Wakefields in the LCLS undulator vacuum chamber

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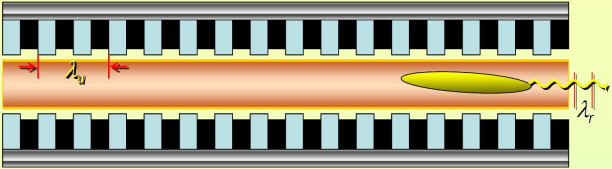
Introduction

Motivation for this talk is to show some underlying physics principles, assumptions behind the calculation of the roughness impedance, and expected effect of the wakes on the performance of the LCLS.

Outline

- Introduction and first model of roughness impedance
- Small-angle approximation
- Resonant mode model, experimental papers
- Resistive wall impedance in LCLS undulator
- Surface roughness tolerances for the undulator vacuum chamber (thanks to H.-D. Nuhn)

Wakefields and Physics of SASE FEL Radiation



The radiation wavelength in an FEL is

$$\lambda_r = \frac{\lambda_u}{2\gamma^2(1 + K^2/2)}$$

The energy of the beam should be kept constant over the length of the undulator within $\Delta\gamma/\gamma \sim \rho$. For the LCLS, with 1 nC beam, $\rho \approx 3 - 5 \times 10^{-4}$.
A uniform energy change (like incoherent radiation of the beam) for the whole beam can be compensated by tailoring K. However, wakefields tend to generate ΔE that varies along the bunch.

Wakefields in LCLS - First Studies

The importance of wakefield in the undulator was realized long time ago. LCLS Design Study Report 1998: resistive wakefield, various elements in the undulator.

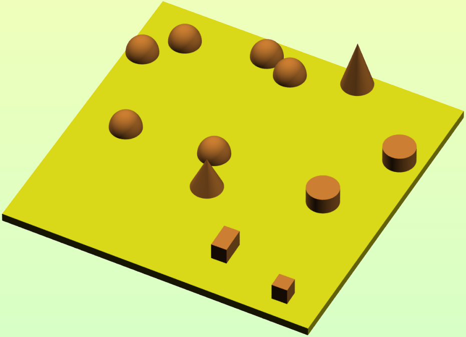
Table 8.8 The total longitudinal and transverse wakefield effects, for a Gaussian axial distribution, due to the various types of objects in the LCLS undulator. Given are the average energy loss, $\langle\delta\rangle$, the rms energy spread, σ_δ, and the relative correlated emittance growth, $\Delta\varepsilon/\varepsilon_0$, of a 100 µm betatron oscillation.

Type of Objects	$\langle\delta\rangle$/%	σ_δ/%	$\Delta\varepsilon/\varepsilon_0$/%
Resistive Wall (SS)	0.340	0.350	260
Resistive Wall (Cu)	0.060	0.060	8
Flange Gaps	0.008	0.003	0.08
Pumping Slots	0.006	0.002	0.06
BPMs	0.019	0.007	0.007

Wakefields in LCLS - Roughness Models

It was pointed out by Bane, Ng and Chao in 1997 that the surface roughness of the vacuum chamber in the undulator introduces an additional impedance.

Roughness was represented as a collection of small bumps on the surface with simple shapes. It was assumed that the bunch length (Gaussian distribution) σ_z is much larger than the size of the bumps, $\sigma_z \gg l$, then the impedance is inductive. For the LCLS nominal parameters: $L = 100$ m, $Ne = 1$ nC, $\sigma_z = 30$ μm, $b = 2.5$ mm, $E = 15$ GeV, require $\sigma_\delta < 0.05\%$



$$r < 40 \text{ nm}$$

M. Cornacchia initiated a study of the roughness impedance issue at SLAC.

Small-Angle Roughness

From "Handbook of surface metrology" by J. J. Whitehouse

Surface roughness covers a wide dimensional range, extending from that produced in the largest planing machines having a traverse step of 20 mm or so, down to the finest lapping where the scratch marks may be spaced by a few tenths of a micrometre. These scales of size refer to conventional processes. They have to be extended even lower with non-conventional and energy beam machining where the machining element can be as small as an ion or electron, in which case the scale goes down to the atomic in height and spacing. The peak-to-valley height of surface roughness is usually found to be small compared with the spacing of the crests; it runs from about 50 μm down to less than a few thousandths of a micrometre for molecular removal processes. The relative proportions of height and length lead to the use of compressed profile graphs, the nature of which must be understood from the outset. As an example figure 2.2 shows a very short length of the profile of a cross-section of a ground surface, magnified 5000 ×.

