Recent developments in high-gradient SCRF

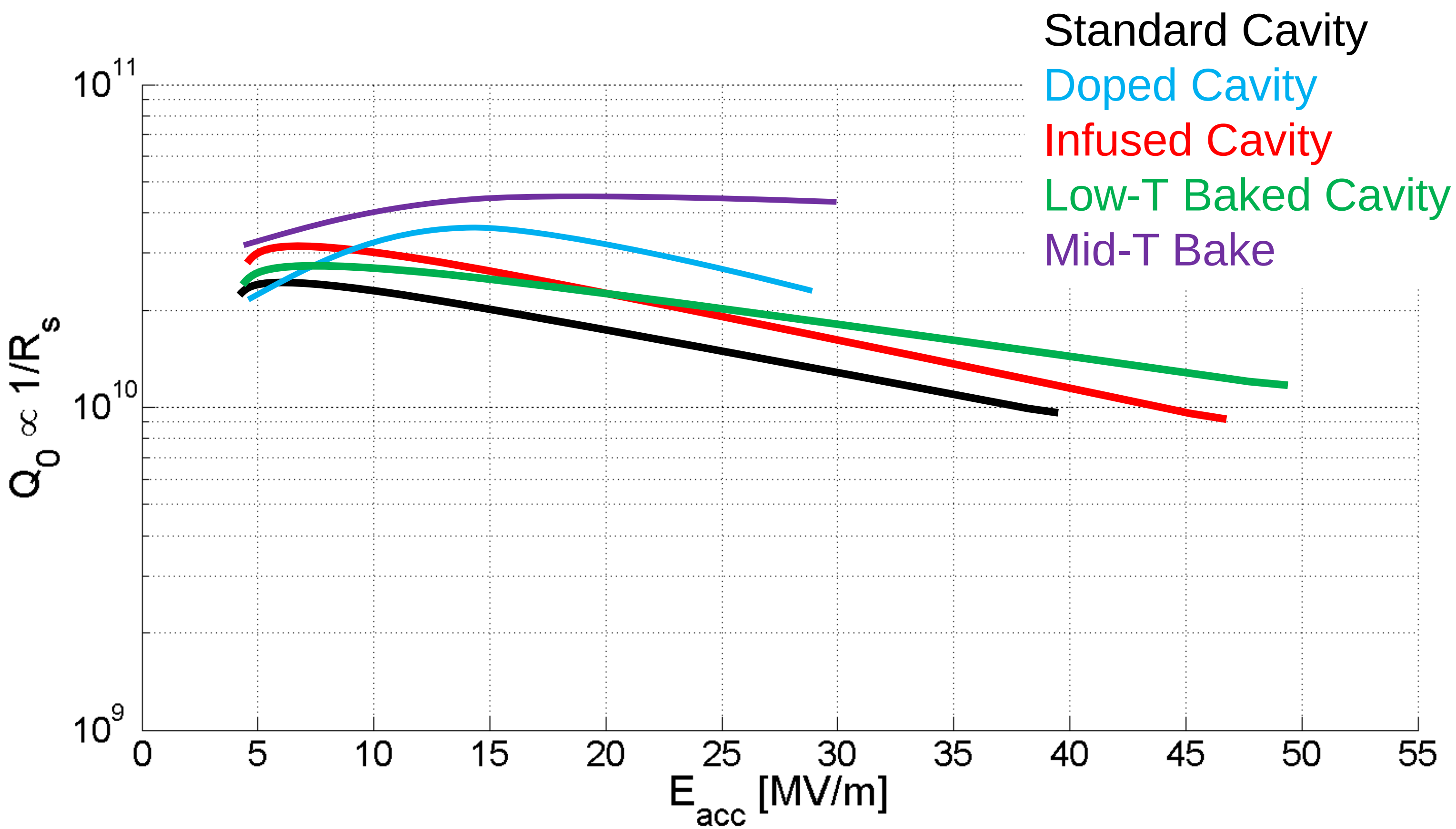
Marc Wenskat (UHH)

