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VEPP-5 INJECTION COMPLEX PERFORMANCE IMPROVEMENT FOR TWO COLLIDER OPERATION

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Abstract

VEPP-5 Injection Complex (IC) is designed to supply BINP RAS colliders with high energy electron and positron beams. Recently constructed K-500 beam transfer line connects IC to both VEPP-4M and VEPP-2000 colliders. IC two collider operation was successfully started in 2016. Nowadays, research on improvement of IC performance is carried out, in particular 10.94 MHz RF cavity was installed instead of 700 MHz one and a new 10 A electron gun installation is expected to be in winter 2018-2019. Moreover, streak-camera based longitudinal beam profile measurements in IC damping ring were carried out and BPM system in the damping ring was upgraded. Operation experience of IC and results of longitudinal beam profile measurements are reported.

INTRODUCTION

VEPP-5 Injection Complex (IC) [1–4] supplies VEPP-2000 [5–7] and VEPP-4M [8] colliders with high energy electron and positron beams via recently constructed K-500 beam transfer line [9]. VEPP-2000 switched to IC as its main injector in 2015, VEPP-4M - in summer 2016. Since that time IC has shown the ability to support operation of both colliders routinely. The layout of BINP accelerator facilities is presented in Fig. 1.

IC consists of electron gun, 270 MeV electron linac, isochronous achromatic U-turn, optional conversion system, 510 MeV positron linac and dumping ring. Damping ring (DR) stores both electron and positron beams for further extraction to the K-500 beam transfer line.

Current IC parameters are presented in Table 1. Number of particles of $1.2 \cdot 10^{11}$ corresponds to 200 mA circulating beam in the 27.4 m long DR, which is more than twice project parameters [3, 10]. However, our research is aimed to improve operational stability of the facility.

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Table 1: IC Beam Production Parameters

Parameter	Value
Energy (2017/2018 runs)	385-420 MeV
Inj./extr. repetition rate	up to 12.5 Hz / 1 Hz
e- storage rate @ 12.5 Hz	$2 \cdot 10^{10}$ /s
e+ storage rate @ 12.5 Hz	$3 \cdot 10^{9}$ /s
Max e-/e+ extraction	up to $1.2 \cdot 10^{11}$

BEAM USER REQUIREMENTS

Since IC supplies both BINP colliders simultaneously, it must fulfill their requirements imposed on beam current, injection repetition rate and collider operation cycles.

VEPP-4M facility has two operating modes: HEP program and SR experiments. For the HEP program 5-10 minutes injection time in the booster is enough to obtain 120-160 mA current for both types of beam ($I_{DR} \approx 2.72\ I_{V3} \approx 13.36\ I_{V4M}$), which is sufficient to reach the desired luminosity. VEPP-3 booster cycle takes 10-15 minutes and after that it is ready for another sort of particles. HEP experiments take 1-2 hours. While SR experiments require 10 minutes electron injection every 5 hours.

VEPP-2000 collider constantly requires beam injection due to small beam lifetime (500 sec) caused mostly by Touschek effect in 24.18 m ring. To achieve the desired luminosity beam current must be 200 mA ($I_{DR} \approx 0.81\ I_{BEP} \approx 0.88\ I_{V2}$) in VEPP-2000 ring, it should not be reduced more than 10%. Thus, adding new portion of 10^{10} particles at least every 50 sec is needed.

While electron storage rate in the DR is not an issue, the requirement to supply 10^{10} positrons every 50 sec was challenging due to small conversion efficiency for positron production. It was required to minimize polarity switching

