PROTON - ANTIPROTON COLLIDING BEAMS

VAPP-NAP Group,

Institute of Nuclear Physics of the Siberian Division of the USSR Academy of Sciences,

Novosibirsk, USSR

(presented by A.N. Skrinsky)

Abstract

In the work reported here the possibilities of producing proton-antiproton colliding beams are discussed. Special attention is paid to physical and technical aspects of electron cooling. The current status of VAPP-NAP project is described.

In this report practical possibilities of performing proton-antiproton experiments at the highest energy available are analysed. These experiments are assumed to be obviously of great interest even under the condition that the proton-proton reactions at the same energy are already studied.

First of all let us consider the potentialities of machines now in operation or being put into operation. In the near future proton energies up to 500 GeV will be reached in Batavia. Let us estimate the attainable luminosity of antiproton-proton experiment with 200 GeV and 400 GeV antiprotons by extrapolation of the available data on the antiproton production. The reaction energy (e.g. the total energy in the center of mass system) will be 20 GeV and 28 GeV respectively. It is assumed that the very hard problem of separating the antiprotons from the much larger numbers of π^- and K^- is solved in some way that does not decrease the luminosity (maybe using Cherenkov counters), and the antiproton channel accepts an energy spread of about 1 per cent. Then the luminosity will be 10^{27} cm^{-2} sec^{-1} at 20 GeV and 10^{24} cm^{-2} sec^{-1} at 28 GeV (for 10^{14} accelerated protons per pulse). The proton target thickness is taken to be equal to the nuclear absorption effective length (5 m in liquid hydrogen). This luminosity is large enough for the study of the reactions with cross sections close to the common nuclear cross sections of about 1 millibarn. However, that is not sufficient for the charge-exchange reactions, especially interesting in the case of proton-antiproton collision; cross sections are expected to be 10^{-31} cm^2 in this energy range.

A considerably greater luminosity with maximum accelerator energy may be obtained by putting the synchrotron in the antiproton acceleration regime. The protons accelerated in one cycle are ejected in one revolution and produce antiprotons in a conversion target, the latter being captured in a special storage ring during the time between the acceleration cycles. In the next cycle the antiprotons are transferred into the synchrotron and accelerated up to the energy required. Before ejection, the accelerated protons should be gathered in a bunch as long as the storage ring circumference in order to make complete use of them. The storage ring admittance should be equal to that of the synchrotron. Using very strong focusing elements in the conversion system, one can obtain a conversion efficiency in such a phase-space volume of about 10^{-6}, the antiproton storage ring in this case must be designed for an operation energy about 10 GeV. This version gives proton-antiproton luminosity near to 10^{32} cm^{-2} sec^{-1} up to a reaction energy of 32 GeV. This luminosity value will already be sufficient for a large number of specific reactions. The purity of the produced antiproton beam is of great importance.

Some interesting possibilities to study proton-antiproton interactions are provided by the CERN storage rings. The accumulation of antiprotons produced in $\bar{\Lambda}^0$ - decay may give a luminosity of 10^{25} cm^{-2} sec^{-1} at the reaction energy of 55 GeV [1].

The antiproton-proton project that is now under construction in Novosibirsk may yield a reaction energy up to 45 GeV and a luminosity of 10^{32} cm^{-2} sec^{-1} if estimated in the same rough and optimistic way. Unfortunately, the realization of our project is progressing much more slowly than it is technically possible.

In the Novosibirsk project it is envisaged to construct the antiproton-proton ring VAPP with a maximum energy of 2 x 23 GeV that is to serve at the same time as the main proton accelerator with the possibility of high intensity at an energy up to 23 GeV (Fig. 1). Accelerated and ejected in one revolution, protons are directed into a special conversion system of high efficiency. Antiprotons with a momentum of about 1.8 GeV/c are injected into the antiproton storage ring NAP where they are "cooled". After a sufficient compression of the antiproton beam, another pulse of antiprotons is injected. The accumulating cycle is repeated the number of times required. After that, the critically compressed antiproton beam is injected into the main storage ring. The required amount of protons is then injected and with the energy set to the level required in a given experiment, the beam-beam collision is performed.