ILC@DESY – 23.11.2020

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

General R&D

See 168th ILC@DESY

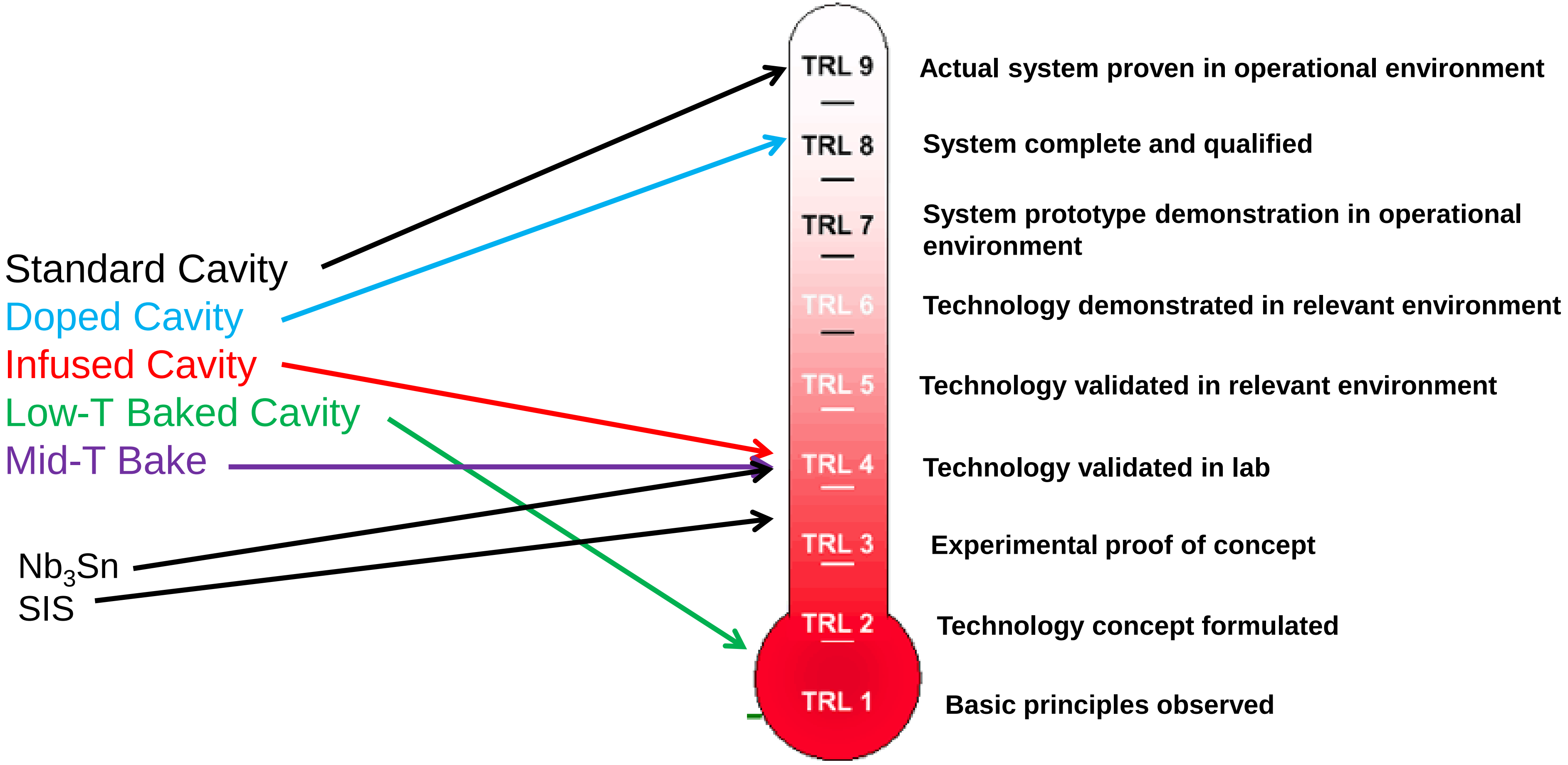


[Reschke et al., Phys. Rev. Accel. Beams, 20, 042004 (2017)]
[Grassellino et al., SUST, 26, 102001 (2013)]
[Grassellino et al., SUST, 30, 094004 (2017)]
[Grassellino et al., arxiv 1806.09824]
[Posen et al., Phys. Rev. Applied 13, 014024]

<u>Cavities limited by quench</u>

Technology Readiness Level

Developed by NASA in 1970



Status of Infusion R&D

Enables pulsed @ high energy and cw @ medium energy operation

- FNAL: No problems – focus on “Quantum Technology”
- Cornell: Stopped R&D – want USP & process deemed to unstable
- Jlab: Reduced R&D – focus on LCLS-II HE Upgrade and new Doping Recipe
- KEK: Succeeded beginning of 2020 with first infusion after 3y and several fails
- IJC: Started Infusion R&D and had same problem as DESY
- DESY/UHH: 12 Infusion runs – only 3 with unchanged performance. Major invest in (i) upgrade of ZM furnace (ii) refurbishment of HIII furnace (iii) purchase of new UHV furnace for single cells

TRL 4: Technology validated in lab

TRL 5: Technology validated in relevant environment

