ANALYZING SURFACE ROUGHNESS DEPENDENCE OF LINEAR RF LOSSES *

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Abstract

Topographic structure on Superconductivity Radio Frequency (SRF) surfaces can contribute additional cavity RF losses describable in terms of surface RF reflectivity and absorption indices of wave scattering theory. At isotropic homogeneous extent, Power Spectrum Density (PSD) of roughness is introduced and quantifies the random surface topographic structure. PSD obtained from different surface treatments of niobium, such as Buffered Chemical Polishing (BCP), Electropolishing (EP), Nano-Mechanical Polishing (NMP) and Barrel Centrifugal Polishing (CBP) are compared. A perturbation model is utilized to calculate the additional rough surface RF losses based on PSD statistical analysis. This model will not consider that superconductor becomes normal conducting at fields higher than transition field. One can calculate the RF power dissipation ratio between rough surface and ideal smooth surface within this field range from linear loss mechanisms.

INTRODUCTION

RF loss induced by roughness is considered in many RF components, such as micro strip transmission line, wave guide and RF resonator. It can be understood as the RF electromagnetic field penetrates the surface and there the induced current will pass and cause RF loss. [1] However, in a RF wave view, the incident wave is reflected, scattered and absorbed by the rough surface. Inside of a resonator, the reflected, scattered wave contributes to standing wave field, while the absorbed RF wave is attributed to the RF surface loss. These two perspectives may both be used to describe the same RF loss.

In a resonator, only several specific RF standing wave modes can exist to meet the boundary condition which is the resonator geometry. The electric and magnetic field at one location is combination a of EM components of those plane waves. Within the resonator, E and M are separated in space and interchange their energy over a distance. Thus the peak E and M field are always not the same location. With special EM setup, TE, TM, TEM are used to describe the EM field direction, if presumed direction is beam axis. In some sense, it is very tedious and difficult to expand the field into plane wave expansion. If so, the incident direction should also be from all directions. Therefore, a RF loss calculation method is required and independent of direction. It also covers all frequencies or wavelengths.

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METHODOLOGY

A rough surface will cost more RF loss. [2] One simple reason is that the surface current have more current path. In another word, the RF wave as more radiation absorption surface. This RF loss will contribute into power consumption and aggravate the quality factor.

If we consider a 2D random rough surface Z= f(x) in Fig.1. We can expand the magnetic field into Fourier series as in x and z direction. [3]

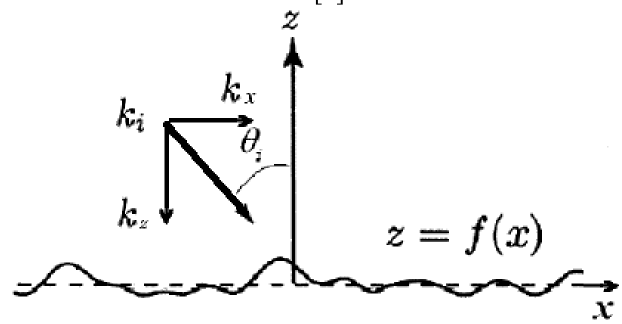

Figure 1: A plane wave incident impinging on a rough surface with incident angle θ_i.

$$\psi(x,z) = \int_{-\infty}^{\infty} dk_x \exp\left(-jk_x x + jk_{1z} z\right) \widetilde{\psi}(k_x)$$

Where $k_{1z} = \sqrt{k_1^2 - k_x^2}$ and $k_1 = \frac{1-j}{\delta}$. Here δ is the skin depth $\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$ and σ is the superconducting conductivity. The physics behind this equation is that the total magnetic field is combination of field component at each spatial wavelength. In another word, the total magnetic field can be expanded into magnetic contribution from each wavelength in spatial frequency.

