HELICAL UNDULATOR FOR CONVERSION SYSTEM

OF THE V L E P P PROJECT

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Abstract

The range of required undulator parameters is discussed to provide the conversion efficiency greater than unity and the secondary beam polarization $P \gtrsim 0.6$, together with parameters of the conversion target and optics to collect the secondary particles.

The design, the manufacture technology and testing results are presented for two versions of undulator unit sections, i.e. the pulsed air-core one with the period $\lambda = 0.6$ cm and the axis field amplitude $H_\perp = 6.0$ kG and the superconducting one with the period $\lambda_0 = 1$ cm and field amplitude up to 5 kG. The problem is considered of the undulator protection against the radiation damage from the primary and radiated beams.

The conversion scheme of VLEPP project is based on the use of high energy electron beam undulator radiation circularly polarized up to high degree for pair production in a heavy material target which provides high yields of longitudinally polarized positrons and electrons [1].

The main characteristics of the undulator radiation essential in producing of positron (electron) beams with high phase-space density and polarization degree are radiation energy $\hbar\omega = 4\pi\hbar c\gamma^2 k/\lambda_0(1+p_\perp^2 + \gamma^2\theta^2)$, $k = 1,2,3...$, and the spectral density $dN_\gamma/d\omega = \alpha p_\perp^2 L/\gamma^2 c \sum_k F_k(\frac{\omega}{\omega_k})$ and polarization degree P of the photons [2]. Here γ stands for primary electrons' energy divided by their rest energy, $p_\perp$ is dimensionless transverse momentum of particles when they are passing through the undulator field, determined by the field amplitude $H_\perp$ and period λ_0, $p_\perp \gg \lambda_0 H_\perp$, θ is the radiation angle with the primary beam direction, α is the fine structure constant, L is the undulator length. Functions F_k present the relative contribution of different harmonics to radiation with the energy $\hbar\omega \leq \hbar\omega_k$, where $\hbar\omega_k$ is the k-th harmonic maximum energy. The radiation polarization degree depends similarly on the ratio ω/ω_k for all harmonics.

The polarized portion of the spectrum ($P \gtrsim 0.5$) belongs to the range $\omega/\omega_k \gtrsim 0.65$, while in the range $\omega/\omega_k < 0.5$ polarization becomes negative. It means that the higher harmonic ($k \geq 2$) polarization turns out to be negative in the energy range where the first harmonic radiation is highly polarized i.e. in $\omega_1 \geq \omega \geq 0.65\,\omega_1$. Thus to raise the total polarization degree of radiation in the energy range above specified, the higher harmonics must be suppressed to the utmost as compared with the first one. This suppression is made by choosing the value of $p_\perp$ below the one corresponding to the peak intensity of the first harmonic, i.e. at the cost of a certain loss in the radiation spectral density.

The peak spectral density dependence on λ_0, practically absent in the photon spectrum, will occur in electron and positron spectra $\frac{d^2N}{dEdt} = \int \frac{dN_\gamma}{dE'} \frac{d\sigma(E',E)}{dE} dE'$ due to the energy dependence of the pair production cross section σ. At low photon energies ($\hbar\omega \sim 5\div10$ MeV) this dependence is predominant in determination of the primary beam minimum energy according to the undulator period attainable.

At rather high energies when multiple scattering on the length of the order of 1 radiation length unit does not result in considerable particle loss at the converter exit, the dependence on λ_0 becomes insignificant affecting basically the beam transverse emittance. Thus λ_0 reduction from 6 mm down to 3 mm which is attainable in the proposed alternate design of the air-core undulator will mean first of all lowering the primary beam energy E_0 required from 150 GeV down to $\sim$ 100 GeV while the same conversion efficiency and beam polarization will hold.

The conversion efficiency at $E_0 = 150$ GeV, $\lambda_0 = 0.6$ cm, L = 150 m and $p_\perp^2 = 0.1$ is characterized by producing one secondary particle per one primary particle in the energy range of $\Delta E = 8\div10$ MeV, transverse emittance of $\epsilon = 2$ MeV/c·cm, time interval of $c\Delta t \leq 0.3$ cm at polarization degree P = 0.65 after particle collection past the converter and acceleration on 50 MeV with the gradient of $dE/dX = 0.5$ MeV/cm and guiding longitudinal magnetic field $H_\parallel = 2$T. Particle spectra and polarization degree distribution are shown in fig. 1.

