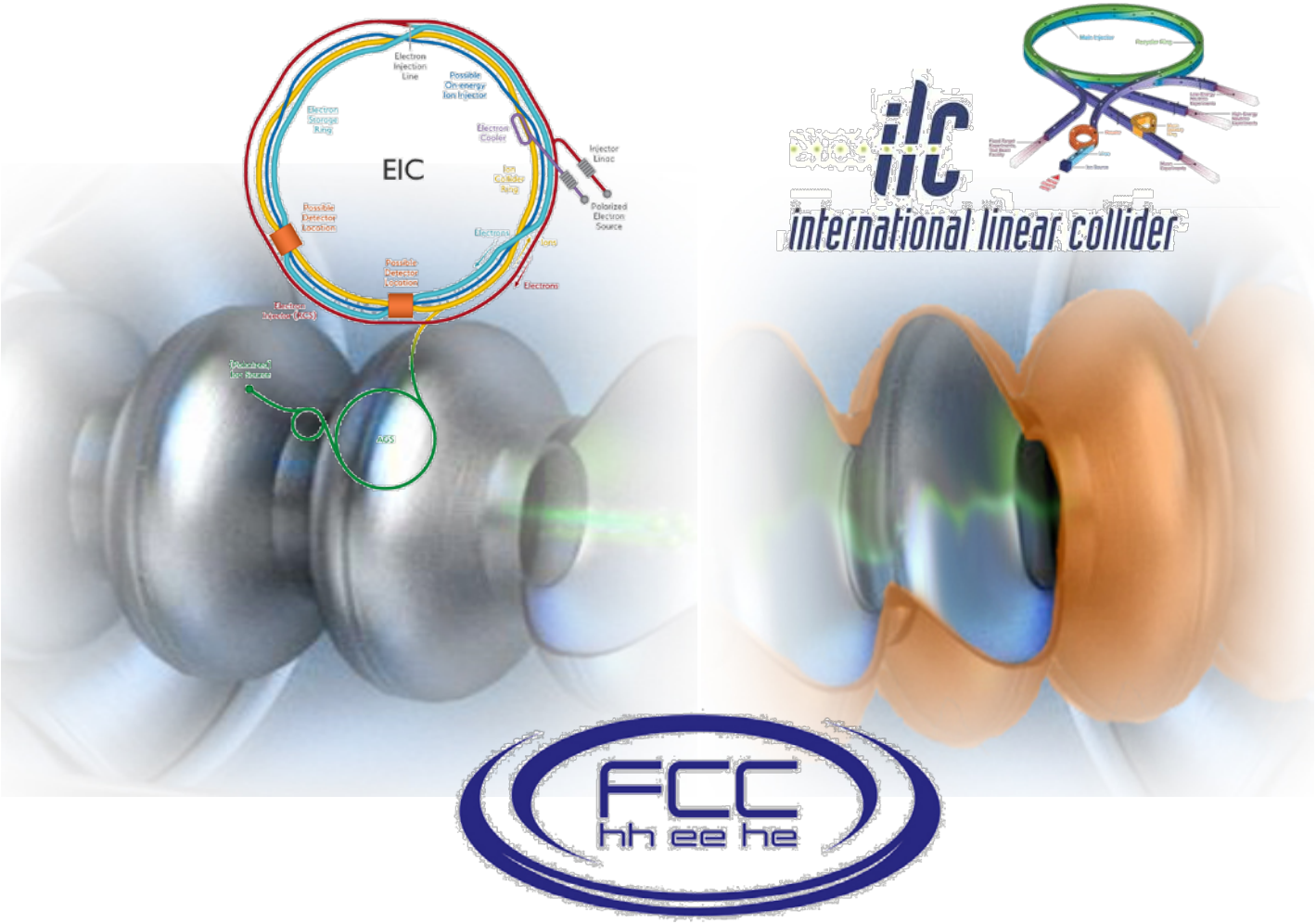
Next-Generation Superconducting RF Technology based on Advanced Thin Film Technologies and Innovative Materials for Accelerator Enhanced Performance & Energy Reach

Snowmass 2021

AF7: Accelerator Technology R&D

LOI - 205

C. Antoine, S. Anlage, J. Delayen, F. Gerigk, A. Gurevich, T. Junginger, S. Keckert, G. Keppel, J. Knobloch, T. Kubo, O. Kugeler , D. Manos, C. Pira, T. Proslier, U. Pudasaini, C.E. Reece, R.A. Rimmer, G.J. Rosaz, T. Saeki, A.-M. Valente-Feliciano, R. Vaglio, R. Valizadeh, W. Venturini Delsolaro, P. B. Welander, M. Wenskat



Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

Background

Superconducting RF Technology has been the building block for many high-energy physics accelerators, essentially based on bulk niobium (Nb). Over the past decades, the RF performance of bulk Nb cavities has continuously improved with material and surface developments (nitrogen surface doping, infusion…).

Long-term solutions for superconducting radio-frequency (SRF) surfaces further efficiency enhancement ?

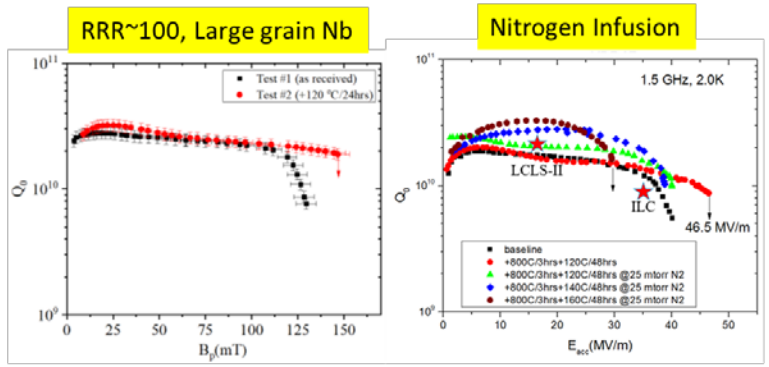
Methods and materials deliberately producing the sub-micron-thick critical surface layer in a controlled way.

