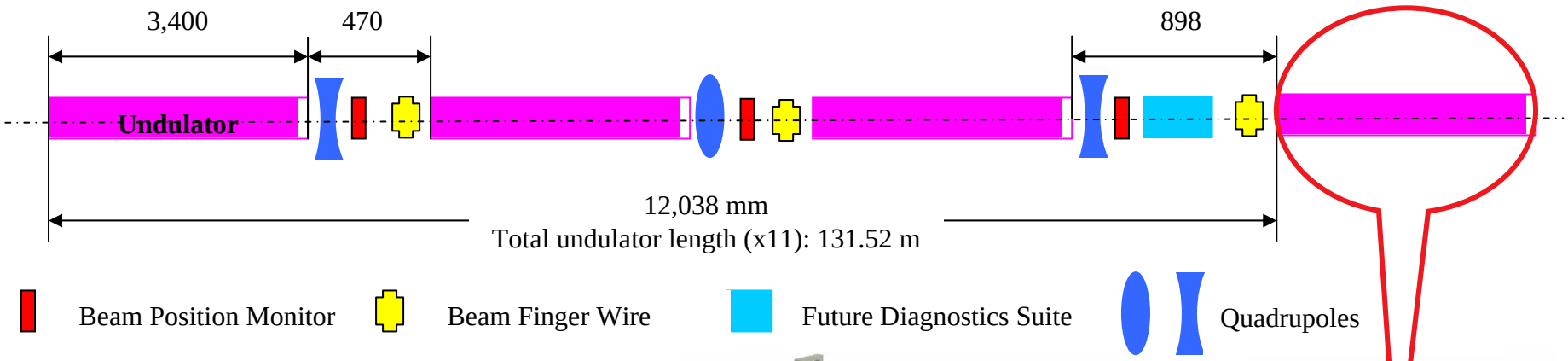
Undulator Vacuum Chamber Requirements

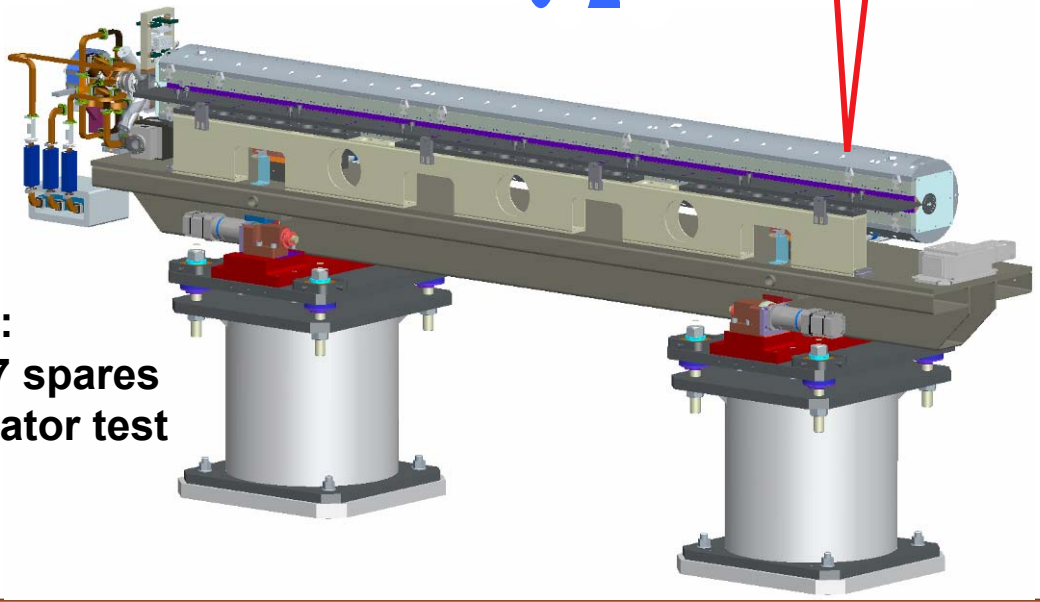
Heinz-Dieter Nuhn, SLAC / LCLS

February 22, 2007

- Vacuum Chamber Overview
- Vacuum Chamber Requirements
- Requirements due to Wakefields
- Surface Roughness Wakefields
- Finite Permeability of Stainless Steel

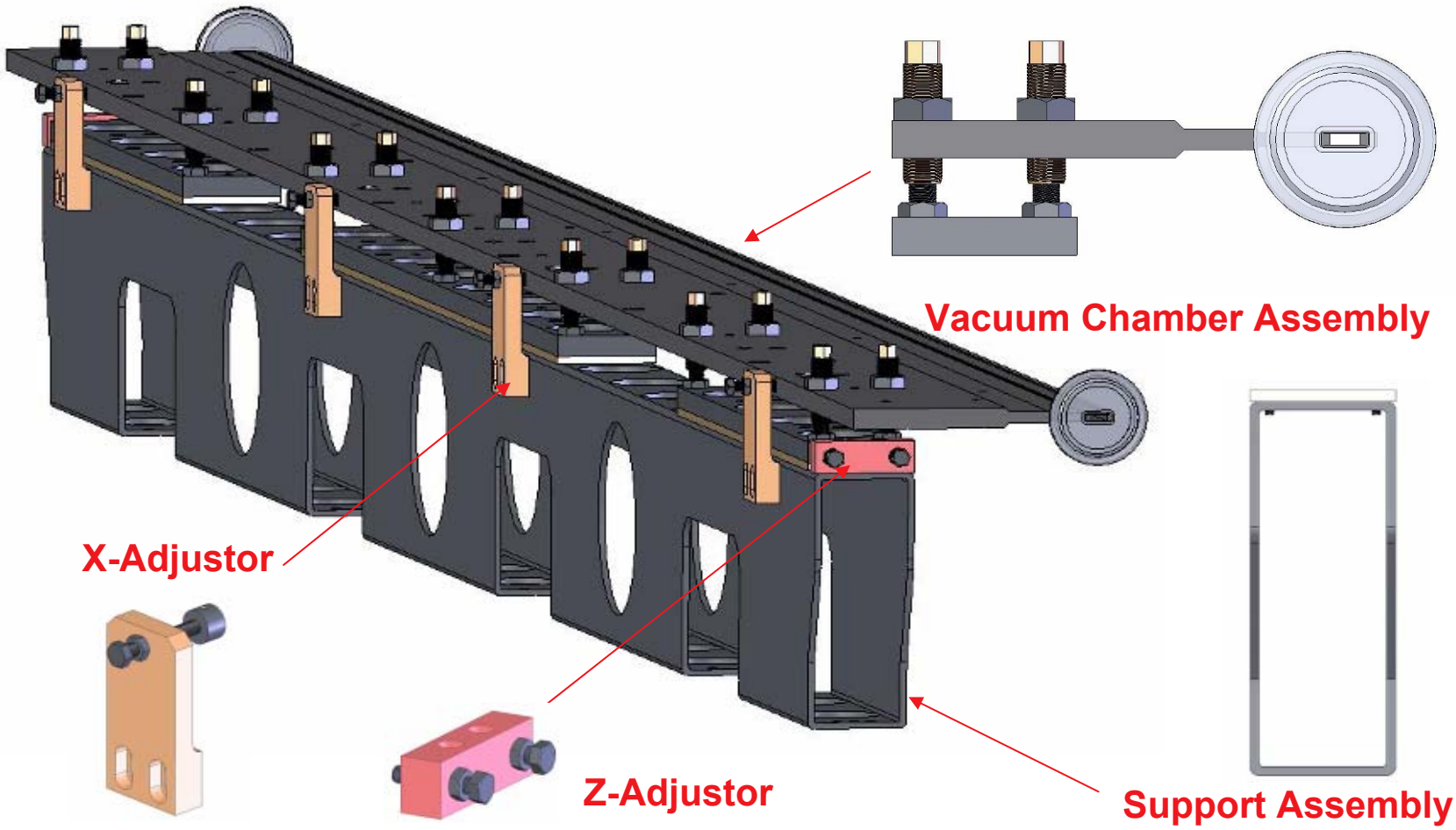
Undulator Segment Chamber Overview





Fabrication plan for vacuum chamber:
- **33 production vacuum chambers & 7 spares**
- **1 mock-up chamber for single undulator test**
- **1 vacuum chamber for prototype**

Production Vacuum Chamber Ass'y



LCLS Undulator Vacuum System Requirements

- A continuous vacuum chamber will run throughout the Undulator System.
- The Vacuum System will be designed to produce an average pressure of less than 10^{-6} Torr.
- The vacuum chamber axis shall be aligned to the undulator axis to within ±200 µm.
- The beam-stay-clear radius around the undulator axis is 2.3 mm.
- The material of the vacuum chamber surface seen by the electron beam will be Al, with a minimum thickness of 100 nm. The inner dimensions of the vacuum chamber inside the Undulator Segment shall be 5 mm full height measured at the undulator axis. An oval cross section is permissible. If a base material other than Al is used, its permeability must me sufficiently small to not change the magnetic field on the beam path by more than 0.015 % of the peak undulator field.
- Of importance is the impedance that the vacuum chamber presents to the beam and is the cause of wakefields. There are three main contributors to the impedance of the vacuum chamber: its <u>electrical surface conductivity</u>, its <u>surface roughness</u>, and its <u>geometric shape</u>. The goal is to keep the contribution from surface roughness and geometric shape small (less then 10 %) compared to the contribution from the finite electrical conductivity.

