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A phenomenological cost model for high energy particle accelerators

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TECHNICAL REPORT

A phenomenological cost model for high energy particle accelerators

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ABSTRACT: Accelerator-based facilities have enabled forefront research in high-energy physics for more than half a century. The accelerator technology of colliders has progressed immensely, while beam energy, luminosity, facility size, and cost have grown by several orders of magnitude. The method of colliding beams has not fully exhausted its potential but has slowed down considerably in its progress. In this paper we derive a simple scaling model for the cost of large accelerators and colliding beam facilities based on costs of 17 big facilities which have been either built or carefully estimated. Although this approach cannot replace an actual cost estimate based on an engineering design, this parameterization is to indicate a somewhat realistic cost range for consideration of what future frontier accelerator facilities might be fiscally realizable.

KEYWORDS: Manufacturing; Accelerator Subsystems and Technologies; Acceleration cavities and magnets superconducting (high-temperature superconductor; radiation hardened magnets; normal-conducting; permanent magnet devices; wigglers and undulators); Overall mechanics design (support structures and materials, vibration analysis etc)

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1 Introduction

The forecast for the far future of colliders beyond say, the 2030's, requires an understanding of several factors: scientific goals and desired energy reach, the possible available resources, and a foresight of suitable accelerator technology of the future. Affordable cost of the frontier facility is crucial. As of today, the world's particle physics research budget can be estimated to be roughly 3 B\$ per year. Under the assumption that such a financial situation will not change by much in the future and that not more than 1/3 of the total budget can be dedicated to construction of the next energy frontier collider over approximately a decade, one can estimate the cost of a globally affordable future facility to be about or less than 10 B\$ (in current prices). The desired features of such a flagship machine are [1]: ideally, an energy reach significantly ($> \times 10$) exceeding that of the LHC (14 TeV center-of-mass energy), a length not exceeding ~ 10 km, and an AC wall power consumption under ~ 100 MW. To understand whether there are opportunities for building such an accelerator within the above-mentioned constraints (which by themselves can not be considered as hard limits, but, rather as a guidance for discussion) and within present or reasonably extrapolated existing technologies, an analysis of the known costs of large accelerator facilities is needed.

2 Analysis of known costs of large accelerator facilities

There are several factors which need to be taken into account while discussing the costs of 17 large accelerators of the past two decades:¹ a) firstly, some of the facilities had been seriously considered for construction and well estimated but not built, e.g., the Superconducting Super Collider (SSC) in Texas, the Very Large Hadron Collider (VLHC) in Illinois, SLAC's proposal for the Next Linear

¹Though many accelerators have been built in the past and their construction costs are known, we limit ourselves only to the machines which are most relevant to our discussion of the mid-term and long-term future of high energy physics — namely, those built or designed relatively recently so their accelerator technologies are not too obsolete now due the progress in the field, and whose construction costs can be scaled to the present using standard inflation indices with a reasonable degree of accuracy.

Collider (NLC), the linear $e + e -$ collider TESLA at DESY; others are still under consideration — the International Linear Collider (ILC), Project X at Fermilab, CERN’s Super Proton Linac (SPL), the Compact Linear Collider (CLIC), the Beta-Beam and Neutrino Factory projects; and there are several which have been built or are currently being built — Fermilab’s Main Injector proton synchrotron (MI), Brookhaven’s Relativistic Heavy Ion Collider (RHIC), the Spallation Neutron Source (SNS) at ORNL, CERN’s Large Hadron Collider (LHC), the European Spallation Source (ESS) at Lund and X-ray Free Electron Laser (XFEL) at DESY, and the Facility for Antiproton and Ion Research (FAIR) at Darmstadt. b) secondly, the scope of the facility construction significantly varied and many facilities heavily piggybacked on either existing infrastructures, or tunnels, or injection complexes — RHIC and LHC are the most notable examples — while others were/are true “green field” facilities, c) thirdly, while almost all accelerator facilities have in common such components as accelerator tunnels and high power electrical infrastructure, they differ significantly in the major accelerator technologies they are built upon — such as normal-conducting (warm) or superconducting magnets or RF linacs. The most important difference for the above listed projects is often the methodology of the cost estimates. The cost estimates of some construction projects include the industrial contracts for major items like civil engineering, the accelerator elements and corresponding labor requirements (such approach is often referred as “European accounting”) while other estimates include full accounting of all associated expenses (“US accounting”). For example, all scientific facilities supported by the US DOE Office of Science are required to prepare and report estimates of “the total project cost” (TPC) which includes not only the cost of the technical components and conventional systems and associated labor, but also costs of the required R&D, development of the engineering design, project management, escalation, contingency, overhead funds, project-specific facility site development, sometimes — detectors, etc. The difference between the TPC and “European accounting” was analysed in detail during discussions on the US participation and contributions to international projects such as TESLA, ILC, and the International Thermonuclear Experimental Reactor (ITER) and estimated to be in the range (factor of) 2.0–2.5 [2]. Finally, one can also add that even the TPC estimate for not-yet-built facility is itself over simplified as it does not include, for example, the unpredictability of the contract bidding process [3], and, moreover, “...costing a new project in advanced technology is not just an accounting task, but rather an attempt to organize complexity and uncertainty” [4].