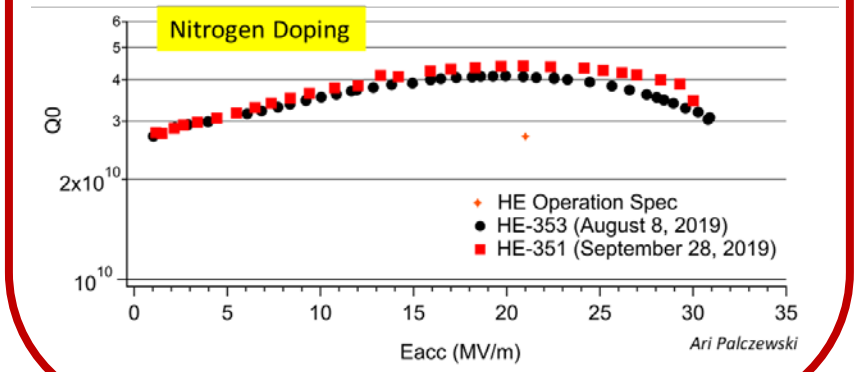
- Other forms of Nb and other superconducting materials to improve SRF cavity performance beyond the Nb sheet material intrinsic limits.
- Higher efficiency & quality control
- Fully engineered and truly application-tailored SRF surface strategies

dramatically reduce capital and operating costs for future accelerators
lower the cost-of-entry of SRF technology
for large scale facilities and compact accelerators.

Latest advances to extract the maximum performance from established bulk Nb technology

Doping/Infusion, new shape designs, large grain



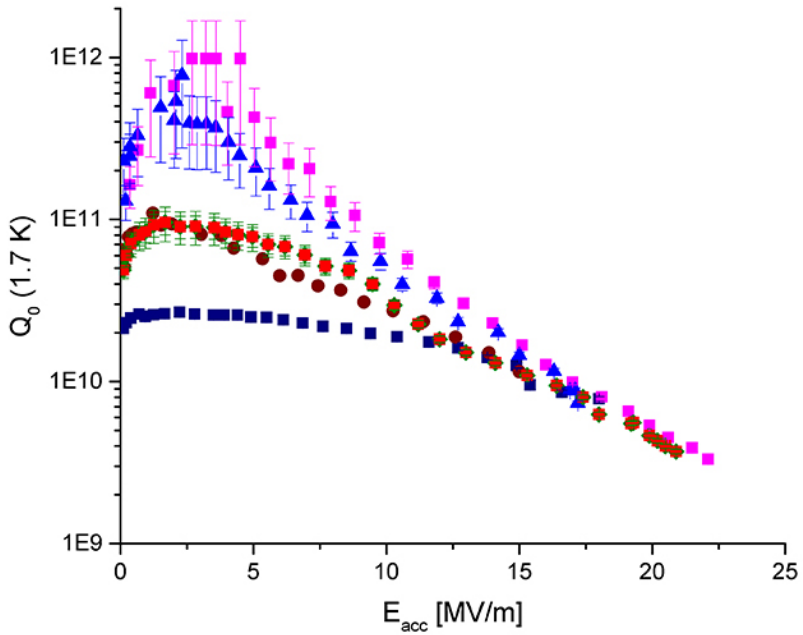


Next Generation Nb/Cu SRF Cavities Based on Advanced Coating Technology for CW Accelerators

Nb/Cu Technology proof of principle with LEP2, LHC, ALPI machines

Great potential for cost savings and operational advantages for machines operating at lower frequency and relatively modest gradients

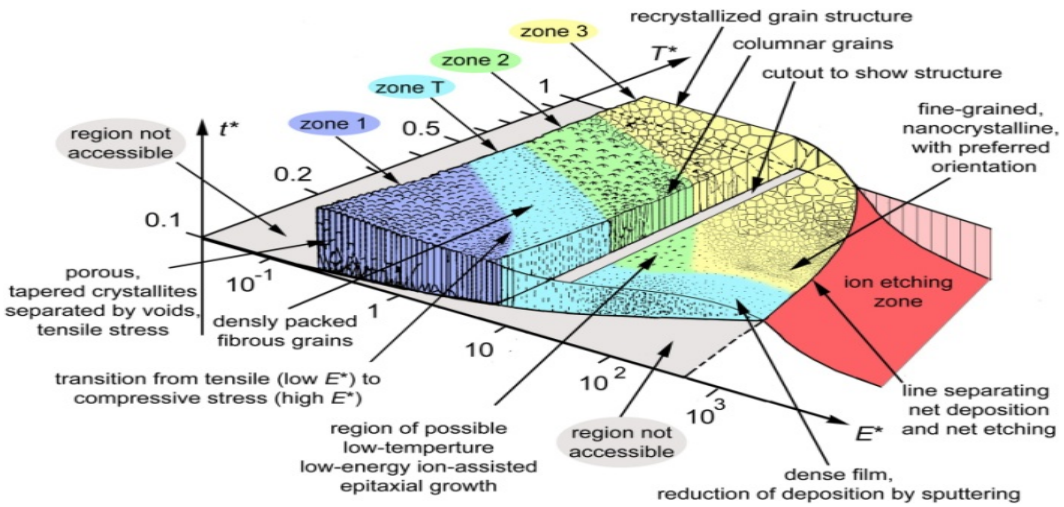
high current storage ring colliders : FCC, EIC and CEPC



- Increased temperature stability due to Cu substrate higher thermal conductivity
- Operation at 4.5 K, generating capital and operational cost savings
- Material cost saving, particularly for low frequency structures
- Easily machinable and castable structures

Perspectives for significant cryomodule simplification.

Novel deposition techniques exploiting species energetics offer opportunities to improve and manipulate film structure and performance

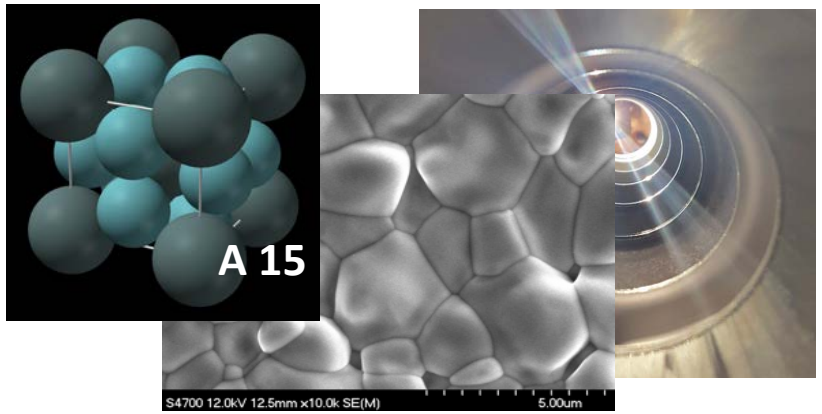


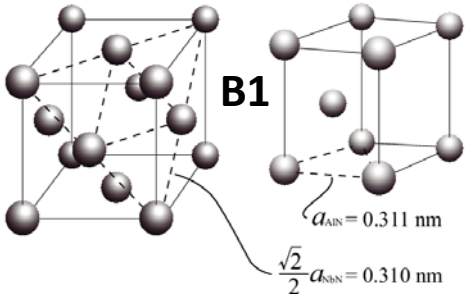
Anders, André. "A structure zone diagram including plasma-based deposition and ion etching." *Thin Solid Films* 518.15 (2010): 4087-4090.

