超伝導空洞の物理
高Q値・高加速勾配空洞の実現に向けて

Physics of superconducting cavity: towards realizations of high-Q and high gradient cavities

KEK / 総研大

National University The Graduate University for Advanced Studies [SOKENDAI]

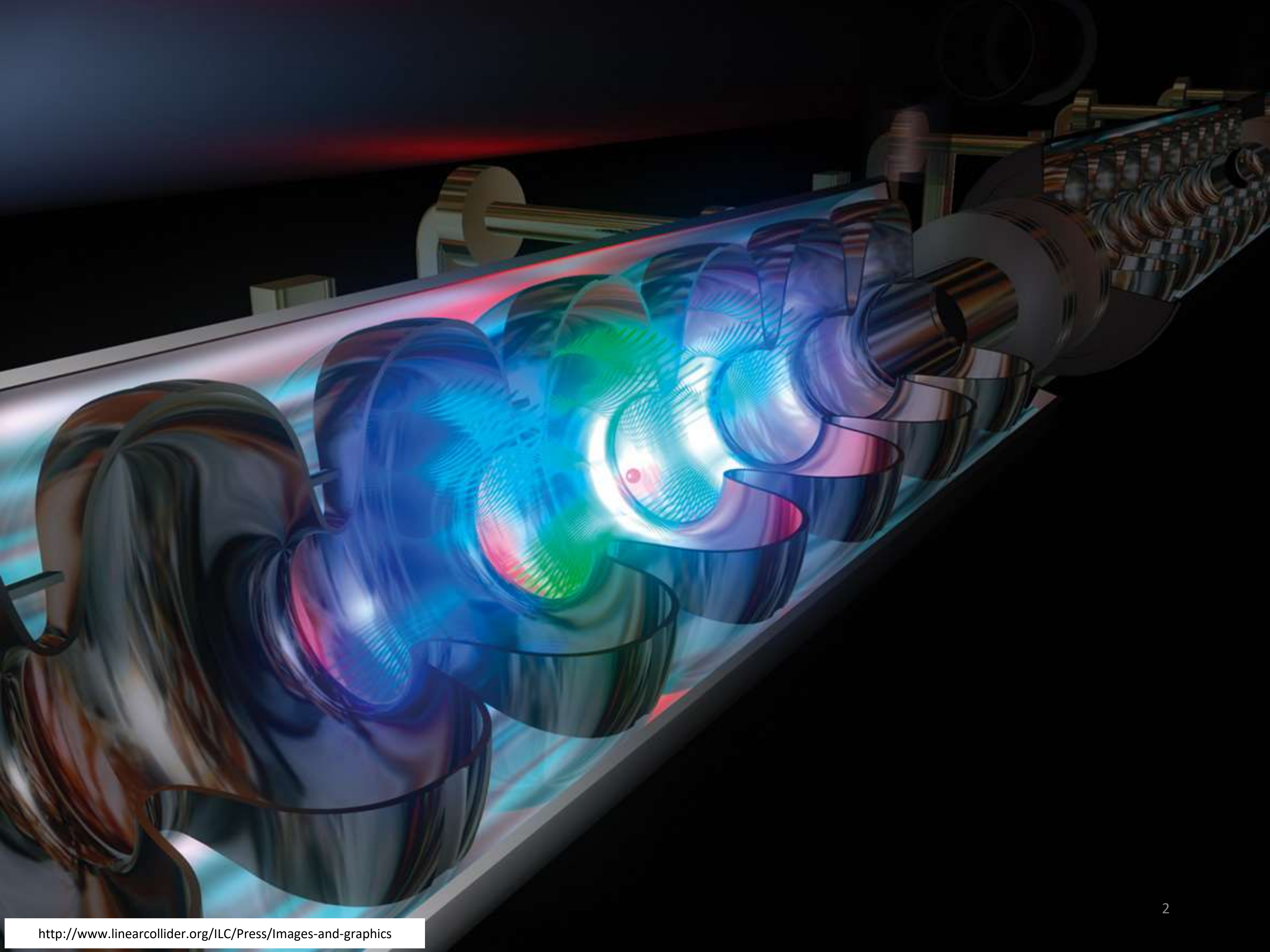
久保 毅幸

KUBO, Takayuki

科研費 KAKENHI #17H04839

第14回日本加速器学会年会（2017年8月1日）

Picture
http://www.linearcollider.org/ILC/Press/Images-and-graphics



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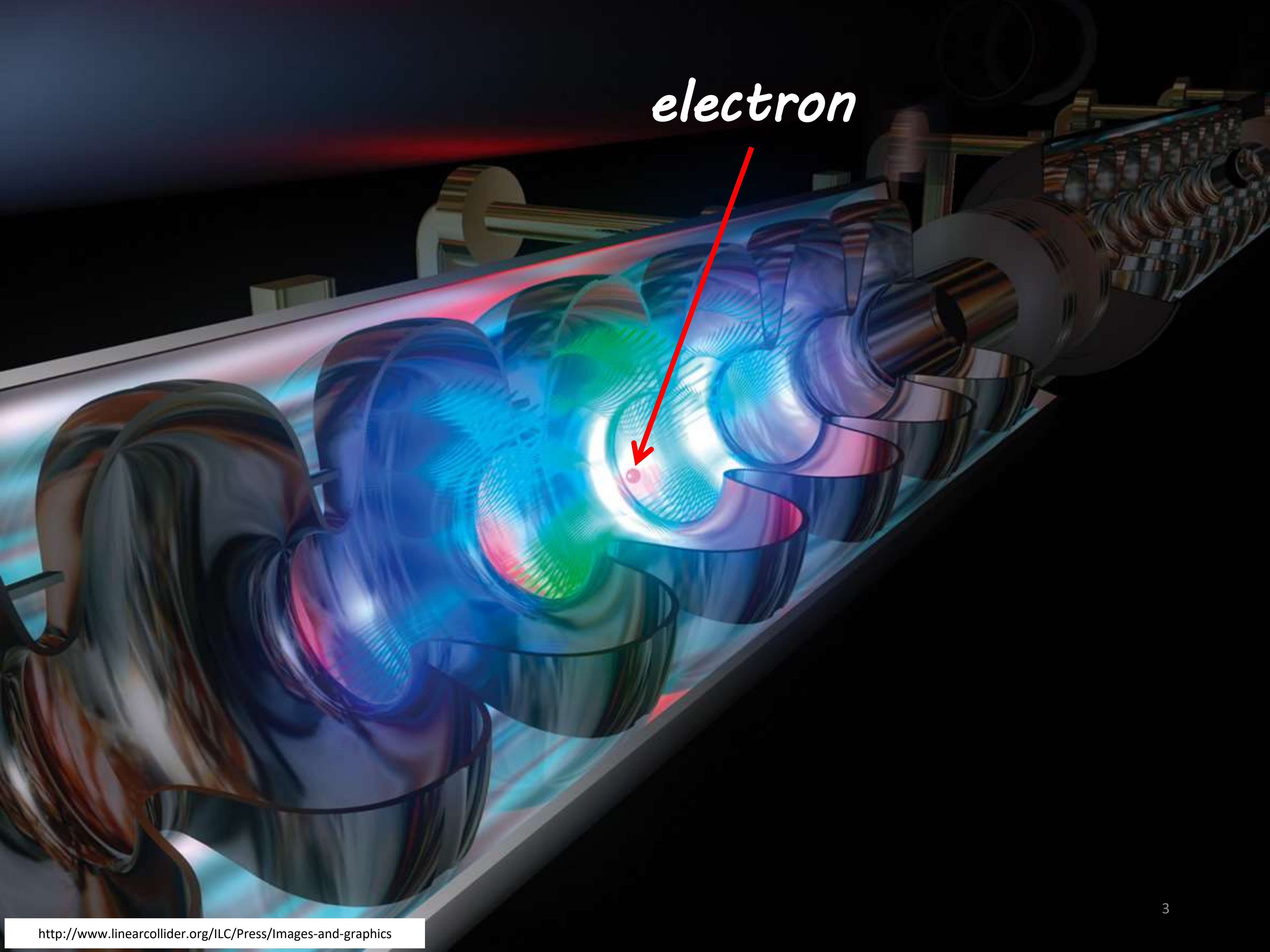

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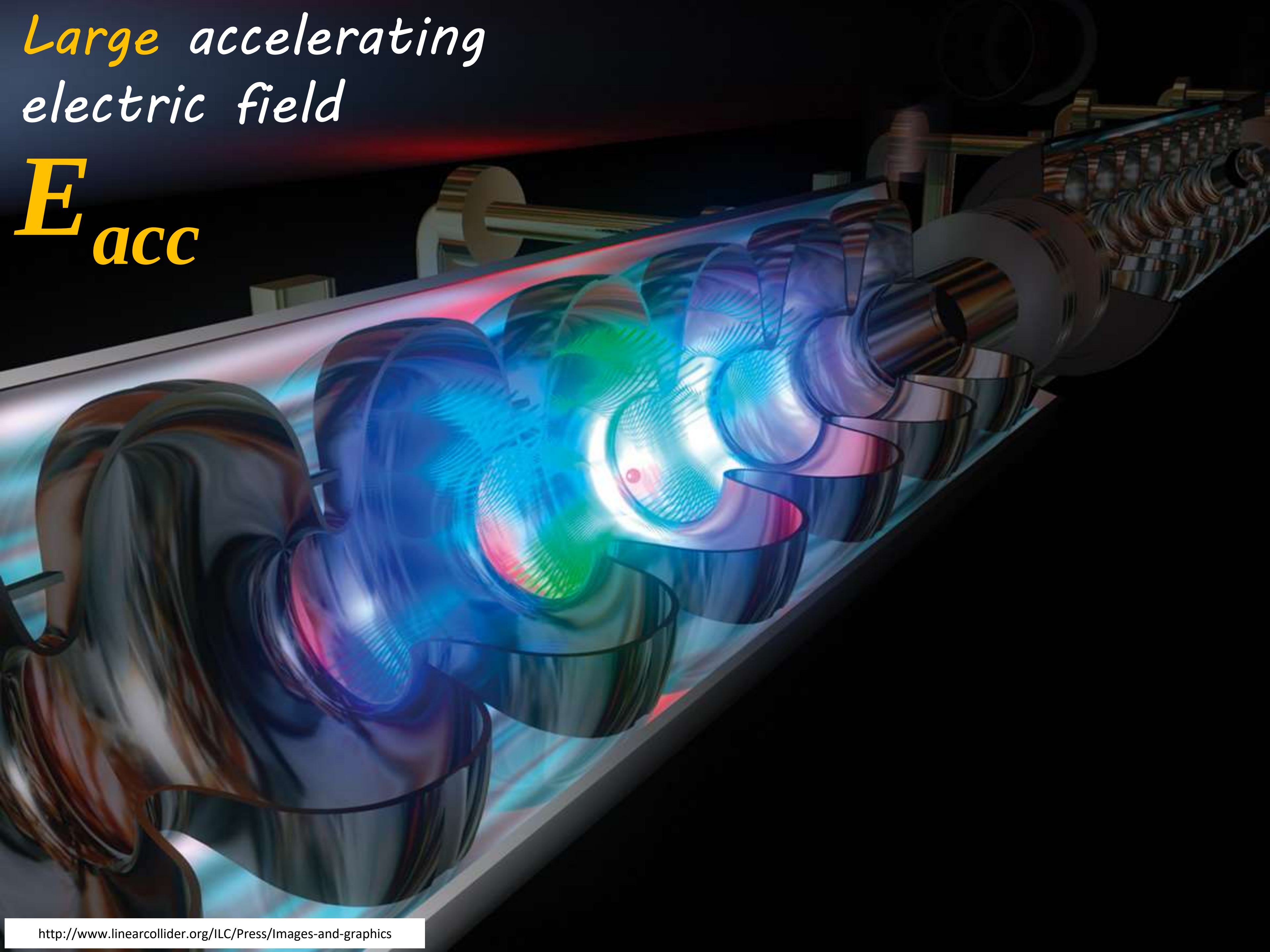

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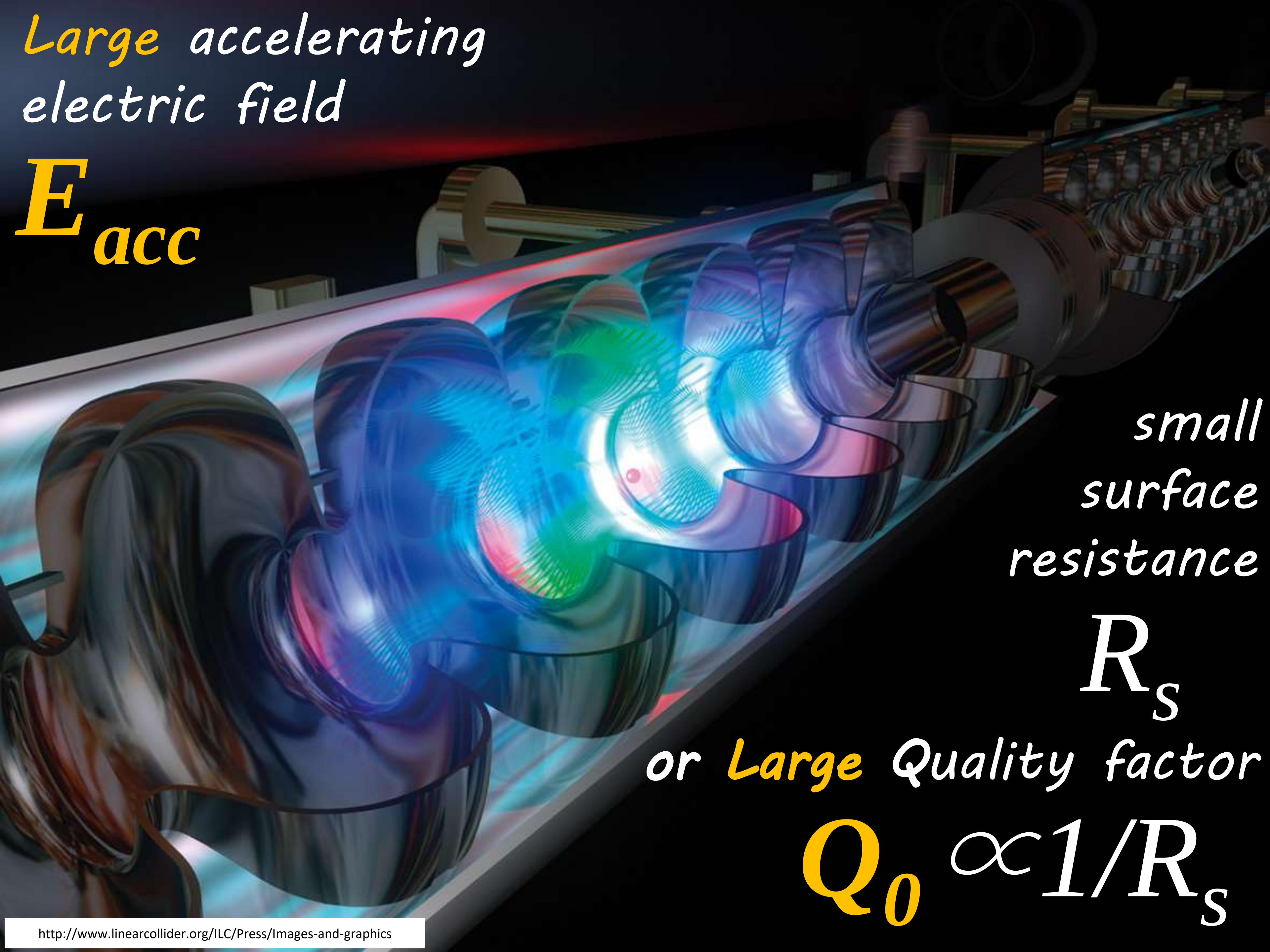
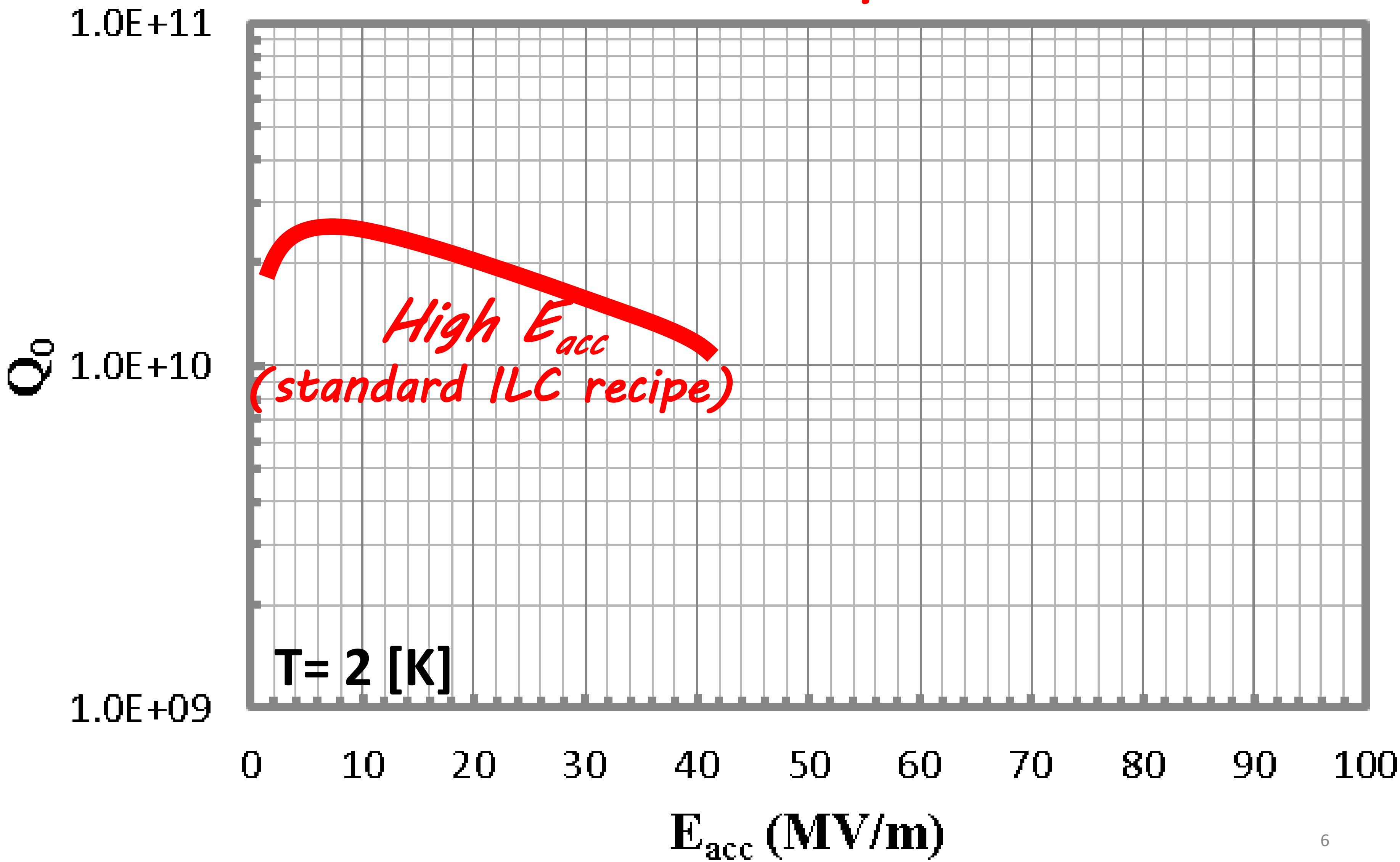


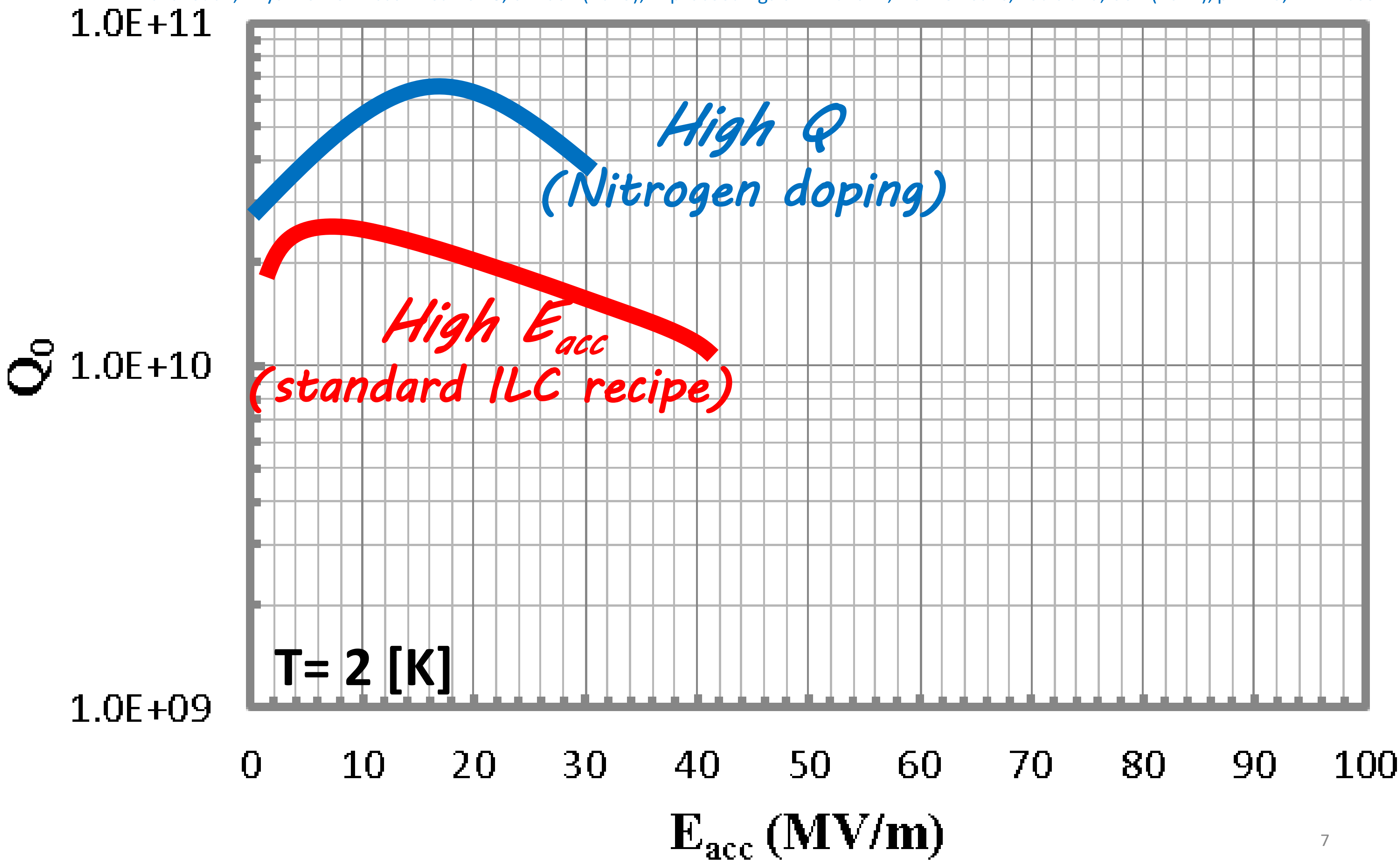
http://www.linearcollider.org/ILC/Press/Images-and-graphics

Nb cavity processed by the standard ILC recipe

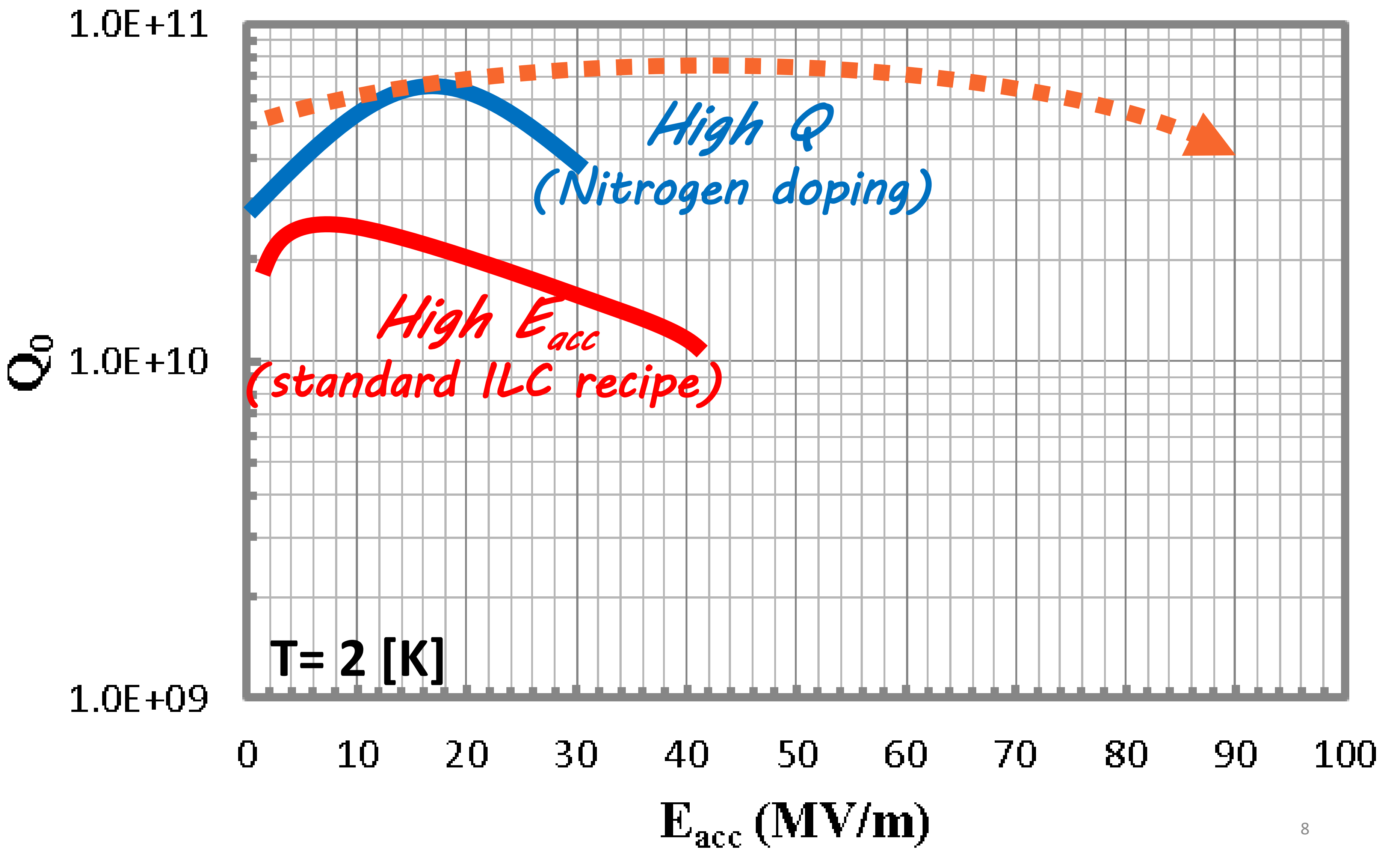


Nb cavity processed by the N or Ti doping recipe

A. Grassellino et al, Supercond. Sci. Technol. **26,** 102001 (2013)
P. Dhakal et al., Phys. Rev. ST Accel. Beams **16**, 042001 (2013); in proceedings of IPAC2012, New Orleans, Louisiana, USA (2012), p. 2426, WEPPC091



We want to go beyond the limits of the present technologies!



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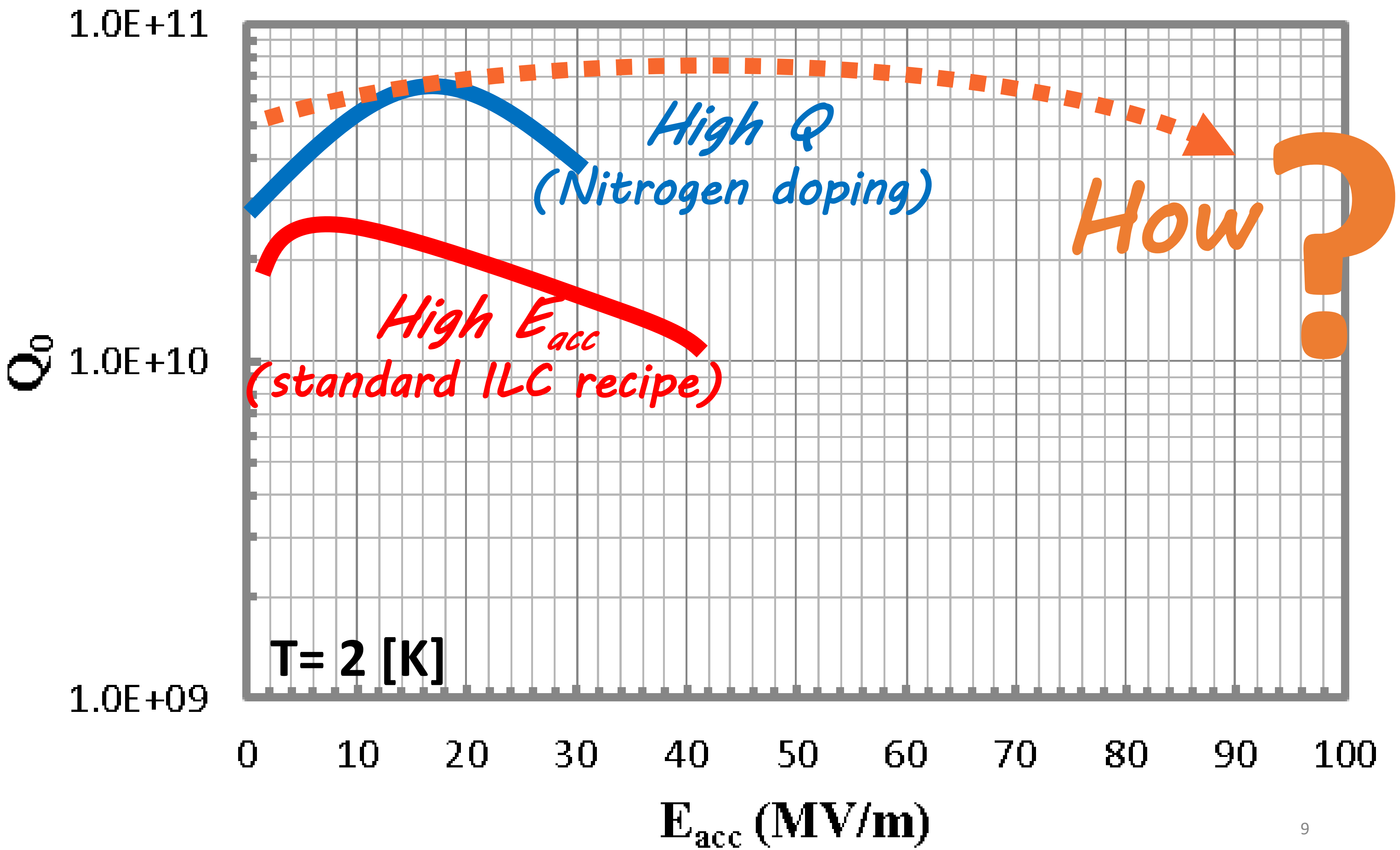
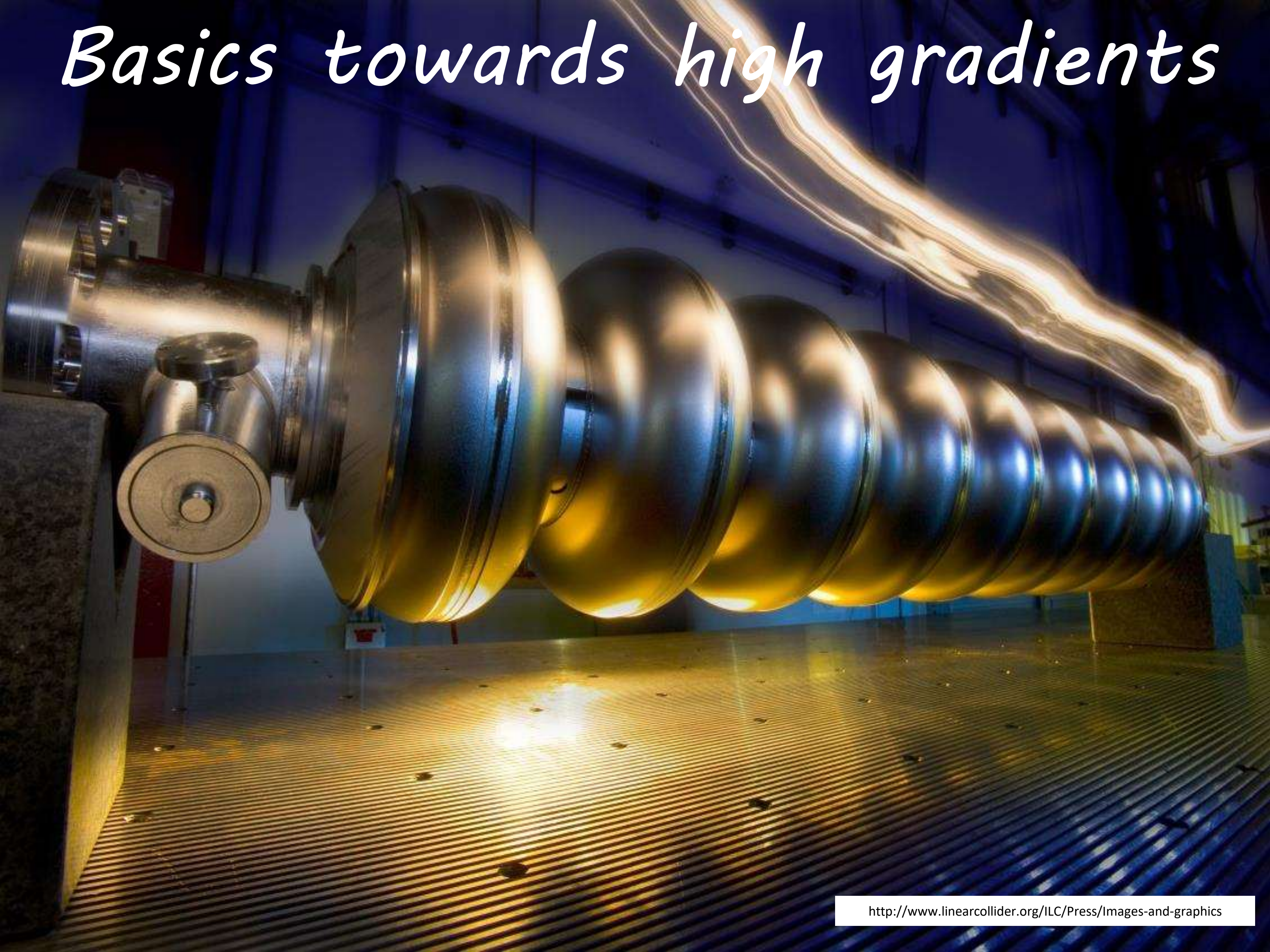