Let us consider the most significant features of our project in the physical engineering and constructive aspects, paying special attention to the electron cooling.

The VAPP storage ring is a strong focusing racetrack; the semi-circles' radius is 45.5 m; the dimensionless betatron frequency (in the circular part) is about 6.2; the length of each straight section with a unit transfer matrix is 40 m. The circular part of the storage ring contains 40 periodic cells each consisting of two nonlaminated magnets. The magnet length is 3.5 m; the flat part is 2.3 m; the alternating gradient parts each of 1.1 m length (Fig. 2). The maximum field strength in the flat part is 20 kG; in the focusing parts the same value is reached at the aperture limit and 10 kG on the central orbit; the gradient is 2 kG/cm. There are 0.2 m long technical sections between the magnets. The magnet winding consists of two coils commuted through each semicircle. The main coil current is 25 kA, power is 3.5 MW.

Table 1

MAIN PARAMETERS OF THE INSTALLATION VAPP

Circumference of ring	366 m
The halfring mean radius	45.5 m
Length of straight section	40 m
Maximum momentum of protons	21.4 Gev/c
Q_V	6.1 + 2
Q_H	6.2 + 2
Momentum compaction factor	0.022

Magnet

Maximum field of bending magnets	20 kG
Field of F, D magnets	10.1 kG
Gradient of F,D magnets	1.8 kG/cm
Bending magnet length	224 cm
F,D magnet length	111 cm
Maximum current to magnet coils	25 kA
Maximum power dissipation	3.5MW

Vacuum system

Chamber material	stainless steel
Chamber inside dimension	27x80 mm
Distributed pumps	1.5 l/cm sec
Ionpumps (40 pieces)	150 l/sec
Design pressure	10^{-9} Torr

The focusing in the straight sections is performed by quadrupole lenses occupying 25 per cent of its length. A separate supply of the lenses is envisaged. The injection and ejection systems, as well as RF system, are placed in one of these straight sections. The other straight section is intended for physics experiments. The storage-ring vacuum chamber (Fig. 3) provides a useful aperture of 6 x 2.7 cm^2. The rest of the volume is occupied by a distributed pump that works in the storage ring guide field and provides a pumping rate of 2 $\ell\ cm^{-1}\ sec^{-1}$ and an average pressure of about 10^{-9} torr. In the technical sections, there are external pumps with a pumping rate of 150 $\ell\ sec^{-1}$ and pick-up stations. In the long straight section allotted to physics experiments, special pumping giving 10^{-11} torr is envisaged.

At the first stage, the B-5 synchrotron with 200 MeV energy will be used as the proton injector for VAPP. The injection into the storage ring will be performed by successively filling RF buckets (RF frequency is about 100 times greater than that of the revolution). At such an energy one can accumulate up to 10^{13} protons. After acceleration to the maximum energy, the protons will be compressed into a short bunch (its minimum length of about 1 m is determined by the initial energy spread).

Focusing of the protons to a spot of about 1 mm diameter onto a converter will be performed by the special X-type lens used formerly in VEPP - 2. The converter is a tungsten rod of a diameter equal to that of the focused proton beam and with the nuclear absorption length. The antiprotons produced along the whole converter length are focused by the 1 MG field generated by the current running through the target[2]. On the converter output, the effective diameter of the 1.8 GeV/c antiproton beam is about 2 mm, the emittance of the antiprotons being about 60 mrad - cm. Then the antiprotons are focused by the X-lens mentioned before. The antiproton transfer channel matches the antiproton phase space with that of NAP including momentum matching (the antiprotons are injected into NAP on the orbits corresponding to their momenta). The designed conversion efficiency is about 10^{-5} antiprotons captured in NAP per one initial proton.

The antiproton storage ring NAP (Fig. 1) consists of four zero-gradient quadrants with a curvature radius of 3 m and of 7 m long straight sections allotted to injection and electron cooling. The radial aperture allows the capture of an antiproton beam with a momentum spread up to 5 per cent. To make the betatron frequencies (Q_H = 1.18, Q_v = 1.38) independent of the particle momentum,the cutting line of each magnet is pointed to the common center of the machine. The vacuum chamber (Fig. 4) has a useful aperture of 40 x 8 cm^2 and the storage ring admittance is 70 mrad - cm. Vacuum pumping is mainly provided by distributed pumps. The expected operation pressure is 10^{-9} torr.

