FEEDING BINP COLLIDERS WITH THE NEW VEPP-5 INJECTION COMPLEX

F. Emanov*, A. Andrianov, K. Astrelina, V.V. Balakin, A. Barnyakov, O.V. Belikov, D.E. Berkaev, M. Blinov, Yu.M. Boimelshtain, D. Bolkhovityanov, A.G. Chupyra, N.S. Dikansky, A.R. Frolov, Ye.A. Gusev, G. Karpov, A. Kasaev, V. Kokoulin, A.A. Kondakov, I. Koop, I. Kuptsov, G.Ya. Kurkin, R. Lapik, N. Lebedev, A. Levichev, P. Logatchov, Yu. Maltseva, P. Martyshkin, A. Murasev, D. Nikiforov, A.V. Pavlenko, V. Pavlov, A. Petrenko, V. Podlevskih, V. Rashchenko, S. Samoylov, S. Shiyankov, A. Skrinsky, A. Starostenko, D.P. Sukhanov, A.G. Tribendis, A.S. Tsyganov, S. Vasiliev, V. Yudin, I. Zemlyansky, Yu. Rogovsky, A. Novohatsky,
BINP, Novosibirsk, Russia
A.L. Romanov, Fermilab, USA

Abstract

VEPP-4 and VEPP-2000 e+e- colliders are switching to feed from VEPP-5 Injection Complex via newly constructed K-500 beam transfer line. Since first operation of K-500 at the end of 2015 injection complex delivered e+ and e- beams to VEPP-2000 facility and is getting ready to work with VEPP-4. Upgraded injection chain demonstrated ability to provide design luminosity to VEPP-2000 and techniques of reliable operation are now under development. The design and operation experience of Injection Complex and transfer lines will be presented.

INTRODUCTION

Injection complex was introduced in 1994 as e+/e- beam source of VEPP-5 project [1], which also included VEPP-3/4M electron-positron collider complex, charm-tau factory, phi-factory(abandoned collider project), linear accelerator (or synchrotron as alternative) for increasing injection complex beam energy to VEPP-4M and charm-tau factory experiments energy and beam transfer lines. It was later decided to build 250 m beam transfer line from injection complex to BEP in order to provide particles for VEPP-2000 [2].

First 2010-2013 run of VEPP-2000 showed 30 time lower luminosity than designed value $10^{32} cm^{-2} \cdot c^{-1}$, which was limited by insufficiency of positrons. Since injection complex had demonstrated acceptable performance by 2013/2014 season [3] upgrade of VEPP-2000 injection chain was performed in 2014-2015 [4]. VEPP-3 injection systems were switched to injection complex in summer 2016. The resulting layout of BINP colliders with injection complex is shown on Fig. 1

INJECTION COMPLEX

Injection complex is linear accelerator based e+/e- beams source with damping ring (see Fig. 2). It consists of electron gun, bunchers, 270 MeV electron linac, conversion system, 510 MeV positron linac, injection channels and dumping ring. Key designed parameters of VEPP-5 Injection Com-plex are presented in Table 1.

Table 1: VEPP-5 Injection Complex Design Parameters

parameter	value
Max. Beam Energy	510 MeV
Max. number of e- or e+ per bunch	$2 \cdot 10^{10}$
Energy spread in the bunch	0.07%
Longitudinal bunch sigma	4 mm
Horizontal emittance	0.023 mm mrad
Vertical emittance	0.005 mm mrad
beam transfers rate	1 Hz

Linear Accelerator

Linear accelerator is S-band and consists of four modules. Each module includes SLAC 5045 klystron, SLED-type [5] power compressor and 3 or 4 accelerating structures. Both linacs include 14 accelerating structures [6], which are round disk-loaded waveguide (see Fig. 3). The main design parameters of linear accelerators is presented in Table 2.