If we use a second order small perturbation methods, setting

$$\widetilde{\psi}(k_x) = \widetilde{\psi}^{(0)}(k_x) + \widetilde{\psi}^{(1)}(k_x) + \widetilde{\psi}^{(2)}(k_x)$$

In first approximation, a fixed constant magnetic field H_0 is applied on the surface. Thus, the equation above becomes:

$$H_0 = \int_{-\infty}^{\infty} dk_x \exp\left(-jk_x x + jk_{1z} f(x)\right) \widetilde{\psi}(k_x)$$

Basically, we have done a Fourier transform to redistribute the magnetic field into each surface spatial wavelength in x direction.

By balancing this equation to second order, we obtain:

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$$\widetilde{\psi}^{(0)}(k_x) = H_0\delta(k_x)$$
$$\widetilde{\psi}^{(1)}(k_x) = -jk_1 H_0 F(k_x)$$
$$\widetilde{\psi}^{(2)}(k_x) = H_0 \int_{-\infty}^{\infty} dk'_x F(k_x - k'_x) F(k'_x)\left(-k_1 k'_{1z} + \frac{k_1^2}{2}\right)$$

For now, we have calculated the RF magnetic field on this given surface. The power absorbed by the conductor, for a given width w in y direction and length L in x direction, can be calculated from the Poynting vector.

$$P_a = \frac{w}{2\sigma}\mathrm{Re}\int ds \frac{\partial\psi}{\partial n}\psi^*$$

We simplify the results:

$$\langle P_a\rangle = \frac{wL}{2\sigma\delta}|H_0|^2\left\{1 + \frac{2h^2}{\delta^2}\left[1 - \frac{\delta}{h^2}\int_{-\infty}^{\infty} dk_x W(k_x)\,\mathrm{Re}\sqrt{k_1^2 - k_x^2}\right]\right\}$$

In order to get rid of the external field, we normalize the power dissipation with that of a smooth surface.

$$\frac{\langle P_a\rangle}{P_{a,\mathrm{smooth}}} = 1 + \frac{2h^2}{\delta^2} - \frac{4\pi}{\delta}\int_0^{\infty} dk_\rho \left\{k_\rho W_{2D}(k_\rho)\,\mathrm{Re}\sqrt{\frac{-2j}{\delta^2} - k_\rho^2}\right\}$$

$W_{2D}(k_\rho)$ is the 2D PSD from an isotropic surface.

Researcher have combined TM and TE wave mode into this equation into a 2D problem. They also avoid the assumption that surface field is a constant.

One should note:

1. The RMS and decay parameters (penetration depth) ratio, h/δ, is critical for characterizing the increased losses.
2. Third term reduces to h^2/δ^2, when the k_ρ is small. The second/third term have net contribution if $1/\delta$ and k_ρ are comparable.
3. Generally, higher $W_{2D}(k_\rho)$ brings additional loss.

APPLICATION TO SRF SURFACES

To obtain more accurate RF loss ratio, one needs to extend the PSD into as broad a frequency range as possible. Since all characterization method shave cut-off frequencies, one can at most get an extended PSD. The recent extended frequency range is 1/1.2 cm^{-1}–1/10 nm^{-1}, over 6 decades, with white light interferometry and atomic force microscopy. Because the magnetic field is expanded into horizontal spatial wavelength, the PSD frequency should cover the RF wavelength and beyond. Though an approximation methods is introduced by using Inverse Abel transforms to extend limited range, but obtaining 1D PSD with wider frequency range could improve later calculation accuracy.

$$< W(k_\rho)^{2D} > = -\frac{1}{\pi}\times\int_{k_\rho}^{\infty}\frac{dk_\rho}{\sqrt{k_x^{\,2} - k_\rho^{\,2}}}\frac{d}{dk_x} < W(k_x)^{1D} >$$

$$< W(k_x)^{1D} > = 2\times\int_{k_x}^{\infty}\frac{k_\rho dk_\rho}{\sqrt{k_\rho^{\,2} - k_x^{\,2}}} < W(k_\rho)^{2D} >$$

This transformation also permits the transformation of the high-frequency behavior of the spectra of one dimensionality to be transformed into the high-frequency behavior of the other without knowledge of their low-frequency behavior.

