A I000-Gev Cybernetic Proton Accelerator Studies

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I. The development of high-energy physics for the latest decades displays very distinctly trends towards a continuous and exponential rise of maximum attainable energies, supplemented by an urge to increase simultaneously the intensities of accelerated beams. More than 5 years ago 30-Gev accelerators began to operate in the United States and in Europe, the start of a 70-Gev accelerator is coming in the USSR, while designs of accelerators for higher energies in the range of 200-I000 Gev are advanced and studied in several countries by now.

The question of what can physics get by advance into the field of superhigh energies was discussed at special meetings and conferences in the United States, in Western Europe and in the USSR. Due to those discussions the scientific necessity and expediency of the construction of accelerators for energies up to I000-Gev do not give rise to any doubt by now. When constructed, such accelerators would help to get answers to many important questions which can already be put, even not refering to those arising each time when a new energy range is entered. In connection with the latest advances in colliding beams experiments an idea of possibility to substitute superhigh energy accelerators with two colliding beams of moderate energies arose. But a close look at the problem shows that usual "classic" accelerators with fixed targets and colliding beams installations do not compete but supplement each other. Colliding beams installations expand the possibilities of accelerators with stationary targets in studying primary particles interactions, but are not valid for a number of experiments, e.g. for experiments on secondary beams of short living high energy particles.

2. At the Radiotechnical Institute, Academy of Sciences of the USSR, superhigh energy accelerators studies (in the range of hundreds Gev) began in I960. So far as the strong focusing proton synchrotron is the only checked installation to accelerate heavy particles to high energies, our group, as well as research groups in the United States and in Western Europe, have chosen it to be a prototype of a superhigh energy accelerator. When the maximum energy (and so dimensions) of a strong focusing accelerator increases, it becomes more and more difficult to satisfy tolerances on magnetic field perturbations and on magnet units fabrication and adjustment. For these reasons it was proposed to supplement the usual "classic" accelerator scheme with a system of betatron oscillations automatic beam control. Now it is a common practice to use an automatic synchrotron oscillations beam control system which reduces significantly amplitudes of forced synchrotron oscillations and essentially relaxes tolerances on the magnetic field and frequency and amplitude of the RF voltage, similarly the application of betatron oscillations automatic control system reduces amplitudes of forced betatron oscillations and relaxes tolerances on magnetic field perturbations and magnet units adjustment. Advantages of betatron oscillations control are not exhausted by relaxation of tolerances on magnet units. Forced betatron oscillations supression (i.e. supression of closed orbit distortions) allows to reduce significantly the vacuum chamber cross section (and, consequently, to reduce the total magnet system weight). When the chamber dimensions are fixed, it allows to accelerate beams of larger cross sections and consequently of greater intensities.

The major conceptions of such a superhigh energy accelerator, called "cybernetic", were published in I96I-I962 [I]. The results of preliminary studies of a I000-Gev accelerator were presented at I963 International Conference on High Energy Accelerators in Dubna [2]. The comparison of various possible accelerator schemes resulted in the choice of three-stage scheme: linear accelerator-booster (intermediate cyclic accelerator) - main accelerating ring.

Later on the specification of parameters and accelerator elements design took place. The experience of other superhigh energy accelerators studies [3-5], as well as the results of our investigations on models were taken into account. For example a I-Gev small aperture proton cybernetic accelerator was constructed and is now being put into operation at the Radiotechnical Institute [6] to investigate the behaviour of the cybernetic accelerator. The experience of this accelerator study and results of its systems adjustment are also taken into account in the latest version of the cybernetic accelerator.

3. The most essential features of each stage of the accelerating installation are input and output energies and its transmission ability (as for the intensity). The chosen maximum energy of the main synchrotron (I000 Gev) results by one hand, from technological and economical possibilities (the magnet system weight and cost of a I000 Gev accelerator are still of the order of the weights and costs of operating accelerators), and, by the other hand, from unreliability of data extrapolation from the energy range of tens Gev to much more high energies. The input energy of the main ring was chosen to be I8 Gev. This energy results in sufficiently high injection field, small frequency modulation in the main ring and, which is also very essential, the possible maximum intensity of the main ring at this energy is greater than the booster one. A significant rise of this energy would greatly complicate the booster almost without facilitating the main ring operating conditions.

