



Magnetic measurements with the FLASH infrared undulator

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ARTICLE INFO

Article history:

Received 30 September 2009

Received in revised form

1 December 2009

Accepted 3 December 2009

Available online 29 January 2010

Keywords:

FEL

Undulator

Infrared radiation

ABSTRACT

The FLASH free-electron laser at DESY, Hamburg, has been equipped with an infrared electromagnetic undulator which provides radiation in the mid- and far-infrared range. It will be used both for electron beam diagnostic purposes and as a powerful radiation source synchronized to the VUV and soft X-ray pulses of the FEL. This paper summarizes the undulator construction, the main design features, and the magnetic measurements undertaken to verify the device performance prior to installation.

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1. Introduction

The FLASH free-electron laser at the Deutsches Elektronen-Synchrotron (DESY), Hamburg, is a running user facility providing radiation in the vacuum-ultraviolet and soft X-ray range [1,2]. It has been equipped in 2007 with an infrared electromagnetic undulator, tunable over a K-parameter range from 1 to 44, producing radiation up to 200 μm at 500 MeV and up to 50 μm at 1 GeV [3,4]. The purpose of the device is two-fold. First, it will complement the ongoing intensive program of longitudinal electron beam diagnostics with coherent radiation [5], allowing a new approach due to the comparatively narrow-band nature of the radiation. So far, broad-band synchrotron and transition radiation has been employed. Second, it will be a powerful source of intensive infrared radiation naturally synchronized to the FEL pulses, as both are generated by the same electron bunches. This is therefore well suited for precision pump-probe experiments [6].

The undulator was manufactured by the Joint Institute for Nuclear Research (JINR) in Dubna. The design was closely adapted to the installation requirements in the FLASH tunnel. Initial functioning tests and characterizations were undertaken at JINR, followed by more extensive measurements at DESY. Fig. 1 shows the infrared undulator installed in the FLASH tunnel. In the meantime, the device has been fully commissioned.

A summary of the main design features and key measurement results will be presented in this paper. The construction is described in Section 2, the basic field tuning in Section 3, and the final fine tuning, field mapping and transient studies in Section 4. A detailed report covering all measurements can be found in Ref. [7].

2. Undulator construction

The undulator is a planar electromagnetic device with 9 full periods, each 40 cm long, and 44 coils. The main design parameters are listed in Table 1. Transverse and longitudinal control arms underneath the base allow for a precise alignment of the horizontal position, vertical lift is provided by coarse-thread screws.

2.1. Yokes

A maximum field of 11 kG is required to reach the long wavelengths which are required by both applications. A yoke thickness of about 250 mm would have been required to stay in the non-saturated regime. Due to restrictions on weight and power consumption, the yoke thickness had to be limited to 150 mm, resulting in a strongly saturated steel yoke with induction values of 19–21 kG [8].

The undulator yoke is made of two ferromagnetic girders of plain low-carbon steel, type AISI/SAE 1010. The poles are milled to 50 μm precision, each is 100 mm wide. The yokes are supported

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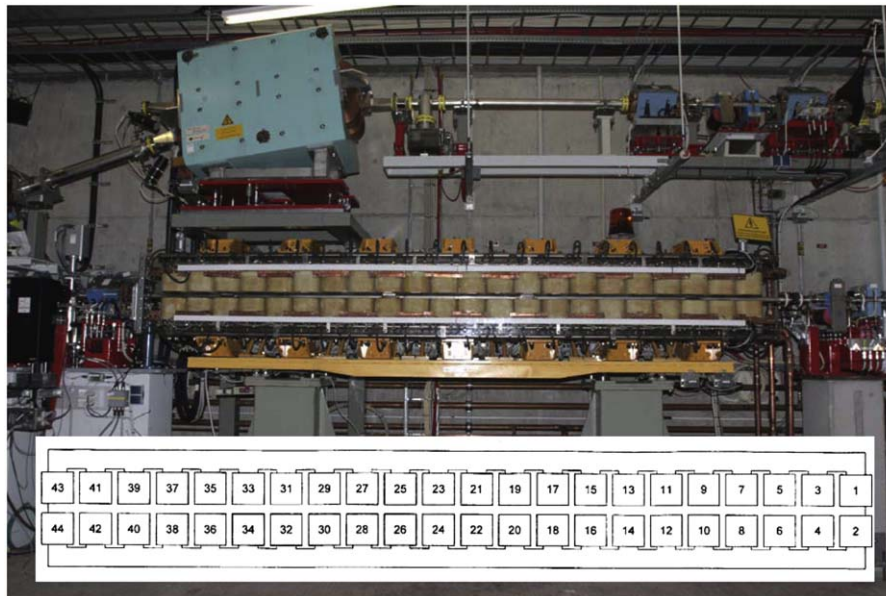