Basics towards high gradients



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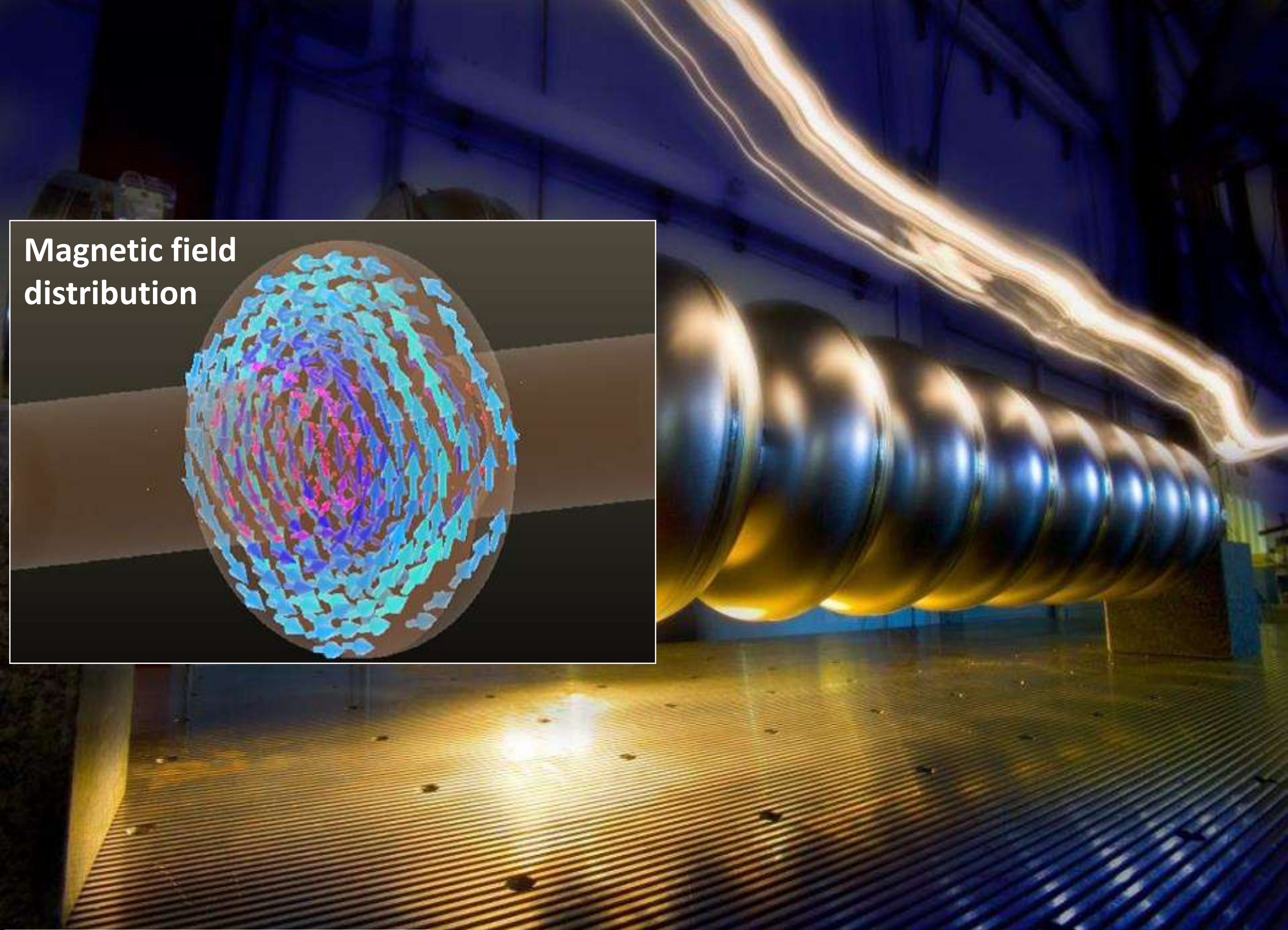

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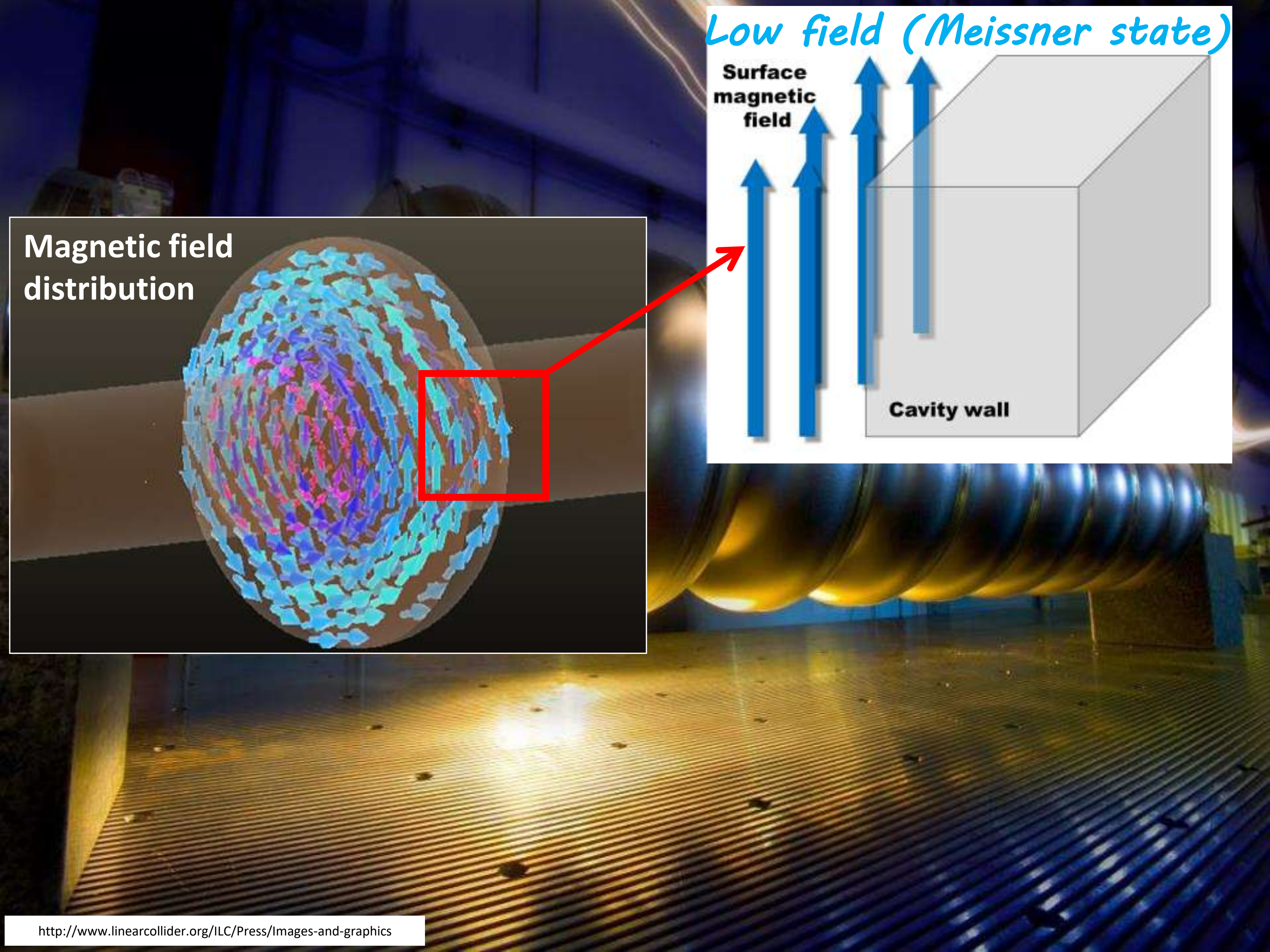
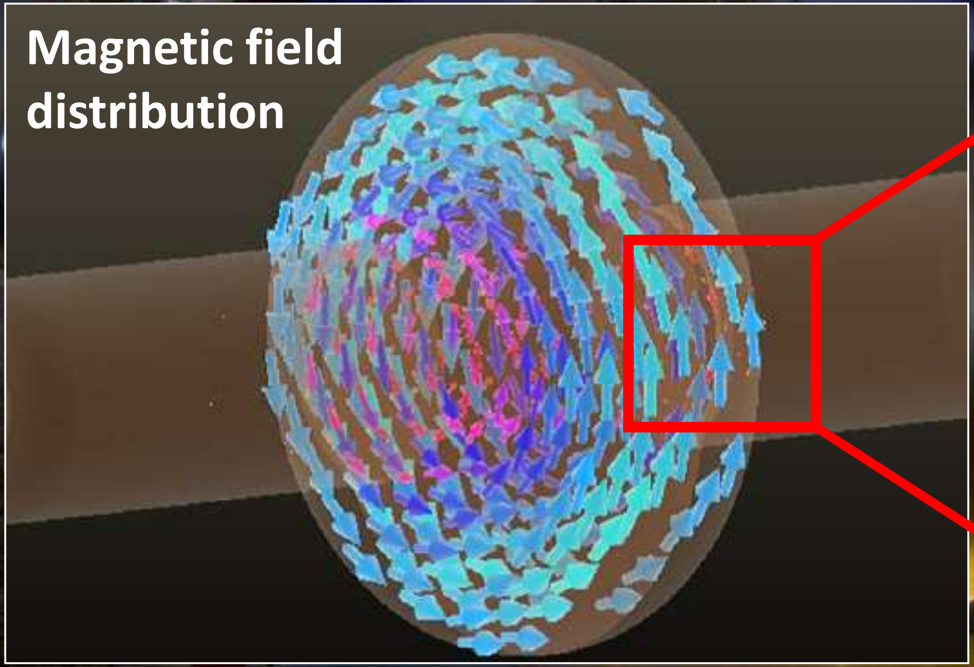
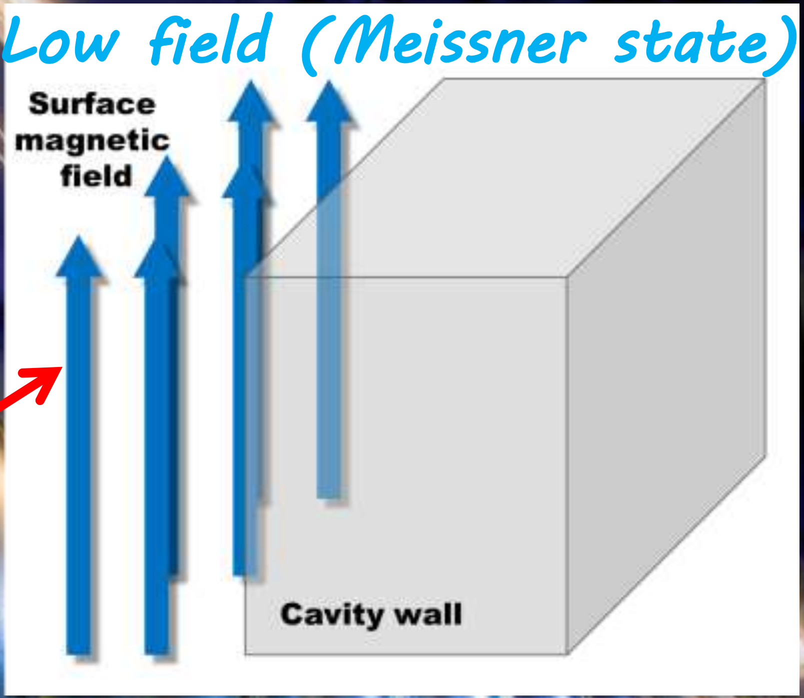
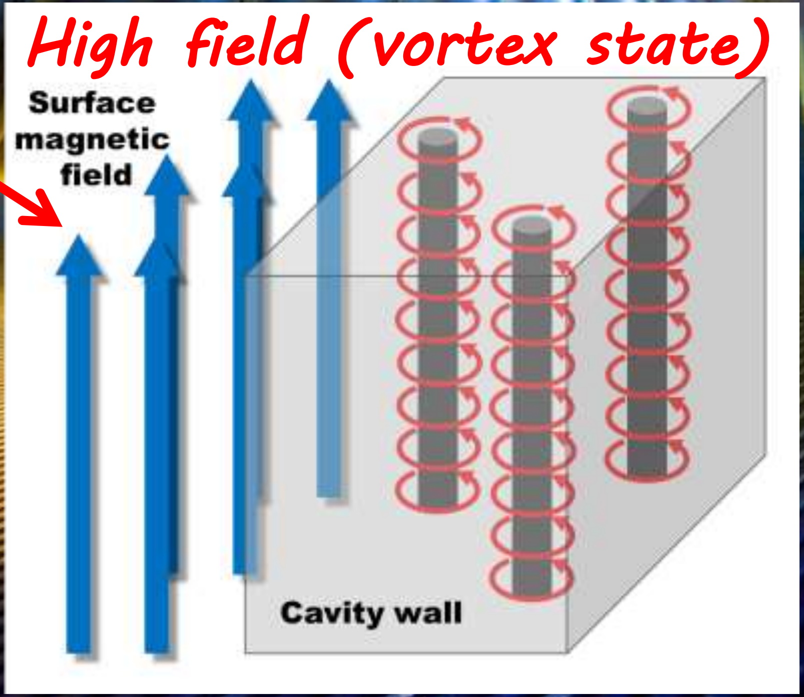


Low field (Meissner state)
Surface magnetic field
Cavity wall
Magnetic field distribution
http://www.linearcollider.org/ILC/Press/Images-and-graphics







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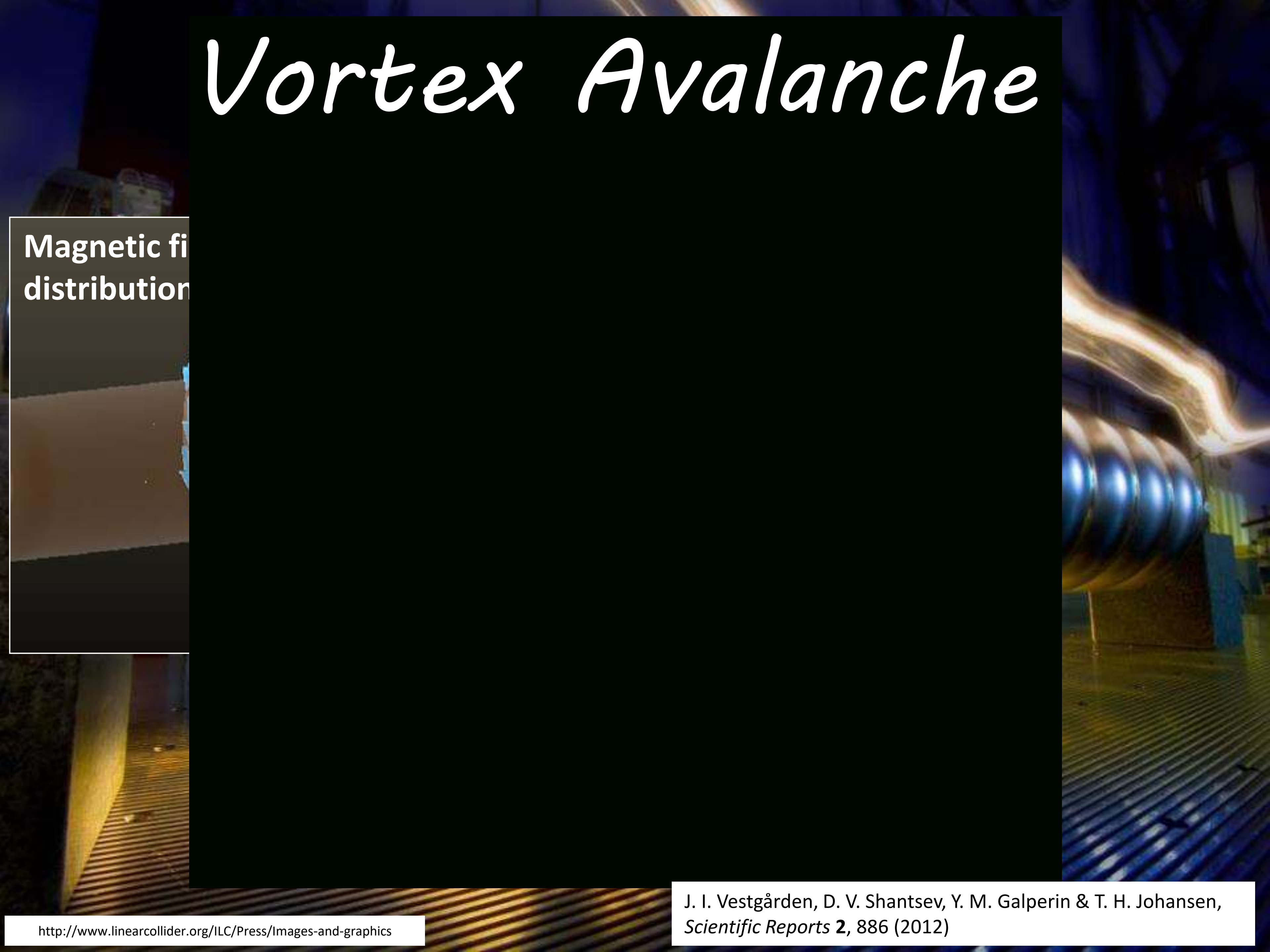
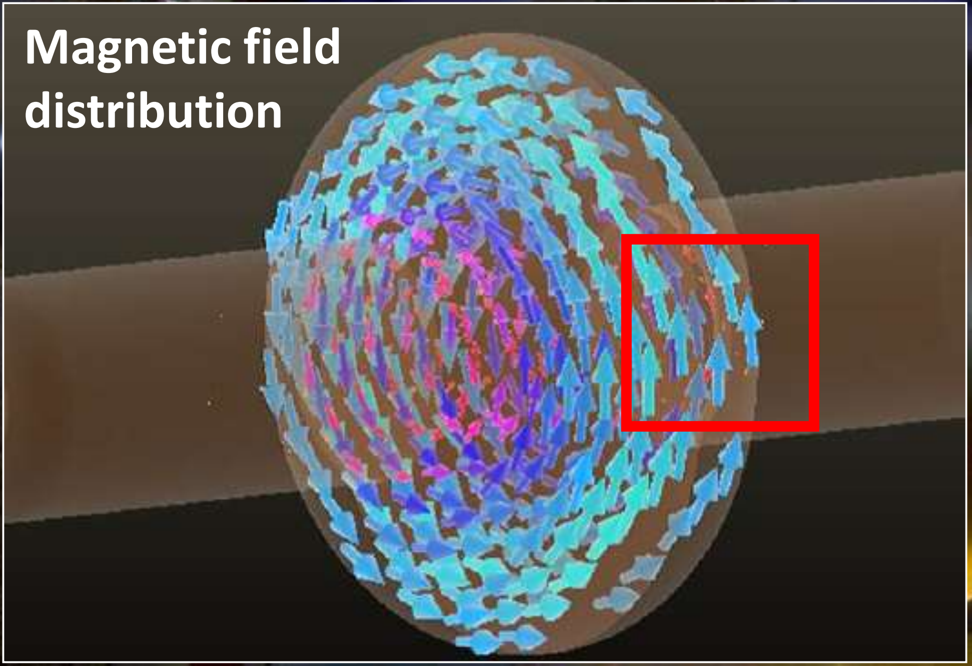
Vortex Avalanche



J. I. Vestgården, D. V. Shantsev, Y. M. Galperin & T. H. Johansen, *Scientific Reports* **2**, 886 (2012)

http://www.linearcollider.org/ILC/Press/Images-and-graphics



To achieve a high field, a material that can withstand against the vortex penetration up to a high magnetic field should be used.

http://www.linearcollider.org/ILC/Press/Images-and-graphics

So we use Nb as the material of SRF cavity.

The lower critical field of pure Nb is

B_{c1}~170 mT (E_{acc}~40MV/m for TESLA cavity),

which is larger than other superconductors.

※ The other reason is

the thermal conductivity.

Today I do not talk about this topic

Interactions.org, Particle Physics News and Resources, http://www.interactions.org/cms/?pid=1900

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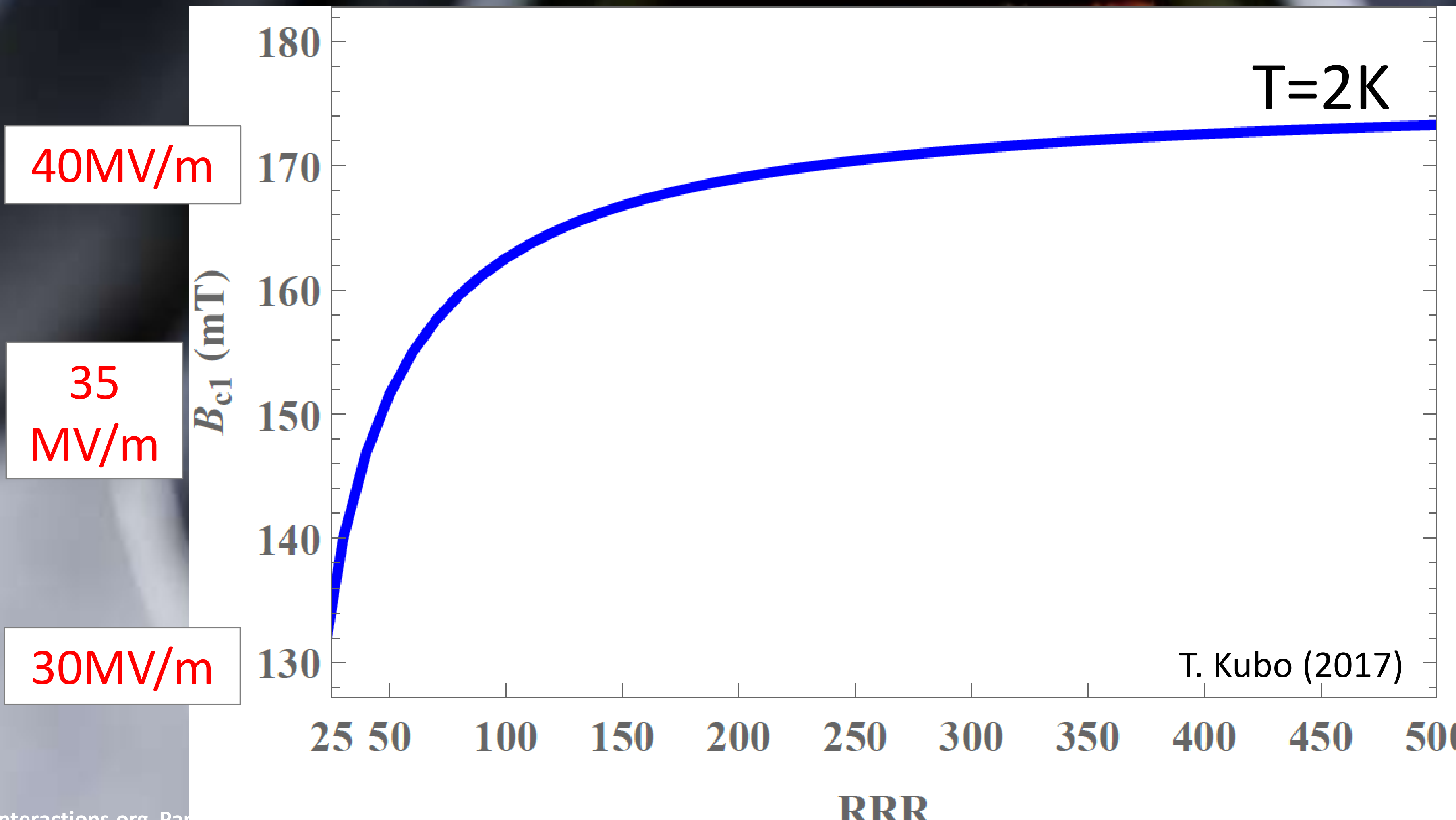

Even if ultra pure Nb was used, achieving B_{c1}~170 mT (E_{acc}~40MV/m) was not a straight forward task.

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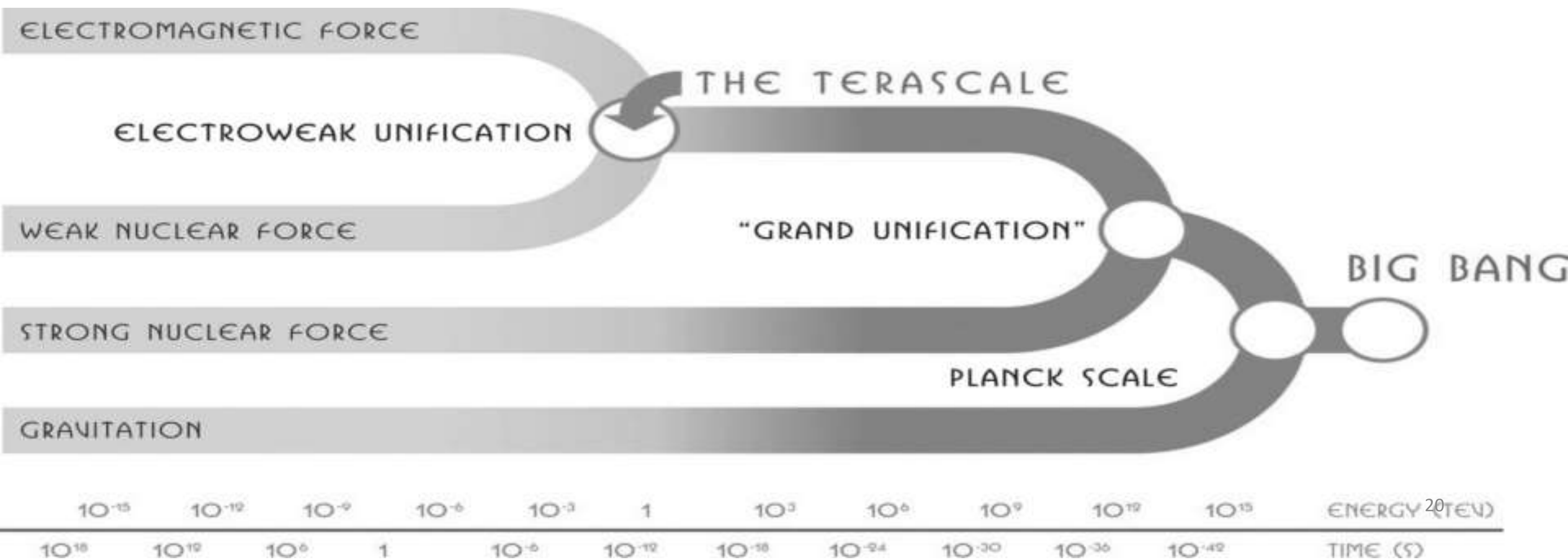
How did SRF researchers achieve E_{acc}>40MV/m?

ILC recipe



ELECTROMAGNETIC FORCE
THE TERASCALE
ELECTROWEAK UNIFICATION
WEAK NUCLEAR FORCE
"GRAND UNIFICATION"
BIG BANG
STRONG NUCLEAR FORCE
PLANCK SCALE
GRAVITATION
10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 1 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} ENERGY (TEV)
10^{18} 10^{12} 10^{6} 1 10^{-6} 10^{-12} 10^{-18} 10^{-24} 10^{-30} 10^{-36} 10^{-42} TIME (S)

Step	WHY	COMMENTS
Forming		
EB Welding	Clean welding	Nb = getter material. If RRR/ 10 @ welding => Q_0/10
~~Ti purification~~	RRR enhancement	RRR 300-400 now commercially available
~~Chemical~~ etching 100-200 µm (BCP, EP, CBP)	Remove contamination and damage layer	Limitation : BCP ~ 30MV/m; EP => >40 mV/m but lack of reproducibility
Annealing 800°C, 2h (or 600°C, 10h)	Get rid of hydrogen	Source of H: wet processes. H segregates near surface in form of hydrides (= bad SC)
Electropolish ~~Chemical polish~~ 5-20 µm	Remove diffusion layer (O, C, N)	Diffusion layer < ~1µm in bulk, a little higher at Grain Boundaries
Specific rinsing	e.g. remove S particles due to EP	Under evaluation. HF, H_2O_2, ethanol, degreasing,…
High pressure rinsing (HPR)	Get rid of dust particles	Not always enough (recontamination during assembly)
Assembling	Ancillaries : antennas, couplers , vacuum ports…	**In clean room, but recontamination still possible**
Baking, 120°C,12-48hr	Decrease high field losses (Q-drop)	Unknown mechanism, first 10 nm of the surface in concern.
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Test RF	Cavity's performance	First naked cavity in vertical cryostat, then dressed in horizontal cryostat/ accelerating facility
He processing, HPP	Decrease field emission	RF power with/ without He to destroy field emitters (dust particles). NB field emission : principal practical problem in accelerators

C. Antoine

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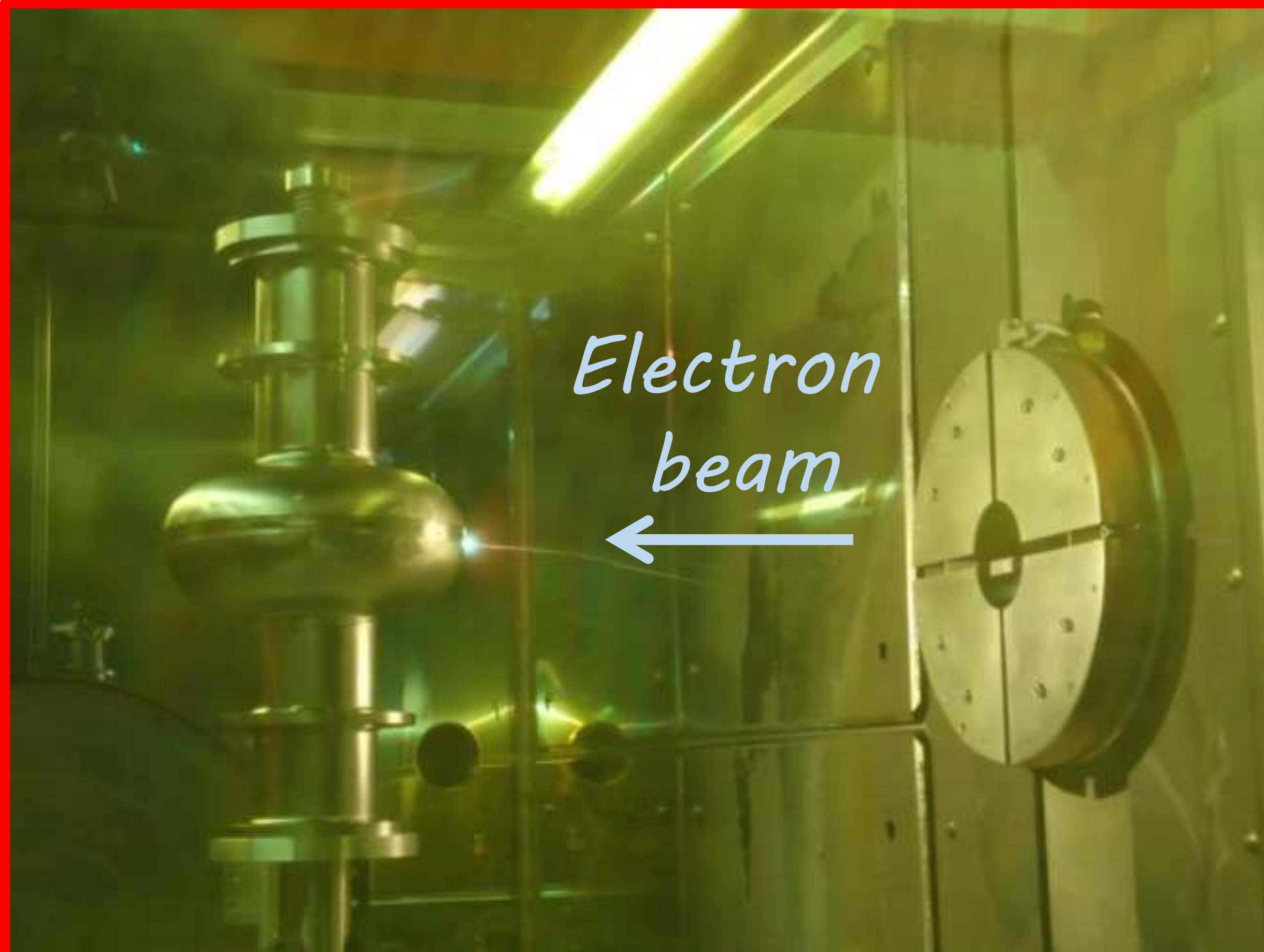

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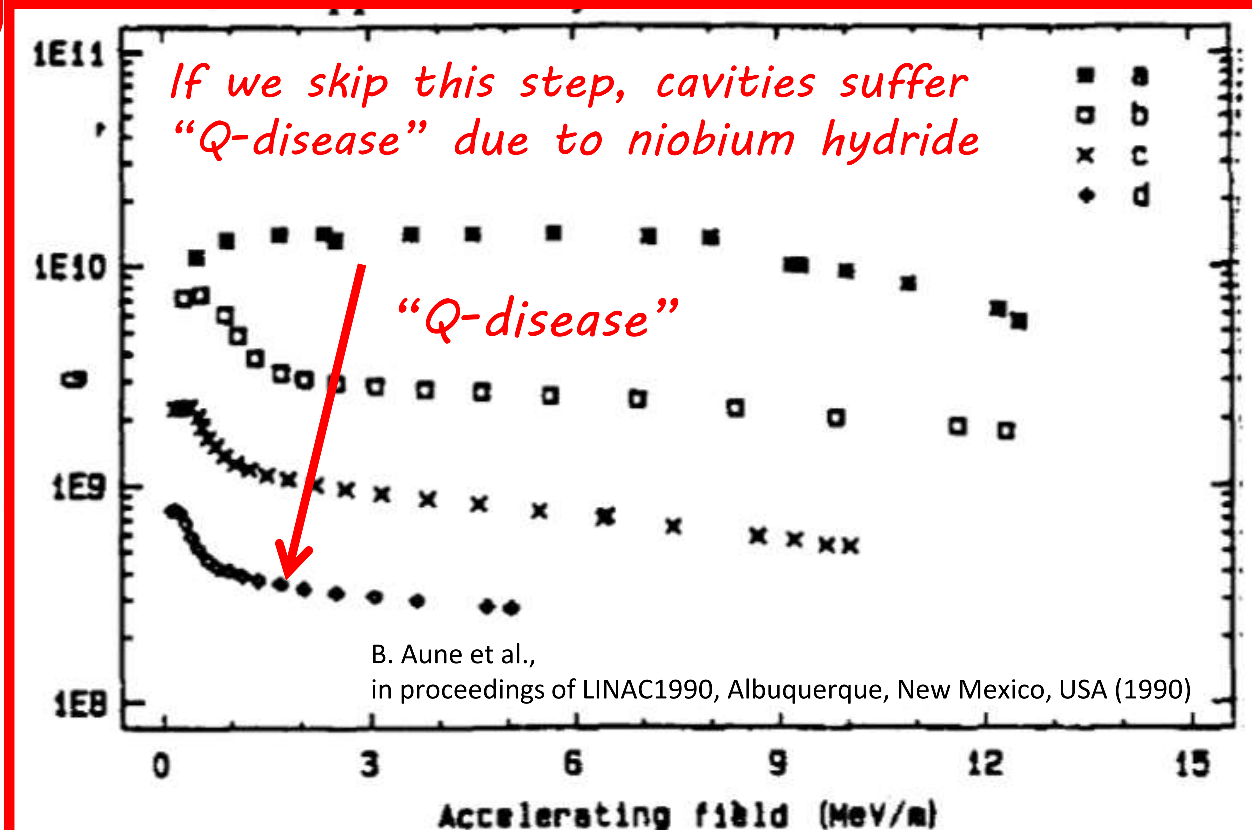

B. Aune et al., in proceedings of LINAC1990, Albuquerque, New Mexico, USA (1990)

C. Antoine

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C. Antoine

27/04/2013

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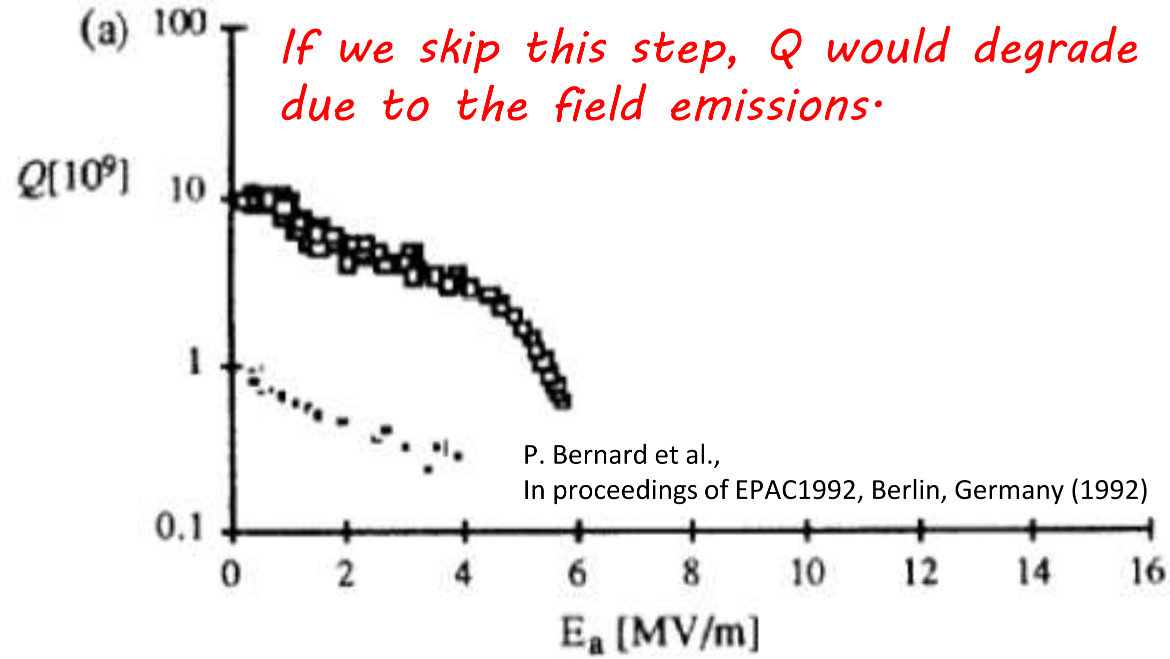
If we skip this step, Q would degrade due to the field emissions.



