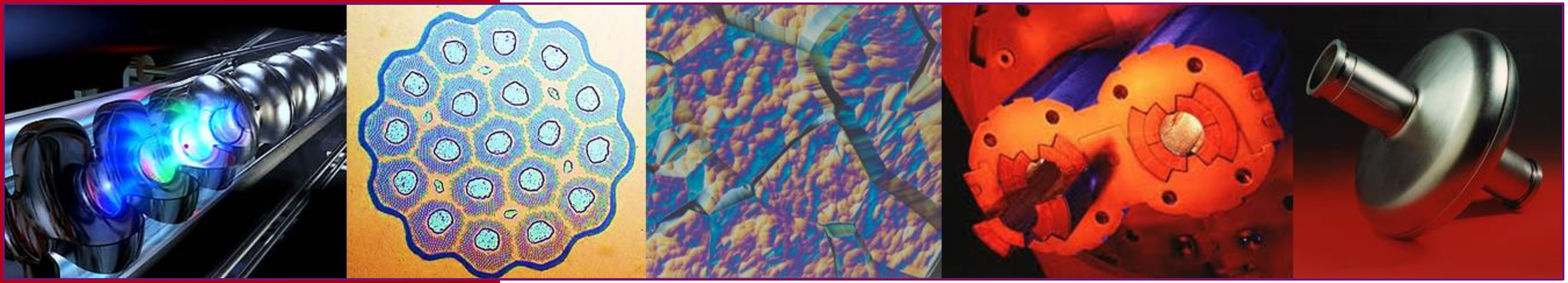
SUPERCONDUCTIVITY IN ACCELERATORS
PART II : MIXED STATE



JUAS 2025| Claire ANTOINE

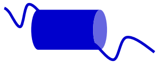
MAGNETS VS RF CAVITIES

www.cea.fr

WHY DO VORTICES ARE SO IMPORTANT ?

Magnets ≠ RF Cavities !!!! !!!!

- **Magnet (DC) :**
  - One aims at very high current densities with 0 resistance
  - It means:
    - Mixed state
    - Non moving, trapped vortices (medium fields: $H<H_{irr}$)
    - Defects are voluntarily introduced to ↑ pinning and ↑ λ (↓↓ H_{C1} et ↑↑ H_{C2})
    - $J < J_C <<< J_D$



- **Cavities**
  - One aims at very high field with minimal dissipation (but ≠0 ☹)
    - H variable, H_{max}~H_{SH} (= f(H_C))
    - Vortices cannot keep pinned at this frequency => very high dissipations (!),
    - One has to prevent Vx entering: keep in **Meissner state !**
    - Reduce # of defects (promoting early Vx penetration), => ↑↑ effective H_{C1}

- **Good SC for magnet applications are bad for cavities!**
- **And vice versa !**

For the recall:
1 => vortex, many => "vortices"

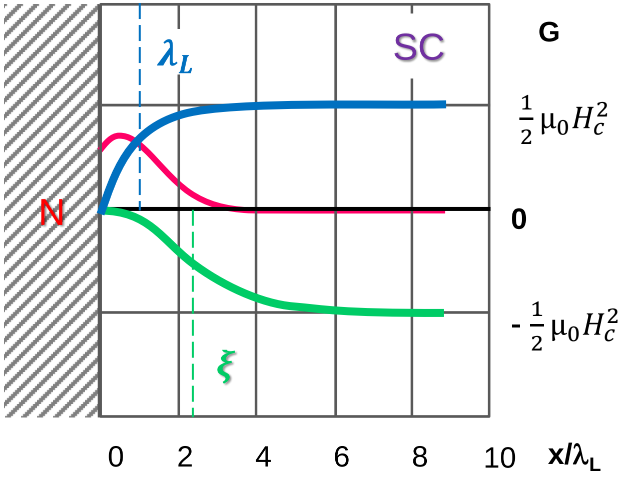
VORTICES (I): PENETRATION INSIDE THE SUPERCONDUCTOR

H>H_{C1}: VORTEX = ENERGETICALLY FAVORABLE

🟦 Magnetic energy
🟩 Condensation energy
🟥 Free energy

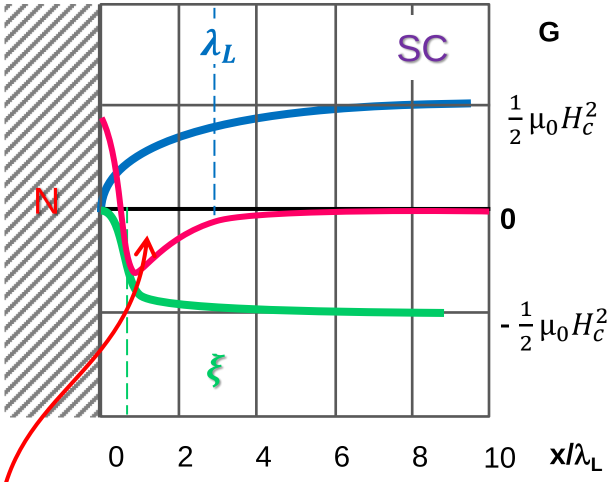
Magnetic energy → $\delta g_m \sim \mu_0 \frac{H^2}{2}\left(1-e^{-\frac{x}{\lambda_L}}\right)$ → *B ≠0 over λ*

Condensation energy → $\delta g_c \sim m\mu_0 \frac{H_C^2}{2}\left(\frac{n(x)}{n_s}\right)$ → *ns grows over ξ*



SC $\boldsymbol{type\ I\ \lambda_L < \xi}$,

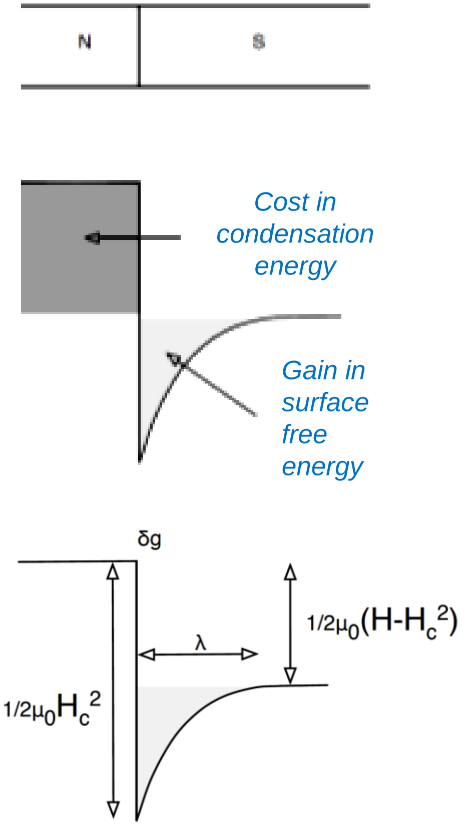
here κ ~ 0,35, @ H = 0,7 Hc



SC $\boldsymbol{type\ II\ \lambda_L > \xi}$,

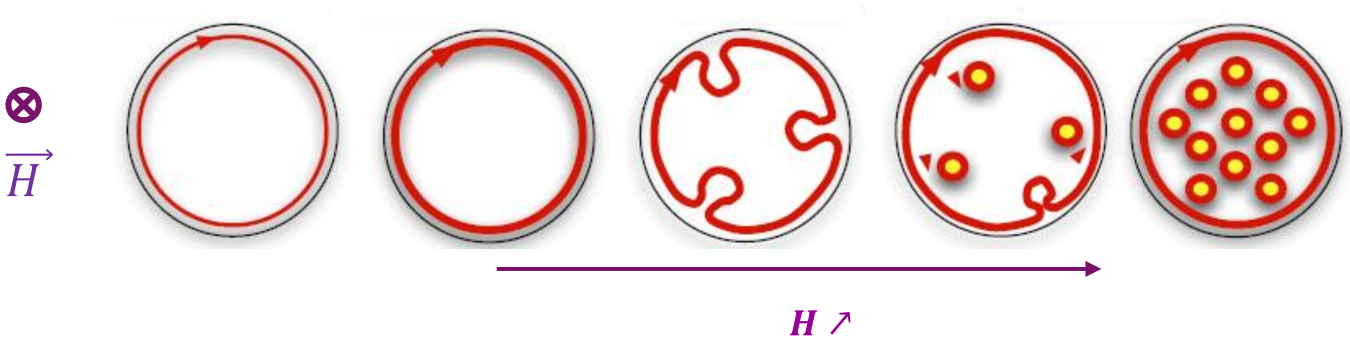
here κ ~ 2, @ H = 0,7 Hc

Free energy < 0



- **Creation of a normal/SC interface is energetically favorable in type II SC**
- **At equilibrium (transition) $|g_n| = |g_s|$ except close to the surface**

H>H_{C1}: VORTEX = ENERGETICALLY FAVORABLE



Thin sample, ⊥ field

Minimization of free energy:

This holds only for $\xi < \lambda$
=> Type II SC

- Normal zones as small as possible (∅~ 2ξ);
- Magnetic size ∅ ~2 λ *(Vx = normal zone w. 1 flux line + screening current).*
- Number of Vx is the one that minimize ΔG/L *(depends on applied H) and sample dimension*
- Vortices repel each other *(but attract antivortices)*
- Surface stabilizes the apparition of the SC mixed state
  - Nucleation always occurs at surface, Vx always emerge ⊥ to the surface
  - In ⊥ field : boundary conditions are unchanged
  - In // field : $E^{Surf}_{nucleation} < E^{Bulk}_{nucleation}$ → surface superconductivity can be observed in specific geometries (B_{C3}) *(on a thickness << λ_L).* ²

VORTEX PENETRATION WITH B // SURFACE

Surface barrier

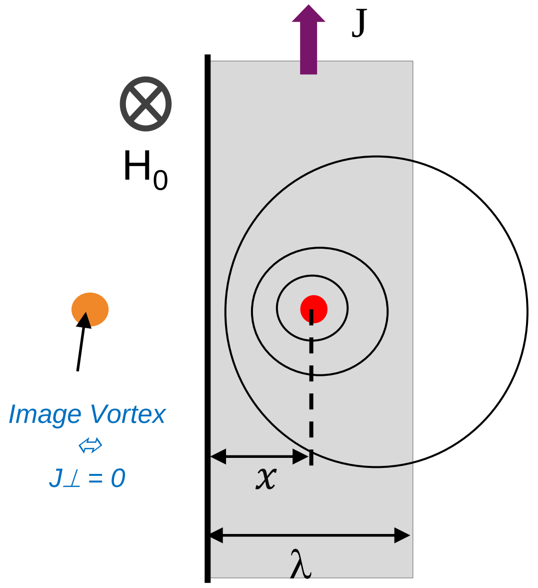
(Bean & Livingston, 1964)

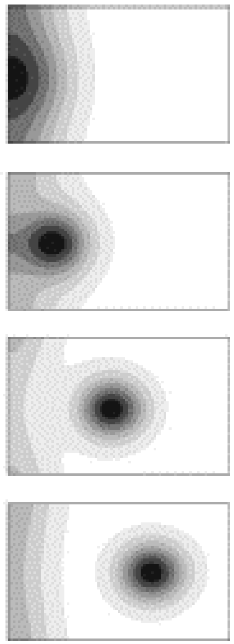
- Boundary conditions ($J_\perp = 0$) ≡ “image” vortices
  - Supercurrent tends to push Vx inside
  - Image antivortex tends to pull it out
- Before entering the material Vx have to cross a surface barrier:
  - Vx thermodynamic potential :

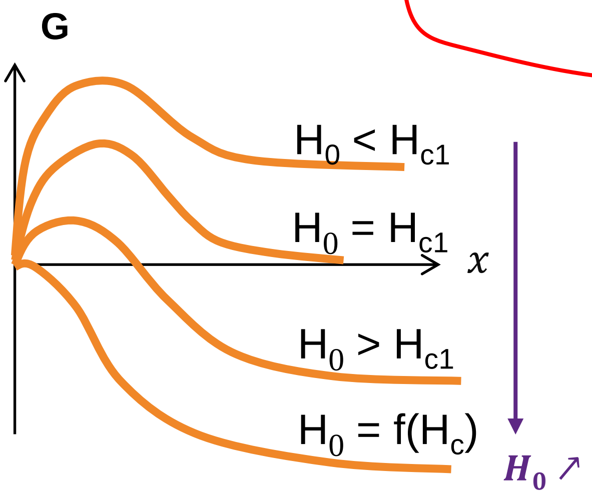
$$G(x) = \phi_0 \left[H_0 e^{-x/\lambda} - H_v(2x) + H_{C1} - H_0 \right]$$

Meissner

Image



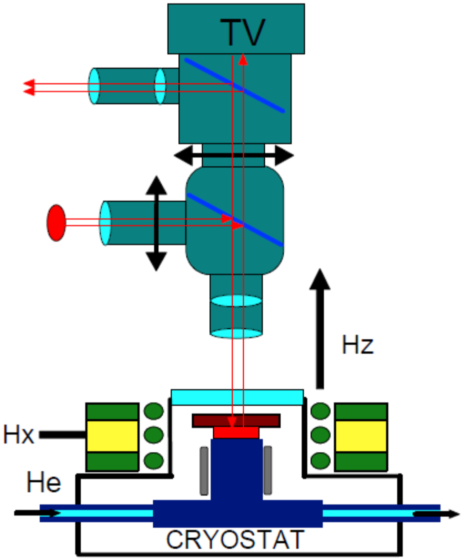


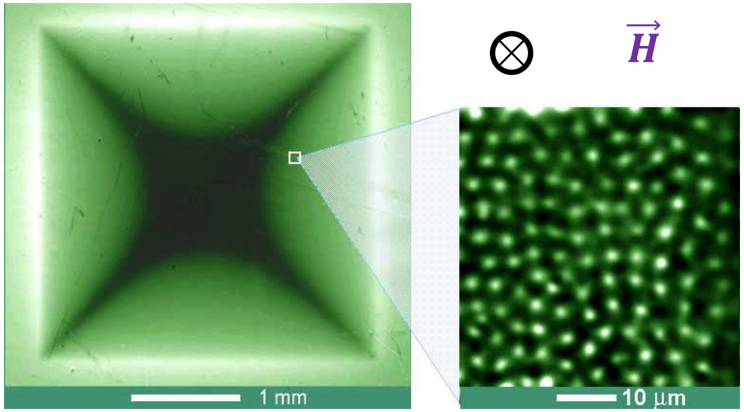


- “Ideal surface”
  - Barrier disappears only at H_{SH}~$f(H_C) > H_{C1}$
  - Rationale used to predict SRF limits
- BUT
  - If ∃ localized defect w.: $H_C^{Local} \ll H_C^{bulk}$ (or $T_C^{Local} \ll T_C^{bulk}$) => early penetration of 1 or several Vx there

