New and Improved Methods for Characterizing Nb Surface Roughness

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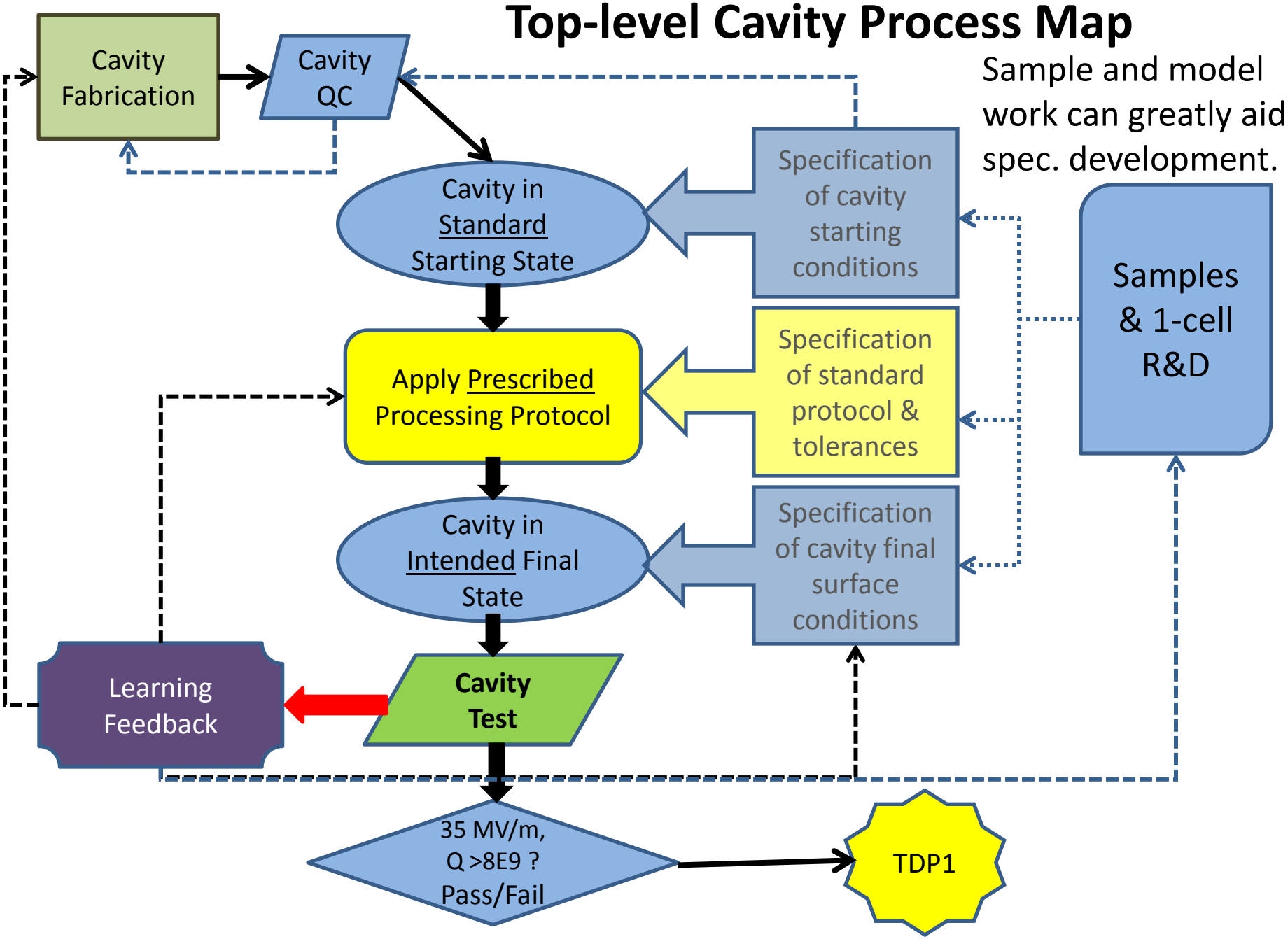
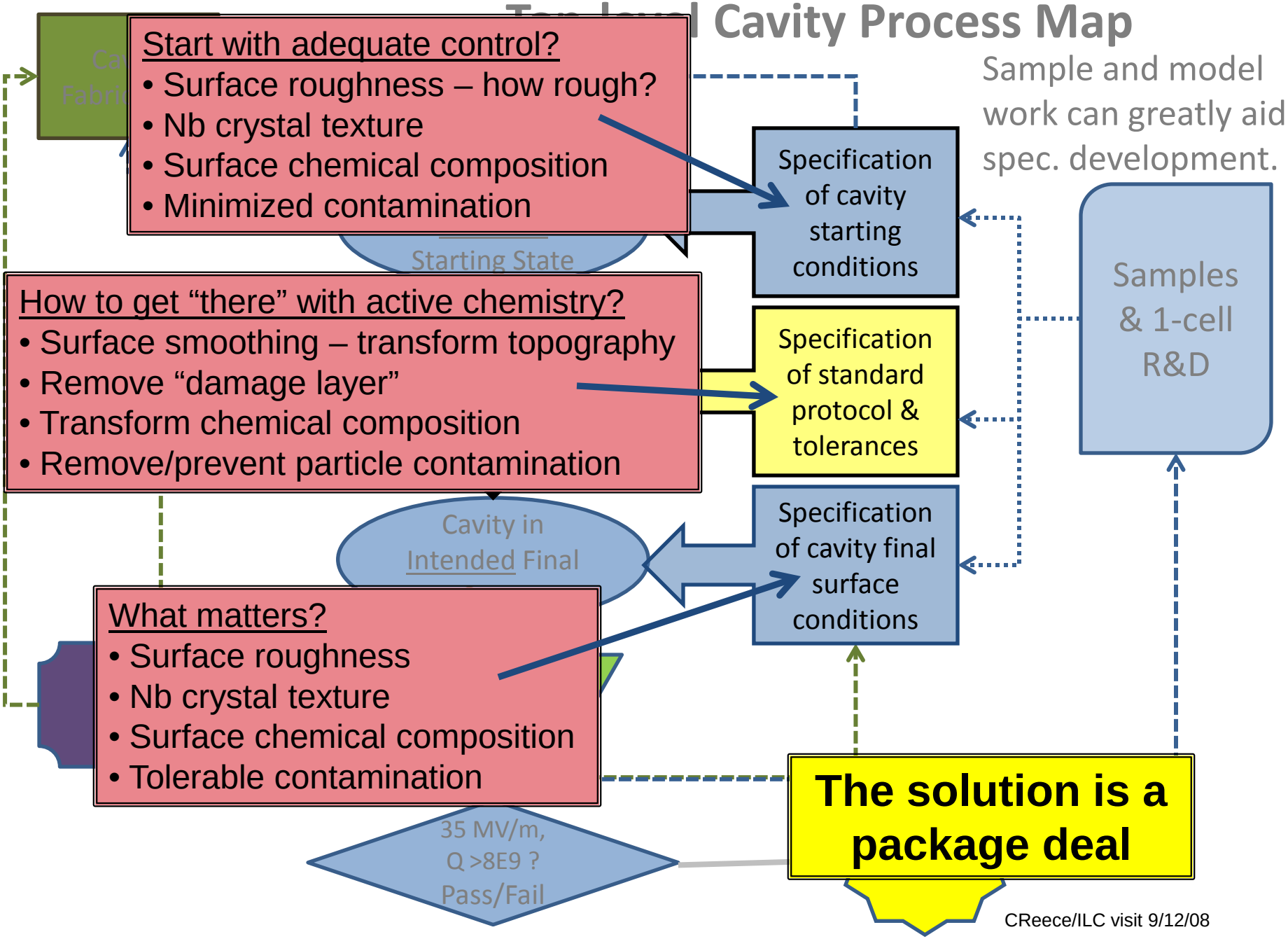
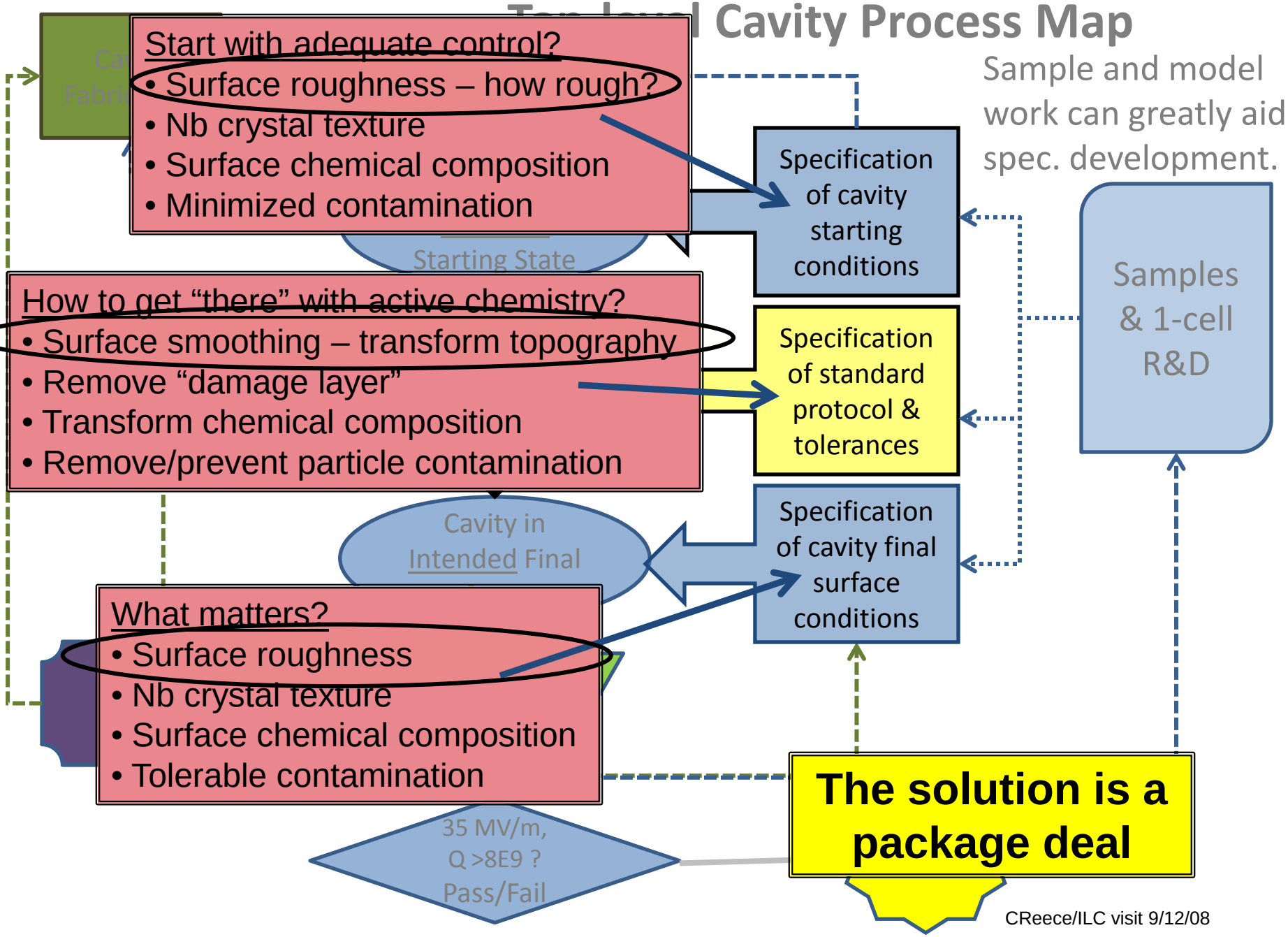
Top-level Cavity Process Map



