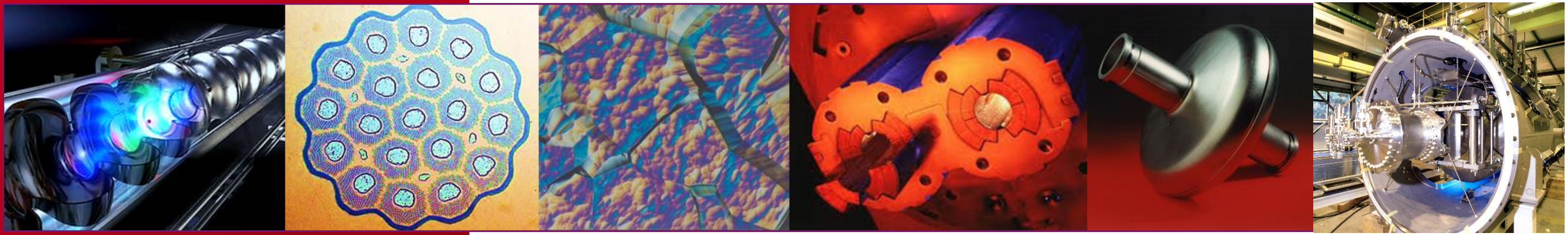
DE LA RECHERCHE À L'INDUSTRIE

SUPERCONDUCTING THIN FILMS FOR RF CAVITIES IN LOW EMITTANCE RINGS



9th Low Emittance Rings Workshop | *Feb. 2024*

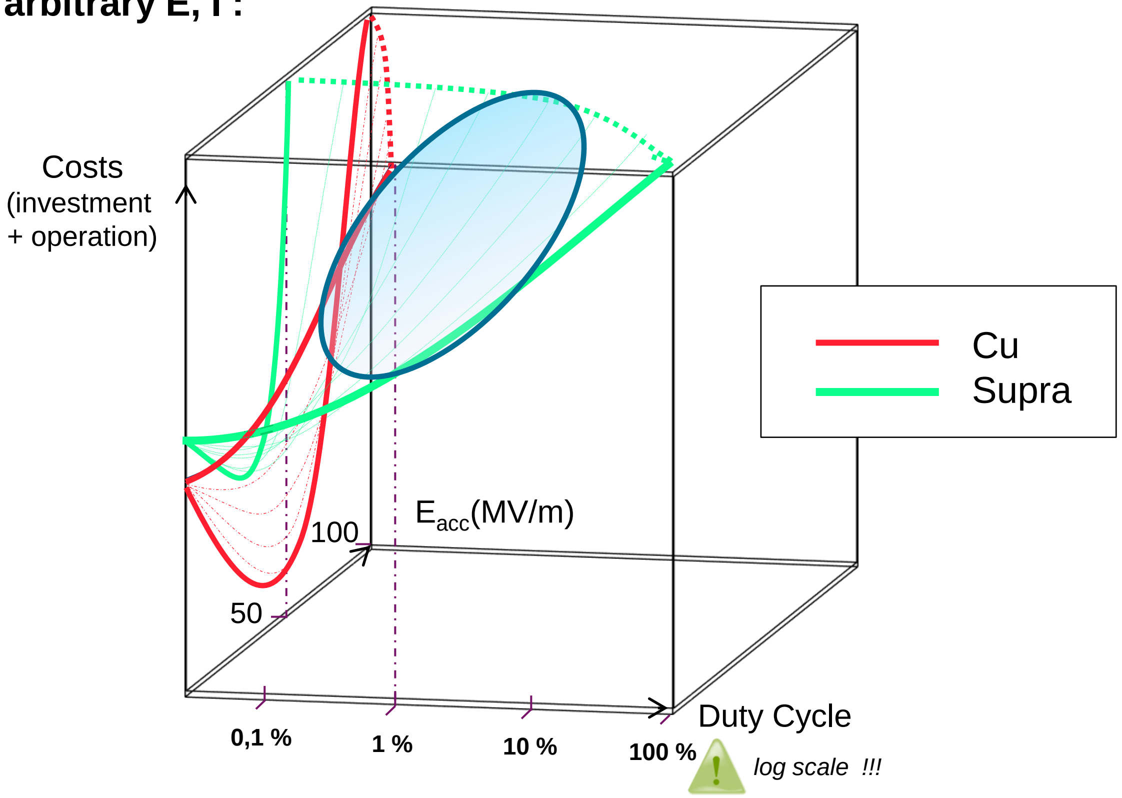
C. Z. ANTOINE

www.cea.fr

SOME COSTS ELEMENTS

- **Linac costs**
  - ~ 1/3 tunnel, construction
  - ~ 1/3 niobium, cryo
  - ~ 1/3 RF, beam control
- **∃ Optimum accelerating field**
  - Low field => longer machine => cost ↑
  - High field => RF costs ↑ for Cu and cryogenic costs ↑ for SC
- **Cost↑ with Duty Cycle.**
- **Other example: CLIC vs ILC** *(e+/e- collider, Higgs factory)*
  - ILC : D.C. = 0,5 % @ 1,3 GHz
  - CLIC : D.C. = 0,001 % @ 12 GHz
- **Superconductors**
  - ∃ thousands of SC
  - <10 are actually used
  - SC materials optimized for magnet = not adequate for SRF !

For an arbitrary E, I :



WHICH KIND OF CAVITIES FOR LOW EMITTENCE RING ?

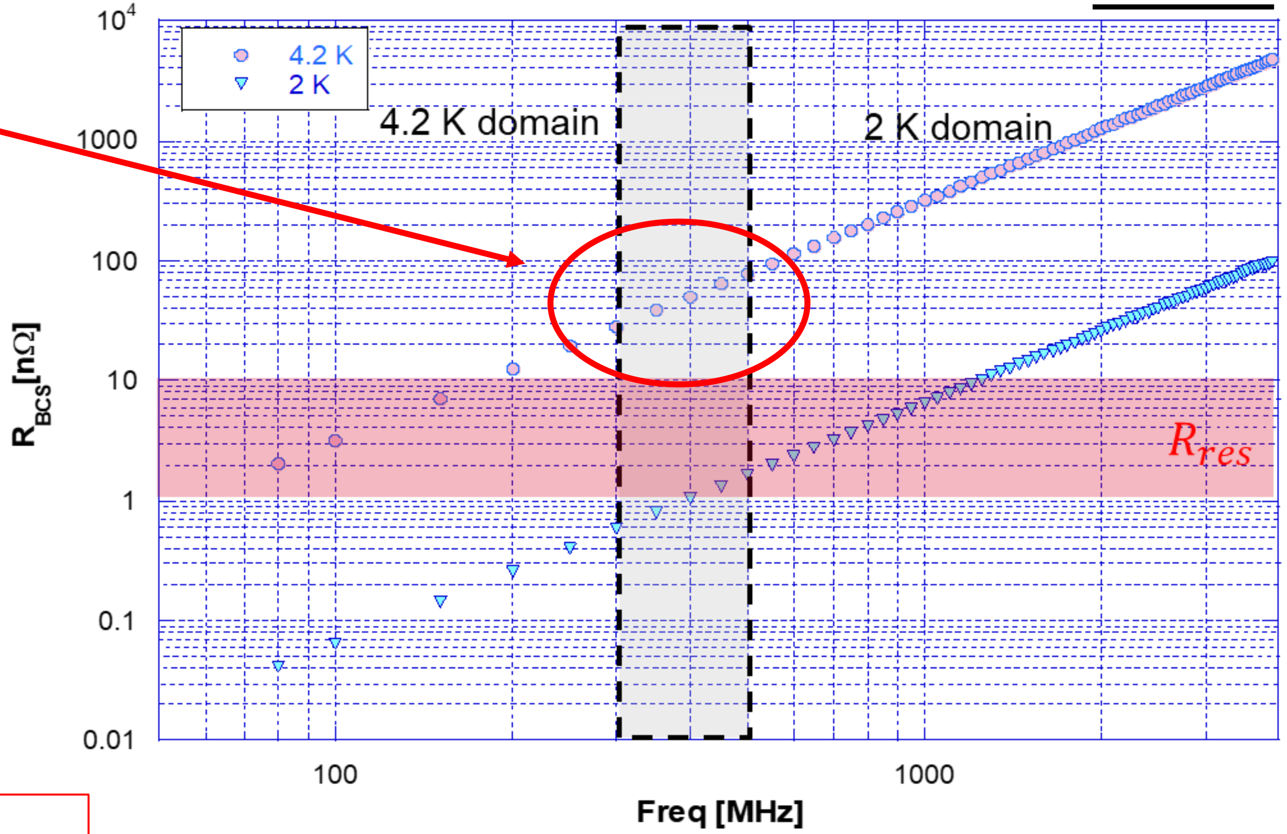
"As a rule of thumb it is preferable to reduce the BCS contribution as low as the residual resistance"

- **Relatively low frequency**
  - Obviously already in the 4.2 K domain
- **Bulk vs thin film Nb ?**
  - Usually not too high gradient required => Nb/Cu technology OK
  - Higher gradient could mean less cavities
- **Better than Nb? => necessarily also thin films**
  - But fabrication much more difficult

At stakes : COST REDUCTION !!!
Cooling power: can we go to cryocooling ?

- **Cryomodules 5-30 W**
- **2.7 W @ 4.2 K cryocoolers available**
- **10 W expected this year**

Bulk Nb

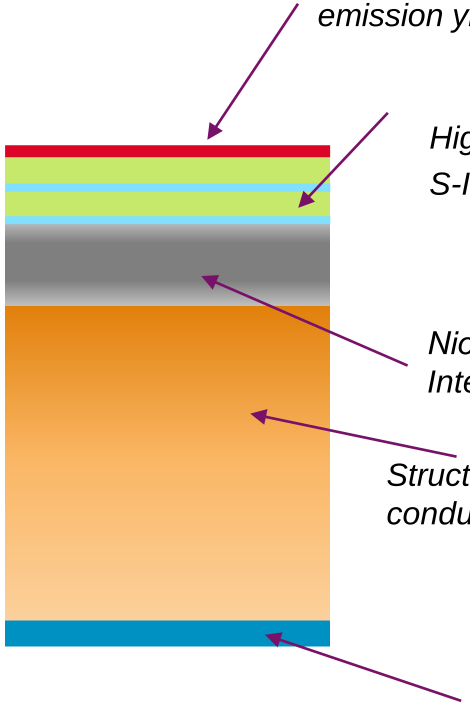


From N. Bazin https://accelconf.web.cern.ch/srf2023/talks/satut01_talk.pdf

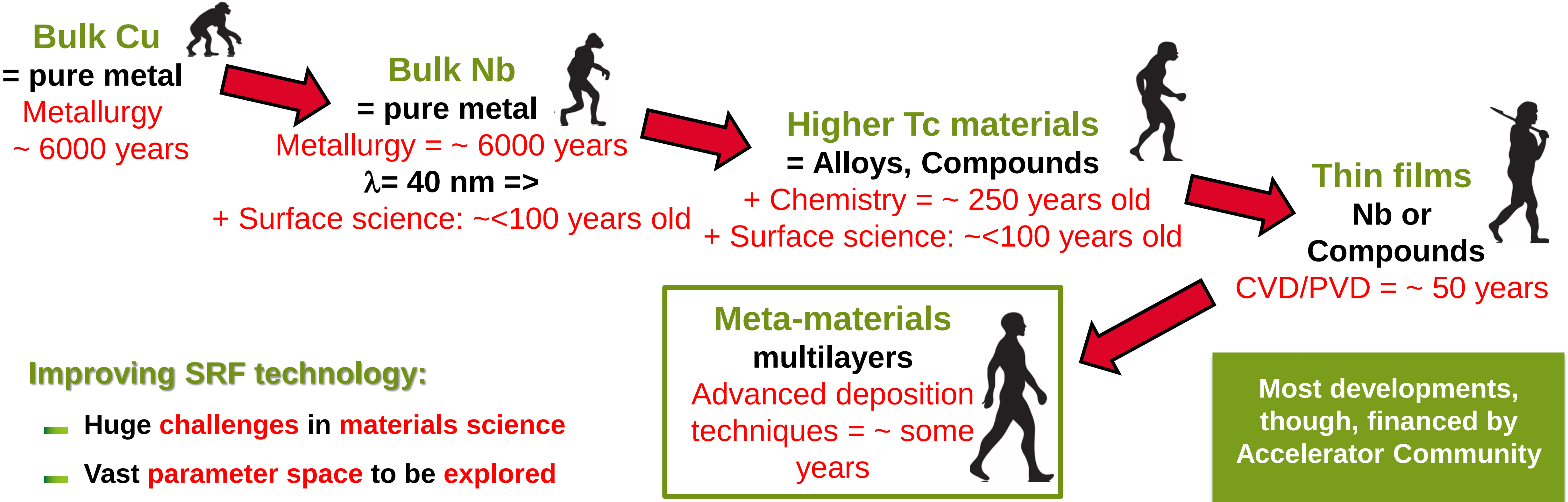
WHAT IS A GOOD THIN FILM SUPERCONDUCTOR ?

- **A compromise between:**
  - High superconducting/RF performance (High Tc, High superheating field)
  - Easy fabrication process,
    - ≡ high reproducibility at "industrial scale"
    - Easy process to go from 1-cell to multi-cells or complex shapes
    - Easy process to adapt to various frequencies
  - Tunability
    - Beware of brittle materials !
  - Low sensitivity to trapped flux upon cooling down
    - Few crystalline defects or a structure not too sensitive to them (e.g. SIS)
- **Thin films on copper are the only route to help cost savings**
  - Cu: cheap manufacturing
  - Higher operation temperature: lower operation costs
  - Higher gradients: lower capital costs
- **Cryogenic savings are still small compare RF consumption**
  - e. g. SOLEIL: cryogenic costs~ 1.85 GWh/y.   RF costs (rejuvenated system) ~5.1 GWh/y.

Future:
Functionalized Material?



WHAT IS SO DIFFICULT ABOUT SRF TECHNOLOGY ?



Bulk Cu
= pure metal
Metallurgy
~ 6000 years

Bulk Nb
= pure metal
Metallurgy = ~ 6000 years
λ= 40 nm =>
+ Surface science: ~<100 years old

Higher Tc materials
= Alloys, Compounds
+ Chemistry = ~ 250 years old
+ Surface science: ~<100 years old

Thin films
Nb or Compounds
CVD/PVD = ~ 50 years

Meta-materials
multilayers
Advanced deposition techniques = ~ some years

Improving SRF technology:

- **Huge challenges in materials science**
- **Vast parameter space to be explored**
- **Underfinanced for years:**
  - **Accelerators considered as dirty hardware by fundamental materials scientists**
  - **Materials science considered as alchemy by (most) accelerator scientists**
  - **Materials science is what allowed SC magnets to reach its present industrial development**

Most developments, though, financed by Accelerator Community

Not enough (compared to e.g. magnet history)

Recall: SC materials optimized for magnet = not adequate for SRF !

