Radiation Protection Dosimetry (year), Vol. 0, No. 0, pp. 0–0
DOI: 10.1093/rpd/nc0000

APPLICATION OF PARTICLE ACCELERATORS IN RESEARCH

Giovanni Mazzitelli
Laboratori Nazionali di Frascati – INFN – Via E. Fermi, 40 00044 Frascati, Roma

Received month date year, amended month date year, accepted month date year

Since the beginning of the last century, accelerators started to play a fundamental role as powerful tools to discover the world around us, how the universe has evolved since the big bang and to develop fundamental instruments for every day life. Although more than 15.000 accelerators are operating around the world only very a few of them are dedicated to fundamental research. An overview of the preset high energy physics (HEP) accelerator status and prospective are presented.

Accelerators in research are widely used in many fields of fundamental physics from elementary particles, astrophysics and cosmology to solid state, nuclear and atomic physics. They are also essential tools in chemistry and biology, where the light produced by particles circulating in the accelerator, the synchrotron radiation, is tuned to “see” molecules, atoms and nuclei structures. Recently, many spallation sources appeared in the world finalized to produce neutrons in order to study condensed matter and material science.

Anyhow most of accelerators have been mainly devoted to medicine, diagnostic and radiotherapy and today also to food preservation, sterilization, as well as to the element analysis and archeology, opening an impressive scenario of application in every day life (1).

HIGH ENERGY PHYSICS ACCELERATORS

The first typology of accelerators introduced above is typically called “colliders” or high energy physics (HEP) accelerators. They play an important role not only as an important tool for discovery but also because they can be considered as the “Formula 1” of accelerators, where most of research and development of new technologies are actually carried out.

Nowadays we are able to describe the universe surrounding us with the so-called “standard model”, a powerful and very accurate theory developed during the 20th century describing the interaction between the fundamental components of matter discovered up to now: quarks and leptons (2). The main tools to understand such fine structure of nature have been accelerators and HEP detectors, a sort of very accurate microscopes able to “see” the deep constituents of nuclei.

This kind of research is nowadays very expensive and performed in a few places all over the world: LHC-CERN (Switzerland), DAFNE (Italy), VEPP (Russia), BEPCII (China), KEKB (Japan), TEVATRON and RHIC (U.S.A.).

Up to the ‘50^{th} accelerator based experiments were done with the same scheme used by Rutherford during is pioneering study about the nuclei composition: a probes, composed - if possible - of elementary particles, collide on a target made of complex nuclei. Probes, generated initially by natural radioactive source, were substituted by electrostatic accelerators and, after 1930, by synchrotrons and linear accelerators (LINAC) (3). This method of investigation strongly limited the number of interesting events to be studied and their clearness, because of the target complexity.

In 1960, B. Tousheck, a physicist working at Laboratori Nazionali di Frascati (Italy), developed and tested the first particle accumulator, AdA, and mater anti mater collider (4). The experiments on target were quickly substituted by lepton accelerators (colliders) and their “onion like detectors”, where the “target” became the beam circulating in opposite direction.

Table 1. Collider’s history in the world

1961	AdA	Frascati	Italy
1964	VEPP2	Novosibirsk	URSS
1965	ACO	Orsay	France
1969	ADONE	Frascati	Italy
1971	CEA	Cambridge	USA
1972	SPEAR	Stanford	USA
1974	DORIS	Hamburg	Germany
1975	VEPP-2M	Novosibirsk	URSS
1977	VEPP-3	Novosibirsk	URSS
1978	VEPP-4	Novosibirsk	URSS
1978	PETRA	Hamburg	Germany
1979	CESR	Cornell	USA
1980	PEP	Stanford	USA
1981	Sp-pbarS	CERN	Switzerland
1982	p-pbar	Fermilab	USA
1987	TEVATRON	Fermilab	USA
1989	SLC	Stanford	USA
1989	BEPC	Beijing	China
1989	LEP ,	CERN,	Switzerland
1992	HERA	Hamburg	Germany
1994	VEPP-4M	Novosibirsk	Russia
1999	DAΦNE	Frascati	Italy
1999	KEKB	Tsukuba	Japan

1999	PEP-II	Stanford	USA
2000	RHIC	Brookhaven	USA
2003	VEPP-2000	Novosibirsk	Russia
2008	BEPCII	Beijing	China
2009	LHC	CERN	Switzerland

FACTORIES AND FRONTIER ACCELERATORS

Fundamental parameters of accelerators can be summarized as follow:

- Energy (momentum) and energy spread (E, ΔE)
- Timing structure (continue, bunched, microbunched beam)
- Beam Intensity (typically connected to timing structure)
- Transversal spatial distribution (Σ_x, Σ_y)

These "ingredients" are not independent of each other and the effort of accelerator physicists is to play with the various parameters in order to maximize essentially two quantities (5). First, they try to increase the energy available for the collision in order to discover new particles and their behavior. The machines involved in this kind of research are called **frontier** accelerators. Second, they try to increase the number of events to be studied, with the aim to deeply understand known phenomena and find if there is any expected or unexpected violation of the postulated theory. These accelerators are called **factories** of particles.

