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# POWER BUDGETS AND PERFORMANCE CONSIDERATIONS FOR FUTURE HIGGS FACTORIES*

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*Abstract*

A special session at eeFACT'22 reviewed the electrical power budgets and luminosity risks for eight proposed future Higgs and electroweak factories ($C^3$, CEPC, CERC, CLIC, FCC-ee, HELEN, ILC, and RELIC) and, in comparison, for a lepton-hadron collider (EIC) presently under construction. We report highlights of presentations and discussions.

## INTRODUCTION

During the Snowmass Community Summer Study in Seattle [1], questions arose on the feasibility of power and luminosity numbers communicated for various collider proposals. The Accelerator Frontier Implementation Task Force (ITF) had received many inputs on various collider concepts and just released their evaluation report [2]. While many comparative evaluations were extremely helpful and welcome, the ITF specifically mentioned that they had not reviewed luminosity and power consumption projections (i.e., they used proponents' numbers of luminosity and power).

The following ICFA Workshop eeFACT'22, organized at Frascati in September 2022, was charged with helping the broader accelerator and HEP community by taking a look at the luminosity and power consumption projections for various $e^+e^-$ Higgs factories and providing an "expert comparative evaluation" for them [3]. Given the strength of the cohort of anticipated participants, such "independent" evaluation was expected to be very helpful.

For this purpose, a special session was set up during eeFACT'22 [4], where representatives from all major proposals were invited to present and discuss their respective numbers and the underlying assumptions [3].

## POWER CONSUMPTION

The power consumption estimates, including the underlying assumptions and level of completeness and maturity, differ significantly between proposals. The special session at eeFACT'22 [4], addressed this theme, with pertinent brief presentations from all $e^+e^-$ Higgs and Electroweak Factory proposals. The eeFACT'22 discussions and presentations [3, 5–12], resulted in the power budgets compiled in Table 2.

For CEPC, the 260 MW power required for the Higgs factory operation is significantly lower than the value of 340 MW, which had been submitted to the ITF.

The annual power consumption in TWh numbers does not look fully consistent across various machines. As an example, for the FCC-ee, the annual power consumption is higher than the product of instantaneous power and effective physics time, since power needs during annual hardware commissioning, beam commissioning, operational downtimes, technical stops, machine development periods and shutdowns are also taken into account [13], as sketched in Table 1.

Table 1: Electrical power consumption for FCC-ee at 240 GeV c.m. energy [13] (slightly adapted), yielding a total of 1.52 TWh per year.

| Mode | # days | Power [MW] |
|---|---:|---:|
| beam operation | 143 | 301 |
| downtime operation | 42 | 109 |
| h.w. & beam commissioning | 30 | 139 |
| machine development | 20 | 177 |
| technical stop | 10 | 87 |
| shutdown | 120 | 61 |

We note that this was the first attempt to get a detailed comparative accounting of the power consumption needs, that several numbers are still missing for CERC, $C^3$, RELIC, etc., and that some of the numbers have not been fully critically assessed. Hence, this comparative analysis will need to be continued.

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Table 2: Electrical power budgets for the proposed Higgs and Electroweak factory colliders, and, for comparison the EIC, based on invited contributions to the special session at eeFACT'22 [4]. NI: Not Included; NE: Not Estimated; –: Not Existing. ‡ILC parameters correspond to the luminosity upgrade. The total ILC power includes 4 MW margin, the one for HELEN 3.3 MW (here as part of the general services). *For HELEN, the "detector" number refers to the power required for the beam delivery system, machine detector interface, interaction region, and beam dumps, the "injector magnets" number to damping ring with wigglers. †For RELIC, the 2.5 GeV damping rings and transfer lines would use permanent magnets.