HE roadmap: *Identified axis of R&D on thin films*

1. Continue R&D niobium on copper

- Fabrication cost reduction
- Reaching same performances as bulk Nb (1,3-0,4 GHz, various shapes) on single cells, then on multi-cells

2. Intensify R&D of new superconductors on Cu

- Same performance (Q_0) as Nb @ 4,2 K instead of 2 K
- A15 compounds (Nb_3Sn, Nb_3Al, V_3Si) and MgB_2

3. Pursue multilayers (SIS structures)

- Reaching higher gradients (and Q_0 !)
- Going from sample to cavities

4. Intensify Cu cavity production and surface preparation.

- No welding, smooth surfaces, possible diffusion barriers
- Large series production

5. Develop 3D printing and/or innovative cooling techniques.

- Cryocooling, inbuilt circulation

6. Infrastructures and Manpower

- Dedicated characterization set-ups
- Dedicated thin film infrastructures

CERN-2022-001

EUROPEAN STRATEGY FOR PARTICLE PHYSICS

Accelerator R&D Roadmap

European Strategy Update

LDG Laboratory Directors Group

Yellow book (green !?) CERN -2022-001

Other projects with similar strategy:

- **Basic R&D in numerous SRF labs**

Europe

- **IFAST WP 9 thin films => 2025**
  - Task 9.1: strategy
  - All European partners except CERN and DESY
  - CERN, DESY, and JALB invited to participate in the strategy meetings

USA

- **Snow mass White Papers => next 10Y**
  - Last edition: 2021
  - 1 white paper on thin films, (AF7 Accelerator Technology R&D)
  - IFast participants participated to the writing

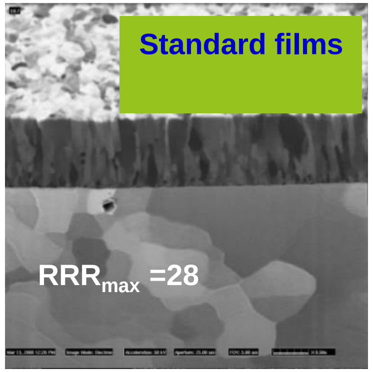
Internat!

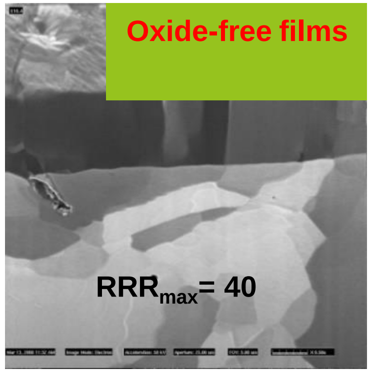
- **TF SRF Workshops 2022 and 2024**
- **TTC-Meetings-thin films: ~ 2-3/year**
  - Bringing the community together

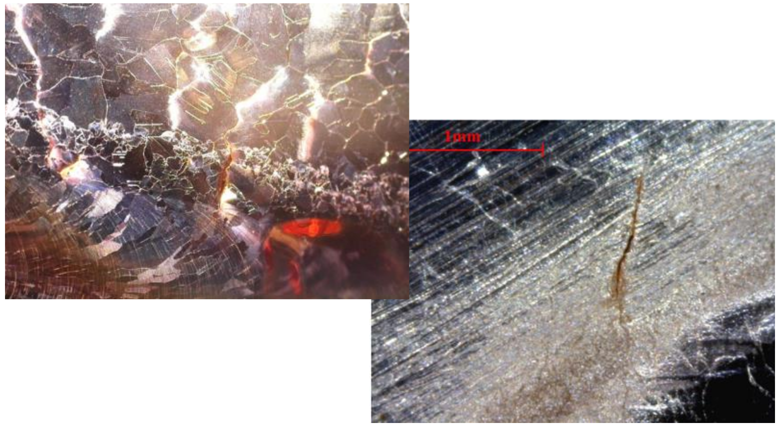
NB Same strategy valid for other applications than HE:

1-Nb ON Cu: WHAT’S NEED TO BE DONE ?

- **Densification of the layers**
  - Large parameter space to be explored (but narrower than for compounds materials)
  - Very promising results these last years… **after nearly 50 years of very slow progress**
  - Energetic deposition techniques => less porosities
- **Substrate developments**
  - Copper cavities, No welding !
  - Smoothness
  - Intermediate layer (diffusion barrier, interlayer) might be needed
  - Other material can be explored (Al, W)







Bad adhesion/degradation of films on welding

*[data from CERN +
AM Valente-Feliciano]*

1. Nb ON Cu: WHAT'S LEFT TO BE DONE?

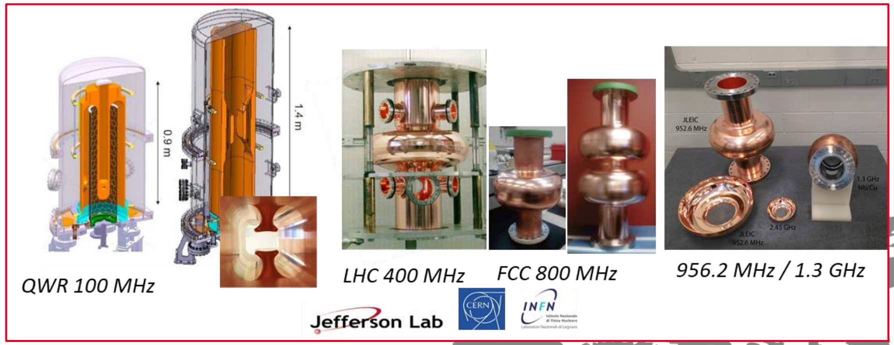
- **Cavity (substrate) fabrication**
  - Seamless cavities (Picoli/ INFN: Spinning, CERN electrodeposition)
  - Split cavities (STFC, CERN)
  - Additive fabrication with cooling capillaries (CEA)
  - Improved sagging at the weld (everybody concerned, but not active ?)

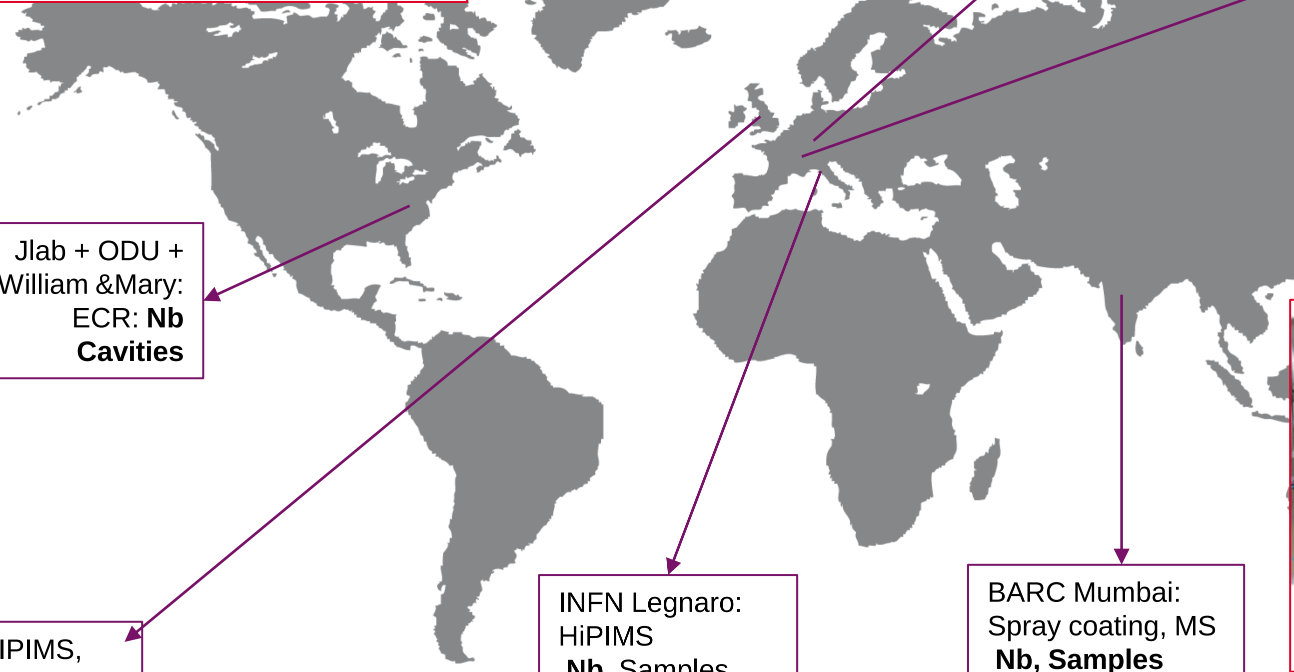
Was identified as **Axis # 4**
In fact, mandatory for axis # 1, # 2, # 3

- **Surface preparation :**
  - EP (CERN, INFN, CEA)
  - SUBU (CERN , INFN)
  - Plasma EP (INFN)
  - CBP (existing facilities for Nb cavities can be adapted)
  - Flash annealing (HZDR), laser treatment (RTU)
  - Interlayers (*CEA*)
- **Deposition**
  - DC/pulsed magnetron sputtering ?
  - HIPIMS (INFN, CERN, STFC, Usiegen, *CEA) Jlab*
  - *Other energetic deposition technique Jlab*
- **Post treatment**
  - Flash annealing (HZDR), laser treatment (RTU)
  - Capping layer (*CEA*) diffusion barrier, SEY modification….

Energetic deposition techniques or post annealing to get the proper crystalline structure

1-Nb ON Cu





USI: Siegen
HIPIMS
Nb, samples

CERN
HIPIMS
Nb, Cavities

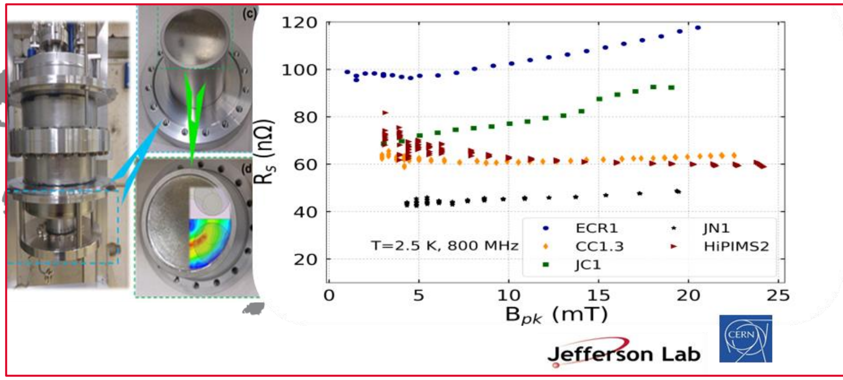
Peking U. Beijing,
CAS, Lanzhou:
Nb, samples

Jlab + ODU +
William &Mary:
ECR: **Nb**
Cavities

STFC:PVD: DC, pulsed, HIPIMS,
Nb Samples

INFN Legnaro:
HiPIMS
Nb, Samples

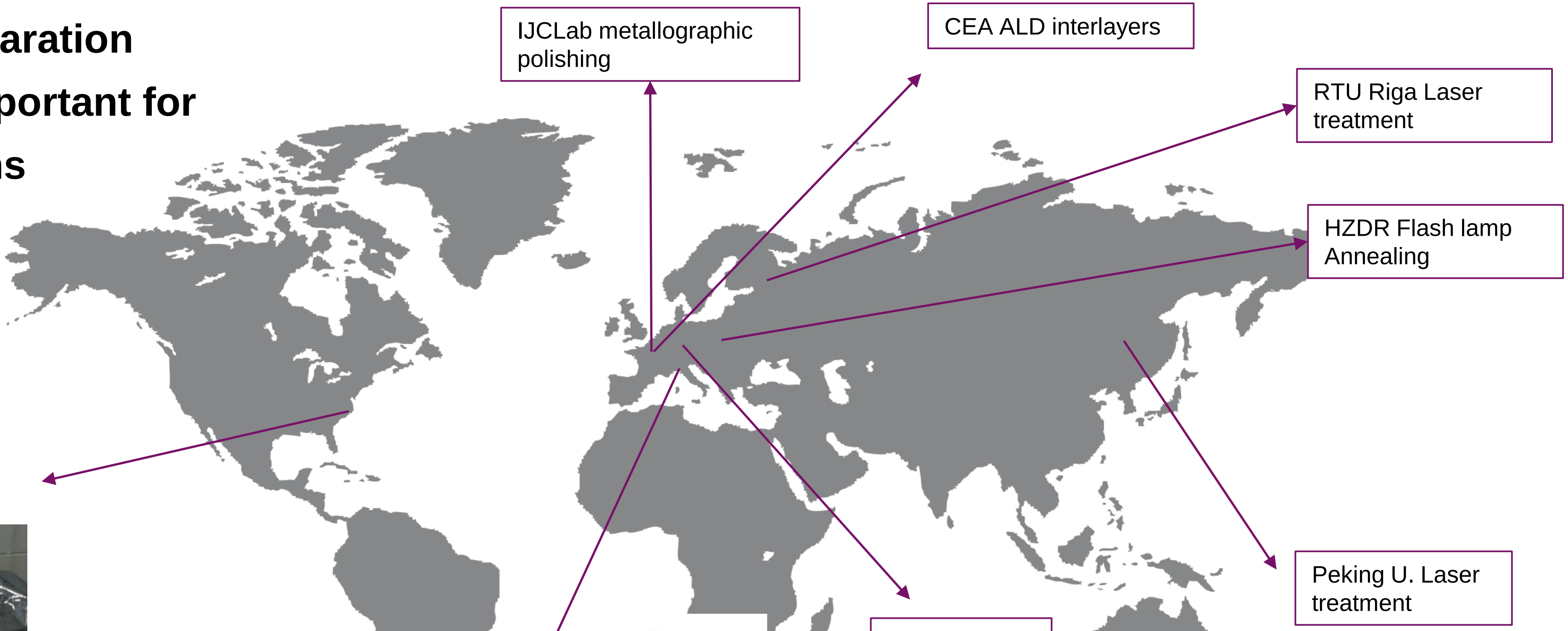
BARC Mumbai:
Spray coating, MS
Nb, Samples



- **Samples => 1^{rst} prototypes: 1^{rst} trials this year**

4- SUBSTRATE DEVELOPMENT/ PREPARATION (COPPER)

- **Seamless fabrication**
- **Surface preparation**
- **Also very important for other SC films**



IJCLab metallographic polishing

CEA ALD interlayers

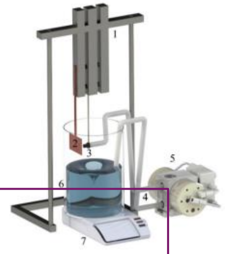
RTU Riga Laser treatment

HZDR Flash lamp Annealing

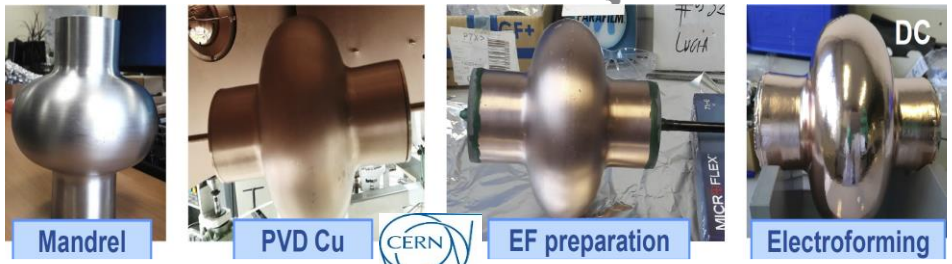
Peking U. Laser treatment

CERN

Jlab and coll:



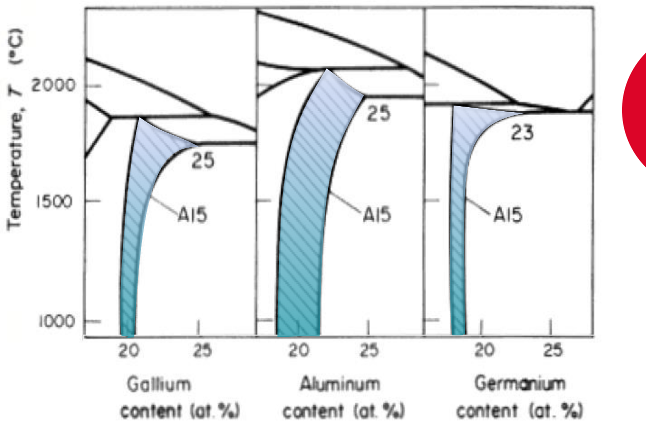
INFN
Spinning
Plasma
electropolishing



2-HIGHER T_C MATERIAL: NbN, Nb_3Sn (A15), MgB_2

- **Issues with non metallic SC compounds (e.g. Nb_3Sn, MgB_2)**
  - Higher T_Cs, H_{SH}, but smaller H_{C1}, ξ
  - **Brittle, no forming is possible, only films** *(OK for SRF, but a more complex fabrication route is needed)*
  - Usually **several phases**, not all of them SC
  - Risk of non homogeneity
- **Thick films: often an intermediate steps toward SIS (see later § 4)**
  - Thick films provide an intermediate step with high Q_0, but limited E_{acc} (high sensitivity to defects)
  - Several of the labs that are developing higher Tc materials are also developing SIS (reduced sensitivity to defect) => see § 4

Nb_3Ga (19K) Nb_3Al (20K) Nb_3Ge (23K)



A15

MgB_2 !!!

