Commissioning of the SIBERIA-2 and First Beam Results

V.Arbuzov, A.Bulygin, A.Filipchenko, E.Gorniker,
A.Kalinin, V.Korchuganov, G.Kulipanov, G.Kurkin,
E.Levichev, Yu.Matveev, V.Sajaev, V.Ushakov,
V.Vescherevich,
Budker Institute of Nuclear Physics
Novosibirsk 630090, Russia.
A.Kadnikov, Yu.Krylov, S.Kuznetsov, D.Odintsov, S.Pesterev,
V.Stankevich, V.Ushkov, A.Valentinov, Yu.Yupinov, A.Zabelin,
KSRS, Moscow, Russia

The 2.5 GeV electron storage ring SIBERIA-2 is the first dedicated synchrotron radiation source in Russia. By joint efforts of the teams from the Budker INP (Novosibirsk) and the Kurchatov Institute (Moscow) the injection of 450 MeV electrons was obtained. In this paper we will briefly describe our commissioning experiences and present the achieved beam parameters.

I Introduction

At present the Budker INP is commissioning a set of SR sources in the Russian Scientific Center "Kurchatov Institute" (Moscow) [1]. The facility is intended for SR experiments in the *0.1 – 2000Å range of SR wavelengths and a 2.5 GeV electron energy.*

The facility comprises the dedicated storage ring SIBERIA-2 at a 2.5 GeV energy of stored electrons, the *SIBERIA-1* storage ring at a 450 MeV electron energy. An injection part includes a 80 MeV linear accelerator and two transport beam lines TBL-1 and TBL-2.

II Linac

The unbunched beam (E=40 keV, I=4 A) formed by the diode gun is injected directly to the first cavity of the lattice, which is a regular half-cell. The beam bunching arises already in this first cavity.

The accelerating structure of the linac is Andreev's modified structure with disks and washers (DAW structure) [2]. It works at $TM_{02\pi}$-type mode. The accelerating structure is 6 m long in order to reach the desired energy. A 2.8 GHz klystron station whose pulse duration is 8 mks and output power is up to 18 MW serves as a power supply source.

At present the linac injects a 79 MeV electron beam into SIBERIA-1 at a repitition rate 1Hz with pulse current of 65 mA at energy spread 1%, 18 ns pulse duration and a beam emittance

0.03 mrad·cm. In the course of injection into SIBERIA-1 the single-trapping current achieves 23 mA on the equilibrium orbit.

III SIBERIA-1

The SIBERIA-1 storage ring is a 450 MeV booster for SIBERIA-2 and, in addition, an independent SR source in the VUV and soft X-ray ranges [3], with a characteristic radiation wavelength from the bending magnets of 61.3$\AA$ [3]. It is a low-focusing storage ring whose orbit is 8.68 m long. This storage ring comprises four 90 bending magnets and four 60cm-long straight sections separating these magnets.

At present a computer-controlled process of electron acceleration from injection energy to 450 MeV takes 20 s. Both beam extraction and beam injection are done in the vertical plane. A periodicity of the electron beam extraction is of $40 \div 50$ s at the current 100-140 mA. The pulse duration of the extracted beam is $2\sigma_s = 2ns$, natural horizontal and vertical emittancs are $8.6 \cdot 10^{-7}$m·rad and $8.6 \cdot 10^{-9}$m·rad with standard energy spread of $3.9 \cdot 10^{-4}$.

IV Storage ring SIBERIA-2

IV.1 Magnet system

The magnetic lattice of SIBERIA-2 was optimized to obtain intense spectral flux and to reach high spectral brightness of the radiation source [3],[4]. It consists of 6 mirror-symmetrical cells, each containing a horizontal achromatic bend and a gap with a zero dispersion function. The basic parameters of the SIBERIA-2 storage ring are listed in Table 1.