Top-level Cavity Process Map



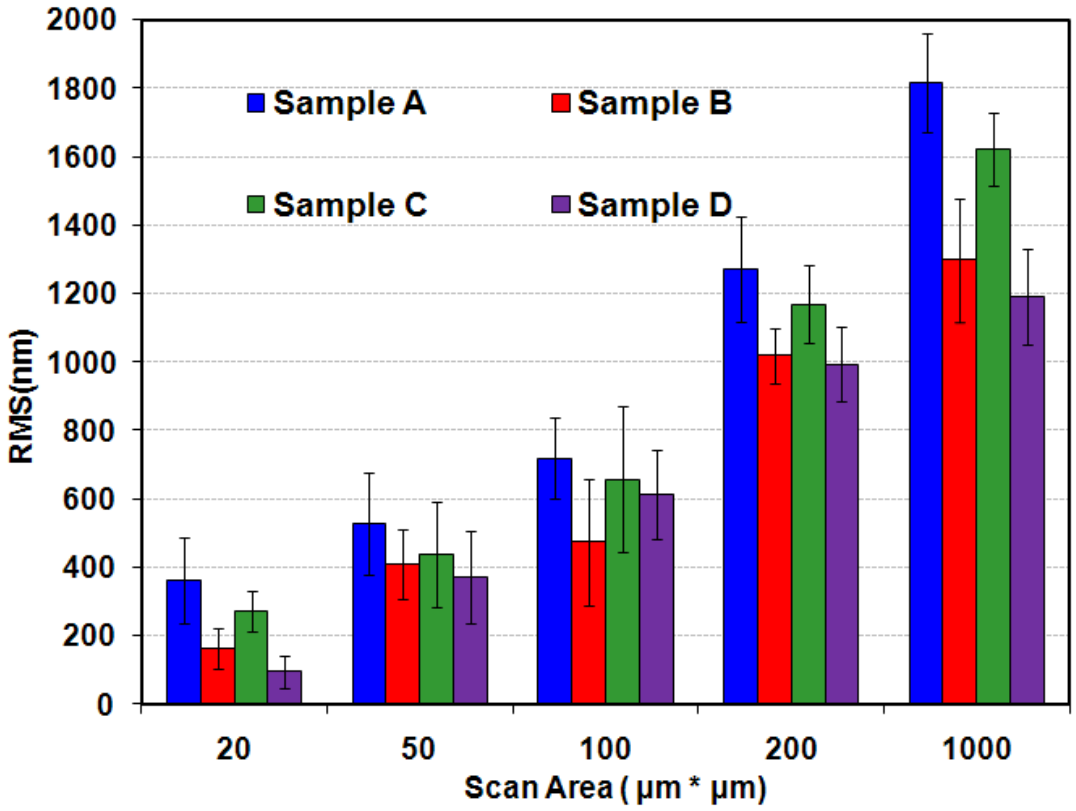
Top-level Cavity Process Map



Nb Roughness

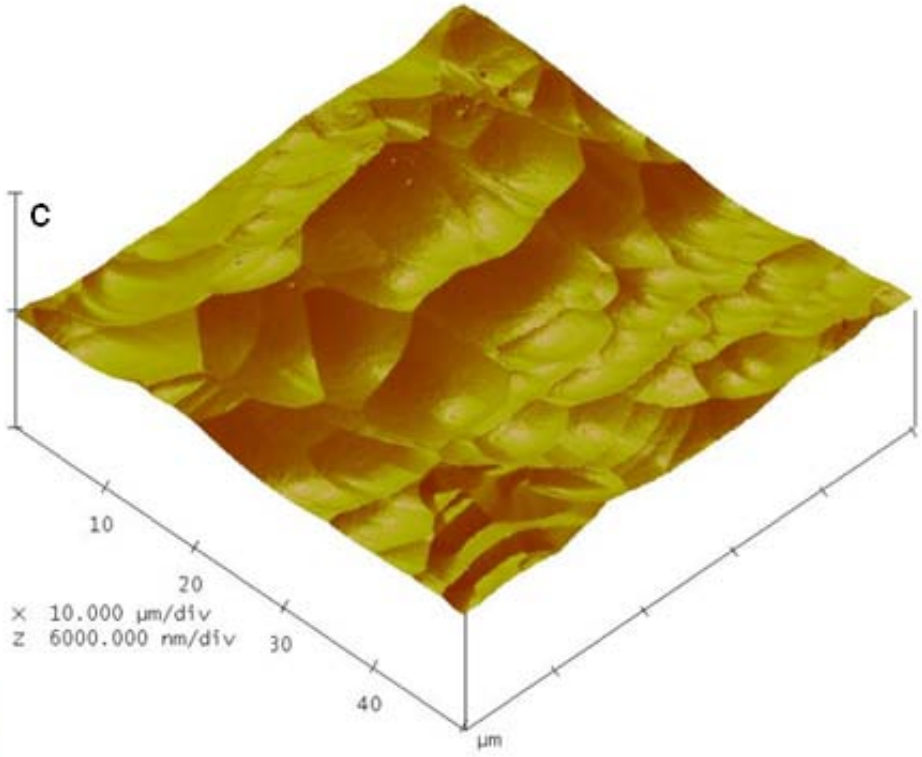
- Roughness characterization
  - R_a, R_q, PSD, AF, CL
  - Height and slope histograms
- AFM & profilometry data
- Data processing
- Topographic power spectral density (PSD) of niobium
  - BCP fine grain Nb
  - 30 C EP fine grain Nb
  - CMP “nano-polished” Nb
  - CMP with very light BCP
  - BCP single-crystal Nb
- Topographic models for interpreting PSD
- Summary

