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Development of cryogenically cooled permanent magnet undulators for PETRA IV

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Abstract. Cryogenically cooled permanent magnet undulators (CPMUs) are an improvement of the in-vacuum undulators (IVUs) which are widely used at various synchrotron radiation facilities and free-electron lasers in order to improve the photon flux towards shorter wavelengths. Especially beamlines with the need for high energy photons will benefit from shorter period insertion devices (IDs). For the planned ultra-low emittance photon source PETRA IV at Deutsches Elektronen-Synchrotron (DESY), we are designing CPMUs with a hybrid magnet structure based on PrFeB magnet material. First prototyping was done on magnet keepers and the pole-tuning mechanism. In addition, options for force-compensation are assessed. Crucial components are the link rods connecting the in-vacuum girders with load bearing out-of-vacuum girders. Simulations on the impact of their arrangement on the bending of the magnet structure and their thermal behaviour are presented.

1. Introduction

CPMUs exploit the strongly enhanced coercivity and improved remanence of permanent magnet material at liquid nitrogen temperatures to push the performance of IVUs even further [1]. The technique can be regarded as mature, since several of these devices are successfully being operated at facilities around the world. For the planned upgrade of the currently operating storage ring PETRA III at DESY into the ultra-low emittance photon source PETRA IV it is also planned to implement this advanced undulator scheme for some beamlines. The current H6BA cell design for the PETRA IV lattice will allow for insertion devices of up to 4.3 m length in the standard straight sections. For CPMUs the taper sections, interfacing the in-vacuum magnet structure and the vacuum system of the storage ring, will reduce available magnetic length considerably. Currently we are aiming for 3.8 m long magnet structures for the CPMUs.

2. Magnet girder bending and link-rod arrangement

For IVUs, the space restrictions inside the vacuum chamber require a slim and compact design of the magnet girders. Hence, attracting magnetic forces of up to several 10 kN will cause a bending of the magnet structure and thus a variation of the magnetic gap. Since these forces are not static but will vary with the operating gap of the undulator, they cannot be compensated during tuning of the device. Besides force compensation there are several other options for minimising the bending of the in-vacuum girders, e.g. the choice of material and their cross section. Also, the number and the arrangement of the link-rods to the load bearing out-of-vacuum girders play an important role.

