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MAKING AN X-RAY UNDULATOR READY FOR COMMISSIONING: PROCEDURES SUBSEQUENT TO FABRICATION UNTIL TUNNEL INSTALLATION

Bora KETENOĞLU*

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Abstract: In this study, sequence of events for an X-ray undulator generating Free Electron Laser (FEL) pulses down to hard X-rays of the electromagnetic spectrum, are discussed in detail. As soon as an undulator arrives to a Magnetic Measurements Hutch (MMH), a series of treatment steps start to make it ready for commissioning, beginning with a high-precision magnetic alignment procedure. Once Hall probe and undulator are accurately aligned to each other, then gap-dependent measurements begin to create tuning lists. After completion of mechanical tuning of poles, MMH 3D-coordinates have to be transformed to the coordinates of tunnel, where many undulator cells will be sequenced one after another along a linear path. Here, all optical, mechanical and magnetic procedures that an X-ray undulator experiences before commissioning, are thoroughly explained. Furthermore, effects of different types of Hall probes on magnetic measurements, are discussed as well. Finally, whole algorithm subsequent to fabrication until tunnel installation (i.e. optical and magnetic alignment, pole tuning, phase jitter therapy etc.), are summarized by means of the results of magnetic measurements taken in three identical MMHs of European XFEL facility.

Keywords: X-ray FEL, undulator, magnetic measurements, pole tuning

Bir X-ışını Salındırıcısının İşletime Hazır Hale Getirilmesi: Üretimin Ardından Tünele Kurulana Kadar İzlenen Prosedürler

Öz: Bu çalışmada, elektromanyetik spektrumun sert X-ışınları bölgesinde Serbest Elektron Lazeri (SEL) üreten bir X-ışını salındırıcısının başından geçen olaylar silsilesi detaylıca tartışılmıştır. Bir salındırıcı Manyetik Ölçüm Laboratuvarı'na geldikten sonra işletime hazır hale gelebilmesi için, yüksek hassasiyetli manyetik hizalama prosedürü ile başlayan bir dizi iyileştirme adımı başlar. Hall probu ve salındırıcı birbirlerine hassas bir şekilde ayarlandıktan sonra, ayar listelerinin oluşturulabilmesi için salındırıcı yapının farklı farklı açıklık değerleri için ölçümler başlar. Kutupların mekanik olarak ayarlanmasından sonra, Manyetik Ölçüm Laboratuvarı'nın 3 boyutlu koordinatları, salındırıcıların doğrusal bir yol boyunca ard arda sıralanacakları tünel koordinatlarına dönüştürülmelidir. Burada, bir X-ışını salındırıcısının işletimden önce başından geçen tüm optik, mekanik ve manyetik prosedürler tüm detaylarıyla açıklanmıştır. Ayrıca, birbirinden farklı tipte Hall problarının manyetik ölçümler üzerine etkileri de tartışılmıştır. Sonuç olarak, üretimin ardından tünele kurulana kadarki tüm algoritma (optik ve manyetik hizalama, kutup ayarlanması, faz hatalarının iyileştirilmesi vb.), European XFEL tesisinin özdeş üç Manyetik Ölçüm Laboratuvarı'nda alınan sonuçlar ile özetlenmiştir.

Anahtar Kelimeler: X-ışını SEL, salındırıcı, manyetik ölçümler, kutup ayarlanması

*Department of Engineering Physics, Faculty of Engineering, Ankara University, 06100 Tandoğan, Ankara
Corresponding Author: Bora Ketenoğlu (bketen@eng.ankara.edu.tr)

1. INTRODUCTION

Today, accelerator-based fourth generation light sources, namely FELs, are state-of-the art tools for natural sciences research such as biology, physics, environmental and energy research, astrophysics and the science of extreme states, materials science, chemistry, electronics etc. Main distinctive features of FELs compared to conventional lasers are: tunability, brilliance, power and ultra-short time structure. Thanks to particle accelerators, electrons can freely run under ultra high vacuum, that is to say they are not bounded to any atomic nucleus, tunability of wavelength automatically comes out. Furthermore, again thanks to particle accelerators, billions of electrons can be occupied and intensely compressed in a bunch, FEL pulses attain a peak brilliance of 10^{30}-10^{34} photons/s/mm/mrad^2/0.1%BW as well as a peak power of typically some Giga Watts (GWs) (see Figure 1), where BW is bandwidth of photon pulses.