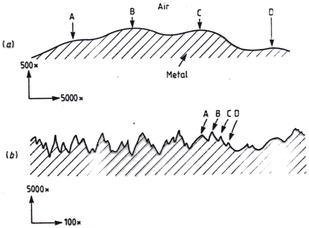
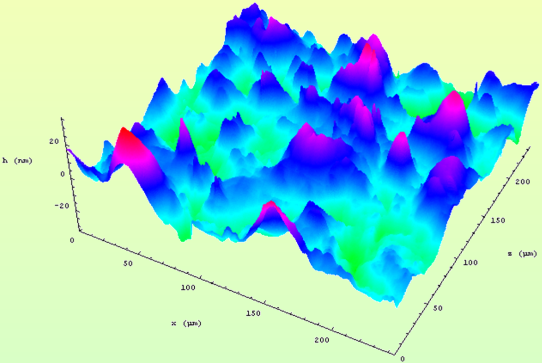


Figure 2.2
Distortion caused by making usable chart length.

In reality the profile of roughness is often shallow, or small-angle (Stupakov, 1998).

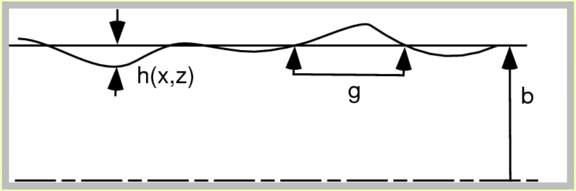
Small-Angle Roughness

An example of a measured profile for a stainless steel sample (from H.-D. Nuhn's talk)



The rms angle at the surface is $\sqrt{\theta_x^2} \approx \sqrt{\theta_z^2} \approx 1$ mrad. The previous roughness model is not applicable.

Small-Angle Roughness



A theory was developed that expresses the wake in terms of the wall surface profile $h(x, y)$ (Stupakov, 1998) assuming that

- $h \ll g$ or $|\nabla h| \approx \theta \ll 1$ – small-angle approximation
- $g \ll \lambda \sim \sigma_z$, – the extension of the bumps along the surface (the correlation length) is much shorter than the bunch length
- round pipe

Small-Angle Roughness Impedance Theory

In the limit $g \ll \sigma_z$, the impedance is inductive. Inductance *per unit length* of the pipe (b is the pipe radius)

$$L = \frac{Z_0}{2\pi c b} \int_{-\infty}^{\infty} \frac{\kappa_z^2}{\sqrt{\kappa_x^2 + \kappa_z^2}} S(\kappa_z, \kappa_x) d\kappa_z d\kappa_x$$

where $S(\kappa_z, \kappa_x) \propto \left| \int h(z,x) e^{-i\kappa_z z - i\kappa_x x} dz dx \right|^2$. The direction z is along the beam axis. Grooves along the axis ($k_z = 0$) do not contribute to the impedance.

Scaling of the impedance

$$L \propto h^2/g \sim h\theta$$

The algorithm is implemented in Mathematica notebook and can be used for evaluation of roughness properties of measured samples.

First Measurements

Surface profile was measured using Atomic Force Microscope at NIST, Boulder, Colorado, of an undulator pipe (Stupakov, Thomson, Carr & Walz, 1999). A high quality Type 316-L stainless steel tubing from the VALEX Corporation with an outer diameter of 6.35 mm and a wall thickness of 0.89 mm, with the best commercial finish, A5, corresponding to Ra = 125 nm.

Sample size	h_{rms} (nm)	$(Lb)_1$ (pH)	$(Lb)_2$ (pH)
108×108 μm	98	4.1×10^{-4}	2.8×10^{-4}
85×85 μm	84	4.0×10^{-4}	3.9×10^{-4}
65×65 μm	109	3.5×10^{-4}	1.9×10^{-3}
104×104 μm	186	7.0×10^{-4}	2.7×10^{-4}

Product Lb for measured samples.