TRL 6: Technology demonstrated in relevant environment

Not just technology development – but also science!

What if…

- Infusion @ 160°C looks like a Doped Cavity (both introduce N into Nb)
- Mid-T Bake has „anti-Q-Slope“ like Doped Cavity (UHV Bake @ 300°-400°C)
- Infusion below 160°C (w./ N) looks like 120°C bake (w./o. N) but different Offset

What if all these annealing procedures do the same thing!

What is „the same thing“?

Why does “this thing” influence the rf properties?

„Impurity Tailoring“

Mixture of several models, measurements and ideas

- Hydrogen is bad – tends to accumulate near the surface, form lossy hydrides
- Native Nb-Oxides seem to have lossy TLS-Oscillations

→ Near-Surface Lattice is not in the perfect shape

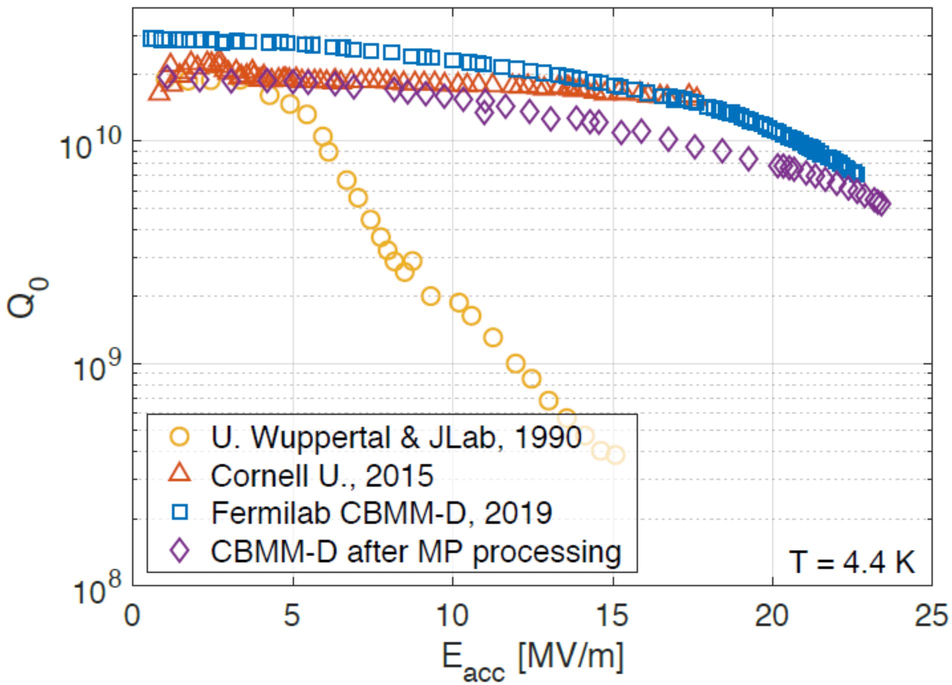
- Annealings do one thing: modify concentrations of H, N, O and vacancies
  - Vacancies and interstitial N or O can trap hydrogen / prevent hydride formation
  - Modify Nb-Oxides to form less defective phases
  - Shift induced currents away from the lossy surface region by manipulating λ_L
  - Spread currents over larger volume, effectively increase applicable gradient
  - Change DOS, electron-phonon coupling and qp relaxation times