We investigate SRF surfaces with current polishing methods and materials polished are large/fine/single grain Nb sheets. Buffered chemical polishing, electropolishing and mechanical centrifugal barrel polishing samples are characterized by Atomic Force Microscopy (AFM) and White light interferometry (WLI). Note that these two characterizations have different lateral resolutions and scan scopes which determine the spectral frequency ranges.

1D averaged PSD is calculated by following the routine introduced previously. [4] Such routine includes proper detrending, windowing and averaging.

In this study, the R_q and PSD are used to derive power ratio. Rq value from 4 different locations on each sample is averaged and summarised in Table 1.

Table 1: Averaged R_q with AFM and WLI

Samples	Single crystal	"Standard" fine-grained				
Treatment	After30 µm BCP	Nano polished	+100 µm BCP	+50 µm EP	Centrifugal Barrel Polishing (CBP)	
					Fine Grain	Large Grain
Atomic force microscopy ~5×5µm						
R_q(nm)	1.99	2.84	4.89	4.40	2.76	1.20
Atomic force microscopy ~100×100µm						
R_q(nm)	7.05	13.5	392.90	74.30	70.8	7.71
White light interferometry ~234×312µm (20x magnification)						
R_q (nm)	35.7	1.63	1500.4	291.7	151.8	13.5
White light interferometry ~930×1244µm(5x magnification)						
R_q (nm)	391	5.24	2008.5	642.8	335.5	49.0

One can generalize that Rq value decrease from BCP>EP>CBP Large grain> CBP Fine grain> Single crystal>Nanopolishing samples.

Averaged 1D PSD from AFM/WLI are combined in Fig.2.

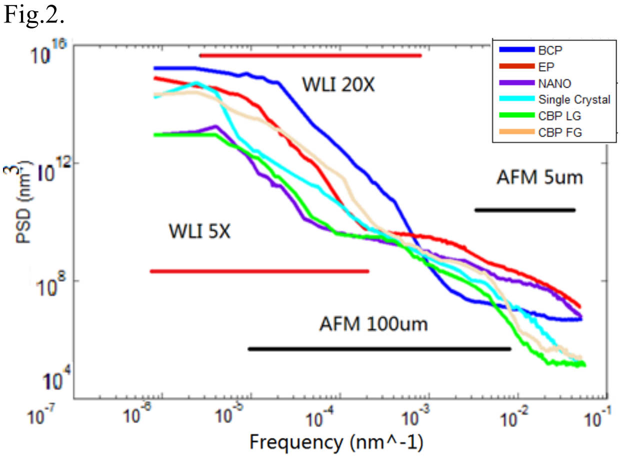

Figure 2: Joint 1D PSD models from AFM/WLI are shown and the characterization frequency domains are indicated.

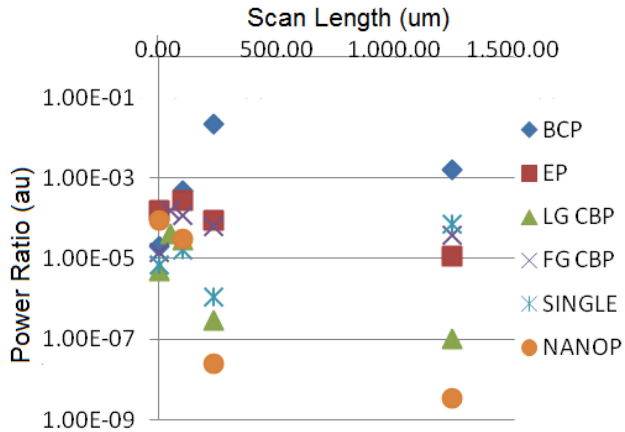

Figure 3: Power Ratio calculated from 1D PSD.

