Experimental Study of the Duke Storage Ring Dynamic Aperture *

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Abstract

The Duke storage ring was designed with a large dynamic aperture for UV-VUV Free Electron Laser (FEL) operations. During commissioning of the Duke storage ring, experiments were performed to measure the horizontal, vertical, and energy apertures. The experimental methods used for the aperture measurements are presented in this paper. The measured results are discussed and compared with the computer simulations.

I. INTRODUCTION

The Duke storage ring lattice was designed with a large 6-D dynamic aperture [1], [2], [3]. The success of the Duke storage ring commissioning [4] has indicated a large 6-D aperture. These indications include:

- after accomplishing the one-turn injection, the stored electron beam current was achieved at the first attempt without using any correctors.
- 115 mA of stored beam current was stacked at the injection energy of 283 MeV using one kicker which kicks both the stored and injected beams.
- the captured beam current per shot was not significantly affected by the change of the RF voltage.

To confirm the observation of the large aperture, experiments were performed to measure it directly.

The measured the aperture is determined by either the dynamic aperture or the physical aperture, whichever is smaller. The physical aperture of the real lattice strongly depends on the closed orbit. The dynamic aperture can not be directly measured if the physical aperture is smaller.

From the computer simulations [1], the transverse dynamic aperture of the Duke storage ring lattice is large than the physical aperture defined by the vacuum chambers. For the ideal design orbit, the horizontal physical aperture is 56 mm-mrad, and the vertical physical aperture is 16 mm-mrad. At 1 GeV, the energy dynamic aperture from simulations is larger than 5% depending on the transverse orbit. The energy aperture is therefore limited by the physical aperture defined by the RF voltage (the RF energy acceptance).

II. TRANSVERSE APERTURES

A. Experimental Setup

The transverse apertures are measured using a kicker, a screen, and a vertical dipole (septum) as shown in Fig. 1. The injection kicker provides a horizontal kick to both the injected and stored beams. The inserted screen at the northwest corner is used for the kicker calibration. To measure the horizontal aperture, we use the injection kicker to kick the stored beam horizontally.

The septum [5] is the last dipole in the four-dipole injection chicane. The septum bends the injected beam vertically 9 degrees into the horizontal plane of the stored beam. At the same time the septum allows the stored beam to pass through its V-shape notch without experiencing any magnetic fields. To measure the vertical aperture, we vary the septum current to inject electron beams with different vertical angles.

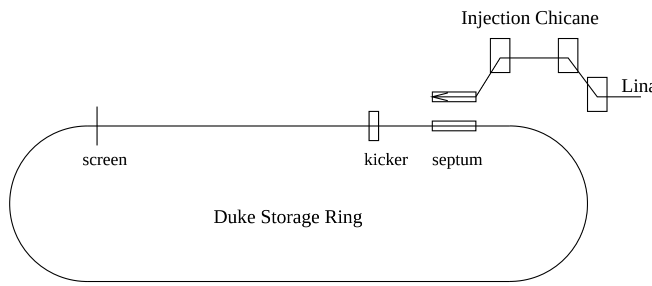

Figure. 1. Experimental setup for the transverse aperture measurement.

B. Horizontal Aperture

The horizontal aperture measurement requires the calibration of the injection kicker. To calibrate the kicker, we insert a screen at the northwest corner to measure the injected beam position while varying the kicker voltage. The horizontal kick generated by the kicker is calculated in Eq. 1, where M is the transfer matrix between the kicker and the screen. According to our transfer matrix measurements [6], the measured matrix is very close to the designed one. We can approximate m_{12} with its designed value.

$$\begin{aligned} \begin{pmatrix} x \\ x' \end{pmatrix}_{screen} &= (M) \begin{pmatrix} x \\ x' \end{pmatrix}_{kicker} \\ (\Delta x)_{screen} &= m_{12} \ \left(\Delta x'\right)_{kicker} \end{aligned} \tag{1}$$

From the kicker calibration measurement, the horizontal kick $(\Delta x')_{kicker}$ is approximately a linear function of the kicker voltage (Fig. 2.)

The horizontal aperture is measured with a reasonable amount of stored beam current (a few miliamperes). After adjusting the kicker voltage, the stored beam is kicked horizontally. The beam loss is measured after the kick. The horizontal aperture is defined by the kick which kills all the beam during the kicker turn-on time.

