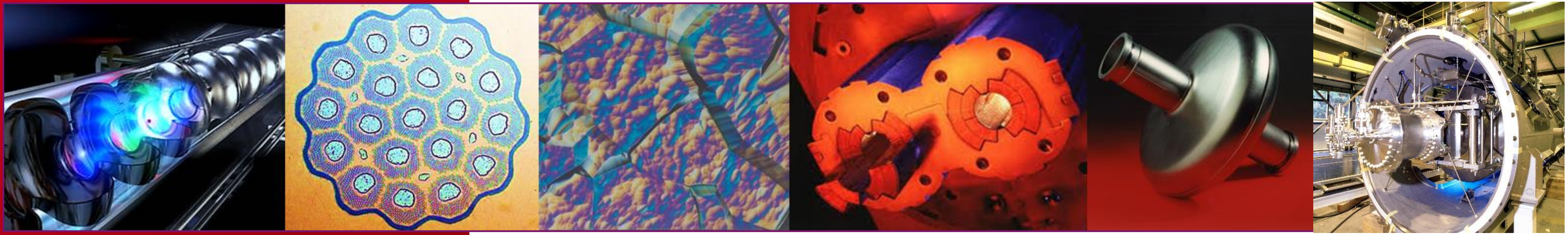
DE LA RECHERCHE À L'INDUSTRIE

TFSRF 2024

INTRODUCTION TALK

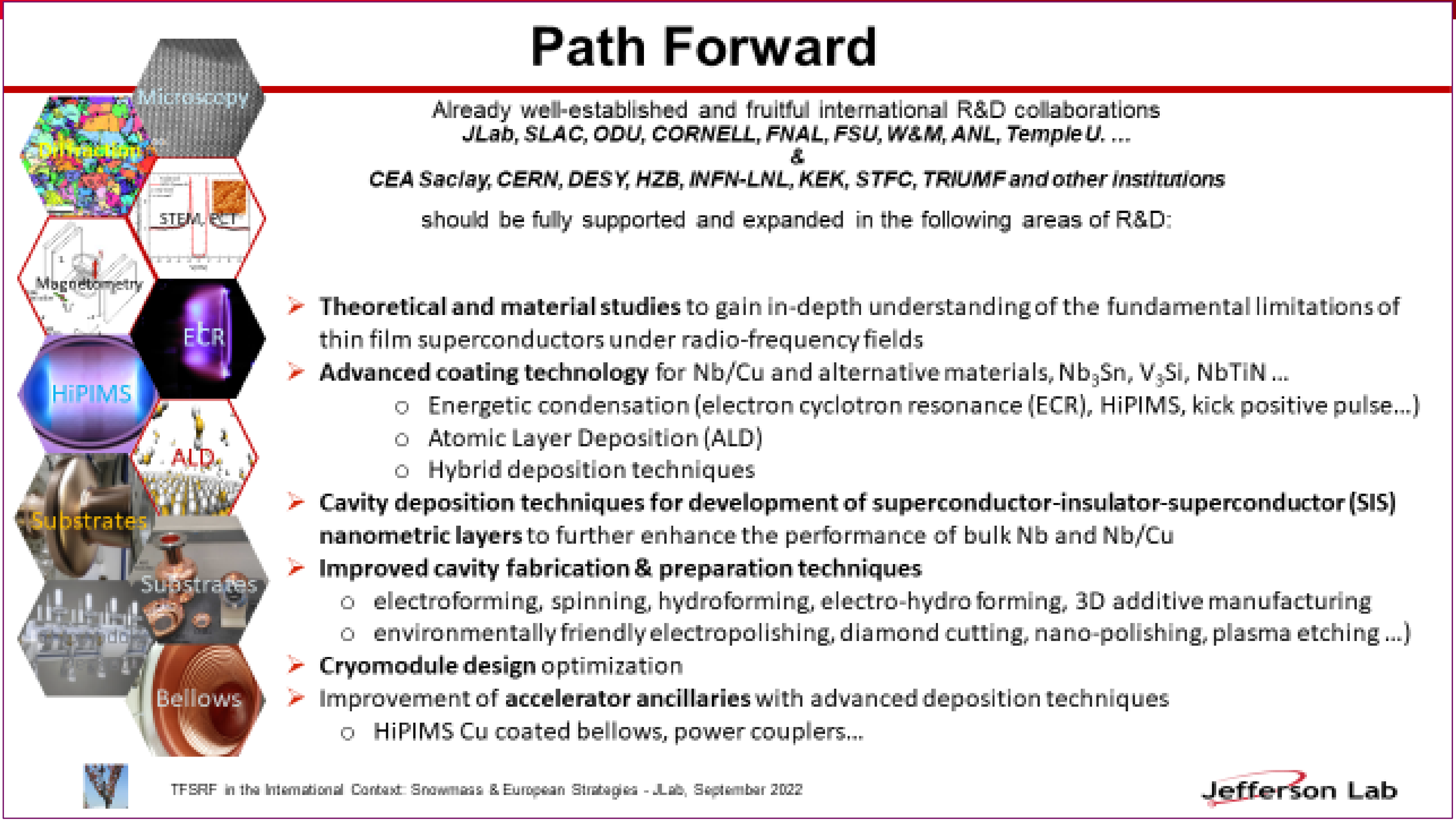


Orsay, France September 2024

C. Z. ANTOINE

www.cea.fr

LAST EDITION (2022 AT JLAB)…



Path Forward

Already well-established and fruitful international R&D collaborations
JLab, SLAC, ODU, CORNELL, FNAL, FSU, W&M, ANL, Temple U. ...
&
CEA Saclay, CERN, DESY, HZB, INFN-LNL, KEK, STFC, TRIUMF and other institutions

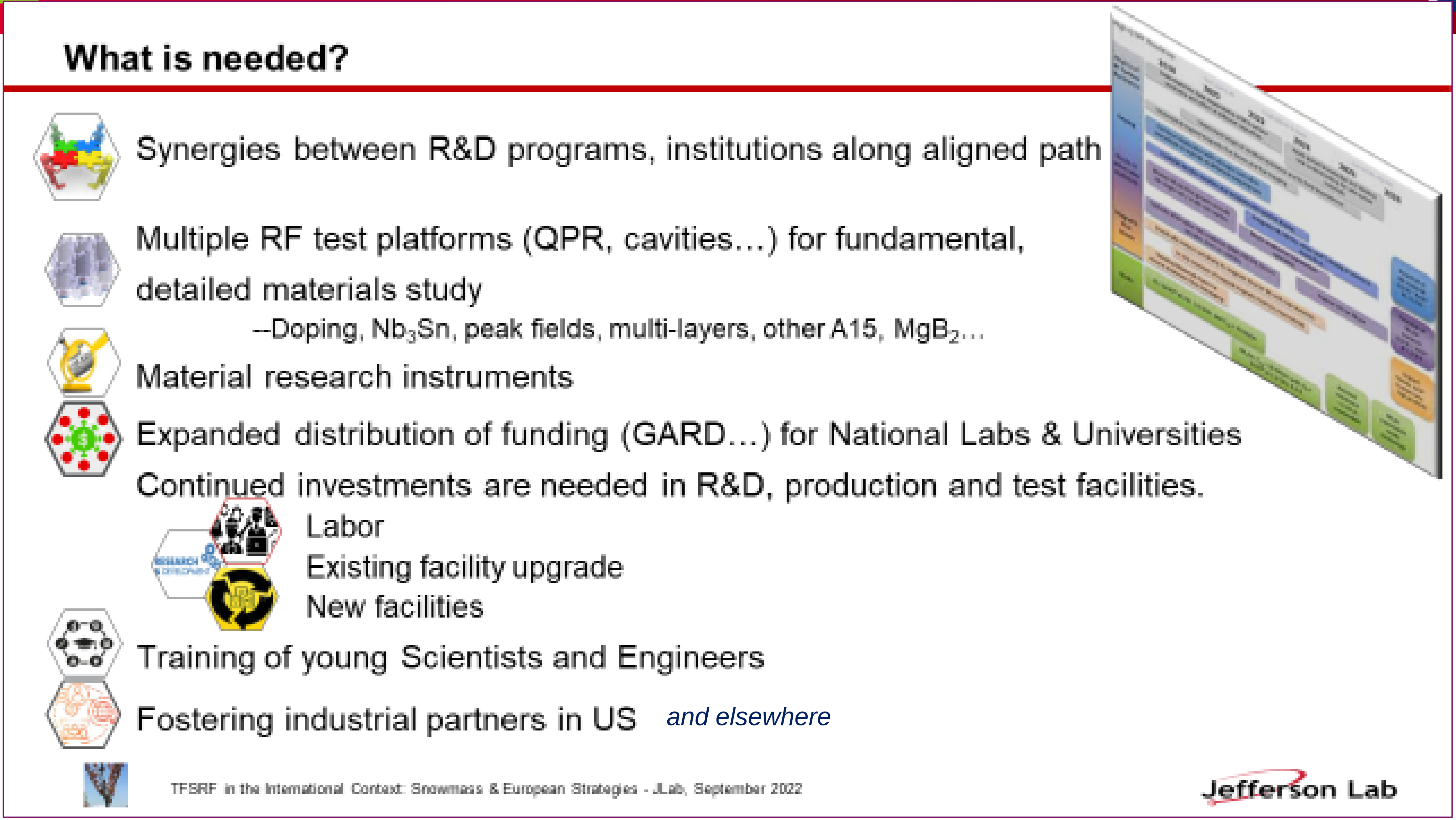
should be fully supported and expanded in the following areas of R&D:

- **Theoretical and material studies** to gain in-depth understanding of the fundamental limitations of thin film superconductors under radio-frequency fields
- **Advanced coating technology** for Nb/Cu and alternative materials, Nb_3Sn, V_3Si, NbTiN ...
  - Energetic condensation (electron cyclotron resonance (ECR), HiPIMS, kick positive pulse...)
  - Atomic Layer Deposition (ALD)
  - Hybrid deposition techniques
- **Cavity deposition techniques for development of superconductor-insulator-superconductor (SIS) nanometric layers** to further enhance the performance of bulk Nb and Nb/Cu
- **Improved cavity fabrication & preparation techniques**
  - electroforming, spinning, hydroforming, electro-hydro forming, 3D additive manufacturing
  - environmentally friendly electropolishing, diamond cutting, nano-polishing, plasma etching ...)
- **Cryomodule design** optimization
- Improvement of **accelerator ancillaries** with advanced deposition techniques
  - HiPIMS Cu coated bellows, power couplers...

TFSRF in the International Context: Snowmass & European Strategies - JLab, September 2022

Jefferson Lab

LAST EDITION…



What is needed?