| **Proposal** | **CEPC** | | **FCC-ee** | | **CERC** | | **C$^3$** | **HELEN** | **CLIC** | **ILC‡** | **RELIC** | | **EIC** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Beam energy [GeV] | 120 | 180 | 120 | 182.5 | 120 | 182.5 | 125 | 125 | 190 | 125 | 120 | 182.5 | 10 or 18 |
| Average beam current [mA] | 16.7 | 5.5 | 26.7 | 5 | 2.47 | 0.9 | 0.016 | 0.021 | 0.015 | 0.04 | 38 | 39 | 0.23–2.5 |
| Total SR power [MW] | 60 | 100 | 100 | 100 | 30 | 30 | 0 | 3.6 | 2.87 | 7.1 | 0 | 0 | 9 |
| Collider cryo [MW] | 12.74 | 20.5 | 17 | 50 | 18.8 | 28.8 | 60 | 14.43 | – | 18.7 | 28 | 43 | 12 |
| Collider RF [MW] | 103.8 | 173.0 | 146 | 146 | 57.8 | 61.8 | 20 | 24.80 | 26.2 | 42.8 | 57.8 | 61.8 | 13 |
| Collider magnets [MW] | 52.58 | 119.1 | 39 | 89 | 13.9 | 32 | 20 | 10.40 | 19.5 | 9.5 | 2 | 3 | 25 |
| Cooling & ventil. [MW] | 39.13 | 60.3 | 36 | 40 | NE | NE | 15 | 10.50 | 18.5 | 15.7 | NE | NE | 5 |
| General services [MW] | 19.84 | 19.8 | 36 | 36 | NE | NE | 20 | 6.00 | 5.3 | 8.6 | NE | NE | 4 |
| Injector cryo [MW] | 0.64 | 0.6 | 1 | 1 | NE | NE | 6 | 1.96 | 0 | 2.8 | NE | NE | 0 |
| Injector RF [MW] | 1.44 | 1.4 | 2 | 2 | NE | NE | 5 | 0* | 14.5 | 17.1 | 192 | 196 | 5 |
| Injector magnets [MW] | 7.45 | 16.8 | 2 | 4 | NE | NE | 4 | 13.07* | 6.2 | 10.1 | 0† | 0† | 5 |
| Pre-injector [MW] | 17.685 | 17.7 | 10 | 10 | NE | NE | – | 13.37 | – | – | NE | NE | 10 |
| Detector [MW] | 4 | 4.0 | 8 | 8 | NE | NE | NE | 15.97* | 2 | 5.7 | NE | NE | NI |
| Data center [MW] | NI | NI | 4 | 4 | NE | NE | NE | NI | NI | 2.7 | NE | NE | NI |
| Total power [MW] | 259.3 | 433.3 | 301 | 390 | 89 | 122 | 150 | 110.5 | 107 | 138 | 315 | 341 | 79 |
| Lum./IP [$10^{34}$ cm$^{-2}$s$^{-1}$] | 5.0 | 0.8 | 7.7 | 1.3 | 78 | 28 | 1.3 | 1.35 | 2.3 | 2.7 | 200 | 200 | 1 |
| Number of IPs | 2 | 2 | 4 (2) | 4 (2) | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 1 (2) |
| Tot. integr. lum./yr [1/fb/yr] | 1300 | 217.1 | 4000<br>(2300) | 670<br>(340) | 10000 | 3600 | 210 | 390.7 | 276 | 430 | 79600 | 79000 | 145 |
| Eff. physics time / yr [$10^7$ s] | 1.3 | 1.3 | 1.24 | 1.24 | 1.3 | 1.3 | 1.6 | 2.89 | 1.2 | 1.6 | 2 | 2 | 1.45 |
| Energy cons./yr [TWh] | 0.9 | 1.6 | 1.51 | 1.95 | 0.34 | 0.47 | 0.67 | 0.89 | 0.6 | 0.82 | 2 | 2.2 | 0.32 |

# PERFORMANCE CONSIDERATIONS

## *C$^3$ [5]*

The design of and performance projections for C$^3$ look solid – The performance of the proposed modules, including realistic average gradient and cryogenic power required, is still to be demonstrated.

## *CERC [6]*

CERC assumes cavity $Q$ values of $10^{11}$, which are a little higher than the present state of the art. Emittance preservation over 100s of kilometer at values smaller than for CLIC needs to be shown in simulations including alignment errors, wake fields, and optical corrections. The burnoff of particles at the high target luminosity due to radiative Bhabha scattering and beamstrahlung may be much higher than the assumed loss rate, which also means that a more powerful positron source might be required. The possible impact on overall power consumption is to be examined.

