Superconducting Undulators Development at European XFEL

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European XFEL

SLAC, 22 April 2022

Outline

- SCU development plans at the EuXFEL
- SCU afterburner
- S-PRESSO
- Summary

Motivation for SCU at EuXFEL

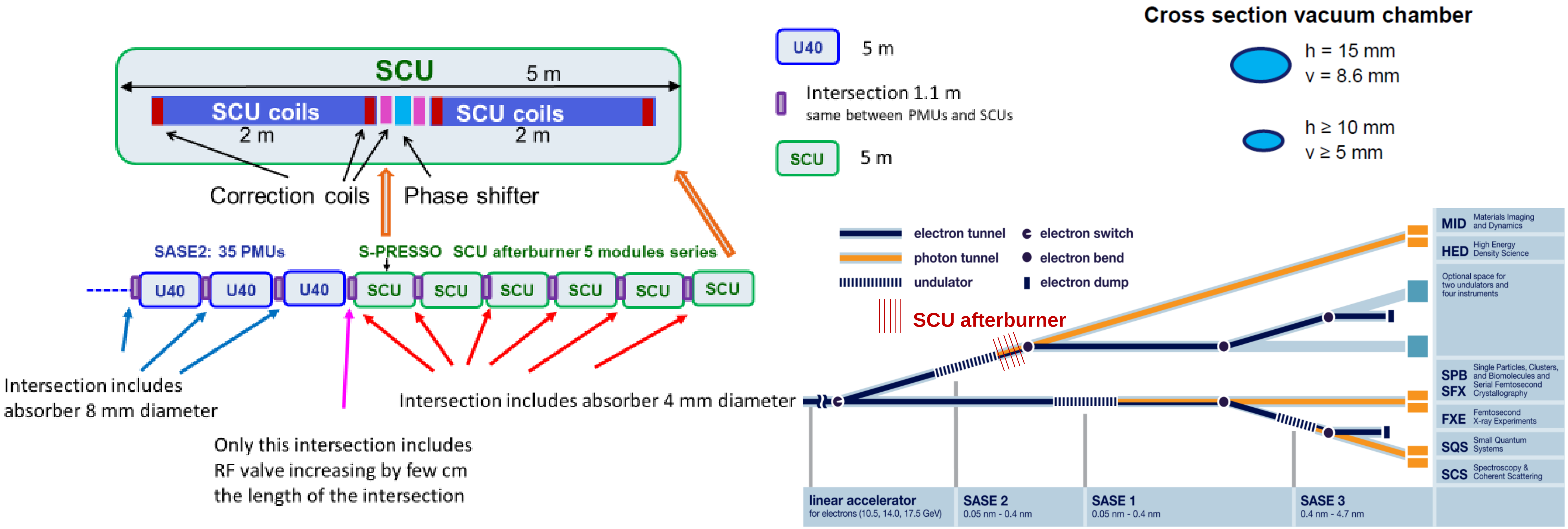
- EuXFEL is investing on the development of the technology for SCUs for its facility development program
- SCU afterburner for SASE2 undulator beamline will
  - allow lasing above 30keV
- A future possible whole undulator beamline at the EuXFEL would allow to:
  - generate photon energies of ~100keV
  - enhance the tunability range from hard to soft X-rays at the same electron beam energy
  - keep the photon energies generated now in pulsed mode operation, if the linac would be upgraded to CW operation.
    - ► CW operation will be possible at 8 GeV, while now the maximum electron beam energy is 17.5 GeV

SCU development plans at the EuXFEL

- SCU afterburner
- **S-PRESSO**: **S**uperconducting undulator **PRE-S**erie**S** m**O**dule to be produced before the five modules of the SCU afterburner
- Vertical and horizontal test stands for SCU at DESY-site
- Additional activities on SCUs
  - EuXFEL R&D project on Advanced SCU coils. In collaboration with Mechancal Enginering Group. Postdoc: V. Grattoni
  - LEAPS activity on pulsed wire method to determine the magnetic field profile of long structures (~2 m) with short periods (<20 mm). Postdoc: J. Baader

slide courtesy: S. Casalbuoni

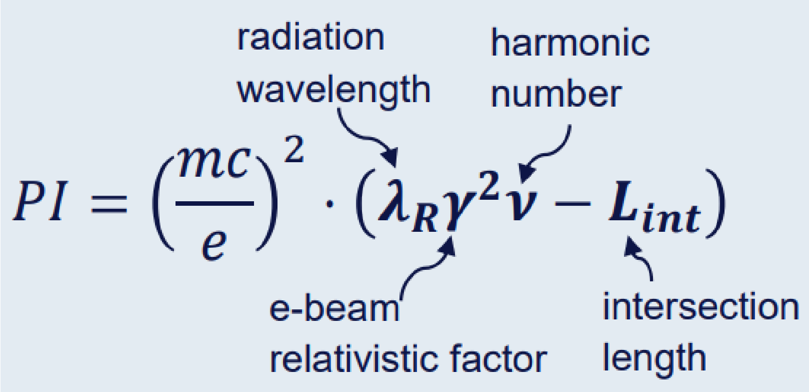
SCU afterburner



- The cooling scheme of S-PRESSO and of the afterburner modules will be based on **cryocoolers**

SC phase shifter for the cold intersection

- Requirements for the phase shifter:
  - The phase shifter guarantees continuous tunability between the photon energy tanges offered by the possible energies at the EuXFEL with a phase integral of $PI = 1.5 \times 10^{-5}\ T^2 m^3$
  - The available intersection length for the phase shifter is $L_{int} = 1.1m$



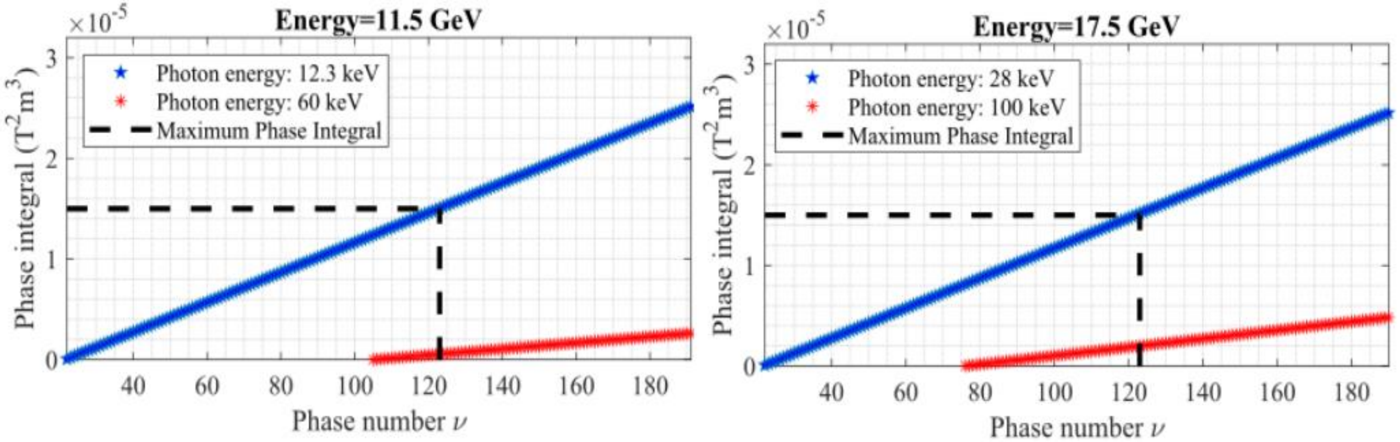
$$PI = \left(\frac{mc}{e}\right)^2 \cdot \left(\lambda_R \gamma^2 \nu - L_{int}\right)$$