By comparing several versions the booster injection energy was chosen to be 800 Mev. Similarly to injection into the main ring the intensity attainable in the booster rises when its injection energy increases. At the same time the booster operating conditions are also facilitated. At the injection energy of 800 Mev and with chosen booster parameters the number of particles, stacked in the main ring, equals to 3.10^{13} (or 10^{14} with multiturn injection into the booster) which seems to be a reasonable upper limit from the point of view of the main ring radioactivity level. Further increase of the booster injection energy would greatly complicate and raise cost of the initial accelerating stage - linear accelerator. It is worth noticing that there is no experience in proton linacs construction for the listed energy range. That is why a rather conservative figure for the linear accelerator energy seems to be reasonable.

4. Thus, the discussed accelerating installation comprises three main units (Fig.I):

a. A 800 Mev linear proton accelerator with peak pulse current I00 mA, pulse duration I0 μ sec (which is sufficient for three-turn injection into the booster), beam emittance $6\pi \cdot 10^{-4}$ rad x cm and pulse rate 20 cps.

b. A I8 Gev booster with intensity 2.10^{12} particle/pulse (with one-turn injection) and 6.10^{12} particles/pulse (with multiturn injection) and pulse rate 20 cps.

c. A I000 Gev main ring with intensity 3.10^{12} part./pulse (with one-turn injection) and 10^{14} particles/pulse (with three-turn injection) and pulse rate 0.3 cps.

For the booster and the linear accelerator inject particles into the main ring only during a small fraction of the total time while being themselves unique accelerating installations it is provided for in the study to utilize them experimental use within intervals between injection into the booster and the main ring.

At the transport channels from one accelerator stage to another it is necessary to introduce special matching systems to transform phase space volume of the beam, leaving the preceding stage to the shape conformable to the features of the following stage.

Such a matching is necessary for synchrotron and for betatron oscillations.

The major input and output parameters of the accelerating stages are listed in the table I.

The linear accelerator and the booster are described in detail in separate papers, presented at this conference [7,8]. Only the main ring will be discussed in this paper.

5. The main ring accelerator is set within a ring housing tunnel which is supposed to be constructed by the underground drifting, being used in large scale in the USSR in subway construction. The tunnel deeping figure (I8 m) is set by radiation safety reasons. In the lower part of the tunnel communications are placed while in the upper part - the accelerating ring itself: gradient magnet units, magnet correcting systems, RF accelerating cavities, injection and extraction systems, high vacuum pumps and other equipment which is to be in the very vicinity of the ring electromagnet (Fig.2).

The ring magnet consists of I2 superperiods, separated by matched long straight sections of I40 m length. Five of them are occupied by RF accelerating system, one by injection system, two by ejection systems and one more by internal target facilities. Each superperiod (Fig.3) contains 20 cells of FOFDOD type (the two cells, adjacent to the long straight section, are shortened to facilitate matching with the long straight section). Each cell contains 4 focusing and 4 defocusing magnet units of 6.8 m length. Gradient magnets have no correcting pole windings: compensation of saturation, field gradient and nonlinearities correction are performed by special multipole magnets placed in straight sections between magnet units. It seems to us to be reasonable to separate magnet functions spatially, particularly in the accelerator with beam controle.

We considered it to be reasonable to choose as high magnetic field strength as is economically and practically justified. The choice of high magnetic field strength results in reduction of the constructional expenses. We have chosen rather high peak magnetic field of I6 kgauss at equilibrium orbit. In future we also intend to consider the possibility of utilization of the separated functions magnet structure.

6. The chosen methods of ring magnets adjustment (the second differences radial adjustment and the first differencies vertical adjustment) with technically feasible accuracy results in orbit deviations which are several times tolerable ones. A magnetic parameters beam control system is provided for in the accelerator. Correcting magnets distributed nearly uniformly around the whole ring, are used in this system. They are interconnected through a computer which processes information in accordance with a given control programme. Within the united complex of automatic systems controling the r.f. amplitude and frequency, integral and local magnetic field values and magnetic field derivatives, separate subsystems due to stabilize the betatron oscillations can be singled out:

I) Equilibrium orbit control system. The same system (when the correcting programme is appropriatly altered) can be used to correct field within the first revolution. The system power and time constant should be chosen in such a way as to stabilize operation not only at injection, but during the whole accelerating cycle.

2) Magnetic gradient control system (i.e. the system of betatron oscillations number stabilization and stopband diminishing). Coherent betatron oscillations are excited to determine betatron oscillations frequency and space harmonics of the gradient. (After measurement the excited oscillations are damped). In accordance with measured data a correction is introduced through special quadrupoles.

