A CLIC DAMPING WIGGLER PROTOTYPE AT ANKA: COMMISSIONING AND PREPARATIONS FOR A BEAM DYNAMICS EXPERIMENTAL PROGRAM*

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Abstract

In a collaboration between CERN, BINP and KIT a prototype of a superconducting damping wiggler for the CLIC damping rings has been installed at the ANKA synchrotron light source.

On the one hand, the foreseen experimental program aims at validating the technical design of the wiggler, particularly the conduction cooling concept applied in its cryostat design, in a long-term study.

On the other hand, the wiggler's influence on the beam dynamics particularly in the presence of collective effects is planned to be investigated. ANKA's low-alpha short-bunch operation mode will serve as a model system for these studies on collective effects. To simulate these effects and to make verifiable predictions an accurate model of the ANKA storage ring in low-alpha mode, including the insertion devices is under parallel development.

This contribution reports on the first operational experience with the CLIC damping wiggler prototype in the ANKA storage ring and steps towards the planned advanced experimental program with this device.

INTRODUCTION

With the successful commissioning of a superconducting damping wiggler prototype in the ANKA storage ring in February 2016, a major milestone in the validation of key technologies for the CLIC damping rings has been reached.

The target luminosity of the proposed multi-TeV linear e^+-e^- collider CLIC [1] requires an ultra-low emittance of the electron and positron beams injected into the main LINAC with a fast repitition rate of 50 Hz. That will be achieved through radiation damping in the CLIC damping rings [2], which to this end will be equipped with about 100 m of superconducting wigglers installed in the long straights of the racetrack-shaped rings.

The experimental test of a CLIC damping wiggler prototype at ANKA is part of the international R&D program on experimentally validating key technologies for CLIC that was initiated with the release of the CLIC Conceptual Design Report. The prototype was jointly specified by CERN and KIT and designed and manufactured by BINP.

* This work was partially supported by the German Ministry for Education and Research under contract no. 05K12VK1

On the side of the wiggler's basic magnetic parameters, the design goals of the CLIC damping rings favor high magnetic flux density amplitudes in a period length range of 50 mm to 60 mm [3]. Two technological routes are followed in the R&D on the CLIC damping wigglers: the established Nb-Ti-superconductor technology providing flux density amplitudes in the range of 2.5 T to 3.5 T in the target period length range, and the technically more challenging Nb_3Sn technology giving access to the 3.5 T to 4 T-range [4]. The prototype now tested at ANKA represents the Nb-Ti baseline design.

The objectives for the study are implied by the need for an experimental verification of the assumptions forming the basis of the CLIC damping ring design. In the following section we describe these objectives and the results achieved so far.

OBJECTIVES AND RESULTS

Modular Design

The R&D program for the CLIC damping wigglers foresees tests of beam vacuum chambers with different surfaces or surface coatings (Cu, NEG, amorphous carbon) and possibly different geometries as well as two different magnet technologies. These studies are enabled by a modular cryostat design employing indirect cooling of the magnet and the beam pipe, independently. It was demonstrated during the offline tests that magnet and beam pipe can be accessed and exchanged with about two weeks effort, including warm-up and cool-down.

Cryogenic System and Quench Performance

The cryostat design of the CLIC damping wiggler prototype adopts a concept successfully tested with the superconducting undulator at APS [5]. The magnet is conduction-cooled through plate heat exchangers connected to thermosiphon pipes. A closed two-phase Helium cycle is realized using an internal liquid Helium reservoir equipped with cryocoolers for recondensation. The beam pipe is thermally insulated from the magnet and cooled independently by a second pair of cryocoolers [6].

The main magnet parameters are summarized in Table 1. The magnet consists of horizontal racetrack coils wound in two independently powered sections (inner and outer) around

Table 1: Principle Wiggler Parameters

Period length	[mm]	51.4
Number of main poles		68
Magnetic pole gap	[mm]	17
On-axis field amplitude	[T]	2.9

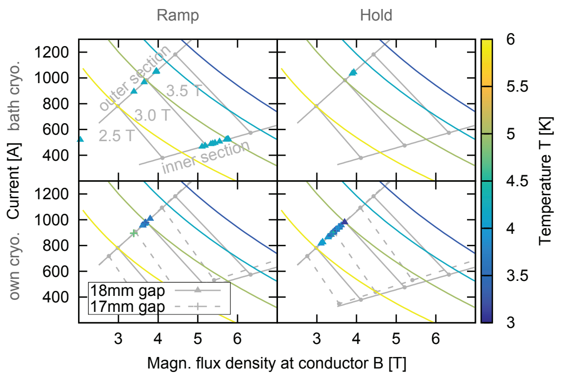

Figure 1: Quenches of the wiggler marked on the load lines of inner and outer coil sections during current ramps (left) and at constant current (right), in liquid Helium bath (top) and in own cryostat (bottom). Each point marks a quench, color-coded according to the temperature immediately before the quench. The colored lines represent the critical condition for different temperature levels, the labelled gray lines depict the corresponding on-axis field for the original (18 mm gap) and the final (17 mm gap) magnet configuration, respectively.

soft magnetic steel poles which are thermally linked to the plate heat exchanger. The coil sections are electrically interconnected through low-resistance cold-weld splices. Each of these about 400 splices is additionally thermally linked to the plate heat exchanger.