Table 1: Basic required parameters of SIBERIA-2

Energy	E	2.5 GeV	RF harmonic number	q	75
Circumference	C	124.13 m	RF frequency	f_{RF}	181.14 MHz
Number of superperiods	N	6	Maximum current:		
Betatron numbers	ν_x, ν_z	7.75 7.72	multibunch mode	I	300 ma
Horizontal emittance	ϵ_x	$7.9 \cdot 10^{-8}$ m·rad	Lifetime	τ	5 hrs

All magnetic elements of the storage ring include 24 bending magnets, 72 quadrupole lenses, 36 sextupole lenses, 12 octupole lenses and 96 dipole steering magnets.

The SIBERIA-2 observation system consist of:

-moving probes which include the luminophor screens and TV-cameras transferring the beam images to the monitors of a control room. This permits to observe the injection processes and a first beam turn.

-24 BPMs to measure the beam coordinates both at the stationary orbit and in one turn pass. These will also be used for the tunes measurements with the pulse excitation of electron beam also.

-two optical stations using SR and consisting of the photoamplifiers with a high time resolution, the dissectors for observing the beam sizes in stationary cases and during injection process.

The betatron tunes can be measured with the help of a special station by means of the resonant excitation of the betatron oscillations. Also one can excite the oscillations 'instantaneously' with separate plates by means of the short pulse thyristor generator and with the help of fast BPM it is possible to have a spectrum of betatron oscillations within a decoherence time. There are the moving scrapers to measure the apertures.

IV.2 RF system

The RF system of SIBERIA-2[5] includes two accelerating cavities, two waveguides and two RF generators operating at 181.14 MHz frequency. It provides 1.8 MV voltage at the cavities (with taking into account the flight coefficient), the accelerating voltage is 1.5 MV to have a 0.3 A maximum stored current and a 2.5 GeV energy. To increase reliability the RF system is two-channel. The main accelerating copper cylindrical cavities are excited by E_{010}-type oscillations.

V Status

V.1 History

Nowdays the efforts are making to achieve the project parameters at the first Russian 2.5 GeV dedicated light source SIBERIA-2 that was made in the Budker INP (Novosibirsk) for the Kurchatov Institute (Moscow). The history of the last few beam sessions on SIBERIA-2 is as follows:

Mid. of 1994: Electrons were firstly extracted from the 450 MeV booster ring SIBERIA-1 and transfered through 20 m line to the SIBERIA-2 septum. A light spot on the luminofore probe inside the SIBERIA-2 vacuum chamber showed the injected beam.

Febrary 1994: The SIBERIA-2 magnetic elements alignment was completed and few thousands turns were registrated by loss counter monitors, PM tubes and pick-up stations.

April 1995: On April 16, 1995 for the first time a circulating beam was obtained in SIBERIA-2 at the injection energy 354 MeV. A single shot injection provided a current of 0.5-0.6 mA while the current extracted from SIBERIA-1 was equal to 100-140 mA. A revolution frequency range to capture the electrons into the RF bucket was Δf=100 Hz (f_0=2.41543 MHz). In parallel, the first RF generator was put into operation and the cavity parasitic modes were canceled up to few GHz. Maximum RF voltage at the cavity was equal to 0.6 MV, it is allows us to accelerate the beam to the nominal energy of 2.5 GeV. A synchronizing system provides the possibility to inject the electron bunch into each third RF separatrix. The achieved beam life time about of 200-400 s and the injection duration of 40-50 s let us to have the current into 4-8 separatrises simultaneously.

June 1995: Practically all the diagnostic systems (COD, betatron tunes, dissector tubes, movable luminofor probes, etc) were tested. A tune measurement by the RF-knock is possible with the absolute accuracy of 10^{-4}. Fig.1 shows a typical betatron tune spectrum.

V.2 Injection into the SIBERIA-2

The nominal injection energy of 450 MeV was achieved on June 18, 1995 and the beam was transported from SIBERIA-1 to SIBERIA-2 with the efficiensy better than 90%. The decision

