NUMERICAL CALCULATIONS OF SUPERHEATING FIELD IN SUPERCONDUCTORS WITH NANOSTRUCTURED SURFACES*

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ABSTRACT

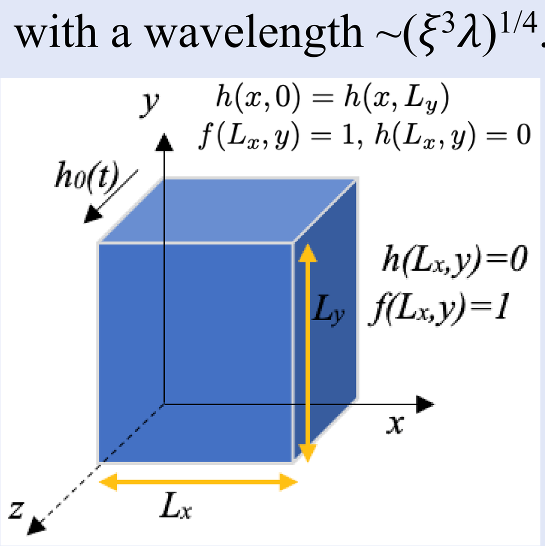
We report calculations of a dc superheating field H_{sh} in superconductors with nanostructured surfaces. Numerical simulations of the Ginzburg-Landau (GL) equations were performed for a superconductor with an inhomogeneous impurity concentration, a thin superconducting layer on top of another superconductor, and S-I-S multilayers were performed. The superheating field was calculated taking into account the instability of the Meissner state with a nonzero wavelength along the surface, which is essential for realistic values of the GL parameter κ. Simulations were done for the materials parameters of Nb and Nb_3Sn at different values of κ and the mean free paths. We show that the impurity concentration profile at the surface and thicknesses of S-I-S multilayers can be optimized to reach H_{sh} exceeding the bulk superheating fields of both Nb and Nb_3Sn. For example, a S-I-S structure with 90 nm thick Nb_3Sn layer on Nb can boost the superheating field up to ~500 mT, while protecting the SRF cavity from dendritic thermomagnetic avalanches caused by local penetration of vortices.

INTRODUCTION

- The superheating field is the maximum magnetic field H that can be screened by a superconductor in the vortex-free Meissner state [1].
- Recent advancements in Nb cavities have pushed H_{sh} to its theoretical limit, prompting the exploration of surface nano-structuring techniques to further increase H_{sh}[2,3,4].
- The goal of this study is to investigate the influence of the Ginzburg-Landau parameter κ on H_{sh} for superconductors with a nanostructured surface.

NUMERICAL CALCULATION OF SUPERHEATING FIELD

Breakdown of the Meissner state at H_{sh} occurs via a periodic modulation of the order parameter with a wavelength $\sim(\xi^3\lambda)^{1/4}$.



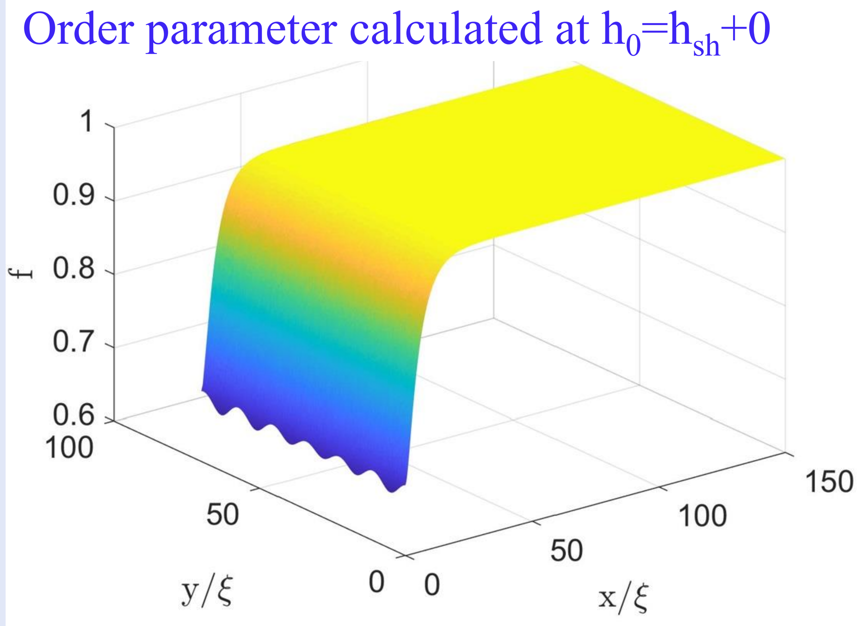
GL equations:

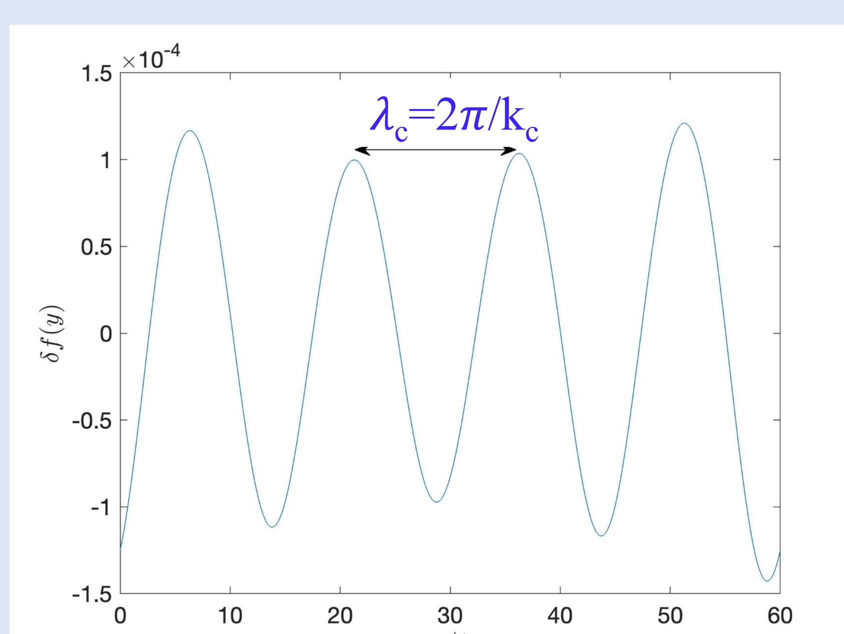
$$\dot f - f + f^3 - \nabla^2 f + \frac{\kappa^2}{f^3}\left[(\partial_x h)^2 + (\partial_y h)^2\right] = 0$$
$$\nabla\cdot\left(\frac{\nabla h}{f^2}\right) = \frac{h}{\kappa^2}$$

$$f = \Delta/\Delta_0,\ h = H/\sqrt{2}H_c$$
$$h_0(t) = \theta(t-t_0)(0.01t_0 + 0.00005(t-t_0)) + 0.01t\theta(t_0-t)$$

$\Delta(x,y,z)$- amplitude of the complex order parameter $\psi=\Delta e^{i\theta}$, Δ_0 is equilibrium order parameter in the bulk, All lengths are in the unit of ξ, k_c-critical momentum, $\theta(t)$- Heaviside step function, t_0 was chosen such that $h_0(t_0)<h_{sh}$.

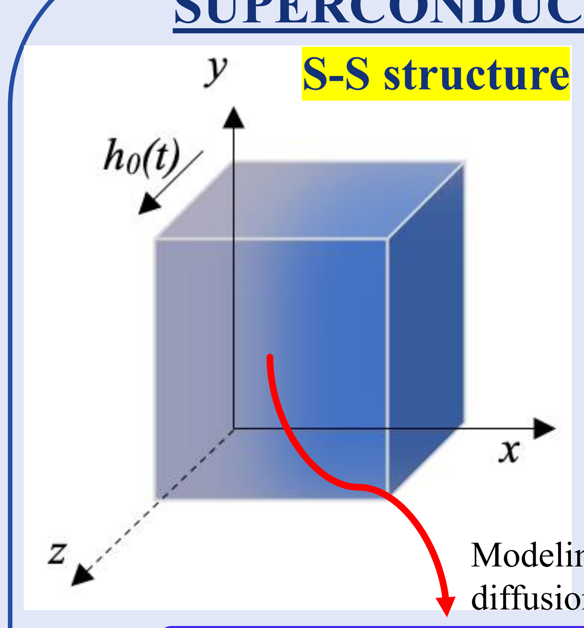
Order parameter calculated at $h_0=h_{sh}+0$

