Proposal to study
effects of Wall Roughness
at ATF/BNL

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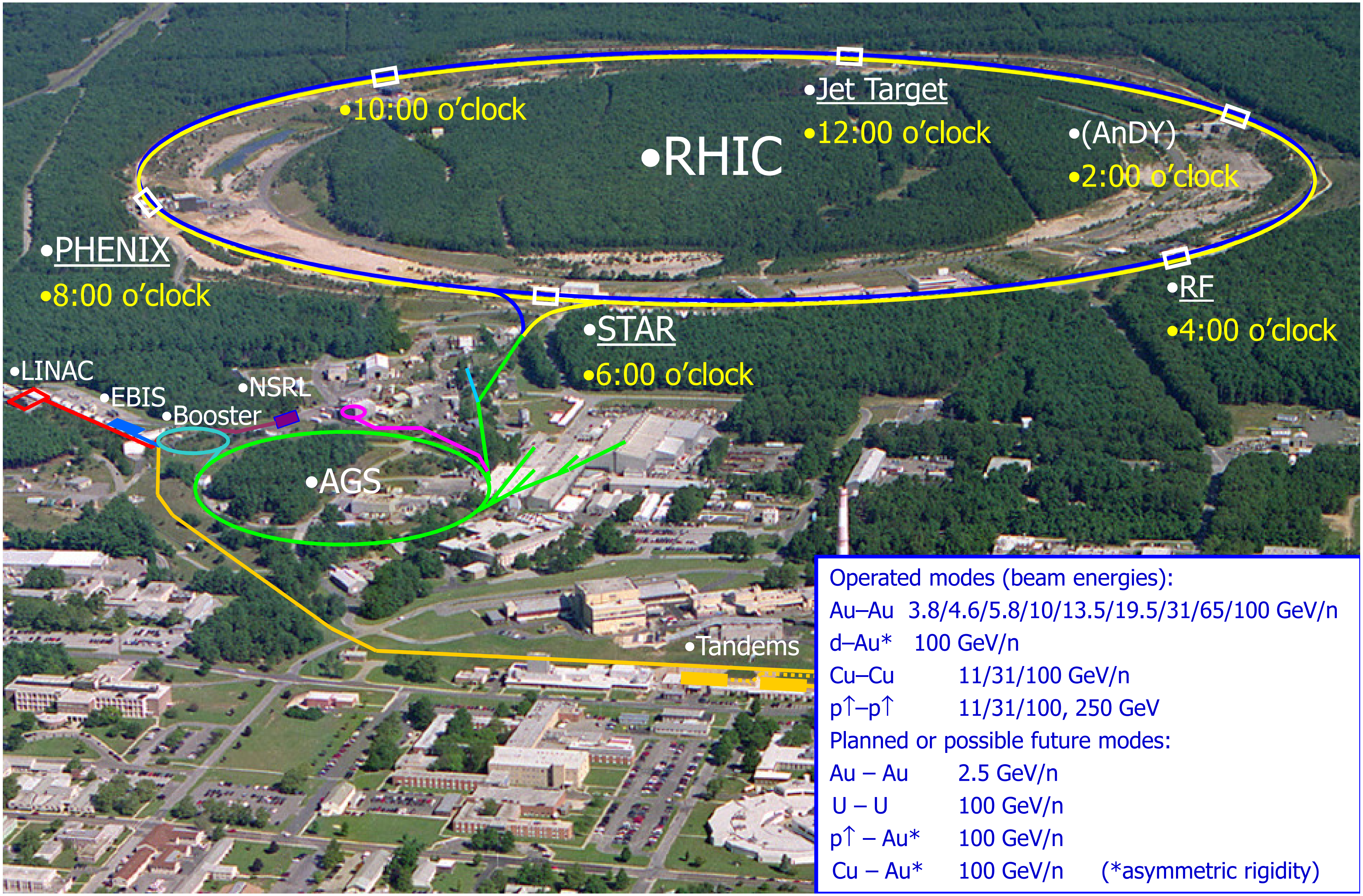
Motivation

- Wake fields due to the Wall Roughness and their impact on electron beam - critical question for the design of Electron Ion Collider at BNL (eRHIC).

- Important for many other projects and applications.

- Imposing very strict requirement on surface roughness by application of several processing techniques (to avoid potential problems) is not always the best practical solution.

RHIC – a High Luminosity (Polarized) Hadron Collider



Operated modes (beam energies):

