CRYOGENIC IN-VACUUM UNDULATOR AT DANFYSIK

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Abstract

Danfysik [1] has built a cryogenic in-vacuum undulator for Diamond Light Source, with a period length of 17.7 mm and an effective K of 1.7 at cryogenic temperatures. The undulator is hybrid-type, with Vanadium Permendur poles and NdFeB magnet blocks. In order to verify the performance of the device under cryogenic conditions, an in-vacuum measuring system is required. We present the magnetic measurements at room temperature and under cryogenic in-vacuum conditions. The magnet assembly cannot be baked, due to a choice of high-remanence, low coercivity magnet grade. We discuss the vacuum performance of the undulator

INTRODUCTION

Danfysik has historically been strong in the planar undulator business, providing end users with both high performance in-vacuum devices as well as regular planar devices for FEL applications [2]. We have also recently successfully completed our first Apple-II type device[3]. As the demand for cryogenic undulators developed, we were keen to accept this challenge, to further expand our undulator portfolio.

Through our technology transfer agreement with the insertion device group at the ESRF, we were able to obtain design assistance, and help with the data acquisition system.

MAGNETIC DESIGN

The magnetic design has been carried out using RADIA[4]. To achieve the required field of 1.04 T at 5 mm gap, at 150 K, the poles are made 33 mm wide, with a 4x4 mm chamfer towards the gap. The magnet blocks are made from NdFeB with a minimum remanence of 1.30 T. By assuming an increase in the remanence of 8-10 %, the suggested design will yield a K value of 1.7 at 150 K, at a magnetic gap of 5 mm. We designed the undulator at an average magnetic gap, to allow for gap loss due to shimming and CuNi foil, see Figure 1.

As the device was shimmed at room temperature, we optimized the end design[5] such that the gap variation was minimized at this temperature.

The stability of the design towards demagnetization, was checked by performing Vectorfields OPERA calculations. We found that by choosing a magnet grade with a minimum intrinsic coercivity of 1670 kA/m at 20 ^{o}C, our design is safe from ambient temperatures up to 60 ^{o}C. We designed a small chamfer on the magnet blocks to eliminate demagnetization nearest to the neighboring pole. Our magnet sample, Vacodym 776 TP, from Vacuumschmelze[6], were delivered with a minimum remanence of 1.31 T, and low angular field defects. The magnetic specifications, as agreed upon with Diamond Light Source, are shown in Table 1.

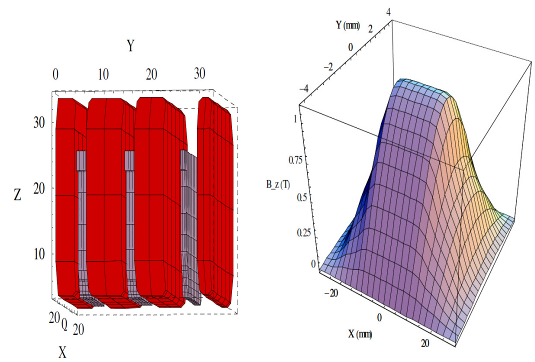

Figure 1: Magnetic Design using RADIA.

Table 1: Magnetic Specifications for Cryogenic Undulator

	Specification
Configuration	Cryogenic, hybrid, in-vacuum undulator
Device Length	2050 mm
Period Length	17.7 mm
# poles	226
Phase error	3.5
Normal and skew first integrals(|x|< 10 mm	± 50 Gcm
Normal and skew first integrals(10<|x|< 20 mm)	± 100 Gcm
Normal and skew second integrals(|x|< 10 mm	± 10000 Gcm^2
Normal and skew second integrals(10<|x|< 20 mm)	± 20000 Gcm^2

MAGNETIC MEASUREMENT

In order to measure the magnetic performance of the undulator under cryogenic, in-vacuum conditions, a special measuring system was needed, such that we could perform both Hall measurements, as well as stretched-wire measurements.

Hall Probe Bench

The measurement system was similar to the one used by the ESRF which is described by Chavanne et.al in ref.[7]. In our case, we used an acquisition speed of 10 mm/s, compared to Chavanne et al. For the cryogenic measurements, this meant that the Hall probe temperature change during the scan was much larger than seen in Ref[7]. However, due to accurate temperature compensation of the probe, this did not present a problem for us. We also did not find it necessary to perform yaw correction of the Hall probe, using 2 lasers. Also, due to the length of the measuring chamber, the performed Hall scans, did not extend into the fringe-field, which meant that the Hall scans had to be artificially corrected for this during the subsequent analysis.

The main shortcoming of the design was related to the flatness of the guide rail relative to the magnetic mid-plane. This meant that at the smallest magnetic gaps, the phase error was over-represented, by around 0.3 degrees.

RESULTS

Here, we present the magnetic results. As we were using a different measuring system under cryogenic conditions, the performance of this system was verified during the commissioning phase, by comparing the results to our results obtained after the undulator shimming phase. Of particular importance was the vertical alignment of the guide rail relative to the undulator. This was found to have a large impact on the measured phase error, mostly evident at the smallest gaps.

Phase Error

Unlike the prototype, device described in Ref.[7], which was not shimmed to have a low phase error, this device had a phase error specification of 3.5 degrees. This places large demands on the temperature gradient along the girder. The average thermal contraction was measured by comparing the relative peak positions as measured with the Hall scan. It was found that, at 157 K, an average thermal contraction of 0.00306 mm/mm was seen. This corresponds to a total contraction of 6 mm, for the entire device. The obtained phase error is shown in Figure 2, at a number of gaps.

