

CYBERNETIC ACCELERATORS

Alexander L. Mints

USSR Academy of Sciences
Moscow, USSR

Summary

This report describes the history, principles of design and some features of cybernetic proton accelerators developed and investigated in the USSR to obtain super-high energy particles up to 1000 GeV. A description of a 1 GeV scale model of the large machine and the results of investigations carried out on it are given. It is shown that the use of superconducting magnet units permits to obtain energies as high as 4000 GeV with an orbit of about 17 km long.

The audience of this accelerator Conference in Chicago fortunately requires no further arguments in favour of the importance of obtaining super-high energy proton beams of high intensity for experimental work. The 76 GeV accelerator near Serpukhov, USSR, and further projects concerning the increase of particle energy and beam intensity provided by this machine, the successful building of a larger proton synchrotron at Batavia, Illinois and the design of the West-Europe big accelerator under the scientific and engineering aegis of the CERN-staff -- all these facts show that the fixed-target strong focusing proton synchrotron continues to remain the leading system in super-high energy accelerator design.

The development and use of superconducting magnets in the proton synchrotron design is an attractive perspective. Such synchrotrons will be very effective and economical in construction and operation if small aperture is used. We see a possibility of using sufficiently small aperture accelerators if we apply automatic control of transverse beam motion during its movement along its orbit. Those who watch closely the translation series published by the U.S. Atomic Energy Commission should have noticed the two volumes devoted to the Soviet design of 1000-GeV cybernetic proton accelerator and to the program of physical experiments to be carried out on this machine at this energy level.¹

I shall briefly remind you the history of the research and development of cybernetic accelerators.

In 1961 the USSR Committee for the Use of Atomic Energy proposed to several groups of scientists to elaborate projects for super-high energy accelerators. One of these groups proposed a new principle to be used for the design of a 1000 GeV proton synchrotron with a very small aperture.² Autocorrection of magnetic field characteristics particularly for the compensation of coherent betatron oscillations was to be used. This autocorrection was to follow the data corresponding to the particle beam position in the vacuum chamber.

The main operation principles of the cybernetic accelerator and the preliminary data

of the first design of a 1000 GeV machine were reported by us in 1963 at the Dubna International accelerator Conference.³ At the same Conference a paper was presented containing the main data of a scale model accelerating protons up to 1 GeV.⁴ In 1967 this model was realized. Investigations were carried out on a small aperture accelerator with a vacuum chamber of elliptical cross-section with the dimensions of 16 mm x 21 mm. 1 GeV protons were obtained by means of this accelerator model. Various experiments have been carried out. Among these the successful operation of the small aperture accelerator with digital computers should be mentioned. At a number of international and national conferences my collaborators and myself reported basic theoretical positions of the behaviour of cybernetic accelerators, some improvements in the 1000 GeV accelerator system design, the future use of cybernetic accelerators with superconducting magnets to attain particle energies higher than 4000 GeV.⁵⁻¹³ It has been demonstrated that systems for the production of main magnetic field and correcting fields were expedient to be separated from one another. I should like to say a few words about these things.

While working out the 1000 GeV accelerator design we adopted a structure the basic parts of which were the three accelerator steps: a linear proton accelerator serving as an injector of particles with an energy of 0.8 GeV, then a booster-ring accelerator to bring the proton energy up to 18 GeV and a final accelerator ring producing internal and external proton beams with the energy of 1000 GeV.^{14,15} The maximum magnetic field in the gap of the final accelerating step was to be 16 kG. It made it possible to have an orbit length of about 17 km.

The construction of the accelerator is planned to be effected in three stages. After the completion of the first stage the accelerator is to give 500 GeV proton beams (the accelerating period will be 2.5 sec). After the second stage is completed the accelerator will give 1000 GeV proton beams (the acceleration period will be shortened to 1 sec). An iron core electromagnet will be used at the first and second stages of accelerator design. A superconducting magnet must be provided for the third stage and the proton beam energy will rise up to 4000 GeV. The experiments carried out on the 1 GeV scale model have convinced us that if the magnet field in the final ring was corrected in accordance with the theory a vacuum chamber of elliptical cross-section could be adopted 66 mm wide in radial direction and 40 mm high.

In the 1000 GeV final accelerator ring the energy gain will be 56 MeV per turn. When the booster ejection energy equals to 18 GeV the radio frequency tuning of the accelerating stations output circuits installed

around the final ring is not a difficult job as the modulation index is small $\Delta f/f=0.12\%$. The final accelerator will operate at 20 pulses per minute. All the accelerating stations will require RF power of 23 MW.