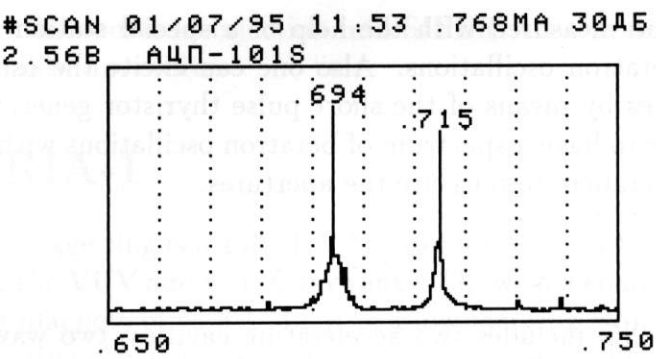

Figure 1: Typical spectrum of betatron oscillations during exitation.

was made did not try a "soft optics" mode but start with the project lattice together with the chromatic sextupoles. The signal from a fast PMT in the visible light region indicates that the major beam loss (around 85%) occures during the first two turnes (830 ns) and a rest of the beam decrease in a factor of 3 during the next 200-250 turnes. Resulting charge efficiensy was around 6%. The real repetition frequency was equal to 2.41541 MHz while the project one is 2.41519 MHz. The measured frequency range ±100 Hz is related to the horizontal aperture at the center of achromat $X_m = \pm 4$ mm.

V.3 Magnetic lattice tuning

A first measured tune point was $\nu_x = 7.573$ $\nu_z = 7.376$ that is relatively far from the project one (7.70, 7.72) and the chromaticity was not corrected ($\xi_x = -5.4$, $\xi_z = 8.2$) in spite of the project chromatic sextupoles were switched on. A successive lattice tuning was made by two quadrupole families located in the dispersive-free region.

Chromatic sextupoles seriously change the betatron function and lead to the tune shifts due to closed orbit distortions. In our case a separate corrector exitation create COD with the maximum displacement at pickup azimuths of $X = 6.1mm$, $Y = 7.9mm$ and so results in the tune shifts of $\delta\nu_x = 0.017$, $\delta\nu_y = 0.020$. After the chromaticity was compensated we had $\xi_x = -0.2$, $\xi_y = -0.58$. Note an existence of rest quadratic dependence of betatron tune from the momentum of particles.

With the tune point (7.685, 7.721) the charge injection efficiensy increased up to the 15%, the revolution frequency shifted to the project value (2.41528 MHz) and the possible frequency detuning became of 800 Hz which corresponds to the horizontal aperture to 3.2 cm.

V.4 COD measurement

The COD measurement that was done by pick-up stations, movable probes and in quadrupoles shows sistematic orbit shift inside the ring. We think that during the tuning of the magnetic optics we tried to obtain the orbit with minimun declination from the ideal orbit. But after the shifts we knew that there is the error in the pick-ups alignment of 2 mm inside the ring. That's why we hope that the bulk of the COD will be compensate easily by the proper magnetic field and RF frequency in SIBERIA-2. Besides, one more reason of COD is two parts of vacuum chamber that made from the stainless steel ($\mu = 1.02$) which locate in the BM13 and BM43 bending magnets at the opposit superperiods. Computer simulations of the influence of these parts show that the possible COD can has the amplitude of 4 mm.