Table 2

MAIN PARAMETERS OF THE INSTALLATION NAP

Circumference of ring	46.1 m
Bending magnet radius	3 m
Length of straight section	7.1 m
Maximum momentum of antiprotons	1.8 Gev/c
Q_V	1.38
Q_H	1.18
Momentum compaction factor	0.983
Magnet cutting angle	28°
Magnet maximum field	20 kG
Maximum current to magnet coils	5850 A
Maximum power dissipation	4.5 MW

R.F. system

Number cavities	2
Harmonic number	2
	1
Frequencies	13 MHz
	6.5 MHz
R.F. voltage maximum peak	1.5 MV

Vacuum system

Vacuum chamber material	stainless steel
Vacuum chamber inside dimension	81x420 mm
Design pressure	10^{-9} Torr

Electron cooling device

Maximum energy of electrons	600 kev
Current of electron beam	100 A
Electron beam cross section diameter	5 cm
Design damping time of antiprotons	100 sec
Maximum focusing field	1 kG

The chosen scheme of antiproton injection (Fig. 5) allows a complete usage of the whole storage-ring's free aperture. The antiprotons are injected in the vertical plane at the entrance of the straight section, the septum magnet standing apart from the aperture. Inflector electrodes, with an aperture of 40 x 16 cm^2 in the beginning occupy 5 m length of the straight section. The field of the oppositely travelling wave (electric field strength of 100 kV/cm) puts the beam on the equilibrium orbit. The inflector pulse duration is about a third of the revolution time.

A short bunch of antiprotons with the total accepted energy spread makes a quarter of a synchrotron oscillation in the field of the special RF cavity (the second harmonic of the revolution frequency), and after that the RF field is turned off rapidly. As a result of that, the initial energy spread (and the corresponding beam width) is 5 times decreased so that before the beginning of cooling the antiproton beam size should be 8 x 8 cm^2.

The electron cooling system (to be analyzed in detail below) decreases the energy spread and the betatron oscillation amplitudes of the antiproton beam in some hundred seconds. After that the beam is compressed by successively switching the RF-voltage of the first and second harmonics in a short bunch, and a new pulse of antiprotons is injected into the free bucket; then the whole process is repeated. For this regime, the expected maximum of accumulated antiprotons is of the order of 10^{10}. The operation at a higher proton injection energy allows one to accumulate 10 times more.

Having completed the accumulation of antiprotons, the beam is cooled to the minimum possible size and injected into the main storage ring VAPP. By this moment, in VAPP there is already a short bunch of protons with the required (by the beam-beam collision effects) intensity. Then the guide field should be increased to the value required by the experiment. If it appears to be necessary to change the β function with a beam in a storage ring, without variating the betatron frequency, it will be done. Using beam intensities of 10^{13} for protons and 10^{10} for antiprotons, one can obtain the luminosity value of 10^{31} cm^{-2} sec^{-1}.

Now let us consider the electron cooling in some detail [3].

In the case of heavy particles the only means to introduce the incoherent friction into the motion is by making use of Coulomb interaction. This is possible by making the cooled beam pass through a dense target. The ionization loss in the target results in the damping of betatron oscillations. In the relativistic energy range the damping rate for the energy oscillations is practically equal to zero; therefore, a certain dependence of the loss upon the radius should be introduced, thus redistributing the decrements of the betatron and synchrotron oscillations. The combined effect of the ionization friction and Coulomb scattering yields a stationary beam angular spread $\Theta_{st} = (\frac{zm}{\gamma M})^{\frac{1}{2}}$. Using the sufficiently low β function value in the position of the target, one can obtain a sufficiently small beam emittance after cooling. However, at relativistic energies, the lifetime of antiprotons (and protons) by nuclear interaction turns out to be less than the damping time so that it makes no sense to use such a technique for antiprotons. But this method can be used in μ-meson cooling.