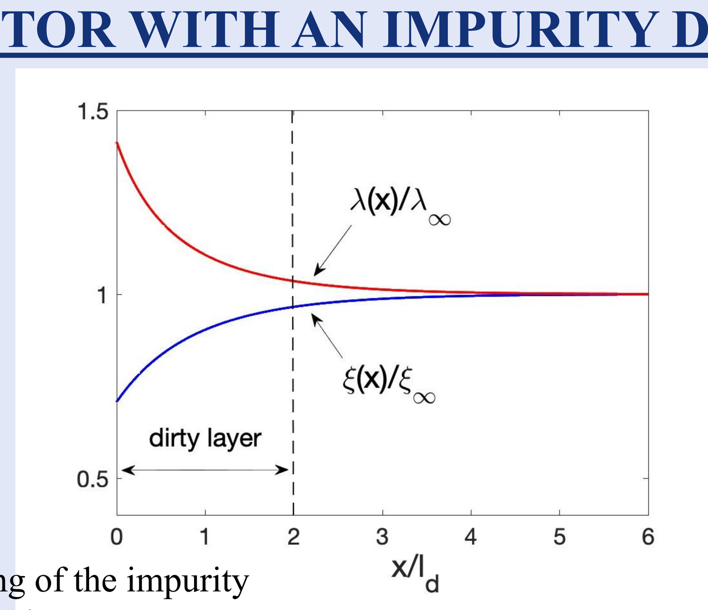




A snapshot of $\Delta f\ (y,0)$ at $h_0=h_{sh}+0$.

SUPERCONDUCTOR WITH AN IMPURITY DIFFUSION LAYER



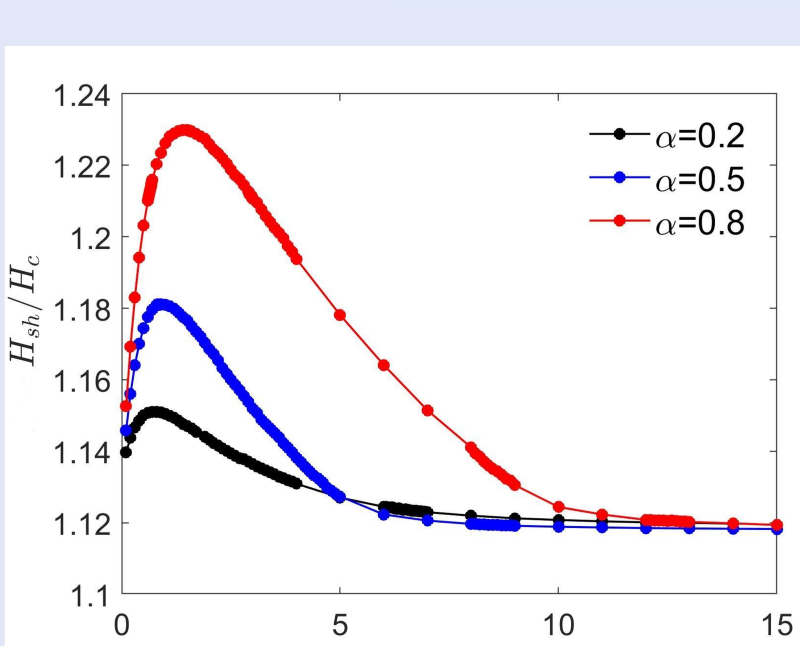


- The parameter α models the reduction of $\xi(0,y,z)$ and enhancement of $\lambda(0,y,z)$
- l_d is a thickness of the diffusion layer

