NEW TRENDS IN PARTICLE ACCELERATION

L.S. Shirshov[1]

Institute for High Energy Physics, Protvino, Russia

Sir J.J. Thomson discovered the electron 100 years ago using a small glass tube, which was shorter than 27 cm. The 27 km long Large Electron Positron collider CERN (LEP2) began its final year of operation at a record energy of 104 GeV per beam. The base elements of this collider are superconducting accelerating cavities (7 MV/m). Results from LEP2 have already put down the mass of the Higgs particle to the 108 – 190 GeV range [1, 2].

If someone had told J.J. Thomson that his identifacation of the electron in 1897 in his Cambridge Laboratory would lead to greater understanding of electricity and, thus, to huge and tangible benefits, he likely would have been pleased. Thomson's motivation, like that of most of high energy physicists, was to discover a fundamental truth [3].

- The Future of Particle Physics [4].
- Current status of elementary particle physics [5].
- Particle Physics — One Hundred Years of Discoveries. An Annotated Chronological Bibliography [6].

Table 1. *e^+e^- Collider Parameters.*

N	Name	Start Date	Beam Energy [GeV]	Luminosity $[10^{30} cm^{-2} c^{-1}]$	Bunch Lenght [cm]	Circumference [km]
1	VEPP-2M (BINP)	1974 [1997]	0.7 [0.55]	5 [100]	3	0.018
2	BEPC (China)	1989	2.2	10	5	0.2404
3	VEPP-4M (BINP)	1994	6	50	5	0.366
4	CESR (Cornell)	1979	6	600 (1996)	1.8	0.768

A factory is an accelerator facility that is optimized to produce some kind of particles copiously for high-energy physics studies [7]. Three high-current e^+e^- colliders to study the mechanism of CP-invariance violation started in 1999: the collider in Frascati (Italy) will study K-mesons and those in Japan and USA, B-meson decays. Parameters of the facilities are given in Table 2.

Table. 2. *Factory Parameters.*

N	Name	Start Date	Beam Energy [GeV]	Luminosity $[10^{30} cm^{-2} c^{-1}]$	Bunch Lenght [cm]	Circumference [km]
1	DAΦNE (Frascati)	1999	0.51 (0.75 max.)	135 [540]	3	0.0977
2	Φ-factory (BINP)	?	0.55	2500	1	0.047
3	KEKB (KEK)	1999	e^- x e^+:8x3.5	10000	0.4	3.016
4	PEP-II (SLAC)	1999	e^- x e^+:9x3.1	300	1	2.2

Note that to be able to observe B-mesons decays in flight (not at rest), the colliding electrons and positrons must have unequal energies. Both B-factories at SLAC and KEK started collecting data in 1999, leading to first results. Each of them single-experiment projects based on novel asymmetric

---

[1] Leonid Shirshov — e-mail: shirshov@mx.ihep.su

electron-positron colliders, were challenging on the accelerator front. With high luminosity B-factories now in operation at PEP-II and KEKB the CLEO collaboration at CESR(Cornell) is looking for altnernative opportunities after some 20 years of making milestone contributions to the physics of B-mesons.

The colliders LEP1 and SLC were constructed for precision measurements of the properties of Z^0 bosons. The LEP2 machine was built to study the creation W^+W^- boson pairs and to search for new particles [8]. This collider with superconducting cavities operates in the same 27 km long tunnel in which LEP1 worked before it. The biggest electron-positron collider is the LEP2 ring now running at the cms energy above 200 GeV. This represents the limit of possibility for this kind of ring. The electrons and positrons emit so much synchrotron radiation, and the intensity grows so rapidly with increasing energy that it is impractical to contemplate machines at much higher energies.