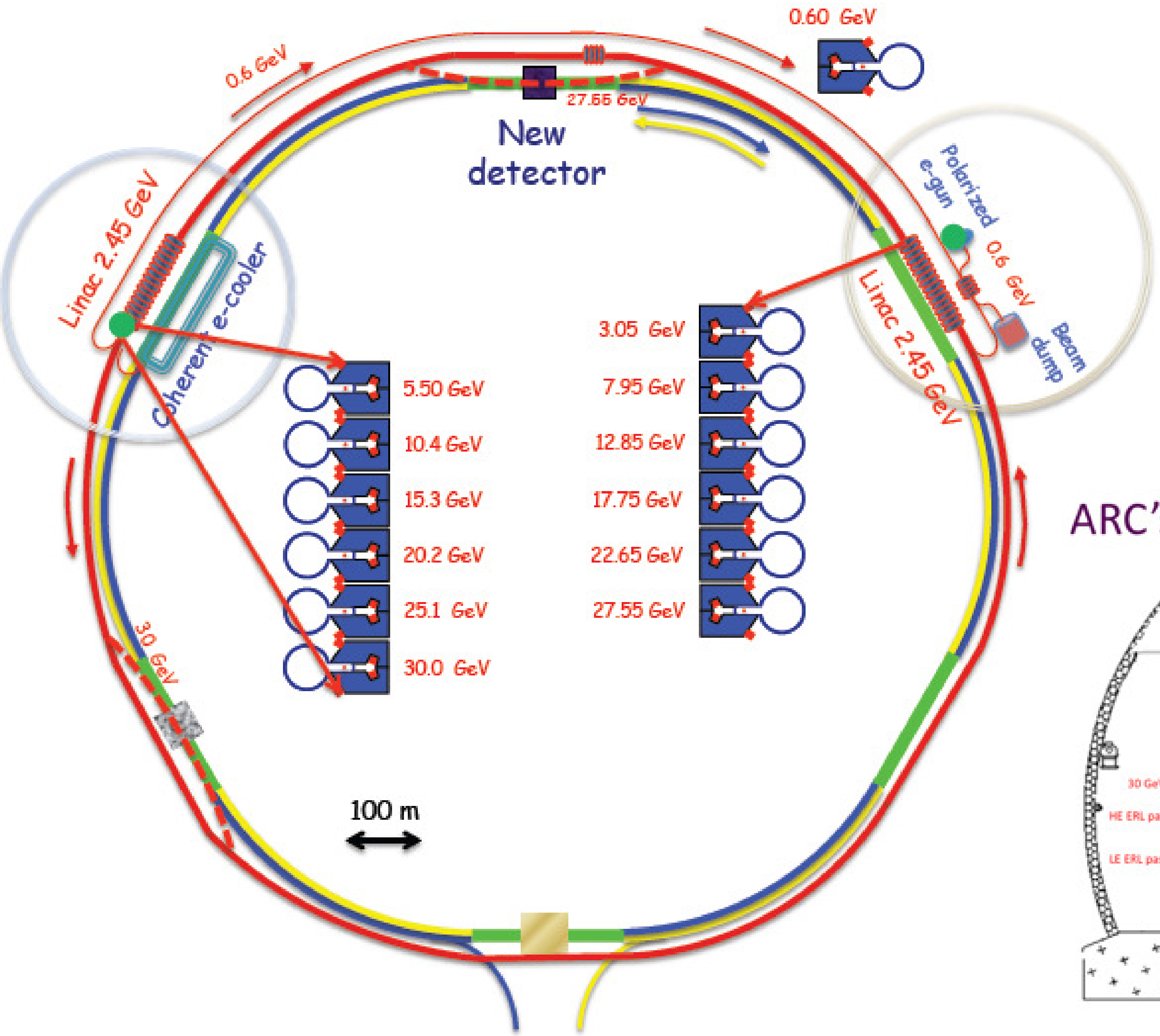
Au–Au	3.8/4.6/5.8/10/13.5/19.5/31/65/100 GeV/n
d–Au*	100 GeV/n
Cu–Cu	11/31/100 GeV/n
p↑–p↑	11/31/100, 250 GeV

Planned or possible future modes:

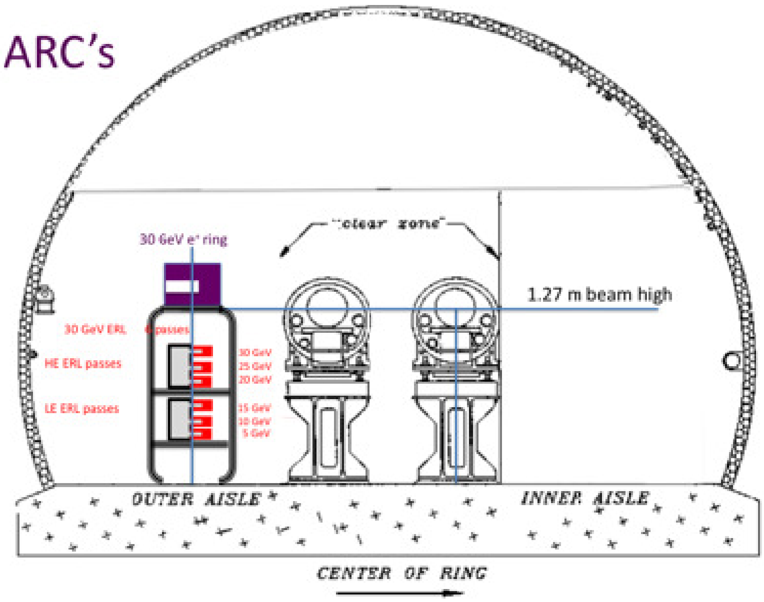
Au – Au	2.5 GeV/n
U – U	100 GeV/n
p↑ – Au*	100 GeV/n
Cu – Au*	100 GeV/n

(*asymmetric rigidity)

eRHIC layout (working version)



For the eRHIC project, electron beam with high peak current has to go through the present tunnel of the Relativistic Heavy Ion Collider (RHIC) 6 times to reach the top energy (at which electron beam will collide with the ion beam) and then additional 6 times to be decelerated before going to the dump.



Wall Roughness (WR) wake field/impedance 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.**

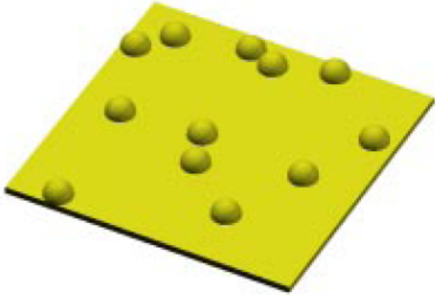
   This model can lead not just to energy spread but also to energy loss due to propagation of synchronous modes (used, for example, for Cornell ERL design).

