COMMISSIONING OF THE DUKE STORAGE RING*

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Abstract

The commissioning of the 1 GeV Duke Storage Ring began in November, 1994 with the demonstration of injection, storage and ramping to 1 GeV at the first attempt. The ring is now operational. The Duke project is unique in that the storage ring and linac were designed, constructed and commissioned by a small new University laboratory, operating on a low budget. The team is comprised of six accelerator physicists and graduate students, eight engineers, and fifteen technicians.

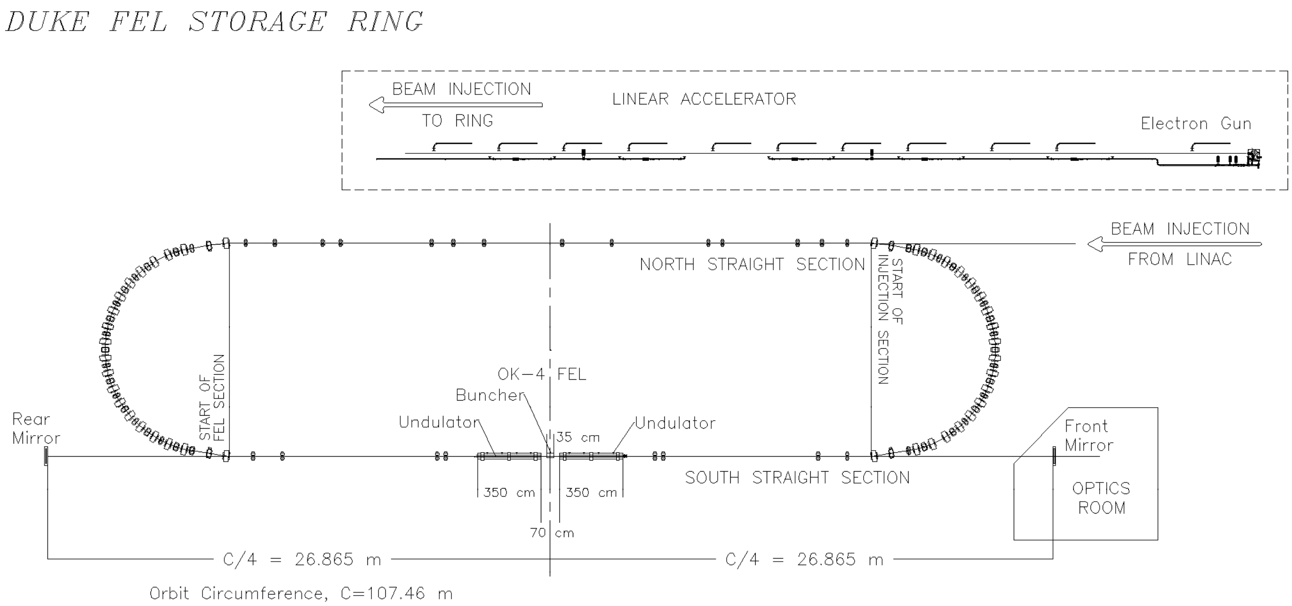

Figure 1. Layout of the Duke FEL storage ring and 280 MeV linac-injector.

I. INTRODUCTION

The new design of the Duke storage ring lattice was initiated in February of 1991 and was completed in October the same year [1,2]. The circumstances leading to the design of the ring's novel modified second-order achromatic lattice is presented elsewhere [3]. Our experience with the Duke storage ring has shown that this lattice is very "tolerant". The use of precise magnetic measurements for control [4,5] in combination with precise alignment [6] was the key to trouble-free commissioning.

II. DUKE STORAGE RING

The unique “third generation” 1 GeV Duke storage ring is designed to drive UV and soft X-ray FELs as well as to produce high brightness synchrotron radiation from the bending magnets and insertion devices. The facility is comprised of the 1 GeV storage ring, the 280 MeV linac-injector and linac-to-ring (LTR) channel.

