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TRENDS OF DEVELOPMENT OF ELECTRONIC CYCLIC ACCELERATORS,(U)

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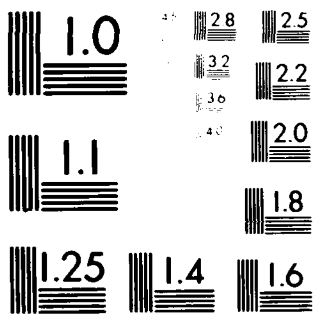

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FOREIGN TECHNOLOGY DIVISION

5. TRENDS OF DEVELOPMENT OF ELECTRONIC CYCLIC ACCELERATORS

by

A. A. Kolomenskiy

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

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5. TRENDS OF DEVELOPMENT OF ELECTRONIC CYCLIC ACCELERATORS.

(Review).

A. A. Kolomenskiy (physical institute im. P. N. Lebedev of the AS USSR).

1. Contemporary state of electronic cyclic accelerators.

The electron accelerators are characterized by the diversity of types and large difference in their fundamental characteristics. By average/mean intensity the accelerators are distinguished to six orders: from 10^{10} to $\sim 10^{15}$ electrons per second, while on the energy - almost to four orders: from ~ MeV to 20 GeV. Linear accelerators, as a rule, considerably exceed cyclic ones and on the average, and on pulse intensity. However, with an increase in the energy and the entrance into the region of the energies, which exceed 1 GeV, synchrotrons begin to overtake linear accelerators in the average/mean intensity. Furthermore, according to such essential characteristics as energy spread, porosity and beam extension in the time, cyclic accelerators thus far, as a rule, they incorporate advantages before the linear ones. Let us examine the briefly separate types of electronic cyclic accelerators.

1.1. Betatron.

In the betatrons - oldest electron accelerators - a number of electrons in the impulse/momentum/pulse usually composes several units on 10^9, and the pulse repetition frequency 50-60 per second. The majority of betatrons works in energy range 25-50 MeV and up to now it is utilized in the physical first of all photonuclear investigations. Betatrons have the numerous technical uses/applications (X-ray inspection, X-ray therapy, etc.), but gradually they are displaced by linear accelerators.

A basic improvement in the characteristics of beam it is possible to expect from the betatrons with the time-constant magnetic guiding field (of type of circular F-M cyclotron or FFAG), calculated for the energy to 150-200 MeV. In them it is possible to carry out such mode/conditions, during which the share of useful time grows/rises and under specific conditions can reach values of ~0.1-0.2. instead of value ~10^{-3}, characteristic for the usual betatrons. In accordance with this the intensity of beam can be raised to 10^{13} electrons per second and even it is more (with the high monochromaticity). Confidence in the fact that such values can be actually/really achieved/reached, is based on the experience, obtained during the starting/launching and the experiments on the installations, installed in FIAN and in laboratory MURA (Madison, USA). Report about the development of high-current betatrons with the stationary leading field and the quasi-continuous beam is represented to the present conference the group of colleagues of FIAN. The design of this type of installation on 150 MeV is conducted also at the University of Iowa (USA).

1.2. Microtron.

The microtrons in the region of energies from 5 to 30 MeV give electron beams with a good intensity and the monochromaticity. Most powerful/thickest pulse microtrons on 30 MeV give current 50-100 mA in the impulse/momentum/pulse by the duration of the order of microseconds.

New step/pitch would become the creation of the microtron of continuous or quasi-continuous action. The state of the contemporary technique of the generation of SVCh large power allows/assumes the construction of this microtron on 30-40 MeV at the average/mean power of generator 150 kW in the range of wavelengths 15-20 cm. In the

In the mode/conditions of the long impulses/momenta/pulses, which correspond to 90o/o of useful time, the accelerator could give energy to 100 MeV, having a diameter of magnet 4 m and a weight 50-100 t.

