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COLLIDING BEAMS - PRESENT AND FUTURE

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COLLIDING BEAMS - PRESENT AND FUTURE

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1. First serious discussions on the possibility of carrying out the experiments in elementary particle physics with colliding beams were started twenty years ago (to be more exact, in 1956). Of course, the increase in energy of reaction with colliding beams compared to conventional scheme: "accelerated particle - stationary target" was known long before. But only in the middle of the fifties did the progress in physics and accelerator technology enable one to set up experiments in this quite new class.

The pioneering role in the development of colliding beams in our country belongs to Professor A.M.Budker who headed the entire work in this direction up to his death in 1977.

Not so long before there was the wide scepticism concerning colliding beams. Many people thought it too complicated in implementation to make it really productive in practice. At present, one can already say that the colliding beam method is the main method in the physics of ultimate high energies and one of the main methods in elementary particle physics in the whole. This method provides now a considerable part of the fundamental data in physics.

In the report presented here I shall touch on the history of the colliding beam method, go on to the present status, and try to outline the near and subsequent future of the method.

2. From the very beginning and up to the present moment, the basis of colliding beam experiments were cyclic storage rings of charged particle which were developed just for these experiments. The use of cyclic storage rings was very natural, since the usefulness of the installation for experiments in elementary particle physics is determined primarily by the

following two values: beam energy E which determines the energy of reaction (the energy in the centre of mass system of colliding particles):

$$E_{react} = 2E$$

and the luminosity of the installation L which after multiplying it by the reaction cross-section gives the number of events per unit time. In the simplest case $L = \frac{N_1 N_2}{S} f$, where N_1, N_2 are the numbers of particles in each bunch, S is an effective area of the cross-section for the beams at the interaction point, f is the frequency of collisions which in this case is the same as the revolution frequency of the particles in the storage ring. The attempt to obtain the required luminosity caused development in cyclic storage rings which enable one to store a large number of particles (10^{10}-10^{-14}) and to ensure the multiple (10^{10}-10^{12} times in practice during the lifetime of particles) collisions for particles of colliding beams and also to obtain sufficiently small transverse size for the beams (at present - down to 10^{-3}cm^2).

The first electron and positron beams were stacked at the storage ring "Ada". Even with the intensities obtained with this installation (currents of the order of a fraction of a milliampere) the first effect of a big current has appeared, namely, the effect of particle scattering inside bunches on the beam life-time.

Since that time many effects connected with the long life-time of the beam and with the particle interactions have been studied which enabled to eliminate many primary limits appeared due to this effect.

3. The first colliding beam experiments in elementary particle physics were the experiments for verification of the quantum electrodynamics validity for small distances with scattering electrons on electrons which have been carried out in 1965 at Stanford (Stanford storage rings) and at Novosibirsk, INP (VEP-1 installation).

The first experiments with electron-positron colliding beams on the study of the pion pair production under electron-positron annihilation in the region of ρ-meson resonance were performed in 1967 at Novosibirsk (VEPP-2).

Since that time electron-positron storage rings have been designed and built at ORSAY, Frascati, Cambridge, Stanford, Hamburg and Novosibirsk and now energies up to 2 x 14 GeV (and 2 x 20 GeV in the near future) are becoming available. The experiments on these storage rings have already provided a lot of physical data the fundamental importance of which is known world wide. Modern possibilities and the possibilities of the near future can be easily seen in Fig.1 where the energies and luminosities of the electron-positron storage rings are given.

4. Together with the urge towards higher and higher energies of electron-electron interactions, a very important direction is an increase of luminosity for the standard energy regions. The installation VEPP-2M was the first machine specially designed for solving the problem of the luminosity increase. The experiments on VEPP-2M was started in 1974. The luminosity reached in VEPP-2M is an order of magnitude higher than the summary luminosity of all the rest of the electron-positron storage rings in the energy range up to 2 x 0.7 GeV.

There is still much reserve for increasing the luminosity in new installations without new ideas. The luminosity of the up-to-date electron-positron installations is determined by the effects of particle motion perturbation with the field of the colliding bunch. The ultimate luminosity for the single-bunch beam is about:

$$L_{ult} = \frac{\gamma^2}{r_e} \cdot \frac{(\Delta\nu) \varepsilon_x f_0}{\beta_0}$$

where r_e is the classical radius of the electron, γ is the relativistic factor, $\Delta\nu$ is an admissible shift for the betatron oscillation frequency, f_0 is the revolution frequency, β_0 is the β-function value at the collision point, ε_x is the radial emittance of the beam.