Fig. 1. The infrared undulator installed in the FLASH tunnel. Beam enters from the right. Immediately to the left (outside of the picture) is the dump magnet, separating the electron beam from the VUV and infrared radiation. Above the undulator is the electron beam bypass that puts a limit on the vertical size of the device. The numbering of the 44 poles is illustrated. A pole pair as referenced in the text consists of one top and one bottom coil.

Table 1
Design parameters of the electromagnetic infrared undulator.

Gap	40 mm
Period length	400 mm
Pole length/width	100/140 mm
Number of full periods	9
Number of poles	44
End termination pattern	+1/8, -1/2, +1, ..., -1, +1/2, -1/8
Iron yoke length	4.3 m
Maximum field/K-value	12 kG/49
Number of turns of central main coils	64
Conductor cross-section	$8.5 \times 8.5 \text{ mm}^2$, $\varnothing 5.3 \text{ mm}$ bore
Maximum current density	8.7 A/mm^2
First/second field integral	$< 200 \text{ G cm}$, $< 20 \text{ kG cm}^2$
Maximum magnetic force	237 kN
Cooling water flow	100 l/min
Water temperature rise at 435 A	20 °C
Maximum temperature gradient (water cut-off)	0.4 °C/s
Maximum current	435 A
Voltage at 435 A	208 V
Maximum total power	87 kW
Total weight	4490 kg

by a C-shaped frame made from non-magnetic steel, keeping the variation of the undulator gap by magnetic forces below $20 \mu\text{m}$. Alignment marks are mounted on the top yoke.

The excitation coils are wound around the poles. All 44 coils of top and bottom girders are connected in series and powered by a single supply. The first two pole pairs at both ends have different numbers of conductor turns to facilitate end termination.

2.2. Central main coils

The central pole pairs 3–20 have coils consisting of four layers of 16 turns each. The windings are made of square copper pipe with $8.5 \times 8.5 \text{ mm}^2$ cross-section and a cooling channel of 5.3 mm diameter (conductor cross-section 50 mm^2). At the maximum coil current of 435 A, the current density is 8.7 A/mm^2 and the power dissipated by one regular undulator period (four coils) is 2.5 kW.

The insulation thickness between windings is 0.8–1.0 mm. Each coil has a correction winding of 270 turns (wire diameter 1 mm, resistance 4.1Ω), providing the option to tune the Ampere-turns up to 2% of the maximum value. This allows to compensate perturbations of the magnetic field related to imperfections of the magnetic system. The correction windings are isolated by a double coating with heat-resistant enamel.

2.3. End coils

The first and last pair of coils have 1/8 of the turns of the central main coils (1 conductor layer, 8 turns), the second and second to last 1/2 (3 conductor layers, 32 turns). This allows a first-order field integral compensation with a minimal corrector coil current in a wide magnetic field range. The end coils are made of the same conductor material as the main coils and are powered in series with them. The turn ratio does not correspond to the usual ratio of 1/4 and 3/4, as this would result in a more difficult field integral compensation due to the oversaturation of the yoke at high excitation currents. For the chosen ratio, minimal currents in the correctors are required at 300 A excitation.

The correction windings for the end coils are made from 212 turns of copper wire of 2.5 mm diameter, with a maximum allowable current of 15 A. The correction winding of the first pole pair can provide a field correction of up to 60%, the winding on the second pole pair of up to 18% of the nominal maximum field.

Due to the oversaturated magnetic field in the yoke at high excitation, the field in the centre of the undulator gap depends on the individual position of each coil. Therefore, these can be adjusted mechanically in the vertical direction within 1 mm to compensate positioning errors.

2.4. Circuits

The electric scheme of the correction coil circuits allows short-circuiting (disabling) and reversing individual coil pairs, variable resistors provide a fine tuning of the relative strengths of the correction coils. These degrees of freedom, which are not remotely

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