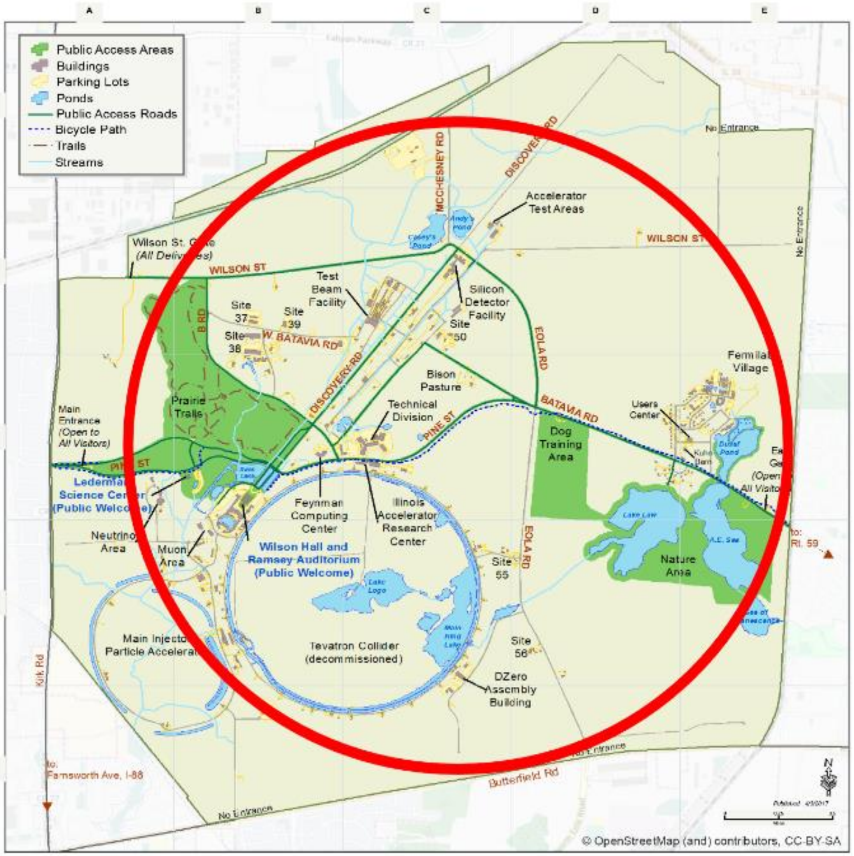
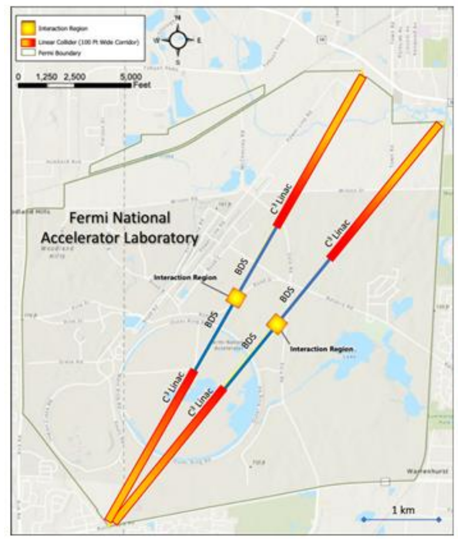
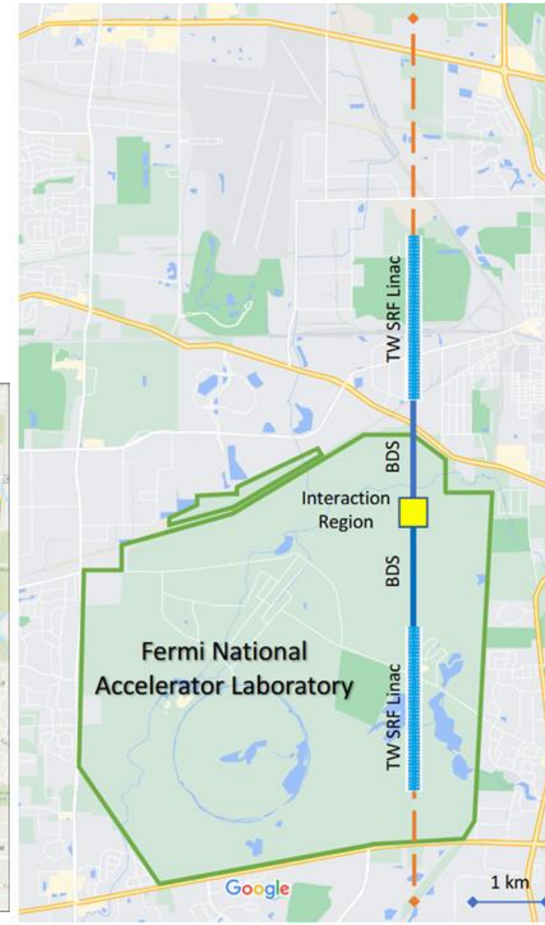
250 GeV cme Fermilab Site-Fillers





