Wake fields and energy spread for eRHIC ERL

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Outline

- From effects which were considered so far (CSR, Resistive wall, RF cavities and Wall roughness) wake potential for eRHIC is dominated by

  - RF cavities & Resistive wall

  Estimates of these dominant effects were done using well established formulas, so that we present only final result without going into details (due to lack of time).

- In this presentation, we concentrate on discussion of effects which may be less settled (under discussion at ERL's workshops) which we believe are negligible for eRHIC with an explanation why:

  - Coherent Synchrotron Radiation (CSR) and its shielding

  - Wall roughness and realistic surfaces

Wake fields/Impedance (only monopole longitudinal)

Wake field - the radiation by point charge whose electromagnetic field can be disturbed by beam environment. "Wake fields" – since they remain usually behind the exciting particle. The wake field can influence the motion of trailing particles.

$$W_{\|}(s) = -\frac{1}{q}\int_{-\infty}^{\infty} dz\, E_z\left(r_{beam}, r_{exciting\, charge}, z, t = \frac{z+s}{c}\right)$$

wake function (function of the distance or time delay between the exciting and test charges)

It is often easier to solve for fields in frequency domain, thus concept of coupling impedance (related to wake function by a Fourier transform)

impedance: $$Z_{\|}(\omega) = \int_{-\infty}^{\infty} \frac{dz}{c} W_{\|}(z)\exp(-j\omega z/c) \qquad W_{\|}(z) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} Z_{\|}(\omega)\exp(j\omega z/c)$$

Wake potential - wake function for charge distribution:

wake potential: $$V(z) = \int_{z}^{\infty} dz'\, \rho(z') W_{\|}(z - z')$$

energy loss: $$\Delta E = eq\int_{-\infty}^{\infty} dz \rho(z) V(z)$$

Summary for eRHIC ERL

Total contribution (after 12 passes) 20 GeV scenario (highest charge)

	Energy loss [MeV]	Rms energy spread [MeV]	Power loss [MW]
CSR	suppressed	suppressed	
Resistive wall	14 (for Al)	14.7	0.7
Cavities	36	14.4	1.8
Wall roughness	suppressed due to large l_c/r_h	<2	

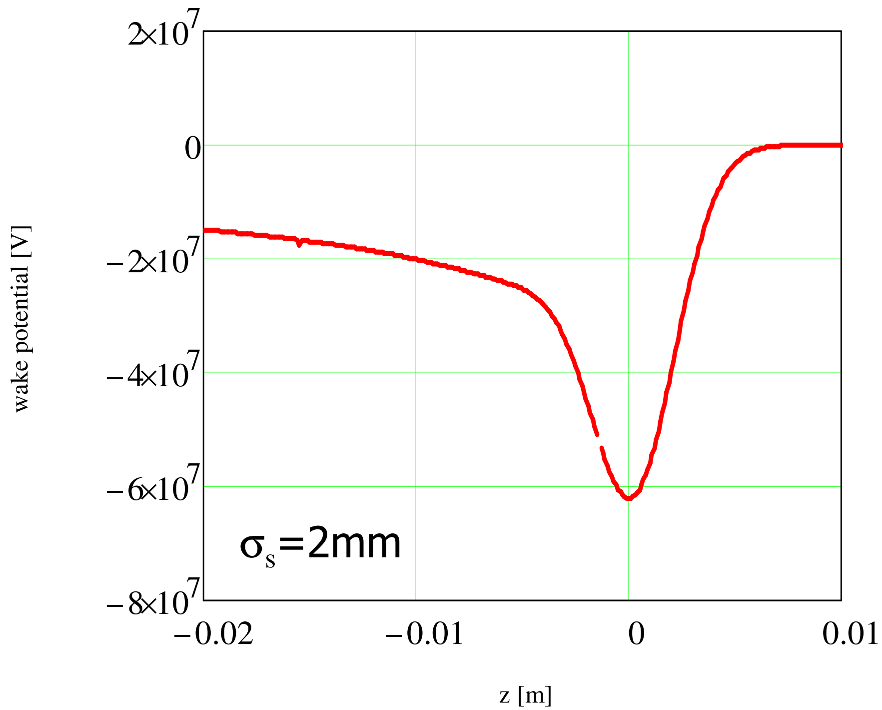
Baseline parameters:

bunch charge	3.54nC
rms bunch length	2 mm
vacuum chamber full height	5 mm

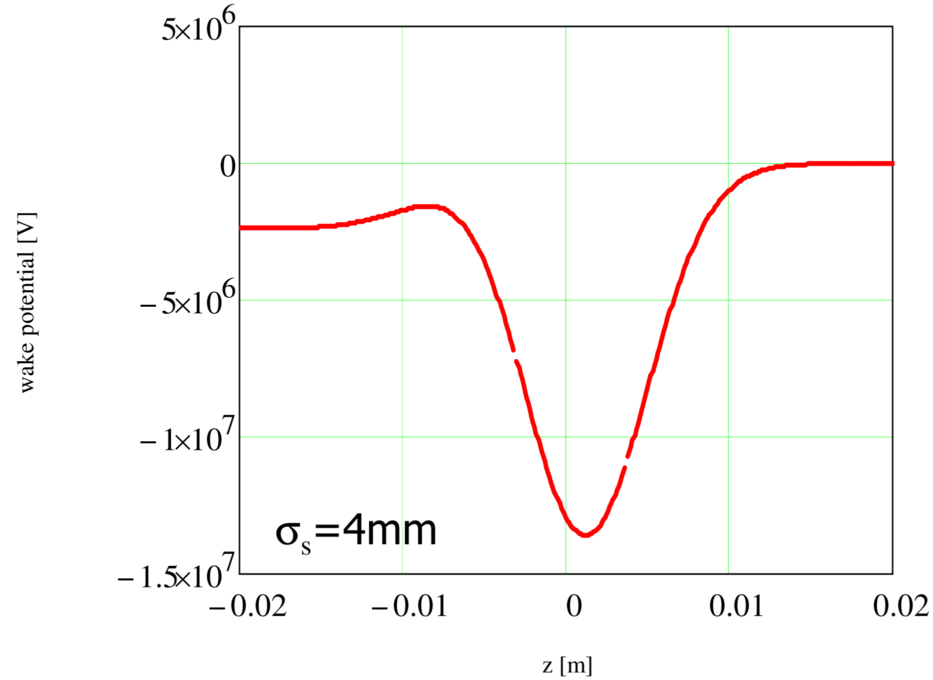
Total RMS energy spread coming into 400 MeV injector after deceleration: 20.6 MeV (for rms bunch length σ_s=2 mm).

Total wake potential for eRHIC (RW and RF cavities)

20 GeV
(6-pass ERL)



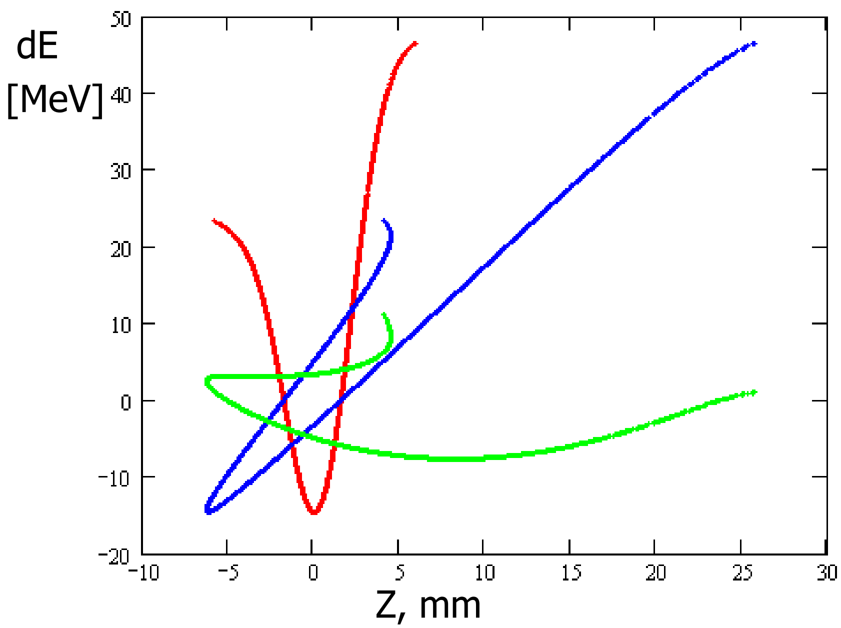
5 GeV, 1st stage
(6-pass ERL)



Requires energy loss and energy spread compensation.