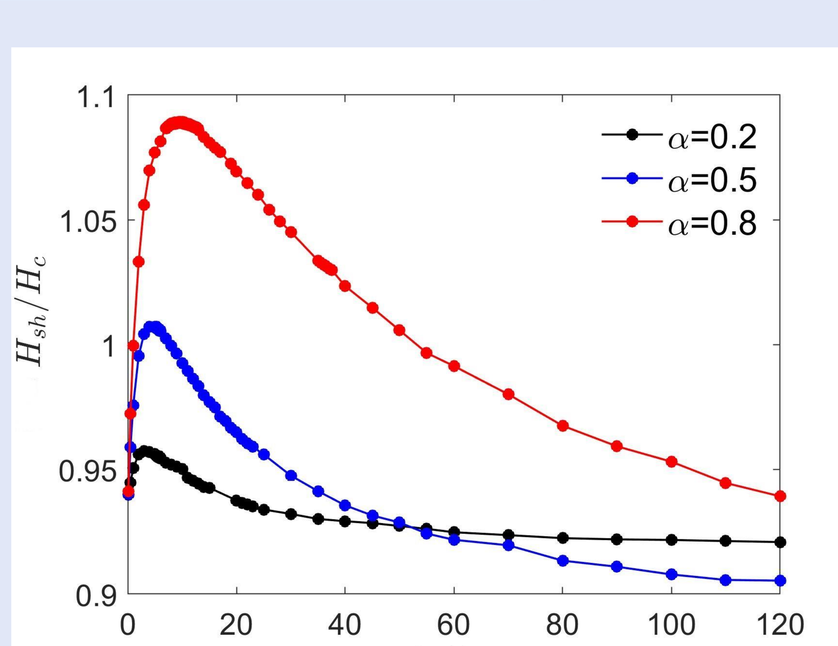
$$S_\gamma = \xi^2(x)/\xi_\infty^2 = \lambda_\infty^2/\lambda^2(x) = 1 - \alpha\exp(-x/l_d)$$

GL equations:

$$\dot f = f - f^3 + \nabla\cdot(S_\gamma\nabla f) - \frac{\kappa^2}{S_\gamma f^3}\left[(\partial_x h)^2 + (\partial_y h)^2\right]$$
$$\nabla\cdot\left(\frac{\nabla h}{f^2}\right) = \frac{S_\gamma}{\kappa^2}h + \frac{1}{S_\gamma f^2}(\partial_x S_\gamma\cdot\partial_x h)$$

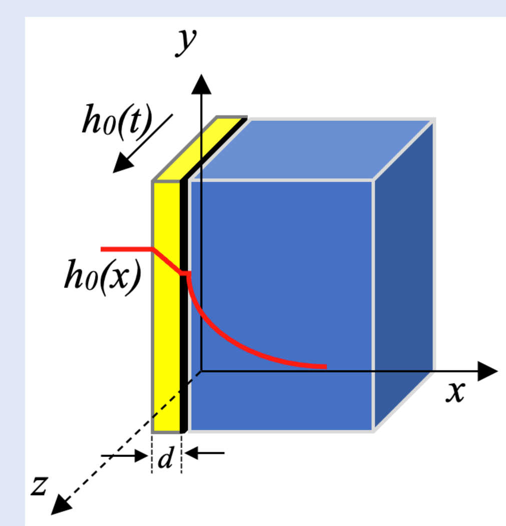


H_{sh} vs l_d for different α at κ=2.



H_{sh} vs l_d for different α at κ=10.

S-I-S STRUCTURES



Geometries:
- Nb_3Sn-I-Nb_3Sn
- Dirty Nb_3Sn-I-Nb_3Sn
- Nb_3Sn-I-Nb

Assumption: The I-layer is thick enough to fully suppress the Josephson coupling between the S-overlayer and the bulk.

GL equations (Film):
Same materials present both sides

$$\dot f_1 = f_1 - f_1^3 + \frac{\xi_1^2}{\xi_2^2}\nabla^2 f_1 - \frac{\xi_1^2}{\xi_2^2}\frac{\kappa_1^2}{f_1^3}\left[(\partial_x h_1)^2 + (\partial_y h_1)^2\right]$$
$$\nabla\cdot\left(\frac{\nabla h_1}{f_1^2}\right) = \frac{h_1\xi_2^2}{\xi_1^2\kappa_1^2}$$