Table 2. Running and future proposed colliders parameters.

name	**type**	**site**	**energy (GeV)**	**Luminosity (cm-2s-1)**	**scope**
DAΦNE	e+e-	Italy	1.05	450	Φ factory
BEPC-II	e+e-	China	2.3	1000	τ factory
KEK-B	e+e-	Japan	8/3.5	$2.1*10^4$	B factory
VEPP-2000	e+e-	Russia	1-2	100	factory
TEVATRON	p+p-	USA	1000	286	frontier
RHIC	*heavy ion*	USA	100 TeV/n		frontier
LHC	p p	CERN	3500	10^4	frontier
VEPP-4M	e+e-	Russia	6	20	frontier
future proposed accelerators and upgrade					
ILC	e+e-	-	500	10^4	frontier
CLIC	e+e-	CERN	3000	10^4	frontier
D(T/V)LHC	p p	CERN	$\leq 4*10^7$		frontier
SuperB	e+e-	Italy	7 /4	10^6	B factory
SuperKEK-B	e+e-	Japan	8/3.5	$8*10^5$	B factory

The Lepton Collider Factories

Circular accelerators boosted strongly research in sub nuclear physics because of three fundamental improvements. First, particles collide in the center of mass so that a greater amount of energy is available for collisions. Second, the two beams circulating can be composed of matter and antimatter (e.g. electrons and positrons) so that the colliding particles annihilate in an energy state, that soon after decays in any kind of possible new particles according to the well known Einstein equation $E=mc^2$, where E is the energy available in the center of mass, c the speed of light and m the mass of the new created particles (6). Third, the target, in a lepton collider, could be structure-less, and consequently the produced events would be very clean respect to those with a "probe-on-target", being the target generally very complex.

In lepton colliders the fundamental parameter to be maximized is the luminosity:

$$L = \frac{N^{e+}N^{e-}}{\Sigma_x \Sigma_y} \times f_{collision}$$

$$N_{events} = L * \sigma$$

$N^{e-/e+}$ is the number of particles per beam circulating, Σ_{xy} are the transversal cross sections of the two beams, f is the frequency of collision. The luminosity times the cross section (σ) of the production for a given process provides the rate of the expected events (7).

The standard way to improve luminosity, used in the last 15 years, has been to increase the number of colliding particles (beam currents and numbers of circulating bunches – multi bunch accelerator) and decrease the beam transversal dimensions making a beam flat as much as possible. In a multi bunch accelerator, separated vacuum chambers are needed for the two beams, which cross with a certain angle in the interaction region (IR). At present such strategy has reached a limit because of high instability phenomena due to collective and beam-beam effects.

Three different paths have been chosen around the world to overcome the today limitations. In Russia, at VPEP2000, the idea is to collide high current round beams, that are not squeezed too much, and beam-beam instabilities are kept far away. At KEKB, Japan, the crab cavity (8) scheme has been tested in order to lower beam tail effects, that grow up when the collision area, in which the beam transversal dimensions are squeezed (mini beta waist), is smaller than the longitudinal size of the colliding beams. The idea is to use a RF cavity to rotate the beam in order to obtain head on collisions and minimize the tail effects. The tests are promising and the same scheme is foreseen to be used for the upgrade of Large Hadrons Collider at CERN in the future (9).

At DAFNE, a new scheme for the compensation of tail and beam-beam effects has been tested successfully in 2009 (10). This scheme, called crab waist compensation, is based on the introduction of sextupole magnets close to the interaction region in order to optimally compensate the beam phase at the interaction point.

The idea is to introduce a large Piwinski angle (11):

$$\phi = \mathrm{tg}(\theta)\sigma_z/\sigma_x$$

where θ is the crossing angle and σ_z and σ_x are the longitudinal and horizontal beam dimension at the IP. This quantity is obtained in DAFNE by means of a large crossing angle and long bunches with a very low horizontal emittance (small transversal dimensions): when beams are colliding in such condition a large gain in the luminosity is obtained because of geometrical factors, smaller collision area, lower synchro-betatron resonances and reduced horizontal tune shift. In the meantime the synchrotron instability induced by a large collision angle were compensate by the introduction of "well located" sextupoles around the IP. DFANE collider, in 2009, has shown the feasibility of the crab waist sextupoles compensation scheme, improving the collider luminosity about 3 times. On this idea are based the new super B factories that are designed and under final approval in Japan and Italy (12).