radiation wavelength

harmonic number

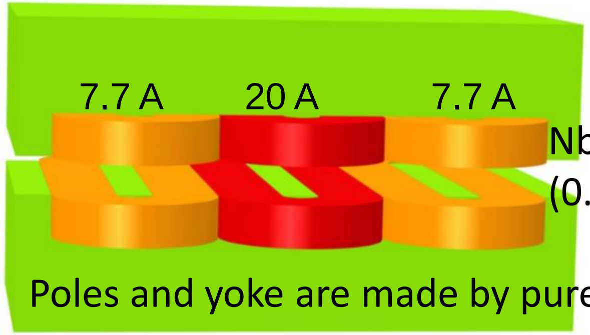
e-beam relativistic factor

intersection length



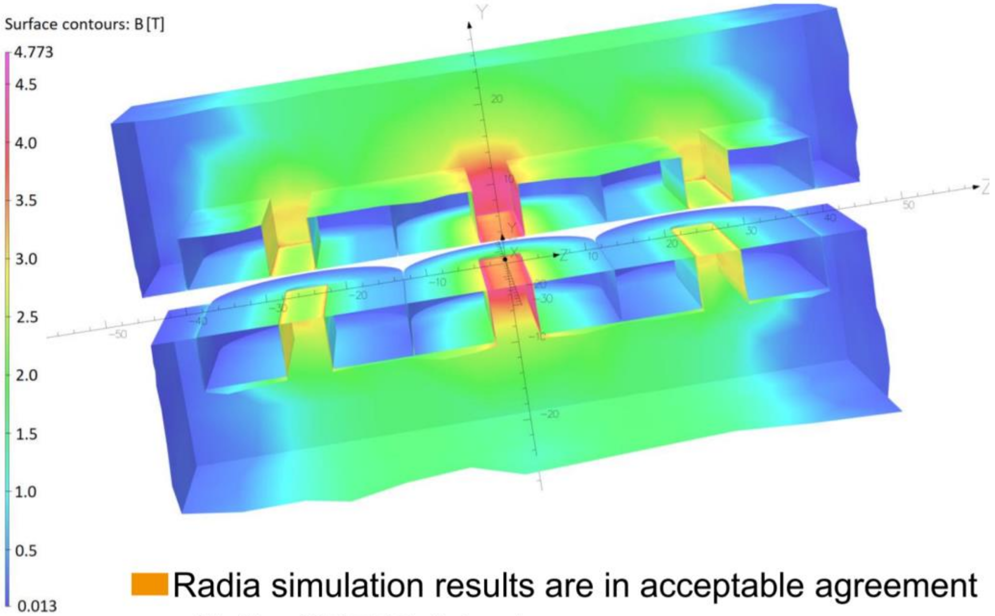
  - The magnetic length of the phase shifter should be minimized to have a compact magnetic structure
  - The magnetic length is defined as the length of the interval in which the first field integral I_1 is above $4 \times 10^{-6}\ Tm$
  - The conditions on the field integral are the following:
    - ▶ $I_1 < 4 \times 10^{-6}\ Tm$
    - ▶ $I_2 < 1 \times 10^{-4}\ Tm^2$

SC phase shifter for the cold intersection

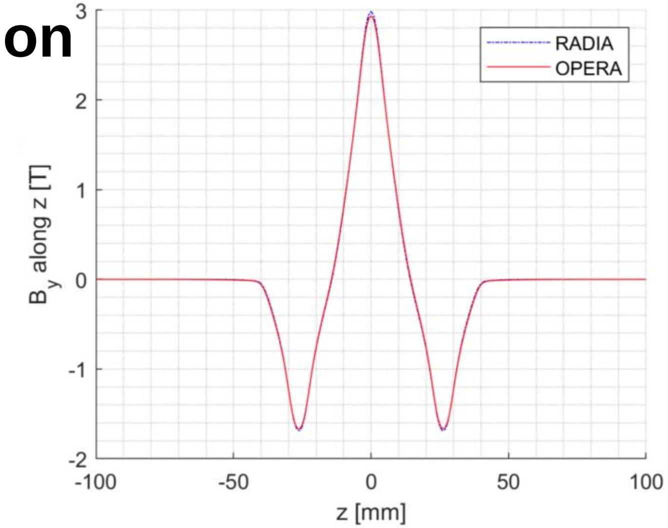


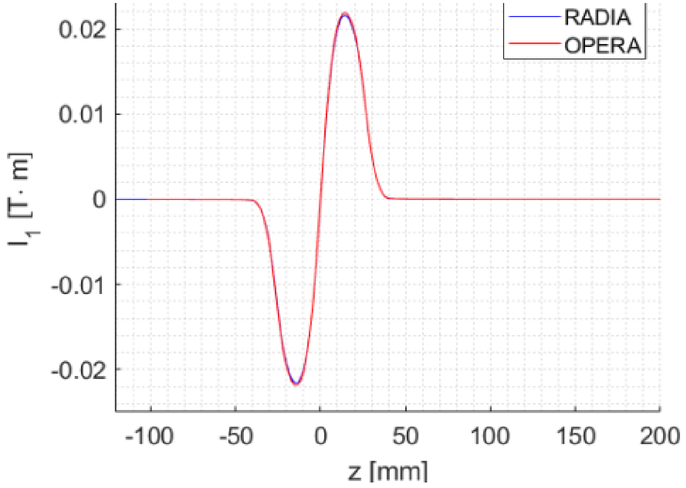
NbTi wire d_{bare} = 0.225 mm
(0.254 mm ins.)

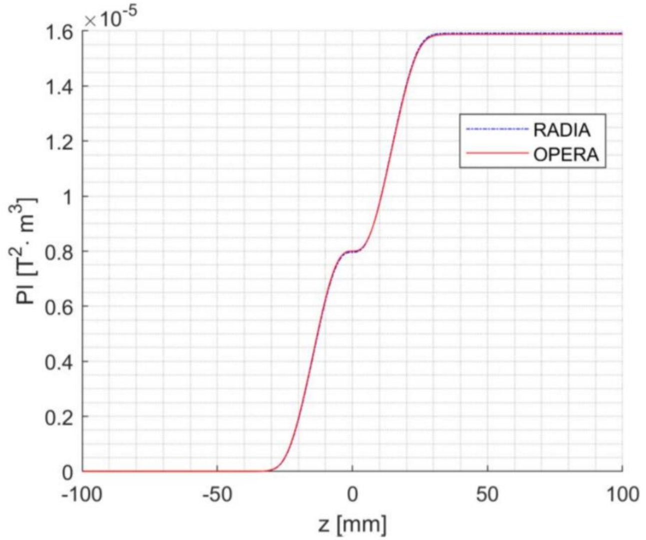
Poles and yoke are made by pure iron (ARMCO)



- Radia simulation results are in acceptable agreement with the OPERA-3d outcome







Physical length 90 mm

Magnetic length 242 mm

Requirements on field integrals are satisfied:

