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Oliver.bruning@cern.ch

Report

LHeC Cost Estimate

Oliver Brüning
CERN, Geneva, Switzerland

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Abstract

This report looks at the cost estimate for the Linac-Ring option using the ERL layout from the LHeC CDR and evaluates cost variations as a function of the electron beam energy. The report only evaluates the added cost for the electron beam generation, acceleration and the preparation of collisions with a hadron beam in an existing hadron storage ring.

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Contents

1 General Comments

This report aims at the preparation of a rough cost estimate for the electron accelerator complex of the LHeC / FCC-eh using the ERL design presented in the LHeC CDR [1]. The analysis aims at identifying the main cost driver items for the Linac-Ring construction and evaluating variations in the size and energy reach for the electron facility to estimate the cost dependence on key performance parameters for the LHeC machine. The report only evaluates the added cost for the electron beam generation, acceleration and the preparation of collisions with a hadron beam in an existing hadron beam storage ring. The report also compares the cost estimates to budget estimates from other projects for comparison after applying appropriate cost indexation.

2 Synchrotron Radiation Power and Return Arc Radius of Curvature

The LHeC CDR limits the synchrotron radiation power to ca. 50MW. We keep the same target value for the first estimate of the ERL option and derive the minimum acceptable bending radius for the ERL return arcs from this criterion. The SR power radiated in the last, high energy return-arc amount to 40% of the total SR radiation power (sum of all the other, lower energy return arcs. For a maximum beam energy of 60GeV, the required ERL circumference corresponds then approximately to 1/3 of the LHC and 1/11 of the FCC circumference, including 400m in the straight part of the ERL for beam delivery system. For the scaling of the required ERL return arc as a function of the beam energy we use an analytical estimate for the emitted synchrotron radiation power. The emitted synchrotron radiation power for a single electron is given by [2][1]:

$$P = \frac{e^2\, c\, \gamma^4}{6\, \pi\, \epsilon_0\, \rho^2} \tag{1}$$

Integrating Equation (1) over the return arc and assuming $N_b$electrons per bunch with a bunch spacing n_b seconds, one obtains for the synchrotron radiation power emitted over a given return arc of the ERL:

$$P_{arc} = \frac{N_b}{n_b}\frac{e^2\, \gamma^4}{6\, \epsilon_0\, \rho} \tag{2}$$

The analytical estimate for the SR power in the high-energy return arc is approximately 75% of the simulated SR power using a lattice simulation tool (smooth bending radius versus the sum of several magnets with smaller bending radius). We keep the same target value for the first estimate of the LHeC / FCC-eh options and derive the minimum acceptable bending radius for the ERL design as a function of the beam energy via scaling using Equation (2). For the scaling, we estimate the total synchrotron radiation power as a function of the radius of curvature of the ERL ring by multiplying the analytical estimate from the smooth radius approximation in Equation (2) by a factor 3.5 in order to account for the contribution of the other return arcs and the difference due to a realistic magnet configuration.

3 SRF Cryo-Module cost

For this estimate we follow the costing for the European XFEL [3]-[5] and CERN in-house estimates developed for the SPL study and assume the SRF system as described in the LHeC CDR: a 7.5 meter long cryo module with four 5-cell 802MHz cavities.

The XFEL RF system is similar in length to that of the LHeC system, albeit optimized for a very different operation mode (pulsed versus CW and low current versus high beam current operation) and using different SRF systems (1.3GHz versus 802MHz). The XFEL cryo-module follows the design of the ILC

[1] Using SI unites

developments. References [3] – [5] specify the total XFEL cost at 1.22B€ in 2005 costing. Adjusting this budget for inflation to 2017 prices requires an adjustment of ca. 20% [13]. The TDR specifies that ca. 28% of this cast is assigned to the accelerator part. However, this ratio changed slightly over the project execution and was in the end closer to 22%. This, results then in a total XFEL accelerator cost of 322M€ in 2017 accounting and a **unit price of 3.76MCHF per 12.2-meter-long XFEL CM** [assuming a CHF/€ exchange rate of 1.18 as of April 2018]. This cost includes the cost for the HOM and power couplers and the SRF power sources [estimated at approximately 38% of the total SRF cost]. In the following we assume that the LHeC linacs will require a comparable cost for the couplers and RF power sources, even though the RF power requirements are intrinsically different between the XFEL and the LHeC ERLs. Assuming further, that the CM cost scales approximately with the length (probably a very optimistic assumption which we will correct later by adding a 30% correction to account for the nonlinearity of the scaling and the higher cost due to the increased cavity and CM volume when going from a 1.3GHz to a 802MHz and when going from a pulsed to a CW RF system), one can estimate a price of **2.3MCHF per FCC-eh / LHeC ERL CM with a length of 7.5 meter**.