Table 1 summarizes an attempt to present the cost ranges — sometimes as large as $\pm 35\%$ — for the 17 recent large accelerator projects in the same TPC-methodology. These values reflect “present day” dollars, i.e., corresponding inflation and currency conversion indices [5] are accounted for. The table convincingly shows that in general, the cost of the facility is higher if the beam energy is higher, but at the same time it also hints that the cost per TeV (or GeV) depends on the technology of choice and that facilities that require higher beam and site power tend to be more expensive.

These observations lead to the following approach: one can de-compose the cost of each accelerator into only three parts which in aggregate total the known TPC (see table 1). As we will now demonstrate, each part can be parameterized by the single, most relevant parameter of the facility. First, the cost of civil engineering and construction (tunnels, surface buildings, connecting shafts, halls for experimental detectors, injection beamlines, beam dump halls, civil construction for injectors, tunnel infrastructure, etc.) will be parameterized by the total tunnel length L ; the

Table 1. Cost estimates of large accelerator facilities. Energy is center-of-mass energy for colliders and maximum beam energy for single beam machines. TPC stands for “Total Project Cost” (see text); technology types — “SC/NC Mag” for superconducting/normal-conducting magnets, “SC/NC RF” — for superconducting/normal-conducting RF systems. The numbers for the total length include injector complex tunnels.

	Cost (B\$) Year	Energy (TeV)	Accelerator technology	Comments	Length (km)	Site power (MW)	TPC range (Y14 B\$)
SSC	11.8 B\$ (1993)	40	SC Mag	Estimates changed many times [6–8]	87	~ 100	19–25
FNAL MI	260M\$ (1994)	0.12	NC Mag	“old rules”, no OH, existing injector [9]	3.3	~ 20	0.4–0.54
RHIC	660M\$ (1999)	0.5	SC Mag	Tunnel, some infrastructure, injector re-used [10]	3.8	~ 40	0.8–1.2
TESLA	3.14 B€ (2000)	0.5	SC RF	“European accounting” [11]	39	~ 130	11–14
VLHC-I	4.1 B\$ (2001)	40	SC Mag	“European accounting”, existing injector [12]	233	~ 60	10–18
NLC	~ 7.5 B\$ (2001)	1	NC RF	~ 6 B\$ for 0.5 TeV collider, [13]	30	250	9–15
SNS	1.4 B\$ (2006)	0.001	SC RF	[14]	0.4	20	1.6–1.7
LHC	6.5 BCHF (2009)	14	SC Mag	collider only — existing injector, tunnel & infrstr., no OH, R&D [15]	27	~ 40	7–11
CLIC	7.4–8.3B CHF(2012)	0.5	NC RF	“European accounting” [16]	18	250	12–18
Project X	1.5 B\$ (2009)	0.008	SC RF	[17]	0.4	37	1.2–1.8
XFEL	1.2 B€ (2012)	0.014	SC RF	in 2005 prices, “European accounting” [18]	3.4	~ 10	2.9–4.0
NuFactory	4.7–6.5 B€ (2012)	0.012	NC RF	Mixed accounting, w. contingency [19]	6	~ 90	7–11
Beta- Beam	1.4–2.3 B€ (2012)	0.1	SC RF	Mixed accounting, w. contingency [19]	9.5	~ 30	3.7–5.4
SPL	1.2–1.6 B€ (2012)	0.005	SC RF	Mixed accounting, w. contingency [19]	0.6	~ 70	2.6–4.6
FAIR	1.2 B€ (2012)	0.003–.08	SC Mag	“European accounting” [20], 6 rings, existing injector	~ 3	~ 30	1.8–3.0
ILC	7.8 B\$ (2013)	0.5	SC RF	“European accounting” [21]	34	230	13–19
ESS	1.84 B€ (2013)	0.0025	SC RF	“European accounting” [22, 23]	0.4	37	2.5–3.8

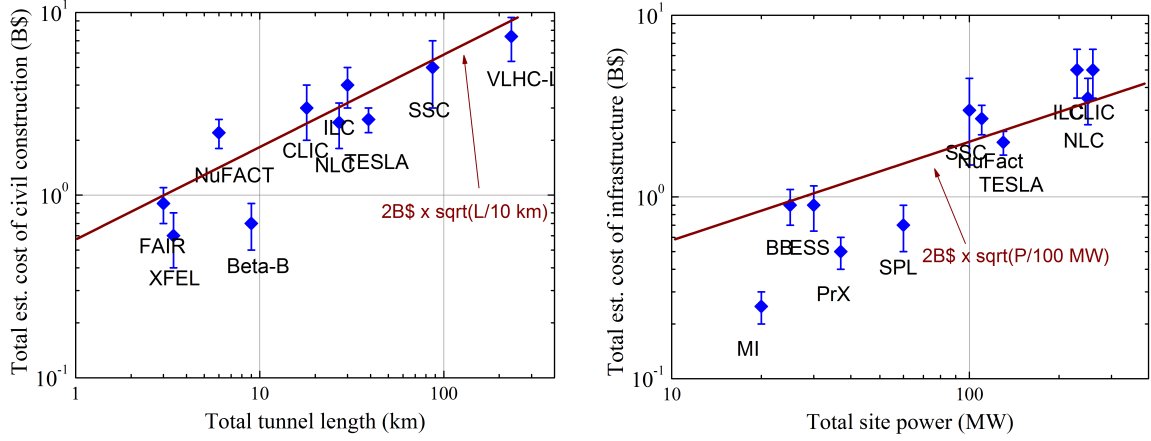


Figure 1. a) left — total estimated cost of the civil construction for accelerator facilities vs cumulative length of their tunnels; b) right — total estimated infrastructure cost of the accelerator facilities vs their electric power consumption.