CCC

HELEN



16-km collider e+e- ring

https://arxiv.org/abs/2203.08088

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

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ITF's Look Beyond Higgs Factories

	CME (TeV)	Lumi per IP (10^34)	Years, pre-project R&D	Years to 1st Physics	Cost Range (2021 B$)	Electric Power (MW)
FCCee-0.24	0.24	8.5	0-2	13-18	12-18	280
ILC-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC-0.38	0.38	2.3	0-2	13-18	7-12	110
HELEN-0.25	0.25	1.4	5-10	13-18	7-12	110
CCC-0.25	0.25	1.3	3-5	13-18	7-12	150
CERC(ERL)	0.24	78	5-10	19-24	12-30	90
CLIC-3	3	5.9	3-5	19-24	18-30	~550
ILC-3	3	6.1	5-10	19-24	18-30	~400
MC-3	3	2.3	>10	19-24	7-12	~230
MC-10-IMCC	10-14	20	>10	>25	12-18	O(300)
FCChh-100	100	30	>10	>25	30-50	~560
Collider-in-Sea	500	50	>10	>25	>80	»1000

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

Factors and Limits

- Main factors to consider feasibility of future colliders used to be
  - Feasibility of ***E***nergy
  - Feasibility of ***L***uminosity
  - Feasibility of ***C***ost
- The *European Strategy* (2019) and *Snowmass'21* discussions revealed additional limits:
  - ***Time*** to construct and commission
  - ***Societal limits***: # of experts, size of facility, radiation, etc
  - ***Environmental impacts***: power consumption, carbon footprints, scarcity of resources (*He*, *Nb*, *W*, etc), excavated materials, etc

Here we will only briefly touch some important points

Limits on Energy

- Synchrotron radiation defines linear vs circular if $U_{SR} < E$

$$U_{SR} = C_\gamma \frac{E^4}{\rho} = 88.46 \frac{\mathrm{r_0}}{\mathrm{r_e}} \left(\frac{\mathrm{m_e}}{\mathrm{m_0}}\right)^3 \frac{E^4[GeV]}{\rho[m]}$$

- for e-/e+: $E_{cm} \leq 500\ GeV \left(\frac{\rho}{10km}\right)^{\frac{1}{3}}$
- for muons: $E_{cm} \leq 600\ TeV \left(\frac{\rho}{10km}\right)^{\frac{1}{3}}$
- for protons: $E_{cm} \leq 10\ PeV \left(\frac{\rho}{10km}\right)^{\frac{1}{3}}$

- Production and survival: unstable particles such as muons

$$\frac{dN}{dt} = -\frac{\mathrm{N}}{\gamma\tau_0};\ \gamma = \gamma_i + z\frac{d\gamma}{dz}$$

where τ_0 is the lifetime, $\tau_0 \sim 2.2\mu s$ for muons… requires fast acceleration

for muons $G \gg 3\ \mathrm{MeV\ m^{-1}}$

for τ-leptons $G \gg 0.3\ \mathrm{TeV\ \ m^{-1}}$

- Staging efficiency (losses) per stage for M stages ≥ $\eta = 1 - 1/M$

- Technology within limited space /area:

Circumference 100 km , B<16 T , ***E*<50 TeV**
Circumference 40,000 km, B=1 T, ***E*<1.3 PeV**
Length 50 km , G<0.1 GV/m, ***E*<5 TeV**
Length 10 km, G<1 TV/m, ***E*<10 PeV**

Limits on *Luminosity* (some)

- General Equation

$$L = f_0 n_b N^2 / 4\pi\sigma^2$$

  - *sheer beam power*

$$P_b = f_0 n_b N \gamma m c^2$$

$$L = P_b^2 / (4\pi\gamma n_b \varepsilon \beta^* m^2 c^4) \propto P_b^2 / E$$

  - *e/p SR rad. power*

$$L \propto (\xi/\beta^*)(P_{SR}/2\pi R)(R^2/\gamma^3))$$

  - *μ→ν radiation dose*

$$D \propto (dN/dt)E^3/\Phi$$

flux dilution factor

$$L \propto B \frac{D\Phi}{E^2} \frac{N}{4\pi\epsilon_n\beta^*}$$

  - *LC power, BS, jitter*

$$L \propto (P/E)(N_\gamma/\sigma_y)$$