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OPTICS STUDIES ON THE OPERATION OF A NEW WIGGLER AND BUNCH SHORTENING AT THE DELTA STORAGE RING*

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Abstract

The 1.5-GeV electron storage ring DELTA is a synchrotron light source operated by the TU Dortmund University. Radiation from hard X-rays to the THz regime is provided by dipole magnets and insertion devices like undulators and wigglers. To provide even shorter wavelengths, a new 22-pole superconducting 7-T wiggler has been installed. The edge focusing of the wiggler has a large impact on the linear optics of the storage ring. Measurements regarding its influence and simulations were performed. In addition, a second radiofrequency (RF) cavity has been installed to compensate the increased energy loss per turn due to the new wiggler. As a consequence of the higher RF power, the electron bunches are shorter compared to the old setup with only one cavity. In view of reducing the bunch length even more, studies of the storage ring optics with reduced momentum compaction factor were performed.

THE DELTA STORAGE RING

DELTA is a 1.5-GeV storage ring operated by the TU Dortmund University providing synchrotron radiation in user operation at eight beamlines. Three beamlines are served by dipole magnets, one is served by a permanent magnet undulator (U55), one is served by an electromagnetic undulator (U250) and a superconducting wiggler serves three beamlines at the same time. The main parameters of the storage ring are listed in Table 1.

Table 1: Main Parameters of the DELTA Storage Ring

Beam energy	1.5 GeV
Circumference	115.2 m
Beam current (single-/multibunch)	20/130 mA
Horizontal emittance	18 nm rad
Relative energy spread	7×10^{-4}
Typical bunch length (FWHM)	100 ps

A NEW 7-T SUPERCONDUCTING WIGGLER

The more than 20-years old superconducting wiggler was replaced in 2020 by a new 7-T device which was built by the Budker Institute for Nuclear Physics in Novosibirsk [1]. The old wiggler had two operation modes [2], a symmetric mode with a sinusoidal field distribution, 10 periods and a maximum field of 2.69 T and an asymmetric mode with a more complex field distribution, a reduced number of periods but an increased magnetic field up to 5.3 T. The new superconducting wiggler has a maximum field of 7 T and 9 periods [3]. In contrast to the old wiggler, the helium consumption is almost zero. The main parameters of the wigglers are listed in the Table 2.

Table 2: Main Parameters of the Old (Symm. and Asymm. Mode) and the New 7-T Wiggler

Parameter	**Symm.**	**Asymm.**	**New**
Maximum peak field (T)	2.69	5.3	7.0
Period length (cm)	14.4	28.8	12.7
Periods	10	5	9
Maximum K-value	36	149	83
Critical photon energy (keV)	4.1	7.9	10.5
Helium consumption (l/week)	130		0

Influence on the Linear Optics

Assuming the wiggler to be a sequence of dipole magnets, the edge focusing which leads to a tune shift in the vertical plane can be estimated as [4]

$$\Delta\nu_y = \frac{\pi L K^2 \langle\beta_y\rangle}{2\lambda_w^2\gamma^2} \propto B^2 \tag{1}$$

with the length of the wiggler L, the undulator parameter K, the mean vertical beta function at the position of the wiggler $\langle\beta_y\rangle$, the period length λ_w and the Lorentz factor γ. Since the wiggler is not placed in a symmetry point of the ring, it also causes an asymmetry of the vertical beta function.

The vertical tune shift $\Delta\nu_y$ as function of the magnetic field B was calculated using the optics code *elegant* [5] and was determined experimentally by measuring the tune while increasing the magnetic field of the wiggler. The results are shown in Fig. 1.

In the model, no periodic solution was found without adjusting quadrupole strengths above a wiggler field of 6.5 T and in the measurement the beam was lost at the half-integer resonance between 6.5 T and 7 T. The difference between the measurement and the model might be explained by deviations of the design lattice and the real magnet configuration.

