Beyond Niobium SRF materials:

Thin films and new multilayer superconductors

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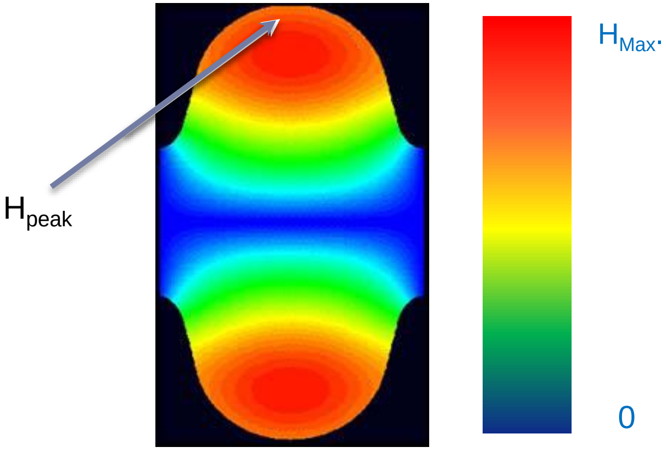
Ultimate limits in SRF-1

- Superconductivity only needed inside :
  - Thickness ~ < 1 µm => thin films
    - (onto a thermally conductive, mechanically resistant material, e.g. Cu)
- Issues : getting “defect free” superconductor

- $Q_0 \alpha\ 1/R_S \alpha\ T_C$
- $E_{acc} \alpha\ H_{RF}$
- Limit = transition of the SC material @ H_{peak}
  - Which transition should we consider!???



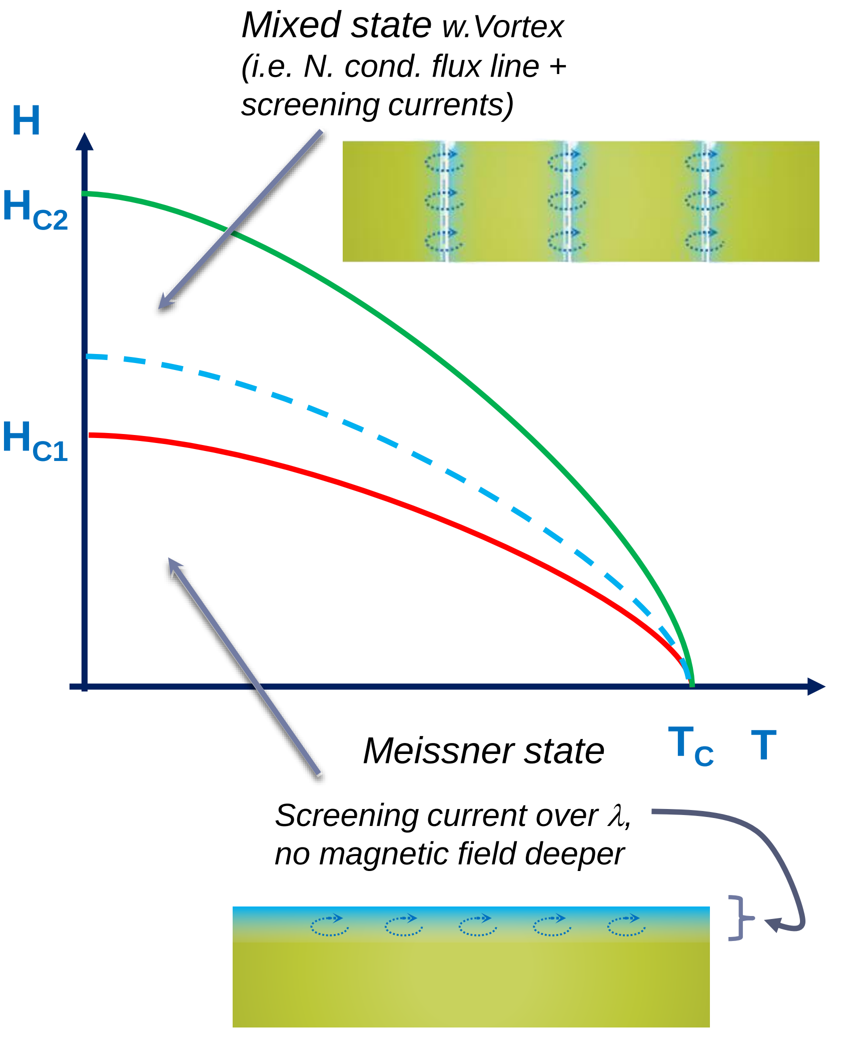
B field mapping in an elliptical cavity

Ultimate limits in SRF-2

- SC phase diagram
  - All SC applications except SRF: mixed state w. vortex
    - » Vortices dissipate in RF !
  - SRF => Meissner state mandatory !
  - H_{C1} = limit Meissner/mixed state
  - Nb highest H_{C1} (180 mT)
  - « Superheating field » (?) :

Metastable state favorized by H// to surface

- » Difficult to get in real life !



Mixed state w.Vortex (i.e. N. cond. flux line + screening currents)

Meissner state

Screening current over λ, no magnetic field deeper

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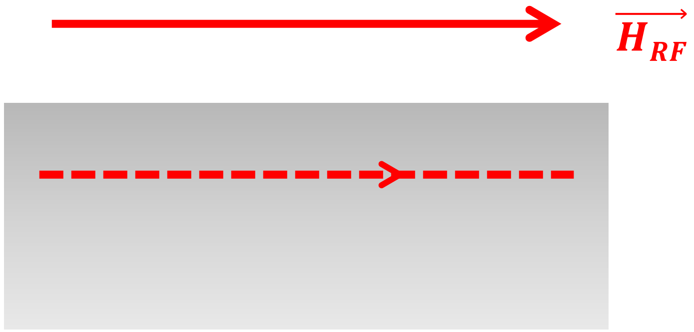
Vortex penetration

- Ideal case
  - Field // surface, => surface barrier (boundary conditions)
  - Field // surface start to enter SC @ $H_{SH} > H_{C1}$
  - @ $H \geq H_{SH}$ Vortex oscillate in RF → dissipations
  - Most favorable SC : Nb_3Sn, MgB_2 (high T_C, high H_{SH})



Nb_3Sn: reaching H_{SH} ?

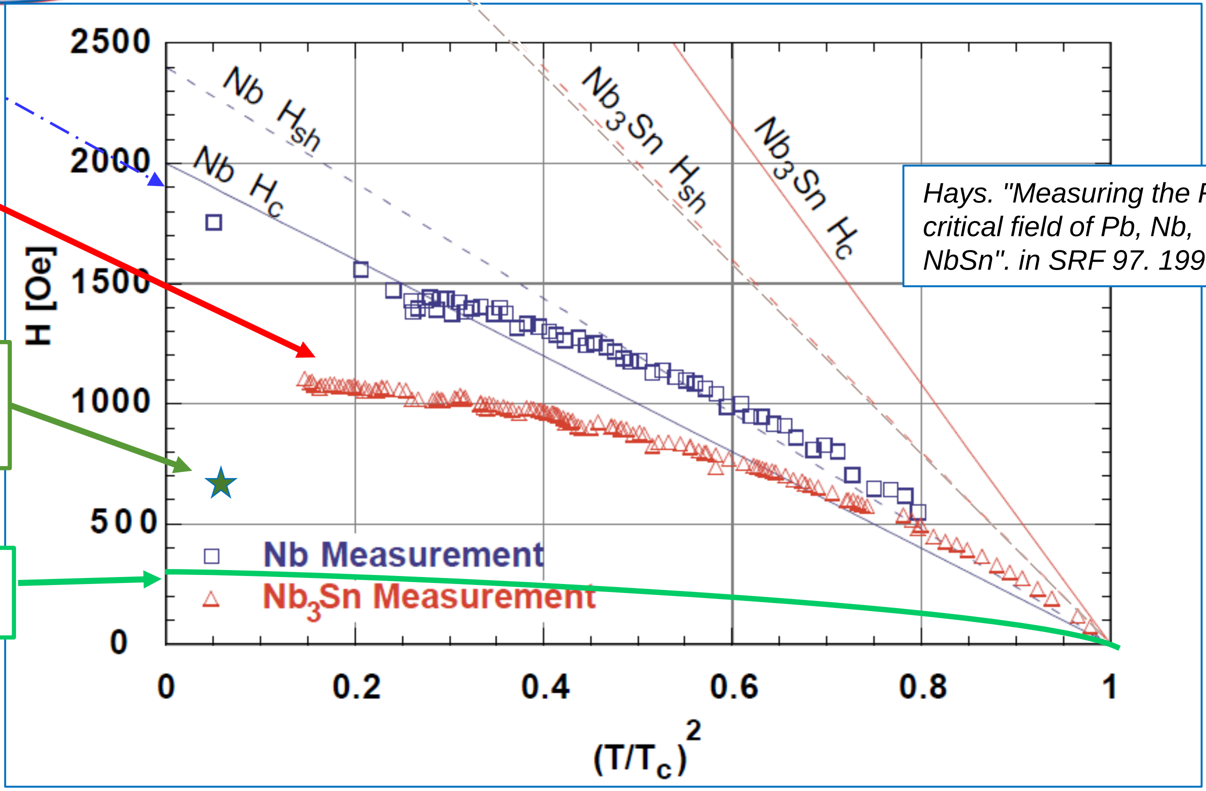
H_{SH}^{Nb3Sn}
(~ 400 mT @ 0 K)