Tolerance: $(Lb)_{tol} = 4 \times 10^{-3}$ pH. Caveats: the condition $g \gg \sigma_z$ is barely satisfied. Gaussian bunch shape was assumed.

Small-Angle Roughness Impedance Theory

The requirement $g \ll \sigma_z$ for the correlation length is too restrictive. A more general theory was developed that drops this assumption (Stupakov, 2000) A more complicated expressions for the impedance:

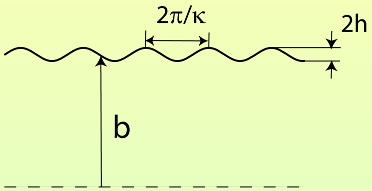
$$\mathrm{Re} Z_l(\omega) = \frac{4\pi k}{cb^2} \int dk_z \, dk_x \frac{k_z^2 |S(k_x, k_z)|^2}{\sqrt{2k|k_z| - k_z^2 - k_x^2}}$$

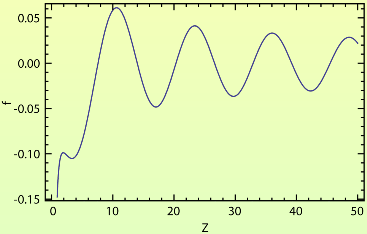
This formula is more difficult to evaluate because of (integrable) singularities in the integrand.

A simple result can be worked out for a sinusoidal corrugation on the wall.

Sinusoidal corrugation

A round pipe of radius b with a sinusoidal corrugation of the wall





In the limit $h \ll 2\pi/\kappa$, the longitudinal wake for a point charge on the axis

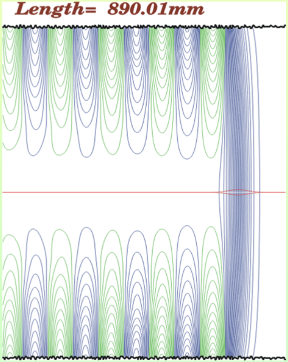
$$w(s) = \frac{h^2 \kappa^3}{b} f(\kappa s)$$

This wake should be convoluted with the longitudinal charge distribution of the bunch. Scalings for the wake per unit length for a Gaussian bunch of length σ_z

$$W(s) \sim \frac{h^2 \kappa}{b \sigma_z^2}, \qquad \sigma_z \gg \kappa^{-1}; \quad W(s) \sim \frac{h^2 \kappa^{3/2}}{b \sigma_z^{3/2}}, \qquad \sigma_z \ll \kappa^{-1}$$

Resonant Mode Model

Novokhatski and Mosnier (1997) proposed a model where roughness was treated as a dielectric layer on the surface of a flat metal surface. They concluded that a single resonant mode can propagate in a metallic pipe with rough surfaces, and can be excited by the beam.



Novokhatski, 2005

It turned out that the mode exists only in the large-angle approximation; it is not supported by the small-angle roughness (Stupakov, 2000).

Experiments

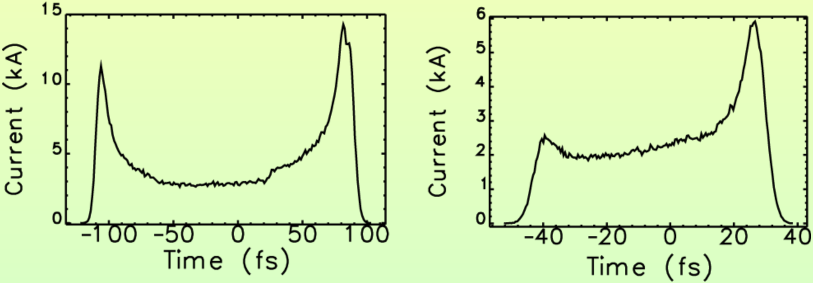
There were proposals to measure roughness impedance in a dedicated experiment, with artificially increased roughness of the pipe surface. Novokhatski et al. (PAC, 1999) proposed to measure the energy spread of the beam generated by the impedance, and the radiated RF power.

Hüning et al. (PRL, 2002) from DESY measured induced energy profile in a beam propagating through a sandblasted pipe. They confirmed the prediction of the resonant mode model.

