ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-MOXAT0106

REALIZATION, TIMELINE, CHALLENGES AND ULTIMATE LIMITS OF FUTURE COLLIDERS

V. Shiltsev[1,*], Fermilab, Batavia, IL 60510, USA

Abstract

This paper consists of two parts: in first, we briefly summarize the US particle physics community planning exercise "Snowmass'21" that was organized to provide a forum for discussions among the entire particle physics community to develop a scientific vision for the future of particle physics in the U.S. and its international partners. The Snowmass'21 Accelerator Frontier activities include discussions on high-energy hadron and lepton colliders, high-intensity beams for neutrino research and for "Physics Beyond Colliders", accelerator technologies, science, education and outreach as well as the progress of core accelerator technologies, including RF, magnets, targets and sources. We also discuss main outcomes of the Snowmass'21 Implementation Task Force which was changed to carry our comparative evaluation of future HEP accelerator facilities, their realization strategies, timelines, and challenges.

In the second part, we present an attempt to evaluate limits on energy, luminosity and social affordability of the ultimate future colliders - linear and circular, proton, electron positron and muon, based on traditional as well as on advanced accelerator technologies.

SNOWMASS'21

Snowmass is a particle physics community study that takes place in the US every 7-9 years (the last one was in 2013). The Snowmass'21 study (the name is historical, originally held in Snowmass, Colorado) took place in 2020-22, it was organized by the the American Physical Society divisions (DPF, DPB, DNP, DAP, DGRAV) and strived to define the most important questions for the field and to identify promising opportunities to address them, to identify and document a scientific vision for the future of particle physics in the U.S. and its international partners - see [1]. The P5, Particle Physics Project Prioritization Panel, chaired by H.Murayama (UC Berkeley), has taken the scientific input from Snowmass'21 to develop (by the Spring of 2023) a strategic plan for U.S. particle physics that can be executed over a 10 year timescale in the context of a 20-year global vision for the field.

Snowmass'21 activities are managed along the lines of ten "Frontiers": Energy Frontier (EF), Neutrino Physics Frontier (NF), etc, with the Accelerator Frontier (AF) among them. More than three thousand scientists have taken part in the Snowmass'21 discussions and about 1500 people participated in the final Community Summer Study workshop (Seattle, July'22) in person and remotely. In general, the international community was very well represented and many scientists from Europe and Asia have been either organizers of sessions and events, or conveners of topical groups, or submitted numerous Letters of Interest (short communications) or White Papers (extended input documents).

More than 300 Letters of Interest and 120 White Papers have been submitted to the Snowmass'21 AF topical groups. There were more than 30 topical workshops, 8 cross-Frontier *Agoras* (5 on various types of colliders: $e+e-/\gamma\gamma$, linear/circular, $\mu\mu$, pp, advanced ones and three on experiments and accelerators for rare processes physics), and several special cross-Frontier groups were organized such as *the eeCollider Forum, the Muon Collider Forum, the Implementation Task Force* (see below), the 2.4MW proton power upgrade design group at FNAL, etc.

Most important outcomes of the Snowmass AF deliberations are presented in the topical groups' reports and summarized in the Accelerator Frontier report (all available in [2]):

Facilities for Neutrino Frontier: The needs of neutrino physics call for the next generation, higher-power, megawatt and multi-MW-class superbeams facilities. There is a broad array of accelerator and detector technologies and expertise to design and construct a 2.4 MW beam power upgrade of the Fermilab accelerator complex for the LBNF/DUNE Phase II, a world leading neutrino experiment, expand the volume of Liquid Argon detectors by 20 ktons, and build a new neutrino near-detector on the Fermilab site.

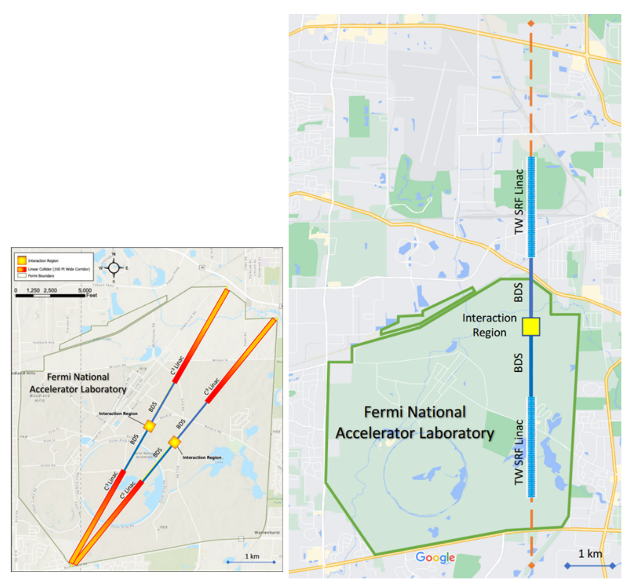

Figure 1: Possible placements of future linear e^+e^- Higgs/EW factory colliders C^3 and HELEN on the Fermilab site map - both about the same length: (left) 250 GeV c.m.e. options with a 7-km footprint, and (right) higher c.m. energy options (12 km dashed line) (from the AF report [2]).