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***Storage Ring**:* The layout of the Duke storage ring and linac is shown in Figure 1. The ring itself is a strong focusing race-track with two 34 meter long straight sections. The south straight section lattice is designed to optimize FEL operation with 7 to 28 m long FELs. The north straight section is used for injection and installation of the RF system and synchrotron radiation insertion devices. The main parameters of the Duke storage ring are listed in Table 1.

All dipoles on the Duke storage ring, including those in the injection chicane, are fed by one 560 kW PEI power supply, while all quadrupoles have individual power supplies. This feature provides flexibility for the lattice design.

Arcs: Each arc is divided into ten strong focusing FBDB (FODO) cells to provide low natural emittance of the electron beam. Details of the design are described in [3].

South straight section: The lattice of this section comprising 8 quadrupoles has bilateral symmetry with 3.5 m horizontal and vertical β-functions at its center. This lattice is optimized to facilitate operation of the 8 m long OK-4 UV/VUV FEL [7]. We also designed an alternative lattice for this straight section to accommodate a future 26 m FEL [8].

Table I. Designed Parameters of Duke Storage Ring

Operating energy [GeV]	0.25 - 1.0
Ring circumference [m]	107.46
Arc and straight section length [m]	19.52; 34.21
Revolution frequency [MHz]	2.7898
RF frequency [MHz]	178.547
Number of dipoles and quadrupoles	40; 64
Betatron tunes, Qx and Qy	9.111, 4.180
Orbit compaction factor, α	0.0086
Natural chromaticities, Cx and Cy	-10.0, -9.78
Compensated values, Cx and Cy	+0.1; +0.1
Acceptances [mm mrad], Ax and Ay	56.0, 16.0
Energy acceptance, $\Delta E/E$, of ring	>±5.0%
limited by existing RF	±2.8%
Maximum β-functions [m], x and y	13.6, 21.3
Maximum η-function [m]	0.245

North straight section comprising 14 quadrupoles, is a more diverse lattice: it provides optimal conditions for the 3.75 m NIST undulator (soft X-ray spontaneous source), RF-cavity and injection.

Ring RF system comprising a RF cavity, a circulator, and a 55 kW QEI power amplifier, is described in [9]. ***Duke Storage Ring injection*** system includes a 280 MeV linac, a LTR channel, achromatic vertical chicane, and ferrite kicker. Injection is in the horizontal plane to accommodate insertion devices with small vertical gaps.

The 280 MeV Linac- injector comprising a microwave electron gun, 11 SLAC accelerator sections, and low and high energy spectrometers, was commissioned in October 1994. The linac description can be found elsewhere in these proceedings [13]. A chopper (the gun kicker) installed after the microwave gun forms 25-50 nsec electron bunch trains which define the filling pattern (5 to 10 buckets) in the ring. The linac delivered about 2-2.3 nC of the charge per shot, which transfers to 5-6 mA of average current in the ring.

The ring has one injection kicker (instead of designed three). The ring kicker is described in [10].

The timing system, originally developed at Stanford and adjusted to the new RF frequency at Duke, provides synchronization of the linac and storage ring pulsed systems, namely the gun and ring kickers.

The injection chicane, comprised of three 9° dipoles and a Lambertson type septum magnet, provides a 60 cm vertical bump of the electron trajectory. The chicane dipoles are identical to those on the ring and are fed by the same power supply. This arrangement matches the energies of the ring and chicane which is also used as a spectrometer. The last 3 meters of the chicane employ a vacuum pipe with 8 x 12 mm inside cross-section for differential pumping between the storage ring and linac .

Vacuum system: The ring has stainless steel vacuum chambers with smooth transitions. Synchrotron radiation absorbers are located in the arcs. However, we are presently using temporary end-of-arc vacuum chambers without absorbers and with sudden jumps of the vacuum pipe cross-section. These chambers do not allow operation at full energy with full current. They are also the main source of longitudinal impedance for the ring.