R_q – limited usefulness

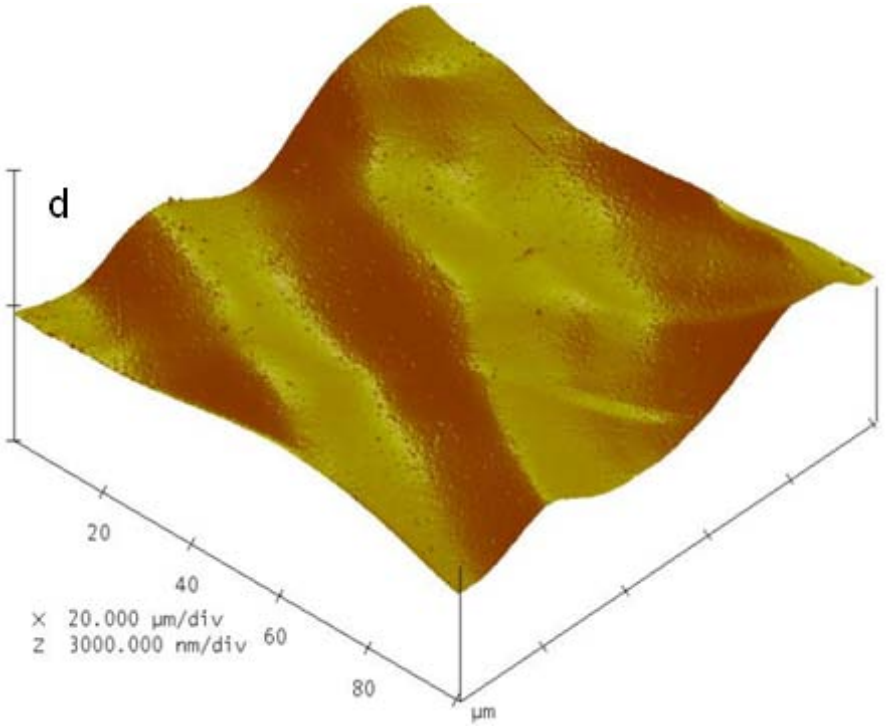


R_q roughness values of Nb samples after different polishing (BCP /EP) calculated from AFM and stylus profilometer measurements taken at different scan lengths.

AFM Characterization of Nb surfaces



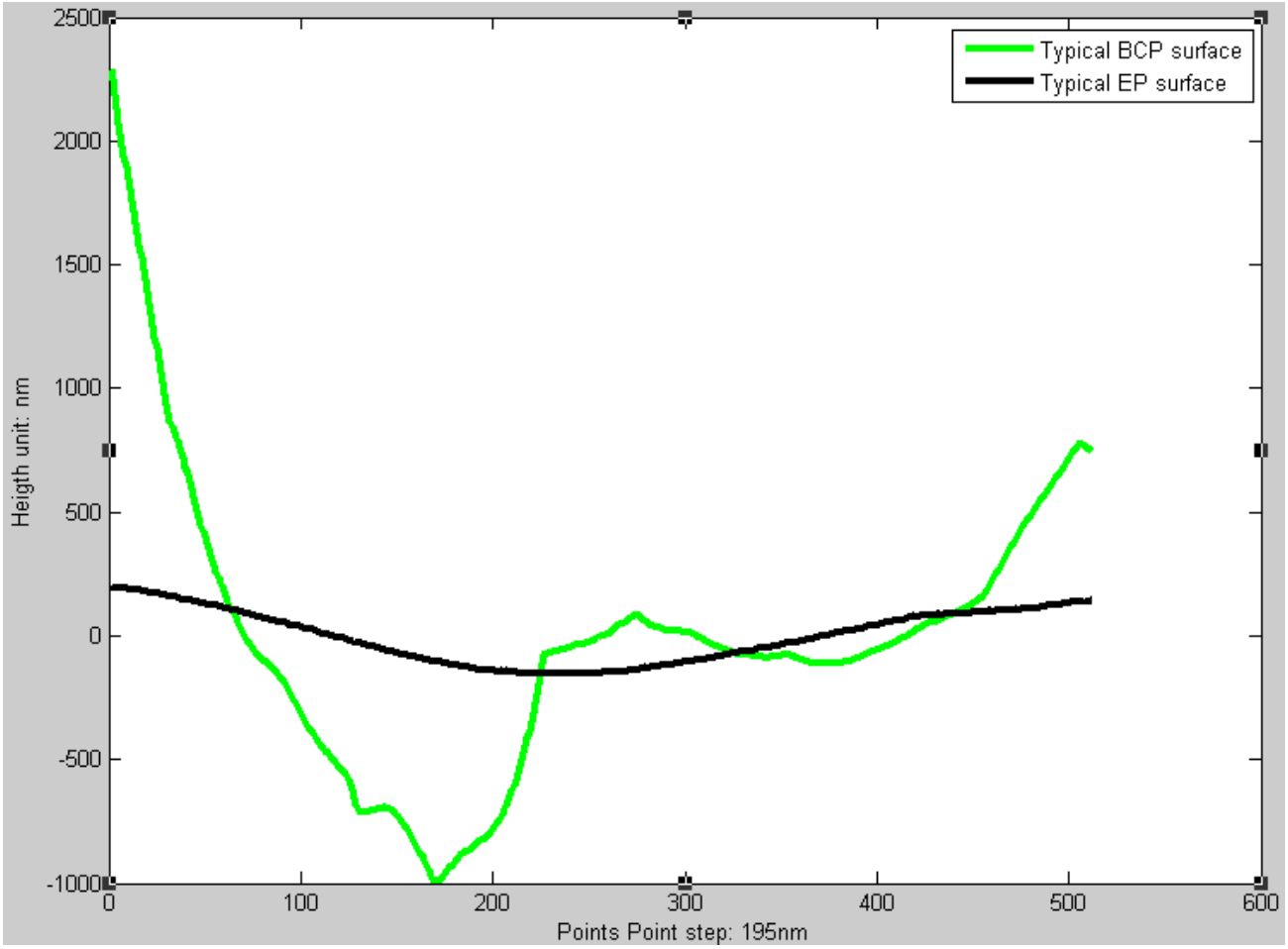
Fine grain Nb - BCP



Fine grain Nb – EP (@ 30 C)