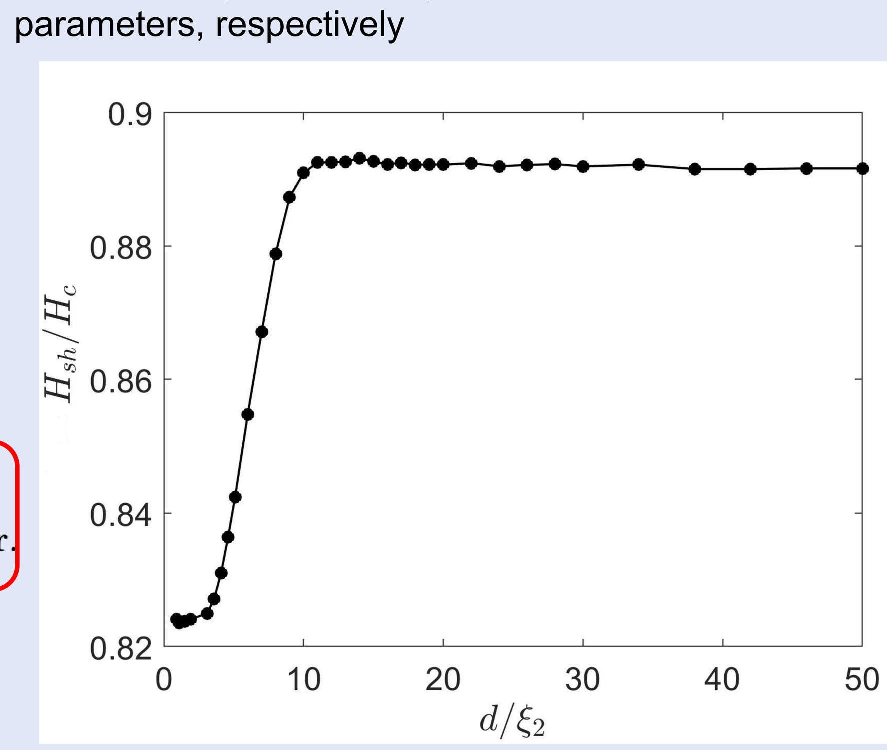
GL equations (Film):
Different materials present both sides

$$\dot f_1 = \zeta f_1 - f_1^3 + s\nabla^2 f_1 - \frac{\tilde\kappa^2}{f_1^3}\left[(\partial_x h_1)^2 + (\partial_y h_1)^2\right]$$
$$\nabla\cdot\left(\frac{\nabla h_1}{f_1^2}\right) = \frac{\lambda_2^2 h_1}{\lambda_1^2\zeta\kappa_2^2}$$
$$\zeta = \frac{1-T/T_{c1}}{1-T/T_{c2}},\qquad s = \frac{\xi_1^2}{\xi_2^2}\zeta,\qquad \tilde\kappa^2 = \frac{\xi_1^2\lambda_1^4}{\xi_2^2\lambda_2^4}\kappa_2^2\zeta^3$$

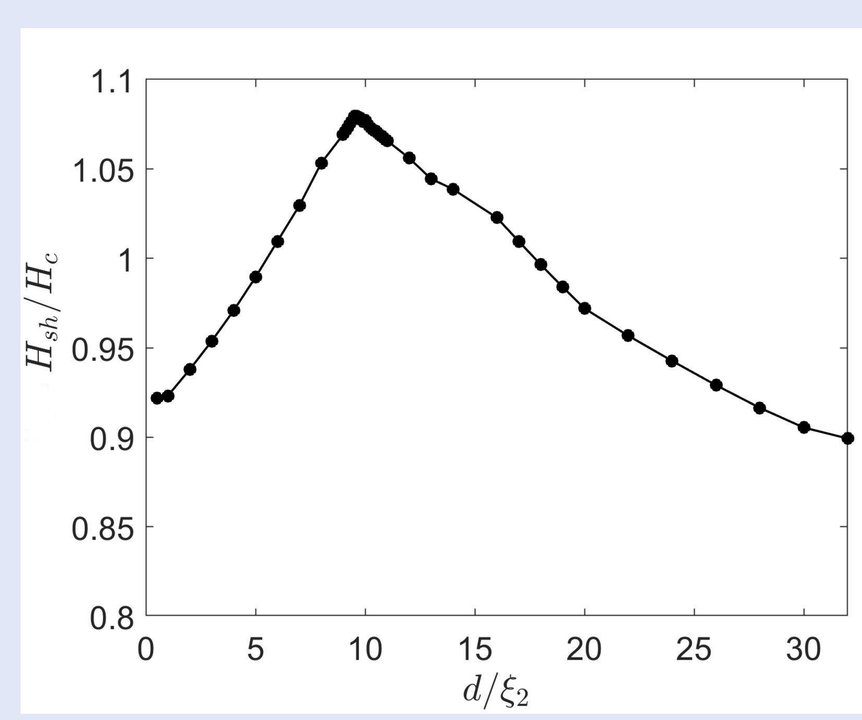
* The subscript 1 and 2 represent film and bulk parameters, respectively