The LCLS-II RF system is similar in length to that of the European XFEL and LHeC RF systems and is developed for CW operation. The LCLS-II CM are also based on the ILC design and are of comparable length as the XFEL CM. The LCLS-II CM cost is specified at 2.1M$ [6]. Some of these costs are inflated and include fab/yield risk, especially for Nb and cavities. The split of the order between multiple vendors add also additional pricing for the overall cost. The total savings, with these factors removed, could be about 10% ➔ **ca. 2MCHF per cryo module.** It takes 3 or 4 person-years to assemble and test a CM, assuming all needed infrastructure is fully ready and commissioned. In the US, this represents another 35% cost increase, bringing the **total cost for a completely tested and assembled CM to around 3.5MCHF**, which agrees well with the XFEL costing.

The JLab CBAF 12 GeV upgrade quotes a cost of 2.6M$ per 100MeV for the CM [for 10MeV real-estate gradient this corresponds to a 10 meter long CM] and 1.7M$ for the RF power per CM at 1mA and 10M$ at 10mA claiming an increased power efficiency for the high current operation [20]. For the ERL cost estimate we use the smaller cost for RF power, assuming that most of the power can be recovered in the ERL. Scaling the CM length to that of the LHeC, this results then to an approximate cost of **ca. 3.2MCHF for a 7.5m long LHeC CM [setting 2010 dollars equal to todays CHF according to [13] and the exchange US Dollar/CHF rate of July 2018]**.

Another comparison can be made with the SRF system for the CBETA facility currently under construction at Cornell University. The cost for the cryo-module is specified to 3.52M$ [7] which fits also well to the EU-XFEL estimate. This cost was also used as an estimate for the LCLS-II cost estimate and includes labour without overhead and all couplers and gate valves.

From the LCLS-II, CBAF and CBETA costs, we estimate an average price of ca. 3.4MCHF for a 7.5 meter long 1.3GHz CM including RF power.

Albeit optimized for operation with protons rather than electrons, the SNS SRF system is closer in frequency to the LHeC SRF system than the XFEL and LCLS-II and the CBAF systems. The SNS SRF system features two different types of SRF sections: one medium-β [β = 0.61] section and one high-β [β = 0.81] section [18]. With a frequency of 805MHz and a cryomodule length of 4.2m [medium-β] and 6.3m [high-β] consisting of three [medium-β] and four [high-β] 6-cell cavities per CM. Accounting for an additional 1.5 meter for each CM for the installation interfaces [Slot Length] one obtains for 11 medium-β and 15 high-β CM a total SRF linac length of ca. 180 meter with a total CM length of ca. 141 meter. Reference [19] specifies the total SNS SRF cost at 110M$ in 2010 dollars, yielding an average cost of ca. 0.32M$ per CM meter. Reference [20] estimates the cost for the RF power to ca. 70% of the CM cost for an ERL installation, yielding an approximate cost of ca. 0.54M$ per CM meter with power. **Scaling this cost to the LHeC CM length, one estimates a cost of approximately 4MCHF per 7.5m long LHeC CM [setting 2010 dollar approximately equal to 2018 CHF according to [13]].**

The XFEL CM cost is clearly smaller than all other estimates, but it benefitted from a larger production series and requires less RF power. We account for these effects and for the increased CM volume and Nb quantity when scaling from a 1.3GHz to a 802MHz RF system by applying a 30% tariff to the XFEL costing.

In the following, we assume then a price of ca. **3MCHF per FCC-eh / LHeC CM**, assuming that this cost includes the couplers and RF power sources.

Assuming an RF voltage of 18.7MV per cavity and an active cavity length of 0.935 meter one can estimate the number of required FCC-eh / LHeC CM for the two ERL linacs. For the LHeC and FCC-eh ERL baseline design of 60GeV with two 1km long 10GeV linacs, one arrives at 267 CM with 4 5-cell cavities per CM, **projecting a total of ca.**

[1] 805MCHF for the baseline 60GeV FCC-eh / LHeC superconducting RF system.

