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Five-pole superconducting wiggler for the dedicated SR source TNK

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Two five-pole superconducting wigglers with maximum fields of up to 7–8 T for research in materials science will be installed at the X-ray lithography storage ring TNK. Their preliminary design, radiation properties and the effects on beam dynamics are described.

1. Introduction

For experiments in the short-wavelength region two superconducting wigglers are planned to be used at the TNK SR source [1]. They will be inserted in the dispersion-free straight sections where the values of amplitude functions are $\beta_x = 6$ m and $\beta_z = 0.2$ m. The critical wavelength for an energy $E = 1.6$ GeV and field amplitude $H_{max} = 8$ T will be $\lambda_c = 0.9$ Å. Particular fields of research that will benefit from the five beamlines (for each wiggler) include high-resolution X-ray topography, EXAFS, X-ray fluorescence trace analysis, energy dispersion diffractometry, small-angle scattering, etc.

2. Second source problem

For experiments with high spatial resolution using the radiation from a strong-field wiggler the problem of the second source point always arises, when two beams (for a three-pole wiggler) converge to one observation point. The distance between two source points is equal to the maximum displacement of the electrons from an ideal orbit. To eliminate the second source two approaches are usually used:

(i) A set of slits is located along the beam axis.

(ii) An additional weak-field outer pole is used to reduce the intensity of the second source and to shift the radiation spectrum to the soft region.

In the second approach, which was chosen in our case, each outer pole is split into two parts: a long one with low field to suppress the second source and a short one with a field that should be enough to compensate the orbit deflection in the central part of the wiggler.

For an electron energy $E = 1.6$ GeV and the length of an auxiliary pole $l_1 = 20$ cm, the required field value will be $H_1 = 0.7$ T.

3. The effects on beam dynamics

The potentially damaging interactions of the wiggler with beam dynamics depend on the detailed magnetic characteristics of the wiggler and have to be taken into account not only by wiggler matching but, first of all, at the stage of wiggler design and coil–iron geometry definition.

(i) The equilibrium orbit distortion outside the wiggler occurs when the condition $\int_w H \, ds = 0$ is not exactly satisfied. It is planned to compensate for the distortion by using three different currents for the central, first and second outer poles. At the injection energy the residual magnetization of the poles should be taken into consideration. The possible vertical orbit distortion will be compensated by a set of steering magnets along the ring.

(ii) The shift of betatron tunes is due to both the edge focusing and the magnetic field dependence of the horizontal coordinate x. For strong-field wigglers the second effect may be equal to or even more than the first. In our case the central pole is displaced by 5.5 mm in the x direction from the wiggler axis for trimming to zero the horizontal tune shift $\Delta\nu_x$ at a field of 8 T [2]. Once the pole geometry had been determined the minimization of the vertical and horizontal tune shifts during the wiggler switching-on was considered. The resulting maximum values of $\Delta\nu_x = 0.02$ and $\Delta\nu_z = 0.007$ can be easily compensated by gradient corrections in the adjacent quadrupole lenses.

(iii) While the magnetic field in the wiggler is low enough the emittance is reduced due to additional energy losses (zero dispersion was assumed), but with the increasing dispersion generated by the wiggler itself it can blow up fast. The longitudinal length of the central pole can be determined from the equality between the resulting emittance at the maximum field and the undisturbed one. In our case, for an energy $E = 1.6$ GeV and maximum field produced in the central pole, $H_{max} = 8$ T, the length of the central pole is found to be $d = 15$ cm.

(iv) The changes in the chromaticity, damping times, energy spread, etc., are expected to be caused by the wiggler dispersion only, because at the azimuth of wiggler location the machine dispersion function and its derivative are equal to zero. The maximum dispersion function produced by the wiggler magnet is $\eta_{w\,max} = 1.2$ cm. For $E = 1.6$ GeV and $H_{max} = 8$ T, the additional energy losses will be $\Delta U = 21$ keV and the rms energy spread is expected to be increased by 30% for one installed wiggler.

