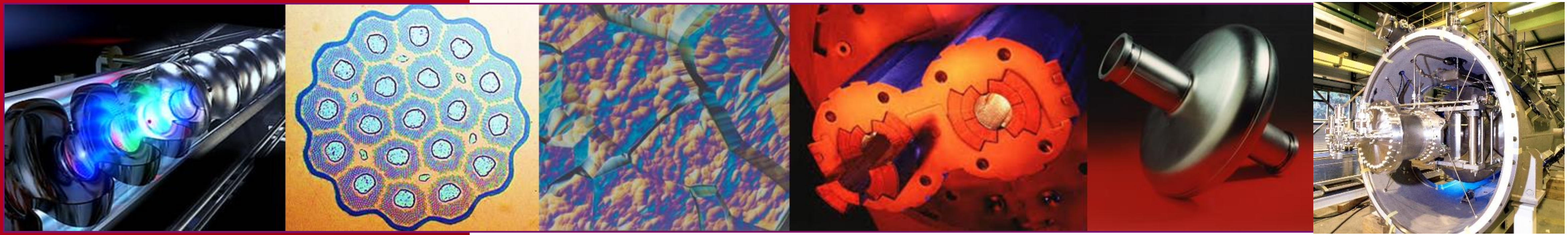
DE LA RECHERCHE À L'INDUSTRIE

ACCELERATOR R&D ROADMAP - RF PANEL -THIN FILMS



C. Z. ANTOINE

www.cea.fr

ACCELERATOR R&D ROADMAP - RF PANEL -THIN FILMS

1rst shot

- 2020-2021
- Yellow report (which is green…)

The goal of the roadmap is to document the collective view of the field on the next steps for the R&D programme, and to provide the evidence base to support subsequent decisions on prioritisation, resourcing and implementation

Implementation survey (2023-2024): checking how the roadmap is implemented

Identified axis of the roadmap

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

Other projects with similar strategy

- **Basic R&D in numerous SRF labs**
- **IFAST WP 9 thin films => 2025** (*Europe*)
  - Task 9.1: strategy
  - All European partners except CERN and DESY
  - CERN, DESY, and JALB invited to participate in the strategy meetings
- **Snow mass White Papers => next 10Y** (*USA*)
  - Last edition: 2021
  - 1 white paper on thin films, (AF7 Accelerator Technology R&D)
  - Ifast participants participated to the writing
- **TF SRF Workshops 2022 and 2024** (*Internat!*)
- **TTC-Meetings-thin films: ~ 2-3/year**
  - Bringing the community together

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 testing infrastructures)
- **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 !**

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

2. HIGHER T_C MATERIAL AND 3. SIS STRUCTURES

- **Cavity (substrate) fabrication**
  - Same as previously
- **Surface preparation :**
  - Same as previously.
  - Possibly intermediate Nb “thick film” as interlayer (cf axe #1)

Axis # 4

Hopefully first prototypes for the end of IFAST (Apr. 2025)

- **Deposition**

	CEA	CERN	INFN	STFC	U.Hamburg	U.Siegen	Cornell U	FNAL	JLab	Temple U	KEK	Peking U+ CAS	BARC
technique	ALD	HiPIMS	HiPIMS	HiPIMS DC/pulsed MS	ALD	HiPIMS	Thermal Electro-deposition	Thermal	ECR (NbN) Thermal (Nb_3Sn)	Hybrid CVD/PVD	ALD DCMS	Several methods	Spray coating
NbN-NbTiN	X			X		X			X		X	X	X
Nb_3Sn		X	X	X			X	X	X			X	
V_3Si				X									
MgB_2				X						X		X	
SIS	X			X		X	X (NbN)	(X)	X		X	(X)	

- **Post treatment**
  - Flash annealing (HZDR), laser treatment (RTU)
  - Capping layer (*CEA*) diffusion barrier, SEY modification….