Advantages:

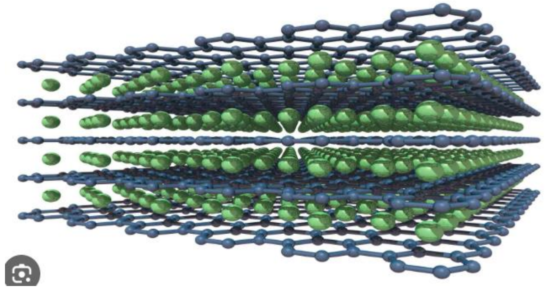
- Very high T_C **~40 K =>** *(higher temp operation)*
- Semimetal, cheap *(fertilizer !)*
- Low ρ_n *(lower R_S)*

Disadvantages:

- Orientation issues *(in polycrystalline materials !)*
- RF dominated by lower gap ☹ !
- Still better than Nb :

Δ^{Nb}= 1.5 meV < Δ_π^{MgB2}= 2.3 meV < Δ^{Nb3Sn}= 3.1 meV <Δ_σ^{MgB2}= 7.1 meV

- Sensitive to H_2O *(capping necessary ?)*
- Thin film routes difficult to achieve



2-HIGHER T_C MATERIAL:

- **Milestones at five years:**
  - i. A15 (Nb_3Sn, V_3Si, etc.): reach same performance as Nb_3Sn on Nb at 4.2K on several cavity geometry (1.3–0.6 GHz).
  - ii. MgB_2: feasibility (critical temperature > 30 K) on 1.3 GHz cavity.
  - iii. Study the influence of mechanical deformations and induced strain (0.1 %) of cavities on the RF performances of A15 and MgB_2 alloys.

Only thermal way mature enough to deposit inside cavities (US only)
Europe is aiming for Nb_3Sn on copper.
Development is not so advanced

Who in Europe !? Only Temple U is close to deposit inside a “real” cavity

Who in Europe !? Only experiment on samples so far

- **Wished/recommended collaborations/connections ?**
  - Same remark as before, in Europe: IFAST + CERN
- **New/upgraded technology infrastructure required ?**
  - Access to clean room, RF test…, **See point 6**

In Europe: CERN (Nb_3Sn), and IFAST (Nb_3Sn, MgB_2) but IFAST: small budget and needs to be supported after April 25

~ 50 k€/ year and /partners

Expertise exist in Europe

But is dispersed among the vast space to be explored (A15, NbN, SIS…)

Same people pursuing several key points, with limited budget

2-3-HIGHER T_C MATERIAL AND SIS STRUCTURES

FNAL: Nb_3Sn
SIS in future

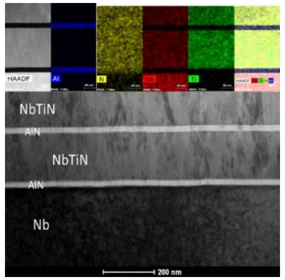
Cornell: Nb_3Sn
SIS NbN

DESY, Hambourg: ALD
SIS NbN, NbTiN

USI: Siegen
HIPIMS
Nb, NbN,
NbTiN
SIS

Temple U.+ LANL
MgB_2, hybrid
CVD/PVD SIS

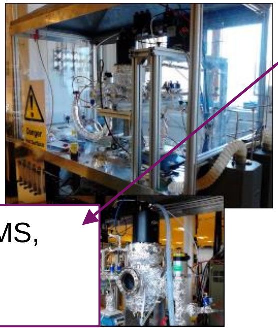
CERN
HIPIMS
Nb, Nb_3Sn



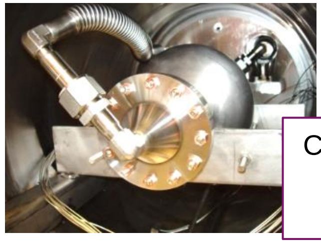
Jlab + ODU +
William &Mary:
ECR: **Nb** NbN,
Nb_3Sn, NbTiN,
SIS

Peking U. Beijing,
CAS, Lanzhou:
Nb, Nb_3Sn, MgB_2

KEK and coll :
ALD, IBS, DCMS
SIS



STFC:PVD: DC, pulsed, HIPIMS,
(PE)CVD, (PE)ALD
Nb, NbN, Nb_3Sn, MgB_2, SIS



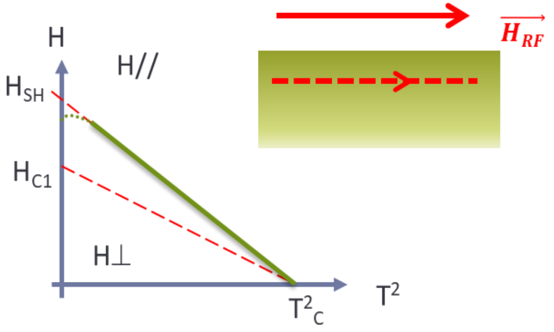
CEA Saclay:
ALD
NbTiN SIS

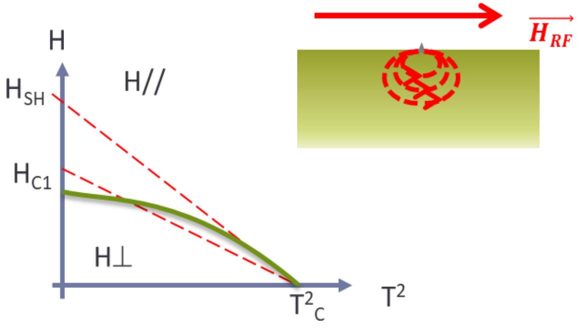
INFN Legnaro:
HiPIMS
Nb, Nb_3Sn

BARC Mumbai:
Spray coating, MS
Nb
RMS, NbN

3-SIS: MULTILAYERS CONCEPT OR HOW TO MAKE THEORY FACE REALITY

For the recall SRF cavity must operate in Meissner state ! No flux line please !

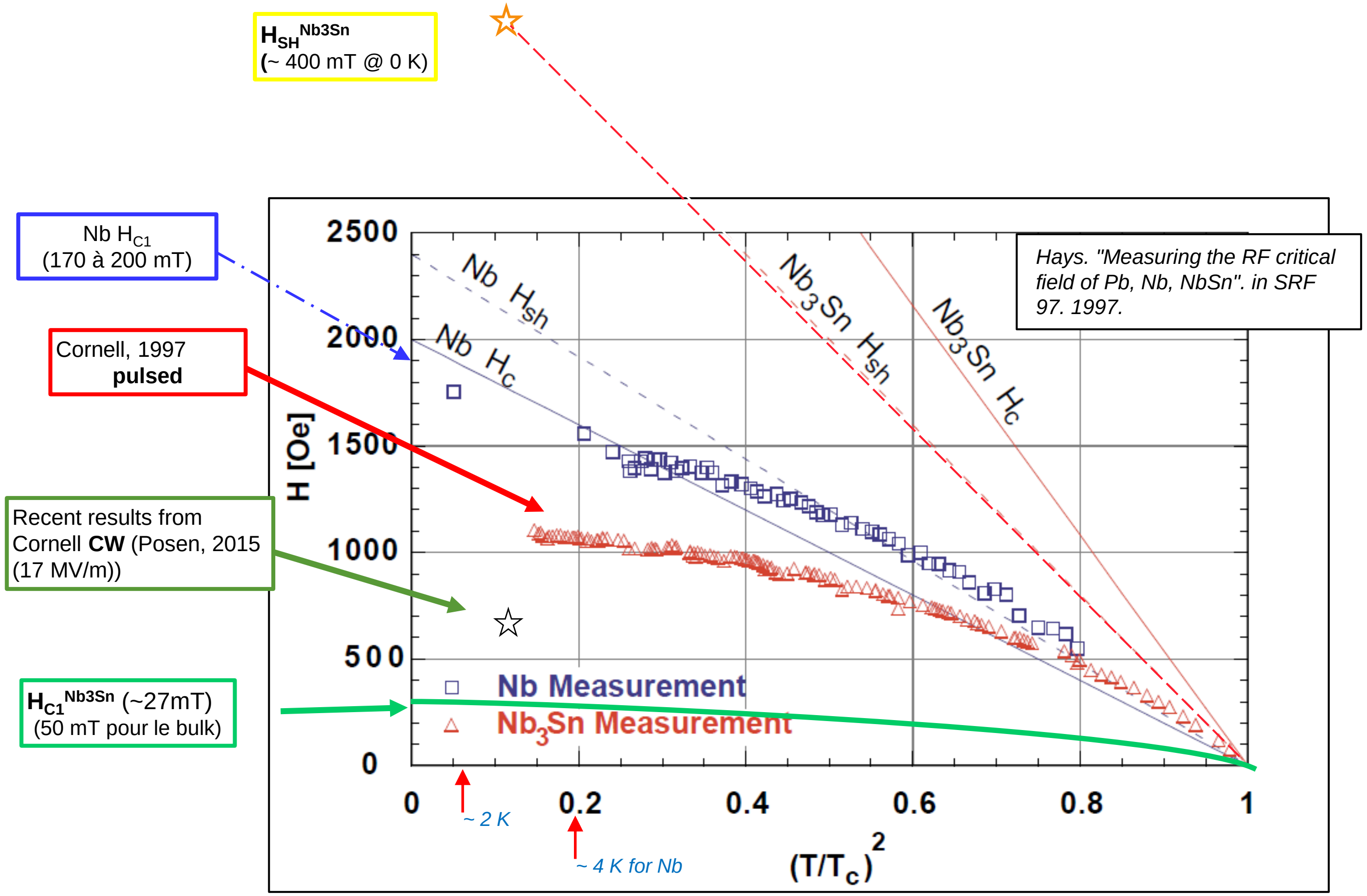




- Ideal (w/o defect)

- Real world
(∃ defects on surface)

Nb_3Sn EXAMPLE



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?)

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

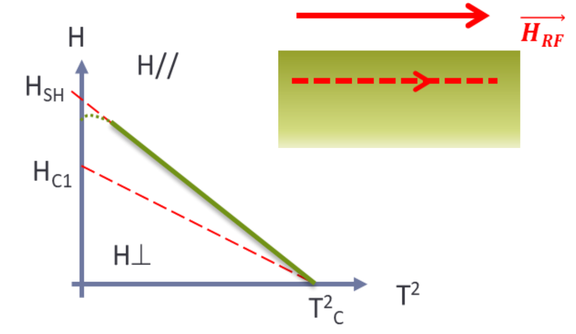
- **Vortices enter more easily at lower temperature (counter intuitive !?)**
  - @ T~T_C : H is low => low dissipations => easy to thermally stabilize
  - à T<<T_C : H is high=> even if small defect => high dissipations => Favors flux jumps

Dissipations :

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

3-SIS: MULTILAYERS CONCEPT OR HOW TO MAKE THEORY FACE REALITY

For the recall SRF cavity must operate in Meissner state ! No flux line please !



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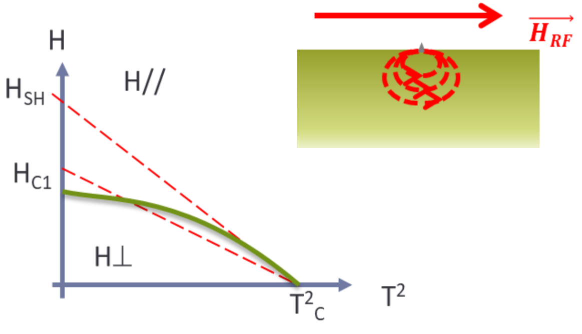
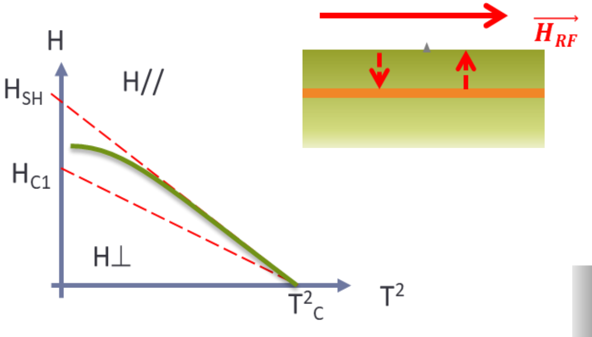
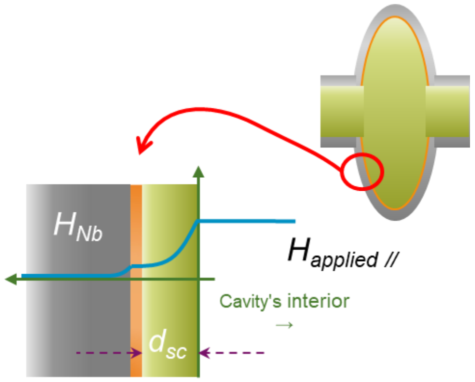


