RECOMMISSIONING OF DUKE STORAGE RING WITH A HOM-DAMPED RF CAVITY AND A NEW STRAIGHT SECTION LATTICE FOR FELS *

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Abstract

The Duke FEL lab operates a unique UV/VUV storage ring FEL and an FEL driven nearly monochromatic, highly polarized, high intensity Compton gamma-ray source. The Duke storage ring light source is undergoing several phases of upgrade in order to significantly improve its light source capabilities and performance. The recent upgrade in 2004 included an upgrade of the RF system with a high-order mode damped RF cavity and a new 34 meter long straight section lattice designed to host new FEL wigglers. This upgrade was completed in August 2004, followed by the storage ring and light source commissioning. This paper provides an overview of this upgrade project and reports the commissioning experience of the Duke storage ring and light sources.

INTRODUCTION

Since its first commissioning in November 1994 [1], the Duke storage ring has been developed as a dedicated storage ring free-electron laser (FEL) light source which has demonstrated lasing in a wide wavelength range from 194 nm to 2 microns. Colliding with the electron beam, the FEL also serves as a driver for a Compton light source – High Intensity Gamma-ray Source (HIGS), producing nearly monochromatic and highly polarized gamma beams. The HIGS has produced gamma beams from 2 to 58 MeV with its flux peaked at about 16 MeV.

Table 1: The Duke storage ring parameters.

Operation Energy [GeV]	0.27 - 1.2
Linac injection Energy [GeV]	0.274
Circumference [m]	107.46
RF frequency [MHz]	178.55
Harmonic number	64
Horizontal emittance (@1 GeV) [nm]	18
Natural chromaticity (ξ_x, ξ_y)	$-10, -9.8$
Betatron tunes (ν_x, ν_y)	9.11, 4.18
Momentum Compaction (α_c)	8.6×10^{-3}

To improve the FEL power and gamma-ray flux as well as the reliability of the light sources, the Duke storage ring is undergoing several major upgrades, including the development and construction of a booster synchrotron injector for top-off operation [2], a higher-order-mode (HOM) damped radio-frequency (RF) cavity, a next generation OK-5 FEL with four electromagnetic wigglers and variable polarizations in a new south straight section lattice, and a modified north straight section lattice to accommodate the booster injection and future light sources. The fully upgraded light source facility is shown in Fig. 1. To reduce and manage the risk associated with these upgrades, we have developed a plan to upgrade the OK-5 FEL in three phases. During the first two phases, the OK-4 FEL is preserved as the user light source to enable substantial user operation between different phases of upgrade. Fig. 2 shows the three phases of the OK-5 FEL straight section lattice. Duke storage ring parameters are listed in Table I.

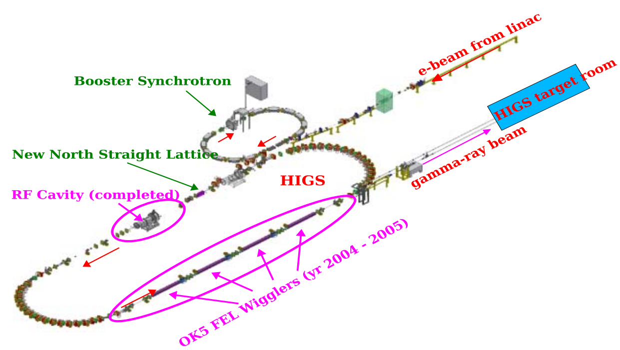

Figure 1: Fully upgraded Duke storage ring light source facility in 2006 with a HOM-damped RF cavity, a new 0.25 – 1.2 GeV booster, a new straight section for the OK-5 FEL, a second new straight section for booster injection and future light sources.

