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Accelerator Technologies and Science: Progress and Outlook

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For over half a century, high-energy particle accelerators play a key role and shape modern nuclear and particle physics. They are also the instruments at the forefront of research for material science and biology. The physics needs continuously push us to invent novel ways to increase energy and improve the performance of accelerators, reduce their cost and make them more power-efficient. Over the past several years we witnessed remarkable progress in accelerator technology and beam physics: a) advances in accelerators for nuclear physics, basic energy sciences, neutrino research and rare processes, and colliders include new facilities such as FRIB, XFELs, and China SNS, beam power records at Fermilab and J-PARC, luminosity records in the LHC and SuperKEKB; b) impressive breakthroughs in the physics of beams like the demonstration and practical use of several new beam cooling schemes, and plasma acceleration to $O(5\text{ GeV})$ energies — with the beam quality good enough to support the FEL process; c) core technology advances, such as attainment of record-high RF accelerating gradients, magnetic fields and the field ramping rates, and development of MW-class beam targets. One can envision the bright future ahead for the accelerators worldwide with many leading facilities under construction – NICA, XFELs, High Luminosity LHC upgrade, PIP-II, ESS, FAIR, etc – which will become operational in due time, and great progress toward frontier accelerators such as Higgs factories (linear or circular) and multi-TeV pp, $\mu\mu$ or e^+e^- colliders.

Here we briefly overview the most notable accelerator facilities which recently became operational and are now employed for research in nuclear physics, basic energy sciences, neutrinos, and high energy particle frontier. We also present upcoming and planned future facilities and outline their main goals, challenges, and required R&D. Focus will be given to the core accelerator technologies such as magnets, RF acceleration, and targets as well as leading beam physics developments such as beam cooling, colliding beams and plasma acceleration.

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There are growing demands for more powerful, more productive, and more sophisticated particle accelerators as uniquely effective instruments for research in material science and biology, nuclear and particle physics, and other areas. Accelerator designers and builders continue to come up with new proposals and projects and invent new ways to improve the performance of accelerators, increase beam brightness, power and/or energy, and make them more cost- and power-efficient. Here, we outline the most notable developments in the field of accelerators and beams since 2017 : facilities for nuclear physics, basic energy sciences, neutrinos, high energy particle physics which came into operation since the previous PANIC-2017 conference; upcoming and planned future facilities and their main goals, challenges, and required R&D; advances in the core accelerator technologies such as magnets, RF acceleration, and targets; and beam physics breakthroughs in beam cooling, colliding beams and plasma acceleration. More detailed discussion on these topics can be found in Refs.[1–3].

1. New Accelerators and Upgrades

There are more than 30,000 particle accelerators in operation around the world. Most of them employ low energy beams ($\ll$ 1 MeV) and are used in industry. Less numerous are high energy accelerators for research - just over a hundred - and recently we have seen many new ones getting into operation.

Accelerators for nuclear physics: In October 2017, the Continuous Electron Beam Accelerator Facility (CEBAF) team at TJNAF in the US completed the 12 GeV electron beam energy upgrade of its continuous wave (CW) superconducting RF (SRF) accelerator [4]. A 30 MeV 10 mA CW SRF electron linac of the Advanced Rare Isotope Laboratory (ARIEL) has been commissioned at the TRIUMF lab in Canada in 2017-2019 [5]. Last year, the Facility for Rare Isotope Beams (FRIB) has been built at the Michigan State University in the US. It operates the SRF linac with 80.5 MHz to 322 MHz cryomodules [6] to accelerate a variety of ions upto 200 MeV/u energies with the design total beam power of 400kW. In April 2021 all 46 cryomodules have been commissioned to achieve 212 MeV/u. Besides these new machines, one should mention an outstanding success of the STAR/PHENIX and ALICE experiment operations at the RHIC at BNL (USA) and LHC at CERN, respectively. Since 2017 RHIC delivered more than 10 nb^{-1} of integrated luminosity in collisions of 4-100 GeV/u ions (Au, Zr, etc.) and over 0.5 fb^{-1} in 510 GeV center-of-mass-energy (c.m.e.) polarized pp collisions (with polarization degree up to 55%). The LHC ALICE experiment got ~1 nb^{-1} in Pb-Pb collisions at 5 TeV c.m.e., and 0.3μb^{-1} in Xe-Xe collisions (comparable luminosity also delivered to the CMS, ATLAS and LHCb experiments).