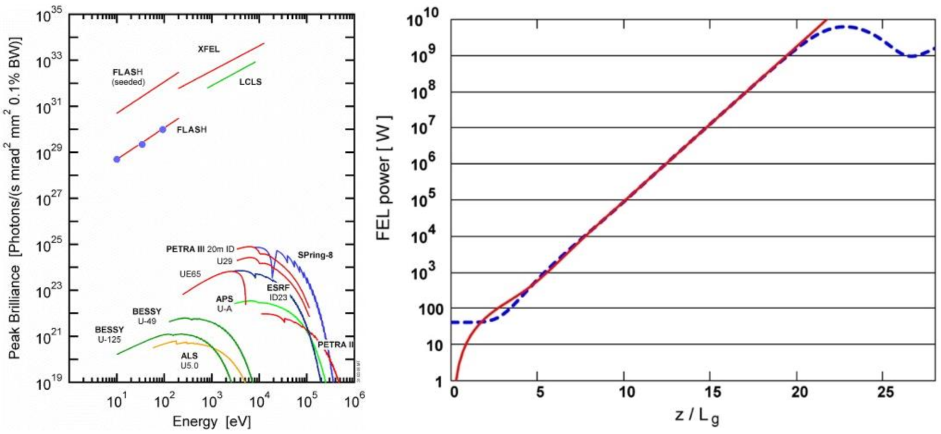

Figure 1:
Peak brilliance of accelerator-based light sources vs photon energies (left) <(Robinson, 2010)>, saturation of FEL power along the undulator line having a peak value of some GWs (right) <(http://photon-science.desy.de/facilities/flash/the_free_electron_laser/how_it_works/physics_of_fels/index_eng.html)>

On the other hand, it is the time structure of electron bunches that directly specifies FWHM length of an FEL pulse and as well as the time seperation between two consecutive FEL pulses. As an illustration, the time structure of European XFEL facility is shown in Figure 2 (Altarelli, 2010). As soon as the electron bunches arrive to the undulator line, they are forced to make a slalom by periodic magnetic forces, resulting in generation of femtosecond FEL pulses.

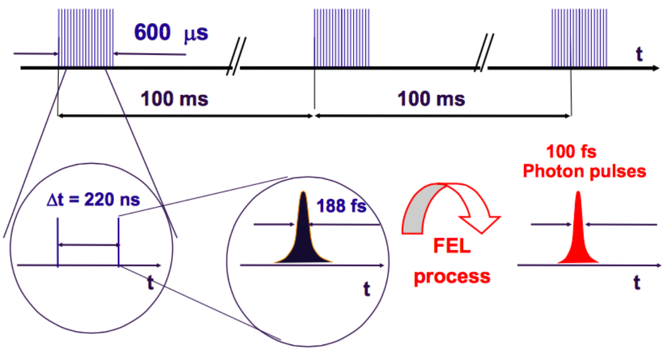

Figure 2:
The time structure of European XFEL facility <(Altarelli, 2010)>

2. THE UNDULATOR

The undulator is a device that makes radiation brighter and more coherent. As to the monochromaticity characteristics of undulator radiation, one can simply suppose that the "t-axis" of the red pulse in Figure 2 is replaced by "wavelength-axis", then the black arrows indicate wavelength spread $\Delta\lambda/\lambda$ (namely FWHM monochromaticity). For FELs, $\Delta\lambda/\lambda$ is typically around 10^{-4} (Abela et al., 2007), fulfilling the concept of "laser" more than enough.

Considering design issues, there are two different types of undulators, called planar and helical. Although helical undulators provide circular polarization, which may sometimes be an essential requirement for dedicated user experiments, mechanical tuning of a helical undulator is pretty hard to achieve. That's why almost all FEL facilites prefer to use planar undulators due to their user-friendly nature in terms of pole tuning process. A planar undulator can simply be defined as "assembly of alternating dipole magnets on parallel girders" as shown in Figure 3 (Patterson and Abela, 2010).