The XFEL, Cornell and LCSL-II cryo modules benefitted significantly from the extensive TESLA and ILC R&D efforts. The development of a new 802MHz RF system will certainly require optimization efforts on its own that cannot just be extrapolated from the ILC studies (for example sources of microphonic noise [thermo-acoustic oscillations, noise from the pumping etc.] and the implied mitigation through stabilization rings or other measures). It appears therefore reasonable to assume an additional budget item that addresses the need for outstanding R&D and technological optimization for the new 802MHz RF system for ERL operation. To account for such R&D costs we look at the CERN SPL study. The bare SPL cryo-module cost has been estimated at 2.34MCHF (one, 4-cavity SPL module [8]). The CERN internal estimates specify additional cost for the RF power couplers, power generators, LLRF and vacuum interfaces amounting to ca. 3.75MCHF per CM, yielding a total of ca. **6.1MCHF / CM for the complete prototype CM system**. This is approximately a factor 2 higher than the XFEL based cryo-module estimate. In the following we assume that this higher cost needs to be applied to the production of prototype cryo-modules and provide in the LHeC cost estimate a budget line for the production of 5 such full cryo-module prototypes:

[2] 31MCHF for the CM prototype development.

4 Injector and Dump

The injector complex of an ERL consists of a cryo module with individually powered and tunable cavities of the same frequency as the main accelerator cavities. The injector corresponds therefore in some sense to a one-off prototype of the SRF system and we assume here for the cost estimate for the ERL injector the quoted price for 5 of the CERN in-house produced SPL cryo-modules [8] plus an overhead for the return arcs to produce an ERL based injector. In addition to this we assume ca. 2.5MCF for the source and for the dump each and arrive at

[3] 40MCHF for the complete injector and

[4] 5MCHF for the source and beam dump system.

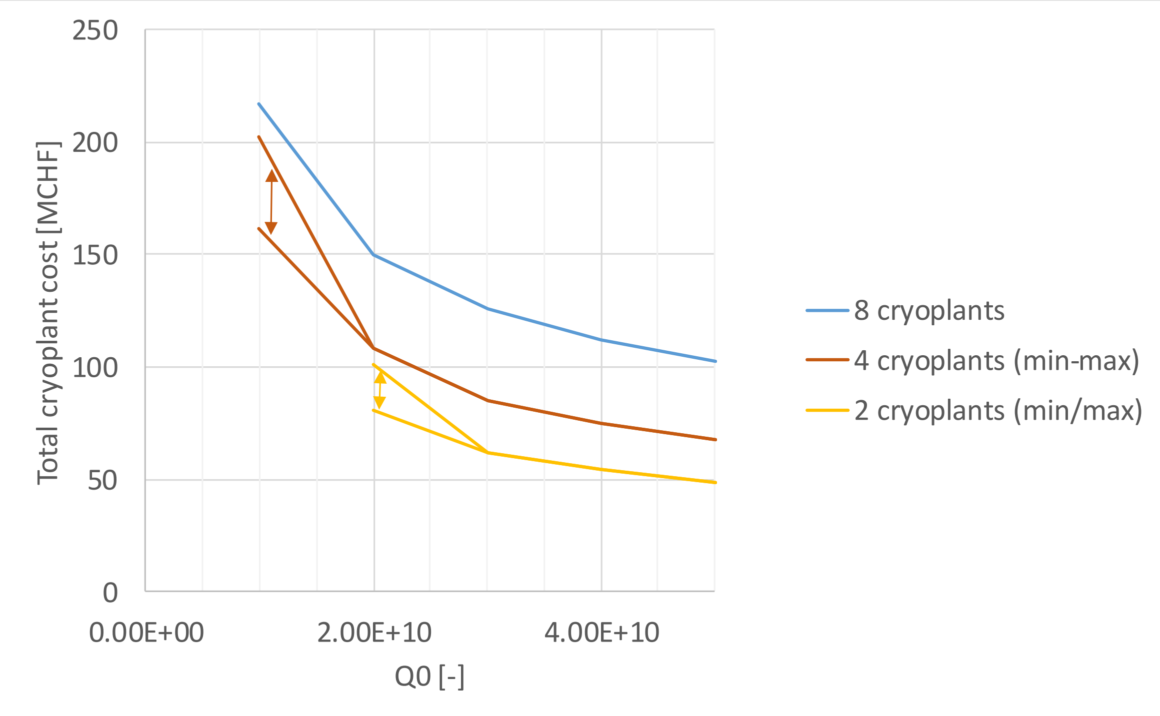

Figure 1: the cost scaling of the required cryogenic infrastructure versus the attainable Q_0 of the superconducting cavities and otherwise constant length of the linacs. The plots assume the baseline linac length of 1km for each of the two ERL linacs.