[*] shiltsev@fnal.gov

ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-MOXAT0106

Facilities for Rare Processes Frontier: Several possibilities for Rare Processes Frontier (searches for axions, charged lepton flavor violation, dark matter) have been identified that call for broad use of existing and future facilities, such as the SLAC 4-8 GeV electron linac, Fermilab's PIP-II proton linac beam and PAR (PIP-II Accumulator Ring), etc.

Facilities for the Energy Frontier: The Energy Frontier community calls for an active program toward post-LHC colliders. In particular, the world community has called for a Higgs/EW Factory as the next major accelerator project and this might be followed by a O(10 TeV/parton c.m.e.) collider. At present, there are as many as eight Higgs/EW factories under consideration, and also about two dozen energy frontier collider concepts that go beyond HL-LHC in their discovery potential.

In the course of the AF discussions, clearly identified was the need of an integrated future collider R&D program in the US DOE Office of HEP to engage in the design and to coordinate the development of next generation collider projects such as: FCC-ee (circular collider), C3/HELEN/CLIC (linear Higgs factory colliders, the first two fitting the Fermilab site - see Fig.1), multi-TeV Muon Collider, and FCC-hh, in order to enable an informed choice by the next Snowmass/P5 ca. 2030. The proposal of such a program will need to be approved by the P5.

General Accelerator R&D, Education, and Training Major goals for the accelerator R&D for the next decade have been identified as: a)development of efficient high intensity high brightness $e+$ sources and multi-MW proton targets for neutrino production (2.4 MW for PIP-III, 4-8 MW for a future muon collider); b) design and testing of 16 T dipoles, 40T solenoids, and $O(1000$ T/s) fast cycling magnets; c) development of efficient RF sources and 70-150 MV/m C^3 and 70 MV/m TW SRF cavities and structures, exploration and testing of new materials with the potential of sustaining higher gradients with high Q_0; d) demonstration of collider quality beams in advanced acceleration methods, efficient drivers and staging, and development of self-consistent parameter sets of potential far-future colliders based on wakefield acceleration in plasma and structures; e) focus in the beam physics should be on experimental, computational and theoretical studies on acceleration and control of high intensity/high brightness beams, high performance computer modeling and AI/ML approaches, and design integration and optimization, including the overall energy efficiency of future facilities.

There is also a recognized need to strengthen and expand education and training programs, enhance recruiting (especially international talent), promote the field (e.g., via colloquia at universities), and creating a national undergraduate level recruiting program structured to draw in women and underrepresented minorities (URM), with corresponding efforts at all career stages to support, include and retain them in the field.

	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

Figure 2: Main parameters of the submitted Higgs factory proposals (FCCee, ILC, CLIC, C^3, HELEN, and CERC - ERL based collider in the FCCee tunnel) and multi-TeV colliders (CLIC, ILC, 3 TeV and 10 TeV c.m.e. Muon Collider options, FCChh, and 1900-km circumference "Collider in the Sea"). Years of the pre-project R&D indicate required effort to get to sufficient technical readiness. Estimated years to first physics are for technically limited timeline starting at the time of the decision to proceed. The total project cost ranges are in 2021$ (based on a parametric estimator and without escalation and contingency). The peak luminosity and power consumption values have not been reviewed by ITF and represent proponent inputs. (Adapted from the ITF report [3].)

Implementation Task Force

A very important and useful development of the Snowmass'21 Accelerator Frontier was organization of the Implementation Task Force [3] charged with developing metrics and processes to facilitate comparisons between projects. More than 30 collider concepts have been comparatively evaluated by the ITF using parametric estimators to compare physics reach (impact), beam parameters, size, complexity, power, environment concerns, technical risk, technical readiness, validation and R&D required, cost and schedule – see Fig. 2. The significant uncertainty in these values was addressed by giving a range where appropriate. Note that by using the proponent-provided luminosity and power consumption values (for a fully operational facility including power consumption of all necessary utilities), ITF chose not to evaluate the risk of not achieving this aspects of facilities' performance.