Table 2: Injection Complex Linear accelerators design parameters

parameter	value
Max. Beam Energy	280, 500 MeV
RF frequency	2855.5 MHz
Max. number of e- in beam	10^{11}
Max. number of e+ in beam	$6.3 \cdot 10^9$
Energy spread e+, e-	3%, 1%
repetition rate	50 Hz

Conversion System

In order to produce positrons we accelerate electron beam to 270 MeV and send it to tantalum conversion target.

---

[*] F.A.Emanov@inp.nsk.su

ISBN 978-3-95450-181-6

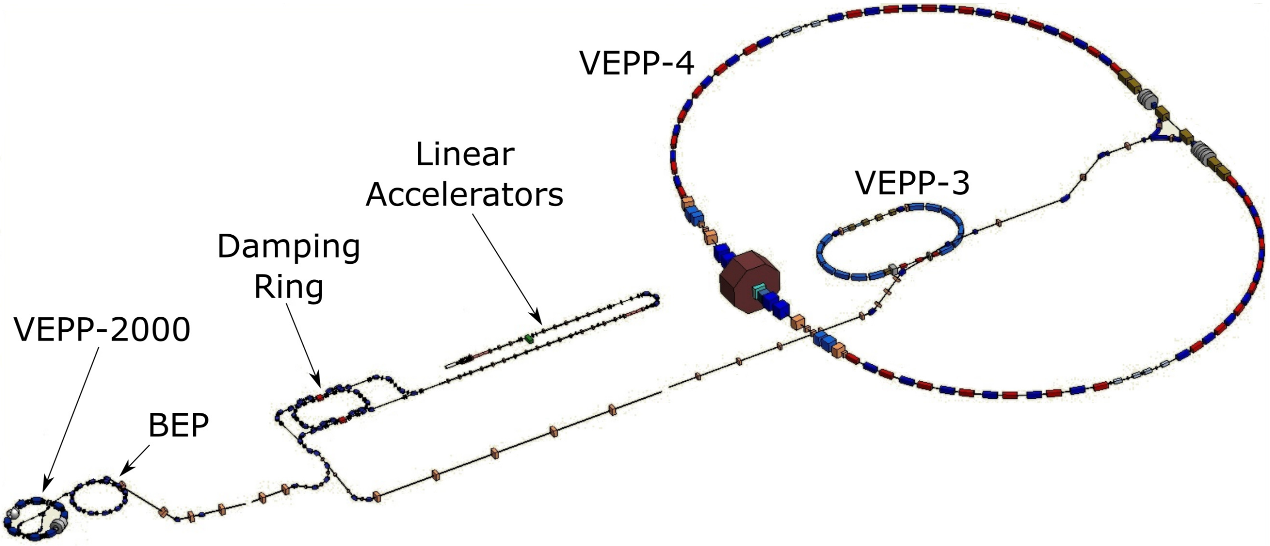

Figure 1: Injection complex and colliders.

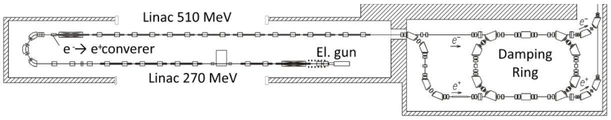

Figure 2: Layout of injection complex.

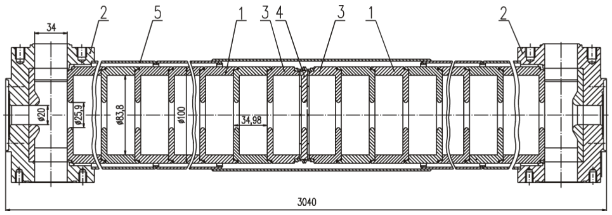

Figure 3: Linac RF structure. 1 regular cell, 2 wave type transformer, 3 junction cell, 4 junction diaphragm, 5 cooling circuit.