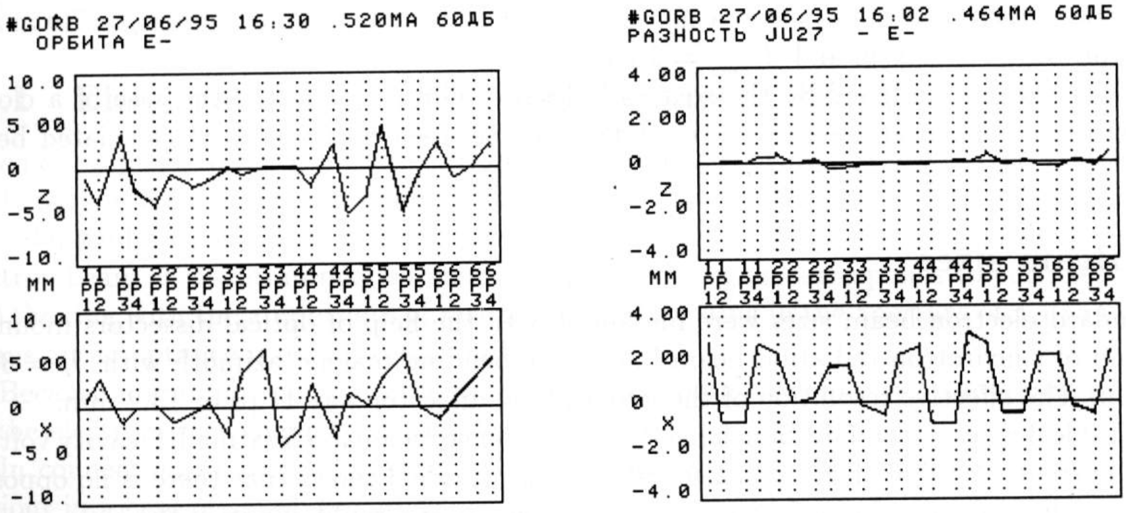

Figure 2: Typical closed orbit (left) and orbit distortion corresponding to dispersion function of SIBERIA-2 (right).

V.5 Achromats

A difference of two closed orbit distortions measured by pickups corresponding to two different revolution frequences of electrons with a shift of 100 Hz is presented by fig.2. This coordinate difference is in average in a good accordance with calculated dispertion function at achromatic bends and corresponds to 0.4 cm orbit displasement (a momentum compaction $\alpha = 0.0086$).

The achromatic bends are clearly distinguished at this picture . The achromat tuning merit is rather good, i.e. if calculated maximum dispertion in the achromats is equal to 80 cm then a dispertion value at a dispertion free straight sections is as large as -10 cm. Note there is a visible modulation of a dispertion function with a period of one half of storage ring circumference.

V.6 Amplitude function measurements

The measured average values of beta-functions and the relevant calculated ones corresponding to real currents in the quadrupole lenses are given in the Table 2

Table 2: Measured and calculated average beta-functions in Siberia-2

Lens	Measured		Calculated	
	betax(m)	betay(m)	betax(m)	betay(m)
F1	12.5	7.0	11.6	5.5
D1	2.5	11.2	3.5	13.5
F2	2.1	0.9	1.8	0.6
D2	5.0	9.3	5.0	13.3
F3	19.3	5.5	17.4	5.4
D3	5.8	7.8	6.3	8.8

Perhaps, besides a satisfactory agreement (about 20%) of calculated and measured average beta-functions their real values have rather large bittings, so that the minimum $\beta_x = 7.9$ m and $\beta_y = 2.5$ m, $\beta_{x_{max}} = 19.6$ m and $\beta_{y_{max}} = 6.1$ m.

The bittings are explaned by the sextupole lenses influence arised in the case of a closed orbit distortion. They also result in the differences between measured and calculated beam sizes.

V.7 Beam sizes

The standard electron beam sizes were measured with the help of optical dissectors mounted at the end of sinchrotron radiation beam line of the bending magnet azimuth with $\beta_x = 3$ m, $\eta = 0.0$ m. The effective resolution of the longitudinal dissector was 44 ps or 13.2 mm.

The Table 3 gives a standard bunch length depenedance on an accelerating RF cavity voltage at small current. A value of $\sigma_s \cdot \sqrt{U}$ also listed in this Table 3 shows that there is no opposite square root dependance of bunch size and RF voltage, as one could expect if the sizes are due to quantum fluctuations.

Table 3: Bunch length versus RF cavity voltage

U, kV	σ_s, cm	$\sigma_s \cdot \sqrt{U}$	I, mkA
20	4.30	19.23	150
30	3.35	18.35	150
35	3.02	17.87	150
45	2.47	16.56	110
50	2.24	15.84	40

In fact the real longitudinal size is more bigger than a natural one which is of 1.34 cm at 20 kV cavity voltage. A standard horizontal size at the observation azimuth is equal to $\sigma_x = 0.37$ mm and at injection point $\sigma_{x0} = 0.85$ mm, so a horizontal emittance is of $4.56 \cdot 10^{-6}$ cm-rad.

The calculation Touschek beam parameters at $U_{RF} = 40$ kV, $I = 0.5$ mA, $\epsilon_y/\epsilon_x = 0.01$ and 1 cm aperture limitations in achromats gives $\sigma_s = 2.91$ cm, $\epsilon_x = 2.03 \cdot 10^{-6}$ cm-rad (quantum flactuations - $\epsilon_x = 0.26 \cdot 10^{-6}$ cm-rad), $\tau = 560$ s.