The continuous recondensation of Helium vapor leads to an under-pressure inside the Helium tank and in turn to under-cooling of the liquid Helium. Therefore, in equilibrium conditions, the magnet reaches temperatures around 3 K, even during beam operation (cf. Fig. 2). However, the maximum stable current reached in the magnet coils turned out to be lower than expected from the magnet tests performed in a liquid Helium bath [6]. Figure 1 summarizes the quenches of the magnet. The maximum on-axis field amplitude reached during ramping was 3.2 T, both in the bath cryostat and in the wiggler's own cryostat. In the case of indirect cooling, however, holding quenches occur after periods of seconds to several hours in the outer, high current coil sections and basically uncorrelated with the magnet temperature. The physical origin of this instability is not yet satisfactorily explained. The stable field is limited to 2.9 T by this effect, however, the wiggler can routinely be operated at this field level also in the storage ring under beam operation conditions, as shown in Fig. 2.

The main effect of operating the wiggler in a storage ring — and particularly in the CLIC damping rings — is the deposition of heat on the cold beam pipe. In the damping rings the dominating heat source is expected to be the synchrotron radiation emitted by the upstream wigglers. Depending on the absorber scheme and the beam pipe geometry, the heat deposited on the beam pipe can reach up to 50 W [3]. In normal operation conditions at ANKA the total beam-induced heat load is not exceeding 4 W [7]. To simulate the heat load expected in the CLIC damping rings, the beam pipe is equipped with resistive heaters placed upstream and downstream of the magnet. Figure 3 shows the beam pipe and magnet temperatures as a function of time during an experiment with these heaters. The last configuration chosen with 50 W applied downstream represents the worst case scenario for the damping rings. The wiggler is operable at full field also under these conditions, albeit the ramp speed needs to be reduced to avoid additional eddy current heating. The normal operation conditions at ANKA are much less challenging. Figure 2 shows the magnet and beam pipe temperatures together with the operation parameters of the storage ring in a typical week of ANKA user operation with regular operation of the CLIC wiggler at full field.

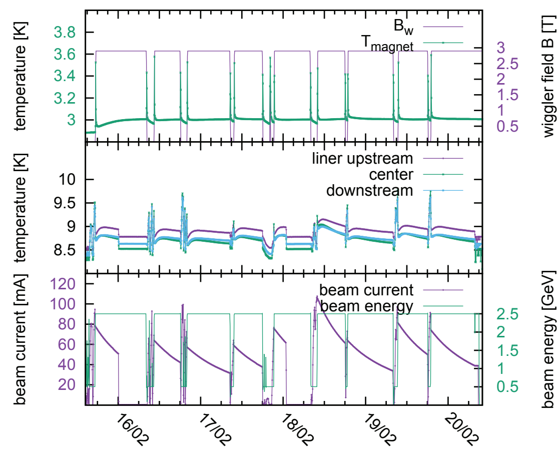

Figure 2: Magnet and beam pipe temperatures during a typical week of ANKA user operation.

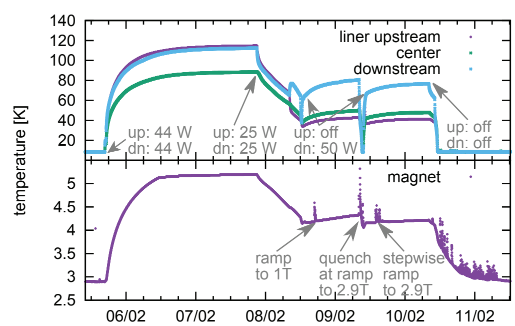

Figure 3: Beam pipe and magnet temperatures during a heat load test using resistive heaters attached to the beam pipe upstream (up) and downstream (dn) of the magnet.

ISBN 978-3-95450-147-2

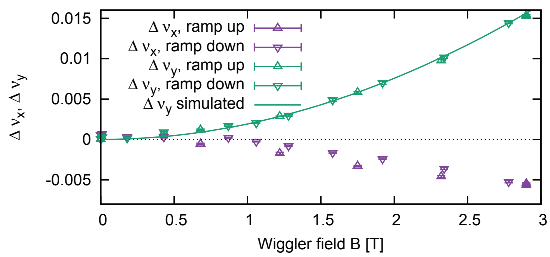

Figure 4: Horizontal and vertical tune shift as a function of wiggler field.