## *RELIC [6]*

RELIC also assumes cavity $Q$ values of $10^{11}$, and a "real-estate" gradient of 12.5 MV/m in the linac sections (excluding spreaders and combiners). Such a gradient either has already been demonstrated or is close to demonstrated values. The evolution, manipulation and optimisation of the energy spread in the linac and of the bunch length in the arcs and in the interaction region probably require more studies. The electric power estimates should undergo a proper engineering evaluation.A complete accelerator and interaction-region design, validated by particle tracking, is also required to confirm the assumed particles losses. As for CERC, the luminosity related burnoff due to radiative Bhabha scattering and beamstrahlung will need to be compensated by newly injected positrons and electrons.

## *FCC-ee [7]*

Achieved klystron efficiency is typically lower than targeted. An R&D plan has been established. A faster R&D program is executed for the twin project CEPC in China. To preserve and reuse energy, FCC is studying a waste heat management system. Two other possible energy-saving measures for FCC-ee were pointed out during the discussion [14]: (1) Energy recovery from the fast ramping booster should be considered. (2) Magnet design & magnet powering should be optimized to minimize the cable losses.

## *CEPC [8]*

The CEPC design is similar to FCC-ee. CEPC is supported by an impressive R&D effort including massive hardware prototyping, comprising SRF cavities, cryomodules, high-efficiency klystrons, collider magnets, booster dipoles, and combinations of electrostatic separators with weak magnets for beam separation and combination, with an ambitious timeline. Earliest start of tunnel construction is in 2026.

## *CLIC [9]*

The CLIC project aims for a 10 micron alignment over 200 m distance. The CLIC studies include using renewable energy sources, at about 10% of the project cost. CLIC operation would reduce CERN energy consumption by a factor 2 from the current level.

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### *ILC [10]*

The ILC has published its Technical Design Report in 2013 and is technically ready to enter an engineering design phase followed by start of construction after four years. Presently, an ILC Technology Network (ITN) is being set up to conduct further R&D on high priority items, in particular economisation of cavity and cryomodule production, positron source and the main beam dump.

Concerning the beam energy, the most important issue is achieving a sufficient average acceleration gradient with sufficient margin in beam operation. ILC design parameters have been demonstrated for industrially produced cavities [15] and cryomodules [16]. Production and operating experience from E-XFEL [17–19] and LCLS-II [20] will provide valuable input during the ITN and Engineering Design phase. Differences between the ILC and E-XFEL cryomodule designs such as a power distribution system with variable splitters will facilitate operation at maximum gradient.

Achieving the necessary accelerating gradient will be ensured by rigorous Quality Assurance during production; a 10 % overproduction of cavities is foreseen for a selection of cavities that meet the specifications. Based on the E-XFEL production experience [21] there is high confidence that projected yield and associated cost for overproduction can be achieved.

As for the luminosity performance, the critical issues concern beam intensity limitations (in particular positron source and main dumps), beam damping (damping ring design), low emittance beam transport (damping ring extraction kickers), final focussing (feedback, overall focus design) and availability. Issues connected to individual components such as kickers or the rotating positron source target will be addressed in the ITN phase by prototyping or engineering designs (main dumps).

To ensure performance of larger systems such as the damping rings or the final focus system, simulations and tests at dedicated test facilities have been conducted. These activities are planned to be continued by the ITN, e.g., at the Accelerator Test Facility [22] at KEK.

At eeFACT'22, it was suggested that the SRF target values for ILC be benchmarked against the performance of operating machines such as E-XFEL and LCLS-II, in particular the SRF gradients, static heat loads, and cryoplant efficiency. Understanding the operational performance of the E-XFEL and LCLS-II is important for a future Higgs factory, like ILC or HELEN, which will need to reach the desired energy without tripping off too often.

### *HELEN [11]*

The HELEN approach makes use of recent advances in the SRF technology (high gradient travelling wave structures and high $Q$ values) and looks promising. This modified design could also be an attractive option for the ILC. In the discussion, questions were raised about traveling wave phase stability.

### *EIC [12]*

The EIC, now under construction, offers a valuable benchmark for the power consumption budgets.

## STATIC HEAT LOADS

Concerning static heat loads, the best values from LCLS-II cryomodules are reported to be 5 times larger than those which had been assumed for the ILC. Based on operational experience, the 2-K static heat load per 8-cavity cryomodule is expected to be about 11 W for LCLS-II-HE [20], which is about two times higher than the value of 6 W estimated for LCLS-II in 2014 [23], and an order of magnitude higher than the static heat load per cryomodule of 1.32 W at 2 K, which had been predicted for the ILC in 2017 [24].