Since the stored beam contains many bunchs, its envelope usually exceeds the kicker turn-on time. To ensure that the beam is killed by the kicker, the longitudinal profile of the stored beam is therefore also monitored during the measurement.

From the measurement, we find that a stored beam with energy 278 MeV is killed by a kicker voltage of 11.75 kV, which

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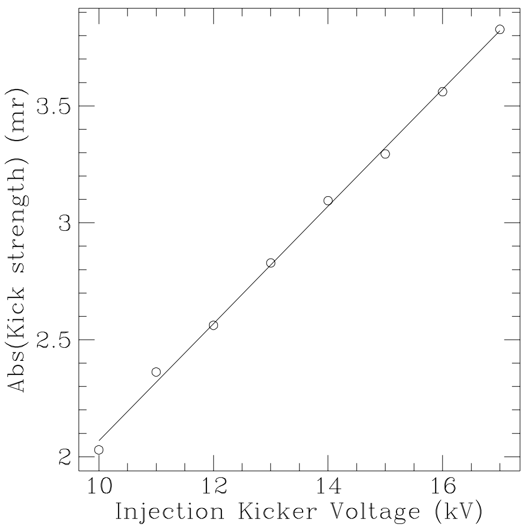

Figure. 2. Injection kicker calibration at 278 MeV.

corresponds to a kick of 2.94 mili-radian. Assuming that the stored beam passes through the center of the kicker, the horizontal aperture can be calculated using Eq. 2. The measured horizontal aperture is 43 mm-mrad, which is about 77% of the ideal physical aperture limited by the vacuum chamber.

$$\begin{aligned} A_x &= \left(\beta_x x'^2 + 2\alpha_x x x' + \gamma_x x^2\right)_{kicker} \\ &= \left(\beta_x x'^2\right)_{kicker} \quad \text{if } x = 0 \\ \text{where} \quad & \beta_x = 4.911\text{m} \end{aligned} \tag{2}$$

The measured horizontal aperture is probably limited by the physical aperture due to the closed orbit distortions, rather than by the dynamic aperture. As indicated by the preliminary closed orbit measurements, the horizontal orbit offset in the arc focusing quadrupole (QF) is about 3 mm. With the vacuum chamber opening of 13.5 mm and $\beta_x = 2.5$ m, the estimated available physical aperture is about 44 mm-mrad.

C. Vertical Aperture

The vertical aperture is measured by observing the captured beam current per shot in the storage ring while varying the septum current. The experimental procedures are summarized here:

- optimize the injection and the storage ring configuration.
- measure the average captured beam current per shot from injection.
- repeat the above measurement while varying the septum current to provide a vertical angle to the injected beam.
- record the range of the septum settings which allows the injected beam to be captured.

The range of septum settings which allows beam capture is used to compute the vertical aperture. The maximum vertical angle of the injected beam is calculated in Eq. 3. Note that the septum setting is calibrated in terms of the electron energy in MeV, so that the range in angle $\Delta y'$ is:

$$\Delta y' = \frac{\frac{\Delta E}{2}}{E_0} \times \frac{\pi}{20} \tag{3}$$

Assuming the vertical displacement of the injected beam is small, the vertical aperture can be calculated from Eq. 4. :

$$A_y(\text{mm} - \text{mrad}) = \beta_y (\Delta y')^2, \quad \text{where } \beta_y = 5.949\text{m} \tag{4}$$

In our measurement, the injected beam has the energy of 280.5 MeV and $\Delta E = 4$ MeV. From Eq. 4, the measured vertical aperture is 7.5 mm-mrad, which is 47% of the ideal vertical physical aperture.

Similar to the horizontal aperture, we believe that the measured vertical aperture is limited by the physical aperture due to the orbit distortion, not by the vertical dynamic aperture. From the orbit measurement, the vertical orbit offset in dipoles is about 3 mm. With vacuum chamber opening of 8.5 mm and $\beta_y \approx 4$ m, the estimated vertical physical aperture is about 7.6 mm-mrad.

