ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СОАН СССР

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ПРЕПРИНТ И Я Ф 78-74

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Новосибирск

1978

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A b s t r a c t

In the storage rings and traditional cyclic accelerators the obtaining of the beam polarization is hampered at high energies by depolarization effects connected mainly with the energy dependence of a spin precession frequency. In this work the ways of controlling this dependence are considered, using additional fields introduced into straight sections. In particular, use of spin flips around the directions in the orbit plane allows elimination of the energy dependence of the effective precession frequency. Possible schemes providing the conservation of polarization during acceleration are presented. Under stationary conditions for electrons and positrons it is possible to suppress substantially the depolarizing influence of quantum energy fluctuations during radiation by using the method of spin flips in straight sections

Last years are marked by the growing interest to experiments with polarized high energy particles /1/. According to modern ideas such experiments can provide the important information on the nature of interactions and the structure of elementary particles.

The only way to obtain high energy polarized protons (antiprotons) which seems available today, is to obtain such particles in a polarized state at comparatively low energies with the subsequent acceleration. The sources of polarized protons, which exist or under design can provide practically interesting intensities /1-3/. One can speak of the obtaining polarized proton beams with intensities close to those of unpolarized ones. Such a possibility appears when one uses charge exchange injection of polarized protons into a cyclic accelerator and their accumulation with the help of electron cooling /3/. One can hope to obtain polarized antiprotons (protons) with the aid of nuclear scattering by a polarized target applying the electron cooling to compensate for multiple Coulomb scattering /4/.

For electrons and positrons the natural mechanism of the radiative polarization exists. In some cases the more efficient way of polarization can be that using colliding polarized photons, for example, those of the laser radiation /5,6/. One can't also exclude the possibility to accelerate these particles in the polarized state from a source*).

The common problem for accelerators and storage rings of both light and heavy particles is the elimination of depolarizing effects connected with distortions of a magnetic system and the field inhomogeneity. Recent theoretical and experimental studies of this problem provide the foundations for optimism. This report is devoted to a short review of known and new possibilities of increasing the polarization stability.

Acceleration of polarized particles

Depolarization during the acceleration occurs due to passing of a large number of resonances between the spin precession frequency in the main field (proportional to the energy) and frequencies of the perturbing fields on a particle trajectory.

*) Recently a method of obtaining polarized positrons and electrons by pair production in collisions of polarized photons has been proposed /7/.

In the usual situation with the field vertical over the whole orbit the following resonances are passed during the acceleration (at the moment we neglect small synchrotron oscillations):

$$\nu_0 \equiv \gamma G \approx \nu_K \equiv K_z \nu_z + K_x \nu_x + K_\theta \,, \qquad (1)$$

where $2\pi\gamma G$ is an angle of spin rotation around the vertical direction with respect to a velocity per turn (γ is a relativistic factor, $G=(g-2)/2$ is ratio of an anomalous gyromagnetic ratio to a normal one), ν_z and ν_x are the numbers of vertical and radial betatron oscillations per turn K_z, K_x, K_θ are integers.

After passing each resonance the coupling of average vertical projections is determined by the following formula /9,10/ (the condition of intermixing of the spin precession around the field over the phases usually holds*)):

$$\langle S_z^+ \rangle = \langle (2e^{-2J_K} - 1) S_z^- \rangle,$$

where the parameter $J_K = \pi |w_K|^2 (4|\dot{\nu}_0 - \dot{\nu}_K|)^{-1}$ is determined by the rate at which the resonance $\dot{\nu}_0 - \dot{\nu}_K$ is passed and its strength $|w_K|$ $(\pi |w_K|^{-1}$ is the time of vertical polarization flip in an exact resonance).

The variation of the polarization degree can be small at fast $(J_K \ll 1)$ or at slow passing $(J_K \gg 1)$. The condition of the polarization conservation after acceleration is:

*) It may happen that during the time of acceleration at electron accelerators for small energies the intermixing of horizontal spin components doesn't occur. In this case after passing coherent resonances $\nu_0 = K_\theta$ the polarization direction changes rather than its degree decreases /8/.

$$4\sum_{J_K \ll 1} J_K + 2\sum_{J_K \gg 1} e^{-2J_K} \ll 1 \,. \qquad (2)$$

It is necessary to exclude intermediate resonances because they lead to depolarization of the beam.

