Magnetic tuning procedures for the large scale production of undulator segments for the European XFEL

Yuhui Li, the European XFEL, WP71

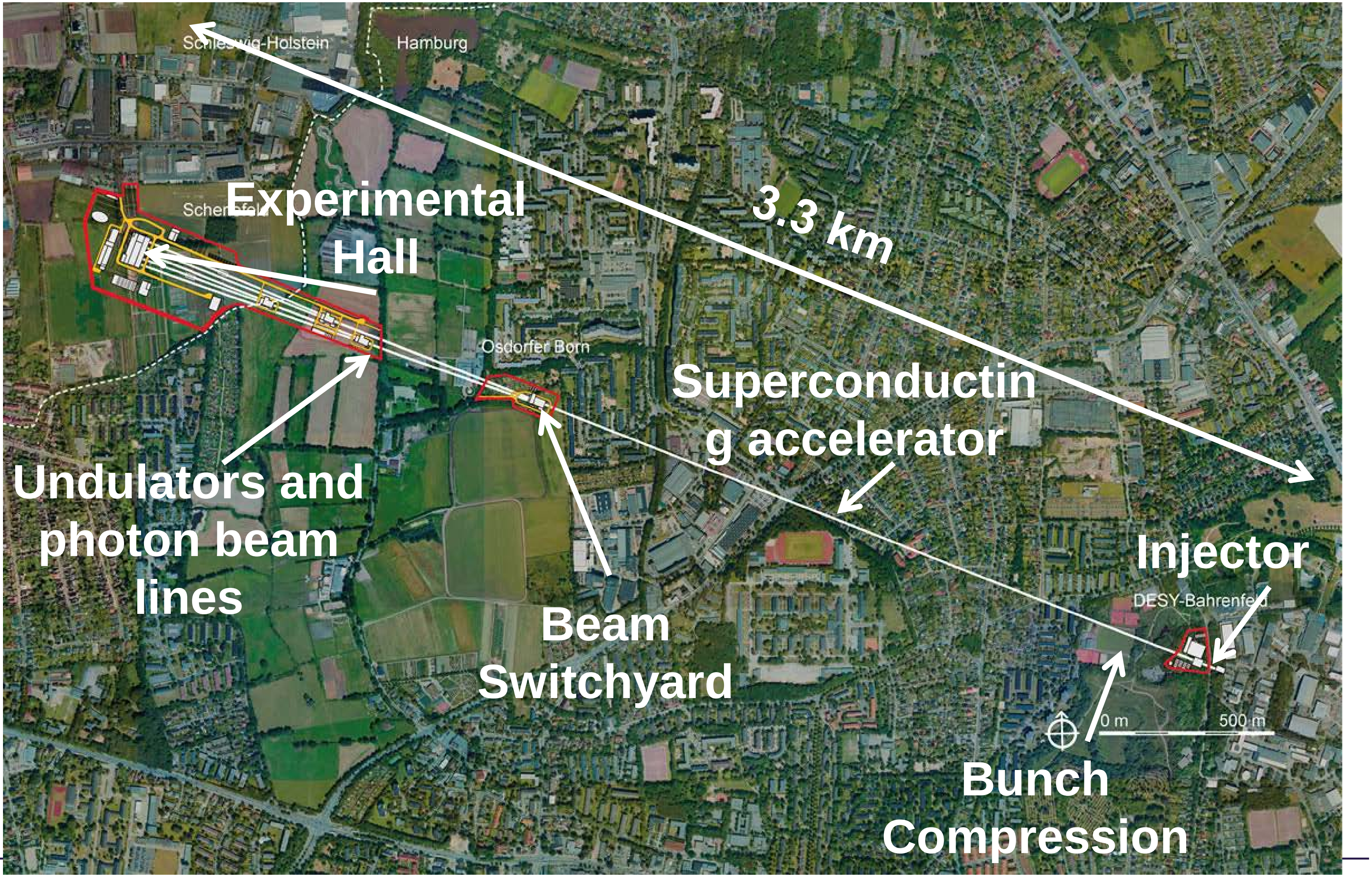
Content

- Definition of tasks
- Overview of the undulator system for the European XFEL
- Undulator segment specifications
- Standard treatment: Pole height tuning, the basic tuning method to achieve specs.
- Special treatment: Shimming, the method for gap dependent errors
  - Gap dependent kicking errors
  - Gap dependent phase error
- Conclusion

Characteristic features of large scale production

- Preconditions
  - Large numbers: 91 undulators with 5m long, totally 450m.
  - Industrial Production: Limited cost, Save own resources.
  - Choice of proper technology
  - Limit tuning effort by proper choice of specifications
- Magnetic properties
  - Fast production, est. 3 weeks per undulator for:
    - commissioning of control system
    - alignment on magnetic bench
    - magnetic measurement & tuning
    - transfer measurement of magnetic axis (survey)
  - Clear procedures, which can be quickly adopted.

The Map of the European XFEL



3.3 km

Experimental Hall

Superconducting accelerator

Undulators and photon beam lines

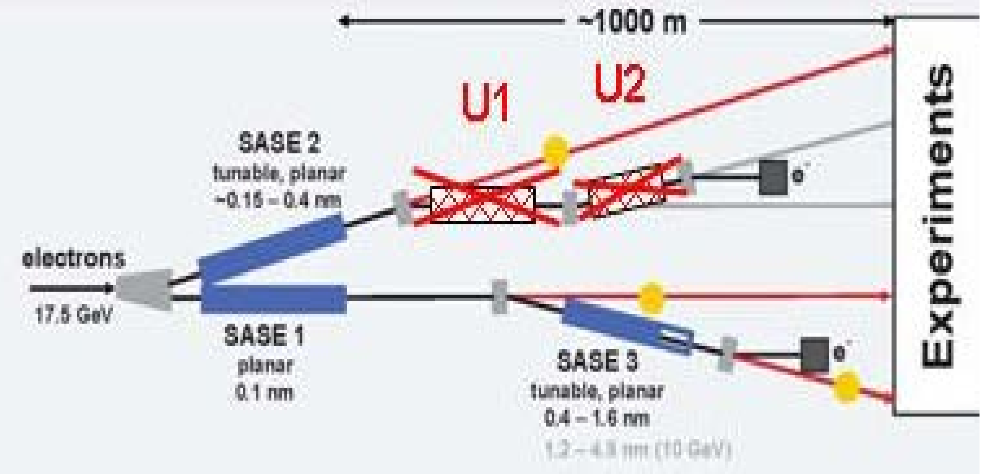
Injector

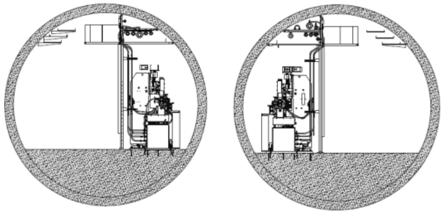
Beam Switchyard

Bunch Compression

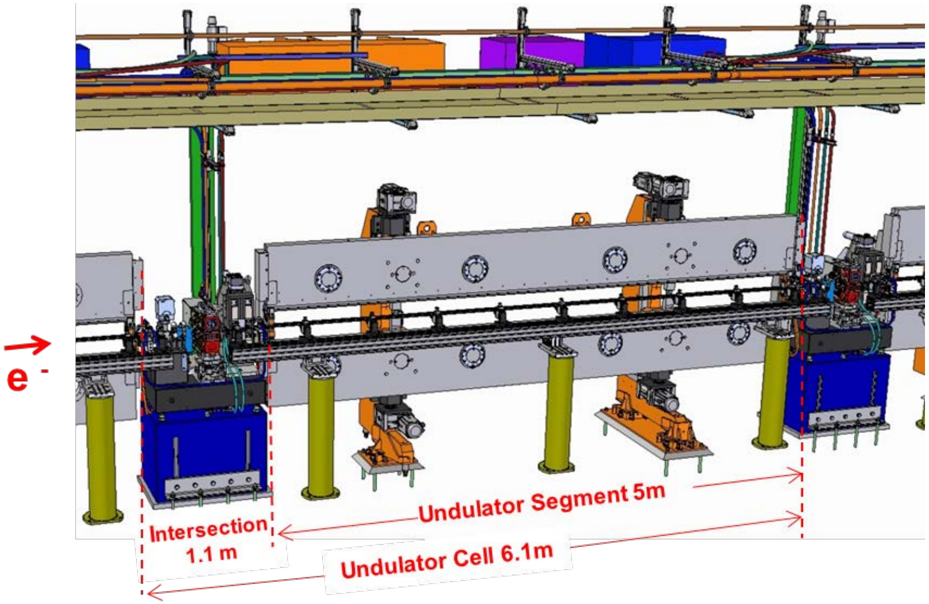
Overview of the Undulator Systems

WP71 Scope & Responsibility: Organization, production & installation either in house or through numerous IKCs of the Undulator Systems