Another promising trend is the "superconducting" microtron in which as the accelerating system must serve the superconducting resonator or linear accelerator (LU). Let us note that in the combination of linear and cyclic accelerator is generally included one of the important contemporary tendencies.

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The difficulties of constructing this microtron are connected not only with the creation superconducting LU, but also with the complication of the configuration of the magnetic field: by presence of two or more separate sectors, with the need for magnetic lenses for the adjustment of the defocusing actions stray field, etc. The efforts/forces, connected with the creation of the superconducting microtron, are justified, apparently, with the energies >100 MeV. Are at present known the projects: Stanford university (USA) on 200 MeV from LU to 10 MeV and University of Illinois (USA) on 600 MeV with LU to 30 MeV. To judge the prospect of these installations still early.

Finally, are possible the compromise versions, example of which is the proposition of the physiotechnical institute (Leningrad) about the construction of microtron on 400-500 MeV with the current 10-100 μA and porosity 10-100, the being based on the improved linear accelerator usual type on 14 MeV. The major advantage of this microtron the authors see in the monochromaticity of beam, substantially best, than in the linear accelerators.

1.3. Synchrotron.

There are several generations of these machines, which compose basic part of the electron accelerators to the high energies. After the first generation, on which were mastered basic principles, followed the second generation with energy on the order of 300 MeV, designed for the photoproduction of π-mesons. The basic group of the installations, which act at present (order of ten machines), compose synchrotrons to energy on the order of 1-1.5 - GeV among which there are the weakly-focusing and strongly-focusing installations. With rapid rates they were constructed and launched the strong-focusing synchrotrons to the "intermediate" energies: 2.1 GeV at Cornell (USA) and 2.3 GeV in Bonn (FRG).

In the 60's enters into the system a series of large strong-focusing synchrotrons to the energy ~6 GeV (see the Table): CEA in Cambridge (USA), DESY in Hamburg (FRG), NINA on 4-5 GeV in

Daresbury (England) and APYC on 6 GeV in Yerevan, enumerated installations give to 10^{11} particles per pulse, which in the repetition frequency 50-60 Hz corresponds $(3-6)\cdot10^{12}$ electrons per second.

The basic parameters of the largest electronic synchrotrons.

(1) Параметр	NINA	CEA	Ереван (2)	DESY	Cornell
(3) Максимальная энергия электронов, Гэв	4	6	6	7	10
(4) Число электронов в импульсе	10^{12}	10^{11}	10^{11}	10^{11}	10^{11}
(5) Магнитное поле при инжекции, гс	64	35(125)	66	42	50
(6) Энергия инжекции, Мэв	40	28(100)	50	40	150
(7) Максимальное поле, гс	6430	7600	7920	8100	3300
(8) Радиус орбиты, м	20,7	26,4	25,1	31,7	100
(9) Число импульсов в сек	50	60	50	50	60
(10) Вертикальный зазор в фокусир. секторах, см	6,2	5,1	6,0	5,6	2,54
(11) Общий вес железа, т	362	290	400	570	185
(12) Общий вес меди, т	40	39	25	80	25
(13) Дата запуска	12/66	9/62	10/67	2/64	3/68

Key: (1). Parameter. (2). Yerevan. (3). Maximum energy of electrons, GeV. (4). Number of electrons in impulse/momentum/pulse. (5). Magnetic injection field, G. (6). Energy of injection, MeV. (7). Maximum field, G. (8). Radius of orbit, m. (9). Number of impulses/momenta/pulses in s. (10). Vertical clearance in focusing sectors, cm. (11). Total weight of iron, t. (12). Total weight of copper, t. (13). Date of starting/launching.