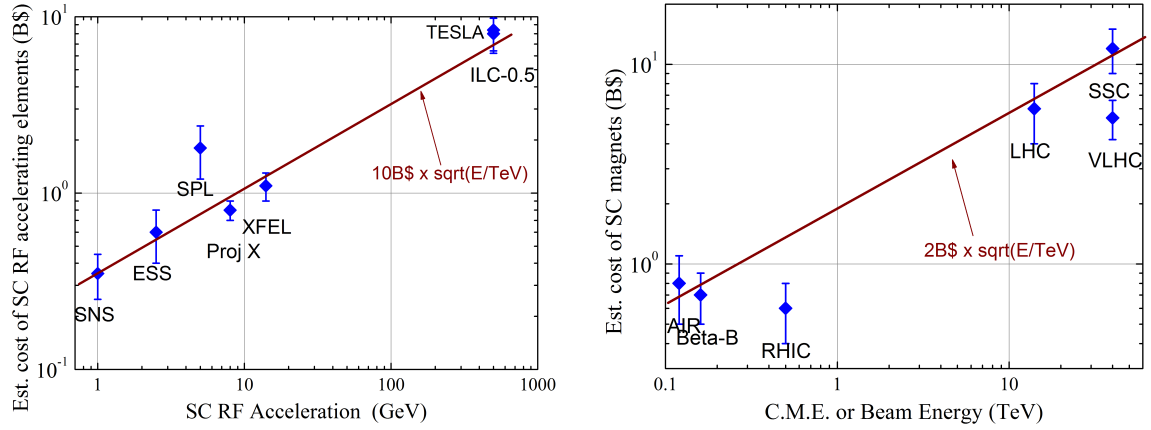


Figure 2. a) left — estimated cost of the accelerating elements for accelerator facilities based on SC RF vs total beam acceleration; b) right — estimated cost of the SC magnets and associated elements vs collider center of mass energy / single beam energy.

cost of the accelerator components (RF cavities/modules, cryostats, input couplers, all magnets, beam instrumentation and feedback systems, vacuum systems, RF systems, injection and ejection, beam delivery systems for colliders, beam collimation and dumps, etc.) will be parameterized by the the center-of-mass energy E (or beam energy for single beam facilities); and finally, the cost of the facility infrastructure (electric power feeders and stations, cable trays, power distribution, main power connection, cryoplants and cryogenic distribution system, cooling and ventilation systems, safety systems, auxiliary systems, control systems, klystrons, magnet supplies, etc.) will be parameterized by the total site's electric power P . Refs. [3], [6]–[23] do provide sufficient information on the cost breakdown of the TPC among these three parts.

Figures 1 and 2 present the summary plots of this analysis. As shown in figure 1a, the civil construction-related share of the TPC (not surprisingly) on average grows with the length of the tunnel. The error bars reflect uncertainties in both the TPC and its breakdown among the three

main parts. The least square fit to the power function $y = aL^b$ gives coefficients $b = 0.55 \pm 0.12$ and $a = 1.1 \pm 0.4$ (the length L is in units of 10 km and the cost in B\$). Significant dispersion in the parameters reflects the obvious spread of costs due to specific features of the accelerator tunnels and a variation of other parameters, e.g., tunnel diameter, etc. With all that, it is quite remarkable that within about $\pm 30\%$, a rather simple scaling of the civil construction cost of $2 \text{ B\$} \times (L/10 \text{ km})^{1/2}$ describes the data — see straight solid line in figure 1a. Figure 1b shows that a similar type of scaling law can be used to describe the cost of the power infrastructure-related parts of the TPC, namely $\approx 2 \text{ B\$} \times (P/100 \text{ MW})^{1/2}$ — with approximately the same fractional accuracy (the actual power law fit parameters are $b = 1.0 \pm 0.2$ and $a = 1.7 \pm 1.1$ if the site power in the units of 100 MW and the cost in B\$). Much bigger cost differences are associated with accelerator technologies. For example, the estimated cost of the accelerating elements for accelerator facilities based on SC RF is on average five times that of the SC magnet based facilities — see figures 2a and 2b — the former can be approximated by $10 \text{ B\$} \times (E/\text{TeV})^{1/2}$ (see the solid straight line in the figure, the power law fit with $b = 0.53 \pm 0.04$ and $a = 9.1 \pm 1.4$) while the latter is close to some $2 \text{ B\$} \times (E/\text{TeV})^{1/2}$ (the power law fit with $b = 0.46 \pm 0.08$ and $a = 1.2 \pm 0.27$). There are only a few facilities in our table 1 which employ normal-conducting RF structures or normal-conducting magnets, but following the same functional trend, their shares of the cost of accelerator components can be approximated as $8 \text{ B\$} \times (E/\text{TeV})^{1/2}$ and $1 \text{ B\$} \times (E/\text{TeV})^{1/2}$ correspondingly.