Example of energy spread compensation

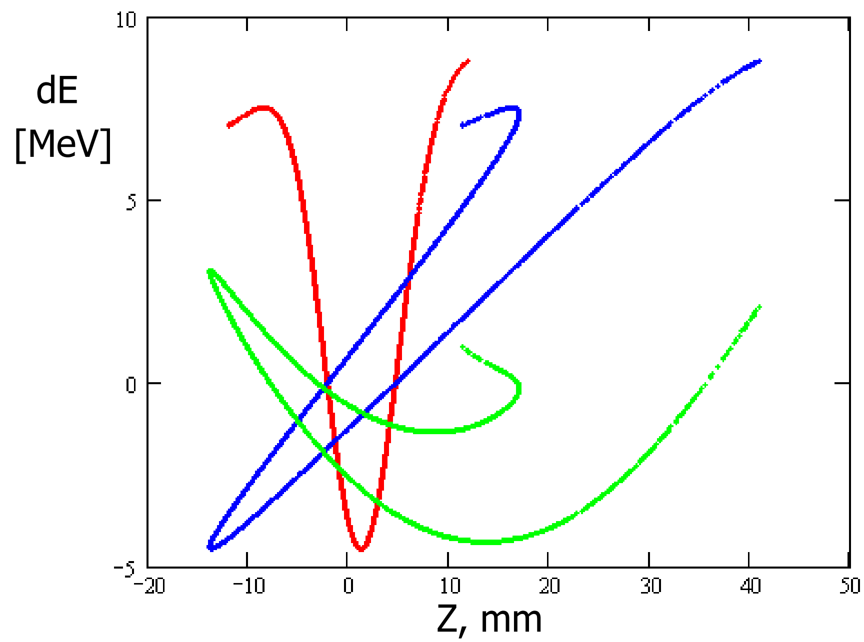
20 GeV
(6-pass ERL)



Stretching beam (blue) at 400 MeV by introducing longitudinal dispersion (M56=0.15 m) and adjusting the phase of the pre-injection linac (green):

energy spread at 10 MeV reduced from +/- 30.5 MeV to +/- 9.4 MeV

5 GeV, 1st stage
(6-pass ERL)

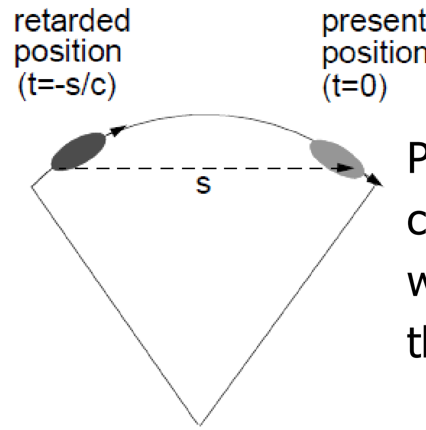


Stretching beam (blue) at 100 MeV by introducing longitudinal dispersion (M56=0.3 m) and adjusting the phase of the pre-injection linac (green):

energy spread at 10 MeV reduced from +/- 6.7 MeV to +/- 3.7 MeV

CSR (estimate without taking into account beam pipe shielding effect)

$$\left(\frac{dE}{d(ct)}\right) = -\frac{2q^2}{3^{1/3}R^{2/3}}\int_{-\infty}^{s}\frac{ds'}{(s-s')^{1/3}}\frac{d\lambda(s')}{ds'}$$



Particles radiate coherently at wavelength larger than bunch length.

For Gaussian distribution:

energy loss: $$< E >= -0.35\frac{r_e N_e L_{eff}}{\gamma(R^2\sigma_{es}{}^4)^{1/3}}$$

energy spread: $$\sigma_E = 0.25\frac{r_e N_e L_{eff}}{\gamma(R^2\sigma_{es}{}^4)^{1/3}}$$

For eRHIC, without shielding effect, σ_E would be 13MeV.

used parameters:

Bunch charge	**3.54nC**
Rms bunch length	2 mm
Vacuum chamber height	5 mm

Shielding of CSR (analytic theories, sampled)

Examples of analytic treatment of shielding: Schwinger'45; impedance: Warnock'90 [1]; wake function: Murphy-Krinsky-Gluckstern'96; Agoh-Yokoya'94 [2]; Mayes-Hoffstaetter'09 [3].