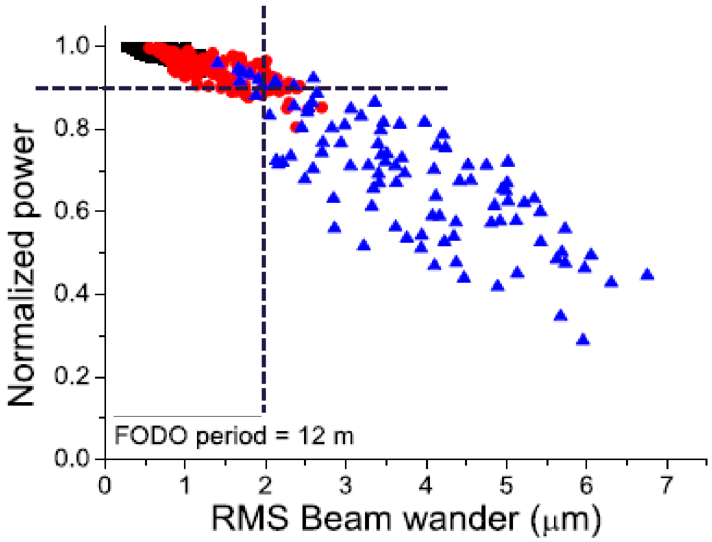
Downstream View

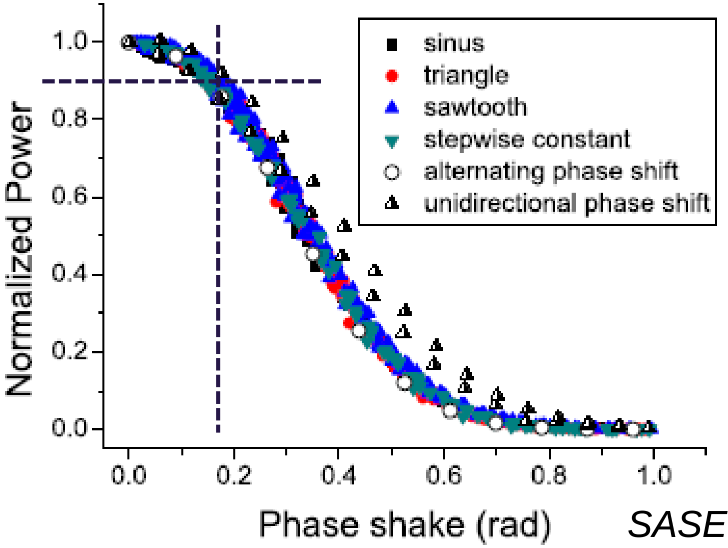


	SASE1/2	SASE3
λ_0 [mm]	40	68
Operational Gap Range [mm]	10-20	10-25
K-Range	3.9–1.65	9.3-4
Radiation Wavelength Range [nm]		
@ 17.5 GeV	0.147-0.040	1.22-0.27
@ 14.0 GeV	0.230-0.063	1.90-0.42
@ 8.5 GeV	0.625-0.171	5.17-1.15
# of Segments	35	21
System Length [m]	213.5	128.1

Specification --- FEL Tolerance Simulations

- Good undulator field is required for the EXFEL





SASE1, 0.1nm

Y. Li, B. Faatz, J. Pflueger, Phys. Rev ST-AB 11, 100701 (2008)

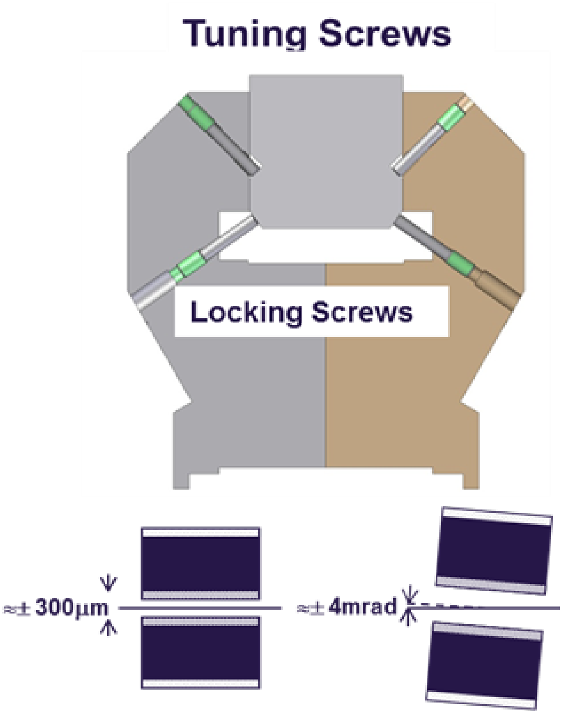
- FEL works only on 1st harmonic
- Physically beam wander smaller than 2µm (RMS 2nd integral < 120 Tmm^2) and RMS Phase jitter smaller than 10 Degree.
- Technically the even tighter specification is achievable.

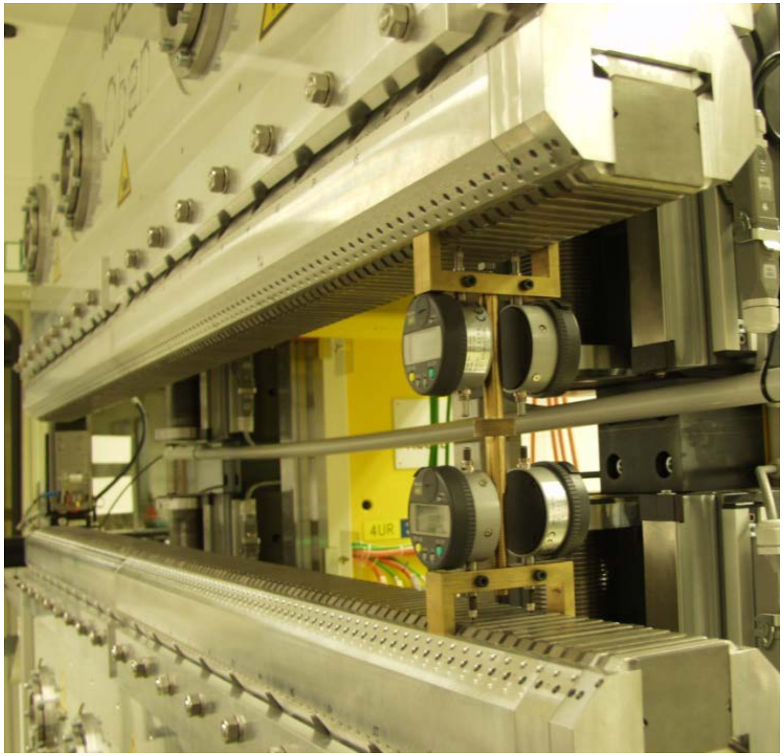
Specifications

Property	U40	U68
Operational gap range (mm)	10 – 20	10 – 25
Tuning gap (mm)	14	16
B_y RMS trajectory (Tmm^2)	≤ 70	≤ 150
B_z RMS trajectory (Tmm^2)	≤ 50	≤ 50
B_y and B_z kicks (Tmm)	$\leq \pm 0.15$	$\leq \pm 0.15$
The maximum K at 10 mm	≥ 3.9	≥ 9.0
RMS phase jitter (degree)	≤ 8	≤ 8
Minimum RMS phase jitter at (degree)	≤ 2.5	≤ 2.5

I. Pole height tuning

The Pole height tuning --- basic tuning





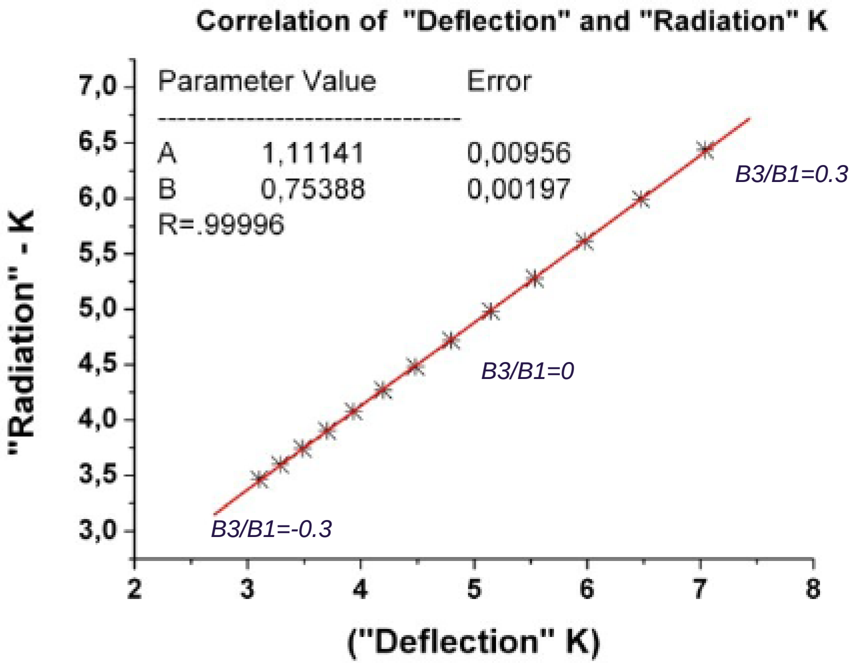
- **No Shims are used**
- **All errors are tuned by moving Poles**
- **Bipolar Field Corrections**

U40: 246 pairs of poles

U68: 144 pairs of poles

B_Y and B_Z tuning is combined

Tuning Strategy – Vertical Field Tuning



J. Pflueger, W71 report 2011-14

Deflective Local K

$$K_j = \frac{e}{2mc}\int_{z_j-\frac{\lambda_0}{4}}^{z_j+\frac{\lambda_0}{4}} B_y(z)dz = \frac{e}{2mc} I1y_j$$

