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TNK – synchrotron radiation source for submicron technology applications

V.V. Anashin, E.I. Gorniker, N.G. Gavrilov, V.N. Korchuganov, G.N. Kulipanov, E.A. Kuper, G.Ya. Kurkin, V.S. Kuzminykh, E.B. Levichev, Yu.G. Matvejev, A.S. Medvedko, V.N. Osipov, S.P. Petrov, V.M. Petrov, A.N. Skrinsky, E.M. Trakhtenberg, V.A. Ushakov, A.G. Valentinov, V.G. Veshcherevich, P.D. Vobly and N.I. Zubkov

Institute of Nuclear Physics, 630090 Novosibirsk, USSR

A general presentation on the main storage ring of the Zelenograd Technological Research Center is given. The TNK SR source is intended to create a basis for the industrial realization of advanced X-ray lithographic technology. A modern analytical center for materials science will be established, based on the TNK facility.

1. Introduction

SR sources have opened new possibilities in the development of advanced investigations and industrial technologies. Perhaps one of the first applications is the creation of the prospective industrial technology of X-ray lithography and, on this basis, the manufacture of very large scale integration circuits with a degree of integration equal to 10^7 components on one crystal, super-high-speed chips with a delay time of 10–100 ns and systems on one crystal with the number of components as large as 10^8.

Two additional approaches are seen to be natural in the development of storage rings for microelectronics. The first is the construction of a storage ring as the SR source, not only for X-ray lithography but also for a great deal of problems in materials science arising when fabricating devices with submicron structures. The second is the creation of relatively simple compact superconducting storage rings for large scale industrial replication of X-ray masks by the methods developed on multipurpose storage rings [1,2].

Since 1985, at the Institute of Nuclear Physics (Novosibirsk) a synchrotron radiation source – the electron storage ring TNK – has been built for the Zelenograd Technological Research Center based on the Institute of Physical Problems (Zelenograd). The facility is intended for submicron technology applications.

The TNK includes (fig. 1) a linac injector (80–100 MeV) [4], a small storage ring booster (450 MeV), a main storage ring (1.2–1.9 GeV), two transport lines for electrons, and 39 SR beam lines.

2. Requirements for storage rings used as a SR sources for microelectronics [5]

(a) The exposure time τ_{exp} and, hence, the productivity of an X-ray lithography station having an optical X-ray lithography scheme is basically determined by two parameters: the source brightness B and the required spatial resolution δa [7]:

$$\tau_{\text{exp}} \sim \frac{1}{B \delta a^5}.$$

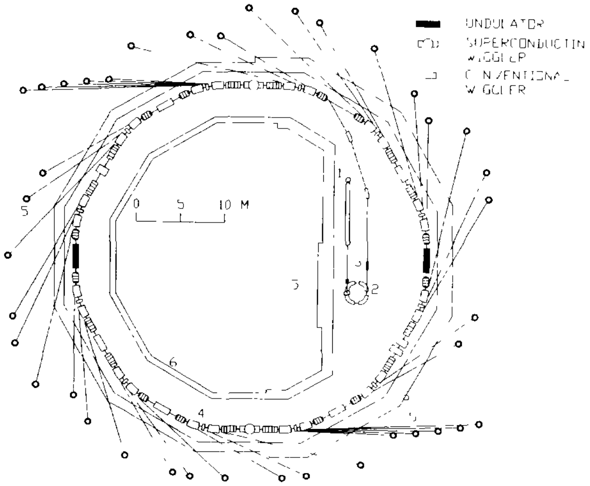

Fig. 1. Layout of the TNK facility: (1) linac, (2) small ring, (3) transport lines, (4) main ring, (5) SR beam lines, (6) shielding walls.