[1]:

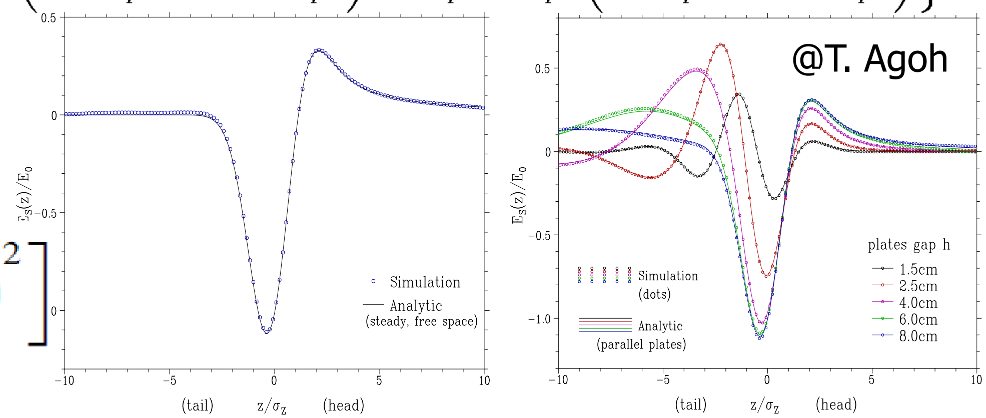
$$\frac{Z(n,\omega)}{n} = \frac{2\pi^2 Z_0}{\beta}\frac{R}{h}\sum_{p(odd)\geq 1}\Lambda_p\Big[\frac{\beta\omega R}{nc}J_n'(\gamma_p R)\big((J_n'(\gamma_p R)+iY_n'(\gamma_p R)\big) + \Big(\frac{\alpha_p}{\gamma_p}\Big)^2 J_n(\gamma_p R)\big(J_n(\gamma_p R)+iY_n(\gamma_p R)\big)\Big],$$

[2]:

$$Z(\omega) = Z_0\frac{2\pi}{h}\left(\frac{2c}{\omega\rho}\right)^{1/3}\sum_{p=0}^{\infty}\Big\{\mathrm{Ai}'(\beta_p^2)\Big(\mathrm{Ai}'(\beta_p^2) - i\mathrm{Bi}'(\beta_p^2)\Big) + \beta_p^2\mathrm{Ai}(\beta_p^2)\Big(\mathrm{Ai}(\beta_p^2) - i\mathrm{Bi}(\beta_p^2)\Big)\Big\}$$

Asymptotic expression for impedance with shielding (strong shielding)

$$Z(k) = \frac{\pi Z_0}{kh^2}\left[e^{-2\pi^3\rho/3k^2h^3} - \frac{3i}{2}C_5\left(\frac{k^2h^3}{\pi^3\rho}\right)^2\right]$$



[3]:

$$\frac{d\mathcal{E}_{\text{images}}}{ds}(s)\Big|_B = Nr_c mc^2\sum_{n=1}^{\infty}2(-1)^n \times\left\{\frac{-\kappa\lambda(s_{\alpha,n})}{r_{\alpha,n}}\Bigg|_{\alpha=-(\kappa L_m-\theta)}^{\alpha=\theta} + \int_{-(\kappa L_m-\theta)}^{\theta}d\alpha\,\frac{\beta^2\cos(\alpha)-1}{r_{\alpha,n}}\lambda'(s_{\alpha,n})\right\}$$

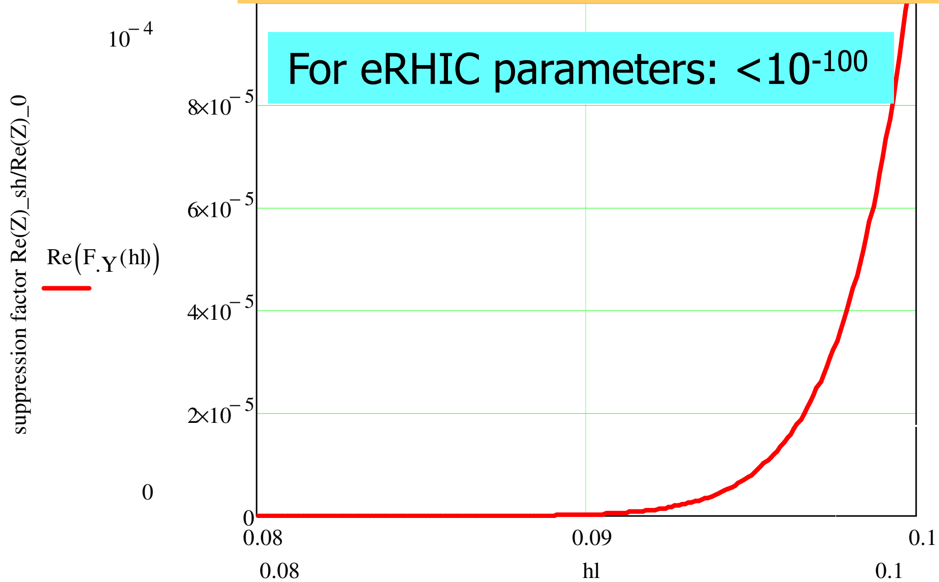
For eRHIC, with R=200m, for 2mm rms bunch length, even h=2 cm gap size gives very strong shielding:

$$x_{th} = \frac{2\pi^3 R\sigma_z^2}{3h^3}$$

$$x_{th}(0.02) = 2.067\times 10^3$$

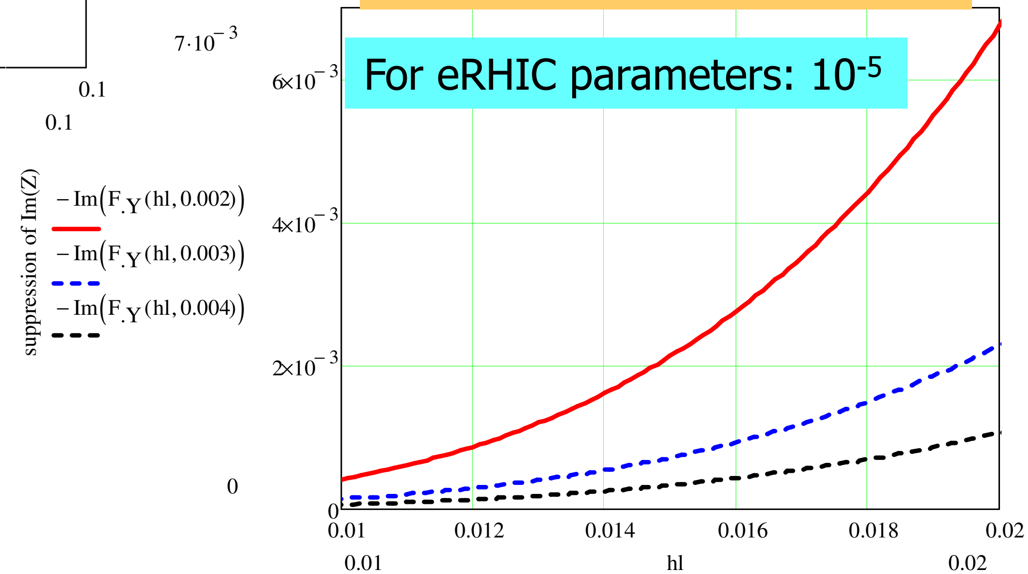
CSR for eRHIC parameters

energy loss suppression factor



vacuum chamber full gap [m]

energy spread suppression



vacuum chamber full gap [m]

For eRHIC, effect of CSR
is negligible due to shielding.

Some questions/issues for CSR shielding

When we started looking into these questions (for other design parameters for which shielding was less pronounced) we got the following input:

- Should not expect significant effect from shielding for energy spread, mostly just energy loss suppression (this can be quantified from analytic expressions as shown in previous slides).

- There is a lack of dedicated experiments on CSR shielding to quantify its effect on the beam:

1. **One experiment (H. Braun et al., 2001) did not show expected theoretical reduction (with shielding) even for energy loss due to CSR.**
2. **Another experiment (Kato et al., Phys. Rev. E, 1998) studied synchrotron radiation rather than effects on the beam – also some issues were reported, like disagreement with theory for small gap sizes, etc.**

Simple, well-controlled experiment was desired to address these issues.

Such experiment was proposed at ATF @BNL (April 2009) and conducted during 2009-2011 (several stages: first with rough plates and more recently with polished plates).

