Theory of Multilayer Coating for proof-of-concept experiments

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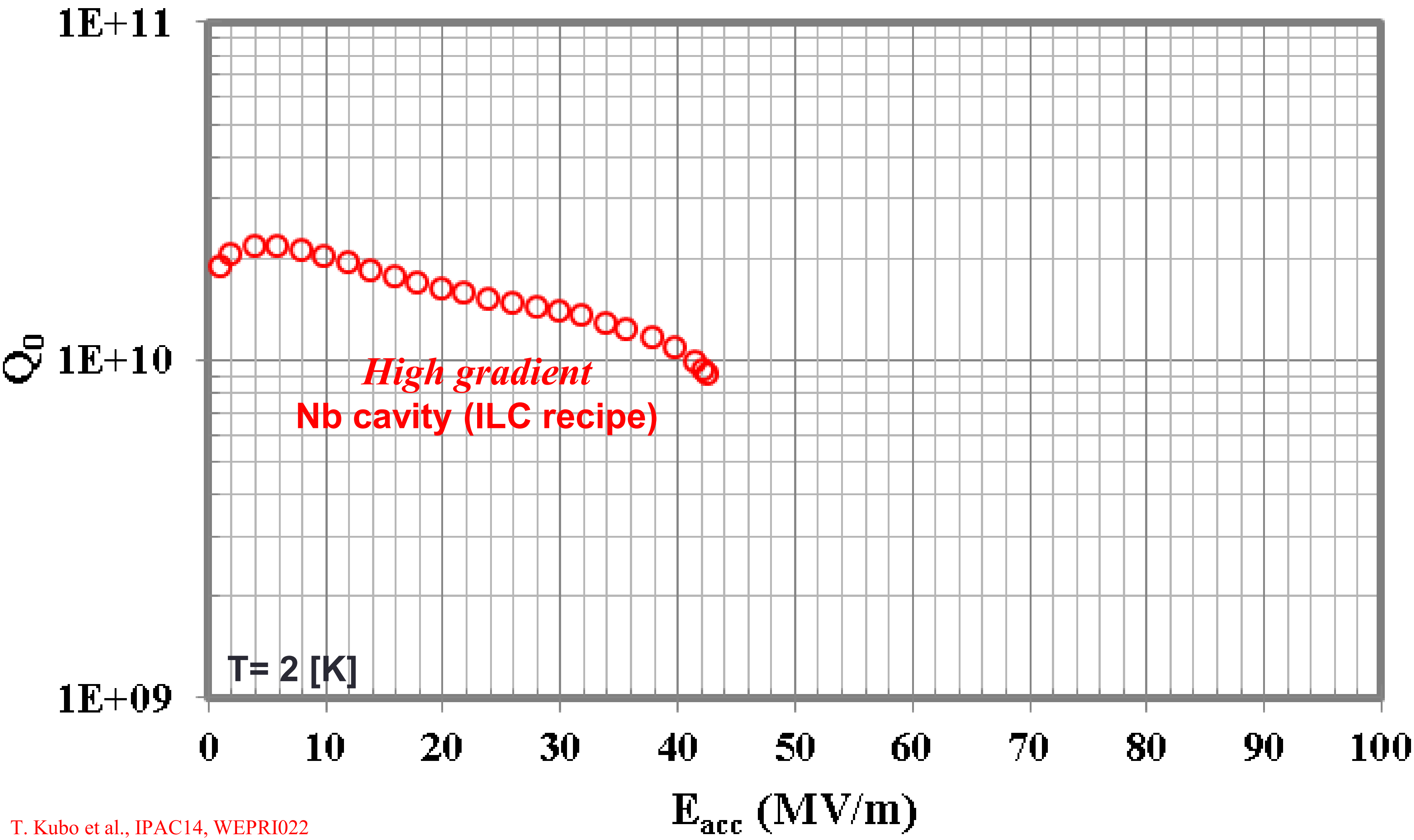
This work was supported by Japan Society for the Promotion of Science KAKENHI:
Grant-in-Aid for Young Scientists (B), Number 26800157,
Grant-in-Aid for Challenging Exploratory Research, Number 26600142,
and Photon and Quantum Basic Research Coordinated Development Program from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

科研費 KAKENHI

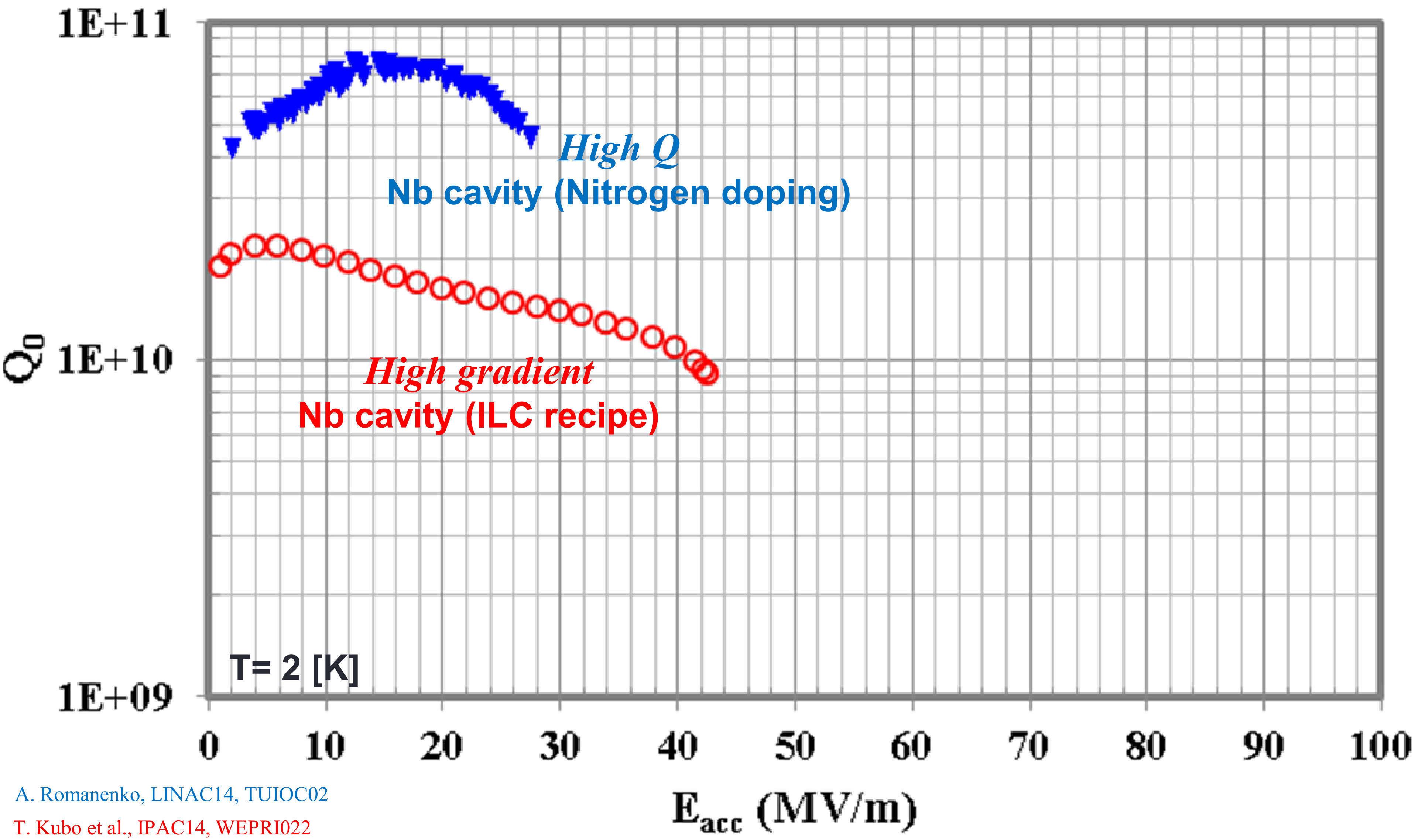
Nb cavity processed by the ILC recipe



T. Kubo et al., IPAC14, WEPRI022

Breakthrough by the nitrogen doping

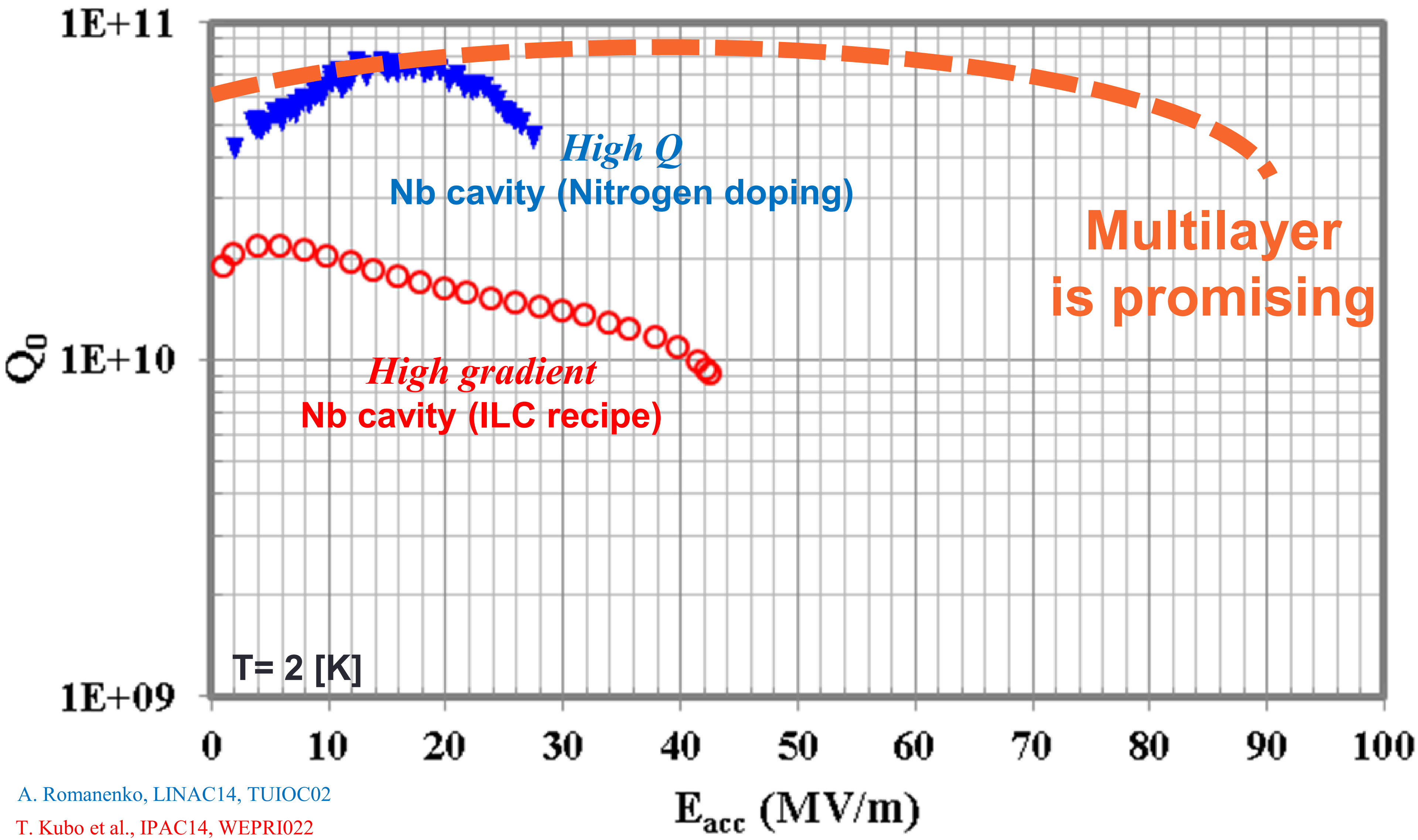
A. Grassellino et al, Supercond. Sci. Technol. **26,** 102001 (2013)



A. Romanenko, LINAC14, TUIOC02

T. Kubo et al., IPAC14, WEPRI022

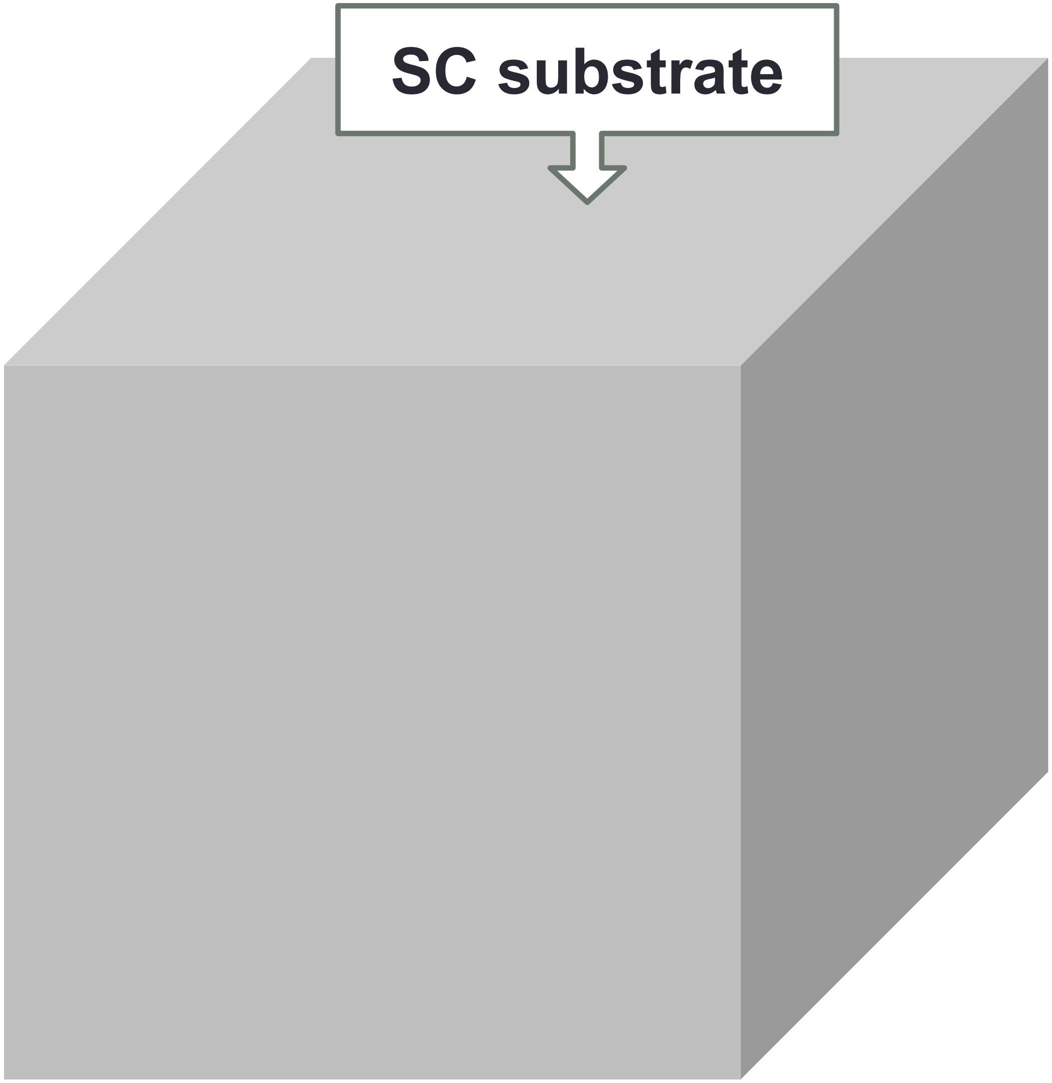
We want to go beyond Nb!