Fascinating new ideas – completely new approaches – fundamental new understanding
But: Where can we go with niobium? only so far…

Beyond Niobium

Nb_3Sn

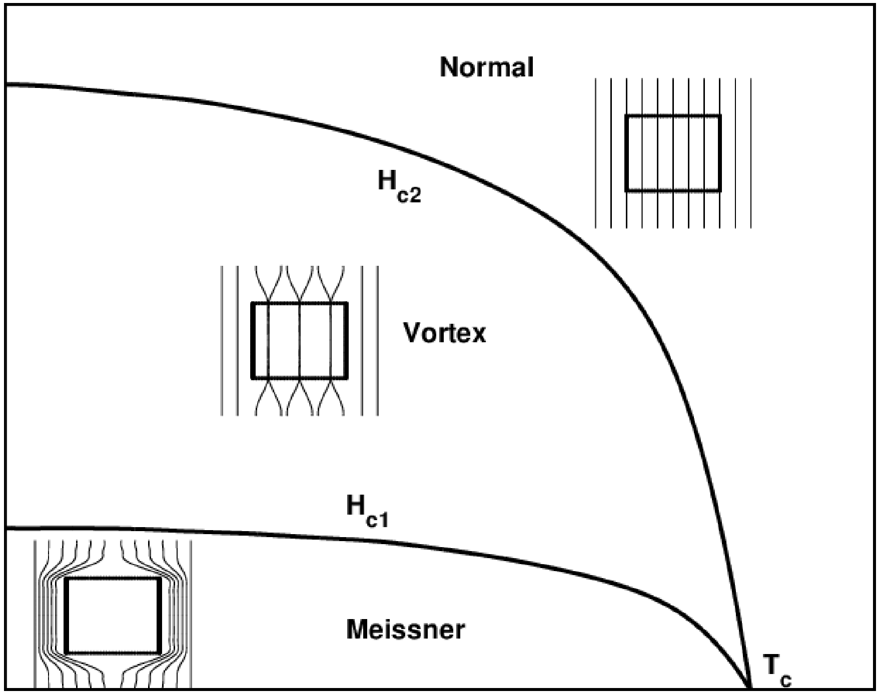
- Nb_3Sn has higher T_c (18 K vs. 9.2 K) and higher H_{sh} (450 vs. 220 mT) than Niobium
- Studied since 1990s (Wuppertal, Karlsruhe, Jlab) – Recent “breakthrough” at FNAL **[Posen et al., https://doi.org/10.1088/1361-6668/abc7f7]**
- In short: Impressive behavior in terms of Q – not so much in terms of E_{acc}



Simulations and Measurements exist – indicating a fundamental limit of 93 mT or 22 MV/m

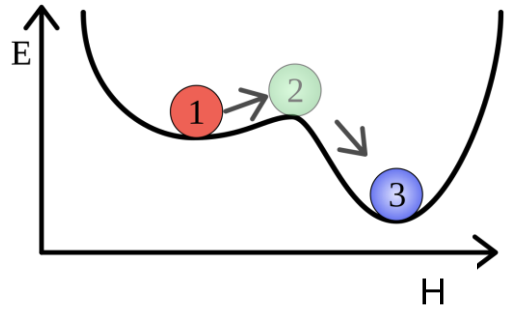
Beyond Niobium – Part II

- Nb is Type II SC
  - $B_{c,1}$ is 170mT → 39MV/m
  - $B_{c,2}$ is 300mT
- B_{sh} is 230mT → 53MV/m



What is Superheating?

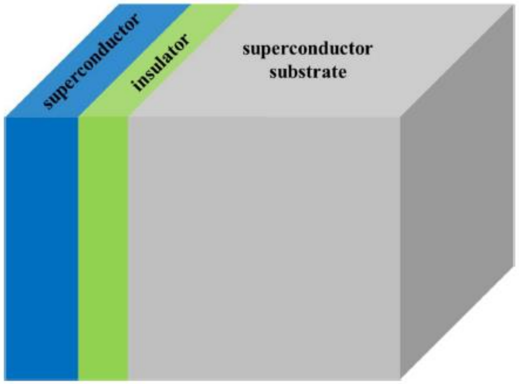
- When does the flux enter?
  - Meissner to Shubnikov phase are local minima w.r.t. magnetic field as parameter



- Bean-Livingston studied intermediate state: Vortex near a surface
  - Attractive mirror-vortex
  - Repulsive surface current or “screening current”