The nuclear scattering of antiprotons might be obviated by substituting an electron cloud for a usual target. However, the creation of an electron cloud with the required density is practically impossible.

The solution of the problem lies in the use of an electron beam with the mean velocity equal to that of the cooled particles. Then the interaction cross section is sharply increased since now it is determined by the velocity spread in the beams; therefore, the damping time will have an admissible value at realistic densities.

If for a moment we neglect the regions of electron beam injection and ejection, one can assume that the antiprotons, in their rest frame, are plunged into an electron gas when passing through the electron beam. The electron gas temperature is determined by the distribution of the electron velocities. Antiprotons can be cooled to the same temperature value and correspondingly the antiprotons' velocity spread can be obtained to be $\sqrt{\frac{M}{m}}$ times less than that of the electrons.

Under real conditions the process of electron cooling is, of course, much more complex than the simple thermal relaxation [4]. The complications are connected with the particularities of antiproton motion in a storage ring and with the difference between an electron beam and a "travelling thermostat".

The changing rate of antiproton oscillation amplitudes consists of two parts: a dissipative one as a result of the frictional forces in the electron medium and a diffusive one due to the interaction fluctuations. The diffusive term always tends to increase the oscillation amplitude. The dissipative term essentially depends on the electron distribution function form and can even change its sign in various cases.

Now let us consider the most simple and useful case when the electron distribution function is spatially uniform and close to the Maxwellian form in the rest frame of the antiprotons. For the case in Fig. 6 the average power of the frictional forces is plotted against the amplitude of one-dimensional oscillations. If the amplitude of the antiproton velocities is greater than that of the electrons, the damping time is determined by the antiproton velocities and by the order of magnitude as follows:

$$\tau_1 \approx 0{,}05\,\frac{M}{m}\cdot\frac{\gamma^5\beta^3\theta_a^3}{n r_e^2\, c L \eta \ln(\theta_a/\theta_e)}$$

where $\gamma = \varepsilon_a/Mc^2$, ε_a = antiproton energy, θ_a = the initial antiproton angular spread in the laboratory system, (for longitudinal degree of freedom, the relative pulse spread must be substituted for θ_a), θ_e = electron angular spread, n = electron beam laboratory density, r_e = classical radius of the electron, c = velocity of light, L = Coulomb logarithm, η = relation of the cooling-part's length to the orbit perimeter. If at the same time the oscillation amplitudes for the other degrees of freedom are also large, the damping time expression will differ from that given above by the absence of the term

$$\ln(\theta_a/\theta_e)$$

In the range of small antiproton oscillation amplitudes, the damping will be exponential (the linear region) and its rate is determined by the electron velocities:

$$\tau_2 \approx 0{,}2\,\frac{M}{m}\,\frac{\gamma^5\beta^3\theta_e^3}{n r_e^2\, c L \eta}$$

The average amplitudes of the antiproton velocities, for that case, tend to

$$v_e\sqrt{\frac{m}{M}}\,.$$

Let us consider now the influence of some deviations from that ideal case on the cooling process. For example, let the mean electron velocity be different from the equilibrium antiproton velocity by the value Δv. If the difference is less than the "thermal" electron velocity, the damping character remains the same both qualitatively and quantitatively. In the case that, for the same degree of freedom, the difference in velocities exceeds the electron thermal velocities, the antiproton small oscillations in this degree of freedom become unstable and the antiproton velocity amplitude tends to Δv. Thus in such a case the cooling is going up to "velocities equality" not to the temperatures equalization.

There is an inevitable difference in electron and antiproton velocities in the regions of the electron beam's injection and its ejection. The influence of these sections is estimated to increase the damping time by a factor $[1 + (\rho/\ell)\theta]$ where ℓ = the cooling section length, ρ is the input-output radius, θ is the spread of electron and antiproton beams. Practically this value is fairly close to unity. The contribution of these sections to the diffusion term is also negligibly small.