7. Particles are accelerated in 5 long straight sections. For needed frequency deviation is small enough (0.I2%) nontuned cavities or accelerating wave guides can be used. The accelerating structures with 20 cavities in each structure are arranged within each of 5 long straight sections. Each structure is energized from a single accelerating station.

A wave guide version has been studied together with the cavity-type accelerating system [II,I2]. The examination of the particle dynamics and technical features displayed possibility and advisibility of operating at 240 Mc frequency, which is twice the upper value of the booster accelerating frequency. The wave guide version features were optimized so that it was fit as for the current 3.10^{13} particles per pulse as for 10^{14} particles per pulse. In each of 5 long straight sections it is supposed to arrange 6 wave guides of 20 m length each.

The major parameters of the main ring are listed in Table 2.

Parameters of the betatron oscillations within matched long straight sections are shown in Fig.4.

Conclusion.

The results of the I000 Gev cybernetic proton synchrotron design study demonstrate, that such an accelerator, comprising an 800 Mev linear accelerator-injector, an I8 Gev booster proton synchrotron and the main I000 Gev proton synchrotron can be realized starting from existing and by now verified elements and designs. The total accelerator cost is not excessively great, and the necessary total steel weight (about 20 thousands tons) for the most bulky element-accelerator electromagnet very modest.

Assistance of the following persons was essential for the I000 Gev accelerator (the main synchrotron) study: Dzergatch A.I., Sosensky N.L., Antonov Yu.N., Batskikh G.I., Vladimirov V.V., Kaminsky N.K., Yudin L.A., Kuzmina N.I., Lyubimov E.B., Skepskij G.P., Kurasov V.V., Urlin B.M., Medvedev P.I., Belozerova G.I.

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II. W.Schnell. V-th International Conference on High Energy Accelerators, Frascati, I965, Roma, I966, p.38.
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DISCUSSION (condensed and reworded)

E.D. Courant (BNL): What will be the time constant of the cybernetic control and correction system?

Vasilyev: We will have two control systems, i.e., one for adjusting the first turn and one for the whole cycle. For the first turn we will have a rather narrow bandwidth of several cycles and for the whole cycle we will have a bandwidth of several hundred cycles.

Table I.

Parameters	Units	Linac (output)	Booster input	Booster output	Main synchrotron input	Main synchrotron output
Kinetic energy	Gev	0.8	0.8	I8	I8	I000
Equivalent radius R_c	m	-	I50		27I7	
Acceleration freq.	cps	20	-	20	-	0.5
Number of oscillations Q	-	-	$\frac{12.75}{7.75}$		$\frac{34.25}{31.25}$[I]	
Frequency f	Mc	~200 (I000)[2]	~I00	~I20	~I20	~I20
Equilibrium phase φ_s	degrees	-	0(45)[3]	0	45	45
Accelerating voltage U_m	Mv	-	0.5(4.5)	4.5	79	79
Separatrix $(\Delta p/p)_c$	%	± 0.78	± 0.I5[4]	± 0.6	± 0.6	± 0.6
$(\Delta\varphi)_c$	degrees	78[5]	360 (I37)	360	I37	I37
Bunch parameters $\Delta p/p$	%	±0.I8÷±0.55	±0.03[4]	± 0.07	± 0.I5[6]	± 0.0I5
$\Delta\varphi$	degrees	I4÷42[5]	2.24[4]	33	33	I0
Synchr.oscillat. Δz	cm	-	0.4	0.2	0.3	0.03
Beam emittance ϑ	cm x rad	$6\pi \cdot 10^{-4}$	$9\pi \cdot 10^{-4}$[7]	$7\pi \cdot 10^{-5}$	$\pi \cdot 10^{-4}$	$1.9\pi \cdot 10^{-6}$
Ampl.result.from ϑ a_s	cm	-	I.2	0.35	I.I	0.I5
Current (n.of par.)		I00 mA	$1.7 \cdot 10^{12}$[8]	$1.7 \cdot 10^{12}$	$3 \cdot 10^{13}$	$3 \cdot 10^{13}$
Number of particles (max)			$2.8 \cdot 10^{12}$		$1.5 \cdot 10^{14}$	-

Notes: I.The denominator corresponds to the Q without long straight sections.
2. In brackets is listed the value of f of the second part of the linear accelerator.
3. Here and further in brackets are listed the values of parameters in middle part of the cycle.
4. After debuncher.
5. At I000 Mc/s frequency.
6. Corresponds to phase deviation listed one line lower.
7. Emittance values correspond to one-turn injection.
8. Taking into account the 25% loss of particles during beam transfer.