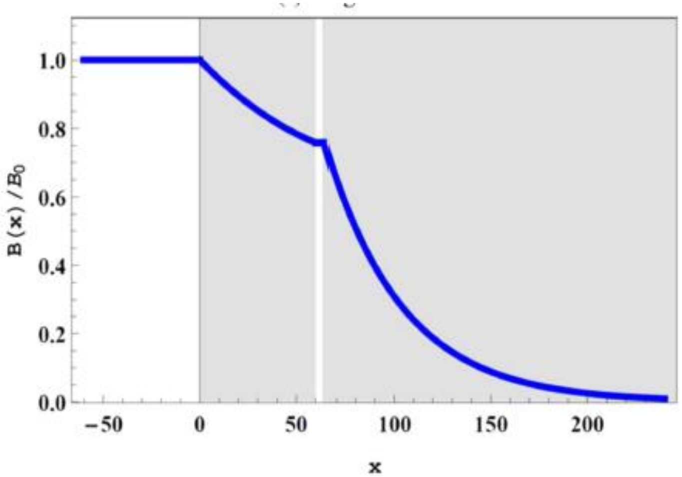
Welcome to „our mirror world“

- Increase “mirror-surfaces”
- Insulator is important!
  - Add mirror-surfaces
  - Prevent Josephson Junctions
  - Trapp vortices in top-layers



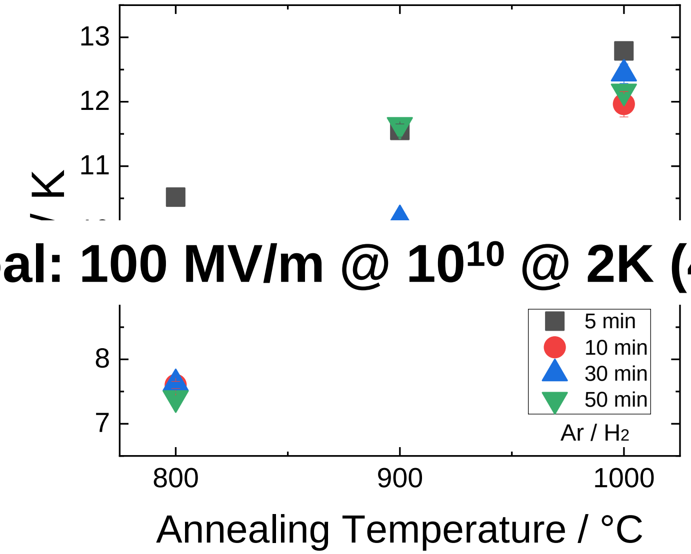
[Gurevich, Appl. Phys. Lett. 88, 012511 (2006)]

- Use higher T_c superconductors → less losses!
- RF field on surface can be several times above B_{sh} of Nb → Higher Gradient



S-I-S R&D

- 4 Groups study these layered structures
  - IJC – JLab – KEK/U Tokyo – U Hamburg/DESY
- We use a coating technique easily applicable to cavity geometry (ALD) while Jlab and KEK uses Sputtering techniques
- Started ~1y ago but have an excellent Network (CHyN, Nanolab, IExp, MSL) and collaborations (IJC, HZDR, RWTH, U Siegen) with promising results



NbTiN

Goal: 100 MV/m @ 10^{10} @ 2K (4K??)

Summary

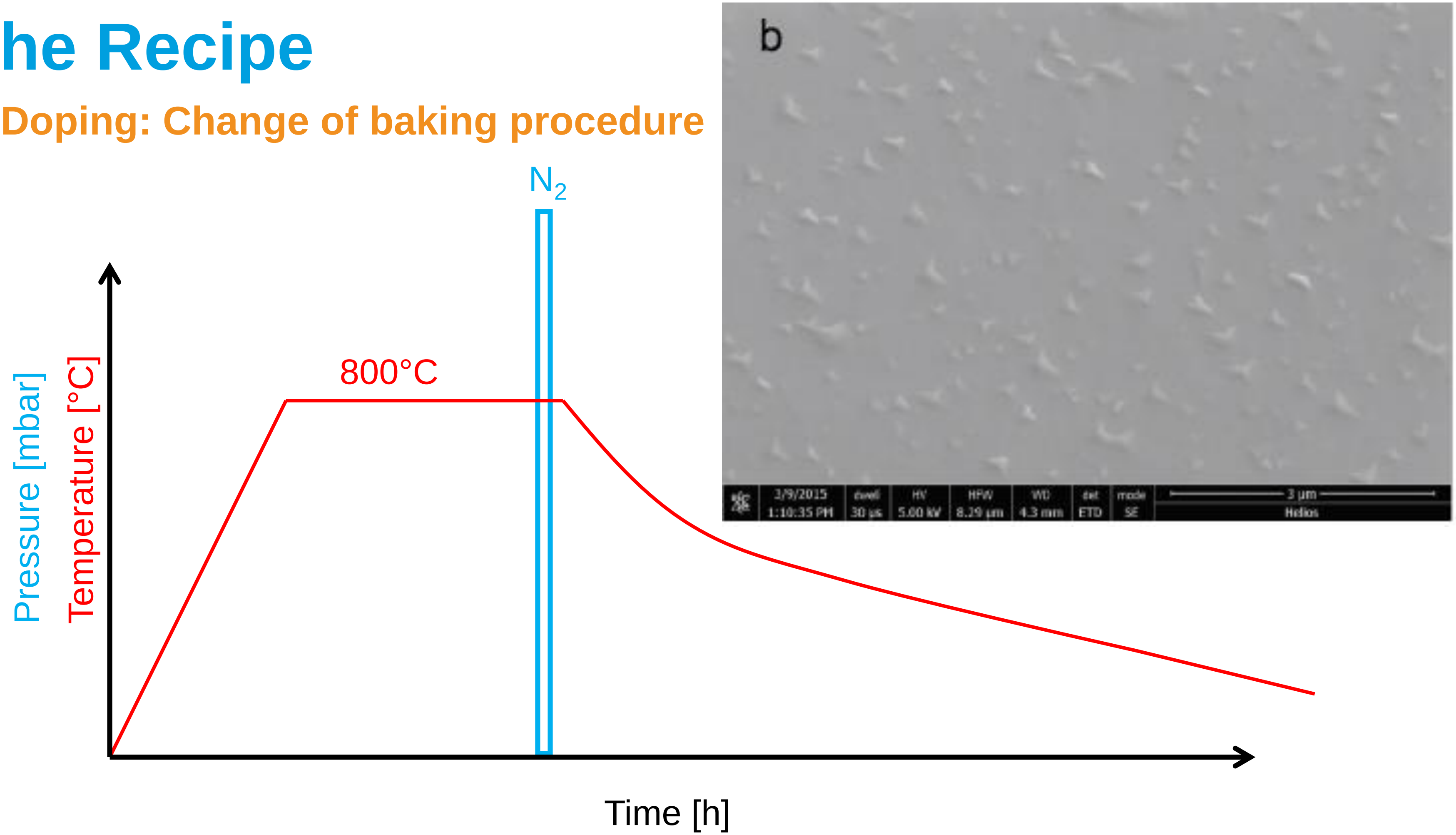
- SRF community shifts its focus a bit
  - US: Goes Quantum or LCLS-II HE, Everyone else tries to find USP
- Still no final picture – It’s a bit like the “Teilchenzoo” before Gell-Mann / Eightfold Way → Window of opportunity
- Draw more and more material scientists and theorists into our field
- Beyond Nb R&D picks up speed