Optical Local K

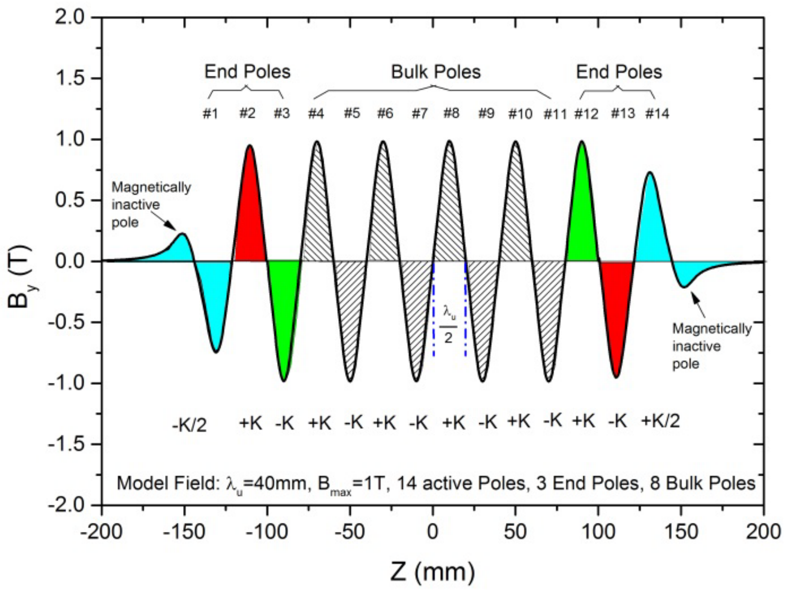
$$K_j = \frac{2e}{mc}\sqrt{\frac{PI(z_j+0.25\lambda_u)-PI(z_j-0.25\lambda_u)}{\lambda_u}}$$

PI: Phase Integral

$$PI(z) = \int_{-\infty}^{z}\left(\delta_a + \int_{-\infty}^{z_1} B_y(z_2)dz_2\right)^2 dz_1$$

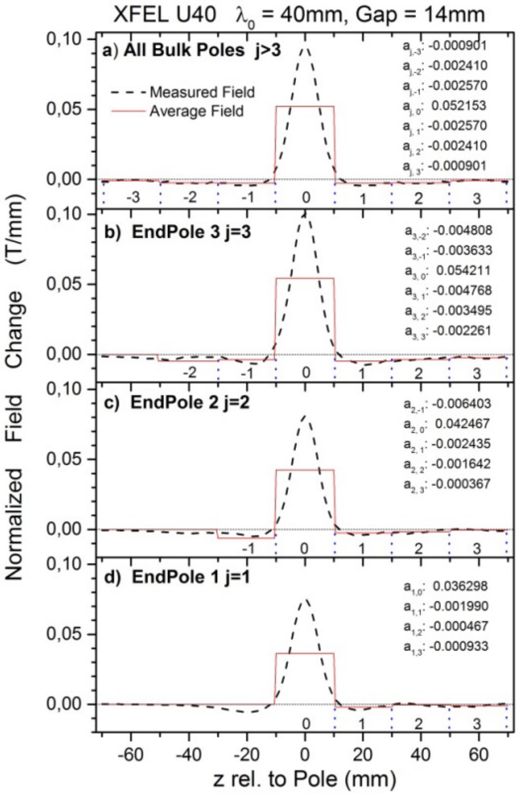
- Deflective K is defined. It is correlated with the optical K. For a given harmonic distribution, there is unique one to one correlation.
- Phase error ⟺ Optical K ⟺ Deflective K
  Beam wander ⟺ Deflective K
  } Unifying Deflective K to all poles

Tuning Strategy – Vertical Field Tuning



$$
\begin{array}{lcccccccccccc}
S_1 & = & a_0 \cdot p_1 & + & a_1 \cdot p_2 & + & a_2 \cdot p_3 & +....+ & a_{i-1} \cdot p_i & +.....+ & a_{N-1} \cdot p_N \\
S_2 & = & a_{-1} \cdot p_1 & + & a_0 \cdot p_2 & + & a_1 \cdot p_3 & +....+ & a_{i-2} \cdot p_i & +....+ & a_{N-2} \cdot p_N \\
S_3 & = & a_{-2} \cdot p_1 & + & a_{-1} \cdot p_2 & + & a_0 \cdot p_3 & +....+ & a_{i-3} \cdot p_i & +....+ & a_{N-3} \cdot p_N \\
\cdot & = & & & & & \cdot & & & & \cdot \\
\cdot & = & & & & & \cdot & & & & \\
S_j & = & a_{1-j} \cdot p_1 & + & a_{2-j} \cdot p_2 & + & a_{3-j} \cdot p_3 & +....+ & a_{i-j} \cdot p_i & +....+ & a_{N-j} \cdot p_N \\
\cdot & = & & & & & \cdot & & & & \cdot \\
\cdot & = & & & & & \cdot & & & & \cdot \\
S_N & = & a_{1-N} \cdot p_1 & + & a_{2-N} \cdot p_2 & + & a_{3-N} \cdot p_3 & +....+ & a_{i-N} \cdot p_i & +....+ & a_0 \cdot p_N
\end{array}
$$

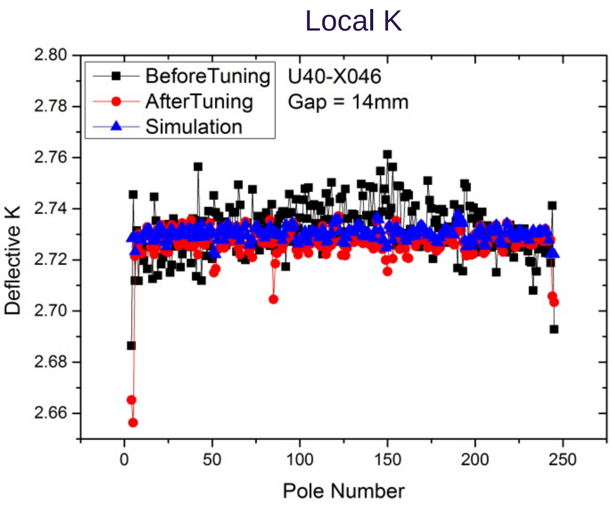
$$
A = \begin{pmatrix}
a_{11} & a_{12} & a_{13} & 0 & 0 & 0 & 0 \\
a_{21} & a_{22} & a_{23} & a_{24} & 0 & 0 & 0 \\
a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & 0 & 0 \\
0 & a_{42} & a_{43} & a_{44} & a_{45} & a_{46} & 0 \\
0 & 0 & a_{53} & a_{54} & a_{55} & a_{56} & a_{57} \\
0 & 0 & 0 & a_{64} & a_{65} & a_{66} & a_{67} \\
0 & 0 & 0 & 0 & a_{75} & a_{76} & a_{77}
\end{pmatrix}
$$

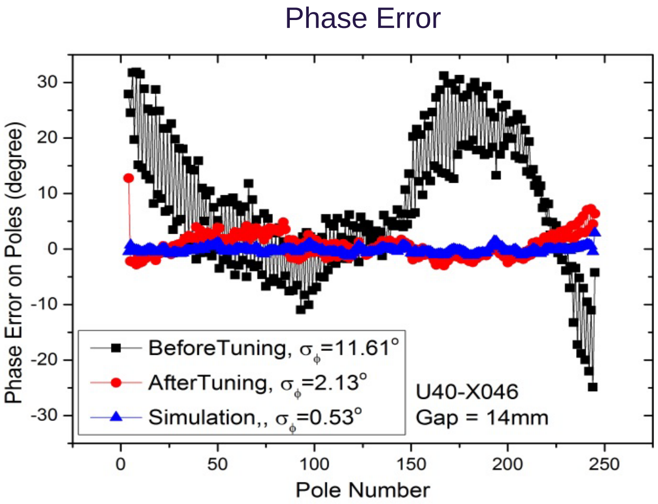


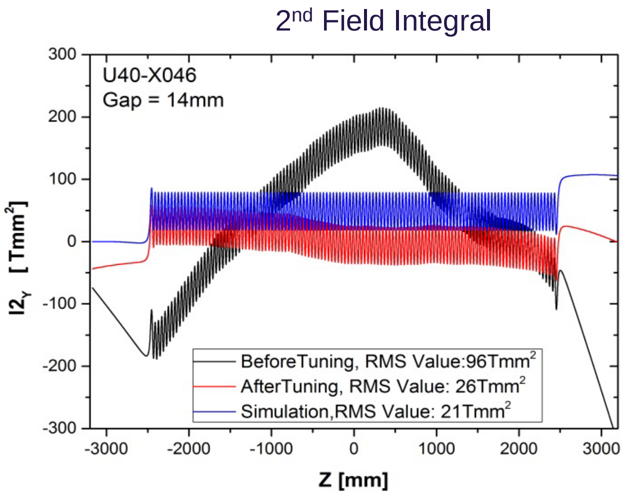
The Characteristic Coefficients a_i were measured for U40/U68:

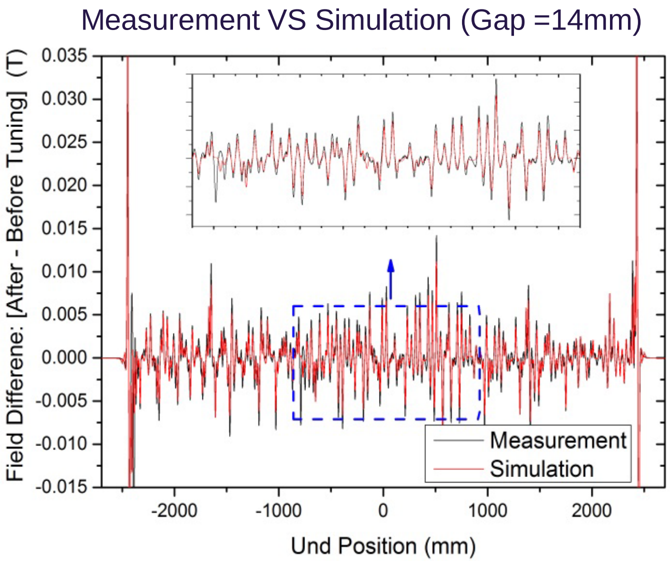
- For the 3 poles next to the end 'End Poles'
- For all other poles 'Bulk Poles'
- Tuning done at the 'Tuning Gap': U40, 14mm ; U68, 16 mm
- **Most Poles need to be tuned**
- **Both ending poles & bulk poles are corrected**
- **One Tuning Step is (usually) sufficient**
- **Simulation of tuning effect**