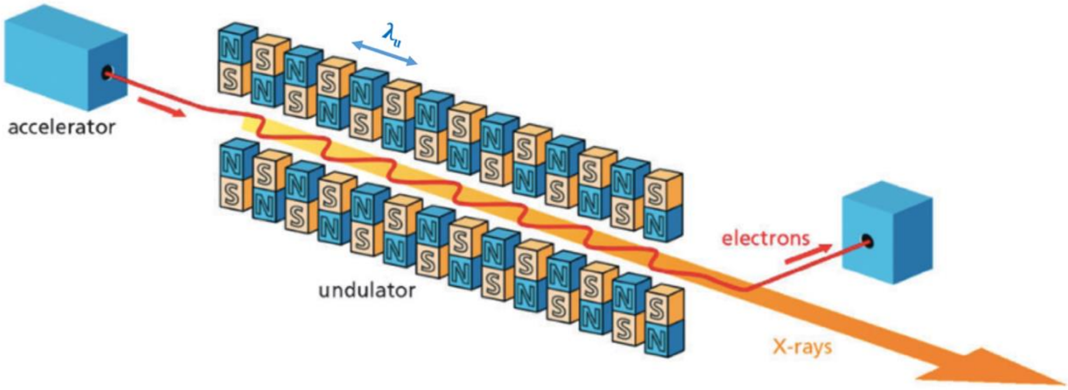

Figure 3:
Schematic view of a planar undulator <(Patterson and Abela, 2010)>

3. PROCESSES SUBSEQUENT TO FABRICATION UNTIL TUNNEL INSTALLATION

After an independently fabrication of the frame and the magnetic structures, they first arrive to the hall for a series of treatment processes. As soon as mechanical mounting of magnetic structures onto the girders are completed just out of the MMH, then the undulator moves in for magnetic measurements. While waiting for temperature stabilization at 21 ^{o}C inside the MMH for 24 hours, control system of the undulator (motor resolvers, linear encoders etc.) is fully checked for troubleless operation. As seen in Figure 4, European XFEL's 5m-long undulators are controlled by 4 independent motors, providing the possibility of girder tilting up to a few hundreds of microns.

Because of the fact that two linear encoders are unattached to the frame, which are mounted on both ends of girders, they directly measure the gap with an accuracy of 1 micron. As soon as the control group gives green light to magnetic measurements staff, frame and girders are first aligned to each other via an optical levelling device. Afterwards, an algorithm of magnetic alignment process is performed, resulting in an exact on-axis 3D positioning of the Hall probe. Then, subsequently analyzing gap-dependent measurements results, tuning lists are generated by means of a dedicated software.

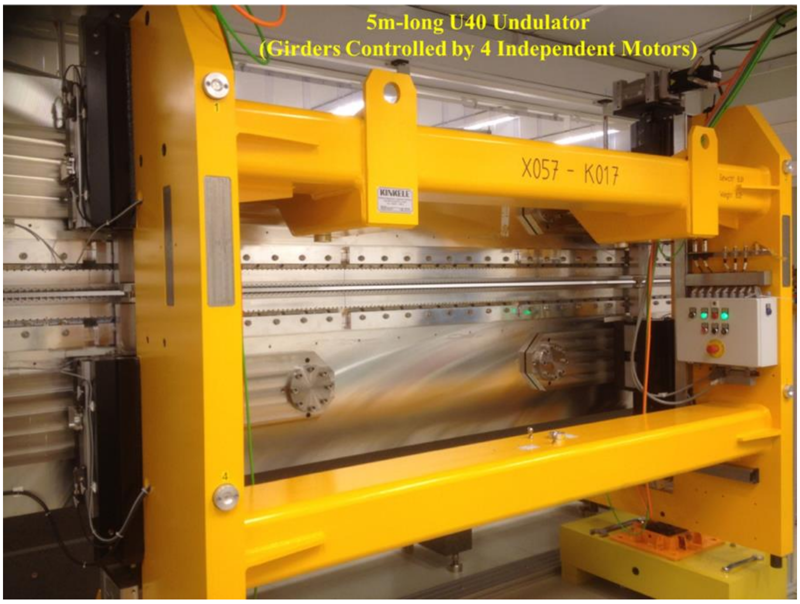

Figure 4:
European XFEL's 5m-long planar undulator <(Photo credit: Bora Ketenoğlu)>