(v) Nonlinearities produced by the wiggler magnets can result in such serious problems for the machine operation as amplitude-dependent tune shift, resonance width enhancing, beam lifetime limitation, dynamic aperture reduction, etc. Therefore, efforts were made to minimize the harmonic field integrals. Whereas the integral $\int(d^2H_z/dx^2)\,ds$ can be reduced by finding the required ratio between the horizontal sizes of the central and the first outer poles, the intergals $\int_w(d^3H_z/dx^3)\,ds$ and $\int_w(d^3H_x/dz^3)\,ds$ could be trimmed to a minimum only by decreasing the poles' transverse dimensions. In our case their values are:

$$\int_w (d^2H_z/dx^2)\,ds = -0.5 \text{ kG/cm};$$

$$\int_w (d^3H_z/dx^3)\,ds = 1.4 \text{ kG/cm}^2;$$

$$\int_w (d^3H_x/dz^3)\,ds = -1.4 \text{ kG/cm}^2.$$

Comparison with the maximum values of the gradients of regular multipole magnets ($(H''l)_{max} = 9.8$ kG/cm and $(H'''l)_{max} = 8.6$ kG/cm^2) shows that they can be used for exact cancellation of nonlinear wiggler perturbations and, hence, interactions with the beam are not expected.

4. Wiggler design

The main parameters of the wiggler are listed in table 1; the parameters of the superconducting coils are shown in table 2.

The wiggler magnet consists of five pairs of superconducting coils with ARMCO iron poles. The oval coils are formed by the parts of two different radii circumferences. The coil–iron geometry is a reasonable compromise between the different requirements for obtaining an 8 T field and for beam dynamics.

Table 1
Parameters of the 8 T wiggler magnet

Maximum field on beam axis	
central pole	8 T
auxiliary pole 1	−3.3 T
auxiliary pole 2	−0.7 T
Poles gap	3 cm
Vacuum chamber aperture	2 cm
Rotation angle in central pole	70.7 mrad
Total magnetic length	100 cm
Stored energy	150 kJ

During the consideration of the coils the following requirements were taken into account:

(i) The peak magnetic field in the inner part of the coil must not exceed the critical field for the chosen NbTi superconductor.

(ii) To provide homogeneity of the stress concentrations in the coil it was found highly desirable to have the coil thickness ≤ 3 cm. Therefore, the main coil is planned to be divided into two sections with the same current but with different diameters of the superconductor.

(iii) To avoid the degradation of the superconductor by cooling down and strong magnetic forces, the winding has to be impregnated with epoxy resin and set in a shroud. Stretching of the wire during winding is also desirable.

(iv) To reduce the dissipated flux and stored energy as well as enhancing the field at the beam, the magnetic flux through the central pole should be decreased.

The superconducting magnets are placed in two (upper and lower) helium vessels, connected to each other by four helium lines. The cryostat and a liquid nitrogen shield are installed on thermocompensated racks inside the outer vacuum volume made from ARMCO. A helium consumption of < 5 l/h is expected. The electron beam

Table 2
Parameters of the superconducting coils

	Central pole		Aux. pole 1	Aux. pole 2
	1 sect.	2 sect		
Height [mm]	86	86	86	86
Thickness [mm]	10.4	19.8	17.9	5 5
Number of turns	750	2678	1740	522
Diam of superconductor [mm]	1 0	0.7	0.85	0 85
Peak field in the coil [T]	8.1	6.3	3.5	
Current [A]	200	200	123.5	30
Average current density in the coil [kA/cm^2]	16.8	31.4	13.9	3 3

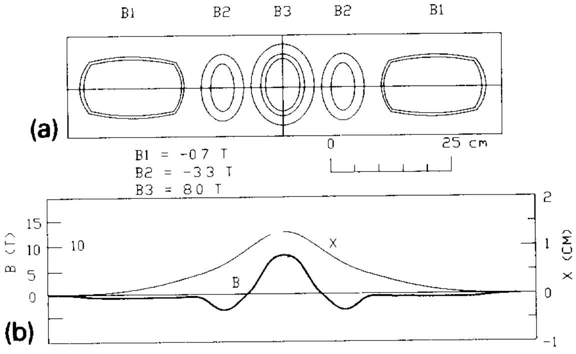

Fig. 1 (a) Cross-sectional top view. (b) Vertical magnetic field and beam trajectory

tube is made from stainless steel and is cooled by liquid nitrogen.