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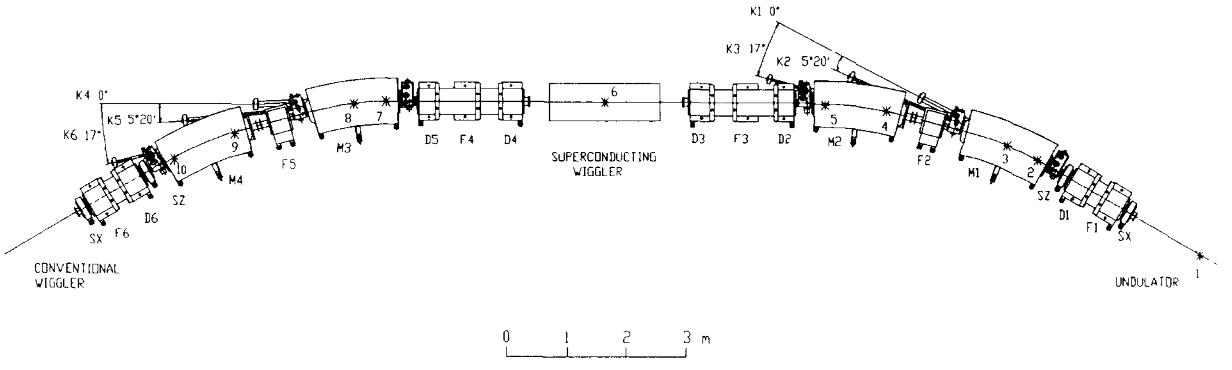

Fig 2 Cell of the main storage ring: M – dipoles, D and F – quadrupoles, SX and SZ – sextupoles, * – radiation points

To reach a spatial resolution equal to $\delta a \sim 0.1$ μm with the exposure time $\tau_{\mathrm{exp}} \sim 1$ s, a SR source is needed with the brightness $B = 10^{17}$–10^{18} photons/(s mm^2 mrad) in the wavelength interval $\Delta\lambda/\lambda \sim 0.2$–$1$.

(b) The optimal radiation wavelength for X-ray lithography is obtained when the diffraction broadening of an X-ray image determined by both the wavelength and the spacing between the masks and the resist becomes equal to the spatial resolution of the resist, determined by the passage length of photo- and Auger-electrons. The spectral domain of interest is 4–20 Å.

(c) According to estimations, to provide a spatial resolution $\delta a \sim 0.1$ μm during an exposure time $\tau_{\mathrm{exp}} \sim 1$ s, the SR energy density from the storage ring bending magnets should be equal to $J \leqslant 2$ W/cm at a distance $L = 20$ m from the radiation point in the $\lambda = 8$–20 Å range. This corresponds to a 300 mA electron current at the electron energy $E = 1.5$ GeV.

(d) The photochemical processes of depositing oxide and metallic films require VUV radiation in the wavelength range of 1000–2000 Å. For large scale production, flux enhancement up to 40–100 mW/cm is needed over the full area of the wafer.

(e) X-ray express topography and X-ray fluorescence trace element analysis require a radiation wavelength of 1–2 Å. For electrons at an energy of 1.6 GeV, this range can be obtained with a 7–8 T superconducting wiggler.

3. The main storage ring

The main storage ring is designed to achieve a low horizontal emittance of the electron beam (which is the most important condition for increasing the spectral brightness) and the optimal spatial and angular sizes of the electron beam at the radiation azimuths.

The magnetic lattice of the main ring incorporates six mirror-symmetrical superperiods, each containing an achromatic bend and two dispersive and dispersion-free straight sections. Three straight sections are used for the installation of the injection system and rf cavities, while the others are for the installation of five multipole wigglers, two superconducting five-pole wigglers and two undulators (fig. 2).

From the functional point of view, each half of the superperiod consists of two parts (fig. 3). The first, comprising the quadrupoles F1, D1, F2 and bending magnets B1 and B2, is responsible for the achromatic bend and high β_x, β_z betatron functions in the undulator straight sections. The second part, comprising quadrupoles D2, F3, D3 and the dispersion-free straight section, allows the betatron tunes to be changed without disturbing the achromatic bend, as well as locally compensating for the betatron tune shifts due to the wiggler influence, thereby preventing the rise up to noticeable beating in the structural functions of the ring.

In the undulator straight section, the betatron functions are large enough to obtain a low divergence electron beam.

High field superconducting wigglers are located in the dispersion-free straight sections ($\eta = \eta' = 0$) and can be used for reducing the emittance.