After completion of mechanical tuning of the poles, final measurements are performed to check whether the tuning is successful or not. Table 1 (Li et al., 2015) summarizes the specifications for two different types of XFEL.EU undulators (called U40 and U68), where the values 40 and 68 represent the period of the undulator, symbolized as "λ_u" in Figure 3.

When tuning the poles, one of the most critical parameter that has to be kept under control, is the phase jitter. A predominant negative effect on "gap-dependent phase jitter therapy" is the mechanical girder bending, resulting from considerably increasing magnetic forces especially for smaller gaps down to 10 mm. In Figure 5 (Ketenoğlu et al., 2015), phase jitter profile of a U68 undulator is plotted for gap=16 mm. Red plot shows its status subsequent to fabrication and blue line shows how successful is the pole tuning therapy, with RMS values of 4.43 deg and 0.59 deg respectively.

Table 1. Specifications for European XFEL undulators <(Li, 2015)>

Parameter [Unit]	U40	U68
Operational gap range [mm]	10-20	10-25
Period length [mm]	40	68
Tuning gap [mm]	14	16
B_y RMS trajectory [Tmm^2]	≤ 100	≤ 210
B_z RMS trajectory [Tmm^2]	≤ 70	≤ 70
Entrance and exit B_y and B_z kicks for all gaps [Tmm]	$\lvert \leq 0.15 \rvert$	$\lvert \leq 0.15 \rvert$
Entrance and exit B_y and B_z kicks for tuning gap [Tmm]	≈ 0	≈ 0
K parameter @ minimum gap (g_{min}=10 mm)	≥ 3.9	≥ 9
RMS phase jitter for all gaps [deg]	≤ 8	≤ 8
RMS phase jitter for tuning gap [deg]	≤ 2.5	≤ 2.5

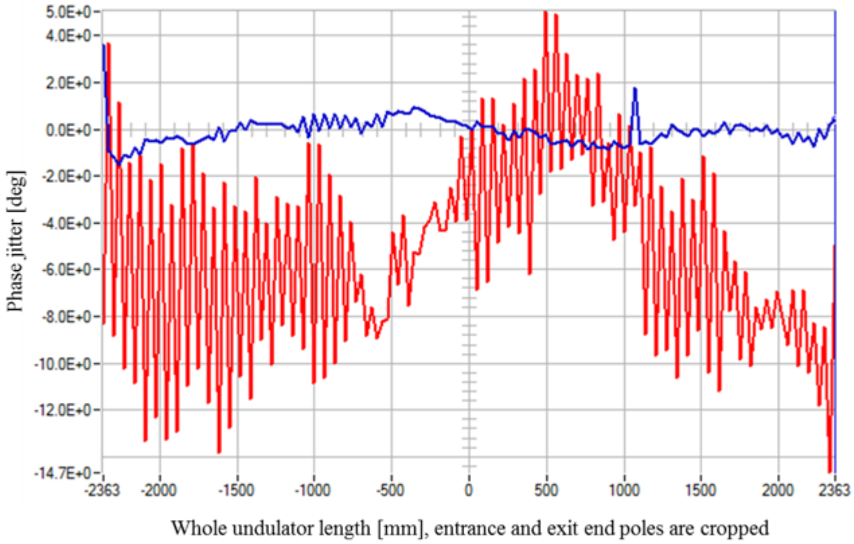

Figure 5:
Phase jitter profile for gap=16 mm along a U68 undulator <(Ketenoğlu et al., 2015)>

On the other hand, gap dependency of phase jitter is plotted in Figure 6 (Ketenoğlu et al., 2015) for the same U68 undulator, where the label PEG means "Phase Error for Gap" (e.g. pink colour is the phase error plot for gap=20 mm). The effect of mechanical girder bending on gap-dependent phase jitter profile is clearly seen in Figure 6.