The power ratio is shown in Fig.3 and by inverse Abel transform, the 2D PSD are shown in Fig.4.

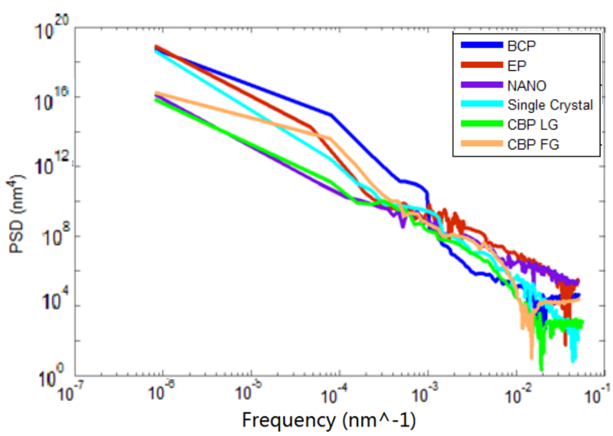

Figure 4: 2D PSD calculated from various surfaces.

Power ratio index are illustrated in Fig.5.

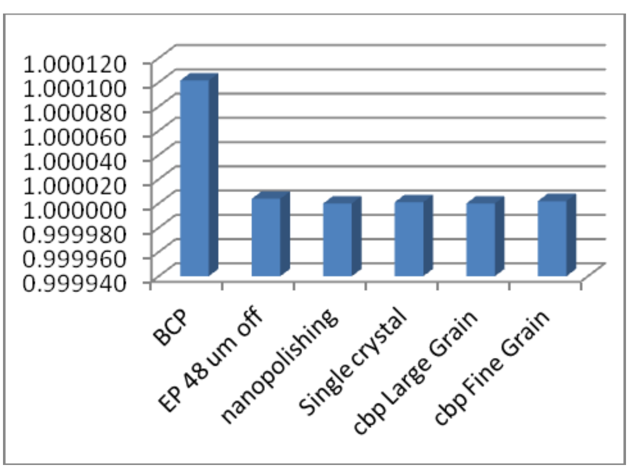

Figure 5: Power Ratio from 2D isotropic PSD.

BCP surface show higher ratio, but other surfaces suggest almost the same close to 1.

DISCUSSION

One can see from power ratio equation that the last term is an integration of 2d PSD.

$$\frac{\langle P_{a,\mathrm{rough}}\rangle}{P_{a,\mathrm{smooth}}} = 1 + \frac{2h^2}{\delta^2} - \frac{4\pi}{\delta}\int_0^\infty dk_\rho \left\{ k_\rho W_{2D}(k_\rho)\,\mathrm{Re}\sqrt{\frac{-2j}{\delta^2} - k_\rho^2} \right\}$$

Without the Re(…), the integrand is simply the square of RMS height. One can infer that if the k_ρ is small enough compared with $2/\delta$, then the Re(…) term reduced into $1/\delta$. In that limit the second and third terms cancel each other. The total power ratio becomes one. This gives substantiates the interpretation that features at larger wavelength have less RF power loss than the small high frequency features. Another understanding is that only features with lateral extent comparable to the penetration length give a significant effect on the additional power loss ratio. Applying this analysis to variously prepared niobium surfaces typical of those in SRF cavities, we find that linear RF losses depend negligibly on roughness for any of the characteristic surfaces considered. On the other hand, SRF materials are particularly susceptible to non-linear and temperature-dependent losses. The non-linear losses are reflected in the observed Q drop with increasing surface magnetic field. We are examining the influence of topography on such losses separately [5].

CONCLUSION

Spectral study suggested that surface roughness doesn't contribute much in the linear RF loss, because current practical surface a smooth enough at a wavelength closed to penetration depth.

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