P. Bernard et al.,
In proceedings of EPAC1992, Berlin, Germany (1992)

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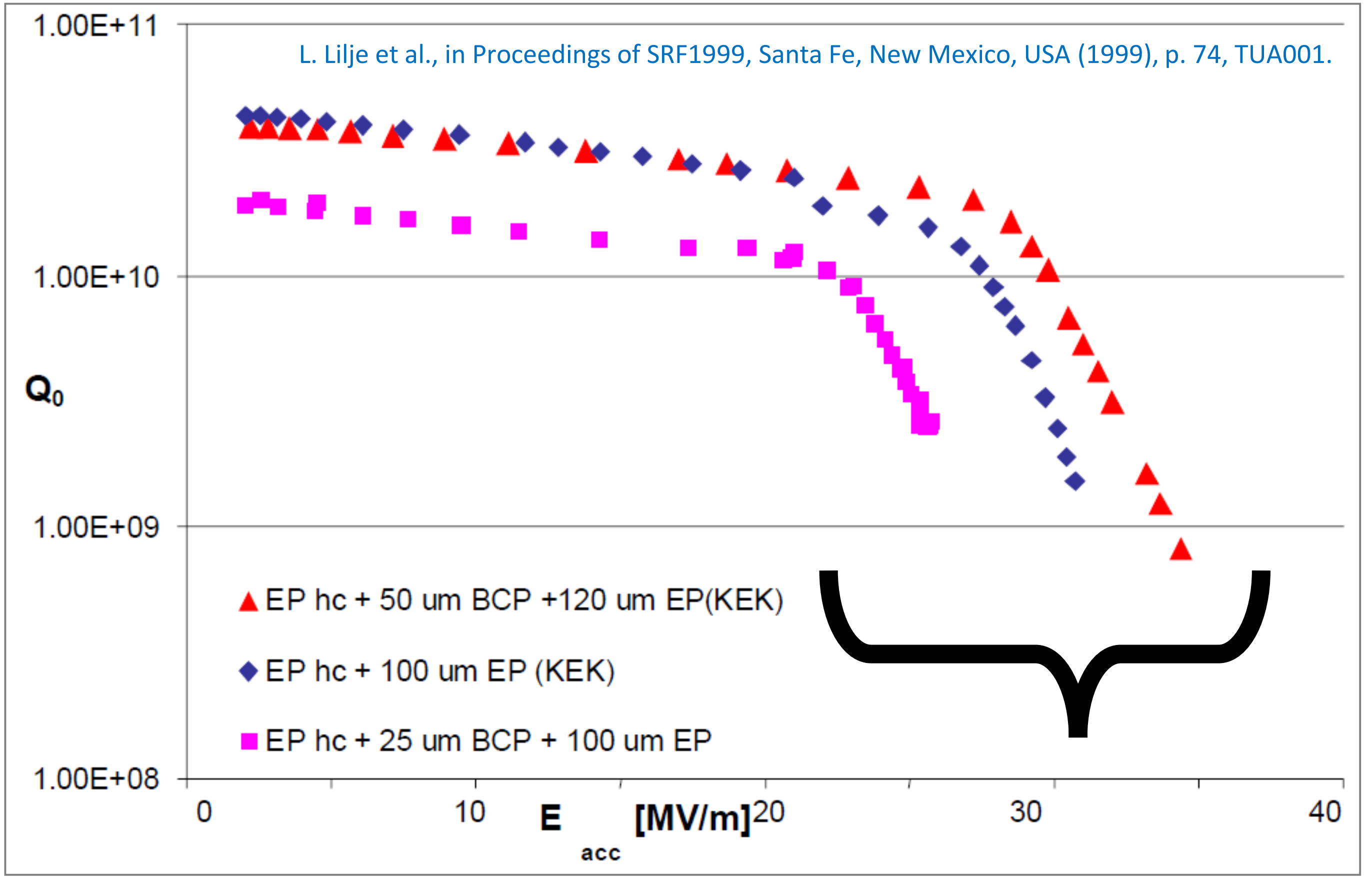
What is the 120℃-48hours bake?

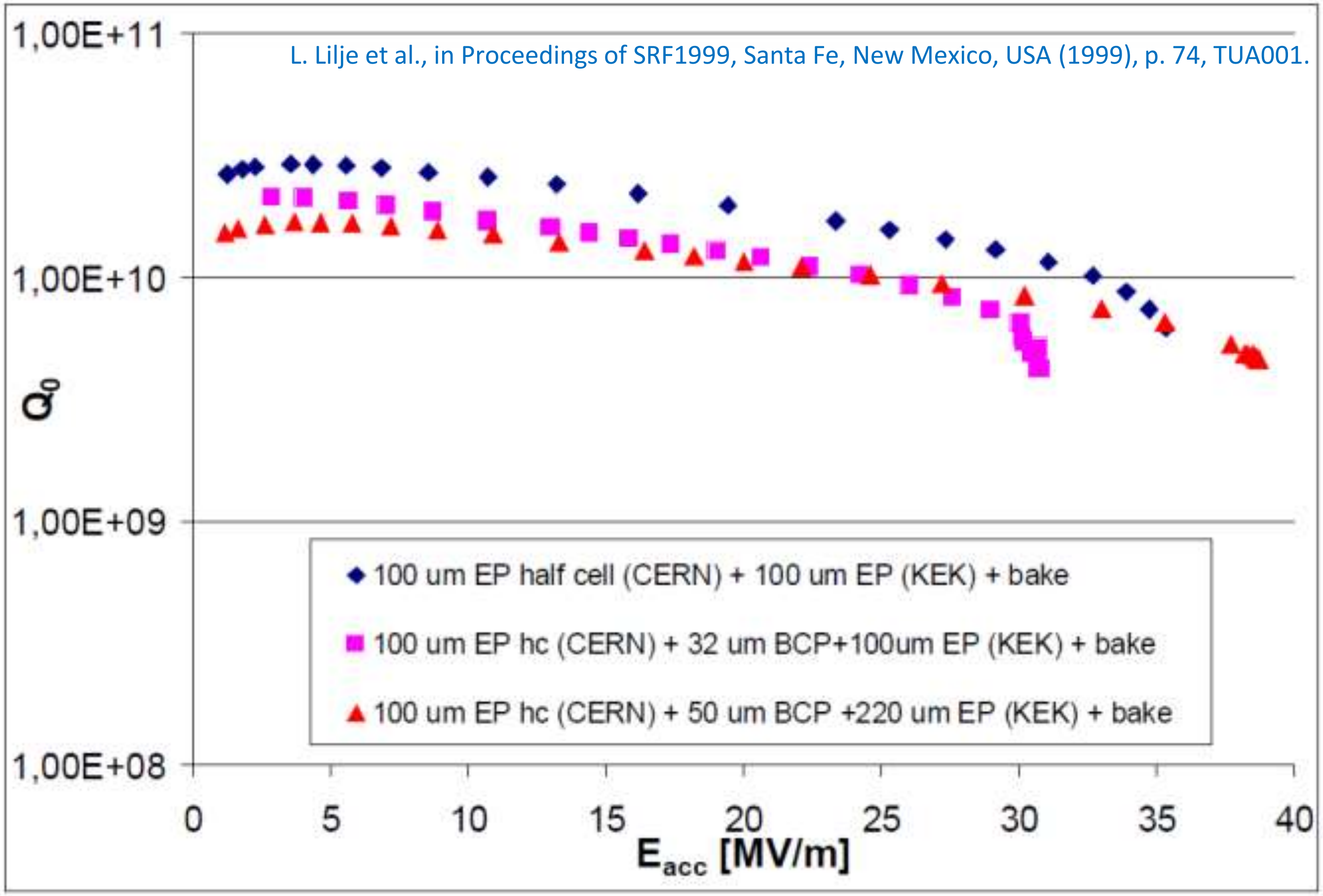
Without baking



High field Q-drop

What is the 120℃-48hours bake?

With baking

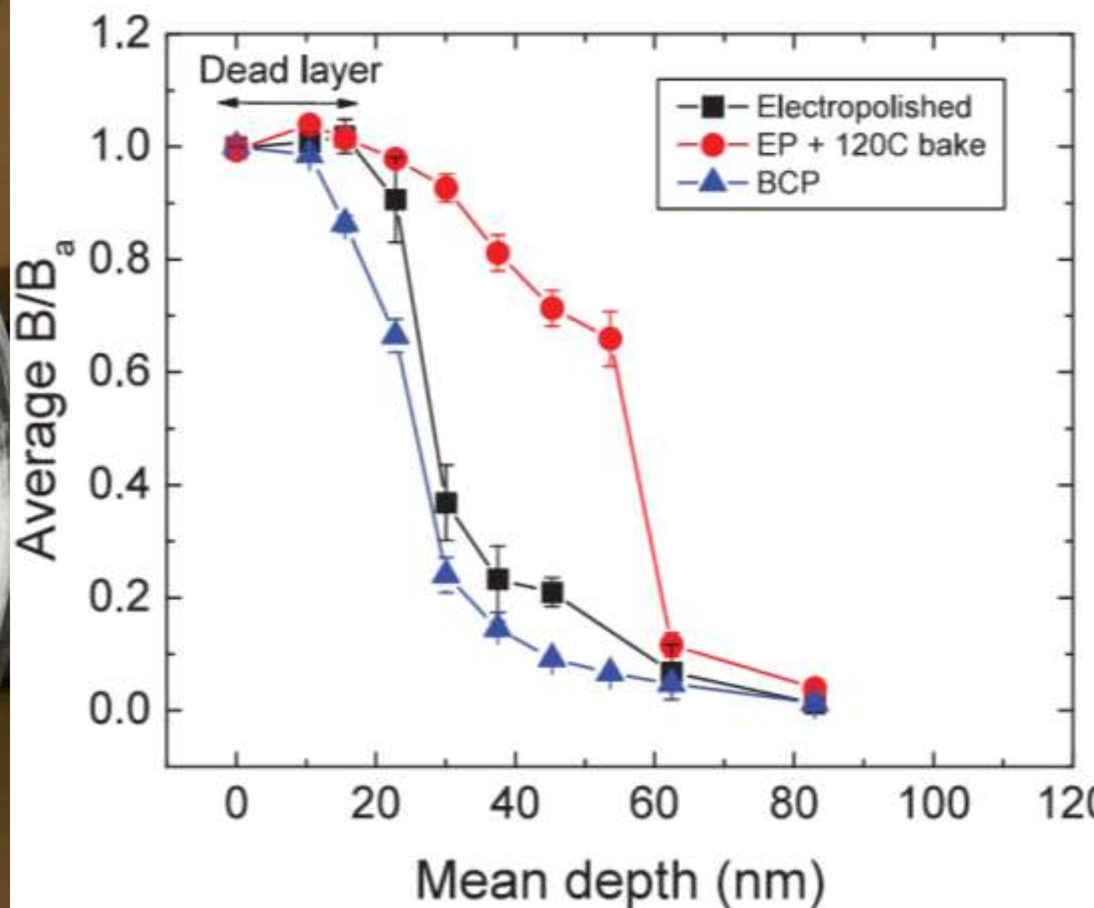


- E. Kako et al., in Proceedings of SRF1995, *Gif-sur-Yvette, France (*1995), p. 425, SRF95C12.
- P. Kneisel et al., in *Proceedings of SRF1995, Gif-sur-Yvette, France (*1995), p. 449, SRF95C17.
- M. Ono et al., in *Proceedings of SRF1997, Abano Terme (Padova), Italy* (1997), p. 472, SRF97C08.
- L. Lilje et al., in Proceedings of SRF1999, La Fonda Hotel, Santa Fe, New Mexico, USA (1999), p. 74, TUA001.

At the present day, we know

Fermilab news at work
http://news.fnal.gov/wp-content/uploads/2016/09/11-0233-27D.jpg

A. Romanenko et al., Appl. Phys. Lett. **104**, 072601 (2014)

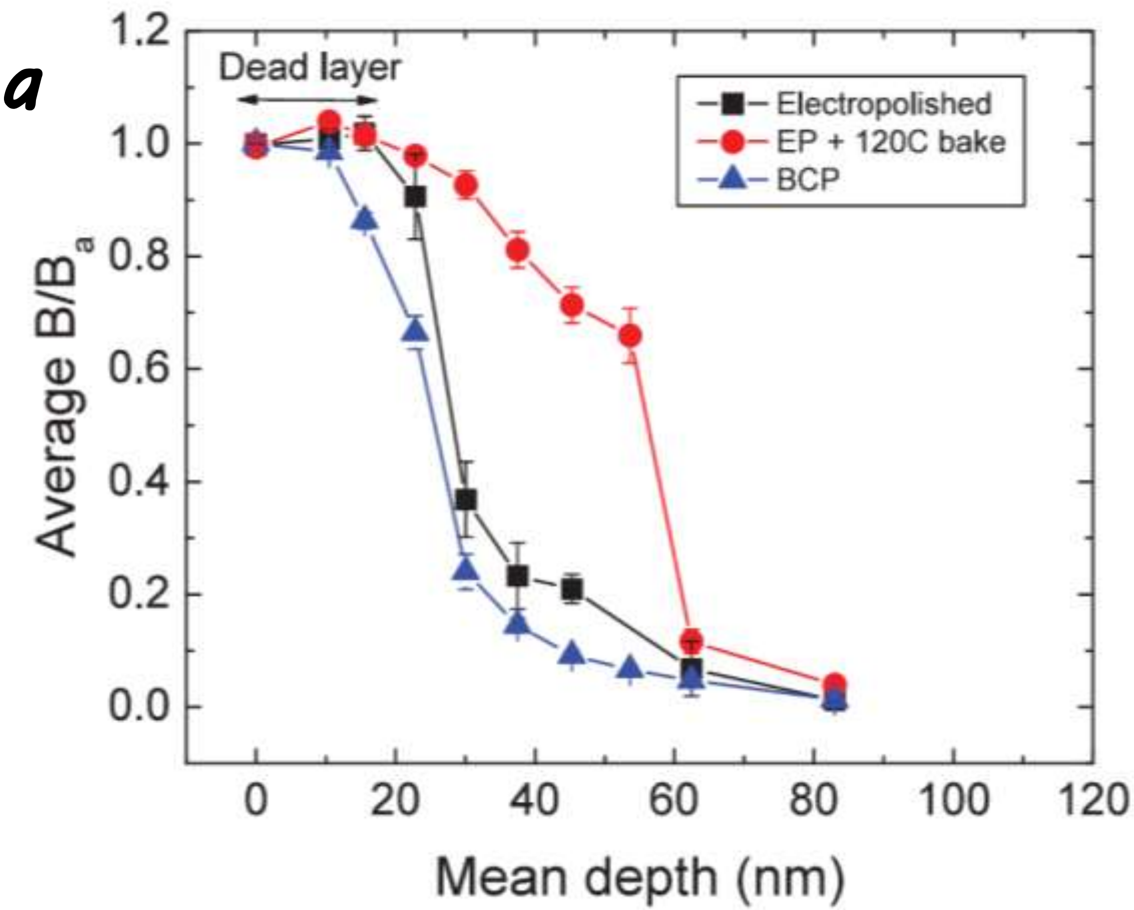


By using Low Energy muon spin rotation technique

At the present day, we know

A. Romanenko et al., Appl. Phys. Lett. **104**, 072601 (2014)

The baked Nb has a layered structure that consists of



At the present day, we know

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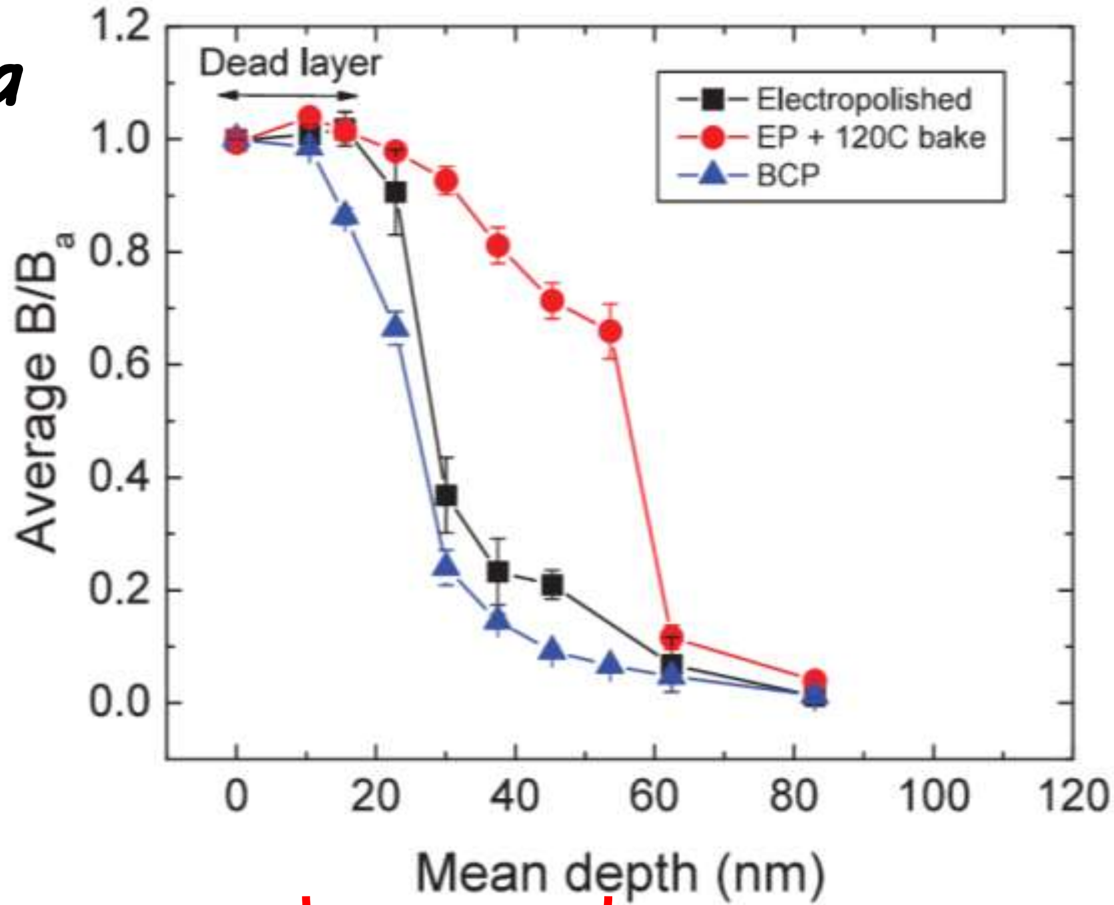
1. dirty Nb layer



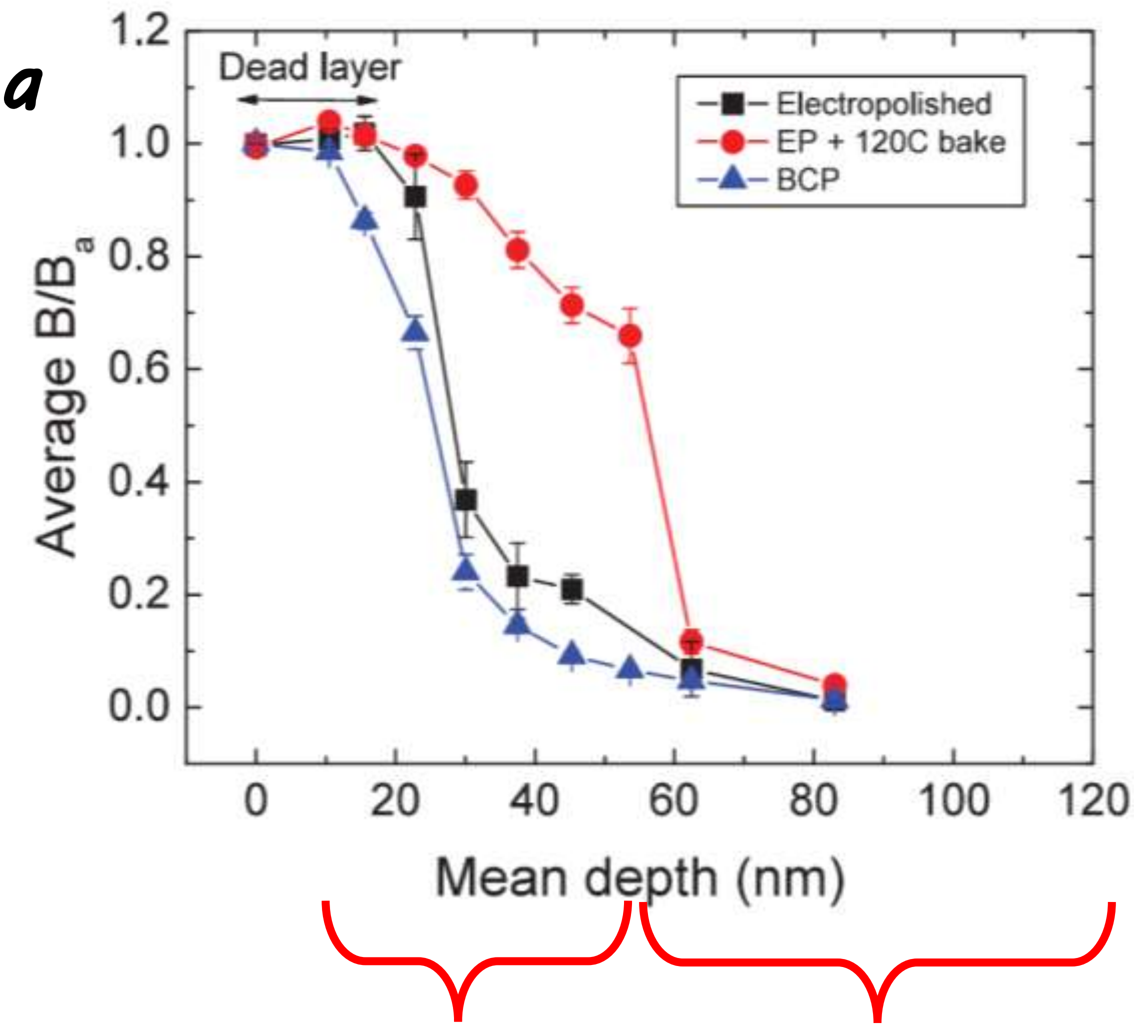
Dirty Nb

At the present day, we know

The baked Nb has a **layered structure** that consists of

1. **dirty** Nb layer and
2. **clean** bulk Nb.

A. Romanenko et al., Appl. Phys. Lett. **104**, 072601 (2014)



Dirty Nb　　Clean Nb

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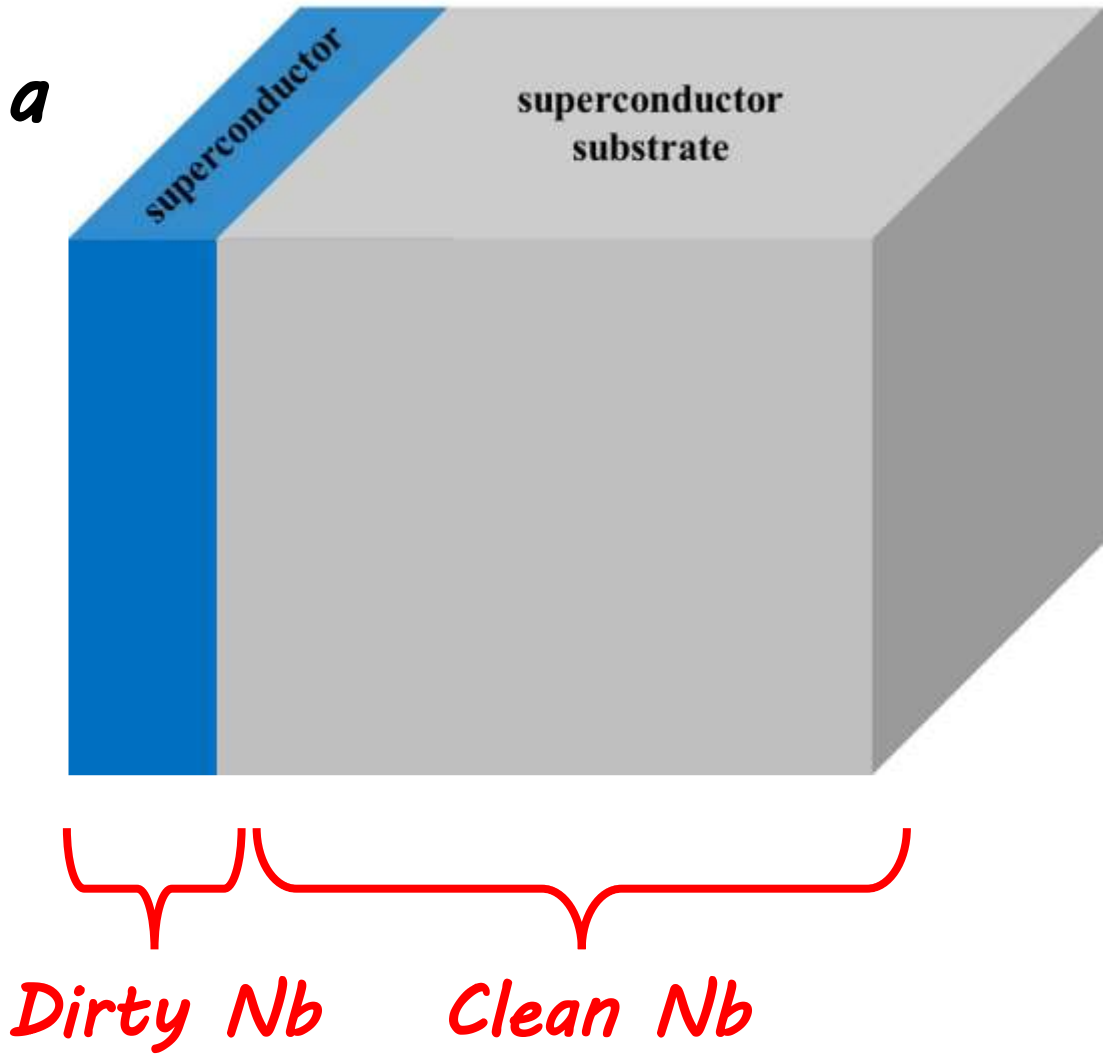


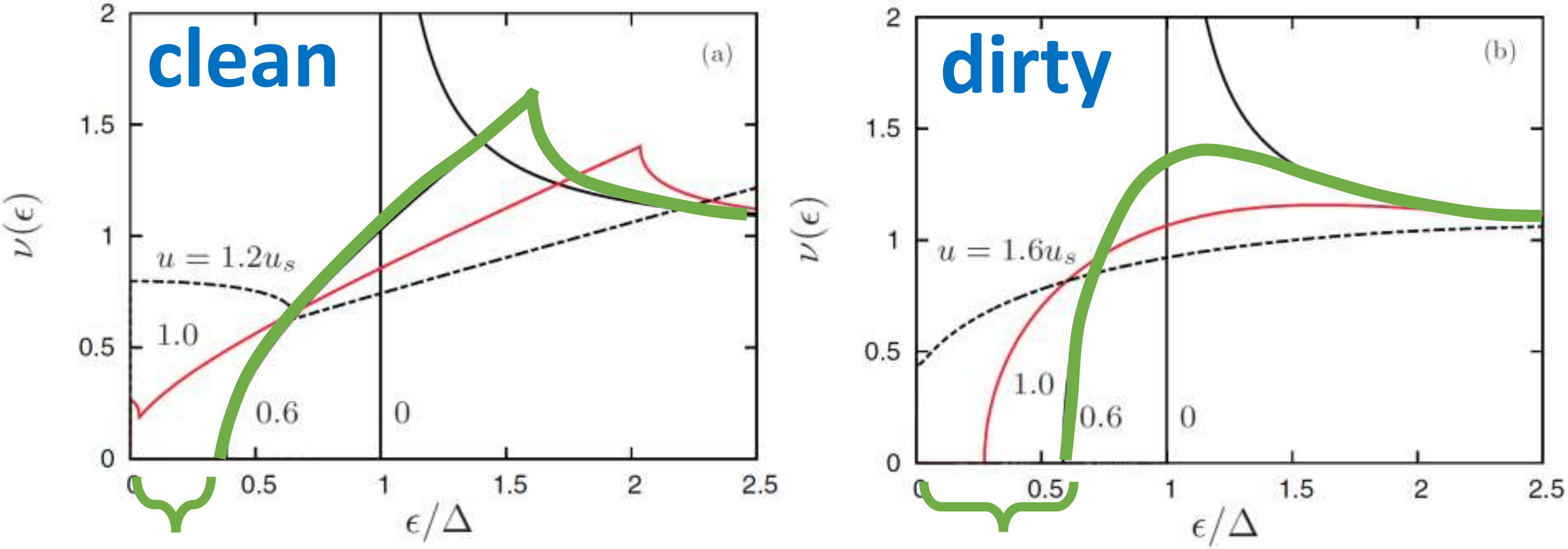
①

Since excited quasiparticles increase and contribute to the surface resistance as the gap decreases, a larger gap is desired. **The gap in the dirty layer is rather well behaved at a high field!**

→ cure the high field Q drop

Note here B_{c1} is a bulk property and given by the bulk clean SC:

B_{c1}～170mT remains after layered.



Gap under a current (narrow!)

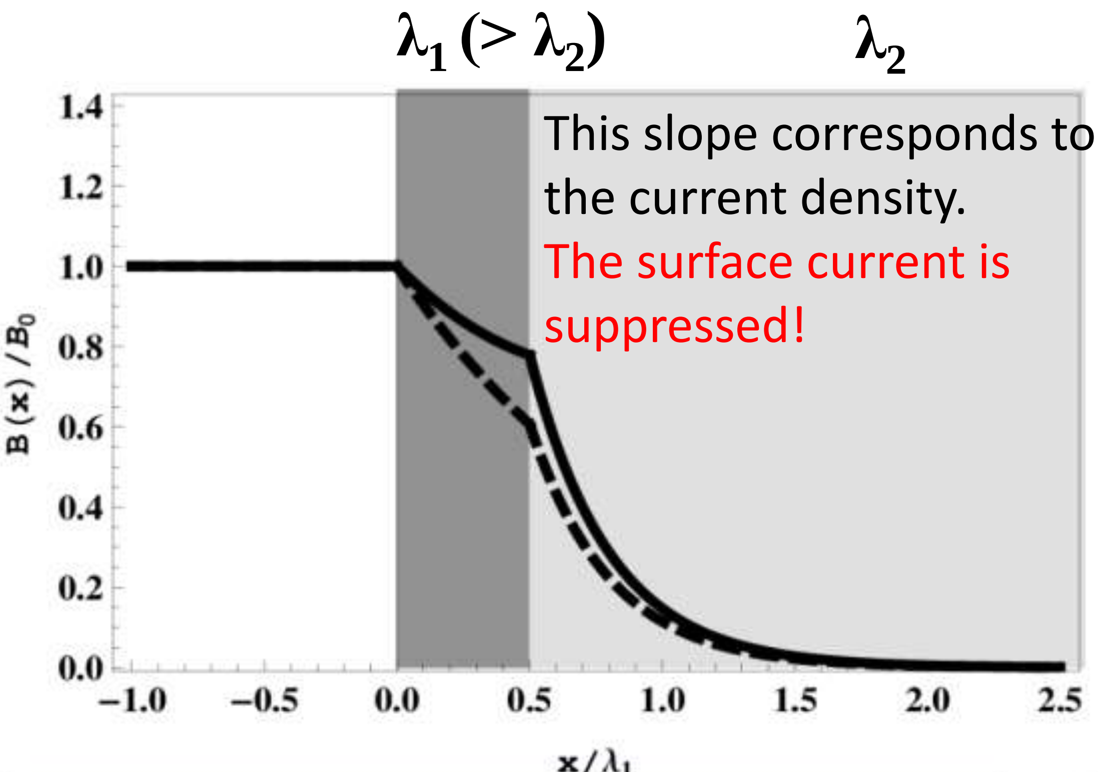
Becomes gapless before arriving at the superheating field!

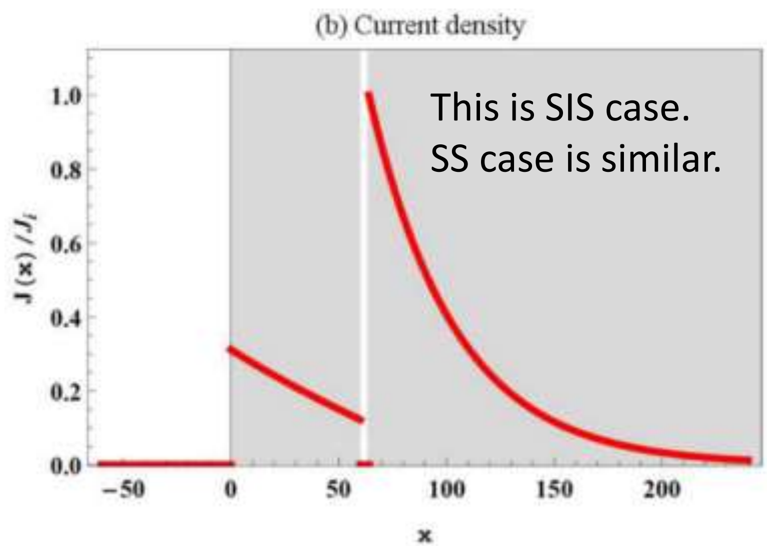
Gap under a current (wider than clean case!)

- F. P-J. Lin and A. Gurevich, Phys. Rev. B **85**, 054513 (2012)
- A. Gurevich, Rev. Accel. Sci. Technol. **5**, 119 (2012)

② The surface current is suppressed.

- The current suppression means an enhancement of the field limit, because the theoretical field limit is determined by the current density.
- The gap reduction due to the current is further prevented.