Recombining all the costs together into a total cost one can now approximate $TPC \approx \sum a_i X_i^{b_i}$ where $X = (L, E, P)$ and b_i and a_i are the fit coefficients. Without losing much accuracy, the formulae can be further simplified by using the same exponent of $b = 0.5$ — the square root dependence — for all three parts, leading to following phenomenological cost model for “green field” large accelerator facilities

$$TPC = \alpha \left(\frac{L}{10 \text{ km}} \right)^{1/2} + \beta \left(\frac{E}{1 \text{ TeV}} \right)^{1/2} + \gamma \left(\frac{P}{100 \text{ MW}} \right)^{1/2} \quad (2.1)$$

where, L is the total length of the tunnel, E is cm energy, P is total site AC power for the facility and α, β, γ are three coefficients, of which β is the only one that varies for different accelerator technologies.

Figure 3 shows that within approximately $\pm 30\%$ the $\alpha\beta\gamma$ -model matches the actual TPCs of all the facilities which we considered in the table 1 above, with the coefficients $\alpha = \gamma = 2 \text{ B\$}$ and technology dependent coefficient β equal to 1 B\$ for NC magnets, 2 B\$ for SC magnets, 8 B\$ for NC RF and 10 B\$ for SC RF. Straight black solid line in figure 3 indicates 1:1 correspondence; horizontal error bars show the TPC range from table 1, vertical error bars reflect $\pm 30\%$ deviations from eq. (2.1) (i.e., the range is about a factor of 2 from minimum to maximum). Four facilities — MI, RHIC, LHC and VLHC-I — are emphasized by quotes “...”, indicating that their known cost estimates do not account for significant “already existing” elements (infrastructure, tunnel or injector complex) — and that possibly explains why they are systematically above the 1:1 line in figure 3 (i.e., the actual known cost is lower than the $\alpha\beta\gamma$ -model TPC estimate of the “green field” facility eq. (2.1)).²

²It has to be noted that there was an earlier study of a 20 GeV neutrino factory in the US [40]. The facility required some 150 MW of site power, had a total of about 3 km of tunnels, some 7.5 GeV of SC RF acceleration and the total cost

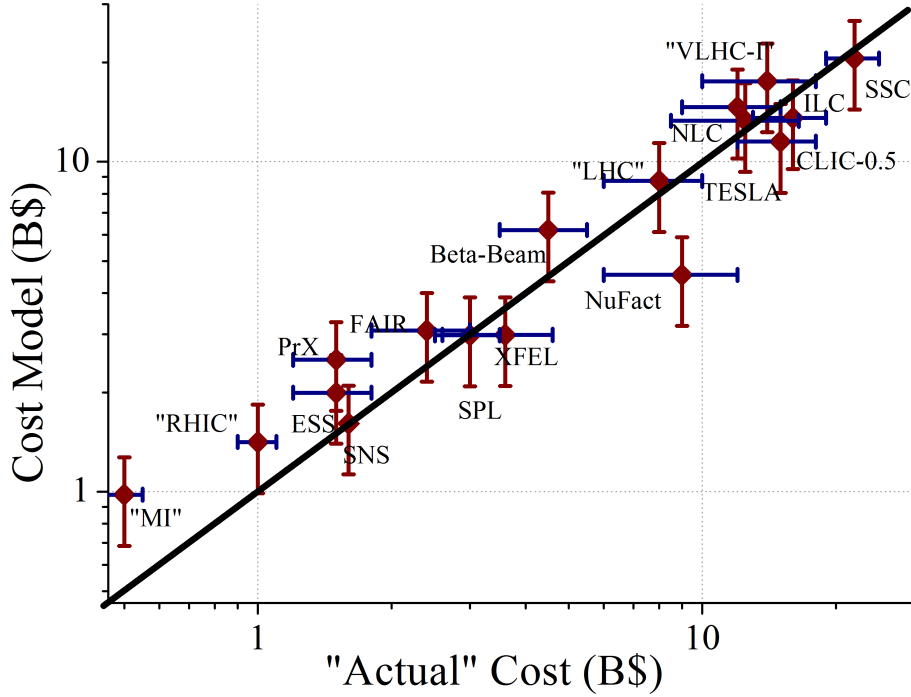


Figure 3. The phenomenological cost model eq. (2.1) vs actual cost for large accelerator facilities.