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Recently considerable attention draws the synchrotron of Cornell university (USA) on 10 GeV which is characterized by some remarkable special features/peculiarities: the radius of curvature of orbit in it about 100 m, which corresponds to uncommonly small magnetic intensity ~3.3 kg; the aperture of magnetic clearance is unprecedented small - entire 3.8x0.35 cm; vacuum chamber in the true sense of word is absent - vacuum is created in the volume, which includes magnets. The latter are characterized by large compactness - their total weight a total of about 200 t. Because of this, and also certain other, in particular, to construction special features/peculiarities Cornell accelerator was obtained relatively economical (cost/value less than 12 mln. dollars). It is already launched to the energy 10 GeV at the intensity ~$3\cdot10^{10}$ of electron in pulse and the repetition frequency 60 Hz. Let us note that the transverse sizes/dimensions of beam with the energy 10 GeV proved to be equal to 1 mm on vertical line and 15 mm on a radius.

2. Basic tendencies in the development of large electronic synchrotrons.

2.1. Increase in energy of injection.

The effectiveness of injection in the synchrotrons, as a rule, it is not possible to recognize high. Thus, in DESY it composes

~25o/o, CEA ~15o/o. Roughly it is possible to consider maximum number of particles in orbit proportional to energy of injection $N_{пред} \sim E_{инж}$. Therefore increase $E_{инж.}$ in this respect, as in the series/row of others, it is extremely desirable. Thus, in CEA convert/transfer with $E_{инж.} = 30$ MeV to $E_{инж.} = 120$ MeV, in DESY prepare to convert/transfer with $E_{инж.} = 40$ MeV to $E_{инж.} = 500$ MeV. Let us note that an increase in the intensity is connected also with the depression of some instabilities about which will go the speech in the review on the collective effects in the accelerators. In this case the accelerating VCh system must be in the state compensate for the radiation losses of more intense beam. However, for the series/row of experiments could be of interest and work with the lowered/reduced energy, but with the substantially enhanced intensity.

2.2. Conclusion/output of electron beams.

Still several years ago conclusion the conclusion/output of electron beams from the synchrotrons was considered as the very difficult matter. Now electron beams are brought out both on that strong-focusing (SEA, DESY, NINA) and on the weakly-focusing (Frascatti) synchrotrons. In order to give idea about the level, at which this is done, it suffices to indicate the Cambridge synchrotron. Concluded there with the effectiveness 70o/o beam are expanded on 1 ms. It it is possible to displace by the target or to derive/conclude outside into four different places of the ring of synchrotron, alternating by any their form on the previously comprised timeline.

2.3. Beam extension in time.

Due to the creation of the flat/plane section of the dependence of current in the magnet on the time and the corresponding increase in the power of 7Ch system is reached the brace of the internal or brought-out electron beam or γ-rays. At present is achieved the brace of the order of milliseconds, which corresponds to several percentages of useful time. There are plans/layouts of an increase in this value to tens of percent (on the Cambridge accelerator).

2.4. Obtaining monochromatic and polarized beams of γ-rays and electrons.

Up to the latter/last time the electron accelerators were utilized predominantly as the sources of the γ-rays of large energy. In this connection it is necessary to mention against all the increasing in recent years development of the effective and promising and polarized beams of γ-rays. The use/application of monochromatic rays/beams makes it possible to increase substantially the accuracy of diverse experiments in photoreactions, and polarized beams give the possibility to obtain qualitatively results in this region.

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The monochromatisized and polarized beams of braking γ - radiation/emission are generated, in particular, during braking of electrons on the crystal targets (diamond, etc.). Works in this direction were developed especially in Frascatti, and also in DESY, with Tokyo, Yerevan, Kharkov, etc. Such beams generate also with Compton scattering of laser photons on the electrons of large energy (work in CEA, Yerevan, FIAN, etc.). Let us note also used for the monochromatization a positron-electronic annihilation and the method of marked photons (on the diagram of coincidences between events, by the caused photon, and by the electron recoil, which escapes from the target - radiator).

Large interest over the long term is of also the development of the sufficiently intense source of the polarized electrons for their further acceleration in the linear accelerator - injector, and then in the synchrotron itself.