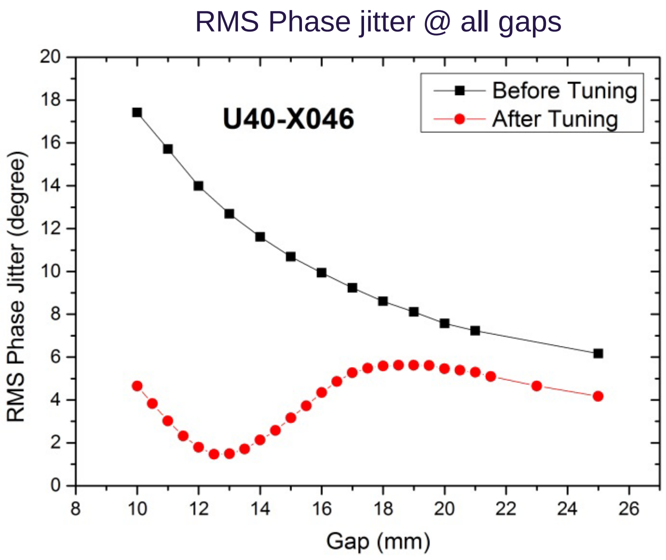
Representative tuning results --- X046


Local K


Phase Error

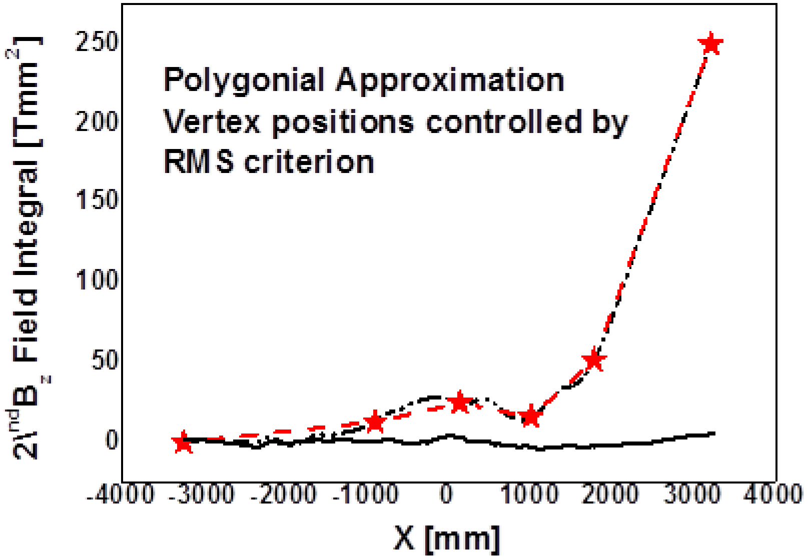

2nd Field Integral


Measurement VS Simulation (Gap =14mm)

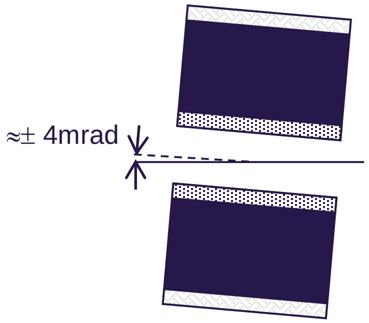

RMS Phase jitter @ all gaps

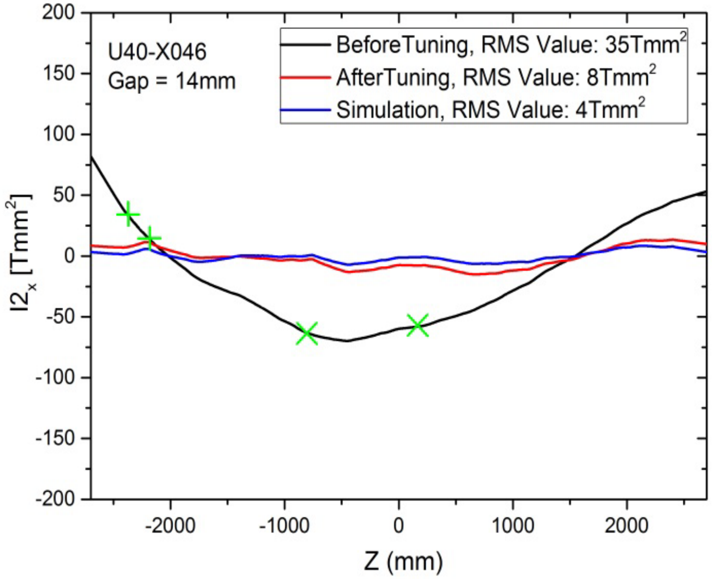
Tuning Strategy – Horizontal Field Tuning

- B_Z is due to errors only.
- Ideal B_Z trajectory 2nd Field Integral is a Null line
- Correction by Tilting Poles



	λ_0 [mm]	Tuning Gap [mm]	Signature [Tmm/mrad]
U40	40	14	0.0127
U68	68	16	0.0325





Minimum number of tuning poles

II. Shimming for gap dependent kicking error

Gap dependent kicking errors

Statement:

- Pole height tuning correct the errors at the tuning gap perfectly
- Normally the field errors at other gaps reduced simultaneously
- Occasionally there are non-negligible gap dependent kicking errors, especially to the U68 in ending poles.

Solutions:

- “Magic Finger” technique is a good solution for gap dependent kicking errors.

  Problem 1: Can’t be applied in the undulator middle.

  Problem 2: Occupies additional space.

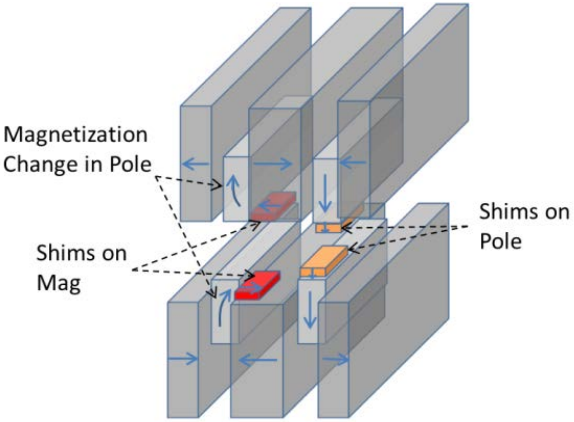
  Problem 3: Adding additional components, which are not needed to most undulators.
- “Shimming” technique:

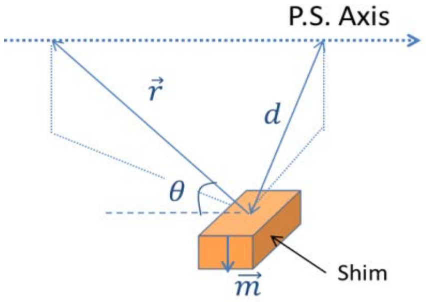
  Reason 1: Applies sufficient corrections to gap dependent kicking errors.

  Reason 2: Can be applied at both ending & middle poles.

  Reason 3: Occupies no additional space. Requires no additional components.
- The same strategy is used for phase shifter tuning. PS results are used to demonstrate the shimming technique.

Gap dependent kicking error tuning





Field integral in two-dimensional system:

$$\int_{-\infty}^{+\infty} B\,dz = \int_{0}^{\pi} \frac{m_{\perp}(3\sin^{2}\theta-1)+3m_{//}\sin\theta\cos\theta}{r^{3}}\,d\theta = \frac{28m_{\perp}}{15d^{3}}$$

Y. Li and J. Pflueger, Phys. Rev. ST-AB 18, 030703 (2015)

- Shim can be placed on either poles or magnets.
- Pole shim adds magnetization perpendicular to the axis. Magnet shim mainly contributes magnetization parallel to the axis but it also gives perpendicular components .
- Only perpendicular magnetization contributes to the vertical & horizontal field integral ($\int B_{\perp}$), parallel magnetization does not contributes.
- In principle pole shimming has stronger influence to the field integral. Unfortunately it narrows the gap and as well it is difficult to stay on pole. Therefore shim on magnet is more practical to use.

Changing the position of shims on magnet and changing its dimension give plenty of non correlated contributions to the gap dependent field integral.

Principle for shimming strategy:

Linearity principle Superposition principle Geometries

Shimming Strategy --- Linearity & Superposition Principle

Two assumptions serve as the basic principle for shimming strategy:

- Linearity principle: The field integral contribution of any shim is proportional to its thickness.