The years of required pre-project R&D is just one aspect of the technical risk, but it provides a relevant and comparable measure of the maturity of a proposal and an estimate of how much R&D time is required before a proposal could be considered for a project start (CD0 in the US system). The time to first physics in a technically limited schedule includes the pre-project R&D, design, construction and commissioning of the facility, and is most useful to compare the scientific relevance of the proposals.

ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-MOXAT0106

The total project cost follows the US project accounting system *but without escalation and contingency.* Various parametric models were used by ITF to estimate this cost, including the cost estimated by the proponents. The cost estimate uses known costs of existing installations and reasonably expected costs for novel equipment. For future technologies, pre-project cost reduction R&D may further reduce the cost estimates used by the ITF.

ON ULTIMATE COLLIDERS

Charged particle colliders – arguably the most complex and advanced scientific instruments – have been at the forefront of scientific discoveries in high-energy and nuclear physics since the 1960s [4]. There are seven colliders in operation and the Large Hadron Collider now represents the "accelerator energy frontier" with its 6.8 TeV energy per beam, 2.1·10^{34} cm^{-2}s^{-1} luminosity and some 1.2 TWh of annual total site electric energy consumption. The SuperKEKB is an asymmetric e^+e^- B-factory with 4 and 7 GeV beam energies, respectively. Since the startup in 2018, it has achieved the world record luminosity (for any collider type) of 4.7·10^{34} cm^{-2}s^{-1}, and aspires to reach 60·10^{34} cm^{-2}s^{-1}– a whopping 30-times over its predecessor KEK-B (1999-2010).

Naturally, the question of the limits of the colliding beams technique of of utmost importance for long-term planning of the particle physics. From the discussion above, one can see the some future energy frontier colliders have been discussed as part of the Snowmass'21 AF and ITF discussions, namely: the 3 TeV CLIC option (100 MV/m accelerating gradient, 50 km long), a 10-14 TeV c.m.e. $\mu^+\mu^-$ collider (10-14 km circumference, 16 T magnets), two roughly 100 km circumference pp colliders - SPPC in China (75-125 TeV c.m.e., based on 12-20 T IBS SC magnets) and FCChh at CERN (100 TeV, 16-17 T Nb_3Sn SC dipoles), and "Collider in Sea" (500 TeV, 1900 km, ~ 4 T magnets). Are those machines at the limit of colliders? Which factors set those limits? Are they different for different types of colliders (linear, circular, lepton, hadron, etc)? Discussion on these important questions has been ongoing for over a decade - see, e.g., in Refs. [4–8].

Any of the future collider projects constitute one of, if not, the largest science facility in particle physics. The cost, the required resources and, maybe most importantly, the environmental impact in the form of large energy consumption will approach or exceed the limit of affordability. The discussion below is a modest update of the analysis Ref. [7] and starts with general introduction to the issue: definitions of the scope and units, approaches to the limits of on the energy, luminosity, and social cost of the ultimate colliders. Then, we take a more detail look into the limits of the circular pp, ee and $\mu\mu$ colliders, linear and plasma-based $ee, \gamma\gamma, \mu\mu$ ones, and briefly discuss exotic schemes, such as the crystal muon colliders. The social cost considerations (power consumption, financial costs, availability of experts, carbon footprint and time to construct) are best defined for the machines based on existing core accelerator technologies (RF and magnets), and less so for the emerging or exotic technologies (ERLs, plasma, crystals, etc).

Each type of the ultimate future colliders to be evaluated on base of feasibility of energy E, feasibility of luminosity L, and feasibility of the cost C. For each machine type (technology) we start with the current state-of-the-art machines – see Ref. [4] – and attempt to make several (1,2,...) orders of magnitude steps in the energy and see how that affects the luminosity and the cost. This study does not include discussion on where are the lower limits on the luminosity or the upper limits of the cost.