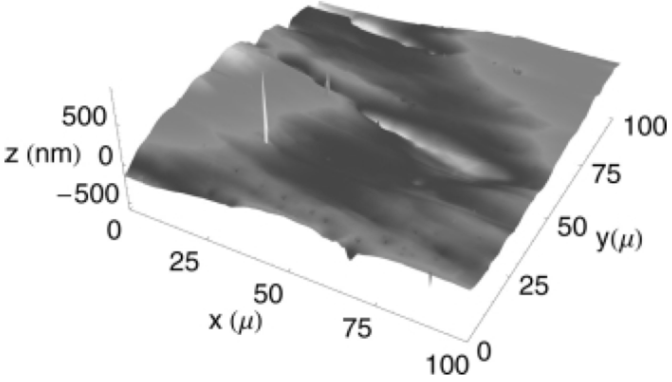
4. **M. Dohlus: ('00, '01): Impedance of corrugated pipe.**

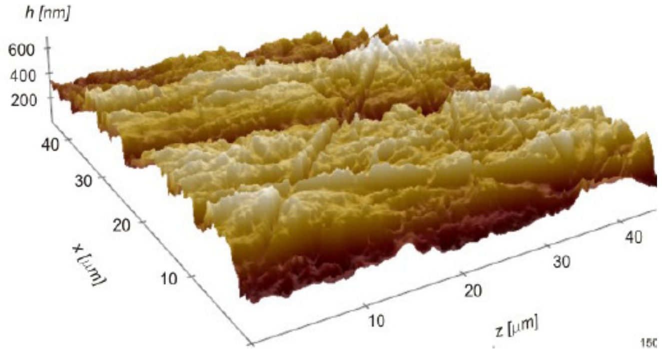
5. **Stupakov ('00): "shallow" corrugated pipe; surface impedance.**

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. Lowest frequency mode becomes suppressed for large aspect ratios of wall roughness.

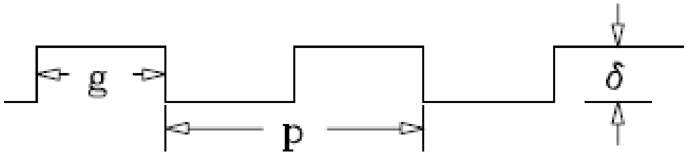






Suppression of lowest frequency synchronous mode for large aspect ratios (Stupakov'00)

Novokhatski:



longitudinal wakefunction of the point charge

frequency ω_0 of the mode

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

$$k = \sqrt{\frac{2\varepsilon}{(\varepsilon - 1)\, b\delta}} \qquad \omega_0 = c\sqrt{\frac{2p}{\delta b g}},$$

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

Stupakov's extension for shallow corrugations:

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

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

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

(even smaller for eRHIC parameters, assuming very large correlation length)

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

Experiments on wall roughness

- **DESY's TTF (M. Hüning et al., PRL'02):**

confirmed existence of synchronous modes and energy loss for small aspect ratios of wall roughness; good agreement with theory for deep structures.

- mode exist independent of randomization of WR in their regime of mode wavelength

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

observed suppression of such mode for wall roughness with large aspect ratios and randomization of WR (for large periods between bumps). Although small, some energy loss was still measured for their range of parameters.

For artificially created surface with large random bumps:

- energy spread: agreement with inductive model

- energy loss: suppression of synchronous mode for wavelength comparable to distance between bumps

ATF@BNL

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Surface-Roughness Wakefield Measurements at Brookhaven Accelerator Test Facility

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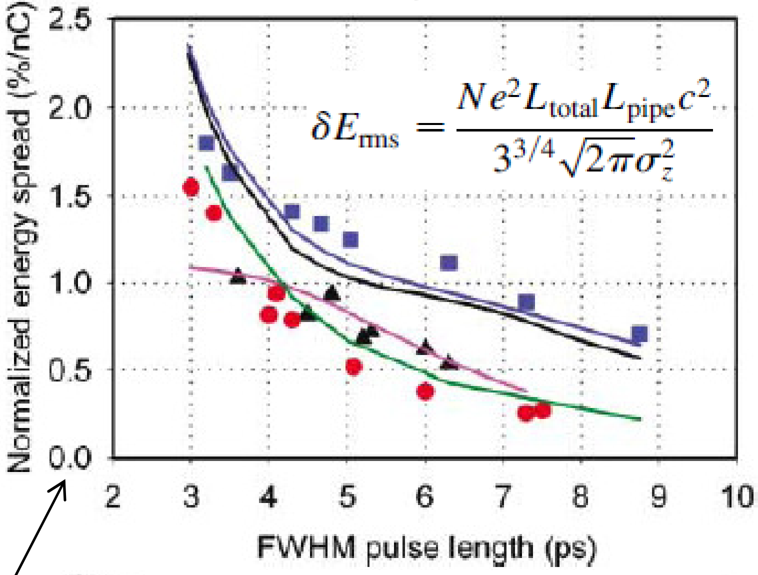
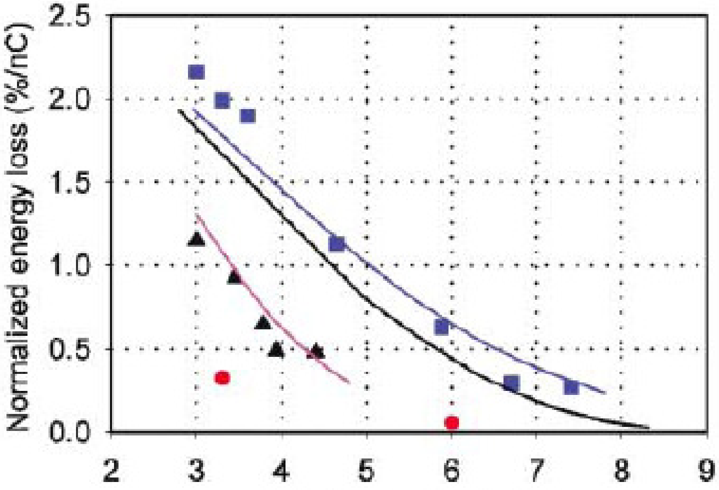
M. H. Woodle,[1] and V. Yakimenko[1]

TABLE I. The physical characteristics of the fabricated beam tubes. The parameters are defined as follows: w = bump width, h = bump height, g = bump separation, and $g*$ = average bump separation.

