IN-VACUUM AND FEL UNDULATORS AT DANFYSIK A/S

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Abstract

Danfysik A/S has recently designed and produced a hybrid in-vacuum insertion device for the Swiss Light Source and for SOLEIL. The first device is designed for a wide good field region while the second is optimized for high peak field.

A quasi-periodic undulator has been built for FEL applications at FOM. The performance of the device is in excellent agreement with theoretical calculations with a high suppression of the higher harmonics of the energy spectra. A conventional undulator has also been built for FEL applications at FZR Rossendorf.

A high degree of software assistance and automation has been developed for the magnet mounting, shimming and magnetic testing of the insertion devices. This allows us to scale up the production to meet demanding large scale FEL requirements.

INTRODUCTION

Danfysik [1] has recently produced two in-vacuum undulators, shimmed one more for DIAMOND and built two out-of-vacuum undulators for FEL applications. A prototype undulator for TESLA and an Apple-II for ASP is in production. Danfysik is now in the position to supply all the main types of insertion devices with tight performance requirements. Our software development allows us to quickly scale up the production and meet the most demanding FEL requirements of many insertion devices in a short time.

IN-VACUUM UNDULATORS

Figure 1 shows the undulator made for the Swiss Light Source and Figure 2 the device produced for SOLEIL. The performance of the undulators is shown in Table 1. Both are hybrid undulators with Samarium Cobalt magnets but with different priorities with respect to the pole design and material. The SLS device is made with iron poles that are 44 mm wide to minimize the field roll off and guarantee a conservative 40 mm wide good field region. The SOLEIL undulator is optimized for high peak field with relative large magnet blocks and Vanadium Permendur poles. The pole profile is designed with chamfers on the sides such that they are only 33 mm wide at the air gap at the expense of a good field region that is only 20 mm wide. The benefit is a 11% higher peak field as compared to the SLS undulator after correction of the period length difference.

For both undulators a significant degree of interaction along the device was observed just outside the good field region in the form of a significant gap dependent variation of the field integrals. This interaction is probably driven by a coupling between magnetic block inhomogeneities that interact via the pole corners. The exact source was difficult to detect and the gap dependent effect difficult to remove. Care should therefore be taken in design of the pole shape if wide good field regions are required.

Figure 1: The SLS undulator without vacuum chamber.

Figure 2: The SOLEIL undulator with vacuum chamber.

Table 1. Results for the in-vacuum undulators. The phase error and integrals are max values at all specified gaps.

		SLS	Soleil
Undulator period	(mm)	19.00	20.00
Gap range	(mm)	4 - 40	5 - 30
Specified min gap	(mm)	5.0	5.5
Undulator length	(mm)	2010	1900
Number of full size poles		194	196
Peak field, 5 mm gap	(T)	0.92	1.05
Effective field, 5 mm gap	(T)	0.86	0.98
RMS phase error	(°)	≤ 2.2	≤ 2.6
Field integrals |x| ≤ 10mm	(Tm)	$\pm 24\cdot10^{-6}$	$\pm56\cdot10^{-6}$
Field integrals on-axis	(Tm)	$\leq 30\cdot10^{-6}$	$\leq 35\cdot10^{-6}$
Second integral on-axis	(Tm^2)	$\leq 0.28\cdot10^{-4}$	$\leq 0.41\cdot10^{-4}$
Pressure after bake-out	(mbar)	$3\cdot10^{-10}$	$2\cdot10^{-9}$

Figure 3 shows the electron orbit calculated from the magnetic field measured at 5 mm gap and Figure 4 shows the phase error for the SLS undulator. The measured on-axis first integrals as a function of gap are shown in Figure 5. The device is only to be used down to 5 mm gap but fulfills the specified requirements down to 4 mm gap.

After the magnetic test the vacuum chamber was installed and the device baked in vacuum at 120ºC. After shipping to SLS the device was remeasured by SLS with their stretch wire bench and they confirmed that the trajectory was still straight within 1µm. The undulator has been installed at the ring where it performs perfectly according to SLS.

Besides the two mentioned hybrids, a pure permanent magnet in-vacuum undulator with 27 mm period and 5mm minimum gap was shimmed for DIAMOND to a RMS phase error below 2.5º, first integrals below $10\cdot10^{-6}$ Tm and second integrals below $0.2\cdot10^{-4}$ Tm^2 at all gaps.