Table 3. *High-Energy* e^+e^- *Collider Parameters.*

N	Name	Start Date	Beam Energy [GeV]	Luminosity $[10^{30} cm^{-2} c^{-1}]$	Bunch Lenght [cm]	Circumference or lenght [km]
1	SLC (SLAC)	1989	50	0.8	0.08	1.45+1.47
2	LEP1 (CERN)	1989	55 (1994)	11	1.8	26.66
3	LEP2 (CERN)	1996	87 (1996) 94 (1997)	34 (68 GeV) 24 (Z^0)	1.8	26.66

Modern colliding beam machines are circular storage rings, within which some combination of counter-rotation beams of electrons, positrons, protons and antiprotons collide with each other. There are grounds for hoping that the Large Hadron Collider (LHC) with a proton beam energy of 7 TeV, whose construction is to begin in the tunnel in which LEP2 is operating, will be completed in 2005 [9, 10].

Table 4. *High-Energy* $ep, pp, p\bar{p}$ *Collider Parameters.*

	Tevatron	HERA	UNK-II	SSC	LHC
Start Date	1987 г.	1992 г.	?	Terminated	2005 г.
Particles	$p\bar{p}$	e, p	p, p	p, p	p, p
Beam Energy (TeV)	0.9-1	e: 0.030 p: 0.82	3	20	7
Luminosity $(10^{30} cm^{-2} c^{-1})$	25 (1995)	16	10^3	10^3	3,8 10^4
Bunch lenght (cm)	50	e:0.83; p:8.5	40	6	7.5
Beam Lifetime (hr)	7-30	10	10	24	10
Acceleration period (s)	86	600	100	1200	1500
Injection energy (TeV)	0.15	e:0.012; p:0.04	0.4	0.45	2
Circumference (km)	6.28	6.336	20.772	87.12	26.659

In 1993 the US Congress canceled the decision to build the Superconducting Super Collider (SSC) [11] after 3 billion dollars had been spent on its construction. In Protvino the ring tunnel longer than 20 km has been completed for superconducting acceleration-storage complex (UNK) with proton energies 3 TeV, but bulding work was stopped.

BNL press release:

“2000 June 12 First Gold Beam-Beam Collision Events at RHIC at 30+30 GeV/c per beam recorded by STAR”

“Cool-down of RHIC started on February 5. In the evening of June 12 beams were successfully cogged and steered at 28 GeV at two interaction regions (STAR and PHOBOS) and collisions were observed. On June 14 and 15 collisions were established at the 8 o’clock (PHENIX) and 2 o’clock (BRAHMS) interaction regions, respectively.

In this first run, RHIC scientists and enineers achieved collisions with beam energies of about 30 billion electron volts (GeV) per nucleon (proton or neutron) — four times more energetic than collisions at CERN. Eventually, the Brookhaven scientists will accelerate the ions to collide at energies of 100 GeV per nucleon in each beam — resulting in collisions approximately ten times more energetic than those at CERN.”

A reason for rejection the BNL project of a Proton-Proton Storage Accelerator Facility ISABELLE, planned to collide protons an energy 2x400 GeV, was the development of SSC project. Another reason was in the difficulties to create a reliable and technologically convenient supeconducting (SC) dipole and quadropole magnets.

It should be noted that the experience gained at the BNL during the development of the ISABELLE magnets was later used in creating SC dipoles for the RHIC project. The construction of RHIC dipole with single layer SC coils has proved to be simple and economic. The iron yoke was used as a force support for the bandage. These magnets were manufactured on the commercial scale.

According to the RHIC project [12, 13], the existing tunnel with a lenght of 3.8 km accommodate two rings containing 1740 SC elements. A single refrigerator with a power of 24.8 kW is capable of cooling the SC magnets to a temperature below 4.6 K.

Table 5. *SC-Magnet Dipole Parameters*

N	Name	Max. B [T]	Field Inject. [T]	I [кА]	T [K]	Number SC-dipole	Lenght [м]	Aperture [мм]
1	Tevatron (USA)	4.4	0.66	4.4	4.6	774	6.1	76
2	HERA (FRG)	4.68	0.23	5.03	4.5	422	8.8	75
3	RHIC (USA)	3.46	0.4	5.09	4.6	396	9.4	80
4	UNK-II (Protvino)	5.0	0.67	5.25	4.6	2176	5.77	80
5	SSC (USA)	6.79	0.68	6.5	4.35	3972	15.2	50
6	LHC (CERN)	8.36	0.58	11.5	1.9	1232	14.2	56

Another example of using SC magnets for holding the proton beam on orbit is the Hadron-Electron Ring Accelerator facility (HERA) for the opposite electron-proton beams with the energies of 30 and 820 GeV, respectively [14]. HERA is the first collider featuring interaction between opposite beams of light and heavy particles.