2.5. Considerable increase in radius of synchrotron.

Upon transfer to all to high energies in the case of protons w meet with the trivial need for an increase of the radius of the magnet of at least ~E. In the electronic synchrotrons this problem substantially it is complicated due to a rapid increase in the losses to the synchrotron magnetic-retardation radiation/emission. In this case $\Delta W_{обор} \sim E^4/R$. In accordance with this sharply are scaled up and cost/value of VCh system, since necessary for the compensation radiation of VCh power it increases as E^8. From the dependence for $\Delta W_{обор}$ it follows, however, that in the principle with any energy it is possible to lower the radiation losses to the reasonable level by the value of the corresponding increase in the radius of synchrotron. Specifically, to to this path they went during the creation of synchrotrons on ~6 GeV, selecting a radius of magnet approximately/exemplarily doubly more than this would be necessary in the absence of radiation/emission.

2.6. Allowed transition to by superconducting or cooled liquid nitrogen to resonators.

One additional way of overcoming the difficulties, connected with the radiation/emission, considered as one of the possible ones for increasing the energy in Cornell, consist in the transition to the superconducting resonators. In them virtually must not be losses in the walls and entire/all VCh power will proceed with an increase in the energy of beam. With the use/application of the superconducting device/equipment with 4.2°K the quality of system can increase 3•10⁴ to ~10⁹. Therefore at the same power of VCh power generators of electrons on the Cornell synchrotron can be will be raised from 10 to 15 GeV. Colleagues, who carry out by this installation, hope even that, utilizing the superconducting systems, after increasing VCh power and boosting/forcing magnetic field, they in the future can approach the record for the electrons energy ~20 GeV. Let us note, true, that by this method are specific complications associated with the effect of radiation/emission on particle dynamics: the anti-damping of radial betatron oscillations and the effect of the quantum fluctuations of radiation/emission.

Another, less being promising, but more real possibility consists of the transition to the resonators, cooled by liquid nitrogen. In this case the losses in the walls can be reduced to ~7 times.

2.7. Use of synchrotron as basic part of accumulator/storage of electrons and positrons.

One of the important tendencies of latter/last time consists in the use by correspondingly of the modified large electronic synchrotrons not only for the particle acceleration, but also as the accumulators/storage for radiating/emitting the contrary electron-positron collisions. The first original experiments of this type were carried out in FIAN[1], and the most complete practical embodiment this procedure obtained on the Cambridge synchrotron.

FOOTNOTE 1. In FIAN was developed also so-called cascade system of accumulation, which consists of two synchrotrons - booster (on 300-400 MeV) and basic (ca 1,2 GeV). Both synchrotrons must be utilized as accelerators-accumulators/storage. ENDFOOTNOTE.

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The conversion of synchrotron into the accumulator/storage with clashing beams requires conducting the series/row of the special actions:

a) the creations of positron accelerator-injector. positrons are obtained with the aid of the electron beam on a target-converter in the linear accelerator - injector and further are accelerated in the following section of linear accelerator. The effectiveness of conversion and capture of positrons in the acceleration with the aid of the special magnetic lenses and other devices/equipment succeeds in raising to the significant magnitude. Let us note that the acceleration of positrons in the synchrotron is of independent interest, besides the use for the contrary collisions:

b) the introduction of the special damping magnets for redistributing the fading between the synchrotron and betatron oscillations;

c) the construction of supplementary magnetic pipe (bypass), comprised of the rotary magnets and the focusing lenses. This is necessary for the beam shaping in the rendezvous point for the purpose of obtaining the high value of luminous density, satisfaction to vacuum requirements, the creation of the necessary conditions for conducting the physical experiments on clashing beams (in particular, it is sufficient long gap/interval, free from the magnetic field);

d) the modification of power-supply system for the realization of the mode/conditions of magnetostatic field, corresponding to energy of the colliding beams (up to 3.5 GeV in the Cambridge accelerator);

e) the creation of the system of the three-dimensional/space separation of the orbits of electrons and positrons (with the aid of the system of electrostatic capacitors/condensers);

f) the creation of the system of the injection of electronic and positron beams into the bypass.