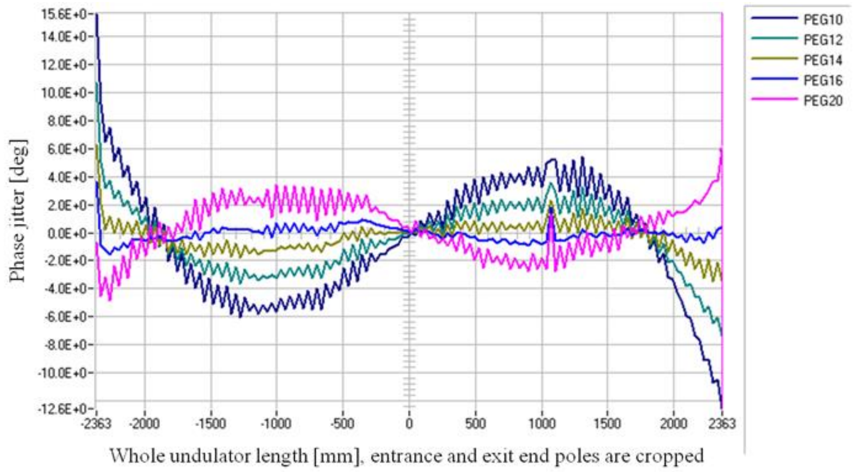

Figure 6:
Gap dependency of phase jitter after tuning <(Ketenoğlu et al., 2015)>

4. EFFECTS OF DIFFERENT TYPES OF HALL PROBES ON MAGNETIC MEASUREMENTS

Measuring an undulator with a Hall probe may simply be considered as: "simulation of electron bunches travelling along the magnetic axis of an undulator with a non-relativistic speed (v « c)". In this respect, effective surface area of the probe has to be as small as possible. For ideal case, probe's effective surface area should fit with normalized emittance of the electron bunches, which is an invariant along whole linear accelerator. In Figure 7 (Ketenoğlu, 2015), a real scaling of two different types of probes (Senis sensor and Bell probe) is represented on cap of peak magnetic fields for gaps 10 mm and 25 mm.

It is clearly seen in Figure 7 (Ketenoğlu, 2015) that 57 times smaller surface area of Senis sensor comes into prominence especially for small gaps down to 10 mm. Considering gap dependency of Senis sensor in terms of peak field measurements, it is completely gap independent due to its 57 times smaller surface area. In other words, using a Senis sensor for gap dependent peak field measurements is much more useful and precise than Bell probe. Furthermore, Senis sensors measure far fewer noise inside the Zero Gauss Chambers. In addition, thanks to integrated electronics of Senis sensors, no external Gaussmeters are required for magnetic measurements setup.

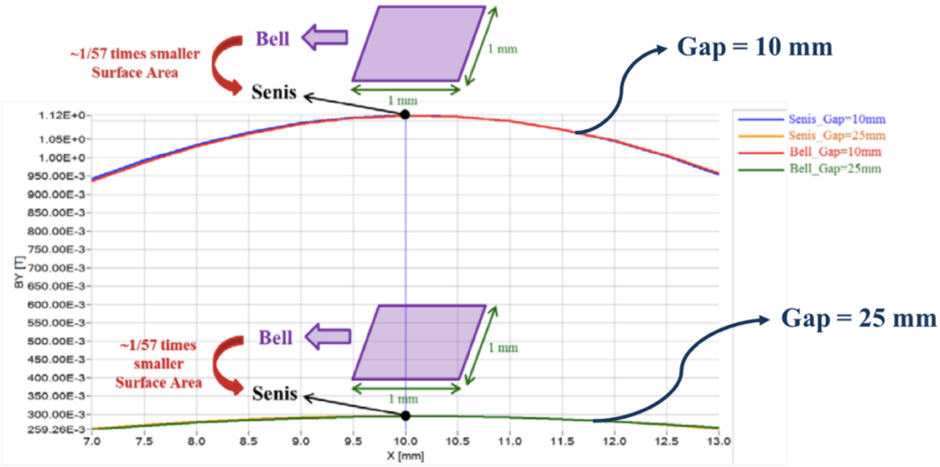

Figure 7:
Real scaling of Senis sensor vs Bell probe for gaps 10 mm and 25 mm <(Ketenoğlu, 2015)>