Zhou et al. (PRL, 2002) from BNL did a similar experiment in a pipe with a dented surface.

Resistive Wall Impedance

It is expected that the dominant wake generated in the undulator will be the resistive wall wake. The low frequency resistivity model is not applicable at the frequencies corresponding to the LCLS bunch.



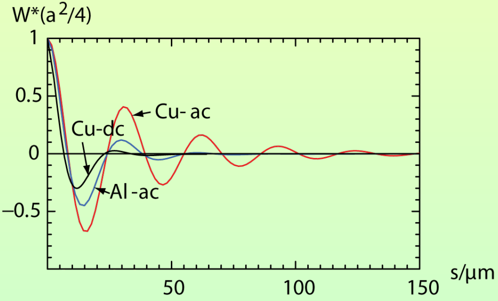
Longitudinal bunch profile for 1 nC (left) and 0.2 nC (right) bunches (the head of the bunch is on the left). Fine structures on the beam involve time scales $\sim$ tens of fs.

Resistive Wall Impedance

At high frequency the metal conductivity depends on frequency ω

$$\sigma(\omega) = \frac{\sigma_0}{1 - i\omega\tau}$$

where τ is the collision time (or relaxation time). For copper, $\sigma_0 = 5.8 \times 10^{17}$ s^{-1}, $c\tau = 8.1$ μm; for aluminum, $\sigma_0 = 3.8 \times 10^{17}$ s^{-1}, $c\tau = 2.4$ μm.

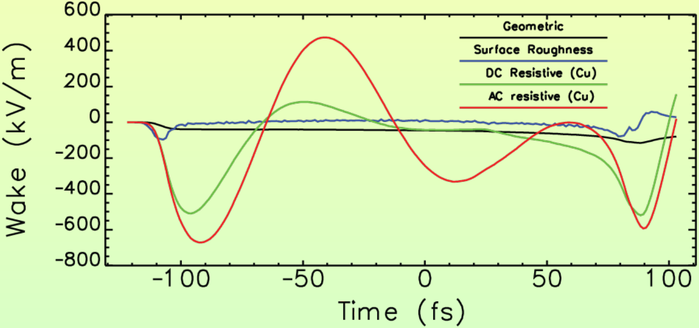


The resistive wake for aluminum is smaller than for copper (Bane, Stupakov, 2004).

The effect of anomalous skin effect is small.

Wakes in the undulator

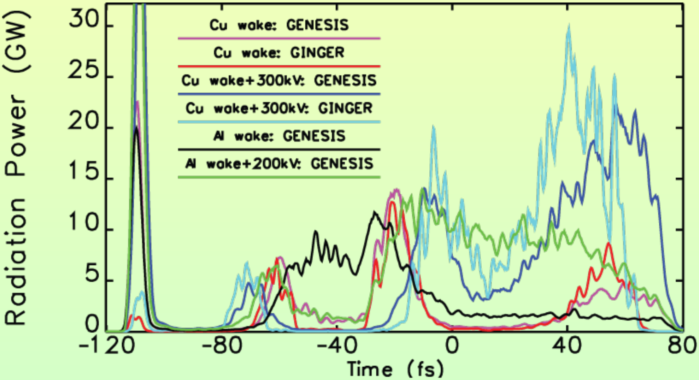
The effect of the wakes on the lasing in the LCLS was studied by Fawley et al. (2005). The GINGER and GENESIS codes were used to simulate radiation in the undulator including the wakes.



Surface roughness of 100 nm over a period of 30 μm was assumed. Negative value corresponds to deceleration. (Energy loss from incoherent radiation is ~ 230 keV/m.)

Radiation Power

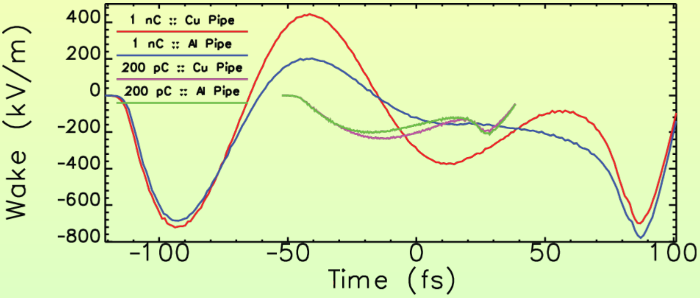
The deleterious effect of the wakes can be offset by tapering the undulator parameter along the path in the undulator. This equivalent to changing the beam energy.