A. Romanenko, LINAC14, TUIOC02

T. Kubo et al., IPAC14, WEPRI022

The multilayer coating was proposed by A. Gurevich, **Appl. Phys. Lett. 88, 012511 (2006)**



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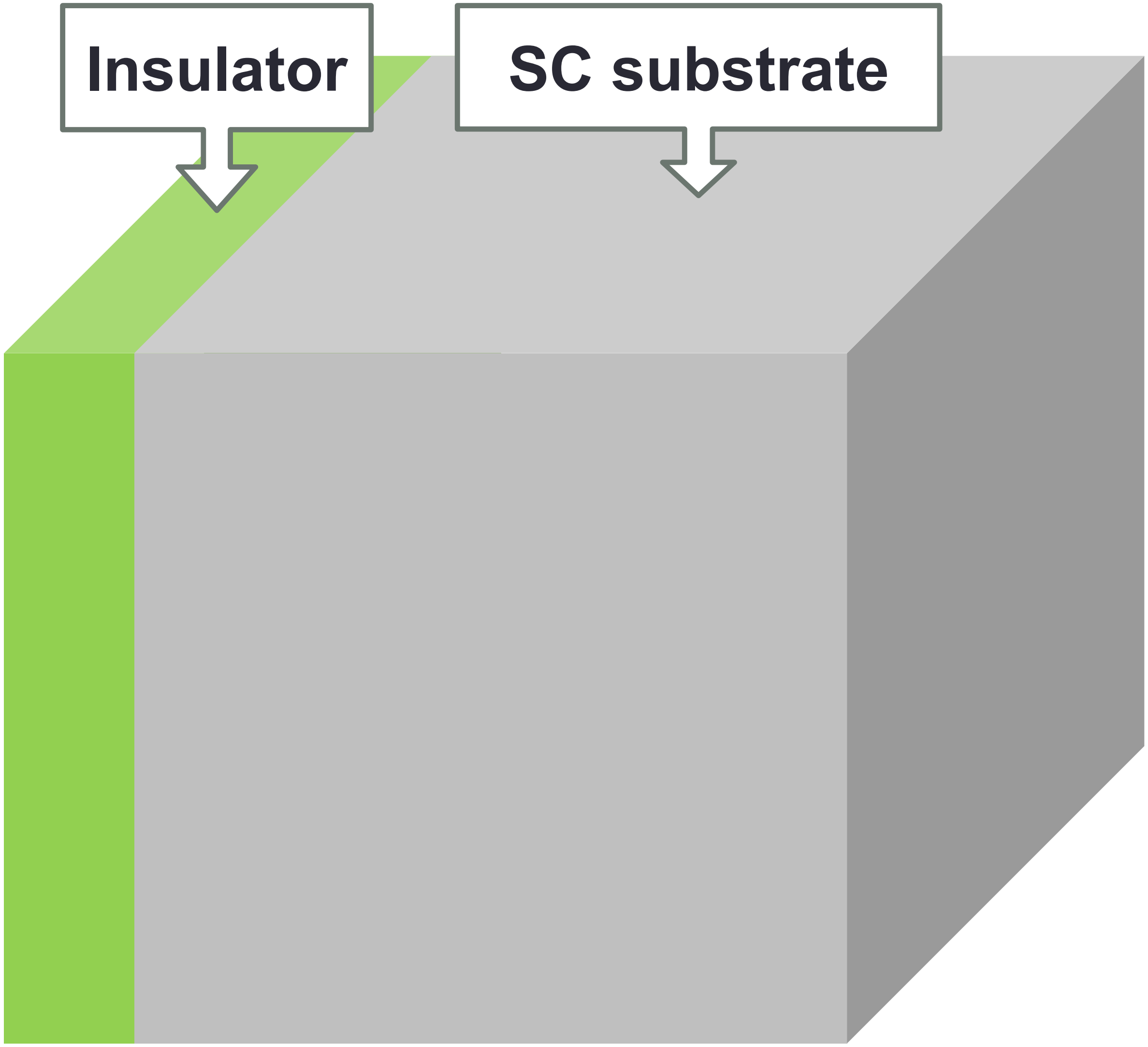

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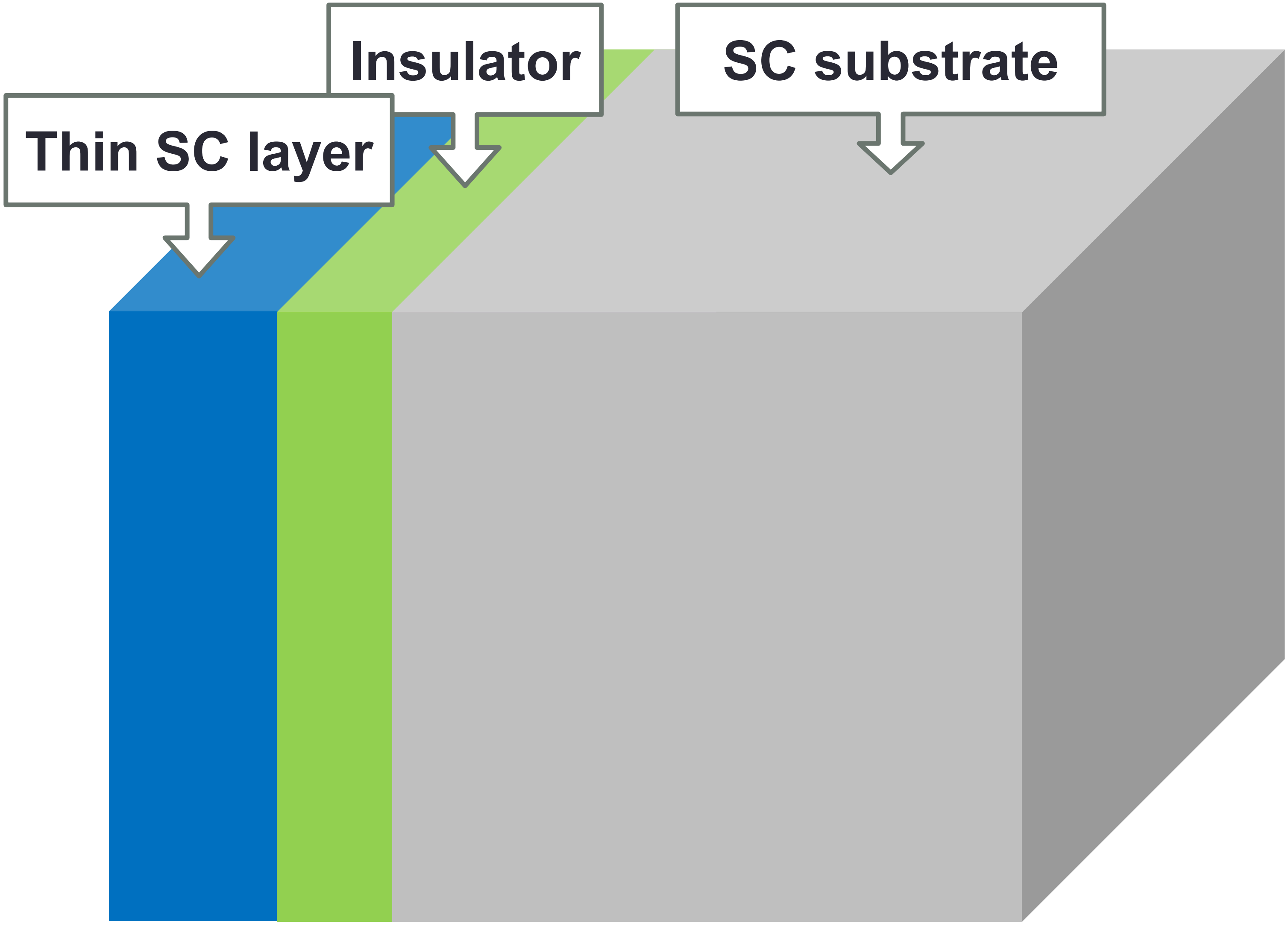
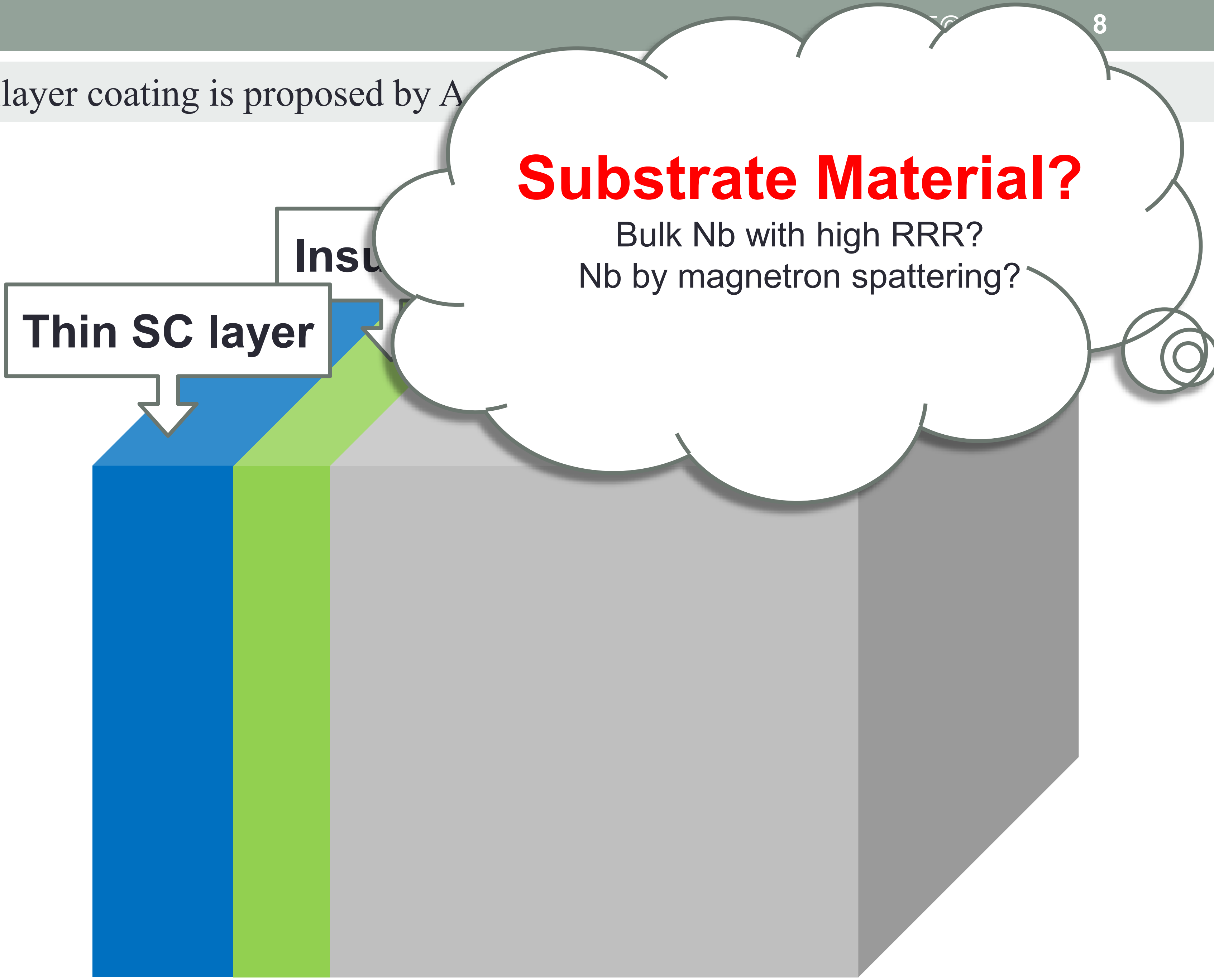
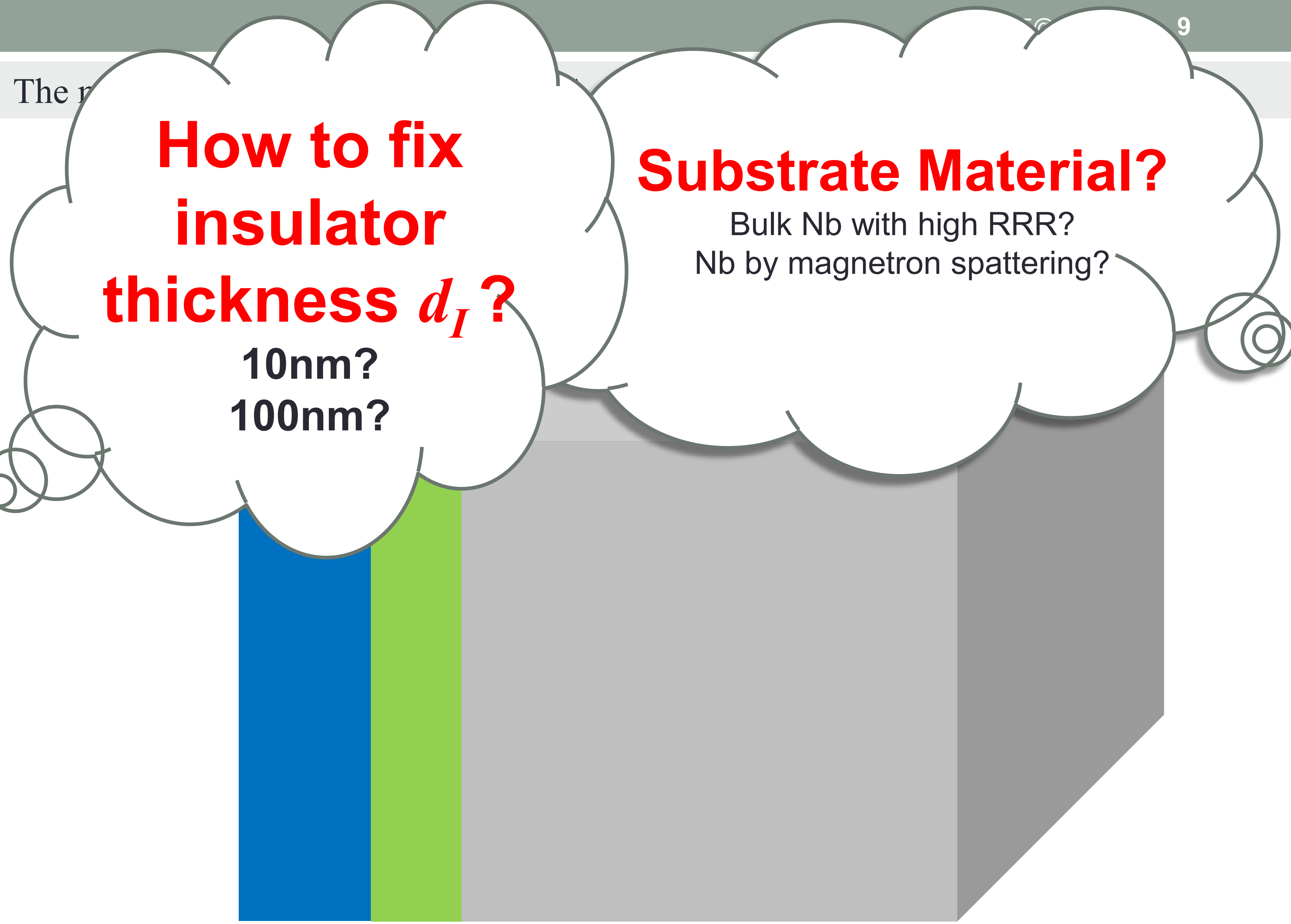


The multilayer coating is proposed by A




The r
How to fix insulator thickness d_I?
10nm?
100nm?
Substrate Material?
Bulk Nb with high RRR?
Nb by magnetron spattering?