CSR SHIELDING EXPERIMENT*

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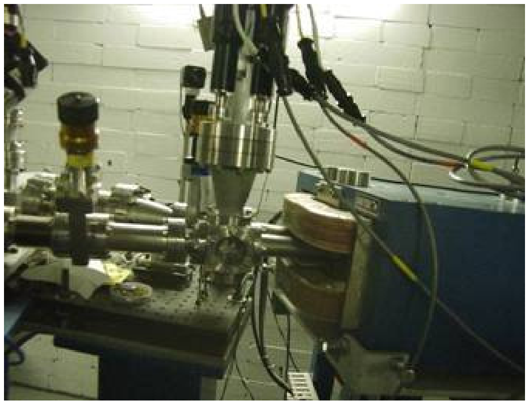
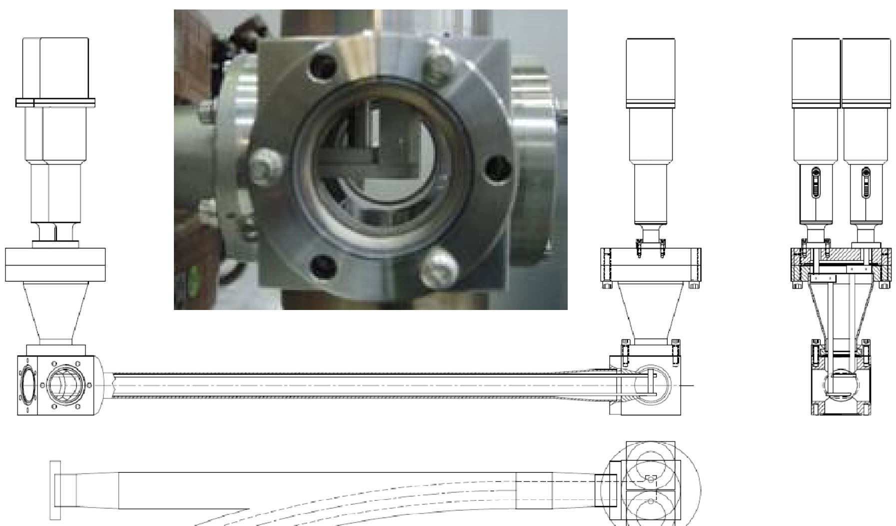
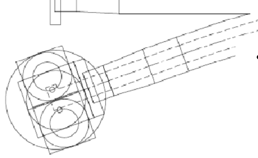


see talk by V. Litvinenko on Thursday:

"Experimental demonstration of CSR shielding at ATF (BNL)"





Two plates with adjustable gap were installed into dipole vacuum chamber

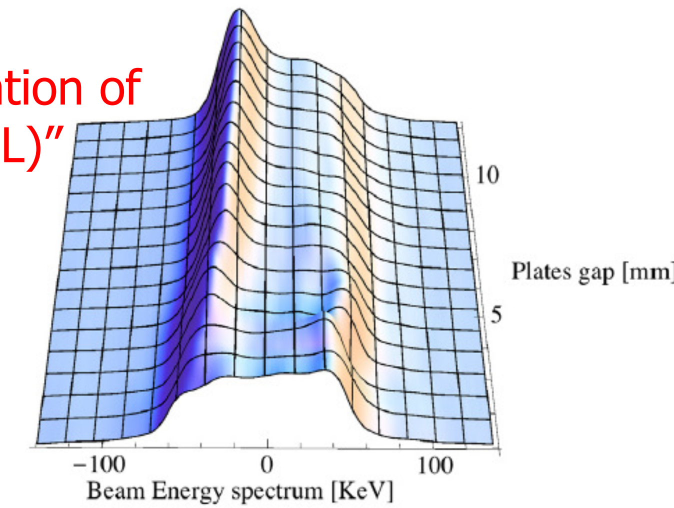


Figure 3: Measured beam energy spectrum as function of the gap between the shielding plates.

CONCLUSIONS

We presented clear experimental observation of suppression of the longitudinal CSR wake in a dipole magnet by two conducting plates. At very small gaps we observed the suppression of both the energy loss and the energy spread induced by CSR. Out analytical results are in good agreement with observations.

Wall Roughness (WR) Models

1. **Bane et al. ('97) (also with Stupakov'98) "The inductive" model – small bumps of various shape. Contribution from a set of bumps is given by the sum of individual bump contributions to the impedance.**

   This is the model which was used to have first "conservative" estimate for eRHIC (used, for example, for LCLS design). ?

2. **Stupakov ('98): "The Statistical" model.**

3. **Novokhatski et al. ('97, '98, '99): "The Resonator/dielectric layer" model.**

   This model can lead not just to energy spread but also to energy loss due to propagation of synchronous modes (used, for example, for Cornell ERL design). (even more trouble?)