Thanks for Listening!

Questions?

The Recipe

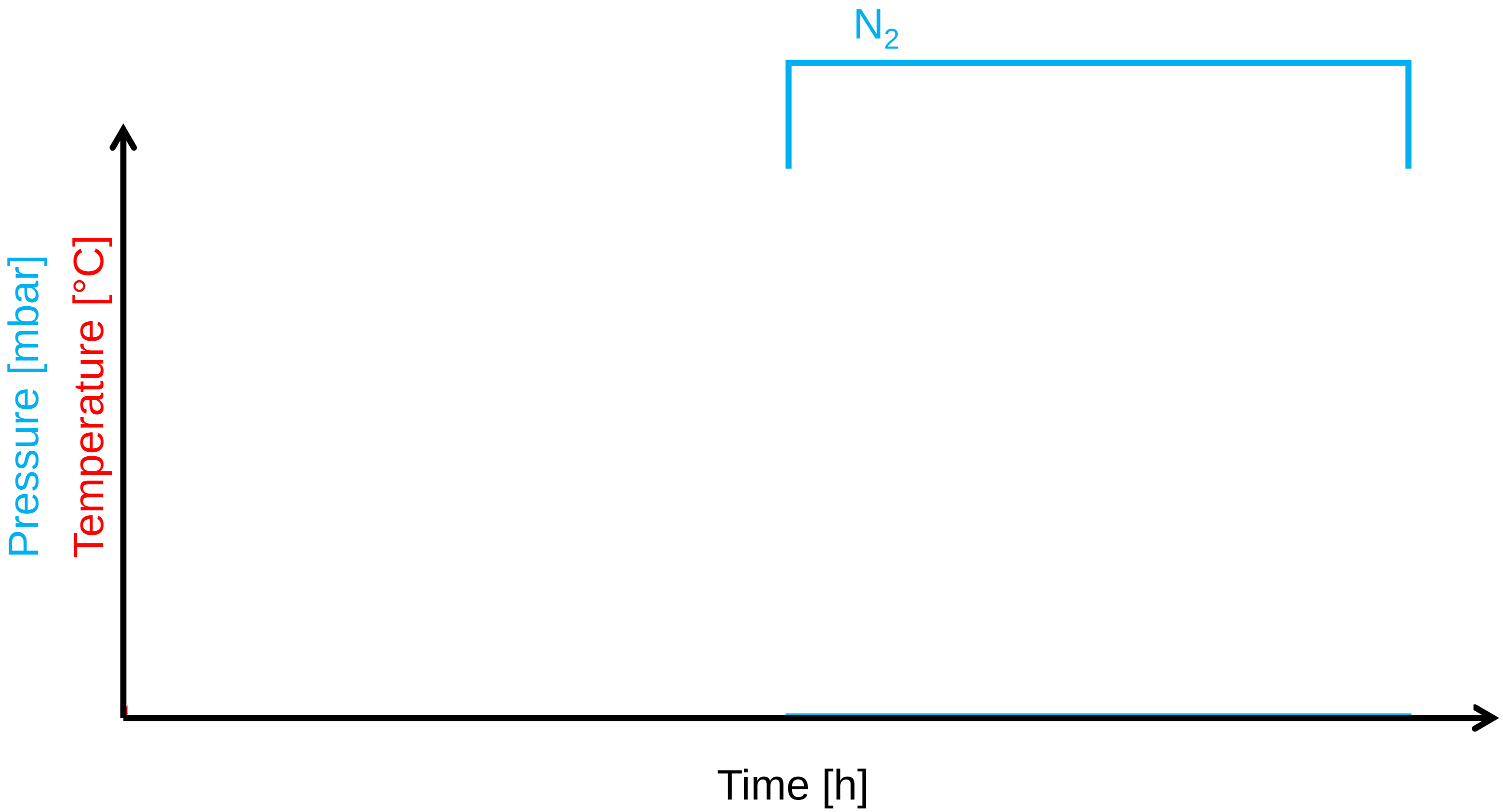
N-Doping: Change of baking procedure



+ 5-10 µm removal of inner layer by chemical etching necessary

The Recipe

N-Infusion

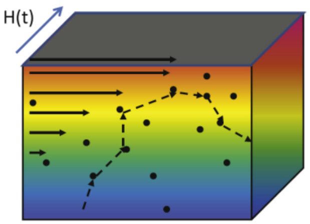


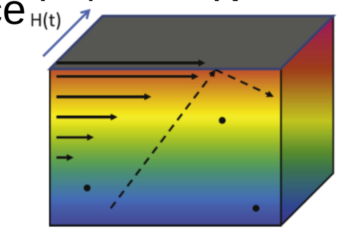
Problem: No one cooks like Grandma

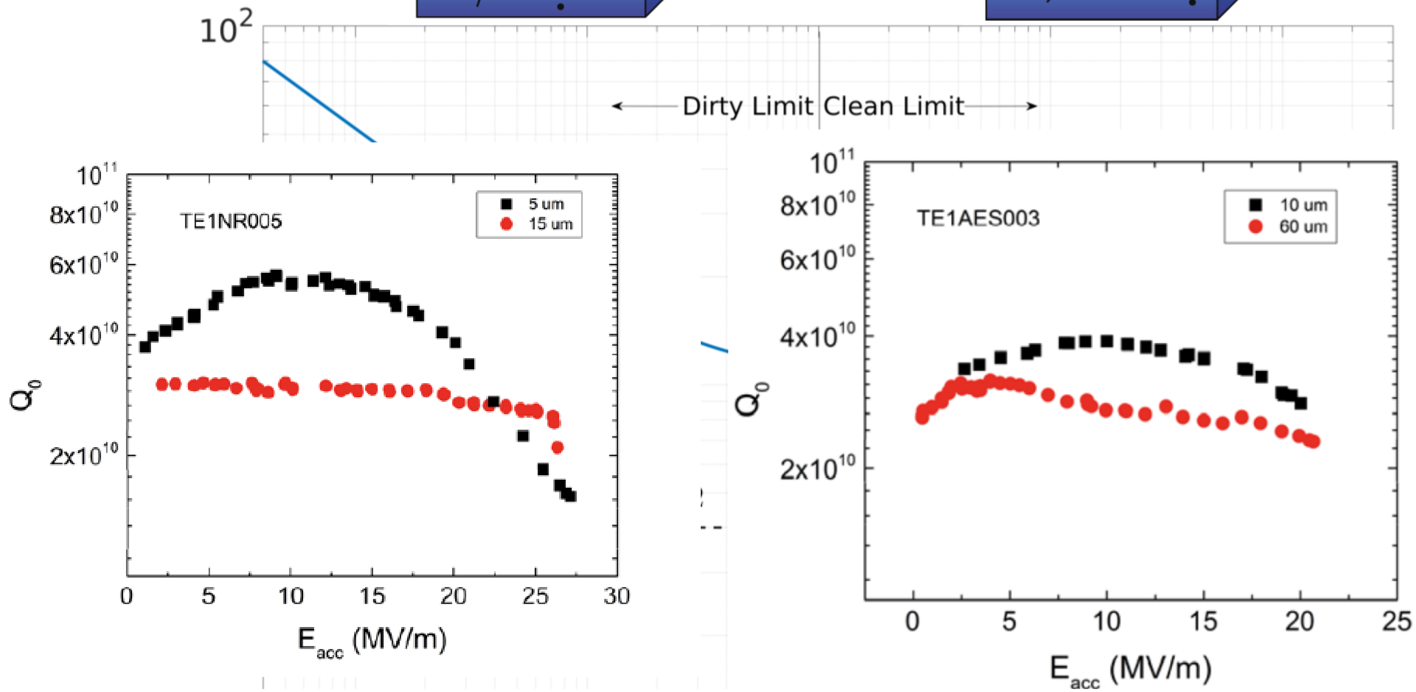
How is the performance affected?