Nb H_{C1}
(170 à 200 mT)

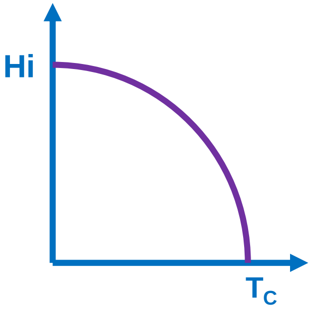
Cornell, 1997
pulsed

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.



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

Dissipations :

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

- Vortices enter more easily at low temperature
  - @ T~TC : H low=> low dissipations => easy thermal stabilisation
  - @T<<TC : H high=> even small defects => vortex penetration and high dissipation
- Reduce defect density (but which ones !?)

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Vortex penetration

- Ideal case
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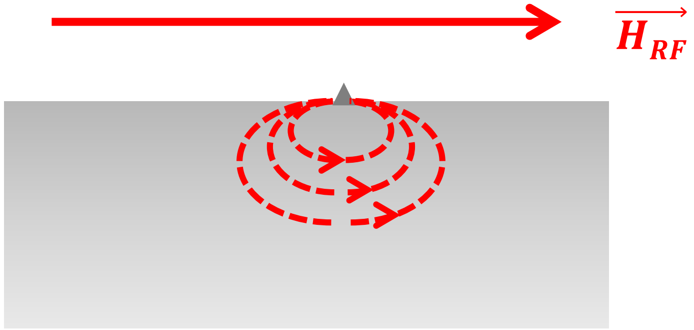
  - @ $H_{SH} > H_{C1}$ Vortex oscillate in RF → dissipations
  - Most favorable SC : Nb_3Sn, MgB_2 (high T_C, high H_{SH})

- Real life: defects at surface
  - Early vortex penetration (bundle) @ H_{C1} (or less !)
  - Formation of current loops
  - Avalanche
  - Oscillations in RF => dissipations
  - What kind of defects do we fear ???



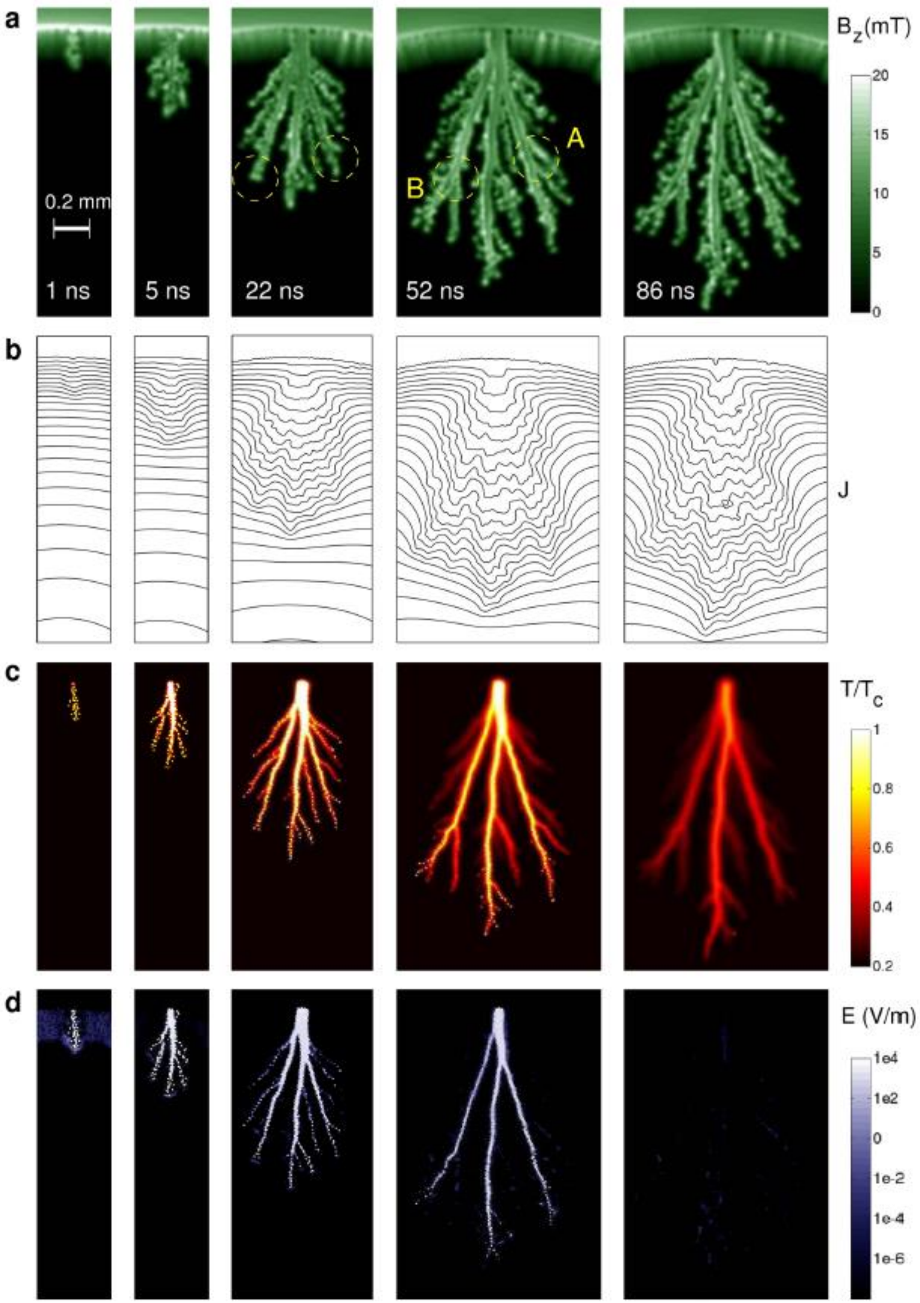
Vortices:

Avalanche penetration

⊗

$\overrightarrow{H}_{appl}$

- ~100 µm in 1 ns (~RF period)=
- Compare with λ (field penetration depth)
  - Nb : ~ 40 nm
  - MgB_2 ~ 200 nm



MgB_2 example
http://www.nature.com/srep/2012/121126/srep00886/full/srep00886.html?message-global=remove&WT.ec_id=SREP-20121127