The automatic orbit position control system envisaged in the cybernetic accelerator carries out an automatic magnetic field correction to guarantee reliable close beam passage along the vacuum chamber axis. Pick-up electrodes give signals of transverse beam position coordinates that are processed by a digital computer. The information about all the magnetic field perturbations given by the computer is used for field correction purposes.

It is important to choose an adequate compensation method to avoid distortions of the magnetic field structure. This function is carried out by correcting magnetic lenses which are installed between all the units of the main magnet.

The control of the orbit shifts will be carried out in two steps: at first during the injection period and then during the acceleration time. The automatic orbit position control system contains 264 sets of pick-up electrodes and 528 correcting lenses provided with special amplifiers energizing their windings. Proper values of current through the lens windings are determined on the basis of probe outputs. For the betatron oscillation frequency control it is necessary to measure the frequency given by the pick-up electrode system and compare it with a standard one. A controlling signal proportional to the difference between the standard frequency and that measured is introduced into the circuit of correcting lens windings. Resonance between the RF accelerating electric field and the particle revolution frequency is also maintained by an automatic control system.

Quite satisfactory agreement of theoretical calculations and experimental data obtained on the accelerator model were observed. Many American and West-Europe scientists who visited the Moscow Radiotechnical Institute had the possibility of first hand acquaintance with the operation of the 1 GeV model.

The magnet of the model consists of 100 units forming a strong focusing FODO-type system. The units are installed in turn inside and outside the orbit. The magnetic structure of the 1 GeV accelerator has 10 superperiods each consisting of 5 magnetic periods. The profile of pole face is very steep with a field index $n=191$. The transversal focusing force of the magnet can be characterized by the number of betatron oscillations per turn $Q = 6.25$. For a magnet with a diameter of 17 m it corresponds to a very strong focusing force. The injection energy is 1 MeV. The maximum dimension of the beam spot in the vacuum chamber is less than 8 mm. The chamber cross-section is only a little greater than the area occupied by betatron and synchrotron oscillations.

There are specific difficulties in obtaining an operational vacuum of $5 \cdot 10^{-7}$ torr in a chamber of such a small cross-section.

Parallel to the chamber an annular ring-shaped pipe (collector) of a much greater cross-section is installed. The collector is connected with the chamber in 20 equidistant points. 5 high-vacuum titanium pumps are connected with the collector which is made of stainless steel. All seals of the vacuum system are manufactured of indium.

In order to insert controlled perturbations into the magnetic field during experiments and to study their effect on the beam behaviour the magnet should be manufactured with as high accuracy as possible. To obtain this high precision the magnet core laminations were manufactured by stamping consecutively with three different stamps, the last and the most precise of them being of special hard alloy. In addition each of the 120 thousand laminations have undergone special heat treatment and afterwards have been shuffled. An individual certificate has been compiled for each of the 100 magnet units. The data of these certificates have been processed by a special computer to determine the optimal arrangement of the units along the circumference of the accelerator. The equivalent geometrical error including the spread of iron characteristics as found from measurements of beam deviations is about $30 \mu\text{m}$.

Two injection modes are provided for the accelerator model: protons are injected at a constant magnetic field, the latter beginning to increase after the particles have been circulating in the vacuum chamber for some hundreds of microseconds; protons are injected at an increasing magnetic field. Particles are injected by a 1 MeV Van de Graaf electrostatic generator. The energy of injected bunches is maintained within 0.1 per cent.

13 accelerating stations are installed along the circumference of the accelerator. The accelerating voltage frequency is 5 times higher than that of particle revolution i.e. it varies from 1.25 to 25 MHz. The suppression of coherent synchrotron oscillations is achieved by usual methods.

Signals induced onto the electrostatic plates of 20 sets of pick-up electrodes amplified by broadband amplifiers and after rectification are converted into signals whose values and signs give the values and signs of beam displacement with reference to the chamber center line in 20 locations. By processing the output signals one can obtain information on the orbit shifts due to any perturbation of the magnetic field. The measured orbit perturbation may be expanded into a set of orthogonal functions characterizing a given magnet field structure and one can perform control in such a way that the magnitudes of the most undesirable components are essentially reduced.