The r

How to fix insulator thickness d_I?

10nm?

100nm?

Substrate Material?

Bulk Nb with high RRR?

Nb by magnetron spattering?

How to fix S layer thickness d_S?

10nm?

100nm?

§ 1
The optimum parameters

1. The magnetic field distribution (and thus the screening current distribution $\mathbf{J} \propto \mathbf{dB/dx}$) in the S layer is different from the naïve exponential decay.

2. When d_S and d_I are thin enough and $\lambda_1 > \lambda_2$, the screening current in the S layer is suppressed, and the surface field can exceed the superheating field of the S layer.

3. However, an extremely thin d_S can not protect the SC substrate. Thus the S layer must have some thickness to decay the magnetic field and protect the SC substrate. The optimum thickness of d_S exists.

1. **T. Kubo** et al., Appl. Phys. Lett. **104**, 032603 (2014) [submitted to arXiv on April 2013; published on January 2014]
2. **S. Posen** et al., in proceedings of SRF2013, p. 788, WEIOC04 [Sep.2013].
3. **A. Gurevich,** AIP Advances **5**, 017112 (2015) [submitted on Sep.2014; published on Jan.2015]
4. **S. Posen** et al., arXiv:1506.08428v1[June 2015].

Important!

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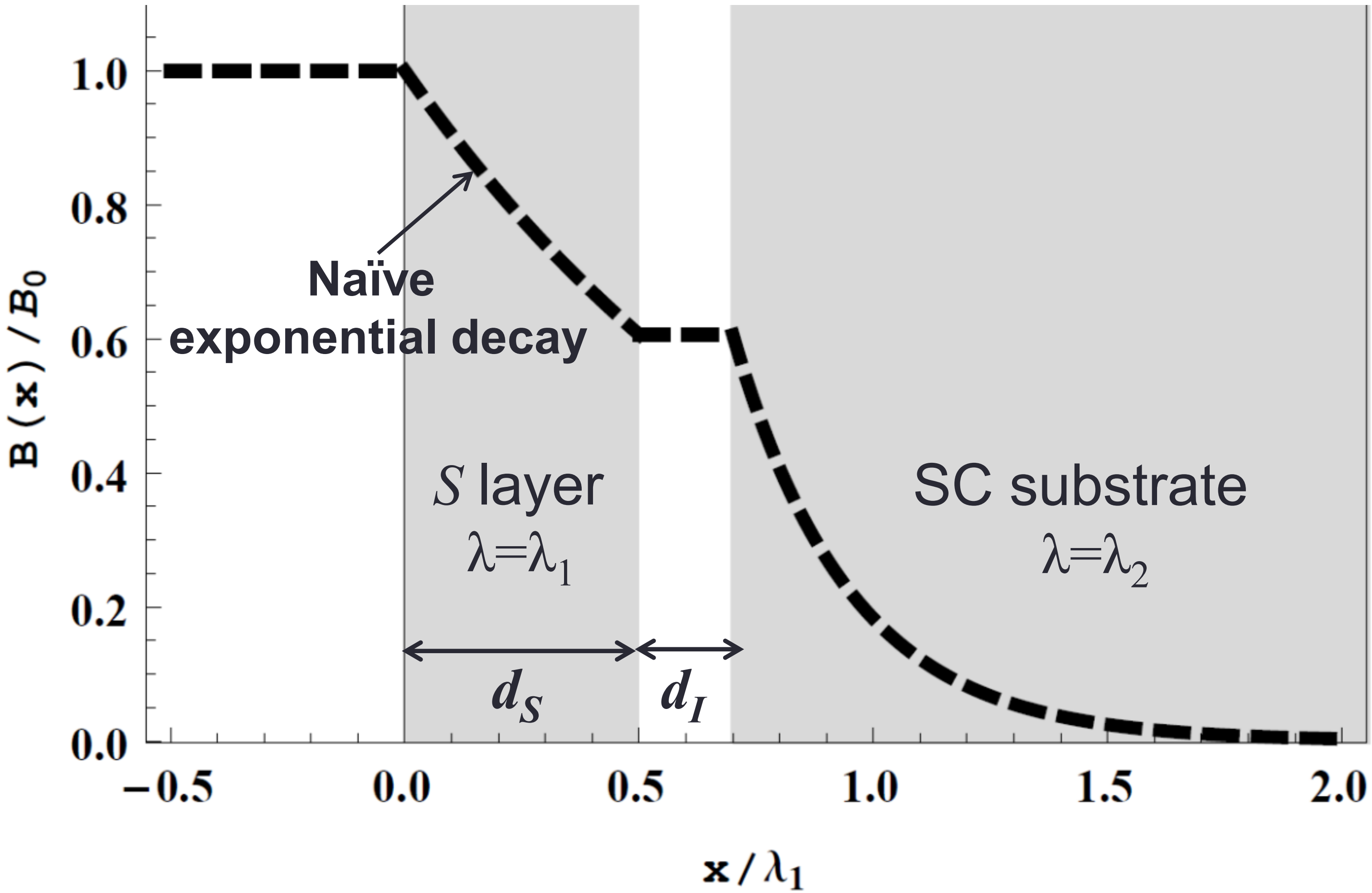

T. Kubo, Y. Iwashita, and T. Saeki, Appl. Phys. Lett. 104, 032603 (2014)
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The derivation processes are explained in detail in proceedings of IPAC13, p. 2343, WEPWO014 [May 2013]

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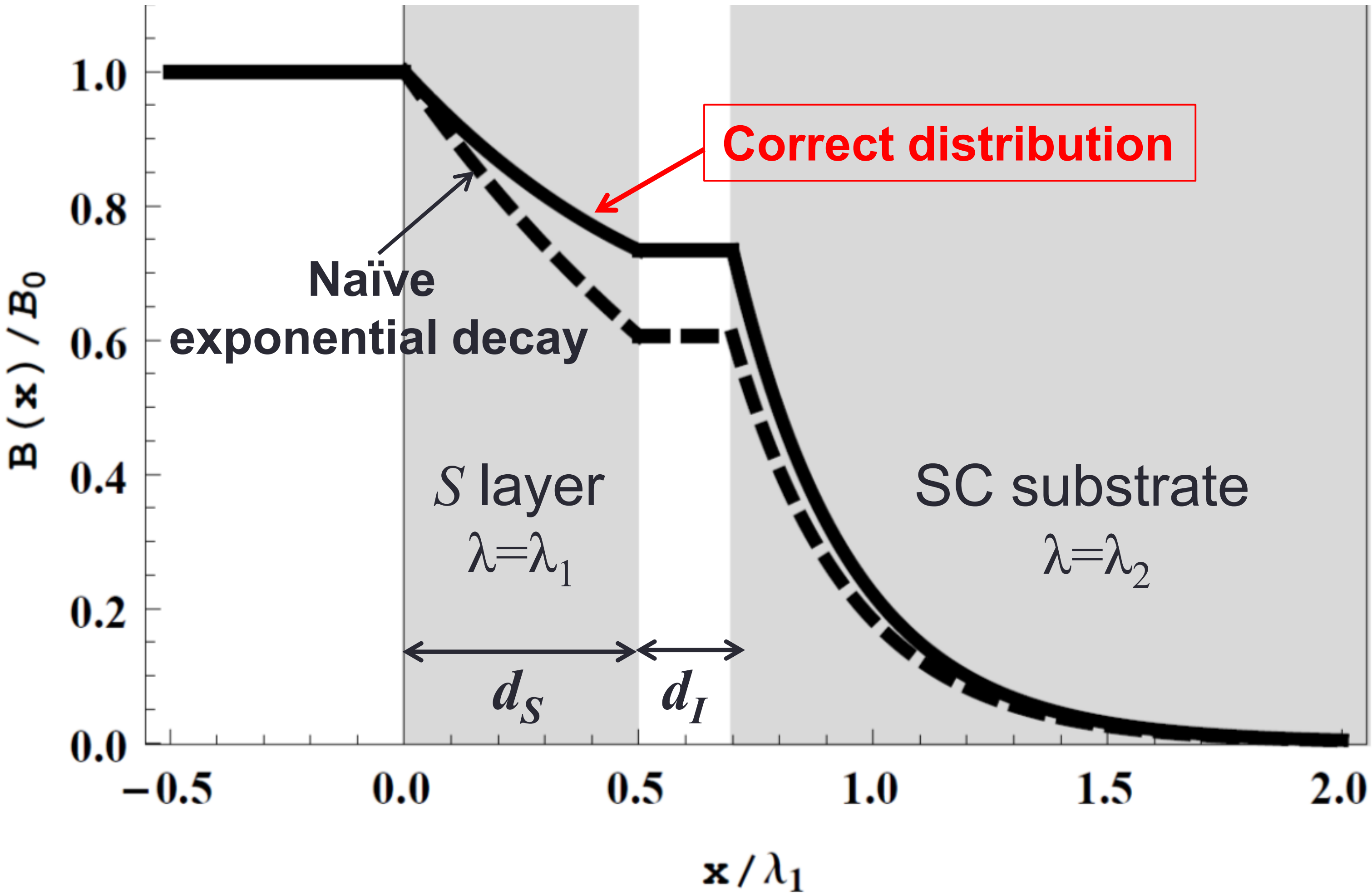

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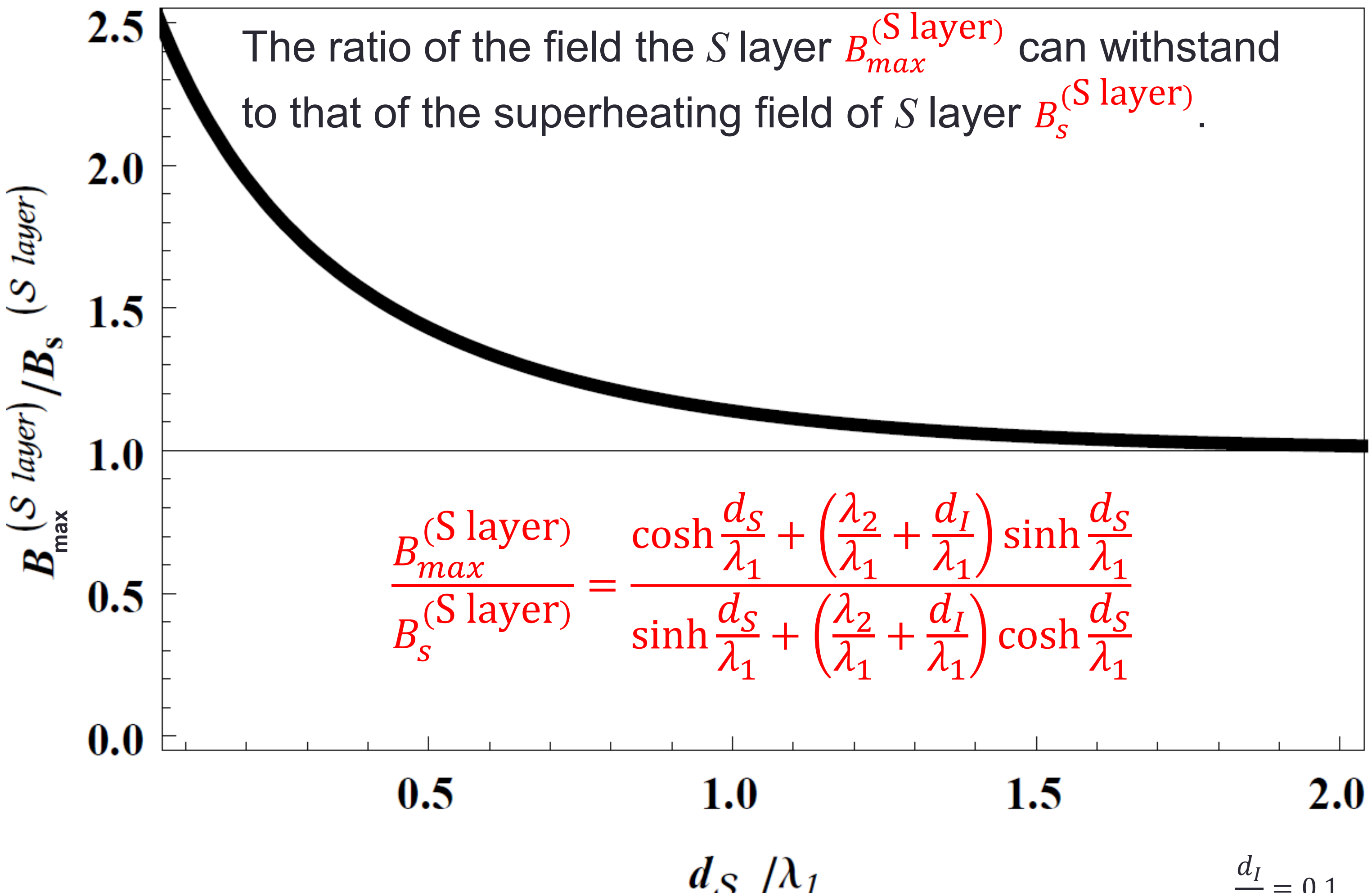

$\frac{d_I}{\lambda_1} = 0.1$ $\frac{\lambda_2}{\lambda_1} = 0.25$ are assumed here.