2. HIGHER T_C MATERIAL AND 3. SIS STRUCTURES

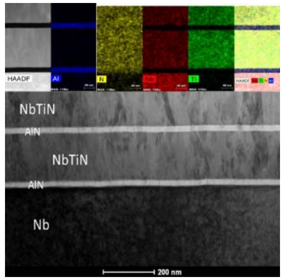
FNAL: Nb_3Sn
SIS in future

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

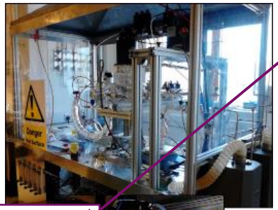


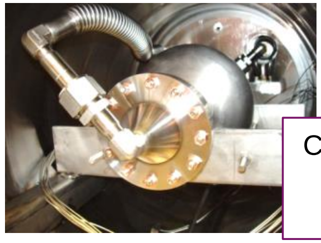
Jlab + ODU + William &Mary:
ECR: **Nb** NbN, NbTiN, SIS

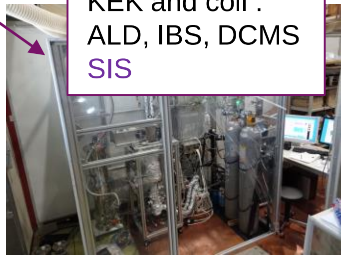
CERN
HIPIMS
Nb, Nb_3Sn

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

KEK and coll :
ALD, IBS, DCMS
SIS





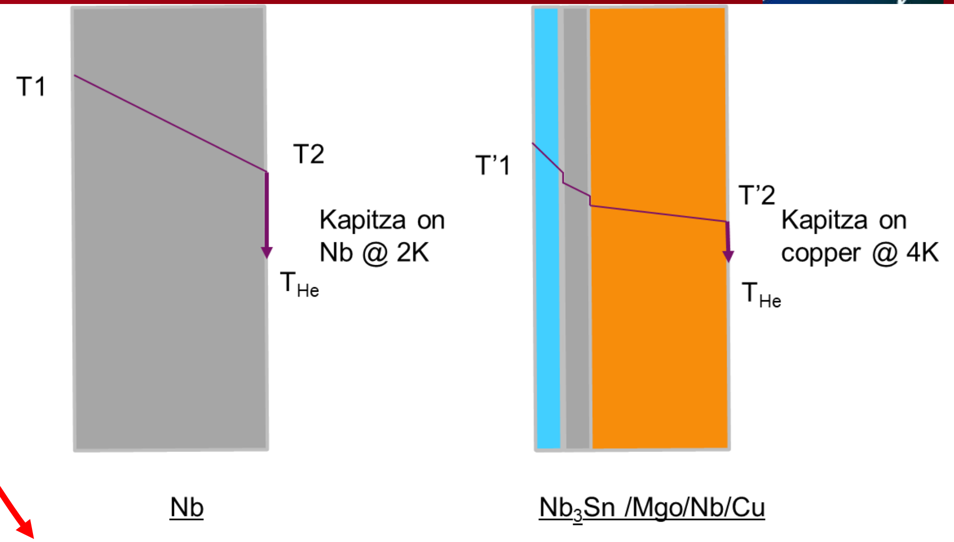


STFC:PVD: DC, pulsed, HIPIMS, (PE)CVD, (PE)ALD
Nb, NbN, Nb_3Sn, MgB_2, SIS

CEA Saclay:
ALD
NbTiN SIS

INFN Legnaro:
HiPIMS
Nb, Nb_3Sn

BARC Mumbai:
Spray coating, MS
Nb
RMS, NbN



What needs to be explored ?