Prototype magnets for the proton ring of HERA were constructed as SC dipoles with both “warm” and “cold” yokes. SC dipoles with cold yoke were selected as the final variant. This construction is more rigid and requires no spesial holders in contact with room-temperature ambient.

The magnet system is the key to the problem for the rise of a proton synchrotron energy and its most expensive component. The main progress in the development of high energy particle accelerators in recent years is related to the achievements in the technology of SC magnet manufacture on a commercial scale. There are sufficiently detailed reviews of the SC magnets for particle accelerators, the most recent being [15]. The proceedings of the CERN accelerator schools cover the problems encountered in the design, manufacture, and operation of the SC magnets [16, 17].

The coils of the modern SC dipoles are made of niobium-titanium alloys. The most significant achievement in the field of SC materials in the past two decades was discovered in 1986 high-temperature superconductivity (HTSC). The prospects of using new HTSC in magnet coils seem to be very intriguing, but technological difficulties and high costs of the materials have presented no such possibility up to now. Those materials are highly brittle and are not used in the coil of existing magnets. At present HTSC are employed as currents leads for reducing the heat leak. H. Hirabayashi considered some variants of using HTSC in the magnets for particle accelerators [18].

During the past decade specialists have extensively developed SC dipoles with bending magnetic field above 10 T. The record 13.5 tesla dipole field in the 5 cm beam aperture was achived at the Lawrence Berkeley National Laboratory in 1997 [19]. R.Scanlan and colleage are investigating the use brittle Nb_3Sn cable to create prototype dipole magnet with 1 meter long. Design and construction of a hybrid -$Nb_3Sn, NbTi$-dipole magnet and 16 Tesla Nb_3Sn-dipole development were reported [20, 21, 22].

The next step forward in advancing the hadron collider energy beyond the LHC could be the Very Large Hadron Collider (VLHC), and the study is focused on technology and cost reduction. Preliminary studies of 100 TeV center-of-mass colliders made with magnets of different field strenght 1.8 T and 12.6 T, were at workshop on VLHC at Snowmass [23]. Two groups has started to study machine called *"Pipetron"*, based on superferric magnets with 1.8 T [24, 25].

The Steering Committee for a future very large collider has been established to coordinate efforts the leading Laboratories in the US to achive a superconducting proton-proton collider with approximately 100 TeV cm and approximately $10^{34}cm^{-2}c^{-1}$ luminosity. The development of the SC magnets is key component the VLHC.

The muon colliders could open another way to lepton collisions at extremely high energies. The $\mu^+\mu^-$ Colliders discussed since the 1960, would be truly much smaller in comparison with to the electron-positron colliders. The main difficulty is the short lifetime of muons (near two microseconds), however, a muons with energy 1 TeV live for 20 ms.

A sketch of a muon collider is as follow: a very intense proton source creates a beam which is extracted and targeted, the pions and decay muons are focussed and collected. The large phase space occupied by the muon beam is diminished by "ionization cooling". Then the muons are accelerated in a racetrack linac before being injected into storage-ring collider [26, 27, 28].

One can see that each component of the facility can support other physical programs [29]. A very intense source of protons with the energy of tens of GeV is a good device for studying properties of the hadrons, including the rare decays of kaons. Perhaps the most promising secondary application is utilization of neutrinos beams created by the decaying muons. Such a program would allow interesting neutrino physics.

The size and cost of future large accelerators needs the framework of an international collaboration. A study of the Neutrino Factory based on a Muon Storage ring is being developed in the framework of the FNAL (Batavia) and IHEP (Protvino). Many of the components of a Neutrino Factory system are at the limit of what technologically possible. The differential subsystem include four long SC solenoids to focus a large emittance muon beam to allow its capture and cooling into the accelerating part of complex [30]. With help of other European laboratories, CERN has started a study on a facility for high-intensity neutrino beams as produced by a Neutrino Factory [31].