T. Kubo, Y. Iwashita, and T. Saeki, Appl. Phys. Lett. 104, 032603 (2014)
[submitted to arXiv on April 2013; published on January 2014]
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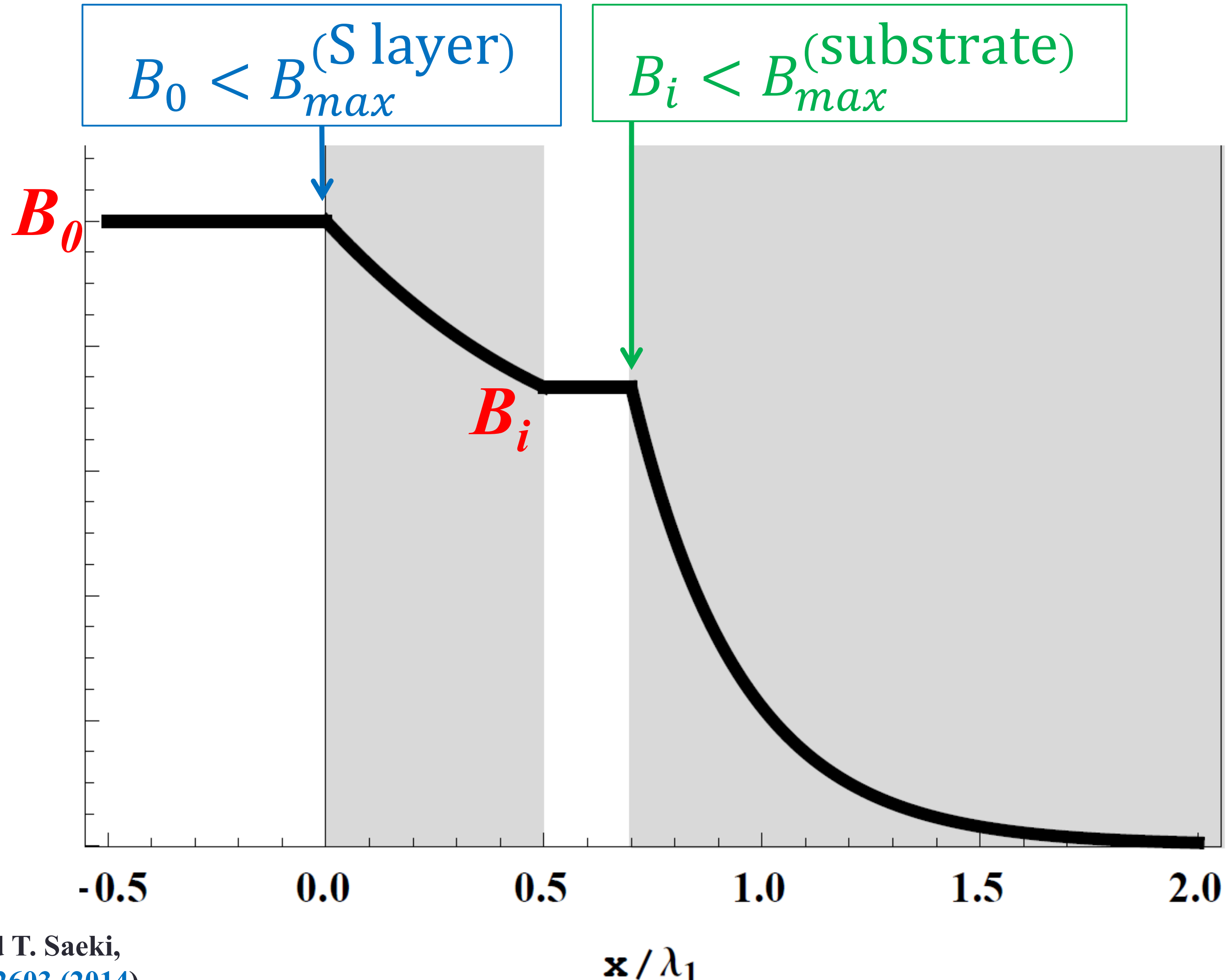
3. However, an extremely thin d_S can not protect the SC substrate. Thus the S layer must have some thickness to decay the magnetic field and protect the SC substrate.



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Formula for the maximum screening field of the multilayer

$$B_{\max}^{(\text{multilayer})} = \begin{cases} B_{max}^{(\text{S layer})} & (\text{if} \quad \gamma B_{max}^{(\text{S layer})} < B_{max}^{(\text{substrate})}) \\ \gamma^{-1} \times B_{max}^{(\text{substrate})} & (\text{if} \quad \gamma B_{max}^{(\text{S layer})} \geq B_{max}^{(\text{substrate})}) \end{cases}$$

where

$$B_{max}^{(\text{S layer})} = B_s^{(\text{S layer})} \frac{cosh\frac{d_S}{\lambda_1} + \left(\frac{\lambda_2}{\lambda_1} + \frac{d_I}{\lambda_1}\right) sinh\frac{d_S}{\lambda_1}}{sinh\frac{d_S}{\lambda_1} + \left(\frac{\lambda_2}{\lambda_1} + \frac{d_I}{\lambda_1}\right) cosh\frac{d_S}{\lambda_1}} \qquad B_s^{(\text{S layer})} = 0.84\, B_c^{(\text{S layer})}$$

$$\gamma = \frac{1}{\cosh\frac{d_S}{\lambda_1} + \left(\frac{\lambda_2}{\lambda_1} + \frac{d_I}{\lambda_1}\right) \sinh\frac{d_S}{\lambda_1}}$$

$$B_{max}^{(\text{substrate})} = 170\text{mT} - 240\text{mT}$$ (if the substrate is Nb)

T. Kubo (2015),
Obtained by using T. Kubo et al., Appl. Phys. Lett. **104**, 032603 (2014) and A. Gurevich, AIP Advances **5**, 017112 (2015)

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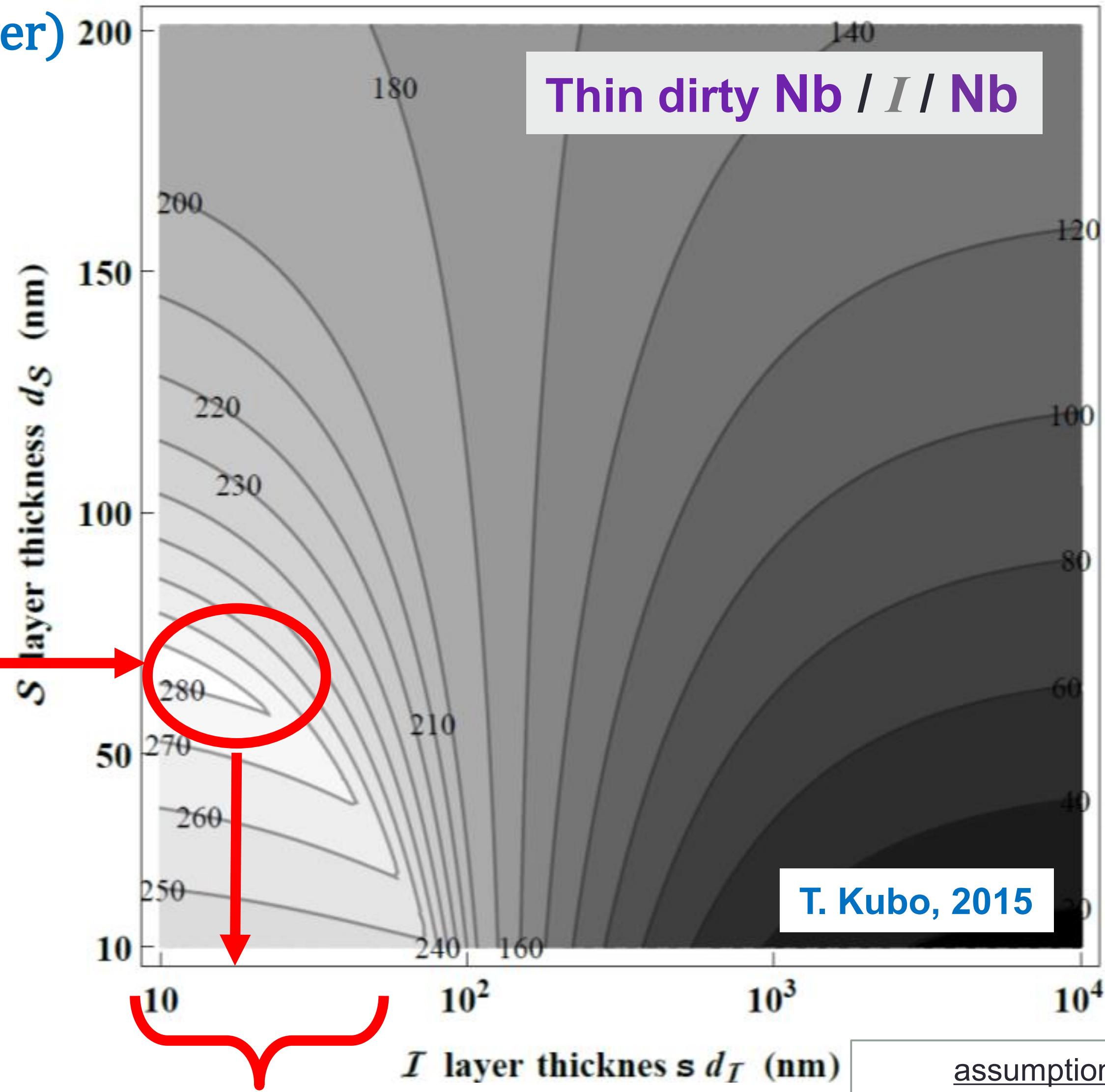
Formula for the optimum thickness of the S layer

$$d_S = \lambda_1 \ln\left[\frac{\lambda_1}{\lambda_1+\lambda_2+d_I}\frac{B_s^{(\text{S layer})}}{B_{max}^{(\text{substrate})}} + \sqrt{\left(\frac{\lambda_1}{\lambda_1+\lambda_2+d_I}\frac{B_s^{(\text{S layer})}}{B_{max}^{(\text{substrate})}}\right)^2 + \frac{\lambda_1-\lambda_2-d_I}{\lambda_1+\lambda_2+d_I}}\right]_{d_I \lesssim \mathcal{O}(10)\text{nm}}$$

T. Kubo (2015),
Obtained by using T. Kubo et al., Appl. Phys. Lett. **104**, 032603 (2014) and A. Gurevich, AIP Advances **5**, 017112 (2015)

- The formulae can be derived by using the discussion of A. Gurevich, AIP Advances **5**, 017112 (2015) and are described by using the superheating field of the quasi-classical theory and thus valid even at $T \ll T_c$.
- The formulae are generalized version of the Gurevich's formulae. The formulae includes effects of insulator layer with a finite thickness. **When $d_I \ll \lambda_1$, the formulae are reduced to the Gurevich's formulae** [A. Gurevich, AIP Advances 5, 017112 (2015)].

Contour plot of $B_{max}^{(multilayer)}$



Optimum d_s～70nm

see also A Gurevich, the 6th international workshop on thin films and new ideas for RF superconductivity, October 2014, Italy and A. Gurevich, AIP Advances **5**, 017112 (2015)

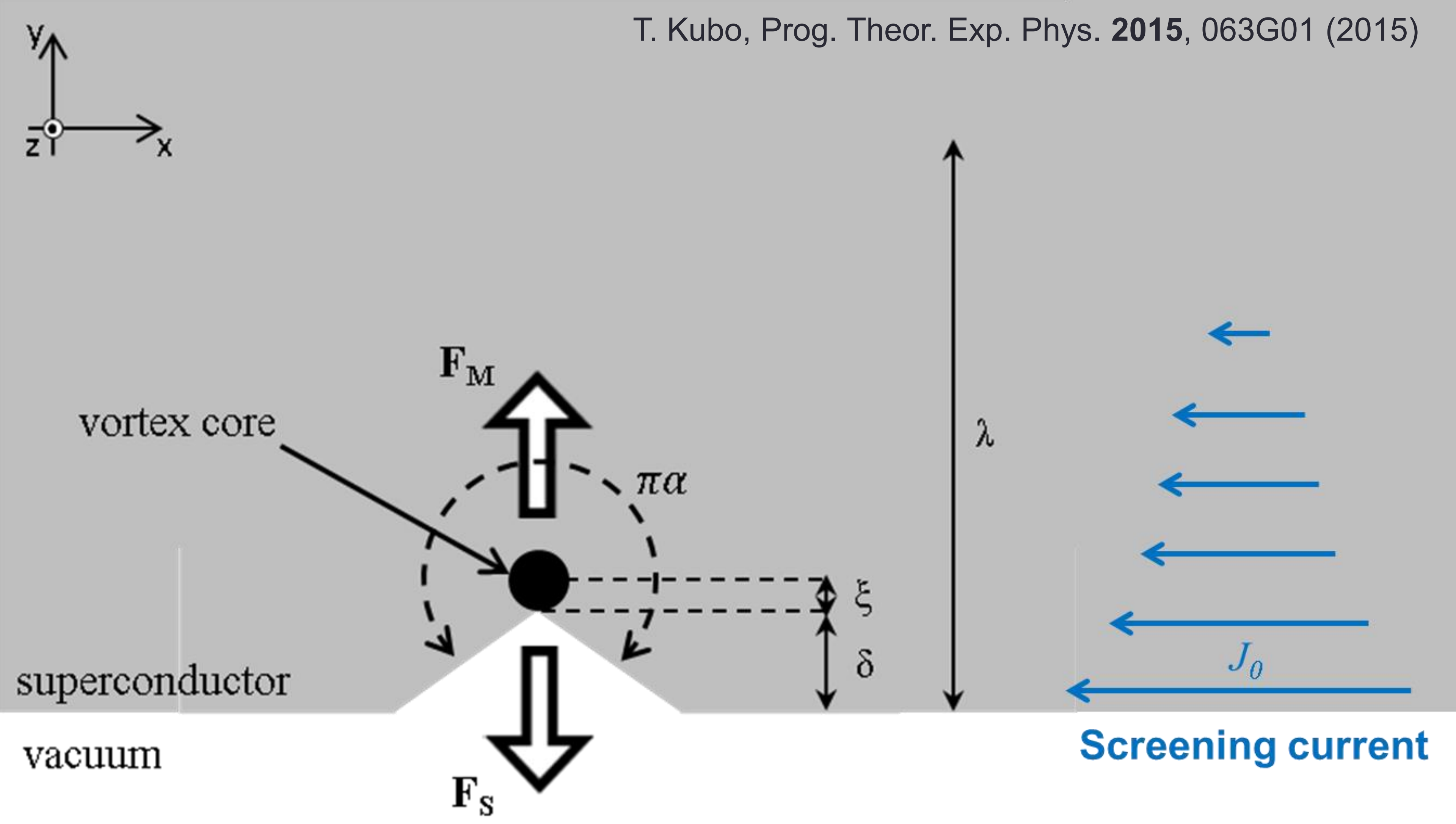
d_I should be thin.
Up to several tens of nm acceptable.