5 Cryogenic Cost

The cryogenic cost for the LHeC / FCC-eh RF system can be scaled from the experience with the LHC cryogenic system. The cryogenic need of the SRF system depends almost linearly on the achievable Q_0 of the superconducting cavities. For $Q_0 = 10^{10}$, the required cryogenic system roughly resembles that of the LHC machine [1]. Figure 1 shows the cryogenic cost as a function of the achievable Q_0 in the SRF cavities for three options: the use of 8, 4 and 2 cryo-plants [9]. For Q_0 smaller than 2 10^{10}, the size of the associated cryo-plant becomes too big and the curve for two cryo-plants therefore stops at Q_0 = 2 10^{10}. Apart from the eventual size limitation of the cryo-plant, the implementation with fewer plants is always more cost effective than an implementation with more cryo-plants. The LHC system is based on upgrades of the existing LEP system and therefore consists of 8 cryo-plants which is not the most efficient implementation when looking at Figure 1. A more cost-effective implementation for the same cryogenic power could be achieved for a new construction with a smaller number of cryo-plants. In the following we assume that this would be possible for a new installation like the LHeC and the FCC-eh. Assuming the baseline two 1km long superconducting linacs with an attainable Q_0 = 2.5 10^{10} for the superconducting cavities, we therefore derive an approximate cost of:

[5] 100MCHF for the associated cryogenic system.

For a given Q_0 value, the cost for the cryogenic system should scale approximately linearly with the length of the superconducting linacs. For the scaling of the cryogenic cost for different design variation of the ERL system we assume that the cryogenic cost scales linearly with the linac length and the attainable Q_0.

6 Civil Engineering

For the cost estimate of the civil engineering we look at three different sources: the costing for the LEP [10] tunnel, a cost estimate from the external consultant Amberg [11], that was prepared in the context of the LHeC CDR and an estimate from the external consulting company ILF [12] prepared in the context of the FCC CDR. The cost for the construction of the 27km long LEP underground tunnel, including 4 caverns and 8 shaft, is quoted at 310MCHF in 1981 [10]. From this, we derive an approximate tunnelling cost of **ca. 11kCHF per meter of underground tunnel**.

The report from Amberg quotes a total cost for the LHeC civil engineering of 239MCHF, including 2 shafts, dump caverns and surface buildings. This estimate translates to an approximate tunneling cost of **ca. 20kCHF per meter of tunnel**, which implies an approximate cost increase of 100% over 30 years wrt the LEP tunnel cost in 1981. This seems to be well in line with the general cost index over that period [13]. The Amberg report also quotes a cost of **ca. 4MCHF per access shaft, ca. 5MCHF per shaft cavern and a total of ca. 18MCHF for surface building**. The most recent cost estimate by ILF Consulting Engineers GmbH, for the tunnel design and construction within the FCC study, quotes a total cost for the ERL related civil engineering works of 394MCHF [458MCHF]. This corresponds to an approximate cost of **21.5kEuros/m and a cost of 33.8MEuros per 175m deep shaft.** The ILF shaft caverns estimates accounts for a cost of 14MEuros. Considering that shorter shafts are required for the LHC infrastructure, this translates to an approximate cost of **17MEuros per LHeC shaft**. In comparison, the cost for the new **HL-LHC shafts is approximately 10.4MCHF per shaft**.