Wakefield Requirements

- The main wakefield sources are
  - Wall Resistivity Wakefields
  - Surface Roughness Wakefields
  - Geometric Wakefields

Undulator Wakefield Parameters

Surface Roughness Parameters

Segment Chambers
5 mm height.; Aspect Ratio >300;

Short Break Chambers
10/8 mm dia.; Aspect Ratio >100;

Long Break Chambers
10/8 mm dia.; Aspect Ratio >100;

Resistive Wall Parameters

Segment Chambers
par plates 5 mm sep, Al AC;

Shielded Bellows
10 mm dia. cir.; Cu AC;

Short Break Chambers
10/8 mm dia. cir.; Cu AC;

Long Break Chambers
10/8 mm dia. cir.; Cu AC;

Geometric Wakefield Parameters

RF Cavity BPMs
10 mm gap @ 10 mm dia.

BFW Cavity
18 mm gap @ 10 mm dia.

Bellows Shielding Slots
35 mm gap @ 10 mm dia., 20 % azim.

Flanges
2 mm gap @ 8/10 mm dia.

Segment to Break Chamber
5 mm x 10 mm ←→ 8 mm dia; 153 V/pC

Break Chamber Diameter Changes
10 mm ←→ 8 mm dia

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Wakefield Budget Summary

Beam Energy = 13.64 GeV

Undulator Length = 132 m

Charge = 1 nC

Core Charge = 0.45 nC

	total		core	
Wakefield Component	$<\delta>$	σ_δ	$<\delta>$	σ_δ
	[%]	[%]	[%]	[%]
Resistive Wall				
Undulator Chamber	-0.142	0.165	-0.022	0.111
Breaks	-0.012	0.024	0.000	0.013
Surface Roughness				
Undulator Chamber	-0.017	0.036	0.004	0.006
Breaks	-0.011	0.023	0.004	0.013
Geometric Wakefields				
Undulator Chamber	-	-	-	-
Breaks	-0.094	0.051	-0.061	0.006
Total	**-0.274**	**0.222**	**-0.075**	**0.116**

Roughness Wakefield Calculations

For a **sinusoidal perturbation** of the chamber surface, $h = h_0 \cos(\kappa z)$, the theoretical wakefield can be solved explicitly [1].

$$w_l(s) = \frac{h_0^2 \kappa^3}{b} \frac{\partial}{\partial \kappa s} g(\kappa s) = \frac{h_0^2 \kappa^2}{b} \frac{\partial}{\partial s} g(\kappa s)$$

$$g(\zeta) = \frac{1}{2\sqrt{\pi}} \frac{\cos(\zeta/2) + \sin(\zeta/2)}{\sqrt{\zeta}}$$

The energy loss per unit charge and per unit distance is obtained by a convolution of the wakefield and the bunch charge distribution

$$W(s) = \frac{cZ_0}{4\pi} \int_{-\infty}^{s} \rho(\bar{s}) w_l(s - \bar{s}) d\bar{s}$$

s	slice position within the electron bunch.
$\rho(s)$	normalized charge distribution of the electron bunch
b	is the radius of the circular vacuum chamber
Z_0	is the vacuum impedance

[1] G.V. Stupakov, "Surface Roughness Impedance", SLAC-PUB-8743 (2000)

Aspect Ratio

The factor in front of the wakefield integral

$$W(s) = \frac{cZ_0}{4\pi}\int_{-\infty}^{s}\rho(\bar{s})\,w_l(s-\bar{s})\,d\bar{s} = \frac{cZ_0}{4\pi}\frac{h_0^2\kappa^2}{b}\int_{-\infty}^{s}\left(\frac{\delta}{\delta\bar{s}}\rho(\bar{s})\right)g\left(\kappa(s-\bar{s})\right)d\bar{s}$$

is proportional to the product of

$$h_0^2\kappa^2 = \left(2\pi\frac{h_0}{\lambda_s}\right)^2$$

We introduce the **aspect ratio AR** for roughness tolerance specification

$$AR = \frac{\lambda_s}{h_0}$$

Equivalence between AR and RMS Derivatives

Assume a single spatial roughness frequency in each direction

$$h_m(x,z) = h_0 \sin(\kappa_{x,0} x)\sin(\kappa_{z,0} z)$$

Calculate rms derivative in z direction

$$z'_{rms} = \sqrt{\frac{1}{\lambda_x}\int_0^{\lambda_x}\left(\frac{1}{\lambda_z}\int_0^{\lambda_z}\left(\frac{d}{dz}h_0 \sin(\kappa_{x,0}x)\sin(\kappa_{z,0}z)\right)^2 dz\right)dx}$$

$$z'_{rms} = \frac{1}{2}h_0\kappa_{x,0} = \frac{h_0\pi}{\lambda_x} = \frac{\pi}{AR} \overset{!}{<} \frac{\pi}{300} = 10.5 \text{ mrad}$$

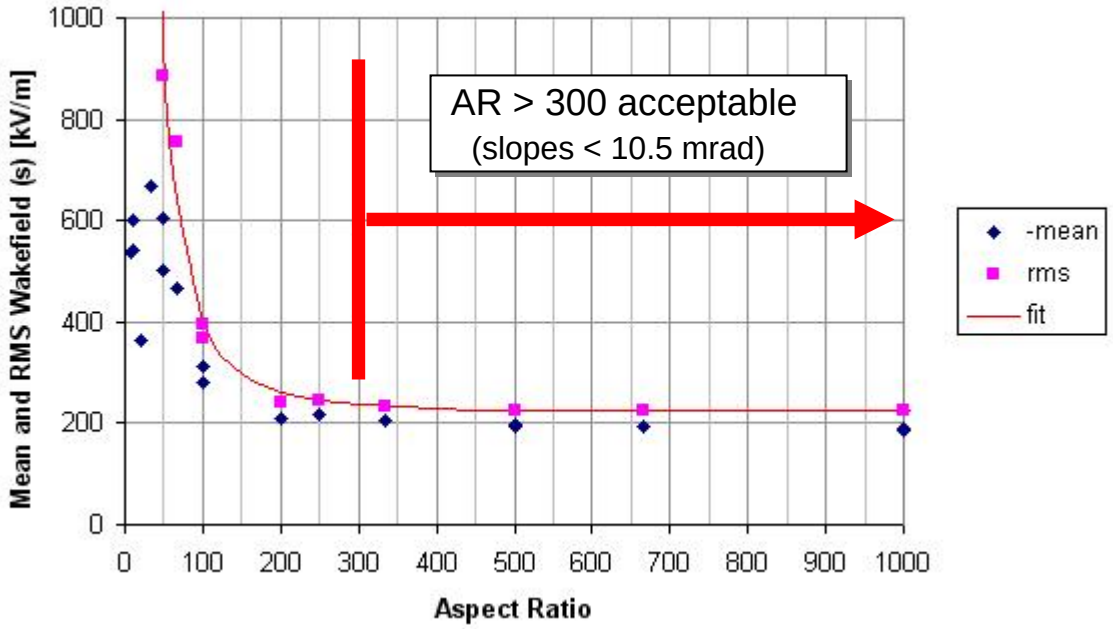
Equivalent in x direction

$$x'_{rms} = \frac{1}{2}h_0\kappa_{z,0} = \frac{h_0\pi}{\lambda_z} = \frac{\pi}{AR}$$