During 1968, on the Cambridge synchrotron will be also completed the works, directed to an improvement in the reliability of the operation of synchrotron as accelerator-accumulator/storage: transition to the ceramic chamber/camera and the new system of vacuum evacuation, which will give reliable vacuum ~10^{-8} mm Hg on entire ring and increase of average/mean VCh power from 100 to 200 kW.

Work with the positron beam is outlined on 1969, the realization of method ??? of clashing beams with the energy to 3.5 GeV on - 1970.

Subsequently on the Cambridge accelerator is planned/glided the transition to new powerful/thick VCh system (by average/mean power ~50 of kW) and the construction of internal bypass for the realization of contrary collisions with the energy up to 5 GeV.

2.8. Possible use/application of systems of cascade acceleration with use of booster synchrotron.

The phase volume of beam in the synchrotron under the action of radiation damping first decreases up to certain energy, and then the effect of the quantum fluctuations of radiation/emission overpowers, and it begins to increase. Energy of electrons in the booster must be selected so that the phase volume of beam with the admission the ring of basic synchrotron would be smallest.

There are serious plans/layouts of the construction of synchrotron for the energy 15-20 GeV in Daresbury (England) with the use of the available there synchrotron NINA on 5 GeV as the booster - injector with the large intensity and a small emittance of beam.

FOOTNOTE 1. About these plans/layouts will be in detail said in the report Dr. M. Crowley-Milling. ENDFOOTNOTE.

The beam crossover, which corresponds to energy 3 GeV, is approximately 1.5 mm on vertical line and 5 mm on a radius. Therefore the aperture of large synchrotron with the energy of injection 3 GeV can be selected very small: 2.5x5.0 cm. Large synchrotron will have a perimeter 6 times greater than NINA, the radius of curvature of its magnet will be equal to 120 m. It is proposed to make four 100-meter straight sections, in two of which will be arranged/located 30-meter linear accelerators. the third gap/interval which will used for injection and beam extraction, it must pass through accelerator NINA in parallel to the existing experimental hall, which will make it possible to utilize this hall simultaneously, also, for the experiments with the beam of large accelerator, and to consequently considerably lower the cost/value of construction, although it will create the specific inconveniences of inconvenience during the operation of accelerator.

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In connection with the special features/peculiarities of area relief 3/4 large rings must pass to tunnel (through the hill); however, the cost/value of tunnelling is not considered excessive, since will be simultaneously solved the problem of radiation shielding of principal part of the accelerator.

VCh system will operate at frequency 816 either 1224 MHz, i.e., on the second or by the third the harmonics of the frequency of accelerator NIMA. For both frequencies are adequate/approaching powerful/thick amplifiers. Estimations show that the beam with the energy 15 GeV and the current 1 μA can be obtained at the power of VCh system 1.1 MW in the impulse/momentum/pulse (300 kW of average). Beam with the energy of 20 GeV by current 3 μA will require 10 MW in the impulse/momentum/pulse (1.8 MW of average).

Another example of synchrotron with a large radius - proposition of Yerevan physical institute about the construction of strong-focusing accelerator to the energy 50-60 GeV. Its mean radius must be equal to 1200 m, the aperture of chamber/camera 2x5 cm, loss of electron to the radiation/emission per revolution with 20 GeV will be 1.6 GeV. Preliminary acceleration to 5 GeV proposes to use in booster synchrotron, placed in the same tunnel, as main accelerator, and having the same perimeter.