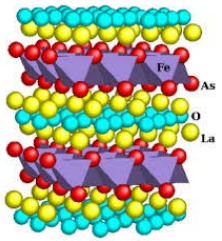
Explore alternative materials with higher critical temperature and critical fields

Alternate Materials and Advanced Structures for Higher Gradients and High Q

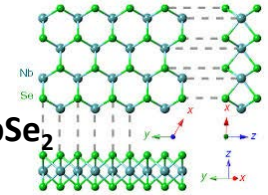
Alternative materials with higher critical temperature and critical field are the prime candidates to disrupt the established bulk Nb technology.



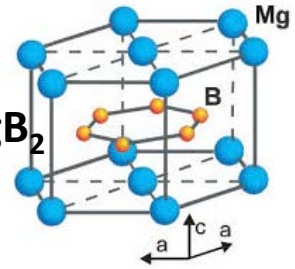




Pnictides

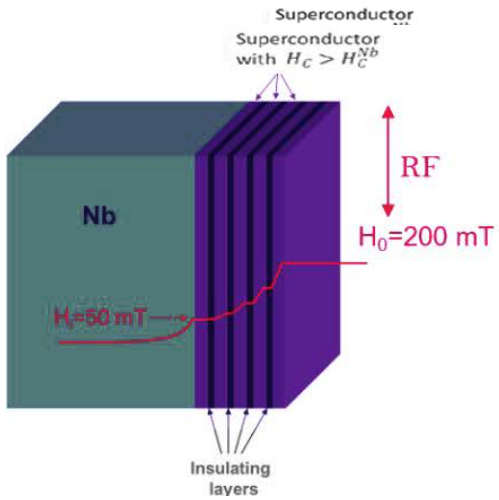


2D-NbSe$_2$

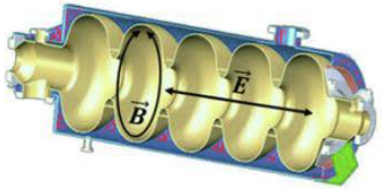


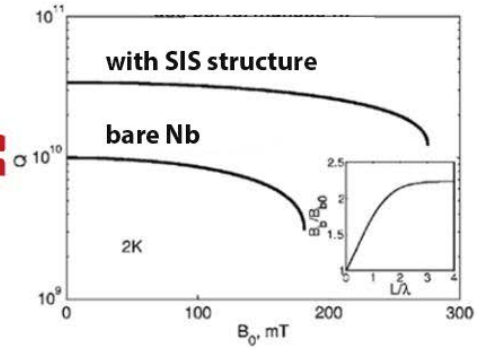
MgB$_2$

Material	T_c [K]	ρ_n($\mu\Omega$cm)	$H_c(0)$ [mT]	$H_{c1}(0)$ [T]	$H_{c2}(0)$ [T]	H_{SH} [T]	$\lambda(0)$ [nm]	Δ [meV]	ξ [nm]	Type
Nb	9.23	2	200	0.17	0.28	0.219	40	1.5	28	II
Pb	7.2		80	N/A	N/A		48			I
NbN	16.2	70	230	0.02	15	0.214	200-350	2.6	<5	II, B1 comp.
NbTiN	17.3	35		0.03			150-200		<5	II, B1 comp.
Nb_3Sn	18	20	540	0.05	30	0.425	80-100	3.1	<5	II, A15
V_3Si	17	4	720	0.072	24.5		179	2.5	<5	II, A15
Mo_3Re	15	10-30	430	0.03	3.5	0.17	140			II, A15
MgB_2	40	0.1-10	430	0.03	3.5-60	0.17	140	2.3/7.2	2.3/7.2	II- 2 gaps
2H-$NbSe_2$	7.1	68	120	0.013	2.7-15	0.095	100-160		8-10	II-2gaps
YBCO	93		1400	0.01	100	1.05	150	20	0.03/2	d-wave
Pnictides	30-55		500-900	0.03	>100	0.756	200	10-20	2	s/d wave

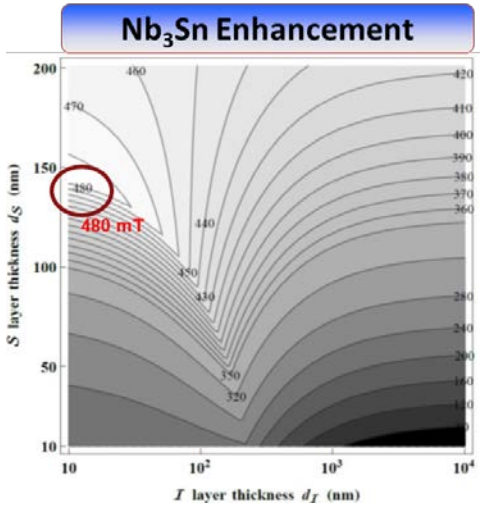


Multicell cavity





Alex Gurevich, Appl. Phys. Lett. 88, 012511 (2006)
Alex Gurevich, AIP ADVANCES 5, 017112 (2015)
T. Kubo, Applied Physics Letters 104, 032603 (2014)



Compact SRF Accelerators for Societal Applications

The emergence of reliable, energy efficient high Q systems, based on highly performing film-based SRF cavities along with transformative development with cryocoolers would impact societal applications ranging from medicine to industry.