A number of other accelerator development and upgrade projects are carried out in parallel to the OK-5 upgrade. During the OK-5 phase I upgrade in 2004, in addition to the installation of a new 34 meter long straight section lattice designed to host the OK-5 wigglers, the HOM damped RF system was installed, tested, and operated. The commissioning experience of this new lattice is one of the main subjects of this paper. The OK-5 phase II upgrade in 2005 focuses on the preparation and installation of two OK-5 wigglers and their related power systems [3]. The dynamics impact of the OK-5 wigglers will be studied with the electron beam. During the phase II and III of the OK-5 upgrade, the installation, testing, and commissioning of the new booster injector are carried out in parallel. During the OK-5 phase III upgrade, two more OK-5 wigglers replace the OK-4 wigglers and a new north straight section lattice is installed to accommodate injection from the booster. Fi-

* Supported by U.S. AFOSR MFEL grant F49620-001-0370 and U.S. DoE grant DE-FG05-91ER40665
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nally, the storage ring and related light sources are commissioned with the new booster synchrotron as the injector and OK-5 FEL as its main user light sources in 2006. In the following sections, different stages of the upgrade are simply referred to as "phase I upgrade", etc.

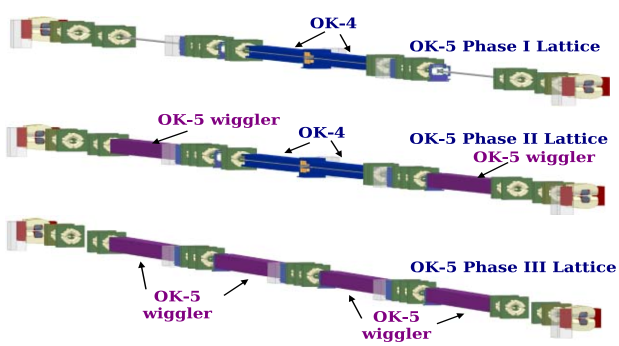

Figure 2: Three phases of the OK-5 FEL straight section lattice.

2004 UPGRADE PROJECTS

The phase I upgrade in 2004 consists of two major projects: one is the installation, testing, and operation of the HOM-damped RF cavity system; the other is the installation of the new straight section lattice to host OK-5 wigglers while retaining the existing OK-4 wigglers in the center of the lattice. The new RF system operating at 178 MHz consists of the low level control electronics, a 140 kW RF generator, and a three-meter long copper-stainless steel bi-metal cavity. The cavity is designed with a large opening on one side with RF power absorbers mounted at the far end to significantly damp higher order modes. With this design, all higher mode Q-factors are reduced by two to three orders of magnitude, resulting in effective HOM damping. Details of this new cavity is described in [4]. This RF system was designed, constructed, and tested by the Budker Institute of Nuclear Physics and delivered to the Duke FEL lab (DFELL) as a turn-key system. Collaborating with the BINP team, the DFELL commissioned this RF system with the electron beam in August 2004. With this cavity significant improvements in longitudinal beam stability have been observed in the one- and two-bunch mode operation, compared with the old cavity without HOM damping. Further tests are necessary to determine whether this new RF cavity is capable of stabilizing the longitudinal beam motion for other bunch modes, such as symmetric four- and eight-bunch operation and for continuous multi-bunch operation.

The performance of the Duke storage ring FEL and HIGS light sources can be significantly improved with a new generation FEL wigglers designed to take advantage of the high electron beam quality in the storage ring. Named as OK-5 wigglers, these new electromagnetic wigglers are designed to produce both linearly and circularly polarized light. Comparing to the existing two OK-4 wigglers, the new OK-5 FEL will employ four sets of four-meter long wigglers, separated by three bunchers, to form a distributed klystron FEL. With much increased complicity of the magnetic structure, the OK-5 wigglers can cause a large dynamic aperture reduction as found in our simulation studies [5], especially for the low energy operation. The phased upgrade allows us to study the dynamics impact of the OK-5 wigglers using the beam based techniques and allow the test of nonlinear compensation schemes using nonlinear magnetic elements such as octupoles. By keeping the OK-4 FEL as the user light source during the upgrade, the user operation can be carried out while dynamics issues with the OK-5 wigglers are being worked out. This approach would allow us to avoid a possible lengthy shutdown, had a severe dynamics problem associated with the OK-5 wigglers been discovered during the final commissioning.