Units and Limits on E, L and C

Everywhere below we will use TeV for the units for E, understood as the c.m.e. equal to twice the beam energy. The units of L are ab^{-1}/yr that is equal, e.g., 10^{35} cm^{-2}s^{-1} over 10^7 sec/yr. For reference, the HL-LHC will deliver 0.3 ab^{-1}/yr. Due to spread of expectations for the machine availability, there might be a factor of ~2 uncertainty in peak luminosity demands for any ab^{-1}/yr value. The units of total facility electric power consumption are TWh/yr and, e.g., at present CERN with operational LHC takes requires P=200MW of the average power and 1.1-1.3 TWh/yr. The cost is evaluated in "LHC-Units". 1 LHCU is the cost of the LHC construction (≃10B$). The cost of large accelerators is set by the scale (energy, length, power) and technology. Typically, accelerator components (NC or/and SC magnets and RF systems) account for 50 ± 10% of the total cost, while the civil construction takes 35 ± 15%, and power production, delivery and distribution technology adds the remaining 15 ± 10% [9]. While the last two parts are mostly determined by industry, the magnet, RF and wakefield accelerator technology is a linchpin of the progress of accelerators and would dominate the accelerator cost without progress from the R&D programs. For most of the future machines, the cost is estimated using $\alpha\beta\gamma$ model $C = \alpha\sqrt{Length} + \beta\sqrt{Energy} + \gamma\sqrt{Power}$ that is claimed to end up with good estimate within a $O(2)$ range [9]. While the $\alpha\beta\gamma$ model still needs to be properly extended to the advanced technologies (plasma, lasers, crystals, etc), it was found to be within a factor of 2 w.r.t. more detail models used in the ITF analysis of the three dozens of already proposed medium- and far-future machines [3].

Synchrotron radiation sets up the first limit of the energy reach if one demands the SR loss per turn to be less than the total beam energy $\Delta E \le E/2$. That defines the absolute c.m.e. limit for the circular colliders as :

$$E[\text{TeV}] \le (m/m_e)^{4/3}(R/10[\text{km}])^{1/3} \ , \qquad (1)$$

that is ~1 TeV for electrons, some 1.2 PeV for muons ($m \approx 210 m_e$) and 25 PeV for protons ($m \approx 2000 m_e$), R is the radius of the machine. Beyond these energies, the colliders will have be linear (thus, needing no dipole magnets). Other energy limits are set by the survival of the particles. Indeed, if, for example, an advanced 5 TeV linear collider consist of

ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-MOXAT0106

M = 1000 5 GeV acceleration stages, then the stage-to-stage transfer efficiency must be better than $\eta = 1 - 1/M$. Also, if the particles are unstable with the lifetime at rest τ_0, then to guarantee delivery to the collision point, the minimum accelerator gradient must significantly exceed $G \gg mc/\tau_0$ – that is, e.g., 0.3 MeV/m for muons and 0.3 TeV/m for tau-leptons [5]. Of course, inevitable might be corollary limits as higher E usually demands higher C, P or facility size. For example, the machine of 100 km circumference with $B \leq 16$T magnets will have $E \lesssim 100$ TeV; or 40,000 km circumference with 1 T magnets will have $E \lesssim 2.6$ PeV; or a linear accelerators with the total length limit of 50 km and gradient $G \leq 0.1$ GV/m will stay under $E \lesssim 5$ TeV; or under $E \lesssim 10$ PeV if the length is 10 km and $G \leq 1$ TV/m.

Performance (luminosity) reach of the ultimate colliders can be limited by a large number of factors and effects – particle production, beamstrahlung, synchrotron radiation power per meter, IR radiation damage, neutrino-radiation dose, beam instabilities, jitter/emittance growth, etc – which are machine specific and will be considered below. But the most fundamental is the limit on the total beam power $P_b = f_0 n_b N \gamma m c^2$. Indeed, from the standard luminosity formula $L = f_0 n_b N^2 / 4\pi\sigma^2$ one gets:

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

see [4] for standard description of the variables. The luminosity scaling with energy $L \propto 1/E$ in Eq.(2) is markedly different from the usual HEP requirement for the luminosity to follow the cross-section scaling $L \propto E^2$.

Of course, there are societal limits on the machine's total cost, total "carbon footprint" and environmental impact. While the total cost C is dependent on the technology (core accelerator technology, civil construction technology, power production, delivery and distribution technology, etc), the probability of (a technically feasible) facility scales down with the cost, possibly as $\propto C^2/(1 + C^\kappa)$, with $\kappa \approx 4 - 5$ as for the real estate sales price distributions. Also, to note: i) the costs of civil construction and power systems are mostly driven by larger economy, ii) having an injector complex available (sometimes up to 1/3 of the total cost) results in potential factor of 2 in the energy reach; iii) the collider cost is usually relatively weak function of luminosity (the latest example is the HL-LHC 1B$ project that will increase luminosity of the 10B$ LHC by a factor of 5); iv) so, one can consider starting future machines with high E and relatively low L in anticipation of eventual performance upgrades (e.g., CESR and Tevatron witnessed L increase by a factor of $O(100)$, LHC by a factor ≥10, etc); v) C is a moderate function of length/circumference; vi) cost is a strong function of E and technology.