assumption
S layer: **Dirty Nb**
$B_c^{(Nb)}$=200mT
$\lambda_1=\lambda^{(dirtyNb)}$=180nm
SC substrate: clean **Nb**
$B_{max}^{(Nb)}$=**240mT**
$\lambda_2=\lambda^{(Nb)}$=40nm

§ 2
A further step forward

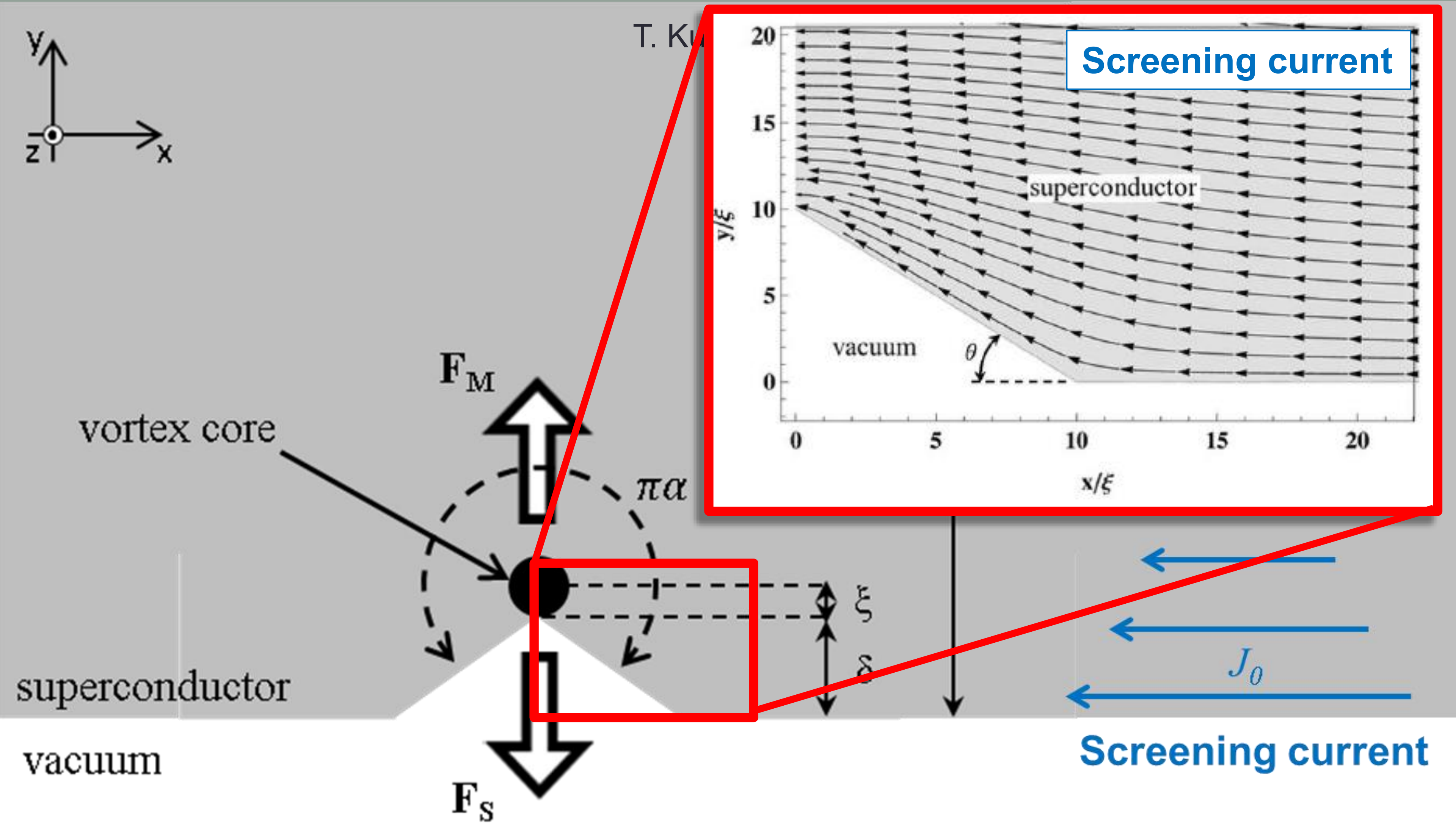
incorporate non-ideal surfaces

T. Kubo, Prog. Theor. Exp. Phys. **2015**, 063G01 (2015)



We assume $\xi < \delta < \lambda$.

Such small defects almost continuously distribute on the surface.



We assume $\xi < \delta < \lambda$.

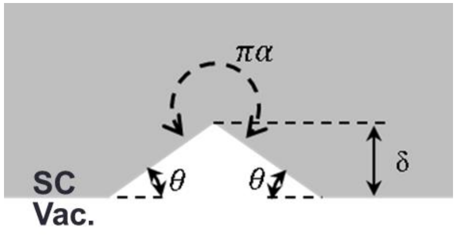
Such small defects almost continuously distribute on the surface.

The superheating field is suppressed due to the enhanced screening current.

$$\widetilde{B}_s = \eta\, B_s$$

Suppression factor

$$\eta = \frac{1}{\alpha}\left(\frac{\Gamma\left(\frac{\alpha}{2}\right)\Gamma\left(\frac{3-\alpha}{2}\right)\alpha \sin\frac{\pi(\alpha-1)}{2}}{\sqrt{\pi}}\frac{\xi}{\delta}\right)^{\frac{\alpha-1}{\alpha}}$$

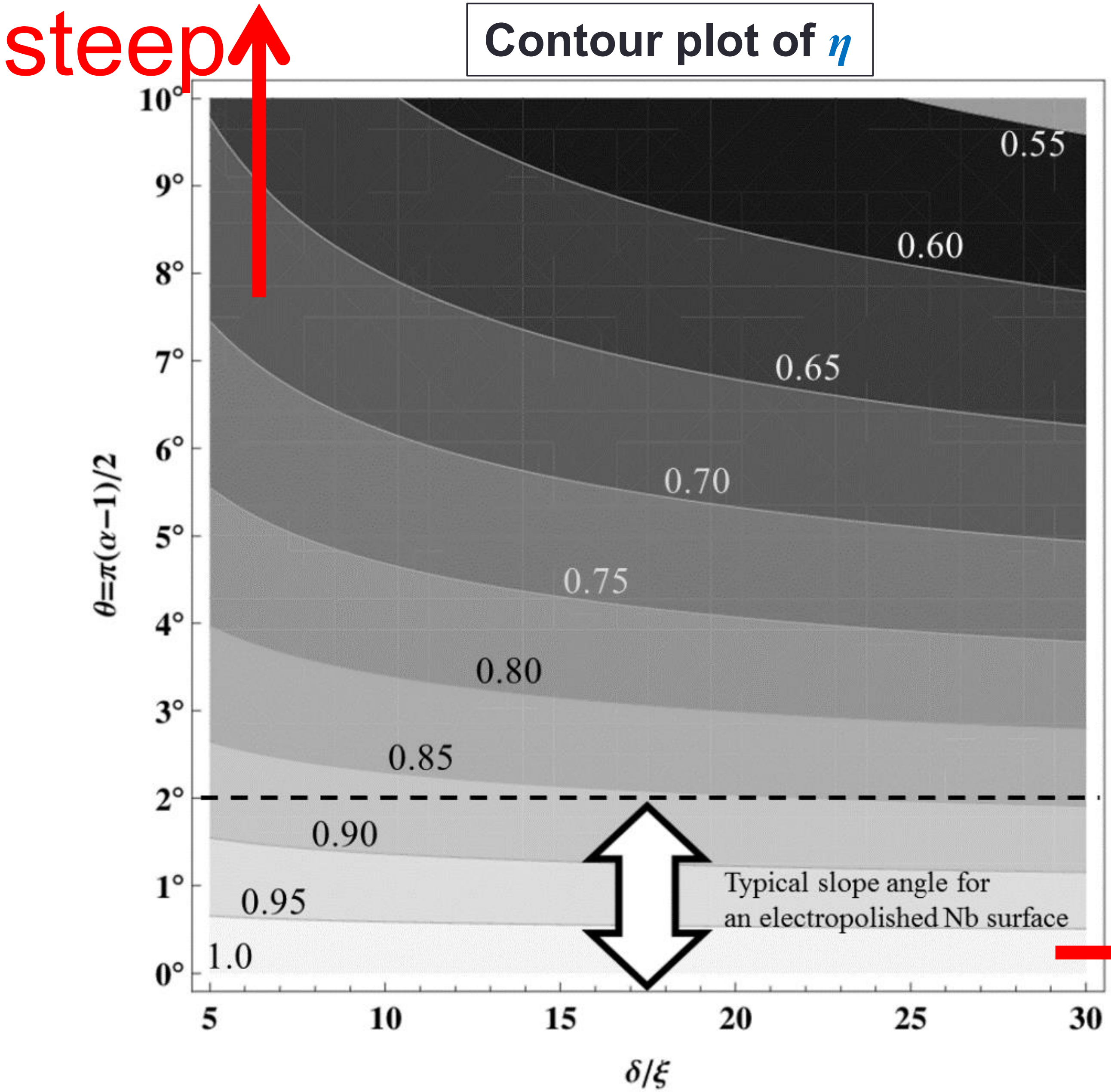


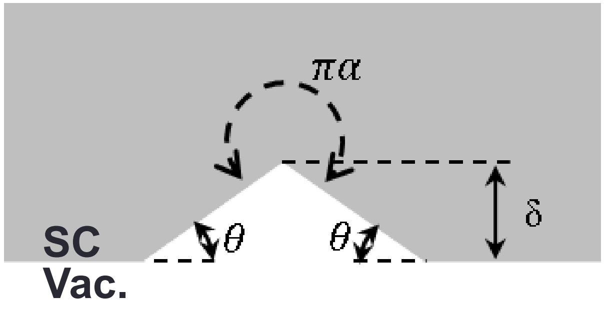
T. Kubo, Prog. Theor. Exp. Phys. **2015**, 063G01 (2015)

We can evaluate a **"suppression factor η"** for materials, if we have **data of surface topographic studies**

(see for example "C. Xu et al. Phys. Rev. ST Accel. Beams **14**, 123501 (2011)").

Contour plot of η





T. Kubo, Prog. Theor. Exp. Phys. **2015**, 063G01 (2015)

The formula for the maximum screening field of the multilayer

$$B_{\rm max}^{\rm (multilayer)} = \begin{cases} B_{max}^{\rm (S\ layer)} & \left(\text{if} \quad \gamma B_{max}^{\rm (S\ layer)} < B_{max}^{\rm (substrate)}\right) \\ \gamma^{-1} \times B_{max}^{\rm (substrate)} & \left(\text{if} \quad \gamma B_{max}^{\rm (S\ layer)} \geq B_{max}^{\rm (substrate)}\right) \end{cases}$$

where

$$\begin{cases} B_{max}^{\rm (S\ layer)} = B_s^{\rm (S\ layer)} \dfrac{cosh\dfrac{d_S}{\lambda_1} + \left(\dfrac{\lambda_2}{\lambda_1} + \dfrac{d_I}{\lambda_1}\right) sinh\dfrac{d_S}{\lambda_1}}{sinh\dfrac{d_S}{\lambda_1} + \left(\dfrac{\lambda_2}{\lambda_1} + \dfrac{d_I}{\lambda_1}\right) cosh\dfrac{d_S}{\lambda_1}} \times \boldsymbol{\eta} \\ \gamma = \dfrac{1}{\cosh\dfrac{d_S}{\lambda_1} + \left(\dfrac{\lambda_2}{\lambda_1} + \dfrac{d_I}{\lambda_1}\right)\sinh\dfrac{d_S}{\lambda_1}} \\ B_{max}^{\rm (substrate)} = 170{\rm mT} - 240{\rm mT} \end{cases}$$

$$B_s^{\rm (S\ layer)} = 0.84\, B_c^{\rm (S\ layer)}$$

η can be estimated by

$$\boldsymbol{\eta} = \frac{\mathbf{1}}{\boldsymbol{\alpha}}\left(\frac{\Gamma\left(\frac{\alpha}{2}\right)\Gamma\left(\frac{3-\alpha}{2}\right)\alpha \sin\frac{\pi(\alpha-1)}{2}}{\sqrt{\pi}}\frac{\xi}{\delta}\right)^{\frac{\alpha-1}{\alpha}}$$

T. Kubo (2015),
Obtained by using T. Kubo et al., Appl. Phys. Lett. **104**, 032603 (2014), **A. Gurevich,** AIP Advances **5**, 017112 (2015), and **T. Kubo**, Prog. Theor. Exp. Phys. **2015**, 063G01 (2015)

The formula for the optimum thickness of the S layer

$$d_S = \lambda_1 \ln\left[\frac{\lambda_1}{\lambda_1+\lambda_2+d_I}\frac{\eta B_s^{(\text{S layer})}}{B_{max}^{(\text{substrate})}} + \sqrt{\left(\frac{\lambda_1}{\lambda_1+\lambda_2+d_I}\frac{\eta B_s^{(\text{S layer})}}{B_{max}^{(\text{substrate})}}\right)^2 + \frac{\lambda_1-\lambda_2-d_I}{\lambda_1+\lambda_2+d_I}}\,\right]_{d_I \lesssim O(10)\text{nm}}$$

where

$$B_s^{(\text{S layer})} = 0.84\, B_c^{(\text{S layer})}$$

$$B_{max}^{(\text{substrate})} = 170\text{mT} - 240\text{mT}$$ (if the substrate is Nb)