- **Working on copper**
  - Thermocurrents (M-M' interfaces)
  - Metal-Metal thermal resistance ?
  - Copper-Helium thermal 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

6. INFRASTRUCTURES AND MANPOWER

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 clean room, RF stands (running testing for machine projects vs R&D)
  - Sample cavities, prototypes @ 6 GHz, 3 GHz, 1.3 GHz… (substrate production cycle)
- **Duplicate existing infrastructure? –** Not overlap, complement to existing, insufficient, facilities
- **Who can pay for that ?**

IN SUMMARY:

Thin Film SRF — *Milestones from the roadmap and delays*	2022	2023	2024	2025	2026
	★	1^{rst} prototypes	★	yield > 50%	
Continue R&D niobium on copper—construction cost saving and securing supply:					
Reach bulk niobium performances on 1.3–0.4 GHz elliptical and various cavity shapes (WOW, SWELL).					
scale up process to multicellular cavities (1.3–0.6 GHz)					
Intensify R&D of new superconductors on Cu—4.2 K operational cost saving					
A15 (Nb3Sn, V3Si, etc.): reach same performance as Nb3Sn on Nb at 4.2 K on several cavity geometry (1.3–6 GHz).					
MgB2: feasibility (critical temperature > 30 K) on 1.3 GHz cavity.		only work on samples			
Study the influence of mechanical deformations and induced strain (~0.1 %) of cavities on the RF performances of A15 and MgB2 alloys.				only Nb_3Sn	
i. A15: reach same performances at 4.2K as bulk Nb at 2 K, scale to other frequencies (elliptical) and investigate the potential for multicell cavities.					
ii. MgB2: reach same performances at 4.2K as bulk Nb at 2 K.					
Pursue multilayers—push for high gradient					
Demonstrate increased acceleration on 1.3 GHz bulk Nb and thin-film Nb/Cu 1.3 GHz elliptical cavity					
scale up to various cavity shapes and multicell elliptical cavities		not possible without additionnal funds			
Intensify Cu cavity production and surface preparation					
Seamless elliptical Cu substrates (mechanical or electro-deposited) starting at 1300 MHz down to 400 MHz					
Optimise air stable chemistries (EP-BCP/without liquid waste, heat treatment, passivation layers, etc.) for Cu surface preparation					
scale up processes to multicell cavities (1.3 GHz)					
Develop 3D printing and innovative cooling techniques.					
mechanical re?sponse (similar to Nb at 4.2 K).					
Demonstrate substrate (cavities) surface roughness					
Demonstrate conduction cooled cavities with selected and optimised innovative heat links and a cryocooler					
i. Demonstrate bulk Nb performances with thin Nb film on 3D printed/electro-deposited cavity at 4.2 K.		not possible until task 1 has succeed => after 2025			
ii. Demonstrate bulk Nb performances with new superconductors (A15, MgB2) film on 3D printed/electro-deposited cavity at 4.2 K.		not possible until task 2 has succeed => after 2025			
iii. Develop proper substrate multicell cavities.	not possible until task i and ii have succeed => after 2025				
Infrastructures and manpower—high-throughput testing					
Dedicated building with thin-film specific state-of-the-art infrastructures (clean rooms, chemistry, rinsing/washing, assembly).				after 2025	
etc.).					
Reinforced International Student and collaboration effort program.		not possible without additionnal fund			
High-throughput RF testing facility to establish repeatable and reliable performance needed in preparation of series production.	Need for manpower and budget (He!) to make them producing results				

CONCLUSION

- **Expertise and good collaboration already exist in Europe**
  - International contacts also exist
  - CERN is officially outside the main loops (!!!???) (albeit there are plenty of horizontal contacts)
- **There is little duplication**
  - Even labs working on the same topic are exploring different routes and/or exploring lab to lab variability
- **Thin films on copper are the only route to help cost savings**
  - Cheaper manufacturing
  - Higher operation temperature (operation costs lower by a factor 3)
  - Higher gradients : lower capital costs
- **Need for strong funding increase**
  - Unless the message goes to the top (government level), few chances to improve the present situation
  - "Official Roadmaps" will help.
- **Industry**
  - Not fully interested in the full technology yet: no business case visible in the near future
    - Industrial fabrication of Cu cavities already there
  - May change once prototypes tested => post IFAST proposals

IN BRIEF

- **We mostly know how to built post-IFAST proposals in an integrated project**
  - Certainly at the European level, including Hamburg U. and CERN
  - Already active collaboration with Jlab, KEK, …
  - We could also benefit by increasing contacts with China (they have a lot of resources and students compare to us, but they tend to start everything from scratch)
- **We must be addressing all the point and get a substantial increase in resources**
  - We need to get to several Funding sources/programs
  - We need some official support if we want to achieve the translation from R&D to "prototyping".