- Synergies between R&D programs, institutions along aligned path
- Multiple RF test platforms (QPR, cavities…) for fundamental, detailed materials study
  - --Doping, Nb_3Sn, peak fields, multi-layers, other A15, MgB_2…
- Material research instruments
- Expanded distribution of funding (GARD…) for National Labs & Universities
- Continued investments are needed in R&D, production and test facilities.
  - Labor
  - Existing facility upgrade
  - New facilities
- Training of young Scientists and Engineers
- Fostering industrial partners in US *and elsewhere*

TFSRF in the International Context: Snowmass & European Strategies - JLab, September 2022

Jefferson Lab

STILL TRUE…

- **…And we will discuss further in the Friday session “Establishing a Thin films Road Map 2025-2030”**
- **In practice: up-grade of existing Strategies**
  - SNOWMASS 2021
  - HE Accelerator strategy
  - R&D programs of most SRF labs

} *Officially: only HE oriented*

Thin films development	Key activities
R&D niobium on copper: Survey 1 Convener: Walter Venturini • On planar samples • On RF cavities • In machines	**Intensify Cu cavity production and surface preparation: Survey 6** Convener: Cristian Pira • Listing all manufacturing processes, advantages and difficulties • Innovative cooling techniques • Deposition techniques improvement
R&D on Nb3Sn on Cu and Nb: Survey 2 Convener: Takayuki Saeki • On planar samples • On RF cavities	**General Characterization/ Surface science: Survey 7** Convener: Reza Valizadeh • Specific Sample measurements
R&D on other new superconductors (other A15, MgB2, Other) on Cu and Nb: Survey 3, Convener: Reza Valizadeh • On planar samples • On RF cavities	**Cavities preparation and RF testing: Survey 8** Convener: Walter Venturini • Available facilities and potential frequency for testing research cavities • Vertical, horizontal and beam loaded tests
Pursue multilayers (SIS structures) : Survey 4 Convener: Anne-Marie Valente-Feliciano • On planar samples • On RF cavities	**Theory: Survey 9** Convener: Alexander Gurevich • What theorists can provide to experimentalists • What experimentalists is expecting from theorists (or where theorist could potentially help with thin film development) • What theorists and experimentalists can do together but are not doing yet
Surface functionalization: Survey 5 Convener: Thomas Proslier • Doping, protective layers, interlayers, low SEY layers, thermal conductivity improvement	**Industrialization: Survey 10** Convener: Oleg Malyshev • What industries are already included? • When are industries needed and can be included? • What can’t be industrialized

RECENT COST ISSUES FOR SRF ACCELERATOR

- **(Bulk) 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
- **But…**
  - High cost ~1 000 €/kg (x 3 over the past years)
  - Must work at 2 K at high frequency …
    - Helium costs have ~ x 5 over the past 5 years
    - Electricity costs have increased ~ x 1.2 to 2 over the past 5 years
- **Still superconducting and less expensive than Nb? => work with higher Tc material / higher temperature…**

INFLUENCE OF FREQUENCY

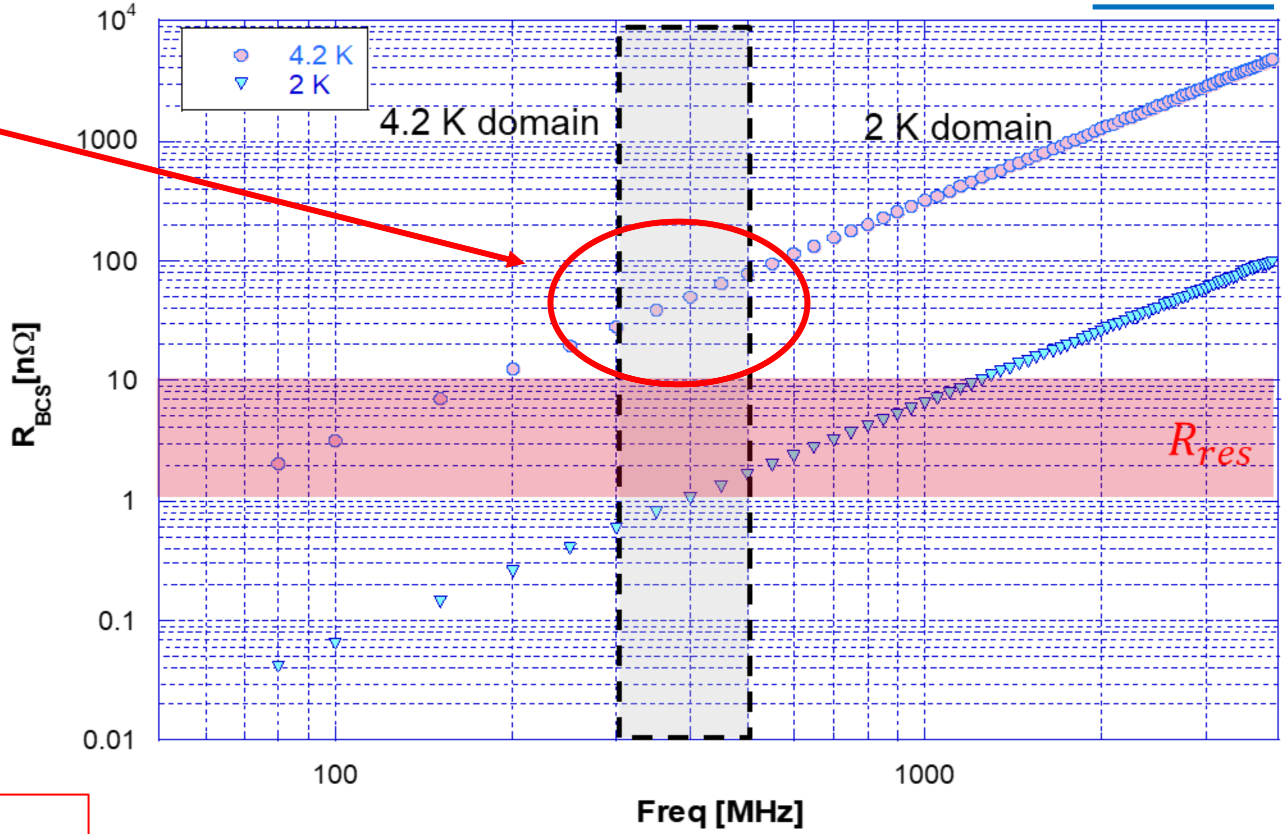
"As a rule of thumb it is preferable to reduce the BCS contribution as low as the residual resistance"

- **Relatively low frequency**
  - Obviously already in the 4.2 K domain
- **Bulk vs thin film Nb ?**
  - If not too high gradients required => Nb/Cu technology OK
  - Higher gradients 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

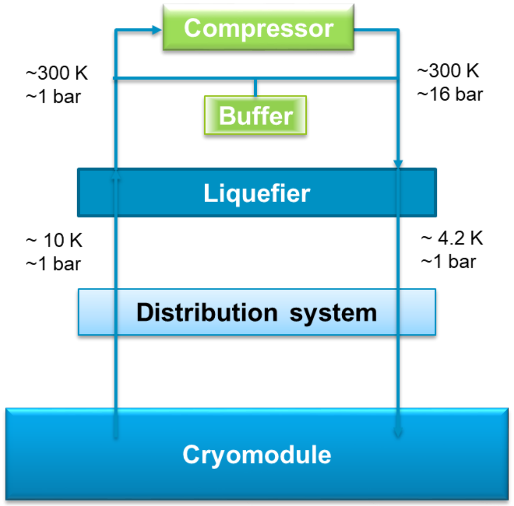
THIN FILMS DEPOSITION

Nb : λ~50 nm => only a few 100s nm of SC necessary (the remaining thickness= mechanical support) **=> Make thin films ! Even more so when you deal with brittle material like Nb_3Sn !**

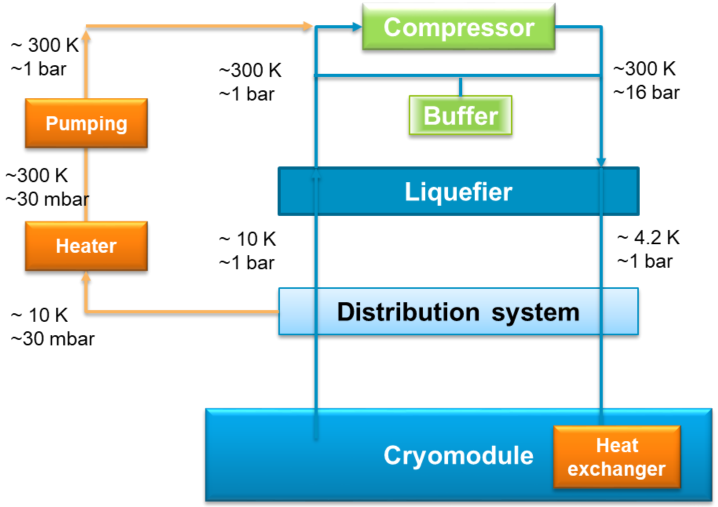
- **Advantages**
  - Thermal stability *(substrate cavity = Copper, Aluminum,… W)* => operation @ 4,5 K possible
  - Simplification of cryostat designs
  - Cost (investment AND operation)
  - Nb on Cu opens route to innovative materials
- **Disadvantages**
  - Fabrication and surface preparation of substrate *(at least)* as difficult as for bulk Nb
  - Steep Q_0 decrease often observed by increase of RF field *(sputtered niobium films)* => increase film densification
  - 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 H_{C1}, defects, pinning centers…)* **=> most of the literature recipes are not fitted for SRF application ☹ ☹ ☹**

- Possible origin of the slope
  - Depinning of trapped flux
  - Low H_{C1}
  - Early vortex penetration due to roughness
  - Current concentration due to porosities (generating local electrical field)

CRYOGENIC SYSTEMS: WORKING @ 4.5 K INSTEAD OF 2 K



4.5 K



2 K

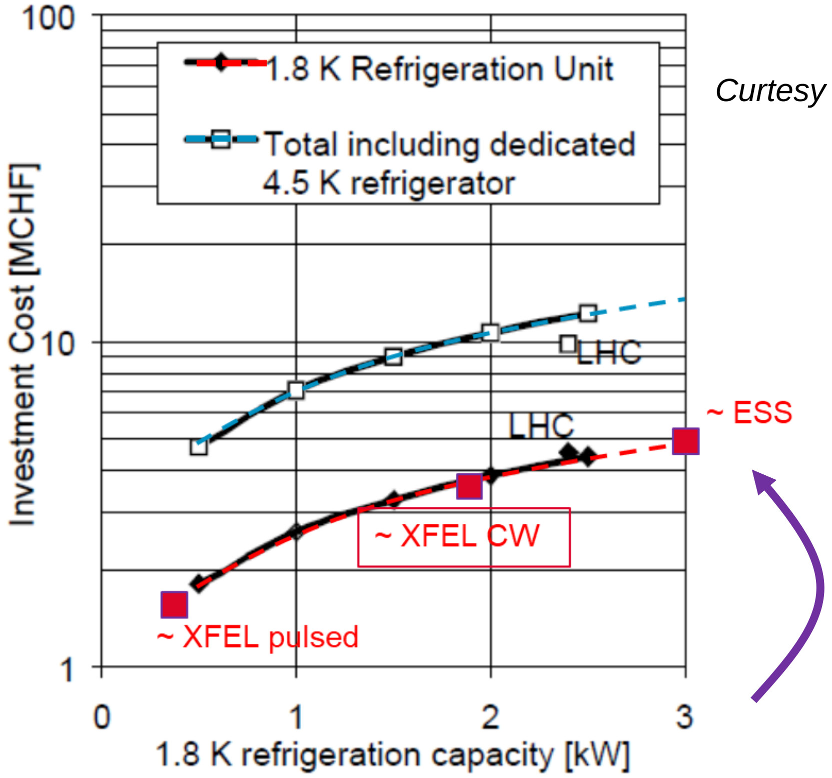


Figure 9. Investment cost of 1.8 K refrigeration

Curtesy P. Lebrun, CERN

~ 35 - 40%
of the total

- **4.5 K instead of 2 K: investment decreased by~35-40 % !!!**

M€ savings !