In Russia, NICA (Nuclotron-based Ion Collider fAcility) is in the final stage of construction. This nuclear physics research facility will collide ions (up to Au), with an option of polarized pp and dd collisions in the range of $\sqrt{s} = 4 - 11$ GeV c.m.e. The collider ring will employ superconducting magnets and several stochastic and electron cooling systems to reach high luminosity in the ion collisions of $\sim 10^{27}$ cm^{-2}s^{-1} [7]. NICA construction started in 2013, it is about 80% done at present, the first beam circulating in the new Booster synchtrotron was achieved in 2021, and the collider commissioning is expected to begin at the end of 2022 - early 2023. The Facility for Antiproton and Ion Research (FAIR) at GSI (Darmshtadt, Germany) envisions construction of a complex of rings and beamlines [8]. The largest of them is the 1.1 km circumference SIS-100 synchrotron that is based on the SC superferric 1.9 T magnets to accelerate protons to 29 GeV and/or ions to 2.9 GeV/u. The groundbreaking has taken place in 2017 and an impressive civil construction is currently underway with a goal of the SIS-100 machine installation in 2022. The Electron Ion Collider (EIC) project at Brookhaven National Laboratory [9] will bring to collisions 275 GeV protons or 100 GeV/u ions with 70% polarization (out of the existing RHIC complex, after upgrades) and 10 GeV electrons (out of a new 5-18 GeV storage ring). With the help of the so called *strong hadron cooling* the collider luminosity will be as high as 100 times that of its predecessor, the electron-proton collider HERA at DESY (Germany, 1992-2007). The project received approving *critical decision* CD-1 from the US DOE in July 2021, its construction is expected to begin in 2024 and operations expected to start early in the next decade.

Accelerators for basic energy sciences: Over the past few decades we have seen a true revolution in the technology of light and X-ray sources with many orders of magnitude boost in brillance of the photon beams [1]. There are two mainstream paths for that - one is construction of the ring-based 4th generation light sources (aka *diffraction-limited storage rings*) employing the *Multi-Band Achromat* (MBA) optics – an advanced focusing electron beam lattice invented in 1996 that allows $\sim$ 100 increase in the photon brightness [10]. The most recent examples include the ESRF EBS-upgrade – a 6 GeV electron storage ring with small horizontal beam emittance of 130 pm has become operational in 2020 in Grenoble (France), and a 3 GeV 150 pm SIRIUS facility got completed at the LNLS (Brazil) in 2021. There are several similar machines (or corresponding upgrades of existing 3rd generation light sources) under construction that are expected to get operational soon, including: in 2024 – the APS-Upgrade at Argonne National Lab (USA, 6 GeV, 70 pm), and SKIF at Novosibirsk (Russia, 3 GeV, 75 pm), in 2025 – SLS at the PSI (Switzerland, 2.7 GeV, 135 pm), in 2026 – the ALS-Upgrade at LBNL (USA, 2 GeV, 70 pm), and HEPS at Beijing (6 GeV, 60 pm), in 2027 – HALF at Hefei (China, 2.2 GeV, 85 pm), and PETRA-IV at DESY (Hamburg, Germany, 6 GeV, 10 pm).

Another path to even higher brilliance is offered by the *self-amplified spontaneous emission (SASE)* free-electron lasers (FEL), also known as X-FELs [11]. The method – first proposed in 1980, with proof-of-principle demonstrations performed in 1985-1998 – employs high-energy (0.1-10's of GeV) high-brightness electron beams out of linear accelerators which are then sent through 10's of meters of special undulator magnets where collective interaction of the electrons with their own radiation leads to exponential growth of the X-ray radiation power. The largest of these machines, the 17.5 GeV European XFEL employing a SRF linac has been commissioned in 2017 at DESY (Hamburg, Germany), followed in 2017 by the 10 GeV PAL-XFEL in Pohang (Korea), the 5.8 GeV SwissFEL at the PSI (Switzerland), and the 0.3 GeV DCLS in China. This year, the Shanghai X-ray FEL user Facility (530 m long, 1.6 GeV) was commissioned in China. Two SRF-based, high repetition rate, high power XFELs will soon get into operation – the 4 GeV LCLS-II at SLAC (USA) in 2022, and 8 GeV Shanghai SHINE facility in China in 2025.