We are small teams, we need some administrative support

SPARES

DESIRED: TAILORED MATERIAL FOR RF CAVITIES

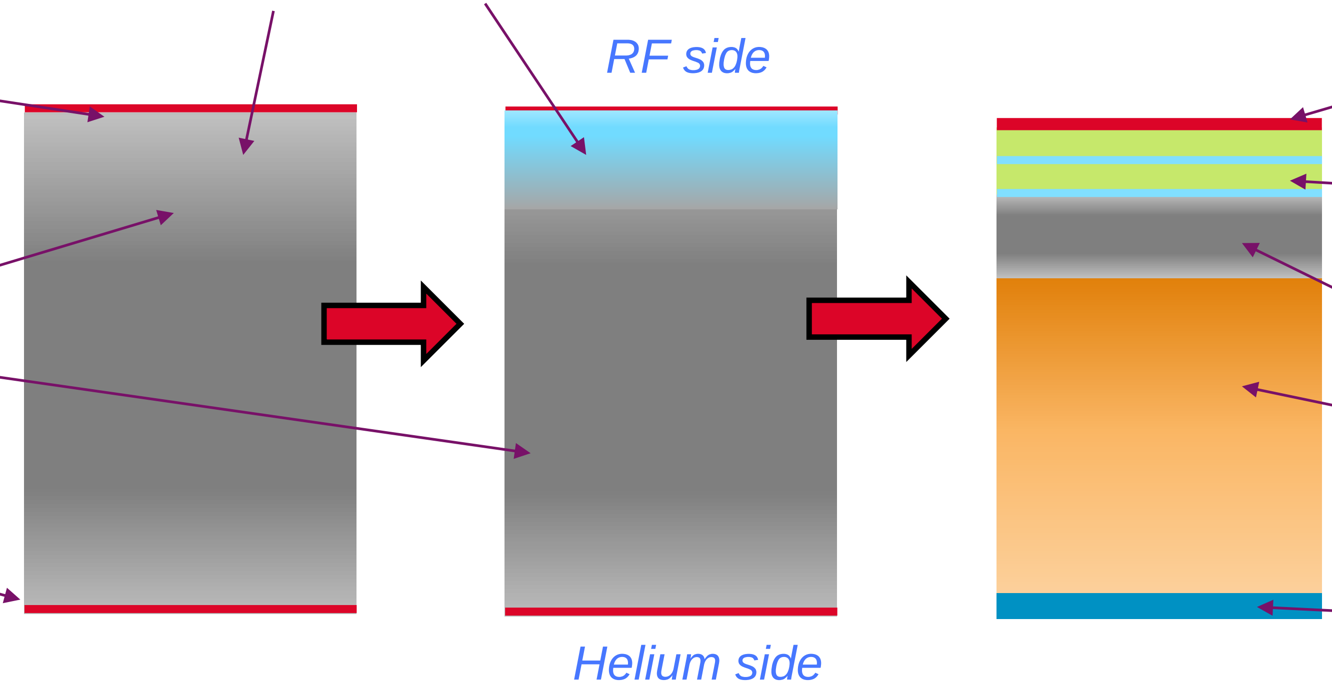
Today: bulk & doped Nb

Future ?

Native oxide
Unstable upon annealing

High purity Niobium
Optimized only for thermal conduction

Native oxide
Not optimized for thermal transfer



Protection, low secondary emission yield

High Tc SC
S-I-S multilayers

Niobium or…not

Structure, high thermal conductivity (Copper ?)

External layer, optimized for thermal transfer

At stakes : COST REDUCTION !!!