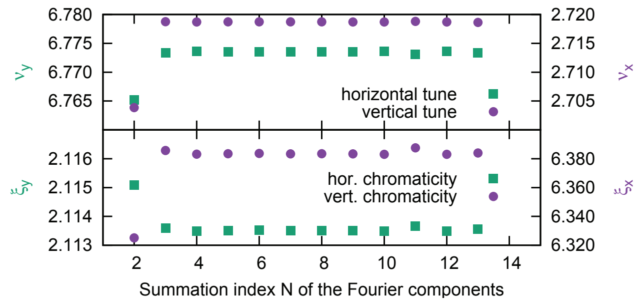

Figure 5: Tune and chromaticity simulations using the ANKA model and Fourier sum representations of the CLIC wiggler's FEM model field with the maximum N of the summation index n.

Linear Beam Dynamics

The first basic experiments on beam dynamics focused on the wiggler's influence on the closed orbit and betatron tunes in order to confirm the field integral compensation settings, the alignment of the wiggler and the results of the offline magnetic characterization.

Before the installation in the storage ring the field integrals of the wiggler were measured with a stretched wire set-up and minimized by adjusting the current distribution in the wiggler's matching coils. A quite significant horizontal field integral was corrected by additional vertical corrector magnets outside the cryostat. From the closed-orbit measurements a slight readjustment of the field integral compensation settings turned out to be necessary.

The betatron tune shifts in the vertical and horizontal plane as a function of wiggler field are shown in Fig. 4. The shift due to the vertical focusing strength of the wiggler agrees with the model calculations. The origin of the (unexpected) horizontal tune shift is still a matter of investigation.

FURTHER EXPERIMENTAL PROGRAM

The central question motivating advanced beam dynamics experiments with the CLIC damping wiggler in the ANKA storage ring is: how reliably can model predictions be made for the beam dynamics in the CLIC damping rings which are dominated (a) by collective effects and (b) by a large number of high-field insertion devices. The low-α_c mode of ANKA will serve as a test case for studying and benchmarking the tools for simulating the beam dynamics in presence of strong collective effects and under the influence of a high-field wiggler, but also for developing instrumentation and methods for determining the associated beam properties and their temporal behavior. A necessary step in preparation of these investigations is to develop a well-founded understanding of the linear and non-linear effects of the wiggler on the ANKA beam dynamics in standard operation mode. Accurate modelling of the storage ring lattice and the wiggler play a key role in this respect.

To simulate the beam dynamics inside ANKA we use `elegant` [8]. The storage ring model is based on known physical properties of the lattice [9] with an additional fit to orbit response matrix measurements using higher order parameters. Using this physical model facilitates the necessary scaling of magnet strengths and beam energy for modelling the low-α_c optics.

The correct modelling of the wigglers is of particular importance for the intended studies. We apply the canonical wiggler model by Wu et al. [10] which is implemented in `elegant` and uses a Fourier representation of the wiggler field in the form

$$B_y = \sum_{m,n} C_{m,n} \cos(mk_x x) \cos(nk_z z) \cosh(k_{y,mn} y). \quad (1)$$

In this way realistic — simulated or measured — field profiles can be represented.

The FFT-based procedures to determine the Fourier coefficients described in [11] in our case turned out to be numerically unstable and lead to wrong model predictions. We therefore followed the approach of fitting the Fourier sum of lowest possible order to the simulated or measured data, additionally postulating the Maxwell conformity condition $k_y = n^2k_z^2 + m^2k_x^2$ [11]. In this way the number of fit parameters is largely reduced and the stability of the simulations at the same time increased. Figure 5 shows the vertical and horizontal tune as a function of Fourier components taken into account in the wiggler model, resulting from tracking simulations using our ANKA model and the according Fourier fit to the field data for the wiggler. As it turns out for the FEM-modelled field data, it is sufficient to take into account Fourier summands up to an order of $N = 4$.

CONCLUSIONS

A prototype for the superconducting CLIC damping wigglers has successfully been installed and commissioned in the ANKA storage ring. This device is the first full-scale superconducting wiggler featuring an indirect cooling scheme based on liquid Helium flow. The complete system proved efficient and reliable under normal operation conditions in the storage ring as well as under additionally applied heat load in the order expected in the CLIC damping rings.

Starting from basic experiments on the wiggler's influence on the linear beam dynamics in the ANKA storage ring, experimental and modelling techniques are under development which allow to experimentally benchmark the model assumptions for the CLIC damping rings.

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ISBN 978-3-95450-147-2