More than fifty vacuum pumps are distributed around the storage ring. Overall vacuum in the ring is $(2\text{-}8)*10^{-10}$ torr without electron beam. Vacuum in the arcs climbs up to $(1.8\text{-}2.8)*10^{-8}$ torr with a 100 mA beam at 280 MeV, and up to $(3.6\text{-}4)*10^{-8}$ torr with a 4 mA beam at 1 GeV. Vacuum is sufficiently good to provide 4 hours lifetime at 1 GeV with 4 mA beam current.

The alignment system is described in these proceedings [6].

Duke Ring diagnostic system comprises the following systems: DCCT for average current measurements with 1 μA resolution (made in BINP); four remotely controlled screens for one-turn tracking; four end-of-arc synchrotron radiation ports equipped with TV cameras, photo-multipliers and a dissector with 20 psec resolution. The tune measurement system is described elsewhere[11].

Duke Storage Ring control system includes advanced intelligent functions for control of lattice modifications, tune and chromaticity controls, magnet normalization, and energy ramp. This system is well described in [4,5].

III . COMMISSIONING OF THE RING

Commissioning of the Duke storage ring proceeded very smoothly and successfully. We did not experience any problems tracking the beam through the LTR, the chicane, and the storage ring from the first shot without use of any correctors. There was no problem storing the beam and ramping the energy from 230 MeV to the design energy of 1 GeV. Later, the beam was ramped to 1.1 GeV as well. This success was achieved with the use of very simple diagnostics.

Table II. Measured Parameters of Duke Ring

Operating energy [GeV]	0.2 - 1.1
Revolution frequency [MHz]	2.7898
RF frequency [MHz]	178.547
Betatron tunes, Qx and Qy	9.118 4.145
Natural chromaticities, Cx and Cy	-10.0, -9.78
Compensated values, Cx and Cy	+0.1; +0.1
Acceptances [mm mrad], Ax and Ay	>56.0, >16.0
Energy acceptance, $\Delta E/E$, of ring	±6.0%
Closed orbit (no correction) x and y, mm	<±5, <±4
Deviation of β-functions , x and y	<±20%
η-function [m] in straight sections	< .005

Table III. Electron Beam Parameters

	Design	Measured
Beam current, mA	100	115
Emittance (@1 GeV) [1]		
Horizontal ,m*rad	$18 \cdot 10^{-9}$	$16\text{-}19 \cdot 10^{-9}$
Vertical,m*rad	$1 \cdot 10^{-9}$	$<1 \cdot 10^{-9}$
Bunch length[2] , ps	33	< 70

The commissioning of the Duke ring has resoundingly demonstrated the effectiveness of the lattice, control system and alignment. Table II comprises the main measured parameters of the ring with the designed objectives.

Stacking the electron beam with 100% efficiency using one kicker (instead of the designed three) was achieved because of the large dynamic aperture of the ring. The measured acceptance of the ring is in very good agreement with physical aperture of the ring [14].

The measured parameters of the electron beam in the Duke storage ring are summarized in Table III.

In addition, two unusual effects were observed during commissioning: capture of 20% of the electrons injected outside the RF separatrix (with higher energy) and stable capture of electrons in a -30 dB level side-band of the RF frequency.

IV. FUTURE PLANS

We plan the following upgrades of the Duke storage ring: 1) smooth end-of-arc vacuum chambers with absorbers to attain the full capabilities of the Duke ring; 2) electronics for the 60 existing strip-line BPMs; 3) reduced injection bunch duration to 5 nsec for single bucket filling; 4.) two additional kickers to simplify injection.

Near term plans include installation and commissioning of the UV/VUV OK-4 FEL and the NIST undulator.

V. ACKNOWLEDGMENTS

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[1] Defined by accuracy of measurements

[2] 3.5 mA, GeV, RF @300kV, required confirmation.