LCLS-II may still have some cryogenic issues to resolve. A more appropriate comparison is with the European E-XFEL. For this E-XFEL, a static heat load of 6.1 W was measured per linac cryomodule [19]. Consequently, in the latest ILC estimates, a static heat load of 6 W per cryomodule is assumed, consistent with actual E-XFEL experience [25].

## CRYO EFFICIENCY

The cryoplant efficiencies at various existing facilities, like LHC, JLAB, and SLAC can be compared with the target efficiency for future projects. The LHC cryoplant efficiency at 1.9 K is 900 W/W (that is the number of Watt at room temperature required for removing one Watt at 1.9 K) [26]. For a proposed 8 GeV SC proton linac at Fermilab a cryo efficiency at 2 K of 790 W/W is considered [27]. The ILC will further improve the 2-K cryoplant efficiency to 700 W/W [28].

## COLLISION SPOT SIZE

As for the final focus – the difference of the vertical spot size observed at the KEK/ATF-2 facility from the expected value, especially at nominal $\beta_x^*$, and its dependence on bunch intensity, resembles earlier findings at the SLC [29, 30] and at the FFTB [31]. The present ATF-2 optics is much relaxed compared with the design, which should greatly lower the optical aberrations. The ATF-2 would offer an opportunity to characterize the higher-order aberrations with beam and to compare them with model predictions.

## POSITRON NEEDS

The Snowmass Implementation Task Force performed a review of the positron needs according to the proponents [32]. For single-pass linear colliders, like ILC and CLIC, the total rate of positrons required equals the number of particles collided per second. For circular colliders, positrons are unavoidably lost due to radiative Bhabha scattering, determined by the luminosity with little dependence on the momentum aperture, as well as due to beamstrahlung along with a limited dynamic aperture. The importance of the beamstrahlung strongly depends on the off-momentum dynamic acceptance and on several beam parameters. Also for ERL-based colliders the radiative Bhabha scattering, together with beamstrahlung, determines the minimum rate of new positrons required. The differential cross section for radiative Bhabha scattering is [33]

$$\frac{d\sigma}{dk} = \frac{4r_e^2\alpha}{k}\left[\frac{4}{3}-\frac{4}{3}k+k^2\right]\left(2\ln(2\gamma)+\ln\frac{1-k}{k}-\frac{1}{2}\right) , \tag{1}$$

where $r_e$ the classical electron radius, $\alpha$ the fine-structure constant, $k = E_\gamma/E_b$, $\gamma = E_b/(m_e c^2)$ and $E_b$ the beam energy.

The total cross section for a particle loss after a single scattering is [33]

$$\sigma = \int_{k_{\min}}^{k_{\max}} \frac{d\sigma}{dk}\, dk , \tag{2}$$

with $k_{\min}$ corresponding to photon energies at the energy aperture ($\sim 2\%$) and $k_{\max} \approx 1$. In addition, Burkhardt and Kleiss [33] introduced a cut-off in the momentum transfer, on an event by event basis, at $q_{\min} = \hbar/d$ with $d$ the average half-distance between adjacent electrons or positrons, in the rest system, namely

$$d = \sqrt{\pi}\left(\frac{\sigma_x^*\sigma_y^*\gamma\sigma_z^*}{N_b}\right)^{1/3} , \tag{3}$$

with $N_b$ the bunch population, and the asterisk indicating rms beam size at the collision point. The applicability of this model needs to be verified; an alternative approach is described, e.g., in Ref. [34]. For FCC-ee and CEPC, we find $d \approx 2\,\mu$m, which is rather similar to the value of $d \approx 3.3\,\mu$m obtained for LEP I [33]. For all three ERL-based machines, namely RELIC, ERLC and CERC, $d$ lies in the range 0.3–0.6 μm.

We use the program BBBREM [36] to compute the cross section $\sigma_{\mathrm{r.b.}}$, which determines the beam lifetime due to radiative Bhabha scattering, including the aforementioned cut-off based on $d$. The corresponding resulting minimum positron production rate required for circular colliders, or for colliders with particle recovery, is

$$\dot{N}_{e^+} = L n_{\mathrm{IP}} \sigma_{\mathrm{r.b.}} , \tag{4}$$

where $L$ denotes the design luminosity and $n_{\mathrm{IP}}$ the number of interaction points with simultaneous collisions. The above is the minimum rate required, since additional particle losses occur due to beamstrahlung, which depends on horizontal beam size, bunch length, bunch charge, and (also) beam energy and momentum acceptance.