5. PEAK FIELD AND K PARAMETER CONCEPTS WITH REAL COMPERATIVE RESULTS

On-axis peak magnetic field (B_{peak}) of an undulator is calculated by Equation 1 (Elleaume et al., 2000), where a is expressed in units of Tesla and b & c are dimensionless. Considering a planar undulator hybrid with Vanadium Permendur configuration, a, b and c coefficients are 3.694, -5.068 and 1.520 respectively (Elleaume et al., 2000). On the other hand, one should also keep the restriction on g/λ_u ratio in mind: $0.1 < g/\lambda_u < 1$ (Elleaume et al., 2000). In other words, since the λ_u value of an undulator is fixed by fabrication, gap range is optimized to $0.1\lambda_u < g < \lambda_u$. In general, thickness of the beam pipe determines the minimum value of gap. For instance, considering the case for European XFEL, thickness of the beam pipe is 10 mm, resulting in a minimum gap value of g_{min}=10 mm as indicated in Table 1 (Li et al., 2015). Furthermore, one of the most important parameter of an undulator is the K parameter (Equation 2), which is directly derivated from peak field. When the K parameter is more than 3, profile of the sinusoidal magnetic field becomes like a saw-tooth shape, hence the name “wiggler” comes out.

$$B_{peak} = a\, exp\left[b\frac{g}{\lambda_u} + c\left(\frac{g}{\lambda_u}\right)^2\right] \tag{1}$$

$$K = 0.934\lambda_u[cm]B_{peak}[T] \tag{2}$$

As clearly seen from Figures 8 and 9 (Ketenoğlu, 2015), the negative effect of Bell probe’s larger surface area becomes dominant for smaller gaps down to 10 mm. In Figures 10 and 11 (Ketenoğlu, 2015), gap dependency of ΔK for three different Senis sensors and reproducibility of a Senis sensor in terms of ΔK/K, are shown respectively. The ΔK/K value of around 10^{-5} is more than enough for lasing process in the tunnel.

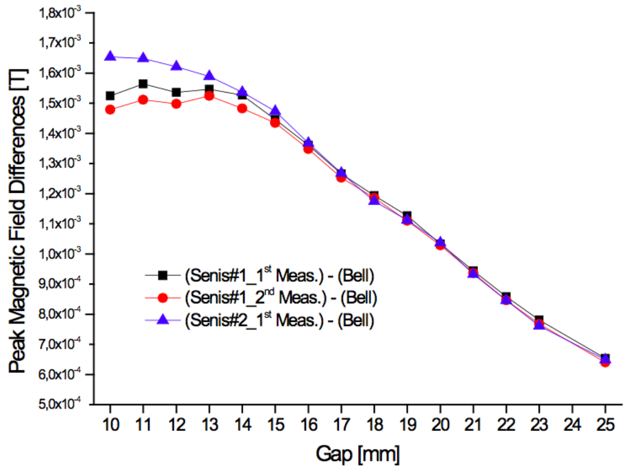

Figure 8:
Gap dependency of ΔB for two different Senis sensors vs Bell probe <(Ketenoğlu, 2015)>

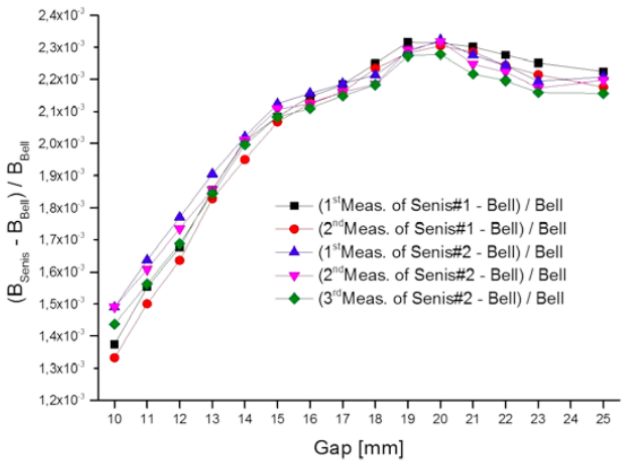

Figure 9:
Gap dependency of ΔB/B for two different Senis sensors vs Bell probe <(Ketenoğlu, 2015)>