If the mean electron velocity on the equilibrium orbit is equal to the stable antiproton velocity, but a sufficiently large radial gradient of the mean electron velocities exists, the synchrotron or betatron oscillations may happen to be unstable.

However, with all the imperfections of such a kind, the oscillation decrements sum remains positive and the following relation is valid:

$$\sum \lambda_i = 8\pi^2 \frac{m}{M} r_e^2 c^4 \frac{L}{\gamma^6} \langle f(\vec{v},\vec{r})\rangle_s$$

where $\langle f(\vec{v},\vec{r})\rangle_s$ is the electron distribution density in the phase space of the coordinates and the velocities are averaged over the antiproton equilibrium orbit. This assertion corresponds to the well-known theorem about the sum of the radiation friction decrements [5].

Besides the diffusion corresponding to the finite value of the electron "temperature", some other factors contribute to the diffusion term that limits the cooling of the antiprotons. In addition to the electron beam density fluctuations, due to the temperature, there may be the coherent fluctuations resulting from external modulations (variations of the accelerating voltage, of the beam current, etc.). In this case the region of the fluctuations spectrum, close to the resonance frequencies of the antiprotons, is dangerous.

A "heating" effect may arise through scattering by the residual gas atoms but even at a pressure of 10^{-9} torr (that is common nowadays) and a cooling time of practical interest, this effect is negligibly small in accumulating antiprotons. However, the critical compression attainable may be limited by this scattering.

Let us now discuss the problem of generating the electron beam needed for cooling. The energetic problem is the first to be solved. At relativistic antiproton velocities, the necessary values of the cooling time require an electron beam power of some hundred megawatts. For an antiproton energy of 10 GeV and greater, the optimum solution of the problem is apparently in using the electron storage ring. One can keep a low electron temperature either by means of radiation friction or by replacing the electrons after their heating.

At the lower energies used in our project, the recuperation of the electron energy is more convenient; accelerated electrons after having passed through the cooling section give their energy to the high-voltage power supply [6]. In this case, the power taken from the high-voltage supply is determined only by the fraction of the main current, the fraction that is lost because of system imperfections and scattering of electrons on the residual gas. Besides that, the slowing down of the beam can never be complete and that leads to additional power loss.

It is very important to provide a low effective electron temperature. A significant complication arises from the necessity of operating with so high an intensity electron beam that space charge results in a strong defocusing. A transport system with focusing that varies along the beam trajectory (say strong focusing) seems to be of little use because of two reasons. Firstly, this version requires that the focusing be tuned to changes in the electron beam current or energy, to keep the transverse velocities at a low value. Secondly, even for a matched regime, the beam current increase would inevitably result in growing modulations of the beam envelope and, therefore, in the increase of the effective electron "temperature". The transport system with a quasi-uniform longitudinal magnetic field, that guides the electron beam from the cathode, has no such defects. For sufficiently high strength of the magnetic field, transverse velocities would be small enough over the total operation current and energy range [6].

In conclusion of this part, we will give here the operating parameters of the electron cooling system now being designed for the antiproton storage ring NAP:

Electron energy	600 kev
Beam current	100 A
Beam cross section	20 cm^2
Electron beam angular spread	$3x10^{-3}$
The cooling section length	2x5 m
(Storage ring circumference	46 m)
Longitudinal field strength	1 kG
Power supply	0.5 MWt
Cooling time for maximum antiproton amplitudes	100 sec

Such a storage ring with electron cooling would allow the superconducting synchrotrons now being designed in Batavia and at CERN to add colliding beams of protons and antiprotons at a luminosity of about 10^{31} cm^{-2} sec^{-1} and a reaction energy in the range of 1000 GeV.

At present an experiment to study the electron cooling of protons at an energy of 100 - 200 MeV is prepared on the storage ring VEPP-3. The recombination of protons in the cooling electron beam is not dangerous since the time required for full recombination is much greater than the cooling time, while those neutrals produced can be used as an indication of the equality of the mean velocities. The electron beam for the experiment is just ready; its parameters are as follows [6]:

Electron energy	75 kev
Beam current	1 A
Beam cross section	1 cm^2
Angular spread of the beam	$5x10^{-3}$
Cooling section length	1.2 m
(VEPP-3 circumference	74.4 m)
Longitudinal field strength	1kG
Power supply	2 kWt
Cooling time	10 sec

The main difficulty of the experiment lies in the acceleration of protons in the storage ring VEPP-3 (the injection energy is 1 MeV). The solution of this problem is now delayed because attention is mostly directed to the electron-positron program.