OPERATING COSTS SAVING : COOLING EFFICIENCY

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

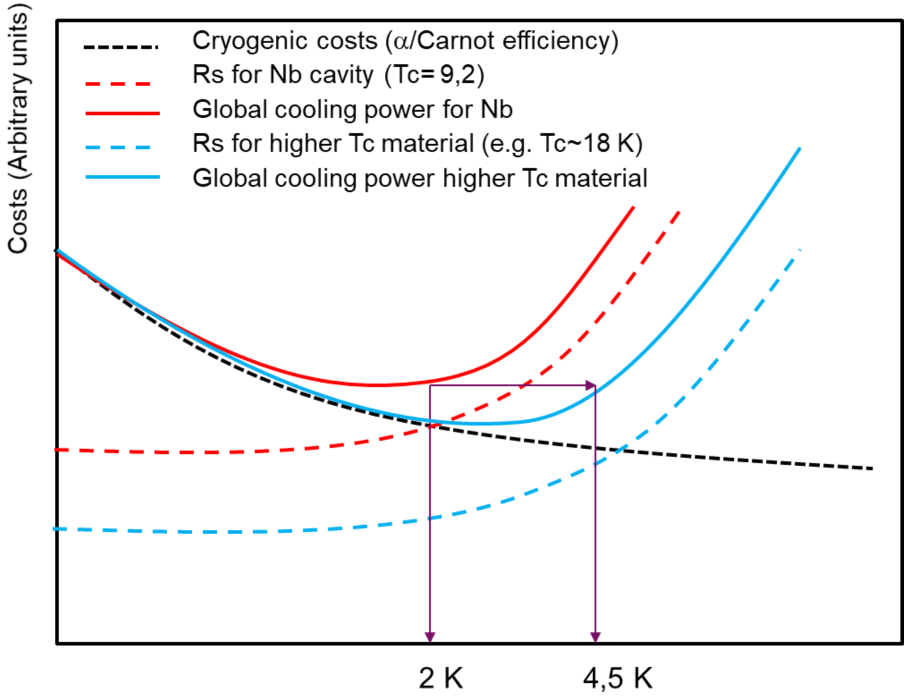
$$\eta_C = \frac{T_c}{T_h - T_c} \approx \begin{cases} 1/70 \ \text{for} \ T_h = 300\,\text{K}, T_c = 4.2\text{K} \\ 1/150 \ \text{for} \ T_h = 300\,\text{K}, T_c = 2\text{K} \end{cases}$$

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

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

- **RF surface resistance**

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

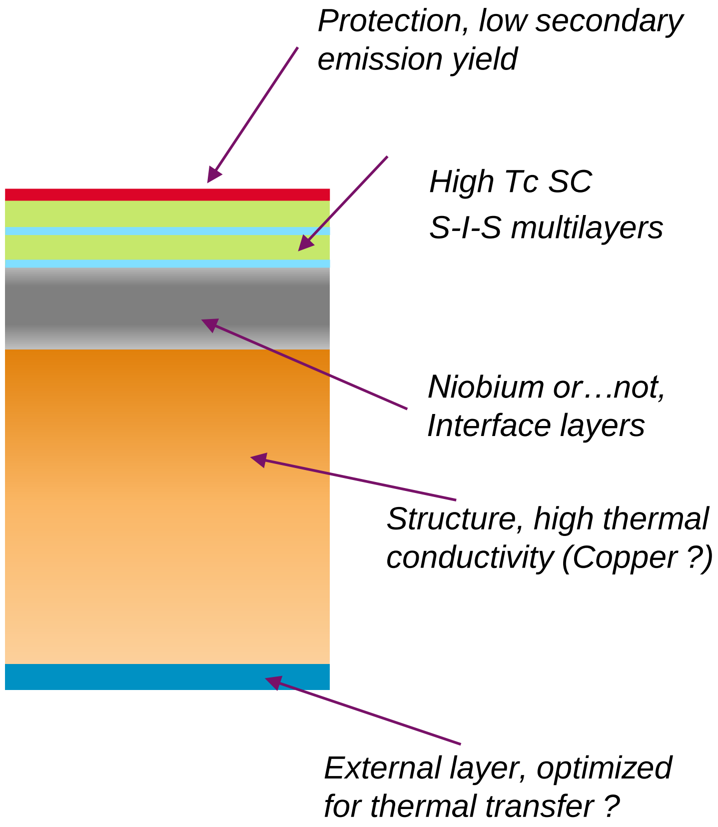


- **Higher Tc materials:**
  - Same cooling power @ 4.5 K instead of 2K
  - Or: lower cooling power at 2 K
- **4.5 K instead of 2 K: plug power divided /3 !!!**
  - Less risks of He pollution
  - Easier maintenance…

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 main route to help cost savings**
  - Cu: cheap manufacturing
  - Higher operation temperature: lower capital, 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?



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**
- **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

Europe

- **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

USA

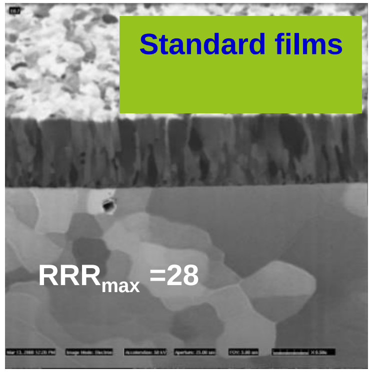
- **TF SRF Workshops 2022 and 2024**
- **TTC-Meetings-thin films: ~ 2-3/year**
  - Bringing the community together

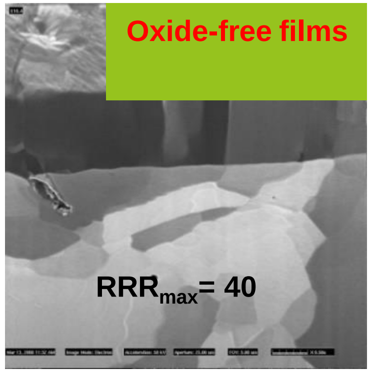
Internat'

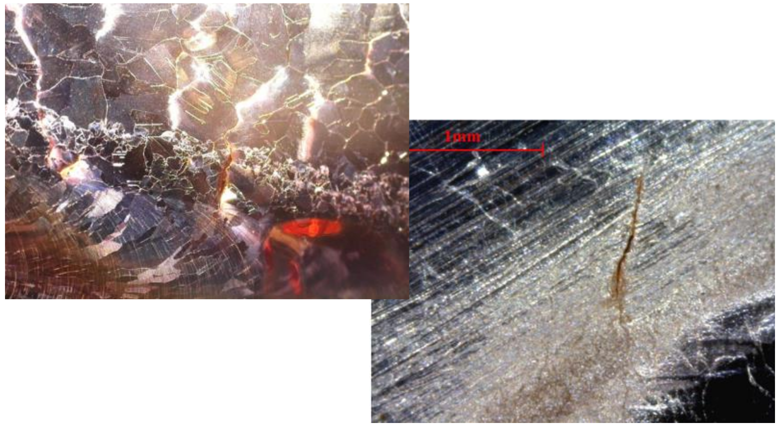
NB Same strategy valid for other applications than HE:

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** *(dead ends, counterintuitive results)*
  - 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)



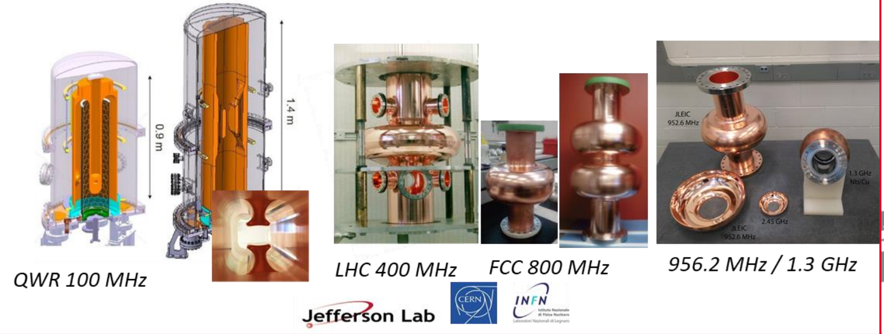


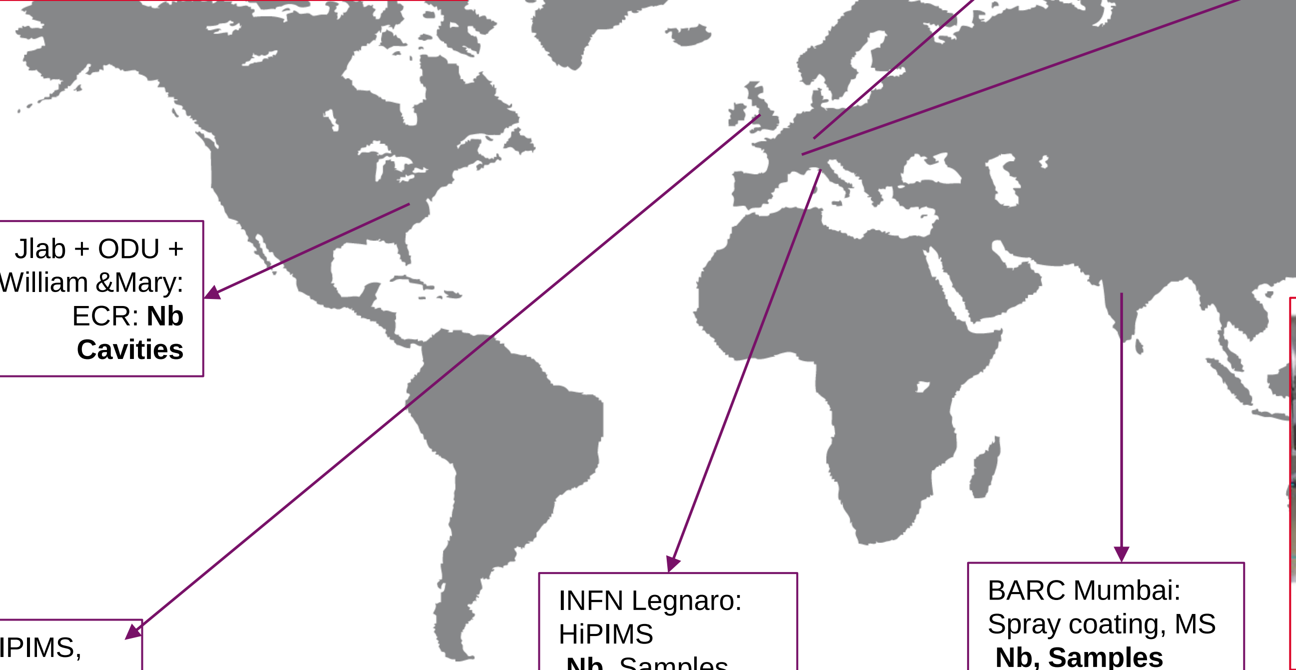


Bad adhesion/degradation of films on welding

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

1-Nb ON Cu





USI: Siegen
HIPIMS
Nb, **samples**

CERN
HIPIMS
Nb, **Cavities**

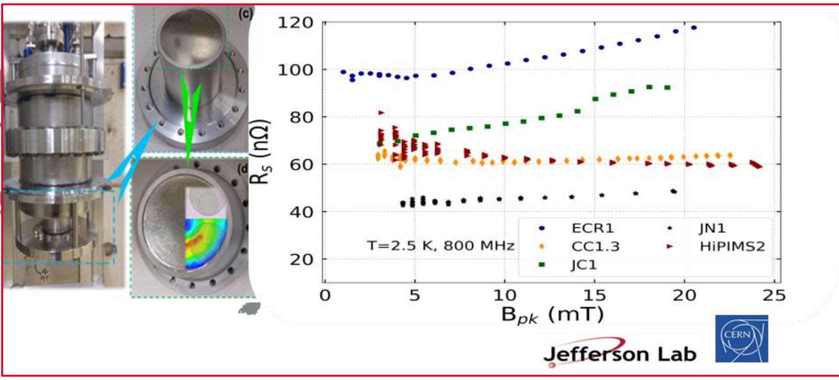
Peking U. Beijing,
CAS, Lanzhou:
Nb, samples