For the following cost estimate, we assume a price **of 25kCHF per meter of tunneling** [using the most recent ILF estimate] and assume the need for two access shafts and access shaft caverns. For this we use the higher ILF estimates of **16MCHF [14M€] per shaft cavern.** We account the access shafts itself with **20MCHF,** which is an average between HL-LHC and the FCC estimates [twice the HL-LHC shaft cost and half the FCC shaft estimate]. For the surface buildings, we use the AMBERG estimate of 18MCHF and the HL-LHC costing of 36MCHF for surface buildings on two sites [➔ ca. 18MCHF per site and apply a cost of **18MHCF** for the LHeC surface buildings assuming that the surface buildings can be concentrated largely on one site]. The HL-LHC project has in addition a total of 33MCHF for auxiliary CE cost. This includes costs for permits, consultancies, landscaping of the sites and temporary labor for the CE team. In the following we assume that the LHeC will require a similar auxiliary CE budget. In addition to the minimum required length of the two linacs and the return arcs, we assume a required space of 400m in each straight section for the beam delivery system [spreader and combiner sections] and the beam dumps, and, a total length of 400m for the transfer lines connecting the ERL to the hadron collider facility. Furthermore, we assume a 50% cost increase for the straight LINAC tunnels to account for a parallel RF gallery and the waveguide connections between the two straight tunnel structures.

For the baseline design of a 60GeV ERL facility with a circumference of approximately 9.1km one obtains thus a cost of approximately

[6] 386MCHF for the civil engineering works.

7 Magnet and Vacuum System Cost

The cost for the full normal conducting magnet system of the LHeC ERL system has been estimated at 140MCHF by the CERN magnet team [14]. This cost is split in 90MCHF for the dipole magnets and 50MCHF for the 6*240 = 1440 quadrupole and 6*580 = 3480 dipole magnets of the 6 return arcs. For the scaling estimate of the cost versus different ERL sizes, we assume that the number of magnets, and thus the magnet system price, scales roughly with the length of the return arcs (and the number of re-circulations) of the Energy Recovery Linac (ERL). The LHeC CDR assumes a radius of curvature of 1km for the return arcs. Combined with the above cost estimates one arrives thus at a cost of approximately **7430CHF per meter magnet system** and **140MCHF for the complete magnet system of the baseline LHeC ERL**.

To this we add the cost of the vacuum and support systems, which has been estimated at CERN to approximately 2500CHF per meter [15], yielding a total **magnet-vacuum system cost of approximately 11.15kCHF per meter**.

For the reference ERL design with 3-recirculations and a radius of curvature of 1km and assuming additional transfer lines of a total length of 400m, this yields approximately

[7] 215MCHF for the baseline ERL magnet-vacuum system approximately.

This estimate can be compared to that of the LEP machine. The LEP cost estimate from 1981 quotes a total magnet-vacuum system cost of 205MCHF. Applying a price index of 1.6 [13] accounting for the inflation from 1981 to today (62CHF of 1981 correspond to 100CHF of 2017) one obtains from the **LEP estimates a cost of ca. 15kCHF per meter**. This cost is approximately twice as high as the estimate for the LHeC / FCC-eh ERL, which seems appropriate if one considers the much higher complexity of the LEP system (magnet currents need to be ramped over a dynamic range of 6 compared to the fixed field operation in the ERL return arcs and the need for better vacuum required for a storage ring - versus an ERL with only 6 beam passages - and higher synchrotron radiation load in LEP).

8 Superconducting Interaction Region Magnets

We estimate the cost for the new superconducting interaction region [IR] magnets for the electron-hadron interaction point [IP] based on the magnet cost of the HL-LHC IR upgrade. The HL-LHC triplet magnets are budgeted as 80MCHF for the triplet system of two new IRs and benefitted of approximately 15 years of magnet R&D through the USLARP program. For a cost estimate of the new e-h interaction region we take half of the HL-LHC magnet budget assuming only one IR and the cost of 5 years of dedicated magnet R&D and magnet model program based on the cost of the USLARP program (13M$ per year in the final years). This leads then to approximately

[8] 105MCHF for the superconducting magnets of a new IR [40MCHF + 5*13MCHF].

9 Auxiliary Systems

The are several remaining systems for the ERL installation that are on their own not expected to be a major cost driver. These systems include, for example:

- Cabling and installation cost
- Surface buildings
- Cooling and ventilation
- Safety and interlock systems
- Transport

For these systems, we assume in the following a place holder of

[9] 69MCHF for other auxiliary systems

which corresponds roughly to the comparable budgets for the HL-LHC project [e.g. cabling, transport and ventilation]].