Change of total Chamber Wakefield with AR

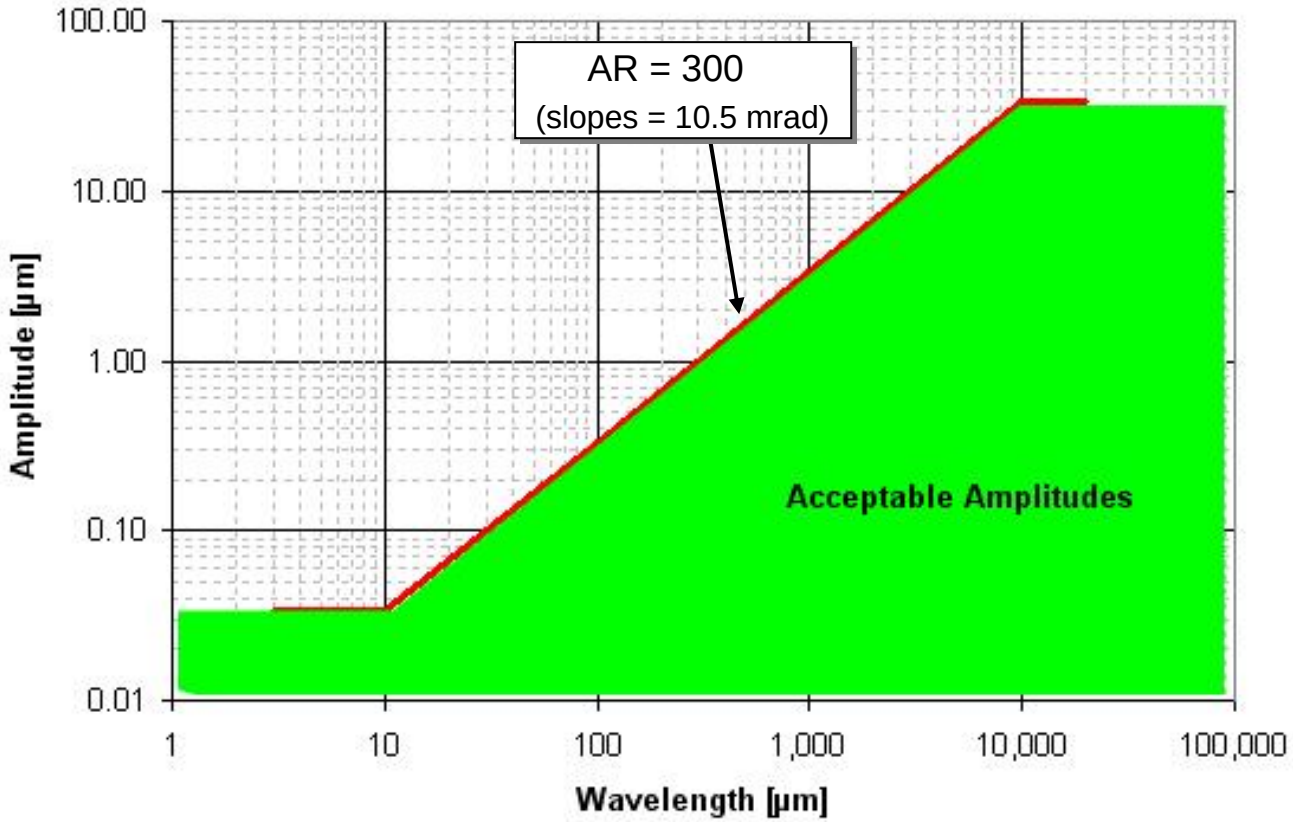
The wakefield tolerances are chosen such that the resistive wall wakefield dominates the other wakefield components, including surface roughness wakefields and geometric wakefields.

The requirement for the Aspect Ratio to be larger than 300 satisfies that condition.

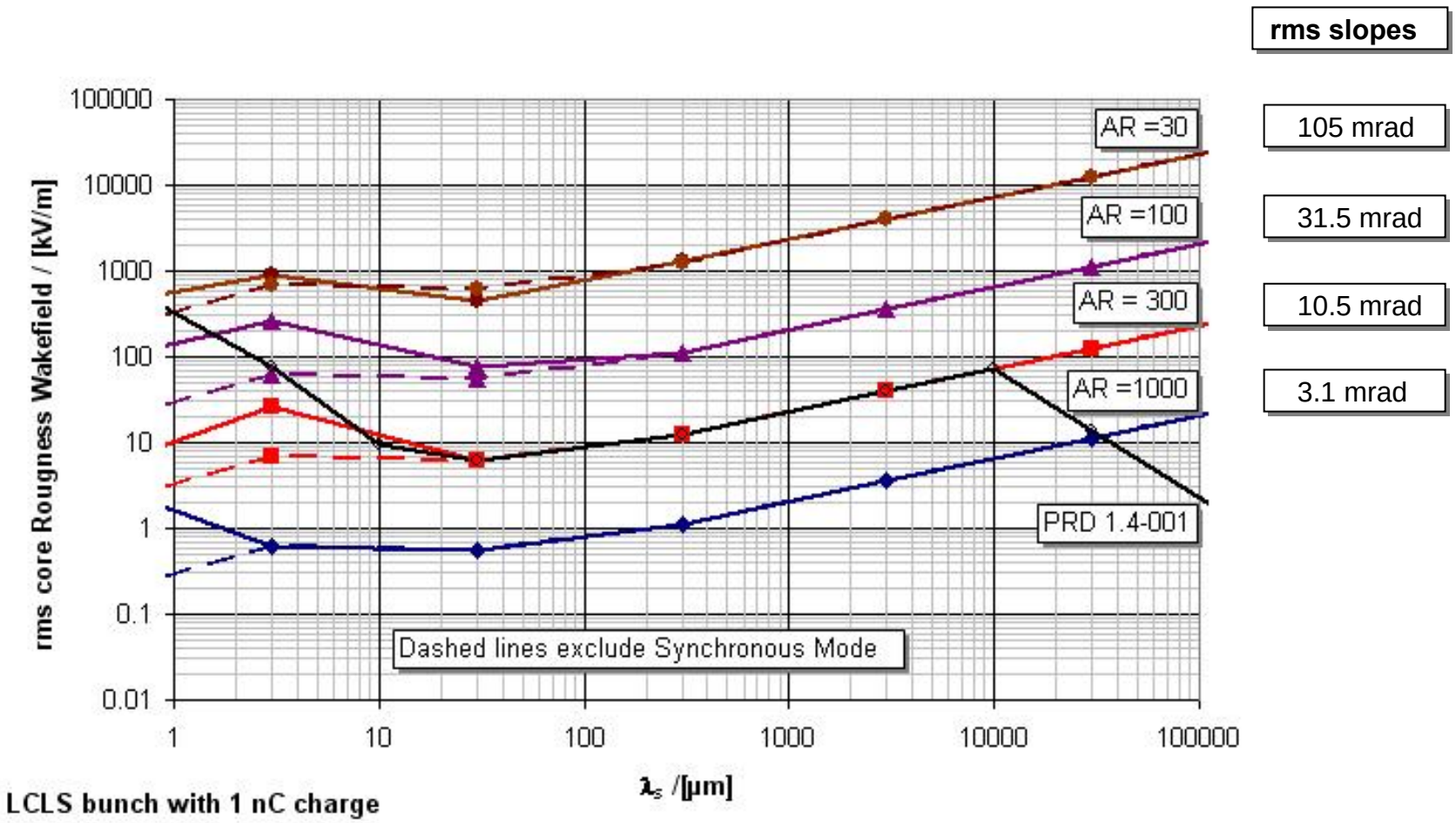


The graph shows the sum over all wakefield contributions.

Roughness Tolerance Specification in PRD 1.4-001



Roughness Wakefields Parameterized by AR



X-ray Optics Metrology Laboratory Report
XFD/Advanced Photon Source

Work request #: M06028A	**Optic:** 4 **bent** stainless steel samples	**Date in / out:** 01-10-06 / 01-17-06
Requester: Lee, Soon Hong	**Measurement:** Surface roughness	**Measured by / report:** J. Qian (2-5874)
Beamline / affiliation: LCLS	**Instruments:** MicroXAM RTS profiler	**Lab coordinator:** L. Assoufid (2-2774)

Surface roughness measurements with the MicroXAM RTS surface profiler, objective 5x, 20x and 50x

1. Samples

4 bent stainless steel samples: #5, #6, #7 and #8 (size: 1” x 1/2”)

2. Instrument used for the measurements

MicroXAM RTS surface profiler
- Mode: EX and phase modes
- Wavelength: white light
- Objective: 5x, field of view: 2.44 mm^2
  20x, field of view: 0.61 mm^2
  50x, field of view: 0.244 mm^2

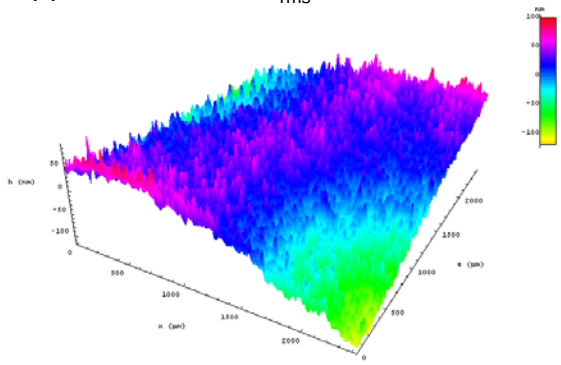
3. Measurements and results

- 5 spots with 2.5 mm separations at flat areas of each sample were measured in phase mode with the 5x, 20x and 50x objectives, respectively.
- 5 spots with 2.5 mm separations at curved areas of each sample were measured in EX mode with the 50x objective.
- Table 1 summarizes the measurement results.
- Table 2 lists the names of the saved files with .asc format.
- Figures 1 to 16 are surface roughness profiles.

This slide and the following slides are from the Report by the APS X-Ray Optics Metrology Laboratory.