Neutron sources: The most powerful to date accelerator-based neutron source - the Spallation Neutron Source (SNS) at ORNL (USA) - comprises a 1 GeV 805 MHz SRF linac and an accumulation ring, and delivers 1.4 MW of proton beam power onto a spallation target since 2007. The 2 MW power upgrade is scheduled for 2025, and be followed by the second target station installation and further beam power upgrade to 2.8 MW. Another leading facility is the China Spallation Neutron Source (CSNS) which operates a 80 MeV H- linac and a booster ring to accelerate protons to 1.4 GeV before extraction and transport to the target [12]. The first neutrons were detected in August 2017, the facility achieved 0.1 MW beam power on target in February 2020, and the planned upgrades aim to get it first to 0.2 MW, then to 0.5 MW.

The European Spallation Source (ESS) is under construction in Lund (Sweden) and will overtake the beam power leadership with its 5 MW 2 GeV pulsed SRF proton linac [13]. The project started 2014 and now is about 80% complete. The first beam was sent through the RFQ in the Fall of 2021 and users program is expected to start in 2023.

High intensity accelerators for neutrino research: The leading accelerator-based facilities for high energy neutrino research are *superbeams* based on conventional beam dump technique: an intense high energy proton beam is directed onto a thick nuclear target producing mostly pions and kaons, which are captured by focusing magnetic horns in order to obtain well directed beam of same charge secondaries. High-energy neutrino beams are products of the decays of charged pions and kaons in a long decay channel [2]. Superbeams strive to operate with a proton beam intensity closer to the mechanical stability limit of the primary targets which is at present $O(1\text{ MW})$. The most powerful accelerators for neutrino research to date are the rapid cycling synchrotron facilities J-PARC in Japan which has reached 515 kW of the 30 GeV proton beam power, and the Fermilab Main Injector delivering up to 862 kW of 120 GeV protons on target. They support neutrino oscillations research programs at the SuperK experiment (295 km from J-PARC) and MINOS (810 km from Fermilab), correspondingly.

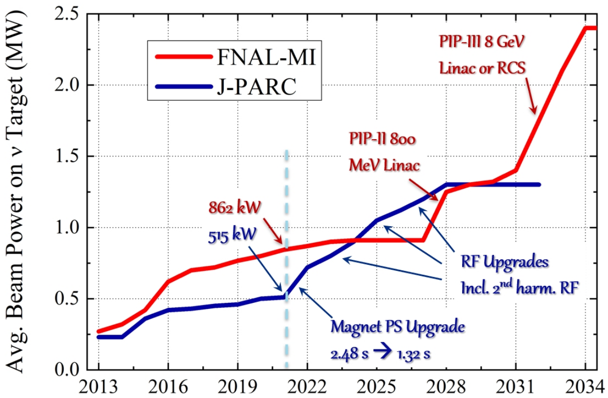

Figure 1: Beam power progress and plans for J-PARC and Fermilab Main Injector - two leading superbeam facilities for neutrino research.

The needs of neutrino physics call for the next generation, higher-power, megawatt and multi-MW-class superbeams facilities. Average proton beam power on the neutrino target scales with the beam energy E_b, number of particle per pulse N_{ppp} and cycle time T_{cycle} as $P_b = (E_b N_{ppp})/T_{cycle}$. Corresponding upgrades of the RF system and magnet power supply ramping rate $1/T_{cycle}$ have been initiated at J-PARC [14], while Fermilab has started construction of a 800 MeV SRF H- PIP-II linac (Proton Improvement Plan-II) [15] that will help to boost N_{ppp} and the Main Injector beam power to above 1.2 MW, and considers further facility upgrades to get to 2.4 MW [16] - see Fig.1.