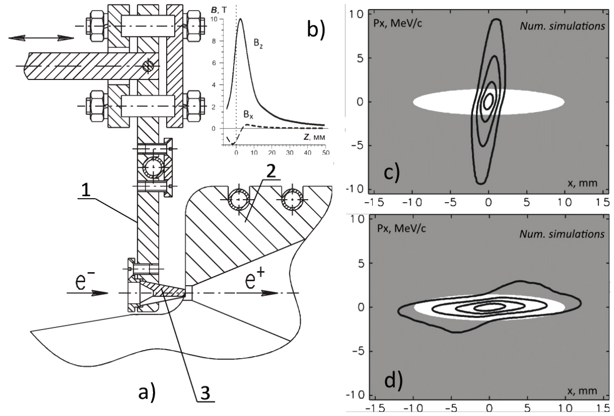

Figure 4: VEPP-5 Conversion system (e focusing not shown). a) 1 movable target holder, 2 magnet flux concentrator, 2 target; b) magnetic measurements; c) positron beam phase portrait after the target (inacceptable linac area is in grey); d) positron beam phase portrait after the flux concentrator.

Then secondary particles pass to flux concentrator (matching device), which is pulsed magnet with 10 T at maximum ”axial” magnetic field (see Fig. 4). We are running flux concentrator at about 7.3 T since increased field just slightly increases number of collected positrons [7] and significantly decreases the device lifetime. Main operating parameters of the flux concentrator are presented in Table 3.

Damping Ring

Injection complex damping ring [1, 8] (see Fig. 5) was designed to inject beams into S-band linear accelerator, accordingly designed longitudinal bunch sigma is 4 mm. Hence damping ring RF frequency was selected to be 700 MHz (frequency ratio is 64). Klystron 100 kWt was used in the damping ring RF system as power amplifier. It was possible to achieve 400 kV resonator voltage being limited to 230 kV due to possible damages to klystron or waveguide. The last klystron failed in 2016 and 1 kWt semiconductor amplifier had been used for a few months. We are now switching to 20 kWt semiconductor amplifier, so 230 kV resonator voltage will be achievable. Since current beam users do not require short beams it is possible to increase injection complex productivity by exchanging 700MHz to 11.94 MHz (RF ratio is 1). This upgrade is under consideration now.

One turn injection with pre-kick of a stored beam is used in a damping ring. Injection system consists of four kickers (see Fig. 5) and their high voltage generators [10]. Designed kickers repetition rate is 50 Hz and it is currently limited to 12.5 Hz due to issue of loads cooling.

Key designed parameters of damping ring are shown in table 4. Electron-optical model of the damping ring was calibrated during initial commissioning [9]. Then orbit was

Table 3: Injection Complex Conversion System parameters

parameter	value
Max. magnetic field	10 T
Common current on the cone surface	120 kA
Max. voltage of the capacitor	1.2 kV
Pulse energy	90 J
Pulse duration	26 mks
Repetition frequency	50 Hz
Max. average power	4 kW

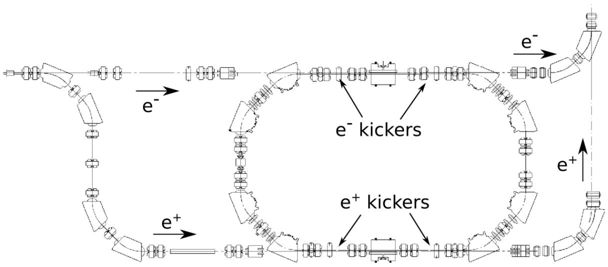

Figure 5: Damping ring layout.

corrected in order to increase available aperture [3].

Table 4: Damping Ring Designed Parameters

parameter	value
Max. energy	510 MeV
Perimeter	27.4011 m
RF ratio	64
RF frequency	700 MHz
Max. beam current	35 mA
damping times h,v,l	11.3, 17.5, 11.9 ms
Energy spread in the bunch	0.07%
Longitudinal bunch sigma	4 mm
Horizontal emittance	0.023 mm mrad
Vertical emittance	0.005 mm mrad

K-500 Beam Transfer Line

K-500 beam transfer line was turned into operation at BINP at the end of 2015. It includes two beamlines: line about 160 m to VEPP-3 and another one about 250m to VEPP-2000. Each of beamlines consists of three main sections: descent from damping ring to K-500 tunnel, regular FODO structure in the tunnel and ramp to corresponding facility. K-500 designed energy is 510 MeV. Electron beams are routinely transferred to VEPP-3 and BEP with transfer coefficient up to 70%. Positrons were transferred only to BEP.