VORTEX & (NEARLY) PERFECT MATERIAL

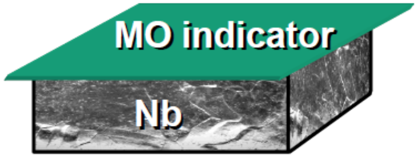
- In ⊥ field : demagnetization effect , local field depends on the shape



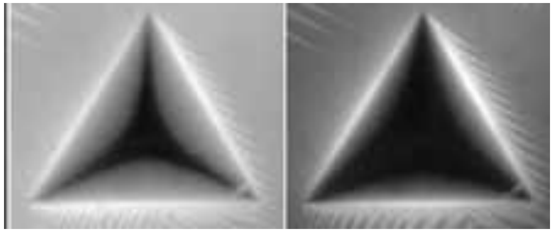


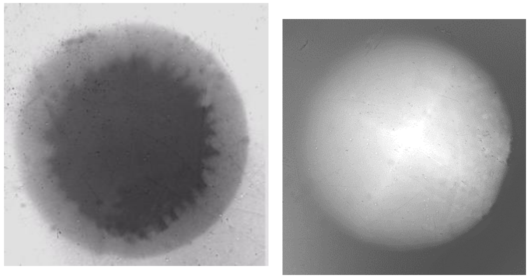
Nb$_2$Se

(Abrikosov Vx lattice)



Dark contrast: B=> 0
Light contrast : B ↗



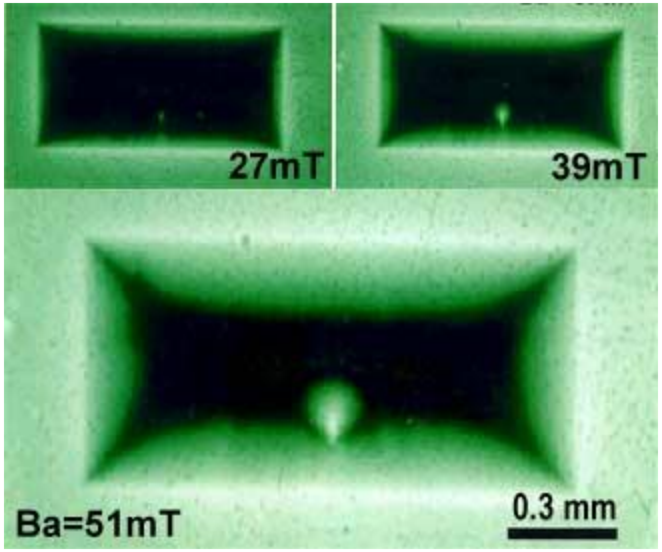


http://www.mn.uio.no/fysikk/english/research/groups/amks/superconductivity/mo/

DEFECTS AND AVALANCHES

- Localized defect effect…

$YBa_2Cu_3O_7$ film w. one single defect ↓



⊗ $\vec{B}$

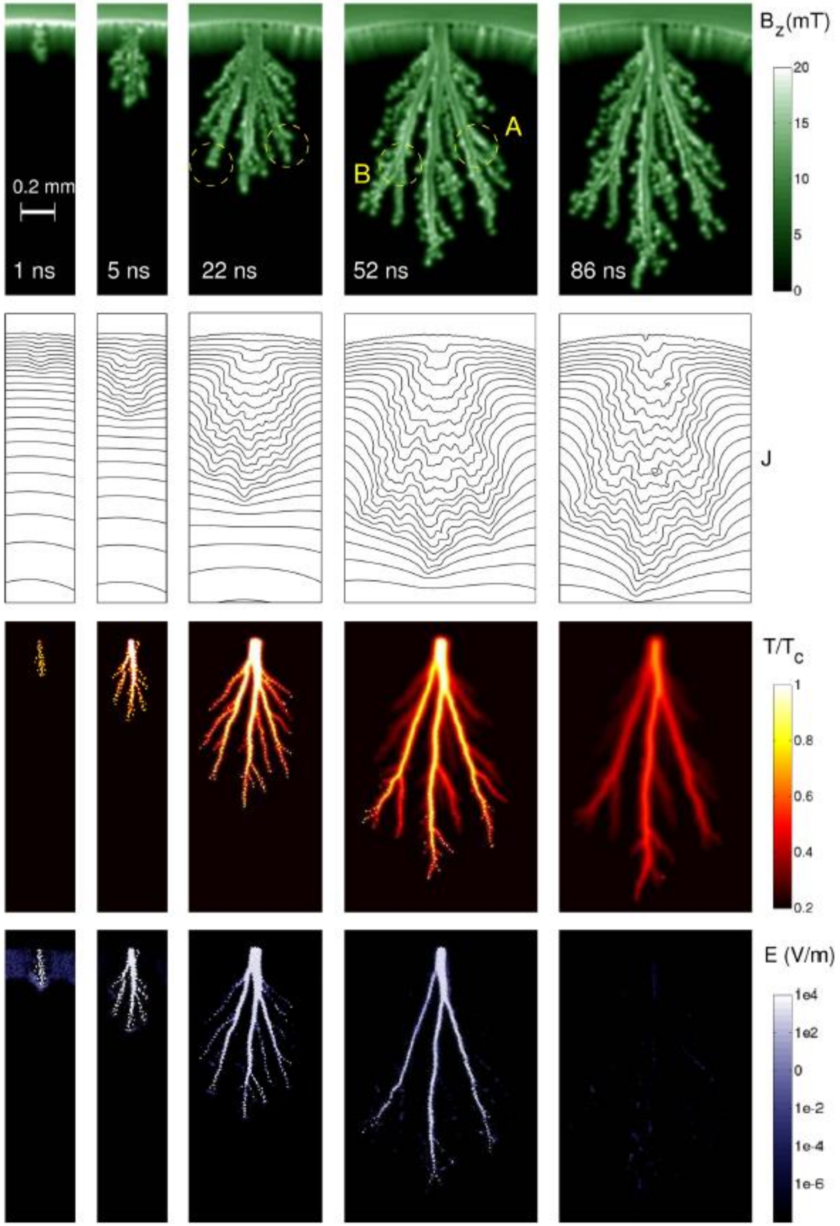
http://www.mn.uio.no/fysikk/english/research/groups/amks/superconductivity/mo/

- Vx penetration (~100 µm) during 1! RF period (ns)

⚠ 

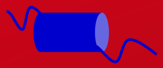
- “flux jumps” ≡ avalanche penetration, observed in transient state (so also expected in RF)

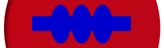
MgB_2 →



http://www.nature.com/srep/2012/121126/srep00886/full/srep00886.html?message-global=remove&WT.ec_id=SREP-20121127

VORTEX IN PRESENCE OF ELECTRIC FIELD AND/OR CURRENT



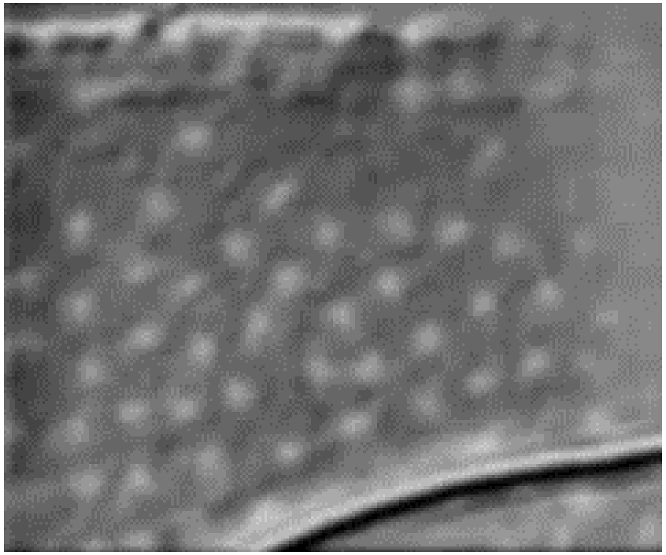
()

MOVING VORTEX

Influence of $\vec{J}$

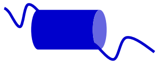
http://www.mn.uio.no/fysikk/english/research/groups/amks/superconductivity/sv/

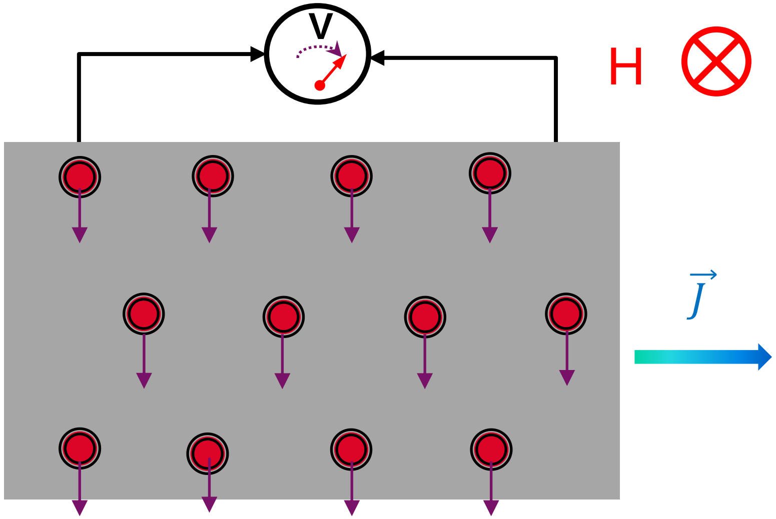
NbSe →
25x35 µm



- Vx submitted to Lorentz force $\vec{F} = \vec{J} \times \vec{B}$
- Vx lattice moves at speed v under the action of $\vec{J}$ (collective movement)
- Generate electrical field $\vec{E} = - v \times \vec{B}$, $(//\vec{J})$
  - Ohm law : if ∃ potential difference, then ∃ R
  - => non negligible resistivity: flux flow resistivity ρ_{ff}
- Lattice viscosity : movement limited by / “viscous” force (Magnus force)
  - Origin: normal zone dissipation
  - $\rho_{ff} = \rho_n B / B_{C2}$ *(B/B$_{C2}$ => vol. fraction of normal e-)*
  - Viscosity $\eta = \phi_0 \, B / B_{C2}$
  - Constant speed v = E/B
- Elastic energy:
  - Tends to keep Vx equidistant in absence of defects (*reminder: inter-vortex distance depends on applied field)*

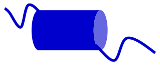
See also :



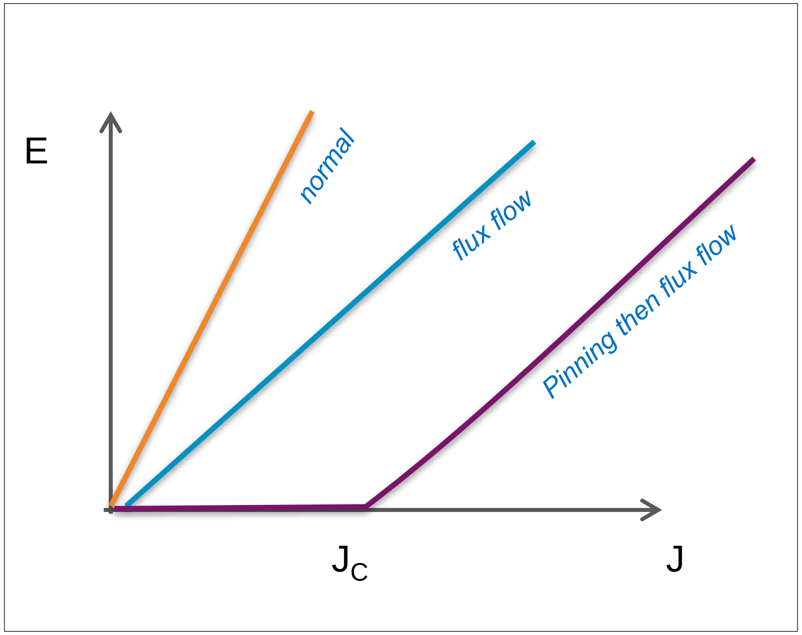


CRITICAL CURRENT DENSITY J_C

For type II SC



- In practice $R \neq 0$ only for $J>J_C$
- For $J<J_C$
  - $R=0$ (for $J \ll$ JC, close to J_C: some flux creep)
  - Vx are pinned on defects