SS case:

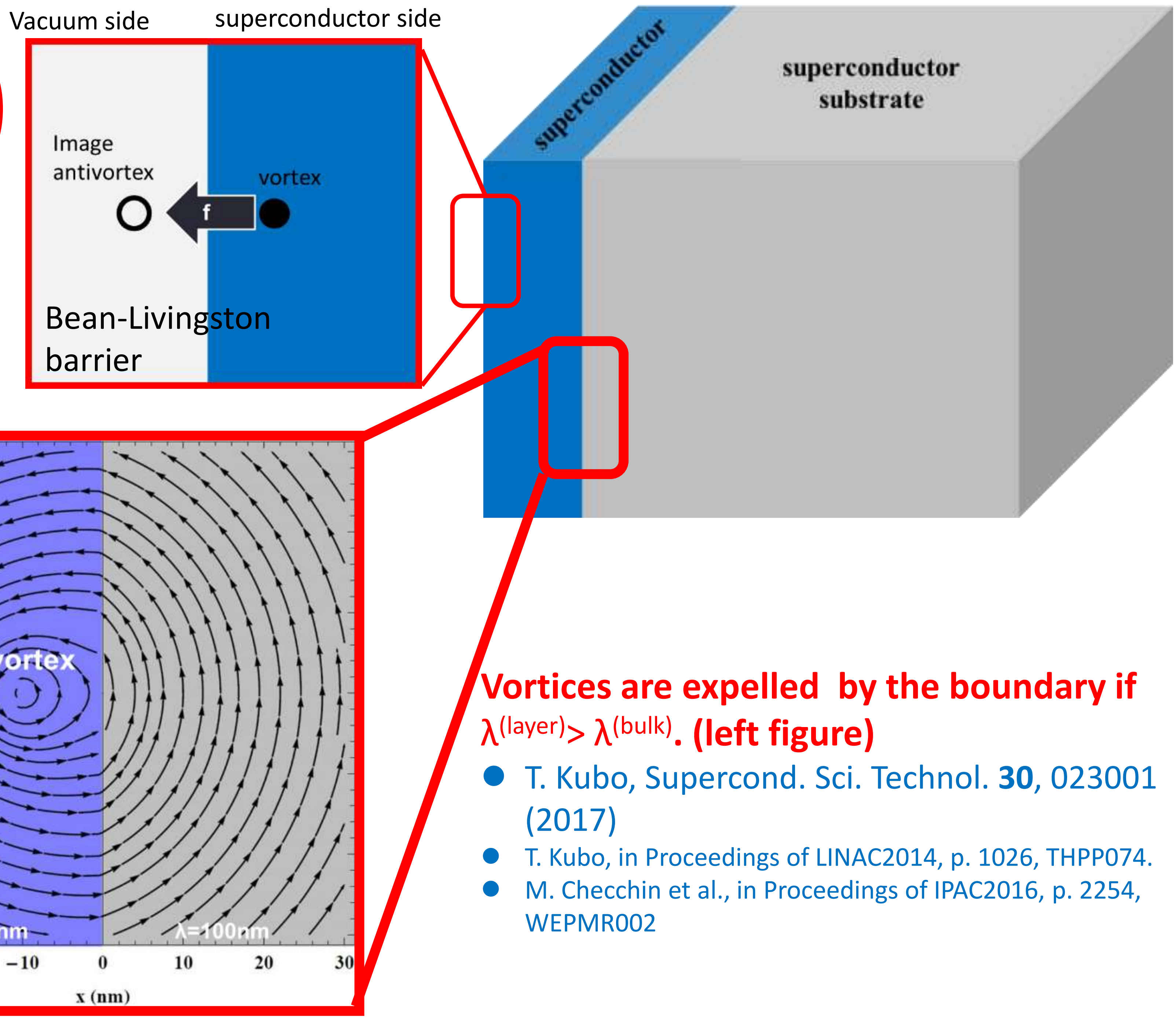
- T. Kubo, in Proceedings of LINAC2014, p. 1026, THPP074.

SIS case:

- T. Kubo et al., Appl. Phys. Lett. **104**, 032603 (2014).
- A. Gurevich, AIP Advance **5**, 017112 (2015).
- S. Posen et al., Phys. Rev. Applied **4**,044019 (2015).

Figures from T. Kubo, Supercond. Sci. Technol. **30**, 023001 (2017)

③



Vortices are expelled by the boundary if $\lambda^{(layer)} > \lambda^{(bulk)}$. (left figure)

- T. Kubo, Supercond. Sci. Technol. **30**, 023001 (2017)
- T. Kubo, in Proceedings of LINAC2014, p. 1026, THPP074.
- M. Checchin et al., in Proceedings of IPAC2016, p. 2254, WEPMR002

References

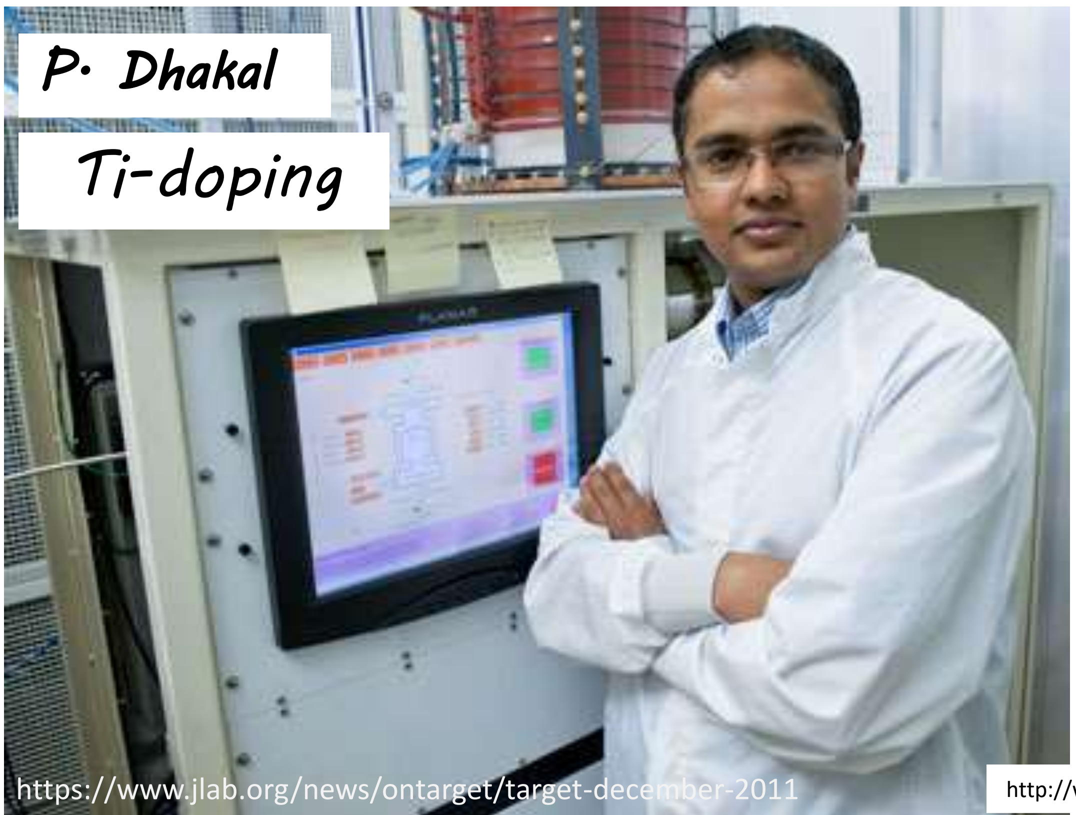
(recent findings related to the ILC recipe)

- F. P-J. Lin and A. Gurevich, Phys. Rev. B **85**, 054513 (2012)
- A. Romanenko et al., Appl. Phys. Lett. **104**, 072601 (2014)
- T. Kubo, Supercond. Sci. Technol. **30**, 023001 (2017)

解説

- T. Kubo, in proceedings of the International Workshop on Future Linear Colliders (LCWS2016), Morioka, Japan (2016).
- T. Kubo, Journal of the Particle Accelerator Society of Japan, 14, 35 (2017).[日本語]

Nitrogen doping



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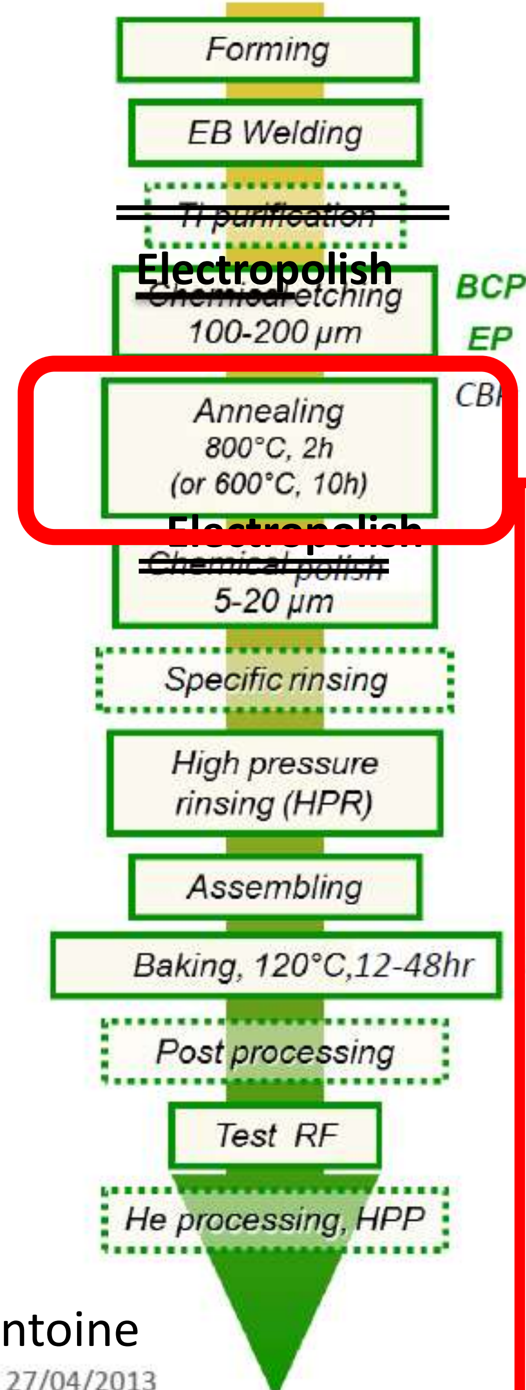
Baking, 120°C,12-48hr	Decrease high field losses (Q-drop)	Unknown mechanism, first 10 nm of the surface in concern.
Post processing	Get rid of "re-contamination" ?	Under evaluation: dry ice cleaning, plasma
Test RF	Cavity's performance	First naked cavity in vertical cryostat, then dressed in horizontal cryostat/ accelerating facility
He processing, HPP	Decrease field emission	RF power with/ without He to destroy field emitters (dust particles). NB field emission : principal practical problem in accelerators

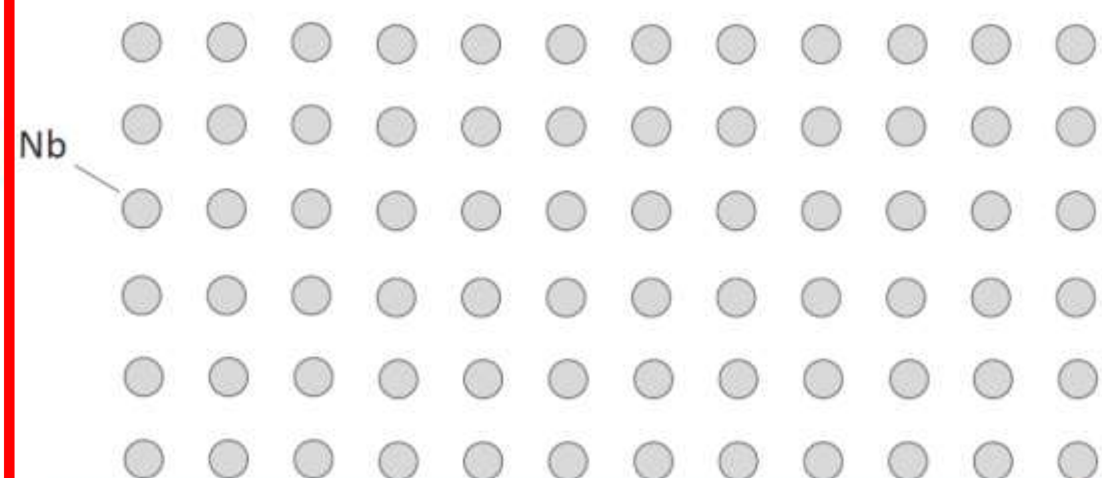
C. Antoine



WHY	COMMENTS
Clean welding	*Nb = getter material. If RRR/ 10 @ welding => $Q_0/10$*
RRR enhancement	*RRR 300-400 now commercially available*
Remove contamination and damage layer	*Limitation : BCP ~ 30MV/m; EP => >40 mV/m but lack of reproducibility*
Get rid of hydrogen	*Source of H: wet processes H segregates near surface in form of*

N-doping treatment

800C UHV, 3 hours → 800C N_2 injection p=25mTorr → 800C N_2 2 minutes → 800C UHV, 6 minutes → UHV cooling → 5 um EP



Fermilab

7 Martina Martinello | LINAC 2016 9/28/2016

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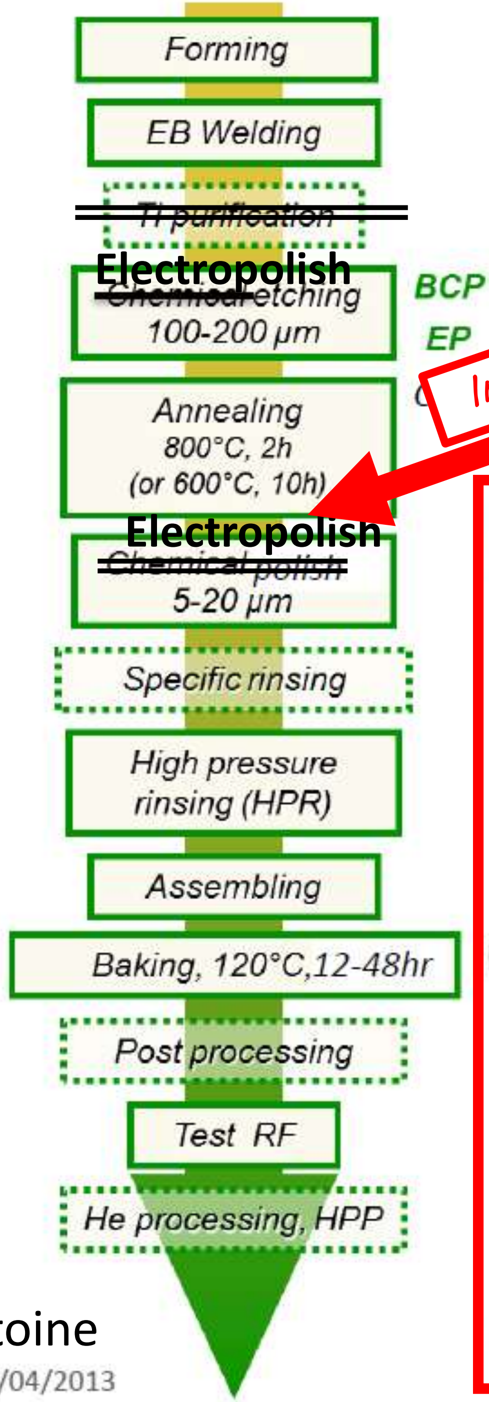
27/04/2013



WHY

Clean welding

RRR enhancement

Get rid of hydrogen

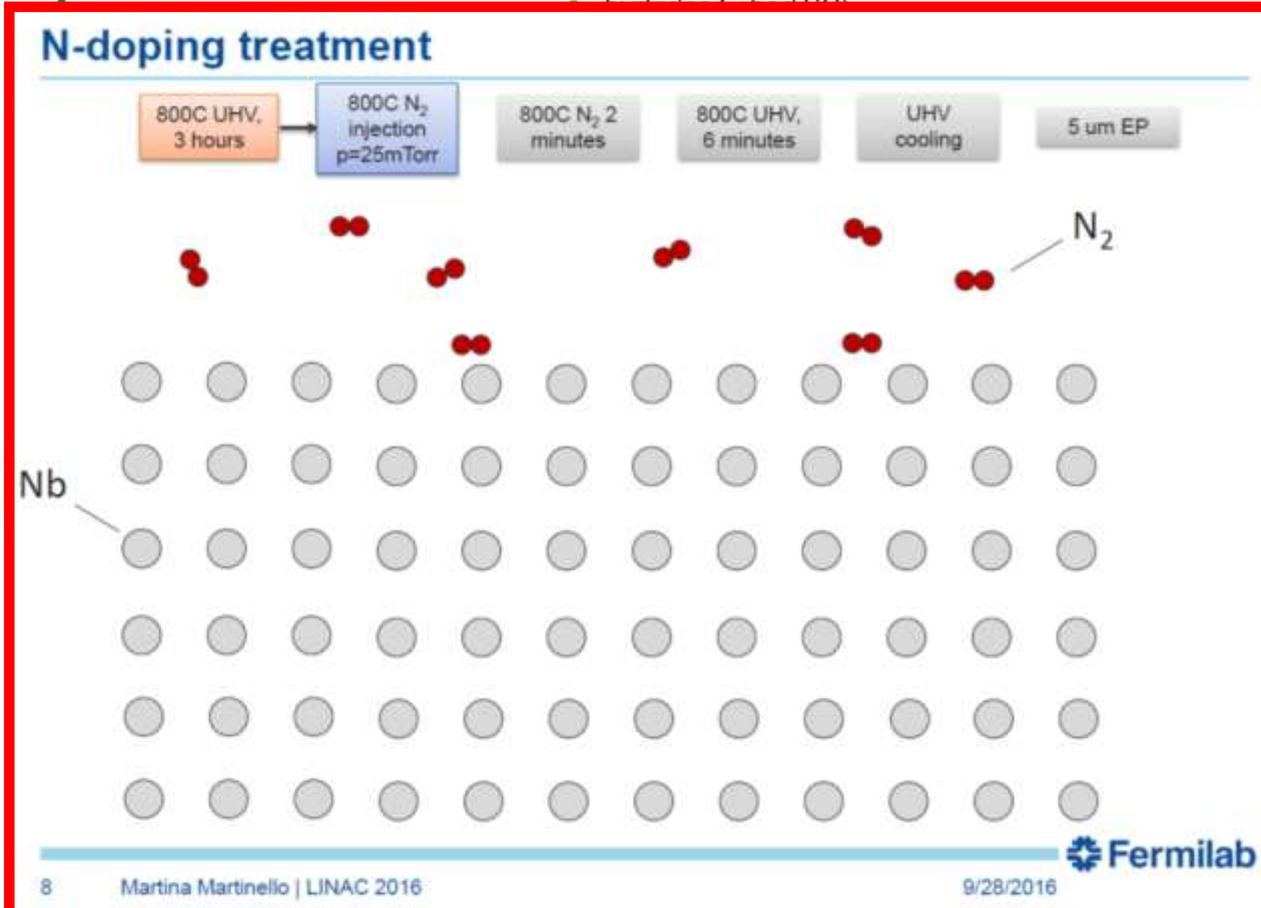
Insert additional step

Inject N_2 gas

($\sim 3 \times 10^{-5}$ Pa)

at 800°C

for 2 minutes



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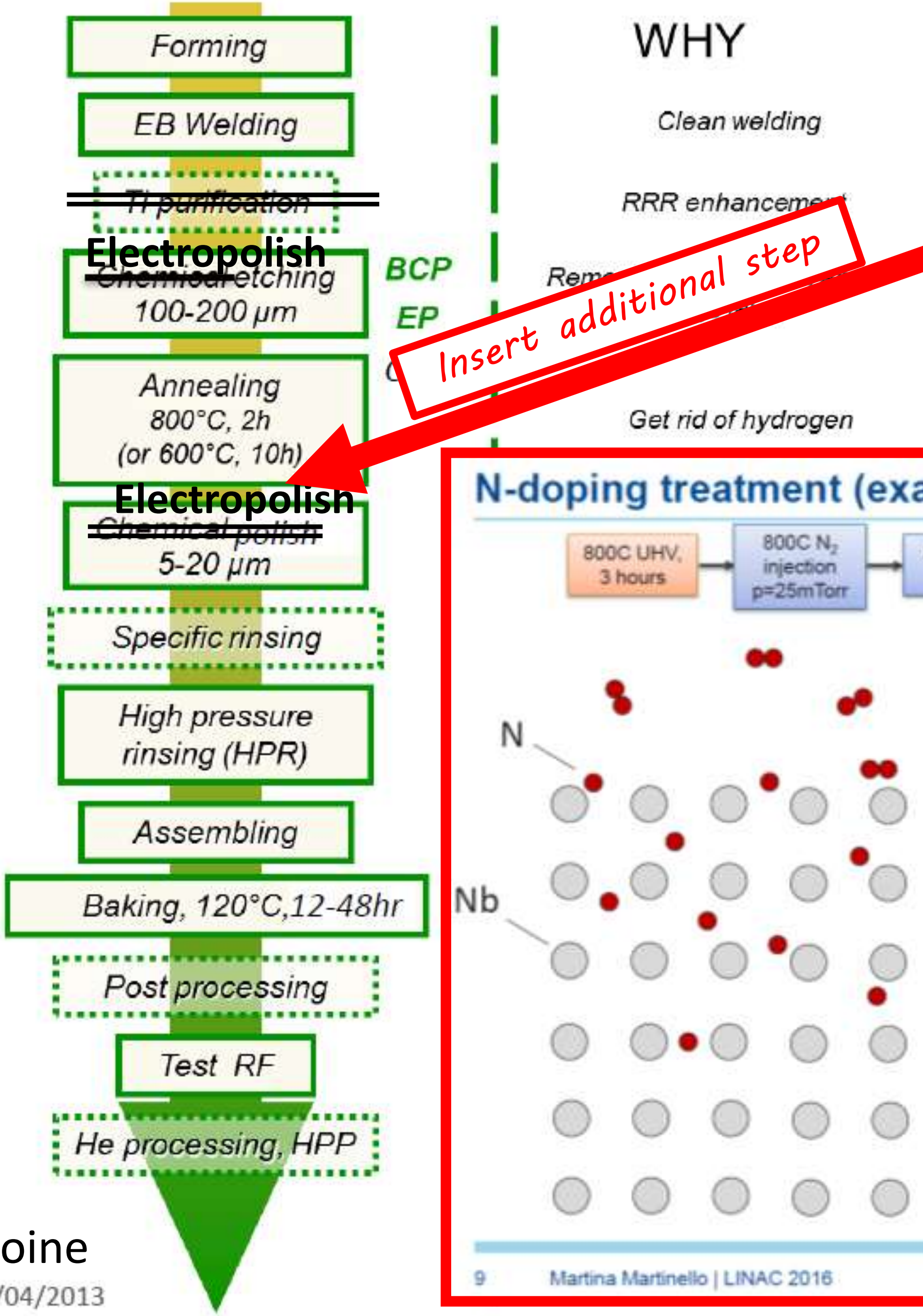

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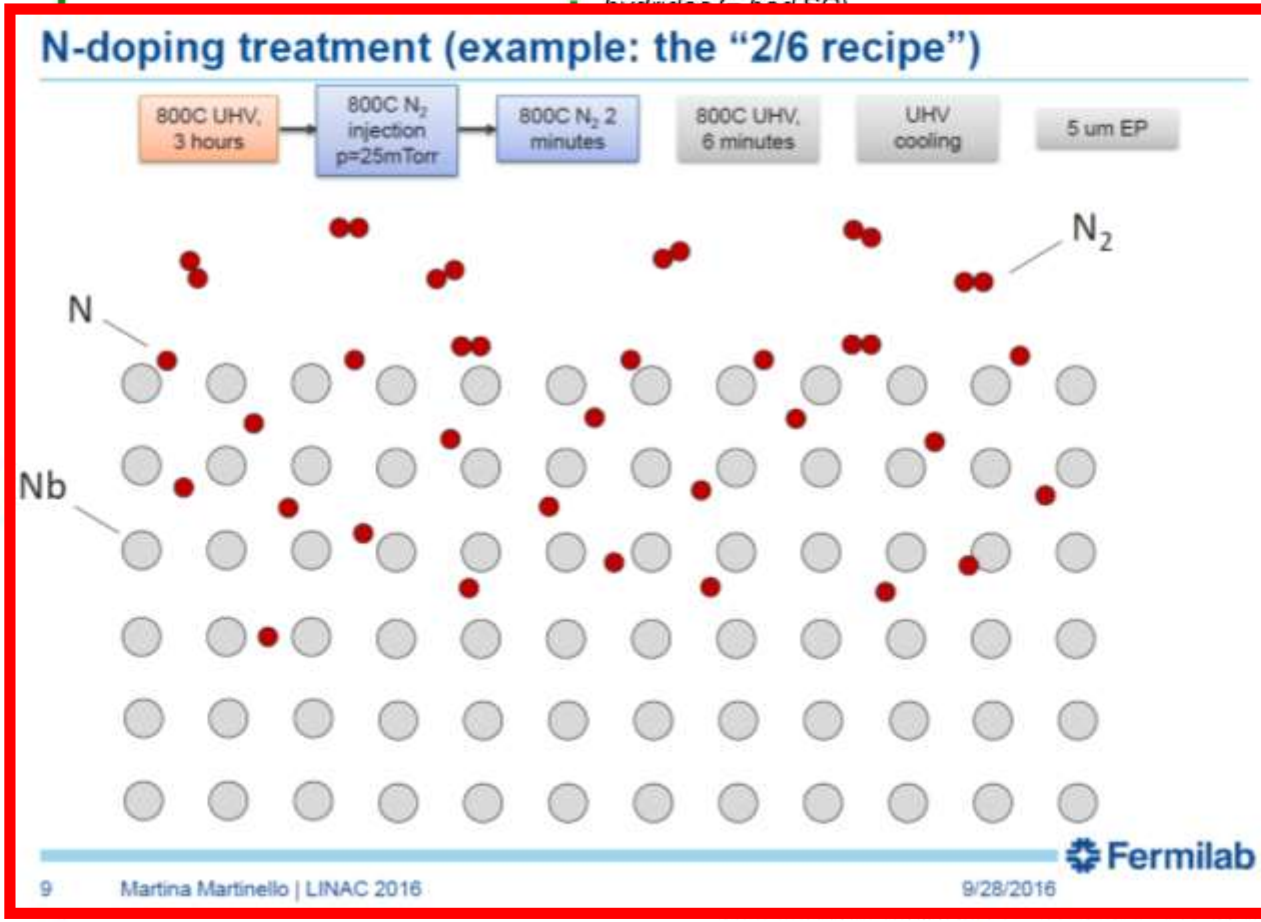

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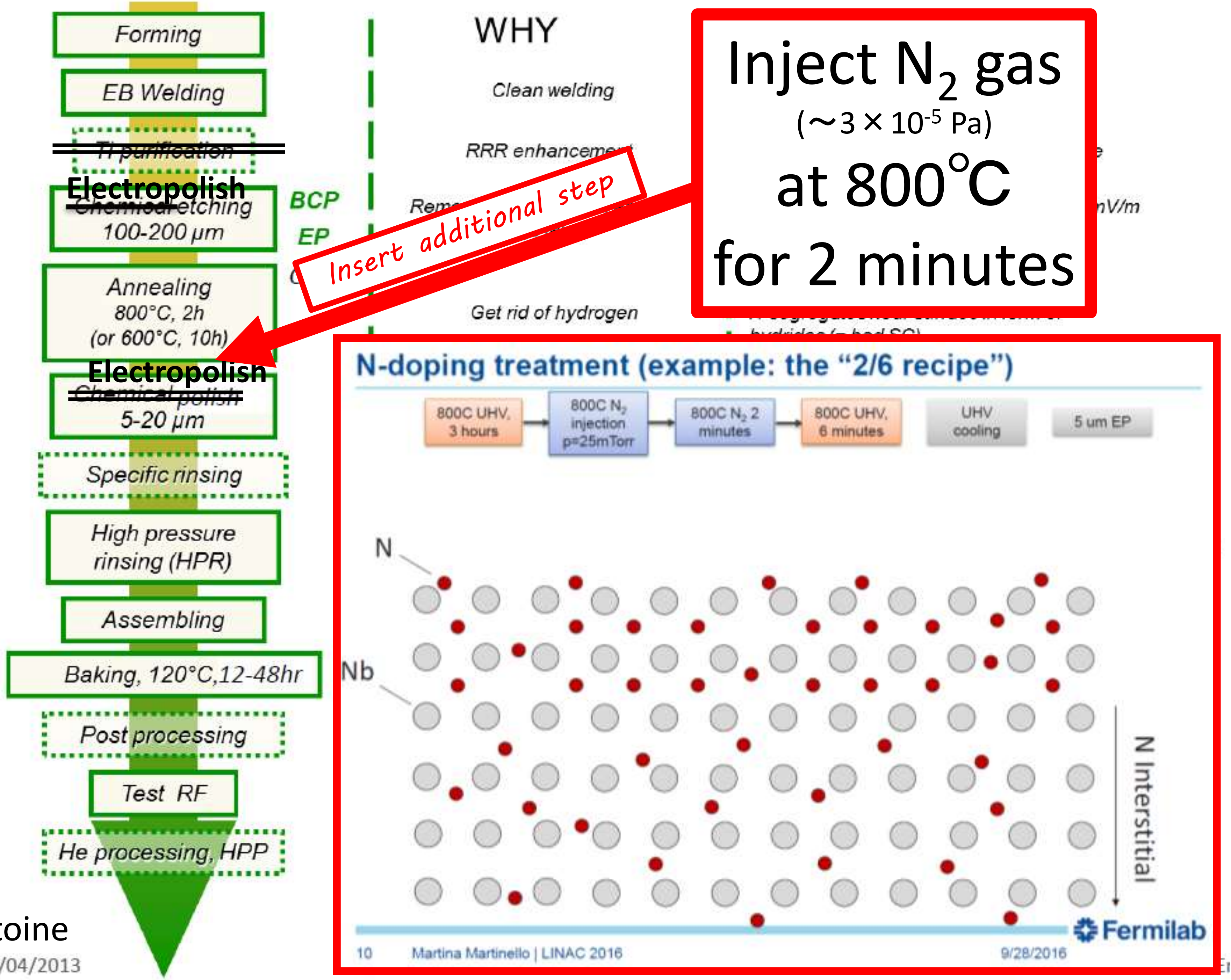

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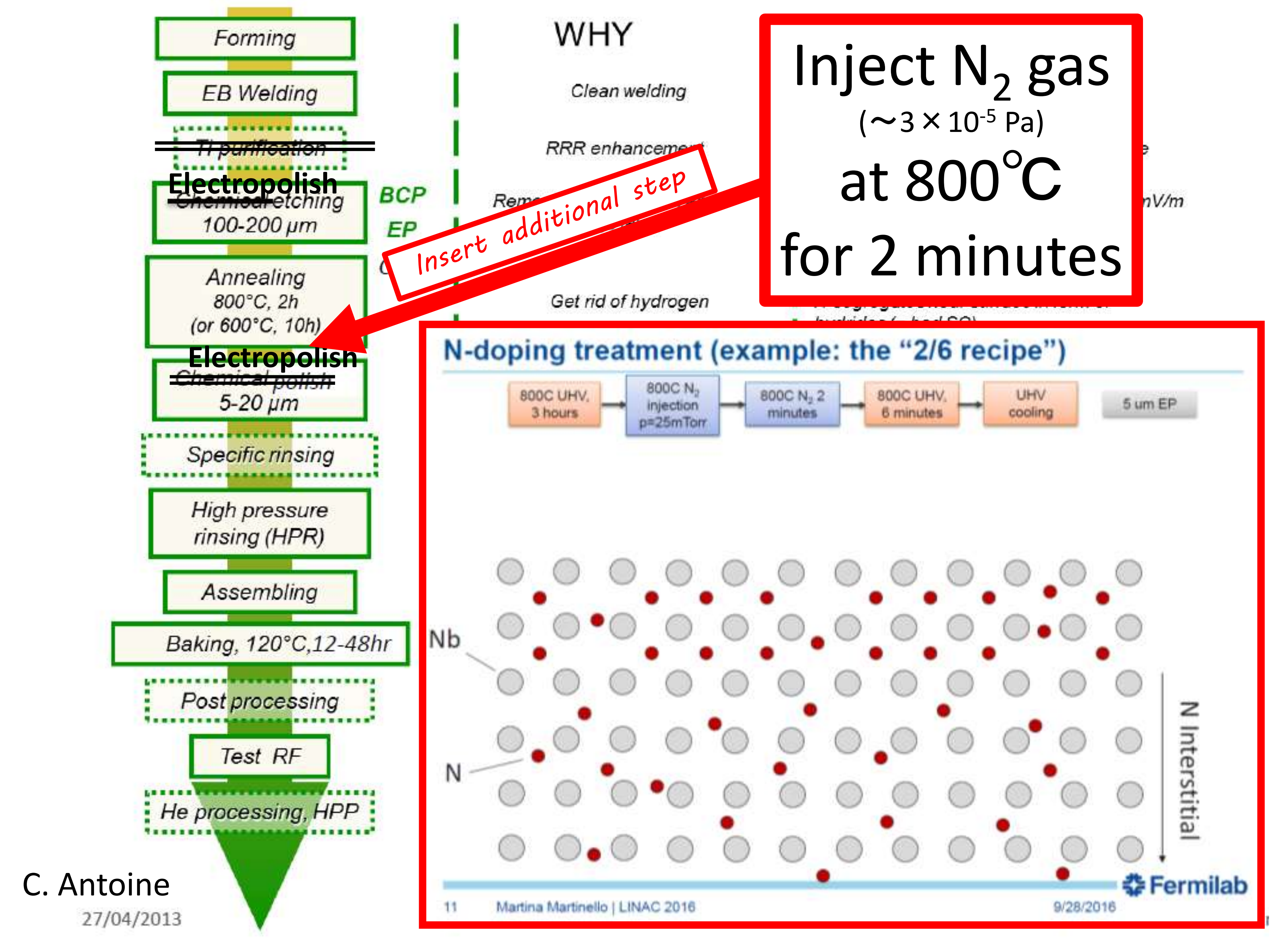

Forming
EB Welding
Ti purification
Electropolish
Chemical etching
100-200 µm
BCP
EP
Annealing
800°C, 2h
(or 600°C, 10h)
Electropolish
Chemical polish
5-20 µm
Specific rinsing
High pressure rinsing (HPR)
Assembling
Baking, 120°C,12-48hr
Post processing
Test RF
He processing, HPP
WHY
Clean welding
RRR enhancement
Get rid of hydrogen
Insert additional step
Inject N₂ gas
(～3 × 10⁻⁵ Pa)
at 800℃
for 2 minutes
N-doping treatment (example: the "2/6 recipe")
800C UHV, 3 hours
800C N₂ injection p=25mTorr
800C N₂ 2 minutes
800C UHV, 6 minutes
UHV cooling
5 um EP
Nb
N
N Interstitial
Fermilab
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27/04/2013

	WHY	COMMENTS
Forming		
EB Welding	Clean welding	Nb = getter material. ↑RRR/ 10 @ welding => Q_0/10
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Electropolish ~~Chemical etching~~ 100-200 µm (BCP / EP / CBP)		mitation : BCP ~ 30MV/m; EP => >40 mV/m t lack of reproducibility
Annealing 800°C, 2h (or 600°C, 10h)	Get rid of hydrogen	Source of H: wet processes H segregates near surface in form of
Electropolish ~~Chemical polish 5-20 µm~~		
Specific rinsing		
High pressure rinsing (HPR)		
Assembling		
~~Baking, 120°C,12-48hr~~		
Post processing		
Test RF		
He processing, HPP		

Electropolish by 5-7µm

N-doping treatment (example: the "2/6 recipe")