The admissible frequency shift $\Delta\nu$ can be increased by removing modulation of the particles position at the collision point due to synchrotron oscillations (nullifying $\Psi_{x,z}, \Psi'_{x,z}$ in the collision region /1/) and by amplifying the radiative damping (introducing "snakes" with high magnetic field or by transition to a superconducting magnetic system for the storage ring).

The transition to superconducting magnets leads to an increase of luminosity also because of increasing the revolution frequency f .

A decrease of β_0-function at the collision point (values now achieved are 4-5 cm) is limited by the difficulty of getting such short bunches with a large number of particles.

The luminosity gain due to the beam emittance increase by the selection of a special magnetic system which ensures the maximum excitation of radial and axial betatron oscillations with the quantum fluctuations of synchrotron radiation, is connected with necessity of corresponding increase in the number of electrons and positrons used.

An increase in number of the particles used in the storage ring can proportionally increase the luminosity in the multi-bunch regime too. In this case, the beam interactions should be removed very carefully from the parasitic points of collisions and the condition should be met for getting maximum luminosity from each pair of colliding bunches. The use of two-track storage-rings provides maximum possibilities for getting higher luminosity.

At present one can see some new ways of reaching higher luminosities. To this end, one can change to the regime of the pulsed collisions in the cyclic storage ring. For this purpose, the ultimately cooled (due to synchrotron radiation) and compressed bunches of electrons and positrons moving along the separated orbits are matched for one turn with quite high accuracy. The beams are colliding during one or many turns until the collision effects increase the cross-sections of the bunches. After that the beams should be one-turn separated and move along the separated orbits until they are completely cooled due to synchrotron radiation.Then this cycle is repeated. The luminosity

can be increased more with compensation for the bunch fields at the collision point in the 4-beam two-track storage ring. For pulsed colliding beams such a compensation should be quite efficient, for in this case there is no problem of the compensation stability.

Preliminary estimations have shown that using this method one can hope to reach luminosity two orders of magnitude higher at an energy of a few GeV.

5. Not only the energy and luminosity of the installation are important. For the colliding beam experiments with complication of the tasks to be solved in the experiments some other parameters of the beam become important the monochromaticity and polarization of the beam, for instance.

Beam polarization enables one to set up qualitatively new experiments. The use of the electron and positron beams obtained with radiative polarization enabled already to increase the accuracy of comparison of the anomalous magnetic momenta for electrons and positrons by two orders of magnitude, to increase the measurement accuracy of the mass of kaons[3] and φ -mesons[4], to obtain the data on the spin of the primary objects which form the jets in the multiple production of hadrons.

The use of the polarized beams is especially important at high energies[5]. The most informative case is the use of longitudinal polarization which can be made stable by adding special magnetic fields[6,7]. So, if the helicities are opposite for the electrons and positrons at the collision point (the natural case for radiative polarization) then the one-photon annihilation channel is "shut down" and the contributions of higher orders and non-electromagnetic interactions are emphasized.

The monochromaticity of the electron-positron beams in the accelerator is quite high (not less than 0.1%) even without the use of special efforts. The energy spread is determined by the quantum fluctuations of the synchrotron radiation of the particle. But there are narrower resonances, ψ - and Υ -mesons, for instance. Therefore, an increase in the reaction energy spread turns out to be quite an essential problem. Of course, it is especially interesting to make this energy spread less than the width of the objects under study (the possible split of the level) and this problem appears to be solvable/8/. But additional monochromatization becomes useful for the experiments much earlier, for, in this case, the the fraction of the processes proceeding through the resonance state increases proportionally.

6. Increasing the energy of electron-positron colliding beams is now of principal importance and will maintain its importance in the future. However, the solution of this problem with the conventional method i.e. with cyclic storage rings, confronts us with ever increasing difficulties which are connected with the disastrous increase in losses due to synchrotron radiation. The difficulty of the problem to construct the electron-positron storage rings at an energy of hundreds GeV that is connected with synchrotron radiation can easily demonstrated by using as an example the LEP project at an energy 2 x 100 GeV/9/. The length of the installation is about 20 km and the continuous power consumption is about 150 MW and practically all this power is consumed by the storage ring as RF power. Conventional type electron-positron storage rings at an energy of 100 GeV also have been considered at our Institute. The most complex part of such a project is the radiofrequency system. We reached the conclusion that it is reasonable to make the cavities superconducting. Quite simple engineering and fabrication solutions were also found for the magnet system, the vacuum chamber with direct absorption of synchrotron radiation by the coolant, an efficient systems for laying out the elements of the storage ring. Another important aspect was recognition of the possibility of using synchrotron radiation for large-tonnage radiation technology, since such a storage device is a generator of high power photon flux in the MeV energy range of quanta - the most penetrating inactivative radiation - with a high efficiency of conversion of RF energy into radiation, which is useful in the processes. At the same time, such a storage ring would be a 10 MW electron accelerator at an energy range from 100 MeV to a few GeV.