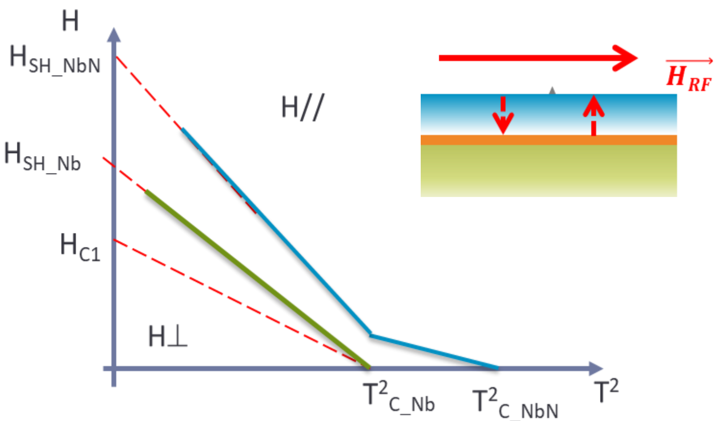
- Real world
(∃ defects on surface)



- Real world
+ dielectric nm layer

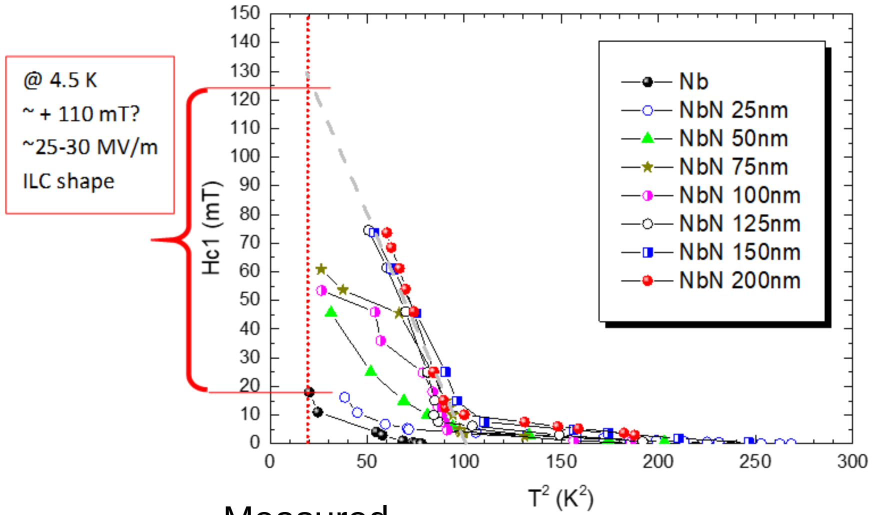


S-I-S

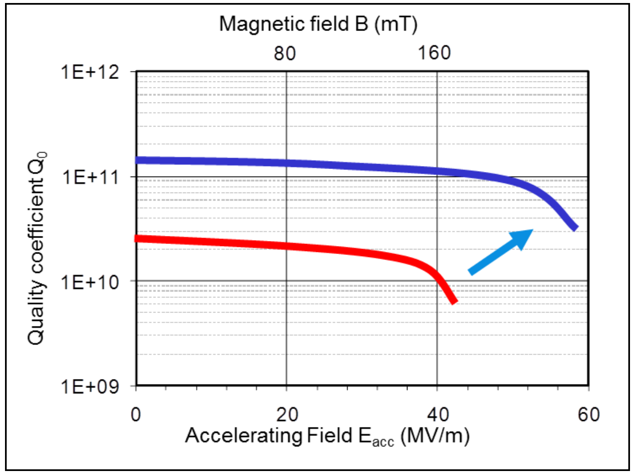


- Dielectric barrier
+ SC w. higher T_C

SIS thick Nb/MgO/NbN samples



Measured



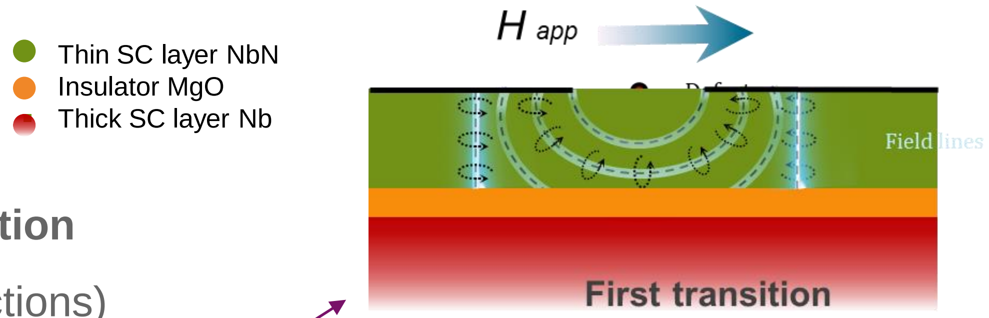
Expected

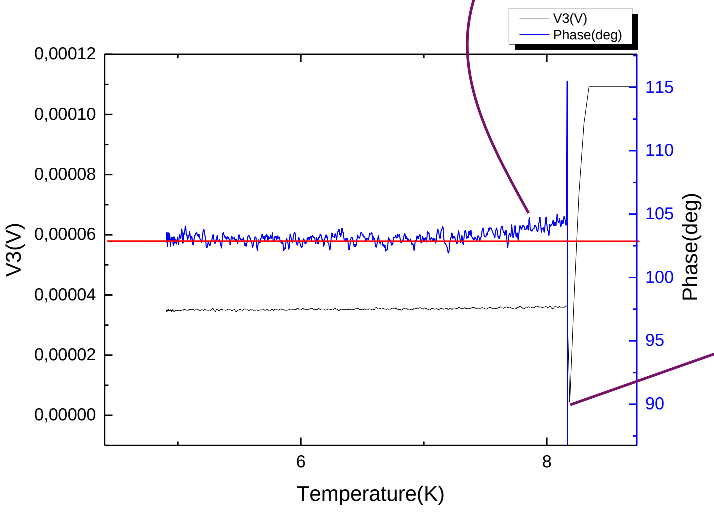
3-SIS:

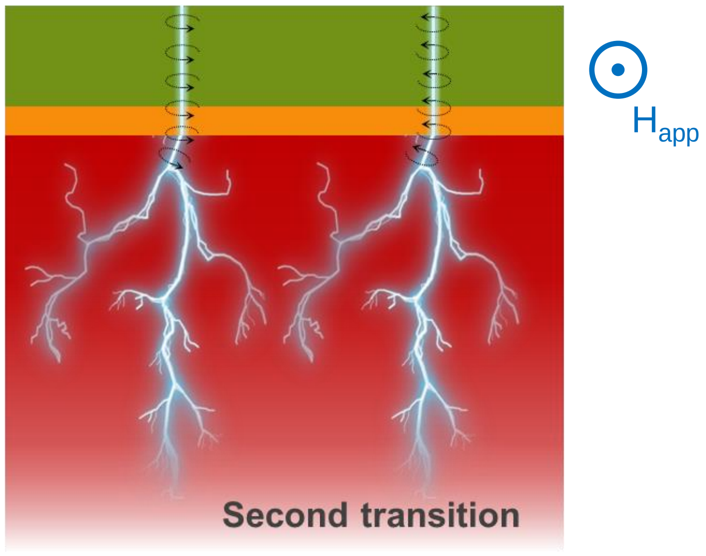
- **Intermediate materials : NbN; NbTiN**
  - Higher T_Cs than Nb, but smaller H_{SH} than Nb_3Sn
  - **Easier to form, less sensitive to local variation of composition**
  - Materials well mastered in the SC electronics (Josephson Junctions)
  - Model material
- **Nb_3Sn, MgB_2 => material of choice for SIS**
  - Does the SIS structure make them less sensitive* to defects ?

  * As shown on NbN

  - Activities at
    - STFC, USI, INFN, CEA (IFAST)
    - DESY
    - Jlab
    - Cornell
    - Temple U. + LANL



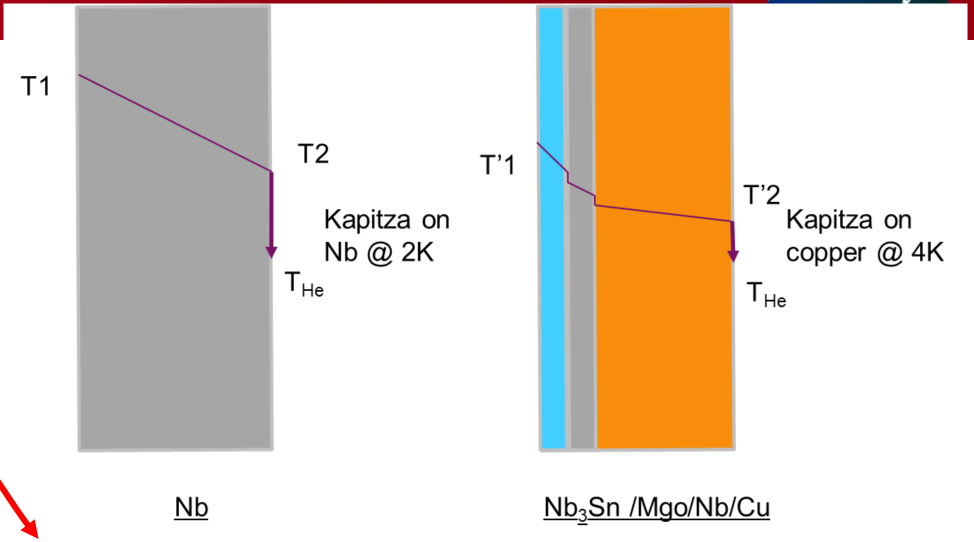




5. NEW COOLING SYSTEMS

What needs to be explored ?

- **Working on copper**
  - Thermocurrents (M-M' interfaces)
  - Metal-Metal heat resistance ?
  - Copper-Helium heat resistance ?
  - Incorporated cooling capillaries (Additive manufacturing)
- **Working > 4 K instead of ~2 K** (short term)
  - Bubble nucleation at the surface ?
  - Stability, frequency sensitivity
- **Working with cryocoolers** (long-medium term)
  - If helium price goes on increasing, might become worth considering
  - 2.7 W @ 4.2 K available, 10 W expected this year
  - e.g. MgB_2 expected to operate at 10 K
  - Already usable for storage rings
- **Topic just starting now**
  - To be included in a future proposal?
  - Specifications to RF



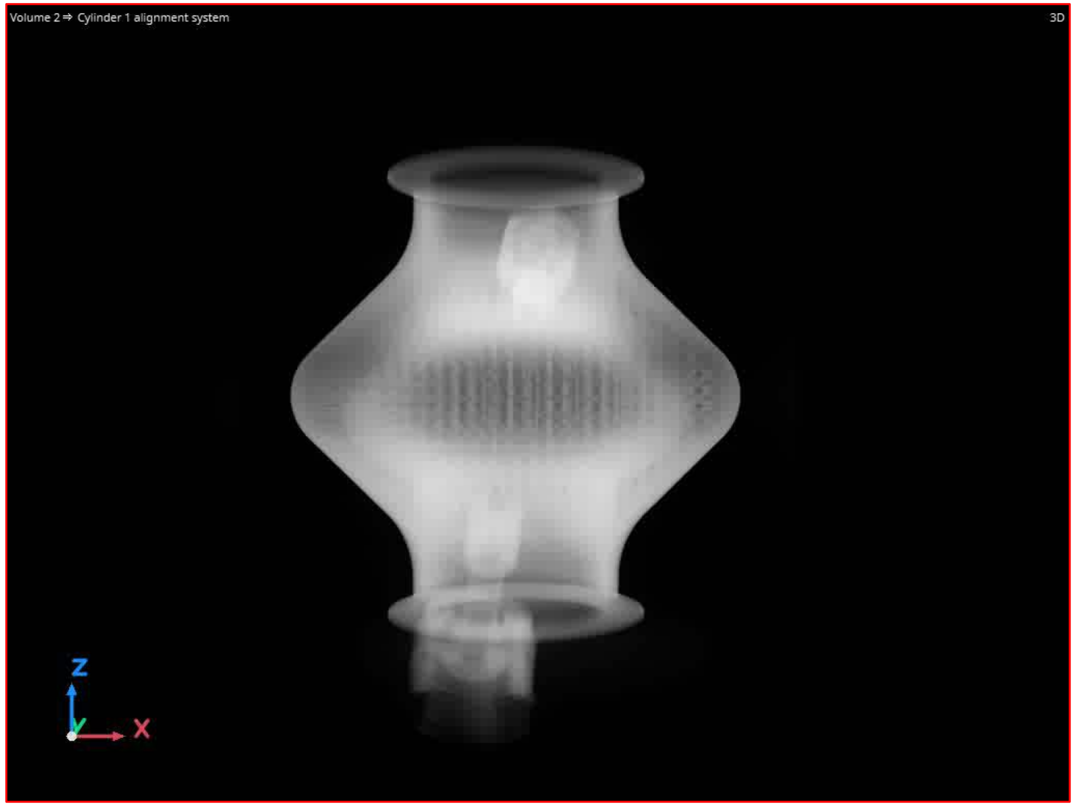
Need to develop our contacts with cryogenists

Modify cavity design?
(RF guys)

ESS cryomodules @ 2K:
Spoke CM ~ 7W
High β CM ~ 30 W

=> Long term commitments and funding

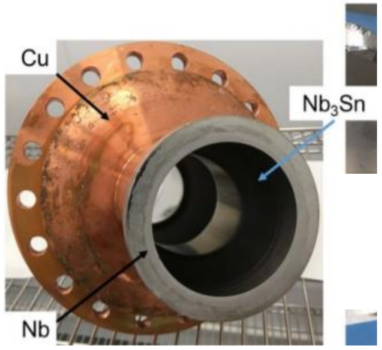
5- NEW COOLING SYSTEMS

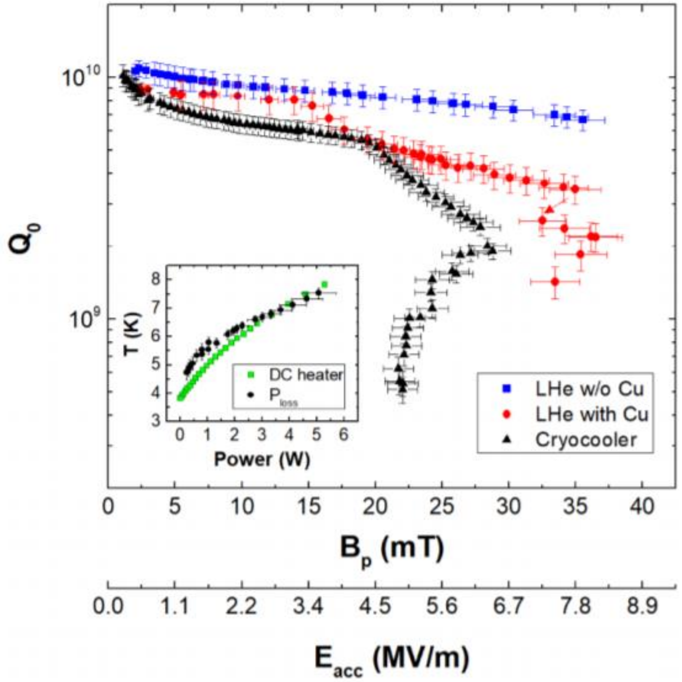


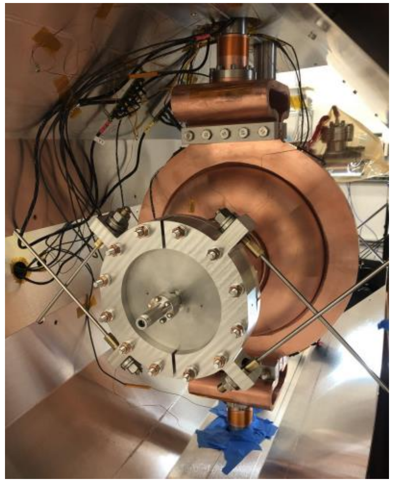
3D add. Fabrication with cooling circulating capillary integrated in the walls (thermosiphon approach)