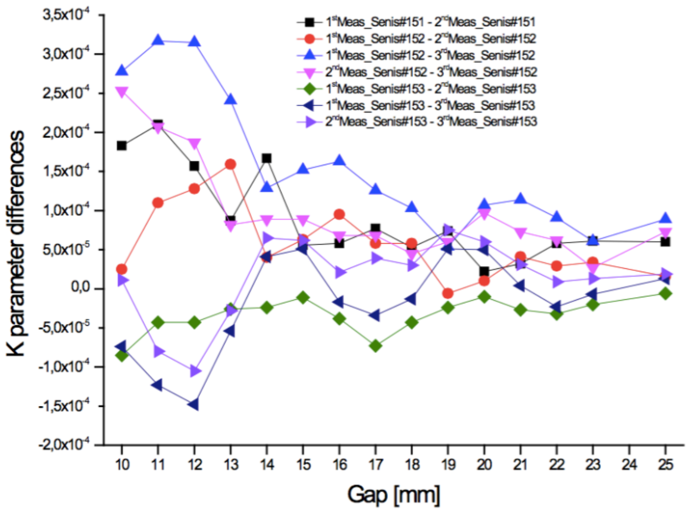

Figure 10:

Gap dependency of ΔK for three different Senis sensors <(Ketenoğlu, 2015)>

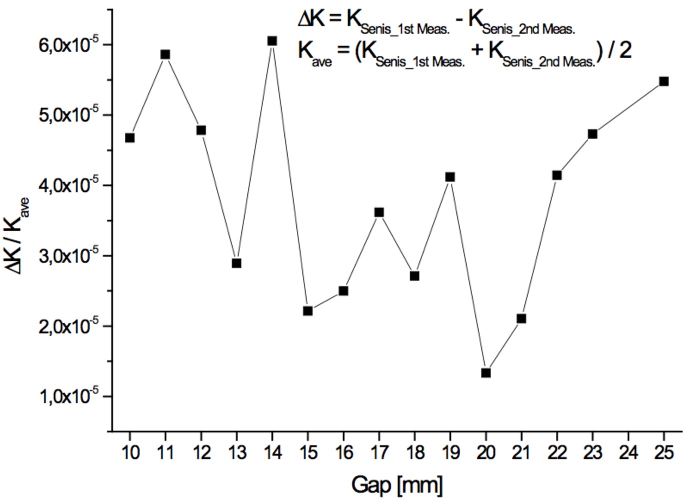

Figure 11:

Reproducibility of a Senis sensor in terms of ΔK/K <(Ketenoğlu, 2015)>

6. CONCLUSION

All optical, mechanical and magnetic procedures for an X-ray undulator generating FEL pulses down to hard X-rays of the electromagnetic spectrum, are discussed in detail. Starting with the mechanical mounting of magnetic structures onto the girders, sequence of events that an X-ray undulator experiences until tunnel installation, are thoroughly explained. Effects of different types of Hall probes on magnetic results are summarized by means of the results of magnetic measurements taken in three identical MMHs of European XFEL facility. It is shown that a state-of-the art probe should be used especially for gap-dependent magnetic measurements.

On the other hand, phase jitter therapy is explained as well. In other words, because of the fact that RMS phase jitter of each undulator has to be less than 8 degrees for whole gap range, importance of phase jitter therapy comes into prominence. As a consequence, original results of XFEL.EU undulators are summarized by gap-dependent measurements of phase jitter, peak magnetic field and K parameter. Finally, the "know how", which is a must for accomplishing such kind of high-tech scientific research facilities, will undoubtedly come in handy for the infrared FEL-oscillator facility of Turkey (namely TARLA), under construction in Gölbaşı campus of Ankara University. In addition, such a "know how" will also be useful for design studies of Synchrotron Radiation (TURKAY) and X-ray FEL (TURKSEL) proposals of the Turkish Accelerator Center project.

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