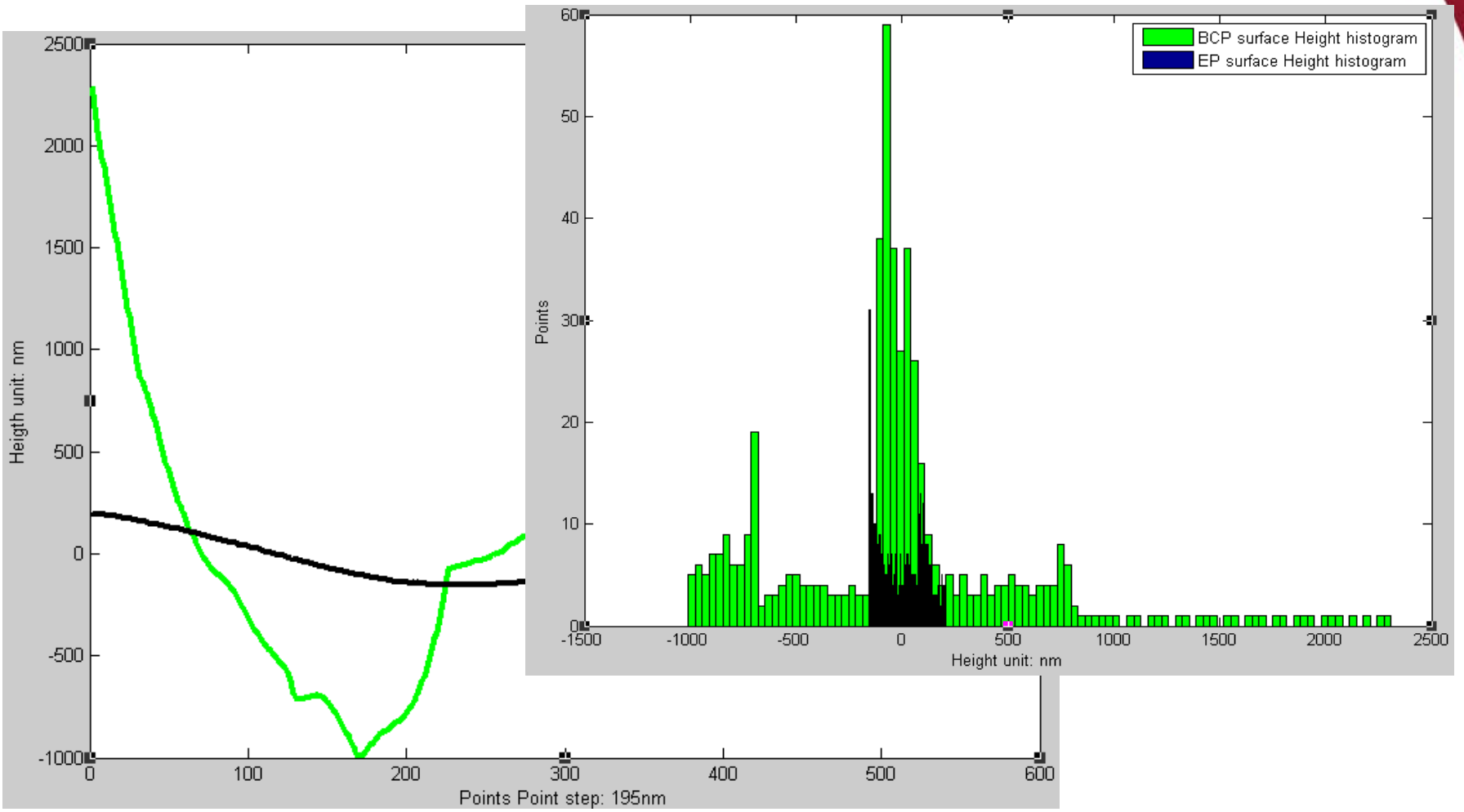
A novel approach to characterizing the surface topography of niobium superconducting radio frequency (SRF) accelerator cavities
Hui Tian et al., Applied Surface Science **257** (2011) 4781–4786

Height and Slope Histogram



Typical BCP/EP polycrystalline Nb surface finishes

Height and Slope Histogram



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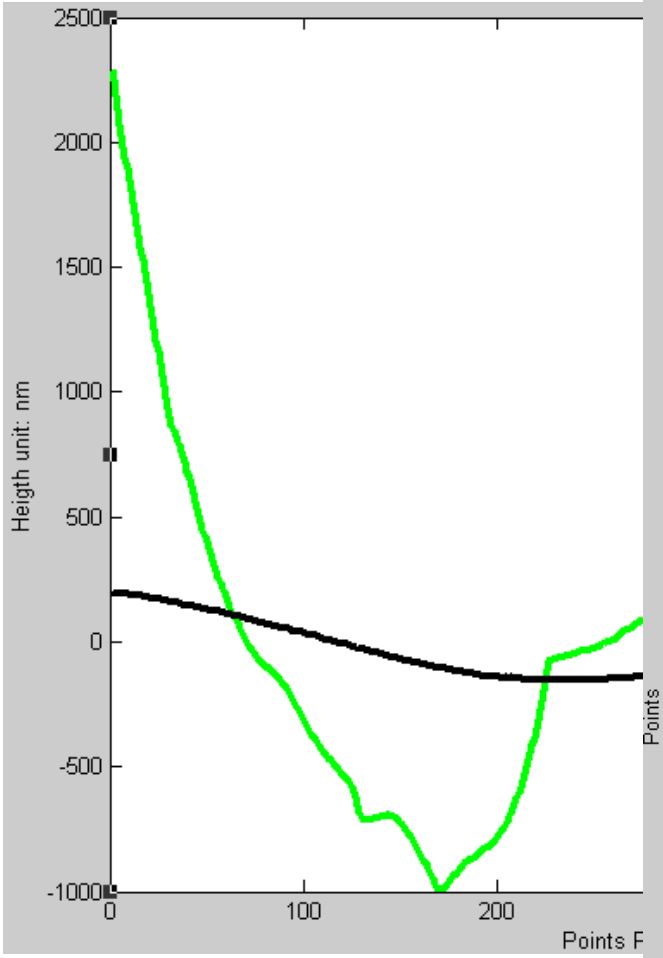
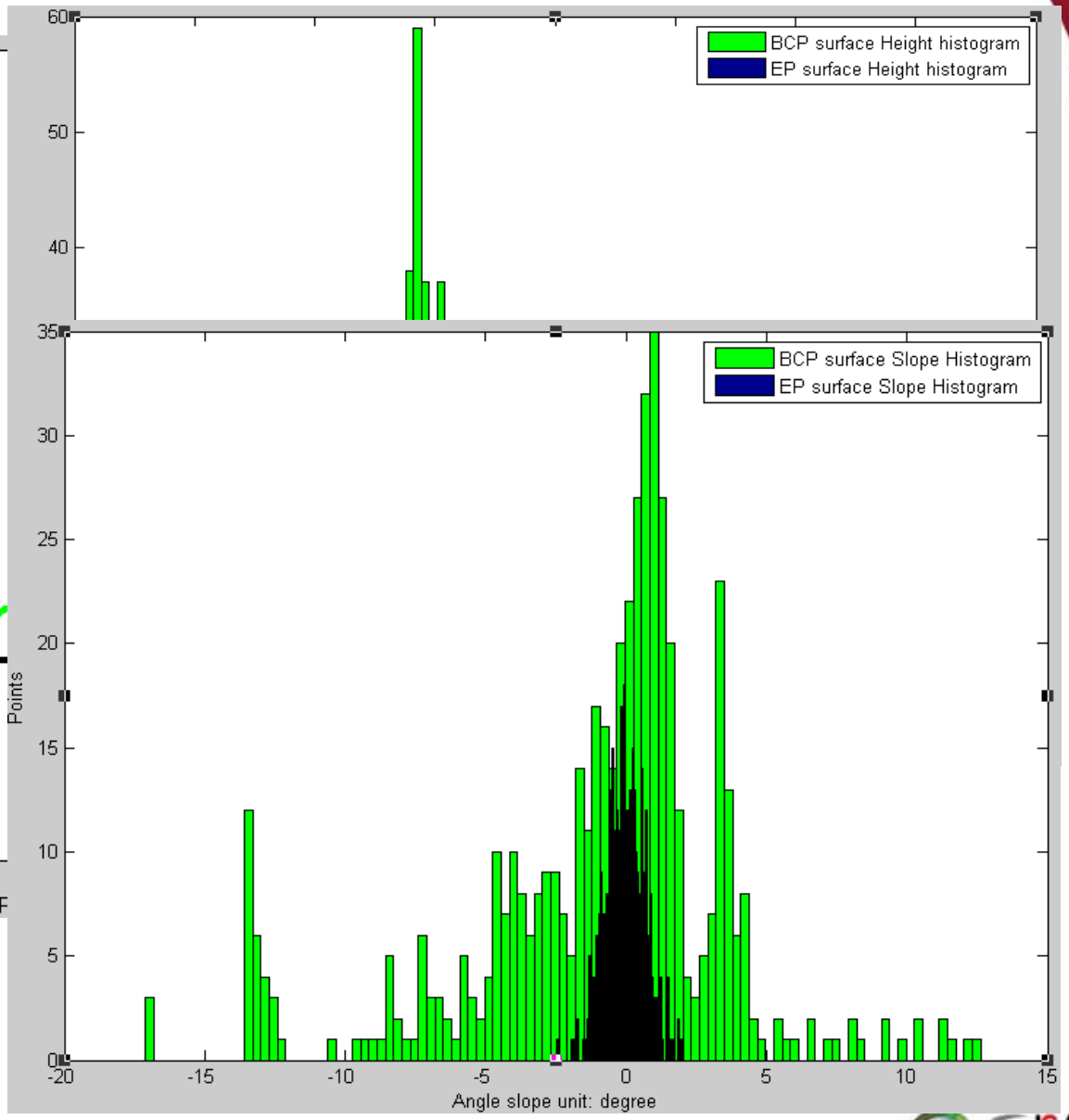




