SRF program in the SNOWMASS 2021 strategy

Snowmass 2021

A.-M. Valente-Feliciano

On behalf of the SRF community

SNOWMASS 2021

Snowmass is a particle physics community study

- ❑ Sponsored by Division of Particles and Fields of the American Physical Society
- ❑ Define the most important questions in the field of particle physics and identify promising opportunities to address them.
- ❑ Assess the future of elementary particle physics, to explore the limits of our technological capabilities, and to consider the nature of future major facilities for particle physics in the US.

https://www.snowmass21.org/

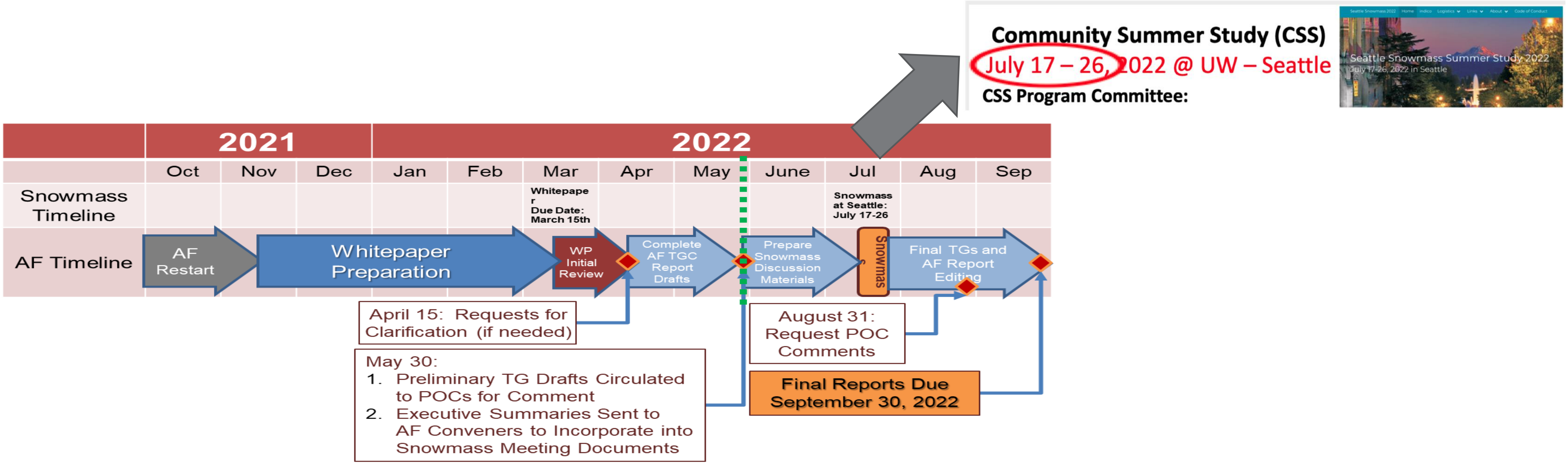
- ❑ Provides input to P5 (Particle Physics Project Prioritization Panel) that develops a strategy for the US HEP program
- ❑ Planning for 2025-2035 with a view toward 2050

The Start of the Snowmass Process

1st exercise in 1982 at Snowmass, Colorado provided a model for the community summer studies open to all active particle physicists in the United States, joined by representatives of the European physics community, the DOE, and the NSF.

Followed by 1990, 2001, 2013, …

Snowmass Timeline & Impact



- ❑ DOE's P5 (Particle Physics Project Prioritization Panel) will take the scientific input from Snowmass and develop a strategic plan for U.S. particle physics that can be executed over a 10 year timescale, in the context of a 20-year global vision for the field.