At low energies, for example, one can use sufficiently fast passings by compensating for harmonics of the integer resonances $\nu_0 = K_\theta$ and applying a system which provides jumps of betatron frequencies at the moments when the resonances with betatron harmonics are passed /11/. Using such methods the argonne group succeeded in acceleration of polarized protons up to the maximum accelerator energy of 12 GeV /12/.

One can also avoid depolarization using slow passings ($J_K \gg 1$). In this case synchrotron oscillations of the precession frequency are important. Taking these oscillations into account results in the splitting of each resonance (1) in a series of modulation resonances. Their strengths decrease with the increase of their number "m". If a resonance is passed quickly without the precession frequency modulation, then the modulation resonances are passed quickly as well. Therefore at $J_K \ll 1$ the account of the synchrotron modulation does not lead to notable effects. At slow passing of the resonances (1) the situation is more complicated. At $J_K \gg 1$ the modulation resonances with low values of "m" are passed slowly, while these with sufficiently high "m" quickly. In this case the simple decrease of the rate at which a resonance is passed is not useful as due to non-idealities of the magnetic system a large probability of intermediate passings exists all the resonances including modulation ones.

Another method of proceeding to adiabatic passing consists increasing resonance strengths by the special introduction of perturbing fields, so that the resonance is in fact tuned off by a distance equal to the strength of harmonics of the introduced field /13/. For example, it is sufficient to increase additionally the resonance strength $|w_K|$ so that to provide the low rate of passing resonances (1), and taking into account the synchrotron modulation ν_0 one has

$$|w_K|^2 \gg \sigma_\nu \cdot \nu_\gamma \tag{3}$$

where σ_ν is an amplitude of the frequency synchrotron modulation ν_0, ν_γ is a frequency of synchrotron oscillations. If the condition (3) holds, the strengths of modulation resonances are exponentially small. It is clear that in this case one can choose parameters so that during the passing with a low rate averaged over synchrotron oscillations modulation resonances are passed sufficiently fast.

The simplest case when a necessary increase of resonance strengths can be achieved is that of integer resonances $\nu_0 = K_0$. If, for example, a constant magnetic field along the particle velocity is introduced into the straight section of the accelerator then the strengths of all integer resonances due to this field are equal:

$$|w_K| = (1+G)\, H_v\, \ell/L .$$

Here H_v is measured in units of the average guiding magnetic field of the accelerator, ℓ/L is a fraction of the orbit which is occupied by the introduced field. This method has been used at the Novosibirsk electron-positron storage ring VEPP-2M to avoid the beam depolarization at the resonance $\nu_0 = 1$ during the energy variation in the experiment /14/.

At higher energies ($\nu_0 \gg 1$) a transverse with respect to the orbit field can be useful, rather than a longitudinal one. For simultaneous compensation of the orbit distortion it is possible to introduce into the straight section the helical field with an integer number of periods transverse with respect to the velocity. This field results in the recovery of the particle velocity direction. The spatial shift can easily be compensated for at the next section by a unidirectional field with a zero average value, not distoring the spin motion.

It is possible that by using the whole set of these methods (jumps of betatron frequencies at the corresponding resonances, additional perturbations for elimination of the depolarizing influence at integer resonances, compensation of the dangerous harmonics) one will be able to increase the energy of polarized protons and go higher than 12 GeV achieved now.

Such methods will be also useful for the acceleration of deuterons up to high energies. Due to the small value of its anomalous magnetic moment (approximately by a factor of 25 lower than that of a proton) a number of resonances appears considerably lower for deuterons than for protons during the acceleration up to the same energy. It is easier to eliminate the depolarizing influence of the resonances with betatron frequencies by jumps of betatron frequencies. The requirements to the throughness of the compensation for harmonics of integer resonances are less severe. For elimination of the depolarizing influence of integer resonances by introducing additional fields the required value of longitudinal fields is slightly less than that for proton of the same energy (by a factor 3), while transverse fields must be considerably higher (for example, for the helical perturbing field the value must be larger by a factor about 10).

2. The difficulties of the acceleration of polarized particles by the methods described above will grow fast because of the increase of the number of resonances, their strengths and scatter of precession frequencies.