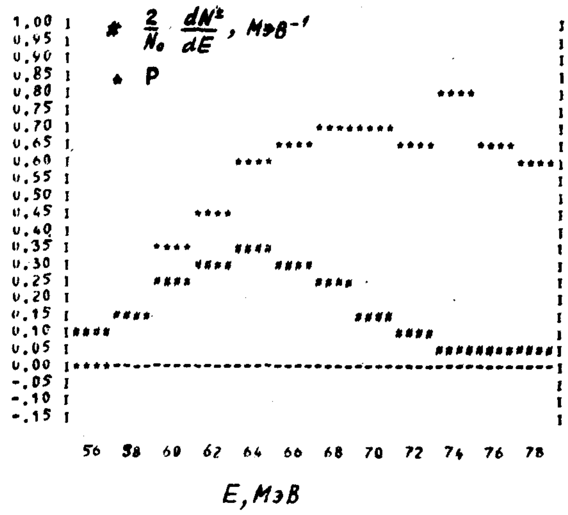

Fig. 1. Spectrum and polarization degree distribution of the positrons collected after the converter and accelerated to 50 MeV with the gradient of dE/dX = 50 MeV/m in longitudinal magnetic field of $H_\parallel$ = 2T. Primary beam energy E_0 = 150 GeV, undulator length L = -150 m, period λ_0 = 6 mm, $p_\perp^2$ = 0.1.

The particle collection past the converter is effected by a short lithium lens placed immediately after the converter (see fig. 2). The spectrum presented in fig. 1 is obtained with the lens spaced 1 mm from the converter which is the tungsten plate 2 mm thick (0.5 radiation length unit). The lens length is 6.5 mm (over the lithium body), the diameter is 7 mm, the entrance and the exit berillium flanges are 1 mm and 0.5 mm thick respectively. The use of the entrance flange as a converter seemed apparent but has been rejected due to large energy deposition in the converter which is incompatible with the lens component. Particle flux density at the converter exit comes to $\sim$ 6 pairs per each primary particle per 1 mm^2, that for 10^{12} particles per pulse gives $\sim$ 300 J/g energy deposited per pulse, thus leaving no hopes for the multi-pulse use of the converter. Besides the complications in the design of particle collection, other consequence is the loss in phase-space density of the beams as the energy range comprising one secondary particle per one primary particle expands from 6 to 8 MeV.

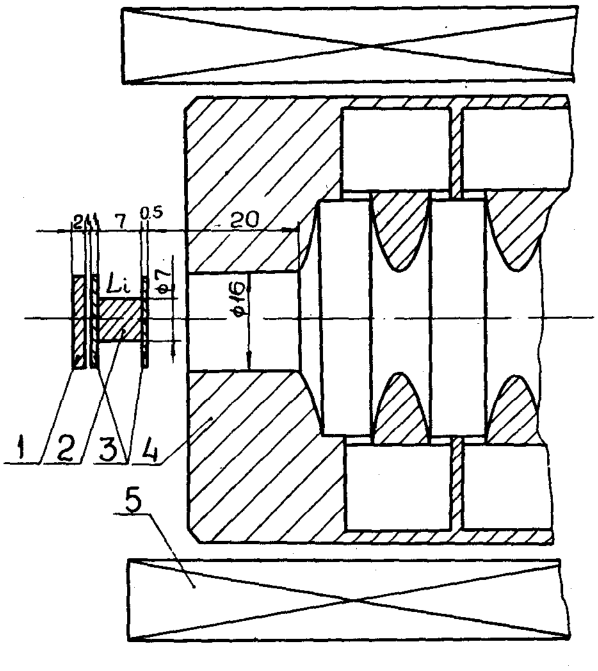

Fig. 2. Schematic view of the conversion assembly. 1 - target, 2 - lithium body of the lens, 3 - lens flanges, 4 - entrance flange of the accelerating section, 5 - solenoid coils.