Vortex penetration

- Ideal case
  - Field // surface, => surface barrier (Bean Livingston)
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- Defect at surface
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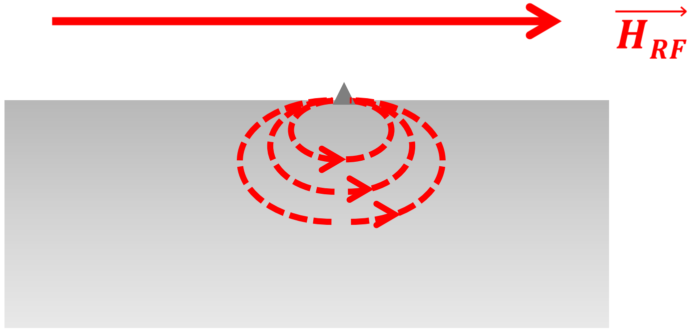
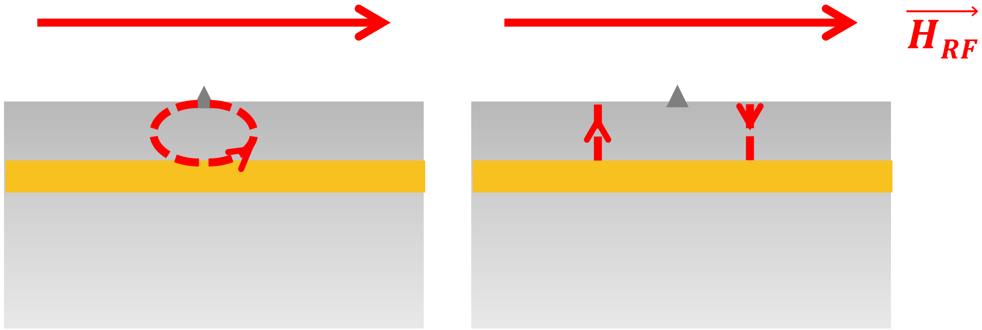
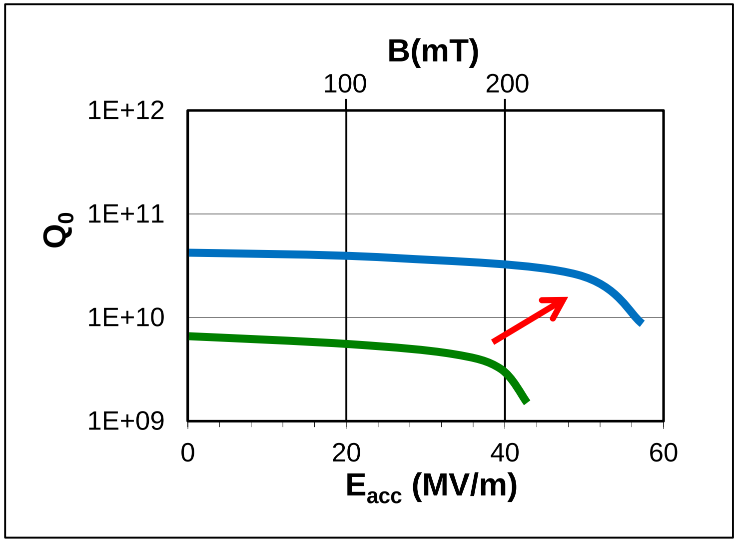


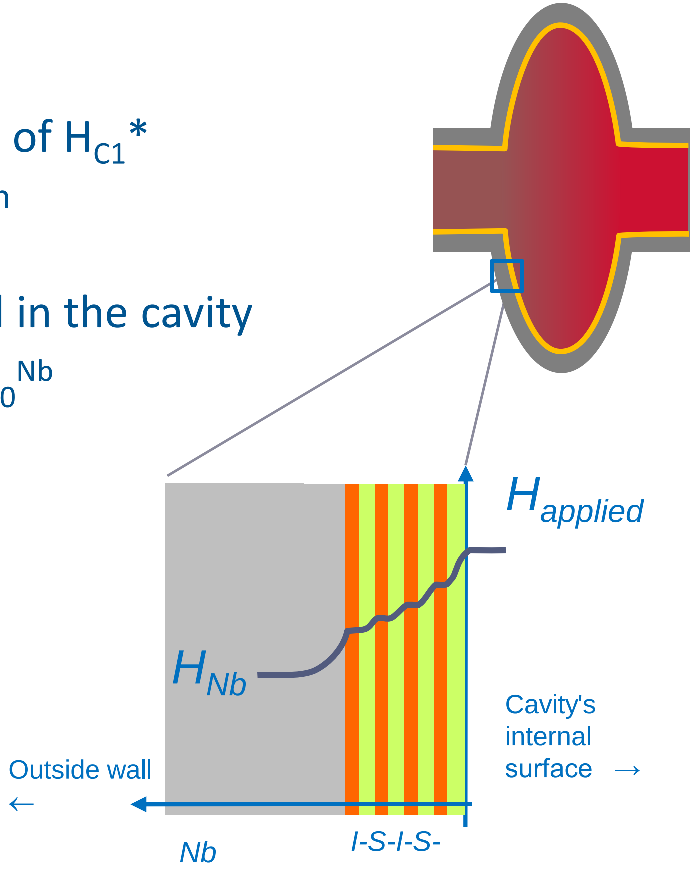
- Dielectric layer
  - Small ⊥ vortex (short -> low dissipation)
  - Quickly coalesce (w. RF)
  - Blocks avalanche penetration
  - => Multilayer concept for RF application
  - Most favorable SC : Nb_3Sn, MgB_2, NbN…



Multilayer concept

- Surface screening and low Rs
  - Thin SC films. d< λ => Artificial enhancement of H_{C1}*
    - Thin layers stand high fields without vortex nucleation
    - Partial screening of $H_{applied}$
  - Niobium surface screening: allows higher field in the cavity
  - $T_C^{NbN} >> T_C^{Nb} => R_S^{NbN} << R_S^{Nb} => Q_0^{multi} >> Q_0^{Nb}$





$$H_{Nb} = H_{appl} e^{-\frac{Nd}{\lambda}} \quad **$$

** In theory 20 nm NbN : H_{C1} x ~200*
*** Simplified model from Gurevich*

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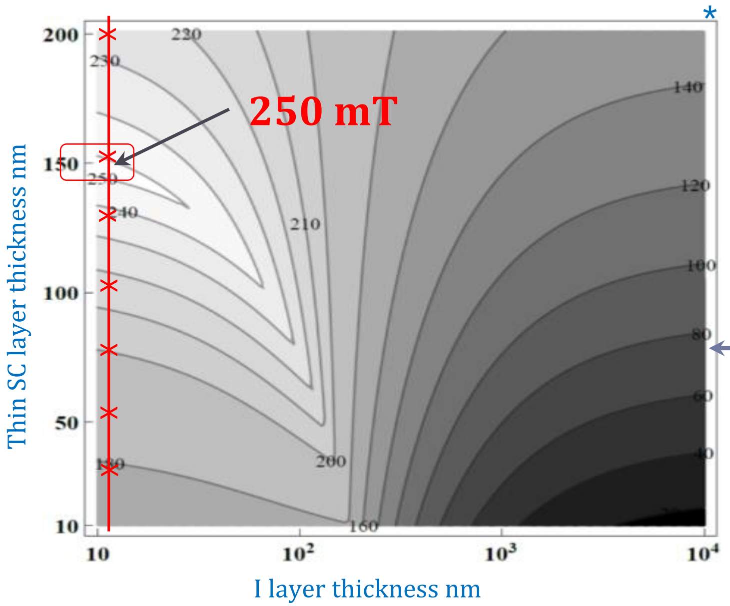
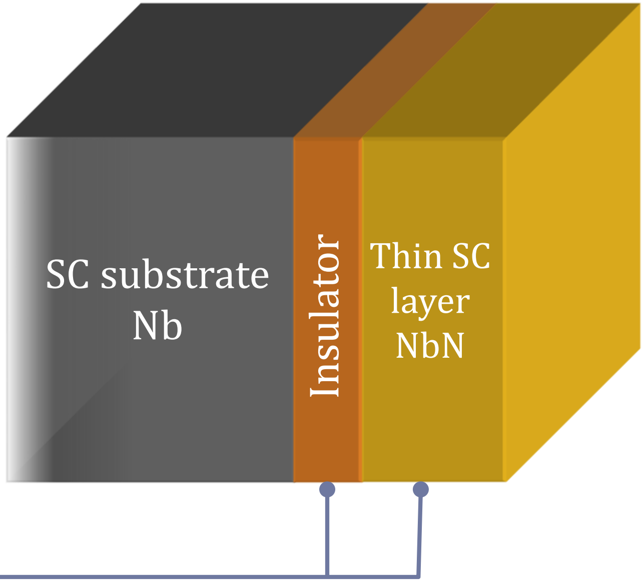
ML developments in WP12

- Optimization of ML structure
  - Series of NbN single layer/MgO/Nb samples
    - Deposited by reactive magnetron sputtering on silicon substrate (collaboration Grenoble INP and CEA INAC)
    - NbN chosen because well mastered /SC electronics
  - Comparison w. recent theoretical developments
- Development of specific sample measurement tools
  - Properties of thin films in SRF operation conditions cannot be done w. conventional techniques

Nb – Insulator – NbN model

- Advanced model: ∃ only for single layer; includes:
  - Boundary conditions
  - Role of Nb sublayer





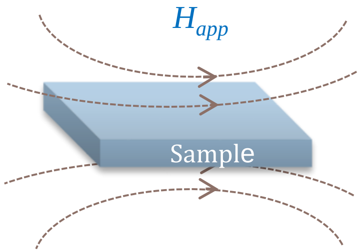
H_{max} optimum $\sim$**250 mT** which is higher than of thick Nb **(170 mT)**

- Prediction for NbN (T_C ~15K, λ = 200 nm)
  - T. Kubo (2014)[3] ~140 nm
  - A. Gurevich (2015)[4] ~160 nm
- WP 12.2 (subtask 2) experimentals:
  - NbN not most favorable on paper…
  - but "easy" to make (cf SC electronics)