Beam tube	Roughness	Total number	Distributed	Length (cm)
1st	Smooth	$\cdots$	$\cdots$	97
2nd	$h = 0.3$ mm $w = 1.2$ mm $g = 6$ mm	~3240	Periodically	97
3rd	$h = 0.6$ mm $w = 1.2$ mm $g = 6$ mm	~3240	Periodically	97
4th	$h = 0.6$ mm $w = 1.2$ mm $g^* = 6$ mm	~2900	Randomly	97

squares show data for periodic large bumps; blue line shows inductive impedance combined with synchronous mode model (IS model) fit for a Gaussian beam and periodic large bumps; black line shows IS model fitting for a parabolic beam and periodic large bumps; dark triangles depict data for periodic small bumps; pink line shows IS model fitting for periodic small bumps; red circles represent data for random large bumps; dark green line shows inductive impedance model (I





length. Blue squares show data for periodic large bumps; blue line shows synchronous mode model (S model) fitting with Gaussian beam; black line shows S model fitting with parabolic beam; triangles represent data for periodic small bumps; pink line shows S model fitting for periodic small bumps; red circles are data for random large bumps.

Application to eRHIC

1. For bunch length >> wall roughness (WR) correlation length: approximation of "long bunch" is valid (purely inductive wake/imaginary impedance) – only energy spread, no energy loss.
2. WR surface with large correlation length (period of corrugation of wall roughness) – reduces inductive wake and suppresses lowest frequency synchronous mode.

- eRHIC: extruded aluminum – assuming characteristic length of few mm based on measured sample (July 2011) with "educated" guess about correlation length:

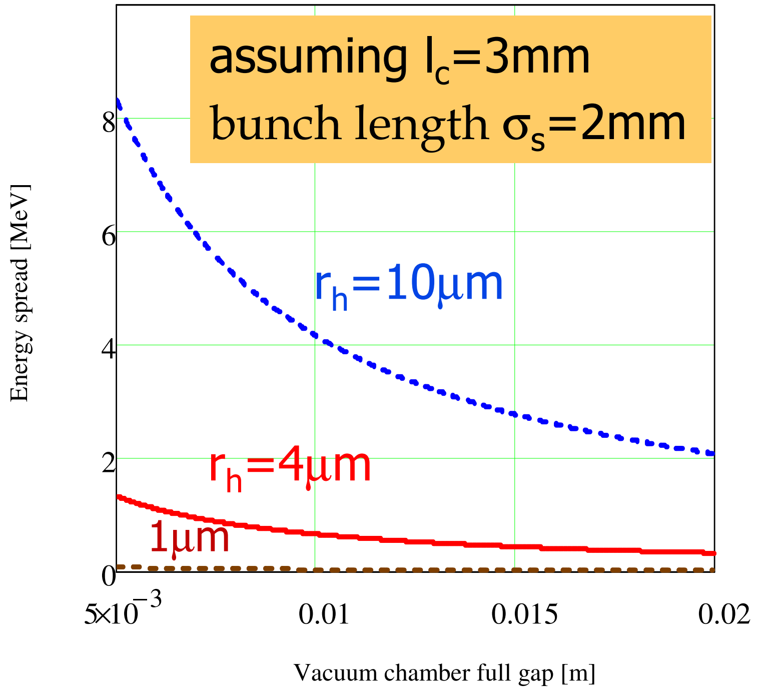
  -inductive wake strongly reduced

  -lowest frequency synchronous mode should be fully suppressed

1) eRHIC – bunch length could be comparable or smaller than the correlation length of extruded aluminum. Should we worry about high-frequency synchronous mode?

2) longitudinal density distribution could happen to be not very smooth (high-frequency content within the bunch)

Wall Roughness (WR) for eRHIC vacuum chambers (2011)



Measurements for a sample of extruded aluminum vacuum chamber (2011):

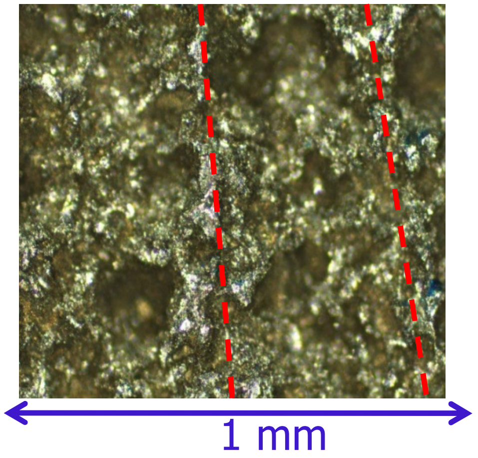
1) Profilometer:

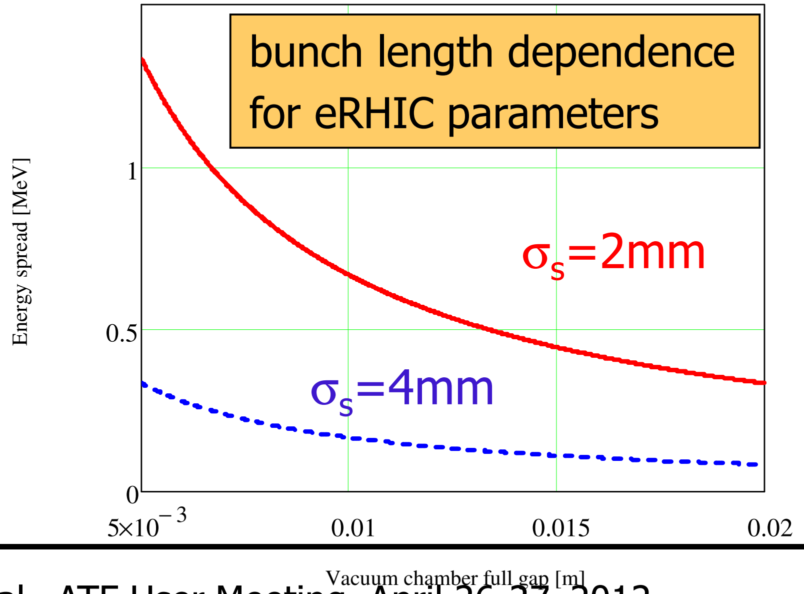
rms height - 4μm, no correlation length info