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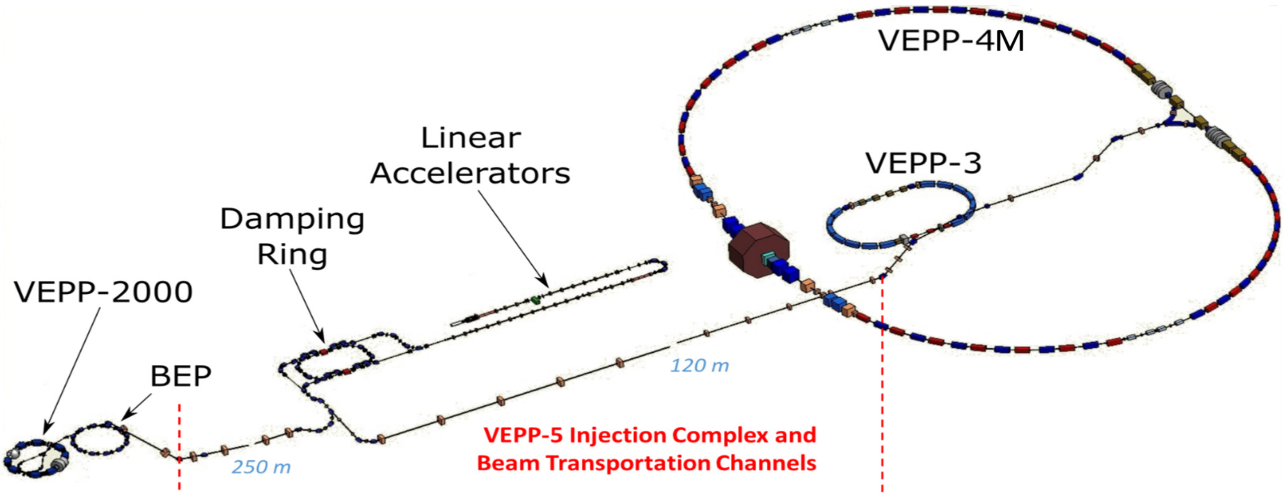

Figure 1: BINP accelerator facility layout.

time for the K-500 transfer line, switching between e- and e+ for the IC and positron storage time in the DR.

K-500 transfer line magnets and power supplies limit minimal switching time between particle type to 26-30 sec [1]. Typical value of transfer losses is near 50%. Switching between e- and e+ in the IC was minimized up to 5 sec by making the energy of both beams equals to 395 MeV at the end of the positron linac. Positron storage rate of $3 \cdot 10^9$/s was achieved. Including transfer losses, for BEP to store, accelerate and extract 10^{10} positrons, 20 sec are required. Thus, IC meets the VEPP-2000 requirements. But further IC performance improvement is essential for reliable operation.

TWO COLLIDER OPERATION EXPERIENCE

VEPP-5 IC has four operating modes: production of electron or positron beams to VEPP-2000 or VEPP-4 (see Fig. 2). To switch between these modes we need to perform a "cycle" for each bending magnet in K-500 transfer line to achieve magnetic field periodicity. Such scheme of transition between the modes is shown in Fig. 3. For example, if IC is required to supply VEPP-2000 with electrons after supplying VEPP-3 with electron beam, then "positrons to VEPP-2000" mode has to be performed first. In case K-500 transfer line operates towards VEPP-4, magnet series called "6M1-4" is switched off, i.e. zero current is set. If cycle is performed from "electrons to VEPP-2000" to VEPP-4 direction, "6M1-4" magnets should be first switched to the positron mode before they will be turned off.

Transition between operating modes takes 30 sec to inverse the magnetic field value in the magnets. This switching time is limited by parameters of DC power converters and the inductance of their loads. Therefore, the maximum switching time between the operating modes is 60 seconds.

IC PERFORMANCE IMPROVEMENT

As a measure of overall IC performance we use positron current injected for a single shot in the DR, since electron production rate is sufficient for the users in all IC operating modes. In this section some methods to improve IC performance and further improvement suggestions are considered.

1st Harmonic Cavity

DR was designed to operate in a single bunch mode with σ_z = 4 mm, hence, RF frequency was selected to be 700 MHz (harmonic number h is 64, RF voltage is 300 kV). Since current beam users do not require short beams, it was proposed to replace 700 MHz cavity with a 10.94 MHz one ($h = 1$, $U_{RF} = 9.5$ kV) in order to increase IC performance. New 1st harmonic cavity was manufactured and installed in summer 2017, it increased positron production rate by 1.5 times.

Electron Gun

During 2016/2017 operation period we observed gradual decrease of IC performance which was mainly caused by aging process of electron gun cathode. The number of electrons emitted from electron gun as function of the whole operation period of the cathode and the positron current accumulated in a single shot during that time are shown in Fig. 4.

As one can see in Fig. 4, the number of electrons emitted from cathode decreased by 3 times in the last half a year of its operation, while positron storage rate in the DR decreased only by 2 times. The latter demonstrates more delicate and accurate IC alignment allows us to partly compensate beam charge losses due to aging process of the electron gun cathode.