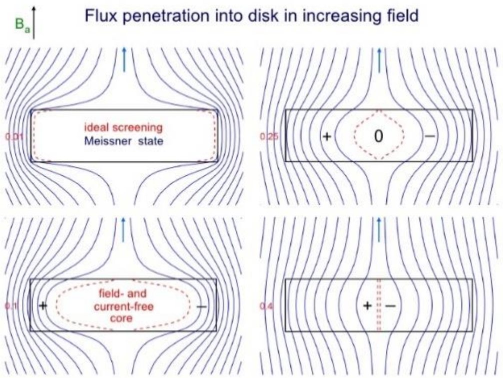
[2] *C.Z. Antoine, et al. APL 102, 102603 (2013).* [3] *T. Kubo et al, Appl. Phys. Lett. 104, 032603 (2014).* [4] *A. Gurevich, AIP Advances 5, 017112 (2015).*

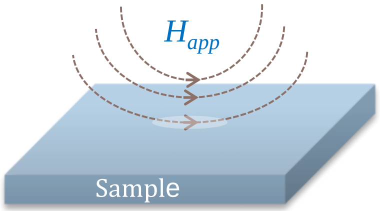
H_{c1} Measurement: need for Local Magnetometer

- Develop new SCs multilayers at higher fields => Need for specific characterization tools
- Conventional Magnetometer (SQUID) gives ambiguous results:
  - Uniform field around the sample
  - Demagnetization (orientation, edge, shape) effects
  - Exact local field configuration not known



SQUID magnetometer principle

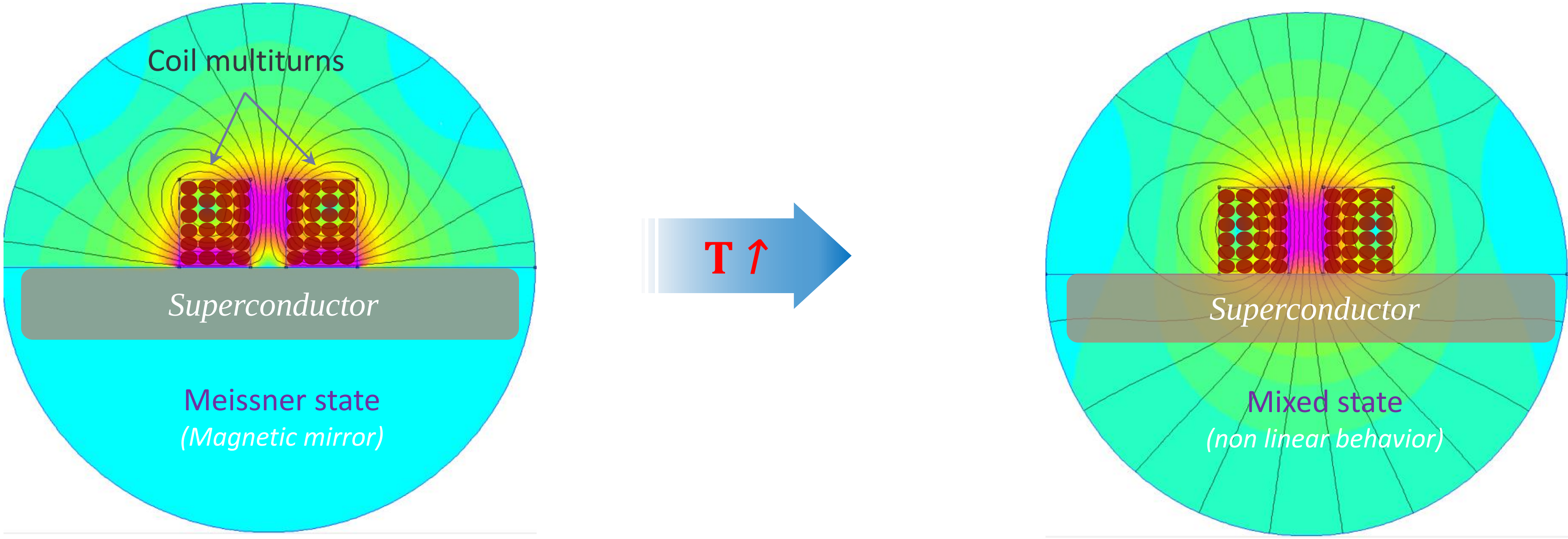




Local magnetometer principle

3rd harmonic measurement of H_{C1} /H_{SH}

- Building a setup ~operating conditions for SRF (2K-20K; H >> 150 mT)
  - (tbc existing facilities[6] : > 4,5 K or 70 K and Bmax ~15-20 mT)
  - Magnet size << sample size (infinite plane approx.)
  - Field decreases quickly away from the coil
  - Measurement of H_{C1} on sample without edge/demagnetization effect
  - Exploring new SCs /multilayers at accelerator operating condition



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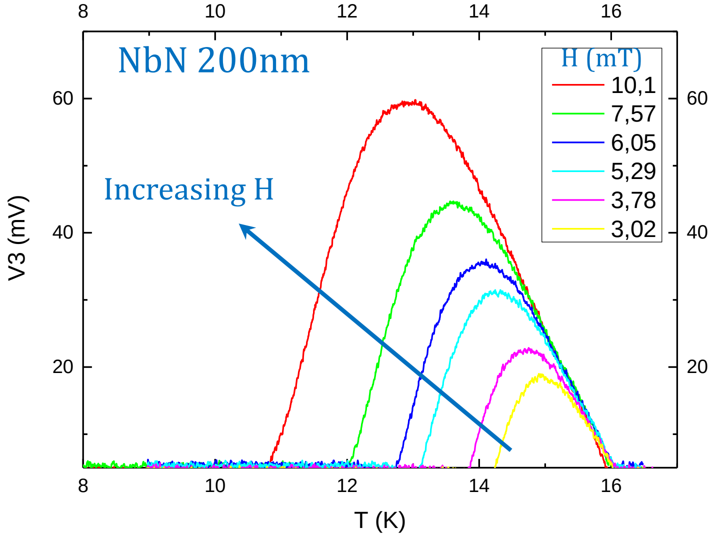
[5] *J. H. Claassen, et al. Rev. Sci. Instrum, Vol. 62, 4 (1991).*

[6] *M. Aurino, et al., Journal of Applied Physics, 98. 123901 (2005).*

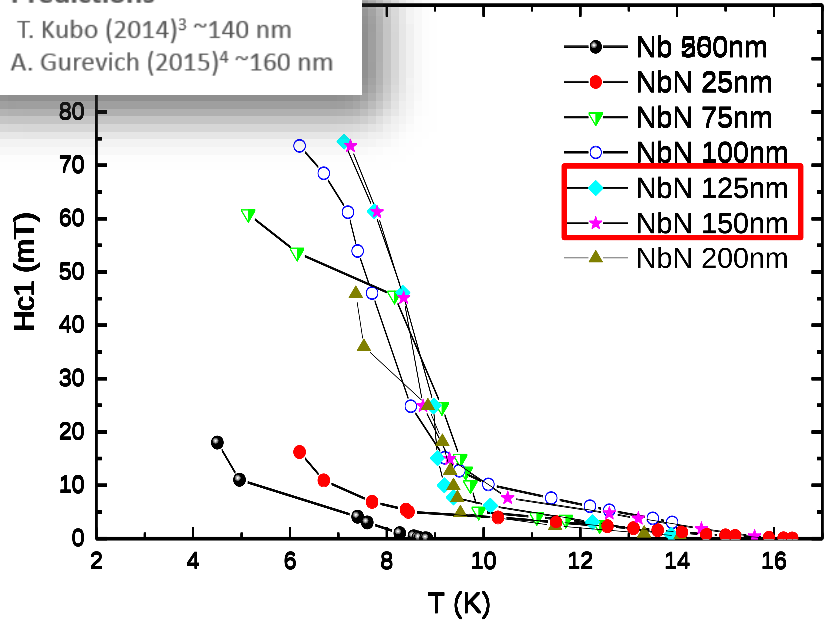
Screening Power of NbN

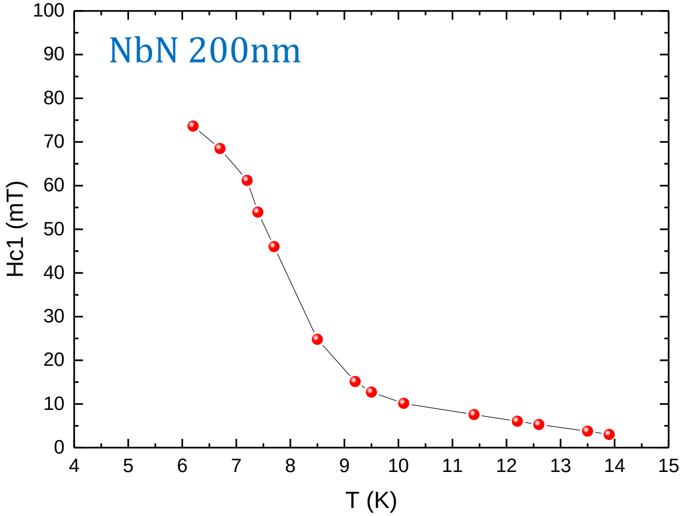
- Series of NbN single layer/MgO/Nb
  - Deposited by reactive magnetron sputtering on silicon substrate (collaboration Grenoble INP and CEA INAC)
  - Insulator = MgO
  - Thick Nb layer to mimic bulk Nb