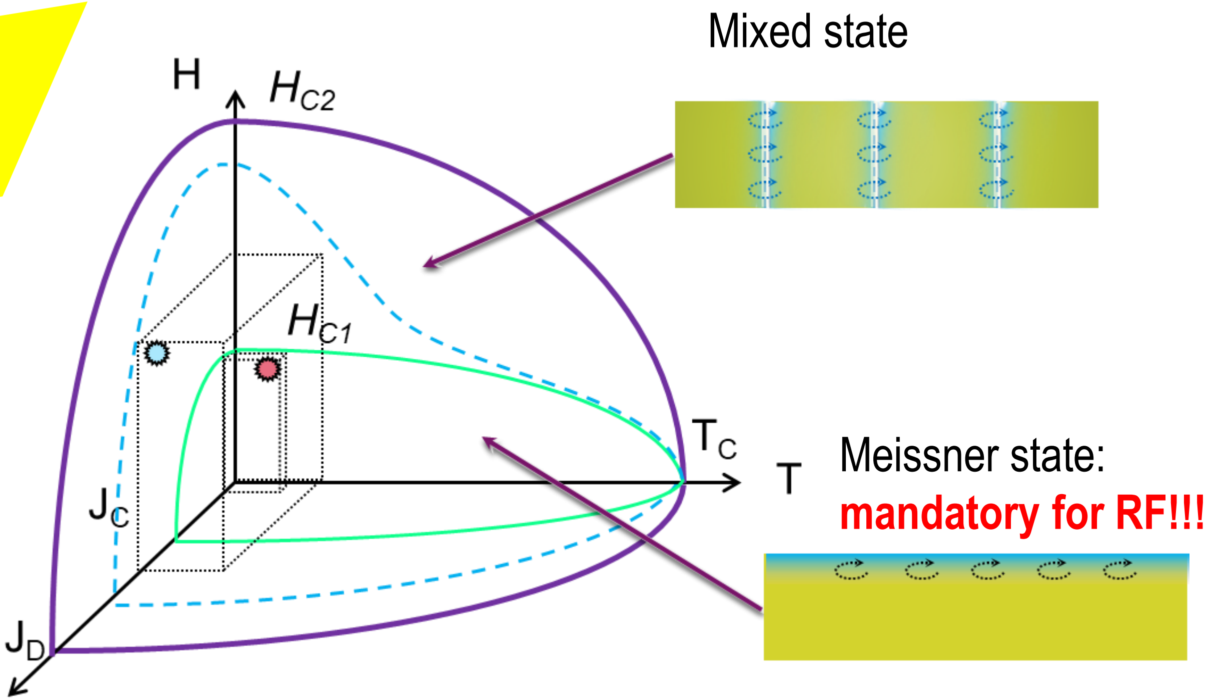
Cooling power (any application); can we go to cryocooling ?

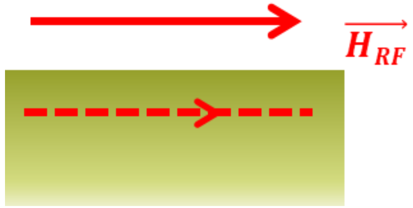
High accelerating fields => shorter machines ?

WHY SUPERCONDUCTIVITY ?

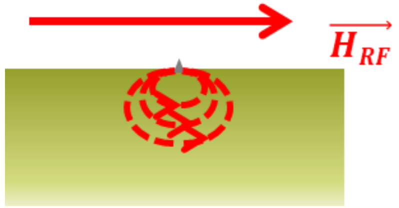
- **∃ thousands of SC**
- **In practice:**
  - ~ 10 are actually used
  - They are all type II
- **Applications…**
  - All applied SC are type II: i.e. low H_{C1} and high H_{C2} => all operate in mixed state…
  - EXCEPT Nb for RF application !!! (high H_{C1})
- **Niobium vs Copper**
  - Surface resistance **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





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



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

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 RF 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**

Most developments, though, financed by Accelerator Community

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