Since newly installed 10.94 MHz RF cavity allows us to operate with longer beams, in order to improve IC performance it was suggested to use electron gun with pulse current of 10 A (up to 20 A) and pulse duration of 10-15 ns instead of 5A and 3 ns, respectively. The gun has already

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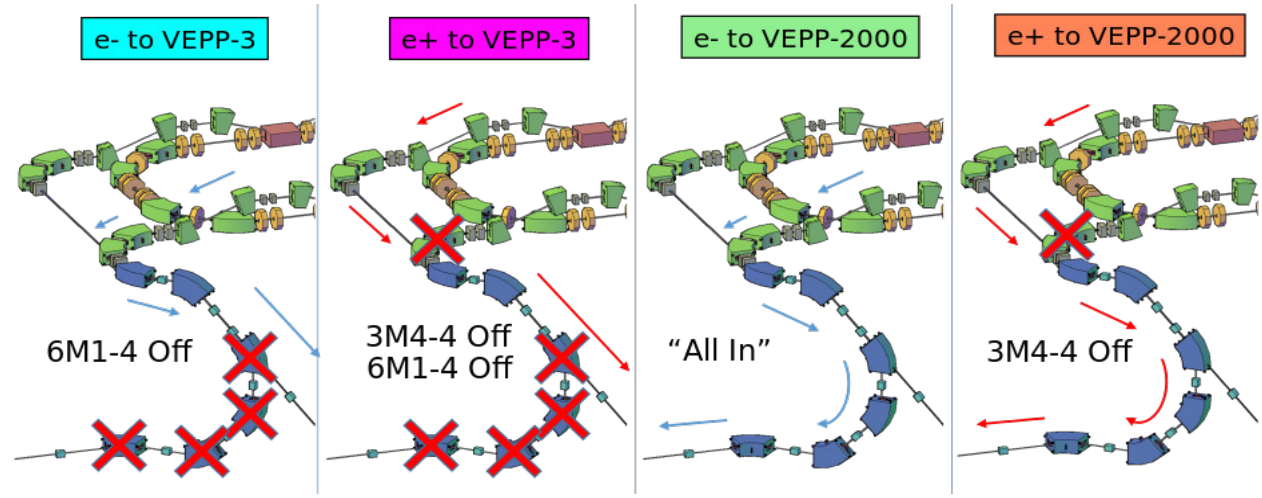

Figure 2: VEPP-5 IC two collider operating modes.

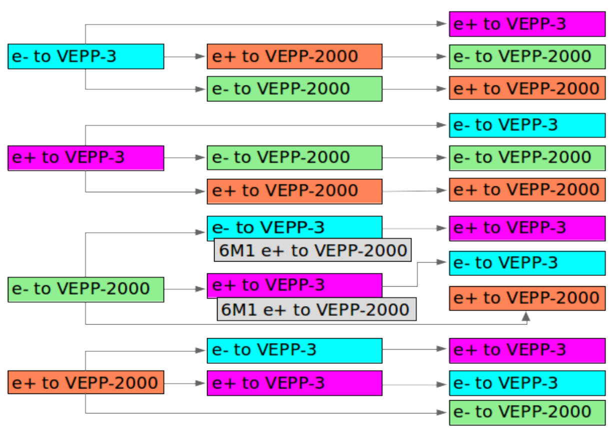

Figure 3: Scheme of transition between the modes to achieve magnetic field periodicity in K-500 transfer line bending magnets.

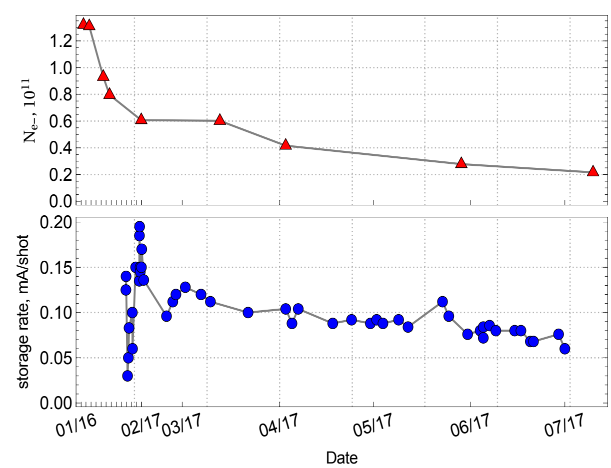

Figure 4: Beam charge emitted from the electron gun (top), single shot storage rate of the positrons in the DR (bottom) as function of operating period of the gun cathode in the 2016/2017 season.

been manufactured and now is under the final stages of bench tests. Its installation is scheduled for winter 2018-2019. We expect this modification to double positron production rate.