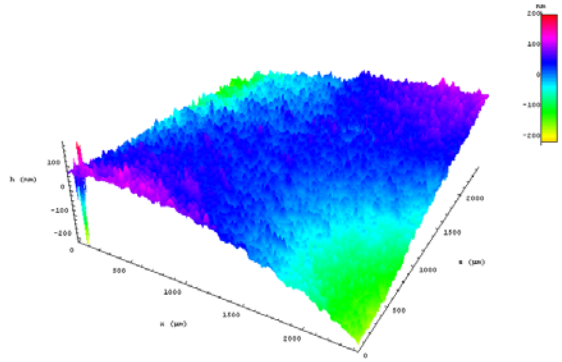
Sample: #8 Mode: PM Objective: 5x Size: 2.438 x 2.438 mm^2

r(z): 3560 mm; h_{rms}: 34 nm **# 1**



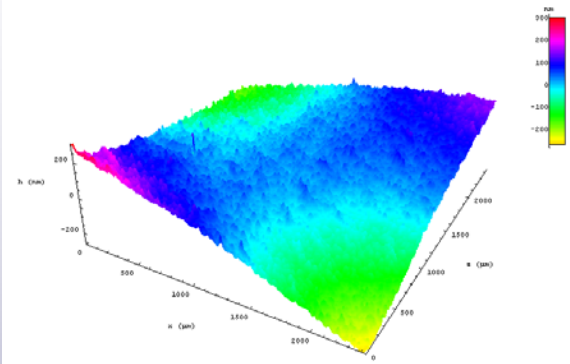
x'_{rms}: 0.6 mrad; z'_{rms}: 0.7 mrad

r(z): 3690 mm; h_{rms}: 50 nm **# 2**



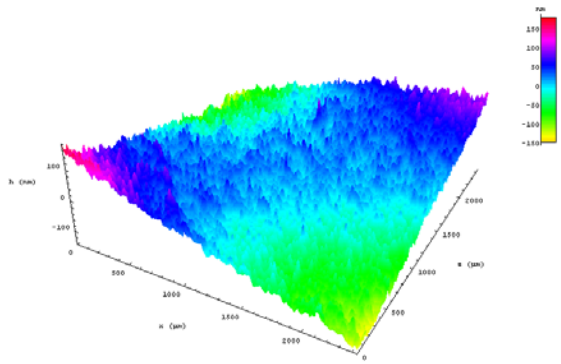
x'_{rms}: 0.8 mrad; z'_{rms}: 1.0 mrad

r(z): 4700 mm; h_{rms}: 77 nm **# 3**



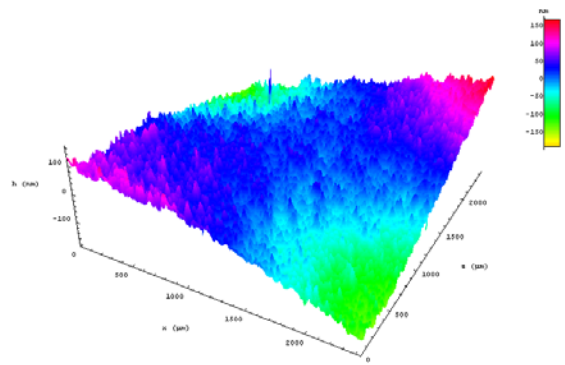
x'_{rms}: 0.7 mrad; z'_{rms}: 0.7 mrad

r(z): 6530 mm; h_{rms}: 45 nm **# 4**



x'_{rms}: 0.6 mrad; z'_{rms}: 0.7 mrad

r(z): 5740 mm; h_{rms}: 52 nm **# 5**



x'_{rms}: 0.7 mrad; z'_{rms}: 0.8 mrad

Comments:

Flat area.

rms derivatives << 10 mrad

Well within tolerance.

Flat Stainless Steel Sample

Heinz-Dieter Nuhn, SLAC / LCLS
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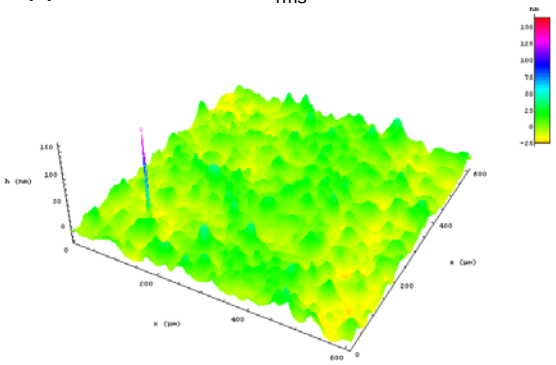
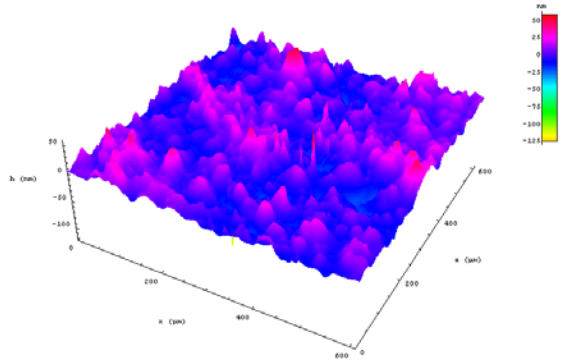
Sample: #8 Mode: PM Objective: 20x Size: 0.610 x 0.610 mm^2

r(z): 4300 mm; h_{rms}: 9.4 nm **# 1**



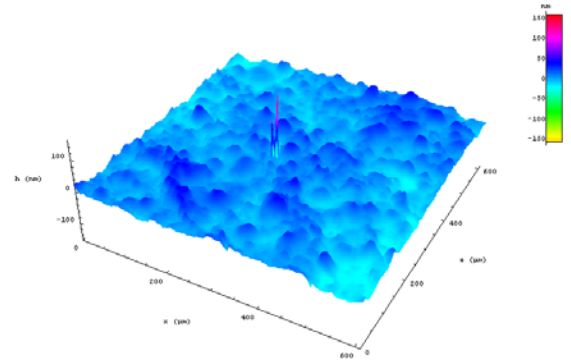
x'_{rms}: 0.9 mrad; z'_{rms}: 0.9 mrad

r(z): 4310 mm; h_{rms}: 10 nm **# 2**



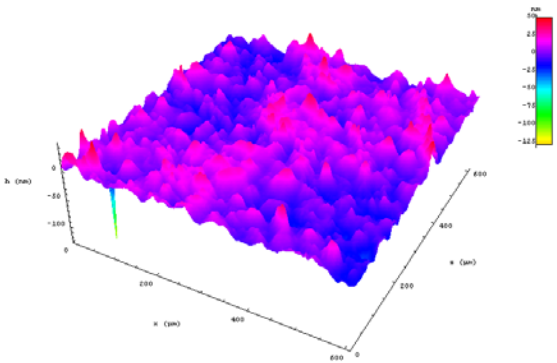
x'_{rms}: 1.1 mrad; z'_{rms}: 1.0 mrad

r(z): 5150 mm; h_{rms}: 11 nm **# 3**



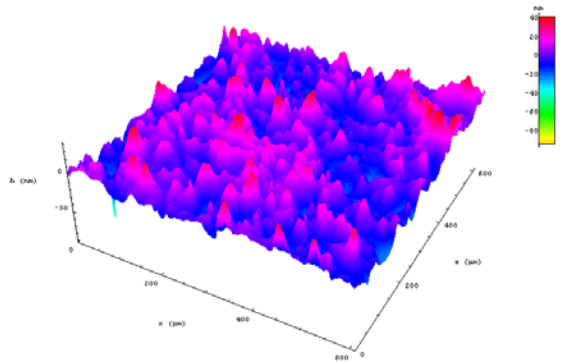
x'_{rms}: 1.4 mrad; z'_{rms}: 1.4 mrad

r(z): 11600 mm; h_{rms}: 9.9 nm **# 4**



x'_{rms}: 0.9 mrad; z'_{rms}: 0.9 mrad

r(z): 5840 mm; h_{rms}: 9.6 nm **# 5**



x'_{rms}: 0.9 mrad; z'_{rms}: 0.9 mrad

Comments:

Flat area.

rms derivatives << 10 mrad

Well within tolerance.

Flat Stainless Steel Sample

Heinz-Dieter Nuhn, SLAC / LCLS
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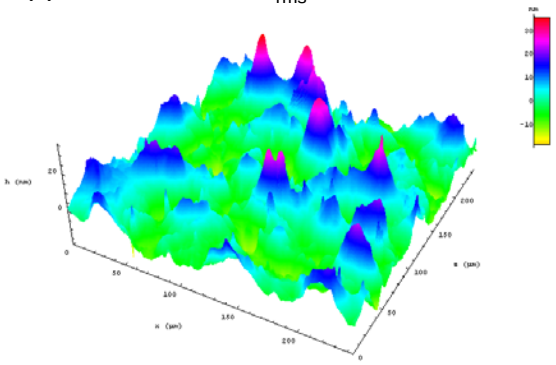
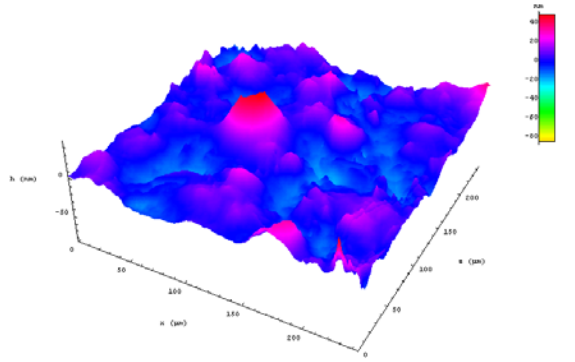
Sample: #8 Mode: PM Objective: 50x Size: 0.244 x 0.244 mm^2