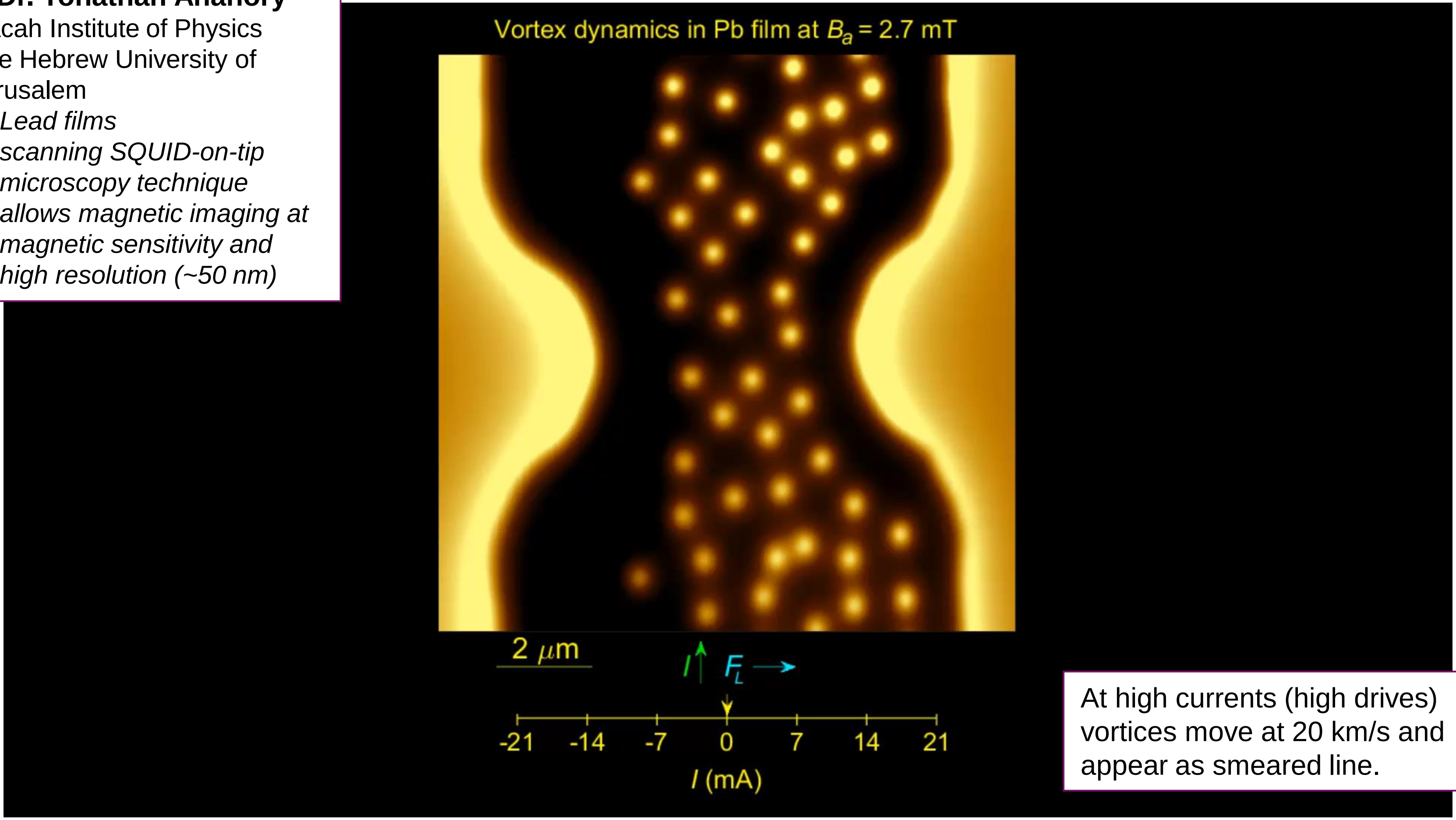
- J_C : current at which flux flow starts
- No dissipation ? => do pin Vx => do artificially create defects (inclusions, grooves, alloying, damaging …)
- For ↗ J_C : ↗ defect density => ℓ ↘
  - ξ ↘ , λ ↗↗, κ ↗↗ and H_{C1} ↘, H_{C2} ↗
  - J_C (extrinsic) $\ll$ J_D (intrinsic)
- RF Cavities : pinning is inefficient, J_C meaning less: always in the flux flow regime (that is why we want to prevent early Vx penetration and flux trapping during cooldown!)

VORTICES AVALANCHES

https://www.eurekalert.org/multimedia/pub/145764.php\

© **Dr. Yonathan Anahory**
Racah Institute of Physics
The Hebrew University of Jerusalem

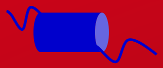
- *Lead films*
- *scanning SQUID-on-tip microscopy technique*
- *allows magnetic imaging at magnetic sensitivity and high resolution (~50 nm)*



At high currents (high drives) vortices move at 20 km/s and appear as smeared line.

VORTEX (II): PINNING ON CRYSTALLINE DEFECTS

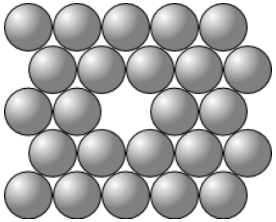
(Introduction)



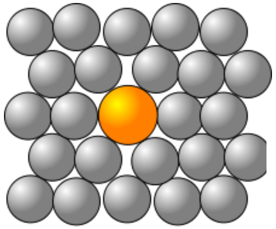
EXAMPLES OF CRYSTALLINE DEFECTS

Punctual:

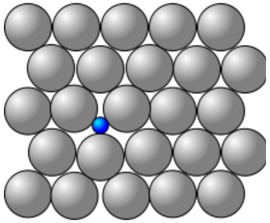
Vacancy



Substitutional atom

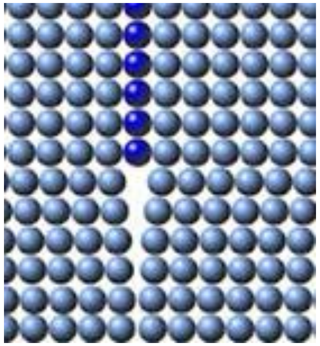


Interstitial atom

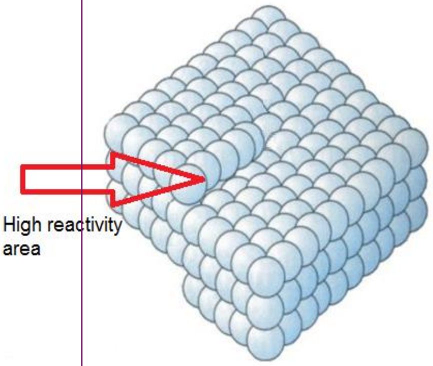


1D:

Edge dislocation

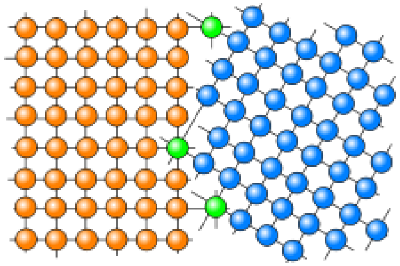


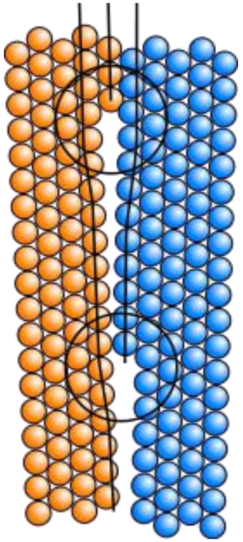
Screw dislocation



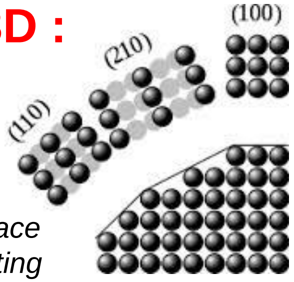
2D :

Surfaces, interfaces (GB)



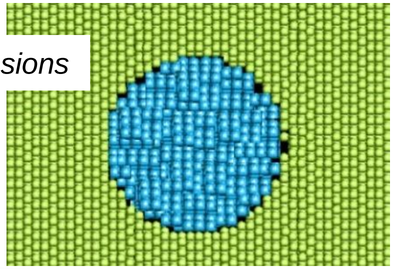


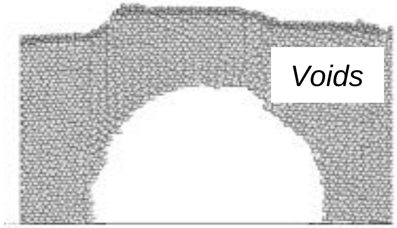
3D :



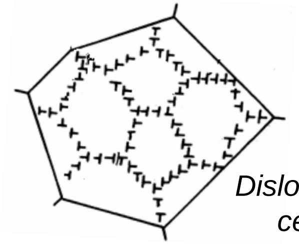
Surface faceting

Inclusions





Voids



Dislocation cells


Springer Series in Solid-State Sciences 178

Teruo Matsushita

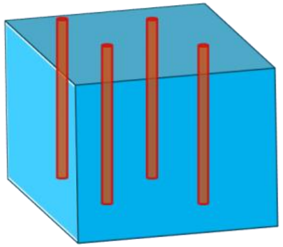
Flux Pinning in Superconductors

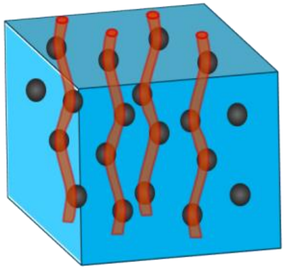
2nd Edition

Springer

MORE DETAILS ON PINNING MECHANISMS

Matsushita : 4 mechanisms from the SC point of view

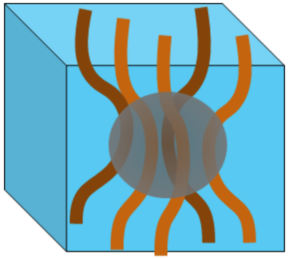




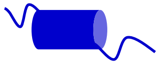
- **A**- Condensation energy variation *(one saves condensation energy if ∃ already a normal zone)*
- **B**- Elastic interactions *(bending of Vx + lattice elastic moduli in SC state < elastic Mod. In normal state, strong interaction with lattice elastic deformation due to crystalline defects-see below)*
- **C**- Magnetic interaction *(if defects >>λ, you can treat it like an interface: image vortex + surface barrier => very strong effect)*
- **D**- Kinetic energy interaction *(areas with ≠ξ => ≠ in Vx velocities ?)*

IN BRIEF : local effects !!!! *(=>2 fluids model not fully OK)*

∃ 2 kinds of efficient pinning :

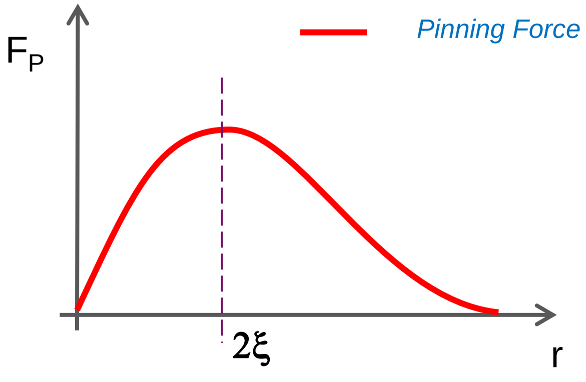


- Strong pinning (surface magnetic pinning) : twinning, voids, non SC aggregates, irradiation defects (columnar), nano-indentations : Dominant mechanism: **A** then **C** then **D**
- Weak pinning centers but many of them: «volume core pinning»
  - Dominant mechanism: **B** ; **B** less efficient than **C** but if they are many pinning centers => results into strong pinning
  - Mechanism **B** efficiency↘ 3D → Interface (G.B) → dislocation → punctual defects

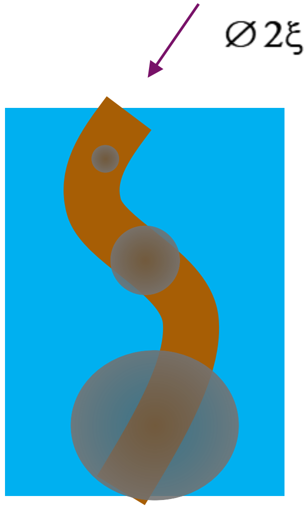


FORCES AT PLAY

Pinning Force vs elasticity

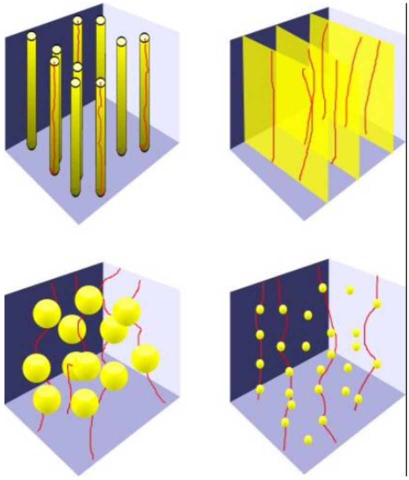


- Efficient pinning:
  - F_P (r) small for r << 2ξ et r >> ξ *r~ defects ∅*
  - F_P (r), J_C maximum for Vx // defects w. lateral size ~2 ξ (columnar defects, plane interfaces)
  - For inclusions ∅ ~ ξ, interspace *d*, J_C=> J_C' ~$J_C L/d$ *(length fraction L occupied by pinning centers w. d interspace)*
  - $E_{elastic} \sim \frac{C_{ii}}{2}\int (\nabla u)^2 d^3r$ (u ~ *Vx displacement /its ideal position, C_{ii} : elastic constants /length unit)*
  - Elastic energy influenced by other elastic deformation of the lattice due to the presence of crystalline def
- Periodicity of the Vx Abrikosov lattice is lost => Vx "polycrystal", even Vx "glass" or "liquid"…
  - ∃ complex phase diagrams of Vx states
  - Weird dynamic properties *(80% of SC literature …)*
  - In some SC (HTC): a new material state was discovered: "Bragg glasses"



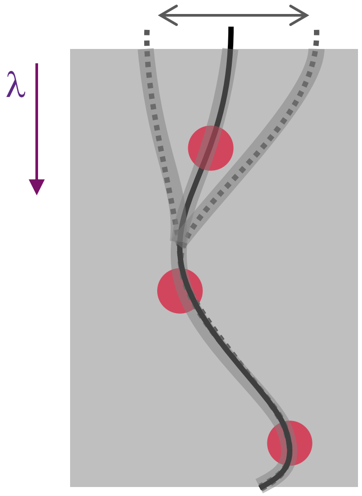
IMPORTANCE OF PINNING

Magnets :



- Pinning efficiency drives Jc (and R=0)
- Whenever possible, pinning features are amplified
  - Modification of the mean free path: impurities, deformation, alloying
  - Artificial pinning : voids, inclusions, topological defects

SRF cavities:



- No pinning at high frequency but…
- If they are pinning centers in the material:
  - They can prevent flux lines from being expelled during cooldown (trapped flux lines => oscillating Vx within ~λ)
  - => hot spots ! (Vx move in RF field => dissipation)

NEXT:

PART III : OPTIMIZATION OF SC MATERIAL

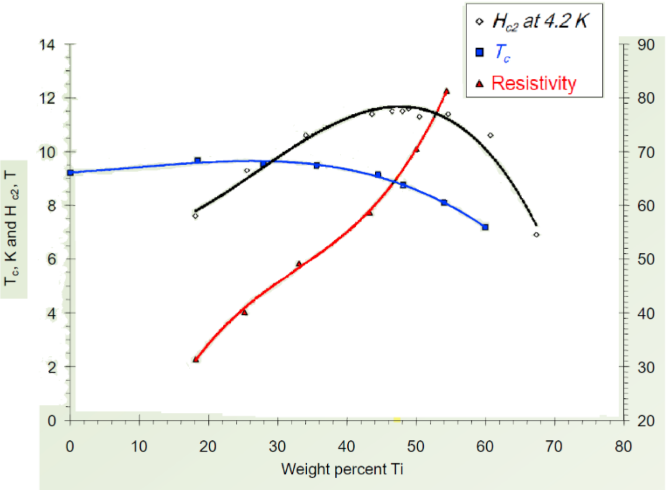
MAGNETS:

- CONDUCTORS MICROSCOPIC DEVELOPMENTS
- OTHER ELEMENTS IMPORTANT FOR DESIGN

NbTi : compromize between Jc and Tc

J_C Optimization

- Composition:
  - H_{C2} optimum for 46-48% Ti (but not Tc)
- Thermal treatments:
  - => Metallic Ti precipitates (OK in DC, danger in RF)
- Forming (wiredrawing):
  - Final microstructure : defects @ the same scale as Vx lattice



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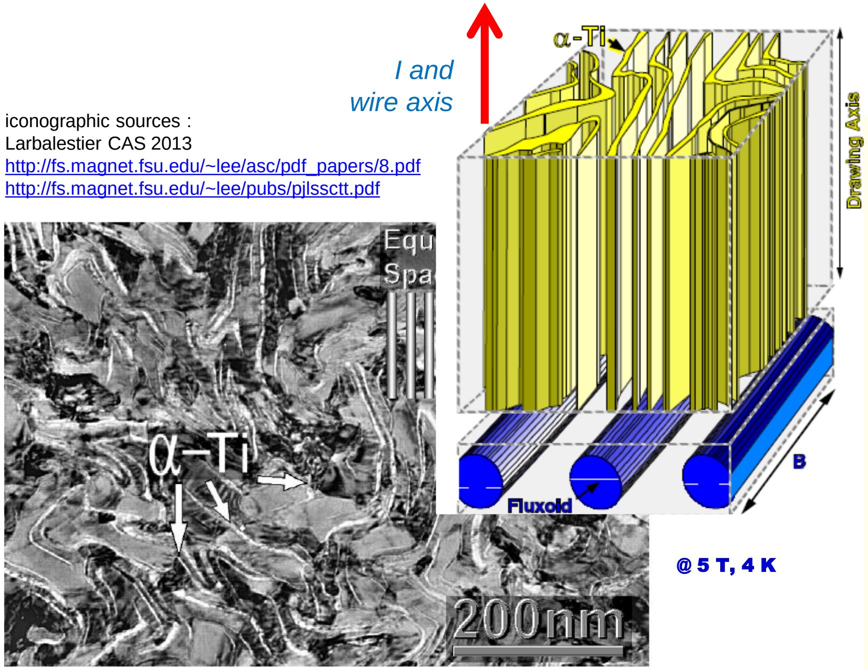
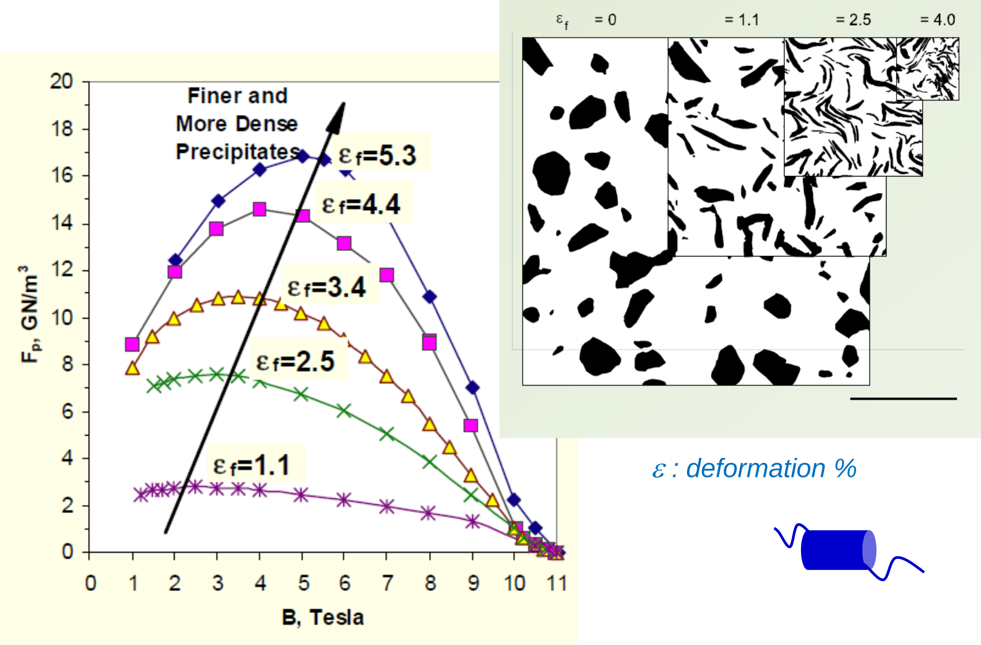
http://fs.magnet.fsu.edu/~lee/pubs/pjlssctt.pdf



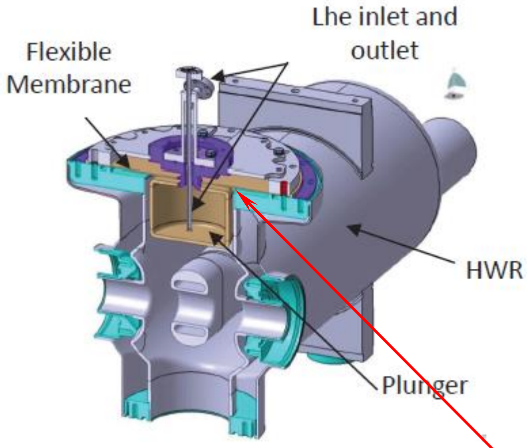


@ 5 T, 4 K

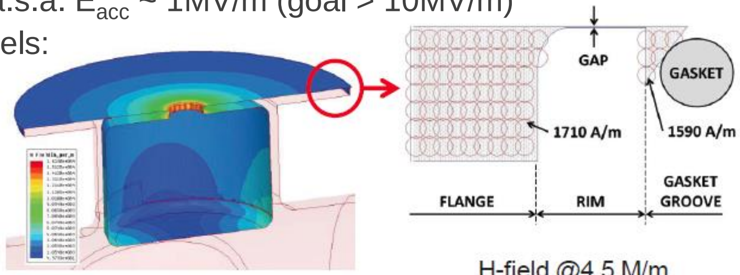
ε : deformation %

DIGRESSION : NbTI IN SRF…

Tuning system : piston/plunger

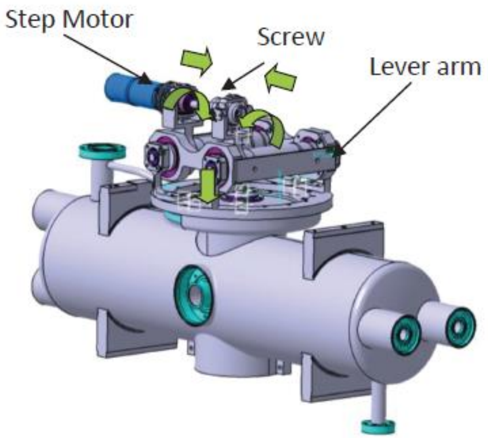


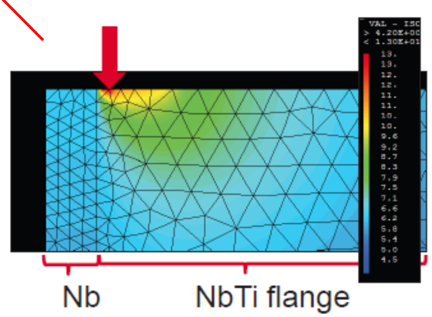
- To keep the same frequency (as in music)
  - This system is based on the mechanical deformation of a metallic membrane
  - NbTi was chosen for mechanical reasons (more rigid than Nb)
  - Important dissipation occurs a.s.a. E_{acc} ~ 1MV/m (goal > 10MV/m)
  - Not predicted by thermal models:
    - Field on the gasket ?
    - Checked => no !

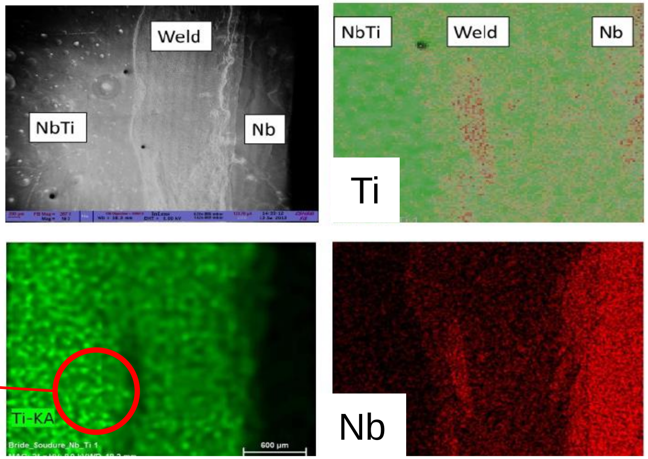


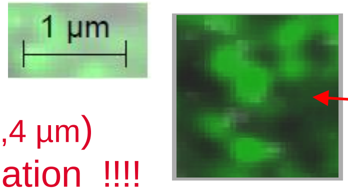
H-field @4.5 M/m

- Thermal simulation:
  - Heat comes from the Nb/NbTi welding area







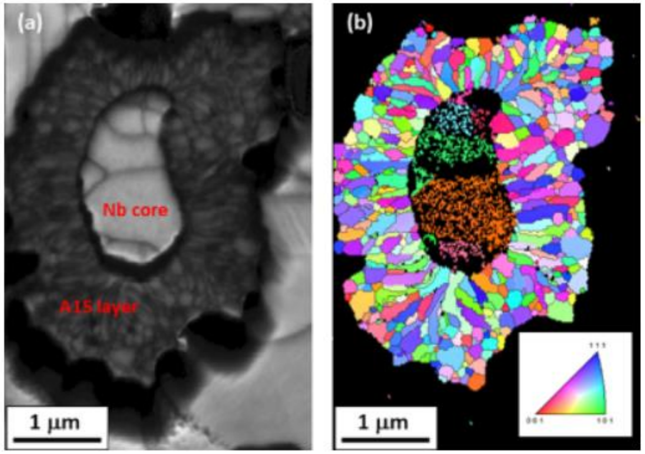


Ti precipitates (∅ ~0,4 µm)
NC Metal => RF dissipation !!!!

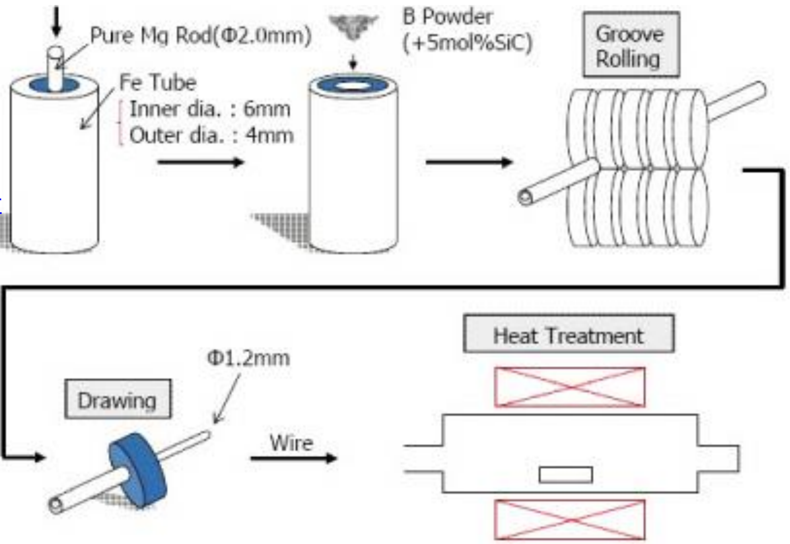
Nb_3Sn, MgB_2: too fragile for winding

- Nb_3Sn Fabrication : e.g. “bronze process”
  - Nb rod are inserted in a bronze (Cu+Sn) matrix, then co-extrudes
    => thin Nb wire surrounded w. bronze.
  - Forming/winding
  - High temperature thermal treatment
    (problem: solving electrical insulation issues !?)

http://iopscience.iop.org/article/10.1088/0953-2048/26/5/055008/pdf



- MgB_2



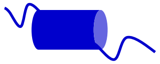
http://iopscience.iop.org/article/10.1088/0953-2048/21/3/032001/fulltext/

- *Contrary to TiN : here grain boundaries ⊥ Jc*

⇒ Not the same pinning law !

- *Jc 1/α ∅ grains*

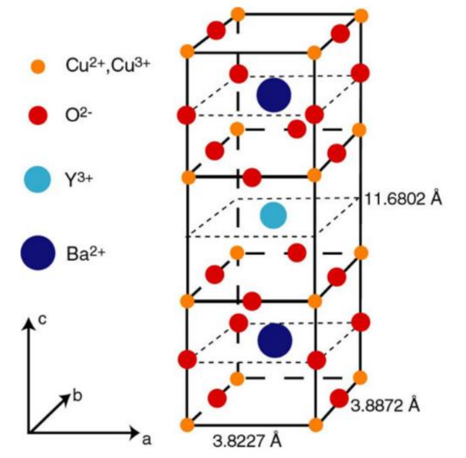
⇒ Pinning occurs on grain boundaries !