Further Performance Improvements

Other approaches to increase IC productivity are under consideration. One option is to improve electron-optical system matching for conversion system and e+ linac. Three additional quadrupoles following conversion system are suggested to be installed (see Fig. 5,a) in order to provide stronger focusing (for better matching of the transverse phase volume of the positron beam with linac acceptance), which was estimated to lead to 25-30% of better IC performance.

According to our calculations, most of the positrons are lost during injection to the DR due to large beam energy spread. In order to reduce energy spread we can increase beam energy at the end of the e- linac by 80-100 MeV by installing a new accelerating structure at its end (see Fig. 5,b).

Another option to reduce energy spread of the positron beam before its injection to the DR is to install a debuncher in the positron injection channel (see Fig. 5,c) [11]. It will also lead to better matching with the DR energy acceptance. Additional RF power source (klystron) for new accelerating structure and debuncher is under development. Electron energy increase is expected to improve IC performance by 1.5 times and debuncher - by 1.5 times as well.

One of the most effective ways to improve IC performance is to increase injection repetition rate from current maximum frequency of 12.5 Hz up to its designed value of 50 Hz. Now injection rate is limited due to insufficient cooling of loads of injection kickers and other IC supporting systems. Also major improvements on machine radiation protection system are required. Thus, the improvement of the IC is expected to increase performance by 3-4 times.

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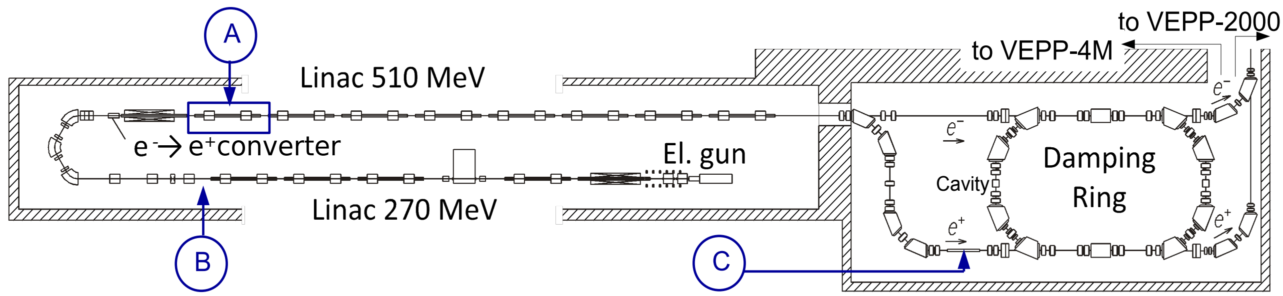

Figure 5: VEPP-5 IC layout with expected improvements of the machine: a - 3 additional quadrupoles for stronger e+ beam focusing, b - additional RF structure to increase e- beam energy, c - debuncher to reduce energy spread of the e+ beam.

Further development of the approaches considered above is needed. According to our estimations, it is possible to achieve positron storage rate of $6 \cdot 10^9$/s with already planned upgrades and about $6 \cdot 10^{10}$/s with all the considered ones.

LONGITUDINAL BEAM PROFILE MEASUREMENTS

To research longitudinal beam size and energy spread of the beam with recently installed 10.94 MHz cavity, longitudinal beam profile measurements in the DR using streak-camera were carried out [12]. Linac produces the beam consisting of 16 bunches, after its injection in RF bucket beam is grouped to a single bunch in ~ 1 ms (100 turns) (see Fig. 6).

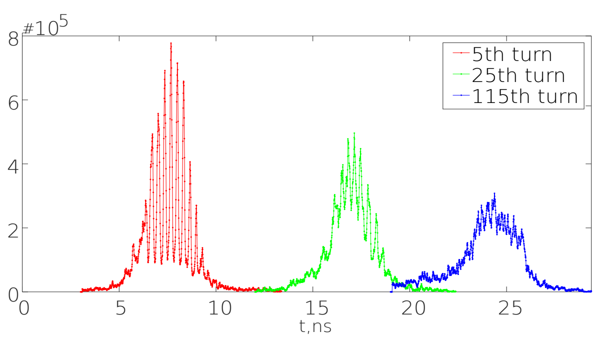

Figure 6: Longitudinal beam profile at the 5th (red), 25th (green), 115th (blue) turns in the DR.