3 Rough cost estimates for possible future facilities

Taking into account all the caveats of the phenomenological eq. (2.1) — that it uses the US-accounting of the TPC of accelerator projects built from scratch in an area where no previous facilities exist, and that it is accurate only to within some 30%, or for range of estimates of about a factor of 2 — one can apply the $\alpha\beta\gamma$ -model to the future facilities employing the technologies similar to the ones of the past (but not necessarily exactly the same to them as the model seemingly reflects the progress in technologies made during the scale up of the past facilities to higher energies). For example, the proposed TLEP $e + e -$ Higgs factory [24] would require $L = 80$ km of tunnel, $P \approx 300$ MW of site power, some $E_1 = 6$ GeV of CW SC RF system and normal-conducting magnets for the $E = 240$ GeV c.o.m collider. Correspondingly, the combination of the costs in the $\alpha\beta\gamma$ -model results in $TPC = 2 \times (80/10)^{1/2} + 10 \times (6 \text{ GeV}/1 \text{ TeV})^{1/2} + 1 \times (240 \text{ GeV}/1 \text{ TeV})^{1/2} + 2 \times (300/100)^{1/2} = 10.4 \text{ B\$} \pm 3 \text{ B\$}$ — that is in decent agreement with a rough estimate of 5.5–7.5 BCHF under the “European accounting” made in ref. [24].

The high-energy CLIC $e + e -$ linear collider [25] with some $L \sim 60$ km of tunnels, $P \approx 560$ MW of required site power, $E = 3$ TeV of normal-conducting RF acceleration would cost about $TPC = 2 \times (60/10)^{1/2} + 8 \times (3 \text{ TeV}/1 \text{ TeV})^{1/2} + 2 \times (560/100)^{1/2} = 23.5 \text{ B\$} \pm 7 \text{ B\$}$. An even higher energy (6 TeV) $\mu + \mu -$ collider [26, 27] would require some $L = 20$ km of tunnels,

of its components was estimated to be about 1.9B\$ in the 2001 US dollars. Taking into account the inflation and prorating from the “European accounting” methodology to the TPC, one can estimate its TPC to be in the range of 5.0-6.2 B\$ in today’s prices. That is very close to our model projection of 4.6B\$, much closer than, e.g., the cost estimate for the European neutrino factory [19] which is more than 40% off our model (see figure 3).

$P \approx 230$ MW of electric power, about $E_1 = 50$ GeV of CW SC RF system in the recirculating linear accelerator (RLA) and SC magnets in the collider ring. All that can be estimated to cost $TPC = 2 \times (20/10)^{1/2} + 10 \times (50 \text{ GeV}/1 \text{ TeV})^{1/2} + 2 \times (6 \text{ TeV}/1 \text{ TeV})^{1/2} + 2 \times (230/100)^{1/2} = 12.9 \text{ B\$} \pm 4 \text{ B\$}$ — i.e., almost a factor of four less expensive per TeV than CLIC. Notably, the existence of the SPL-type proton linac would lower the cost by some 3–4 B\$ of the TPC for the muon collider facility. Of course, there are caveats associated with a muon collider as it is the first-of-a-kind machine to operate with unstable particles and significant R&D is still required to demonstrate its technical and performance feasibility [28].

The recently proposed 100 TeV proton-proton collider FCC [29, 30] will employ SC magnets, and will require a 100 km tunnel and some 400 MW of site power. Therefore, the cost of a such facility can be estimated as $TPC = 2 \times (100/10)^{1/2} + 2 \times (100 \text{ TeV}/1 \text{ TeV})^{1/2} + 2 \times (400/100)^{1/2} = 30.3 \text{ B\$} \pm 9 \text{ B\$}$. Again, if some existing accelerators can be re-used as a part of the needed 5–7 TeV injector, then some 6–10 B\$ can potentially be shaved off the TPC. In comparison, the LHC energy upgrade [31] would need some 20 T SC magnets for a 33 TeV $p-p$ collider in the existing LEP tunnel and an additional ~ 100 MW of electric power, therefore, the cost of such upgrade is expected to be about $2 \times (33 \text{ TeV}/1 \text{ TeV})^{1/2} + 2 \times (100/100)^{1/2} = 4.8 \text{ B\$} \pm 1.5 \text{ B\$}$.

In some cases, one may apply the $\alpha\beta\gamma$ -model to the future facilities which will be based on new, not-yet-fully-tested acceleration methods but will also heavily employ the existing technologies. The Argonne Flexible Collider (AFC) concept of a 3 TeV $e+e-$ machine [32] is based on the dielectric-wakefield acceleration (DWA) principle in which electric fields in the diamond structures are excited by low-energy high-power electron bunches produced by traditional means — namely, in the 0.86 GeV pulsed normal-conducting linacs. Twenty of such drive-beam linacs are needed for the AFC, which will also need some 20 km of tunnels (for the high energy linacs, beam delivery system and damping rings) and about 430 MW of site power. Estimating the costs of these components gives us a lower limit of the total cost of $2 \times (20/10)^{1/2} + 20 \times 8 \times (0.86 \text{ GeV}/1 \text{ TeV})^{1/2} + 2 \times (430/100)^{1/2} = 21.7 \text{ B\$} \pm 7 \text{ B\$}$. Of course, the cost of the DWA accelerating structures is not known yet, and should be added to the TPC.