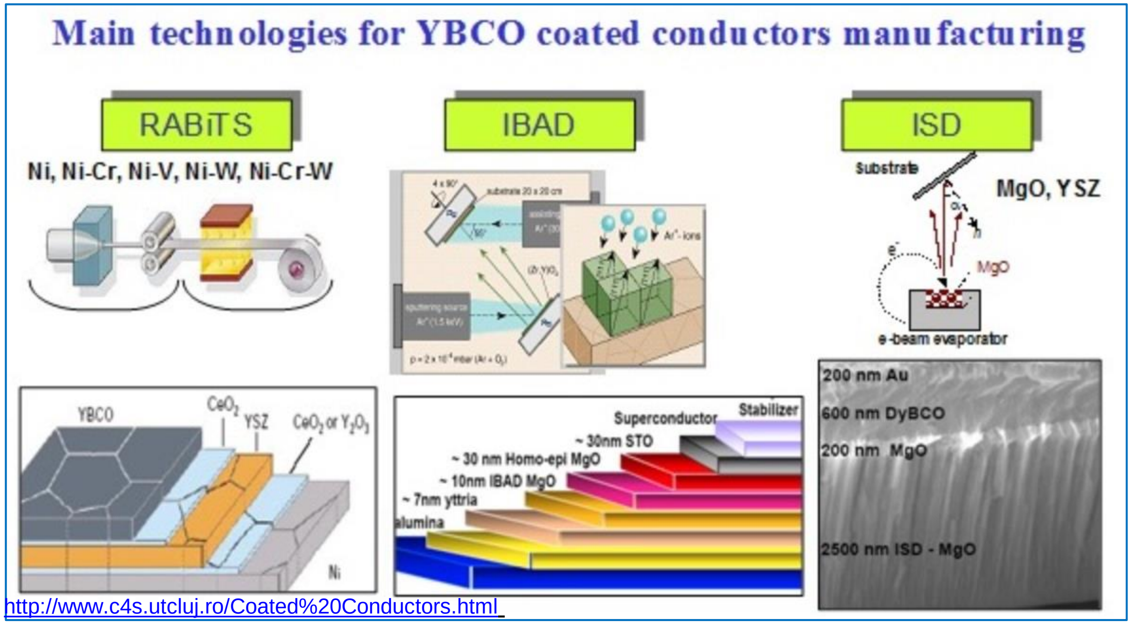


Nowadays : wires are commercially produced, then optimization of cables is done within projects (more details in P. Ferracin’s lecture)

HTS: anisotropy, weak links…

- MonoXt^{al} : Jc maximum for (a,b) planes and minimum when // c axis
  - ξc<<ξa, ξb
- Realistic material : polycrystalline, ceramic, fragile…
  - ξc ≤ disordered area at G.B => grains are decoupled (weak links)
  - Jc when B//(a,b) >>Jc when B//c
  - => try to introduce preferential orientation (epitaxy)
  - => go to composite material: each layer has a role: epitaxy, mechanical strength…





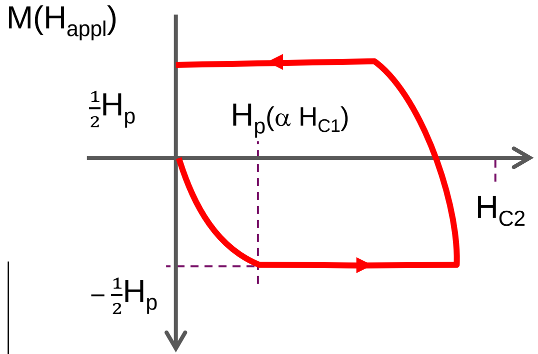
http://www.c4s.utcluj.ro/Coated%20Conductors.html

- *Current limitation when B↗ : either intragrain pinning either transition of some G.B. in the normal state (competition between 2 mechanisms)*
- *IF B // (ab) : intrinsic pinning : flux line tend to place themselves in the insulating planes (very efficient mechanism !)*

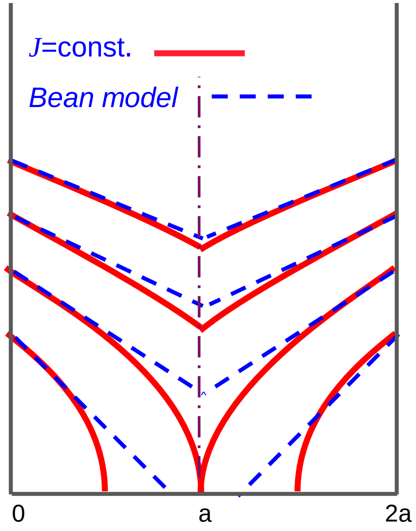
HTC still not much used , but challenges are gigantic (electrical engineering)

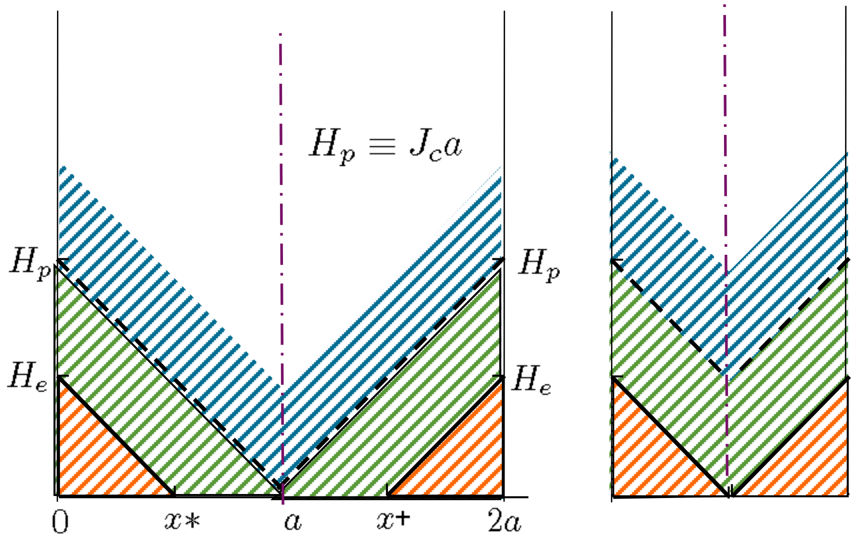
WIRE SIZE INFLUENCE

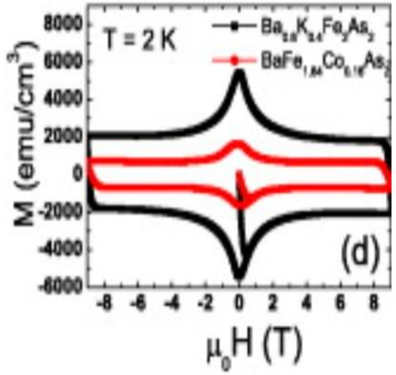
Bean model for a thin slab/wire:



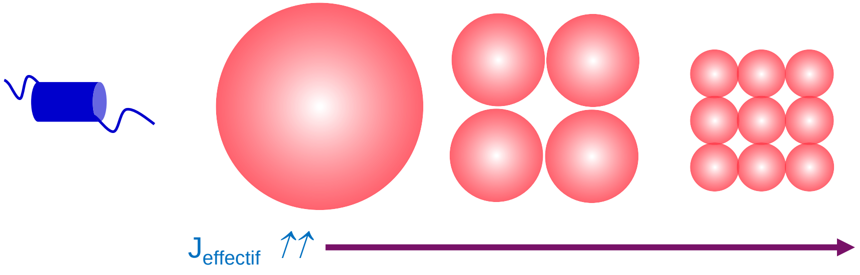
- Hyp. : @ H_{appl}> H_P : - M~cst ~1/2 H_P α $J_C x$ a, can be extended to 3D, e.g. wire
- For a same H_{appl} current density is higher if ∅ is small







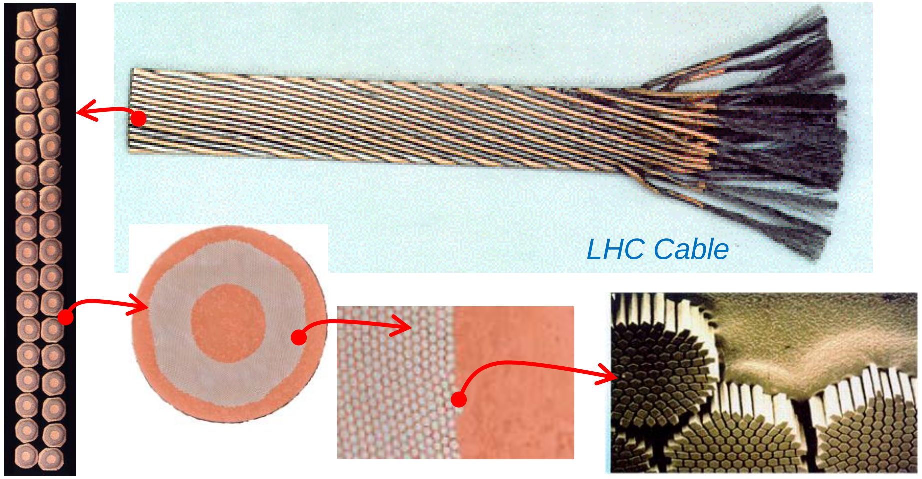
- Consequencies on the SC cable design:

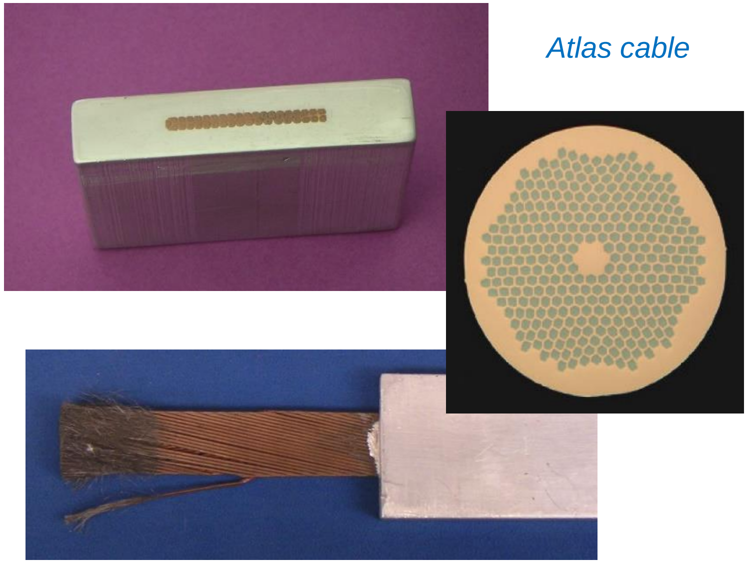


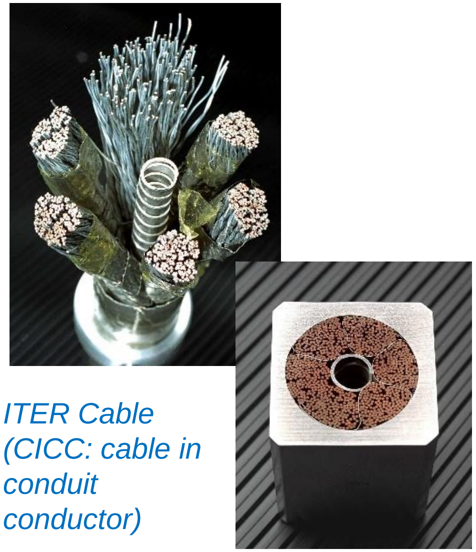
Notes

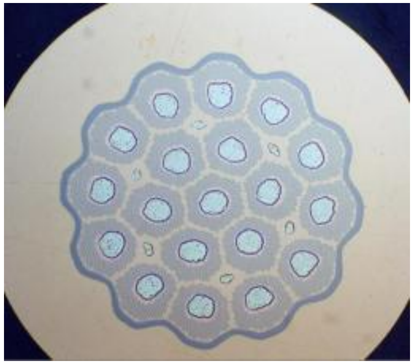
- J_c ↓ when H_{appl} ↗
- Large ∅ favor instabilities (flux jumps, avalanches instead of progressive penetration)
- Final performance depends on history in field, current, orientation compare to field…

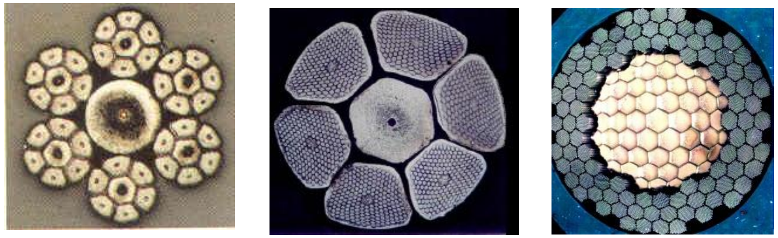
CABLES EXAMPLES


LHC Cable


Atlas cable


ITER Cable (CICC: cable in conduit conductor)


Nb_3Sn Filament


50 Hz developments

CAVITIES:

- THERMAL / SUPERCONDUCTIVITY COMPROMISE
- IMPORTANCE OF SURFACE STATE

-

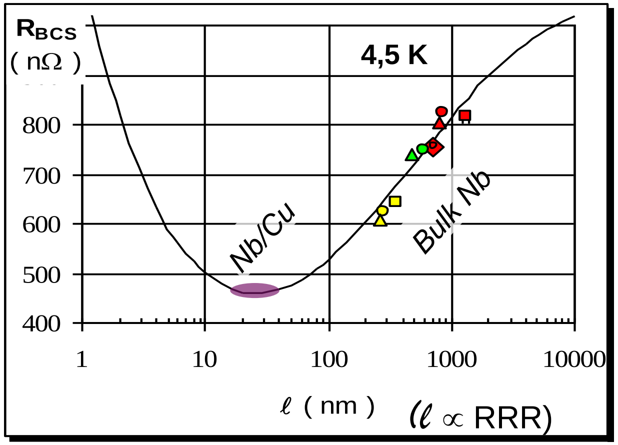
STATE OF THE ART SRF Nb

=> High purity (high RRR) well recrystallized bulk Nb, surface polished

- Surface resistance:

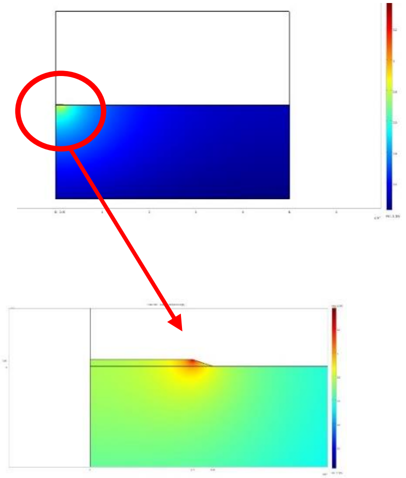
$$R_S = R_{BCS} + R_{\mathrm{Res}}$$

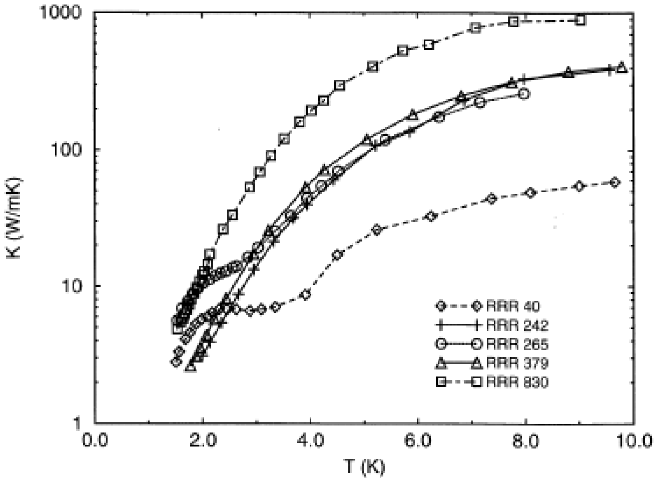
$$R_{BCS} = A(\lambda_L^4, \xi_F, \ell, \sqrt{\rho_n}) \frac{\omega^2}{T} e^{-\Delta/kT}$$