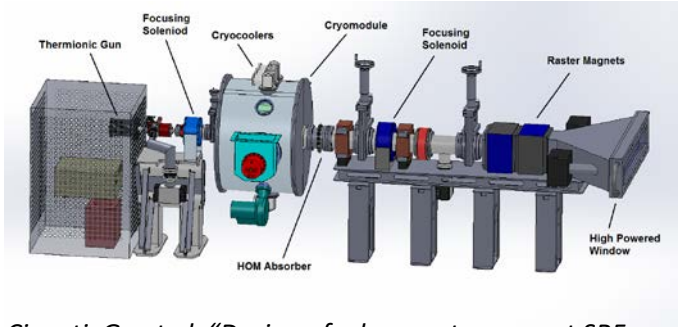
Cost effective compact superconducting accelerators will reduce the footprint and capital investment of

- *Medical machines - cancer therapy, medical radioisotope production*
- *environmental remediation*
- *accelerator-driven systems (ADS) -nuclear waste transmutation,power generation*
- *high-intensity proton accelerators for homeland security (nuclear weapons detection).*

Most critical area of development

Energy efficiency

Compact cavity cooled by cryocoolers for environmental applications



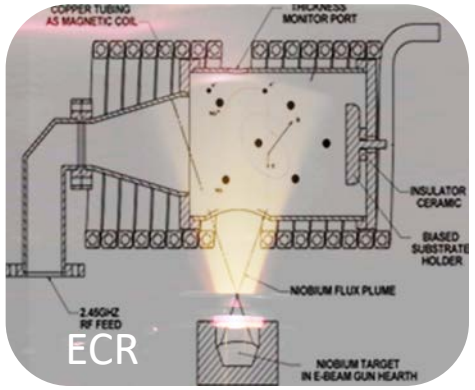
Ciovati, G., et al. "Design of a low-cost, compact SRF accelerator for flue gas and wastewater treatment." (2017).
Ciovati, Gianluigi, et al. "Multi-metallic conduction cooled superconducting radio-frequency cavity with high thermal stability." Superconductor Science and Technology 33.7 (2020): 07LT01.

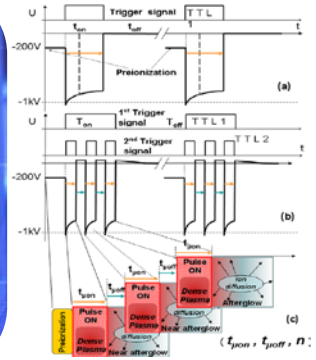
Stilin, Neil et al. "Stable CW Operation of Nb_3Sn SRF Cavity at 10 MV/m using Conduction Cooling." arXiv: 2002.11755: Accelerator Physics (2020).

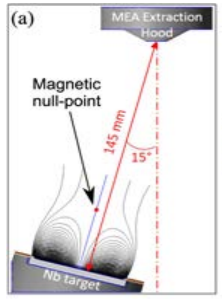
R C Dhuley et al 2020 Supercond. Sci. Technol. 33 06LT01

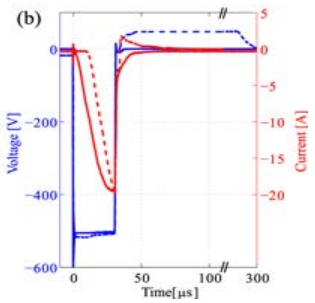
Advances in Thin Film Nb on Cu Technology

Energetic condensation



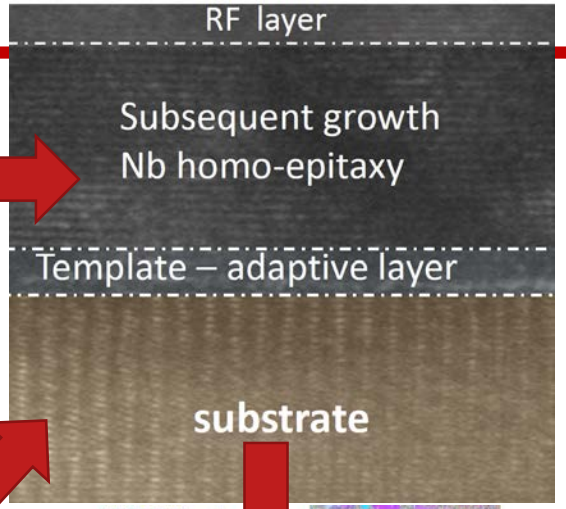


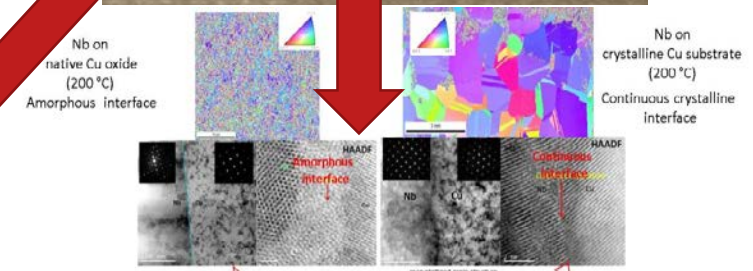


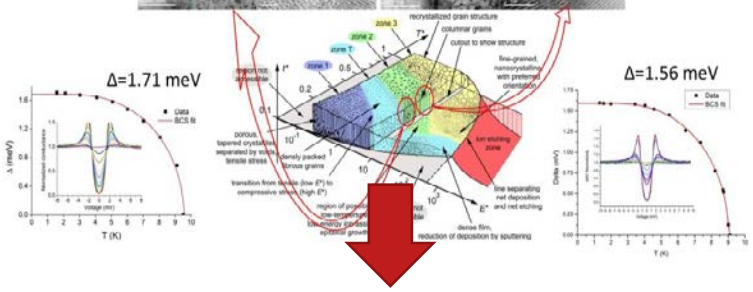


F Avino *et al* 2019 *Plasma Sources Sci. Technol.* **28** 01LT03

HiPIMS + kick pulse



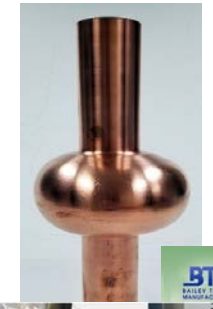




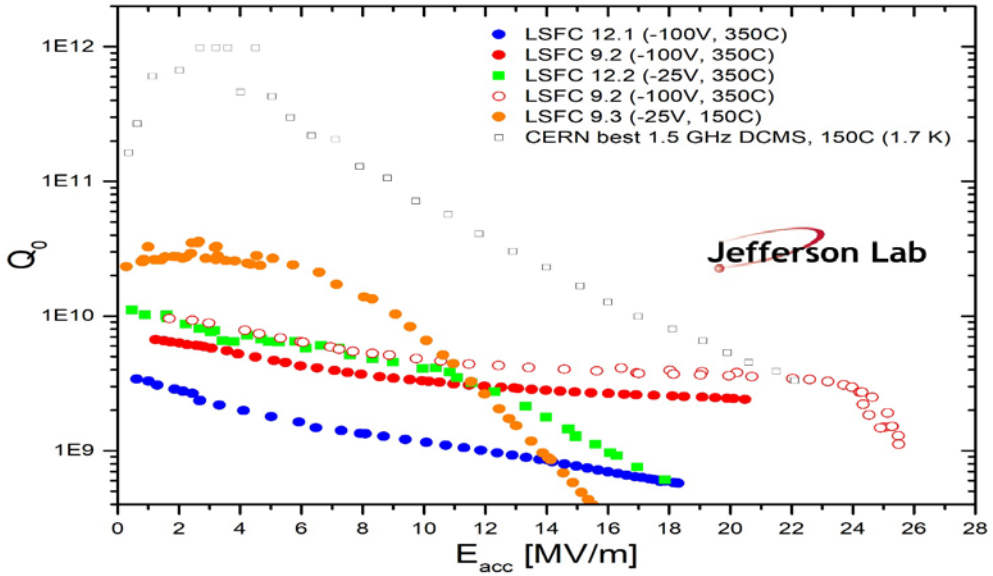
Full control over final SRF performance with strict process protocols