Similarly, it is not possible now to estimate the cost of the main (high energy) beam acceleration components in another high energy $e+e-$ collider proposal based on the beam-plasma-wakefield acceleration (BPWA) [33], but one can at least estimate the cost of its 25 GeV ultra-high power SCRF drive-beam complex, civil construction for 20 km of tunnels for a 10 TeV facility and 540 MW site power infrastructure as $2 \times (20/10)^{1/2} + 10 \times (25 \text{ GeV}/1 \text{ TeV})^{1/2} + 2 \times (540/100)^{1/2} = 9 \text{ B\$} \pm 3 \text{ B\$}$. Just for reference, on average for the 17 facilities listed in table 1, the cost of the main accelerating components (magnets, cavities, etc.) is about equal to the rest of TPC (infrastructure, civil construction, injectors, etc.).

4 Discussion

It is absolutely clear that the proposed phenomenological $\alpha\beta\gamma$ -model eq. (2.1) cannot substitute actual cost estimates based on detailed facility-specific considerations, such as those usually provided in what is called *Technical Design Reports*. There are many important considerations which are omitted in the simplified comparative analysis, e.g., lepton-lepton colliders can explore similar physics at much lower energies than hadron-hadron colliders; very high intensity or high lumi-

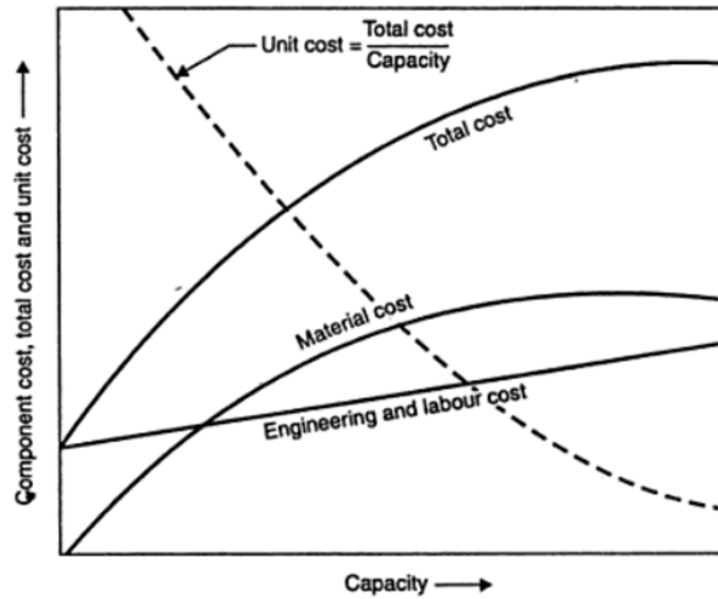


Figure 4. Variation of the costs of power plant versus its capacity [37].

nosity machines tend to cost more not only because of the higher cost of the power infrastructure or/and of the injection complex, but also because of the more sophisticated accelerating elements; the acceleration technology choice has implications on the tunnel and power requirements; or that ion beam facilities for nuclear physics research may look by necessity more complex than HEP facilities (e.g., FAIR has several rings for experiments), etc., etc.

On the other hand, there seems to be enough ground to believe in the validity of this method for estimates of the *cost range* of the TPC of large accelerator facilities. Significant deviation of other estimates for any future facility from the $\alpha\beta\gamma$ -model predication would definitely require an explanation of the difference compared to the model based on the data from 17 other machines.

The functional form of the power-law scaling is actually not that unusual. For example, the analysis of the costs of 270 tunnels worldwide (including industrial, subway, railway, etc.) [34] indicates that, though being dependent on the type of rock excavation and application, on average the cost scales as $L^c D^d$, where L and D are the tunnel length and diameter and the exponents are in the range $c = 0.4-1$, $d = 0.6-1.5$. Similar sets of data for other 100 tunnels in the U.K., Europe, Australia and Americas [35] can be fitted by $c \approx 0.5$ (i.e., as in our model). The power-law cost scaling is typical in the electrical industry, e.g., the cost of the power transformers scales as its MVA rating with a power of about 0.5 [36], the physical explanation being that the MVA capability scales as a power of the transformer magnetic core size (one of the biggest cost drivers).

Similar dependencies are known in the power plant industry — see figure 4 from [37] — the labor and engineering cost has significant intercept and increases slightly with the capacity of the plant, the slope of the material cost curve decreases slightly with increase of the capacity of the plant, and as the result “... the total cost curve shows significant positive intercept at zero capacity which represents the cost of just maintaining an organization of men and plant ready to produce”, and, of course, the cost per unit of capacity goes down for larger plants.

Very similar arguments are valid for the TPC of an accelerator where “zero-acceleration” cost (the positive intercept) is usually quite substantial as it accounts for management, research and development, design work, the cost of an injection complex, and many other things which have to be addressed in addition to the construction of the accelerator proper. As it can be clearly seen from the “total cost” curve in figure 4, the choice of a *square root* fit is, therefore, more than natural as it allows for matching the reality over a wide range of parameter (length, energy, and power).

We should also note that the issue of the performance of the accelerator facility (e.g., luminosity of a collider) is not directly coupled to the facility parameters we used for our cost estimates. Indeed, even if the L, E, P (and cost) are defined, there might be \sim order(s) of magnitude uncertainties related to important details such as beam quality. Attainment of the design or the ultimate performance of the facility can take quite substantial time and effort [38].