✓ $I_1 < 4 \times 10^{-6}\, Tm$

✓ $I_2 < 1 \times 10^{-4}\, Tm^2$

V. Grattoni et al., “Superconducting Phase shifter design for the afterburner at the European XFEL”, SRI2021, submitted

slide courtesy: S. Casalbuoni

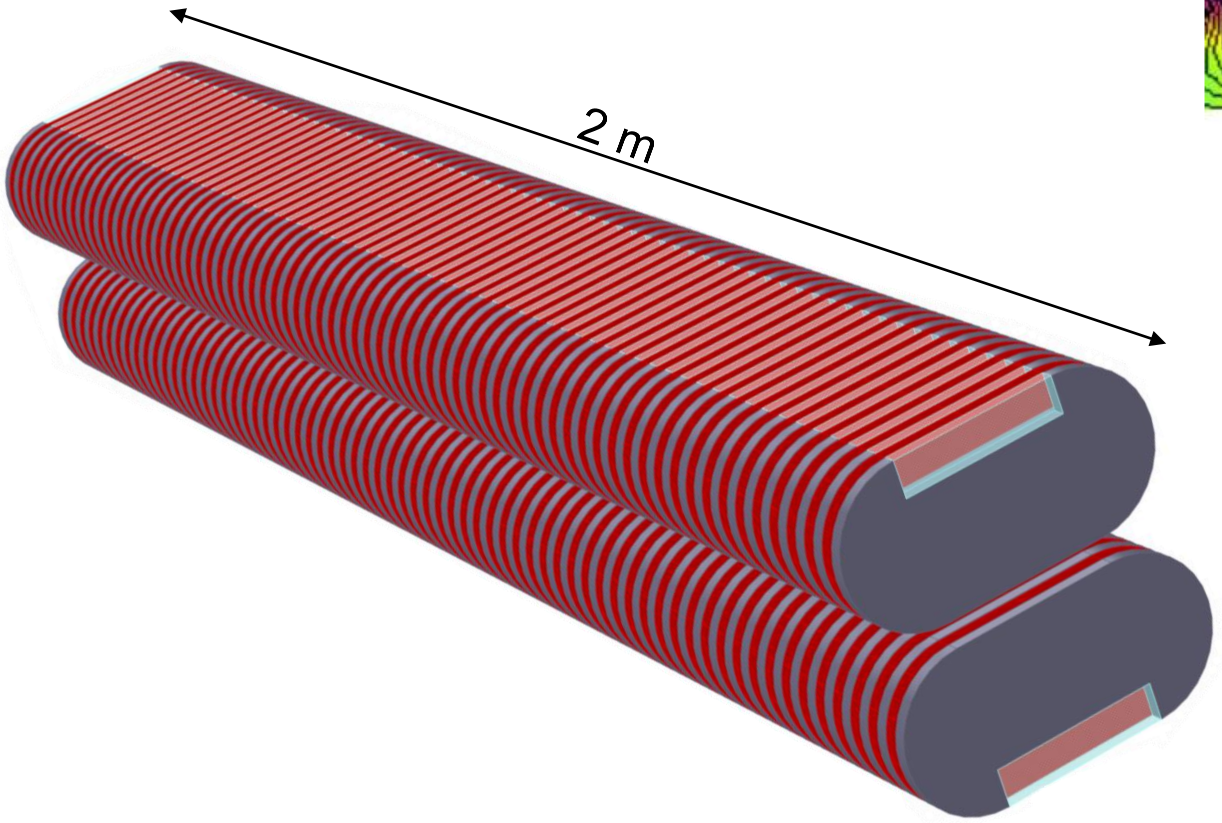
S-PRESSO

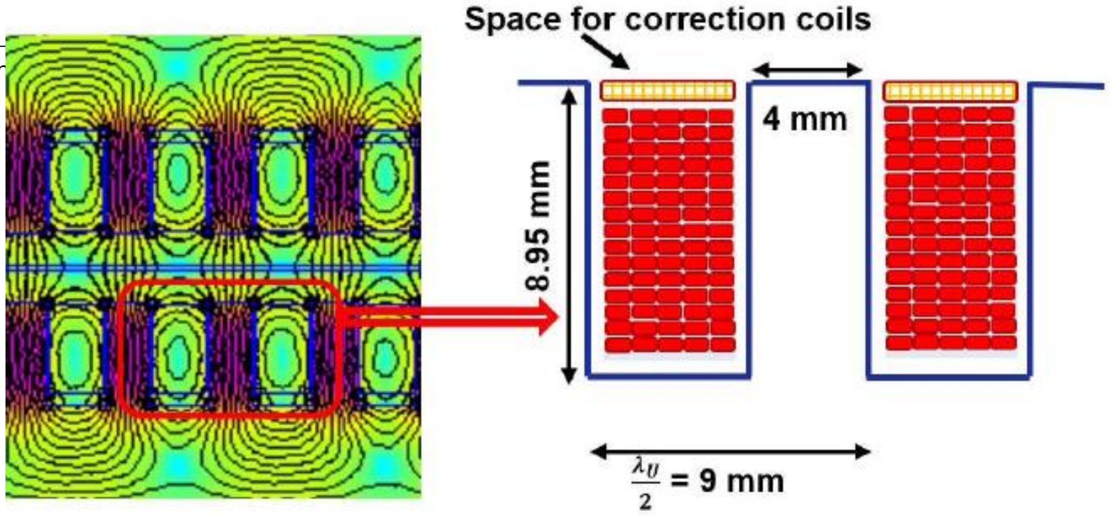
- Aims of S-PRESSO are to test:
  - the alignment of the two 2m long SCU coils in the 5m long cryostat
  - the mechanical tolerances necessary for the FEL process
  - the implementation of the module in the accelerator

- S-PRESSO will be used to
  - amplify the hardest radiation generated by the SASE2 PMUs
    ► in this configuration we will check the performances of S-PRESSO
  - test harmonic schemes to generate larger photon energies

S. Casalbuoni, „A preseries prototype for the superconducting undulator afterburner for the European XFEL", SRI2021, submitted

S-PRESSO parameters





Period	18 mm
Peak field	1.82 T
K	3.06
Vacuum gap	5 mm
First field int. (x,y)	< 0.004 T mm
Second field int. (x,y)	< 100 T mm^2
$\Delta K/K$ rms	<0.0015
Roll off at ±2 mm	$< 5 \times 10^{-5}$
Beam heat load	10 W
Pressure beam vacuum chamber at room temperature	$< 10^{-7}$ mbar

Mechanical tolerances study for S-PRESSO

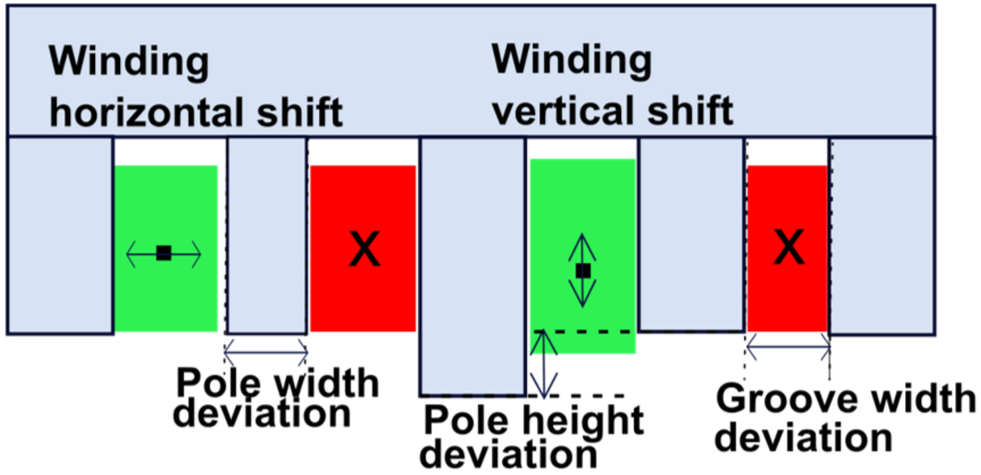
- GENESIS simulations have shown that for $\boldsymbol{\sigma}\left(\frac{\Delta K}{K}\right) = \mathbf{1.5 \times 10^{-3}}$, more than 95% of the mean power with respect to the ideal case can be reached.
  - FEL simulation done considering a whole SCU beamline
- Mechanical tolerances required for S-PRESSO

Pole height	**Winding vert. shift**	**Pole width**	**Coil width**
±20 µm	±20 µm	±10 µm	±10 µm

  - with deviation from the average period length ≤20 μm

Detailed study can be found in the backup slides

Real undulator



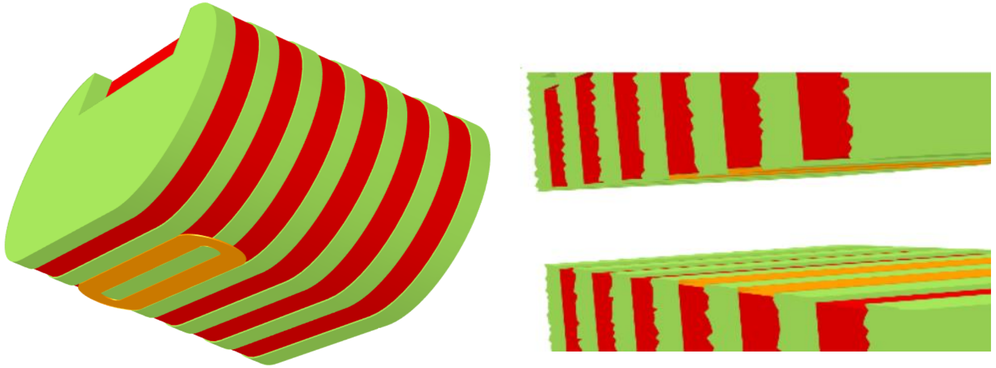
V. Grattoni et al., "An analytical study to determine the mechanical tolerances for the Afterburner Superconducting Undulators at EuXFEL", SRI2021, submitted