Construction time of large accelerator projects to date is usually between 5 and 11 years and approximately scales as $T \propto \sqrt{C}$ [3]. It is often limited by the peak annual spending rate, at present thought to be $O(0.5$ B$/yr) – compare to the world's global HEP budget 4B$ – and on the number of available technical experts (now, about 4500 worldwide). Technical commissioning time ("one particle reaches the design energy") can be as short as one-few years – and it is shorter for known technologies and longer for new ones and for larger number of accelerator elements. Progress towards the design (or ultimate) luminosity is dependent on the machine's "complexity" [10] and for the luminosity risk of 100 (ratio of initial to ultimate L) it can take as long as $T \approx ln(100) \cdot 2$=9 yrs - see also corresponding discussion in the ITF report [3].

Ultimate Colliders

Below we attempt to explore ultimate limits of various types of future colliders.

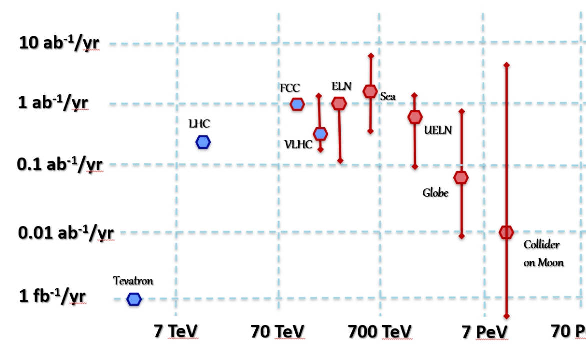

Figure 3: Estimated performance of the circular pp colliders vs c.m.energy.

Circular pp colliders Tevatron (E=2 TeV, B =4.5T, 6.3 km circumference) and 14 TeV LHC (8T, 27km) can be used as reference points while discussing future circular pp colliders. Also, there are parameter sets available for SCC (40 TeV, 6.6T, 87km), SppC (75 TeV, 12T, 100km), FCC-hh (100 TeV, 16T, 100km), VLHC (175 TeV, 12T, 233km), Eloisatron (200 TeV, 10T, 300km), "Collider-in-Sea" (500 TeV, 4T, 1,900km),a very old E.Fermi's concept of "Globaltron" (3-5 PeV, ~1T, 40,000km)) [4,11], and, since very recently, collider on Moon (14PeV=14,000 TeV, 20 T, 11,000km) [12]. Often cited advantages of such colliders are known technology and beam physics and good power efficiency in terms of ab^{-1}/TWh. Their major limitations include i) large size (related to the magnetic field B technological limit), ii) high total facility power; iii) high cost; iv) beam-beam effects, beam burn-off, and instabilities; v) synchrotron radiation power P_{SR} deposition in the SC magnets environment. Considering the beam-beam limit ξ and the P_{SR} per meter to be the major luminosity limitations, one gets $L \propto (\xi/\beta^*)(P_{SR}/2\pi R)(R^2/\gamma^3))$. Fig. 3 presents estimates of performance of circular pp colliders vs c.m.energy. Power consumption of these colliders approaches 3 TWh/yr (about 3 times the LHC one) starting at the 100 TeV FCC. Cost optimization of these gargantuan machines usually ends up with the estimates exceeding 2 LHCU above about E =30 TeV. Of course, under continuous exploration are such cost saving ideas as superferric magnets, permanent magnets, better/cheaper conductors (such as, e.g., iron-based SC cables),

ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-MOXAT0106

graphene, etc. It is highly questionable at present whether they can result in a factor of ~5 saving in the magnet cost per (Tm).

Circular ee Colliders

Due to quickly growing SR power with E, circular *ee* colliders have very limited energy range to expand, even with the use of the ERL technologies [13]. For example, a E ~1 TeV machine will be need to be big (~200-300 km circumference), low luminosity O(10-100 fb^{-1}/yr) and require a lot of expensive RF acceleration, that would drive its cost above 2-3 LHCU.

Circular μμ Colliders

There are parameter sets available for 1.5, 3, 6, 10, 14 TeV circular $\mu\mu$ colliders [4]. Their major advantages are thought to be [14]: i) factor of ×7 in equivalent E reach compared to pp colliders; ii) arguably the best power efficiency in terms of ab^{-1}/TWh and iii) traditional core technologies. Major limitations include efficient muon production, fast muon cooling and potential neutrino radiation hazard.