Compensation of the Impact on the Linear Optics

For operation at 7 T, the influence of the wiggler should be compensated locally around the wiggler to avoid influencing the source points of the other beamlines. The strategy consists of two steps: (i) lower the vertical beta function at the position of the wiggler by adjusting the quadrupole

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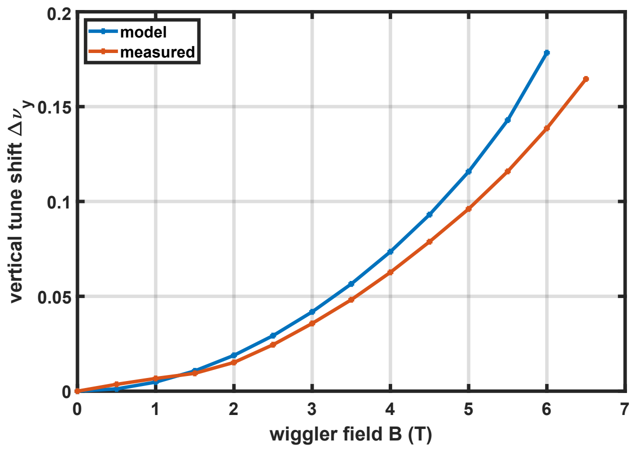

Figure 1: Vertical tune shift $\Delta\nu_y$ as function of the wiggler field B without any compensation. The tune shift given by the optics model is shown in blue, the measured tune shift in red.

strength upstream to reduce the effect, (ii) compensate the residual vertical focusing using quadrupoles downstream of the wiggler. The result of an optimization using the optics code *elegant* is shown in Fig. 2.

The simulation indicates that it is possible to compensate the effect of the wiggler on the linear optics with quadrupoles around the wiggler and keep the optics in most of the ring the same.

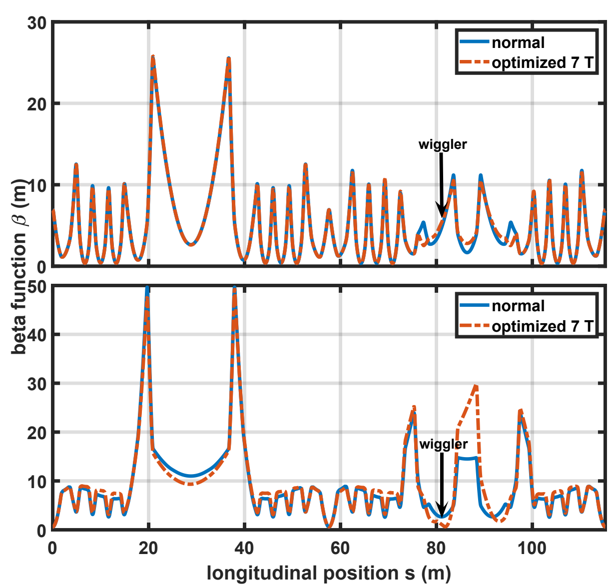

Figure 2: Horizontal (top) and vertical (bottom) beta function β as function of the longitudinal position s without wiggler (blue) and optimized at 7 T (red).

BUNCH LENGTH MEASUREMENTS

The bunch length in a storage ring is given by [6]

$$\sigma_z = \frac{\alpha_c}{2\pi f_s}\sigma_E \propto \sqrt{\frac{\alpha_c}{U_0}} \tag{2}$$

with the momentum compaction factor α_c, the synchrotron frequency f_s and the energy spread σ_E. The bunch length can either be reduced by increasing the radiofrequency (RF) voltage U_0 or by reducing the momentum compaction factor. In order to compensate the additional energy loss per turn induced by the new superconducting wiggler, a second cavity was installed in 2019 [7]. While the old DORIS-type cavity [8] is powered by a klystron, a 75-kW solid-state amplifier was installed for the new EU-type HOM-damped cavity [9].

Bunch Length as Function of the RF Voltage

The bunch length as function of the RF voltage was measured in two different ways, (i) directly using a streak camera [10], (ii) indirectly by measuring the synchrotron frequency with a bunch-by-bunch feedback system [11] and then calculating the bunch length using model values for the momentum compaction factor and the energy spread. The results are shown in Fig. 3.