The methods based on the substantial rebuilding of the spin motion appear more universal and perspective in the region of high energies. Introduction of special sufficiently high magnetic fields in the sections of an accelerator or a storage ring allows to be tuned off not only from the integer resonances, but from those with betatron frequencies as well /15/.

As follows from the general theory of the spin motion in cyclic accelerators and storage rings, at any stationary configuration of the magnetic field in each place of the orbit the equilibrium polarization direction always exists $\vec{n}(\theta) = \vec{n}(\theta+2\pi)$.

This direction is generally varying along the orbit and is not less stable than that along the field during the motion in a homogeneous field. The generalized precession frequency ν (in units of the revolution frequency) is an angle of spin rotation around $\vec{n}$ during one turn, devided by 2π /16/.

Consider the following example (Fig. 1). Introduce into a straight section I a longitudinal magnetic field rotating spin by an angle π around the velocity. To this end a field $H_v = 21E(g\ell)^{-1}$ is needed at the length ℓ, where H_v is the field in teslas, E is the energy in GeV, ℓ is the length in m, g is a particle g-factor. Let us change the longitudinal field H_v proportionally to E during the energy variation. The longitudinal field doesn't distort an equilibrium orbit, the coupling of radial and vertical oscillations due to it can be compensated for (if necessary) by four thin lenses (two at each side of the section with the field H_v).

One can easily see that the longitudinal direction is the stable polarization direction in an opposite section II. In fact, a spin directed along the velocity in the section II appears again longitudinal after one turn of the particle. Outside the section I the equilibrium polarization $\vec{n}$ is the plane of the particle motion and appears energy dependent everywhere but the section II. In the example considered the vertical polarization direction (Outside the section I) appears unstable and gradually disappears due to the scatter of particle orbits. The polarization is stable if during the beam injection it is oriented along $\vec{n}$.

To determine the spin precession frequency ν it is sufficient to trace the motion of the spin oriented transversely to $\vec{n}$. The spin oriented vertically in the section II (transversely to the orbit) after one revolution is flipped, i.e. turns by angle π around $\vec{n}$. Thus, the fractional part of the precession frequency is always equal to $^1/2$ at any energy of the particle: $\cos\pi\nu = 0$. This circumstance distinguishes sharply the considered example from a usual case of the vertical magnetic field for which the precession frequency $\nu_0 = \gamma G$ continuously grows with energy and has a scatter $\sigma_\nu = G\Delta\gamma$.

Let us underline that small deviations of the magnetic system from the described ideal one can result only in the insignificant perturbation of the direction of equilibrium polarization and a deviation of the precession frequency.

Additional fields can be switched on either before the injection (in the example given the particles are injected with longitudinal polarization in the section II) or during the acceleration.

Thus, in this example there are no spin resonances and the polarization degree is conserved adiabatically ($\dot{\nu}_0 \ll 1$) during acceleration.

Note that these spin resonances can also be avoided at smaller values of the angle φ of spin rotation in the section I. Resonances $\nu = K_z\nu_z + K_x\nu_x + K_0$ appear impossible if the following condition is held /15/:
$|\cos(\varphi/2)| < |\cos\pi(K_z\nu_z + K_x\nu_x)|$.

3. At high energies ($\gamma G >> 1$) for spin rotation in the section I around the horizontal direction a transverse with respect to the velocity field must be used, rather than a longitudinal one. To rotate spin by an angle π by a homogeneous field H at the length ℓ 54 kG x m are needed

for protons and 45 kGs·m for electrons independently of the energy. However, the introduction of a radial field distors essentially the orbit at main sections of an accelerator. One can meet the requirements of spin rotation by a given angle and the orbit recovery at the end of the section if the fields varying along the orbit are used. Some examples of spin rotation by an angle π by fields consisting of homogeneous field sections are shown in Figs. 2,3. One can also use to this end the helical transverse magnetic field with an integer number of periods N. To rotate spin by an angle π in the section I $H\ell = 54\sqrt{1+4N}$ kGs·m are needed for protons and $H\ell = 45\sqrt{1+4N}$ kGs·m for electrons. In particular, at N = 1 it makes 120 kGs·m for protons and 100 kGs·m for electrons. A stable periodical direction in the section II lies in the orbit plane at an angle $\arctan(\sqrt{1+4N}/2N)$ with respect to the velocity. The precession frequency ν is again equal to 1/2 at any N.