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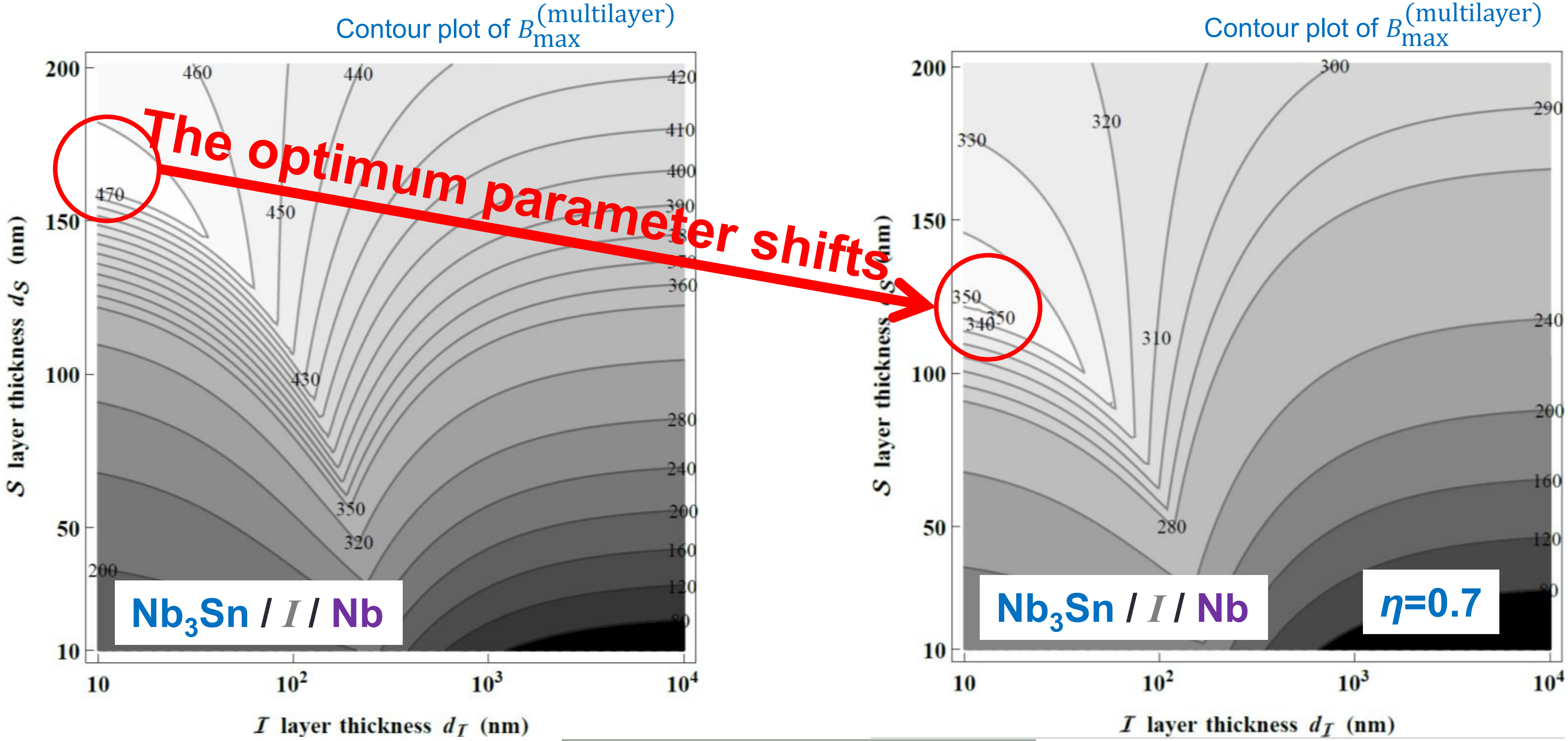
The optimum thickness becomes thin in order to compensate **the suppressed superheating field.**



Optimum d_s∼170nm
Maximum field∼470mT

Optimum d_s∼130nm
Maximum field∼350mT

assumption
S layer: **Nb_3Sn (moderately dirty)**
$B_c^{(Nb3Sn)}$=540mT
$\lambda_1=\lambda^{(Nb3Sn)}$=120nm
SC substrate: clean **Nb**
$B_{max}^{(Nb)} = B_{c1}^{(Nb)}$=170mT
$\lambda_2=\lambda^{(Nb)}$=40nm

Summary

The optimum *S* layer thickness is a function of

- λ_1 , penetration depth of the S layer
- λ_2 ($\lambda_1 > \lambda_2$), penetration depth of the substrate
- d_I (< several tens of nm), thickness of the insulator
- $B_c^{(\text{S layer})}$, thermodynamic critical field of the S layer
- $B_{max}^{(\text{substrate})}$ (170-240mT for Nb).
- η (0< η <1), superheating field suppression factor

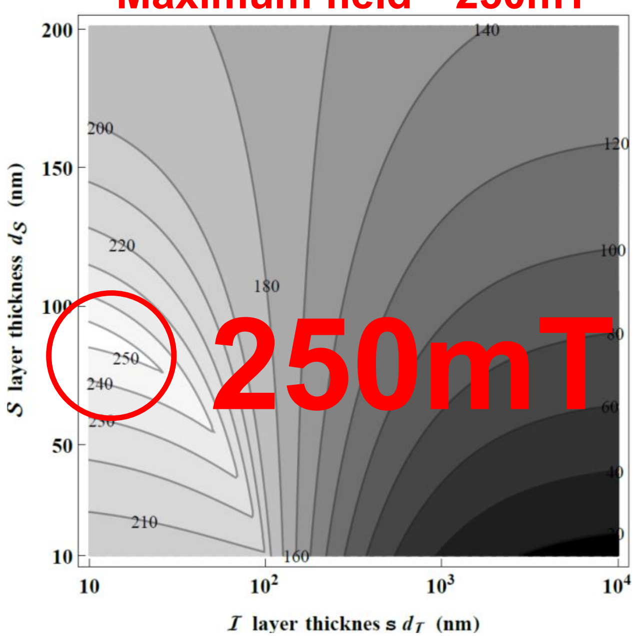
Material parameters and surface topographic studies are necessary in order to obtain the optimum *S* layer thickness.

The defect model and the formula for η may be useful to extract η from surface topographic studies.

Let us go beyond Nb by using the optimum parameters!

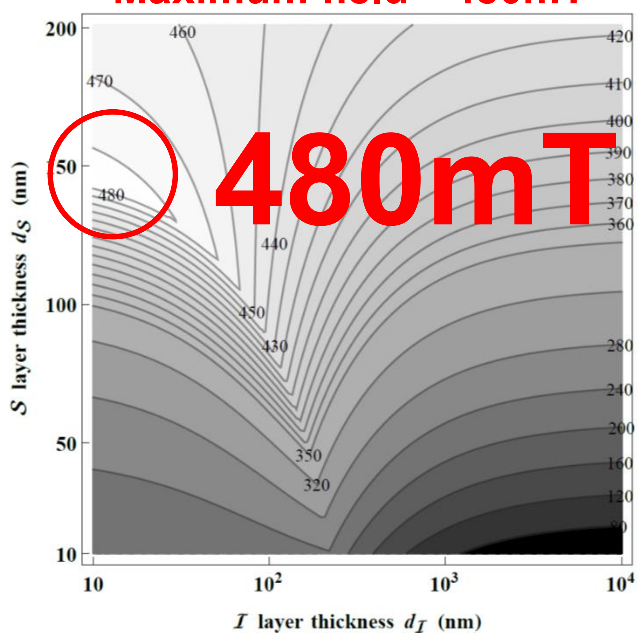
Dirty Nb / *I* / Nb

Optimum d_s~90nm
Maximum field~250mT



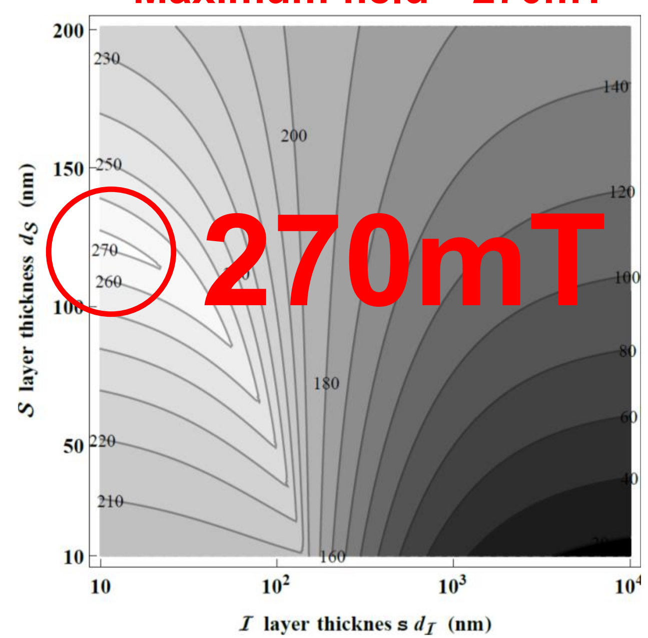
Nb_3Sn / *I* / Nb

Optimum d_s~150nm
Maximum field~480mT



NbN / *I* / Nb

Optimum d_s~130nm
Maximum field~270mT



Appendix for multilayer researchers

The optimum parameters for

Dirty Nb / *I* / Nb

Nb_3Sn / *I* / Nb

NbN / *I* / Nb

are given below!

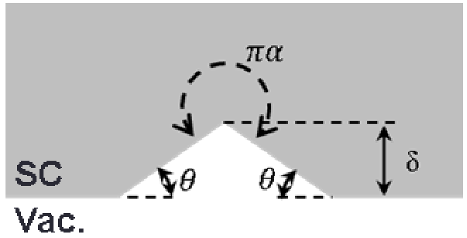
The formula for the maximum screening field

$$B_{\rm max}^{(\rm multilayer)} = \begin{cases} B_{max}^{(\rm S\ layer)} & (\text{if} \quad \gamma B_{max}^{(\rm S\ layer)} < B_{max}^{(\rm substrate)}) \\ \gamma^{-1} \times B_{max}^{(\rm substrate)} & (\text{if} \quad \gamma B_{max}^{(\rm S\ layer)} \geq B_{max}^{(\rm substrate)}) \end{cases}$$

where

$$\begin{cases} B_{max}^{(\rm S\ layer)} = B_s^{(\rm S\ layer)} \dfrac{cosh\frac{d_S}{\lambda_1} + \left(\frac{\lambda_2}{\lambda_1} + \frac{d_I}{\lambda_1}\right) sinh\frac{d_S}{\lambda_1}}{sinh\frac{d_S}{\lambda_1} + \left(\frac{\lambda_2}{\lambda_1} + \frac{d_I}{\lambda_1}\right) cosh\frac{d_S}{\lambda_1}} \times \boldsymbol{\eta} \\ \gamma = \dfrac{1}{\cosh\frac{d_S}{\lambda_1} + \left(\frac{\lambda_2}{\lambda_1} + \frac{d_I}{\lambda_1}\right)\sinh\frac{d_S}{\lambda_1}} \\ B_{max}^{(\rm substrate)} = 170\rm mT - 240\rm mT \end{cases}$$

$$\begin{cases} B_s^{(\rm S\ layer)} = 0.84\, B_c^{(\rm S\ layer)} \\ \boldsymbol{\eta} = \dfrac{\mathbf{1}}{\boldsymbol{\alpha}}\left(\dfrac{\boldsymbol{\Gamma}\left(\frac{\boldsymbol{\alpha}}{\mathbf{2}}\right)\boldsymbol{\Gamma}\left(\frac{\mathbf{3}-\boldsymbol{\alpha}}{\mathbf{2}}\right)\boldsymbol{\alpha}\,\mathbf{sin}\frac{\boldsymbol{\pi}(\boldsymbol{\alpha}-\mathbf{1})}{\mathbf{2}}}{\sqrt{\boldsymbol{\pi}}}\dfrac{\boldsymbol{\xi}}{\boldsymbol{\delta}}\right)^{\frac{\boldsymbol{\alpha}-\mathbf{1}}{\boldsymbol{\alpha}}} \end{cases}$$



The formula for the optimum thickness of the S layer

$$d_S = \lambda_1 \ln \left[\frac{\lambda_1}{\lambda_1 + \lambda_2 + d_I} \frac{\eta B_s^{(\text{S layer})}}{B_{max}^{(\text{substrate})}} + \sqrt{\left(\frac{\lambda_1}{\lambda_1 + \lambda_2 + d_I} \frac{\eta B_s^{(\text{S layer})}}{B_{max}^{(\text{substrate})}} \right)^2 + \frac{\lambda_1 - \lambda_2 - d_I}{\lambda_1 + \lambda_2 + d_I}} \right]_{d_I \lesssim \mathcal{O}(10)\text{nm}}$$

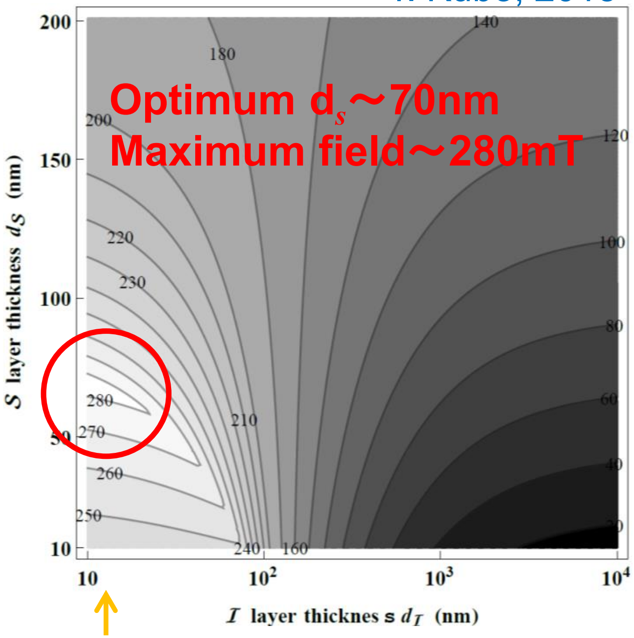
Necessary parameters

S layer:	$B_s^{(\text{S layer})} = 0.84 \times B_c^{(\text{S layer material})}$
	$\lambda_1 = \lambda^{(\text{S layer material})}$
	η (suppression factor)
I layer:	$d_I \sim$ 10-100nm
Substrate:	$B_{max}^{(\text{substrate})}$=170mT - 240mT (if the substrate is Nb)
	$\lambda_2 = \lambda^{(\text{substrate})}$=40nm (if the substrate is Nb)

$$\eta = 1$$

The optimum d_s and the maximum field for Dirty Nb / *I* / Nb system, where Nb substrate is assumed to withstand up to 240, 200, and 170mT.