2) Optical microscope:

20 μm peak-to-valley,

“educated” guess for correlation length ~ few mm?)





l_c=3mm

r_h=4μm

Another question:
contribution from high-frequency modes

- **Several analytic treatments of impedance for wall corrugations of different geometry exist.**
- **As the period-to-depth ratio of WR becomes large, the dominant low-frequency mode is replaced by many weak, closely spaced modes with the wavelength k>π/p (where p is the length of the period or correlation length).**
- **For sinusoidal oscillating corrugation with h << p, analytic wake was given by Stupakov. As noted by K. Bane, for bunch length smaller than p/2π to leading order the wake is given by**

$$W_{WR}(s)=\frac{Z_0 ch^2}{16\pi^{3/2}b}\frac{(2\pi)^{3/2}}{p^{3/2}}\frac{1}{s^{3/2}}$$

$$W_{RW}(s)=\frac{c}{4\pi^{3/2}b}\sqrt{\frac{Z_0}{\sigma}}\frac{1}{s^{3/2}}$$

High-frequency modes (continued)

- **High-frequency content of wall roughness can be characterized by "effective conductivity":**

$$\sigma_{WR} = \frac{c}{2\pi^4} \frac{p^3}{h^4}$$

Example:

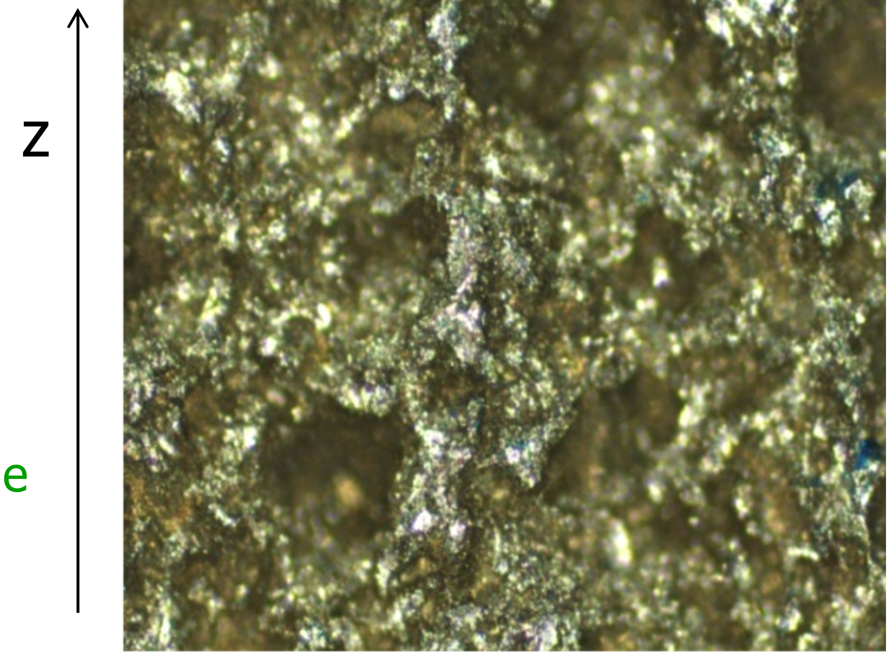
For parameters of LCLS undulator surface

WR gives 0.15 of RW wake amplitude.

For eRHIC:

- accurate measurements/characterization of extruded aluminum surface are needed: in progress.

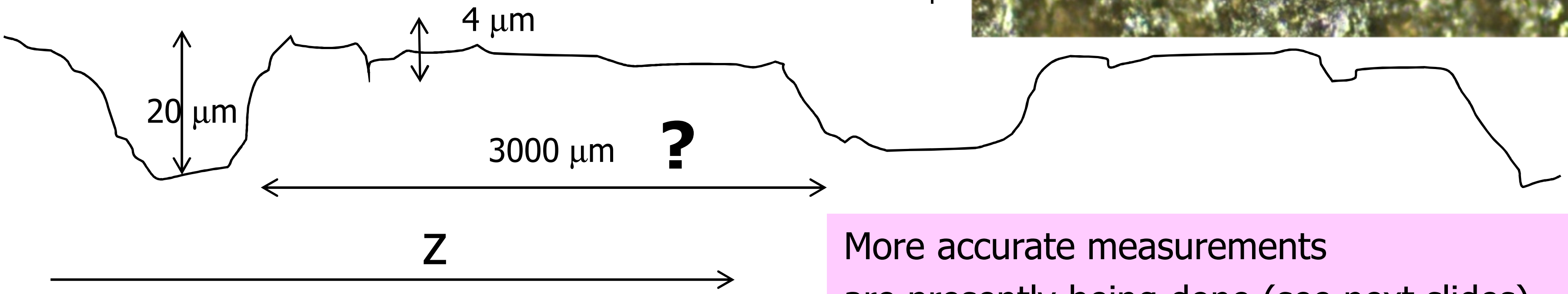
How does unpolished extruded aluminum surface looks like?



Ridges of few mm length (~3 mm ?)