- **Reduced He volume**
- **Efficient cooling**

Multi-metallic conduction cooled Nb3Sn-coated cavity



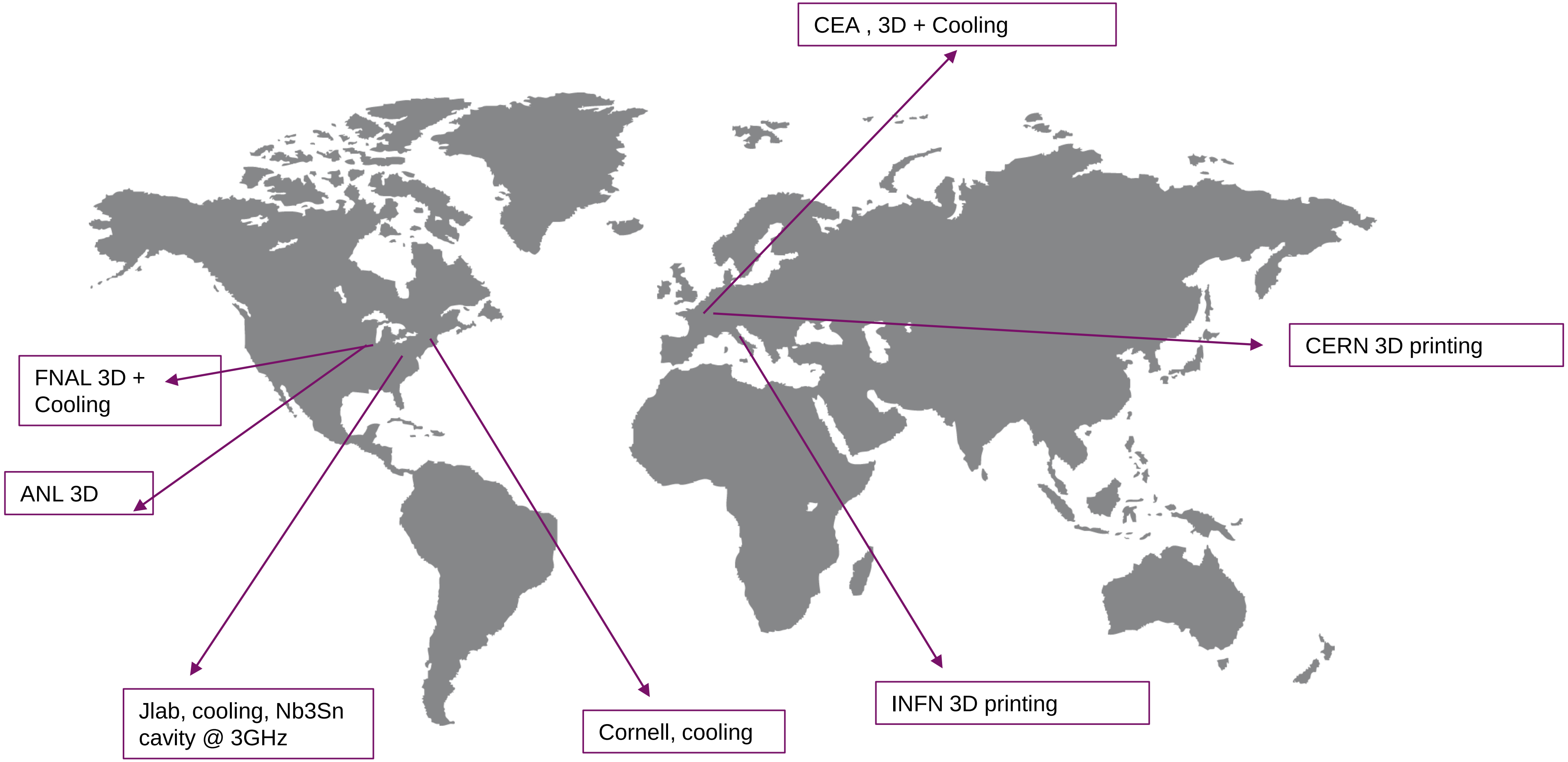




- **Cryocooler**

G. Ciovati et al 2020 Supercond. Sci. Technol. ***33*** *07LT01*
https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.26.044701

5-NEW COOLING SYSTEMS/ 3D PRINTING



CEA , 3D + Cooling

CERN 3D printing

FNAL 3D + Cooling

ANL 3D

Jlab, cooling, Nb3Sn cavity @ 3GHz

Cornell, cooling

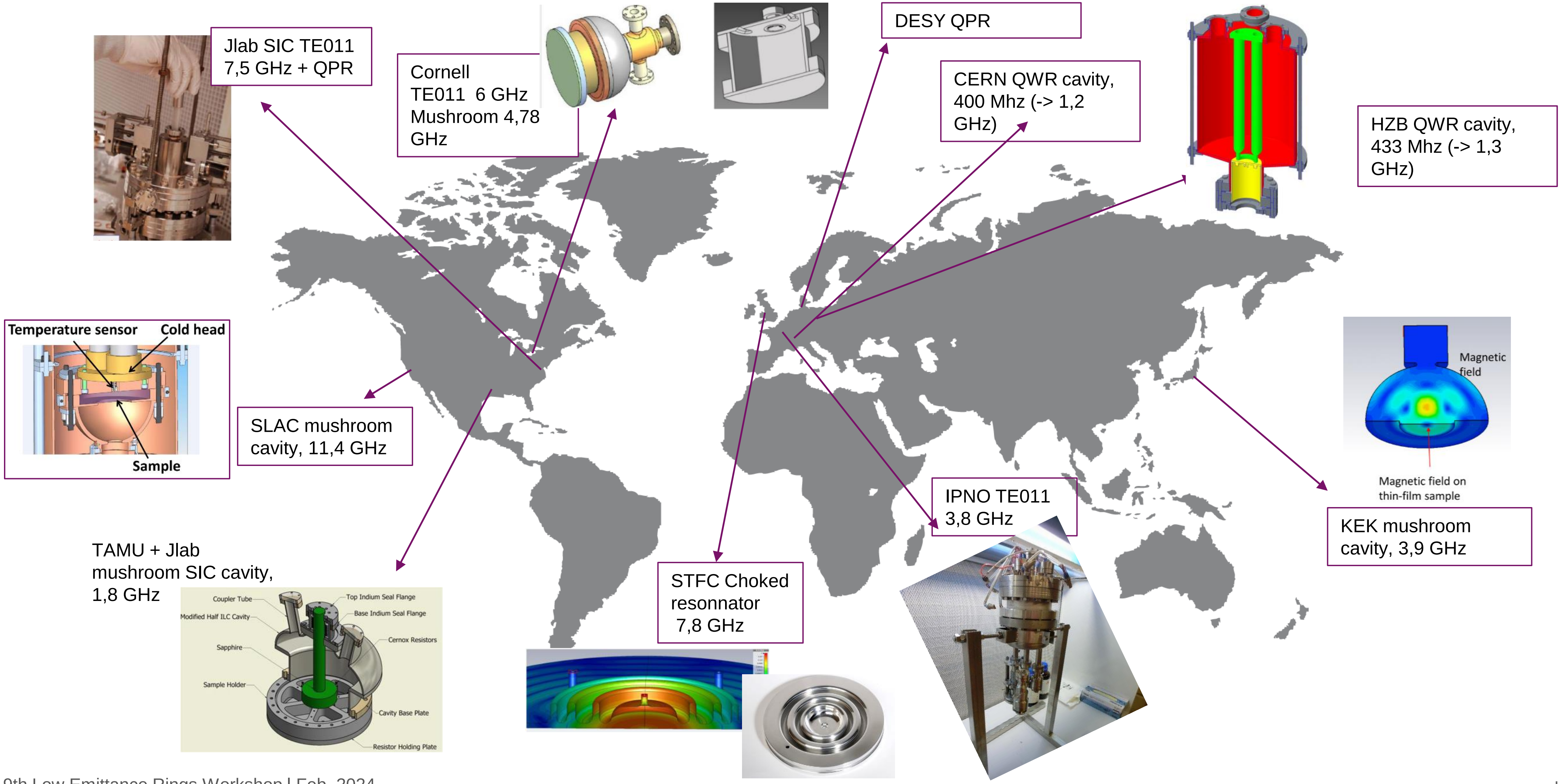
INFN 3D printing

6. CHARACTERIZATION

What is necessary

- **Material characterization (microcopy, X-rays, analysis…)**
  - Local infrastructures + collaboration with academic institutes
- **Superconducting properties**
  - Local infrastructures + collaboration with academic institutes (DC magnetometry, Tc, RRR)
    - Including novel techniques: 3rd harmonics, magnetic field penetration
  - Specific tools under developments (RF properties, vortex penetration close to the operating conditions). New tools are necessary to measure new properties ! They don’t exist on the shelves!
- **RF testing**
  - Access to workshops, clean rooms, RF stands (running testing for machine projects vs R&D)
  - Sample cavities, prototypes @ 6 GHz, 3 GHz, 1.3 GHz… (substrate production cycle)

R_S CHARACTERIZATION/SAMPLE RF CAVITIES



Jlab SIC TE011
7,5 GHz + QPR

Cornell
TE011 6 GHz
Mushroom 4,78 GHz

DESY QPR

CERN QWR cavity, 400 Mhz (-> 1,2 GHz)

HZB QWR cavity, 433 Mhz (-> 1,3 GHz)

SLAC mushroom cavity, 11,4 GHz

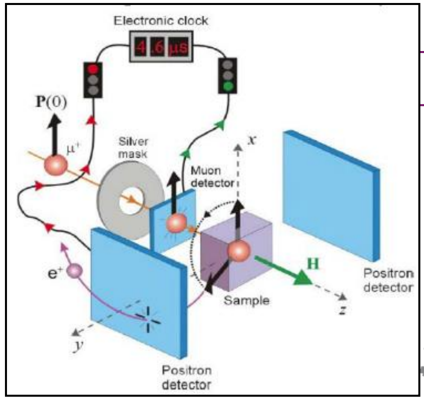
TAMU + Jlab mushroom SIC cavity, 1,8 GHz

STFC Choked resonator
7,8 GHz

IPNO TE011
3,8 GHz

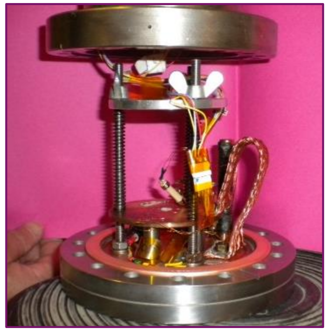
KEK mushroom cavity, 3,9 GHz

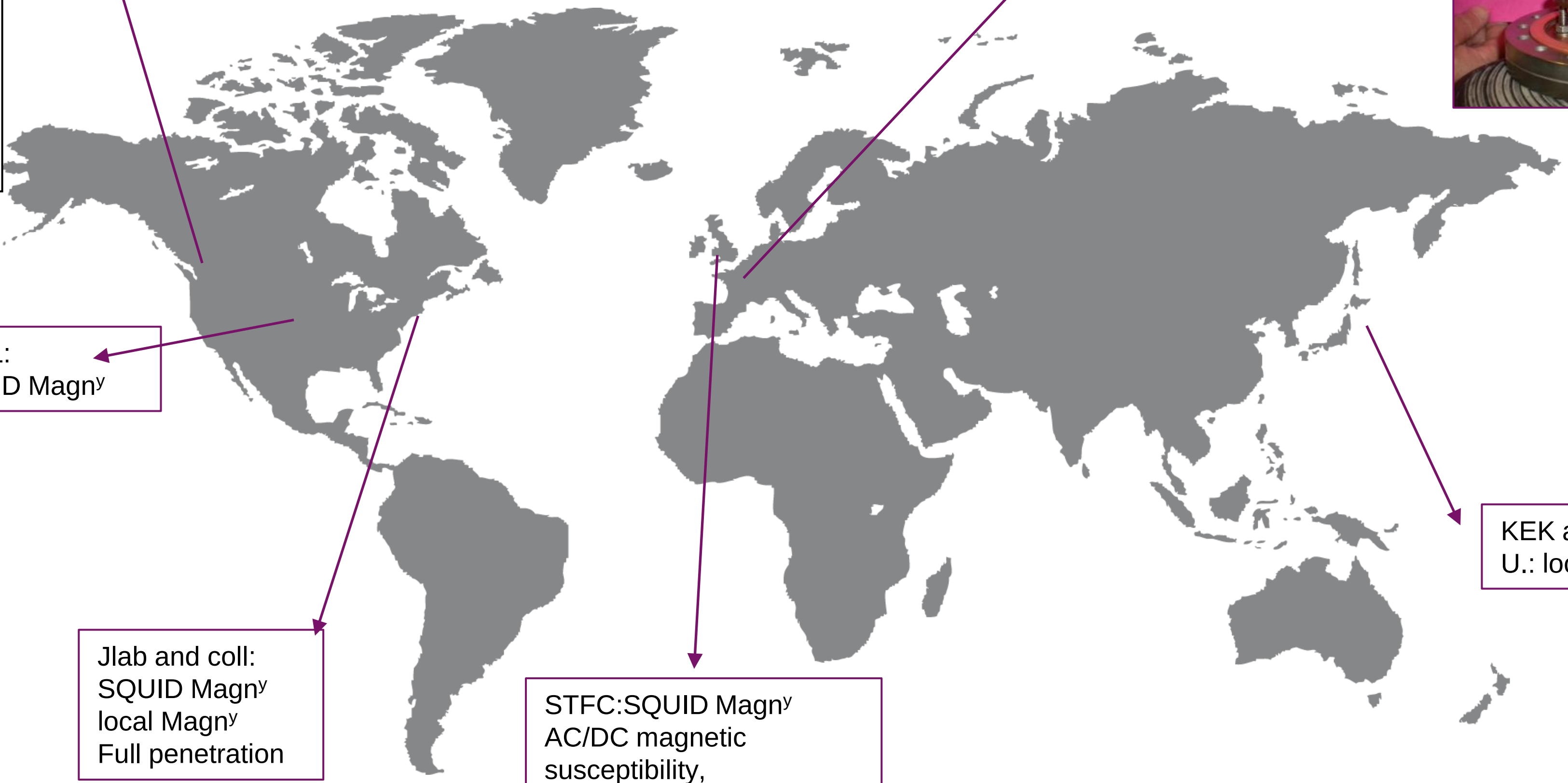
MATERIAL CHARACTERIZATION: SUPERCONDUCTIVITY



Triumf μ-SR

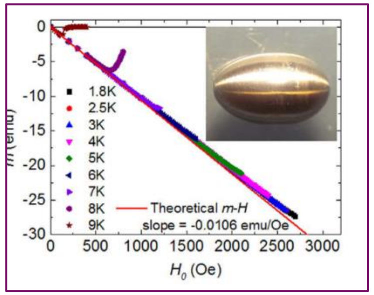
CEA Saclay:
Tunneling microscopy
Local Magnetometry





LANL:
SQUID Magn^{y}

KEK and Kyoto U.: local Magn^{y}



Jlab and coll:
SQUID Magn^{y}
local Magn^{y}
Full penetration

STFC:SQUID Magn^{y}
AC/DC magnetic susceptibility,
Full penetration, Samples cavities

…. AND THEORY (S-I-S & S-S)

Triumf
Junginger
S-S
Proximity effect

Cornell
Sethna/Liarte
(S-S)

ODU-**Gurevich**
(S-I-S & S-S)
Effect of thickness, of Nb sub layer

KEK - **Kubo**
(S-I-S & S-S)
Effect of thickness, of Nb sub layer, and insulator thickness

Gurevich, A., 2006. Enhancement of RF breakdown field of SC by multilayer coating. Appl. Phys.Lett., 88: 012511.
Gurevich, A., 2015. Maximum screening fields of superconducting multilayer structures. AIP Advances, 5(1): 017112.