The Hadron Frontier Colliders

Lepton machines, like the factories described above, thanks to the fact that the interacting particles are structure-less and point-like, are able to generate very clean events corresponding to only one production channel, easy to be analyzed. For such accelerators the energy available in the center of mass is determinated by our technological capability to accelerate particles to the proper final energy, compensating the power loss due to synchrotron radiation that, on the other side, grows up with the third power of the beam energy per mass unit. LEP at CERN, in '90, reached the latest frontier for what concerns lepton circular accelerators and afterward the new frontier accelerators started to use hadrons, which are thousand times more massive than leptons. Hadrons contain "valence" and "sea" quarks (2), which have a momentum distribution falling down at the maximum beam energy and peaked around 1/3, so that in any interaction the final state particles are related not only to a single quark-quark interaction, making the event analysis more complicated.

Currently three hadron machines are running in the world: TEVATRON (Fermilab), RHIC (Brookhaven National Lab's) in USA, and LHC at CERN in Europe. These have to be considered the "stat of the art" of the frontier accelerators: in fact the energy of the colliding beams is pushed up in order to discover new and unknown physic. TEVATRON keeps the record of the maximum luminosity ever reached ($3.15*10^{32}$ $cm^{-2}s^{-1}$) at an energy in center of mass of ~ 2 TeV. LHC has recently collided beams at the higher energy ever reached in the world (7 TeV) and is working to achieve the design luminosity ($\sim10^{34}cm^{-2}s^{-1}$) and stabilize beams.

Both machines have been mainly designed in order to discover the Higgs boson, the last brick of the "standard model" that should be responsible of mass of the fundamental constituents of matter. Up to now, TEVATRON has accumulated a large statistics, but in a range of energy too low respect to the expected mass of the Higgs. LHC has the right expected energy but is starting now to accumulate the needed statistics: a couple of years will be needed to have an evidence of the Higgs boson.

RHIC is the first machine in the world capable of colliding heavy ions in relativistic condition. It got a lot of very interesting results on the behavior of quarks and gluons (bosons who mediate the interaction between quarks). The results are of particular interest not only for nuclear and particle physics but also astrophysics and condensed matter studies because they describe the fundamental interaction that is supposed to have happened in our universe when it started to aggregate 14 billion years ago.

The main challenging issues of a protons or/and ions machines are related to intra-beam scattering, beam-beam effects, magnet vibrations, stochastic cooling and beam scrubbing. Moreover, the use of a large amount of cryogenic and superconducting systems, as shown by the fault of LHC in 2008, plays an important role in the technological challenge of present and future machines (5). The shutdown of TEVATRON is foreseen as the first LHC results will be available, while RHIC is continuously improving techniques to optimize and polarize ion beams. An upgrade of the LHC is foreseen for the next future with the substitution of final focusing quadrupoles and the introduction of crab cavities that should bring the luminosity of the accelerator around $2*10^{35}$ $cm^{-2}s^{-1}$ after 2020 (13).

WHAT NEXT

Collider's future is nowadays limited by our technological capability to efficiently provide the energy lost by charged particles due to synchrotron light emission in curved trajectory. On the other hand, HEP needs to recover "clean events" produced by lepton accelerators, that up to 90s, provided many important successfully discoveries.

The future of accelerators in HEP research foresees essentially two ways to proceed: linear electron-positron accelerators (14) and high mass lepton colliders (like muon colliders) (15). Close to these ones there are hybrid solutions like lepton-hadron colliders and neutrino factories.

The challenging bet of linear colliders is to obtain very high-energy collision and luminosity with accelerators that can be hosted in a typical scale of HEP laboratories. At present there are two main projects: the

International Linear collider (ILC) with 500 GeV energy in the center of mass and a predicted site length of 31 Km and the Compact LInea Collider (CLIC) with the same energy and a length of 13 Km (with the possible upgrade to 3 TeV in 41 Km). The expected luminosity is of order $2*10^{34}$ $cm^{-2}s^{-1}$.

ILC is based on the improvement of the conventional technology for superconducting radiofrequency cavities (able to produce a maximum gradient of order 50 MV/m) and similarly to CLIC the main issues are: to keep the beam emittance at very low values, from the source to the IR (limiting the negative effects mainly due to intra beam scattering) and to assure high alignment stability, strongly needed to maintain in collision beams with transversal dimensions in nanometer scale or even less.

CLIC is based on the two beam acceleration scheme (16): an auxiliary driving high current beam is dumped in a radio frequency cavity structure able to generate an accelerating gradient of about ~100-150 MV/m that, in turn, is used to accelerate the main beam. Such a technology, under test in the CTF3 facility at CERN, is not only very promising to reduce the length of the accelerators but also because it seems to be the only way to obtain hundred TeV energy collisions, a step needed toward the investigation of the physics beyond the standard model (super symmetric theory).