The magnetic system of booster will have to simultaneously serve as reactor for main accelerator. In the synchrotron proposes the acceleration of electrons and positrons, and to also use their contrary collisions. For obtaining the sufficiently high intensity it is proposed to utilize an original system of the multiplication of electrons and positrons during interaction of the brought-out electron beam and positrons with the target. Cascade pumping by the particles of main accelerator must be realized by the following stages:

$e^{\mp}$ (20 Гэв) (1) → конвертер (2) → $7e^{\mp}$ (10–40 Мэв) (3)
(4) → линейный ускоритель → $7e^{\mp}$ (300 Мэв) (3)
(5) → бустерный синхротрон → $7e^{\mp}$ (5 Гэв) (1)
(6) → основной синхротрон → $7e^{\mp}$ (20 Гэв) (1)
(2) → конвертер → $49e^{\mp}$ и т.д. (7)

Key: (1). GeV. (2). converter. (3). MeV. (4). linear accelerator. (5). booster synchrotron. (6). basic synchrotron. (7). and so forth.

Multiplication system possesses in the principle great possibilities, but it is very complicated and needs the experimental check of the cascade shower processes, which occur on the target. In the case of the realization of multiplication system the intensity of the circulating beam will be limited by the power of high-frequency system which must go to covering of the radiation losses of electrons and losses in the walls of resonators. The latter will be ~40 MW at usual temperature, and ~5-7 MW at a temperature of liquid nitrogen.

2.3. On possibility of coincidence in installation to ultrahigh energy of functions of proton and electron accelerator.

In connection with the fact that the accelerators to the ultrahigh energies simultaneously become super-expensive, to expediently, apparently again discuss the possibility of coincidence in one installation (syncarotron) of the acceleration of electrons and protons. This possibility has already been discussed in the past, but the real steps in this direction thus far it was not undertaken. The reason for this, in our opinion, consists in the fact that the corresponding propositions, until now, they were done only post factum, for the already constructed and acting proton synchrotrons, not fitted out for accelerating the electrons.

Not touching upon the economic and technical sides of matter, let us examine synchrotron with radius ~6 km, designed for the acceleration of protons to 3 TeV (3000 GeV). If we in this ring accelerate electrons, then with the energy 200 GeV radiation losses per revolution to the particle it is achieved/reached approximately/exemplarily 24 GeV. However, magnetic field in this case will be only 1.1 kg. With the smaller energies the losses are substantially lowered (proportional to the fourth degree of energy).

The compensation for radiation losses will not be predominant in consumed VCh power, if the process of acceleration occurs fast enough.

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Let us require so that the energy, spent on the compensation for radiation losses (in entire cycle of acceleration), would be equal to energy, which is transferred to electron for achievement of maximum energy. This it is possible to satisfy, selecting the frequency of a change in the field of the equal to 50 Hz, which provides also the high average/mean intensity of beam. Considering a quantity of particles in equal to ~10^{13} which corresponds ~10^{15} particles per second (current on the order of 1 mA), we come to the average/mean power in the beam of order hundred MW. This is, of course, high value, and for its achievement should be applied the totality of cryogenic resonators and waveguides, arranged/located along the ring.

In the case of the protons, which do not test/experience radiation losses, the intensity can be still respectively increased.

As the first turn on this installation can be obtained the beams of electrons and protons with the energy 200-300 GeV with the high intensity. It is necessary to provide also the realization of reactions on the clashing proton-electron and electron-positron beams, which will ensure equivalent energy of order 10^{17} eV (for e^-e^+ collisions) and order 10^{15} eV (for e p of collisions). In the second turn it will be possible to switch over to obtaining of protons with energy on the order of 3 GeV.

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Discussion.

V. P. Dmitriyevskiy.

Which of the accelerators - linear or cyclic - according to its characteristics will engage in the future the basic place?

A. A. Kolomenskiy.

Both directions are developed independently. There is a tendency toward the elimination of the deficiencies/lacks, inherent in each of these types of accelerators. In the future, apparently, will be achieved/reached the synthesis of linear and cyclic accelerator; in this case will be obtained the best qualities of both.

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