High energy physics 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 [3]. There are seven colliders in operation at present: five low energy electron-positron ones (DAΦNE in Frascati, Italy, VEPP-4M and VEPP-2000 in Novosibirsk, Russia, BEPC-II at IHEP, Bejing, and Super-KEKB at KEK, Japan) and two high-energy hadron colliders - RHIC at BNL and LHC at CERN. The Large Hadron Collider represents nowadays "accelerator frontier" with its 6.5 TeV energy per beam, $2.1{\cdot}10^{34}$ cm^{-2}s^{-1} luminosity and some 1 TWh of annual total site electric energy consumption. Since the start of operation in 2009, the LHC has delivered 190 fb^{-1}/IP in pp collisions – mostly over the past few years at 13 TeV c.m.e., exceeding its design luminosity goal by a factor of two. The High-Luminosity LHC upgrade will be completed by 2028 with the goal of reaching 250 fb^{-1}/yr at 14 TeV c.m.e. via doubling the beam current, lower beta-function at the IPs with new Nb_3Sn SC IR magnets, and using *beam crabbing* and *luminosity leveling* techniques [17]. The upgrade will be followed by a decade of operation to get the total integrated luminosity of 3-4 ab^{-1}. The Super-KEKB 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 $3.1{\cdot}10^{34}$ cm^{-2}s^{-1}, and aspires to reach $80{\cdot}10^{34}$ cm^{-2}s^{-1} [18] – a whopping 40-times over its predecessor KEK-B (1999-2010).

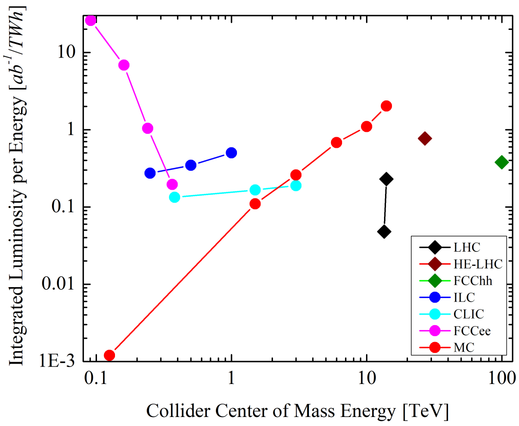

Figure 2: Energy efficiency of present and future colliders. Annual integrated luminosity per Terawatt-hour of electric power consumption as a function of the centre-of-mass energy. The LHC — both present and expected after its high-luminosity upgrade (black diamonds) — is contrasted with a variety of proposed particle colliders: the Muon Collider (MC, red circles), the Future Circular electron-positron Collider (FCC-ee, magenta circles) assuming experiments at two collision points, the International Linear Collider (ILC, blue circles), the Compact Linear Collider (CLIC, cyan circles), the High Energy LHC (HE-LHC, magenta diamonds), and the Future Circular proton–proton Collider (FCC-hh, green diamonds). The effective energy reach of hadron colliders (LHC, HE-LHC and FCC-hh) is approximately a factor of seven lower than that of a lepton collider operating at the same energy per beam.

At present, under consideration are as many as eight Higgs/ElectroWeak factories – e^+e^- colliders such as the CEPC in China and FCCee at CERN, both 100 km circumference, which require O(100 MW) RF systems to sustain high luminosity [19]; or a 11 km long CLIC (CERN) two-beam normal-conducting RF linear accelerator with average 72 MV/m gradient [20]; or the 21 km long International Linear Collider (ILC) based on SRF 31.5 MV/m SRF linacs [21]. There are also about two dozens of energy frontier colliders that go beyond LHC in their discovery potential.

Among them are the 3 TeV CLIC option (100 MV/m accelerating gradient, 50 km long), two 100 km circumference pp colliders SPPC in China (75 TeV cm.e., based on 12 T SC magnets) and FCChh at CERN (100 TeV, 16 T) [22], and more economical 10-14 TeV c.m.e. $\mu^+\mu^-$ collider (10-14 km circumference, 16 T magnets) [23]. Besides technical feasibility and affordable cost, the most critical requirements for the post-LHC energy frontier colliders include the center-of-mass energy reach, the required AC site power consumption (see Fig.2), the required duration and scale of the R&D effort to reach proper readiness - see detailed discussion in Ref.[3].