r(z): 5100 mm; h_{rms}: 7.5 nm **# 1**



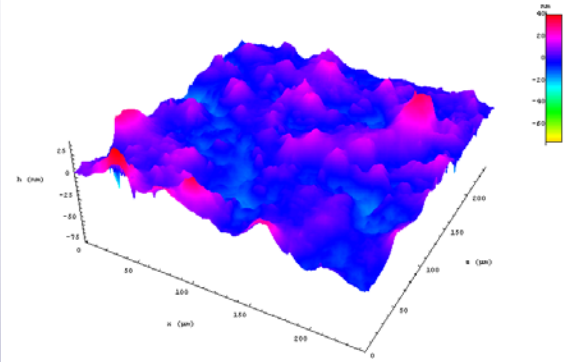
x'_{rms}: 1.0 mrad; z'_{rms}: 1.1 mrad

r(x): -1550 mm; h_{rms}: 9.5 nm **# 2**



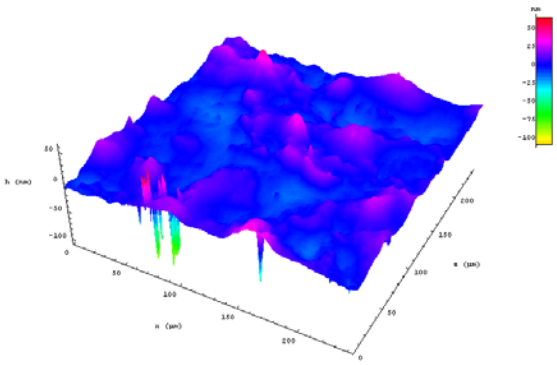
x'_{rms}: 1.3 mrad; z'_{rms}: 1.2 mrad

r(x): 3260 mm; h_{rms}: 7.7 nm **# 3**



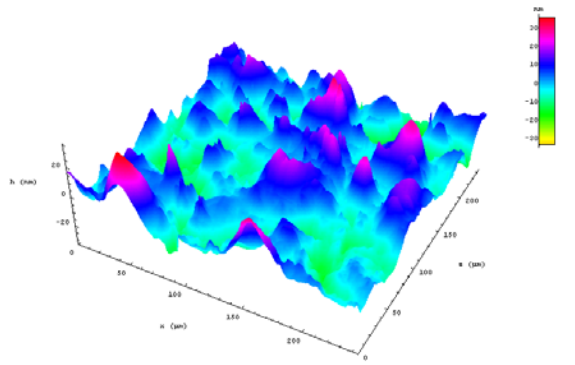
x'_{rms}: 1.3 mrad; z'_{rms}: 1.4 mrad

r(x): -1150 mm; h_{rms}: 8.6 nm **# 4**



x'_{rms}: 2.1 mrad; z'_{rms}: 2.2 mrad

r(z): 2900 mm; h_{rms}: 8.4 nm **# 5**



x'_{rms}: 1.1 mrad; z'_{rms}: 1.0 mrad

Comments:

Flat area.

rms derivatives << 10 mrad

Well within tolerance.

Flat Stainless Steel Sample

Heinz-Dieter Nuhn, SLAC / LCLS
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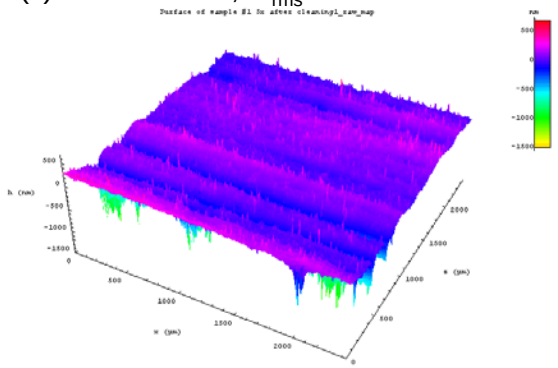
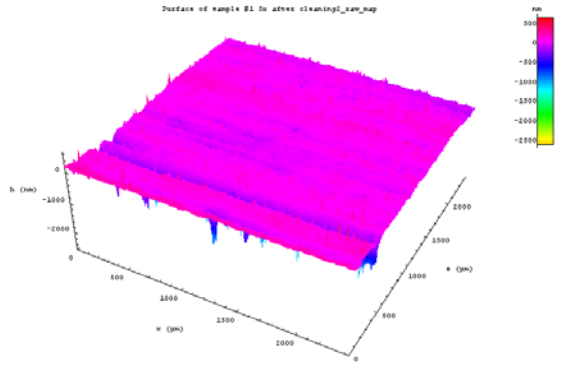
Sample: #1 Mode: PM Objective: 5x Size: 2.438 x 2.438 mm^2

r(z): 2680 mm; h_{rms}: 104 nm **# 1**



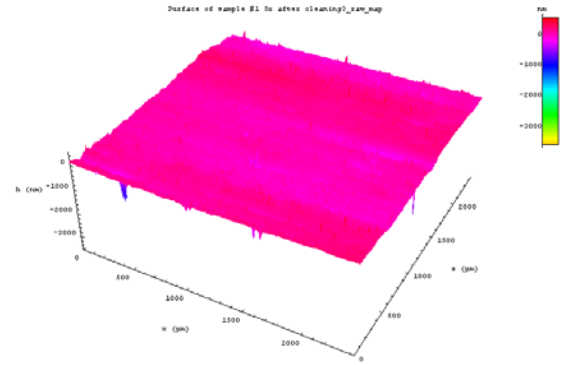
x'_{rms}: 3.7 mrad; z'_{rms}: 11 mrad

r(z): 2291 mm; h_{rms}: 87 nm **# 2**



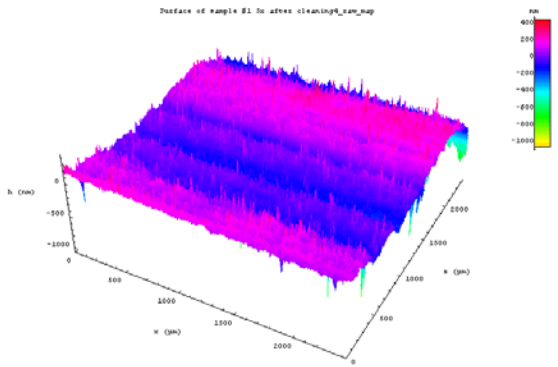
x'_{rms}: 5.4 mrad; z'_{rms}: 12 mrad

r(z): 2618 mm; h_{rms}: 82 nm **# 3**



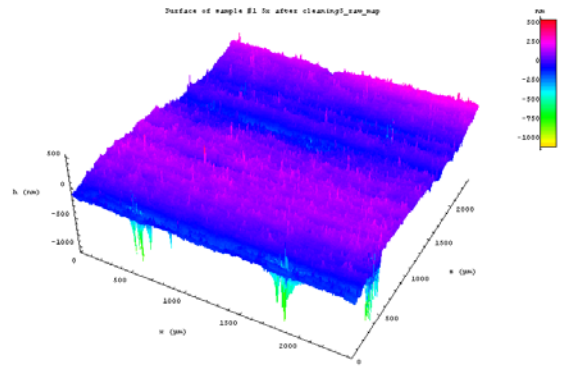
x'_{rms}: 5.4 mrad; z'_{rms}: 11 mrad

r(z): 2472 mm; h_{rms}: 106 nm **# 4**



x'_{rms}: 3.4 mrad; z'_{rms}: 8.7 mrad

r(z): 2360 mm; h_{rms}: 88 nm **# 5**



x'_{rms}: 4.7 mrad; z'_{rms}: 10 mrad

Comments:

Flat area.

rms derivatives <~ 10 mrad

Within tolerance.

Lightly Polished Aluminum Sample

Heinz-Dieter Nuhn, SLAC / LCLS
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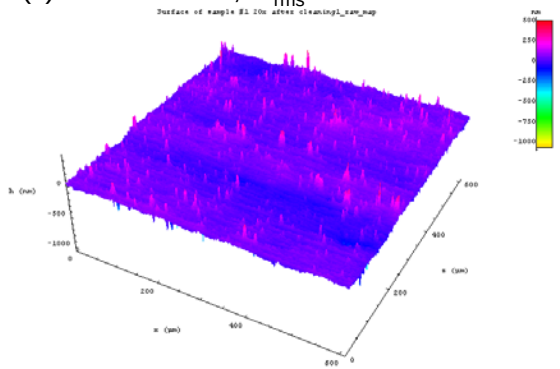
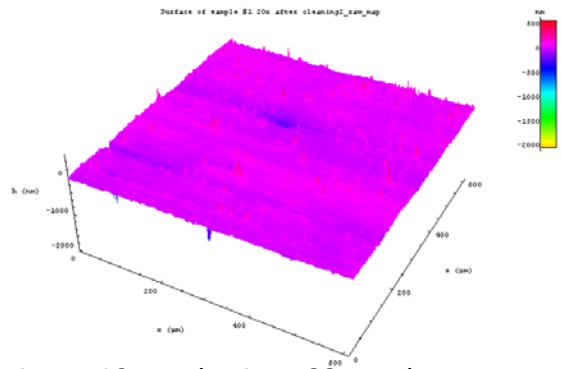
Sample: #1 Mode: PM Objective: 20x Size: 0.610 x 0.610 mm^2