10 Operating Cost Considerations

The electricity cost for running an accelerator installation at CERN was quoted at approximately 30€ per MWh assuming operation during the summer period (April to October) only and assuming a machine shutdown over the Christmas and New Year period [16]. The total CERN Network has a currently (status 2014) a capacity of approximately 260 MW [17]. The total electrical power consumption of the CERN site amounts to approximately 1200GWh [17], half of which is accounted for the LHC machine with approximately 40% of that accounted for the cryogenic system (the SPS machine accounts for approximately 1/3rd of the total CERN electricity consumption). The LHC cryogenic system therefore requires approximately 240GWh per year. Assuming an average electricity price of 30€ per MWh one obtains thus approximately 7MCHF per year for running the LHC cryogenic system. Over a period of 10 years one obtains thus approximately 70MCHF integrated operation cost for running a cryogenic system of the size of the LHC. The average power consumption for the LHC cryogenic system amounts to approximately 35MW, leaving 65MW from the allocated 100MW limit. The LHeC CDR accounted from this approximately 50MW for the synchrotron radiation power.

Table 1: Cost estimate for the LHeC reference ERL with a beam energy of 60GeV based on estimates scaled to 2018 prices.

Budget Item	Cost
SRF System	805MCHF
SRF R&D and Proto Typing	31MCHF
Injector	40MCHF
Magnet and Vacuum System	215MCHF
SC IR magnets	105MCHF
Dump System and Source	5MCHF
Cryogenic Infrastructure	100MCHF
General Infrastructure and installation	69MCHF
Civil Engineering	386MCHF
Total	1756MCHF

Assuming a total power requirement of 100MW for the LHeC machine and assuming 200 days of operation, one obtains a total power consumption of approximately 480GWh per year or

[10] 14.5MCHF annual and 145MCHF integrated operation cost over 10 years for running the accelerator facility with 100MW wall plug power in parallel with the LHC operation.

We address here only the operating cost for electricity and do not comment on the required manpower for the facility operation. Furthermore, an alternative, dedicated operation mode of the LHeC might imply different operating costs than stated above.

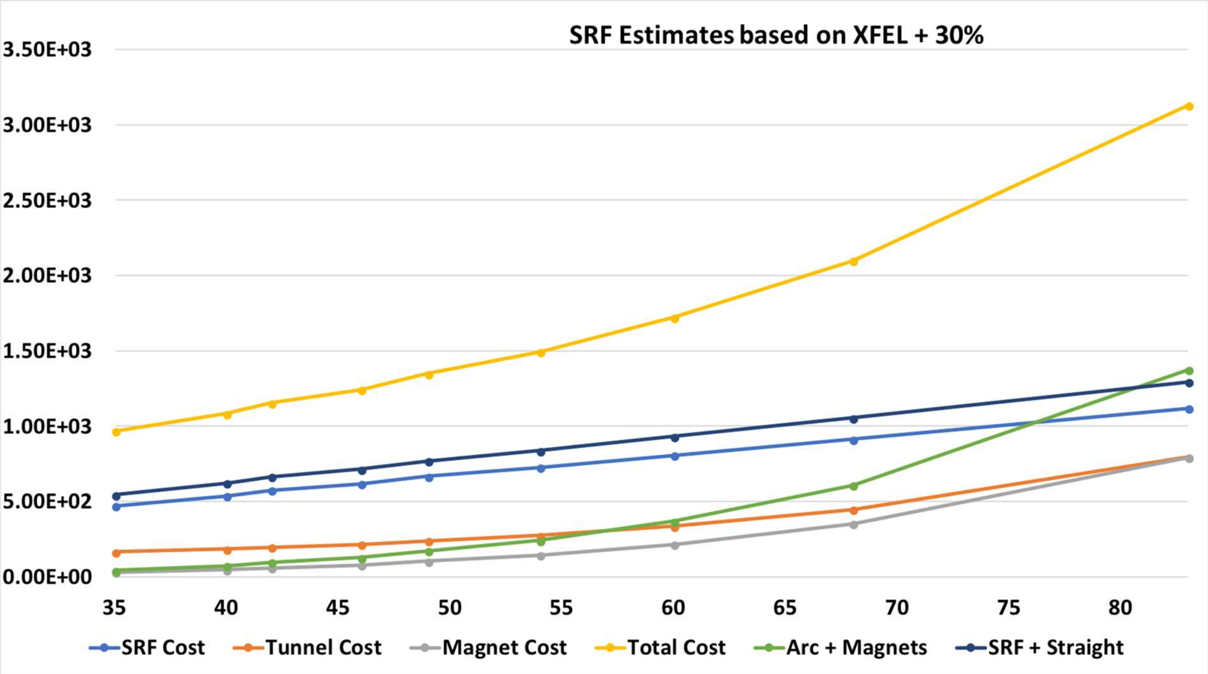

Figure 2: Cost scaling for the LHeC versus beam energy. The vertical axis shows 2018 price estimates in kCHF.