Model can explain … not difference … & Infusion

- Q_0(E) depende…
- Effect has not … mfp cavities
- Difference in Q…



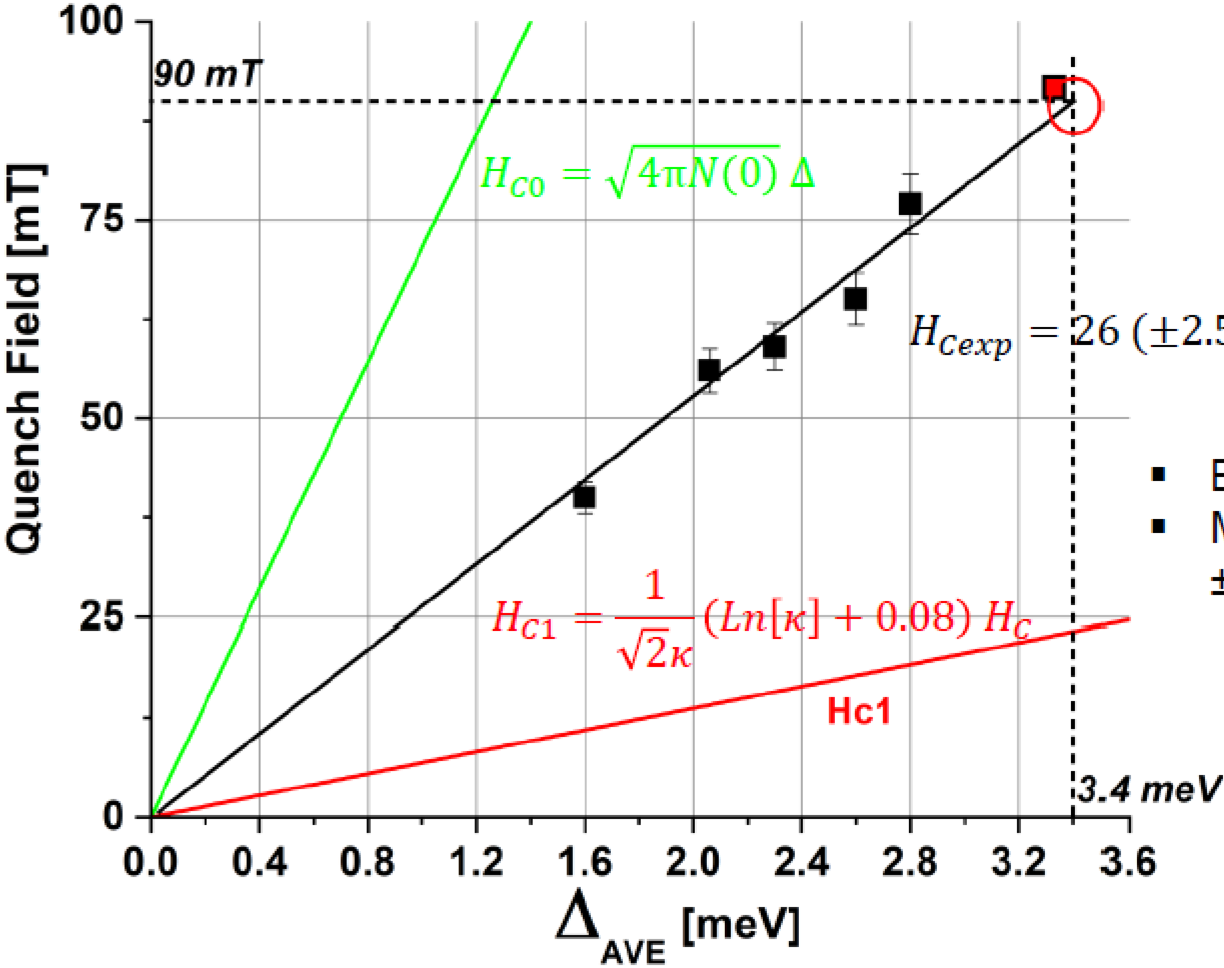




Quench field does not increase/reset with more inner surface removal!

$$R_s = R_{BCS} + R_{res}$$

Quench field vs Average Gap



For large κ ($\lambda/\xi = 24$)

N_0 = 2.5 10^{35} e- / spin / m^3

- Bulk Δ for Nb_3Sn is 3.4 to 3.5 meV
- Max expected Quench field is ~ 91 ± 2 mT = 22 MV/m

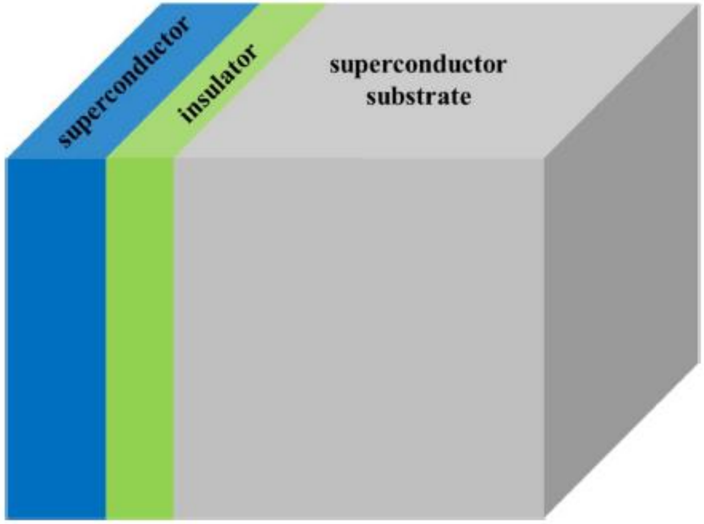
The whole is more than the sum of its parts

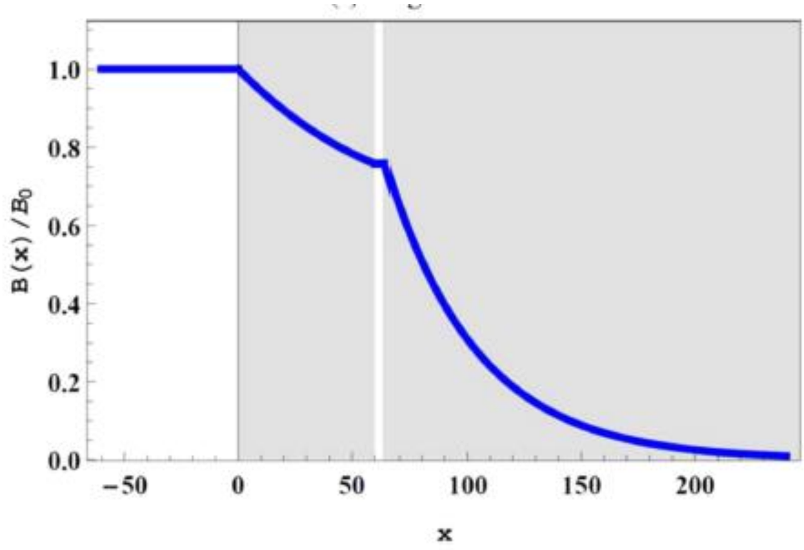
- Putting a superconductor on top of Nb with a higher T_c and/or B_{sh} is not the point

- The insulator plays a crucial role!