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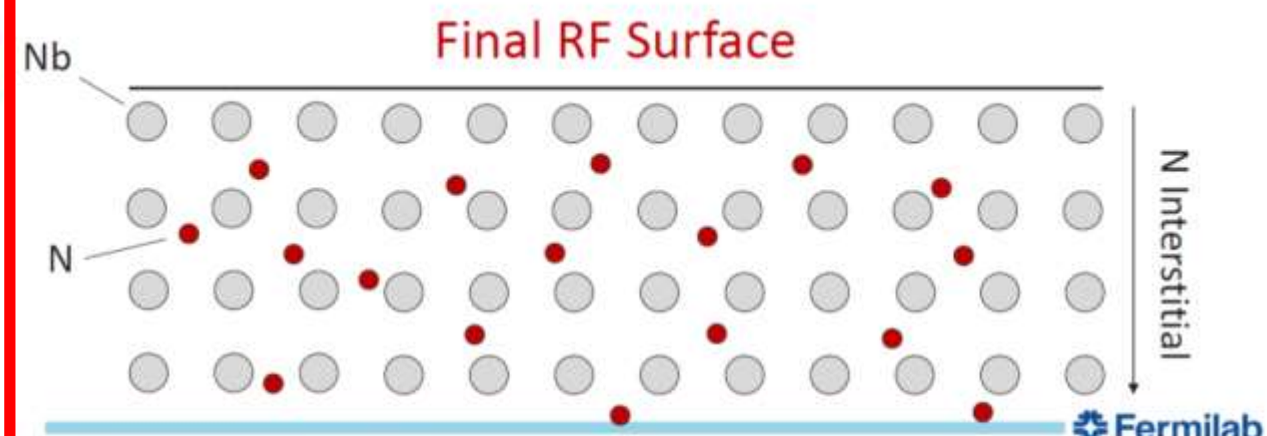

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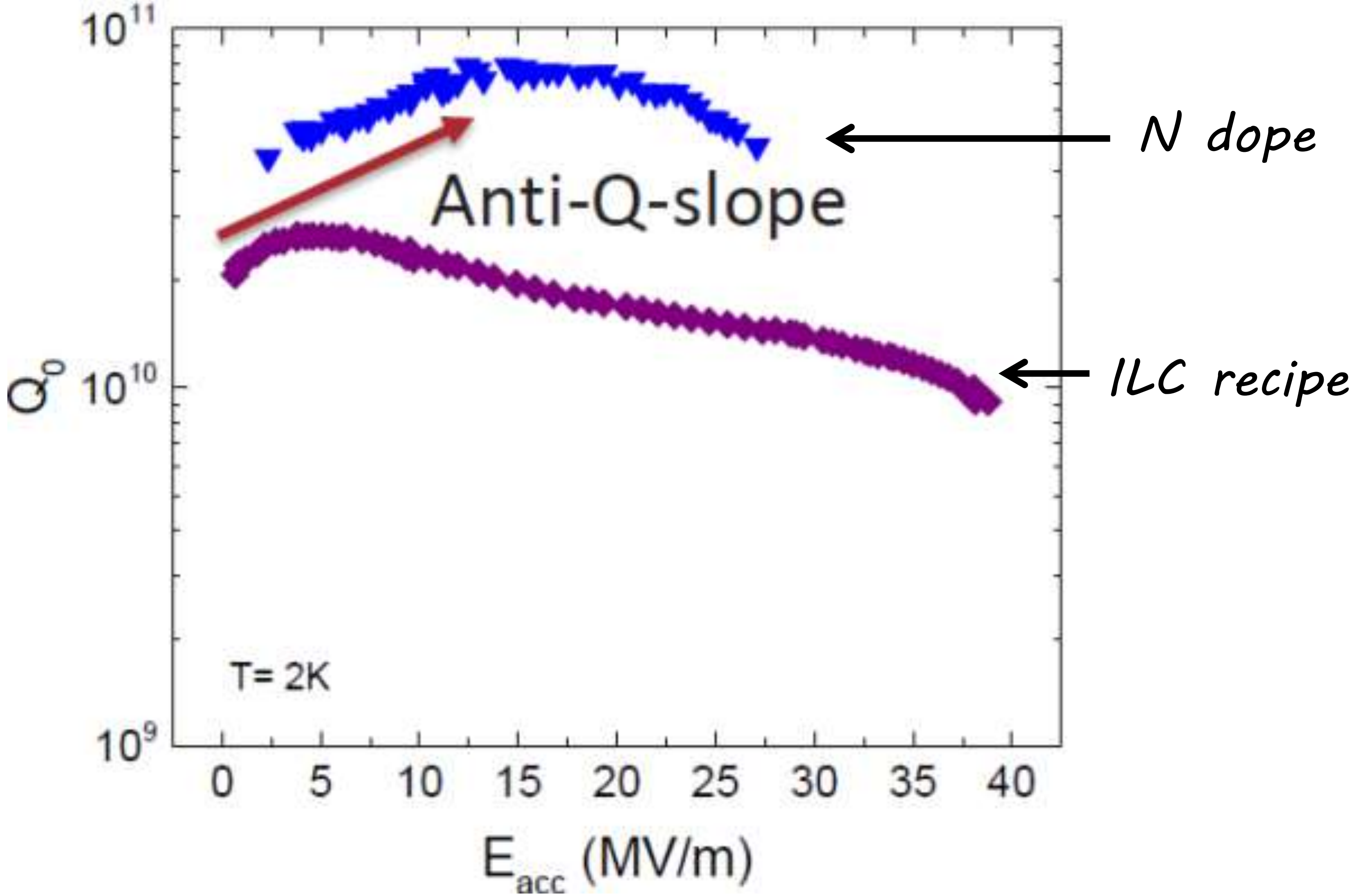
Then we obtain a "high Q"



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

Why does Q increase as the field increases?

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Let us begin with a brief review of the surface resistance of SRF cavity.

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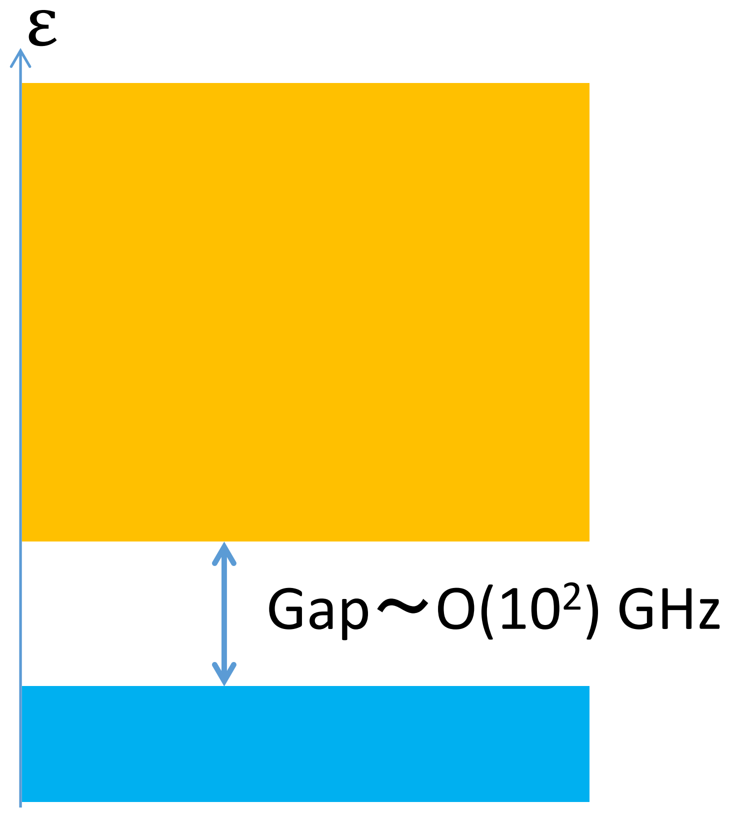

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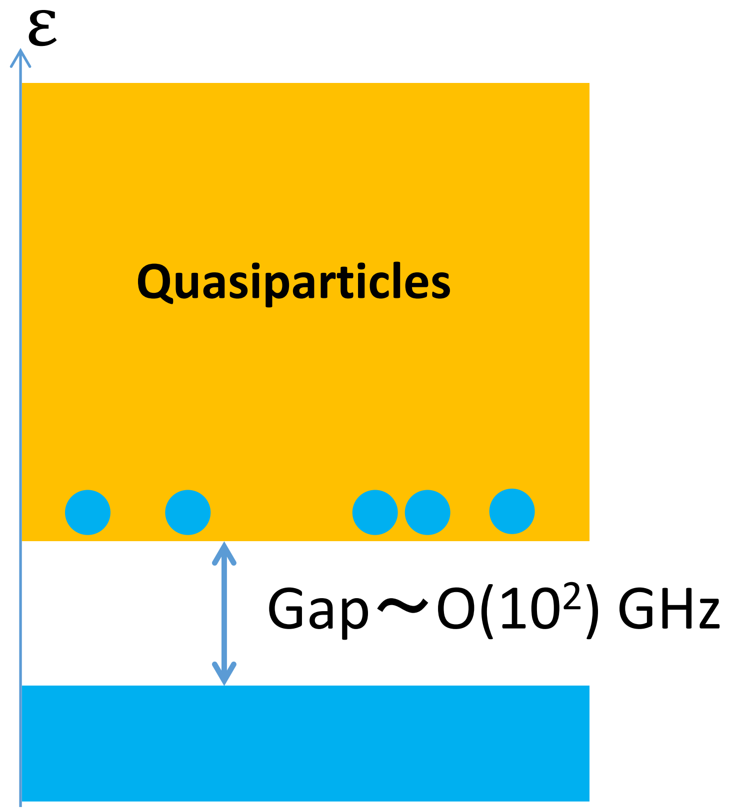
However, when T > 0, Quasiparticles (normal electrons) necessarily exist above the gap.



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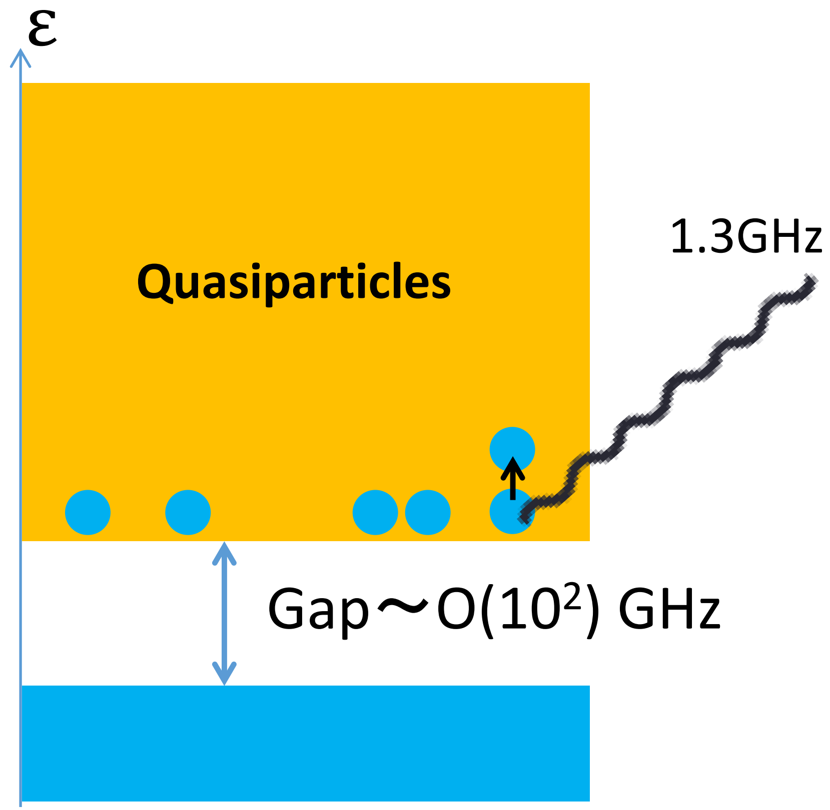
Let us begin with a brief review of the surface resistance of SRF cavity.

The gap is much larger than RF: RF (~GHz) cannot break Cooper pair.

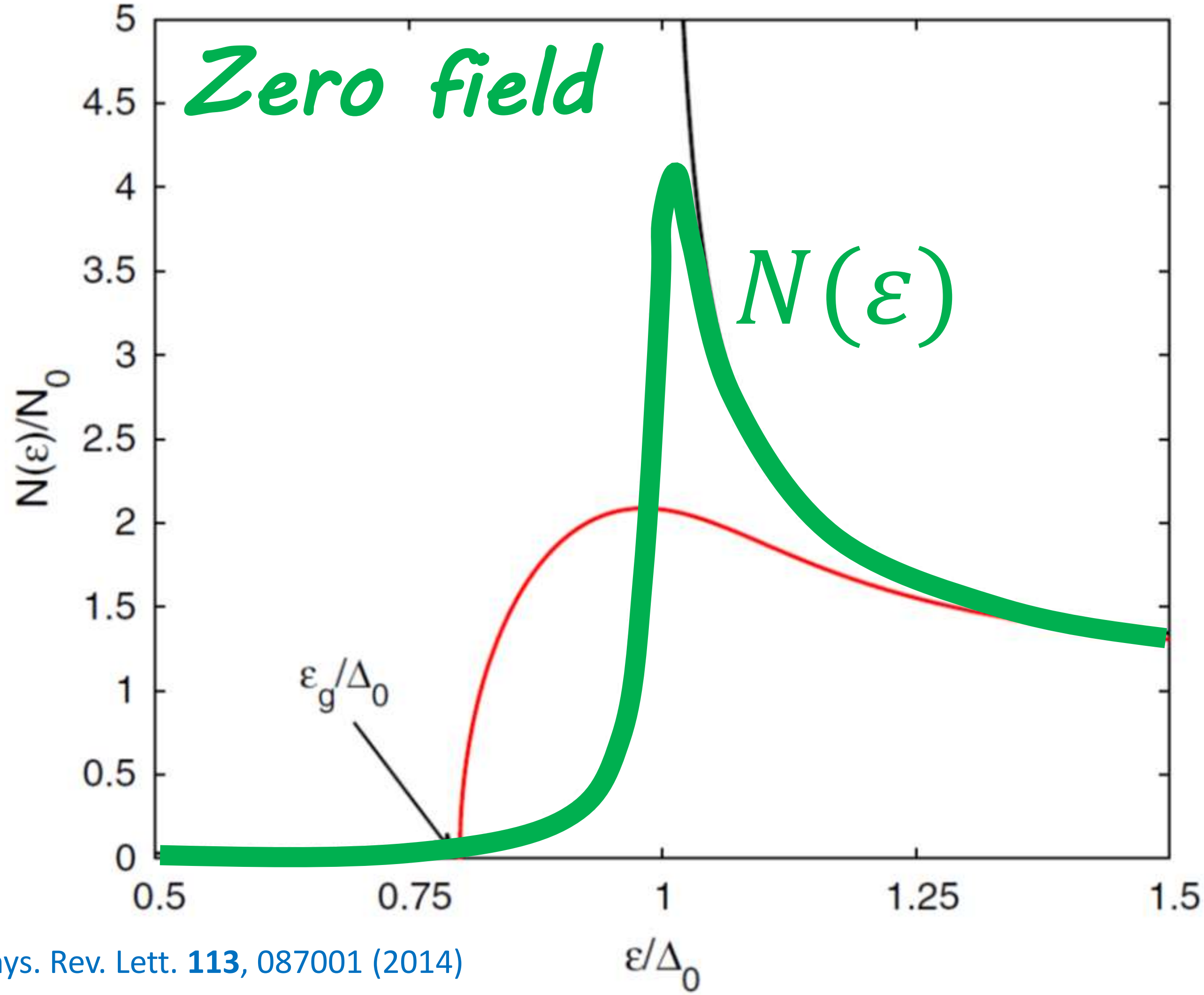
However, when $T > 0$, Quasiparticles (normal electrons) necessarily exist above the gap.
They absorb RF
$\rightarrow$ $P \neq 0$
$\rightarrow$ $R_s \neq 0$

$$R_s \sim \int d\epsilon \, N(\epsilon) N(\epsilon + \hbar\omega) e^{-\epsilon/kT}$$



Why does Q increase as the field increases?

$$R_s \propto \ln \frac{1}{peak\ width}$$



A. Gurevich, Phys. Rev. Lett. **113**, 087001 (2014)

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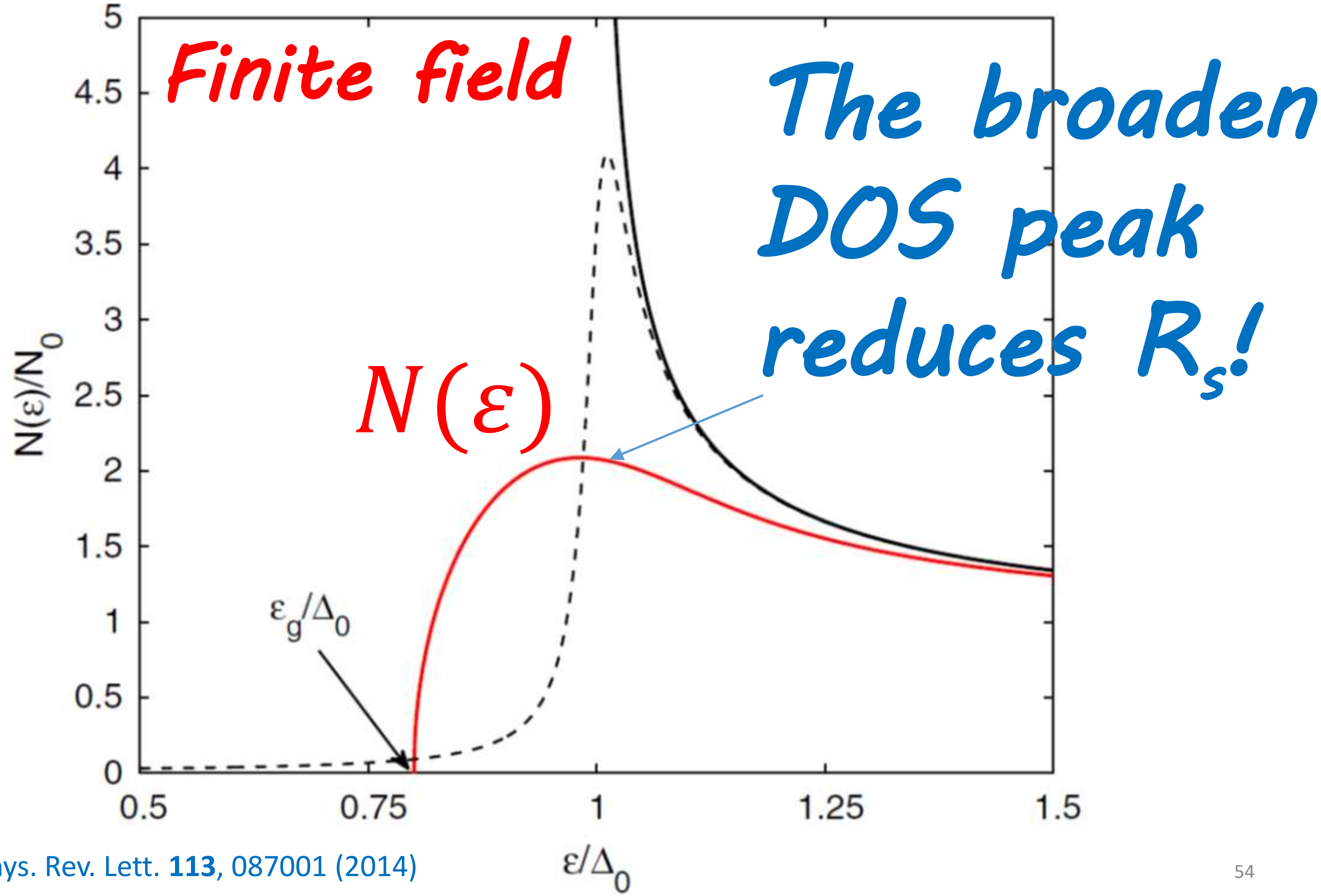


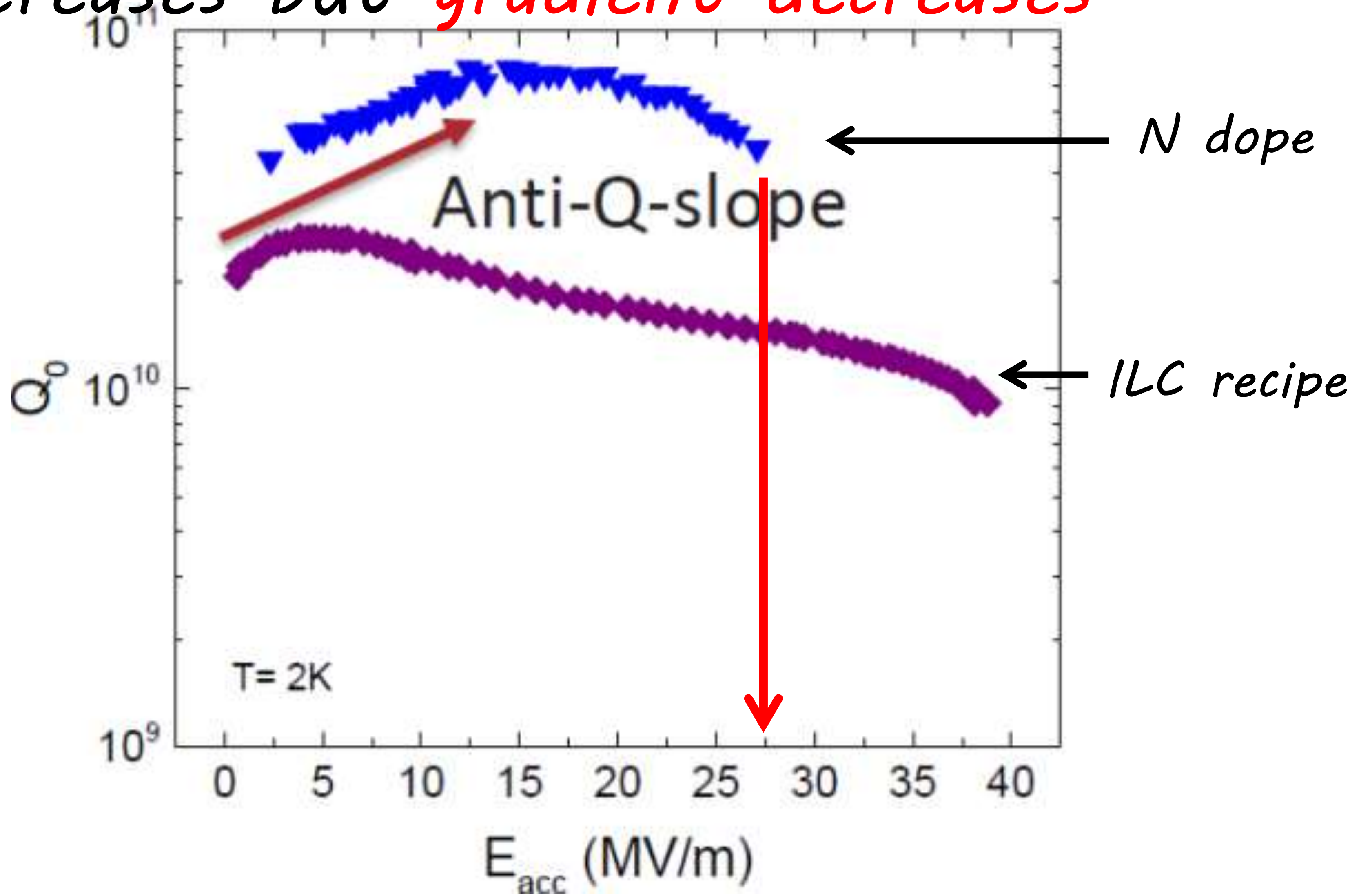
A. Gurevich, Phys. Rev. Lett. **113**, 087001 (2014)

- R_s of ideal dirty SC generally decreases as the field increases: the Q-increase phenomenon is rather natural behavior of dirty SC.

- However, very low RRR(~10) Nb cavities, which are also dirty SC, do not show the "Q-increase". What is the difference between N and other impurities? What is the role of N?

Disadvantage of N-dope:

Q increases but gradient decreases.



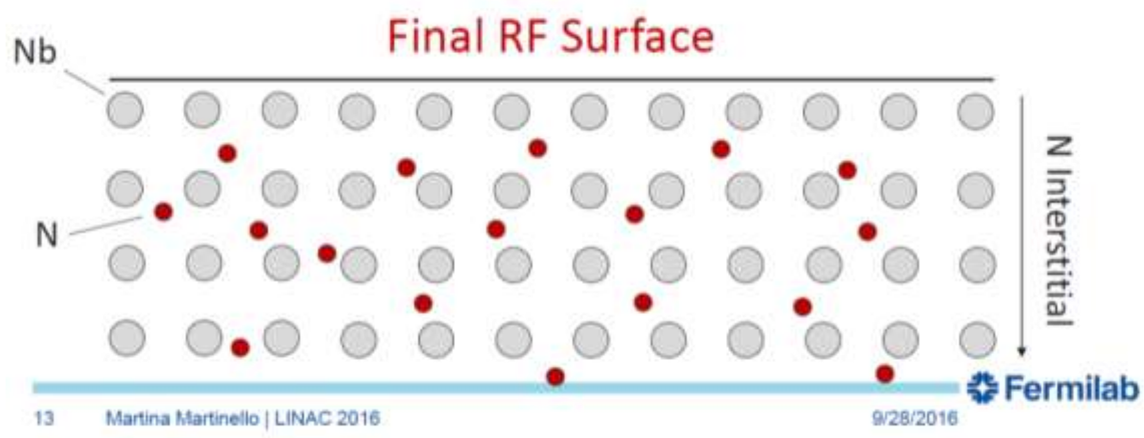
A. Grassellino et al, Supercond. Sci. Technol. **26** 102001 (2013)

The reason is obvious!

Interstitial N reduces mean free path:

RRR=300 (mfp > 700nm) material $\xrightarrow{\text{N-dope}}$ mfp~50nm

M. Martinello et al, Appl. Phys. Lett. **109**, 062601 (2016)

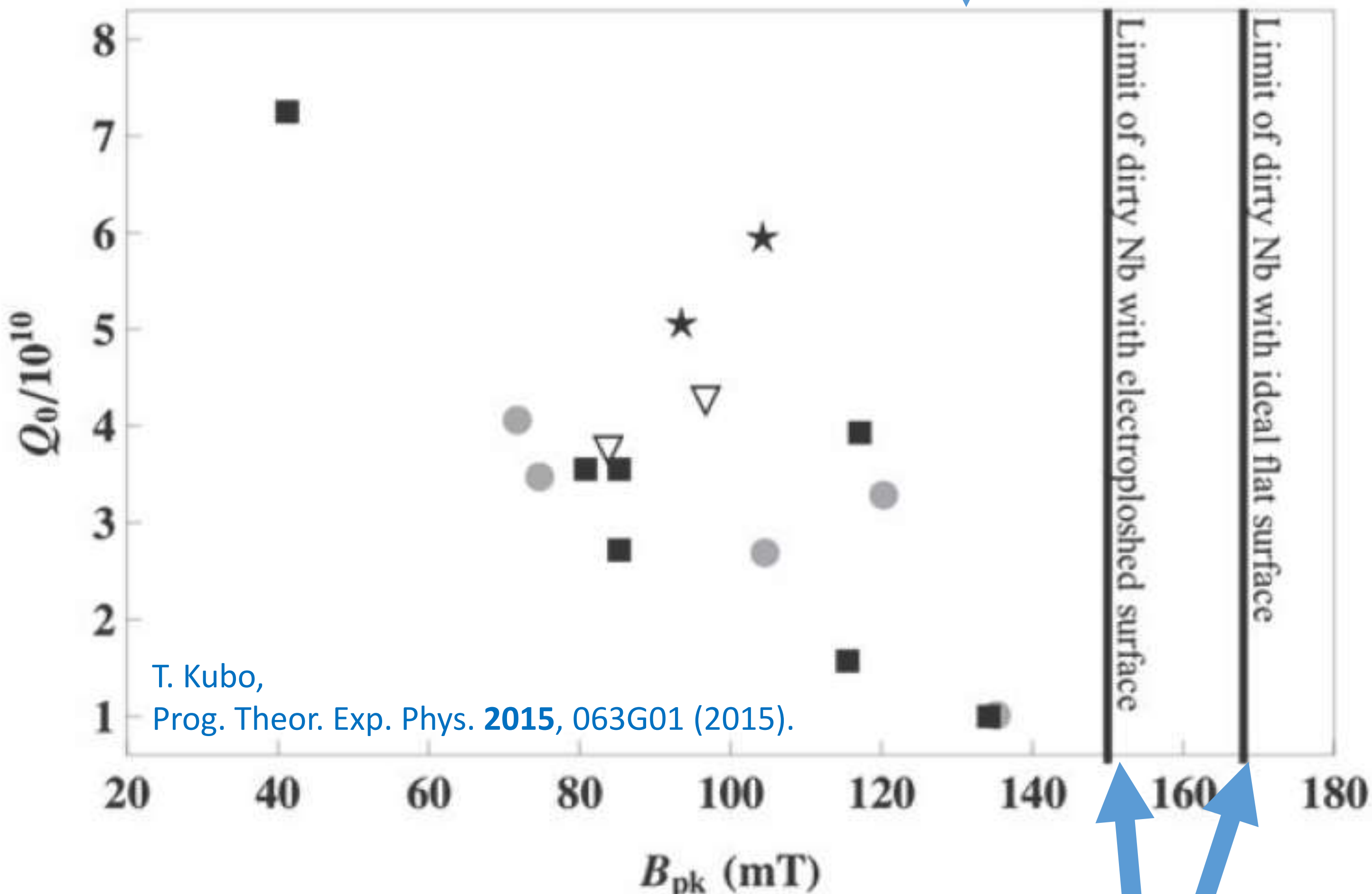


Then B_{c1}=170mT $\xrightarrow{\text{N-dope}}$ B_{c1}=130mT

E_{acc}=40MV/m which corresponds to E_{acc}=30MV/m!!

※Tesla空洞の35MV/m
は150mTに対応

B_{c1} around here



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

Superheating field B_s of dirty Nb

※Tesla空洞の35MV/m
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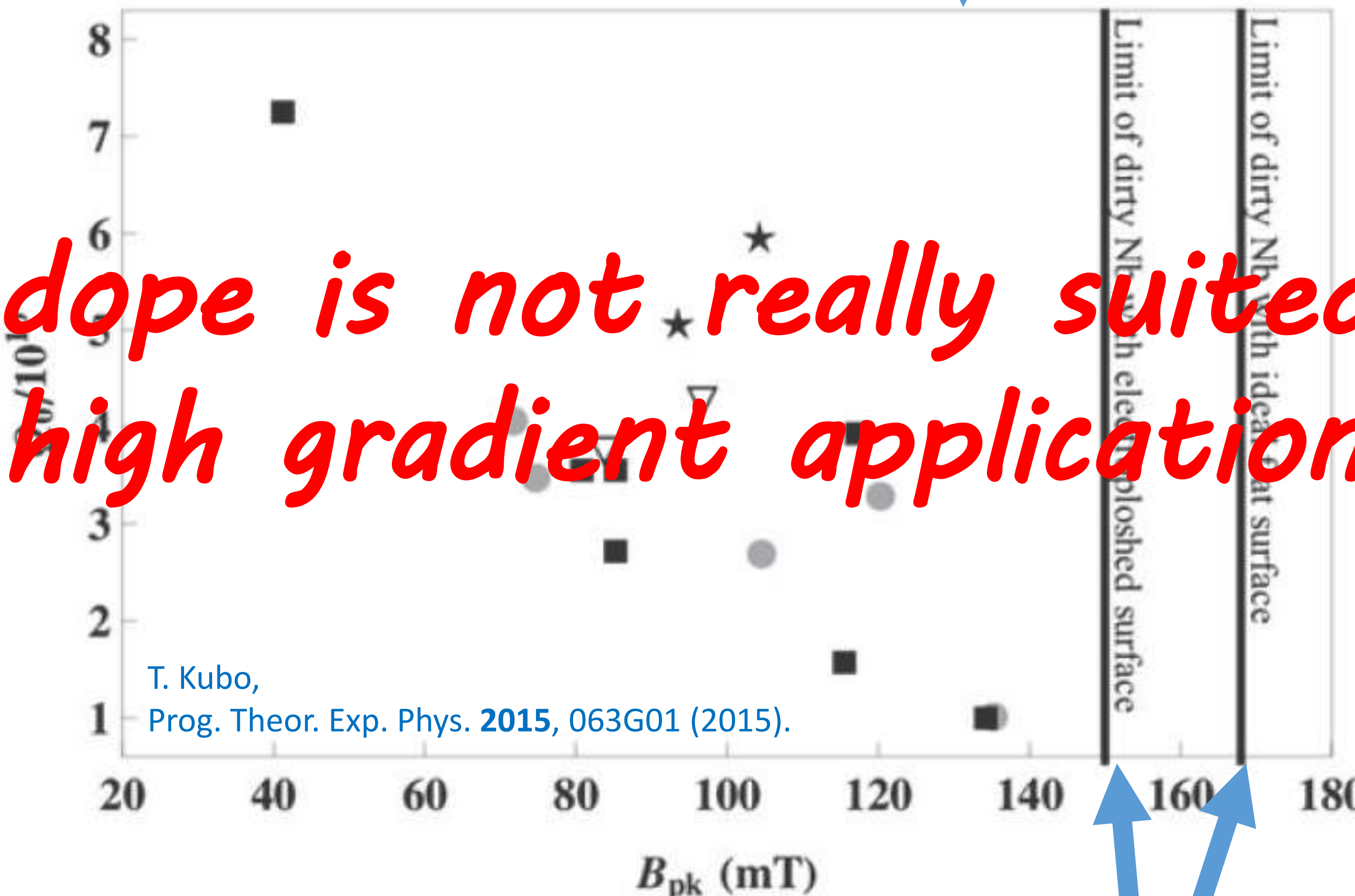


N-dope is not really suited to high gradient application!

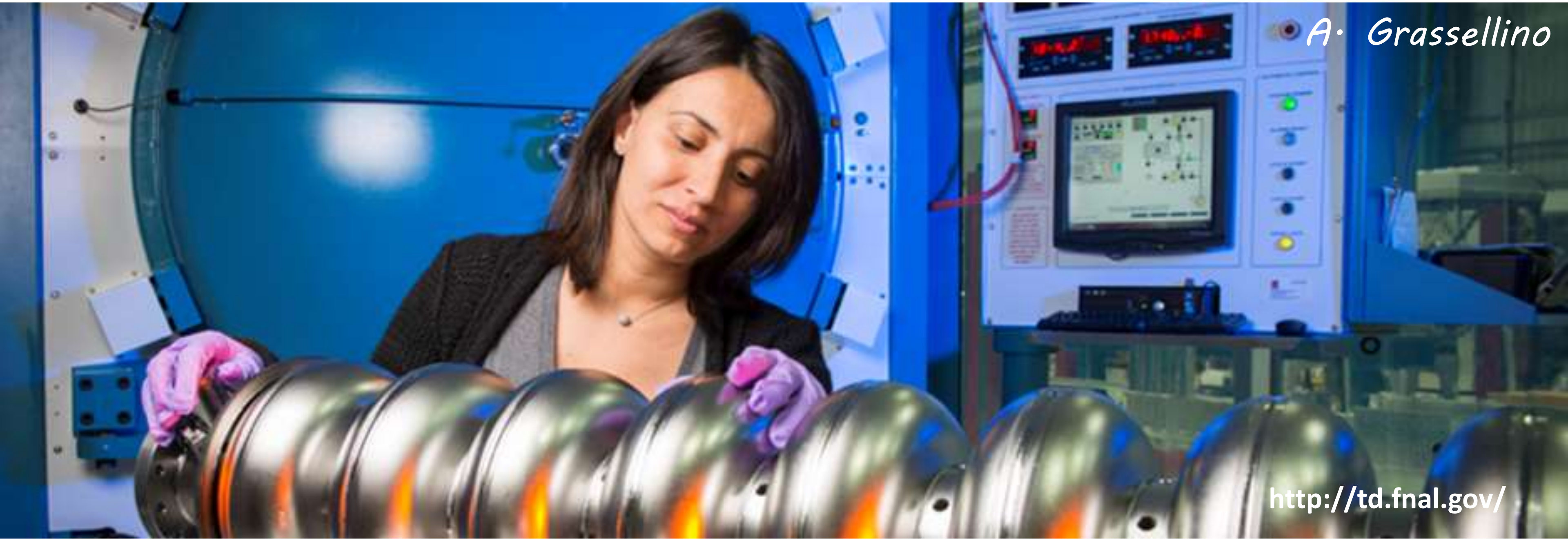
T. Kubo,
Prog. Theor. Exp. Phys. **2015**, 063G01 (2015).