In a small aperture machine it may occur that the beam propagates only a part of the vacuum chamber before hitting its wall. In this case the information on the beam behaviour along the entire circumference of accelerator required for the above-mentioned method is not available. Therefore the use should be made of a step-by-step control system to adjust the "first-turn" beam position. The beam displacement from the chamber center

TABLE 1

The data of the accelerator	Scale model	I Stage	II Stage	III Stage
Ejection energy (GeV)	1	500	1000	4000
Beam intensity (protons/sec)	10^8	2×10^{12}	3×10^{13}	10^{13}
Diameter (m)	17	54.35	54.35	54.35
Maximum magnetic field (kG)	10	8	16	65
Aperture (mm)	22x16	40x66	40x66	66
Magnet weight (t)	16	18000	18000	60 super-conduct.alloy
Repetition rate (p/min)	30	10	20	5
Energy gain per turn (MeV)	0.001	12	56	60
Main ring injection energy (GeV)	0.001	18	18	18
Number of betatron oscillations p/turn	6.25	34.25	34.25	34.25
Number of pick-up electrodes	20	264	264	264
Number of correcting magnetic lenses	40	528	528	528
Radio frequency (MHz)	1.25-25	120	120	120

line is measured at the end of each of many sections into which the magnet structure of the machine is subdivided and the displacement is brought to zero by means of a correcting magnetic lens. An amplified signal coming from pick-up electrodes serves as an input signal for the amplifier that controls the current in the lens windings. This method repeated consecutively in 20 equidistant cross-sections along the chamber enables the beam to pass throughout the entire orbit practically without losses. Within each period of betatron oscillations the orbit position undergoes correction approximately in three points.

Of all the experiments carried out on the accelerator model most interesting are those checking the accelerator main parameters and the possibility of proton acceleration in a small aperture chamber. Of no less significance is the verification of the automatic control system efficiency. It has been shown experimentally that the magnet system ensures such focusing of the beam that all the injected particles accomplish the first turn with no losses. While initial displacements of the beam were as high as 5 mm the step-by-step system brought them within 1 mm. Protons are also normally accelerated when the magnetic field has great nonlinearity vs radius which is typical of high gradient fields.

The computer used in our cybernetic accelerator model is quite a modest one. Its average speed is 10.000 operations per second and its immediate-access memory capacity is 4096 words.

In the 1000 GeV cybernetic proton synchrotron with a 17 km long orbit there are, as I have mentioned before, 264 sections instead of 20 sections adopted for the 1 GeV model. General data of the large cybernetic accelerator corresponding to its three consecutive stages and the data of our 1 GeV accelerator model are given in Table 1.

Initial efforts should be concentrated primarily on the construction of a strong focusing iron-core magnet giving a maximum field of 16 kG. During the I stage operation (500 GeV) the magnet and its feeding devices must work in easier conditions producing a 8 kG magnetic field. The transition to the

III stage should be undertaken only after the capabilities of our cryogenic technology rise up considerably and we elaborate magnets and cryostates maintaining temperatures near 4°K . Then we shall reach 60 - 80 kG fields. Today in our laboratory we have 40 kG pulsed fields. For the design and technology elaboration of magnet units and of all necessary cryogenics machines and apparatus several years are required.

In conclusion I should like to dwell upon the design of superconducting cybernetic proton synchrotrons giving particles within the range of hundreds and thousands of GeV in which existing accelerators with a low repetition rate will be used (for example the Serpukhov synchrotron). The idea of that kind was several times suggested in various accelerator centers. But if so the accelerator machine would be far from optimum. The use of superconducting alloys for manufacturing the final ring magnet enables the builders to achieve an essential decrease in its circumference. The time of particle acceleration, the ejection time and the time of magnetic field break down become longer. Under these conditions the use of the existing "slow" synchrotron injectors becomes quite justified as the operation duty cycle becomes larger.

Main data of one of the versions of a 2000 GeV cybernetic synchrotron with superconducting magnets are shown in Table 2.

TABLE 2

Data	Value
Ejection energy (GeV)	2000
Maximum magnetic field (kG)	65
Average orbit radius (m)	1500
Number of betatron oscillations per turn	32.25
Injection time (sec)	30
Acceleration period (sec)	15
Duration of constant field at ejection (sec)	30
Full cycle duration (sec)	90
Inner vacuum chamber diameter (cm)	6
Superconducting alloy weight (t)	65
Volume of liquid helium in cryostates (l)	55.000

Acknowledgement

I should like to express my thanks to my colleagues doctors A.A.Vasiliev, E.L.Burshtein, B.P.Murin, E.S.Mironov, I.Kh.Nevyashsky, F.A.Vodopianov, G.I.Batskikh, R.A.Meshcherov, N.L.Sosensky, A.I.Dzergach, N.K.Kaminsky and V.P.Alexeev for their collaboration in this work.