Kubo, T., 2016. Multilayer coating for higher accelerating fields in superconducting radio-frequency cavities: a review of theoretical aspects. Superconductor Science and Technology, 30(2): 023001.

WHERE DO WE STAND ?

More support: more prototypes with different routes, faster conclusions

- **Most of the Topic #1 to # 6 are already under development**
  - Work on samples well advanced
  - First prototypes are en route, hopefully successful for the end of IFAST (2025)
  - Urgent need to increase # 6 (Characterization as well as RF testing capacity)
- **Several aspects are not financed yet**
  - Selection of the "ideal superconductor": *must combine superconducting/ RF performance with fabrication easiness, reduced sensitivity to defects, tunability, reduced sensitivity to trapped flux… It needs further optimization.*
  - Tunability and sensitivity to trapped flux: ISAS for Nb_3Sn only
  - Extension from 1-cells to multi cells
  - Extension from 1.3 GHz to other frequencies
  - No theory in Europe: we count on ODU or KEK
- **Need to make plans for the future (after IFAST)**
  - Address the remaining topics … **and get funded !**

At the European level,
***Thin films* investment is**
~1/4th
of nominal prevision in
the HE roadmap…
European blind spot ?

THANK YOU FOR YOUR ATTENTION

Announcement:

11th International Workshop on Thin Films and New Ideas for Pushing the Limits of RF Superconductivity

Sep 16 – 20, 2024

Université Paris-Saclay, France

https://indico.cern.ch/event/1376902/

Sponsored by

iFAST

SPARES

CONCLUSION

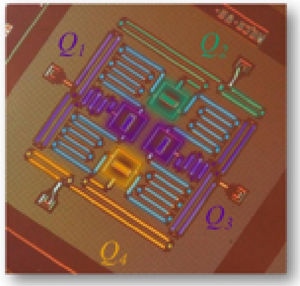
Several M€ potential savings (capital and operating) w. thin film cavities working @ 4,5 K

- **Expertise exist in everywhere in the world, strong collaborative environment**
  - There is little duplication: even labs working on the same topic are exploring different routes and/or exploring lab to lab variability
- **Small teams, working in several direction at the same time** e.g.
  - INFN: seamless copper cavities, copper surface treatments, Nb/Cu, Nb_3Sn (development of targets, development of films, ≠ methods) (~10 persons in the team including masters students)
  - Jlab: copper and niobium substrates, Nb, NbTiN, Nb3Sn, SIS (energetic condensation / conventional PVD) - 4 deposition systems + 1 in construction), home made characterization tools (2.5 scientists, 2 post-docs, 1 technician)
  - CEA: thin films: SIS, multipactor reduction, characterization, new cooling systems … : 3 persons…
- **There is little duplication** *(despite appearances)*
  - Even labs working on the same topic are exploring different routes and/or exploring lab to lab variability
- **Each topic taken separately has chances to success within 5 years**
- **It will not be the case unless strong reinforcement of the existing teams**
  - Students + moderate investments to pursue existing programs
  - Strong reinforcements in the technical supports (access to workshops, clean room, RF test…)
- **Investment to new ideas (e.g. 3 D printing, new cooling system…) should start**
  - They must demonstrate that they can achieve the high surface qualities that we ABSOLUTELY need
  - Investment should not be detrimental to the existing programs that need to be reinforced

Urgent support needed!!!

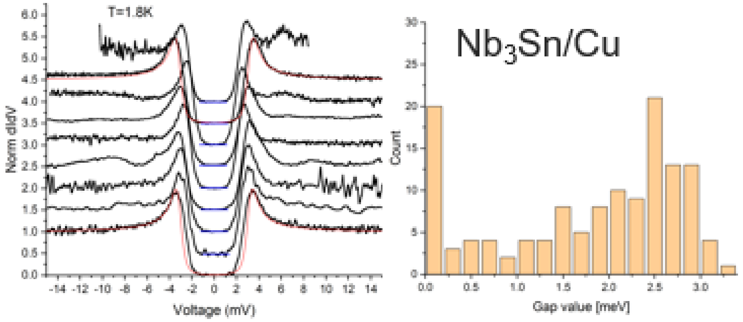
Qubits and cavities - Tunneling and X-ray spectroscopy

Superconducting qubits

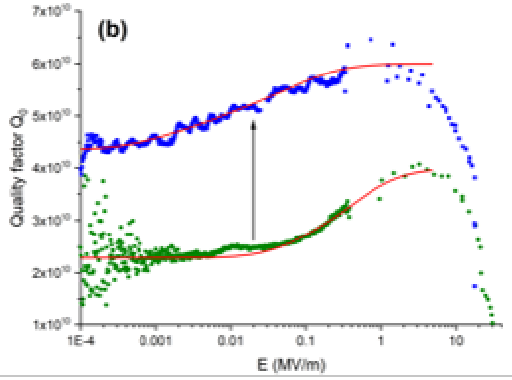


SRF cavities

Thesis of Ivana Curci.



- Common origines for performance limitations: microscopics origins probed by tunneling and x-ray spectroscopy. Materials tested: Ta, Nb, Nb_3Sn.
- Techniques: XPS (chemical composition), XRR (thickness, rugosity, density), XRD (crystalline structure), tunnel spectroscopy (superconducting parameters: gap, factor gamma)
- What methods can be used to overcome / eliminate defects? Surface engineering of oxides by ALD.



Method to study the interface dielectric/superconductor in a controlled way
Various materials, structures and thickness can be tested.

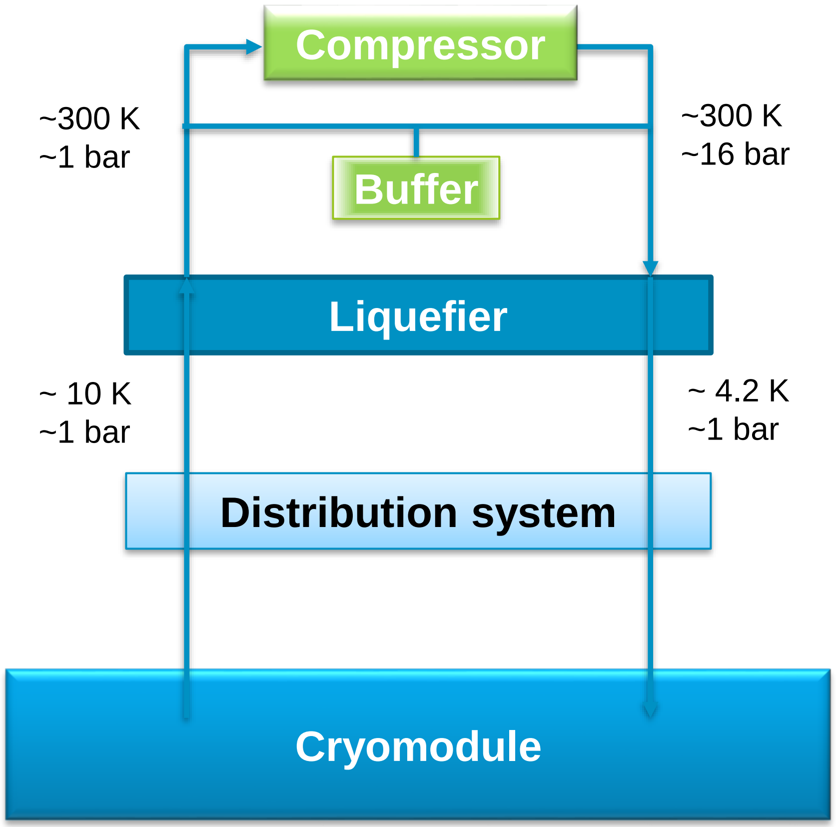
- Applications for Qubits, High Q 3D resonators (detectors, accelerators…)

Autres domaines:

Cavités “détecteur” (faible Eacc mais Bext élevé), ondes gravitationnelles,….

CRYOGENIC SYSTEMS: WORKING @ 4.5 K INSTEAD OF 2 K

4.5 K



Compressor

~300 K
~1 bar

Buffer

~300 K
~16 bar

Liquefier

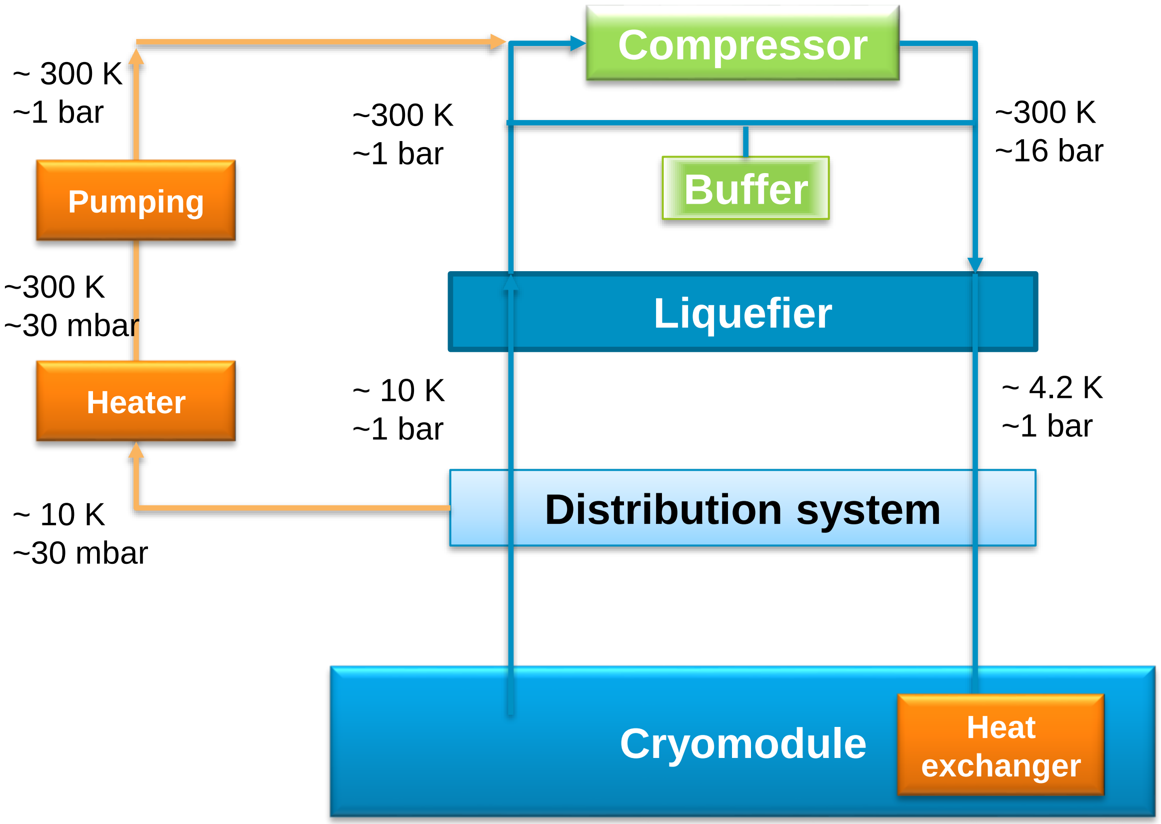
~ 10 K
~1 bar

~ 4.2 K
~1 bar

Distribution system

Cryomodule

2 K



~ 300 K
~1 bar

Pumping

~300 K
~30 mbar

Heater

~ 10 K
~30 mbar

Compressor

~300 K
~1 bar

Buffer

~300 K
~16 bar

Liquefier

~ 10 K
~1 bar

~ 4.2 K
~1 bar

Distribution system

Cryomodule

Heat exchanger

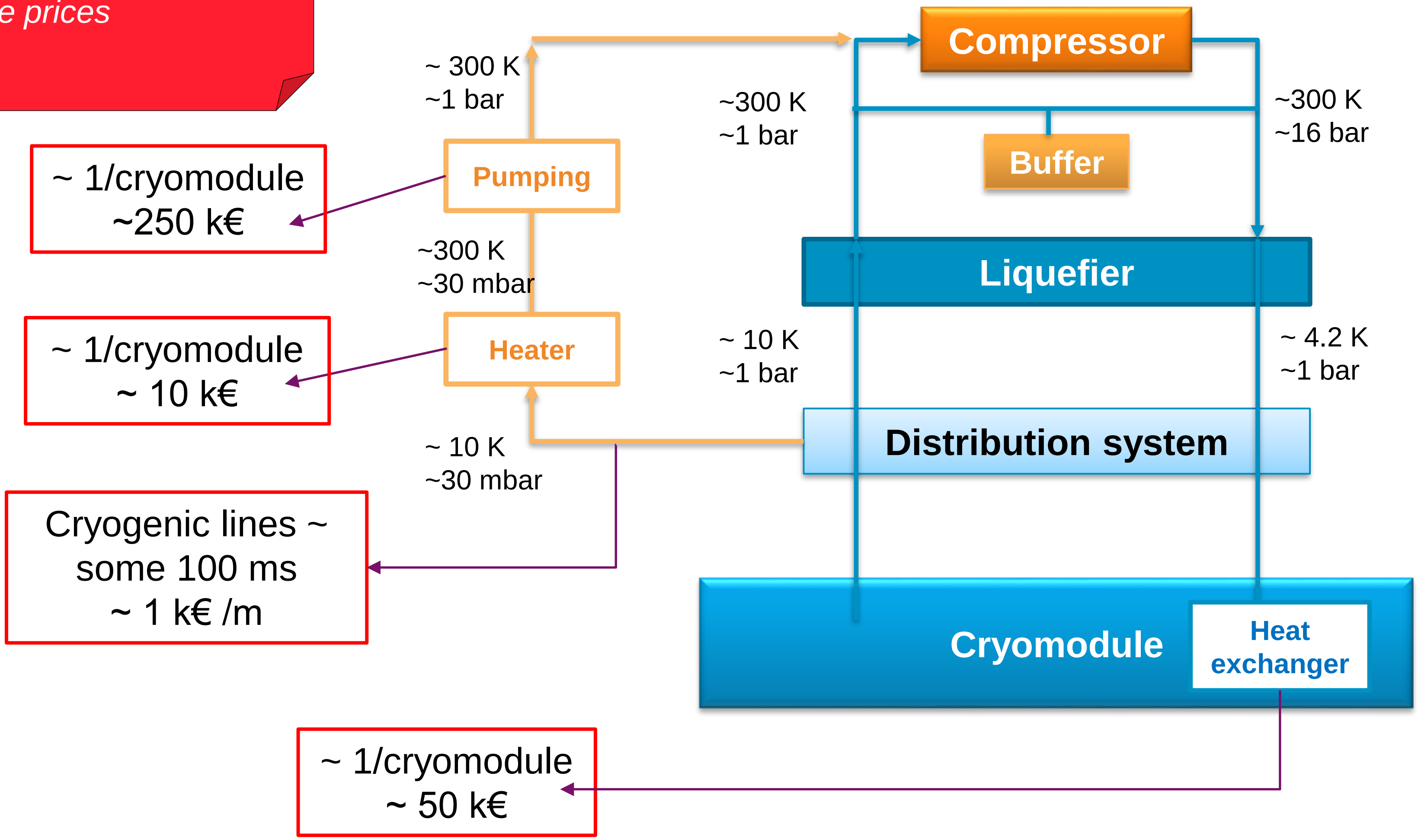
(COARSE) ADDITIONAL BUILDING COSTS @2 K

Figures estimated after smaller installations, large supply might lead to some lower scaling of the prices