The vertical β_z function in the center of the wiggler section is small. This guarantees a small shift in the

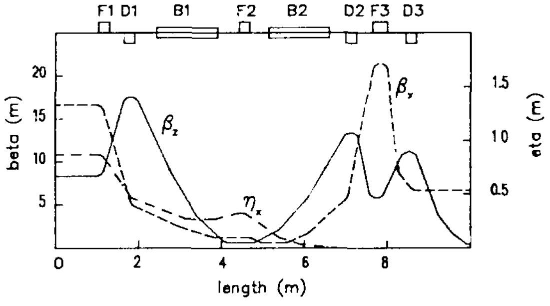

Fig 3. Lattice functions on the half-cell.

Table 1
Main parameters of TNK

Energy, E [GeV]	1.5
Max energy, $E_{\max}$ [GeV]	up to 2
Max. current (multibunch mode), I [mA]	300
Circumference, P [m]	115.73
Natural horizontal emittance, ϵ_x [cm rad]	2.7×10^{-6}
Number of superperiods, N	6
Number of 3 m long straight sections with $\eta = 0$	6
Number of 2 m long striaght sections with $\eta \neq 0$	6
Betatron tunes, ν_x, ν_z	7.73, 7.74
Chromaticity ξ_x, ξ_z	−25, −22
Rf frequency, f_{rf} [MHz]	181.3
Rf harmonic number, q	70
Bunch length (U_{rf} = 400 kV), $2.35\sigma_s$ [cm]	4.4
Magnetic field in bending magnets B1, B2 [T]	1.02, 0.255
Energy loss per turn (without wigglers and undulators), ΔW [keV]	88.3
Lifetime (multibunch mode of operation, I = 300 mA, and coupling factor $\epsilon_z/\epsilon_x = 1\%$) due to the Toushek effect, τ_{T} [h]	5
Duration of SR pulse, τ_{SR} [ns]	0.13
Time interval between SR pulses, T_{SR} [ns]	5.5–386

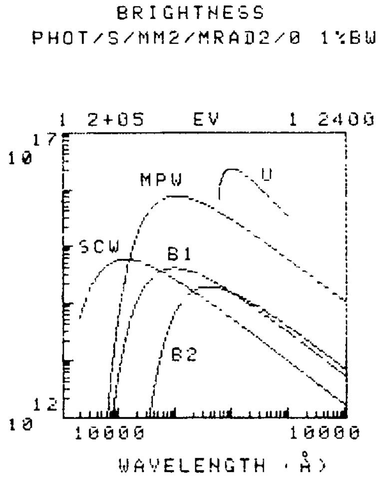

Fig. 4 Average spectra brightness (photons/(s mm^2 mrad^2 0.1%BW)) versus wavelength (Å), with electron beam parameters E = 1.6 GeV and I = 0.3 A. U – undulator (first harmonic, 12 periods, λ_0 = 11 cm), MPW – multipole (lithographic) wiggler (seven periods, B = 1 T), SCW – superconducting wiggler (B = 8 T), B1 – dipole magnet (main field B = 1.09 T), B2 – dipole magnet (weak field B = 0.272 T).

vertical betatron tune when installing high field wigglers.

The designed lattice has a relatively small natural chromaticity. To compensate for the chromaticity, there are two families of sextupole lenses (in the vertical and horizontal directions) in the undulator sections ($\eta \neq 0$).

Optimization of the behaviour of the horizontal betatron and dispersion functions in the bending magnets permits the minimum emittance to be obtained, which is determined by the quantum flactuations. We have

$$\epsilon_{x,\min}\ [\mathrm{cm\ rad}] \simeq 10^{-5}E^2(\pi/N)^3,$$

where E is the electron energy (GeV), N is the number of superperiods, and 10^{-5} is a constant depending on the lattice. Table 1 summarizes the main parameters of TNK.