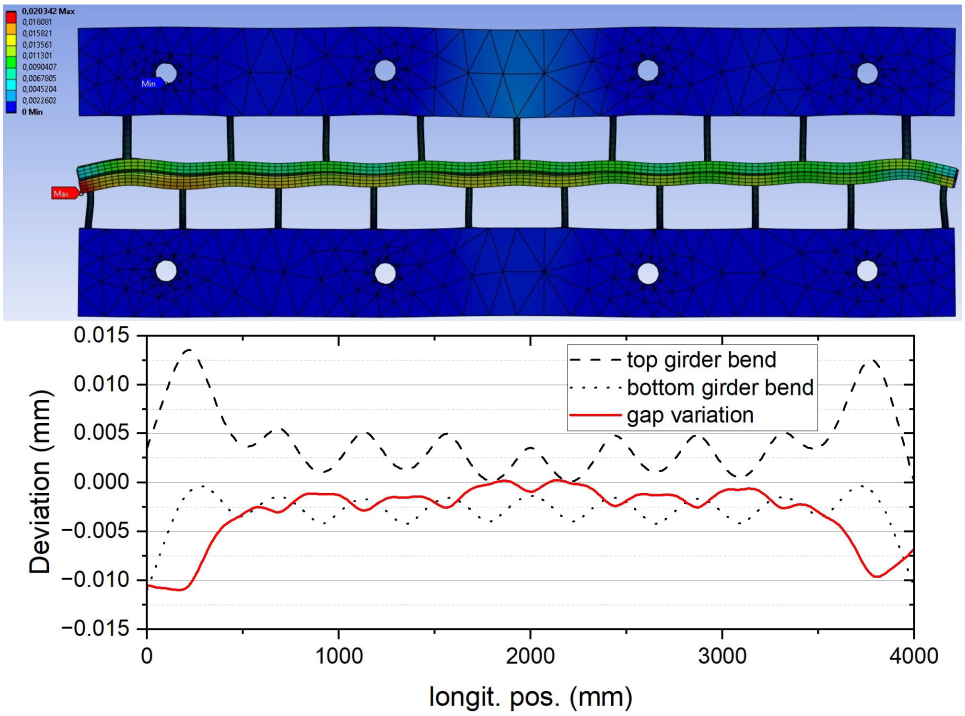

Figure 1. The top picture shows a finite element analysis of the expected girder bending for a 4m long magnet structure and asymmetric arrangement of link-rods. In the bottom graph, the expected gap variation resulting from this bending is shown. The link-rod stiffness and position at the girder ends still needs to be optimised.

2.1 Link-rod arrangement

In contrast to the usual symmetric link-rod arrangement for upper and lower girder we are planning to use a staggered arrangement as sketched in figure 1. Such an arrangement was proposed e.g. by T. Schmidt et al. in [2]. It will cause an in-phase bending of top and bottom girder with an effective gap variation along the magnet structure which is considerably lower than the bending amplitude of the individual girders. The expected resulting negative impact on the r.m.s. phase error of the undulator is reduced thereby from 4° to 2.5°.

In order to mitigate an excessive bending of the individual girders at their ends, reinforced link-rods had to be implemented at these positions. Otherwise, this bending of the girder ends would have a much more severe negative impact on the phase error than what was gained from the staggered arrangement. Moreover, the staggered arrangement of connections to the load bearing support does not grant a common longitudinal position for the top and bottom girder, which may be defined as a fixpoint while the girders are shrinking during the cooldown process. Nevertheless, there is need for further improvement of the phase error. One potential measure would be the implementation of a magnetic force compensation.

2.2 Magnetic force compensation

During gap movements, the magnetic forces between upper and lower girder are changing accordingly. These dynamic load changes account considerably for the phase error, spoiling the performance of the ID. Thus, several approaches for compensating these magnetic forces have been considered. In their design of an in-vacuum wiggler for example, SOLEIL implemented a set of spiral springs on both sides of the magnets along the entire structure [3]. This however limits

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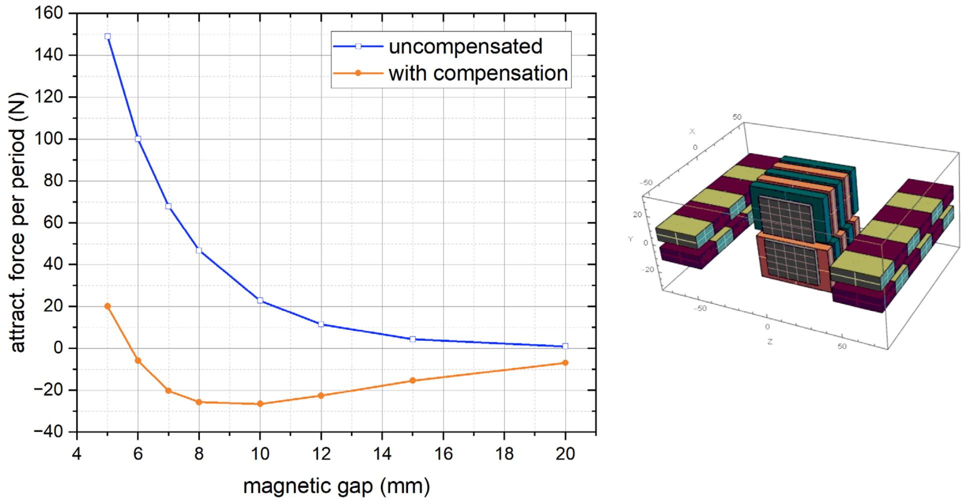

Figure 2. Attractive magnetic forces per undulator period for the plain CPMU magnet structure (blue graph) and including an additional pure permanent magnet structure (orange graph), which has twice the period length. (see sketch on the right)

the lateral access to the magnet structure and is not compatible with the intended use of a conventional Hall-probe setup for magnetic measurements.