Typical BCP/EP polycrystalline Nb surface finishes

Introduction: PSD

- The power spectral density (**PSD**) describes the harmonic content of the surface topography.

$$S(f_x) = \lim_{L\to\infty} \left\langle \frac{2}{L} \left| \int_{-L/2}^{+L/2} dx Z(x) \exp(-i2\pi f_x x) \right|^2 \right\rangle .$$

- With discrete data from digitized profilometry:

$$PSD(f_x)_N(m) = \frac{\Delta x}{N} \left| \sum_{n=0}^{N-1} h(x)_n \exp(-i2\pi nm/N) \right|^2 K(m)$$

Preparation of PSD data

avoiding instrumental and mathematical artifacts

1

Raw profile data

- Mechanic Stylus AFM or basic or optical non contact
- Scan size and resolution can be various.

2

Correction for instrumental errors

- Different equipment requires different Machine Transfer Function (MTF)

3

Correction for non-planar sample

- Z dynamic range limitations
- Substrate effect will be reduced.

4

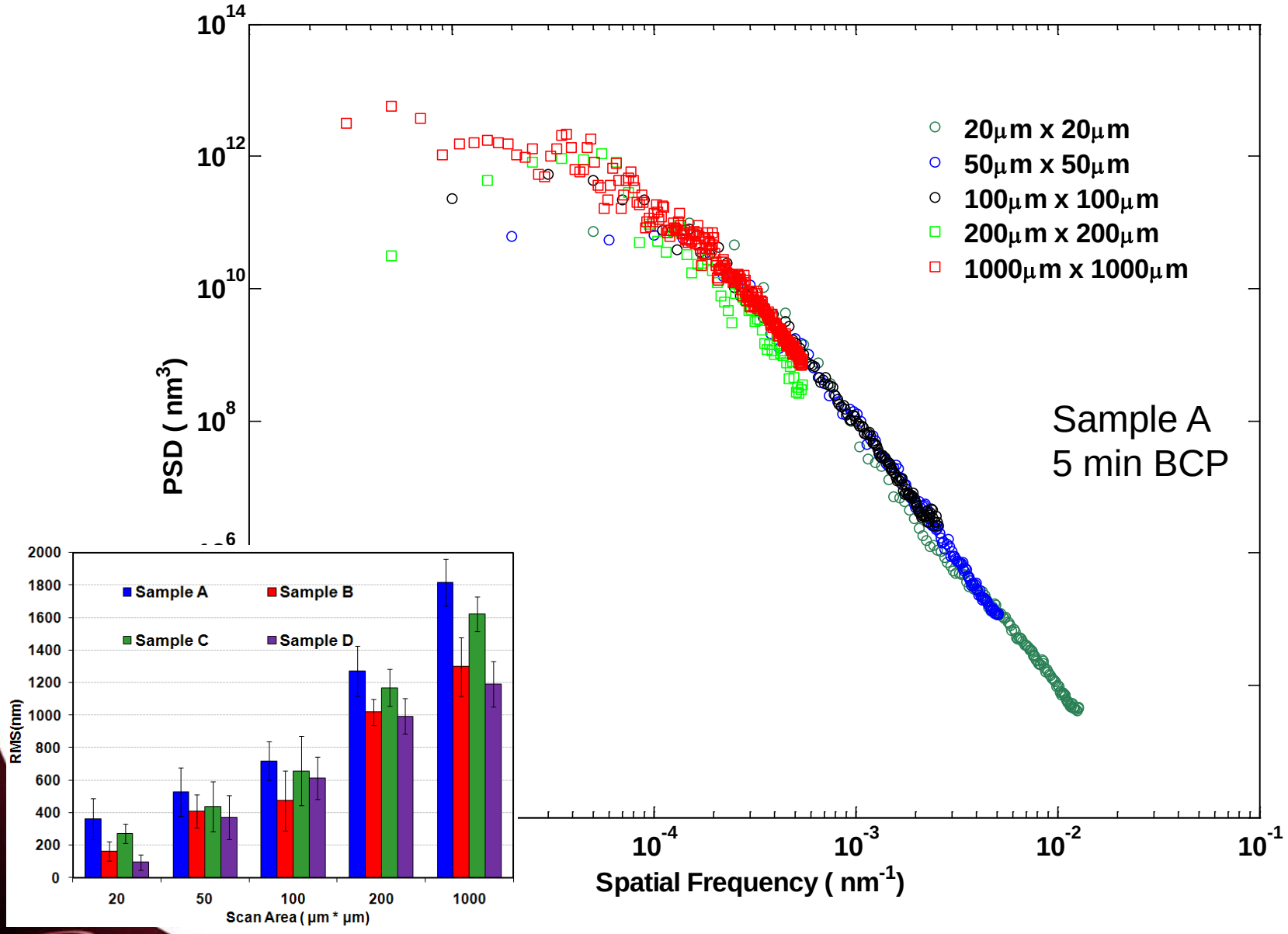
Correction for mathematical artifacts from discontinuous edges

- Discontinuous edges will bring rise at high freq in PSD
- Add various windowing filters