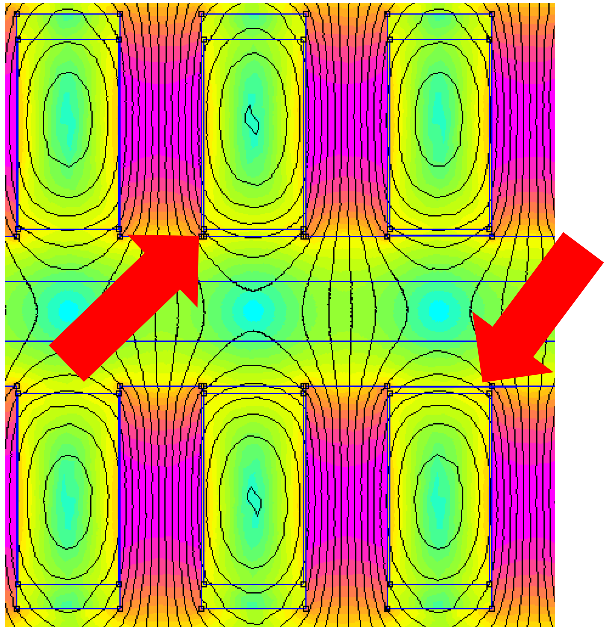
Option for correction scheme

- If the following mechanical tolerances cannot be satisifed

Pole height	Winding vert. shift	Pole width	Coil width
±20 µm	±20 µm	±10 µm	±10 µm

- Shimming with a wire of 0.25mm diameter is considered as correction scheme.
- Several correction coils powered by a maximum of 10 power supplies with max current of 10 A might be applied



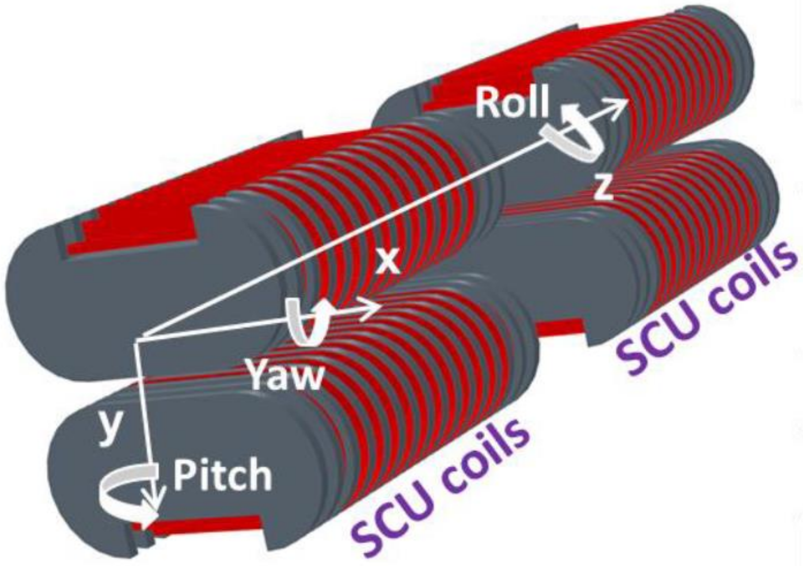


Shimming the coils with a current of 10 A enables a correction up to $\frac{\Delta K}{K} \leq 1.6 \times 10^{-2}$

slide courtesy: S. Casalbuoni

Alignment for S-PRESSO

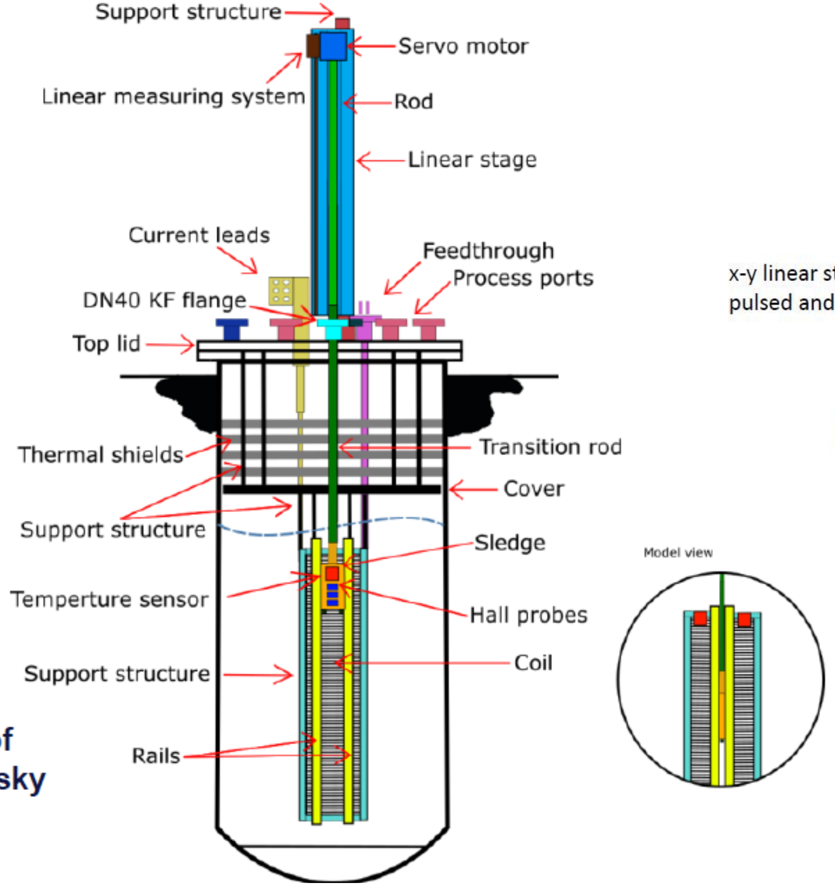
- The allowed misalignment between the two 2 m long coils should be:
  - measurable
  - keep the error budget contribution negligible: $\sigma\left(\frac{\Delta K}{K}\right) \ll 1.5 \times 10^{-3}$ for each set of SCU coils



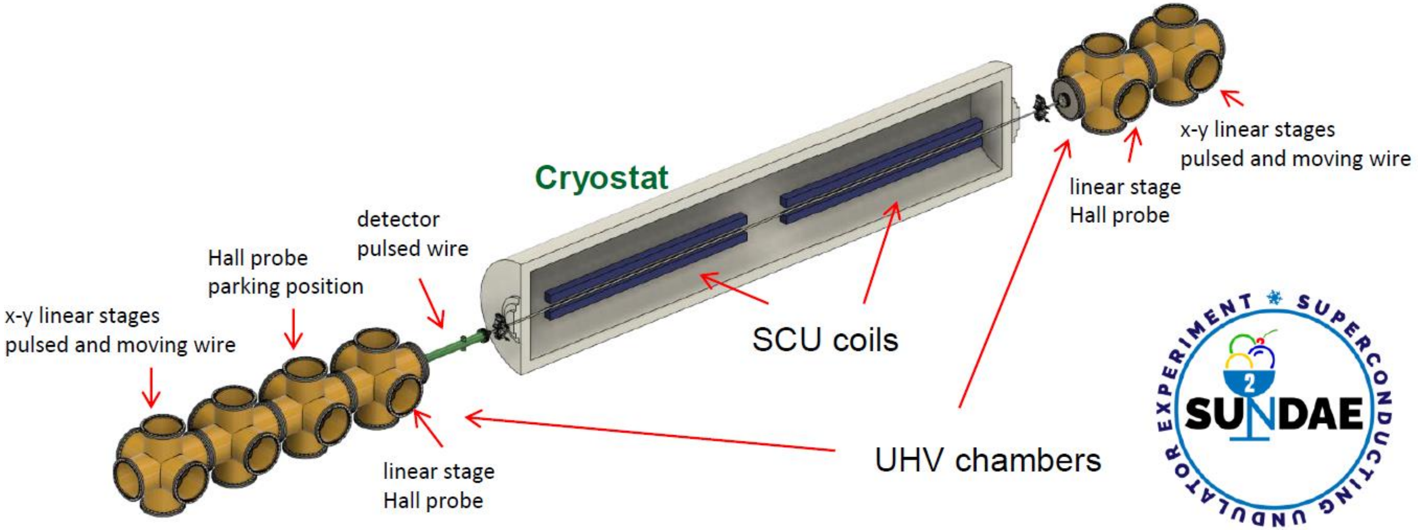
x	± 200 µm
y	± 50 µm
pitch	< 0.1 mrad
yaw	< 0.1 mrad
roll	< 2 mrad

slide courtesy: S. Casalbuoni

Vertical and horizontal test stands for SCU at DESY-site



Courtesy of
P. Ziolkowsky



Courtesy of J. Baader

J. Baader et al., „Requirements and limitations of the pulsed wire technique for measuring short-period long undulators‘ magnetic field“, SRI2021, submitted