4. **M. Dohlus: ('00, '01): Impedance of corrugated pipe.**

5. **Stupakov ('00): "shallow" corrugated pipe; surface impedance.**

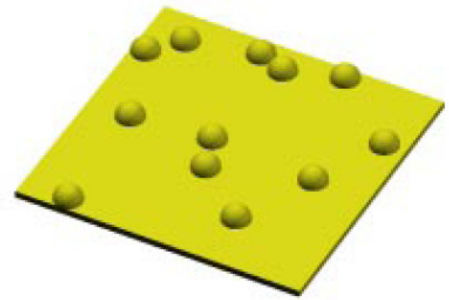
Summary of WR models

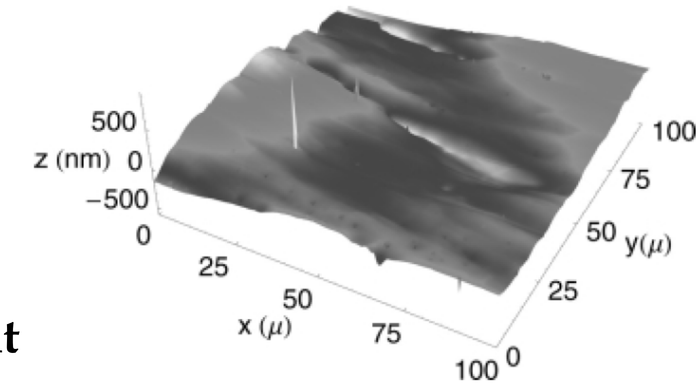
- **Models with identical bumps (height comparable to length) – give largest estimate of impedance. However, such models do not reflect correctly real wall roughness characteristics.**

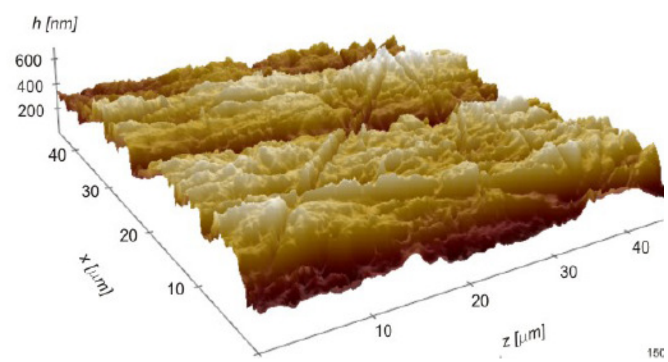
- **The real roughness is typically characterized by the large aspect ratio of the characteristic size along the surface l_c (correlation length) and the height of the bumps r_h. Corresponding models give much smaller impedance.**

- **For short bunches (comparable or smaller than correlation length) one may need to worry about synchronous modes and energy loss even for smooth bunch distributions. More pronounced effect for sharp edge distributions.**

  The effect becomes suppressed for large aspects ratios of wall roughness.







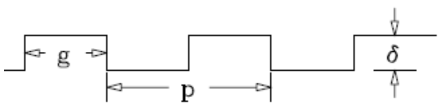
Suppression of synchronous modes for large aspect ratios (Stupakov'00)

Novokhatski:

frequency ω_0 of the mode

$$k = \sqrt{\frac{2\varepsilon}{(\varepsilon - 1)\, b\delta}}$$

$$\omega_0 = c\sqrt{\frac{2p}{\delta b g}},$$



longitudinal wakefunction of the point charge

$$w(s) = \frac{Z_0 c}{\pi b^2} \cos(\omega_0 s / c).$$

valid only for k·p<<1; not applicable for large aspect ratios p/δ (shallow corrugation)

Stupakov's extension for shallow corrugations:

$$w(s) = \frac{2 Z_0 c}{\pi b^2} U \cos(\omega_0 s / c). \qquad U \approx r^4/32$$

Let us estimate the wake for realistic parameters of roughness: $h_0 = 0.28\ \mu$m (corresponding to the RMS roughness of 0.2 μm), $g = 2\pi/\kappa = 100\ \mu$m, and $b = 2.5$ mm. We find $r = h_0\sqrt{b\kappa^3}/2 = 0.11$. The corresponding loss-factor parameter is

$$U \approx 4.5 \cdot 10^{-6},$$

U=2.6e-10 (for eRHIC parameters)

which indicates that the effect of the wake in this regime will be negligibly small.