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

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

INFN Legnaro:
HiPIMS
Nb, Samples

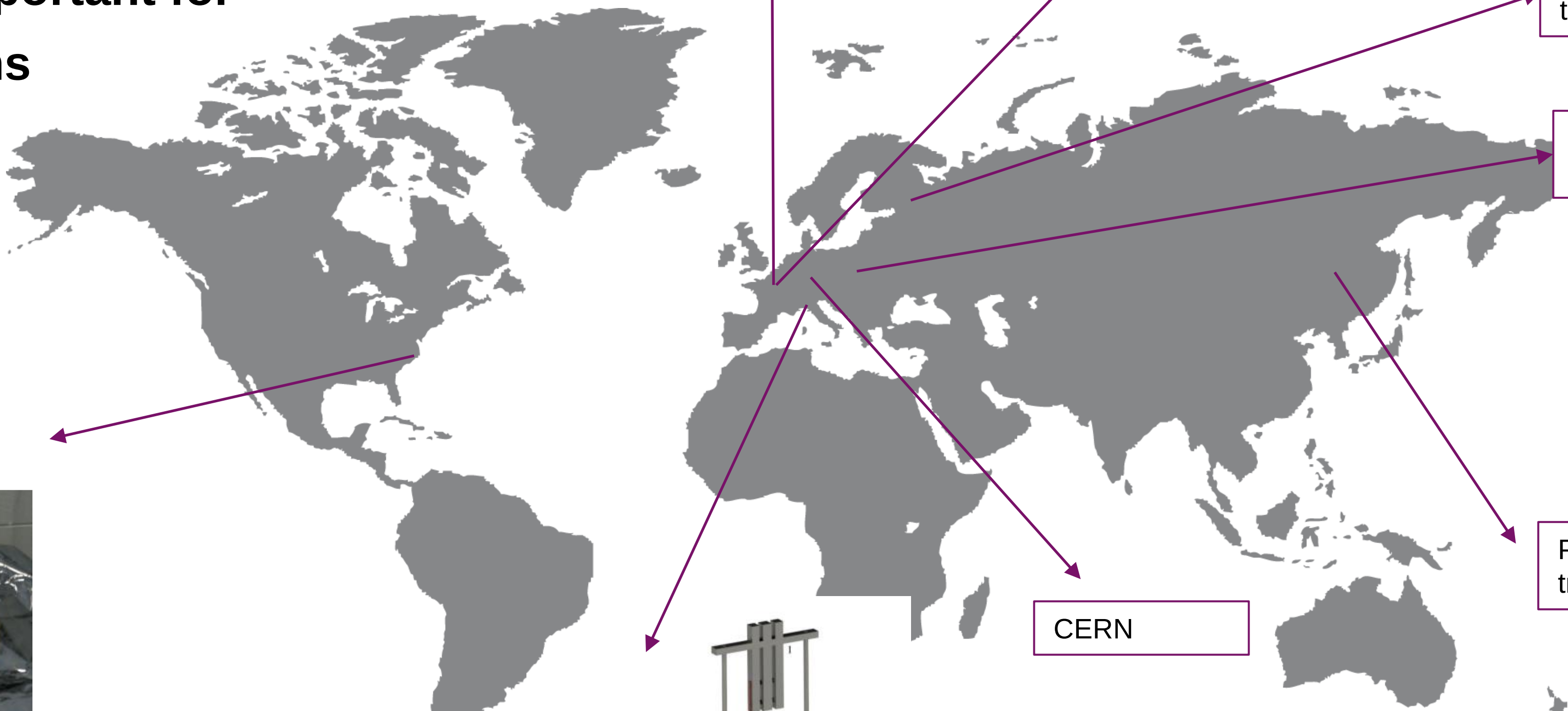
BARC Mumbai:
Spray coating, MS
Nb, Samples



- **Samples => 1^{rst} prototypes: 1^{rst} trials in 2023-2024**

4- SUBSTRATE DEVELOPMENT/ PREPARATION (COPPER)

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



IJCLab metallographic polishing

CEA ALD interlayers

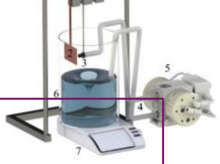
RTU Riga Laser treatment

HZDR Flash lamp Annealing

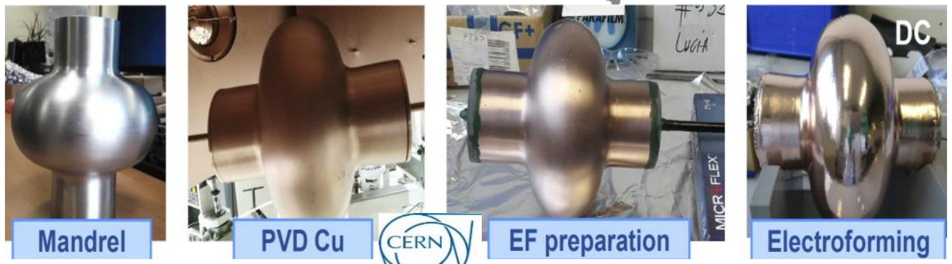
Jlab and coll:

Peking U. Laser treatment

CERN

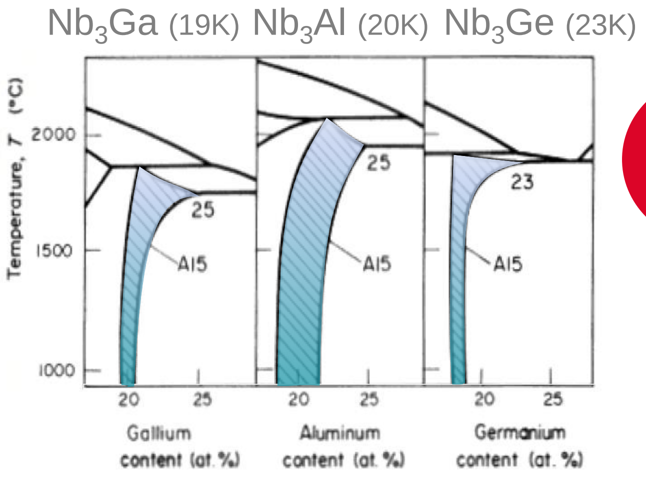


INFN
Spinning
Plasma
electropolishing

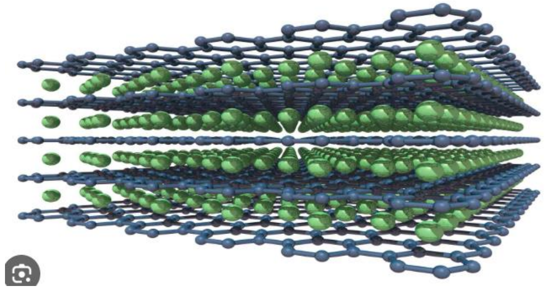


2-HIGHER T_C MATERIAL: NbN, Nb_3Sn (A15), MgB_2

- **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



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.
- **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**

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

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

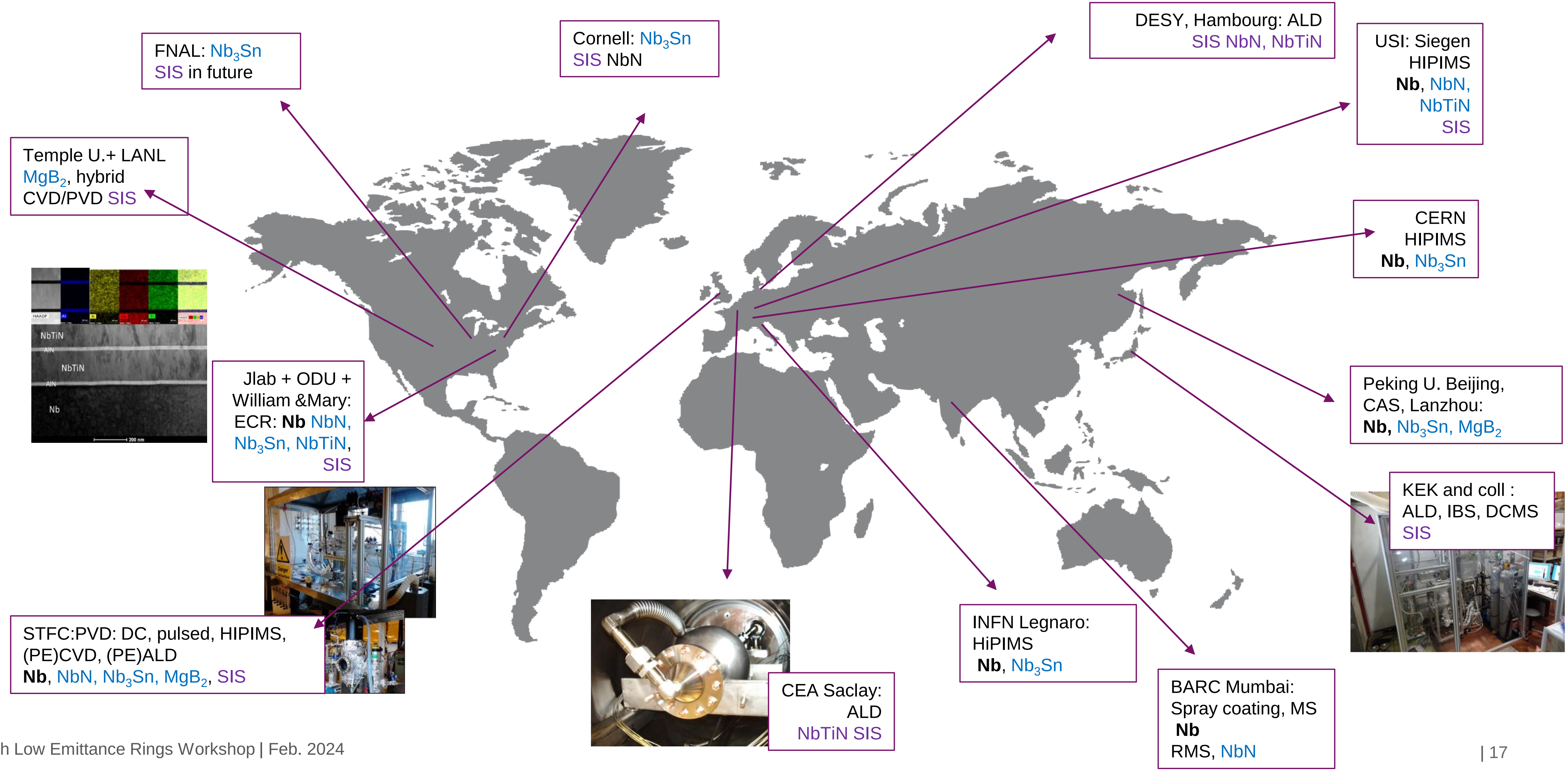
~ 50 k€/ year and /partners

Expertise exist in Europe

But is dispersed among the vast parameter 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