Table 2.

Maximum total energy E_{max}	Gev	I000
Maximum induction B_{max}	kgauss	I6
Injection induction B_i	kgauss	0.3
Orbit circumference L	m	I7069
Field index n	-	7000
Number of cells N	-	240
Number of magnet units in a cell M_o	-	8
Total number of magnet units M	-	I920
Magnet unit length l_b	m	6.8
Amplitude function value (max)		
in a normal cell β_{max}	m	II5
in a matched long straight section β^L_{max}	m	2I6
Formfactor of betatron oscillations F	-	I.46
Vacuum chamber dimentions a x b	mm	33x20
Number of long straight sections N_{ss}	-	I2
Length of a long straight section L_{ss}	m	I42.I2
Number of superperiods N_s	-	I2
Length of a lense l_Δ	m	3.265
Lens magnetic field gradient G_Δ	kgauss/cm	2.5
Frequency modulation $\Delta f/f$	%	0.I2
Harmonic number q	-	6850
Time of acceleration T_a	sec	I
Critical energy E_{cr}	Gev	35
Synchrotron oscillations frequency		
at injection $(\Omega_s/\omega)_i$	-	$7.2 \cdot 10^{-2}$
at ejection $(\Omega_s/\omega)_e$		$7.4 \cdot 10^{-3}$

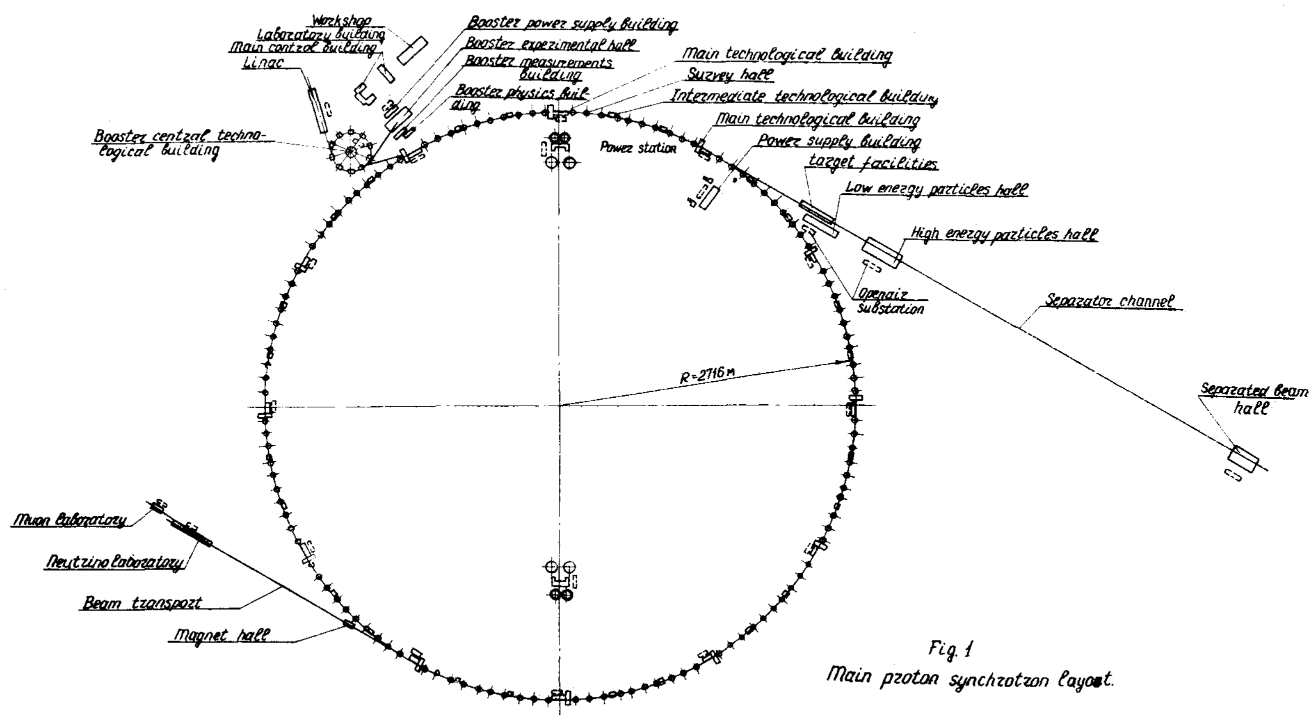

Fig. 1
Main pzoton synchzotzon layout.