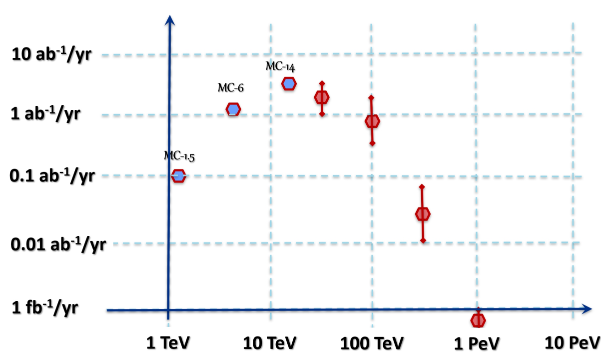

Figure 4: Estimated performance of the circular $\mu\mu$ colliders.

For the muon colliders $L \propto B$ and grows with the average particle production rate $dN/dt = f_r N$. At some energy, neutrino radiation dose $D \propto (dN/dt)E^3/\Phi$ sets the limit and the ultimate luminosity depends on suppression "neutrino flux dilution factor Φ, which some believe can be as high as 10-100:

$$L \propto B\frac{D\Phi}{E^2}\frac{N}{4\pi\epsilon_n\beta^*} . \quad (3)$$

That results in a scaling with energy as $L \propto 1/E^k$, where k=1...2 depending on whether the beta-function at the IP can be reduced as $\beta^* \propto 1/E$ – see Fig. 4. Above approximately 14-30 TeV, the power consumption of the muon colliders exceeds 2 TWh/yr and the construction cost estimates goes over 2 LHCU.

Traditional and Advanced Linear ee Colliders

In principle, linear colliders (LCs) can operate in e^+e^-/e^-e^- and $\gamma\gamma$ regimes (muons are possible, but their sources are expensive and of limited production rate; protons are possible, too, but pp collisions lose factor of 7 ineffective c.m. energy reach w.r.t. leptons) and be based on the NC RF, SC RF, plasma, wakefields, etc. Major advantages of such machines are: i) no SR power losses; ii) RF acceleration is a well developed technology. Their major limitations include: i) luminosity scales with total beam power as $L \propto (P/E)(N_\gamma/\sigma_y)$, ii) the last factor (N_γ/σ_y) determines the beamstrahlung energy spread while small beam size - often used to compensate for the loss of luminosity with E - makes jitter tolerances extremely challenging [15]; iii) plasma and wakefield acceleration is not fully matured acceleration technique yet (there are many unknowns such as the energy staging, production and acceleration of e^+, power efficiency of large facilities, cost, etc). Of course, there are some appealing alternatives under study: positron production and acceleration in plasma can be avoided by switching to *ee* operation and conversion into $\gamma\gamma$ at the IP, the beamstrahlung issues can be solved by colliding ultra-short bunches or switching to $\gamma\gamma$ or $\mu\mu$, etc. But in general, there are always some unavoidable challenges and limits, such as instabilities in the RF structures or plasma cells, jitter/emittance control problems that grow with the number of cells and elements, smaller and smaller beam sizes are required at the IP (approaching the limit of 1 A) [16].

Figure 5 presents estimated luminosities of very high energy linear lepton colliders, starting with the 1 TeV ILC (40 km) and 3 TeV CLIC (50 km). The cost of the latter is already 2.5 LHCU and P is about 3 TWh/yr. Higher energy 10-30 TeV LCs based on beam-plasma, laser-plasma and dielectric plasma wakefield acceleration – see Ref. [3, 17–19]), not speaking of 100 TeV and 1 PeV options, are extremely power hungry and costly beyond any reasonable limits on P and C.

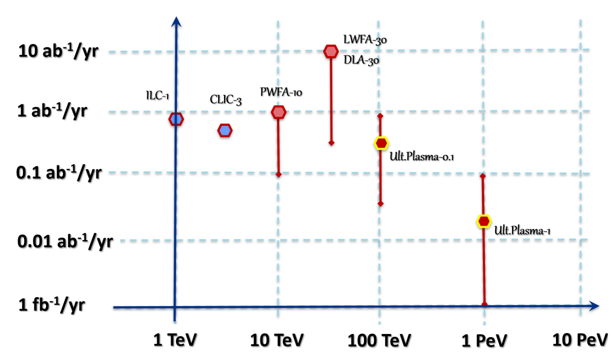

Figure 5: Estimated performance of the linear lepton colliders.