RRR: Residual Resistivity Ratio
RRR 30: commercial grade
RRR 300: SRF grade

- Thermal conductivity:





[Koechlin, Bonin 1996]

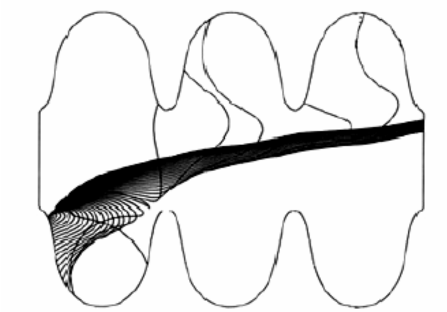
High RRR not required for superconductivity

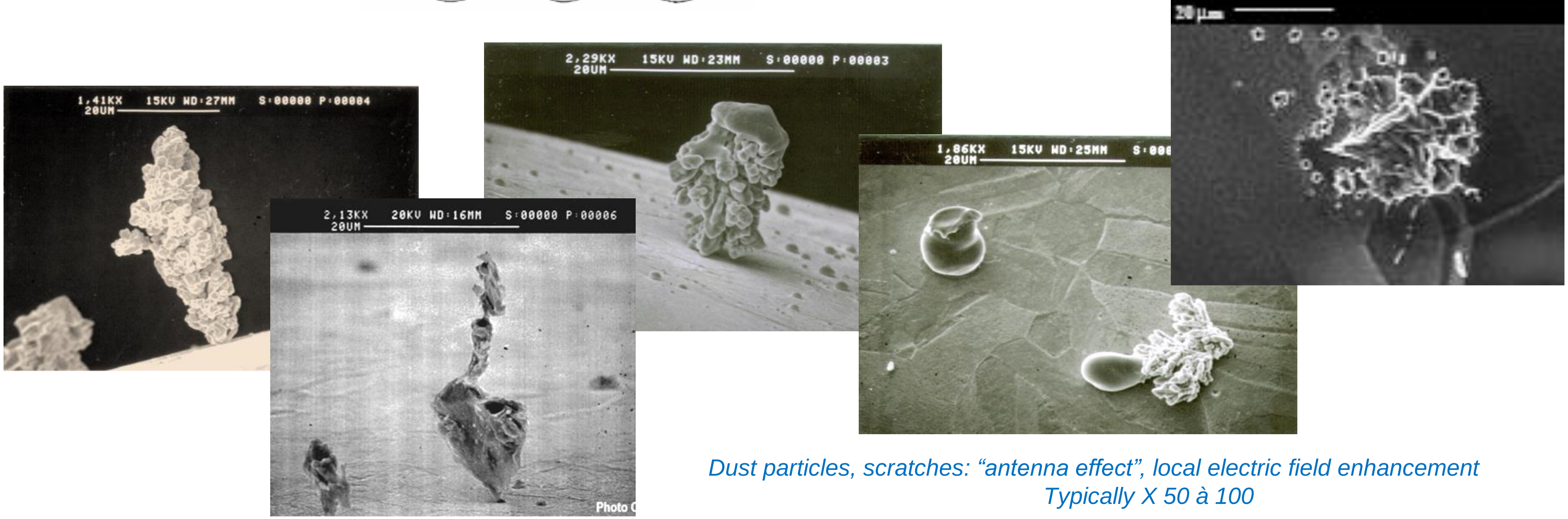
But for thermal stabilization of defects

NEED FOR QUASI PERFECT MATERIAL ON THE SURFACE !

- Clean room handling, High Pressure Rinsing (HPR)
  - No dust particle, no scratch
  - Lowers field emission risk

e- emitted by a field emitting sites disturb the beam





Dust particles, scratches: “antenna effect”, local electric field enhancement
Typically X 50 à 100

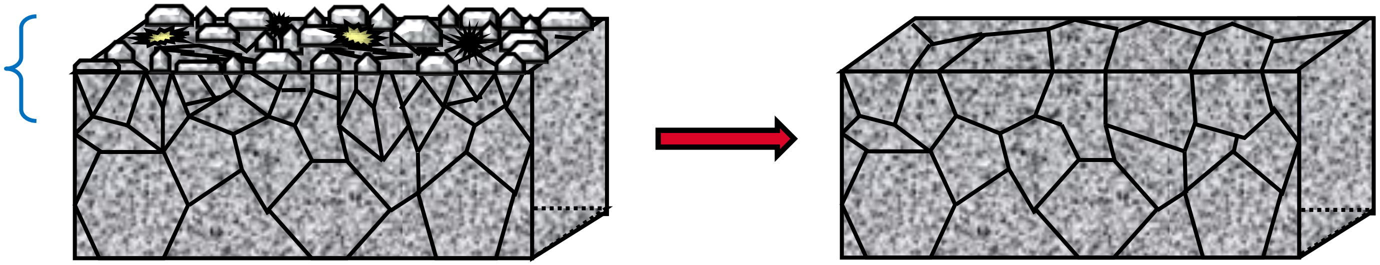
NEED FOR QUASI PERFECT MATERIAL UNDER THE SURFACE !

- Morphology => local field enhancement
- Damage => flux pinning, hot spots
- => Surface treatments, annealing …

To be avoided in SRF !

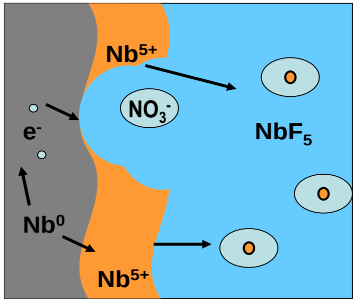
Polycrystalline Niobium, smooth and well recrystallized material

Damage layer contamination, roughness



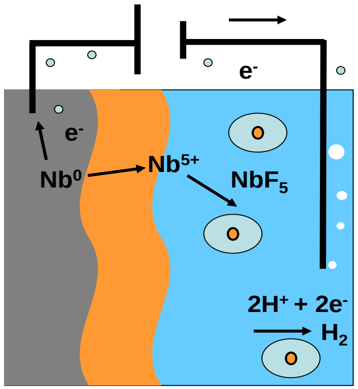
- After fabrication: need to remove 150-200µm on cavity's surface
  - Chemical polishing (BCP) ~ 1 µm/min
  - Electropolishing (EP) ~ 0.3 µm/min
- Basically
  - You oxidize Nb^0 => Nb^{5+} (Nb_2O_5)
  - You dissolve it with HF (NbF_5)

- EP : ∃ Viscous layer
  - "Spikes" are etched first
  - Smoothing effect : grain edges are less sharp, even if some roughness is retained



$6\,Nb + 10\,HNO_3 \rightarrow 3\,Nb_2O_5 + 10\,NO\uparrow + 5\,H_2O$

$Nb_2O_5 + 10\,HF \Leftrightarrow 2\,NbF_5 + 5\,H_2O$



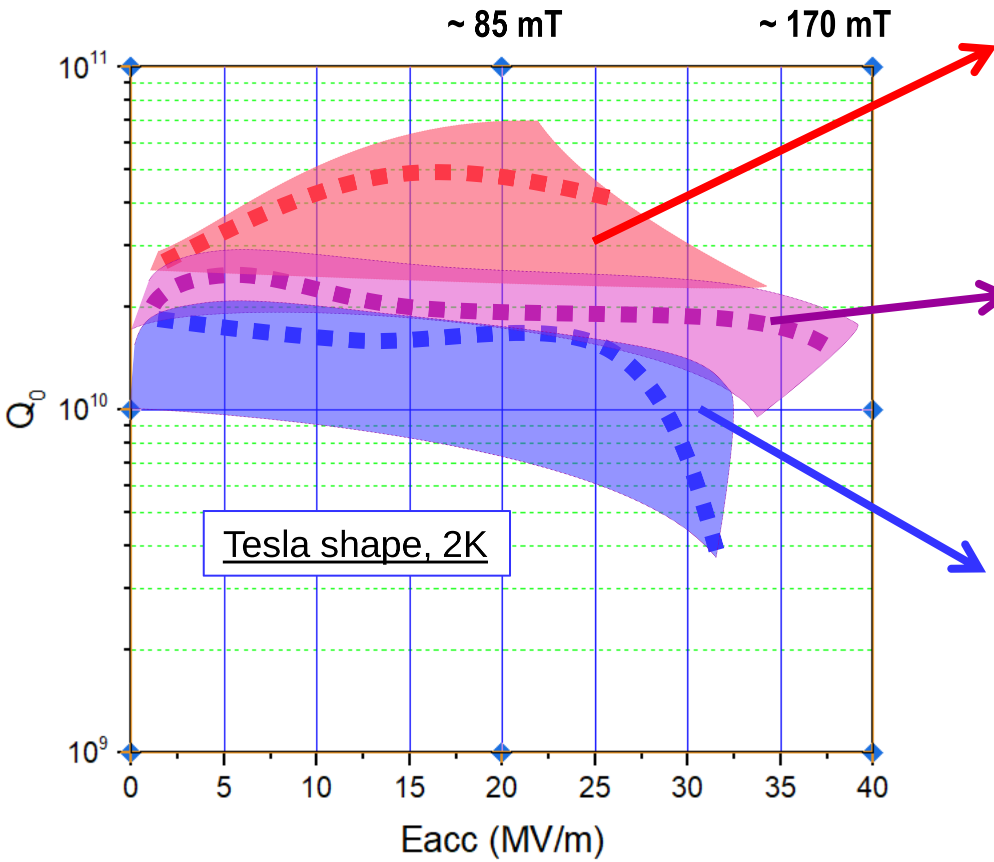
$Nb \rightarrow Nb^{5+} + 5\,e- \rightarrow Nb_2O_5$

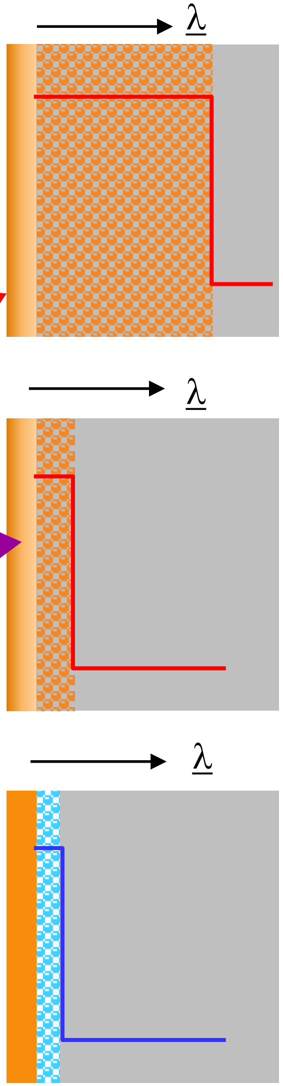
$Nb_2O_5 + 10\,HF \Leftrightarrow 2\,NbF_5 + 5\,H_2O$

Even after best surface treatments they are still a lot of defects at the µm and nm level that have a strong influence on SC properties but are difficult to include in models…

TAYLORED SURFACE COMPOSITION ON Nb

- **Modification of the surface composition:**
  - Adjusting superconducting properties
  - Preserving bulk high thermal conductivity





@ 1rst order:

Extra High Q_0: “N-Doping”, “Medium T baking”

⇒ Diffusion of N and/or O >>λ

⇒ Diminution of ℓ , thus Rs, but also Tc and H_{C1}

Extra High E_{acc}: “N-infusion”, “Low T baking”

⇒ Diffusion of N and/or O << λ

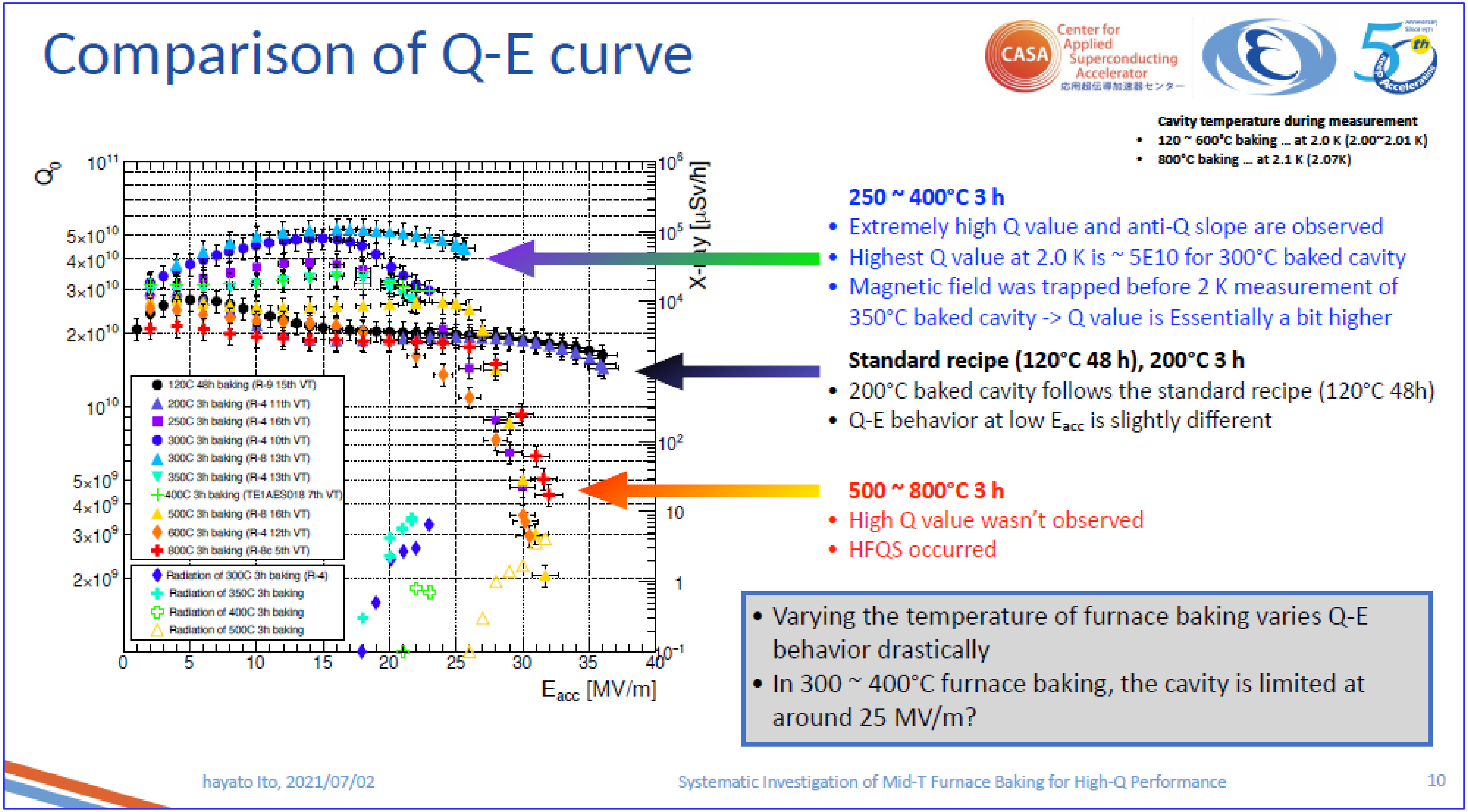
⇒ Prevents Hydride nucleation?