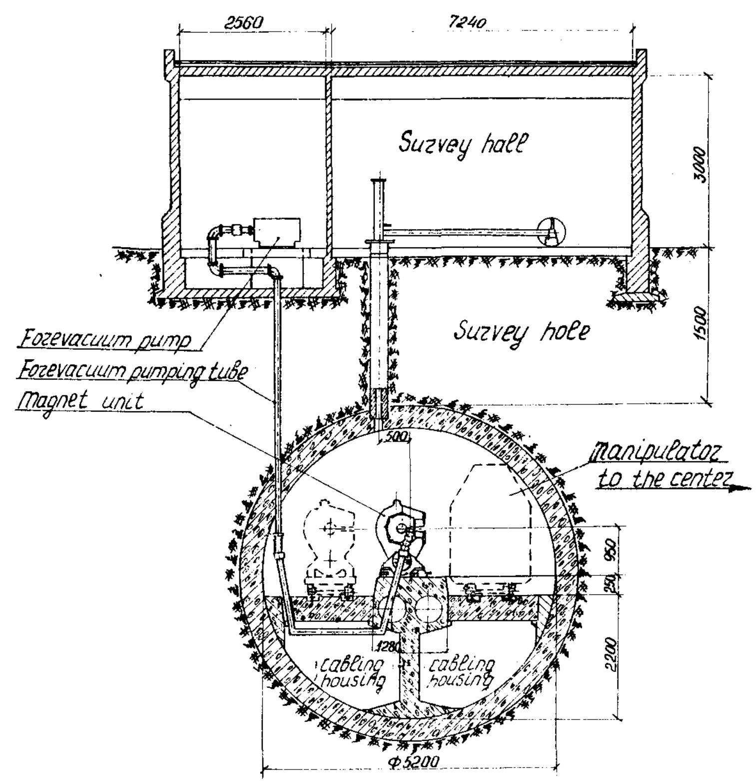

Fig. 2. Main pzoton synchzo-tzon housing tunnel czossection.