  Accelerator subpanel deliberations during last P5 made a significant impact on resources for R&D
- ❑ Contributions provide important input that influences future projects and scientific programs

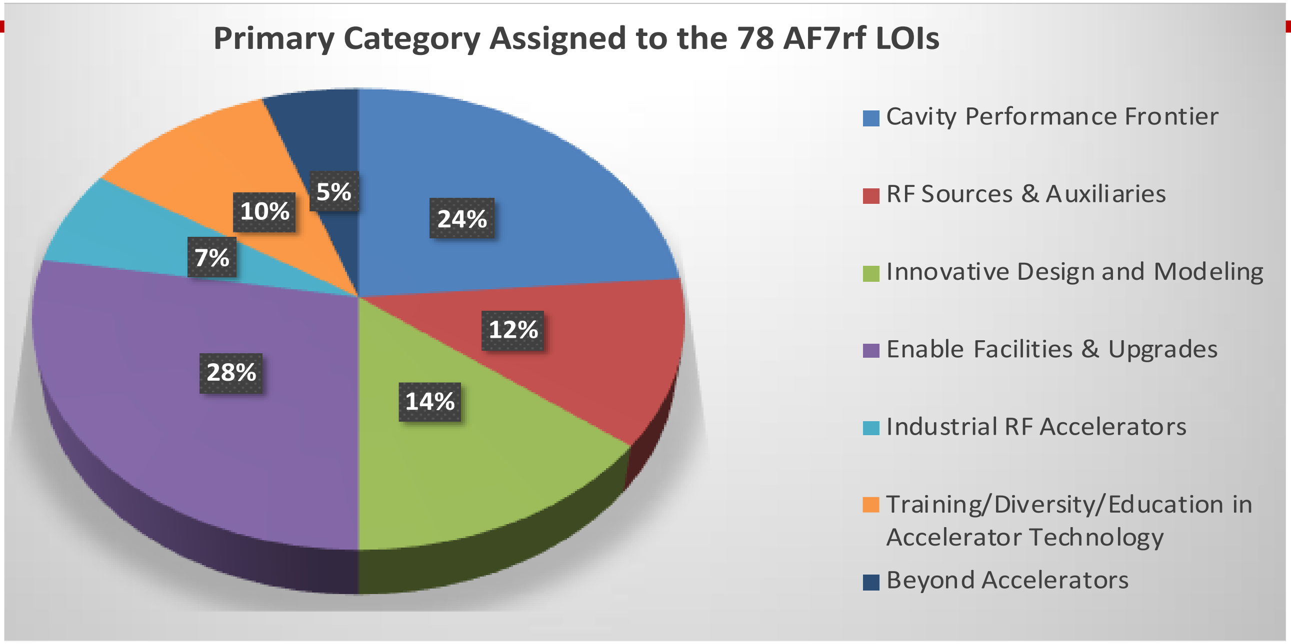
Snowmass Accelerator Frontier

The Accelerator Frontier activities include discussions on high-energy hadron and lepton colliders, high-intensity beams for neutrino research and for the “Physics Beyond Colliders”, accelerator technologies, science, education and outreach as well as the progress of core accelerator technology, including RF, magnets, targets and sources.

Participants submit Letters of Intent, contributed papers, take part in corresponding workshops and events, contribute to writing summaries and take part in the general Snowmass'21 events

1. *What is needed to advance the physics?*
2. *What is currently available (state of the art) around the world?*
3. *What new accelerator facilities could be available on the next decade (or next next decade)?*
4. *What R&D would enable these future opportunities?*
5. *What are the time and cost scales of the R&D and associated test facilities as well as the time and cost scale of the facilities?*

AF07: Accelerator technology R&D - RF systems



- **78 LOIs submitted**
- **18 WP submitted to AF-RF (additional 9 relevant; probably more), now under review**

https://snowmass21.org/submissions/start

- AF7 - Subgroup RF - miniWorkshop on RF Systems and Sources Follow-Up, https://indico.fnal.gov/event/52406/ , Jan. 11th, 2022
- AF7 - Subgroup RF - miniWorkshop on Innovative Design and Modeling Follow-Up, https://indico.fnal.gov/event/52407/ , Jan 18th, 2022
- AF7 - Subgroup RF - miniWorkshop on Cavity Performance Frontier Follow-Up, https://indico.fnal.gov/event/52408/, Feb. 1st, 2022

Working on outline for AF7-rf report; structure informed from submissions & community events