The high energy deposition gives rise to difficulties in the operation of the lens due to hazard of the entrance flange overheating. In fact the local overheating of the flange in the beam entrance spot comes to 300°C per pulse. Although the small size of the heated spot results in a quick temperature drop due to heat redistribution over the flange (according to the relation: $T(t) = T(0)\langle r^2\rangle / (\langle r^2\rangle + 8\lambda t)$, where λ is the thermal diffusivity), so the temperature rise will be 3°C by the time of the next pulse (assuming the flange radius to be large enough). Nevertheless the problem of reliable heat removal from the flanges is important. An additional assurance of its solution comes from the lens operation with liquid lithium pumped through the system thus removing heat over all flange surface. The details of the lens design can be found elsewhere [3].

The undulator (fig. 3) is formed by a double helix fed with opposing currents. For laboratory testing a section has been fabricated 1.01 m long. The conductor cross section was optimized with respect to minimum active loss at specified values of λ_0 and $\rho_\perp$. The calculated active loss is shown in fig. 4 as a function of radial thickness of the coiled conductor. The coil inner diameter is 4.5 mm, duration of the current pulse is 50 msec. The loss minimum is reached at $\Delta r = \lambda_0/4$. To obtain the project goals of λ_0 = 6 mm and $\rho_\perp$ = 0.34 (i.e. field amplitude on axis $H_\perp$ = 6 kOe) the 10 kA current is needed in the conductor with 1.45 x 1.45 mm^2 cross section.

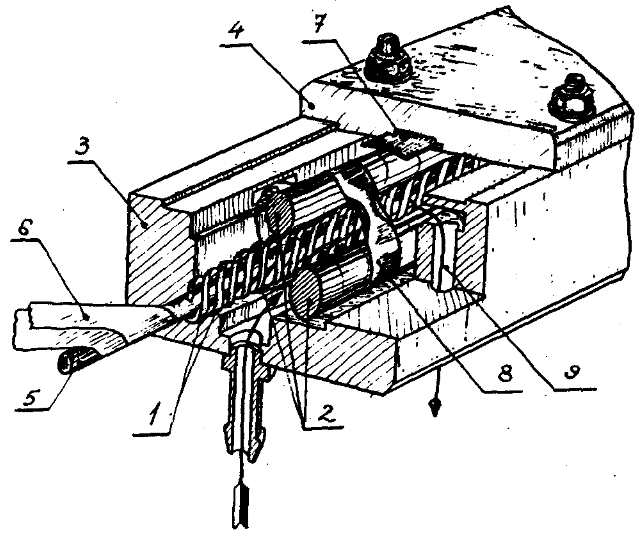

Fig. 3. Pulsed undulator design.
1 - helix, 2 - bars, 3 - casing, 4 - cover, 5 - vacuum pipe, 6 - insulating film, 7 - spring, 8 - binding strip, 9 - channel for cooling water.

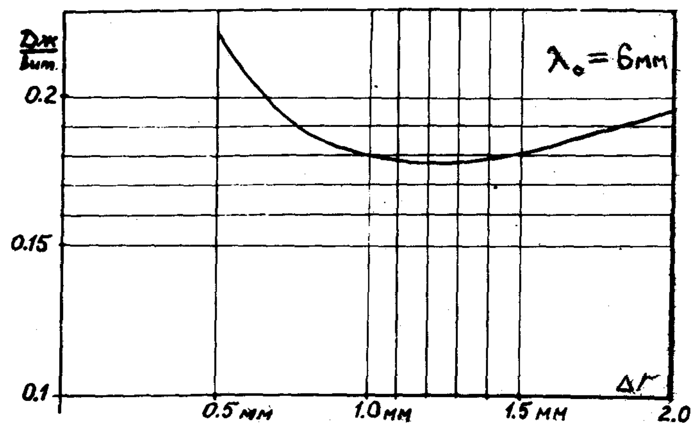

Fig. 4. Energy dissipation in the turns at λ_0 = 6 mm.

The conductor is produced by rolling the round copper wire annealed previously through the shaped rolls. The helix is wound on the calibrated round mandrel 4.5 mm in diameter. After removal of the mandrel the change in inner diameter is not noticed.