- Test SCU coils up to 2m long in liquid or superfluid helium

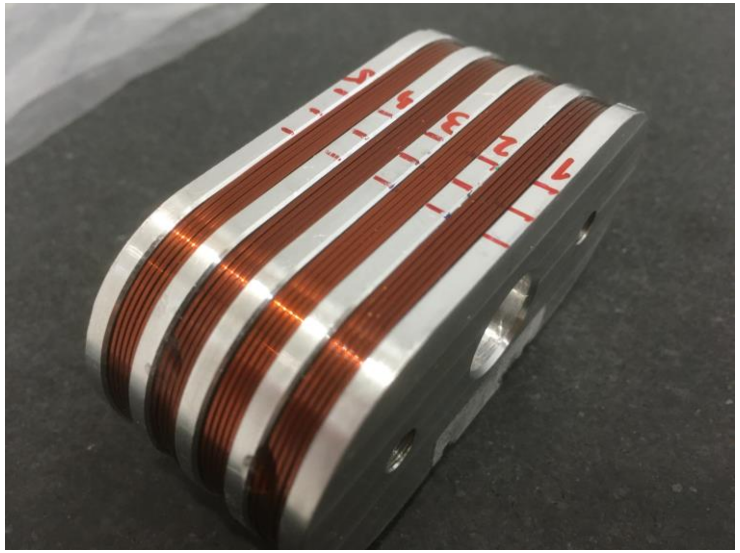
B. Marchetti et al., „Liquid Helium vertical test-stand for 2m long superconducting undulator coils“, SRI2021, submitted

Additional activities on SCUs

- EuXFEL R&D project on Advanced SCU coils

Winding machine

Test coil



Impregnation chamber

Thank you for the attention

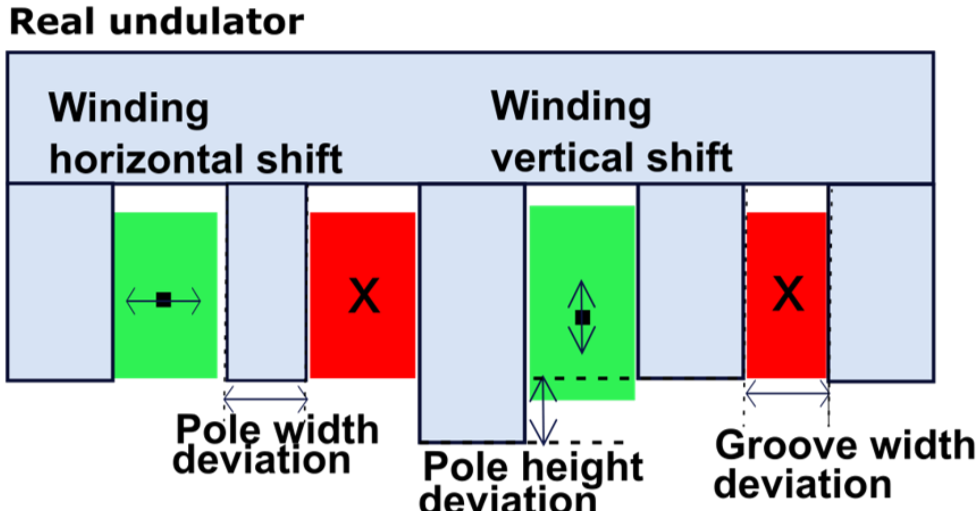
Backup slides

Impact of mechanical deviations on the field

- A shorter undulator (15 periods) is considered to characterize the effect on the magnetic field from different mechanical errors (signatures) with FEMM
- Each parameter of the coil has been varied while keeping the other ones constant and equal to the design value. This procedure allows to find the sensitivity of the K value to the precision of each varied parameter.
- The signature ΔB is defined as follows:

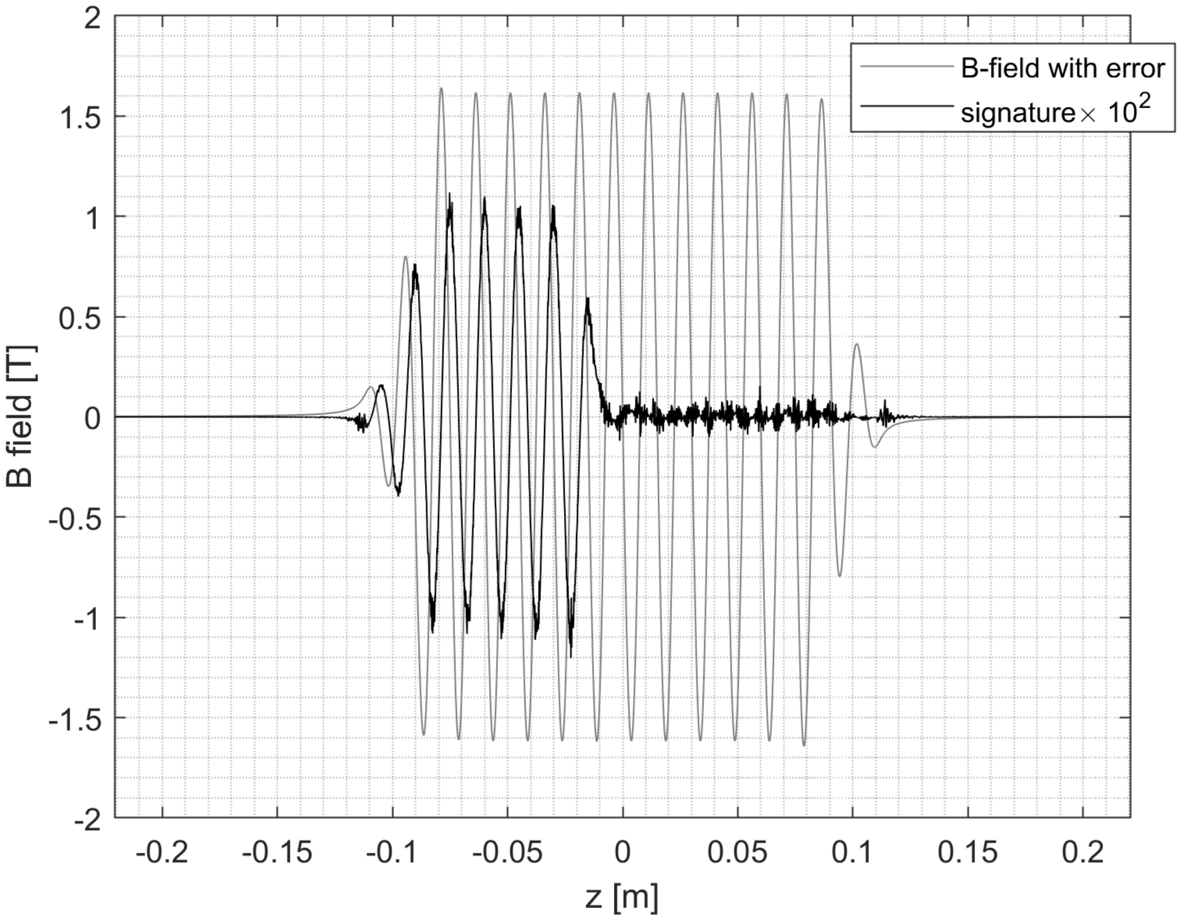
$$\Delta B = \tilde{B} - B_0$$

where B_0 is the ideal field and $\tilde{B}$ is the field with a mechanical error.