This structure nonetheless appears unjustifiably unwieldy. With the transition to still higher energies the scale of conventional storage rings continues to grow quite rapidly (roughly with the square of the energy). Ultimately it may be necessary to come to terms with this, but we would like first to consider other, less cumbersome methods of attaining the goal.

At present it seems promising to use for this purpose two linear accelerators "firing" each other with single short bunches with a large number of particles and an exceedingly small cross-section emittance.

There is hope that with this method electron-positron experiments can be set up at the energies of several hundreds GeV with the luminosity $10^{32} cm^{-2} s^{-1}$/11/.

7. The first installation with the proton colliding beams (ISR) has been operating at CERN since 1971. Its maximum energy is 2 x 33 GeV, the maximum number of stored particles is 10^{14} in each beam, ultimate luminosity is $10^{31} cm^{-2} s^{-1}$. For this period a number of experiments have been carried out which provided valuable information.

At present the decision has been made to build big superconducting storage rings with proton-proton colliding beams at an energy 2 x 400 GeV (ISABELLA) at Brookhaven with a very high design luminosity (up to $10^{34} cm^{-2} s^{-1}$). It is proposed to implement proton-proton experiments in the Main Ring-Doubler/ /Saver facility at Batavia at an energy 300 on 1000 GeV. A project has been developed for accelerating-storage facility (УНК) at Serpukhov at an energy 2 x 3 GeV.

8. But in the near future the new installations with hadron colliding beams will apparently be the already operational: biggest proton sinchrotrons the SPS (CERN) and Main Ring (Batavia). These installations are under transition to the regime of proton-antiproton colliding beams at an energy 2 x 300 GeV. The implementation of these experiments became feasible with the development of the cooling methods for heavy particles: the method of electron cooling (Novosibirsk)/12,

13,14,15/ and the method of stochastic cooling (CERN) /16,17, 18/.

9. A slight historical digression. In the first years after announcing the first proton-antiproton colliding beam project (1966 VAPP-NAP, Novosibirsk /19, 20/) the proton-antiproton experiments at maximum accessible energy were considered by many of scientists as an exceedingly complicated addition to proton-proton experiments at the same energies. Even then, of course, it has been evident that this addition was very important. Since obtaining sufficiently complete data even for the general properties of strong interactions requires as full as possible set of initial states. Therefore both proton--proton and proton-antiproton experiments are required and it is also desirable to have deuteron-antideuteron experiments. Of course, even this set is not exhaustive and with time the demand will arise for meson-neucleon and meson-meson colliding beams. One can show that the luminosity of the anticipated versions of these experiments is sufficient for the study of hadron interactions with cross-section of the order of the total cross-section/21/.

Two more classes of experiments are specific to proton--antiproton colliding beams: first, the study of hadron annihilation, second, the study of two-particle charge-exchange reactions, namely, reactions with conservation of barion charge of each colliding particle. The annihilation cross-section apparently decreases only inversely to the energy of the colliding beams and even at an energy 2 x 1000 GeV the cross--section will be of the order $10^{-30} cm^2$. So, the main problem will be the separation of annihilation processes from the vast majority of the events in the "total" cross-section". At the same time, the cross-section of the process like

$$p + \bar{p} \rightarrow \Lambda^0 + \bar{\Lambda}^0$$

decreases (in the region presently kncwn) as E^{-4} and only with luminosity of the order $10^{32} cm^{-2} s^{-1}$ can one manage to get some data about these processes at energies higher than 100 GeV.