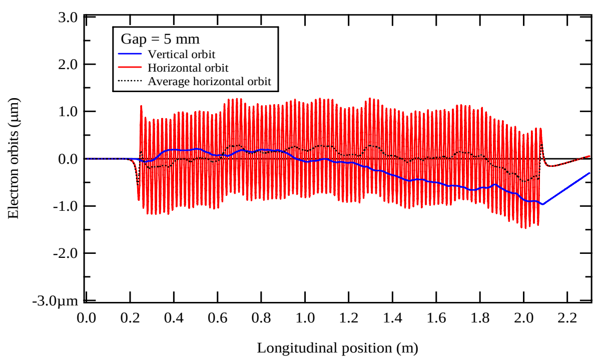

Figure 3: The horizontal and vertical electron trajectory as calculated at 5 mm for the SLS undulator.

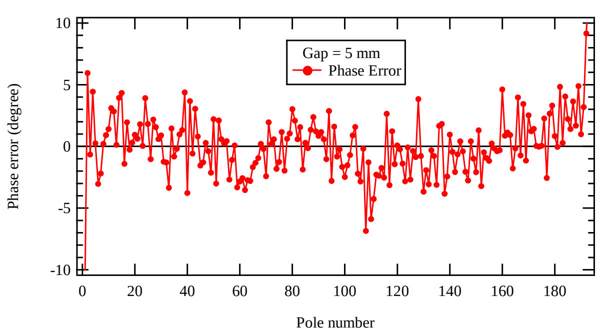

Figure 4: Phase angle error at 5 mm gap for the SLS undulator.

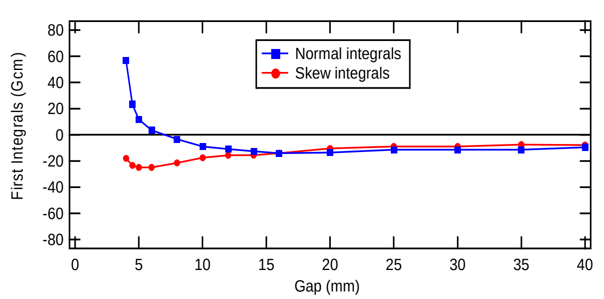

Figure 5: Measured gap dependence of the normal and skew first integrals for the SLS undulator.

A classified class 100.000 clean room has been built at Danfysik for the handling of in-vacuum devices. The facility has filtered air intake, air lock access overpressure and the temperature is regulated to within ±0.5°C.

Our newest 3D Hall probe is based on an ESRF design and has a thickness of only 1.2 mm to allow field measurements at small gaps. Calibration of the longitudinal Hall bench axis using a laser interferometer has shown that the bench is very reproducible with a random jitter of only 0.7 µm. On the SLS device it was found from seven Hall probe scans at 5 mm gap that the uncertainty on the trajectory walk over the 2 meter device is less than 0.2 µm for a 2.4 GeV electron beam (300 Gcm^2) and the uncertainty on the obtained RMS phase error was only 0.03 degree corresponding to 0.24 degree for each half period.

Danfysik has shown that it has the ability to design, build and test in-vacuum devices to stringent mechanical, magnetic and vacuum requirements.

FEL UNDULATORS

A quasi-periodic undulator has been built for the FOM-Institute for Plasma Physics where it is to be used for the intra cavity UV-FEL experiment, FELIX (see Figure 6). The device is based on a standard pure permanent undulator design which is converted into a quasi-periodic device by introducing a setback of selected magnets according to a Fibonacci sequence [2]. The purpose is to shift the higher harmonics of the radiation spectra such that it is mainly the 1.harmonic which is reflected from the cavity mirrors and contributes to the FEL process. The girder and the magnetic array is split in to parts to allow the introduction of a small gap step taper to allow work on harmonic gain enhancement.

Figure 6: The quasi-periodic undulator for FOM.

RADIA calculations [3] of a full length model device were used to optimize the quasi-periodic design. The device was first build as a traditional undulator with a RMS phase error of 2.1 degrees at the minimum gap. It was then converted into a quasi-periodic device by simply introducing the setback of the pre-selected magnets by removing a shim under the magnet keepers. The magnetic performance of the resulting device is in excellent agreement with theoretical calculations with high suppression of the 3. and 5. harmonics (see Figure 7 and Table 2). The estimated flux of the 1. harmonic was reduced to 86% which is just 3% below the value calculated from the quasi-periodic RADIA model. If needed the device can be converted back into a periodic device with very little effort.