☐ **Predictions**

- T. Kubo (2014)[3] ~140 nm
- A. Gurevich (2015)[4] ~160 nm





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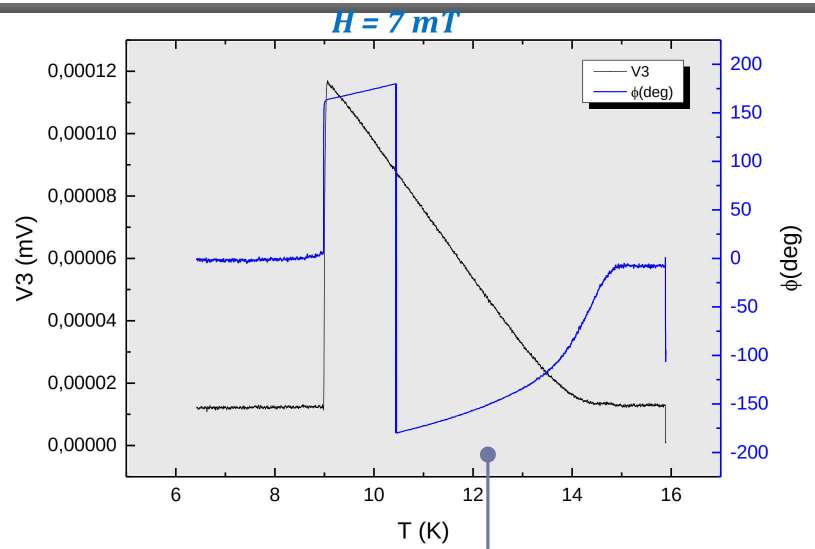
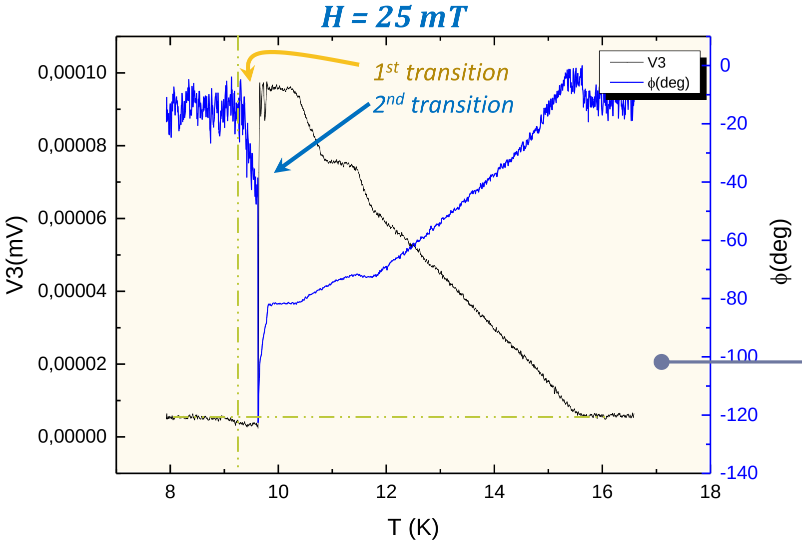
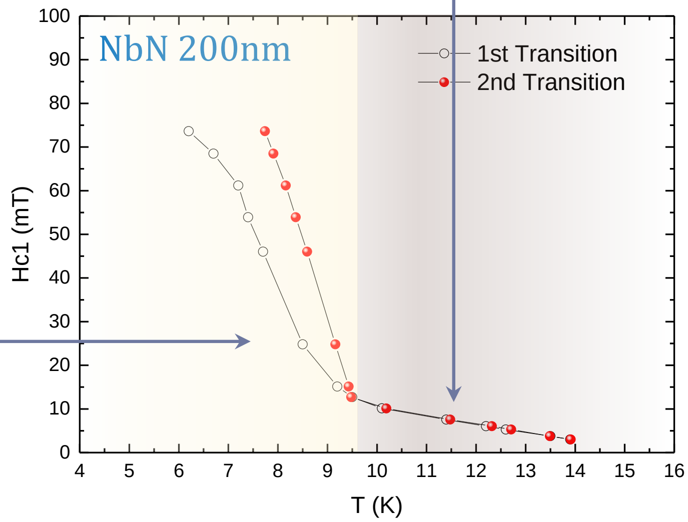
What do we measure ?

- Determination of Hc1
  - Low field => one transition
  - High field => two transitions
    - 1st transition with low dissipation
    - 2nd transition very strong dissipation

- Why do we have two transitions ?

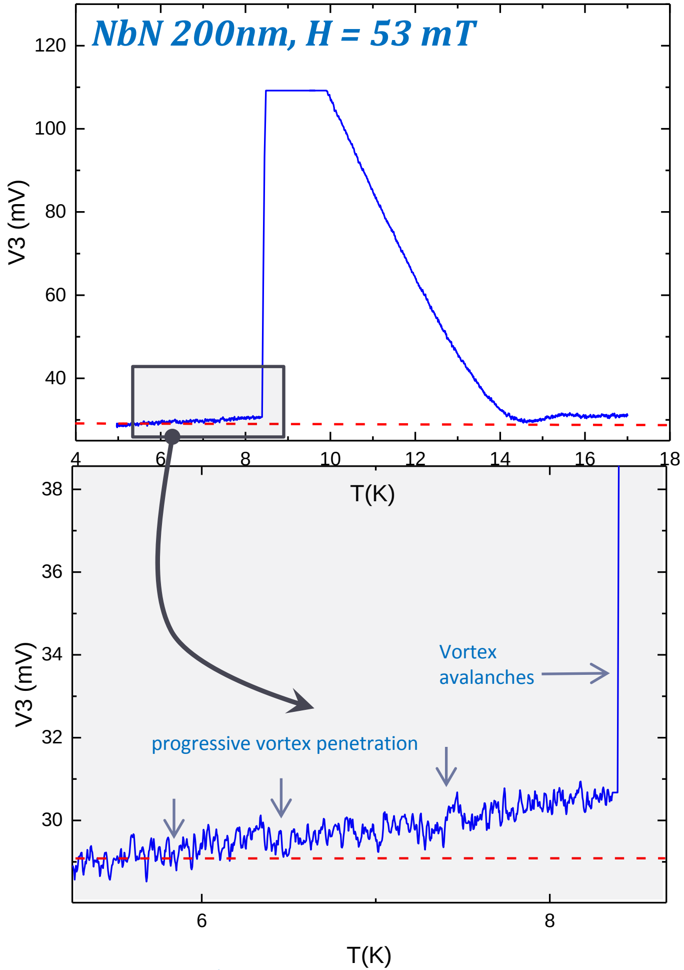


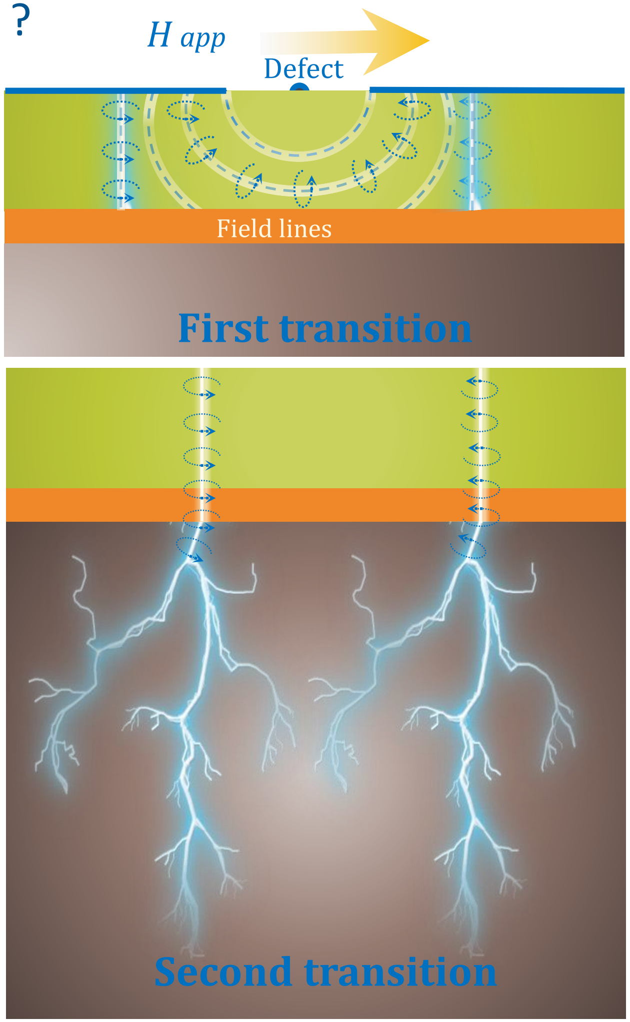




Screening Power of multilayers

- Why do we have two transitions ?