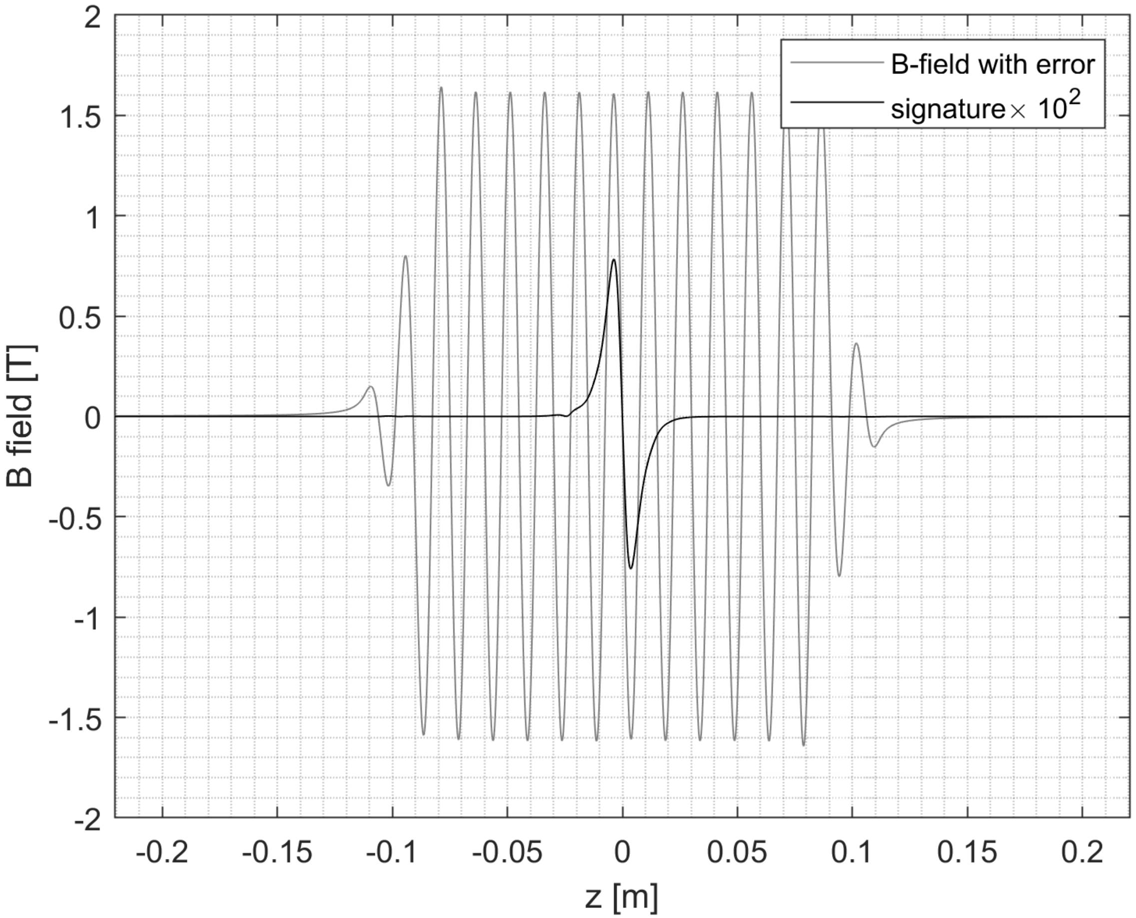


Signatures from FEMM simulations

- Error on one pole of the undulator, width +30µm

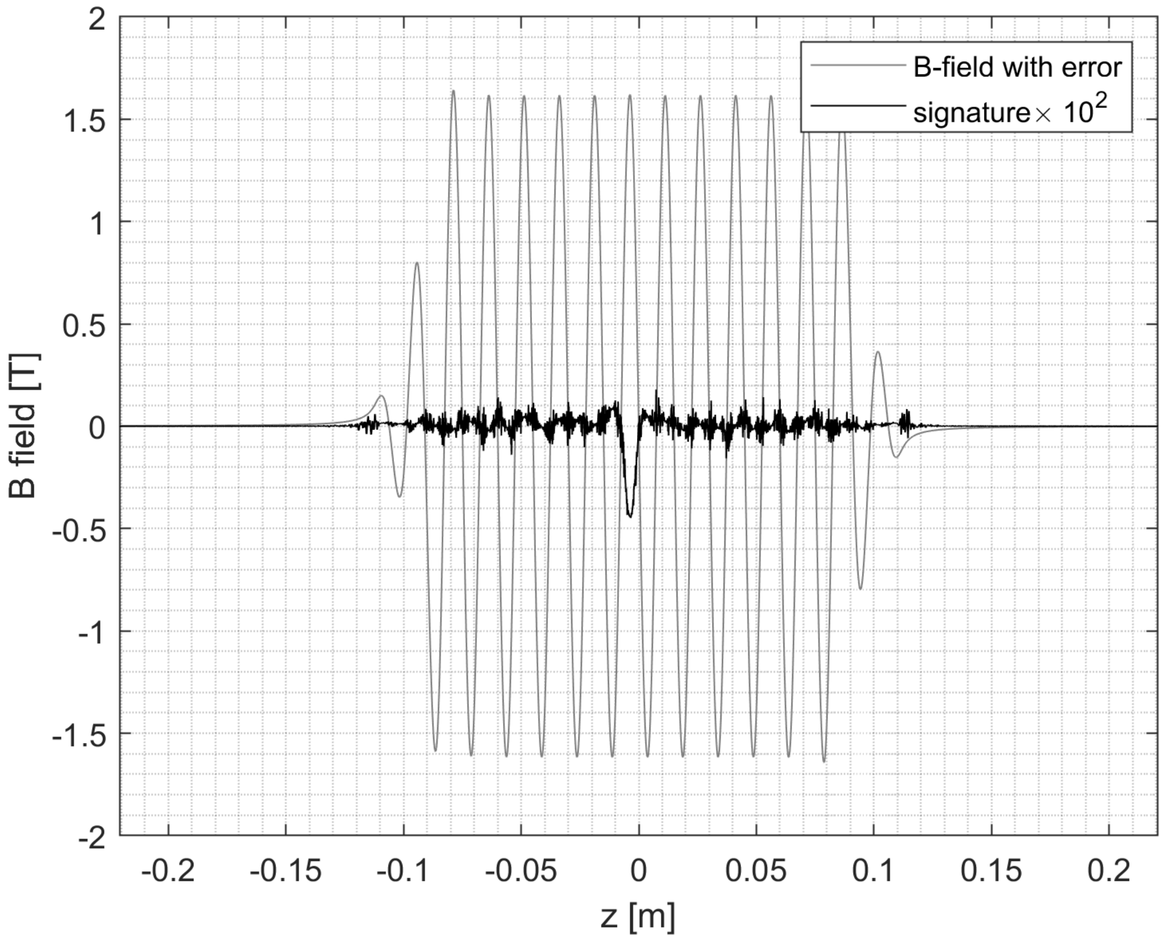


- Error on winding package, vertical shift +50µm



Signatures from FEMM simulations

- Error on one pole of the undulator, height +50µm



- Error on the groove width, and also on the pole width shows a sinusoidal signature

- Error on the winding package
  - is the dervative of a Gaussian function when it is a vertical shift
  - is a Gaussian function when it is a horizontal shift