r(z): 2360 mm; h_{rms}: 41 nm **# 1**



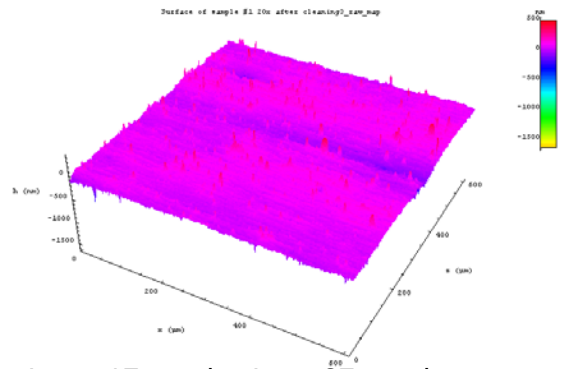
x'_{rms}: 11 mrad; z'_{rms}: 33 mrad

r(z): 1266 mm; h_{rms}: 53 nm **# 2**



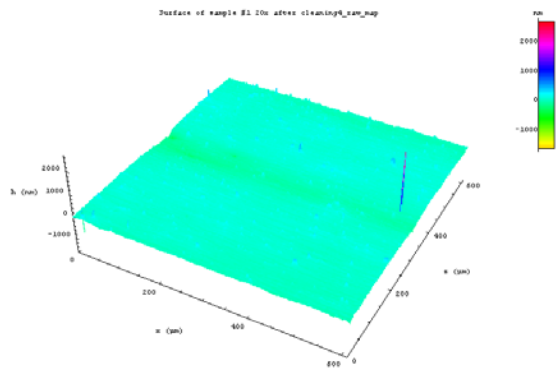
x'_{rms}: 19 mrad; z'_{rms}: 38 mrad

r(z): 827 mm; h_{rms}: 48 nm **# 3**



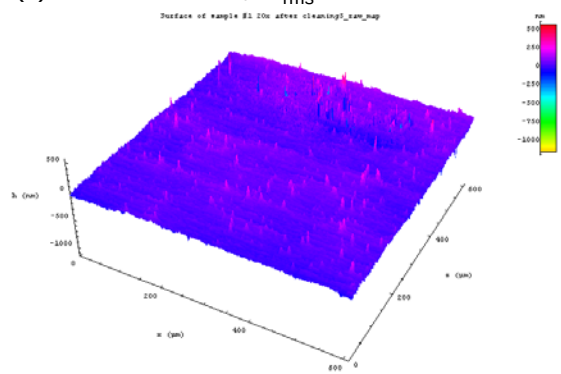
x'_{rms}: 17 mrad; z'_{rms}: 37 mrad

r(z): 1053 mm; h_{rms}: 57 nm **# 4**



x'_{rms}: 16 mrad; z'_{rms}: 36 mrad

r(x): 2412 mm; h_{rms}: 63 nm **# 5**



x'_{rms}: 34 mrad; z'_{rms}: 56 mrad

Comments:

Flat area.

rms derivatives > 10 mrad

Slightly out of tolerance.

Lightly Polished Aluminum Sample

Heinz-Dieter Nuhn, SLAC / LCLS
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LCLS Undulator Wakefield Requirements Summary

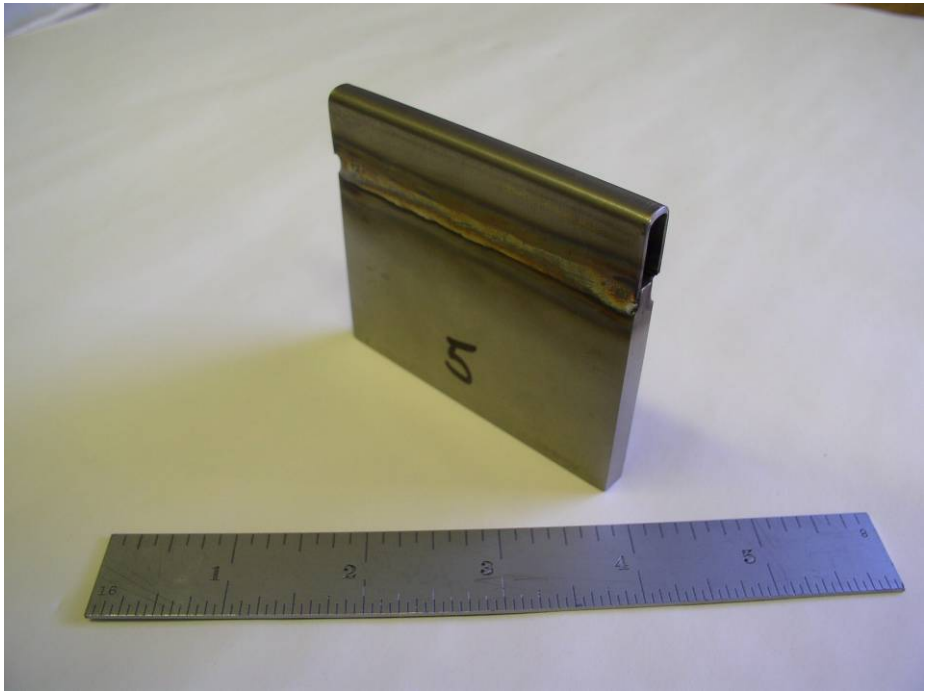
- **Resistive Wall Impedance**
  - **Inner surface material: Aluminum**
  - **Minimum surface thickness: 100 nm**
  - **Minimum cross section ratio (width / height) : 2 / 1 at axis.**
- **Surface Roughness Impedance**
  - **For each spatial frequency component of the surface roughness, the ratio of the corresponding spatial wavelength to the amplitude will be greater or equal to 300 over the 0.01-10 mm period range.**
  - **This is equivalent to a scale-independent slope error of 10 mrad.**
  - **Structures with periods shorter than 10 µm will be kept at amplitude of less than 25 nm.**
- **Geometric Impedance**
  - **The undulator segment vacuum chamber will have a constant cross section without penetrations.**

Finite Permeability of Stainless Steel

- Even though stainless steel is considered non-magnetic, its relative permeability is different from 1, and requires attention.
- It is dependent on machining and temperature treatment.
- During the manufacturing process even treatment of all parts of the vacuum chamber is not guaranteed.
- We don't know what to expect with respect to the distribution of the permeability along the vacuum chamber.

Permeability of Stainless Steels

Magnetic Measurements



Preliminary Permeability Results

Type	As-received	Annealed	After Machining and Forming	Manual TIG Welding	Final Machining
316 LN	1.003	1.003	1.003	1.004	1.008
310S	1.057	1.036	1.033	1.042	1.051
20Cb-3	1.008	1.015	1.015	1.011	1.018
Nitronic 33	1.002	1.022	1.03	1.03	1.126
Nitronic 40	1.004	1.004	1.005	1.052	1.081

from “Magnetic Properties of Undulator Vacuum Chamber Materials for the Linac Coherent Light Source” by SH Lee presented at FEL2005

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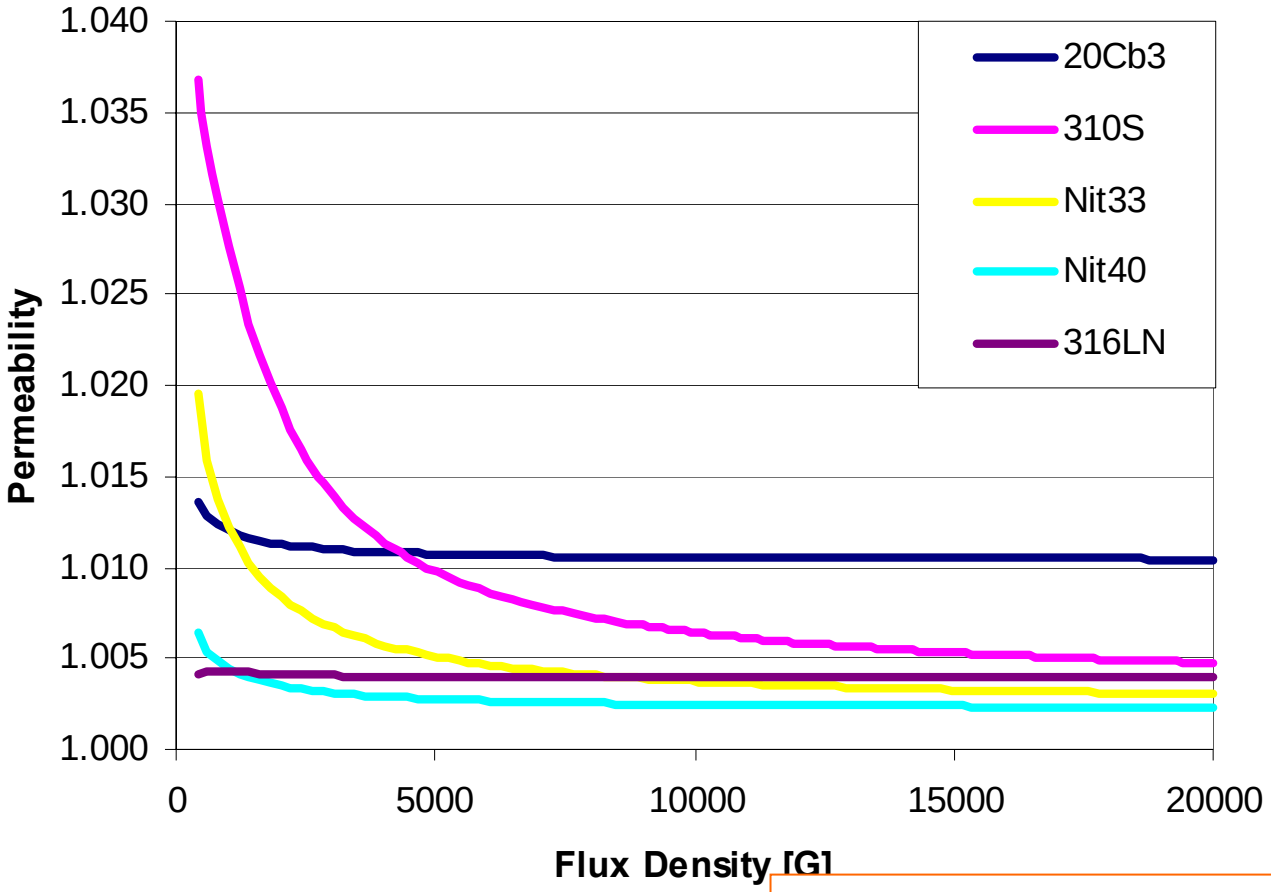
Permeability of Various Materials