For linear colliders without particle recovery, the positron rate required at the collision point is simply

$$\dot{N}_{e^+,\mathrm{LC}} = f_{\mathrm{rep}} N_b n_b , \tag{5}$$

with $f_{\mathrm{rep}}$ the linac repetition rate, $N_b$ the bunch population, and $n_b$ the number of bunches per pulse.

Table 3 shows the computed radiative Bhabha scattering cross sections, $\sigma_{\mathrm{r.b.}}$, for different $e^+e^-$ circular or ERL-based Higgs factory proposals, along with the resulting minimum rates required, for all proposals, and compares the latter with the design assumptions (in the right-most column).

Table 3: Cross section for particle loss due to radiative Bhabha scattering, $\sigma_{\mathrm{r.b.}}$, as computed by BBBREM considering an energy acceptance of 2% and a cut-off based on the parameter $d$ of Eq. (3), the resulting minimum positron production rates required for different circular and ERL based colliders (“min. requ.”), compared with project assumptions compiled for Snowmass’21 [32] (“assumed”). In case of linear colliders without particle recovery, like ILC and CLIC, the required (“min. requ.”) positron rate directly follows from bunch charge and bunch collision rate. Key parameters for almost all projects can be found in Table 2, those for ERLC in Ref. [35].

| **Proposal** | **Energy** [GeV] | $\sigma_{\mathrm{r.b.}}$ [mbarn] | $\dot{N}_{e^+}$ min. requ. [$10^{12}$ e$^+$/s] | $\dot{N}_{e^+}$ [32] assumed [$10^{12}$ e$^+$/s] |
|---|---|---|---|---|
| FCC-ee | 120 | 166 | 0.05 | 6.0 |
| CEPC | 120 | 166 | 0.03 | 3.8 |
| ILC | 125 | — | 131 | 131 |
| ILC ext. | 125 | — | 525 | 525 |
| CLIC | 190 | — | 100 | 100 |
| C$^3$ | 125 | — | 100 | 100 |
| CERC | 120 | 154 | 12 | 0.08 |
| ERLC | 125 | 149 | 0.06 | 0.05 |
| RELIC | 120 | 147 | 0.6 | 0.02 |

We note that for FCC-ee and CEPC significant margins exist, of about two orders of magnitude, between the rates that can be provided from the injector complexes and the rate required to compensate the losses from radiative Bhabha scattering only. This wide a margin is due to the fact that the maximum injector production rate is specified for the more demanding running on the Z pole. We also observe that for the most easily implemented, lowest-luminosity version of the ERLC [35] considered here (namely 1.3 GHz RF cavities at 1.9 K, and pulsed operation), the production rate roughly equals the expected loss rate from radiative Bhabha scattering alone (for other versions a higher positron rate is required). By contrast, for RELIC, as presented, the loss rate due to radiative Bhabha scattering appears to be about 25 times higher than the production rate hitherto assumed, and for the CERC the loss rate is 100 times higher than the production rate. This suggests that for the latter two proposals the injector designs may need to be modified in order to provide significantly higher fluxes of fresh positrons and electrons. However, the respective cross sections still need to be validated, and possibly updated, before definite conclusions can be drawn [37].

## PREDICTING PERFORMANCE

The more mature projects presented here (ILC, CLIC, FCC-ee, CEPC) have fairly established and reviewed performance figures backed by detailed simulations, although

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of course all projects are working towards increasing performance. The newer projects (e.g., RELIC, CERC) do not yet have reviewed performance figures, neither detailed simulations demonstrating how to achieve them.

Past experience with the SLC, which after ten years of operation reached about half of its nominal luminosity [29, 38, 39], present-day struggles with obtaining the SuperKEKB design luminosity [40], and, on the other hand, actual luminosities exceeding design values at previous machines like LEP [41], PEP-II [42] and KEKB [43], highlight the importance of a fair and thorough evaluation of the luminosity risks and of the luminosity potentials. The corresponding work needs to be continued.

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