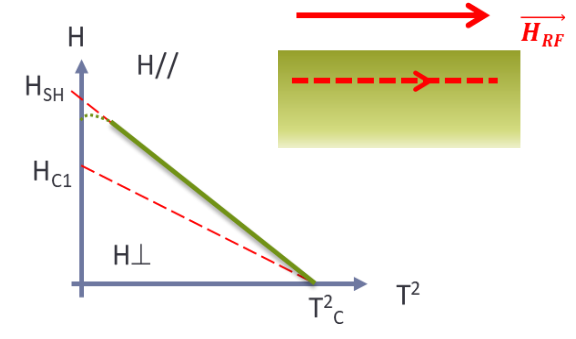
CEA Saclay:
ALD
NbTiN SIS

INFN Legnaro:
HiPIMS
Nb, Nb_3Sn

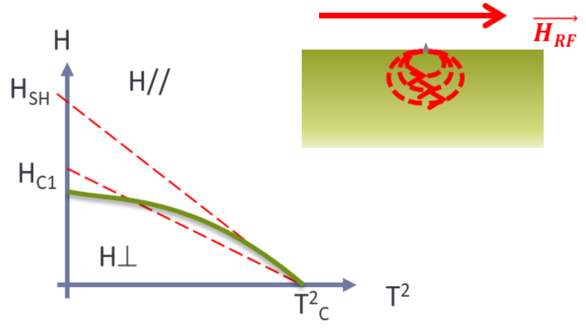
BARC Mumbai:
Spray coating, MS
Nb
RMS, NbN

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

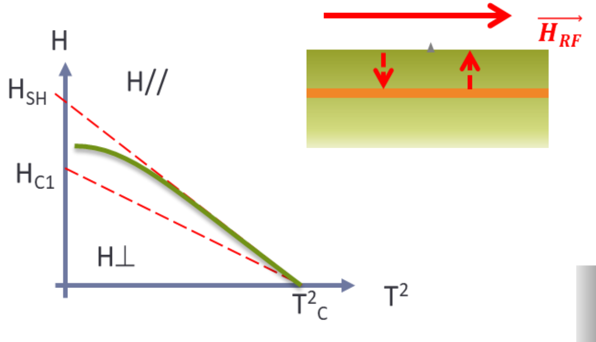
For the recall SRF cavity must operate in Meissner state ! No flux line please !



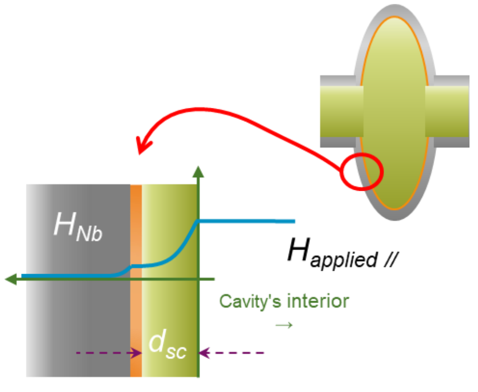
🟩 Ideal (w/o defect)



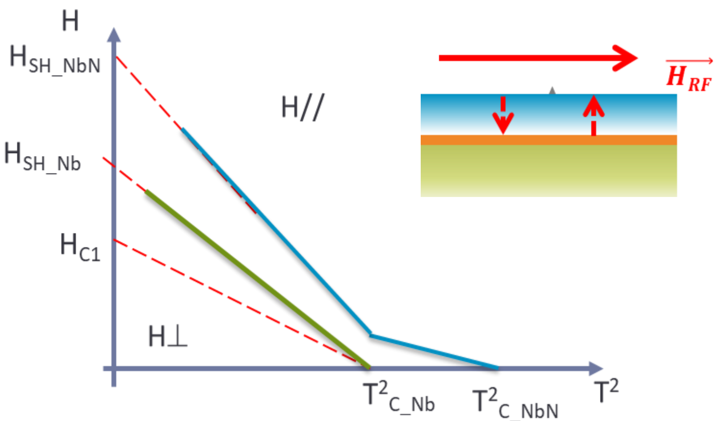
🟩 Real world
(∃ defects on surface)



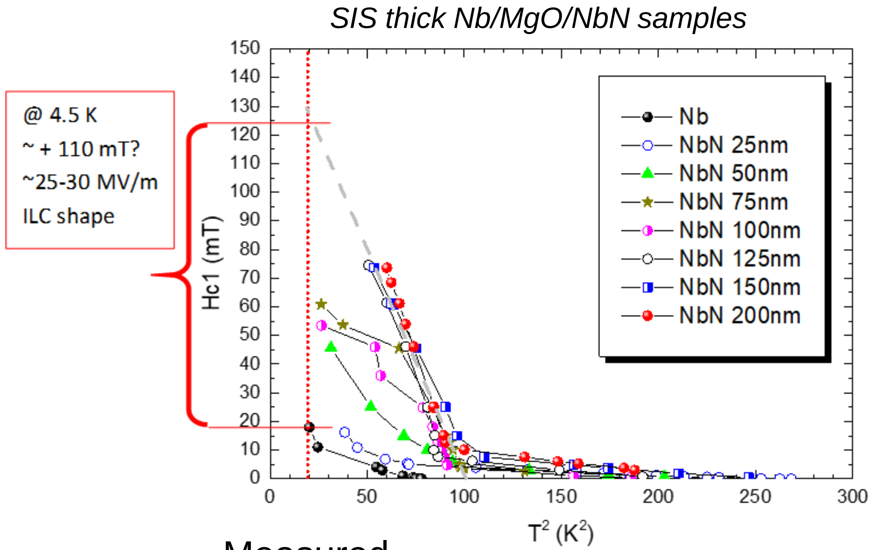
🟩 Real world
+ dielectric nm layer



S-I-S

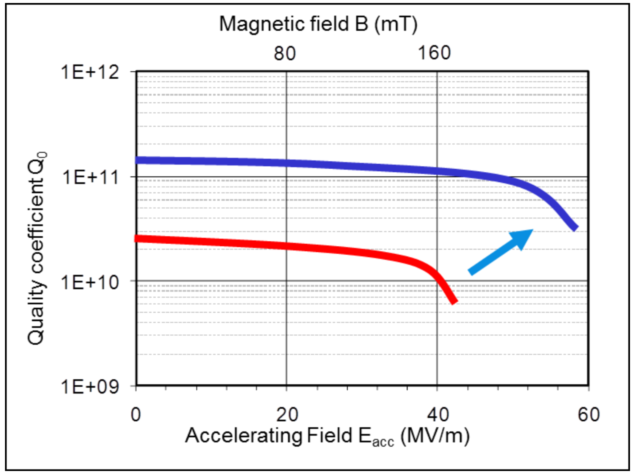


🟩 Dielectric barrier
+ SC w. higher T_C



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

Measured

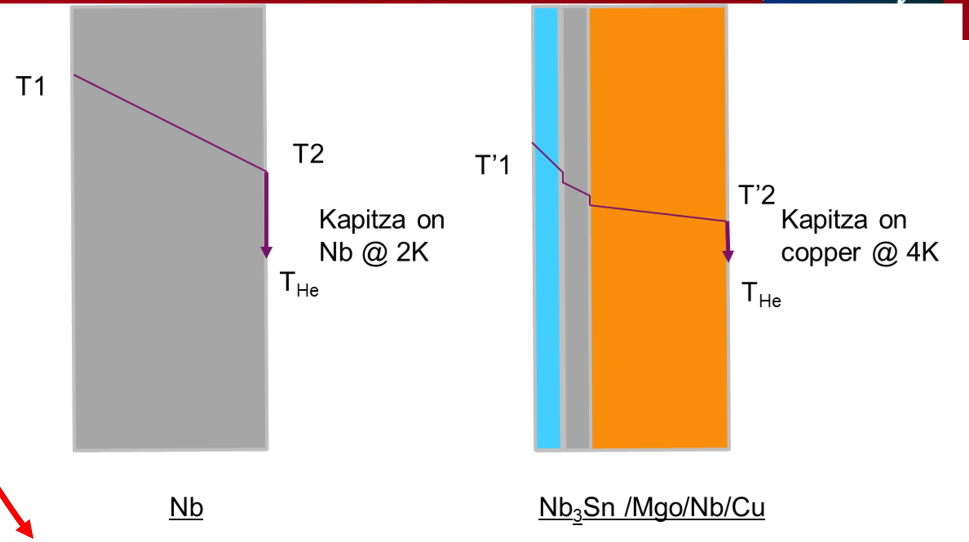


Expected

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



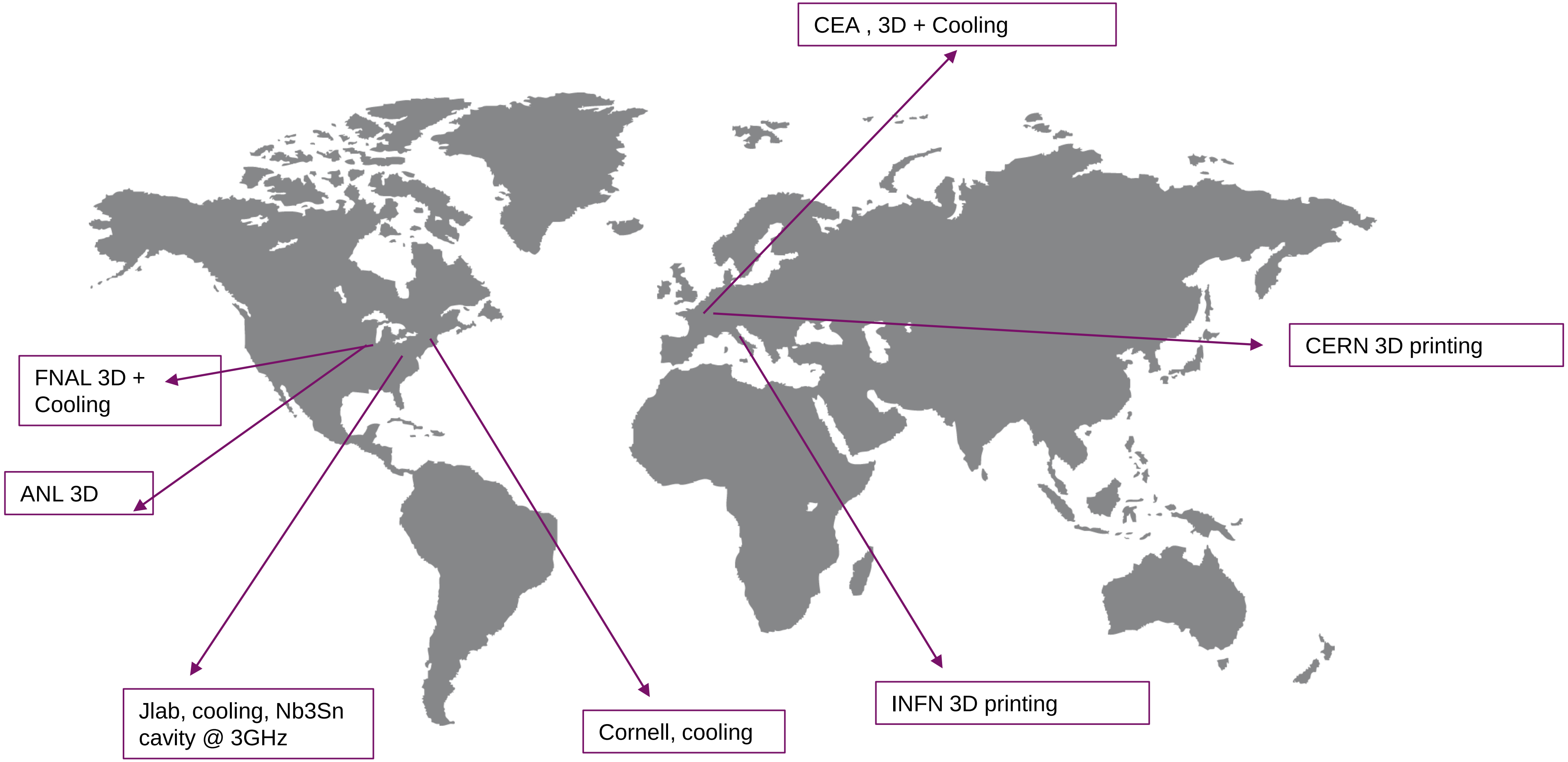
Need to develop our contacts with cryogenists