Superheating field B_s of dirty Nb

References
(related to the N-dope)

- A. Grassellino et al, Supercond. Sci. Technol. **26** 102001 (2013)
- P. Dhakal et al., Phys. Rev. ST Accel. Beams **16**, 042001 (2013)
- G. Ciovati, P. Dhakal, and A. Gurevich, Appl. Phys. Lett. **104**, 092601 (2014)
- A. Gurevich, Phys. Rev. Lett. **113**, 087001 (2014)
- T. Kubo, Prog. Theor. Exp. Phys. **2015**, 063G01 (2015)
- M. Martinello et al, Appl. Phys. Lett. **109**, 062601 (2016)

N infusion
(new ILC recipe?)



They knew

1. The dirty-clean layered structure realized in ILC recipe (120℃-48hours bake) is the **key to high gradients**.

A. Romanenko et al., Appl. Phys. Lett. **104**, 072601 (2014)

2. Nitrogen doping is the **key to high Q**.

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

They considered
"Let us combine 1 and 2"

→ Nitrogen infusion

	WHY	COMMENTS
Forming		
EB Welding	Clean welding	Nb = getter material. If RRR/ 10 @ welding => Q_0/10
~~Ti purification~~	RRR enhancement	RRR 300-400 now commercially available
Electropolish ~~Chemical etching~~ 100-200 µm (BCP, EP, CBP)	Remove contamination and damage layer	Limitation : BCP ~ 30MV/m; EP => >40 mV/m but lack of reproducibility
Annealing 800°C, 2h (or 600°C, 10h)	Get rid of hydrogen	Source of H: wet processes. H segregates near surface in form of hydrides (= bad SC)
Electropolish ~~Chemical polish~~ 5-20 µm	Remove diffusion layer (O, C, N)	Diffusion layer < ~1µm in bulk, a little higher at Grain Boundaries
Specific rinsing	e.g. remove S particles due to EP	Under evaluation. HF, H_2O_2, ethanol, degreasing,…
High pressure rinsing (HPR)	Get rid of dust particles	Not always enough (recontamination during assembly)
Assembling	Ancillaries : antennas, couplers , vacuum ports…	**In clean room, but recontamination still possible**
Baking, 120°C,12-48hr	Decrease high field losses (Q-drop)	Unknown mechanism, first 10 nm of the surface in concern.
Post processing	Get rid of "re-contamination" ?	Under evaluation: dry ice cleaning, plasma
Test RF	Cavity's performance	First naked cavity in vertical cryostat, then dressed in horizontal cryostat/ accelerating facility
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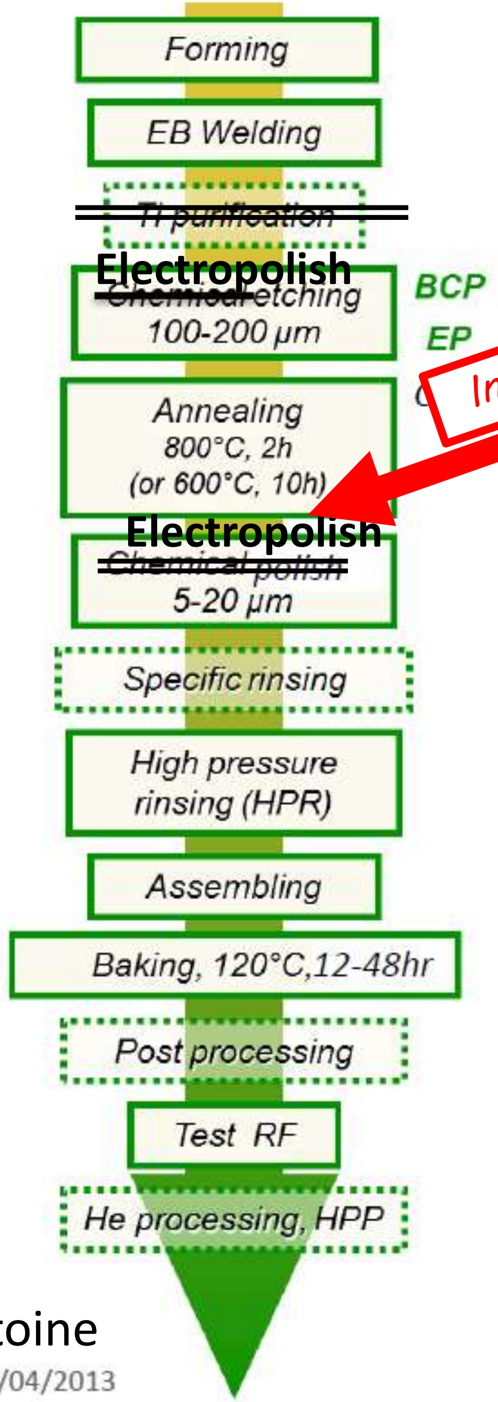
C. Antoine



WHY

Clean welding

RRR enhancement

Get rid of hydrogen

hydrides (= bad SC)

Insert additional step

Inject N_2 gas

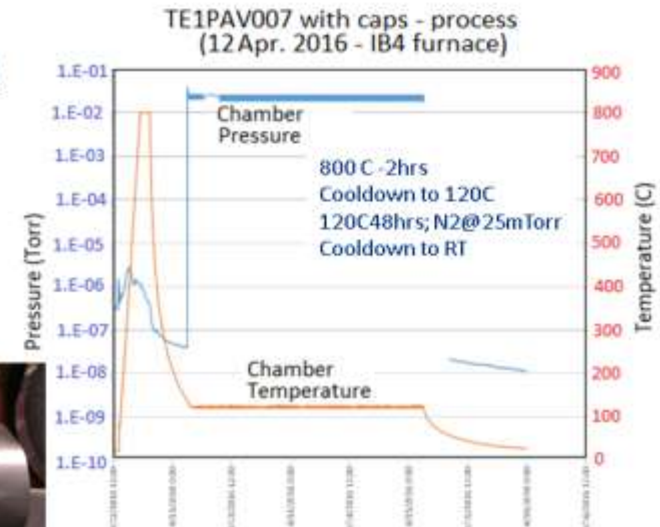
($\sim 3 \times 10^{-5}$ Pa)

at 120℃

for 48 hours

The surface processing sequence

- Bulk electro-polishing
- High T furnace with caps to avoid furnace contamination:
  - 800C 2 hours HV
  - 120C 48 hours with N2
- NO chemistry
- HPR, VT assembly



Fermilab

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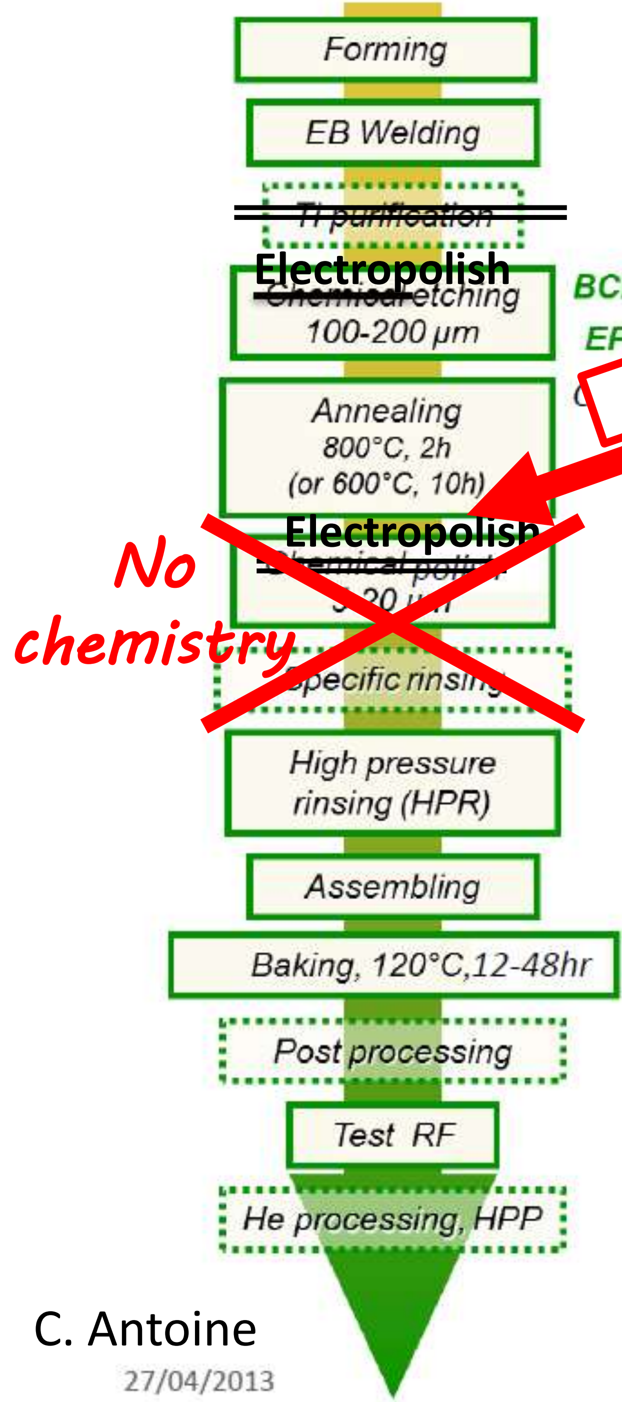

C. Antoine
27/04/2013

WHY

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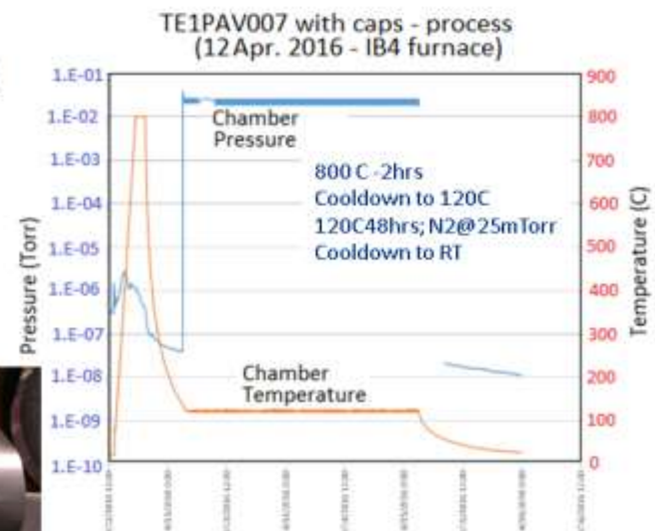
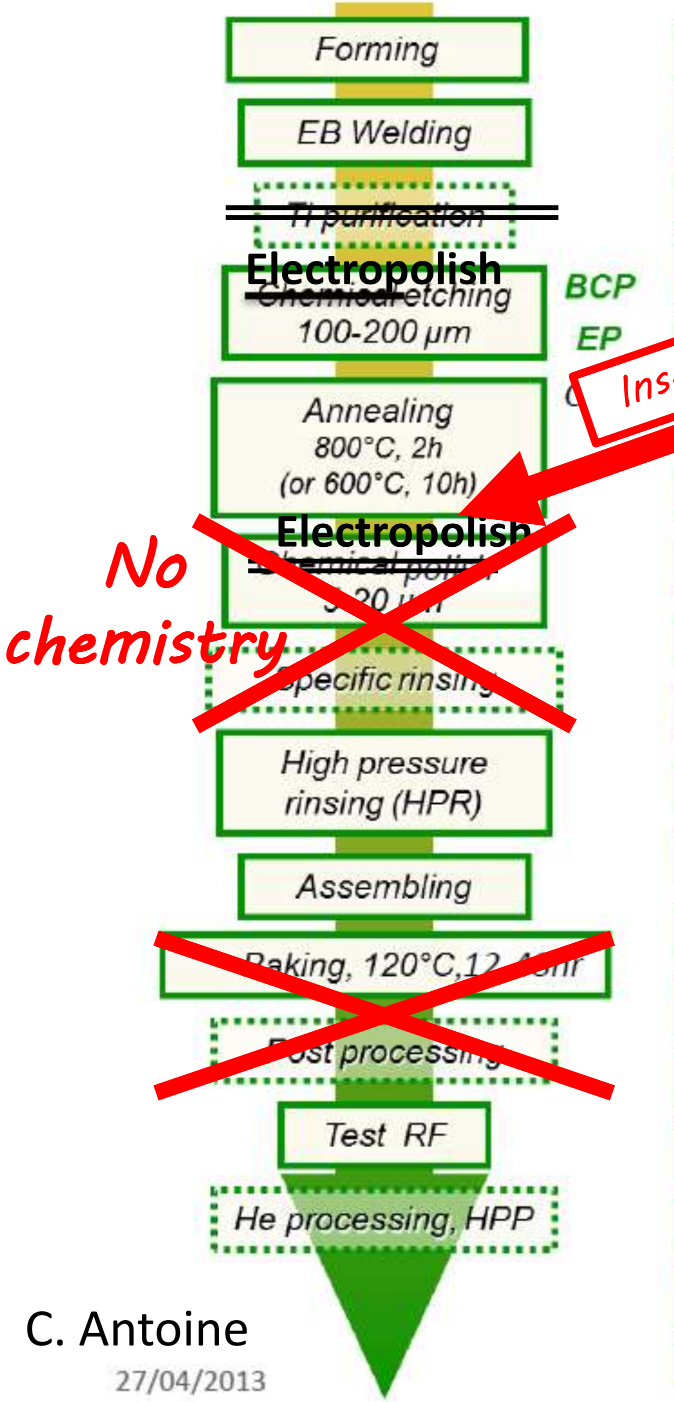


Fermilab

N Solyak | High E, high Q
ECFALC, May 30-Jun 5, 2016, Spain
7



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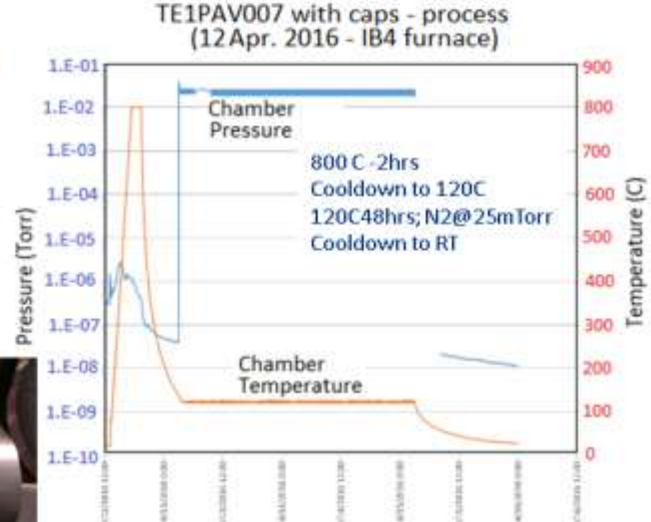
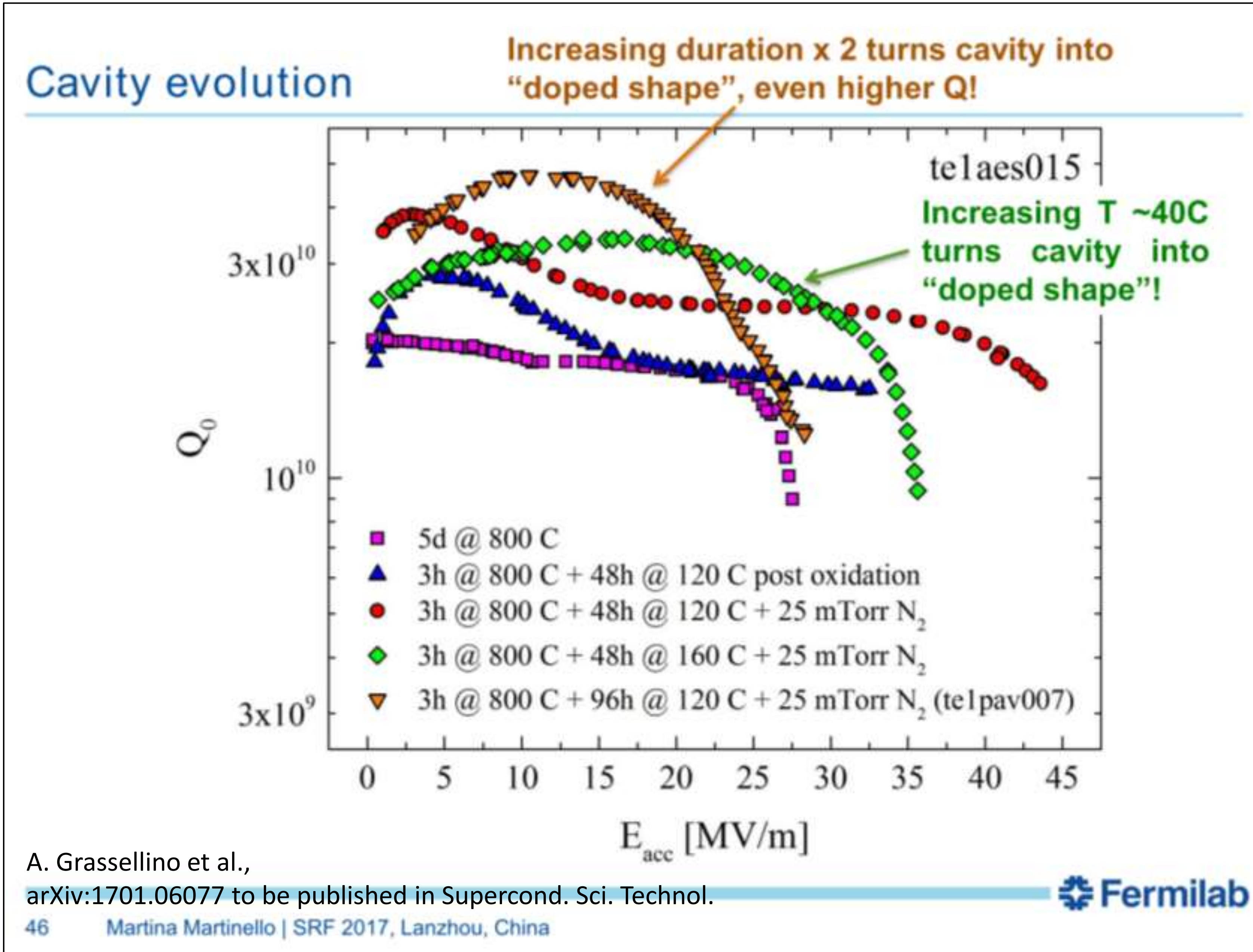


Fermilab

Then we obtain "high-Q & high gradient"



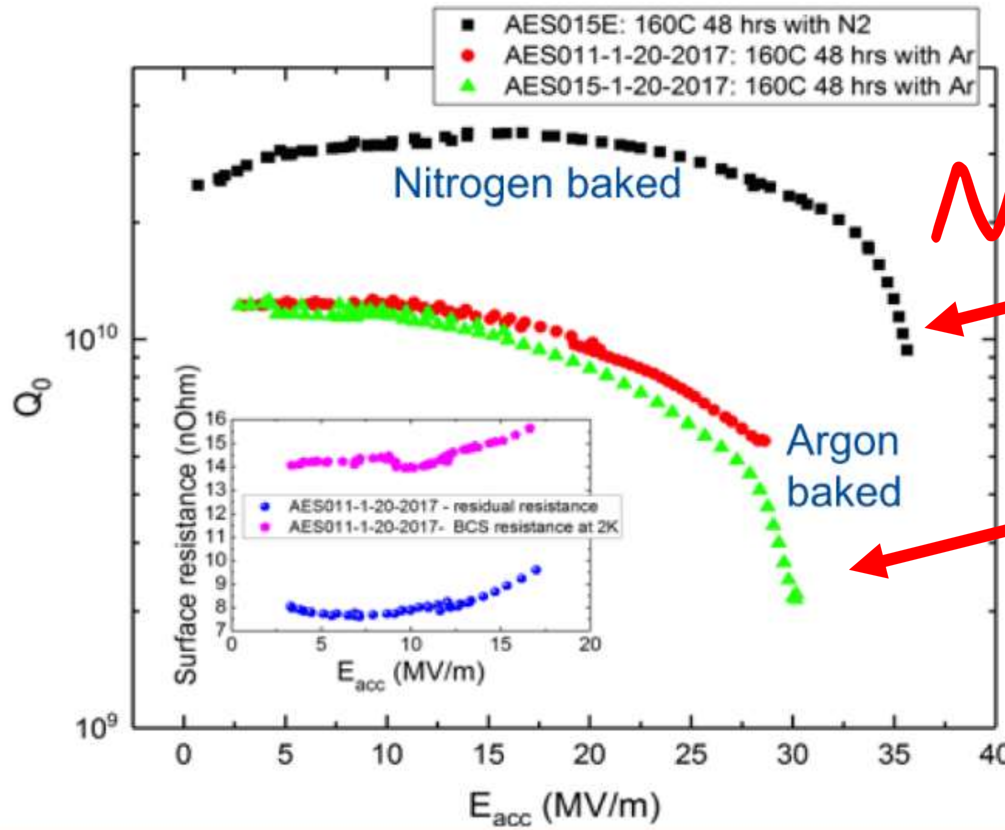
A. Grassellino et al., arXiv:1701.06077 to be published in Supercond. Sci. Technol.

Nitrogen plays a role

Is nitrogen really playing a role at 160C (BCS reversal)?

YES ✓

- Repeated same procedure with and without nitrogen in furnace at 160C (both of comparable ultra-purity 99.9999%)
- Check if other impurities may be the ones responsible for BCS reversal, rather than nitrogen

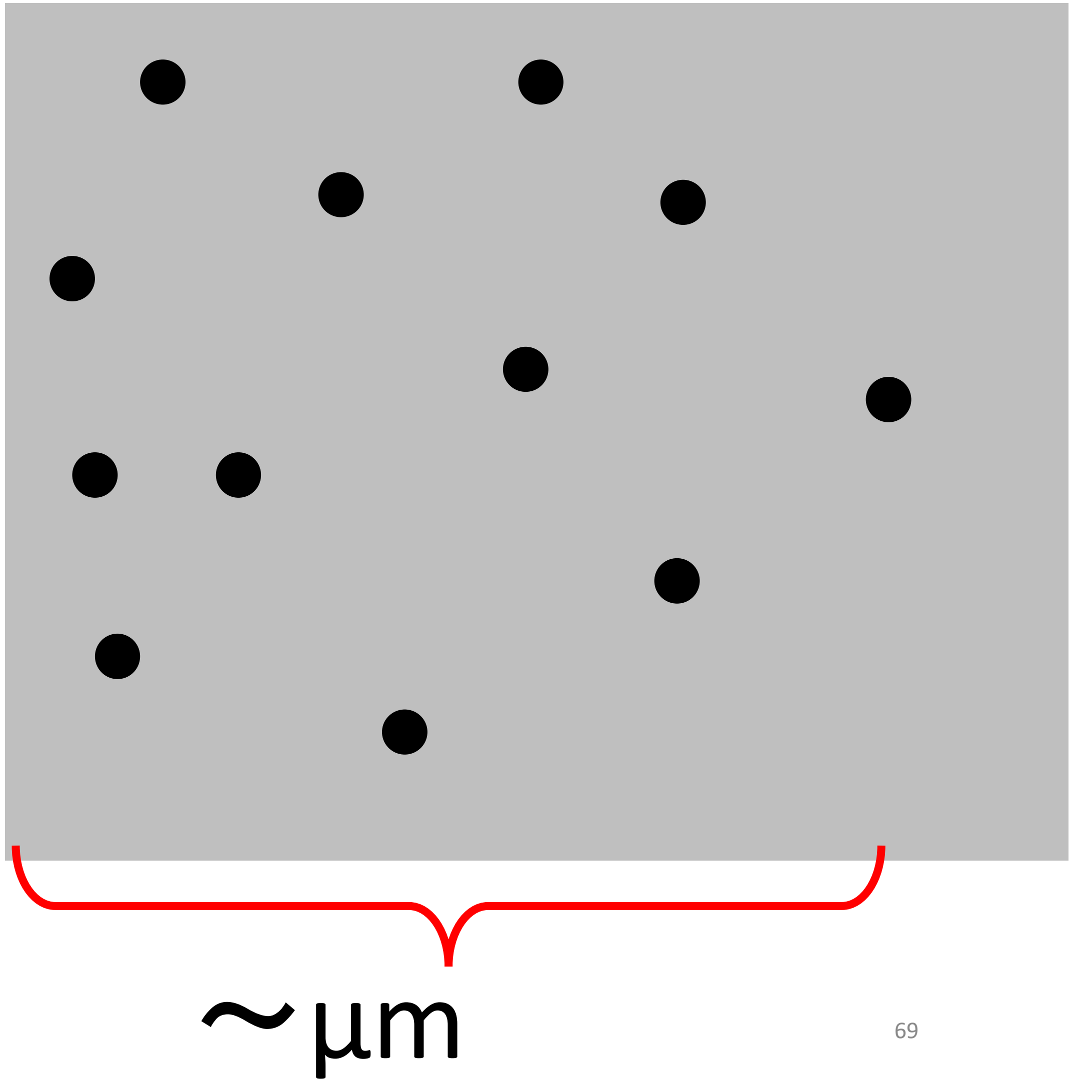


Nitrogen

Argon

Why is the high gradient possible?

Let us remind the small B_{c1} of N-dope comes from its dirtiness at the depth up to μm.



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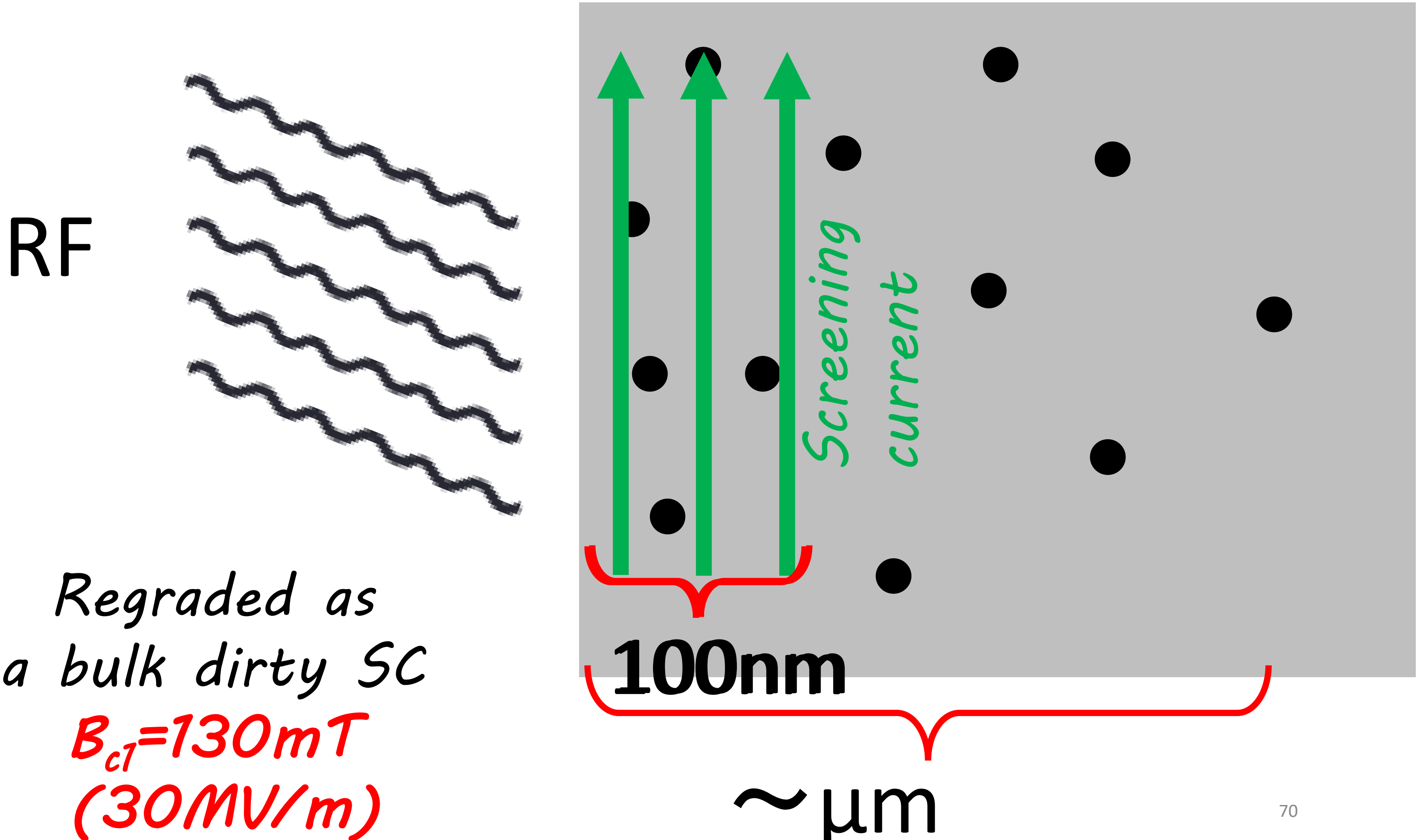
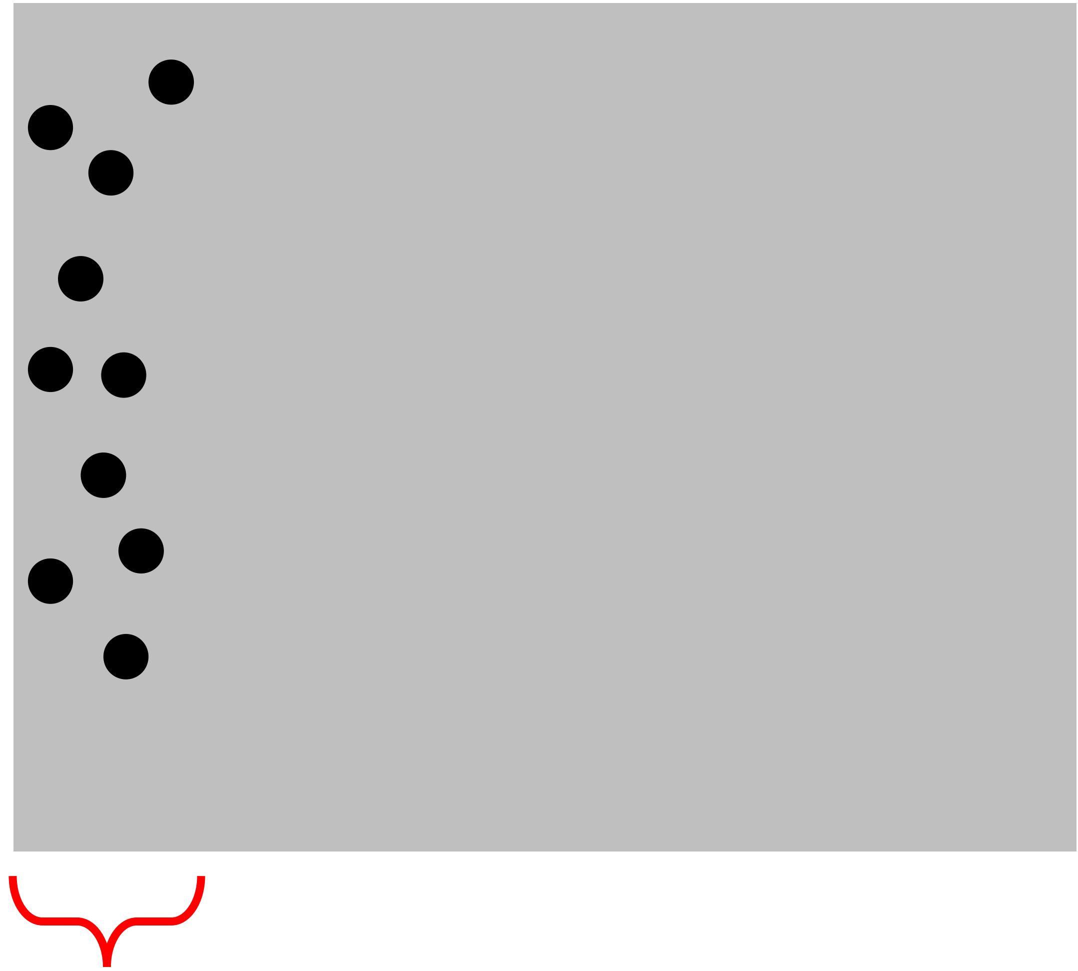


Regraded as a bulk dirty SC

B_{c1}=130mT (30MV/m)

Why is the high gradient possible?

In the N-infusion case, the dirty region is confined in the first tens of nm.