In the schemes presented the particle velocity is recovered to $(\gamma G)^{-3}$ (exact recovery is possible by small field corrections if necessary). The arising spatial shift of the orbit ($\sim \ell(\gamma G)^{-1}$ in Figs 2,3 and $\sim \ell(\sqrt{N}\gamma G)^{-1}$ for a helical field) can easily be compensated for at the next section by a unidirectional field with a zero mean value.

Switching on and off the rotating fields can be done adiabatically during the acceleration with conservation of the stability of spin and orbital motion.

Note also that if it is more convenient to conserve the vertical direction of the equilibrium polarization in main sections one can use two flips around orthogonal horizontal axes in two symmetrical sections (e.g., applying the schemes of Figs 2,3). Here $\vec{n}(\theta)$ changes its sign but $\cos\pi\nu = 0$.

The methods described can be applied to the acceleration of polarized particles up to maximum energies of the accelerators and storage rings (existing or under design) providing that spin resonances do not overlap, i.e. until the spin rotation during one revolution remains small (one means

spin rotation by perturbating fields due to the non-ideal features of the magnetic system and by free vertical oscillations of the particles).

One can estimate the accuracy with which an angle of magnets is known with respect to the vertical in the plane perpendicular to the orbit. For proton accelerators of 1000 GeV, with a radius of 1 km, a frequency of betatron oscillations equal to 20, a number of independent elements of the magnetic system equal to 1000 this value is approximately 10^{-4}. Possible vertical shifts of focusing lenses mustn't exceed 0.1 mm, the vertical beam size mustn't exceed 1 mm at the maximum energy. For each specific facility more accurate criteria can be obtained. Note that these requirements vary proportionally to the energy at a fixed value of the maximum accelerator field.

The question about the possibility to accelerate polarized particles for the energies where resonances overlap remains unanswered. One can't exclude today that further studies will lead to positive results in this energy region as well.

Suppression of quantum depolarization of electrons and positrons

Last years are characterized by the growing interest to obtaining radiative polarization of the beams in high energy storage rings of electrons and positrons (energies of the order of dozens GeV and more). In traditional storage rings at the energy about hundred GeV to eliminate the depolarizing influence of the quantum fluctuations of synchrotron radiation rather serious requirements to the accuracy of magnetic systems are needed /17/. Due to energy dependence of the precession frequency radial magnetic fields appear the most dangerous arising, for example, at random vertical deviations of focusing lenses or at random inclinations of the vertical field magnets. As follows from /17/, the depolarization rate λ_d in storage rings with everywhere vertical field is equal to the following value if non - - correlated perturbing radial magnetic fields are present:

$$\lambda_d = \lambda_0 \frac{11\pi^4}{54} \frac{\nu_0^4 (1+2\cos^2\pi\nu_0)}{\sin^4\pi\nu_0} \sum_{n=1}^{Q} \eta_n^2 \overline{H_n^2} \, |F_n^{[\nu_0]}|^2 , \qquad (4)$$

where $\lambda_0 = \frac{9}{11} \frac{d}{dt} \frac{\overline{(\delta\gamma)^2}}{\gamma^2}$ is a radiative depolarization decrement, Q is a number of sections with radial fields H_n (in units of the average magnetic field of the storage ring), η_n is a fraction of the orbit occupied by the n-th section, $F_n^{[\nu_0]}$ is a characteristic function of the storage ring determined by the energy and vertical focusing. In storage rings with a smooth vertical function the quantity $|F_n^{[\nu_0]}|$ is approximately equal to $\nu_0^2 ([\nu_0]^2 - \nu_z^2)^{-1}$ is an integer part of ν_0 , ν_z is a reduced frequency of vertical betatron oscillations). The formula above is valid as far as the energy spread of the precession frequency $\sigma_\nu = \Delta\nu_0$ is small if compared to the distance between resonances ($\sigma_\nu \ll 1$). In the region $\sigma_\nu \gtrsim 1$ the depolarization rate sharply increases by a factor equal at least $3(2\pi^2 \nu_\gamma^3)^{-1}$ if, as usual, the reduced frequency ν_γ of synchrotron oscillations is much less than unity.