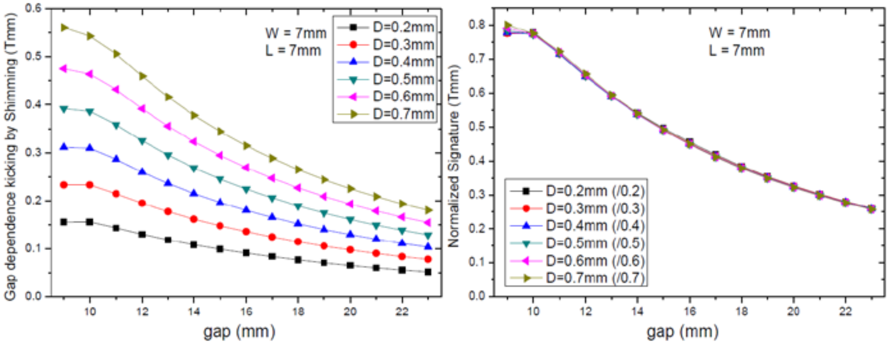
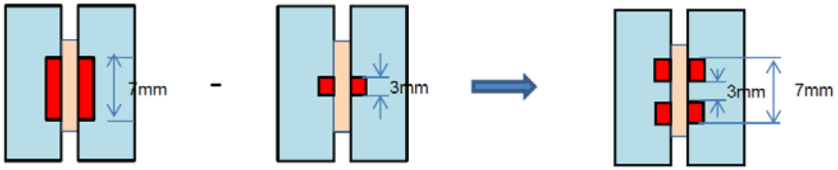
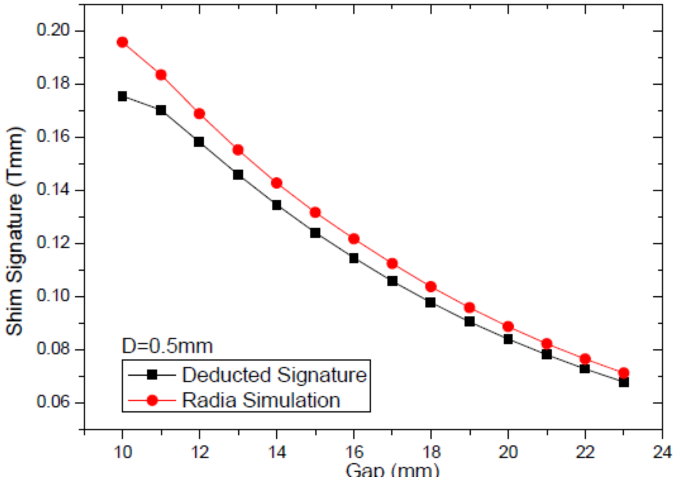


Fig. 6 The demonstration of the linear relationship between the field impact by shims and their thicknesses: The left plot is the signature contributed by the shims with thickness from 0.2mm up to 0.7mm and the right plot is the signature normalized to the thickness.

- Superposition principle: The field integral contribution of a combination of several shims equals to the sum up of every single shim.



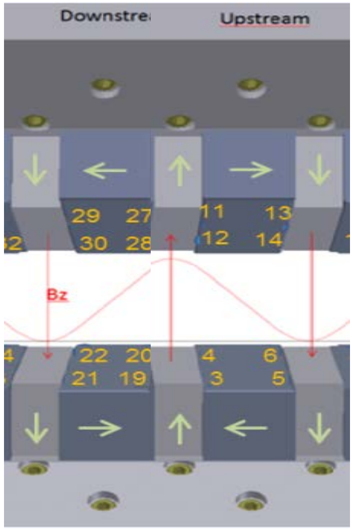


RADIA simulation is done for the test.

These two principles allow us calculating the needed **combination** of shims and their thickness for a specific gap dependent first field integral error, instead of using exhausting “trial & error” method.

Shimming Strategy --- Geometry

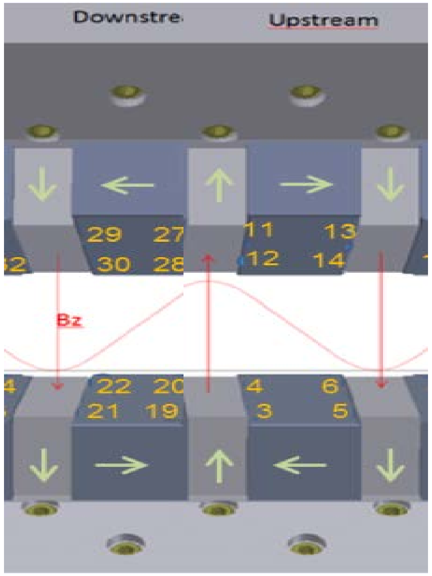
- Each period has two magnets. There are different positions on magnets.
- Tour geometry positions are involved: Original position (O), Mirror position (M), Reverse position (R) and Mirror Reverse position (MR).
- Define x=0 on phase shifter axis. To a shim on the original position make f(x) to present is contribution to field integral as a function of x. Then its contribution on "M" position is f(-x); on "R" position is –f(x) and on the "MR" position is –f(-x).



Combination Principle:

Combination Type	Expression	Effect
"O"+"O"	2f(x)	Integral and gradient doubled
"O"+ "M"	f(x)+f(-x)	Integral doubled, gradient canceled
"O"+ "R"	f(x)-f(x)=0	Integral and gradient canceled
"O"+ "MR"	f(x)-f(-x)	Integral canceled, gradient doubled
"M"+ "M"	2f(-x)	Integral doubled, gradient doubled with reversed sign
"M"+ "R"	f(-x)-f(x)	Integral canceled, gradient doubled with reversed sign
"M"+ "MR"	f(-x)- f(-x)=0	Integral and gradient canceled
"R"+ "R"	-2f(x)	Integral an gradient doubled with reversed sign
"R"+ "MR"	-f(x)-f(-x)	Integral doubled with reversed sign, gradient canceled
"MR"+ "MR"	-2f(-x)	Integral doubled with reversed sign, gradient doubled

Shimming Strategy --- Geometry

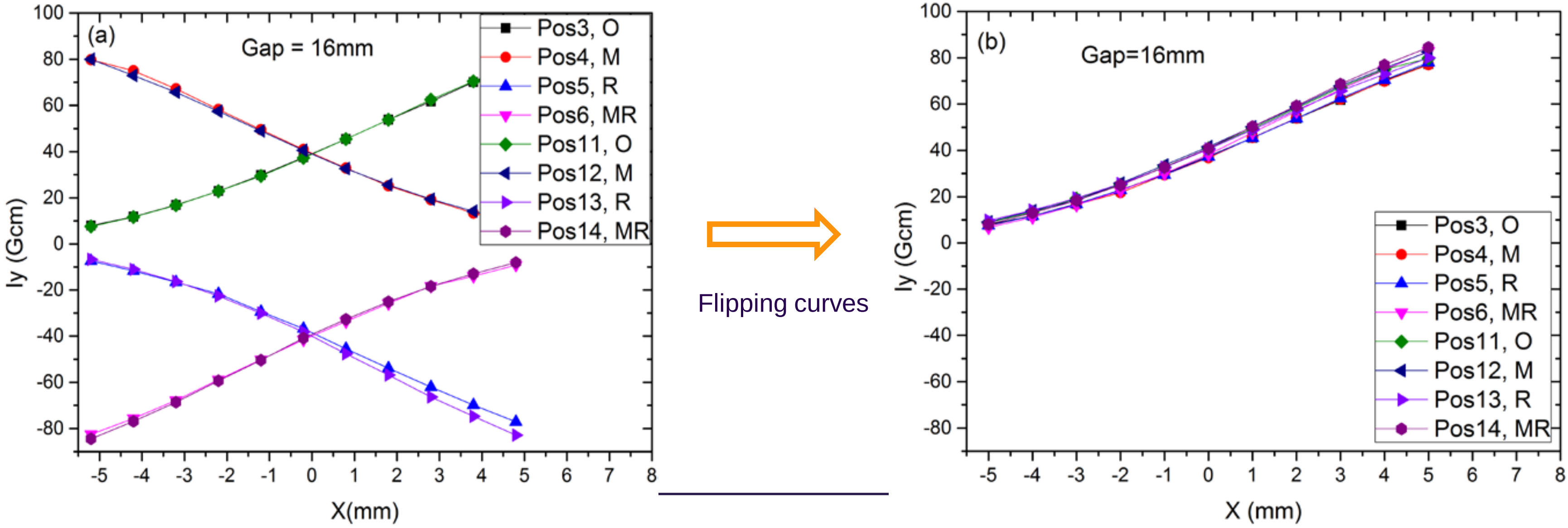


- Define position “3” as the original positions “O”. The geometry relations are:

Vertical field integral **Iy** :
“O” : 3, 11, 19, 27; “M” : 4, 12, 20, 28;
“R” : 5, 13, 21, 29; “MR” : 6, 14, 22, 30