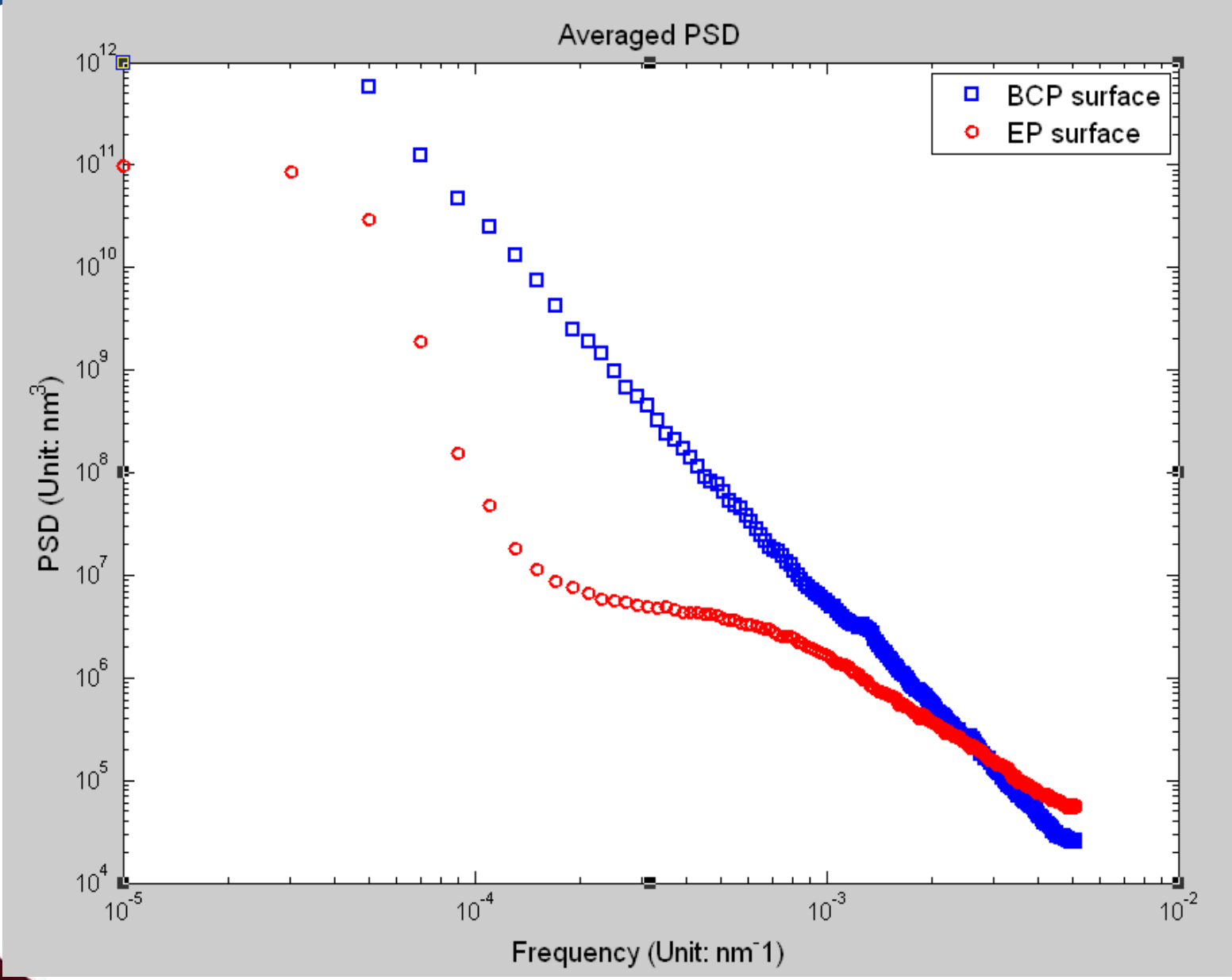
Processed data for analysis

- This analysis addresses characteristic isotropic topographic structure.
- It does not address localized defects.
- PSD is calculated for each of 512 lines in each data set, e.g. each 50 µm × 50µm scan.
- Multiple PSD spectra are averaged to obtain representative topography.

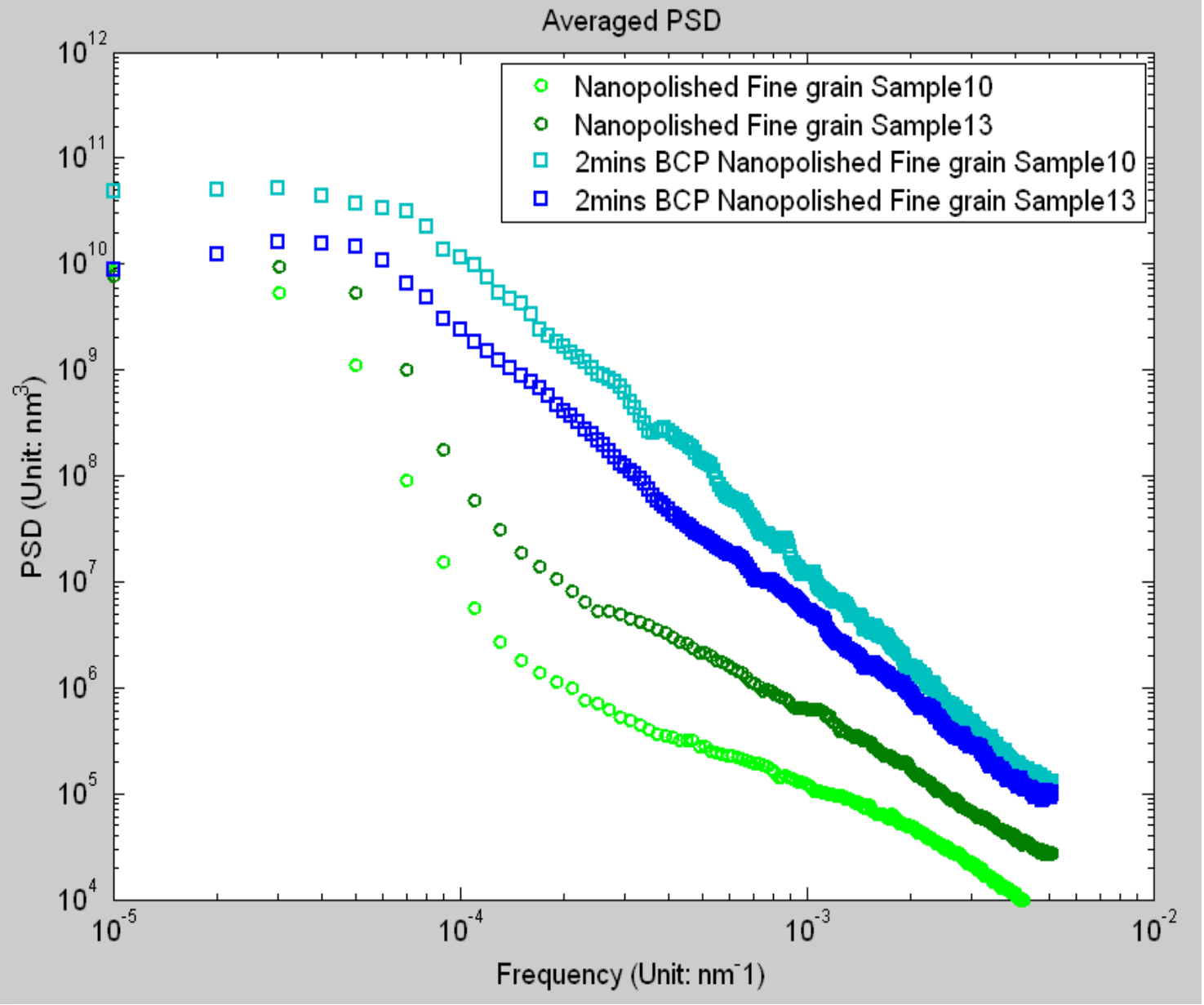
PSD provides coherent description of roughness