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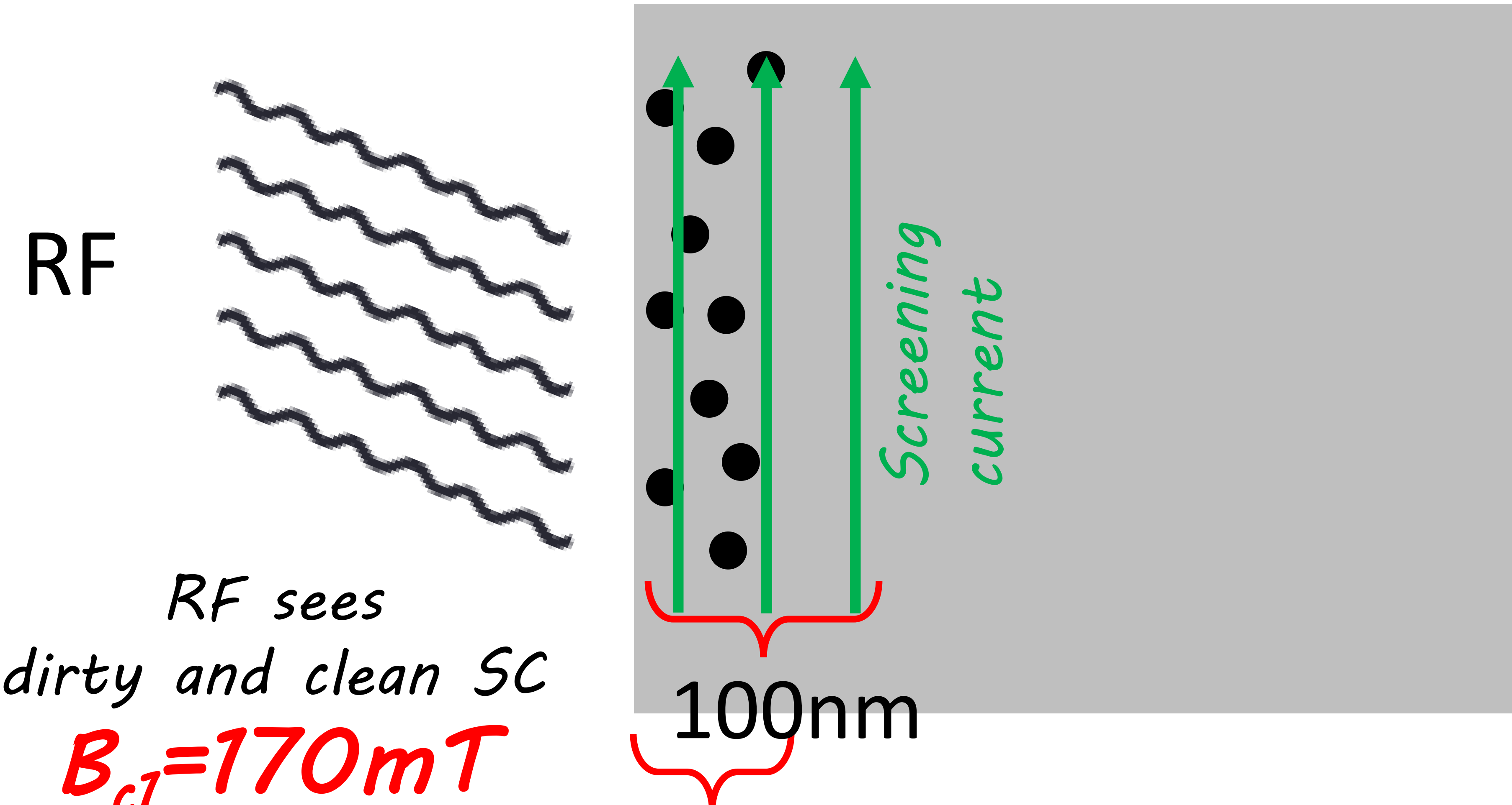


RF sees dirty and clean SC

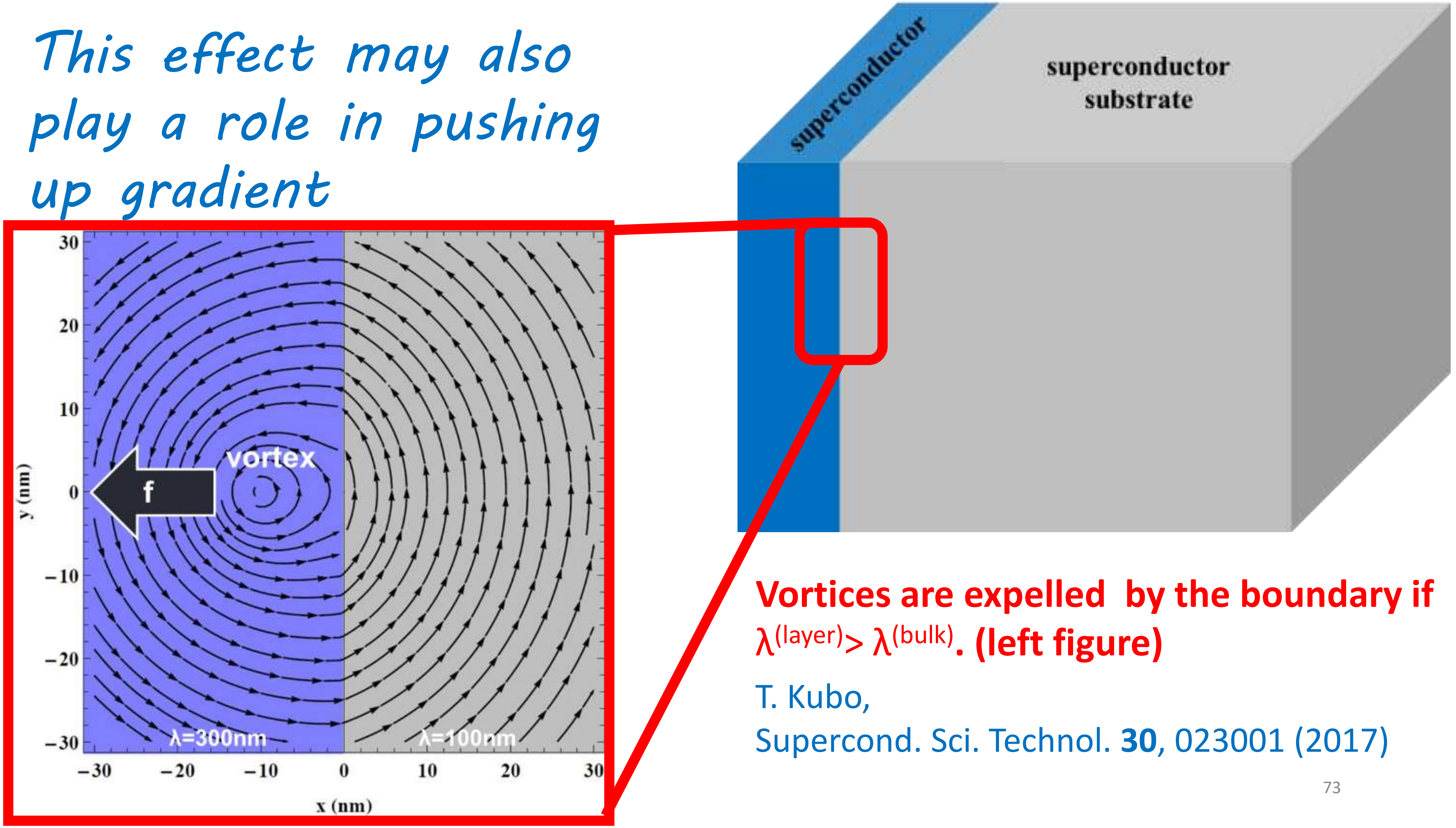
B_{c1}=170mT (40MV/m)

A few tens of nm

Why is the high gradient possible?

In the N-infusion case, the dirty region is confined in the first tens of nm.

This effect may also play a role in pushing up gradient



Vortices are expelled by the boundary if $\lambda^{(layer)} > \lambda^{(bulk)}$. (left figure)

T. Kubo,
Supercond. Sci. Technol. **30**, 023001 (2017)

Why is the high Q possible?

Open Question

- Probably the similar mechanism as N-dope: remind the cavity behavior approaches N-dope behavior when baking T increases.

- What is the role of N?

- N induces high Q, but others do not. This might be the key to understand it.

References
(related to the N-infusion)

- A. Grassellino et al., arXiv:1701.06077 to be published in Supercond. Sci. Technol.

- F. P-J. Lin and A. Gurevich, Phys. Rev. B **85**, 054513 (2012)
- T. Kubo, Supercond. Sci. Technol. **30**, 023001 (2017)
- T. Kubo and A. Gurevich, "Unified Theory of surface resistance and residual resistance of SRF cavities at low temperatures", SRF2017 invited talk.

Flux expulsion

http://www.fnal.gov/pub/today/images/images11/Romanenko.jpg

This is really excellent finding, but we do not have enough time to introduce this today. A. Romanenko, et al., Appl. Phys. Lett. **105**, 234103 (2014)

References

(related to the flux expulsion)

- A. Romanenko, et al., Appl. Phys. Lett. **105**, 234103 (2014)
- T. Kubo, Prog. Theor. Exp. Phys. **2016**, 053G01 (2016)
- S. Huang, T. Kubo, and R. Geng, Phys. Rev. Accel. Beams **19**, 082001 (2016)
- S. Posen et al., J. Appl. Phys. **119**, 213903 (2016)

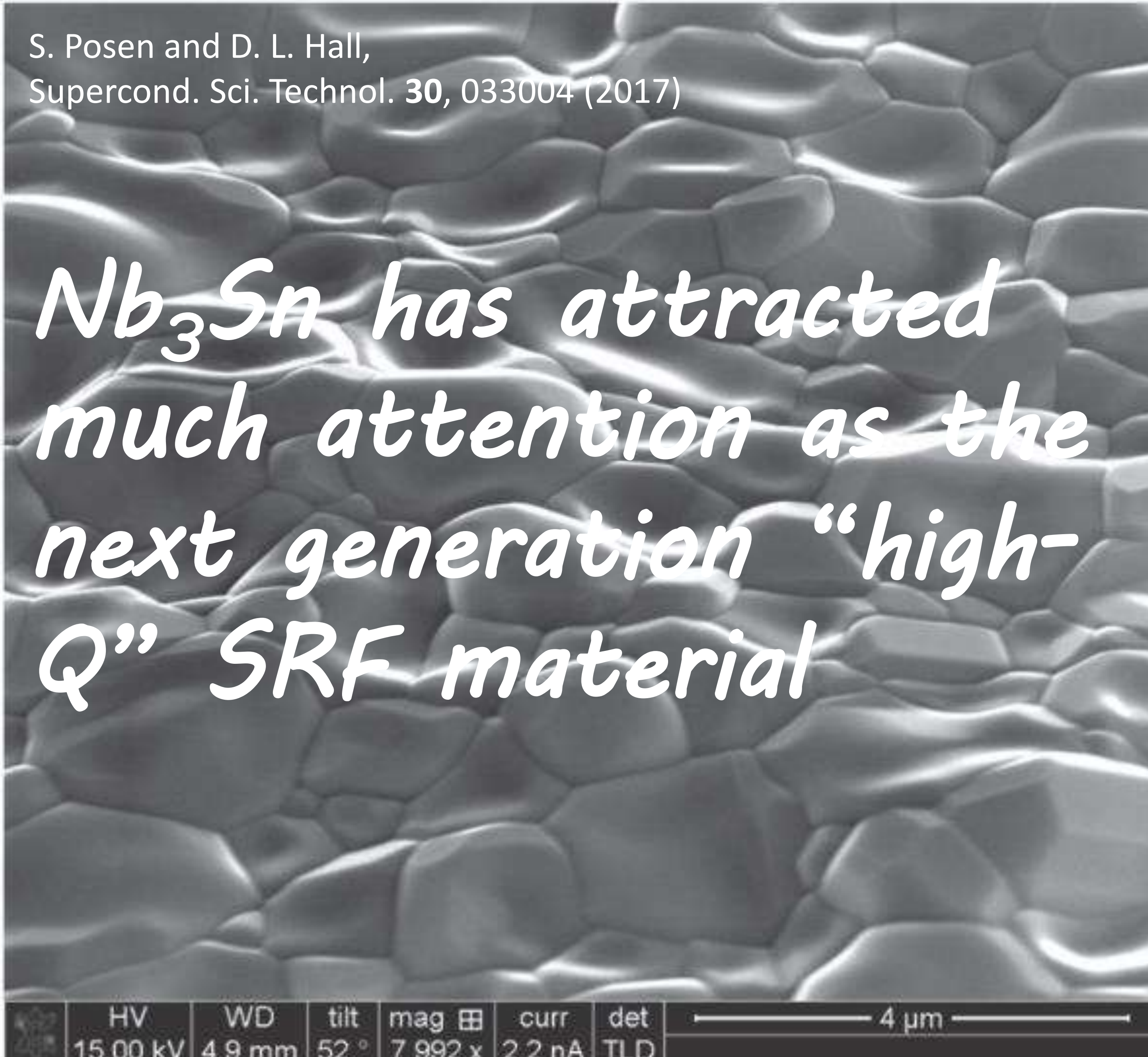
Further high-Q and high-Grad

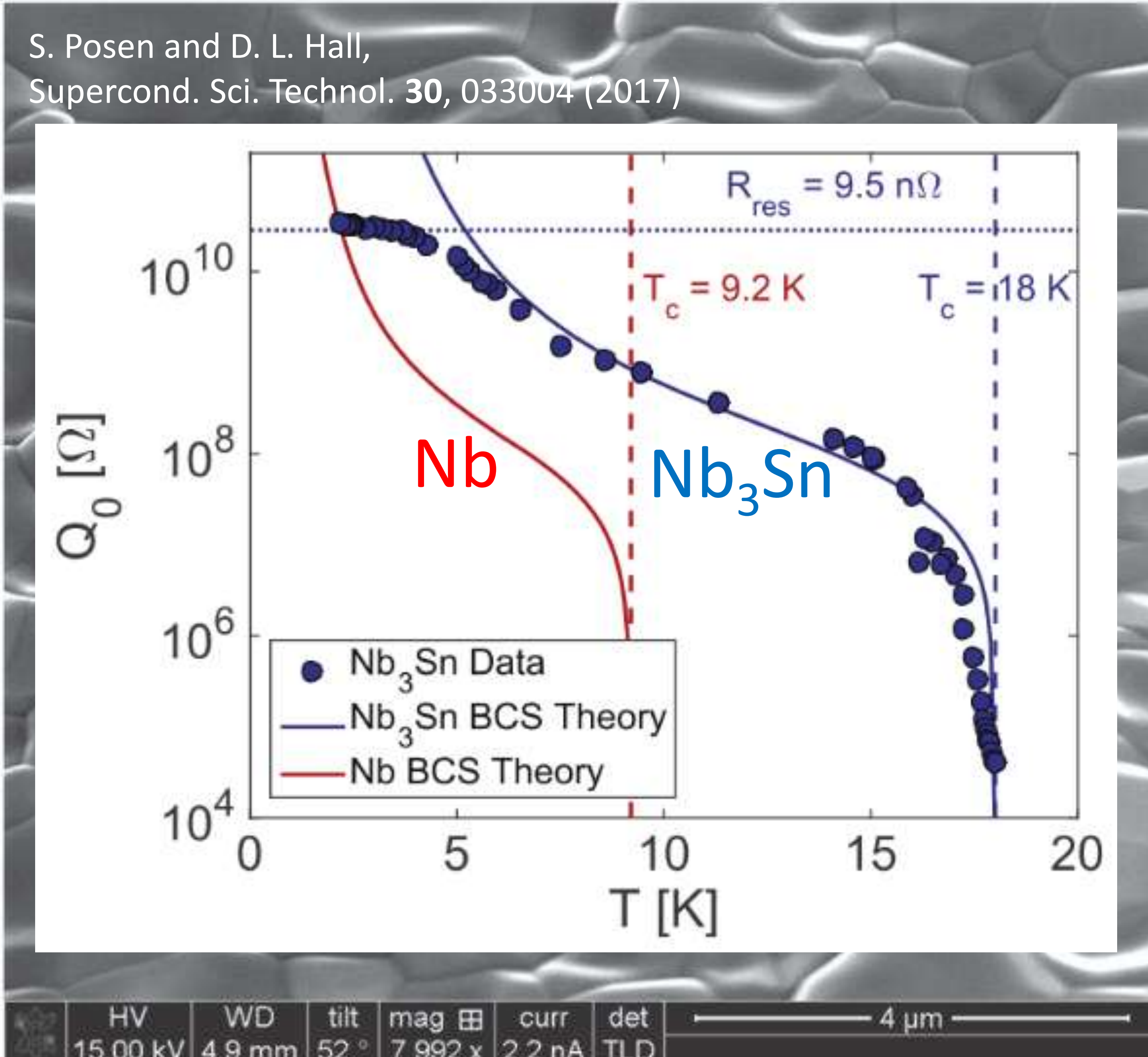
http://news.fnal.gov/2016/06/sam-posen-wins-2016-ieee-past-award/

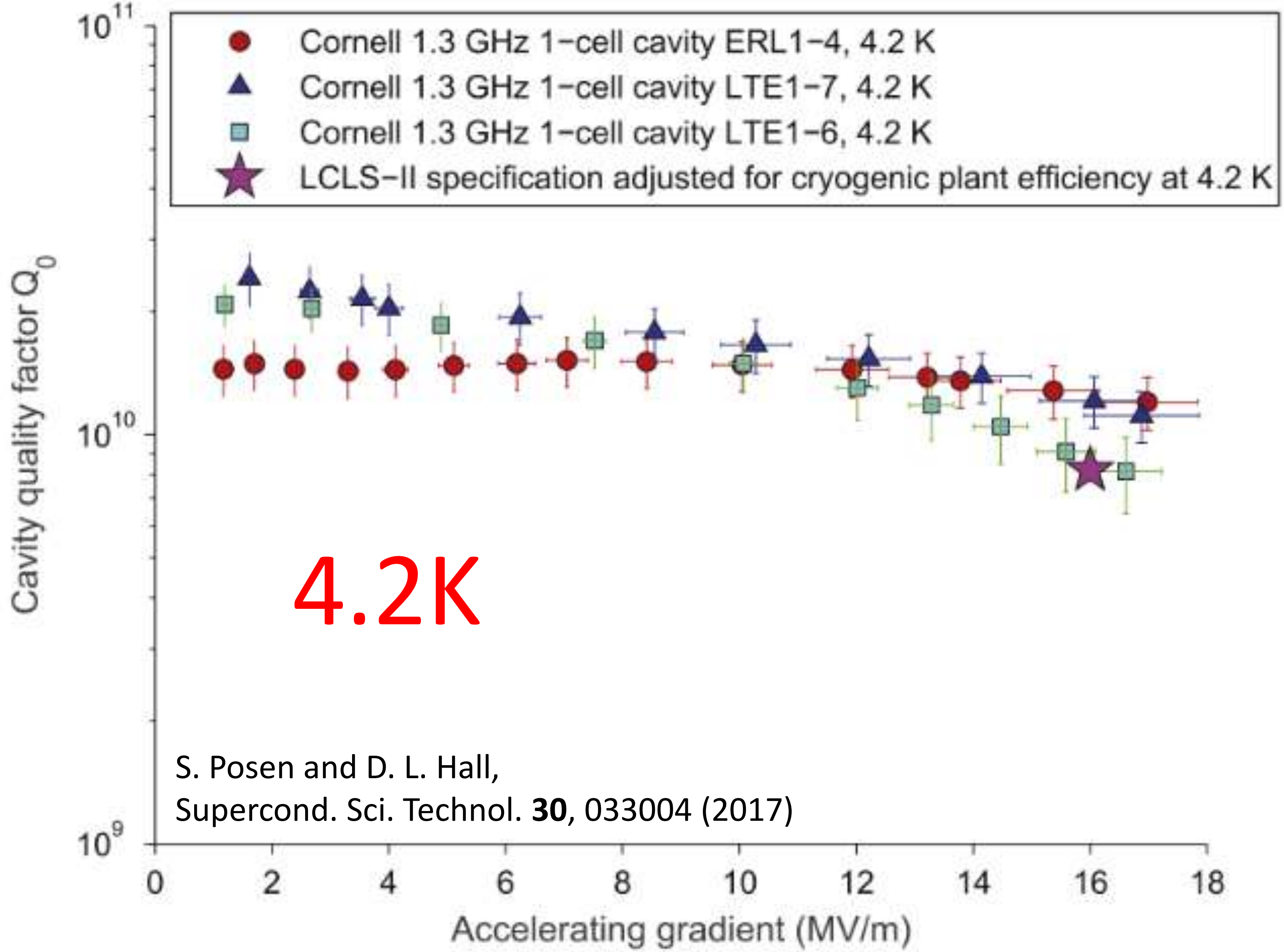
(Ultra) High-Q

S. Posen and D. L. Hall,
Supercond. Sci. Technol. **30**, 033004 (2017)

Nb_3Sn has attracted much attention as the next generation “high-Q” SRF material



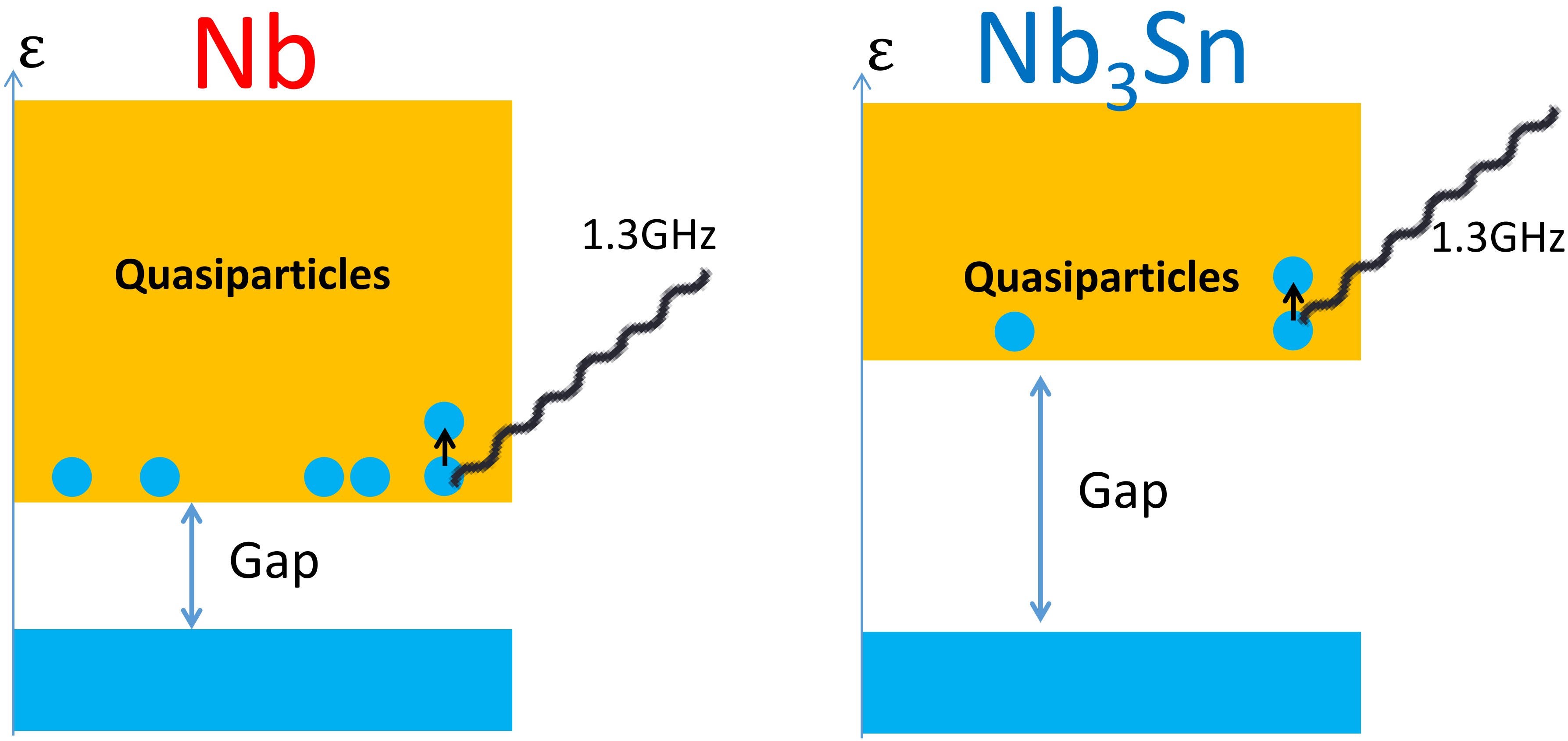

S. Posen and D. L. Hall,
Supercond. Sci. Technol. **30**, 033004 (2017)
R_{res} = 9.5 nΩ
T_c = 9.2 K
T_c = 18 K
Nb
Nb_3Sn
Q_0 [Ω]
10^{10}
10^8
10^6
10^4
0
5
10
15
20
T [K]
Nb_3Sn Data
Nb_3Sn BCS Theory
Nb BCS Theory
HV 15.00 kV
WD 4.9 mm
tilt 52 °
mag 7 992 x
curr 2.2 nA
det TLD
4 μm



S. Posen and D. L. Hall,
Supercond. Sci. Technol. **30**, 033004 (2017)

Why so high Q?

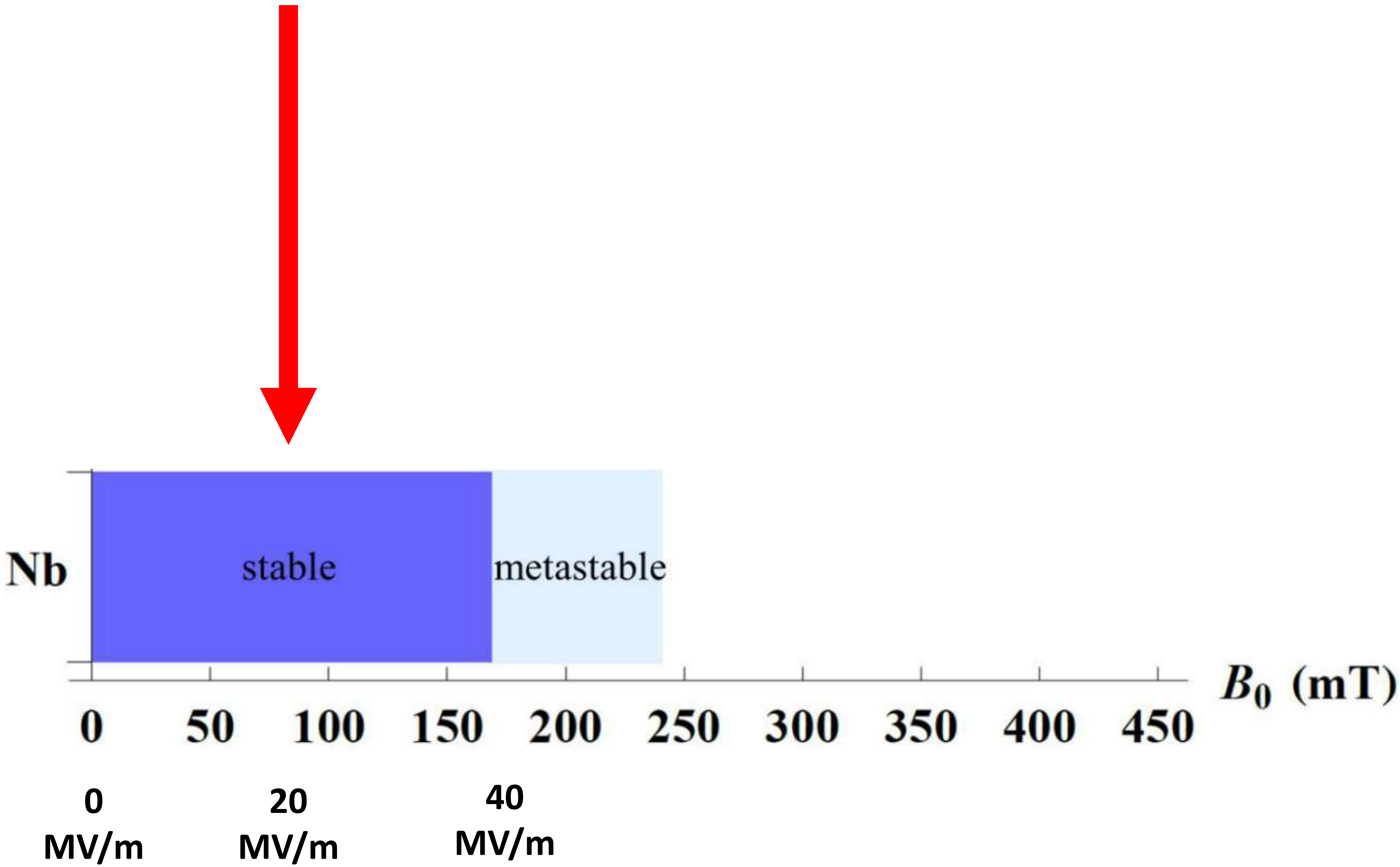
The gap is large, so the number of normal electrons at a given T is exponentially small.



Note that BCS's relation $\Delta = \frac{\pi}{e^{\gamma_E}} k_B T_c \simeq 1.76 k_B T_c$

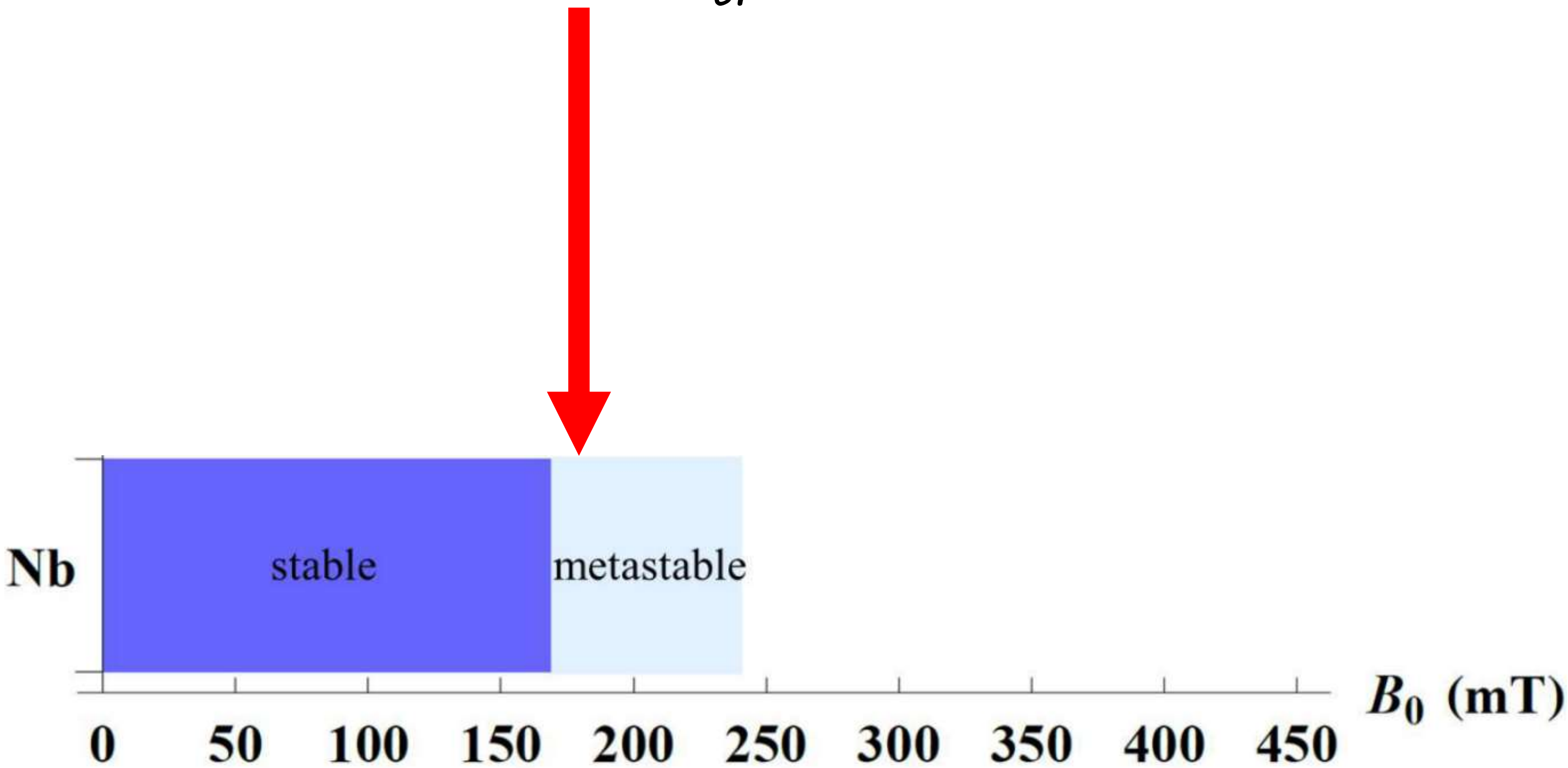
(Ultra) High-Gradient

- Stable Meissner state if $B < B_{c1}$=170mT



T. Kubo, Supercond. Sci. Technol. **30**, 023001 (2017)

- Stable Meissner state if $B < B_{c1}$=170mT
- Metastable at $B > B_{c1}$=170mT



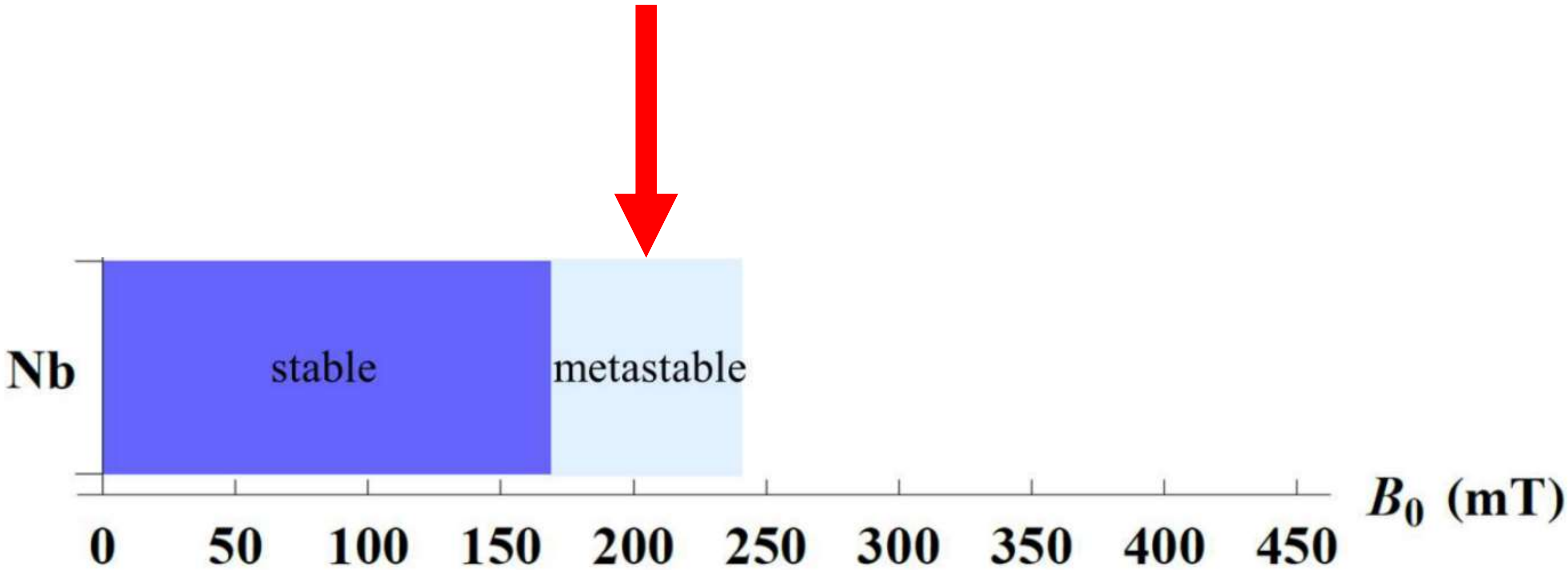
0 MV/m

20 MV/m

40 MV/m

T. Kubo, Supercond. Sci. Technol. **30**, 023001 (2017)

- Stable Meissner state if $B < B_{c1}$=170mT
- Metastable at $B > B_{c1}$=170mT
- The world record exceeds B=200mT, which is close to the ultimate limit!