5. Source properties

The radiation from the wiggler has a horizontal angular size of ~ 3° and is split by radiation absorbers into five beamlines. The transverse aperture in front of the beamlines is 23 mm in the horizontal direction and 15 mm in the vertical direction. Before reaching the experimental station, the photons pass through four Be foils of 800 μm total thickness.

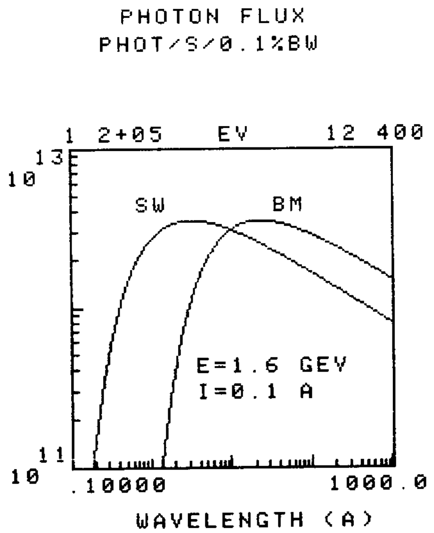

Fig 2. Photon flux for the superconducting wiggler (SW) and the bending magnet (BM).

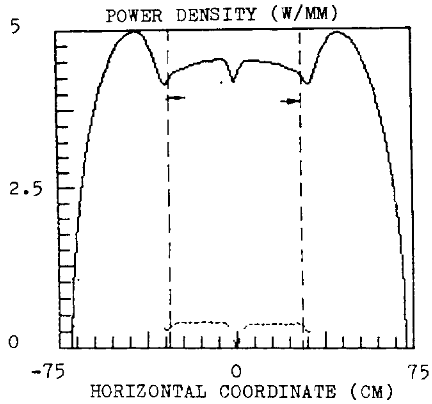

Fig. 3. Radiation power density from the superconducting wiggler. Dotted lines – contributions of the main and the second sources. Solid line – sum over both of them Arrows indicate the area that is covered by five beamlines.

At the azimuth of the wiggler location the electron beam dimensions are $\sigma_x = 0.44$ mm, $\sigma_{x'} = 0.07$ mrad, $\sigma_z = 0.1$ mm and $\sigma_{z'} = 0.04$ mrad.

Fig. 2 demonstrates the vertically integrated spectral flux from the central pole with a field $H_{max} = 8$ T for a 1 mrad horizontal opening angle and a bandwidth of $\Delta\lambda/\lambda = 0.1\%$ in comparison with the flux from a 1.1 T storage ring dipole. The electron beam parameters are energy $E = 1.6$ GeV and current $I = 0.1$ A. In fig. 3 the calculated dependence of radiation power density on the horizontal coordinate x is shown. The distance from the source point is 10 m and the electron parameters are the same as above. One can see that the ratio between the second source and the main source does not exceed 8% and, moreover, on account of absorption in the Be foils, this ratio falls to 0.5%. Note that for a conventional three-pole wiggler with similar parameters this value reaches 40%.

References

[1] V.V. Anashin et al., these Proceedings (9th USSR Nat Conf on Synchroton Radiation Utilization, Moscow, 1990) Nucl. Instr. and Meth. A308 (1991) 45.
[2] V.V. Anashin et al., Nucl. Instr. and Meth. A246 (1986) 99.