K-500 magnets and power supplies limit minimal switching time of particles or direction to about 30 s and time between beam transfers is limited to about 1 s.

Beam Users Requirements

There are two beam users now: VEPP-2000 and VEPP-3/4. It is required to load $4 \cdot 10^{11}$ electrons or positrons to VEPP-3. VEPP-3 acceleration and polarity change time is 7 minutes, then other particles need to be loaded. Beam loading is followed by the experiment time from 40 minutes to a few hours. Beam for VEPP-2000 is to be injected to BEP. 10^{11} electrons and positrons are required to be injected in VEPP-2000 as a full load. Since there are transfer losses it is required to pass twice more particles to BEP. In order to avoid very high beam currents in BEP it is going to be done in 8 injections to VEPP-2000. BEP uses 30 s to accelerate, transfer particles and change polarity. After initial load beam charge should not be reduced more than 10%. Since expected lifetime is about 500 s it is required to reload beams with 10^{10} electron and positrons in about 50 s. Since BEP and K-500 polarity change time is about 30 s it is required to refill each beam in about 30s.

Control System Changes

In order to support joint operation with colliders the following steps are made:

- Common synchronization system was deployed in order to synchronize beam transfers. Reference frequency and ”transfer solution” signals are encoded and transmitted over optical cable from injection complex site to collider site. Returned signal used to implement cable thermal drift compensation. In order to synchronize transfer accepting machine shift RF frequency to meet designated ratio with ramping ring.
- Machine mode control services and GUI applications was implemented as centralized tool to save and control injection complex state and related information.
- Basic semi-hardware automatic tools and procedures implemented for beam storage and transfer.
- Injection complex servers and network infrastructure are preparing to provide high availability.

High-level services and tools are implemented using Python, PyQt, CXv4 [11] control system framework and PostgreSQL databases. The instruments described above allow us to run injection-extraction cycle automatically while we need to manually switch beam user on particles type. This operation mode is acceptable to start operation and accumulate operation data for implementation of full set of automatic procedures.

OPERATION EXPERIENCE

Since VEPP-2000 facility requires to refill each beam every 30 seconds injection complex has to switch between particles much faster in order to have a time for beam storage. An ideal solution is to create electron beam at the same point where positrons are produced. Then both beams will be accelerated in the same fields and almost nothing is to be done to switch between particles. In fact 270 MeV electron beam bypasses the conversion target and hence can not be guided by the same fields as a positron beam. In order to reduce time to switch between particles we need to consistently avoid changing modes of "slow" elements and make equal energy for both beams at linac exit. There are three ways to reduce electron beam energy: to shift accelerating field phase in positron linac, to reduce accelerating field amplitude, and to under fill accelerating structures by starting RF earlier for some linac module. The first way leads to increasing beam energy spread and hence decreasing captured beam charge in the damping ring. We consider this way as unacceptable. The second approach leads to average power difference for electron and positron modes. Hence accelerating structures thermal conditions may be different for electron and positron modes. The last approach is the best but more complicated to implement with injection complex control system. According to our tests both acceptable approaches is good for linac shots repetition rates up to 12.5 Hz. For 25 Hz repetition rate average power difference leads to increasing of mode switching time. Since repetition rate is limited to 12.5 Hz we are reducing accelerating field now to make electron beam energy equal to positron beam energy.

It was not possible to transport electron and positron beams through linacs and inject to damping ring with the same magnetic system setting. In order to reduce particles switching time we achieved electron and positron modes which differs only on fast enough linac quadrupole magnets and linac and damping ring magnetic correctors. This modes was made with energy 395 Mev. Switching between modes can be done within 10 seconds by loading required mode.