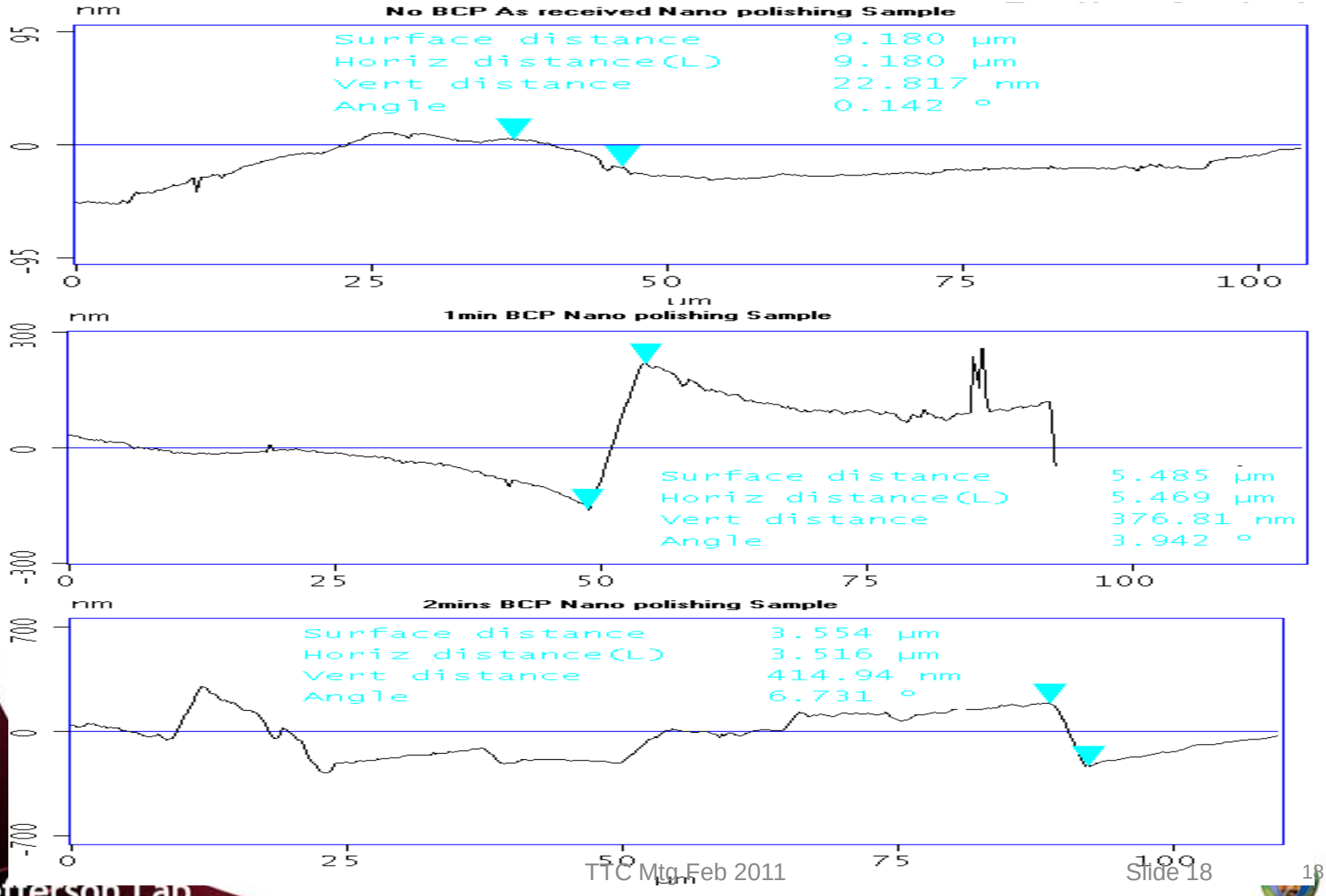
PSD


Averaged PSD
BCP surface
EP surface
PSD (Unit: nm^3)
Frequency (Unit: nm^-1)
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^-5
10^-4
10^-3
10^-2

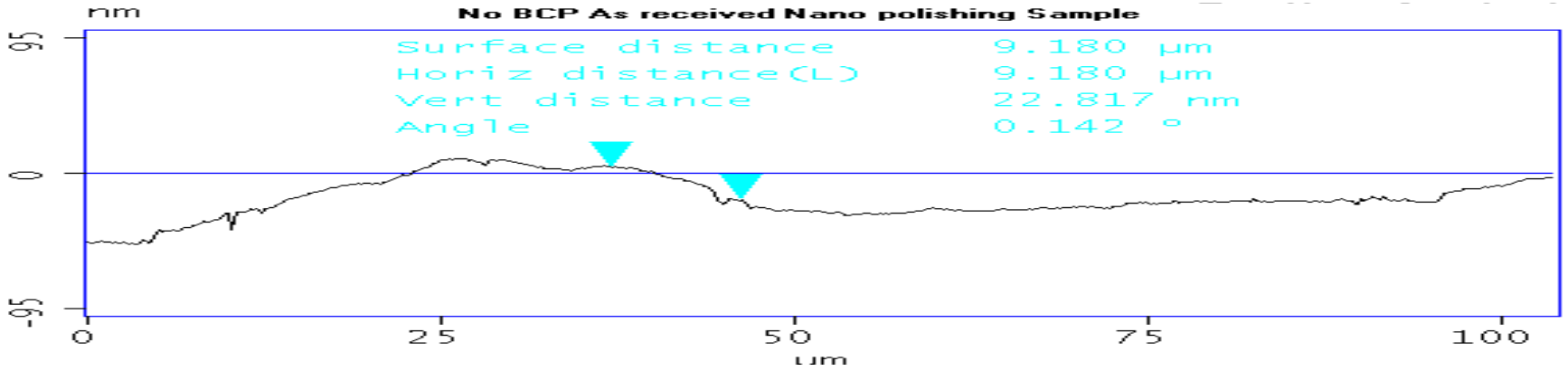
PSD


Averaged PSD
Nanopolished Fine grain Sample10
Nanopolished Fine grain Sample13
2mins BCP Nanopolished Fine grain Sample10
2mins BCP Nanopolished Fine grain Sample13
PSD (Unit: nm3)
Frequency (Unit: nm^-1)
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^-5
10^-4
10^-3
10^-2