After polishing

⇒ Natural oxide layer (5 nm)

⇒ Impurities (H (main), O, C…) segregation at Metal-oxide interface *(see comments for mechanism)*

SAME THING WITH CAVITY REAL RESULTS



Comparison of Q-E curve

Cavity temperature during measurement

- 120 ~ 600°C baking … at 2.0 K (2.00~2.01 K)
- 800°C baking … at 2.1 K (2.07K)

250 ~ 400°C 3 h

- Extremely high Q value and anti-Q slope are observed
- Highest Q value at 2.0 K is ~ 5E10 for 300°C baked cavity
- Magnetic field was trapped before 2 K measurement of 350°C baked cavity -> Q value is Essentially a bit higher

Standard recipe (120°C 48 h), 200°C 3 h

- 200°C baked cavity follows the standard recipe (120°C 48h)
- Q-E behavior at low E_{acc} is slightly different

500 ~ 800°C 3 h

- High Q value wasn't observed
- HFQS occurred

- Varying the temperature of furnace baking varies Q-E behavior drastically
- In 300 ~ 400°C furnace baking, the cavity is limited at around 25 MV/m?

hayato Ito, 2021/07/02 Systematic Investigation of Mid-T Furnace Baking for High-Q Performance 10

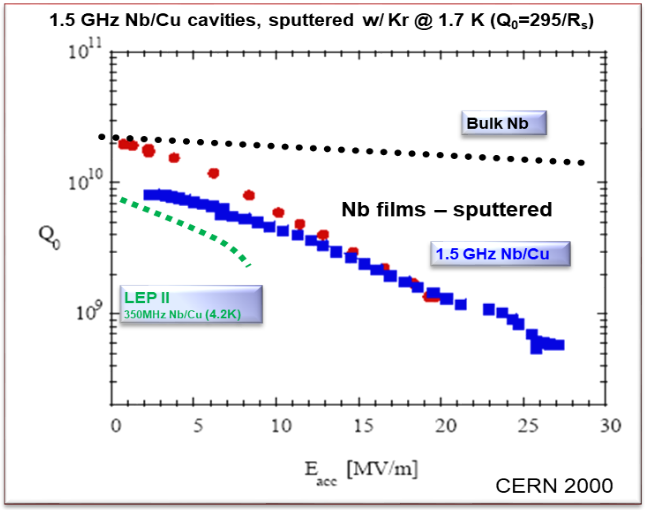
[Ito, SRF 2021]

THIN FILMS

Nb : λ~50 nm => only a few 100s nm of SC necessary

(the remaining thickness= mechanical support, thermal transfer)

=> Make thin films (1-5 µm) !



Advantages

- Thermal stability *(substrate cavity = copper, Aluminum,… W)*
- Cost
- Opens route to innovative materials
- Optimization of R_{BCS} possible *(e.g. by playing with m.f.p)*

Disadvantages

- Fabrication and surface preparation of substrate *(at least)* as difficult as for bulk Nb
- Steep Q_0 decrease often observed by increase of RF field *(sputtered niobium films)*
- Deposition of innovative materials is very difficult *(large parameters space to be explored)*
- Most of the known SC have been optimized for wire applications *(low HC1, defects, pinning centers…)*

  => most of the literature recipes are not fitted for SRF application ☹ ☹ ☹

Recent breakthrough :

- CERN, Jlab were able to produce Nb film with nearly bulk-like behavior *(50 Y. of R&D!)**
- Improved substrate preparation + higher energy deposition techniques

* *one switches from metallurgy (6000 y. old) to thin film technologies (< 1 century !)*

HIGHER TC MATERIAL

- Higher Tc materials, e.g. Nb_3Sn: brittle, poor thermal conductivity => go to films (on copper)
- Compounds: less easy to master than pure metals

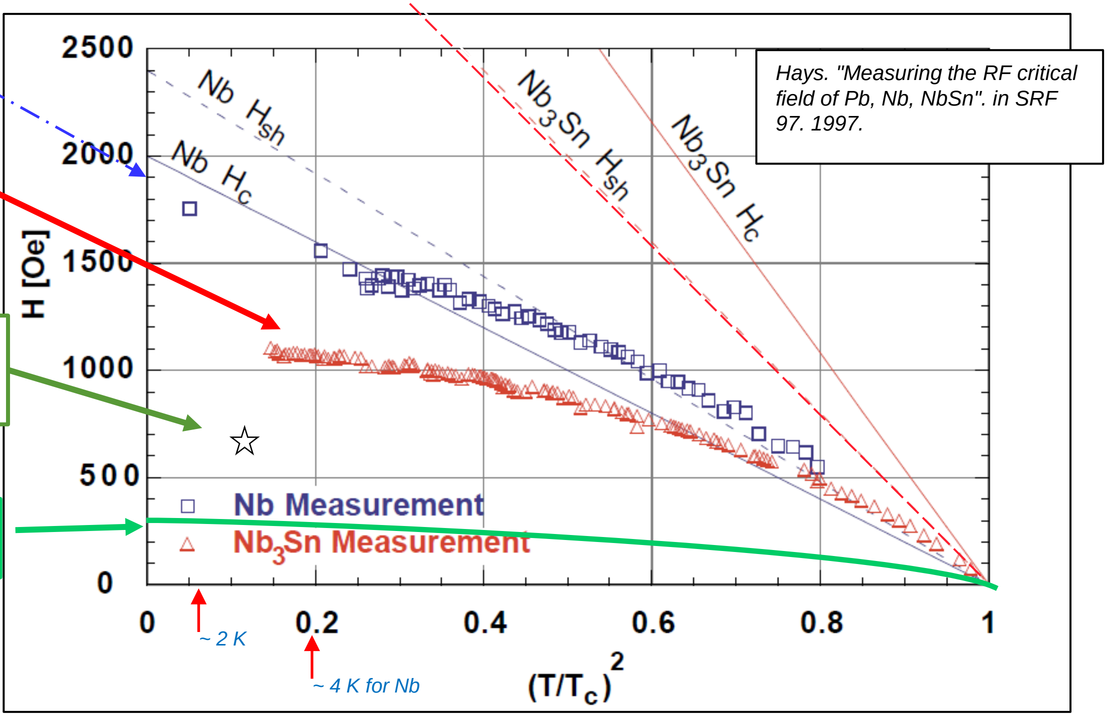
H_{SH}^{Nb3Sn} (~ 400 mT @ 0 K)

Nb H_{C1} (170 à 200 mT)

Cornell, 1997 **pulsed**

Recent results from Cornell **CW** (Posen, 2015 (17 MV/m))

H_{C1}^{Nb3Sn} (~27mT) (50 mT pour le bulk)



Hays. "Measuring the RF critical field of Pb, Nb, NbSn". in SRF 97. 1997.

Nb_3Sn

=> We have to reduce defect density

(yes but which ones?)

$$H_i = Hi^0\left[1-\left(\frac{T}{Tc}\right)^2\right]$$

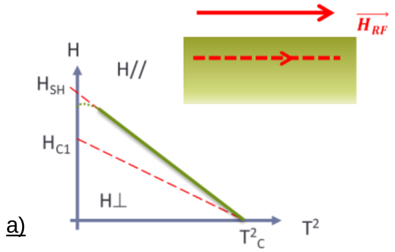
- **Vortices enter more easily at lower temperature (counter intuitive !)?**
  - @ T~T_C : H is low => low dissipations => easy to thermally stabilize
  - à T<<T_C : H is high=> even if small defect => high dissipations => Favors flux jumps

Dissipations :

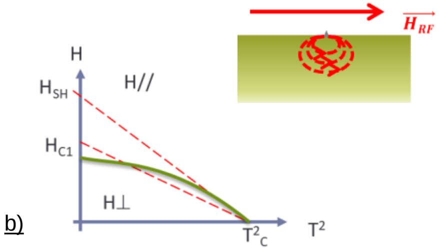
$$\frac{1}{2}\int\int R_s H^2 dS$$

MULTILAYERS SIS STRUCTURES

Enhance Q_0 and E_{ACC} altogether

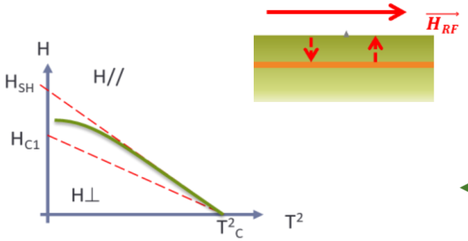


- Ideal (w/o defect)



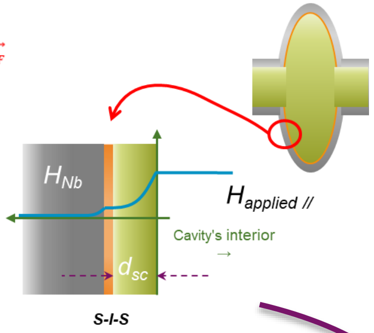
- Real world

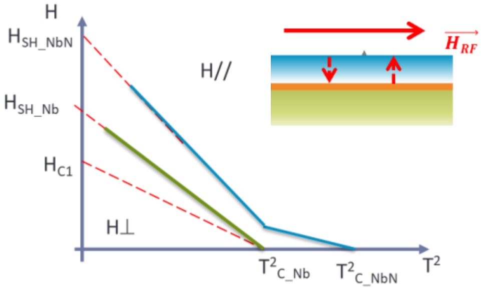
(∃ defects on surface)



- Real world

+ dielectric nm layer

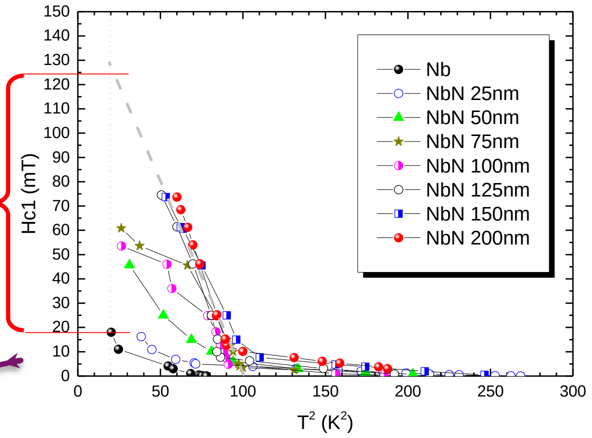




- Dielectric barrier

+ SC w. higher T_C

@ 4.5 K
~ + 110 mT?
~25-30 MV/m
ILC shape

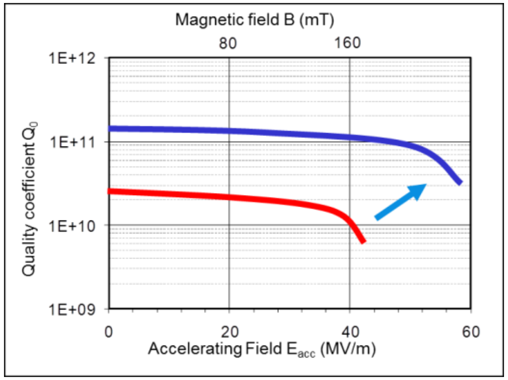


- SIS thick Nb/MgO/NbN samples

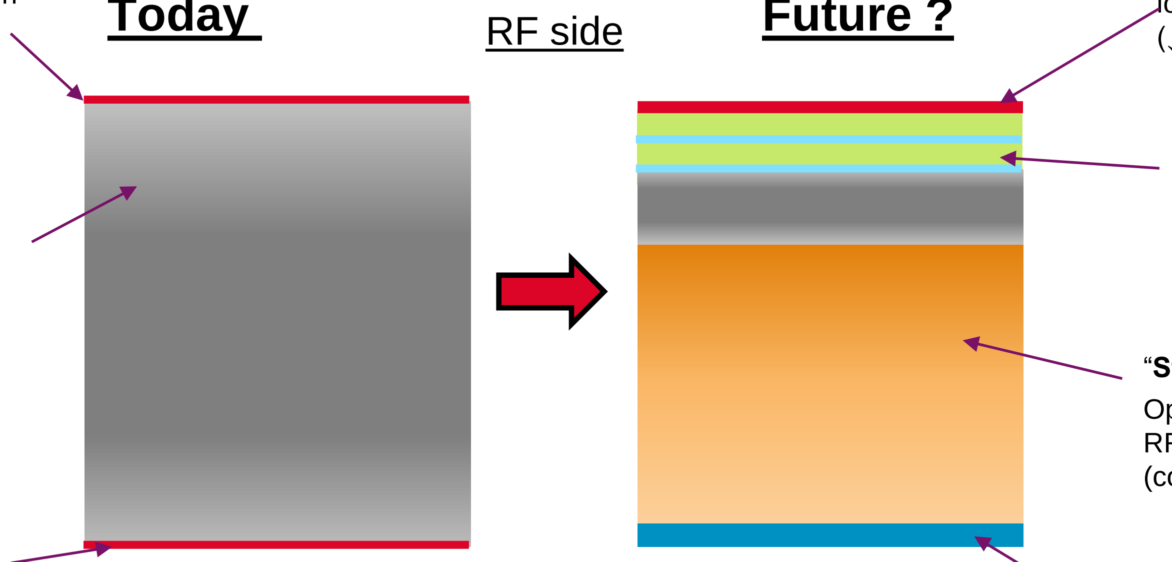
Deposited by MS

Measured by local magnetometry

- Expected performance enhancement in cavities



TAILORED MATERIAL FOR SRF



Today

RF side

Future ?