Besides the financial feasibility, one should take into account the availability of experts. A simple “rule of thumb”, which is based on statistics of construction projects in Japan and widely accepted in the accelerator community, claims that “one accelerator expert can spend intelligently 1 M\$ in one year” [39]. As an illustration, the ILC TDR [21] estimates that some 13,000 man-years (FTEs, or full-time-equivalent) of accelerator scientists, engineers and technicians are needed over some 8 years of construction of the International Linear Collider. So, on average 1,600 trained people will be needed for installation, integration, testing and quality assurance, commissioning and all other related activities associated with 7.8 B\$ worth of materials and services budget — that is about 0.6M\$ per person per year. Despite the lack of a crisp definition of who should be considered “an accelerator expert”, we can estimate that the world-wide community of accelerator physicists and experienced engineers does not exceed 1200–1500 people and the total accelerator personnel (all scientists, engineers, technicians, drafters, etc) is about 4,000–4,500. Therefore, any plans for a really big facility at the scale of a few B\$ to 10 B\$ should take into account the significant time needed to get the required expert workforce together.

Finally, coming back to the aspiration of a flagship machine with $10\times$ the energy reach of the LHC — say, a 100 TeV center-of-mass energy, not exceeding ~ 10 km in length, and with an AC wall power consumption under $O(100\text{ MW})$, one can use the $\alpha\beta\gamma$ -model to estimate the cost of the technology of choice, i.e. the technology cost coefficient β : if technologies of tunneling and electric power distribution will not change by much, i.e. if $\alpha = \gamma = 2$ B\$, then $\beta \approx 0.6$ B\$, requiring technology twice as cheap as that of normal-conducting magnets. While technologies capable of delivering the required average accelerating gradient of $100\text{ TeV}/10\text{ km}=10\text{ GeV/m}$ do exist in principle — those are the acceleration by wakefields in plasma and in crystals [1] — their feasibility has not been demonstrated yet and their current costs are factors of at least 30 to 100 above the desired value of $\beta \approx 0.6\text{ B\$/}\sqrt{\text{TeV}}$. Only a comprehensive R&D program can provide an answer to the question of whether financially feasible accelerator based facilities can provide an order of magnitude increase in energy at the particle physics frontier. Less revolutionary, but equally as challenging is an alternative approach of extrapolating existing technologies for acceleration, civil construction and power infrastructure to much lower “cost per unit” values.

5 Summary

We have reviewed publicly available costs for 17 large accelerators of the past, present and those currently in the planning stage and attempted to reduce them to one methodology known as “the total project cost” (TPC) or “the US accounting”. The costs have been broken up into three major parts corresponding to “civil construction”, “accelerator components”, and “site power infrastructure” in such a manner that they total the derived TPC ranges. We successfully attempted to parameterize the three cost components by just three parameters — the length of the tunnels L , the center-of-mass or beam energy E , and the total required site power P and found that over almost 3 orders of magnitude of L , 4.5 orders of magnitude of E and more than 2 orders of magnitude of P the following cost model works with $\sim 30\%$ accuracy: $Total\ Project\ Cost \approx \alpha \times Length^{1/2} + \beta \times Energy^{1/2} + \gamma \times Power^{1/2}$ where coefficients α , γ and accelerator technology dependent coefficient β are defined in the text. The $\alpha\beta\gamma$ -model has been applied to several proposed collider facilities and we obtained either their TPC ranges or the cost of their parts which are expected to be built on the base of the currently known accelerator technologies. We remark that besides the feasibility of the cost, very important are the feasibility of the performance and availability of expertise for large machine construction projects. Significant investment into the R&D on the novel advanced accelerator techniques or on the cost reduction of the existing technologies is required before one can evaluate opportunities for financially feasible, next generation energy frontier accelerators.

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References

- [1] V. Shiltsev, *High energy particle colliders: past 20 years, next 20 years and beyond*, *Physics-Uspekhi*, **55** (2012) 965.
- [2] P. Garbincius, private communication (2013).
- [3] P. Lebrun and P. Garbincius, *Assessing risk in costing high-energy accelerators: from existing projects to the future linear collider*, *Proc. IPAC2010* (2010) 3392.
- [4] P. Lebrun, *Costing high-energy accelerator systems*, in proceedings of 4th RFTech Workshop, Annecy, France, 25–26 March 2013, <http://lpsc.in2p3.fr/Indico/conferenceDisplay.py?confId=862>.
- [5] CPI Inflation Calculator, http://www.bls.gov/data/inflation_calculator.htm; Historical Exchange Rates, <http://www.oanda.com/currency/historical-rates/>.
- [6] T. Elioff, *A Chronicle of Costs*, Preprint SSCL-SR-1242 (1994).
- [7] S. Wojcicki, *The Supercollider: The Texas Days Reviews of Accelerator Science and Technology*, **2** (2009) 265.
- [8] H.R.70 — *Superconducting Super Collider Termination Act of 1993*, U.S. Congress bill (1993), <https://www.govtrack.us/congress/bills/103/hr70>.