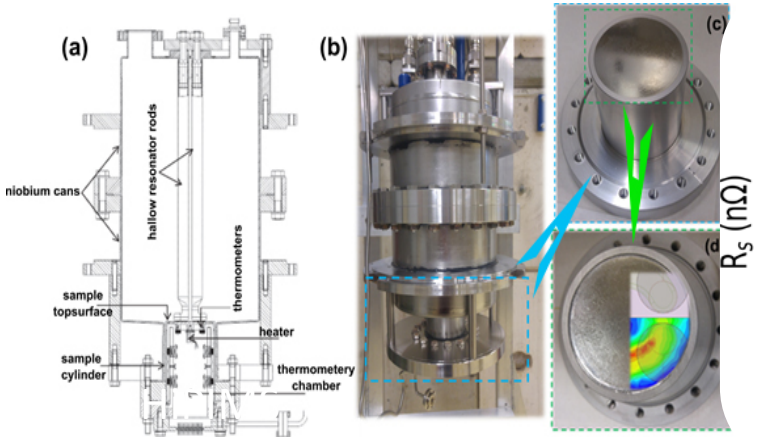
Further tailoring opportunities:
N doping on films

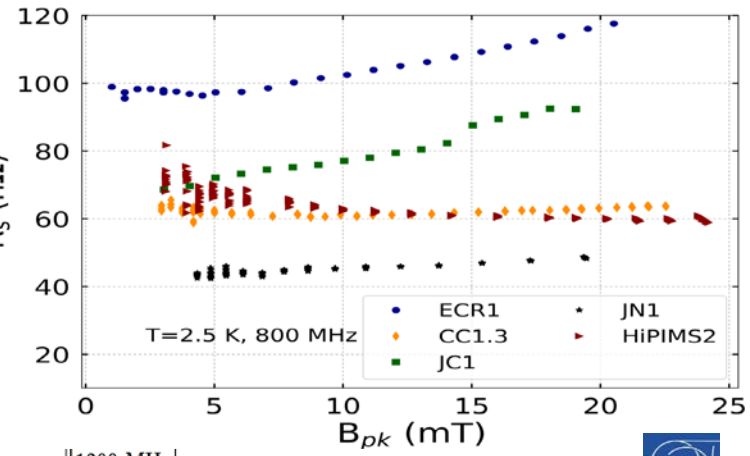
Substrate Fabrication & Processing



Advances in Thin Film Nb on Cu Technology

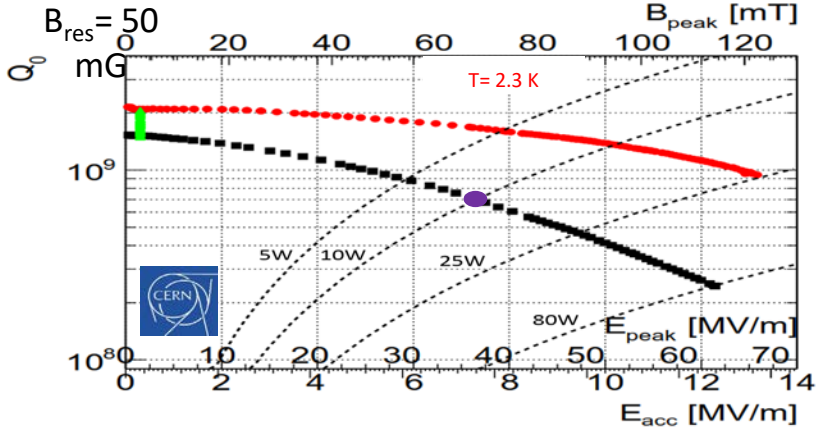




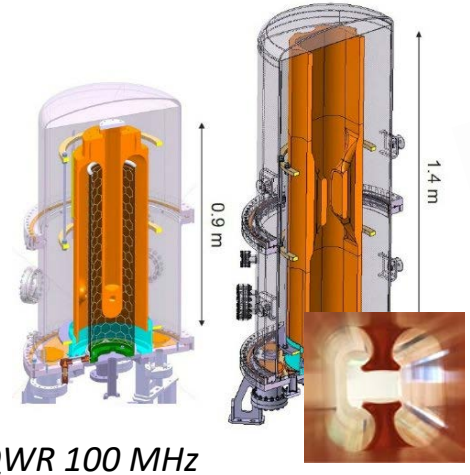


Sample	400 MHz R_{s0} (nΩ)	R_{s1} (nΩ/mT)	800 MHz R_{s0} (nΩ)	R_{s1} (nΩ/mT)	1200 MHz R_{s0} (nΩ)	R_{s1} (nΩ/mT)
ECR	19.7	0.84	65.8	1.14	126.2	1.35
HiPIMS	19.8	0.11	n/a*	n/a*	100.9	0.3
bulk Nb	21.2	0.13	42.1	0.32	120.1	0.69

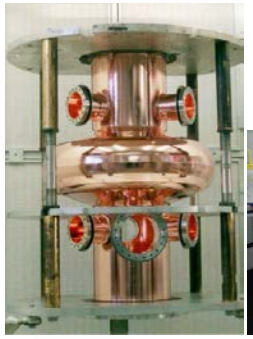
Jefferson Lab



Developments across shapes & frequencies



QWR 100 MHz



LHC 400 MHz

FCC 800 MHz

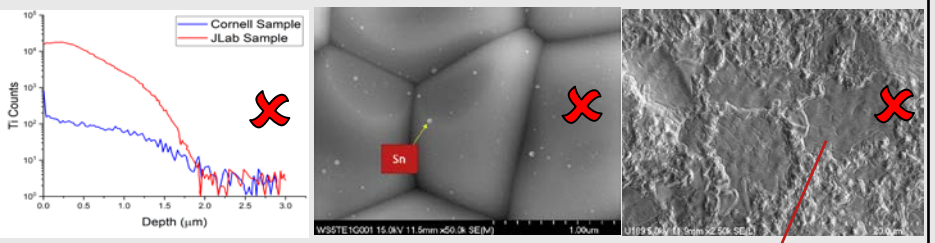
956.2 MHz / 1.3 GHz

Jefferson Lab

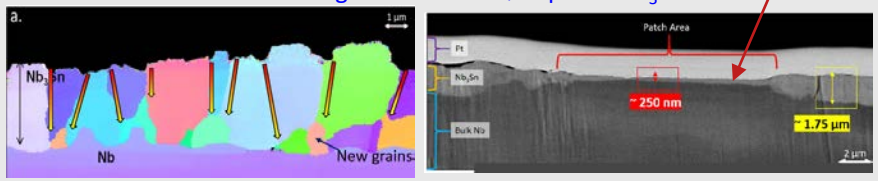
Jefferson Lab

Nb_3Sn Development

Material studies to understand the fundamental growth mechanism linking with RF performance