Experiments on wall roughness

- **DESY (M. Hüning, 2002):**

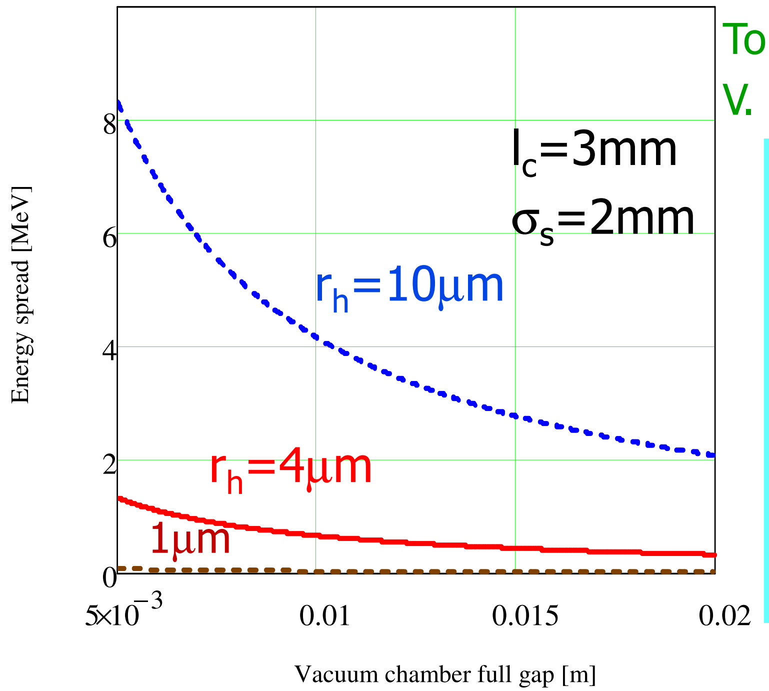
  confirmed existence of synchronous modes and energy loss for small aspect ratios of wall roughness.

- **BNL's ATF (F. Zhou et al., PRL'02):**

  confirmed suppression of modes and thus energy loss for wall roughness with large aspect ratios (in agreement with analytic work by Stupakov and numeric simulations by Novokhatski).

For wall roughness with large aspects ratios we can thus neglect contribution from synchronous modes and use inductive impedance model valid for large aspect ratios.

Wall Roughness (WR) for eRHIC vacuum chambers



To have large aspect ratio of WR: l_c / r_h

V. Litvinenko suggested extruded aluminum for eRHIC.

Measurements for a sample of extruded aluminum vacuum chamber:

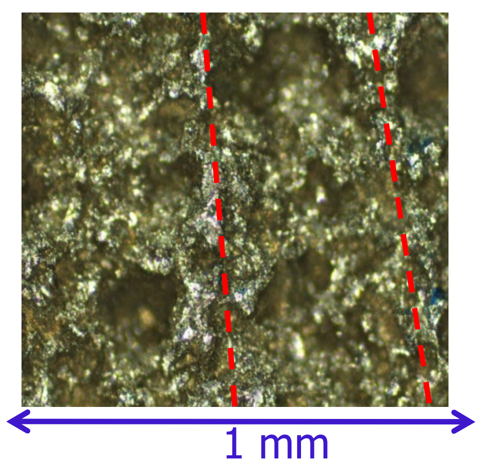
(G. Mahler, T. Rao, A. Fedotov et al.)

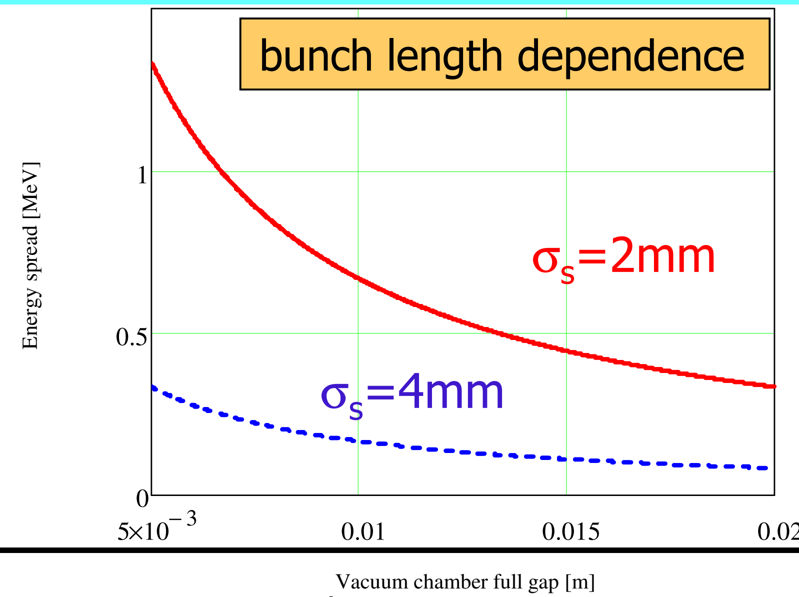
1) Profilometer:

rms height=3-4µm, no correlation length info

2) Optical microscope:

20 µm peak-to-valley, correlation length 3mm)





l_c=3mm

r_h=4µm

Acknowledgements

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Thank you