In recent years, the attitude toward proton-antiproton colliding beams has changed drastically. The quark model has acquired more and more dynamic content, and "public opinion"

is more inclined to consider hadrons as consisting of quarks which interact like point particles. Correspondingly, processes with large momentum transfer proceed via quark interactions, which compose the colliding hadrons. In this case, proton-proton collisions yield the quark-quark reactions and the proton-antiproton collisions give quark-antiquark reactions. In this sense, one can say that in the proton-antiproton colliding beam experiments one can get fundamental information the same as that obtained with electron-positron colliding beams of the same luminosity and an energy equal to 1/3 or 1/6 of the barion energy. Similarly, proton-proton colliding beams are equivalent to electron-electron colliding beams. Of course, for strongly interacted particles such as protons and antiprotons it is impossible to say that they only consist of quarks of the same "polarity". According to recent neutrino data, though, the content of antiquarks in a proton is about 5% (the same as the percent of quarks in an antiproton). Therefore, the quark-antiquark interactions give only a small admixture in pp collisions and the main part in $p\bar{p}$ collisions. In addition, the average energy of the quark-antiquark reactions in the proton-proton collisions will be substantially lower than for the proton-antiproton collisions.

10. A few words about the "strategy" of advancing into the region of maximum energies. One can distinqwish four stages of exploring new regions at energies of hundreds GeV and higher.

In the first stage only interactions of any point-like objects (leptons, quarks) are accessible which enable one to produce as large as possible momentum transfer both at scattering and in production of massive objects (space- and time-like transfers). In the first stage it is not too important for which pairs it will be done. The question of primary importance is the question of having beams available for the first stage experiments. Colliding beams of particles and antiparticles seem to give more experimental information as the systems have less prohibition for generation of new objects. From this point of view, the most advantageous variant for the experiments will be proton-antiproton colliding beams which will provide study of the fundamental quark -antiquark interactions at an energy of one-third (or one-sixth) of the energy of the proton-antiproton colliding pair.

Of course, when we are talking about the study of fundamental interactions of different objects, it is just a way to classify the experiments over the initial states. Each certain class of experiments will also provide vast additional information.

The second stage one can consider the experiments which cover the interactions of all fundamental particles (leptons, quarks, etc.) i.e. the study of lepton-lepton, lepton-antilepton, quark-lepton, quark-antilepton, quark-quark and quark--antiquark interactions. In this case, the choice of coherent particles is determined by which is most realistic to realize.

These problems will be solved soon in the following colliding beam experiments:

a) lepton-lepton and lepton-antilepton- $e^- + e^-$ and $e^- + e^+$

b) lepton-quark and antilepton-quark - $e^- + p$ and $e^+ + p$

(the experiments of this kind ($e^- p$) are already planned at installations at superhigh energies which are being built and designed).

c) quark- and quark-antiquark interactions will primarily studied in pp and $p\bar{p}$ experiments. The feasibility of these experiments, the difficulties that will arise and the now visible ways to overcome them are sufficiently clear from the preceeding paragraphs.

In the third stage it will apparently be important to obtain as complete as possible set of pairs of fundamental particles in the initial state. And finally, for advance in understanding fundamental interactions at ultimate high energies it will become necessary to study the collisions of all elementary particles and even nuclei.

II. In this connection, it is worth paying attention that many of those experiments which now seem exotic and unreal will become available in the not too distant future.

So, quite soon after exploring proton-antiproton colliding beams deuteron-antideuteron experiments will become accessible (for the study of neutron-antineuteron interactions): for the effectivness of stacking antideuterons is only four orders of magnitude lower than that for antiprotons and the luminosity of the order $10^{27} cm^{-2} s^{-1}$ will be achieved immediately and one should not wait too long for progress in this field.

With time, colliding beam experiments with unstable particles will become accessible. Good prospects for muons and pions acceleration are opened up with the use of intense beams in modern and future proton accelerator for the excitation of the linear accelerating structures /21/. This will enable one to obtain mesons with total or even a few times higher energy than that of the main proton accelerator and intensity a few per cent of the initial number of protons.

Using the pions accelerated in this way already up-to-date accelerators SPS and Main Ring it is possible to obtain pion-proton and pion-pion colliding beam luminosity of the order $10^{27} cm^{-2} s^{-1}$ (with the use of a 100 KG storage ring).

The muon colliding beam experiments will also be accessible /22,10/. For this purpose it is required: to obtain very intense bunches of pions with the help of high energy protons (apparently with the use of hadron cascade); to allow the mesons decay in the strong focusing channel; the muon beams generated should be cooled with ionization cooling in a cyclic or linear accelerator (ionization losses should be compensated from the external energy source); to accelerate the cooled muon beams in the linear accelerator up to the required energy; to make the muon bunches collide in the sections with very strong focusing in a special ring whose magnetic field should be as high as possible in order to increase the number of collisions during the life-time of the muons. Evaluations have shown that this way would enable one to achieve the satisfactory luminosity of the order $10^{31}\ cm^{-2} s^{-1}$ at energies of hundreds GeV.

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