Derived from M-H curve measurements



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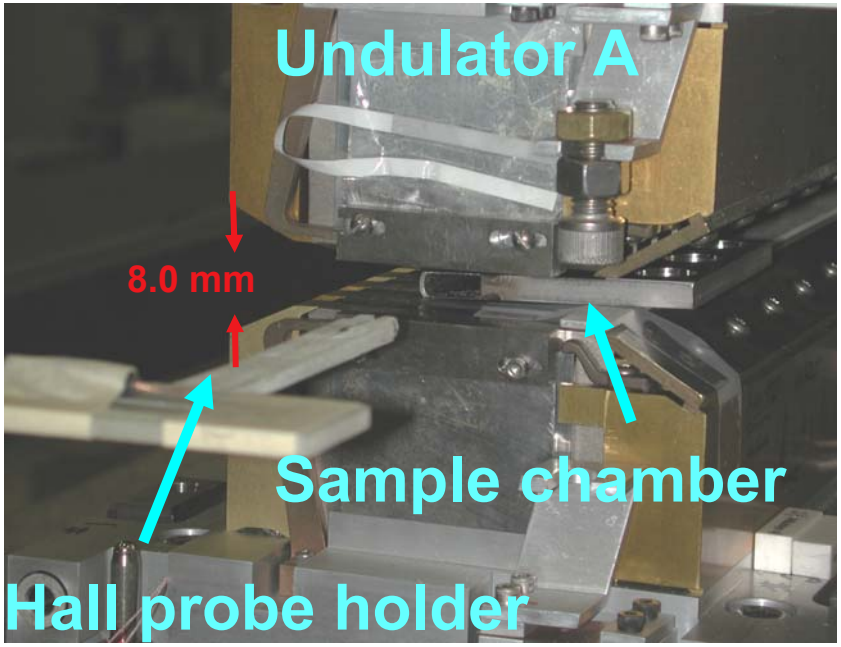
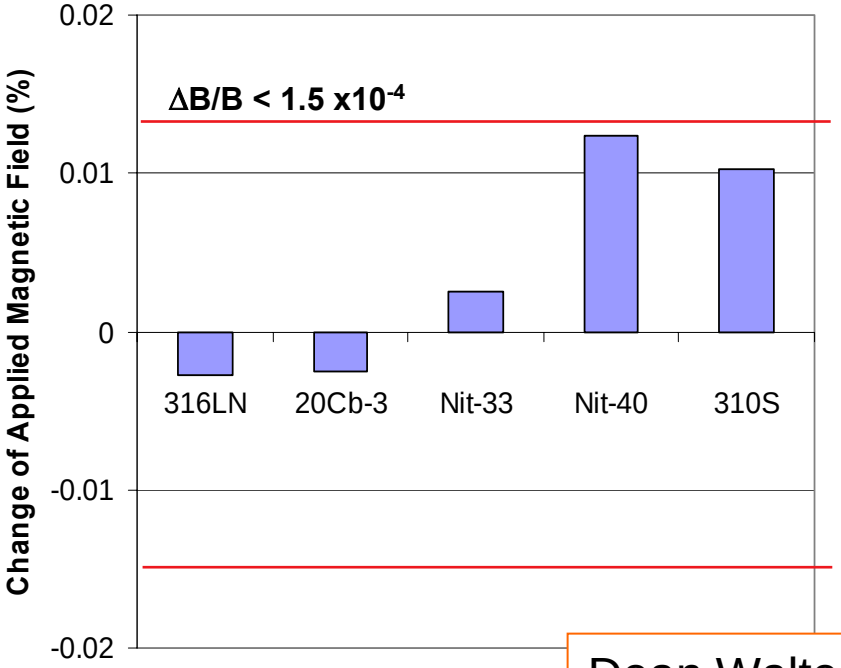
Measurements of Changes of Applied Magnetic Fields

- Sample chambers under APS undulator "A"
  - A 3-inch-long sample vacuum chamber was inserted Into a hybrid permanent magnet undulator with a 3.3 cm period and 8 mm min. gap
  - To Investigate high magnetic field influence to the relative magnetic permeability
  - Peak of applied magnetic field: ~ 1.2 T





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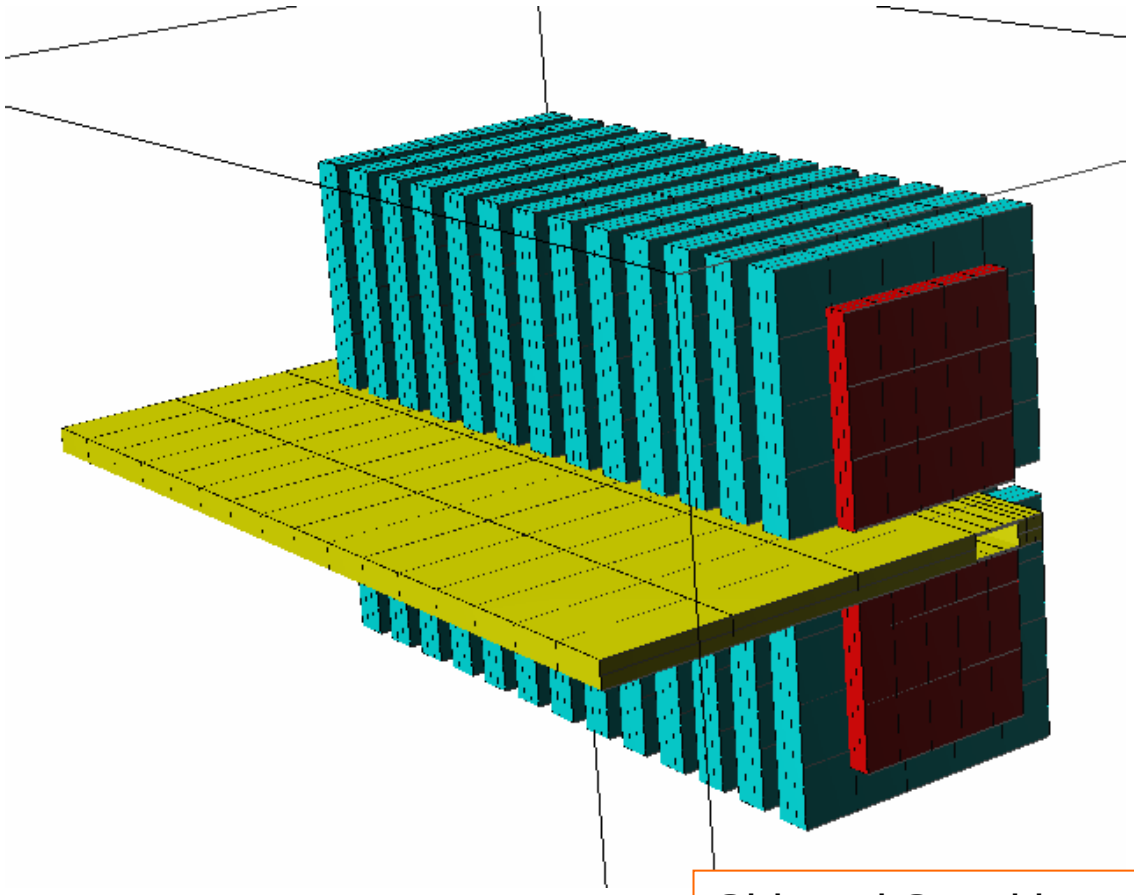
LCLS Undulator and Strongback Model2