One of the possible ways to enhance the role of polarizing processes is application of magnetic snakes ("wigglers") with compensation of the energy dependence of the direction of equilibrium polarization in the wiggler region /18/. A more universal way of depolarization suppression can be suggested which uses flips of the vertical polarization in an even number of sections along the orbit. Using of multiple flips for increasing spin stability can be compared to using of strong focusing instead of the week one for betatron oscillations of the particles. A stable direction $\vec{n}$ of the equilibrium polarization remains vertical in main sections providing that a number of flips is even. However, each spin flip changes its sign. Here depolarizing effects are again due to the non-ideal character of the

magnetic system*).

Sections of spin flips must be optimally placed in such a way, that an angle of spin rotation around $\vec{n}$ be equal to zero in sections with the main field. It means that in case of two sections they must be opposite lying, in case of 4 must be placed in a quarter of the orbit length etc. Thus, the effective precession frequency ν is determined only by sections with additional fields and is energy independent. For a precession frequency hot to be in a resonance with a revolution frequency, the resulting axes of spin rotation lying in the orbit plane must be equal at all sections.

If a storage ring is symmetric then there is no polarizing influence of the main field due to spin reorientation. However, polarization can be provided by a laser or introducing magnetic wigglers.

For a storage ring with 2 M spin flip sections ($M \ll \nu_x, \nu_z$) in an optimal case at $\cos\pi\nu = 0$ the formula (4) is modified):

$$[\lambda_d]_{2M} = \lambda \frac{11\pi^4}{54} \frac{\nu_0^4}{M^2} \sum_{n=1}^{Q} \eta_n^2 \overline{H_n^2} \, |F_n^{[\nu_0]}|^2 \qquad (5)$$

Here $\lambda = \frac{9}{11} \frac{d}{dt} \frac{\overline{(\delta\gamma)^2}}{\gamma^2}$ is a polarization decrement taking into account radiation at the bending sections. By contrast with (4) this formula remains valid at $\sigma_\nu \gg 1$. Its applicability condition is practically always fulfilled:

$$\nu_0^2 \frac{\lambda}{\omega_0} \ll M .$$

Thus the influence of depolarizing factors is decrea -

*) At add number of flips the equilibrium polarization in the main sections appears lying in the orbit plane. Thus $\vec{n}$ is strongly energy dependent and fast depolarization occurs due to energy quantum fluctuations.

sed by at least a factor M^2 and hence the requirements to the magnetic system are M times weaker. After two flips the resonant energy dependence of the depolarization rate is removed as well as the resonant spin diffusion at large energy spread (providing that $\sigma_\nu \gtrsim 1$).

It may prove convenient to use for polarization the fields already introduced in straight sections for spin flips. For example, the magnetic field of Fig. 2 can be used. The sections III where the field is parallel to $\vec{n}$ are made short enough so that the polarizing influence of radiation at these sections is dominant. The degree of radiative polarization is then close to

$$\zeta = \frac{8}{5\sqrt{3}} \langle (\vec{H}\vec{n})^3 \rangle / \langle |H|^3 \rangle$$

($\vec{H}$ is a magnetic field transverse with respect to the velocity) its maximum value $8/(5\sqrt{3})$, whereas the polarization time decreases by a factor $\lambda/\lambda_0 = \langle |H|^3 \rangle / \langle |H_0^3| \rangle$ *)

(H_0 is a main field).

As the spin flip due to fields of Fig. 2 occurs with respect to the velocity, then to tune off a resonance one must perform a flip around another axis at one or several sections. For example, $\cos \pi\nu = 0$, if one uses in one of the sections the scheme of Fig. 3 rotating a spin around the vertical direction.

*) The energy spread increases by a factor about $\sqrt{\lambda/\lambda_0}$.

Figure captions

Fig. 1. Scheme of spin motion with the rotation by 180° around the velocity in section I.

Fig. 2. Scheme of spin rotation around the velocity in a section with the recovery of the particle velocity. The figure plane is perpendicular to the velocity. At sections I, II, IV, V spin is rotated at 90° around field directions, at the section III with a radial field - at 180°. At this section the equilibrium polarization is directed along the field.

Fig. 3. Scheme of spin rotation by 180° around the radial direction. The field in the section II is radial.