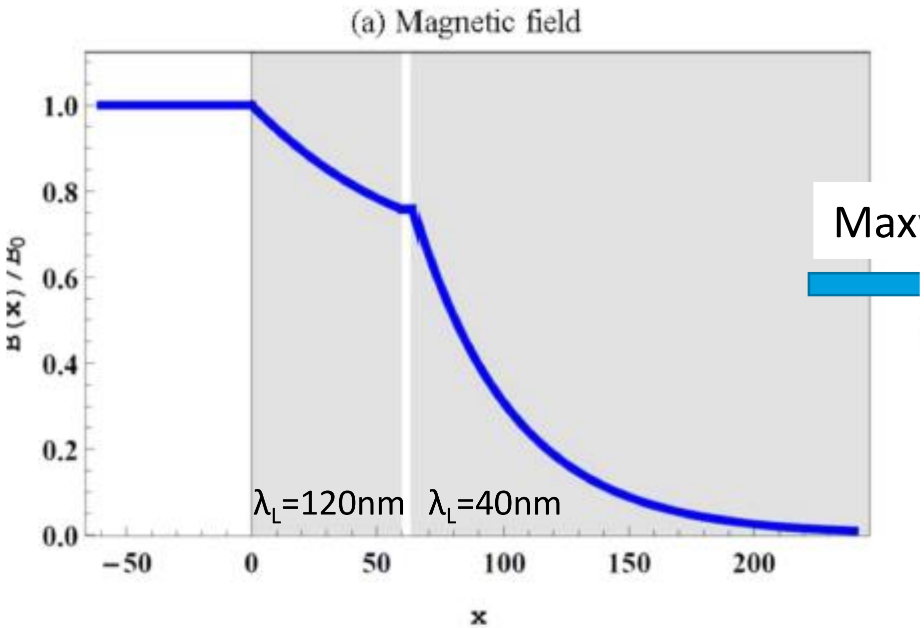
Here comes the insulator

- Benefit is threefold!
- Let some flux enter – but trap it
  - No avalanche leading to a quench
  - Majority of losses in the S layer
- S layer thinner then its λ_L – otherwise its “bulk”
- More “mirrors” create more screening currents means less flux!
- Isolater thickness plays a role, too!





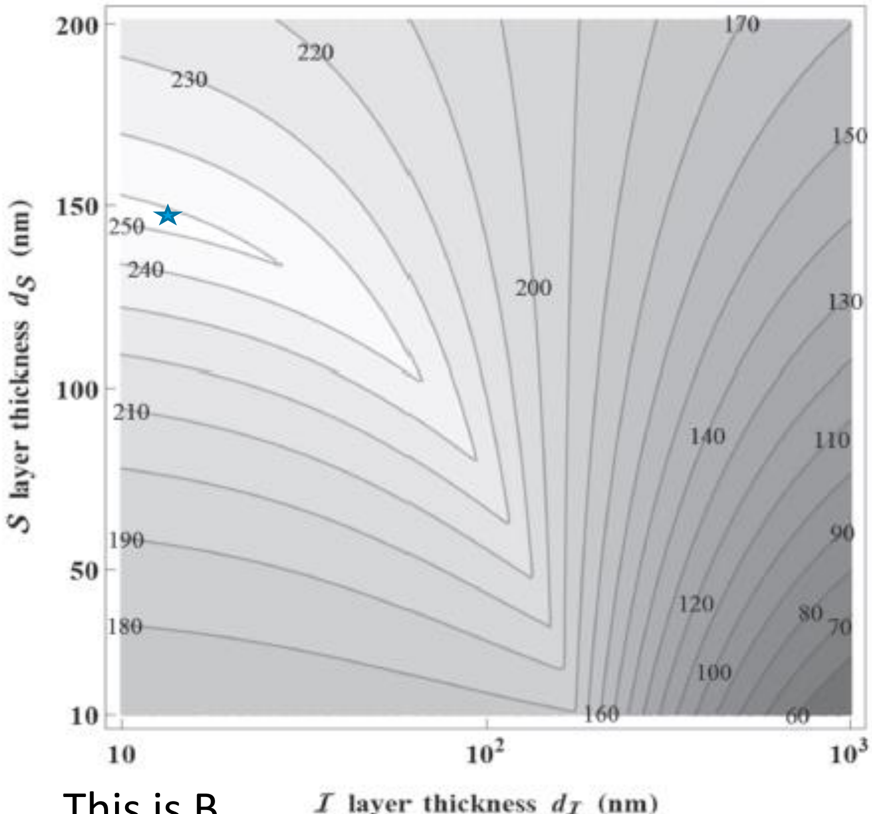
Why insulator is not irrelevant



- Screening current $J(x) \sim -B(x)'/\mu_0 \sim 1/\lambda_L$
- B is attenuated in finite I layer as well
- Hence screening current at I-S interface decreases and mirror current S-I interface
- Hence overall screening performance is attenuated and max. B_c reduced

Optimal thickness?

- If the thickness of the substrate and insulator is relevant – what is the optimal thickness for highest $B_{applied}$?
- Depends on $B_{c,1}$ and λ_L of both S
  - Here NbN – I – Nb



This is B_{max}

What about Q_0?

- Have majority of losses in high T_c superconductor
- R_s is reduced

$$R_s = \left[\frac{1 + r_\lambda^2}{2} \sinh \frac{2d_S}{\lambda_I} + r_\lambda \left(\cosh \frac{2d_S}{\lambda_I} - 1 \right) - (1 - r_\lambda^2) \frac{d_S}{\lambda_I} \right] \tilde{\gamma}_2^2 R_s^{(S)} + \tilde{\gamma}_2^2 R_s^{(\mathrm{sub})} + \tilde{\gamma}_2^2 \mu_0^2 \omega^3 \epsilon'' \lambda_2^2 d_I,$$

- Losses in I-layer is ~ d/nm x 10^{-7} nΩ
- For NbN – I – Nb (150nm/20nm) only ~67% at 2K

What Materials?

- Current candidates
  - as insulator: Al_2O_3 and AlN
  - as supercondutor: NbN, NbTiN, Nb_3Sn
  - Other?
- Questions to be addressed:
  - Al_2O_3 and Nb-Oxides and then coating with elevated T – good idea?
  - Thermal conductivity of insulator? (e.g. strange behavior|T-dependence for NbTiN-AlN-Nb sample from Jlab at HZB QPR)
  - Mechanical stability of film(s) during HPR?