T. Kubo, 2015



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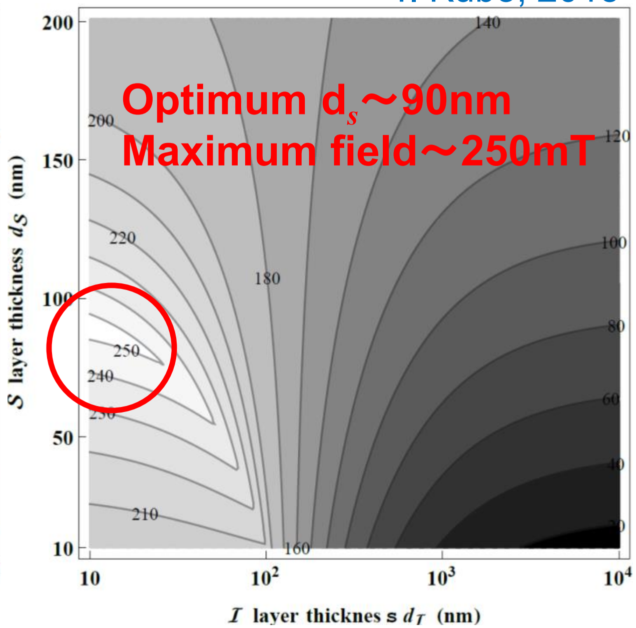

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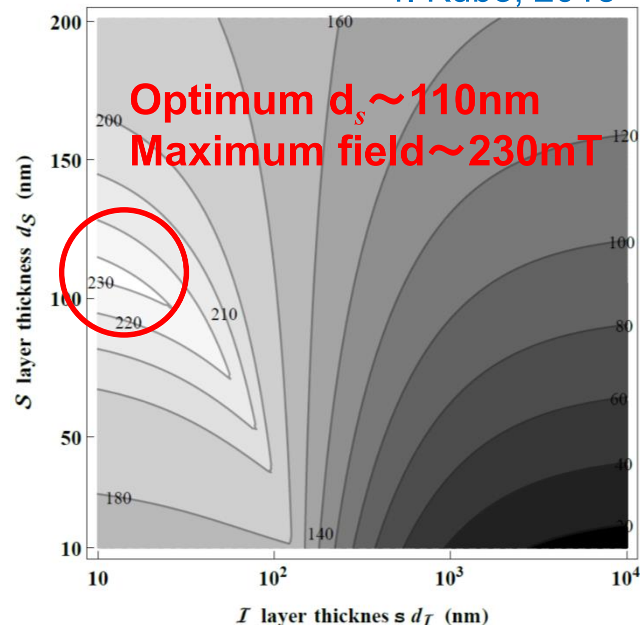


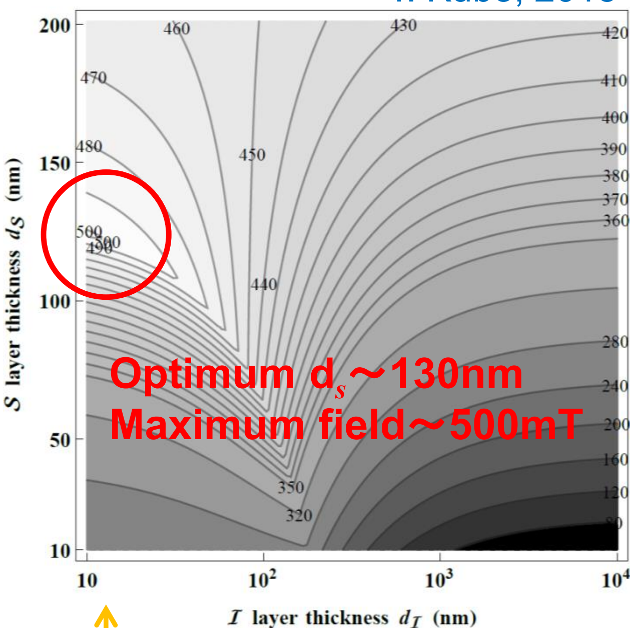
↑ Consistent with the Gurevich's recent result

A. Gurevich, AIP Advances **5**, 017112 (2015) and 6th thin film workshop at Italy

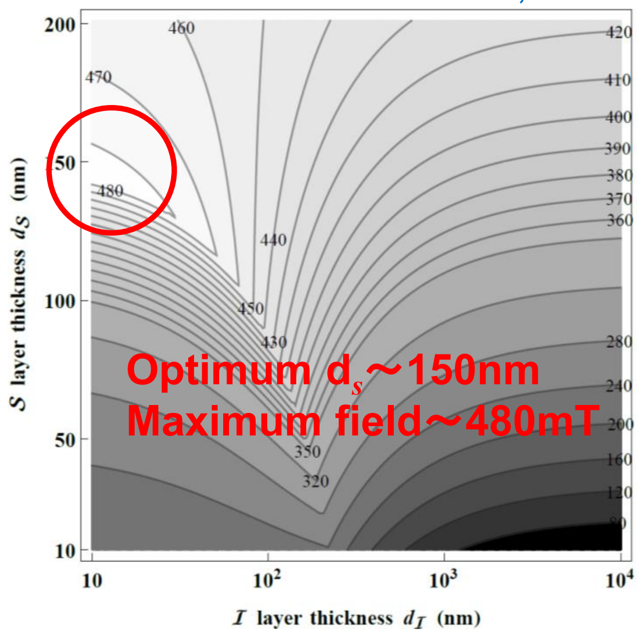
assumption	assumption	assumption
S layer: **Dirty Nb**	S layer: **Dirty Nb**	S layer: **Dirty Nb**
$B_c^{(Nb)}$=200mT	$B_c^{(Nb)}$=200mT	$B_c^{(Nb)}$=200mT
$\lambda_1=\lambda^{(dirtyNb)}$=180nm	$\lambda_1=\lambda^{(dirtyNb)}$=180nm	$\lambda_1=\lambda^{(dirtyNb)}$=180nm
SC substrate: clean **Nb**	SC substrate: clean **Nb**	SC substrate: clean **Nb**
$B_{max}^{(Nb)}$=**240mT**	$B_{max}^{(Nb)}$=**200mT**	$B_{max}^{(Nb)}$= $B_{c1}^{(Nb)}$=**170mT**
$\lambda_2=\lambda^{(Nb)}$=40nm	$\lambda_2=\lambda^{(Nb)}$=40nm	$\lambda_2=\lambda^{(Nb)}$=40nm

The optimum d_s and the maximum field for Nb_3Sn / *I* / Nb system, where Nb substrate is assumed to withstand up to 240, 200, and 170mT.

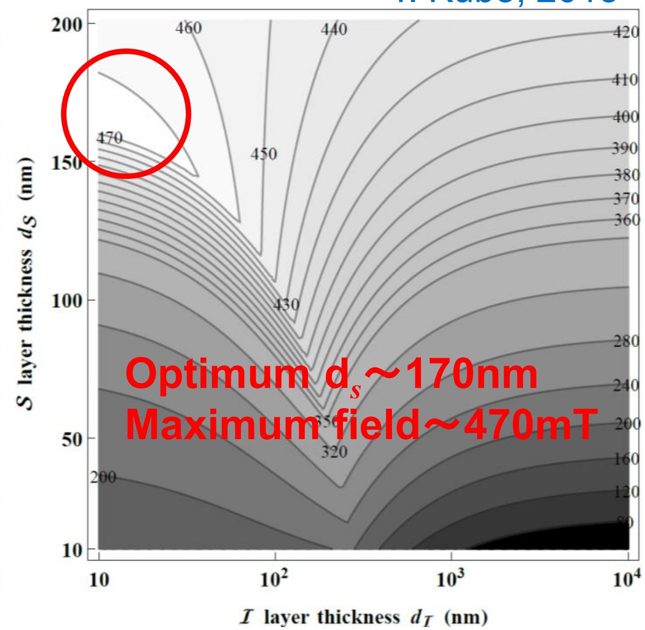
T. Kubo, 2015



T. Kubo, 2015



T. Kubo, 2015



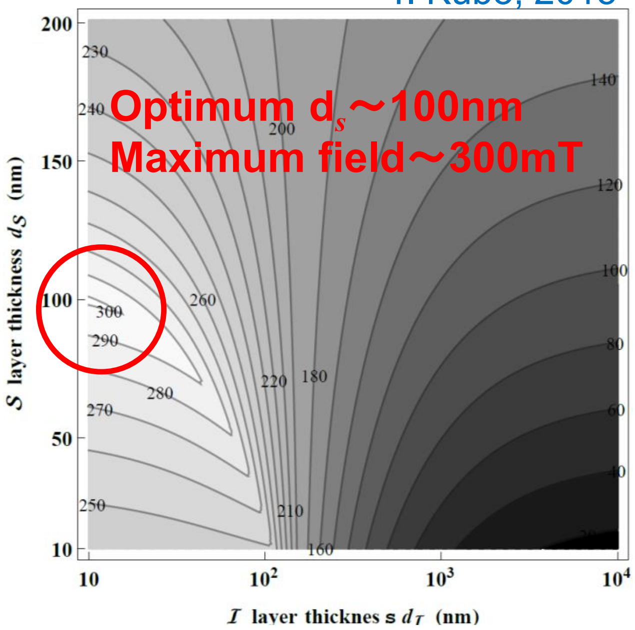
↑ **Consistent with the Gurevich's recent result**

A. Gurevich, AIP Advances **5**, 017112 (2015) and 6th thin film workshop at Italy

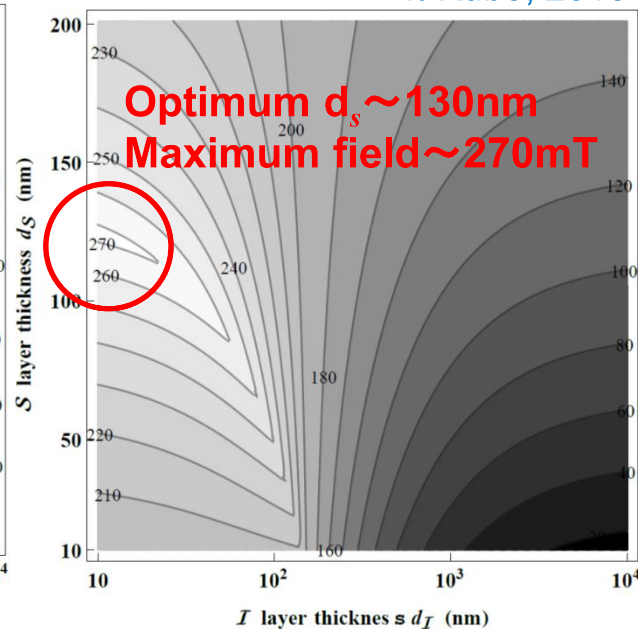
assumption	assumption	assumption
S layer: Nb_3Sn (moderately dirty) $B_c^{(Nb3Sn)}$=540mT $\lambda_1=\lambda^{(Nb3Sn)}$=120nm SC substrate: clean Nb $B_{max}^{(Nb)}$=**240mT** $\lambda_2=\lambda^{(Nb)}$=40nm	S layer: Nb_3Sn (moderately dirty) $B_c^{(Nb3Sn)}$=540mT $\lambda_1=\lambda^{(Nb3Sn)}$=120nm SC substrate: clean Nb $B_{max}^{(Nb)}$=**200mT** $\lambda_2=\lambda^{(Nb)}$=40nm	S layer: Nb_3Sn (moderately dirty) $B_c^{(Nb3Sn)}$=540mT $\lambda_1=\lambda^{(Nb3Sn)}$=120nm SC substrate: clean Nb $B_{max}^{(Nb)}$= $B_{c1}^{(Nb)}$=**170mT** $\lambda_2=\lambda^{(Nb)}$=40nm

The optimum d_s and the maximum field for NbN / *I* / Nb system, where Nb substrate is assumed to withstand up to 240, 200, and 170mT.

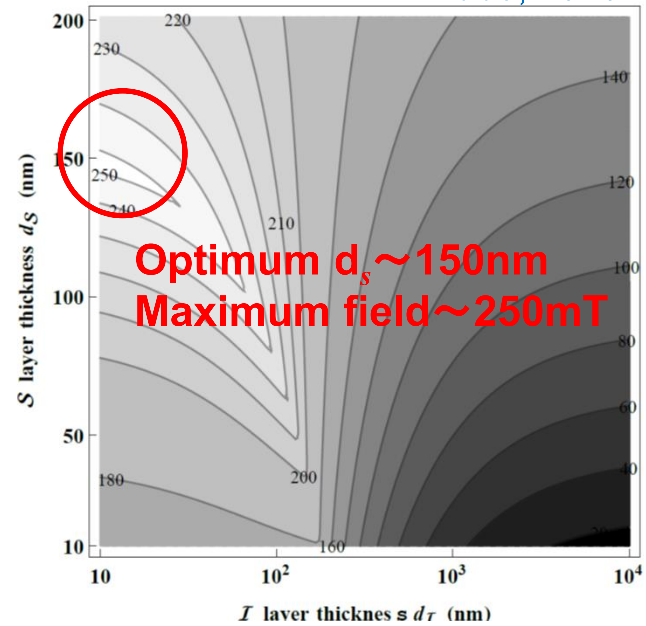
T. Kubo, 2015



T. Kubo, 2015



T. Kubo, 2015



<u>assumption</u>

S layer: **NbN**

$B_c^{(NbN)}$=230mT

$\lambda_1=\lambda^{(NbN)}$=200nm

SC substrate: clean **Nb**

$B_{max}^{(Nb)}$=**<u>240mT</u>**

$\lambda_2=\lambda^{(Nb)}$=40nm

<u>assumption</u>

S layer: **NbN**

$B_c^{(NbN)}$=230mT

$\lambda_1=\lambda^{(NbN)}$=200nm

SC substrate: clean **Nb**

$B_{max}^{(Nb)}$=**<u>200mT</u>**

$\lambda_2=\lambda^{(Nb)}$=40nm

<u>assumption</u>

S layer: **NbN**

$B_c^{(NbN)}$=230mT

$\lambda_1=\lambda^{(NbN)}$=200nm

SC substrate: clean **Nb**

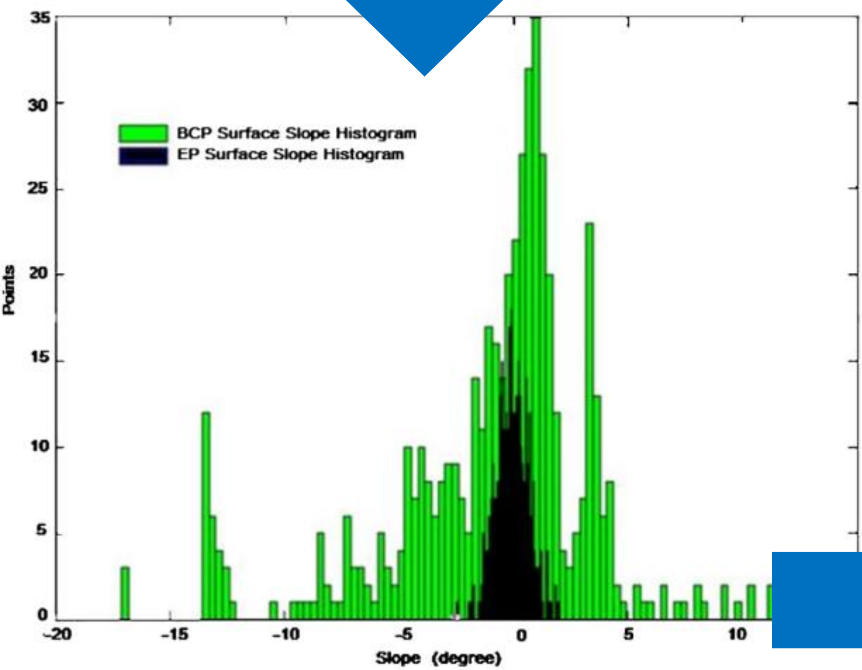
$B_{max}^{(Nb)}=B_{c1}^{(Nb)}$=**<u>170mT</u>**