A conventional hybrid undulator has also been built for IR-FEL applications at FZR Rossendorf. The undulator is 4 meter long with a period length of 100 mm and a minimum gap of 24 mm. The assembly process was very efficient with only 3 weeks spent mounting the magnetic array and less than two weeks for the shimming and final magnetic testing.

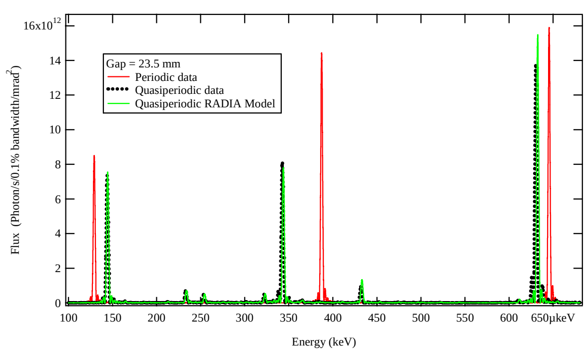

Figure 7: Flux calculated from measured and calculated magnetic fields for the FOM undulator at 23.5 mm gap.

Table 2. Results for the quasi-period undulator for FOM.

		Specified	**Built**
Undulator period	(mm)	60	60.00
Gap range	(mm)	23.5 - 90	23.5 - 90
Undulator length	(mm)	-	2830
K value (periodic device)		≥ 2.5	2.6
Number of periods		46	46
1. harm. reduced to	(%)	≥ 70	≥ 86
3. harm. reduced to	(%)	≤ 12.5	7.0
5. harm. reduced to	(%)	≤ 12.5	5.5
Field roll-off, x= ± 3mm	(%)	≤ 0.2	0.13
Field integrals on-axis	(Tm)	$\leq 100 \cdot 10^{-6}$	$\leq 13 \cdot 10^{-6}$
Second integral on-axis	(Tm^2)	$\leq 1 \cdot 10^{-4}$	$\leq 0.68 \cdot 10^{-4}$

SOFTWARE AND AUTOMATION

The construction, shimming and testing of insertion devices can be a challenging and time consuming process. To manage the process in a simplified and efficient manner we have developed a unique software packed for the assistance and automation of this process running in Igor Pro [5]. For the basic control of the Hall probe bench and integrating coil we use a series of command sets written by the insertion device group at ESRF [6].

At the project start all information concerning the magnets (or magnet keeper modules) such as magnet identifiers, magnetization data and field integrals due to inhomogeneities are loaded into the Igor Pro project. During the process of mounting magnets the program is used to automatic select magnets or magnet modules for the next period to be mounted. In this process the program evaluates a goodness factor for all combinations and selects the best choice. The goodness factor is evaluated from the magnetization data and the field integral contribution of each magnet using preset weight factors for the estimated effect on peak field, phase error and accumulated field integrals, respectively. The weight factors used in this goodness evaluation are chosen at the project start based on the magnetic requirements.

After magnet mounting the device are shimmed by magnet displacements or by in-situ swapping. Displacement shimming of trajectory straightness is a relative simple process. The magnet swapping is a more demanding and complex process but it can be used to both minimize the integrating multipoles and straighten the trajectory and the gap dependent device performance is usually much better after swapping. The software is used to efficiently suggest the magnet swap that gives the largest magnetic performance improvement and keep track of the magnet placements during the swap process. In the following phase shimming the program can suggest the phase error that gives the largest error reduction and keep track of the amount of applied phase shimming along the length of the device. One significant advantage of this program is that the combined result of several shim actions can be estimated such that a full day of work for the technical staff can be preplanned if necessary.

The magnetic measurements on the finished device are run fully automated one gap at a time using flexible batch programs. Each data set is analyzed with one simple command macro that generates report ready graphs. The analysis macros are built up around B2E from ESRF [6].

Using the magnet swapping technique and the described processes it is possible in most cases to avoid correction coils for adjustment of the first and second integrals. No coils were needed on the devices mentioned in this paper.

With our new software development we can produce insertion devices faster with lower demand on the skill level of the technical staff. Thus we are in a good position to scale up for the large scale insertion device production that is needed for many ERL and FEL projects.

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