References

1. 1000 GeV Cybernetic proton accelerator, Translation Series, AEC-tr-6949, USAEC, October 1968.
Program of physical experiment on a 1000 GeV cybernetic proton accelerator, AEC-tr-6936, USAEC, June 1968.
2. Burshtein E.L., Vasiliev A.A., Mints A.L., Petukhov V.A., Rubchinsky S.M., Doklady AN USSR, vol.141, p.590, 1961; and Atomnaya energia, vol.12, p.111, 1962.
3. Burshtein E.L., Vasiliev A.A., Mints A.L. Proc.Int.Accelerator Conference, Dubna, 1963, p.67. M. 1964.
4. Batskikh G.I., Vasiliev A.A., Dzergach A.I., Mints A.L., Sosensky N.L. *ibid.*, p.217.
5. Burshtein E.L., Vasiliev A.A., Dzergach A.I., V Int.Conf.High Energy Accelerators, Frascati, 1965, p.34.
6. Vasiliev A.A. IEEE Trans., NS-14, p.1186, 1967.
7. Mints A.L., Vasiliev A.A., Burshtein E.L. VI Int.Conf.High Energy Accelerators, Cambridge, p.4, 1967.
8. Mints A.L., Vasiliev A.A., Dzergach A.I., Sosensky N.L., Batskikh G.I. *ibid.*, p.352.
9. Vasiliev A.A., Sosensky N.L., Dzergach A.I., Mironov E.S. *ibid.*, p.A-100.
10. Burshtein E.L., Vasiliev A.A. Proc.of the USSR National Accelerator Conference, Moscow, 1968, p.27. M., 1969.
11. Vodopianov F.A., Gutner B.M., Dushin Yu.F., Litvinov V.N. *ibid.*, p.132.
12. Andryushtenko-Lutsenko N.I., Vasiliev A.A., Dzergach A.I., Kuzmin V.F., Rubchinsky S.M., Soloviev G.N. *ibid.*, p.23.
13. Mints A.L., Vasiliev A.A., Burshtein E.L., VII Int.Accelerator Conference, Erevan, USSR, 1969.
14. Murin B.P., Nevyashsky I.Kh., 1000 GeV Cybernetic proton accelerator. AEC-tr-6949, USAEC, Part III, p.264-335. October 1968.
15. Vodopianov F.A. *ibid.*, Part II, p.145-262.