- Error on the pole height is described by a Gaussian function

Correspondent Mechanical Tolerances

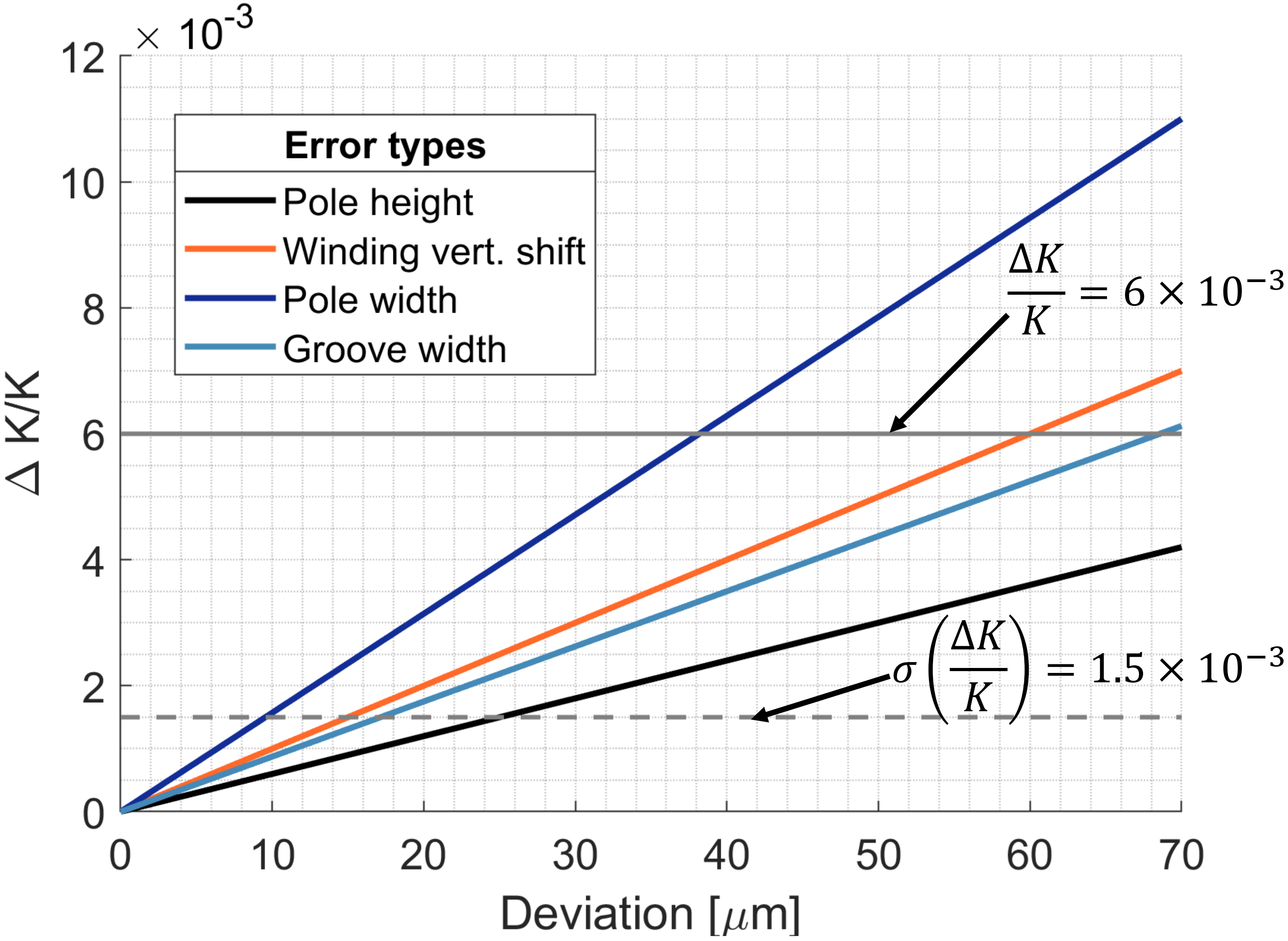
The amplitude of the signature is **linearly related** with the error size for small error amounts

- to find the linear relation, a pair of error sizes are simulated for each error type.

- each amplitude can be related with the max. $\frac{\Delta K}{K}$
  - all the values of the magnetic field positive and negative peaks B_{peak} and the position of the peaks are stored
  - from the difference of the position of consecutive peaks, we get the half period length $\frac{\lambda_u}{2}$
  - We can finally get $\frac{K}{2} = 93.4 \cdot \left|B_{peak}\right| \cdot \frac{\lambda_u}{2}$ and $\Delta K/2$ is calculated between the difference of the max. $\frac{K}{2}$ of the field with and without the error

Correspondent Mechanical Tolerances

- Genesis simulations show that a $\sigma\left(\frac{\Delta K}{K}\right) \leq 1.5 \times 10^{-3}$ should be kept in order to preserve high quality FEL lasing
- The error size for each error type that we can tolerate are shown in the plot



Montecarlo Simulation

- The tolerances used for S-PRESSO are:

Pole height	Winding vert. shift	Pole width	Coil width
±20 µm	±20 µm	±10 µm	±10 µm

- Additionally: deviation from the average period length $\leq 20\ \mu m$

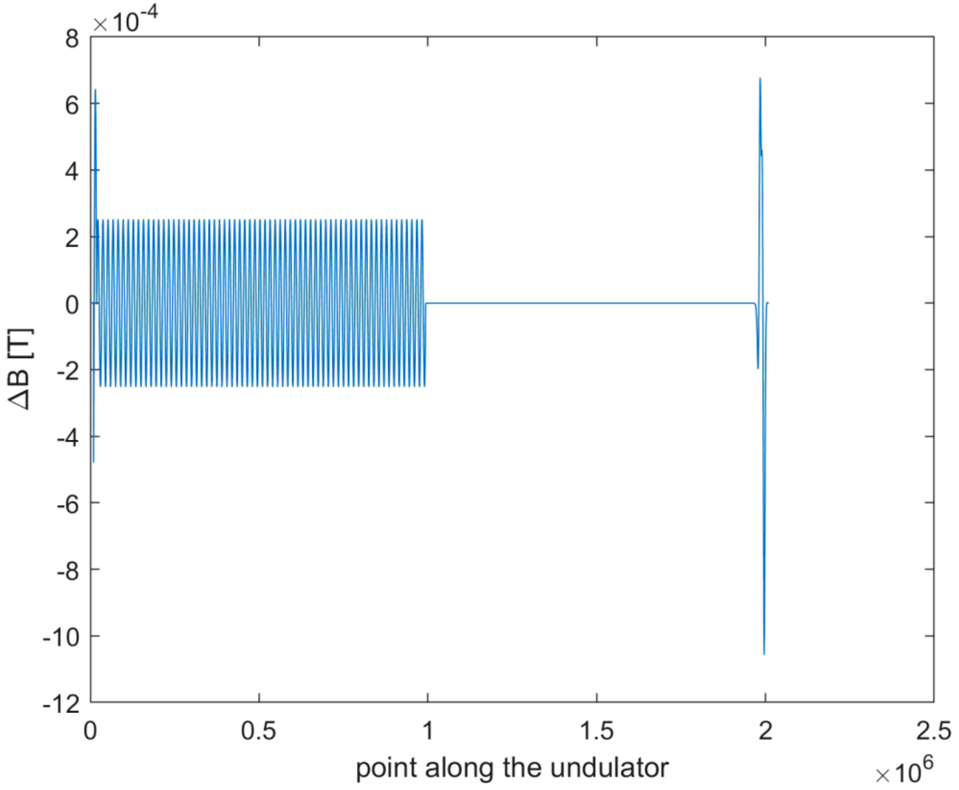
- We apply the four errors at each half period length

Montecarlo Simulation

- The total signature that should be added to the ideal field to get the real field is generated as shown in the video

- The error amount is generated using an **uniform distribution** (worst case) in +/- the range of the tolerance

- For the Montecarlo simulation, we generate **50 different fields**.