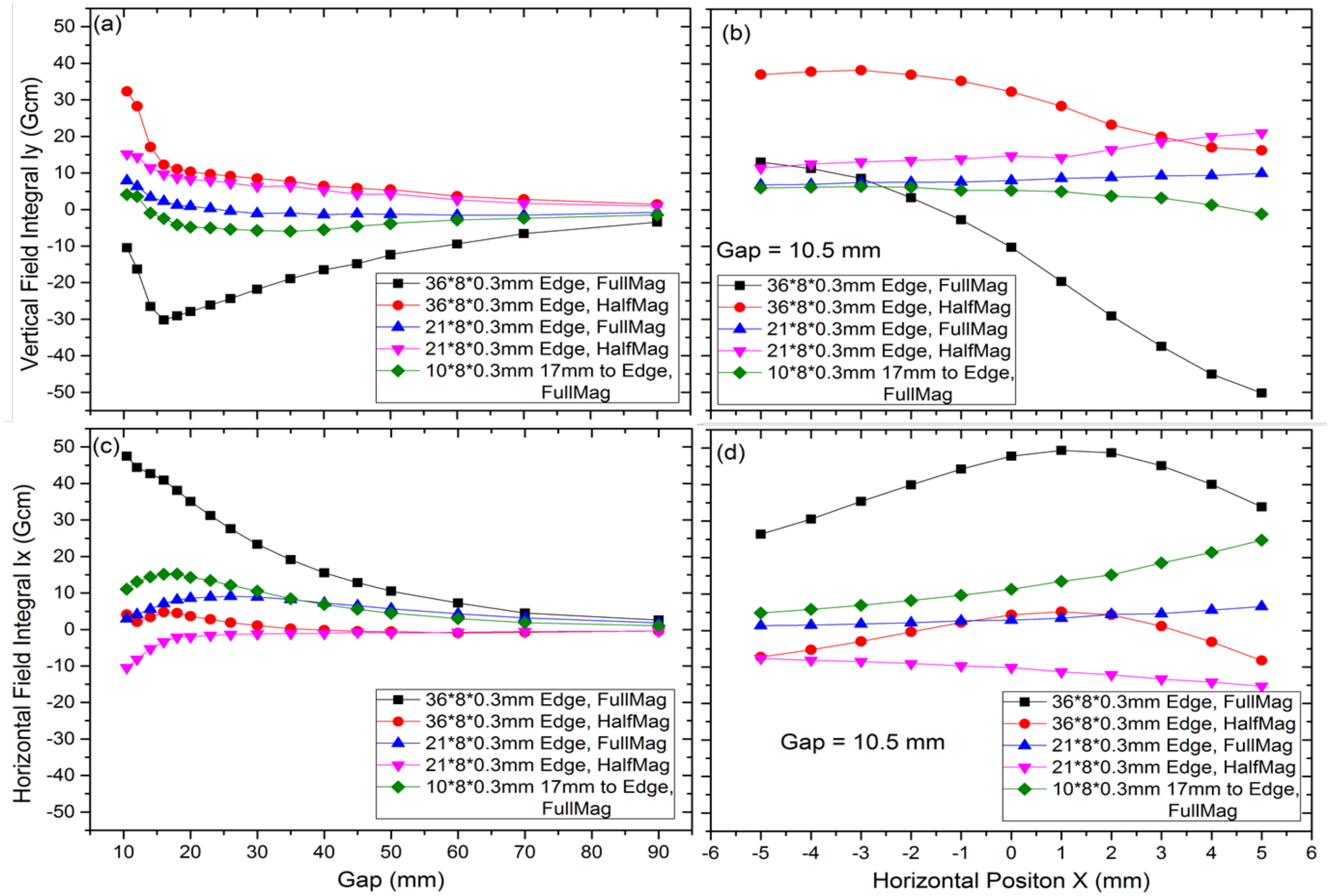
Horizontal field integral **Ix** :
“O” : 3, 13, 19, 29; “M” : 6, 12, 22, 28 ;
“R” : 5, 12, 21, 27; “MR” : 4, 14, 20, 30

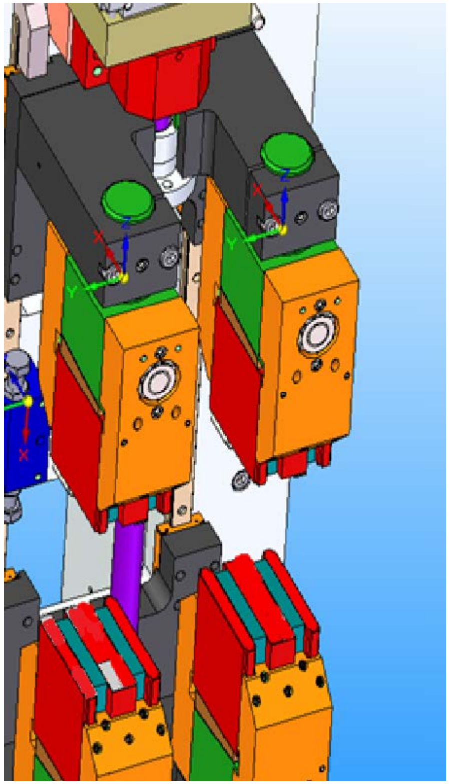
- Equivalence check for **Iy** :



Flipping curves

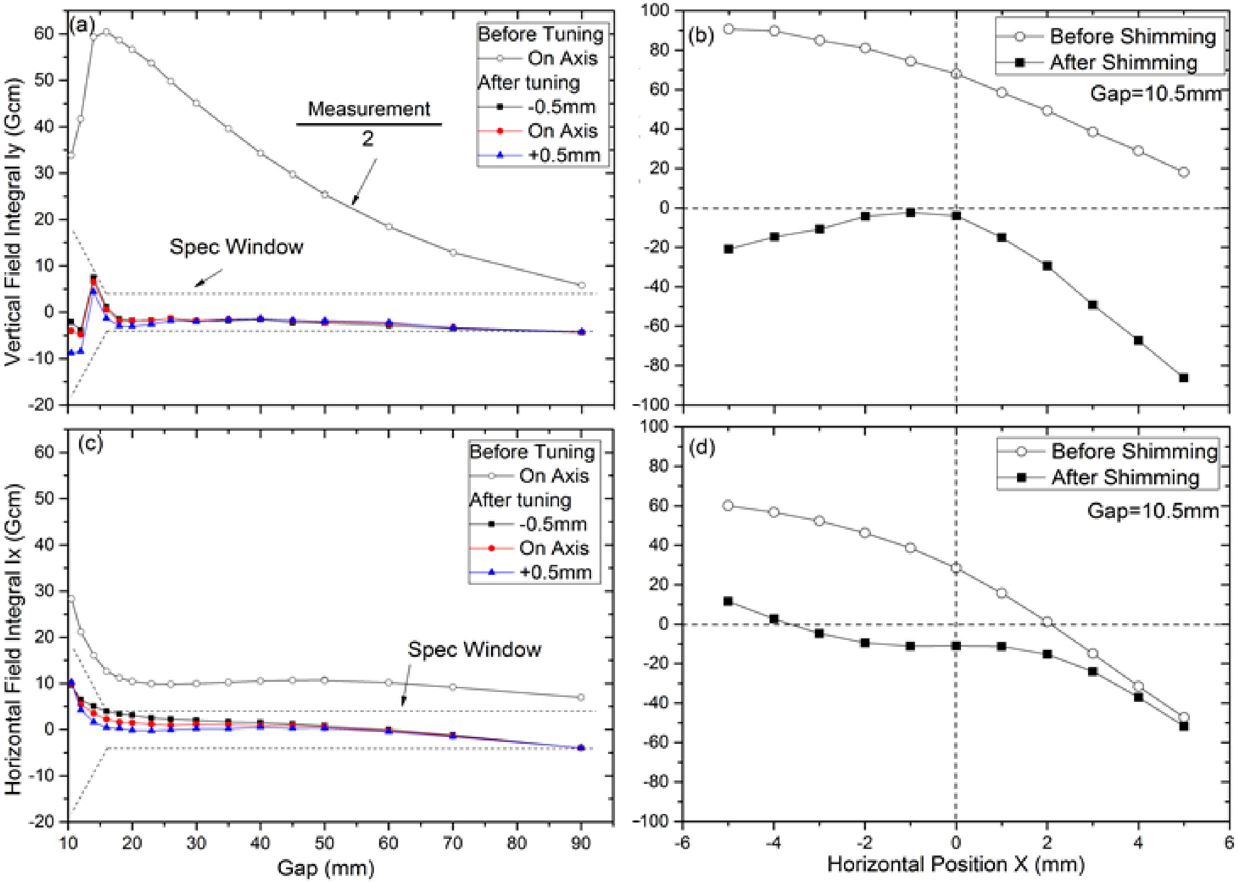
Shimming Signatures





- Five shims with different size and positions are selected for the phase shifter tuning.
- Two types of signatures are involved: The signature for gap dependent integral and the signature for the horizontal gradient.