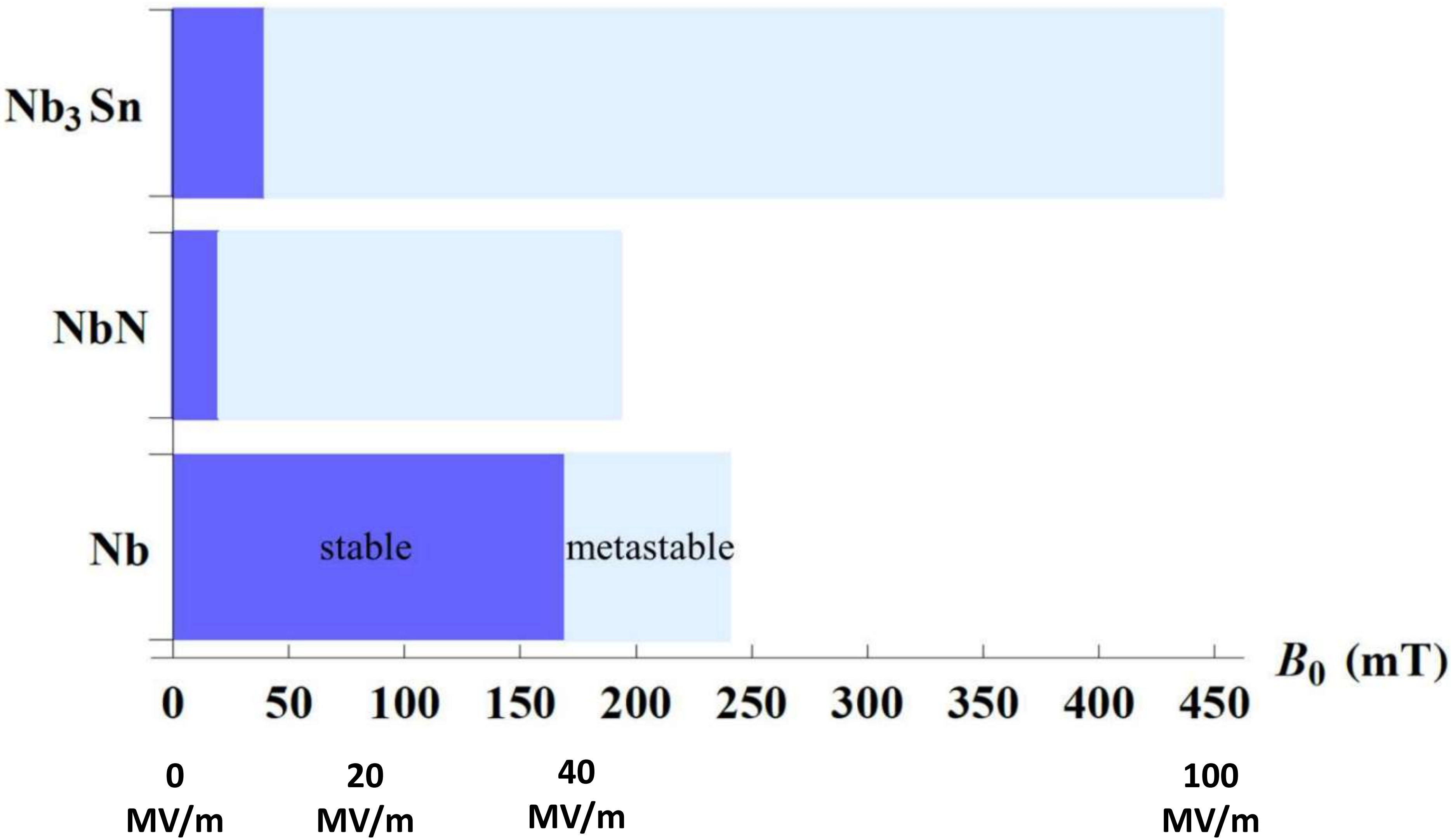
0 MV/m

20 MV/m

40 MV/m

T. Kubo, Supercond. Sci. Technol. **30**, 023001 (2017)

We need to explore new materials!



T. Kubo, Supercond. Sci. Technol. **30**, 023001 (2017)

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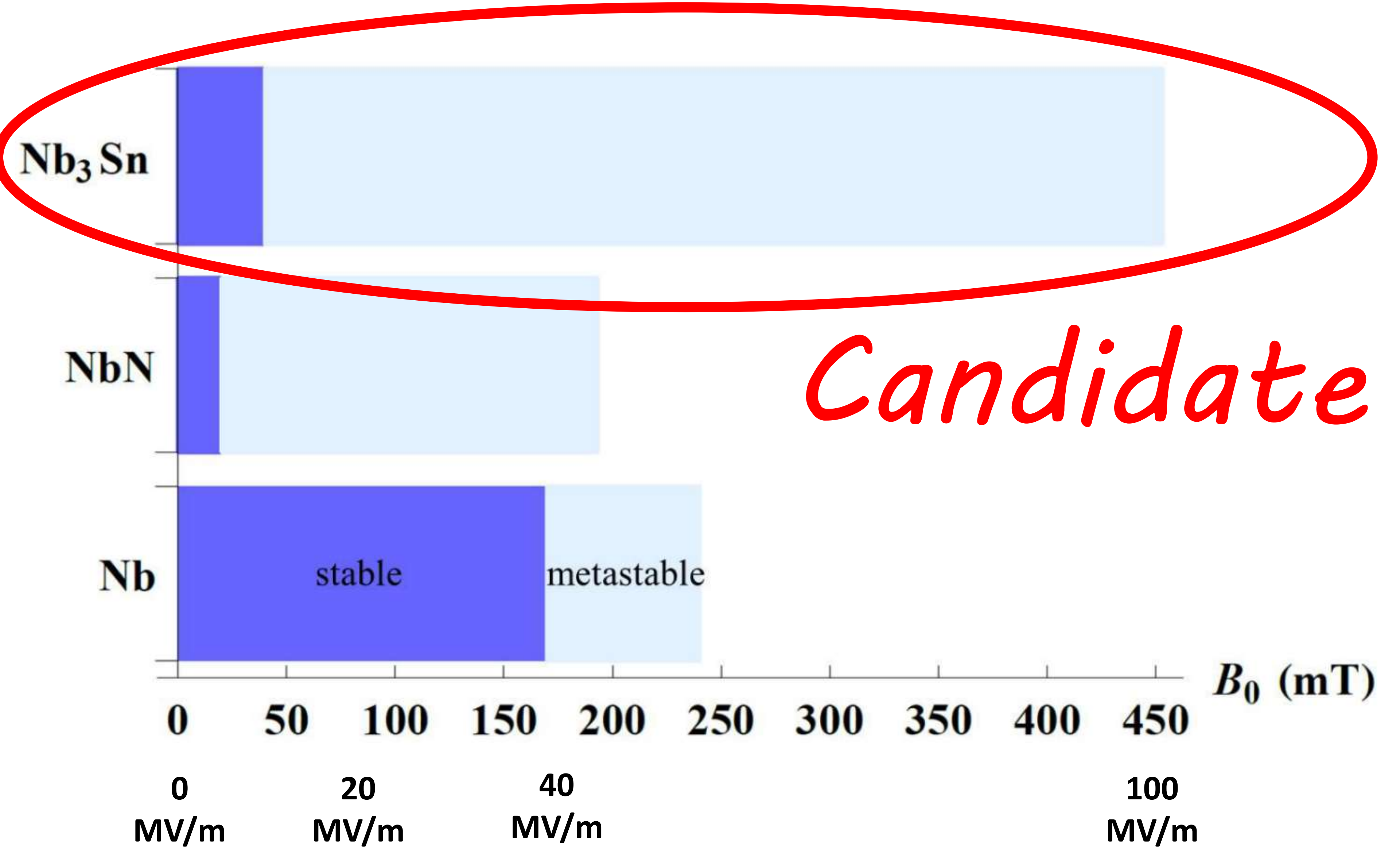
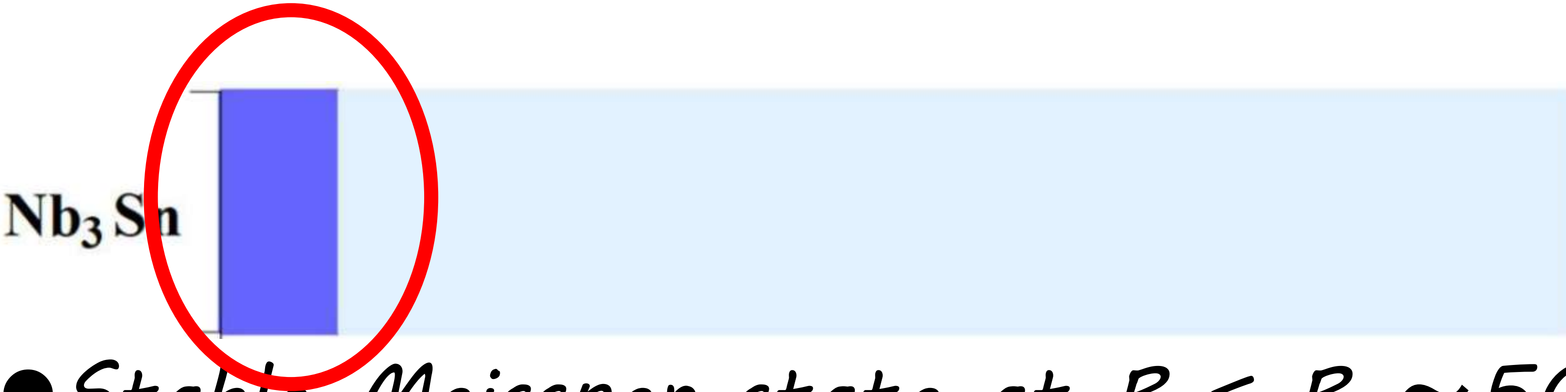
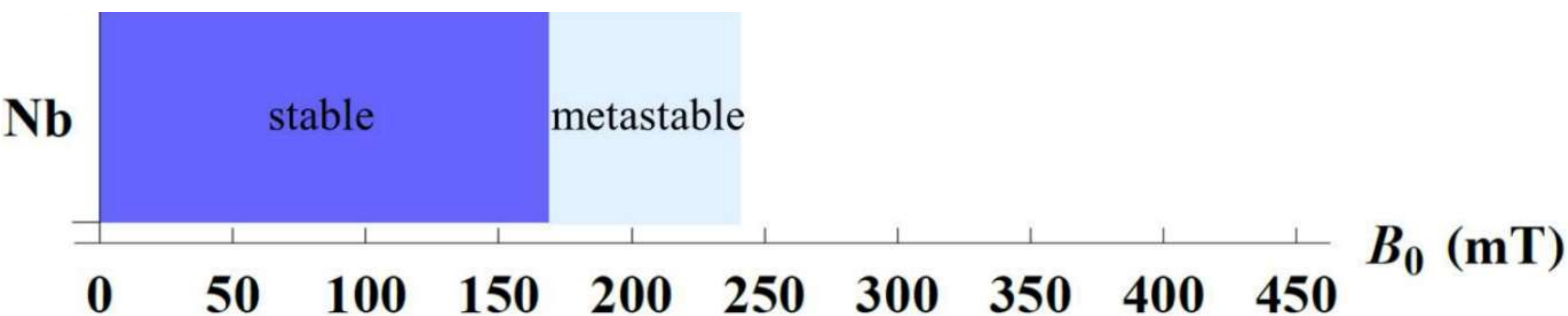


T. Kubo, Supercond. Sci. Technol. **30**, 023001 (2017)

However...



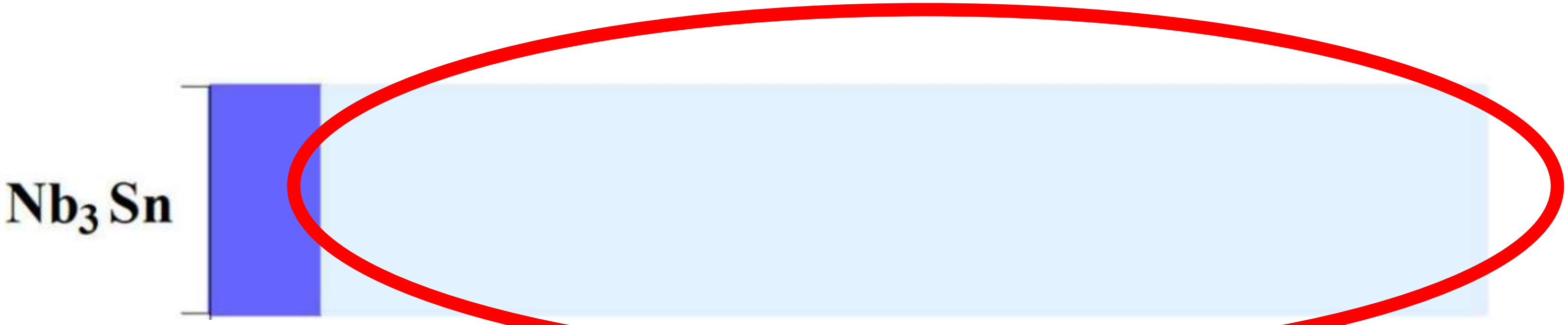
- Stable Meissner state at $B < B_{c1} \sim 50$ mT, which corresponds to E_{acc} = 10-20MV/m



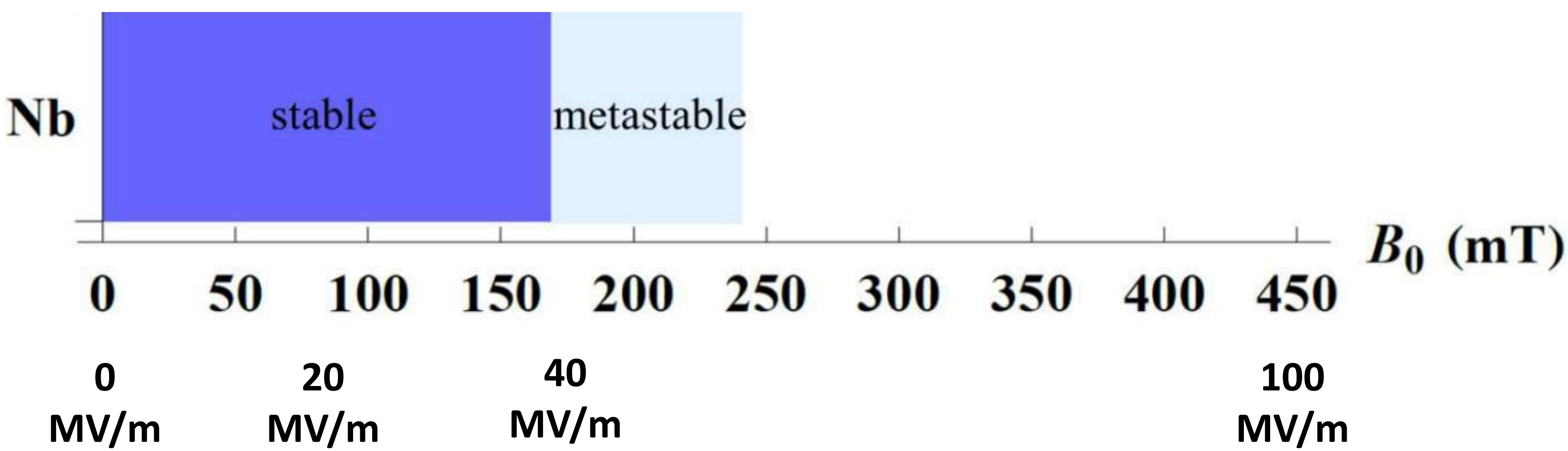
0 MV/m | 20 MV/m | 40 MV/m | 100 MV/m

T. Kubo, Supercond. Sci. Technol. **30**, 023001 (2017)

However...

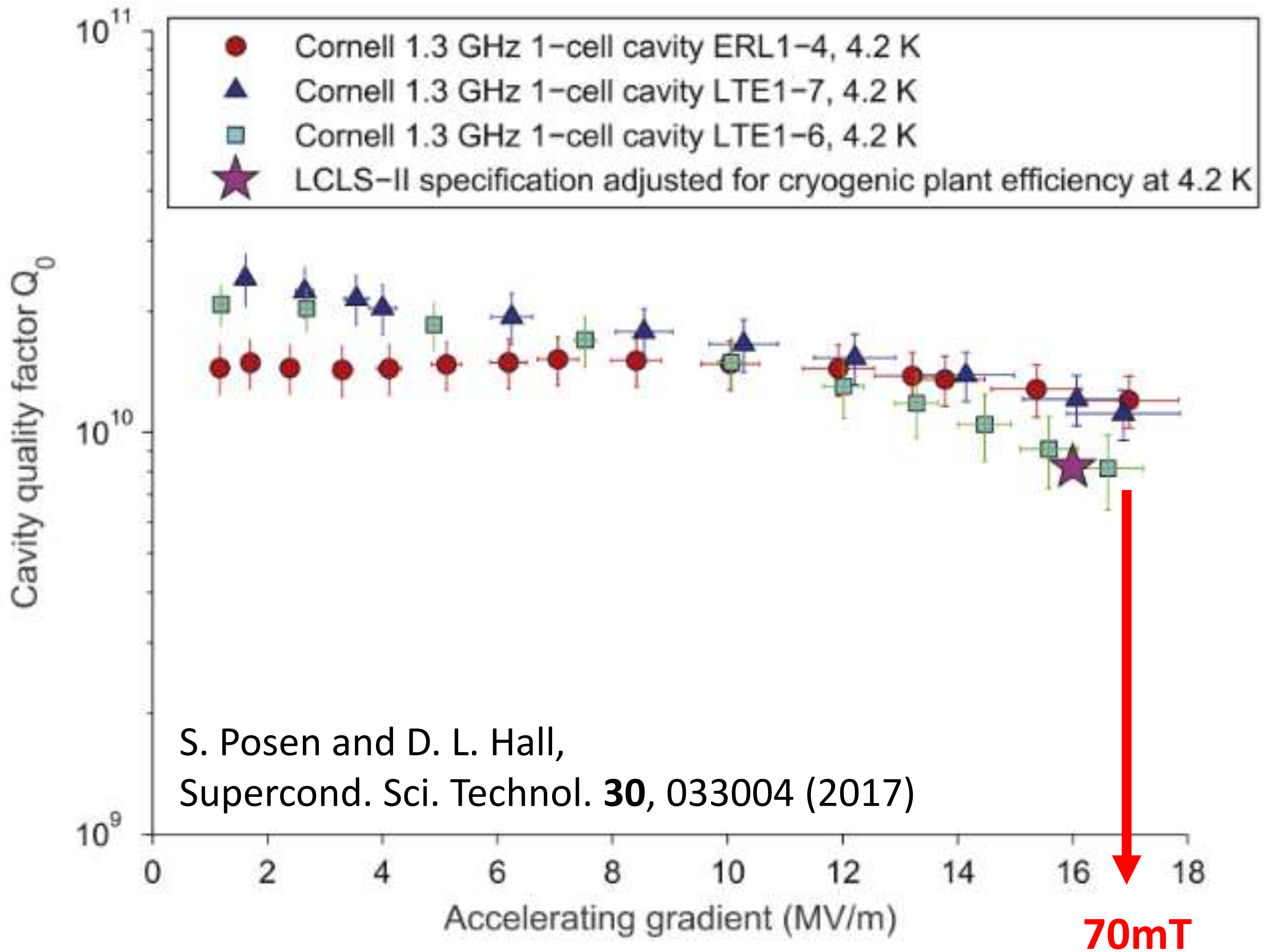


- Stable Meissner state at $B < B_{c1} \sim 50$mT, which corresponds to E_{acc} = 10-20MV/m
- This region is **not stable**!

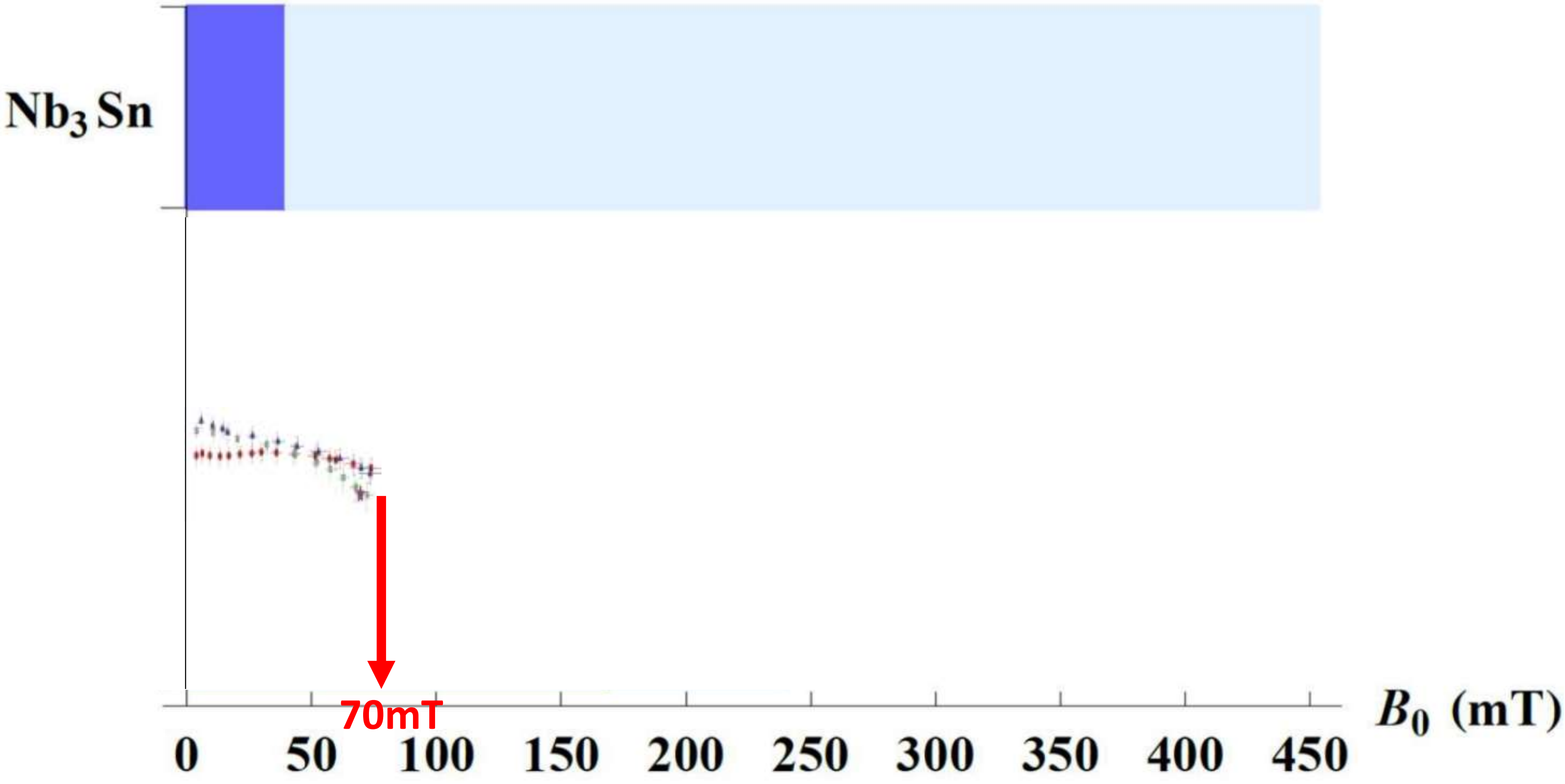


T. Kubo, Supercond. Sci. Technol. **30**, 023001 (2017)

Experimental results have been limited by $B \sim 70mT$ (E_{acc}=17MV/m)



Experimental results have been limited by $B \sim 70mT$ (E_{acc}=17MV/m)



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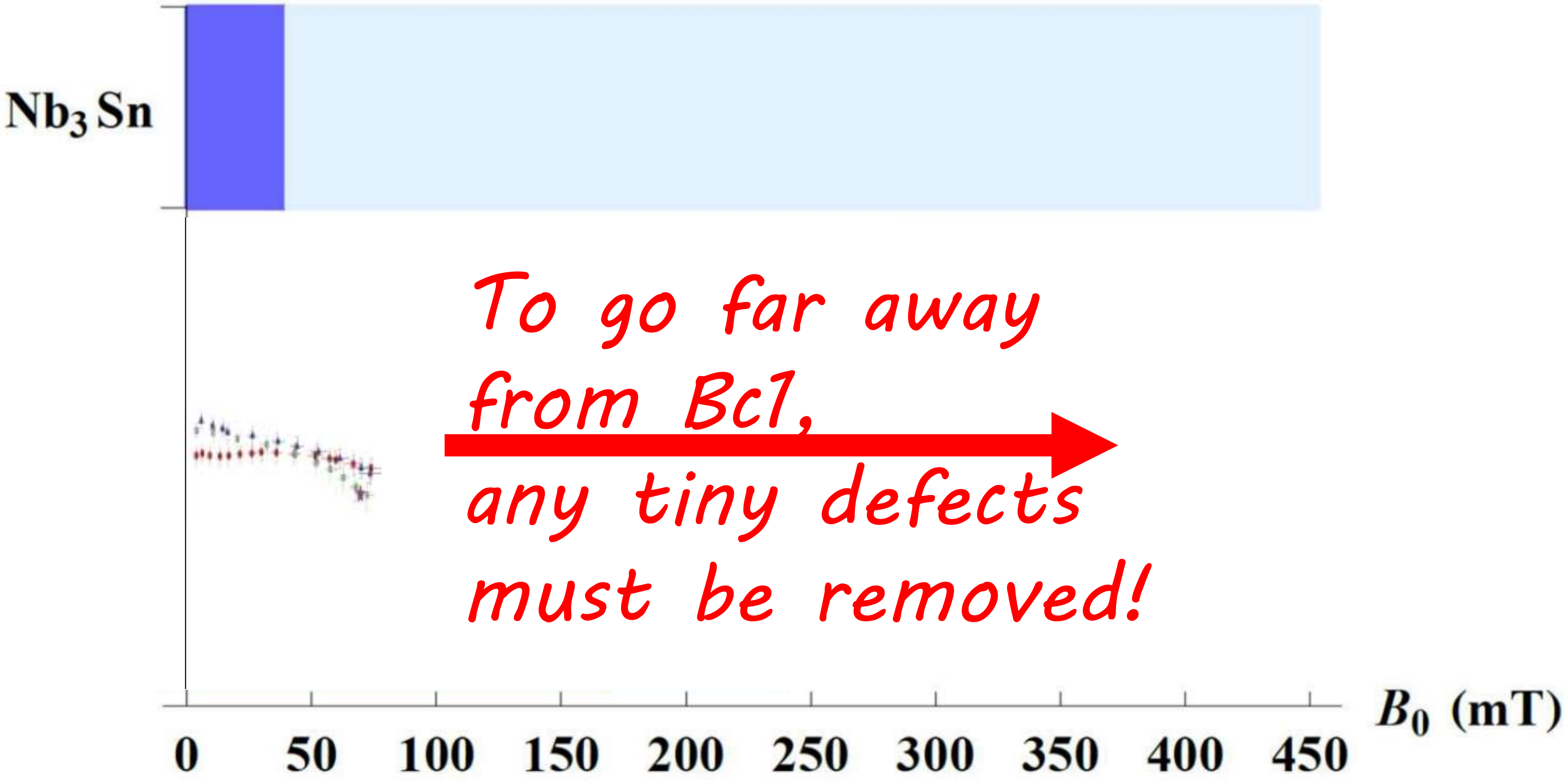


To go far away from Bc1, any tiny defects must be removed!

Experimental results have been limited by $B \sim 70mT$ ($E_{acc}=17MV/m$)

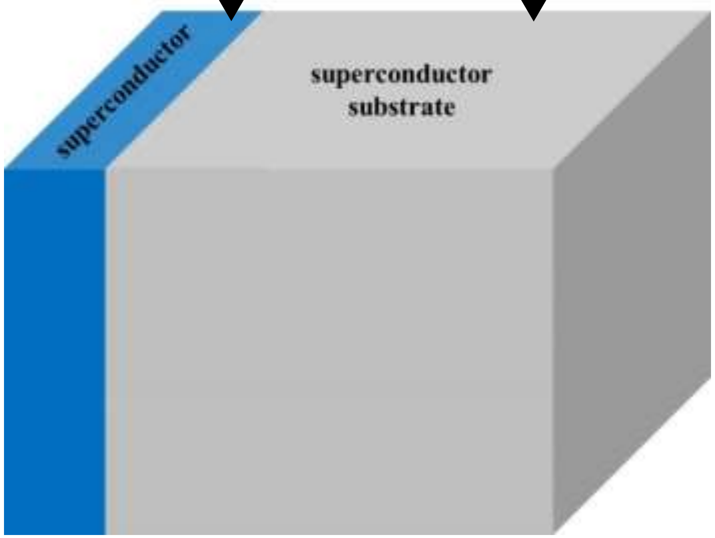
J. I. Vestgården, D. V. Shantsev, Y. M. Galperin & T. H. Johansen, *Scientific Reports* **2**, 886 (2012)

How to avoid the avalanches?

Further advanced layered structures

Dirty Nb_3Sn (～100nm)

Clean Nb

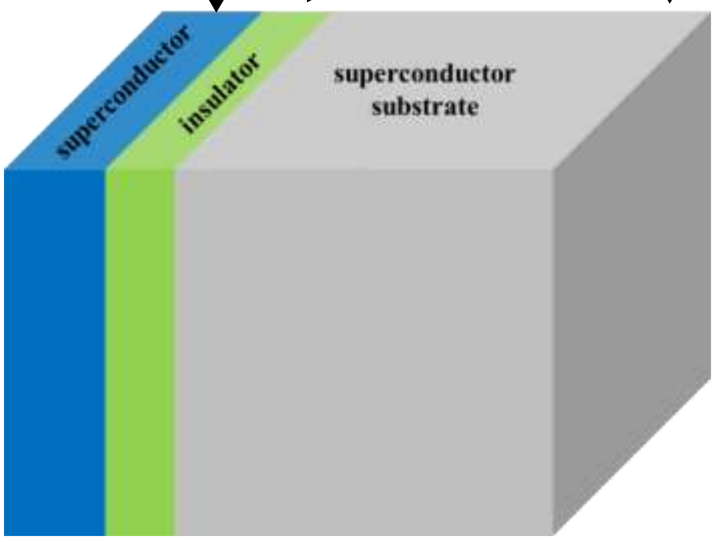


- T. Kubo, Supercond. Sci. Technol. **30**, 023001 (2017)
- T. Kubo, in Proceedings of LINAC2014, Geneva, Switzerland (2014), p. 1026, THPP074.
- See also the discussion section of T. Kubo, Progress of Theoretical and Experimental Physics **2015**, 063G01 (2015)
- T. Kubo, TTC meeting at Saclay France (2016)

The fourfold benefit of the layered structure will improve the maximum E_{acc} and Q_0 : (1) **the reduction of gap is small in the dirty layer**
(2) **suppress the surface current and enhance the theoretical field limit**
(3) **prevent the vortex penetration** by the additional barrier
(4) In addition, since a part of current flows on the low loss surface, Nb_3Sn, **dissipation decreases and Q increases**.

How to avoid the avalanches?
Further advanced layered structures

Dirty Nb_3Sn (～100nm) insulator Clean Nb



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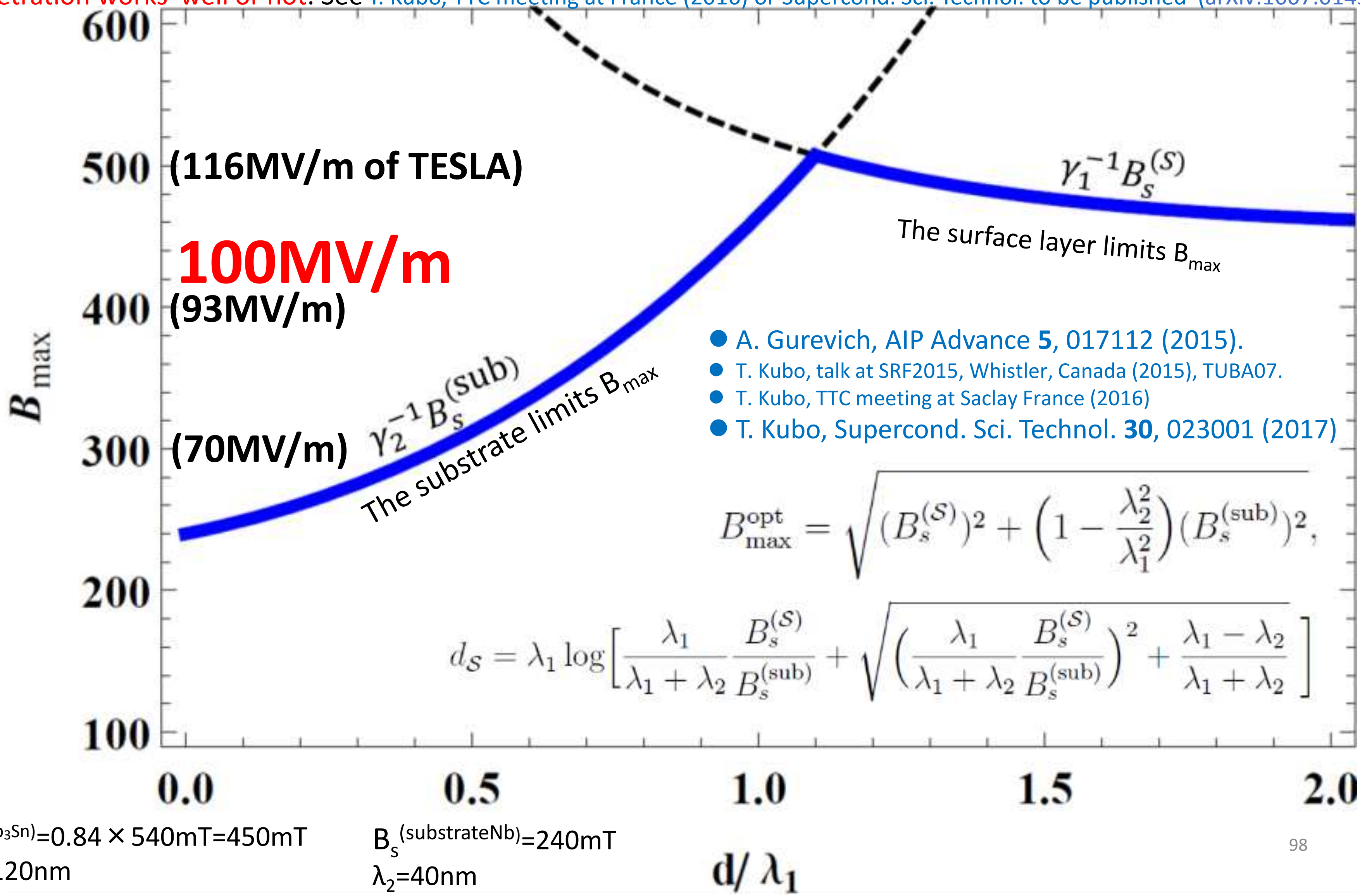
- A. Gurevich, AIP Advance **5**, 017112 (2015).
- S. Posen et al., Phys. Rev. Applied **4**,044019 (2015).
- T. Kubo, Supercond. Sci. Technol. **30**, 023001 (2017)

Furthermore, introducing the insulator layer (1) **prevent the vortex penetration** and (2) **suppress vortex dissipation**, because the vortex core disappears in the insulator layer.

e.g.) Nb_3Sn / thin insulator / Nb substrate or Nb_3Sn / Nb substrate

Note this shows just theoretical field limits. Whether we can achieve them depends on whether a gimmick to avoid vortex penetration works well or not. See T. Kubo, TTC meeting at France (2016) or Supercond. Sci. Technol. to be published (arXiv:1607.01495)



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- T. Kubo, TTC meeting at Saclay France (2016)
- T. Kubo, Supercond. Sci. Technol. **30**, 023001 (2017)

$$B_{\max}^{\rm opt} = \sqrt{(B_s^{(\mathcal{S})})^2 + \Bigl(1-\frac{\lambda_2^2}{\lambda_1^2}\Bigr)(B_s^{(\rm sub)})^2},$$

$$d_{\mathcal{S}} = \lambda_1 \log\Biggl[\frac{\lambda_1}{\lambda_1+\lambda_2}\frac{B_s^{(\mathcal{S})}}{B_s^{(\rm sub)}} + \sqrt{\Bigl(\frac{\lambda_1}{\lambda_1+\lambda_2}\frac{B_s^{(\mathcal{S})}}{B_s^{(\rm sub)}}\Bigr)^2 + \frac{\lambda_1-\lambda_2}{\lambda_1+\lambda_2}}\Biggr]$$

$B_s^{(Nb_3Sn)}$=0.84×540mT=450mT
λ_1=120nm

$B_s^{(substrateNb)}$=240mT
λ_2=40nm

References
(related to Ultra high-Q & high-grad)

Nb_3Sn

- S. Posen and M. Liepe, Phys. Rev. ST Accel. and Beams 17, 112001 (2014).
- S. Posen, M. Liepe, and D. L. Hall, Appl. Phys. Lett. 106, 082601 (2015).
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Layered structure

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Summary

Superficial introduction to hot topics in SRF

- Basics of SRF
- ILC recipe
- N-dope
- N-infusion
- Flux expulsion
- Nb_3Sn for ultra high-Q SRF
- Layered structure for ultra high-G

Too short to introduce these topics!

Please read the references!

Ultra high-Gradient for the ILC 1TeV upgrade!!