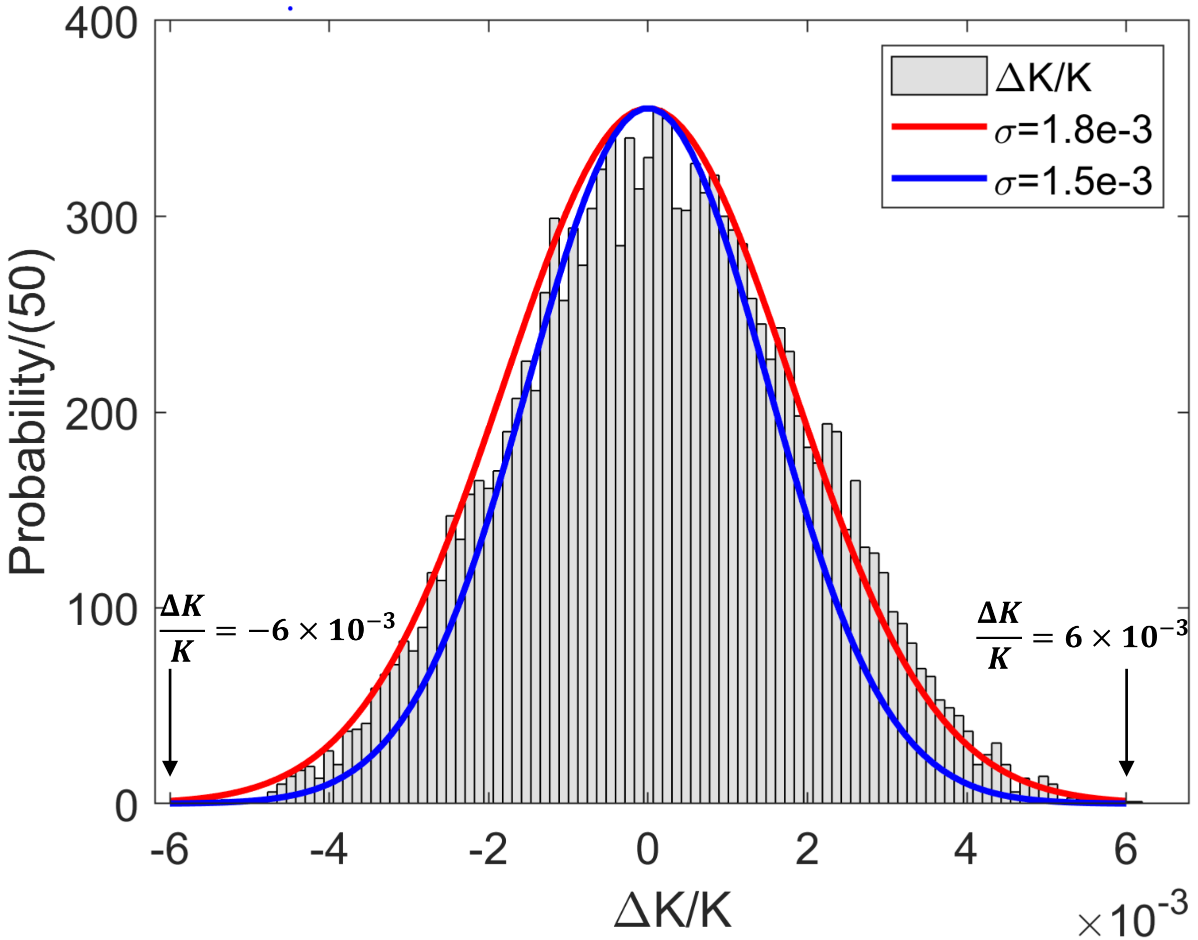


Correspondent errors to the deviation assumed in the GENESIS simulation

- Errors have a **uniform distribution** (worst case) in +/- the values range in the table below

$$\boldsymbol{\sigma\left(\frac{\Delta K}{K}\right) = 1.8 \times 10^{-3}}$$

Mechanical error	Range [μm]
Pole width	10
Groove width	10
Winding vertical deviation (dcentercoil)	20
Pole height	20



- Tolerances are tighter for the period length $\lambda_u = 15\ mm$, while S-PRESSO period is $\lambda_u = 18\ mm$

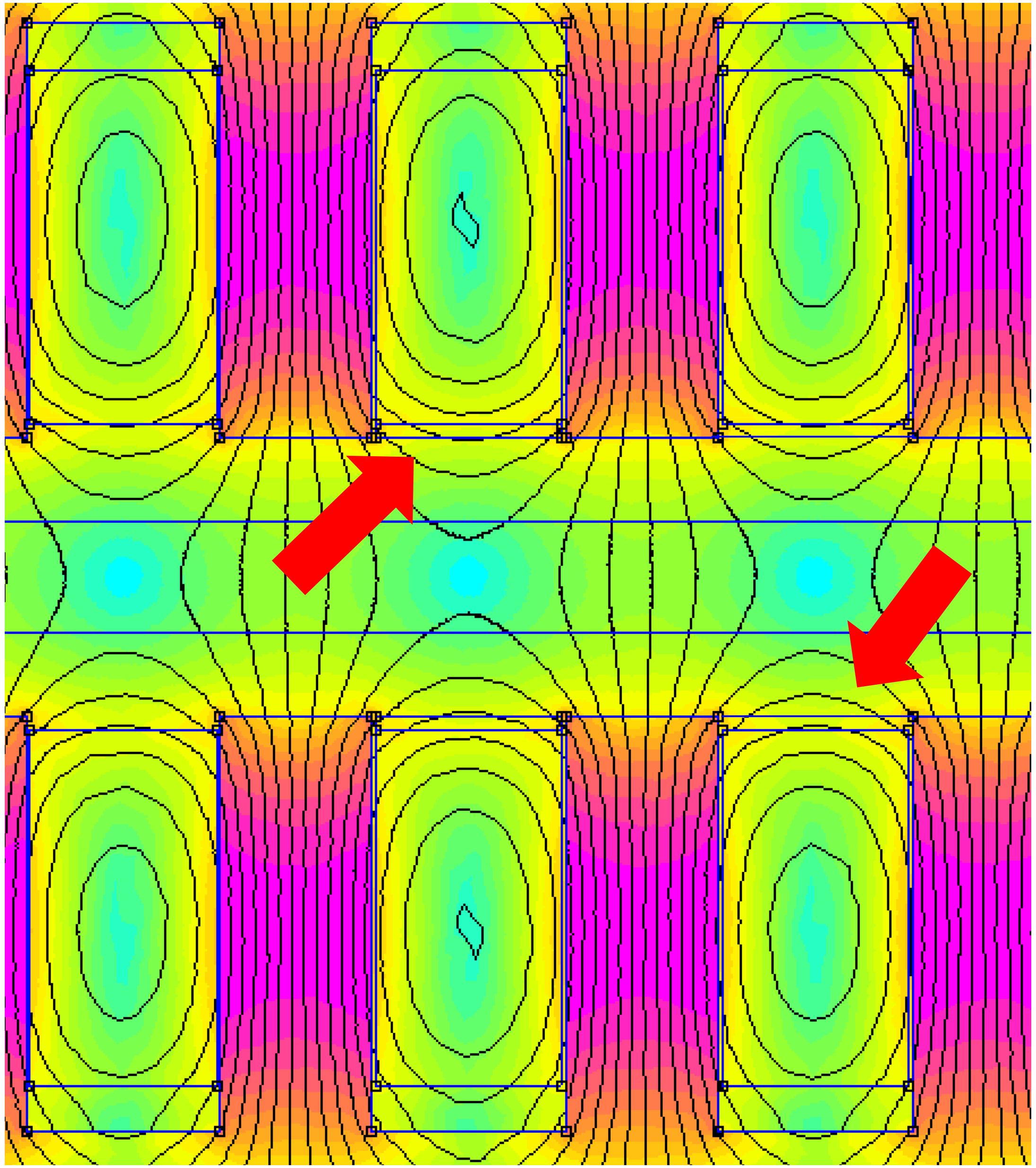
Option for correction scheme

- If the following mechanical tolerances cannot be satisifed

Pole height	Winding vert. shift	Pole width	Coil width
±20 µm	±20 µm	±10 µm	±10 µm

- Shimming with a wire of 0.25mm diameter is considered as correction scheme.
- Several correction coils powered by a maximum of 10 power supplies with max current of 10 A might be applied

Shimming the coils with a current of 10 A enables a correction up to $\frac{\Delta K}{K} \leq 1.6 \times 10^{-2}$



Conclusions

- Genesis simulations confirm that for $\sigma\left(\frac{\Delta K}{K}\right) = 1.5 \times 10^{-3}$, more than 95% of the mean power with respect to the ideal case can be reached.

- The tolerances specified for S-PRESSO are:

Pole height	**Winding vert. shift**	**Pole width**	**Coil width**
±20 µm	±20 µm	±10 µm	±10 µm

- The Montecarlo study shows that we can achieve a $\sigma\left(\frac{\Delta K}{K}\right) = 1.8 \times 10^{-3}$ considering a period length $\lambda_u = 15\ mm$

- If it is not possible to satisfy the mechanical tolerances, shimming the coils with a current of 10 A enables a correction up to $\frac{\Delta K}{K} = 1.6 \times 10^{-2}$