The following main parameters were achieved:

- Beam energy is about 395 MeV for electrons and positrons.
- linac electron production rate is $3 \cdot 10^{10}$/shot.
- Linac positron production rate is $6.3 \cdot 10^9$/shot.
- Electron beam storage rate is 10^{10}/shot.
- Positron beam storage rate is $2.5 \cdot 10^8/s$ at 12.5 Hz repetition rate.
- Transfer coefficient is up to 70% in both directions with 50% typical value.

Current peak production rates are about 10 times greater then former BINP colliders sources. It is enough to start feeding colliders with injection complex but it is steel required to increase positron productivity in order to support high VEPP-2000 luminosity.

CHARGE PRODUCTIVITY

Positron refill required to be done in 30 s and about 10 s injection complex is switching from electron storage mode. Hence there are 20 s to store 10^{10} positrons to support VEPP-2000 luminosity. Therefore required positron storage rate at least 5^8/s not taking to account beam transfer losses. Then positron storage rate should be grater than 10^9/s.

According to our calculations most of positrons are lost during injection to damping ring due to high positron beam energy spread. In order to reduce energy spread we can maximize linac energy or install a debucher in positron injection channel [7]. There are some extra injection losses due to linac single bunch mode is not implemented and hence linac beam is longer than damping ring RF bucket. Since current beam users do not require short beams it was proposed to change 700 MHz cavity to 10.94 MHz one, which allow to accept much longer beam from linac. In that case implementation of linac single bunch mode is not required. Available positron productivity increasing ways with estimated maximum gains is shown in table 4. According to estimations it is possible to achieve positron storage rate about 10^9 with already planned upgrades and about $4 \cdot 10^9$ with all the considered ways.

Table 5: Positron Productivity Increasing Ways

Action	Gain
Switch to 10.91 MHz RF station	2
Increase gun pulse duration	2
Increase operating energy to maximum	1.5
Increase repetition rate	1.5-2
Implement linac single bunch mode	2
Install debuncher	1.5

CONCLUSION

Injection complex achieved acceptable performance for begining of operation and successfully transported beams to BEP and VEPP-3. Charge productivity and operation stability improvement approaches is under consideration now.

REFERENCES

[1] "Physical project VEPP-5," BINP SB RAS, 1995.

[2] Yu. Shatunov et al., "Project of a New ElectronPositron Collider VEPP-2000," EPAC'2000, Vienna, Austria, p.439

[3] P. Logatchev et al., "Status of Injection Complex VEPP-5", Proceedings of RuPAC2014, Obninsk, Kaluga Region, Russia, p. 11-13, TUY02

[4] D. Shwartz et al., "Booster of Electrons and Positrons (BEP) Upgrade to 1 GeV", IPAC'2014, Dresden, Germany, p. 102.

[5] Z.D. Farkas et al., "SLED: Method of Doubling SLACs Energy," HEACC74, p 597.

[6] V.V. Podlevskih, "Accelerating structure and RF load for VEPP-5 injection complex," Dissertation, Novosibirsk, 2003

[7] K.V. Astrelina et al., "Production of intence positron beams at vepp-5 injection complex," JETP 2008, vol. 106, issue 1, pp 77-93.

[8] V.V. Anashin et al., "Damping Ring for VEPP-5 Injection Complex," BINP Preprint, Novosibirsk, 1992, no 9244, http://15.inp.nsk.su/injector/docs/DampingRing.pdf

ISBN 978-3-95450-181-6

[9] A.V. Petrenko, “Calibrating of the electron-optical model of the VEPP-5 damping ring,” Instruments and Experimental Techniques, 2011, Vol.54, issue 1, pp 8-15.

[10] A.I.Butakov, B.I. Grishanov, F.V. Podgorny, “Injection system to damping ring of an electron-positron injection complex VEPP-5,” Proceedings of RuPAC XIX, Dubna 2004.

[11] D. Bolkhovityanov, P.B. Cheblakov, F.A. Emanov, “CXv4, a Modular Control System,” ICALEPCS2015, Melbourne, Australia, WEPGF093.

ISBN 978-3-95450-181-6