- ● Thin SC layer NbN
- ● Insulator MgO
- ● Thick SC layer Nb

- H // surface => surface barrier[7]
- A defect locally weakens the surface barrier
- 1st transition, vortex blocked by the insulator ~100 nm => low dissipation.
- 2nd transition, propagation of vortex avalanches (~100 µm) => high dissipation.
- Dielectric layer = efficient protection !!!

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[7] *B. Bean and J. D. Livingston, Phys. Rev. Lett. 12, 14 (1964).*

Thin films, multilayer R&D

- Scientifically:
  - Very challenging upstream, discovery, R&D
  - Efficiency of multilayer concept demonstrated
    - Field enhancement => higher SRF performances
    - Results close from theory => will help optimization
  - Protection against "avalanches" => can accommodate defective (realistic) material
- Future :
  - EUCARD3 (ARIES) covers only a little of the work to be done
  - Other funding sources needs to be found
- Practically:
  - Many difficulties to (propose and) follow a realistic schedule within EUCARD framework
  - The foreseen program and the collaborations started will be pursued beyond the end of EUCARD2

Team at CEA Saclay

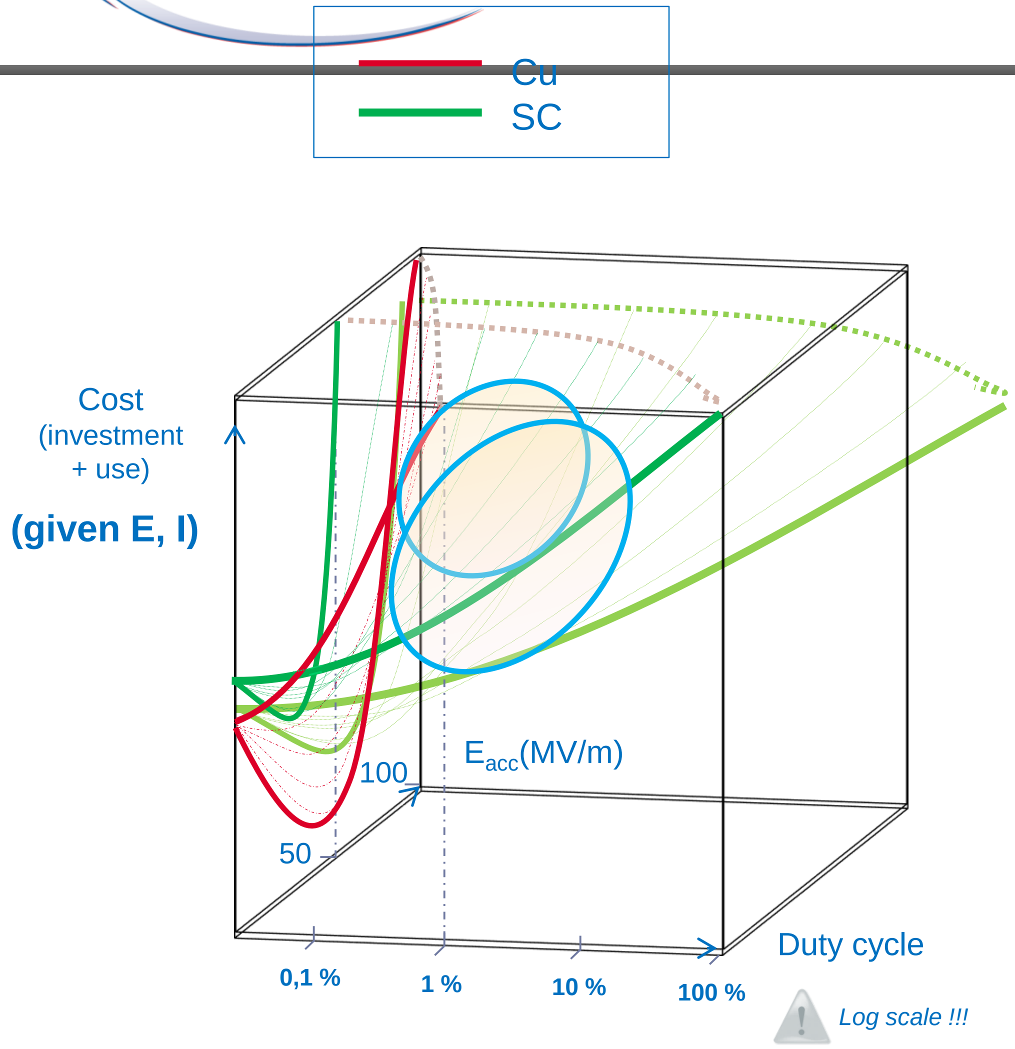
Thank you for your attention

Claire ANTOINE

Muhammad ABURAS