A defference between calculated optic functions and real ones possibly reach 50%. So the accordance of the observed and real values is near the factor two.

V.8 Betatron coupling

When crossing a coupling resonance $\nu_x - \nu_y = 0$ the vertical and horizontal betatron frequency difference was measured and so a coupling factor was achived.

We believe the main different resonance is exited by parasitic skew-quadrupole fields, the vertical sextupoles displacements and the vertical and horizontal CODs.

Coupling factor estimation is headed by the expression

$$K^2 = \frac{\epsilon_x}{\epsilon_y} = 0.5 \frac{\delta\nu_{min}^2}{0.5\delta\nu_{min}^2 + \delta\nu^2}$$

A parabolic approximation of the betatron frequencies difference close to the resonance gives $\delta\nu_{min} = 0.0135$. From this the coupling factor seems to be small and equals to $\epsilon_x/\epsilon_y = 0.014$ at working point $\nu_x = 7.731$, $\nu_y = 7.652$.

VI Future plans

VI.1 Electron storage and energy rump in Siberia-2

When attempting to reach a maximum single turn injected beam it was observed that a capture exists only in a small ±6 kV region of the inflector plate voltage with a 48 kV nominal value.

Taking into account that a 48 kV inflector kick corresponds to 38 mm displacement of input electron beam at a septum magnet azimuth the ±6 kV region corresponds to particles captured into the ring with the amplitudes of rest oscillations existing in the aperture of ±4.75 mm. This means an acceptance is equal to 0.3 cm-mrad.

Because minimum required acceptance for injection is 1.9 cm-mrad it was not possible to fill the electrons in a single bunch mode.

In connection to large horizontal COD we think we encountered the example of beam behaviour in a case of small dynamical aperture.

To increese the DA next works will consist of a more accurate geodesic alignment of sextupoles and the orbit correction.

VI.2 Multibunch mode operation

It was observed that during the injection of bunches:

- it is possible to store the electron bunches in each fourth separatrix, this means one can store 18-20 bunches ;
- the new bunch current value injected does not depend on the current value in the other bunches(for less than 1 mA in each bunch during the,work);
- after filling 3-4 bunches bunch-bunch interaction observed, which excites the phase oscillations in each bunches with the amplitudes as large as less the bunch current;
- sometimes near 1 mA bunch current and more an instability arises with coherent radial-phase oscillations for a single bunch mode .

According to this to avoid the instability the work at RF system has to be done.

VI.3 Energy rumping

To run the process of energy rumping a high stability of the magnetic element power sources is required at a (1-2)E-4 level. During our work with electron beam the stabilization level was (1-2)E-3. So we only tried to increese the energy of electrons and rumped it up to 550 MeV. At this time the satabilization is of the required level.

VI.4 Life time

A life time was about 470 s at a current 0.2-0.5 mA just after an injection moment. Perhaps one minute after injection the life time was decreesing up to 350-400 s because of the degassing from the vacuum chamber walls. The life time was also decreesing at larger current at 450 MeV energy and especially when rumping the energy.

It is interesting to note that a life time increesing up to 700 s in a case of operation at a different resonance. This indicates once more at the small dynamic aperture in the Siberia-2.

So in our case the beam life time and beam sizes are at first governed by rather high vacuum pressure and small dynamical aperture and, at second, by Touschek's intrabeam scattering.

VI.5 Vacuum

Before the last run in June the section of vacuum vessel was opening to change a high voltage ceramic insulator of a preinjector without a following baking out. So the average vacuum pressure in the ring was rather high and equal to $1.5 \cdot 10^{-6}$ Pa, and according to the life time one can expect the vacuum pressure more higher with the electron beam. We need to open the vacuum chamber for an installation of a new nanosecond kicker and two additional 546 MHz cavities in the november 1995 and in the middle of 1996. Before that the aim is to improove the vacuum conditions by means of the degassing with a help of sinchrotron radiation without a baking out.

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