Longitudinal beam size as function of beam current is shown in Fig. 7. As we expected, longitudinal beam size in the DR with 1st harmonic cavity has increased, e.g. beam size is about 18 cm and 1.8 cm @ 17 mA in case of 10.94 MHz and 700 MHz cavities, respectively [13].

As it was observed, the beam length with 150 mA current is about 5 ns, while the BEP bucket length is 5.5 ns (with 180 MHz RF cavity). As a result, to avoid significant particle losses during the beam injection in BEP, one should not store more than 150 mA in the DR.

Moreover, using the same optical diagnostics the longitudinal impedance of the DR was measured. Its imaginary part equals to 5.71±0.5 Ohm (dissector) and 6.15±0.18 Ohm (streak-camera) and its real part equals to 15.68±0.47 Ohm (dissector) [12].

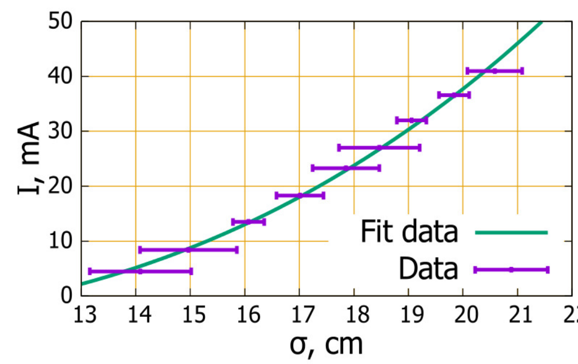

Figure 7: Longitudinal beam size vs beam current @ U_{RF} = 9.4 kV.

DR BPM SYSTEM UPGRADE

In the 2017/2018 season a new series of 16 calibrated BPMs was manufactured and installed in the DR instead of the old ones. Before 2017 accuracy of turn-by-turn measurements was 200 um and orbit measurements was 50 um, with new BPMs it is less than 80 um and less than 10 um, respectively. During October 2018 the last preparations of software modernization are expected to be completed and upgraded BPM system will be used for beam injection observation and orbit measurements. In Fig. 8 transverse turn-by-turn beam position and betatron tune measured with new BPM is demonstrated.

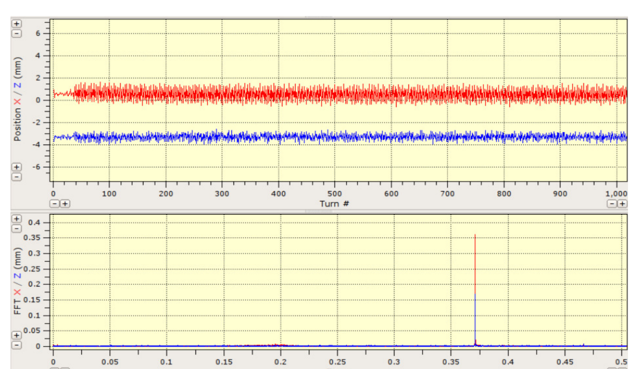
Figure 8: Transverse turn-by-turn beam position and betatron tune measurements using new calibrated BPM in the DR.

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COMPUTER SYSTEM INFRASTRUCTURE AND SOFTWARE

In order to improve reliability of IC control system and reduce maintenance efforts we developed and deployed new infrastructure based on modern network, virtualization and software technologies. Core of our IT infrastructure is Proxmox VE based high availability cluster of 8 nodes which provides redundant hardware for all computer tasks [14].

IC control software is based on CX and EPICS frameworks. At the end of 2017/2018 experimental season we decided to fully migrate base control system software to CX since this framework served more than 90% of IC control hardware. By the time most of migration work has been completed. Most of automatic processes and data processing implemented in application-level software involving microservice architecture. Deployment of automatic software dramatically reduced number of required operator's actions [15].

CONCLUSION

Since 2016 VEPP-5 IC routinely supplies both BINP colliders with high energy electron and positron beams. Sufficient charge production rates and minimal switching times between the operating modes for colliders are obtained. IC performance and operation stability improvements are still required. 10.94 MHz RF cavity instead of 700 MHz one was installed, 10 A electron gun is in progress and further improvements are under consideration. Longitudinal beam profile measurements in IC DR using a streak-camera were carried out. As it was observed, to avoid significant particle losses beam current should not exceed 150 mA in the DR. A series of 16 BPMs was manufactured and installed in the DR for further more accurate beam injection observation and orbit measurements.

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