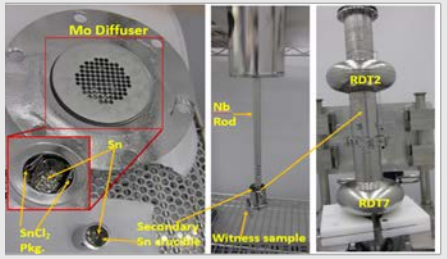


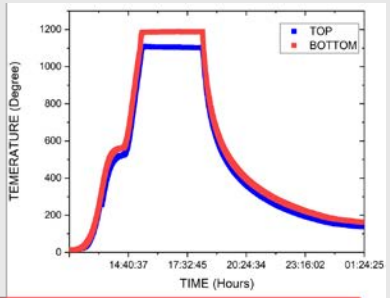
Potential factors contributing to recurrent Q-slopes in Nb_3Sn cavities



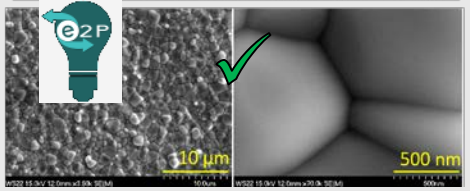
Grain-boundary diffusion primarily controls thin-film growth. Patchy regions lack grain boundaries resulting in RF-affecting thin regions.

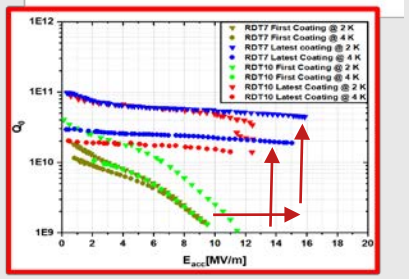
Process Development





No Sn-residues and uniform coating

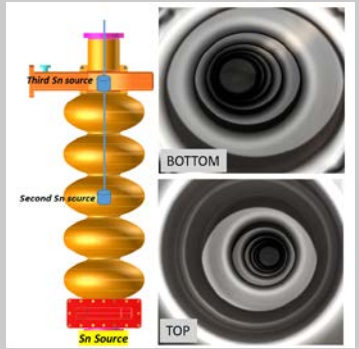




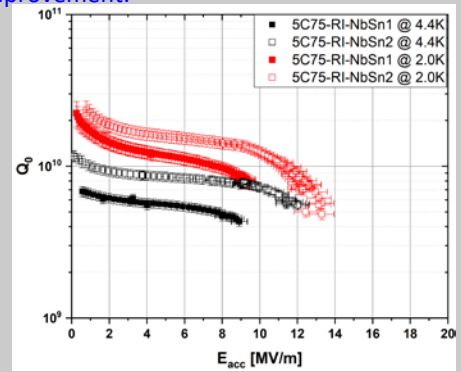
Modification of coating process based on learnings from correlated material and RF studies of Nb_3Sn samples resulted in the removal of recurrent Q-slopes.

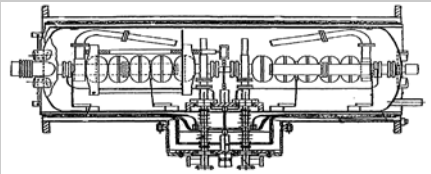
Jefferson Lab

Multi-cell cavity coating for accelerator application



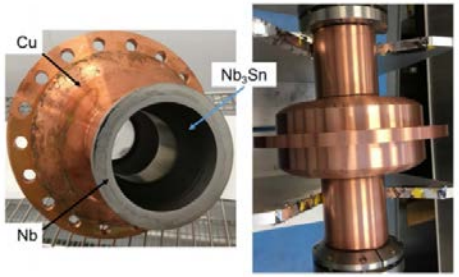
Despite early cavities suffered non-uniformity, enhanced substrate quality and continuously updated coating process resulted in notable improvement.

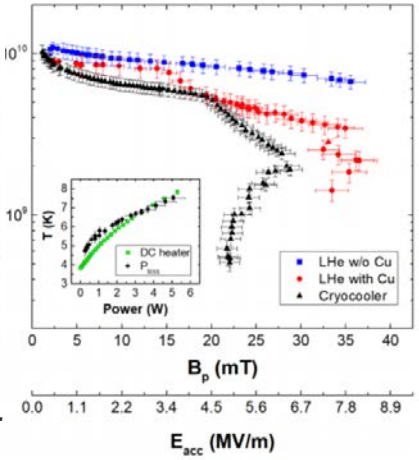




These cavities progress to quarter cryomodule for the first-ever beam test.

Multi-metallic conduction cooled Nb3Sn-coated cavity





G. Ciovati *et al* 2020 *Supercond. Sci. Technol.* **33** 07LT01

- Materials such as Nb_3Sn offer order of magnitude improvements in operating efficiency, and a theoretical pathway to 100 MV/m gradient.
- Recent R&D efforts have demonstrated that the persistent Q-slope and gradient limitation observed in the past are not fundamental but process induced and therefore amenable to improvement.
- Alternative deposition approaches such as sputtering, energetic condensation and atomic layer deposition (ALD) should be fully explored for enhanced properties and conformality.
- Early results with sequential and stoichiometric deposition both on Nb and on Cu are promising and could prove to push the Nb_3Sn technology further.