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 PRINTING



CEA , 3D + Cooling

CERN 3D printing

FNAL 3D +
Cooling

ANL 3D

Jlab, cooling, Nb3Sn
cavity @ 3GHz

Cornell, cooling

INFN 3D printing

6. CHARACTERIZATION

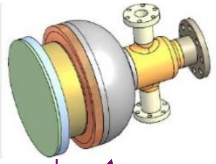
What is necessary

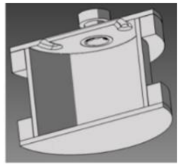
- **Material characterization (microcopy, X-rays, analysis…)**
  - Local infrastructures + collaboration with academic institutes
- **Superconducting properties**
  - Local infrastructures + collaboration with academic institutes (DC magnetometry, Tc, RRR)
    - Including novel techniques: 3rd harmonics, 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

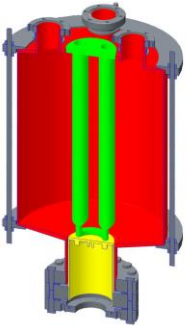
Cornell
TE011 6 GHz
Mushroom 4,78 GHz



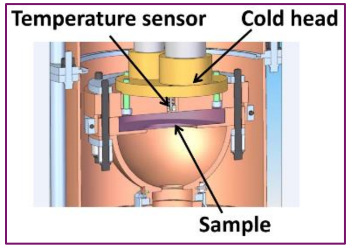


DESY QWR

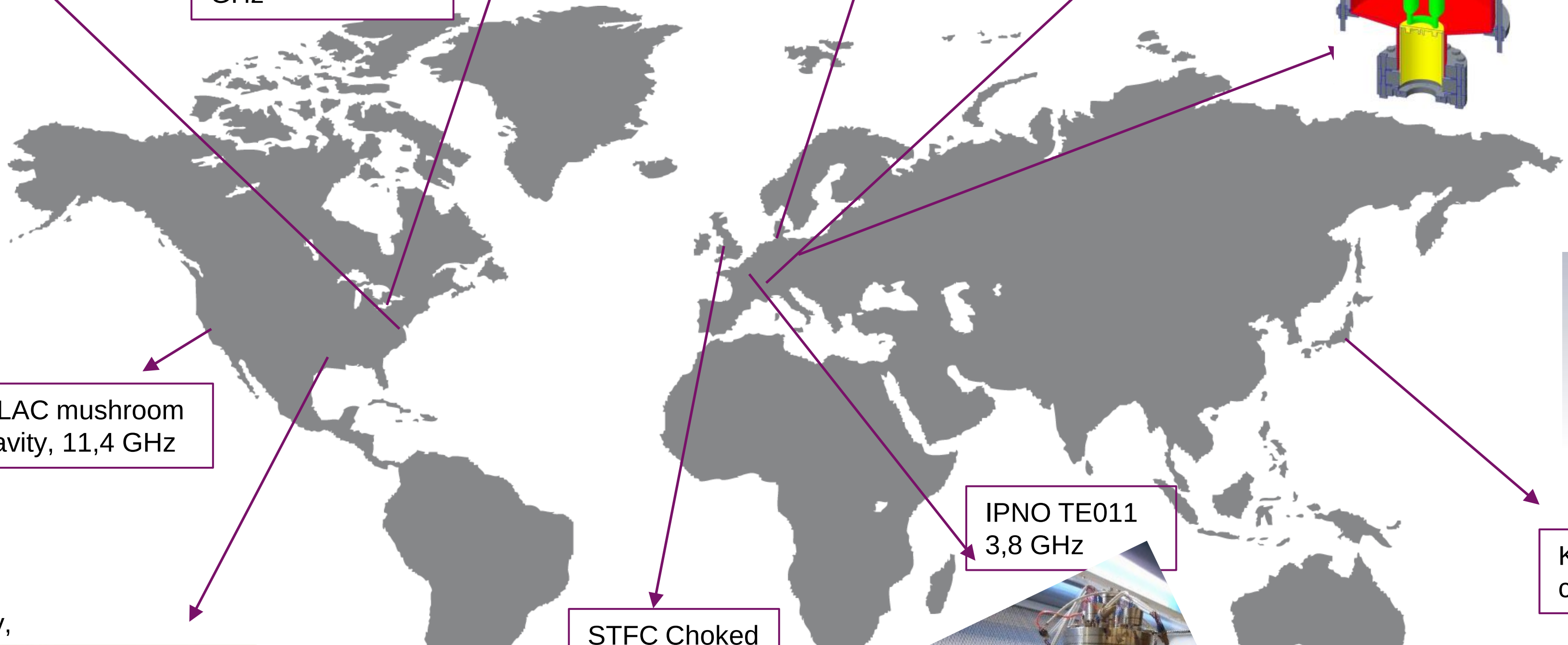
CERN QWR cavity, 400 Mhz (-> 1,2 GHz)

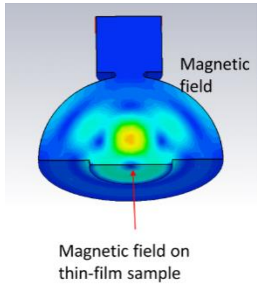


HZB QWR cavity, 433 Mhz (-> 1,3 GHz)



SLAC mushroom cavity, 11,4 GHz

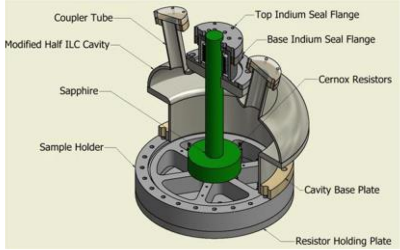




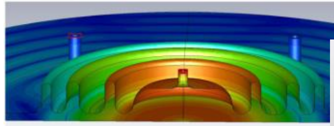
KEK mushroom cavity, 3,9 GHz

IPNO TE011
3,8 GHz

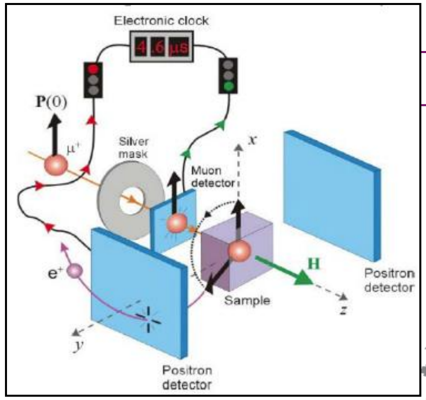
TAMU + Jlab
mushroom SIC cavity,
1,8 GHz

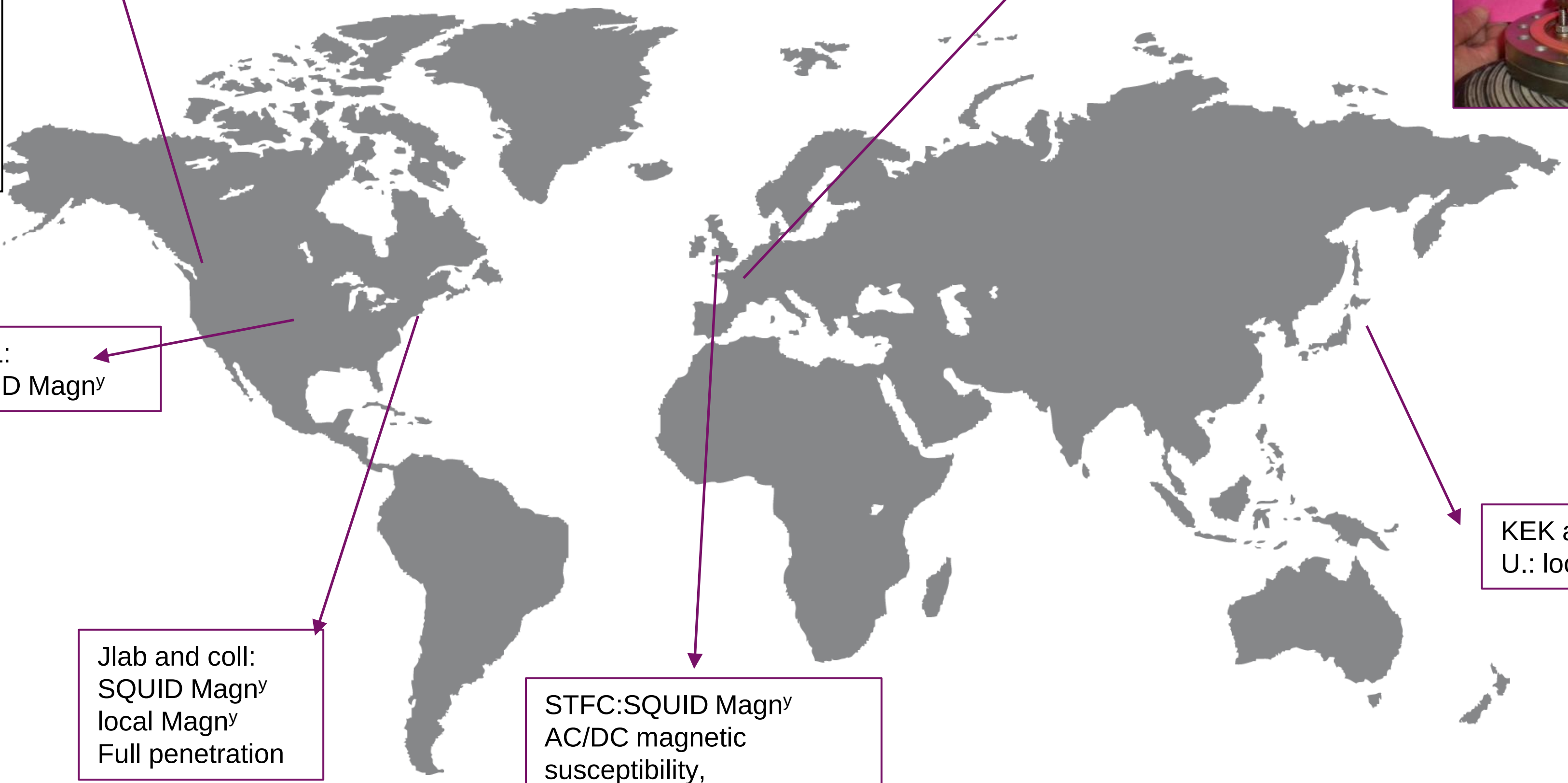


STFC Choked resonator
7,8 GHz



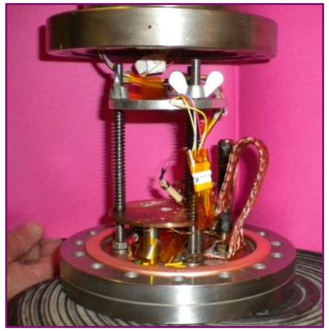
MATERIAL CHARACTERIZATION: SUPERCONDUCTIVITY