To retain the OK-4 FEL during the phase I and II upgrade, the new south straight lattice is modified by adding two pairs of quadrupoles to provide a transition between the OK-4 and OK-5 part of the lattice. A total of 18 quads wired in nine families are used in this bilaterally symmetric lattice. Extensive lattice studies are performed to develop a sophisticated wiggler compensation scheme and a betatron tuning scheme in this straight section. These schemes are implemented as feed-forward controls in the low-level real-time computer.

DSR LIGHT SOURCE COMMISSIONING

The first phase of upgrade was completed in August 2004, followed by the storage ring and light source commissioning. Prior to the commissioning, the HOM-damped RF system was fully tested and brought to the operational status by the visiting BINP RF team. We had anticipated that the main difficulties of the commissioning would come from the much reduced aperture of long vacuum chambers in the OK-5 straight section, in terms of the reduced aperture for injection and associated vacuum issues, and increased transverse impedance.

To deal with the radiation shield issues in the newly constructed booster vault, the storage ring commissioning was initially limited to the second shift operation. The commissioning was started on August 18, 2004. Our initial progress was slowed down by lack of diagnostics in having only one operational insertable screen in the entire ring. With a fast oscilloscope, BPM pickup signals were found useful in guiding the electron beam to complete the first turn circulation in the storage ring. After about 15 hours of commissioning we stored the electron beam for the first time in the third commissioning shift (Fig. 3); the stored beam signal was captured by a photomultiplier attached to a dipole synchrotron radiation port. The photomultiplier signal was very useful in the process of improving the betatron capture of the beam and its FFT result was used to determine the RF cavity frequency in order to capture the beam in the RF buckets.

With the stored beam, we were able to measure the lattice tunes and discovered that the lattice was greatly detuned to compensate for three turned off quads in the linac to ring transport. After the normal lattice was recovered,

0-7803-8859-3/05/$20.00

the injection rate remained poor. This was found to be the result of a failed injection kicker which was damaged by shock waves during the booster vault construction in the adjacent area. While assessing the kicker problem, the storage ring commissioning continued with only one kicker. After repairing the damaged kicker and bringing all the kickers to optimal operation status, we attempted to store more current in multi-bunch mode. Due to a poor vacuum, the multi-bunch operation was initially limited to short bunch trains and lower currents. Progress was made as the vacuum improved: with 32 bunches, the maximum current was 35 mA on Sep. 15, 2004 and 70 mA on Sep. 24, 2004; with 40 bunches, the maximum current was 80 mA on Sep. 28, 2005; with 48 bunches, the maximum current was 103 mA on Sep. 29, 2005, 140 mA on Oct. 14, 2004, and 230 mA on Feb. 28, 2005 after the completion of the vacuum scrubbing.

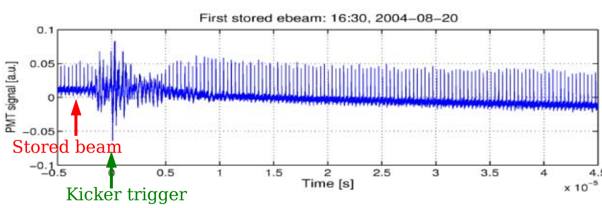

Figure 3: First stored beam captured by a photo-multiplier.

After addressing radiation safety issues in the booster vault, the standard operation with two shifts per day and five days per week started on Sep. 22, 2004. On the same day, the first vacuum scrubbing operation was performed with OK-4 wigglers turned on. As vacuum improved, the typical vacuum scrubbing operation would employ about 100 mA of multi-bunch current at 1.1 GeV and a maximum wiggler current of 3 kA. About seven weeks of vacuum scrubbing operation with only a few hours per day ended on Nov. 6, 2005, resulting in much improved vacuum.