As far as fitting is made of the helix outer diameter, prior to the mandrel removal the winding is passed between metallic plates with specified spacing. As a result the spread of the helix diameter over its length is within 0.1 mm. To fix the helix period the bar 2 has grooves to position the helix turns. The bars holding the helix inside are housed in the casing machined with the accuracy of $\pm$0.05 mm. The upper bar is pressed down against the helix and further to cylindric bars 2 by a strip spring. The bars are bound with a strip 8. The bars are made of ceramic. For development of the assembling technology the bars of fiberglass reinforced plastic are used. The 4 mm in diameter beam pipe 5 made of stainless steel is passed inside the helix thus separating the vacuum volume from the inner volume of the casing where water is circulated to cool the helix winding. Water enters the central couplings, flows through the helix turns and goes outside symmetrically on either side by the outlets 9.

Double distribution water with resistivity of 1 MOhm·cm is used as a coolant at the flow rate of 0.1 l/sec. The heat pick up system tested maintains the continuity of undulator operation. The cover 4 is clamped to the casing with nuts and washers, the indium wire is introduced to seal the casing. The joints of the face and the end flanges are also sealed with indium wire.

The current feedthrough is placed in the middle of the helix. It is designed as a coaxial connected to a break in one of the coils. The vacuum pipe walls are 0.2 mm thick so as to avoid the attenuation of the magnetic field. The pipe insulation is made of four layers of the polyamid film mark B6 (one layer thickness is 0.015 mm). In operating mode the voltage between the coils and the pipe can be as high as 1.5 kV. To provide for reliable operation the insulation is tested after fabrication with 2.5 kV voltage from the megger.

Measurements of the field distribution along the undulator axis were carried out with direct current by a Hall probe moved on a copper rod by a step motor. The measured values were used to decompose the field into Fourier series of longitudinal harmonics. The second harmonic amplitude in the regular part of the helix does not exceed 4% of the fundamental one, and the other are less than 1.5%.

In pulsed operation the undulator was powered by a thyristor generator through a low-inductance stepping down 5:1 transformer operated at repetition rates up to 25 Hz. In the full-scale design powering of several sections is envisaged by one generator through a common step-down transformer. The operating age of the test section corresponds to 10^5 pulses to date.

The general parameters of the pulsed undulator section are listed in the table:

Period	6 mm
Undulator factor	0.34
Field amplitude on axis	6 kOe
Current	10 kA
Pulse duration	$50\cdot10^{-6}$ sec
Energy dissipation	0.18 J/turn
Inductance	1.3 mcH
Voltage	1.19 kV
Resistance	0.064 Ohm

In parallel with the pulsed undulator development the feasibility has been considered of the undulator with superconducting coils. One of the most promising features of the latter is that its normal operation is available irrespectively of the repetition rate of the whole complex.

The superconducting undulator testing section has been fabricated with the period of 10 mm, bore diameter of 6 mm. Winding radial and axial sizes of 5 mm and 3 mm respectively. The coils form a double helix wound in helical slots of the iron core which contributes to the field generated. Each coil has 15 turns of the wire 0.7 mm dia. To improve the field configuration the coils and the core are closed in the iron yoke (see fig. 5). The winding is impregnated with the epoxy compound loaded with aluminium oxide or barium titanate and then is monolithically hardened.

The core assembly is surrounded with the thermal insulator jacket 9 made of 25 layers of fiber glass veil and aluminized lavsan film and fit into the polished steel thin wall sleeve 5 fixing also the rods 10.

The field calculations show that up to the undulator factor value of 0.42 the iron is not saturated, while the current values in the wires are ca. 200 A.