Fermilab

Jefferson Lab

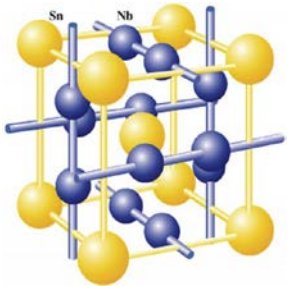
Alternative Materials to Nb & Multilayered Structures

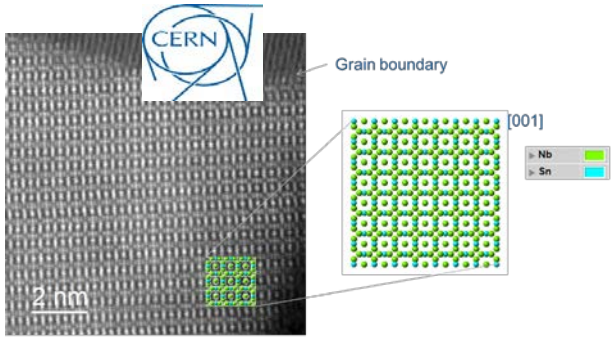
- Develop alternative materials such as NbTiN, NbN, Nb_3Sn Va_3Si, ... with advanced coating techniques.

Especially for low melting temperature substrates (Cu, CuSn, Al…)

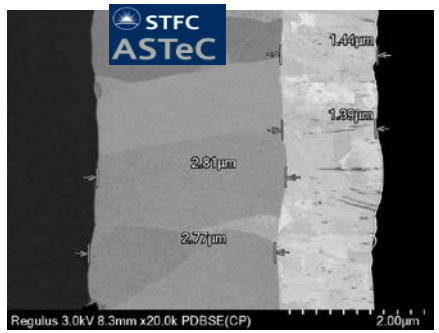
- Newly discovered high temperature superconducting (HTS) materials (pnictides …) would be particularly interesting if any of them turns out to have favorable microwave properties

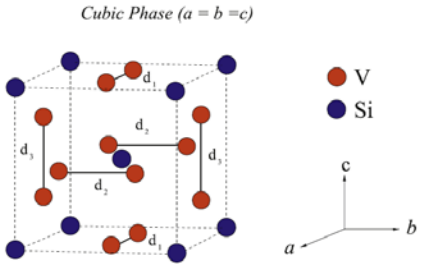
- Advanced coating techniques

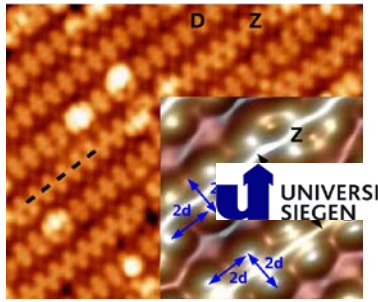




HAADF STEM image of Nb3Sn grain in [001] zone axis and grain boundary

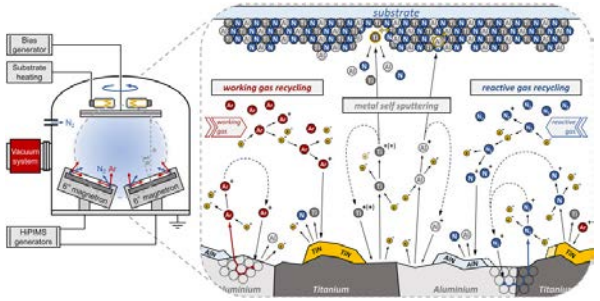




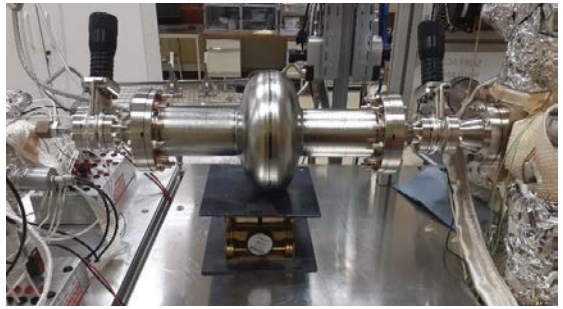


Hauptmann, N., M. Becker, J. Kröger and R. Berndt. "Surface reconstruction and energy gap of superconducting V (001)." Physical Review B 79 (2009): 144522.

Re-HiPIMS

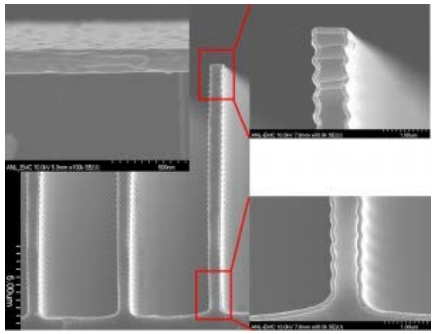


High quality dense films
Improved conformality



ALD

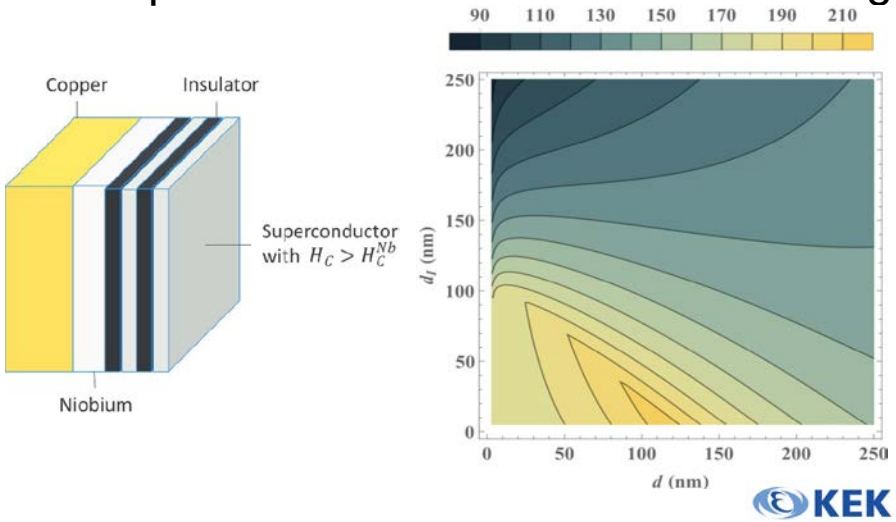
Conformal, self-limiting
nm precision
Precursors difficult