Additional boundary conditions:

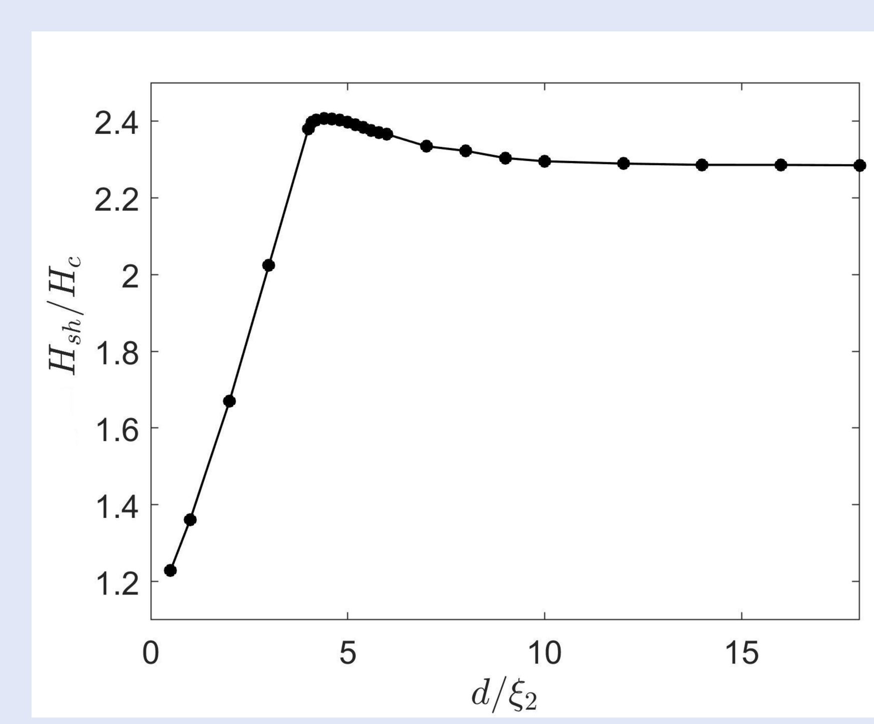
$$h(d+0,y) = h(d-0,y)$$
zero current $\partial_y h(d+0) = \partial_y h(d-0) = 0$ through the I layer.



H_{sh} vs. d for the case of Nb_3Sn-I-Nb_3Sn



H_{sh} vs. d for the case of dirty Nb_3Sn-I- Nb_3Sn



H_{sh} vs. d for the case of Nb_3Sn-I-Nb

SUMMARY

- The Ginzburg-Landau theory was employed to analyze the effect of impurity profiles and high T_c superconducting layers on the dc superheating field in S-S and S-I-S structures.
- Numerical simulations covered the entire range of $1<\kappa<\infty$ and took into account the instability $H=H_{sh}$ at a finite wave number k_c, which is particularly relevant for Nb with κ~1.
- Optimizing the diffusion length can enhance H_{sh} by 5-20% at κ=10 and 2-9% at κ=2.
- A dirty overlayer of Nb_3Sn deposited on a clean Nb_3Sn, can boost the superheating field by about 10%.
- A S-I-S structure consisting of a Nb_3Sn overlayer on Nb can increase the superheating field by approximately 2.2 times as compared to the bulk Nb.

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* Work supported by NSF under Grant 100614-010 and Virginia Military Institute (VMI) # walivepathiranagemr@vmi.edu