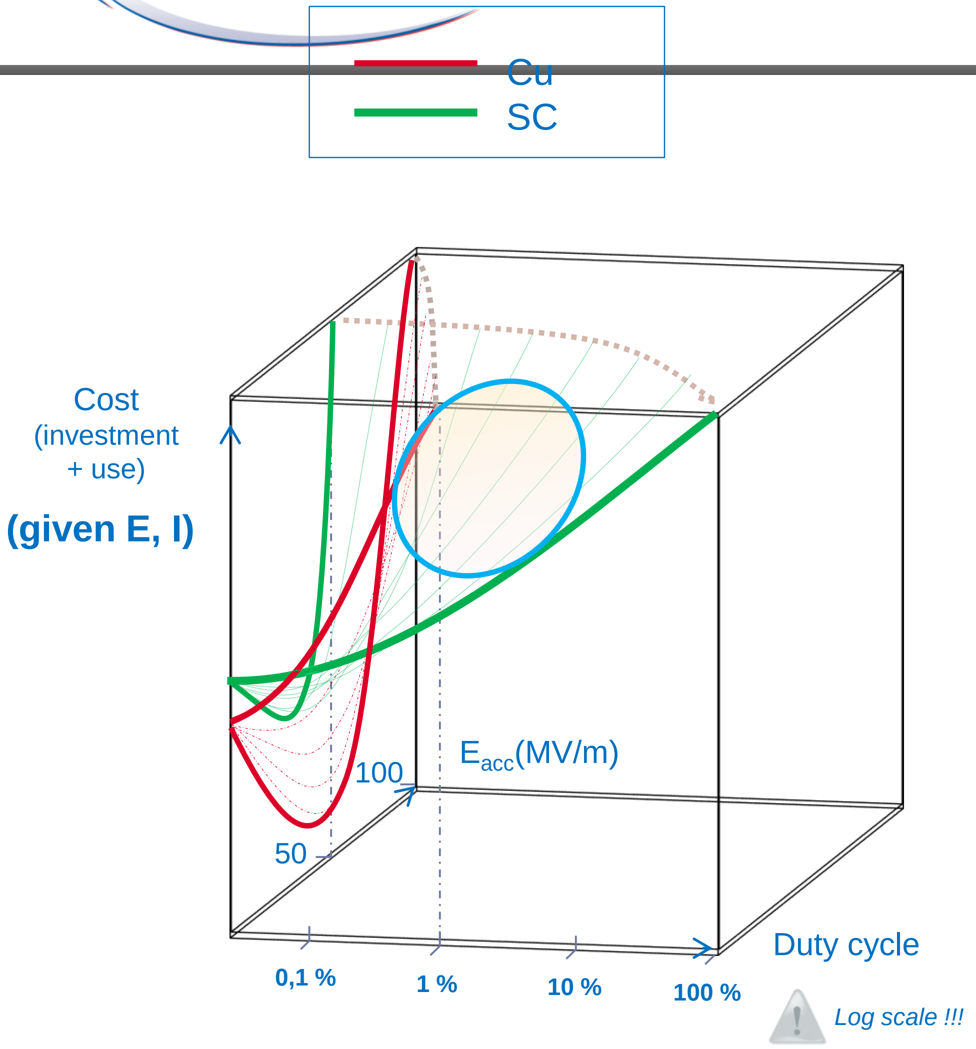
Aurelien FOUR

Costs elements



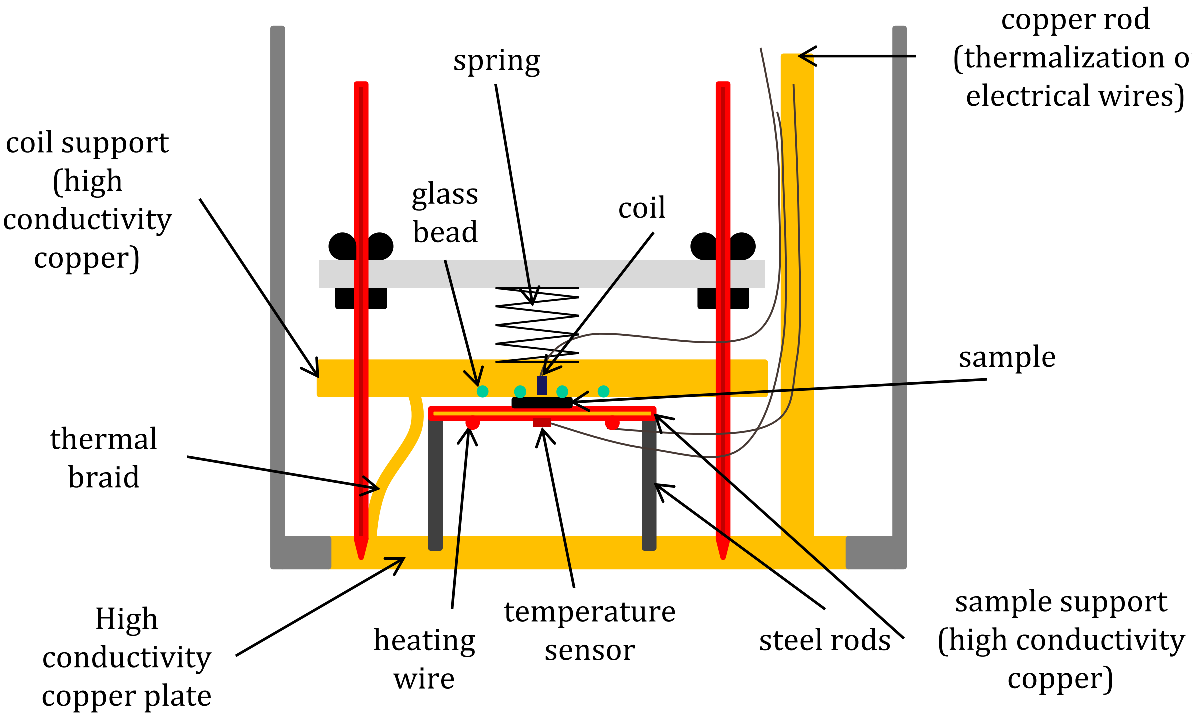
- coûts ↑ avec C.U.
  - ∃ Optimum E_{acc}
    - Low E_{acc} => longer accelerator => fab. costs↑
    - High E_{acc} => RF cost ↑ for Cu & cryogenics ↑ for SC
  - Other example: CLIC vs ILC (e+/e- collider)
    - ILC : C.U. = 0,5 % @ 1,3 GHz
    - CLIC : C.U. = 0,001 % @ 12 GHz
  - Linac costs
    - ~ 1/3 tunnel, building
    - ~ 1/3 niobium, cryo
    - ~ 1/3 RF, beam control

elements de coûts



- coûts ↑ avec C.U.
- ∃ champ accel. Optimum
  - Faible champ => accélérateur + long => coûts ↑
  - Fort champ => coûts RF ↑ pour cuivre et coûts cryogéniques ↑ pour supra
- Autre exemple : CLIC vs ILC (collisionneurs e+/e- usines à Higgs)
  - ILC : C.U. = 0,5 % @ 1,3 GHz
  - CLIC : C.U. = 0,001 % @ 12 GHz
- Coûts linac
  - ~ 1/3 tunnel, BTP
  - ~ 1/3 niobium, cryo
  - ~ 1/3 RF, contrôles faisceau

H_{c1} Measurement, a Local Magnetometer

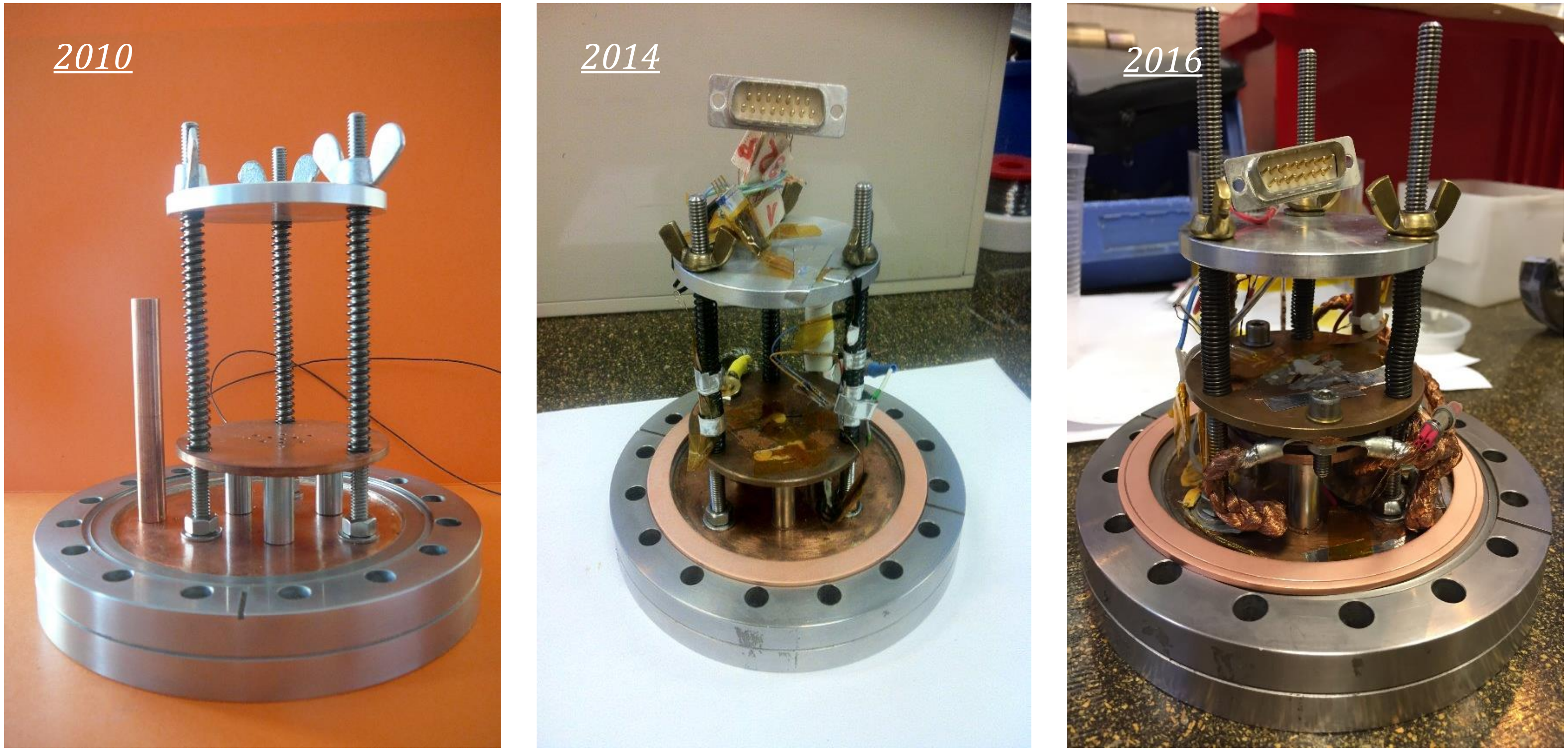


Schematic of local magnetometer

H_{c1} Measurement, a Local Magnetometer

How this magnetometer works ?

- Works have been beginning in 2010



2010

2014

2016

Experimental setup

H_{c1} Measurement, a Local Magnetometer

How this magnetometer works ?