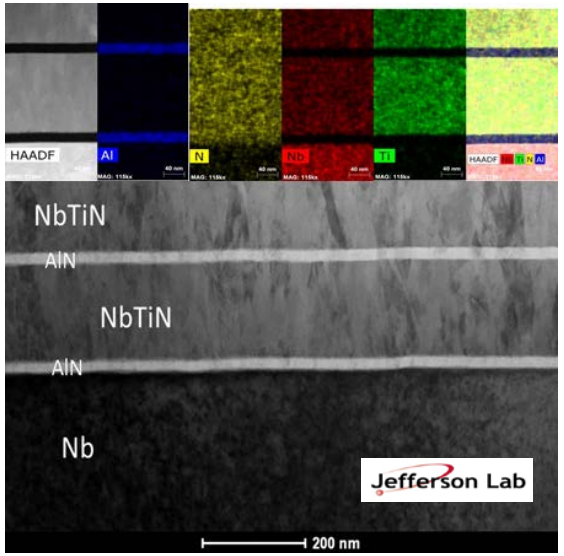


Next-Generation SRF Thin Film Technologies

Alternative Materials to Nb & Multilayered Structures

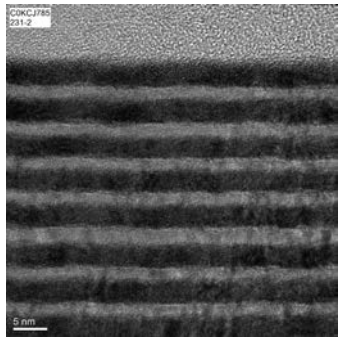
- The combination of such materials with adequate dielectric material in multi-layered structures have been conceived as a performance enhancer for bulk Nb and Nb/Cu film cavities. Theoretical models predict that appropriately fabricated nanometric superconductor-insulator-superconductor (SIS) multilayer films can delay vortex penetration in Nb surfaces allowing them to sustain higher surface fields than any pure material.

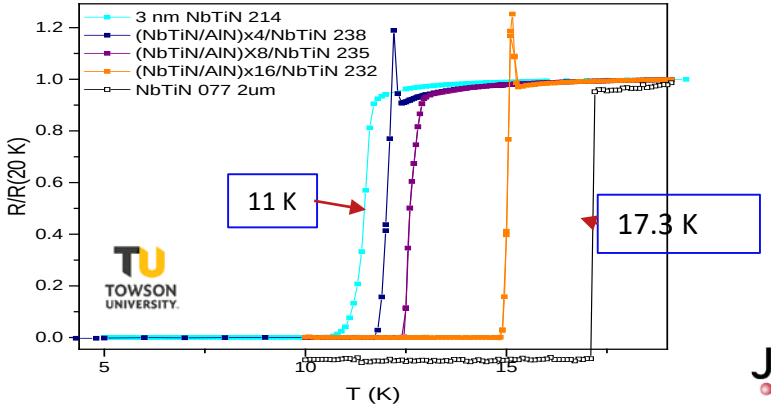




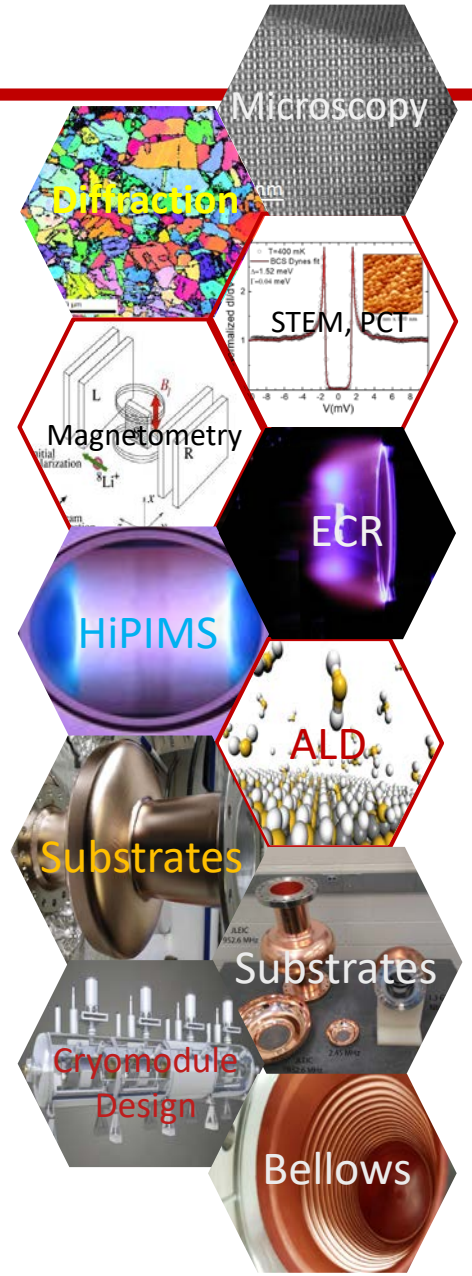
- Cap layers for surface passivation

- Meta-materials for functional surfaces





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…

What do we need?

Synergies between R&D programs, institutions along aligned path

Multiple RF test platforms (QPR, …) 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

Summary

- SRF thin film technology based on advanced coating techniques offers many opportunities to fully engineer SRF surfaces :
  - *Deliberate creation of the most favorable interface or functional interlayer*
  - *Tailoring of the most favorable film(s) structure*
  - *Properties enhancement with doping/infusion*
  - *Control over the final SRF surface with dry oxidation or cap layer protection.*

- Bulk-like performance Nb films, alternative material films and SIS multilayer structures open the possibility of major system simplifications and enhanced performance.
- Such developments would be transformative not only for future high energy physics machines but will also bring forth the opportunity to upgrade existing machines to higher performance in achievable energies and cryogenic & power consumption, within the same footprint.
- Active community in the US and Internationally

Summary

Virtual International *Workshop* on *Nb3Sn* SRF Science, Technology, and Applications (Nb3SnSRF'20)
10- 13 Nov 2020

https://indico.classe.cornell.edu/event/1806/

9th International Workshop on "**Thin films applied to Superconducting RF: Pushing the limits of RF Superconductivity**"
VIRTUAL EDITION
March 15-18, 2021

https://indico.jlab.org/e/TFSRF2021

Acknowledgement

Jefferson Lab
Old Dominion University
Old Dominion University
College of William & Mary 1693
University of Maryland 1856
The Applied Superconductivity Center NHMFL · FSU
Fermilab
North Carolina State University
Cornell University Founded A.D. 1865
II-VI
TRIUMF
e2P
starfire industries
SLAC National Accelerator Laboratory
BTM Bailey Tool & Manufacturing
Los Alamos National Laboratory
Temple University
Universität Siegen
INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Legnaro
KEK
HZB Helmholtz Zentrum Berlin
CERN
Technische Universität Darmstadt
STFC ASTeC
Paul Scherrer Institut PSI
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis
DESY.
cea
Irfu - CEA Saclay Institut de recherche sur les lois fondamentales de l'Univers
IMP
Institut national de physique nucléaire et de physique des particules
cnrs
UHH
KU LEUVEN