Representative Results



- The shimming effect simulated based on the shimming principles agrees quite well with the measurement.
- Both gap dependent kicking and multipole effect can be corrected by shimming.
- Reproduced 96 times for PS

III. Shimming for gap dependent phase error

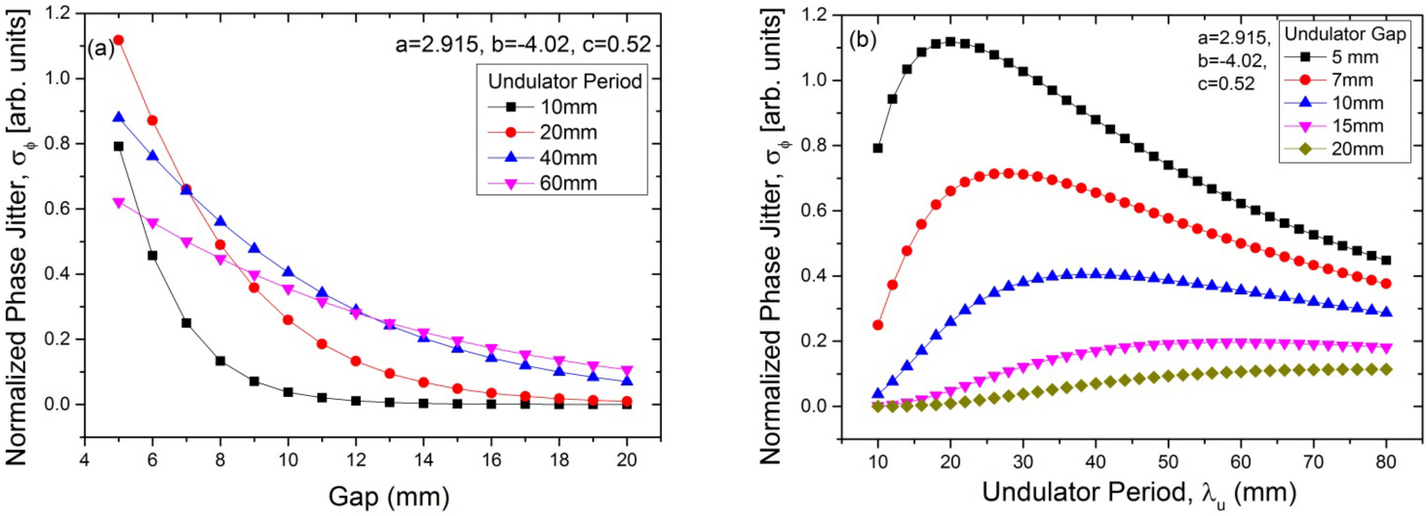
Gap dependent phase errors

Statement:

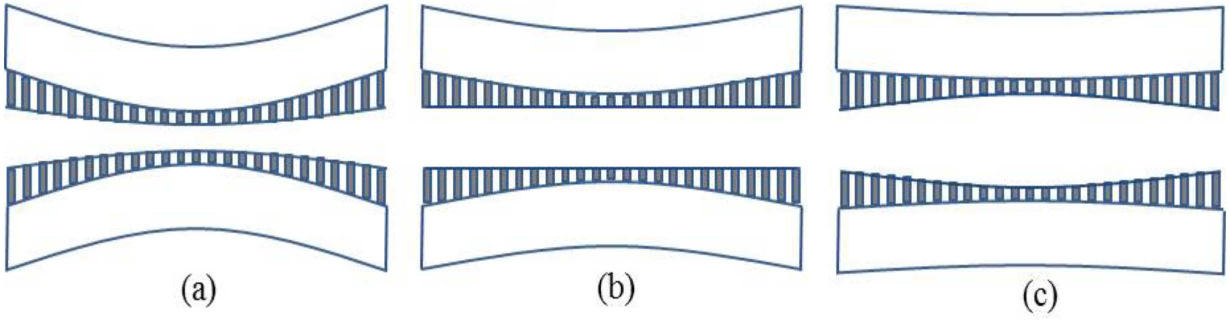
- Individual variations in large scale production. Undulator shows different girder deformation.
- Pole height tuning correct the deformation effect at the tuning gap. However the gap dependent deformation introduce gap dependent rms phase jitter.
- EXFEL takes careful mechanical design. Therefore most undulators have small gap dependent phase jitter, i.e. phase jitter matches the specifications in all gaps. However, there are two exceptions. (Manufacture default?)
- A shimming technique is developed to reduce the phase jitter induced by the girder deformation.

Gap dependent phase errors

- The girder deformation effect to the phase jitter relates to the undulator periods. No specific deformation types are given.



- In the EXFEL, the parabolic deformation is particularly observed:

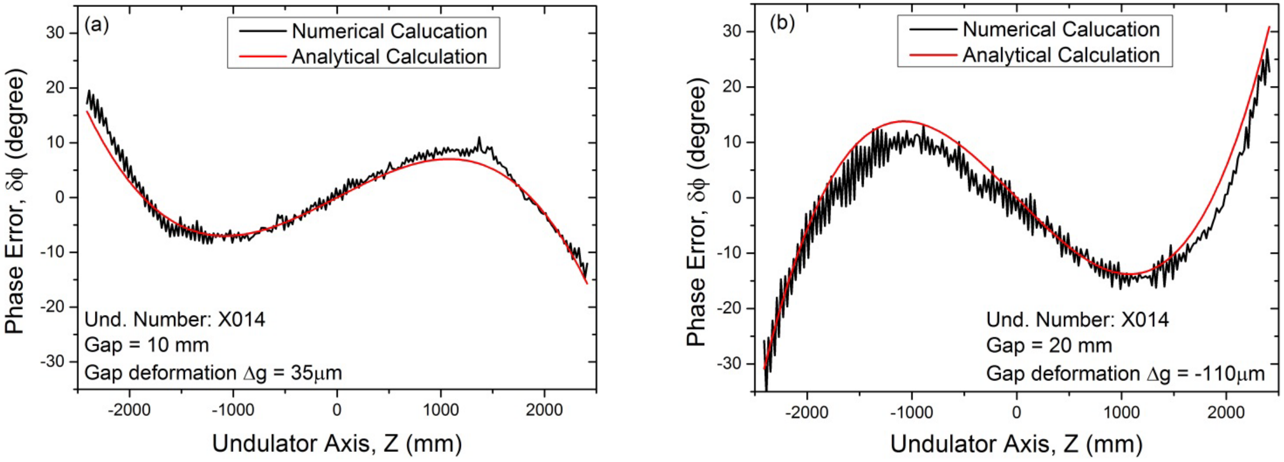


Y. Li, B. Ketenoglu, J. Pflueger, Phys. Rev. ST Accel. Beams **18**, 060704

Tuning Strategy --- Pole Height + Pole Tilt

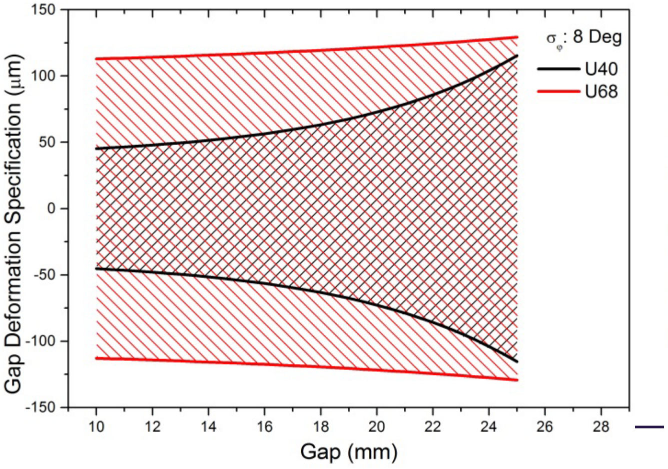
Phase wander by parabolic deformation:

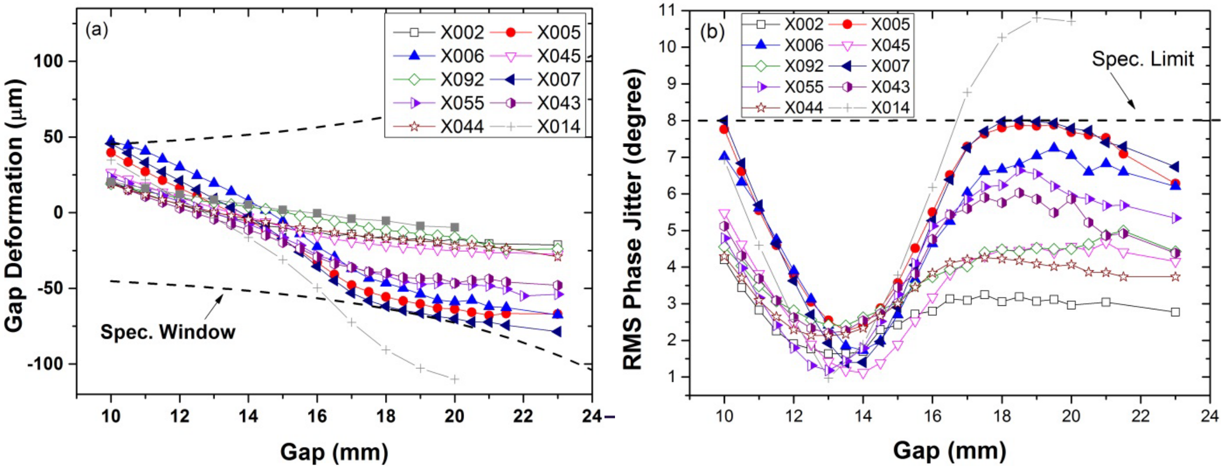
- $$\delta\varphi(z) = -\frac{4\pi}{1+2K^{-2}}\frac{\Delta g}{{\lambda_u}^2}\left(b+\frac{2cg}{\lambda_u}\right)\left(\frac{4}{3L_U^2}z^3-\frac{1}{5}z\right)$$



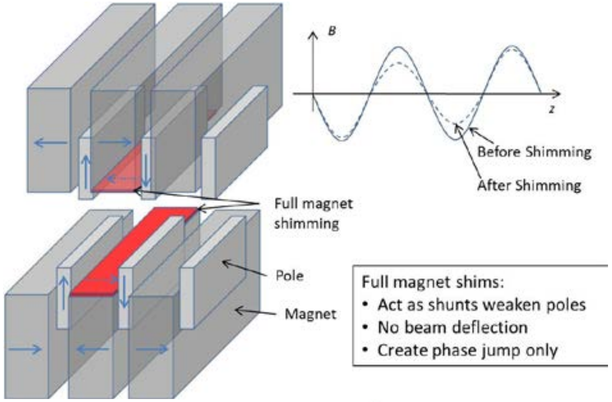
RMS Phase jitter:

- $$\sigma_\varphi = \sqrt{\frac{16}{1575}}\pi\frac{\left|\frac{b}{\lambda_u}+\frac{2c\,g}{{\lambda_u}^2}\right|}{1+2K^{-2}}N_U|\Delta g|$$

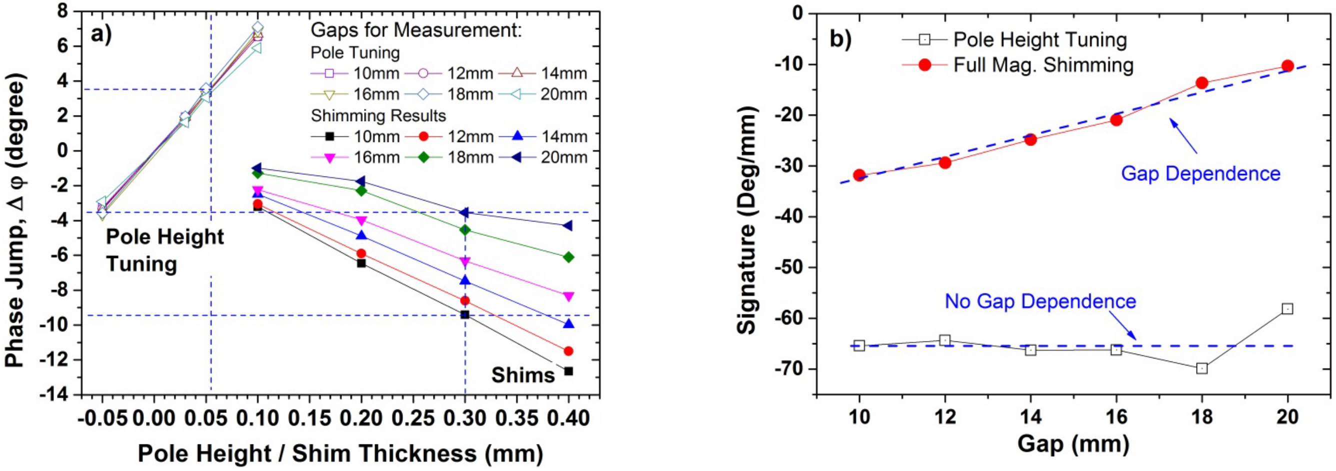




Shimming & Pole tuning effect on phase jump



Full magnet shims:
- Act as shunts weaken poles
- No beam deflection
- Create phase jump only



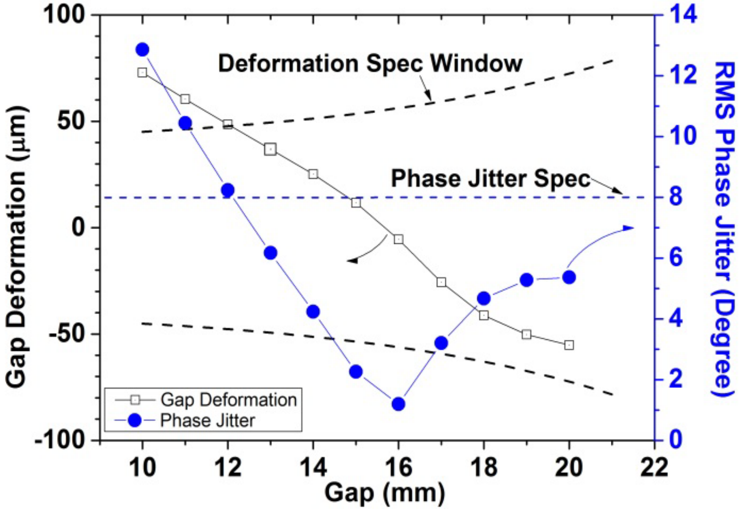
Observations:

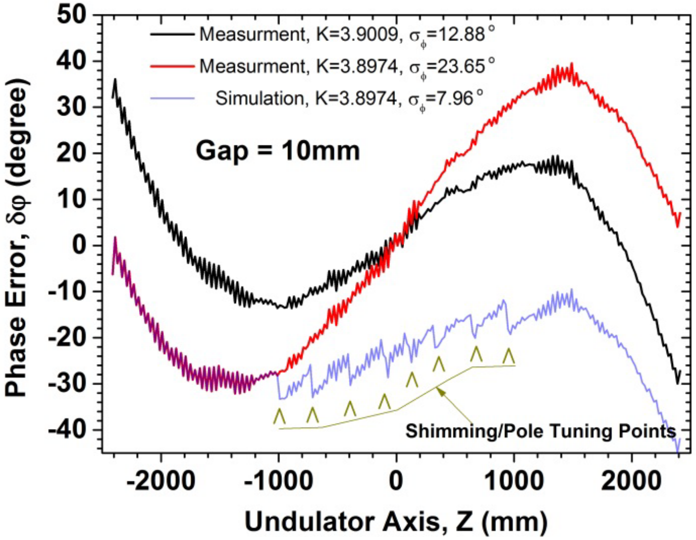
1. Linear relations between phase jump and pole height or Shim thickness
2. Gap dependent effect by shimming, independence by pole height tuning.

Tuning Strategy – Gap Dependent Shimming

Tuning steps:

1. Retune poles so that at 20mm gap the phase jitter is well within specs. At 10mm and 20mm 12.85° and 5.36° are obtained, respectively.
2. The K-parameter for phase error calculation is slightly reduced by 0.0035 or 0.089% from 3.9009 to 3.8974.
3. In the linear section phase shims are placed, each reducing the phase error by a step amount. Shimming effect on phase is reduced as gap getting bigger, no effect at 20 mm.

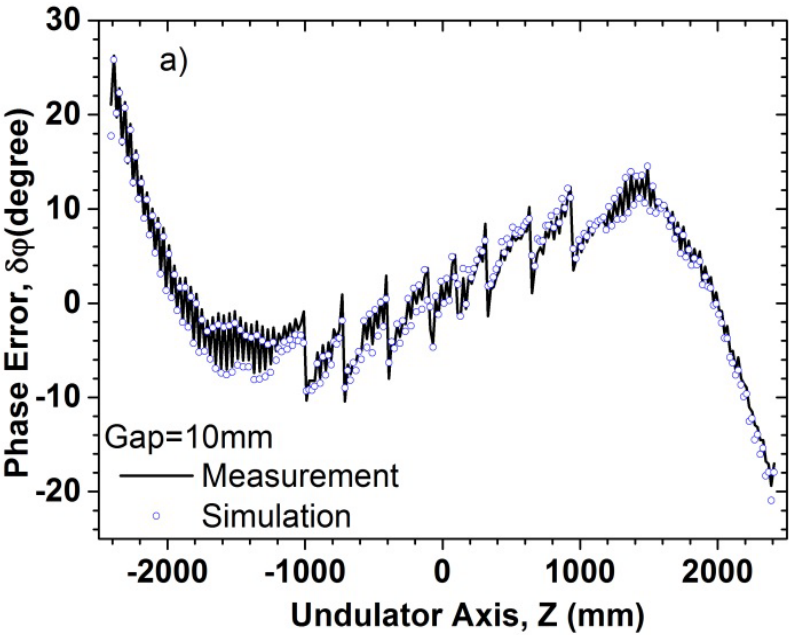


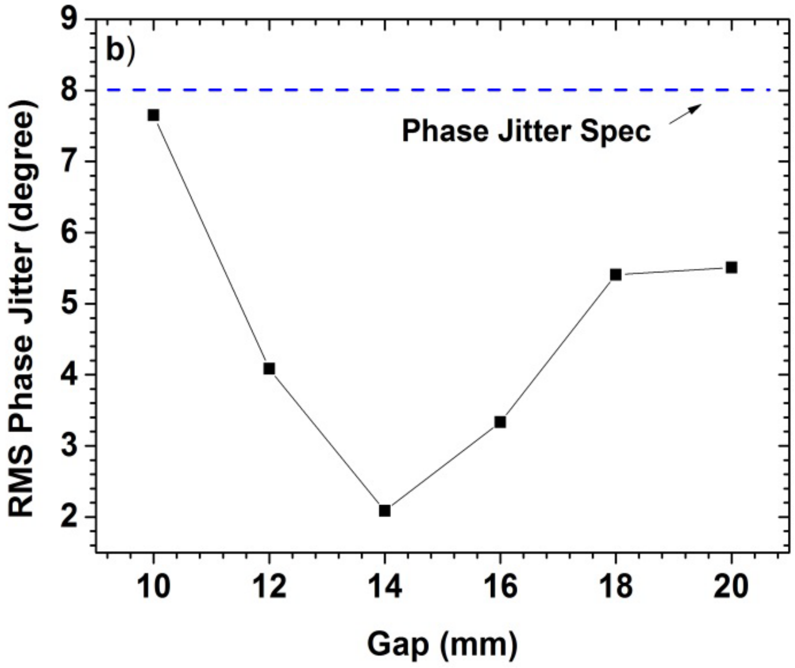


Final results

Statements:

1. Practical results agree with simulation very well
2. Phase errors fulfill the specifications to all gaps.





Conclusion

- EXFEL 91 (~460m) high qualified undulators.
- The tuning and test time is very short (each segment in 2 weeks).
- Systematic tuning strategy and procedure have been established that allows fast tuning and guarantees good field quality.
- It is important to find the linear relationship between tuning effect and tuning method, i.e. finding signature. (Pole height, shim thickness)
- It is important to properly use the principles of superposition and geometry.
- Technically it is convenient to introduce field simulations in order to expect the tuning effect.

Thank you for your attention