In conclusion, just a few words on the current status of the project. The main construction work is completed. More than half of the magnet units for the storage ring VAPP are already made. The technology line for vacuum chamber manufacturing is prepared. The manufacturing of the storage ring NAP as well as the proton synchrotron of the first stage is started. The first data on the generation of the fields of about 1 MG for the conversion system have been obtained.

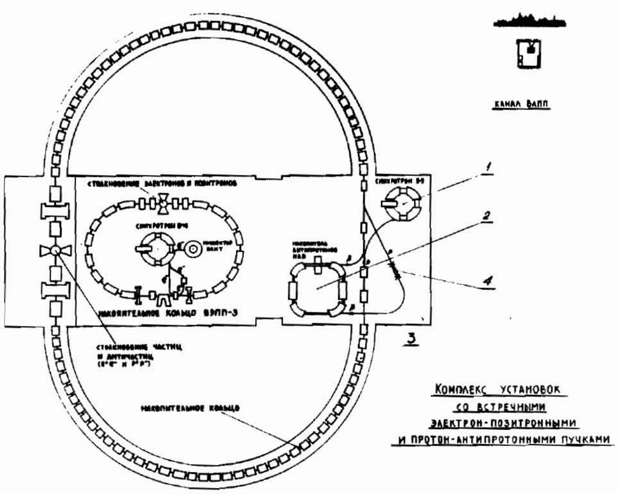

Fig. 1 The general diagram of VAPP-NAP project

1. Synchrotron B-5;
2. Antiproton storage ring NAP;
3. Storage ring VAPP.

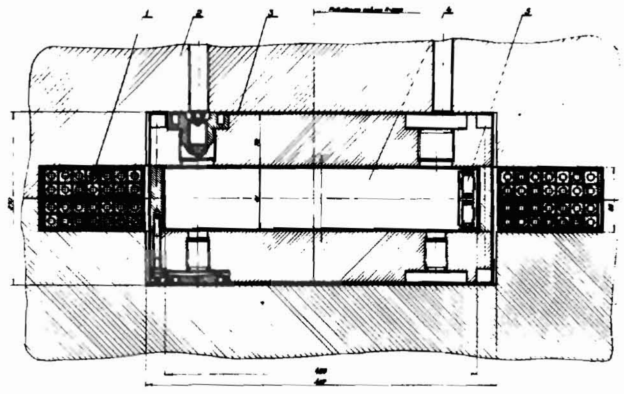

Fig. 4 Vacuum chamber of NAP

1. NAP magnet coil;
2. Magnetic circuit;
3. External vacuum chamber wall;
4. Internal chamber;
5. Ion pump.

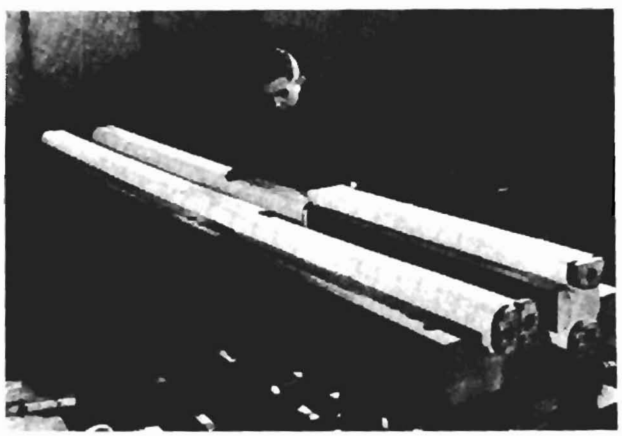

Fig. 2 Magnet of VAPP.