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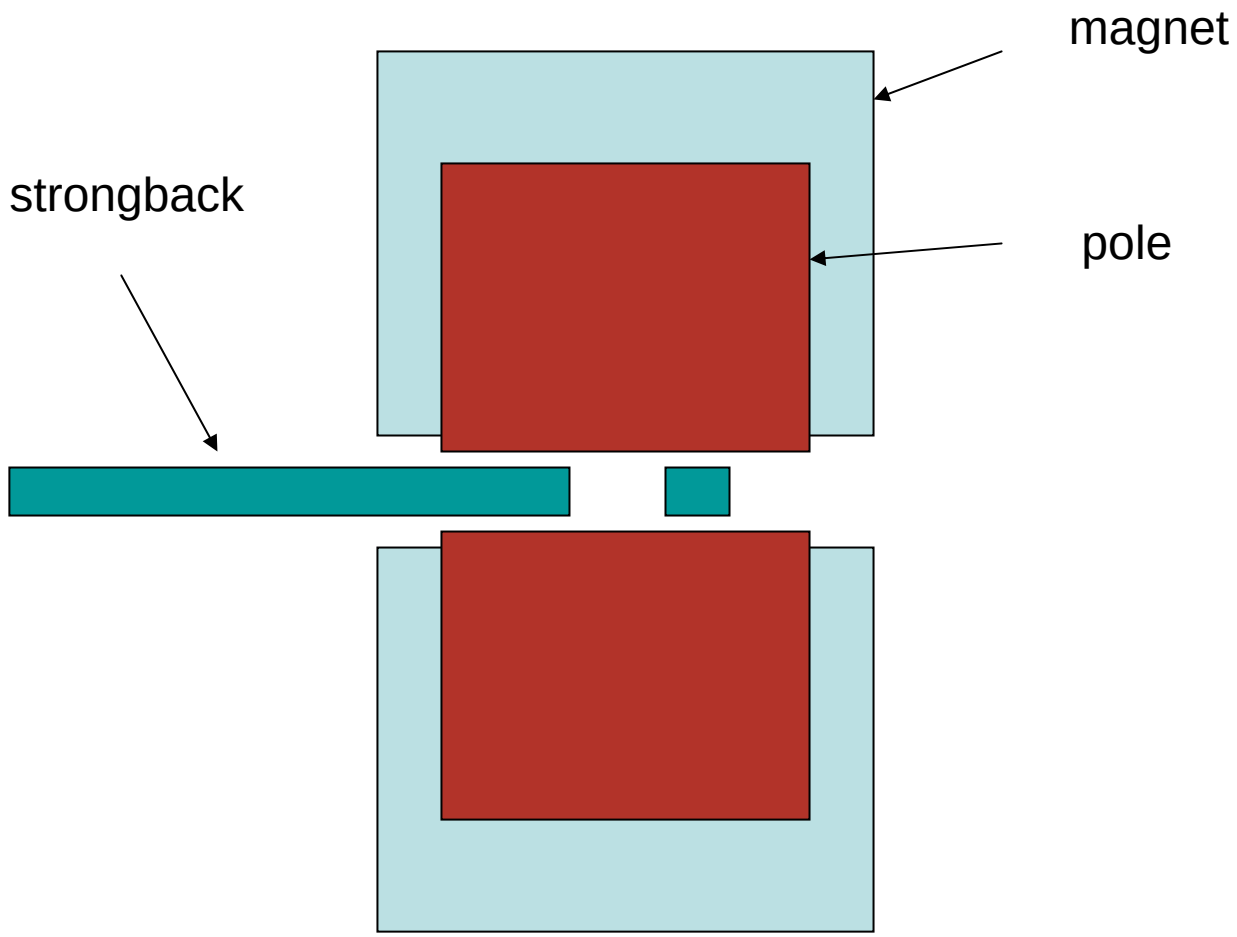
Cross Sectional View of RADIA Model



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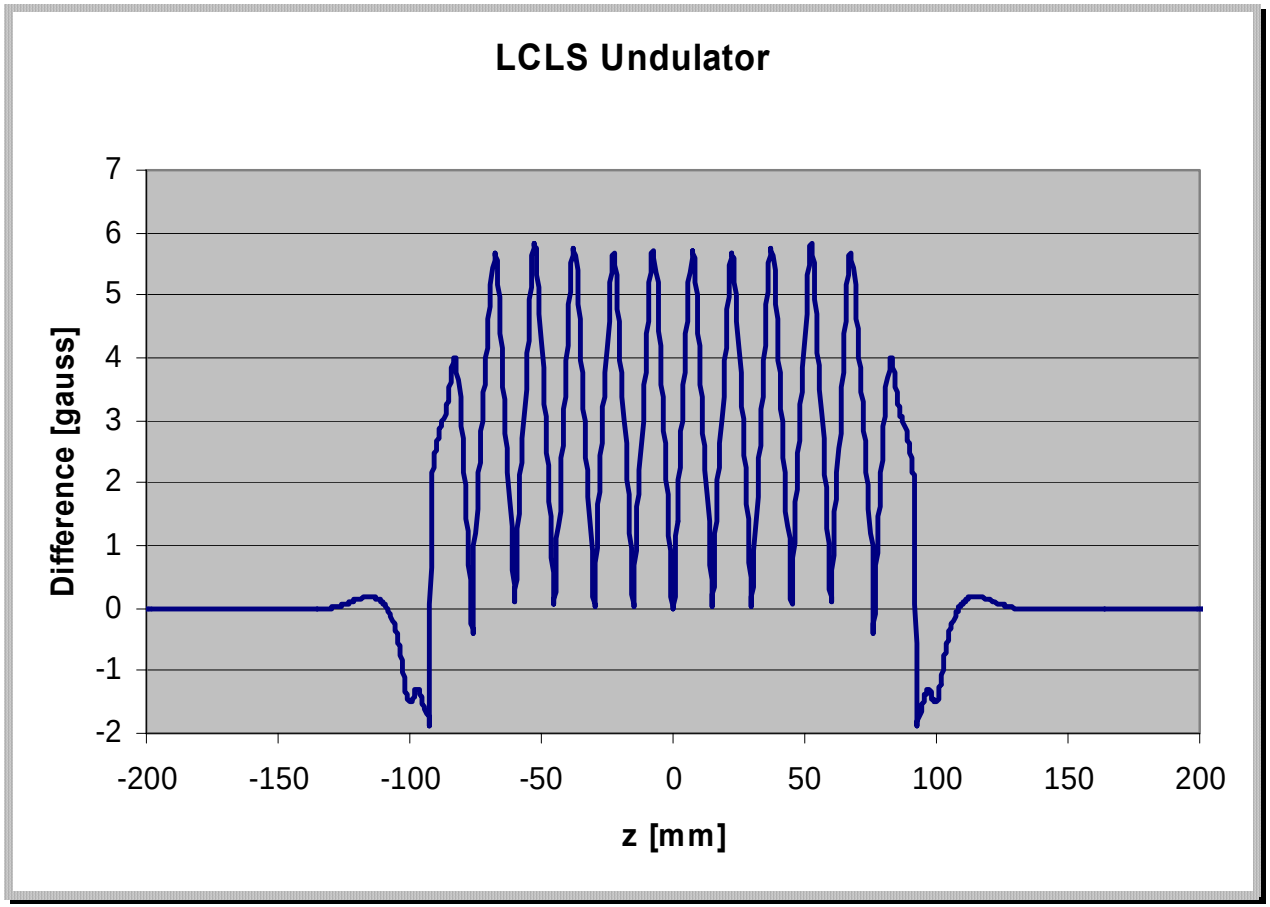
LCLS Undulator

undulator: gap=6.8 mm, strongback: thickness = 6 mm, distance from U-axis = 6.25 mm



In the field of LCLS undulator, the strongback creates a maximum difference of about 6 G due to the non-saturation behavior (constant permeability) of 20Cb-3 up to 2 T.

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Effect on FEL Performance

- The effect of finite permeability on FEL performance depends on the spatial permeability gradients.
- Measurements indicate that, for the selected alloy (20Cb-3). the permeability is constant up to fields of 2 T.
- It is unrealistic to assume that the permeability distribution in the real vacuum chamber can be mapped by measurement.
- Possible assumptions for the permeability distribution are
  1. The permeability is uniform and identical in each undulator chamber.
  2. The permeability is uniform but different in each undulator chamber.
  3. The permeability is non-uniform.
- Consequences of these assumptions are
  1. The permeability just changes the resonance value. Any permeability amplitude can be corrected by adjusting the electron beam energy.
  2. The field changes must stay in the range of +/-0.015 %, Assuming that an average permeability of 1.015 causes a field change of 6 G and that the dependence is quadratic in the susceptibility this corresponds to a range for the permeability between 1.013 and 1.017.
  3. This clearly depends on the actual distributions. A longitudinal harmonic error analysis showed significantly less sensitivity for fluctuating errors

Summary

- The physics requirement for the vacuum chamber are dominated by wakefield considerations.
- Resistive wall wakefields are the dominant component and require the use of aluminum as surface material and the choice of an oblong cross section.
- The present designs avoid geometric wakefields in the undulator vacuum chamber by using a constant cross section.
- Surface roughness wakefields require that the RMS slope of the surface be limited to about 10 mrad over a wide scale range.
- Sufficiently small roughness has been measured for solid stainless steel and aluminum samples. Roughness measurements for the aluminum coated stainless steel chamber have not yet been done.
- The finite permeability is of some concern. Present assumptions of a constant permeability in the range 1.01-1.02 would be acceptable. Any spatial variation in permeability will be difficult to measure and to control.

End of Presentation