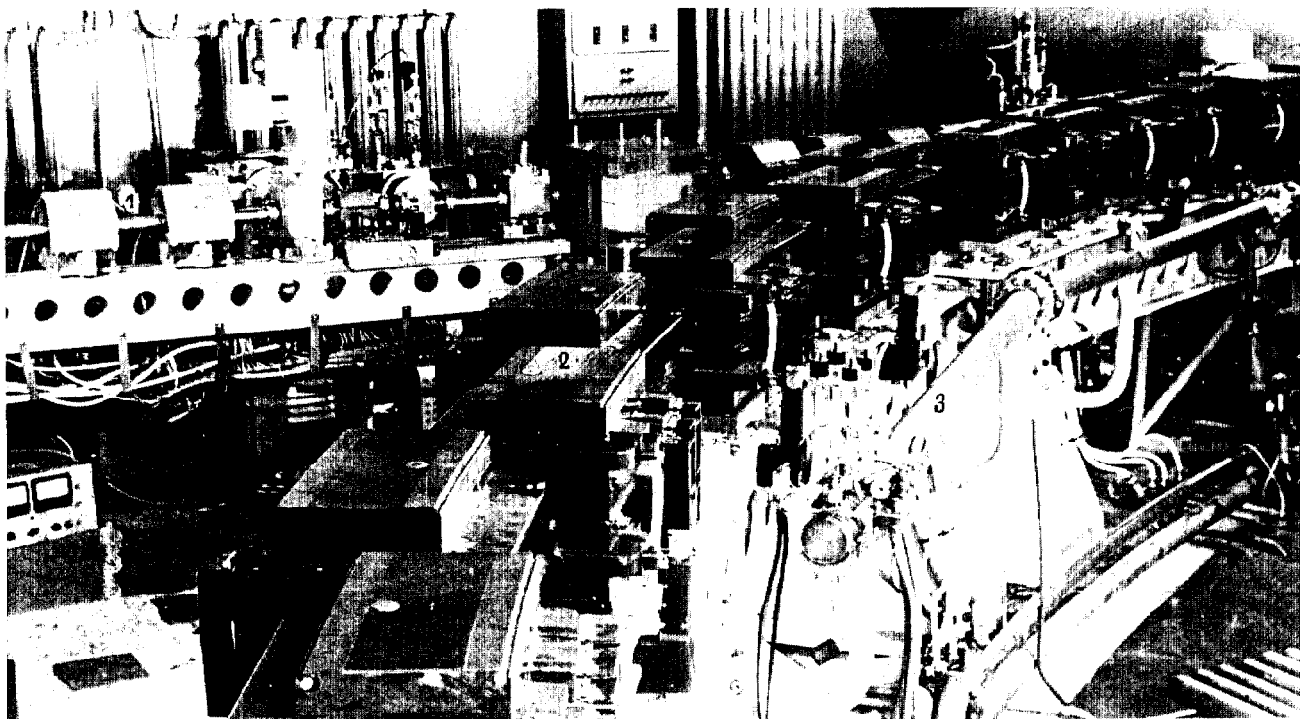


Fig.1. View of 1 GeV scale model of cybernetic accelerator; 1-injection beam guide, 2-magnet unit, 3-pumping system