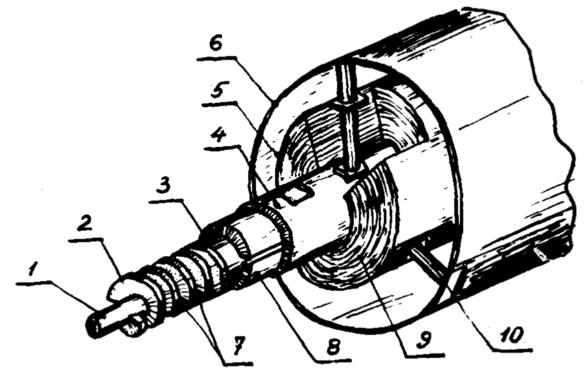

Fig. 5. Superconducting undulator design. 1 - vacuum pipe, 2 - core, 3 - core assembly, 4 - inner shell, 5 - polished sleeve, 6 - outer shell, 7 - turns of the winding, 8 - yoke, 9 - fiber glass veil, 10 - fixing arms of the inner shell.

The section has been tested after fabrication in an immersion cryostat. The field distribution has been measured in liquid helium. Similarly to the field analysis of the pulsed undulator here the field decomposition in longitudinal harmonics spectrum is studied and also the pattern of the fringe fields. The section was powered by a high-current supply with thyristor rectifier. The current was checked with a calibrated shunt and displayed on a digital voltmeter.

The Hall probe advance was carried out by the stainless steel tube sealed to prevent gaseous helium from escaping the cryostat. The Hall probe was mounted on the end of the tube wherein the four wires from the probe were passed. The tube wall thickness was 0.2 mm, its length was 1200 mm, its diameter was 6 mm. The measurements of the field amplitude on the undulator axis as a function of the supply current have completely corroborated the calculation results. The field amplitude of 5 kOe on the axis is attained at supply current of 400 A, i.e. at 6 kA·turns total.

The harmonic spectrum shows that the second harmonic in longitudinal distribution of the field amounts to 1.1% of the first harmonic amplitude, the third harmonic is only 0.23% and the others are negligible in their amplitudes, The analysis is related to the supply current of 200 A per wire ($p_\perp = 0.4$). In addition the field integral over the total length has been measured as a function of the supply current.

The superconducting undulator testing results enable considering this alternative of undulator for conversion system of the V L E P P project in its second phase with the energies of 2 x 500 GeV, wherein the short λ_0 requirement becomes less urgent, provided that the radiation exposure of the undulator due to irreproducible beam position resulting from errors in beam direction at the collision point, would not prevent its reliable operation.

Considering the undulator radiation damage, the shielding of the primary beam head-on incidence at the undulator structure face is absolutely necessary, otherwise it will be instantaneously destroyed in the spots of maximum electromagnetic shower production. This problem can be solved by a secure beam collimation upstream the undulator so as the possible grazing angle at the undulator wall be less than $\sim 10^{-5}$ radian. Under this condition the incidence of the core of the beam with $\langle r^2 \rangle = 0.4$ cm^2 gaussian particle density distribution to a copper wall result in peak (wall) heating on ~ 300 C at beam intensity of 10^{12} particles with the energy of 500 GeV. The temperature distribution over depth will be very narrow with the peak located at $\sim 10^{-4}$ cm from the surface. The incidence of the tails of the transverse beam distribution which are spaced with $\sqrt{\langle r^2 \rangle}$ from the beam center will cause heating on ~ 40 C.

The conversion at primary beam energy of 500 GeV will at first sight be less difficult than at 150 GeV because the undulator period λ_0 is no more strictly limited from below. However a fundamental difficulty will actually arise due to reduction in photon spectrum density and consequently in secondary particles density as $1/\gamma^2$. This will cause extension of the energy spread of the particles to be captured in accelerating regime, thus necessitating beam monochromatization prior to inkection in the damping ring. The possibility of such a monochromatization is actually envisaged in the VLEPP scheme: rearrangement of the time structure i.e. bunch stretching before injection to the damping ring [1] , performed by rotation of the longitudinal phase space volume of the beam in a linear accelerator, provides reduction of the particles energy spread to the same extent that the bunch is stretched, namely to ~ 10 times.

References

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Discussion

W.K.H.Panofsky. What is the depolarisation during convertion?

А.А.Михайличенко. Она мала, т.к. мишень имеет малую толщину 0.5 x_0.

B.Richter. What is the magnitude of the longitudinal field in the lens?

А.А.Михайличенко. Магнитное поле составляет 2 Т.