Examples	XFEL	ESS
cryomodules	~100	~ 40
Pumps	25 M€	10 M€
Heaters	1 M€	360 k€
Linac length	~ 1 km	~ 400 m
Lines	1 M€	400 k€
2 K Total	~ 27 M€	~ 10 M€
Total	80 M€ ?*	~ 50 M€

* *For XFEL, already existing facilities were completed Total price unknown*

2 K



~ 1/cryomodule
~250 k€

~ 1/cryomodule
~ 10 k€

Cryogenic lines ~ some 100 ms
~ 1 k€ /m

~ 1/cryomodule
~ 50 k€

OPERATING COSTS SAVING : COOLING EFFICIENCY

- **Carnot efficiency η_C** *(thermodynamics)*
- **Refrigerator efficiency η_{Th}** *(real life compared to physics)*

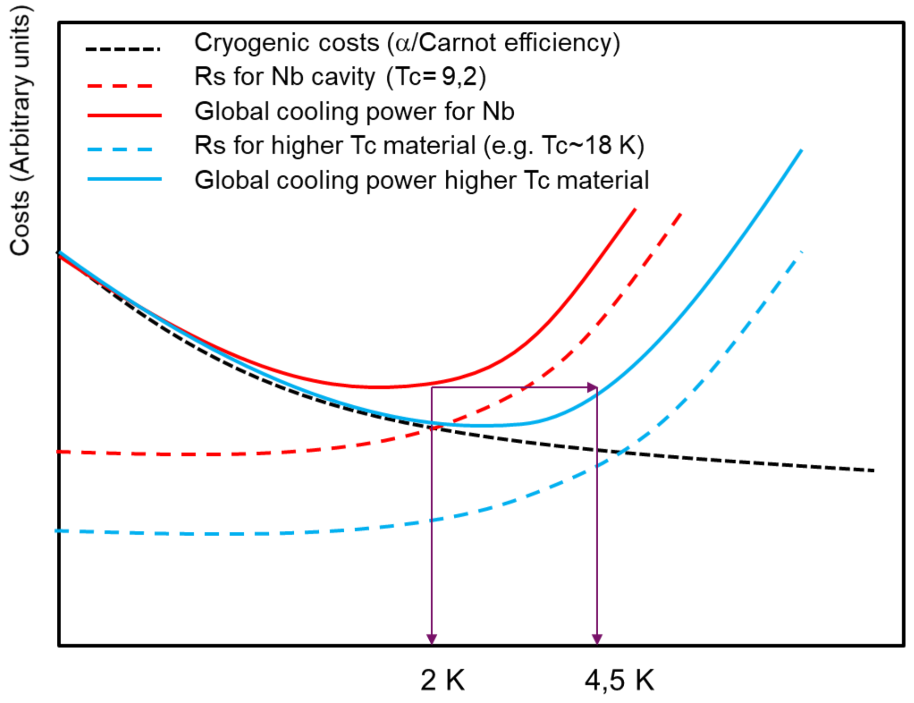
$$\eta_C = \frac{T_c}{T_h - T_c} \approx \begin{cases} 1/70 \text{ for } T_h = 300\,\mathrm{K}, T_c = 4.2\mathrm{K} \\ 1/150 \text{ for } T_h = 300\,\mathrm{K}, T_c = 2\mathrm{K} \end{cases}$$

$$\eta_{th} = \begin{cases} 25 - 30\,\% \text{ at } T = 4.2\,\mathrm{K} \\ 15 - 20\,\% \text{ at } T = 2\,\mathrm{K} \end{cases}$$

  - To remove 1W @ 80K: **~20W** @ 300K is needed
  - To remove 1W @ 4.2K: **~250W** @ 300K is needed
  - To remove 1W @ 2K: **~750W** @ 300K is needed

- **RF surface resistance**

$$\boxed{R_S = R_0 + \frac{A\omega^2}{T}\, e^{-BTc/T}}$$



- **Higher Tc materials:**
  - Same cooling power @ 4.5 K instead of 2K
  - Or: lower cooling power at 2 K
- **4.5 K instead of 2 K: plug power divided /3 !!!**
  - Less risks of He pollution
  - Easier maintenance…

OPERATING COSTS SAVING : COOLING EFFICIENCY

- **Carnot efficiency η_C** *(thermodynamics)*
- **Refrigerator efficiency η_{Th}** *(real life compared to physics)*

$$\eta_C = \frac{T_c}{T_h - T_c} \approx \begin{cases} 1/70 \text{ for } T_h = 300\,\text{K}, T_c = 4.2\text{K} \\ 1/150 \text{ for } T_h = 300\,\text{K}, T_c = 2\text{K} \end{cases}$$

$$\eta_{th} = \begin{cases} 25-30\,\% \text{ at } T = 4.2\text{K} \\ 15-20\,\% \text{ at } T = 2\text{K} \end{cases}$$

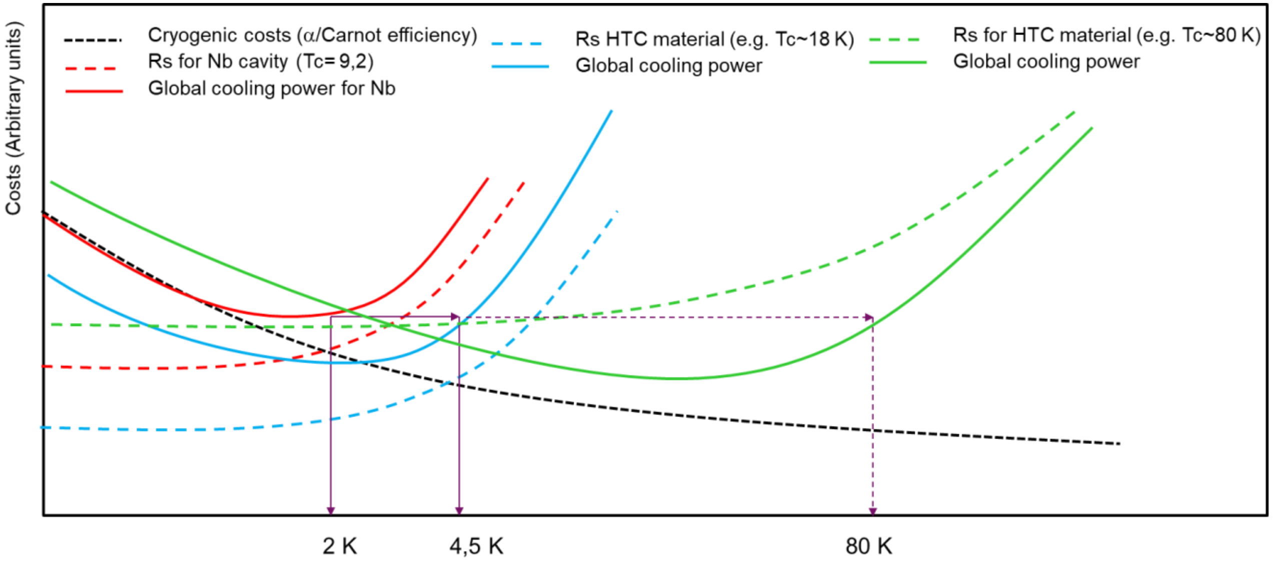
  - To remove 1W @ 80K: **~10 W** @ 300K is needed
  - To remove 1W @ 4.2K: **~250 W** @ 300K is needed
  - To remove 1W @ 2K: **~750 W** @ 300K is needed

- **RF surface resistance**
  - Conventional

$$R_S = R_0 + \frac{A\omega^2}{T}\, e^{-BTc/T}$$

  - HTC

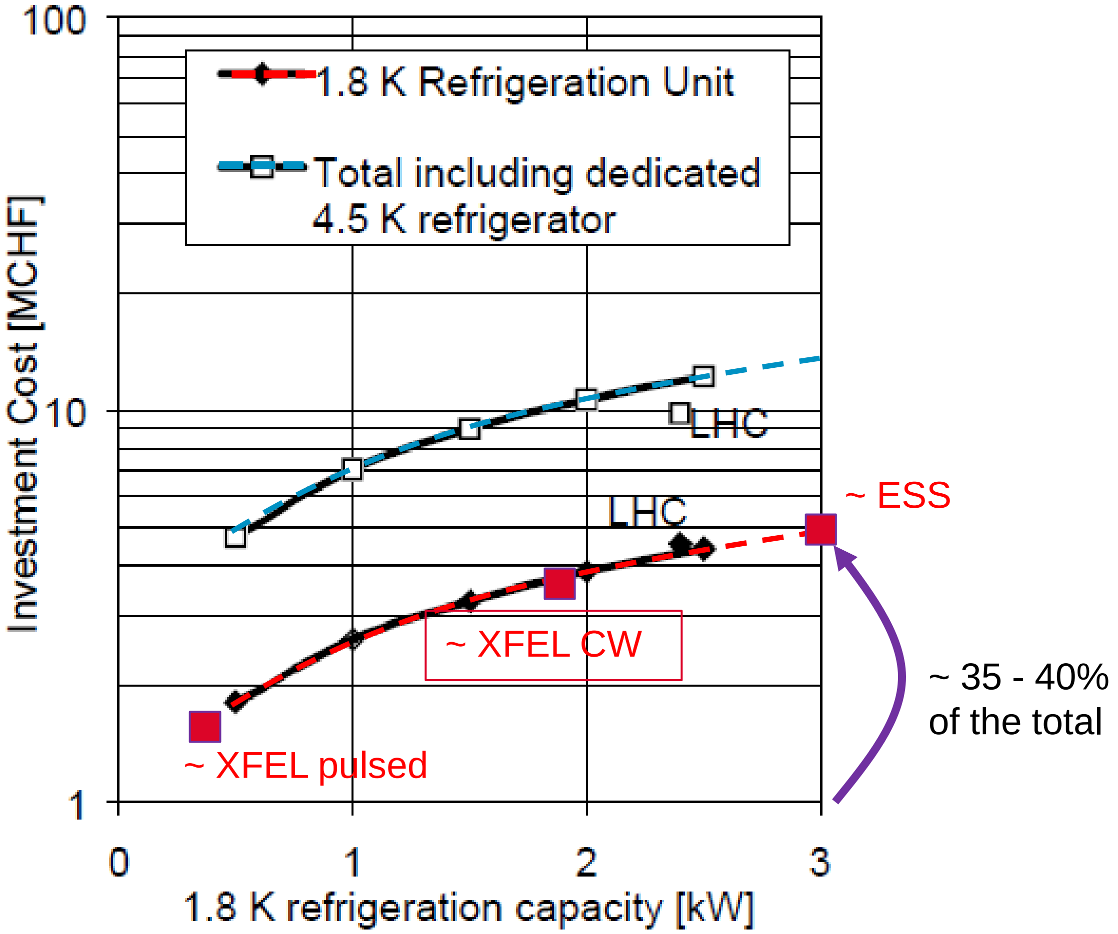
$$R_S(T) \sim R_i + CT^{\alpha}$$



- **One can accommodate higher losses in face of cost savings operation**
  - Same cooling power @ 4.5 K/80 K instead of 2K
  - Or: lower cooling power at 2 K
- **Plug power**
  - 4.5 K instead of 2 K: plug power divided /3 !!!
  - 80 K instead of 4,5 K: plug power divided /25 !!!
  - Easier cryostat design, maintenance…

~ a factor 75 between 2 and 80 K

COST ESTIMATED FROM LARGE CRYOPLANTS (1998 FIGURES)

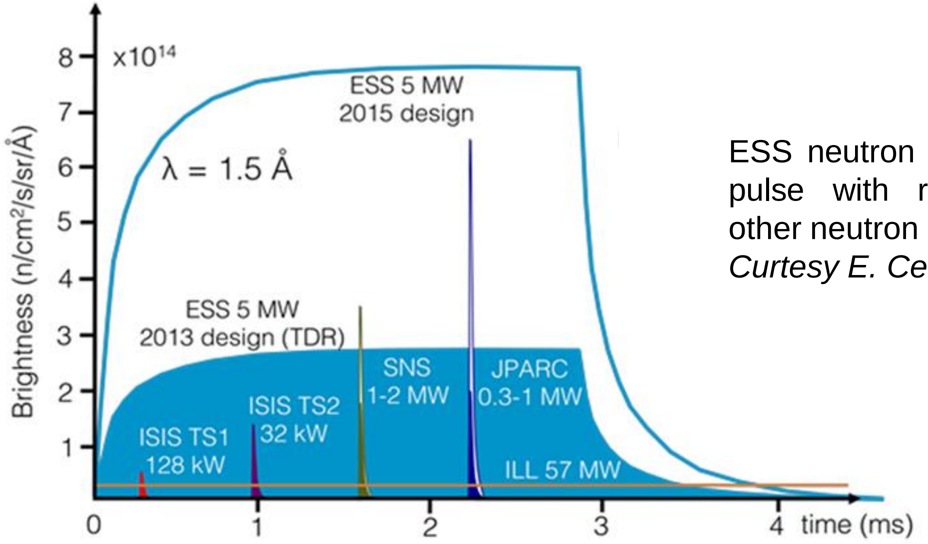


~ 35 - 40% of the total

Figure 9. Investment cost of 1.8 K refrigeration

Curtesy P. Lebrun, CERN

- **LHC project report 317** (S. Claudet, Ph. Gayet, Ph. Lebrun, L. Tavian and U. Wagner, “Economics of large helium cryogenic systems: experience from recent projects at CERN”)
- **4.5 K instead of 2 K: investment decreased by~35-40 % !!!**
  - e.g. ESS cryogenic total cost ~40 M€
  - ~ 15 M€ savings ?