Many electron–hadron colliders are under design around the world: in USA with eRHIC at Brookhaven National Laboratory, ELIC at Jefferson Laboratory and in Europe with LHeC possible upgrades at CERN of LHC (17) and ENC at GSI, Germany. These accelerators will allow investigating the complex nuclei structure, with a point-like probe, easy tunable in energy and intensity, measuring very carefully the Quantum Chromodynamics (QCD) parameters (2).

Last main application of HEP accelerators comes from neutrino factories and muon colliders. Neutrinos are very low mass and charge-less leptons and their interaction is very unlucky. They feel only the weak force so that their study provides almost the unique tool to understand how leptons interact. Neutrinos, in the energy range of 10-20 GeV, can be produced dumping high-energy protons on target, in the same way it is done at CERN and KEK, and successively they can be studied in special underground detectors as OPERA at the Gran Sasso Laboratory (Italy) and SUPERKAMIOKANDE at Kamioka (Japan).

Muon accelerators can be considered as "heavy electron" colliders, where the mass is ~200 times greater than that of electron, reducing of 10^9 times the energy lost due to synchrotron radiation and making in this way possible the lepton collisions in the TeV region. On the other hand, muons decay in neutrinos (and electrons) that can be used as source for very high energy, and flux experiments, overcoming present limits. Test facilities are running to proof operating principles. Neutrino factories and muon colliders need of large funding and so only a common international effort can guarantee they work properly.

CONCLUSIONS

Many accelerator applications in research have not been treated in this paper: synchrotron light source, free electron laser, spallation source, etc, that are essential tools to investigate the nature surrounding us as the most "powerful microscopes" available nowadays. On the other hand, the R&D is continuously improving the technology making available more and more accelerators for health care and diagnostic and other common life applications. There are many other interesting developments, like e.g. plasma acceleration that can increase acceleration gradient of 2~3 orders of magnitude and change drastically the applications of accelerators in every day life.

In conclusion the HEP accelerators, the "Formula 1" of such devices, play a fundamental role in the discovery of the constituents of the universe and its evolution since the big bang. The development of HEP accelerators also leads to improve and acquire technological knowhow, triggering the realization of more accurate, low costs, and efficient conventional accelerators, today widely used in common practice of many medical, scientific and technological fields.

ACKNOWLEDGMENTS

I would like to thank C. Biscari from whom most of the material has been taken, F. Bossi and L. Quintieri for discussions and critical review of this paper. Last but not least A. Esposito, who gave me the opportunity to do this job.

BIBLIOGRAPHY

1. O. Barbalat, Application of particle accelerators, CERN/AC/93-04(BLIT) Rev.
2. D. H. Perkins, Introduction to High Energy Physics, Cambridge University press
3. A. Ghigo, Types of particle accelerators, in proceeding of this conference
4. C. Bernardini, G. F. Corazza, G. Ghigo, and B. Touscheck, Nuovo Cimento 18, 1293 (1960).
5. C. Biscari, Accelerators R&D, in proceedings of EPS-HEP 2009
6. N. Cabibbo and R. Gatto, Electron-Positron Colliding Beam Experiments, Phys. Rev. 124, 1577–1595 (1961)
7. M. Sands, The physics of electron storage ring: an introduction, SLAC-r-121, 1970
8. Z. Dolezal, Super KEKB and Belle II: Status of the KEK Super B Factory, in proceedings of EPS-HEP 2009
9. F. Zimmermann, CERN Upgrade Plans for the LHC and its Injectors, in proceedings of EPS-HEP 2009
10. M. Zobov et al., Test of "Crab-Waist" Collisions at the DAΦNE Φ Factory, Phys. Rev. Lett. 104, 174801 (2010)

11. P. Raimondi, Proceedings of the 2nd SuperB Workshop, Frascati, March 2006.
12. M. Sullivan, e+ e– Factory Developments, in proceedings of EPS-HEP 2009
13. F. Zimmermann, CERN Upgrade Plans for the LHC and its Injecto, in proceedings of EPS-HEP 2009
14. G. Geschonke, The next energy-frontier accelerator - a linear e+ e- collider? in proceedings of EPS-HEP 2009
15. E. Prebys, The Intensity Frontier at Fermilab, in proceedings of EPS-HEP 2009
16. R. Corsini, et al. "Two-Beam Linear Colliders - Special Issues". PAC09 Proceedings, Vancouver. 2009.
17. V. N Litvinenko, LHeC and eRHIC, in proceedings of EPS-HEP 2009