Note that technical facility of IHEP (Protvino) is useful base of studies of a muon storage ring. The accelerating-storage complex UNK is situated in an underground circular tunnel with circumference of 20.77 km. Up to now the long tunnel with a 5.1 m diameter has been excavated and prepared for installing the equipment.

The first stage of UNK includes a proton injection channel from U-70 (commissioned in 1994), ring accelerator in the underground tunnel, buildings of conventional engineering systems. Tunneling has been fully completed and now the ring tunnel has 2nd second long in the world (after LEP), but the UNK tunnel diameter is above the LEP.

70-GeV Proton Synchrotron (U-70) has fast and slow extraction systems and high intensity of the proton beam 1.7x10^{13} ppp [32].

The SLAC Linear Collider (SLC) was the first and only lepton linear collider built so far. The SLC during its final run in 1997-98 has been 3x$10^{30} cm^{-2} c^{-1}$ luminosity. The SLC built upon the existing SLAC linac, was intended as an inexpensive way to explore the physics of the Z^0 boson while demonstrate this new technology. In fact, one of the reason to build the SLC was to develop this technology and the SLC was the first prototype of a new type of accelerator, the electron-positron linear collider [33, 34].

The design plans for the construction of linear electron-positron colliders are still at early stage [35]. Next Linear Collider may start operation after 2010 with energy 500–1000 GeV. The projects NLC, TESLA and JLC envisage the possibility of gamma-gamma and gamma-electron collisions. At present the accelerating field strenght of superconducting cavities for TESLA is as high as 40 MV/m [36].

An overview of the various schemes for future accelerators are given in [37, 38, 39, 40], a good guide to experimental particle physics literature is ref. [41].

References

[1] LEP achieves record energy levels: in *CERN Courier, Vol. 40, N 5, June 2000, p.5.*

[2] Frank Close. The electron century: in *CERN Courier, Vol. 40, N 1, Jan./Feb. 2000, p.15.*

[3] H. Rechenberg. Hundred Years of Electron in Physics. *Proceedings of the XX Workshop on the Fundamental Problems of High Energy Physics and Field Theory, Protvino, Russia, 1997, p.143.*

[4] James D.Bjorken. The Future of Particle Physics *SLAC-PUB-8468, June 2000 arXiv:hep-ph/0006180.*

[5] L.B.Okun. Current status of elementary particle physics *Physics-Uspekhi 41(6), 553-557 (1998).*

[6] V.V.Ezhela et al. Particle Physics - One Hundred Years of Discoveries. An Annotated Chronological Bibliography. *AIP Press, New York, 1996.*

[7] Shin-ichi Kurokawa. B, τCharm, and Φ Factories *The 11 th Symposium on Accelerator Science and Technology, Harima Science Garden City, 1997.*

[8] D.Treille. LEP1 and LEP200: Results and Prospects. *Proceedings of the XX Workshop on the Fundamental Problems of High Energy Physics and Field Theory, Protvino, Russia, 1997, p.78.*

[9] CERN, European Organisation for Nuclear Research.: The Large Hadron Collider, Conceptial Design, CERN 91-03, Geneva, 1991.

[10] L.Foa. Physics at LHC. *Proceedings of the XX Workshop on the Fundamental Problems of High Energy Physics and Field Theory, Protvino, Russia, 1997, p.15.*

[11] Conceptual Design of the Superconducting Super Collider,*SSC-5R-2020, SSC Central Design Group, LBL* (Berkeley, CA 5472), March 1986.

[12] Proposal for a Relativistic Heavy Ion Collider,*BNL 51932*, (March 1986).

[13] Conception Design of the Relastivistic Heavy Ion Collider, *Brookhaven National Laboratory, May 1989.*

[14] Proposal for a large electron-proton colliding beam facility at DESY. *DESY HERA 81-10 (July 1981).*

[15] L.S.Shirshov. Superconducting magnets for accelerators. *Instruments and Experimental Techniques*, Vol.41, N 5, 1998, p.595.