Therefore, for the PETRA IV CPMUs, we favour a solution implemented for example on an IVU at SPring-8 [4]. A preliminary design of the magnet structure, which features additional rows of repulsive magnets along the main structure can be seen in the right inset of figure 2. The graph in this figure shows the expected force compensation from this arrangement. Since the repulsing structures are a pure permanent magnet desing in contrast to the attracting hybrid main structure, the forces cannot cancel out completely. Nevertheless, we expect a reduction of the attracting forces by approximately a factor of 5, which also reduces the load on the outer mechanics and thus allows for a more compact design.

3. Thermal behaviour of link-rods

We are aiming for operating the PETRA IV CPMUs with PrFeB based magnet structures close to the boiling temperature of liquid nitrogen at around 80 K. At smaller temperatures, there is still an improvement in magnetic performance to be expected, but it would require a considerably higher cooling effort. Since there already is a liquid nitrogen distribution infrastructure planned for the monochromators at the beamlines, it is planned to use the same also for operating the CPMUs. Commercially available closed loop liquid nitrogen cryocoolers with a primary circuit phase-separated from the evaporation circuit have proven to be reliable and economic solution.

Chavanne et al. have estimated, that a thermal gradient of less than 0.5 K/m is required to achieve an r.m.s. phase error of less than 2.5° [5]. Thus, a careful design of the cooling channels at or in the magnet girders is mandatory. Also, the total heat budget is an important design criterium. The heat transfer via the link-rods between the in-vacuum girders and the load bearing support at ambient temperatures is a substantial contribution to the required cooling power. Simulations have shown, that the heat transfer can be reduced nearly by a factor of 3 from 6.2 W/rod to 2.1 W/rod when using a tubular design made from titanium instead of conventional steel connectors.

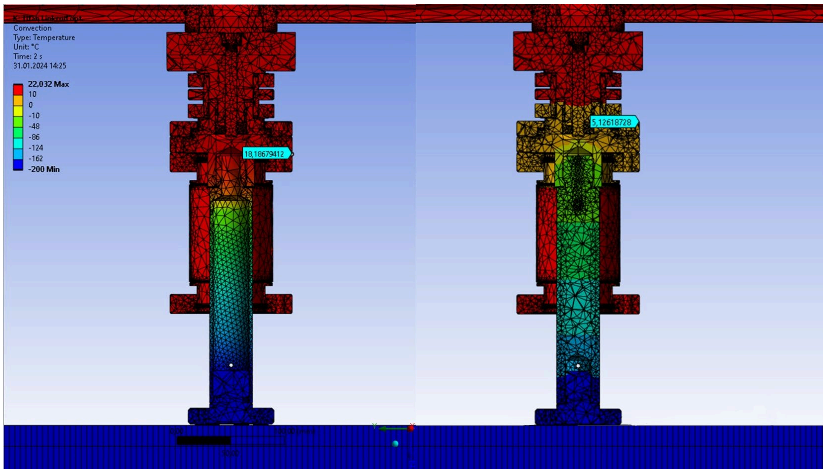

Figure 3. Comparison of thermal gradient simulations for a hollow titanium link-rod on the left and a solid steel link-rod on the right. The expected surface temperatures at the first flange exposed to the ambient atmosphere could be increased by 13 °C.

In addition to the heat budget for the cooling system, another important consideration to be made is potential condensation at components of the CPMU. The air-conditioning in the installation environment will aim for a dew point well above 18 °C. Simulation (see figure 3) have shown that, with the Ti link-rod design mentioned above, temperatures above this threshold can be achieved at the vacuum flanges of the link-rods, even with the in-vacuum girders at -200 °C.

4. Outlook

Currently, a prototype link-rod is being manufactured, in order to verify the thermal simulations experimentally. This will also allow for testing the differential threads implemented in its base for continuous height adjustment in order to correct for long range deviations in the magnetic gap along the structure.

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