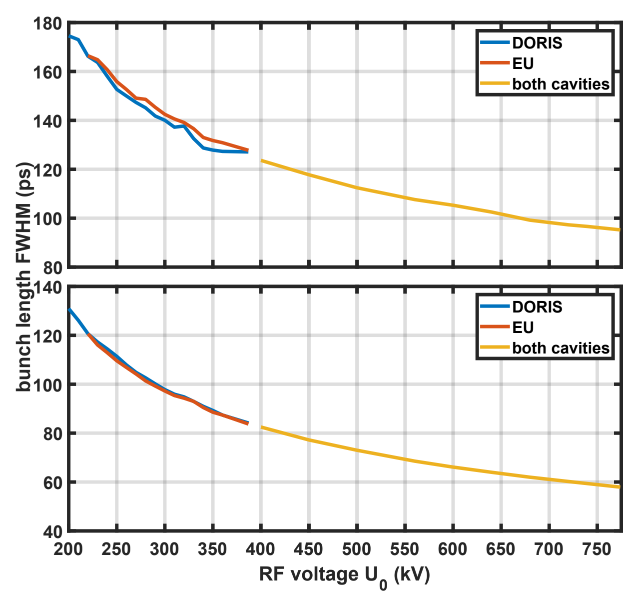

Figure 3: FWHM bunch length measured by a streak camera (top) and deduced from the synchrotron frequency (bottom) as function of the RF voltage U_0. Data are shown for operating only the DORIS cavity (blue), only the EU cavity (red) and both (yellow).

The discrepancy between the two measurement methods might be explained by uncertainties of the model values and timing jitter in the streak camera measurement. Both measurements show a reduction of the bunch length between 25% and 30% comparing the operation of just one cavity with the now standard operation of both resonators. Further

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shortening the bunch length is possible when the new cavity is entirely conditioned and the full power can be applied.

Bunch Length as Function of the Momentum Compaction Factor

In order to reduce the bunch length and to establish a low-alpha operation mode at DELTA, an initial test was performed. A new optics to reduce the momentum compaction factor was simulated using *elegant* and first attempts to implement this optics at the storage ring were made.

For a first test, the optimization was performed without considering the transverse beam size, and the horizontal emittance was increased by a factor of 5. The main parameters of this optics are listed together with the parameters for normal operation in Table 3.

Table 3: Main Parameters of a Optics with Reduced Momentum Compaction Factor

Parameter	**Normal**	**Lower-Alpha**
Horizontal tune	9.30	9.16
Vertical tune	3.23	3.19
Momentum comp. factor	4.8×10^{-3}	1.5×10^{-3}
Relative energy spread	7×10^{-4}	7×10^{-4}
Horizontal emittance	18 nm rad	100 nm rad

The setting with reduced momentum compaction factor was adjusted in a stepwise approach from the standard optics, while the bunch length was measured. The momentum compaction factor was calculated from the measured synchrotron frequency and the bunch length was determined with a streak camera. The results are shown in Fig. 4.

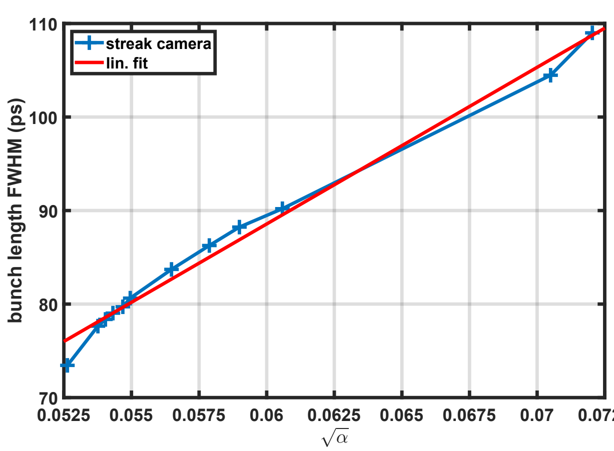

Figure 4: FWHM bunch length measured by streak camera (blue) versus square root of the momentum compaction factor α_c and linear fit to the data (red).

A bunch length reduction of about 30% was achieved but the designed optics were not reached due to beam losses, the cause of which still needs to be investigated.

CONCLUSION

A new superconducting wiggler was installed at the DELTA storage ring and the induced tune shift was measured. Optics simulations with *elegant* indicate that a local compensation of the vertical focusing is possible allowing to maintain the previous beta function at the source points of the other beamlines. Furthermore, a second RF cavity with a 75-kW solid-state amplifier is in operation and bunch length measurements as function of the RF voltage were performed. A first test for an operation with reduced momentum compaction factor has taken place.

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