[16] Superconductivity in particle accelerators *CERN 96-03 (Proceedings CAS CERN Accelerator School, Editor: S.Turner)(Geneva, 1996).*

[17] Measurement and alingement of accelerator and detector magnets *CERN 98-05 (Proceedings CAS CERN Accelerator School, Editor: S.Turner)(Geneva, 1998).*

[18] H.Hirabayashi. Status of High Temperature Superconductor Development for Accelerator Magnets. *Preprint KEK-94-75* Japan, 1994.

[19] B.Schawarzschild. Accelerator Magnet with Brittle Superconductor Sets a Record. *Physics Today, August 1997, vol.50, no.8, part 1, p.19.*

[20] A.Koski and S.L.Wipf. Computation design Study for an Accelerator Dipole in the Range of 15-20 T. *IEEE Trans. on Magnetics, Vol. 32, No. 4, 1996, p.2159.*

[21] S.Caspi et al. Design and Construction of a Hybrid -$Nb_3Sn, NbTi$- Dipole Magnet. *IEEE Trans. on Applied SC (ASC'96), Vol. 7, No. 2, June 1997, p.727.*

[22] T.Elliott et al. 16 Tesla Nb_3Sn-Dipole Development at Texas University *IEEE Trans. on Applied SC (ASC'96), Vol. 7, No. 2, June 1997, p.555.*

[23] D.Denisov and S.Keller. Summary of the Very Large Hadron Collider Physics and Detector Subgroup. *FERMILAB-CONF-97/018-T.*

[24] G.W.Foster and E. Malamud. Low-Cost Hadron Colliders at Fermilab. A Discussion Paper. *Preprint Fermilab-TM-1976*, Batavia, 1996.

[25] A.M.Baldin et al. How a 100 TeV Synchrotron/Collider Based on the Nuclotron-Type Cryomagnetic System Would Look. *Preprint JINR E9-96-343 Dubna, 1996.*

[26] D.V.Neuffer Acceleration to Collisions for the $\mu^+\mu^-$ Collider. *Preprint Fermilab-Conf-96/010, Batavia, 1996.*

[27] Muon colliders move nearer. *CERN COURIER, Vol.37, N.10, December 1997, p.1.*

[28] D.V.Neuffer $\mu^+\mu^-$ Colliders. *Preprint CERN 99-12, Geneva, 16 December 1999.*

[29] F.F.Tikhonin. Muon Colliders: Feature of the Physics Potential. *Proceedings of the XXII Workshop on the Fundamental Problems of High Energy Physics and Field Theory, Protvino, Russia, 1999, p.41.*

[30] N.Holtkamp. Intense muon sources for muon storage rings and colliders. *Proceedings of EPAC 2000, Vienna, Austria, p.103.*

[31] H.Haseroth. Status of studies for a Neutrino Factory at CERN. *Proceedings of EPAC 2000, Vienna, Austria, p.253.*

[32] Catalogue of high energy accelerators *HEACC'98 JINR, Dubna, Sept. 1998.*

[33] R.Assmann et al. SLC - the end game. *Proceedings of EPAC 2000, Vienna, Austria, p.18.*

[34] N.Phinney. SLC Final Performance and Lessons. *Proceedings of XX Intern. Linac Conf. 2000, Monterey, California, USA, p.1.*

[35] T.O.Raubenheimer. Progress in the Next Linear Collider Design. *Proceedings of XX Intern. Linac Conf. 2000, Monterey, California, USA.*

[36] R.Brinkmann. TESLA linear collider design and R@D status. *Proceedings of XX Intern. Linac Conf. 2000, Monterey, California, USA, p.11.*

[37] A.Chao. Accelerators for high energy physics research. *SLAC-PUB-95-6947 (Stanford, USA, 1995).*

[38] E.Keil. Accelerators for the 21 st century *CERN-SL-98-067 (AP) (Geneva, Switzerland, 1998).*

[39] E.Keil. Large circular colliders. *CERN-SL-98-70 (AP) (Geneva, Switzerland, 1998).*

[40] K.H*ü*bner. Future Accelerators *CERN-SL-98-065 (DI) (Geneva, Switzerland, 1998).*

[41] V.V.Ezhela et al. A guide to experimental particle physics literature 1994-1998. *(Berkeley Lab., USA, October 1999).*