Native oxide

Unstable upon annealing

High purity Niobium Optimized only for thermal conduction

Native oxide

Not optimized for thermal transfer

Protective Layer

e.g, diffusion barrier, and/or low secondary emission layer (↓ multipacting)

“RF” layer, Optimized for superconductivity:

- Surface doped Nb
- Thick films (Nb_3Sn, MgB_2…)
- Multilayers SIS structures.

“**Structural/thermal conducting**” layer

Optimized for thermal transfer (high RRR, high m,f,p.), not necessarily Nb (copper, aluminum)

“External” layer

Optimized for thermal transfer (low Kapitza resistance, e,g, anodization)

Helium side

At stakes :

Cooling power (any application!)

Can we go to cryocooling ?

For more details on advanced materials, see SRF2021 tutorial: https://indico.frib.msu.edu/event/38/attachments/159/1143/SRF2021_Tutorial_-_Antoine.pdf

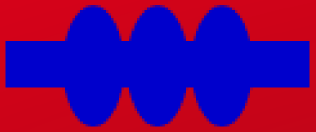
CONCLUSION

CONCLUSION

All advanced technology are limited by material issues

- Once the technology is mastered :
  - Reproducibility issues (lab => large scale production)
  - Production costs
  - Aging problems
  - Not only true for accelerator technology ! (materials for fusion, nuclear power, fuel cells, solar cells , batteries….)
  - Particularly true when a technology is pushed to its ultimate limits (e.g. accelerators)
- Advanced technology project: always a compromise between multiples constraints : mechanical, thermal, stability, superconductivity, costs…
  - Interdisciplinary work mandatory ! (multiple and complementary expertise's are necessary)
  - Do not re-invent the wheel (also meet experts outside the accelerators community !)
  - Be prepared to meet diagnostics issues (Where does the breakdown comes from when many conjugate factors occurs together ? => Diagnostic development)
  - Allow yourself to break traditions (but not too often because it costs money…)

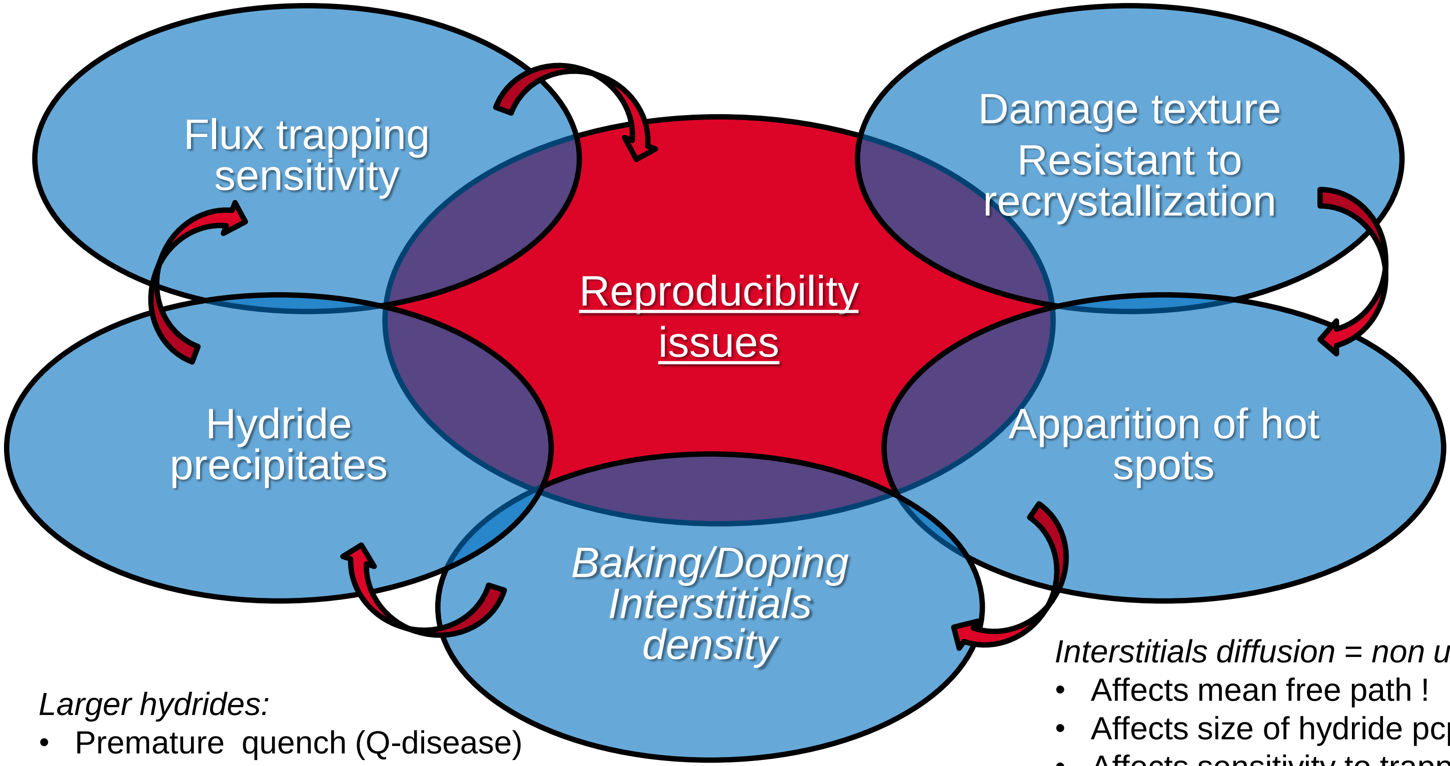
SPARES



DAMMAGE AND SRF PERFORMANCES

Reproducibility

- **Main issue on large scale production**
- **Main issue for lab to lab « recipe » transfer**



Hot spots:

- High dislocation density !
- Pinning centers !
- Vortex oscillating in RF ?
- Trapped or premature entrance ?

Larger hydrides:

- Premature quench (Q-disease)
- Strong pinning centers (flux trapping)
- H diffusion slowed by O/N interstitials

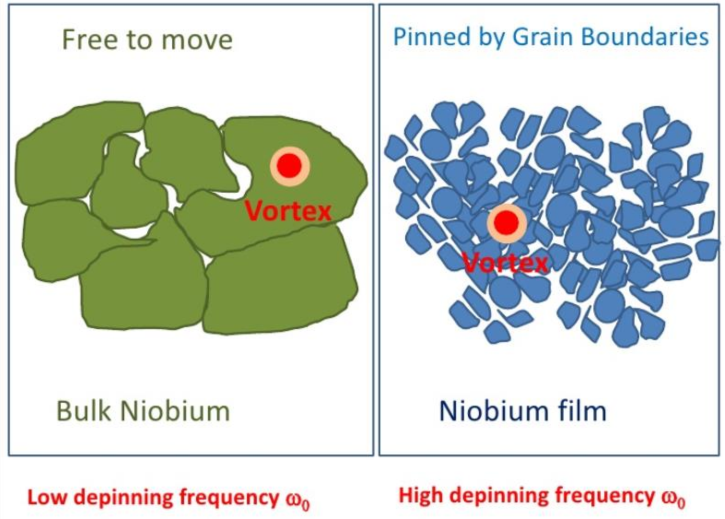
Interstitials diffusion = non uniform when dislocations cells

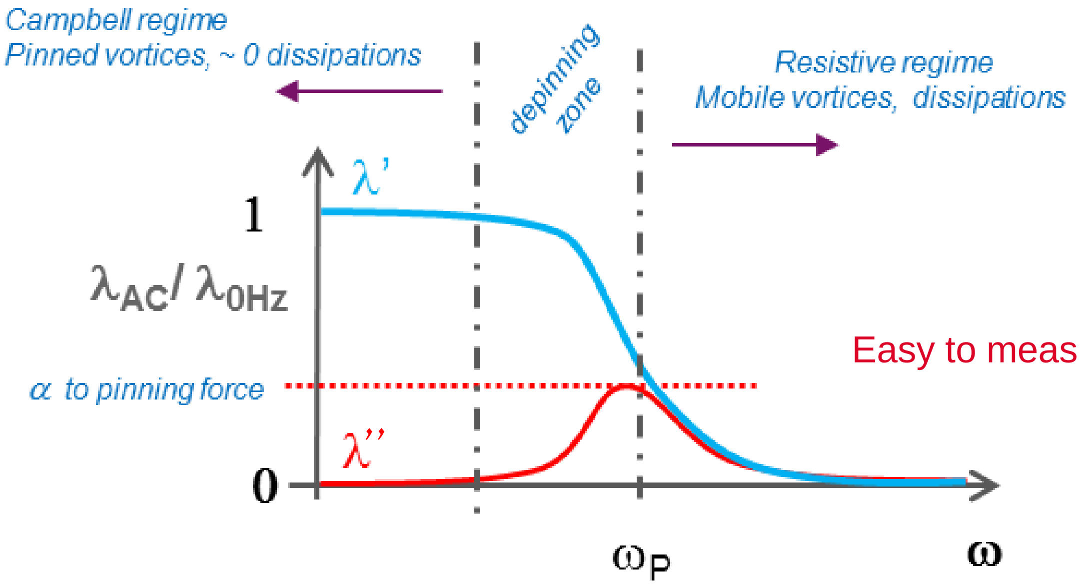
- Affects mean free path !
- Affects size of hydride pcp^{tates} !
- Affects sensitivity to trapped flux !
    - Reduce trapped flux due to hydrides
    - Higher sensitivity to trapped flux at high concentration
- **Optimum distribution is yet to be found !**

CONSEQUENCIES OF GB/GRAIN SIZE

Depinning frequency

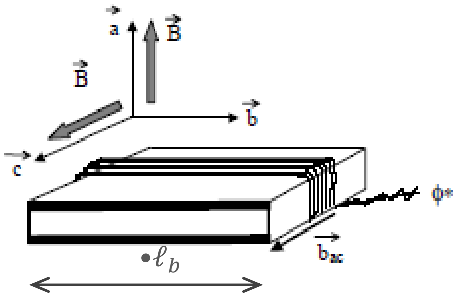
- Theory: see e,g, Palmieri TFSRF 2010
  http://fr.slideshare.net/thinfilmsworkshop/palmieri-rf-losses-trapped-flux
- Measurement of complex (/effective) penetration depth: $\lambda_{AC} = \lambda' + i\lambda''$
  - Typically used to determine pinning force in SC cables





[Electrodynamics of the vortex lattice in untwinned YBaCuO by complex impedance measurements]() Pautrat 2003

Easy to measure:



- $\phi_{ac} = \int b_{ac}\, dS \sim 2\lambda_{ac}\ell_b b_0$
- At low frequency : $\lambda' \sim \delta_{RF}$ (δ_{RF}= penetration depth in normal state)
- At high frequency $\lambda' \sim \lambda'' \sim \lambda_L << \delta_{RF}$

SENSITIVITY TO TRAPPED MAGNETIC FLUX/DEPINNING FREQUENCY

Pinning is very efficient for bulk but not for thin films Nb in the 100 Mhz-1 Ghz range

Lütke-Entrup et al
http://arxiv.org/pdf/cond-mat/9705017.pdf

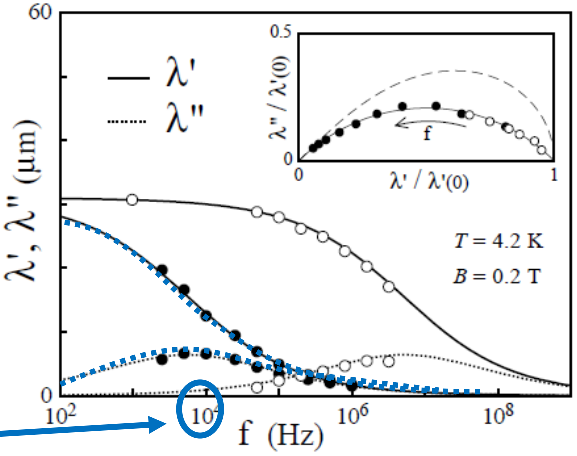
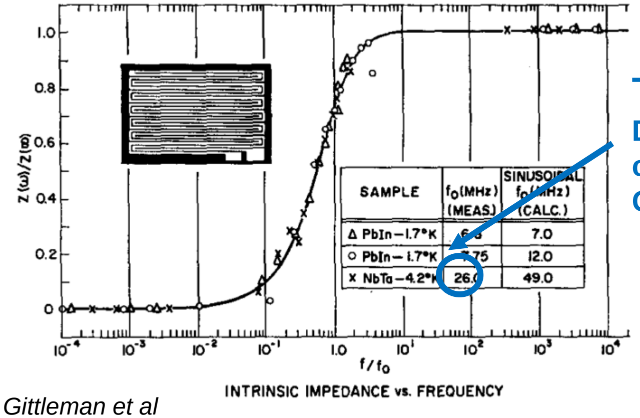


FIG. 2. The frequency dependence of the effective penetration depth $\lambda^* = \lambda' + i\lambda''$ in the thick limit ($d \gtrsim 2\delta_f$). Experimental data: (○) $Pb_{.82}In_{.18}$ ($2d = 1.26$ mm, $\rho_f = 4.8\,\mu\Omega$.cm, $\Omega_d/2\pi = 6$ MHz). (●) pure niobium ($2d = 0.85$ mm, $\rho_f = 4.3\,n\Omega$.cm, $\Omega_d/2\pi = 6$ kHz). Full lines are theoretical

Bulk monoX Nb: 10 kHz



SAMPLE	f_0(MHz) (MEAS.)	SINUSOIDAL f_0(MHz) (CALC.)
Δ PbIn–1.7°K	6.8	7.0
○ PbIn–1.7°K	7.75	12.0
× NbTa–4.2°K	26.0	49.0

Thin films Nb

Depends on quality, can reach some 10 GHz; e.g. here 26 GHz,

Gittleman et al
http://scitation.aip.org/content/aip/journal/jap/39/6/10.1063/1.1656632

See also
D. Janjušević et al
http://journals.aps.org/prb/abstract/10.1103/PhysRevB.74.104501
S. Hall
http://arxiv.org/abs/1507.04105

- High depinning frequency: measured on various SC, various film deposition technique, but can vary with quality of the films.
- e.g.: measurements from Glitterman on Nb_3Sn : ω_0 ~300 GHz!!!
- All thin films show low sensitivity to trapped magnetic flux:

because all the flux is efficiently trapped !!!