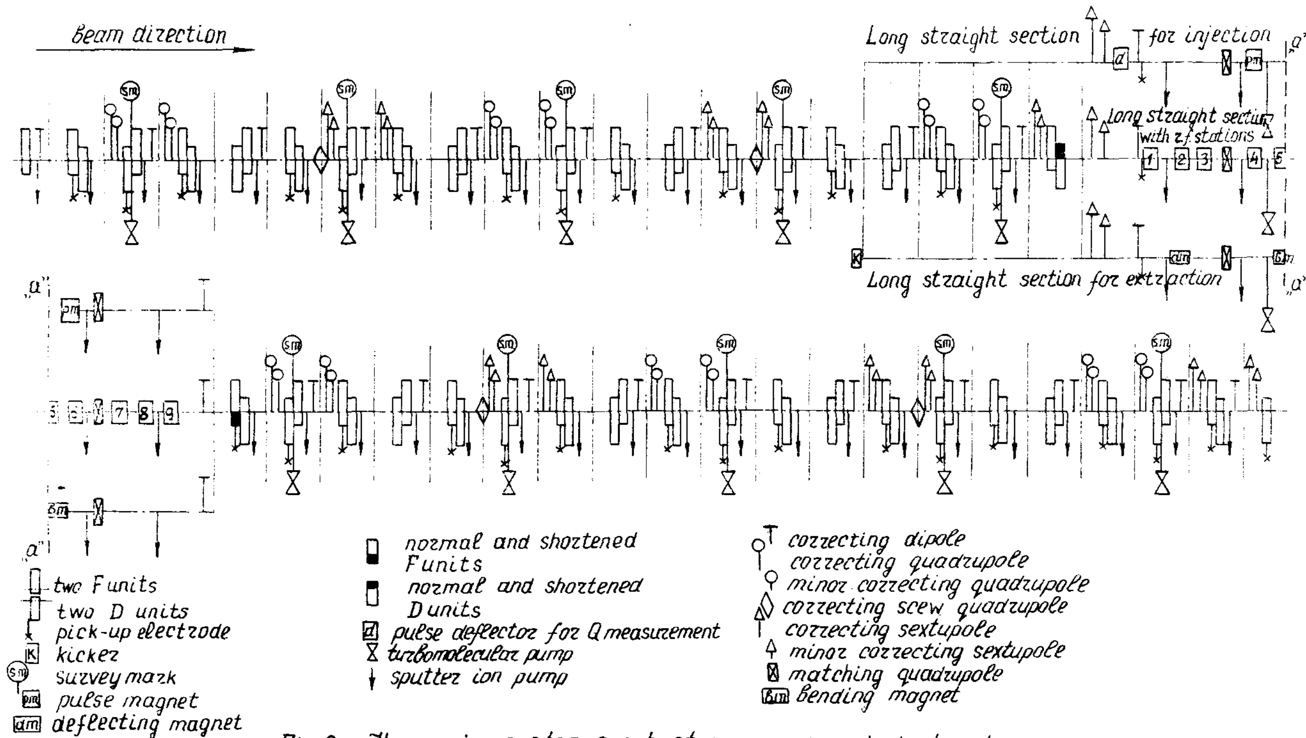

Fig. 3. The main proton synchrotron superperiod structure.

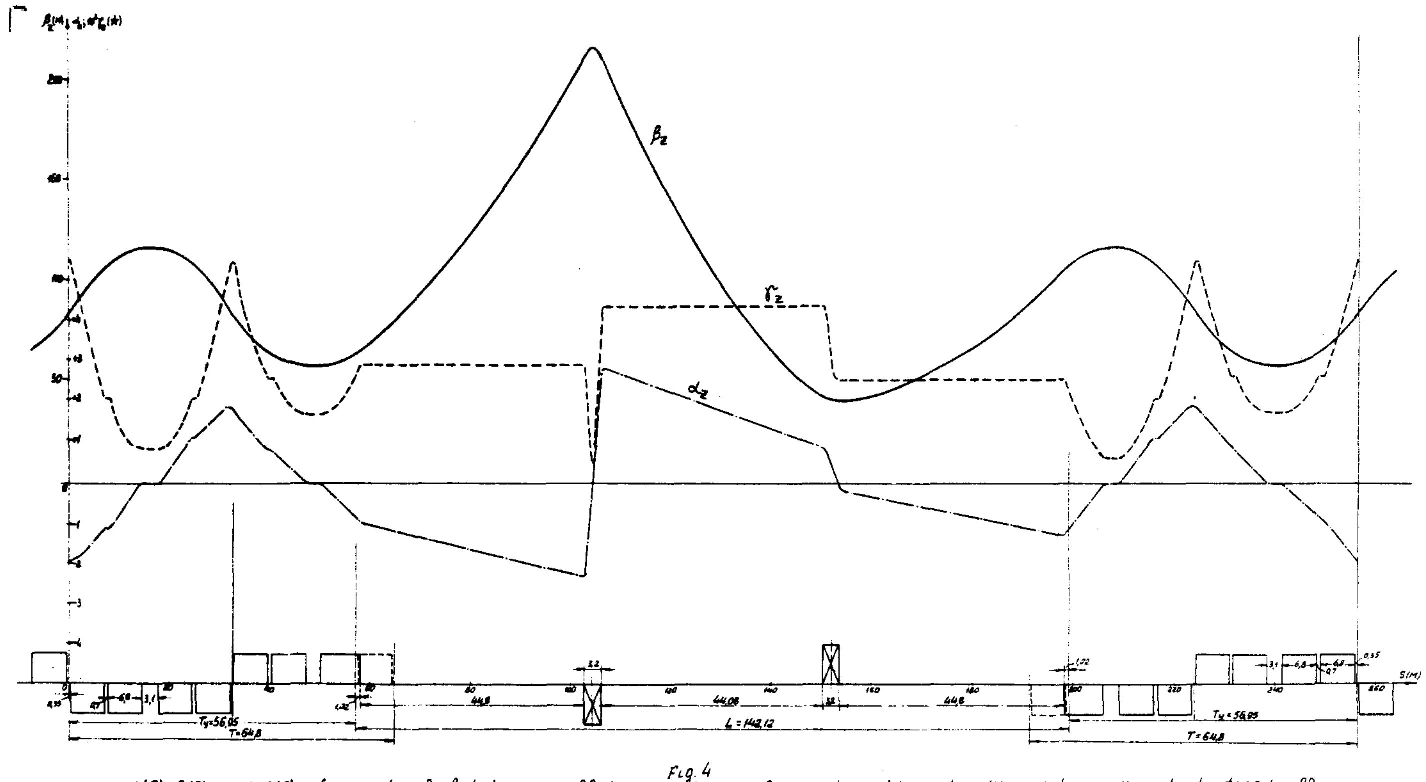

Fig. 4
$\alpha(S), \beta(S)$ and $\Gamma(S)$ for vertical betatron oscillations within a long straight section(L) and two adjacent shortened cells