Peak-to-valley: 20 μm

Along the ridge: h ~ 4-5 μm rms (with profile monitor)



More accurate measurements
are presently being done (see next slides)

Wall Roughness effects for eRHIC:

- In order to have safe and accurate specs on WR of vacuum chambers it would be very useful to have:

1. Accurate measurement of WR for extruded aluminum with analysis:

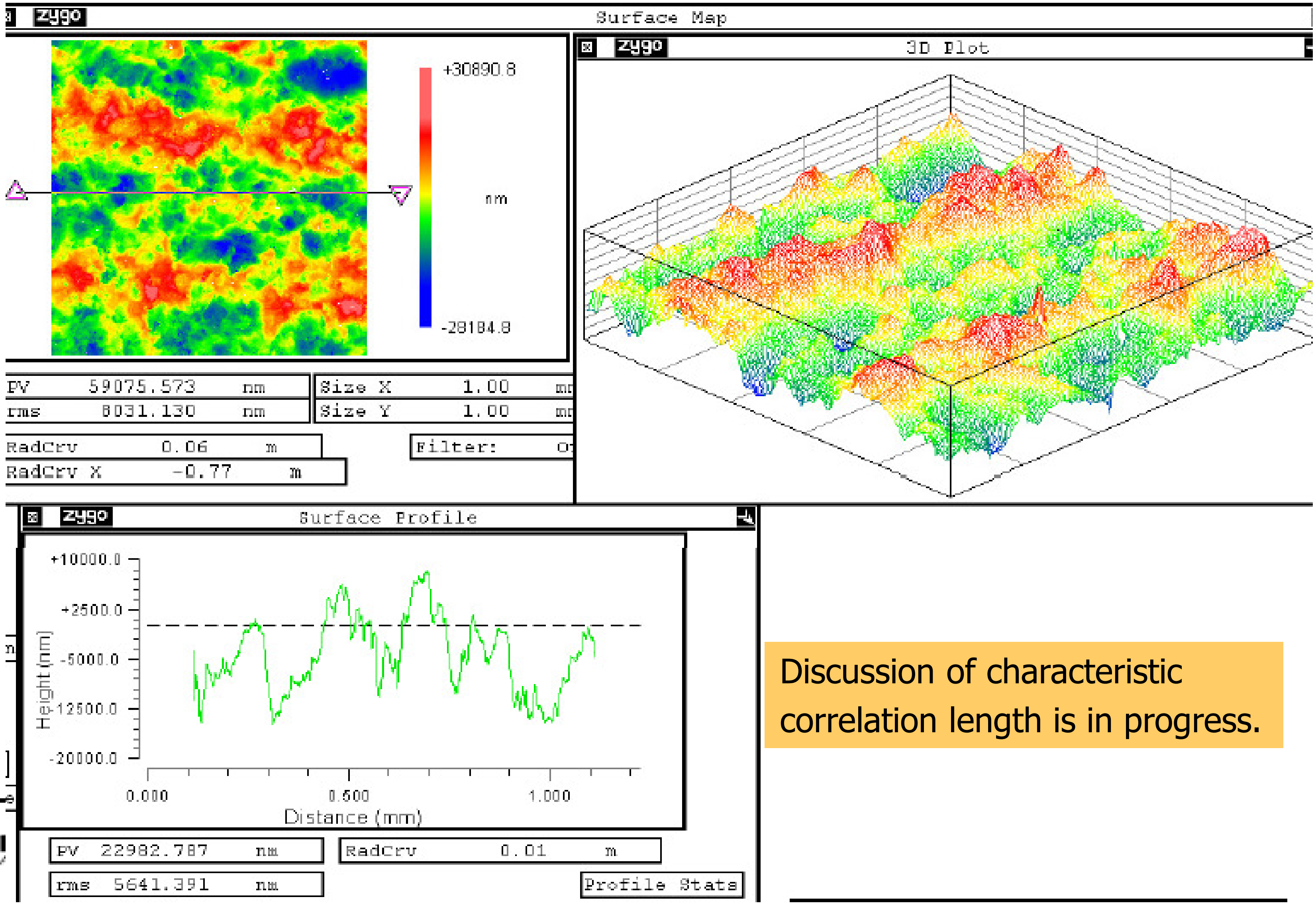
   work in progress (P. Takacs et al.)

2. Beam experiment with two vacuum chambers at ATF

   (various approaches are possible, exact technical setup TBD):

   present proposal

April 2012 measurements and analysis of extruded aluminum surface roughness (Peter Takacs, Instrumentation Division BNL)