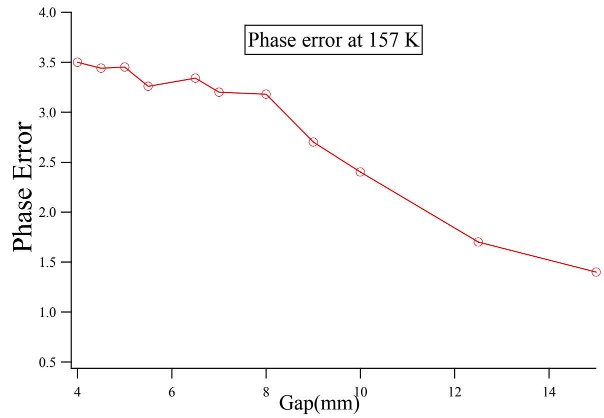

Figure 2: Phase error, as measured under cryogenic conditions at different gaps.

Electron Trajectory

The simulated electron trajectory, as obtained from Hall-scans at cryogenic temperatures is shown in Figure 3. We see at kick for the horizontal trajectory at each extremity, which can be easily corrected with short vertical coils, already installed.

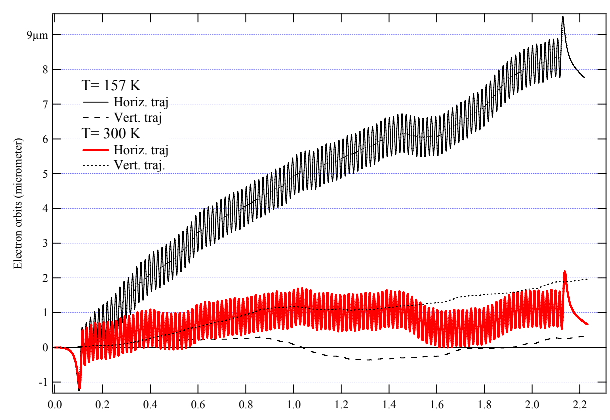

Figure 3: Electron trajectory along the undulator axis, at room temperature,and at 157 K, at 7 mm gap.

Field Increase

The chosen grade of NdFeB, Vacodymn 776, from vacuumschmelze, had not, to our knowledge, been examined at room temperature. Previous investigations, have been done by Benabderrahmane, et.al[8] of Vacodym 764, and this material showed a good remanence increase, at low temperature. As we can see, from Table 2, we observed a field increase of 7-8 %, indicating a remanence increase of 8-9 % for the chosen NdFeB grade.

Table 2: Effective Field Before and After Cooling

Gap	T= 300 K Effective Field(T)	T= 157 K Effective Field(T)	Field increase
4	1.180	1.263	7.03%
4.5	1.070	1.146	7.10%
5	0.970	1.040	7.22%
5.5	0.880	0.944	7.27%
7	0.650	0.707	8.77%
10	0.370	0.402	8.65%

Cycling Stability

To test the cycling stability of the device, we measured the average peak field before and after a complete thermal cycle, which involved heating the girders to room temperature and cooling again to 157 K. We found that immediately after reaching 157 K, the magnetic field was 0.1% below the value obtained before cycling. It was found that after measuring for 8 hours, that the field converged towards the pre-cycling value. We estimated that approximately 24 hours was enough for the structure to thermally equilibrate.. No change in the phase error of trajectory straightness was seen, as a result of thermal cycling.

Vacuum Results

As the magnet arrays were not bakeable, the achieved vacuum performance was of utmost importance. An ultimate pressure of $1 \cdot 10^{-8}$ mbar was achieved, without cooling the magnet array. Once the magnet array is cooled, the pressure decreases further, due to cryopumpin from the magnet array. It is expected that the pressure will decrease by an order of magnitude.

CONCLUSIONS

Danfysik has designed and built a 2 m long cryogenic in-vacuum undulator, to demanding specifications, for Diamond Light Source. As expected, we observed a 8-9 % remanence increase, for our choice of NdFeB grade. Due to a low temperature gradient along the girders, we were able to produce a device with a phase error of 3.5^{o}. The horizontal electron trajectory was found to experience a kick at each extremity, as expected. The vertical electron trajectory was largely unaffected. The device has short correction coils, to counter this kick at each end.

With the completion of this device, Danfysik is now still in a position to supply all the main types of insertion devices with tight performance requirements. We have identified several areas for design improvement, which will be implemented in subsequent devices.

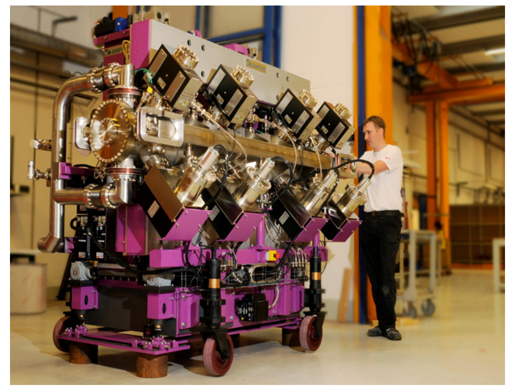

Figure 4: Finished device after factory testing.

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