- [9] *Fermilab Main Injector, Technical Design Handbook*, FERMILAB-DESIGN-1994-01 (1994).
- [10] M. Harrison, T. Ludlam and S. Ozaki, *RHIC project overview*, *Nucl. Instrum. Meth. A* **499** (2003) 235.
- [11] F. Richard, J.R. Schneider, D. Trines and A. Wagner eds., *TESLA Technical Design Report*, DESY-2001-011 (2001).
- [12] VLHC Design Study Group, *Design study for a staged very large hadron collider*, FERMILAB-TM-2149 (2001).
- [13] N. Phinney ed., *2001 Report on the Next Linear Collider: A Report Submitted to Snowmass 2001*, SLAC-R-571 (2001).
- [14] N.Holtkamp, *Commissioning Highlights of the Spallation Neutron Source*, *Proc. EPAC'06* (2006) 29.
- [15] *CERN FAQ: LHC — The Guide*, CERN-Brochure-2009-003-Eng (2009).
- [16] D. Dannheim et al., *CLIC e^+e^- Linear Collider Studies*, [arXiv:1208.1402](https://arxiv.org/abs/1208.1402).
- [17] J. Kerby, *Cost Estimate Development Process*, presented at the *FNAL Director's Preliminary Cost & Schedule Review of Project X*, 16 March 2009 (unpublished).
- [18] European X-Ray Free-Electron Laser Facility GmbH, *European XFEL Annual Report* (2012), http://www.xfel.eu/sites/site_xfel-gmbh/content/e63617/e123754/e212665/European_XFEL_Annual_Report_2012_eng.pdf.
- [19] W. Wildner, A. Kurup, C. Densham and P. Soler, *EUROnu Costing Report*, EUROnu-WP1-05 (2012).
- [20] H.H. Gutbrod et al. eds., *FAIR Baseline Technical Report* (2012), <http://www.fair-center.eu/for-users/publications/fair-publications.html>.
- [21] T.Behnke et al. eds., *The International Linear Collider Technical Design Report, v.1: Executive Summary*, ILC-REPORT-2013-040 (2013).
- [22] <http://europeanspallationsource.se/facts-figures>.
- [23] M. Eshraqi, H. Danared and D. McGinnis, *Design Options of the ESS Linac*, *Proc. IPAC 2013* (2013) 3921.
- [24] M. Koratzinos et al., *TLEP, first step in a long-term vision for HEP*, [arXiv:1306.5981](https://arxiv.org/abs/1306.5981).
- [25] J.P. Delahaye, *The CLIC study of a multi-TeV linear collider*, *Ann. Rev. Nucl. Part. Sci.* **62** (2012) 105.
- [26] S. Geer, *Muon Colliders and Neutrino Factories*, *Ann. Rev. Nucl. Part. Sci.* **59** (2009) 347.
- [27] J.-P. Delahaye et al., *Enabling Intensity and Energy Frontier Science with a Muon Accelerator Facility in the U.S.: A White Paper Submitted to the 2013 U.S. Community Summer Study of the Division of Particles and Fields of the Amer*, [arXiv:1308.0494](https://arxiv.org/abs/1308.0494).
- [28] V. Shiltsev, *When will we know a muon collider is feasible? Status and directions of muon accelerator R&D*, *Mod. Phys. Lett. A* **25** (2010) 567 [[arXiv:1003.3051](https://arxiv.org/abs/1003.3051)].
- [29] C.M. Bhat et al., *Proton-proton and electron-positron collider in a 100 KM ring at Fermilab*, [arXiv:1306.2369](https://arxiv.org/abs/1306.2369).
- [30] A. Ball et al., *Future Circular Collider Study Hadron Collider Parameters*, CERN EDMS Doc FCC-1401101315-DSC (2014), in proceedings of *FCC Study Kick-Off Meeting*, CERN (2014), <http://indico.cern.ch/event/282344/>.
- [31] L. Rossi, *LHC Upgrade Plans: Options and Strategy*, *Proc. IPAC 2011* (2011) 908.
- [32] C. Jing et al., *Argonne Flexible Linear Collider*, *Proc. IPAC 2013* (2013) 1322.

- [33] E. Adli et al., *A Beam Driven Plasma-Wakefield Linear Collider: From Higgs Factory to Multi-TeV*, [arXiv:1308.1145](https://arxiv.org/abs/1308.1145).
- [34] J. Rostami et al., *Planning level tunnel cost estimation based on statistical analysis of historical data*, *Tunn. Undergr. Sp. Tech.*, **33** (2013) 22.
- [35] N. Efron and M. Read, *Analyzing International Tunnel Costs. An Interactive Qualifying Project*, <http://www.wpi.edu/Pubs/E-project/Available/E-project-043012-122558/>.
- [36] Westinghouse Electric Corporation, *Electrical transmission and distribution reference book*, (1964).
- [37] Er.R.K. Rajput, *Utilisation of Electrical Power*, Firewall Media (2006).
- [38] V. Shiltsev, *On performance of high energy particle colliders and other complex scientific systems*, *Mod. Phys. Lett. A* **26** (2011) 761.
- [39] K. Oide, private communication (2013).
- [40] S. Ozaki, R. Palmer, M. Zisman and J. Gallardo eds., *Feasibility Study-II of a Muon-Based Neutrino Source*, BNL-52623 (2001).