$\lambda_2=\lambda^{(Nb)}$=40nm

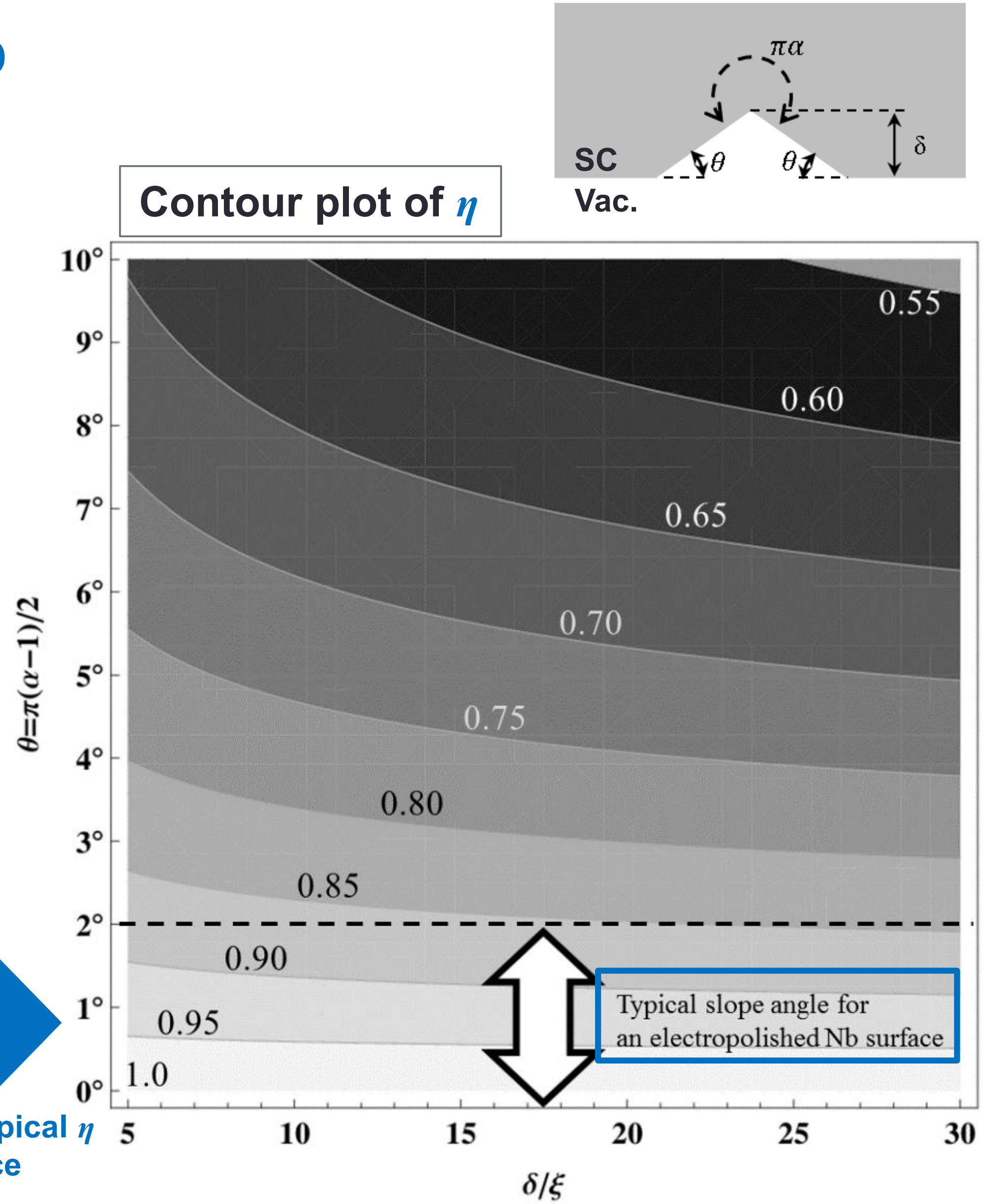
$$\eta < 1$$

Example: electropolished Nb

A surface after EP is studied by C.Xu, H.Tian, C.Reece, and M.Kelley, Phys. Rev. ST Accel. Beams **14**, 123501 (2011), which shows the figure below.



Contour plot of η

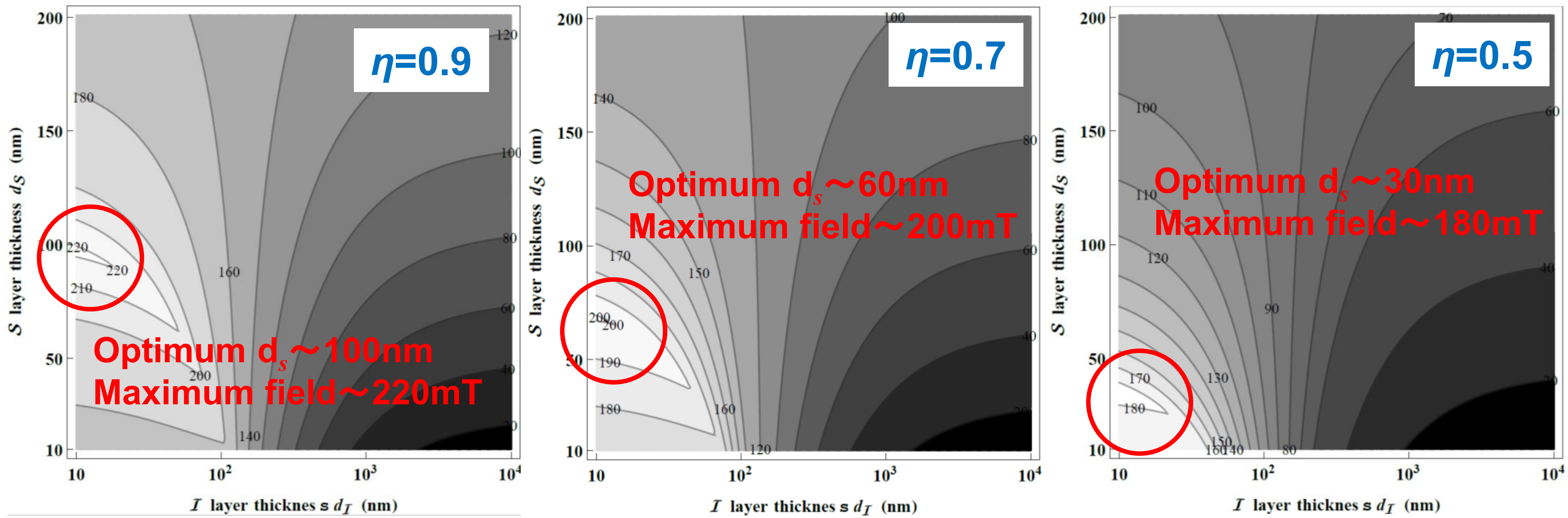


We can find typical η of EPed surface

T. Kubo, Prog. Theor. Exp. Phys. **2015**, 063G01 (2015)

Imperfect Dirty Nb / *I* / Nb

The optimum d_s and the maximum field for Dirty Nb / *I* / Nb system, when the suppression factor due to nano-defects are given by η=0.9, 0.7, and 0.5.
Nb substrate is assumed to withstand up to 170mT.



assumption

S layer: **Dirty Nb**

$B_c^{(Nb)}$=200mT

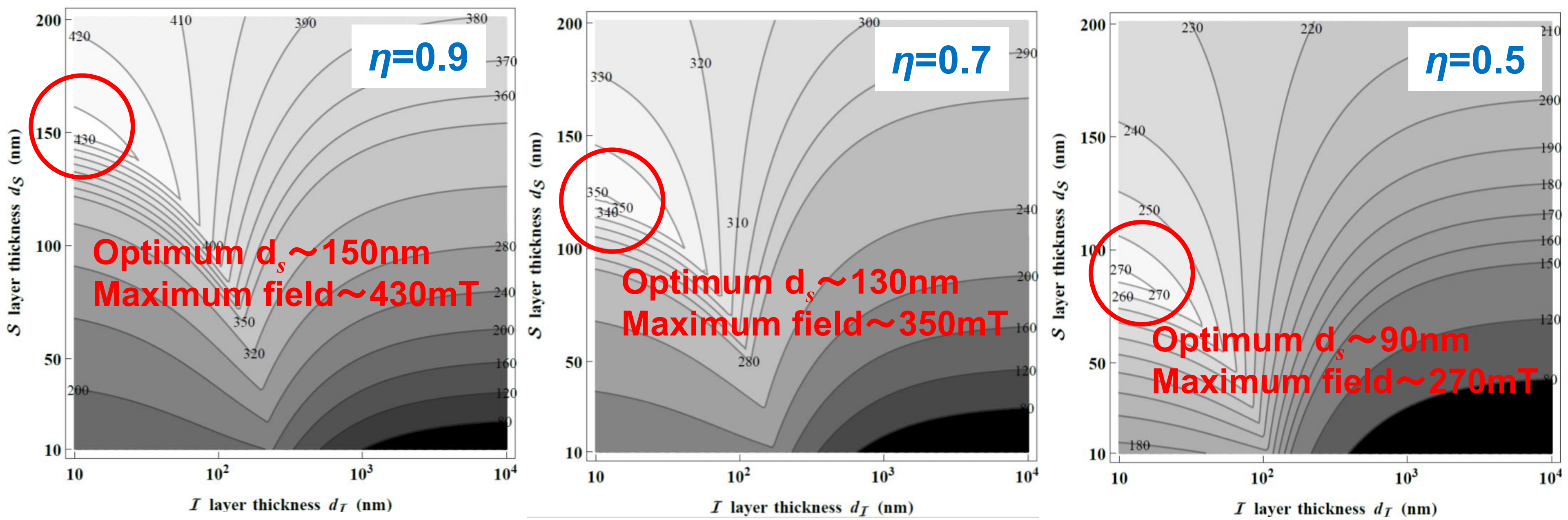
$\lambda_1=\lambda^{(dirtyNb)}$=180nm

SC substrate: clean **Nb**

$B_{max}^{(Nb)}= B_{c1}^{(Nb)}$=**170mT**

$\lambda_2=\lambda^{(Nb)}$=40nm

The optimum d_s and the maximum field for Nb_3Sn / *I* / Nb system, when the suppression factor due to nano-defects are given by η=0.9, 0.7, and 0.5.
Nb substrate is assumed to withstand up to 170mT.



<u>assumption</u>

S layer: **Nb_3Sn** **(moderately dirty)**

$B_c^{(Nb3Sn)}$=540mT

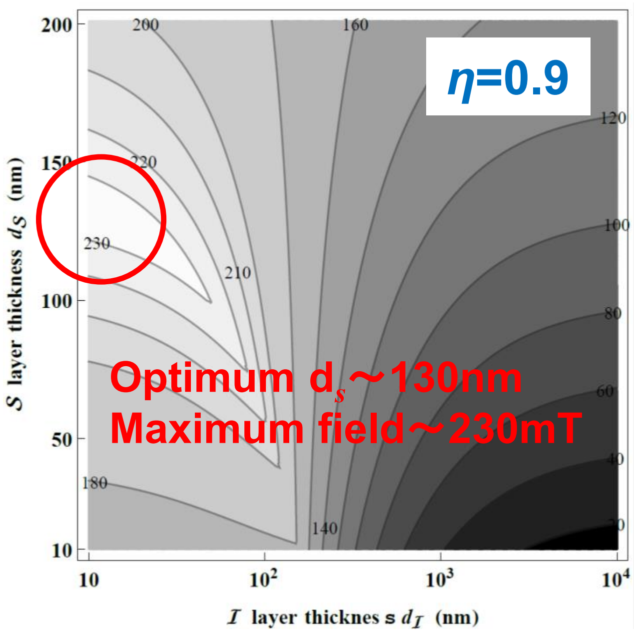
$\lambda_1=\lambda^{(Nb3Sn)}$=120nm

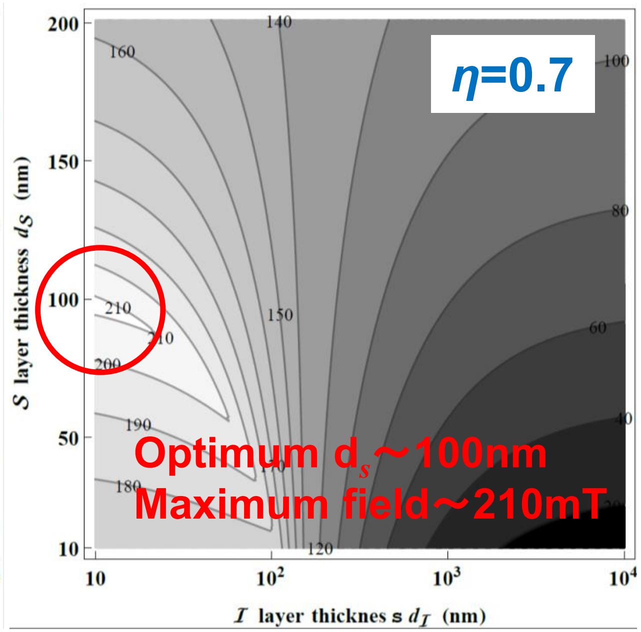
SC substrate: clean **Nb**

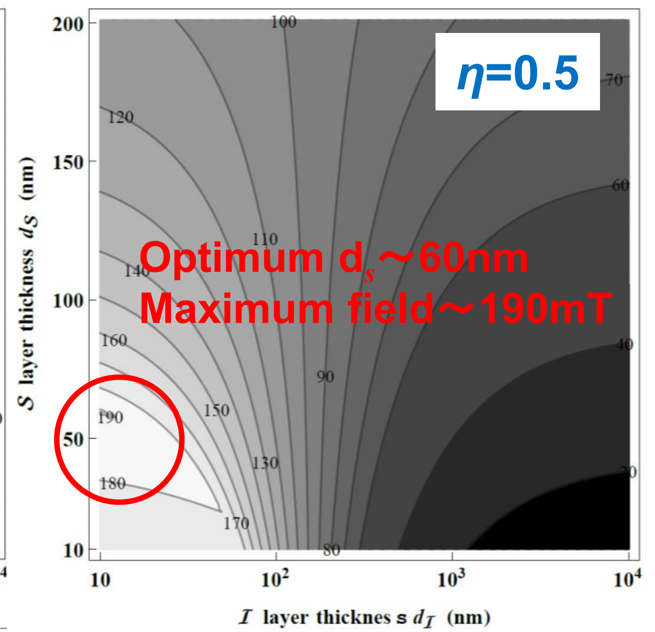
$B_{max}^{(Nb)}= B_{c1}^{(Nb)}$=<u>170mT</u>

$\lambda_2=\lambda^{(Nb)}$=40nm

The optimum d_s and the maximum field for NbN / *I* / Nb system, when the suppression factor due to nano-defects are given by η=0.9, 0.7, and 0.5. Nb substrate is assumed to withstand up to 170mT.







<u>assumption</u>

S layer: **NbN**

$B_c^{(NbN)}$=230mT

$\lambda_1=\lambda^{(NbN)}$=200nm

SC substrate: clean **Nb**

$B_{max}^{(Nb)}=B_{c1}^{(Nb)}$=<u>170mT</u>

$\lambda_2=\lambda^{(Nb)}$=40nm