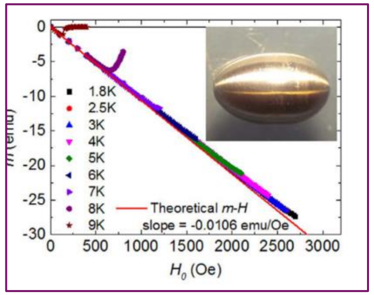
Triumf µ-SR

CEA Saclay:
Tunneling microscopy
Local Magnetometry



LANL:
SQUID Magn^{y}

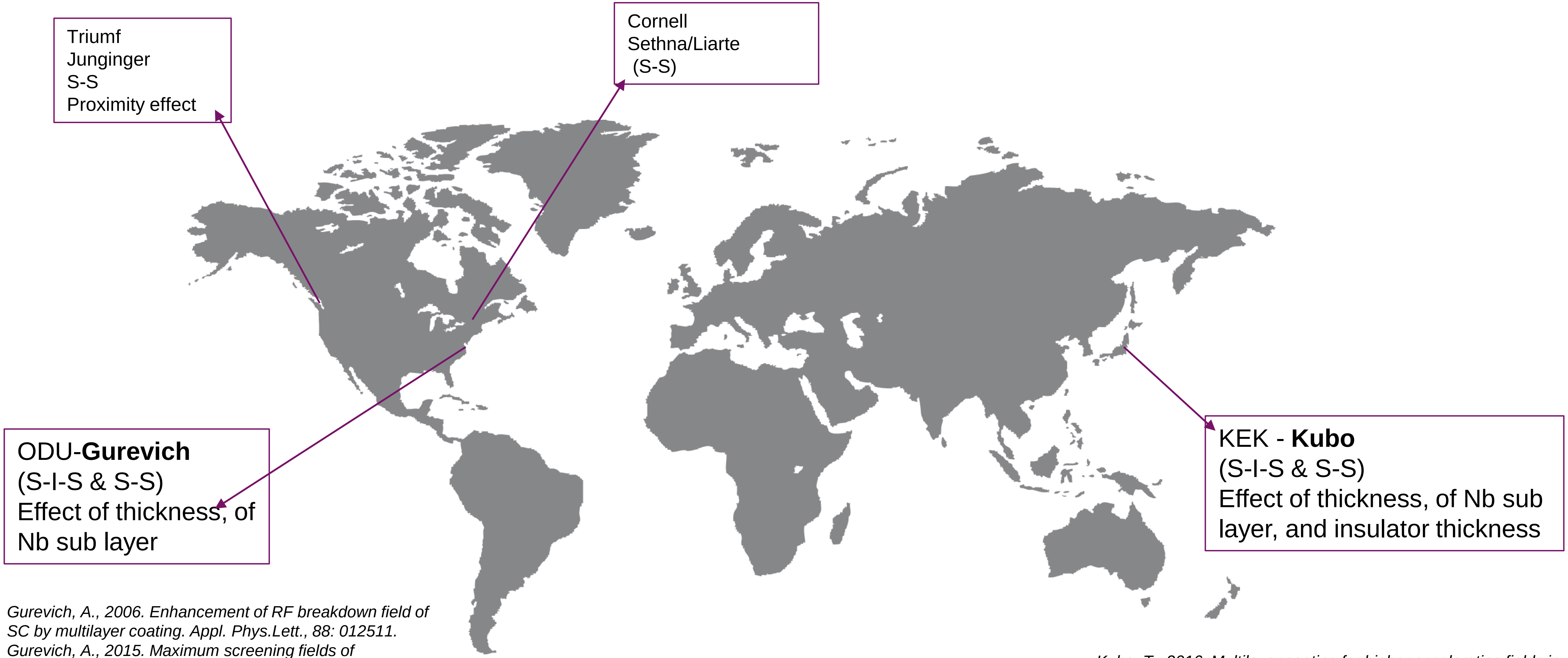
KEK and Kyoto U.: local Magn^{y}



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? (MOSTLY IN EUROPE)

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 ?

CONCLUSION

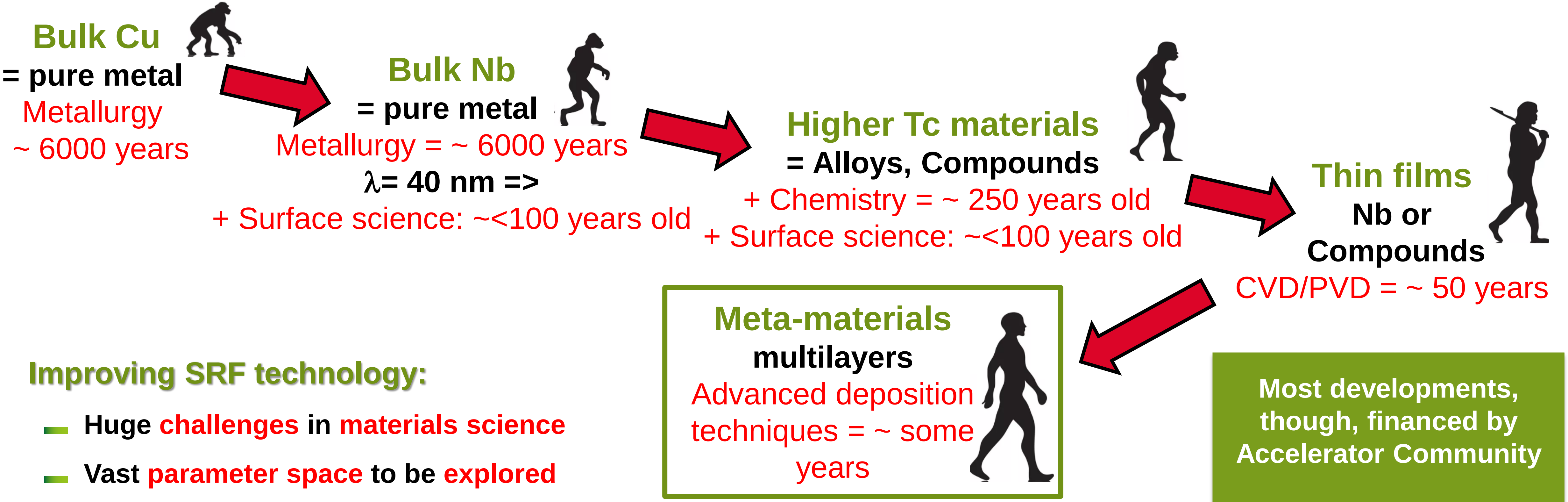
Several M€ potential savings (capital and operating) w. thin film cavities working @ 4,5 K

- **Expertise exist in everywhere in the world, strong collaborative environment**
- **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!!!

SPARES

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**

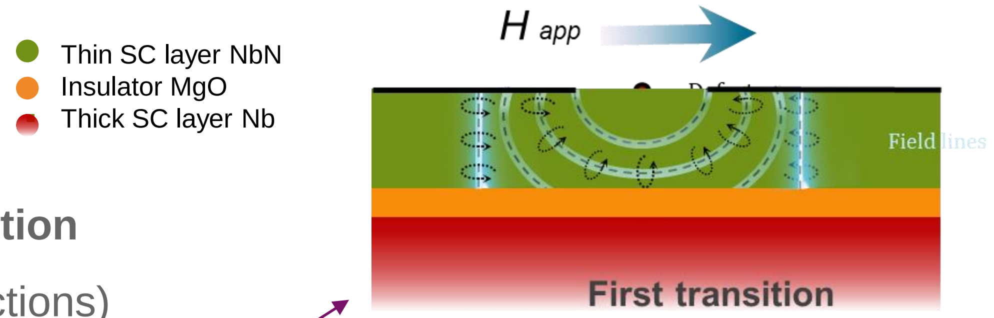
Most developments, though, financed by Accelerator Community

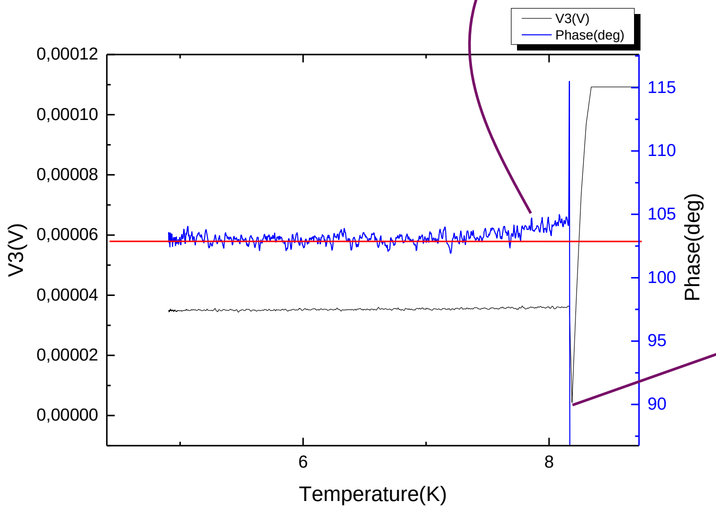
Not enough (compared to e.g. magnet history)

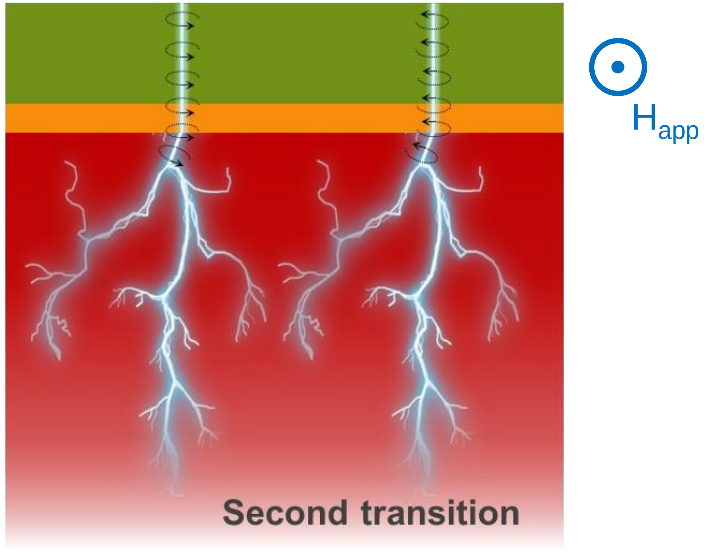
Recall: SC materials optimized for magnet = not adequate for SRF !