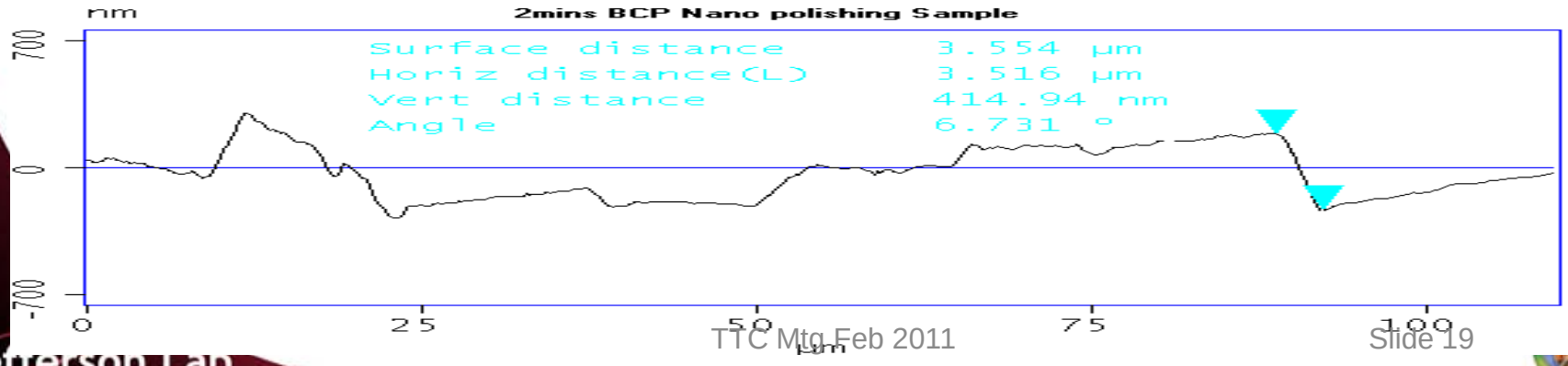
Surface Study



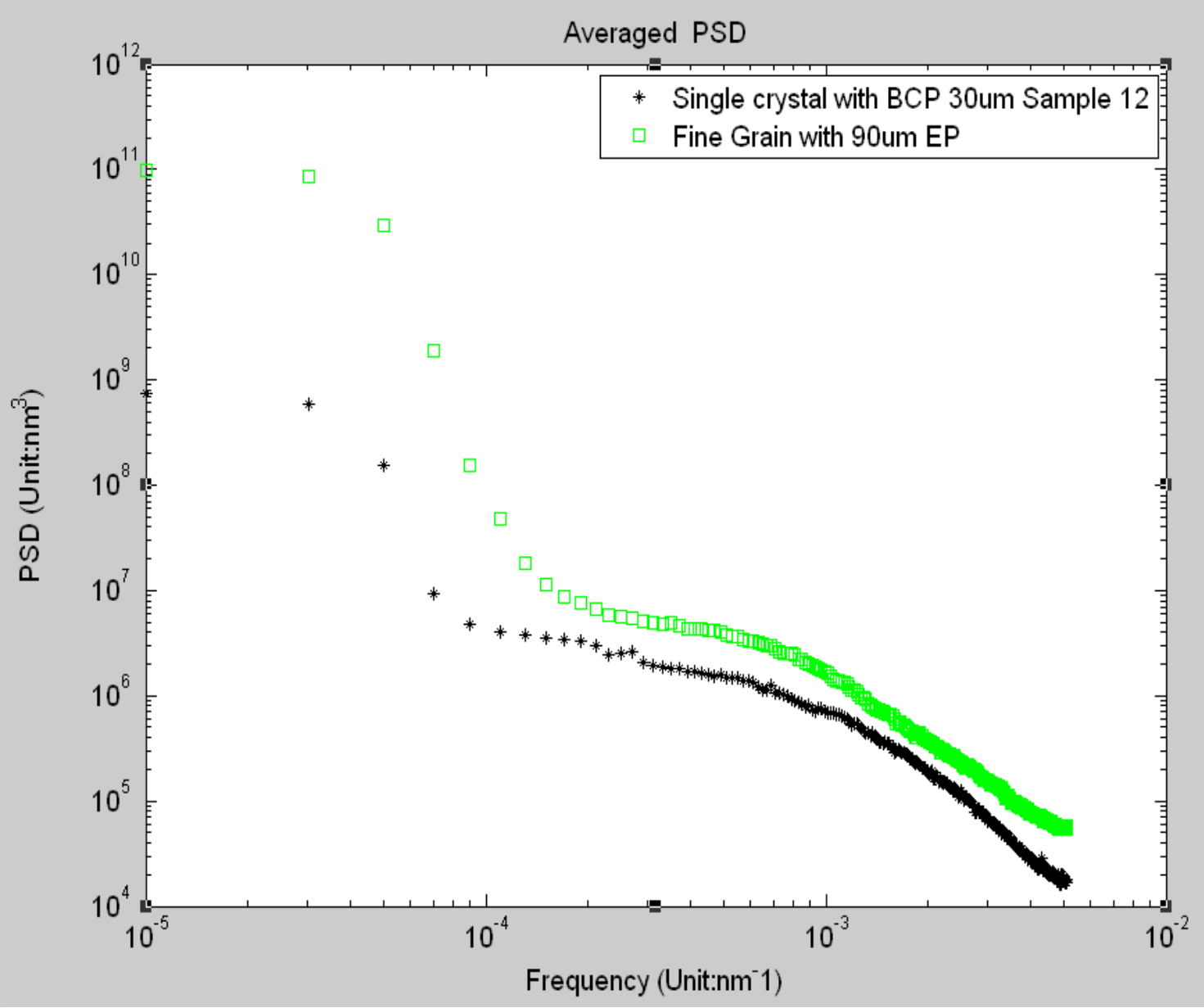
Surface Study



The major changes in PSD come from GB Preferential etching



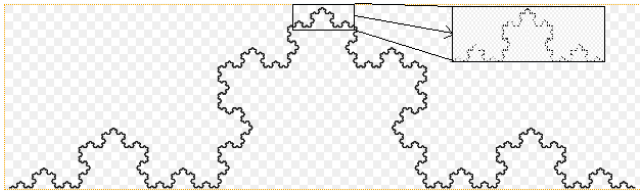
PSD


Averaged PSD
Single crystal with BCP 30um Sample 12
Fine Grain with 90um EP
PSD (Unit:nm^3)
Frequency (Unit:nm^-1)
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^-5
10^-4
10^-3
10^-2

Three models to decompose PSD

Three models of surface roughness are available to help interpret the PSD of a surface (commonly used in optical surface community)

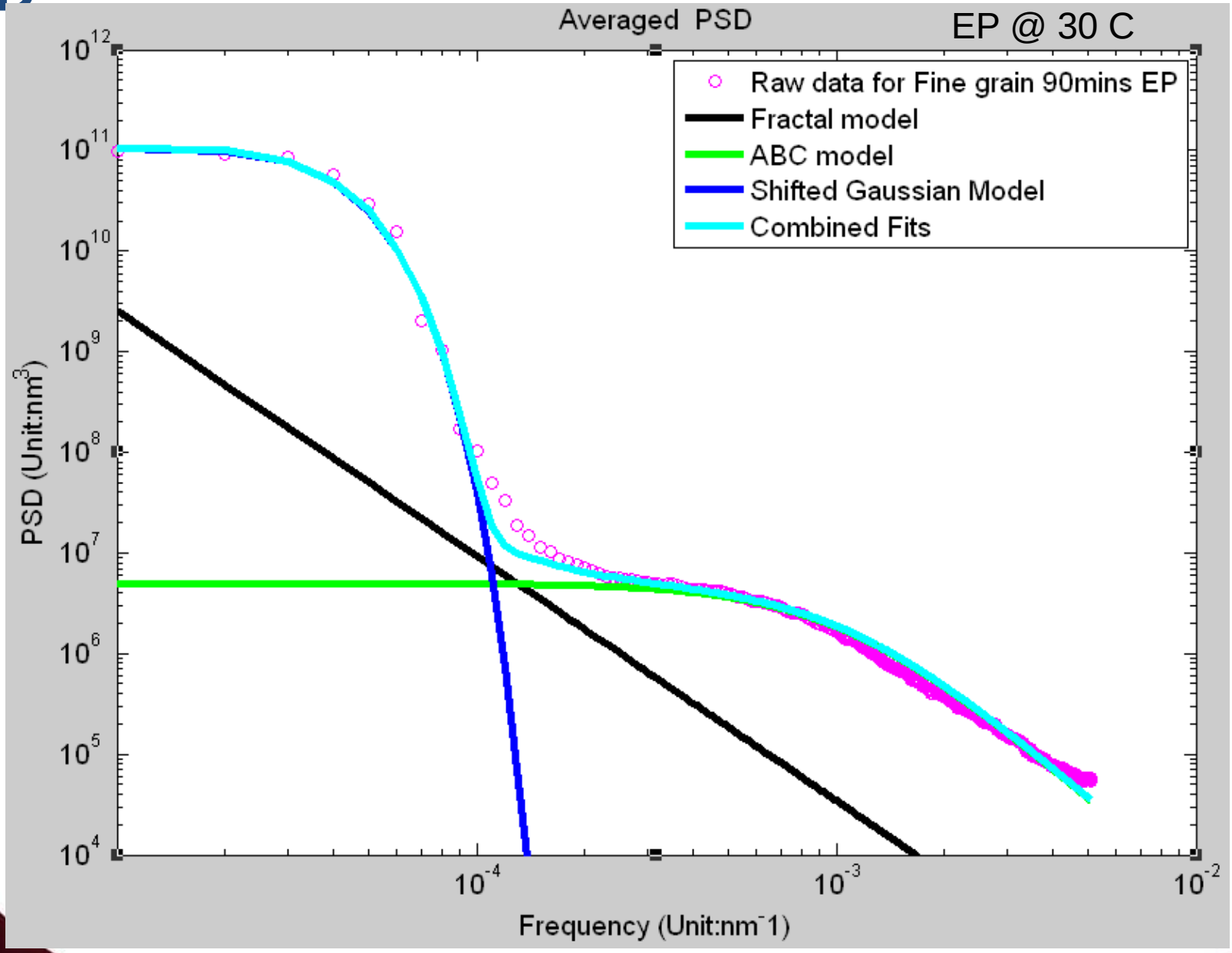
- Fractal structure [11]:
  - Self similar fractal geometry
  - PSD form: $$S(\mathbf{f}) = \frac{\Gamma[(n+1)/2]}{2\Gamma(1/2)\Gamma(n/2)} \cdot \frac{K_n}{f_x^{n+1}} .$$



  - n and K_n are fit parameters
- K Correlation (a.k.a ABC model) [12]:
  - A micro topography (islands) on top of macro topography
  - PSD form: $$g(K) = \frac{A}{(1+(BK)^2)^{\frac{(C+1)}{2}}}$$
  - k is frequency and A,B,C are fitting related RMS and CL
- Shifted Gaussian [13]:
  - Surface with repetitive singularities
  - PSD form: $$g(k) = (\pi)^{3/2}\delta^2\sigma\{\exp[-(k+b)^2\sigma^2/4] + \exp[-(k-b)^2\sigma^2/4]\} .$$
  - k is the frequency and β,σ,δ are fit parameters

R Jahn, J. of Materials Processing Technology **145** (2004) 40-45
D Ronnow, Thin Solid Film **325** (1998) 92-98
G. Palasantzas, Phys. Rev. B **48** N19 1993

PSD


Averaged PSD
EP @ 30 C
Raw data for Fine grain 90mins EP
Fractal model
ABC model
Shifted Gaussian Model
Combined Fits
PSD (Unit:nm^3)
Frequency (Unit:nm^-1)
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^-4
10^-3
10^-2

Summary

- We have realized a schema for systematically acquiring, processing, and interpreting quantitative topographic data from niobium surfaces.
- Topographic structure models developed for describing optical surfaces appear quite applicable to niobium.
- Fine-grain Nb BCP surface is fractal even with just 2 min etch.
- Single crystal BCP surface is smoother than fine-grain 30 C EP surface.

Next:

- We now seek to discriminate EP temperature dependence of topography.
- We seek to correlate specific topographic structure with enhanced rf losses and use specific PSD features as quantitative feedback for further process optimization.