- Works have been beginning in 2010

Insert

Cryostat

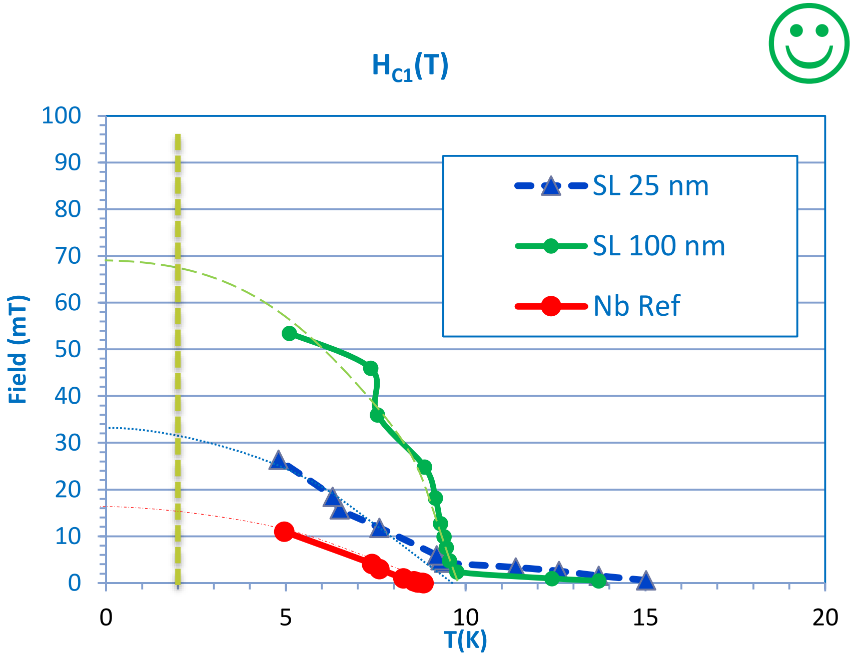
Measurement devices

H_{c1} Measurement, a Local Magnetometer

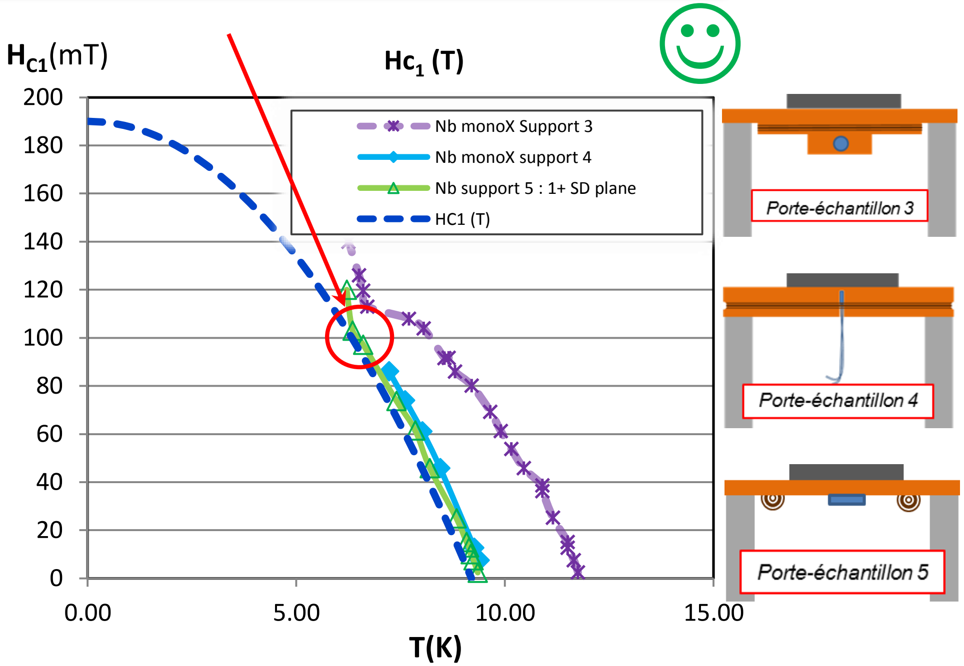
Behind every success, a lot of failures

- Many efforts were achieved to overcome some difficulties
- End of 2016, first successful measurement

Finally, a measurement done correctly until ~100mT



First acceptable results



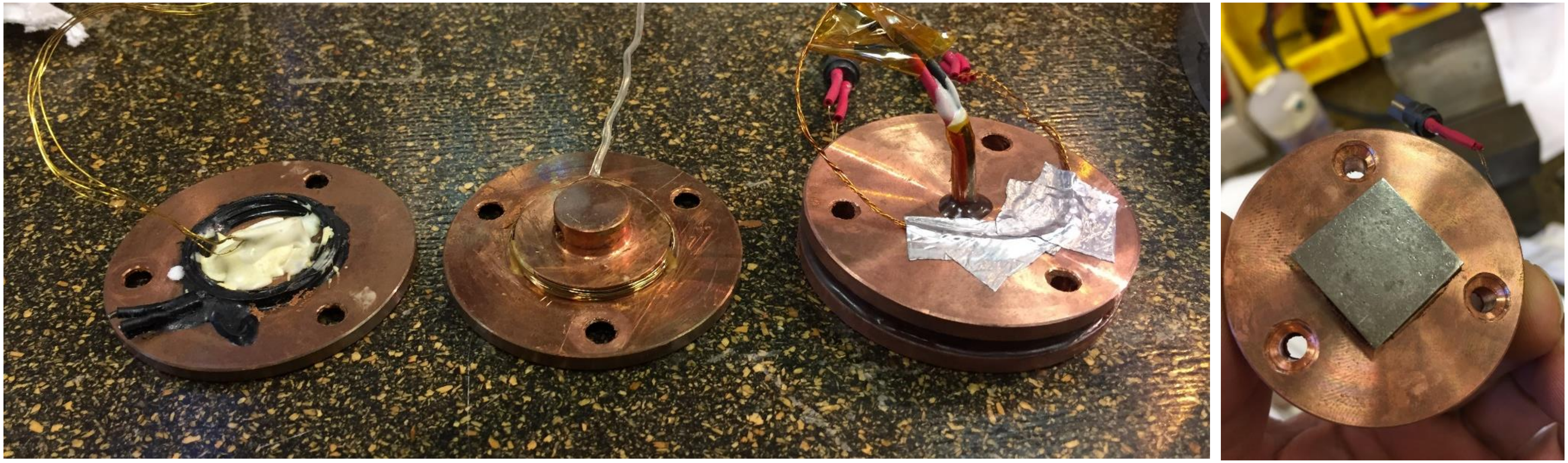
Calibration with a monocrystalline Nb

H_{c1} Measurement, a Local Magnetometer

Behind every success, a lot of failures

- ☐ Many efforts were achieved to overcome some difficulties

Problems !	**Modifications**
Thermal stabilizations	**Add some copper braids**
Calibration (important shift)	**The sample holder**



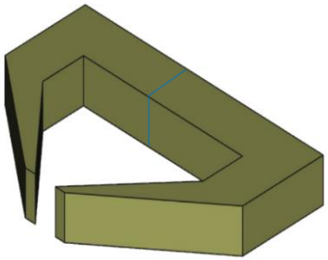
Conclusion and Perspectives

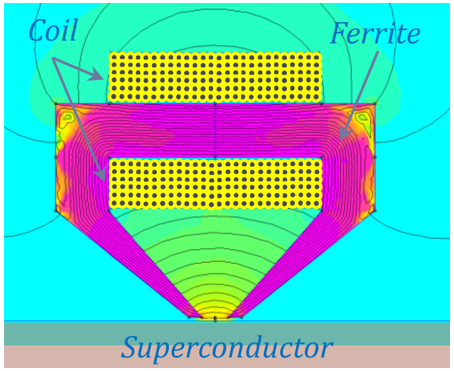
Conclusion

- A local magnetometer has proven to be effective at measuring vortex penetration in conditions close to cavities operating condition.
- We have shown a very promising behavior of NbN layers
- S-I-S multilayers provide best protection of cavities against local penetration of vortices
- Overcome Nb monopoly by higher H_{c1} superconductors multilayers is possible
- Sample gives results close to theory : optimization can be done theoretically
- Deposition methods inside cavities needs to be developed

Perspectives

- Enhancement of the maximum magnetic field applied on the sample, we hope to reach > 250 mT by:
  - Replacement the coil by a ferrite core inductor
  - Novel thermal design of the experimental setup
- Study other superconductors multilayers at higher fields.





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