PV 59075.573 nm

rms 8031.130 nm

Size X 1.00 m

Size Y 1.00 m

RadCrv 0.06 m

RadCrv X -0.77 m

Filter: O

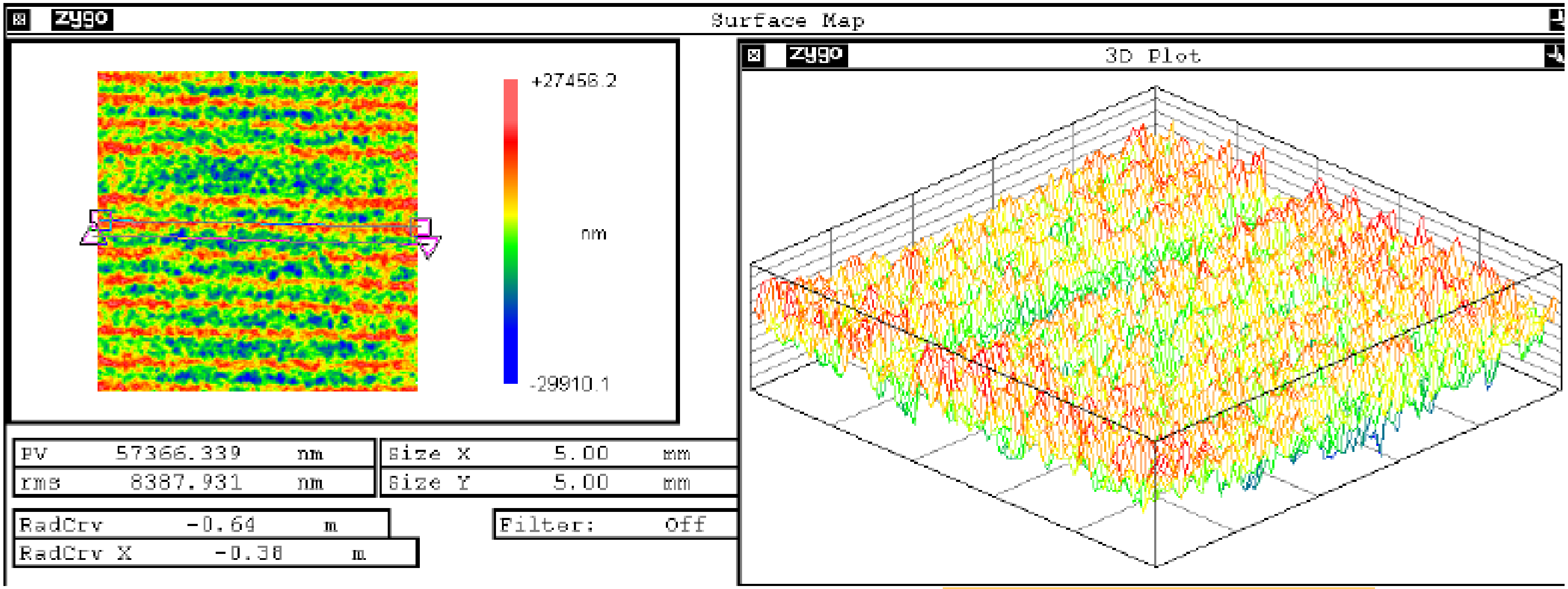
PV 22982.787 nm

rms 5641.391 nm

RadCrv 0.01 m

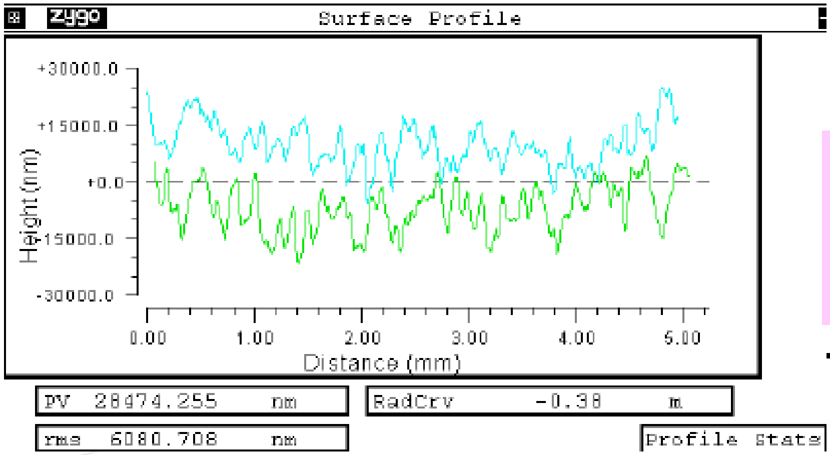
Discussion of characteristic correlation length is in progress.

April 25, 2012 measurements and analysis of extruded aluminum surface roughness (Peter Takacs, Instrumentation Division BNL)



PV 57366.339 nm
rms 8387.931 nm
Size X 5.00 mm
Size Y 5.00 mm
RadCrv -0.64 m
RadCrv X -0.38 m
Filter: Off

Courtesy P. Takacs, BNL.



PV 28474.255 nm
rms 6080.708 nm
RadCrv -0.38 m

Looks like there are rather short characteristic lengths which could be important for beam dynamics.

ATF proposal

Team:

A. Fedotov, I. Pinaev, V. Litvinenko (C-AD, BNL)

M. Fedurin, V. Yakimenko (ATF, BNL), others

Experimental goal:

To have quantitative study of wake fields effects due to Wall Roughness for realistic surfaces and their possible suppression for the surface of extruded aluminum vacuum chamber.

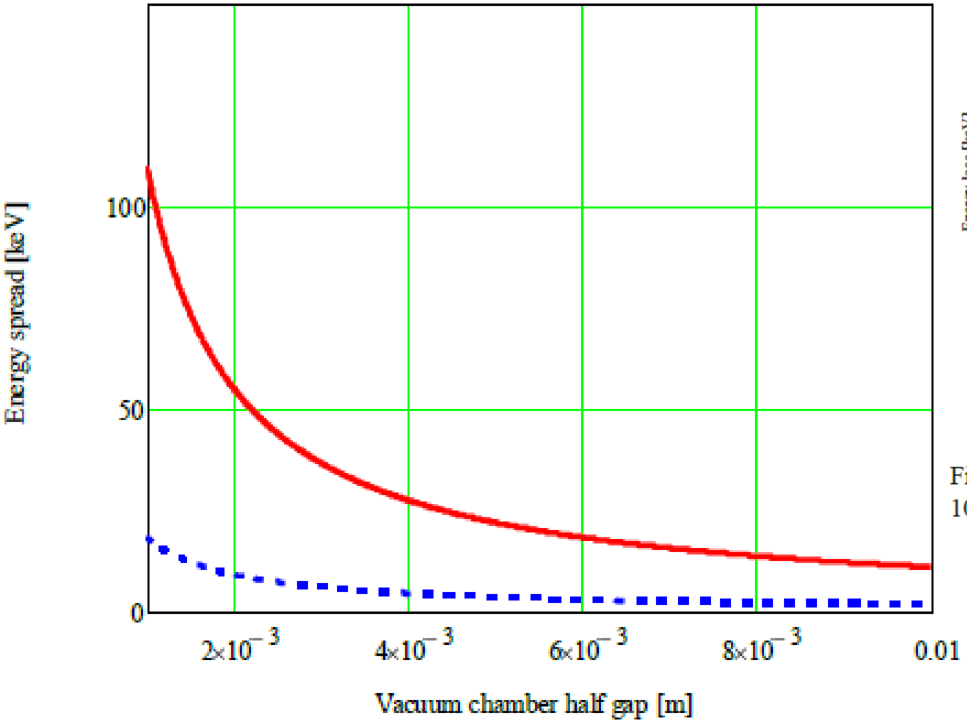
- we want to see reduction of energy spread for extruded surface compared to not extruded surface.