Exotic Linear μμ Colliders

An interesting opportunity of acceleration of muons in structured solid media, e.g., CNTs or crystals [20], promises extreme gradients 1-10 TV/m, continuous focusing and acceleration (no cells, one long channel, particles get strongly cooled betatron radiation), small facility size (10 km for 10 TeV) - and, therefore, promise of low cost - but very low luminosity 0.001-0.1 ab^{-1}/yr at best - see Fig. 6. Of course,

ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-MOXAT0106

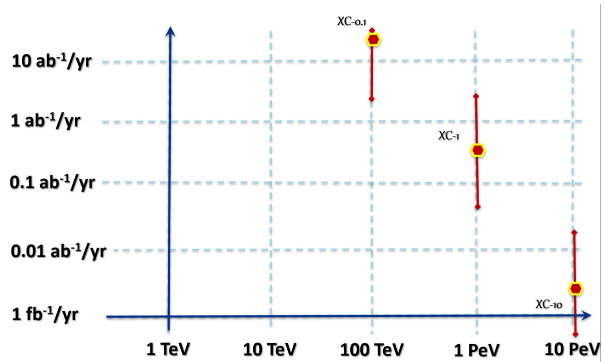

Figure 6: Estimated performance of the linear crystal $\mu\mu$ colliders.

such exotic technique is still under study [21] and awaits the proof-of-principle E336 experiment at the FACET-II [22].

SUMMARY

Recent US particle physics community planning exercise “Snowmass’21" was extremely instrumental as a forum for discussions among the entire particle physics community to develop a scientific vision for the future of particle physics. In particular, the Snowmass’21 Accelerator Frontier outlined community views on future high-energy hadron and lepton colliders, high-intensity beams for neutrino research and for “Physics Beyond Colliders”, beam physics, education and outreach as well as pointed out most promising directions in core accelerator technologies R&D, including RF, magnets, targets and sources. The Snowmass’21 Implementation Task Force report which presented a comparative evaluation of three dozens of proposed future HEP accelerator facilities, their realization strategies, timelines, and challenges, and has become a very useful document for the strategic HEP Planning.

Our analysis of ultimate limits of colliders emphasized the primary factors such as attainment of the highest possible energy E, high luminosity L and within socially affordable C. The cost is critically dependent on core acceleration technology. Employment of already existing injectors and infrastructure can greatly help to reduce C. For most collider types we found that the pursue of high energy typically results in low(er) luminosity. For example, one should not expect more than 0.1-1 ab^{-1}/yr at $E \geq 30$ TeV to 1 PeV. In the luminosity calculations, one might also assume the total facility (and, therefore, the beam) annual power consumption should better be limited to 1-3 TWh/yr.

For the considered collider types we found that : i) for circular pp colliders the overall $E-L-C$ feasibility limit is close or below 100 TeV (~14 TeV cme per parton); ii) for circular ee colliders the limit is below ~1 TeV; iii) for circular $\mu\mu$ colliders the limit is about 30 TeV; iv) for linear RF-based lepton colliders as well as for plasma $ee/\gamma\gamma$ colliders the limit is between 3 and 10 TeV; v) there are exotic schemes, such as crystal channeling muon colliders, which have promise of 0.1-1 PeV c.m.e. though with small Luminosity. All in all, muons seems to be the particles of choice the future ultimate HEP colliders [23].

ACKNOWLEDGEMENTS

This paper is mostly based on various reports and summaries of the Snowmass’21 "Accelerator Frontier" (which author was co-convener of, together with Steve Gourlay and Tor Raubenheimer [2, 25]), presentation at the Snowmass Workshop on the "Physics Limits of Ultimate Beams" [24] (January 22, 2021), IPAC’21 presentation [7] and recent review [4]. Author greatly appreciates input from and very helpful discussion on the subject of this paper with F. Zimmermann, M. Bai, W. Barletta, S. Gourlay, V. Kashikhin, V. Lebedev, M. Palmer, T. Raubenheimer, D. Schulte and A. Zlobin.