Reduced vacuum chamber sizes in the OK-5 straight section limited the injection aperture. This limitation was somewhat worsen by an improper tapering of the vacuum chamber in the transition from the arc to straight section. Compounded with the beta-function beating (with maximum value about 20%), the injection efficiency was rather poor initially. Using the quad scan method, the beta-function was measured around the ring and the location of the aperture limitation was identified. Applying a simple lattice correction, we were able to significantly improve the injection efficiency. An optimal injection was realized with the help of a 2.6 mm injection bump in the north straight section.

The OK-4 lasing at 450 nm was re-established with a single bunch current of 4.3 mA at 455 MeV on Sep. 14, 2004 with a poor beam lifetime of about ten to twenty minutes. As vacuum improves, two-bunch operation became more stable; subsequently, the first gamma beam was produced on Nov. 12, 2004, marking the end of the commissioning. The main commissioning events and related problems are plotted in Fig. 4. As vacuum improved, we started to deliver user beam for various research programs: the multi-bunch user operation resumed on Oct. 12, 2004 and the HIGS nuclear physics program resumed on Dec. 13, 2004.

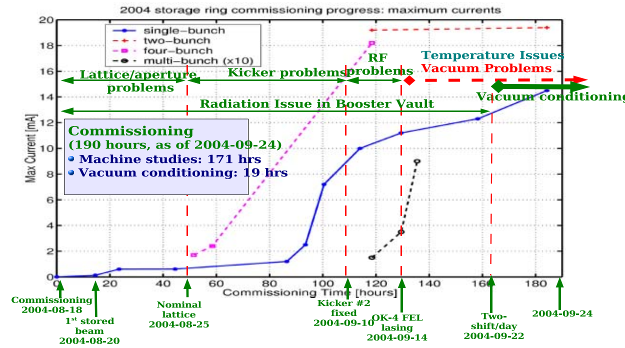

Figure 4: A summary plot of the Duke storage ring and light source commissioning progress in 2004.

SUMMARY AND ACKNOWLEDGMENT

In 2004, we successfully completed the OK-5 phase I upgrade with a new HOM-damped RF system and a new straight section lattice for the OK-5 wigglers. The commissioning of this upgraded storage ring and related light sources was a success. Even with about seven weeks of vacuum scrubbing operation, we delivered the first user beam eight weeks into the commissioning. With improved vacuum, a maximum current of 14 mA in a single-bunch mode and 230 mA in a multi-bunch mode was achieved with the upgraded storage ring. The single bunch current is still lower than the maximum value achieved before the upgrade (about 20 mA). This is attributed to the increased transverse impedance due to the reduced vacuum chamber aperture and the loss of the ability to manipulate the longitudinal instability to increase the single bunch current as was allowed with the old RF cavity without HOM damping. It is expected that our single-bunch and two-bunch current will be significantly increased at a higher injection energy with the booster injector and the operation of a transverse feedback system.

Finally, we would like to thank V.S. Arbuzov, Yu.A. Evtushenko, N.G. Gavrilov, E.I. Gorniker, I.A. Ivantcov, I.V. Kuptcov, G.Ya. Kurkin, I.V. Kuptcov, N.V. Mitianina, A.M. Pavlenok, V.M. Petrov, A.G. Tribendis, from Budker institute of nuclear physics, Russia for installation, testing, and commissioning without the e-beam of the HOM-damped RF system.

REFERENCES

[1] Y. K. Wu *et al.*, IEEE Trans. Nucl. Sci. **44**, p.1753, 1997.

[2] M. Busch *et al.*, these proceedings of PAC 2005, Knoxville, TN, 2005.

[3] V. G. Popov *et al.*, these proceedings of PAC 2005, Knoxville, TN, 2005.

[4] V. S. Arbuzov *et al.*, these proceedings of PAC 2005, Knoxville, TN, 2005.

[5] Y. K. Wu *et al.*, Duke FEL lab internal report, unpublished, 2004.