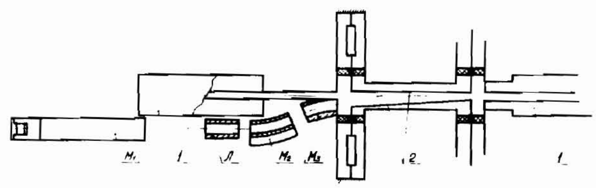

Fig. 5 Antiproton injection diagram

1. NAP magnet;
2. Inflector plates;

$M_1 M_2 M_3$ bending magnets;

Л – lense.

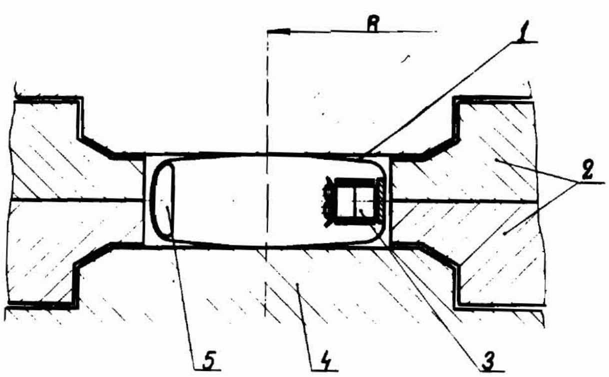

Fig. 3 Vacuum chamber of VAPP

1. Vacuum chamber wall;
2. Windings of magnet coil;
3. Ion pump;
4. Magnetic circuit.

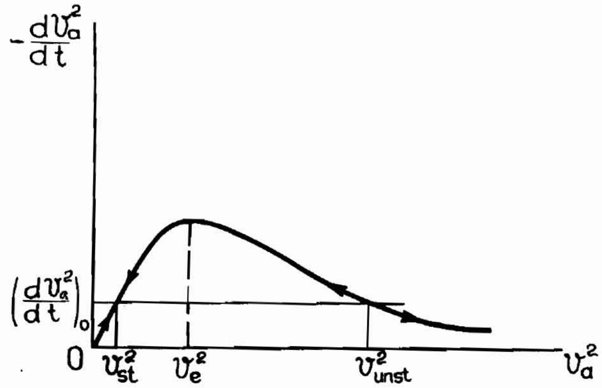

Fig. 6

(v_a) - Antiproton velocity amplitude;

(v_e) - Electron velocity spread;

(v_{st}) - The stable equilibrium velocity amplitude;

$\left(\frac{dv_a^2}{dt}\right)_0$ - Growth velocity because of residual gas;

(v_{unst}) - Unstable equilibrium point.

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DISCUSSION

M.H. BLEWETT : What is your schedule for completing VAPP-NAP ?

A.N. SKRINSKY : It is very difficult to answer definitely. We expect to have the main storage ring completed by the end of 1972. We will try to start electron-cooling experiments this winter.

E.D. COURANT : What is the collision geometry on which you base your estimates of luminosity ?

A.N. SKRINSKY : The given luminosity corresponds to 1 mm diameter; the bunch length is about 0.5 m.

A.M. SESSLER : There is considerable interest in having polarized proton beams in the ISR but I believe it is not easy to make such beams. One possible way is to use a source of polarized protons and accelerate them in the PS (which is not easy as there are resonances to be crossed, but let us assume that these can be crossed by one means or another). However, the resulting polarized beam in the ISR would be too tenuous to be of much interest for colliding-beam physics.

Now I wonder if you, or anyone here at CERN, has studied the application of electron-cooling to this problem. In particular, can one in this way, obtain a dense beam of polarized protons ?

A.N. SKRINSKY : One must cool at low energies.

A. SØRENSSEN : One could use polarized deuterons which are much easier to accelerate without depolarization.

A.M. SESSLER : I agree, still it would be necessary to get sufficient intensity.

F. MILLS : This summer at BNL, Professor Gluckstern has investigated the use of electron cooling at about 30 GeV to increase the luminosity for intersecting storage accelerators with p-p or $\bar{p}$-p. His conclusion, the same as Professor Skrinsky's,is that this is very difficult to do at such energies. On the other hand, the use of a Maschke stacking ring might be useful for this purpose.