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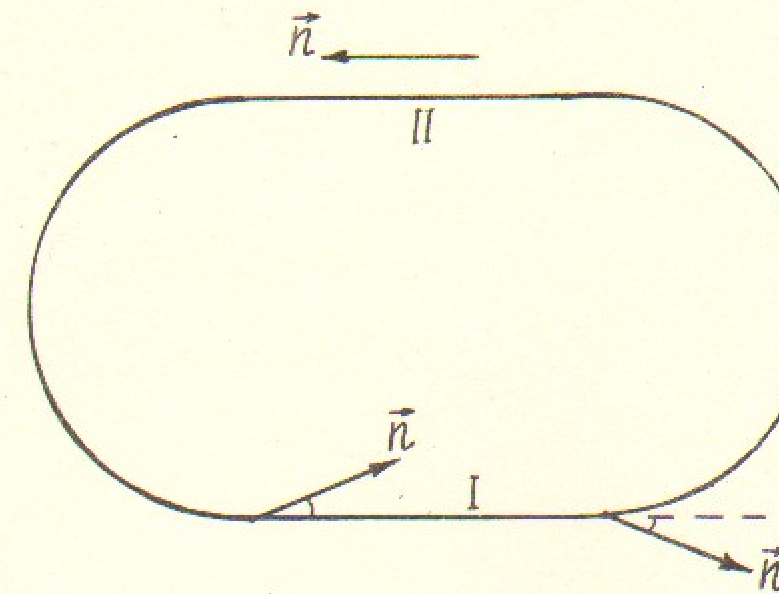

Fig. 1

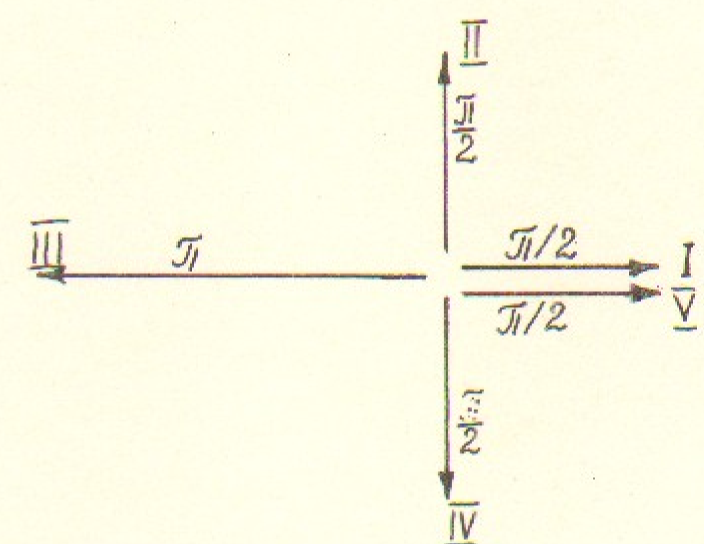

Fig. 2

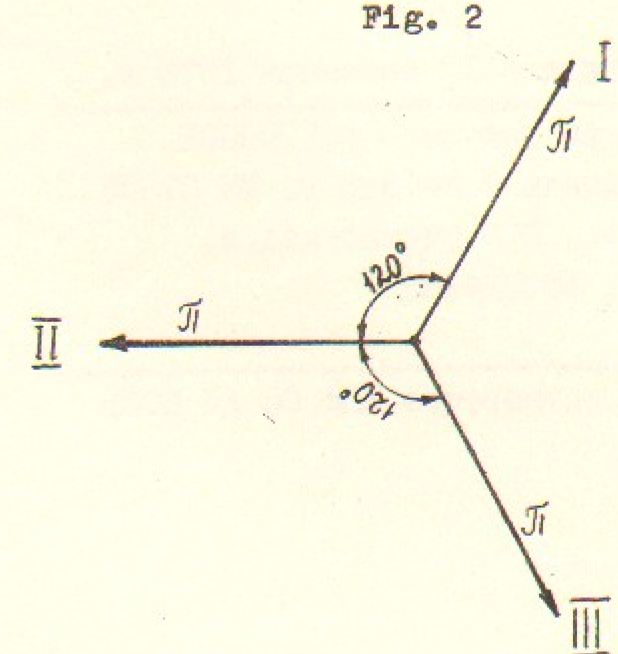

Fig. 3