At best, tapering recovers 80% of the energy by $z = 130$ m for a Cu vacuum chamber.

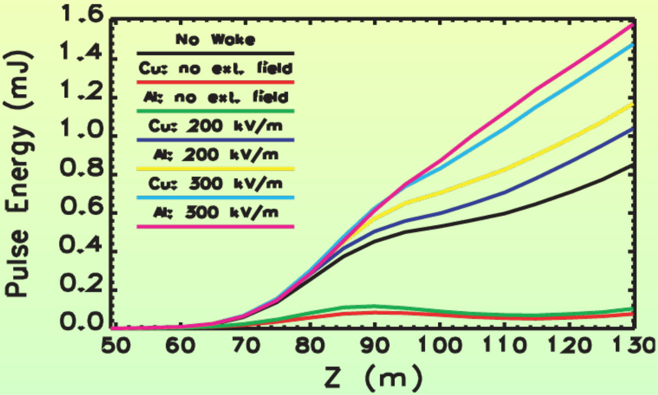
200 pC Bunch

The wake is much smaller for a 200 pC bunch.



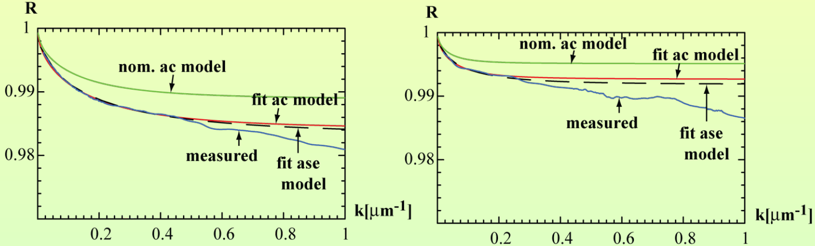
200 pC Bunch—Radiation

The effect of the wake for 200 pC beam can be fully recovered by tapering.



Resistive Wall Wake—Experiment

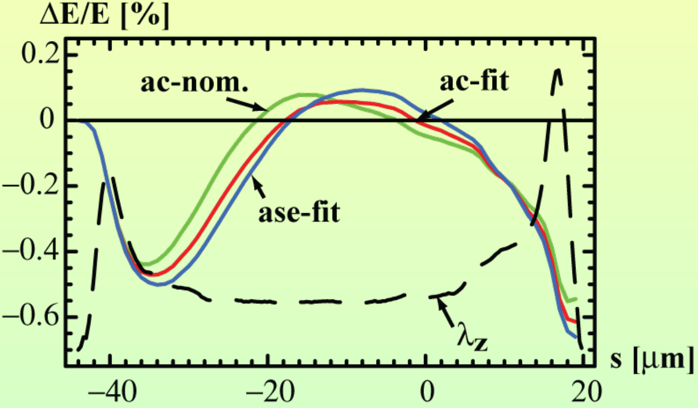
Reflectivity at normal incidence was measured by J. Tu at BNL for samples of Al and Cu, produced at ANL (Bane, Stupakov and Tu, 2006).



Reflectivity versus frequency ($k = 2\pi/\lambda$) for Al (left) and Cu (right). The fitted parameters for Al: $\sigma_f = .63\sigma_{\text{nominal}}$, $\tau_f = 0.78\tau_{\text{nominal}}$. For Cu, the fitted parameters are: $\sigma_f = .66\sigma_{\text{nominal}}$, $\tau_f = 0.67\tau_{\text{nominal}}$.

Resistive Wall Wake—Experiment

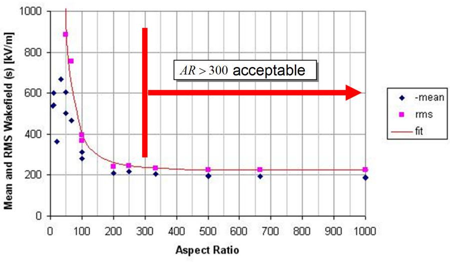
The discrepancy does not change much the wake for the LCLS beam



Energy variation within the bunch at the end of 130 m undulator.