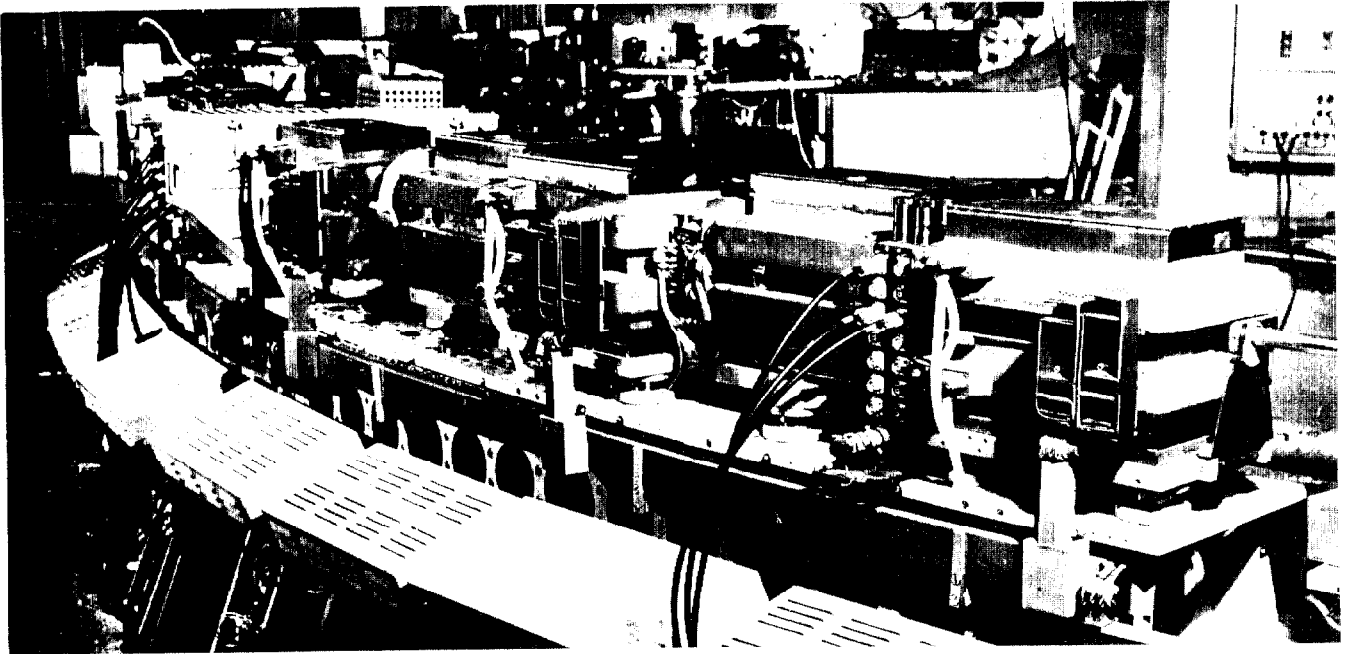


Fig.2. Another view of 1 GeV model

N ТРОЙКИ	10	5	0	-5	-10
1	XXXXXXXXXX		Д		XXXXXXXXXX
2	XXXXXXXXXX		Д		XXXXXXXXXX
3	XXXXXXXXXX		Д		XXXXXXXXXX
4	XXXXXXXXXX		Д		XXXXXXXXXX
5	XXXXXXXXXX		Д		XXXXXXXXXX
6	XXXXXX		Д		XXXXXXXXXX
7	XXXXXX		Д		XXXXXXXXXX
8	XXXXXX		Д		XXXXXXXXXX
9	XXXXXXXXXX		Д		XXXXXXXXXX
10	XXXXXXXXXX		Д		XXXXXXXXXX
11	XXXXXX		Д		XXXXXXXXXX
12	XXXXXXXXXX		Д		XXXXXXXXXX
13	XXXXXXXXXX		Д		XXXXXXXXXX
14	XXXX		Д		XXXXXXXXXX
16	XXXXXXXXXX		Д		XXXXXXXXXX
16	XXXXXXXXXX		Д		XXXXXXXXXX
17	XXXXXXXXXX		Д		XXXXXXXXXX
18	XXXXXX		Д		XXXXXXXXXX
19	XXXXXXXXXX		Д		XXXXXXXXXX
20	XXXXXXXXXX		Д		XXXXXXXXXX
	10	5	0	-5	-10

Смещение от оси камеры
а)

N ТРОЙКИ	10	5	0	-5	-10
1	XXXXXXXXXX		Д		XXXXXXXXXX
2	XXXXXXXXXX		Д		XXXXXXXXXX
3	XXXXXXXXXX		Д		XXXXXXXXXX
4	XXXXXXXXXX		Д		XXXXXXXXXX
5	XXXXXXXXXX		Д		XXXXXXXXXX
6	XXXXXXXXXX		Д		XXXXXXXXXX
7	XXXXXXXXXX		Д		XXXXXXXXXX
8	XXXXXXXXXX		Д		XXXXXXXXXX
9	XXXXXXXXXX		Д		XXXXXXXXXX
10	XXXXXXXXXX		Д		XXXXXXXXXX
11	XXXXXXXXXX		Д		XXXXXXXXXX
12	XXXXXXXXXX		Д		XXXXXXXXXX
13	XXXXXXXXXX		Д		XXXXXXXXXX
14	XXXXXXXXXX		Д		XXXXXXXXXX
15	XXXXXXXXXX		Д		XXXXXXXXXX
16	XXXXXXXXXX		Д		XXXXXXXXXX
17	XXXXXXXXXX		Д		XXXXXXXXXX
18	XXXXXXXXXX		Д		XXXXXXXXXX
19	XXXXXXXXXX		Д		XXXXXXXXXX
20	XXXXXXXXXX		Д		XXXXXXXXXX
	10	5	0	-5	-10

Смещение от оси камеры
б)

Fig.3. Off-axis displacement when the control system is off (a) and when it is on (b)
Д-denotes the middle point between boundaries

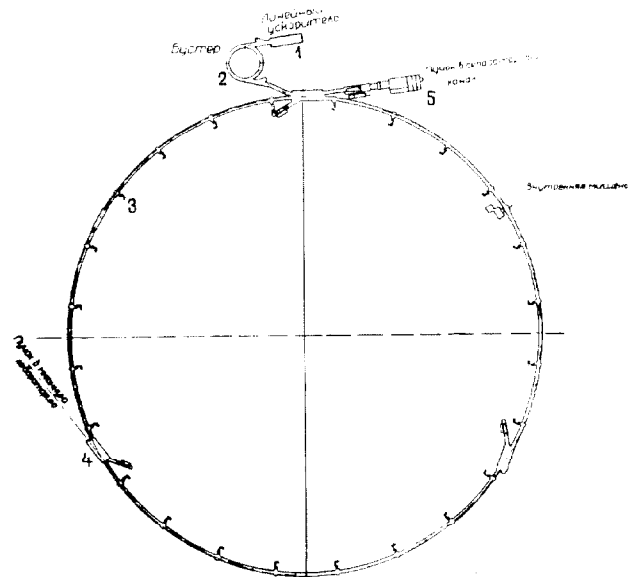


Fig.4. Layout of 1000 GeV accelerator; 1- 0.8 GeV injector linac, 2- 18 GeV booster, 3- 1000 GeV ring, 4-5 beam extraction channels