ESS neutron brightness pulse with respect to other neutron machines
Curtesy E. Cenni

BUILDING COST ESTIMATED FROM LARGE CRYOPLANTS

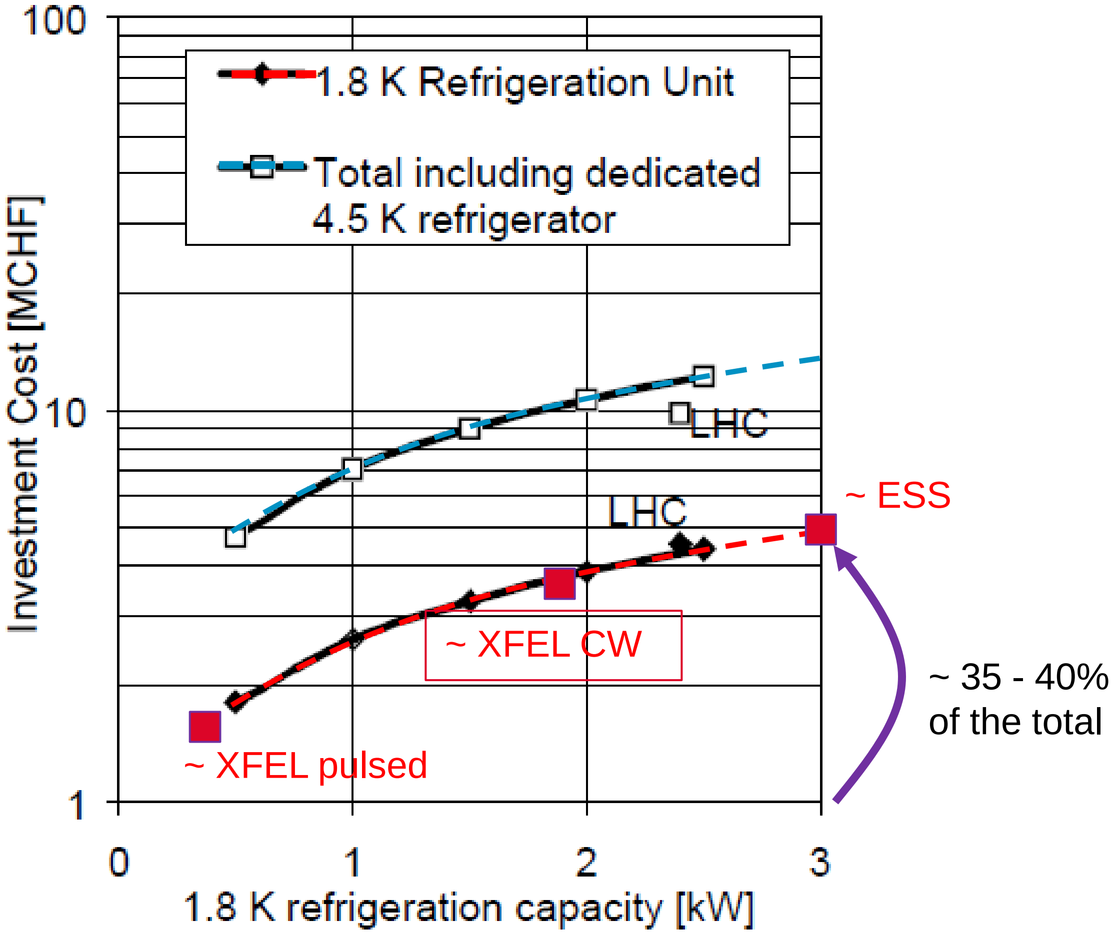


Figure 9. Investment cost of 1.8 K refrigeration

1998 figuresCurtesy P. Lebrun, CERN

- **Cryogeny simplification from 2 to 4.2 K**
  - Costs ~ 35-40 % less
  - 1000 L liq N2 Dewar (made in China) ~ 2000 €
- **Savings going from 4.2 to 80 K ?**
  - 1000 L liq He Dewar (made in China) ~ 6000 €
  - 1000 L liq N_2 Dewar (made in China) ~ 2000 €
  - Cost probably reduced another factor 2 to 3
- **2K investments ~100-250 M€**
- **80 K investments 25 to 50 M€:**

Building costs divided by 4 to 5

CRYOGENS INVENTORY

	ESS	LHC	XFEL
Helium inventory	~ 6 tons	>100 tons	200 tons (?)
Volume	48 m^3	800 m^3	1600 m^3
Cost	720 k€	12 M€	24 M€

- **Liq He ~ 15 k€/m^3; Liq N_2 ~ 0,1 k€/m^3**
  - But superfluid He = very high thermal conductivity (1W/mK) : can dissipate a lot of power
  - liq N_2=>145 mW/mK, but higher Cp…
- **1 W power => cryofluid evaporation:**
  - 1,38 L/h for He
  - 0,14L/h for N_2

W. N_2: inventory AND resupply costs divided by > 150 ?


LHC He tanks © CERN

OVER ISSUES TO FACE

- **How do one prevent early quenches ?**
  - What will be the behavior of GB and other defects ?
  - => issue for future generations ☺
- **How do one deposit 2D films inside a cavity?**
  - Maybe it is an RF design issue
  - Example : split cavities
- **Issues with cavities' sensitivity to vibration**
  - Maybe it is an RF design issue
- **Other Issues ????**

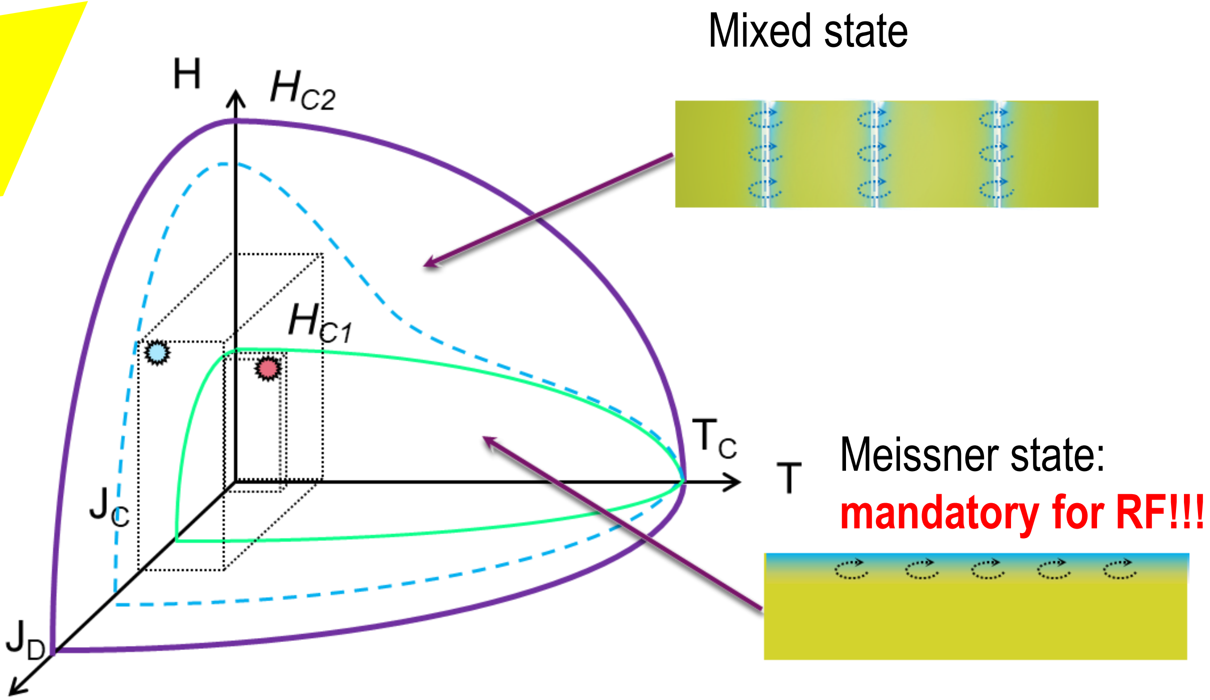
- **At this stage, we need mostly survey…**

[Split Thin Film SRF 6 GHz Cavities (inspirehep.net)](https://inspirehep.net)

WHY SUPERCONDUCTIVITY ?

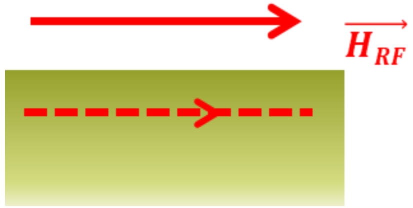
- **∃ thousands of SC**
- **In practice:**
  - ~ 10 are actually used
  - They are all type II
- **Applications…**
  - All applied SC are type II: i.e. low H_{C1} and high H_{C2} => all operate in mixed state…
  - EXCEPT Nb for RF application !!! (high H_{C1})
- **Niobium vs Copper**
  - Surface resistance **10^5** less in RF
  - High accelerating gradients @ high duty cycle, continuous wave (CW)
  - Small field emission, no breakdown. Much lower dark current
- **Better than Nb? => necessarily thin films**
  - But higher density of defects to overcome

Good materials for magnets = bad for SRF

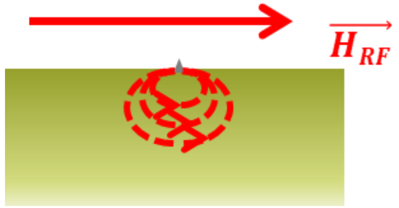


Mixed state

Meissner state: mandatory for RF!!!

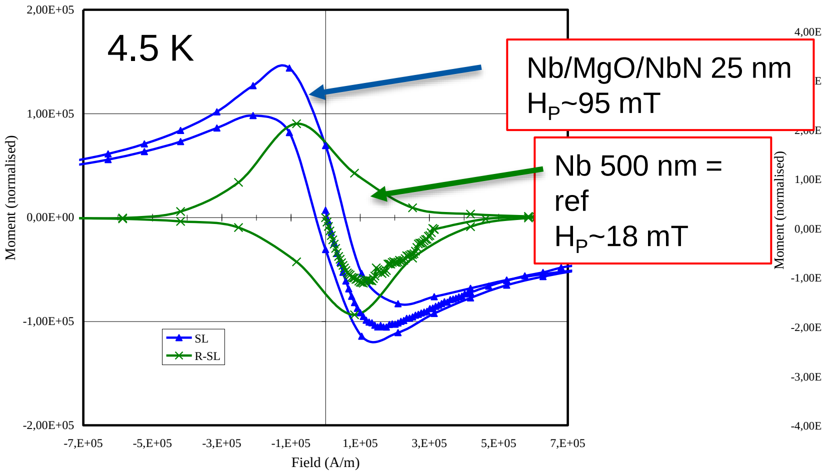


Theory limit: max H_{RF} ~H_{SH}>>H_{C1}



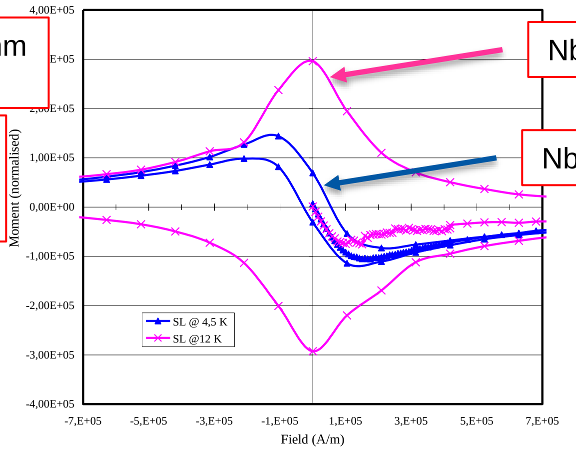
Real life: max H_{RF} ~H_{C1}

SIS : IRREVERSIBILITY => NO VORTEX PINNING <= NO VX ENTRY ?



Nb/MgO/NbN 25 nm
H_P~95 mT

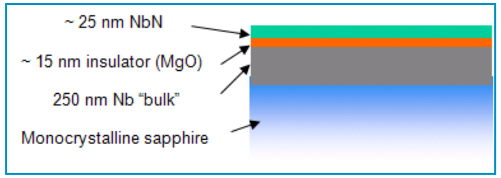
Nb 500 nm = ref
H_P~18 mT



Nb/MgO/NbN 25 nm @ 12 K

Nb/MgO/NbN 25 nm @ 4.5 K

H // sample plane; longitudinal moment



~ 25 nm NbN

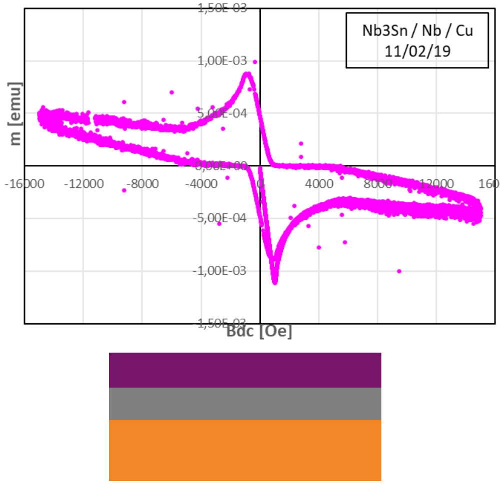
~ 15 nm insulator (MgO)

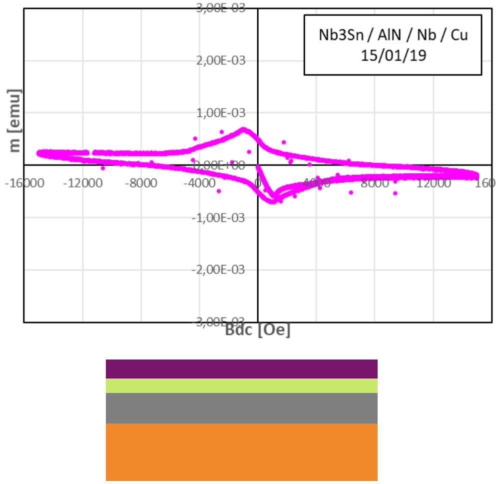
250 nm Nb "bulk"

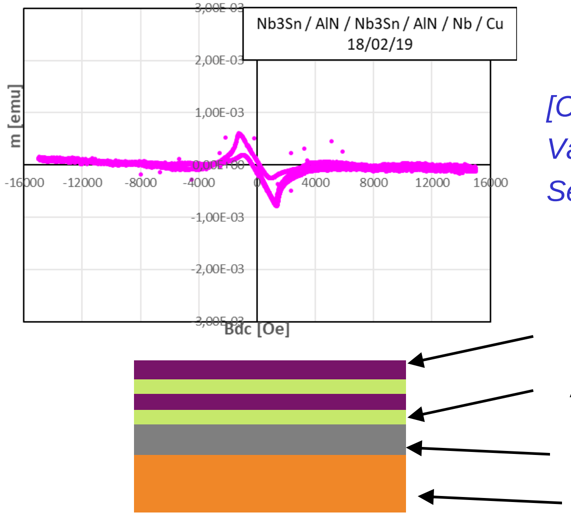
Monocrystalline sapphire

C.Z. Antoine, et al
http://accelconf.web.cern.ch/accelconf/SRF2009/papers/tuppo070.pdf

Each individual layer : ∃ defects, but combination: seems protected







Nb_3Sn

AlN

Nb thick

Cu

[Curtesy R. Valizadeh and E. Seiler, 2019]

SIS : an intrinsically safe structure ?