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

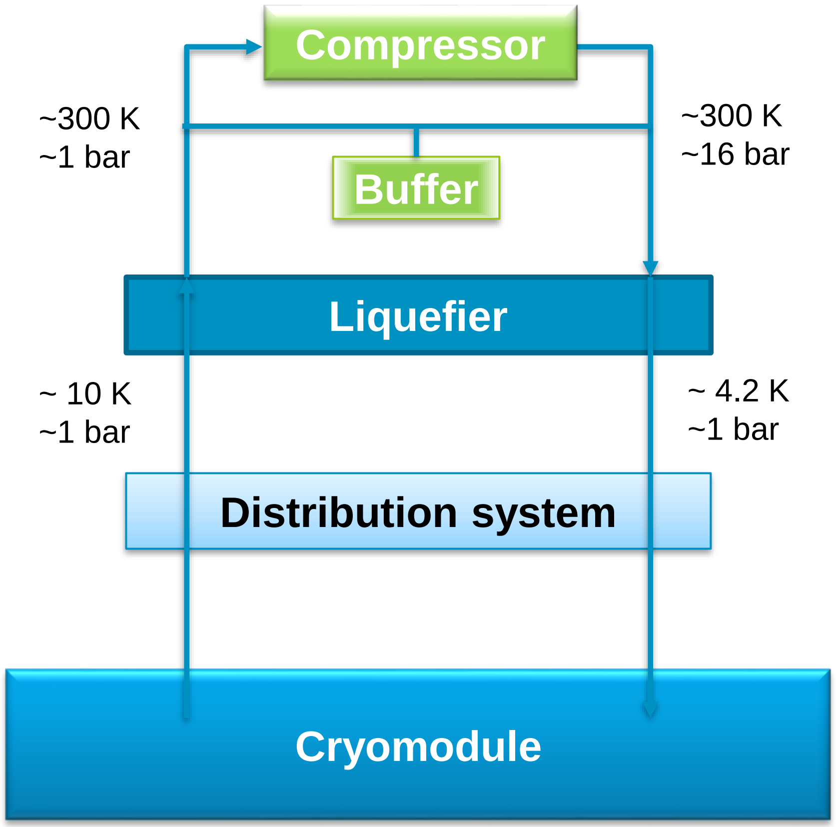






CRYOGENIC SYSTEMS: WORKING @ 4.5 K INSTEAD OF 2 K

4.5 K



Compressor

~300 K
~1 bar

Buffer

~300 K
~16 bar

Liquefier

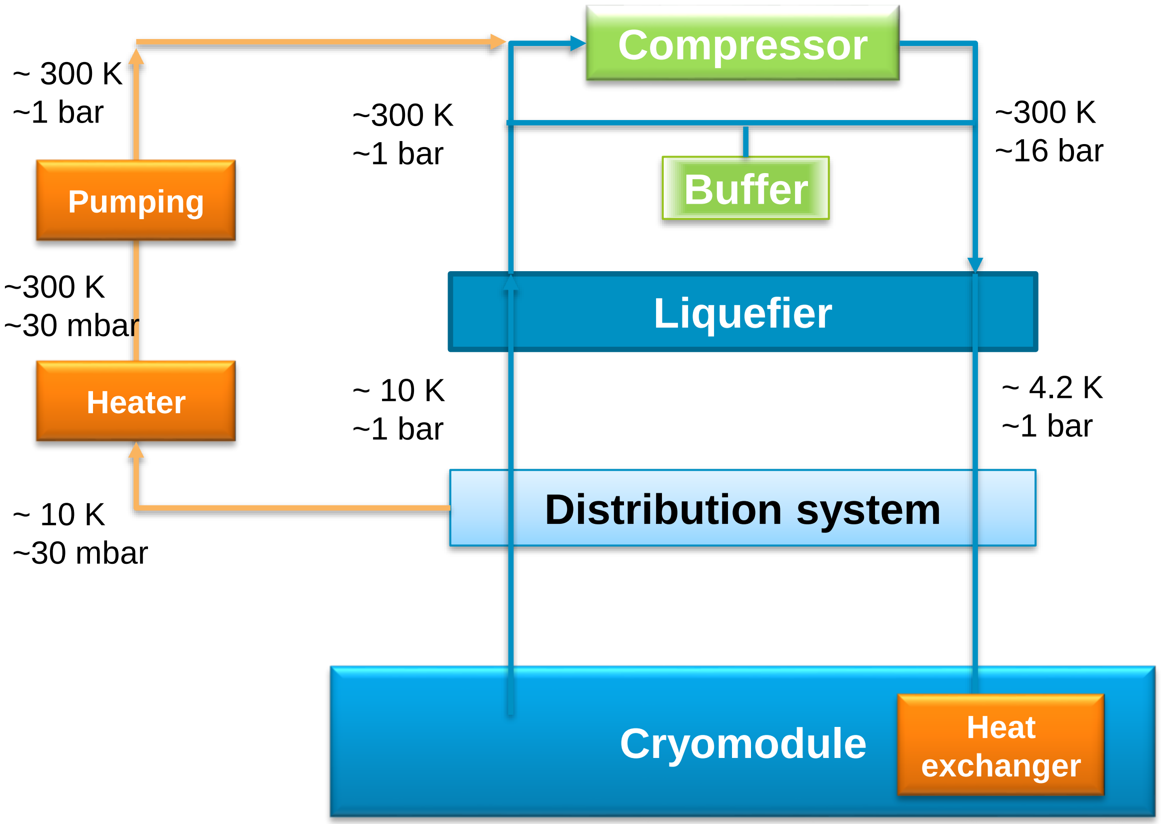
~ 10 K
~1 bar

~ 4.2 K
~1 bar

Distribution system

Cryomodule

2 K



~ 300 K
~1 bar

Compressor

Pumping

~300 K
~1 bar

Buffer

~300 K
~16 bar

~300 K
~30 mbar

Liquefier

Heater

~ 10 K
~1 bar

~ 4.2 K
~1 bar

~ 10 K
~30 mbar

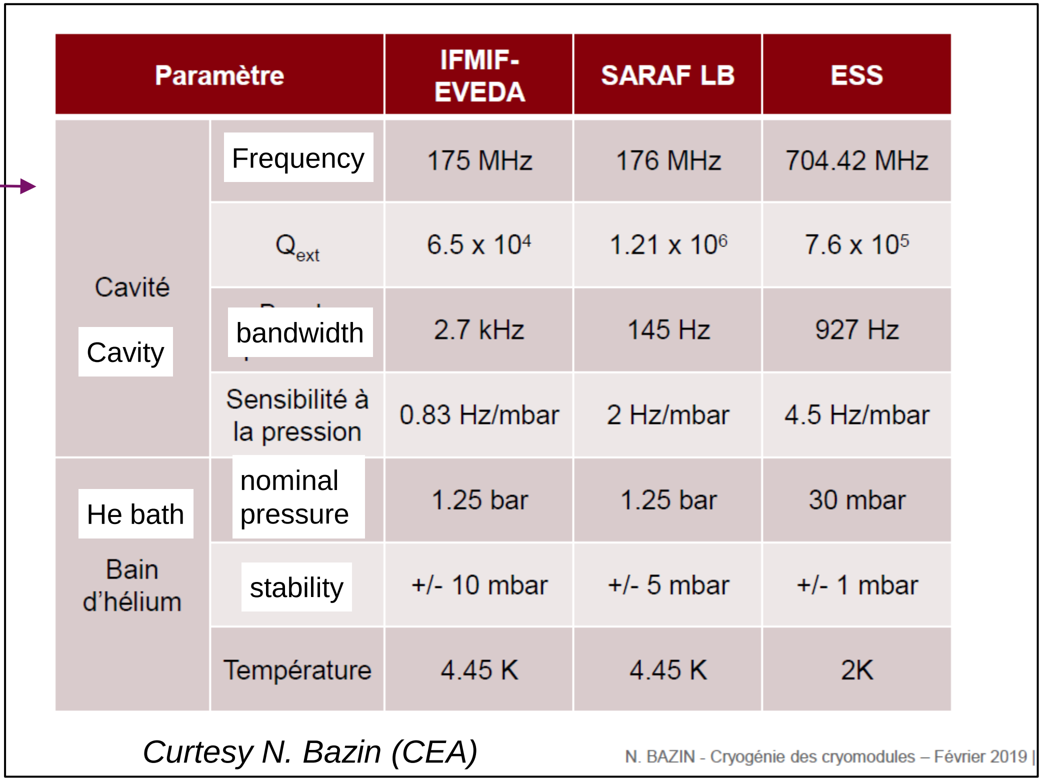
Distribution system

Cryomodule

Heat exchanger

LET’S KEEP OUR HEAD COOL: 4.5 K CHALLENGES

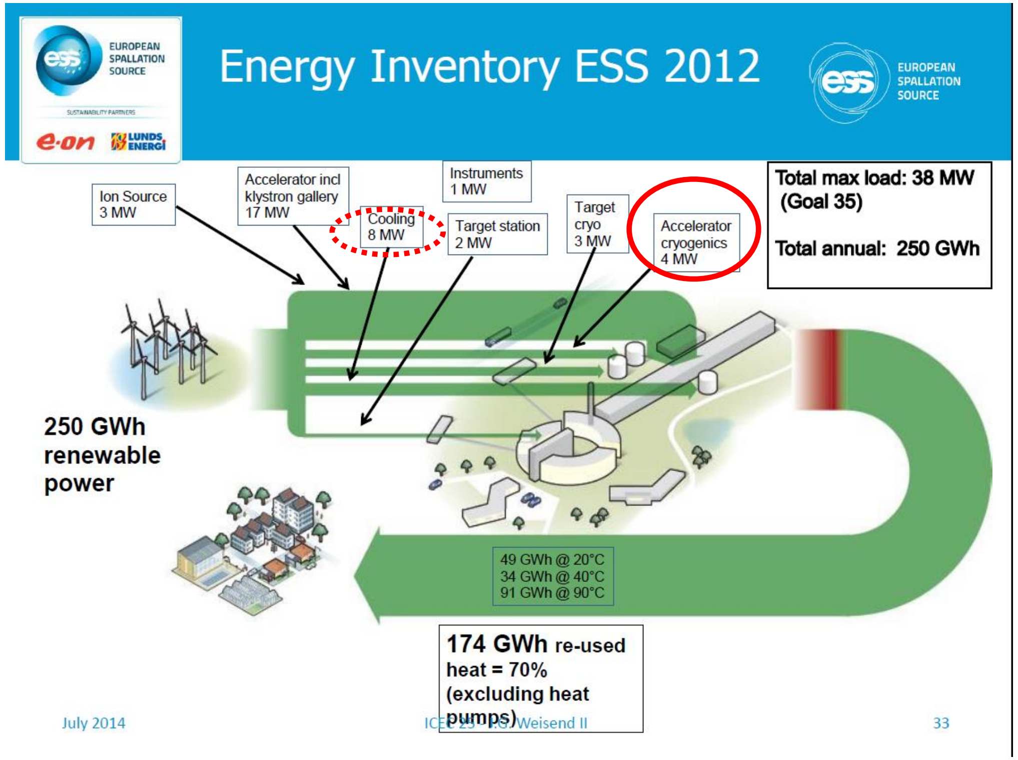
- **Sensitivity to pressure**
  - Pressure stability is lower @ 4.5 K
  - Some cavities are very sensitive to pressure variation
  - **RF design** needs to be reconsidered ?



Paramètre		IFMIF-EVEDA	SARAF LB	ESS
Cavité Cavity	Frequency	175 MHz	176 MHz	704.42 MHz
	Q_{ext}	6.5 x 10^4	1.21 x 10^6	7.6 x 10^5
	bandwidth	2.7 kHz	145 Hz	927 Hz
	Sensibilité à la pression	0.83 Hz/mbar	2 Hz/mbar	4.5 Hz/mbar
He bath Bain d’hélium	nominal pressure	1.25 bar	1.25 bar	30 mbar
	stability	+/- 10 mbar	+/- 5 mbar	+/- 1 mbar
	Température	4.45 K	4.45 K	2K

Curtesy N. Bazin (CEA)

N. BAZIN - Cryogénie des cryomodules – Février 2019 |



Energy Inventory ESS 2012

Total max load: 38 MW (Goal 35)

Total annual: 250 GWh

174 GWh re-used heat = 70% (excluding heat pumps)

July 2014 ICEC 25 - J.G. Weisend II 33

https://indico.cern.ch/event/244641/contributions/1563339/attachments/418312/580973/O0-5_ICEC_2014_ESS_Cryogenics_Talk_Rev2.pdf

- **Power consumed by cavities keeps small**
  - Cryogenics: 10-15 % of the total load
  - Main losses are in RF systems and beam losses
  - A lot of work left for RF guys ☺
  - **Anyhow, every penny counts** (some M€/year)