III. ENERGY APERTURE

A large energy aperture is one of the main design requirements for the Duke storage ring lattice, for it determines the maximum FEL efficiency and the electron beam Touchek life time. As we have seen in the simulation [1], the Duke storage ring is designed to provide a large energy dynamic aperture.

To measure the energy aperture, we utilize the synchrotron oscillation of the stored beam (see Fig. 3). The S-band injection linac (at 2.8 GHz) injects a train of macro pulses separated by 350 ps. The injected macro pulses are captured by the 5.6 ns longitudinal phase space RF buckets of the storage ring. Each RF bucket captures up to 16 macro pulses. The captured beam then circulates in the RF bucket. If the energy dynamic aperture is smaller than the RF energy acceptance, it will cause part of the circulating beam be lost.

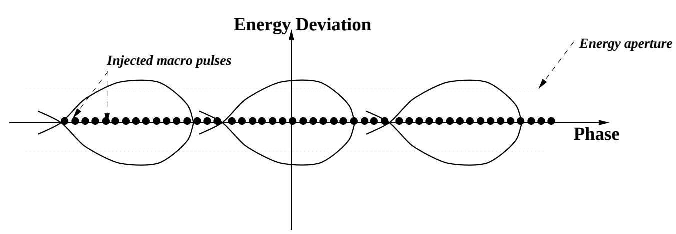

Figure. 3. Energy aperture in the longitudinal phase space.

The energy aperture measurement was performed with a 280.5 MeV beam. We first optimized the transverse orbit and the injection conditions. Then we varied the RF cavity voltage to increase the RF energy acceptance and measured the average captured beam current per shot. The result is plotted vs. the RF cavity voltage in Fig. 4.

At a RF voltage of 50 kV, the average captured beam per shot is slightly lower than the maximum. This is because at this low RF voltage, the separation between two neighboring RF buckets is large, about 230 ps. This separation causes some of the injected S-band macro pulses to miss the RF buckets. With increased RF voltage, the bucket separation decreases and the captured beam current per shot increases. As the RF voltage reaches 250 kV, we observe that the captured beam current per shot falls by about 9% from the maximum value. It indicates that more than one injected macro pulse is lost due to the loss at the energy aperture

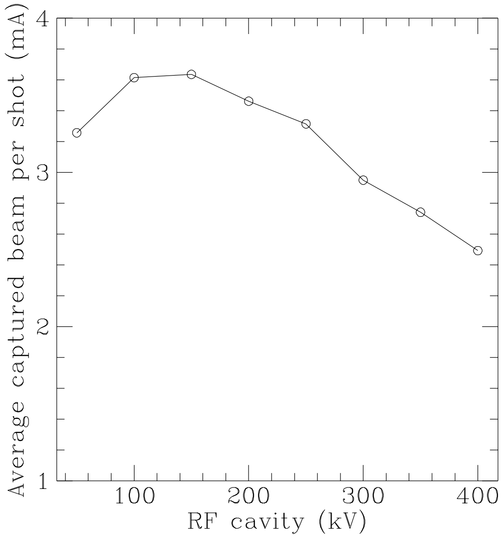

Figure. 4. Measurement on the captured beam per shot at 280.5 MeV.

at the extrema of the macro pulses synchrotron motion. This limitation corresponds to a 3.3% energy aperture.

The measured energy aperture of 3.3% is smaller than the available RF acceptance and the calculated energy dynamic aperture. However the energy aperture depends on the closed orbit and the physical limitation of the vacuum chambers. With improved closed orbit, larger energy aperture is expected.

IV. CONCLUSION AND FUTRUE WORK

From the above measurements, we can conclude that the horizontal dynamic aperture is larger than 43 mm-mrad, the vertical dynamic aperture is larger than 7.5 mm-mrad, and the energy dynamic aperture is larger than 3.3%. These measurements have confirmed that the Duke storage ring does have a large 6-D aperture as designed. The large aperture has helped to speed up the commissioning process and will certainly facilitate FEL operations in the future.

Due to the lack of the beam position monitors (BPMs) electronics, the closed orbit was not optimized during commissioning. The existing closed orbit distortion has limited the physical aperture, thus the measured aperture. In the future, we will improve the closed orbit with the help of BPMs, and experiments will be repeated to verify that the dynamic aperture is not the limiting factor to the available aperture.

V. ACKNOWELEDGEMENTS

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