The storage ring provides for the installation of:

- 20 X-ray lithography stations on the SR beam lines from the arc bending magnets with $\lambda_c \sim$ 6–15 Å, mainly for operation with X-ray masks; the other industrial applications include micromachining [3];
- five X-ray lithography stations on the beam lines from lithographic multipole wigglers. By varying the magnetic field of the wiggler, it is possible to obtain a

Table 2
Values of some parameters of the electron beam at radiation points (E = 1.6 GeV, I = 300 mA, $\epsilon_x = 3.1\times10^{-6}$ cm rad, $\epsilon_z/\epsilon_x = 1\%$, $\sigma_E/E = 6.1\times10^{-4}$)

Radiation point	β_x [cm]	β_z [cm]	η_x [cm]	$\sigma_{x,\mathrm{tot}}$ [mm]	$\sigma_{x'}$ [mrad]	σ_z [mm]	$\sigma_{z'}$ [mrad]
Section 1	1600	792	80	0.86	0.04	0.05	0.006
5°20′	150	390	24	0.26	0.16	0.03	0.03
17°	60	220	10	0.15	0.26	0.03	0.02
Section 2	610	25	0.0	0.43	0.07	0.01	0.02
5°20′ (symmetr.)	95	360	5	0.17	0.25	0.03	0.03
17° (symmetr.)	120	200	25	0.25	0.17	0.02	0.03

Table 3
The main parameters of the insertion devices

Parameter	S/C wiggler	Wiggler undulator	Lithogr. wiggler	Lithogr. wiggler
Period, λ_0 [cm]	31	11	24	24
Full length, L [cm]	100	131	133	182
Period number, N	1	12	5	7
Max. field, B_{max} [T]	8	0.65	1	1
Gap, g [cm]	3	3.2	3.2	3.2
Wavelength, λ_c/λ_{fund} [Å]	0.9	11.2/60–1300	7.3	7.3
Undulator factor, K	230	6.7	22.4	22.4
Max. horizontal angular size, $2K/\gamma$ [mrad]	2 ×74	4.3	14.3	14.3

required spectrum of radiation with any electron energy;

– ten analytical stations on the beam lines of hard X-ray radiation from two superconducting wigglers with $\lambda_c = 1$–2 Å for research in the domains of large-scale express X-ray topography (checking the crystal quality and the quality of produced epitaxial structures), energy dispersive diffractometry, EXAFS, X-ray fluorescence trace-element analysis, analysis of micromolecular crystals, diffractometry of layers and boundaries, small angle X-ray scattering, high resolution topography, and atomically pure surfaces. The presence of an intense flux of hard X-ray radiation with a photon energy of 33 keV will also permit X-ray angiography experiments to be performed;

– two analytical stations on the beam lines of the undulator radiation with $\lambda = 50$–500 Å for the investigation of dry and low-temperature photochemical deposition processes of oxide and metallic films from the gaseous phase, the radiation stimulated etching and photoelectron spectroscopy of the boundaries.

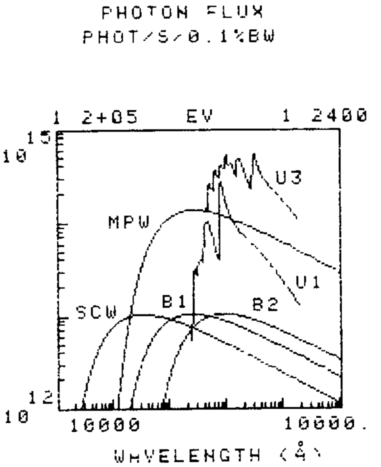

Fig. 5. Photon flux integrated over the vertical opening angle for wigglers and magnets (photons/(s mrad 0.1%BW)) and over solid angle for the undulator (photons/(s 0.1%BW)). The designations are the same as in fig. 4, except for U1 and U3 – the flux from the undulator with undulator parameter $K = 1$ and 3, respectively.

4. Main parameters of the TNK source

Synchrotron radiation from the TNK source is extracted from the bending magnets (beam of 5°20′ and 17°), the wiggler straight sections (section 1) and the undulator straight sections (section 2) identically in each superperiod (see fig. 2).

The values of the β and η-functions, and the rms dimensions and angles of the electron beam at radiation points are shown in table 2.

It is also possible to reduce the horizontal emittance to the value $\epsilon_x = 1.1 \times 10^{-6}$ cm rad (~ three times less than the standard design value) by means of two superconducting wigglers with a 4.5 T magnetic field and 1.5 m in length, which can be installed in the dispersion-free straight sections. The main parameters of the insertion devices of the TNK [8,9] are shown in table 3.

The average spectral brightness and the photon flux in the wavelength interval $\Delta\lambda/\lambda = 0.1\%$ are shown in figs. 4 and 5.

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