- explore possible contribution to energy loss due to high-order modes if any.

Experiment description (details TBD)

- Install system with two vertical plates with controllable gap between the plates inside the vacuum chamber (similar to CSR suppression experiment). One pair from extruded and another one from not extruded aluminum.
- Measurements of surface roughness will be performed on the samples from the plates to allow comparison with analytic models.
- Beam parameters /setup will be chosen to enhance WR effects.
- Energy loss and energy spread will be measured for various values of the gap between the plates.
- Measurements will be performed for different bunch length.
- Alternatively, one can construct two fixed-radius vacuum chambers.
- If necessary, we can create energy correlation and measure enhancement/suppression effects (as was done in previous experiments).

Estimates for ATF parameters
(I=100 A, bunch length 90 μm, chamber length 1m)



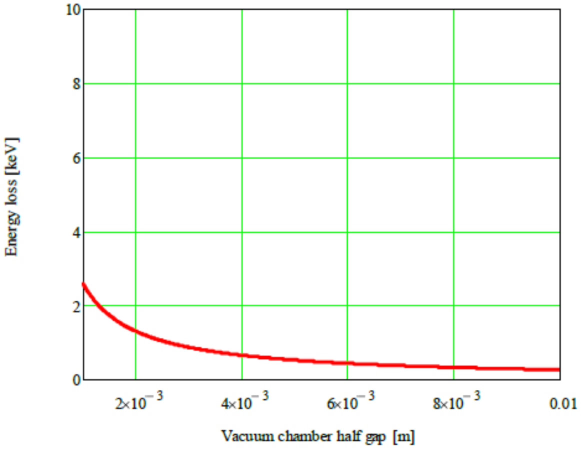
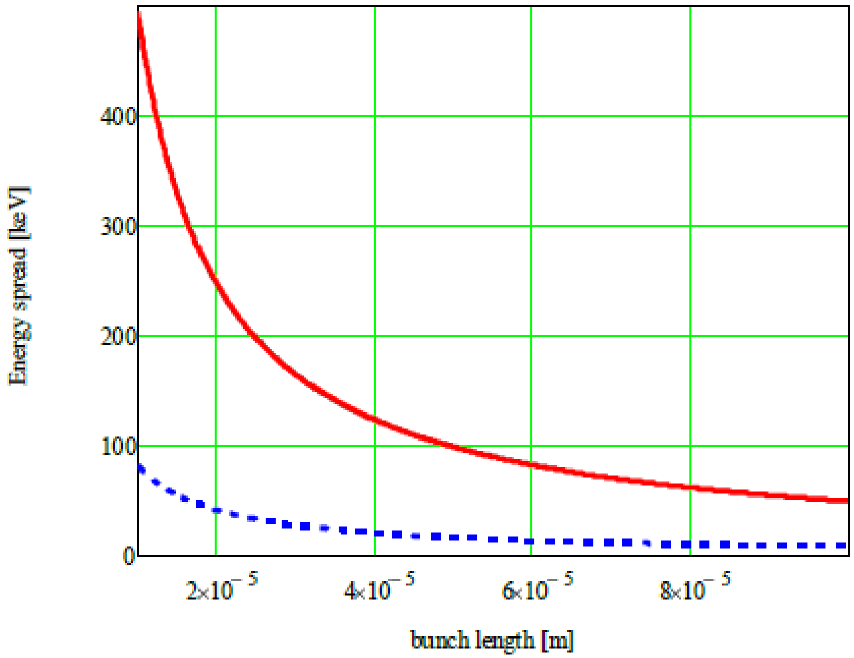


Fig. 3. Estimate of energy loss due to Resitive Wall for aluminum vacuum chamber 100 A, chamber length 1 m, bunch length 90 μm).

Fig. 1. Estimate of energy spread due to wall roughness: 1) red upper curve - rms height 5 μm, correlation length 50 μm; 2) blue dash lower curve - rms height 5 μm, correlation length 300 μm.

Estimates (continued)



bunch length dependence
(stronger than for RW)

Fig. 2. Estimate of energy spread due to wall roughness for vacuum chamber half gap of 2 mm: 1) red upper curve - rms height 5 μm, correlation length 50 μm; 2) blue dash lower curve - rms height 5 μm, correlation length 300 μm.

Resources

- All the diagnostics needed for the experiments is already available at ATF.
- Approximately 1-2 weeks of installation and few weeks divided over multiple runs of data taking are expected.
- ATF is expected to provide help with installation and operations.
- One of the advantage of the setup with adjustable gap is that it will have minimal effect on the clear aperture when plates are retracted (TBD).
- Financial part of the experiment is expected to be covered from C-AD eRHIC R&D funds.

Summary

- **Understanding of Wall Roughness wake fields is an important topic for present design of Electron Ion Collider at BNL's Collider-Accelerator Department.**
- **ATF at BNL is ideally suited for dedicated experiment on Wall Roughness studies. Similar experiment was performed before for artificially created roughness. We want to perform experiment for realistic surfaces, especially for extruded aluminum.**
- **At ATF we can study:**

  - effects of suppression of wake fields due to large correlation length and random surface

  - possible effects of high-order modes of surface roughness.