11 Cost Summary

Table 1 summarizes the individual budget lines for the reference ERL design with 3 re-circulations, a radius of curvature of 1km for the return arcs, a linac length of 1km resulting in a total ERL circumference of 9km plus 400m transfer lines including a 3% overhead wrt the XFEL SRF estimates that include the cost for RF infrastructure [e.g. LLRF and RF power].

Under the assumption of a 100MW energy limit for the operation of the ERL facility, the operation cost of the ERL over 10 years amounts to approximately 10% of the total required capital investment for the facility. This appears to be a reasonable relation and confirms the choice of a 100MW wall plug power limit for the ERL facility.

12 Installation Size and Cost Variations

The total cost for the ERL installation depends on the overall size of the installation and the targeted beam energy. Table 1 clearly identifies the SRF system as the main cost driver for the installation for the baseline 60GeV configuration, even if one assumes the scaled CM price from the XFEL construction without an overhead accounting for the required R&D investment. From a cost optimization point of view it appears therefore interesting to consider also an ERL option with a smaller SRF installation. Assuming a linear scaling of the SRF cost with the linac length and the target electron beam energy, one can significantly reduce the installation cost by reducing the target electron beam energy. One could also reconsider the number of re-circulations for the ERL and assume 4 or 5 instead of 3 re-circulations for the acceleration process. However, this would increase the total beam current in the SRF system and the required cryogenic system – assuming such an increase in the total beam current is acceptable from the beam dynamics and stability point of view. We scale the estimate for the general infrastructure with the total circumference of the ERL facility. Figure 2 illustrates the resulting cost variation as a function of the beam energy while keeping the number of re-circulations in the ERL system at 3 acceleration and

3 deceleration cycles and that minimum radius of curvature in the return arcs is determined by the amount of acceptable synchrotron radiation loss (50MW).

One can observe from Figure 1 that the SRF cost amounts to almost 50% of the total ERL cost for beam energies up to 70GeV. One reference point for the cost variation study could be to initially cut the SRF system in half (e.g. 30GeV beam energy reach with the given SRF parameters), but to keep the radius of curvature in the return arcs compatible with a beam energy of 50GeV and a SRF power loss of 50MW for the determination of the radius of curvature in the return arcs and the length of the linac tunnel compatible with an eventual SRF installation for 50GeV (840m). This would allow to reduce the total cost for the ERL facility while keeping open the possible for operation at 50GeV in case either the SRF system performance can be increased by 60% wrt the accelerating voltage assumed in the LHeC CDR or by installing additional SRF modules at a later point or by installing additional return arcs for a higher number of re-circulations.

For the total circumference of the ERL facility we assume: LINAC length = 1km * 5/6 [830m] and a total arc length of 3040m for beam energy of 50GeV with 50MW SR power limitation. The total length becomes then in this case 5.4km [1/5th of the LHC and 1/18th of the FCC circumference].

Table 2 summarizes the cost for this option, which stays well below 1000MCHF. The total cost for completing the SRF installation for operation at 50GeV would then amount to 218MCHF yielding a total cost for the 50GeV facility of 1122MCHF by adding the missing SRF system. Alternatively, one could hope in this scenario that the SRF performance can be pushed beyond the CDR value of 18MV/m, allowing an increase in the electron beam energy without installing additional SRF modules.

Table 2: Cost estimate for the an ERL installation with a beam energy of 30GeV upgradable to 50GeV by using initially only half of the SRF installation of the LHeC reference case for 60GeV beam energy but the other infrastructure [e.g. return arcs and cryogenics] cost scaled for a 50GeV installation. All entries show 2018 price estimates.

Budget Item	**Cost 30GeV**	**➔ 50GeV**
SRF System	402MCHF	+268MCHF
SRF R&D and Proto Typing	31MCHF	
Injector	40MCHF	
Magnet and Vacuum System	103MCHF	
SC IR magnets	105MCHF	
Dump System and Source	5MCHF	
Cryogenic Infrastructure	41.5MCHF	+28MCHF
General Infrastructure and installation	58MCHF	
Civil Engineering	289MCHF	
Total	1075MCHF	➔ 1371MCHF

13 Acknowledgement

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