Tolerances for Roughness

Based on the existing theory of roughness impedance H.-D. Nuhn formulated tolerances for the surface roughness (LCLS Physics Requirements Document 1.4-001-r3). It requires "Surface roughness wavelength to amplitude ratio ≥ 300".
The tolerance is based on the sinusoidal corrugation model characterized by the amplitude h and the wavenumber κ. The wakefield was obtained by convolution with the simulated longitudinal current distribution in the LCLS bunch. $AR = \lambda/h = 2\pi/\kappa h$.



The graph shows the sum over all wakefield contributions. The wakefield tolerances are chosen such that the resistive wall wakefield dominates the other wakefield components, including surface roughness wakefields and geometric wakefields.

Tolerances for Roughness

This tolerance actually depends on the wavelength of the solenoidal corrugation, but the dependence is relatively weak.

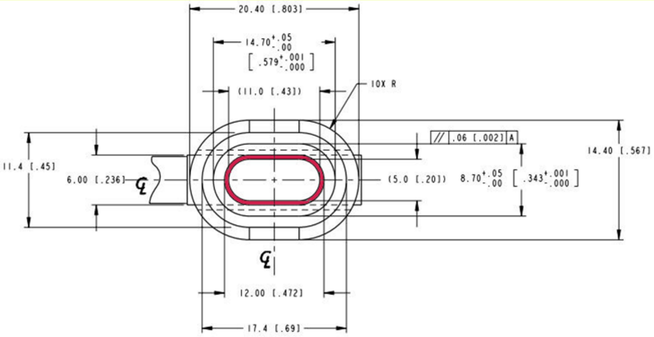
$AR = 300$ corresponds to the rms angle about 10 mrad. The practical requirement is that the rms roughness slope in 5 mm gap chamber be ≤ 18 mrad in the direction of beam propagation, and ≤ 40 mrad in the transverse direction.

This wakefield introduces the rms energy spread in the *core* part of the beam which is $\approx 0.8\rho$ ($\rho = 3.2 \times 10^{-4}$). The wake is computed for the round vacuum chamber.

The contribution of the resistive wall wake is $\approx 3.7\rho$.

Chamber Cross Section

The vacuum chamber is not round.



For a model with two parallel planes, the resistive wall longitudinal impedance is equal to the one for a round pipe with the diameter equal to the gap.

There is an open question of how the tolerance can be relaxed for the rounded parts of the inner surface.

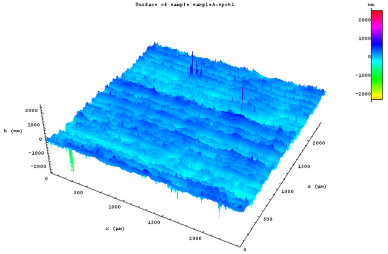
Measured Surface Roughness

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

- **Work request #:** M08033
- **Requester**: WIEMERSLAGE, GREG E.
- **Beamline / affiliation:** LCLS
- **Date:** 12-04-2007

SPOT 1

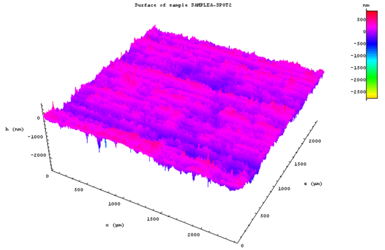
r(z): 702 mm; h_{rms}: 161 nm



x'_{rms}: 9.3 mrad; z'_{rms}: 23.6 mrad

SPOT 2

r(z): 665 mm; h_{rms}: 152 nm



x'_{rms}: 7.7 mrad; z'_{rms}: 22.9 mrad

Conclusions

- The main source of the longitudinal impedance in the LCLS vacuum chamber is resistive wall. This impedance should be calculated taking into account the conductivity dependence on the frequency. Depending on the charge of the beam, it might seriously affect the radiation process in the undulator.
- We expect that the surface roughness will be the second essential source of the impedance. After many years of theoretical research, we have a consistent theory of the SR impedance, and given the properties of the surface, we can calculate the impedance and its effect on the beam.
- The tolerance on the surface roughness is based on the requirement that the surface roughness impedance be several times smaller then the RW impedance. It seems that the tolerance is now practically achievable.