This manuscript has been supported by the Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

REFERENCES

[1] Snowmass’21, `https://snowmass21.org/`

[2] Snowmass Accelerator Frontier, `https://snowmass21.org/accelerator/`

[3] T.Roser*et al.*, “Report of the Snowmass 2021 collider implementation task force”, *arXiv preprint arxiv:2208.06030*. `doi:10.48550/arXiv.2208.06030`

[4] V.Shiltsev and F.Zimmermann, “Modern and future collider”, *Rev. Mod. Physics*, vol. 93, no. 1, p. 015006, 2021. `doi:10.1103/RevModPhys.93.015006`

[5] V.Shiltsev, “High-energy particle colliders: past 20 years, next 20 years, and beyond”, *Physics Uspekhi*, vol. 55, no. 10, p.1033, 2012. `doi:10.3367/UFNe.0182.201210d.1033`

[6] F.Zimmermann, “Future colliders for particle physics — ‘Big and small’ ”, *Nucl. Instrum. Methods A*, vol. 909, p.33, 2018. `doi:10.1016/j.nima.2018.01.034`

[7] V. D. Shiltsev, “General Approach to Physics Limits of Ultimate Colliders”, in *Proc. 12th Int. Particle Accelerator Conf. (IPAC’21)*, Campinas, Brazil, May 2021, pp. 2624–2627. `doi:10.18429/JACoW-IPAC2021-WEPAB017`

[8] M. Bai, F. Zimmermann, and V. D. Shiltsev, “Ultimate limits of future colliders”, presented at the North American Particle Accelerator Conf. (NAPAC’22), Albuquerque, New Mexico, USA, Aug. 2022, paper TUZD3, unpublished.

[9] V. Shiltsev, “A phenomenological cost model for high energy particle accelerators”, *J. Instrum.*, vol. 9, p. T07002, 2013. `doi:10.1088/1748-0221/9/07/T07002`

[10] V. Shiltsev, “On performance of high energy particel colliders and other complex scientific systems”, *Mod. Phys. Lett. A*, vol. 26, no. 11, p. 761, 2011. `doi:10.1142/S0217732311035699`

[11] W. Barletta, “Maximizing the luminosity of eloisatron, a hadron supercollider at 100 TeV per beam”, *AIP Conf. Proc.*, vol. 351, no. 1, p. 56, 1996. `doi:10.1063/1.49331`

ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-MOXAT0106

[12] J. Beacham and F. Zimmermann. "A very high energy hadron collider on the Moon", *New J. Phys.* vol. 24, no. 2, p. 023029, 2022. 10.1088/1367-2630/ac4921

[13] V. Litvinenko, T. Roser, and M. Chamizo-Llatas, "High-energy high-luminosity e+ e collider using energy-recovery linacs"", *Phys. Lett. B* vol. 804, p. 135394, 2020. doi:10.1016/j.physletb.2020.135394

[14] K. Long *et al.*, "Muon colliders to expand frontiers of particle physics", *Nature Physics*, vol. 17, p.289, 2021. doi:10.1038/s41567-020-01130-x

[15] T. Raubenheimer, "Estimates of emittance dilution and stability in high-energy linear accelerators", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 3, p. 121002, 2000. doi:10.1103/PhysRevSTAB.3.121002

[16] D.Schulte, "Application of advanced accelerator concepts for colliders", *Rev. Accel. Sci. Tech.*, vol. 9, p. 209, 2016. doi:10.1142/S1793626816300103

[17] C. Schroeder *et al.*, "Physics considerations for laser-plasma linear colliders", *Pys. Rev. Spec. Top. Accel. Beams*, vol. 13, p. 101301, 2010. doi:10.1103/PhysRevSTAB.13.101301

[18] Input to the European Strategy Particle Physics Update 2018-2020, Granada, Spain, May 2019, #007a, https://cafpe.ugr.es/eppsu2019/

[19] C. Geddes, M. Hogan, P. Musumeci, and R. Assmann, "Report of Snowmass 21 Accelerator Frontier Topical Group 6 on Advanced Accelerators", *arXiv preprint arxiv:2208.13279*. 10.48550/arXiv.2208.13279

[20] T. Tajima and M. Cavenago, "Crystal x-ray accelerator", *Phys. Rev. Lett.*, vol. 59, p. 1440, 1987. doi:10.1103/PhysRevLett.59.1440

[21] T.Tajima *et al.* (eds.), *Beam Acceleration in Crystals and Nanostructures*, World Scientific, 2020.

[22] R. Arinello *et al.*, "Channeling acceleration in crystals and nanostructures and studies of solid plasmas: new oppportunities", *arXiv preprint arxiv:2203.07459*. doi:10.48550/arXiv.2203.07459

[23] I.Strakovsky *et al.*, *Modern Muon Physics: Selected Issues*, Nova, 2020.

[24] C. Schroeder *et al.*, "Physics Limits of Ultimate Beams", https://indico.fnal.gov/event/47217/

[25] S. Gourlay, T. Raubenheimer, and V. Shiltsev, "Challenges of future accelerators for particle physics research", *Front. Phys.*, p. 557, 2022.