2. Accelerator Technology Progress

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 remaining 15 ± 10% [24]. While the last two parts are mostly determined by industry, the magnet and RF technology is a linchpin of the progress of accelerators. At present, the state-of-the-art NC (warm) magnets are being built for the 4th generation light sources, they are of very high quality and reliability and can usually be bought from hi-tech companies. Superconducting NbTi magnets needed for colliders and FELs' undulators operate with fields up to 8.3 T (in the LHC). Recently tested US MDP prototype Nb_3Sn magnet has reached 14.5 T [25]. The fastest rapid cycling magnets show up to 300 T/s ramping rates in the HTS-based SC magnet test at Fermilab [29].

The highest gradient large-scale NC RF system is the 28 MV/m linac of the SwissFEL at the PSI (Switzerland). Up to 100MV/m accelerating beam gradients were achieved in the CLIC 12 GHz structures at the CERN test facility, while up to 150 MV/m gradients were reported in the first test of short 11.4 GHz NC structures cooled to 77 K at SLAC [26]. As for the SC RF, the lagest scale accelerator to date is the 17 GeV 1.3 GHz pulsed linac of the European XFEL at DESY that has an average beam gradient of 25 MV/m with a nominal SRF cavity quality factor of $Q_0 \simeq 1 \cdot 10^{10}$ at 2 K. The full ILC specification on the beam acceleration gradient of 31.5 MV/m have been demonstrated at the FNAL FAST facility [27]. Recent advances in the SRF cavity processing such as the *nitrogen doping* allow further improvement of the quality factor to $(3-6) \cdot 10^{10}$ (hence, saving on the required cryogenic cooling power) and aim for about 50 MV/m gradients in 1.3 GHz structures [28].

An active ongoing accelerator R&D program for future multi-MW proton beams includes developments of more efficient power supplies with capacitive energy storage and recovery, more economical RF power sources such as 80% efficient klystrons, magnetrons, and solid-state RF sources (compare to current ~ 55%), as well as studies of beam target material properties, new forms (foams, fibers), and new target designs (e.g., rotating or liquid targets) [30].

3. Beam Physics Advances

There are many notable recent developments in the physics of beams - see. e.g., Ref.[3] - and here we briefly present only those in the fields of beam cooling and acceleration in plasma.

Beam cooling: Beam cooling refers to the process of increase of the beam phase space density (ideally, 6D and loss-less) or, equivalently, beam emittance reduction. Widely used methods include synchrotron radiation damping, electron, stochastic and laser cooling. Over the past few years, we have seen several novel cooling schemes experimentally demonstrated at operational accelerators [31]. A true breakthrough was demonstration of the *ionization cooling* of 140 MeV/c muons at the MICE experiment at RAL (UK) – some 10% beam emittance reduction was observed in a single pass through the cooling section. In 2020, *"bunched" electron beam cooling* of ions in RHIC ($\gamma \sim 5$) – remarkable by the pioneering use of high quality bunched electron beams from an electron beam RF photoinjector gun (before, only DC electron accelerators were used with limited capability to get to very high energies) – was demonstrated at BNL. Earlier this year another outstanding result was reported by the Fermilab team which has successfully carried out a proof-of-principle experiment on the *optical stochastic cooling* of 100 MeV electrons in the IOTA ring in which the use of undulator magnets - instead of electrostatic pickups in traditional stochastic cooling setups - allowed to expand the feedback system bandwidth by several orders of magnitude to a THz range. Finally, the proof-of-principle tests of a novel *coherent electron cooling* of the record-high energy 26 GeV/u ions have started this year at BNL.

Acceleration in plasma: Electric fields due to charge separation in plasma can sustain unmatched gradients, hence having enormous promise for accelerator technology. To date, several experiments demonstrated O(1-10 GeV) acceleration over 0.1-10 m long plasma channels. There are two remarkable recent (2021) developments on the way to practical plasma-based beam accelerators: i) EuPRAXIA – a 569 MEUR European plasma accelerator project proposal, supported by 50 institutions from 15 countries, and aiming for 5 GeV electron beam acceleration and development of plasma-based FELs – has been included in the ESRFI 10-20 yrs roadmap; and ii) the laser wakefield accelerator at SIOM/CAS in Shanghai (China) has achieved an outstanding quality of the accelerated 0.5 GeV electron beam (produced by a 200 TW laser exciting plasma in a 6 mm He gas jet) sufficient for initiation of the FEL generation of 27 nm light in the downstream undulators – making it the first demonstration of the plasma-based FEL.

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