Key directions for R&D of SRF cavities

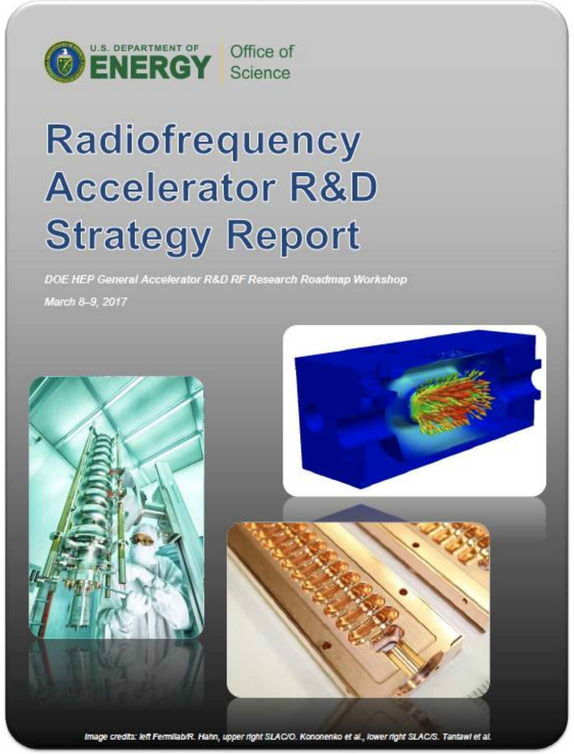
- SRF is a critical technology for several accelerator-based frontier HEP facilities:
  - HL-LHC (crab cavities)
  - LBNF/DUNE/PIP-II
  - Future linear (ILC) and circular (FCC-ee, CEPC) colliders
  - Muon collider
- Other potential applications:
  - Next generation dark sector searches (axions, dark photons…)
  - Quantum computing for HEP
  - Compact accelerators for societal needs
- Synergy with other fields: Nuclear Physics (EIC, FRIB, …), Light Sources / FELs (e.g., LCLS-II/LCLS-II HE), Spallation Sources (SNS upgrade, ESS, …)
- Continued improvements in cavity performance enables new scientific applications when they would have otherwise been either unachievable or too expensive

S. Belomestnykh, S. Posen, D. Bafia, S. Balachandran, M. Bertucci, A. Burrill, et al.
"Key directions for research and development of superconducting radio frequency cavities"
https://arxiv.org/pdf/arXiv:2204.01178

DOE GARD RF accelerator technology roadmap

https://doi.org/10.2172/1631119

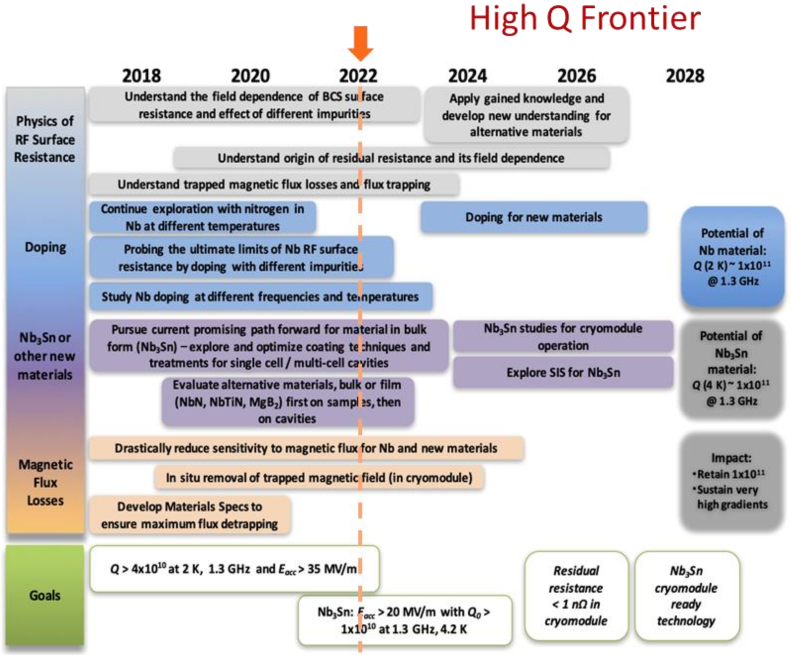
- DOE/HEP General Accelerator R&D (GARD) Program ten-year roadmap was developed by a team of leading researchers with input from the community (domestic and international) in 2017

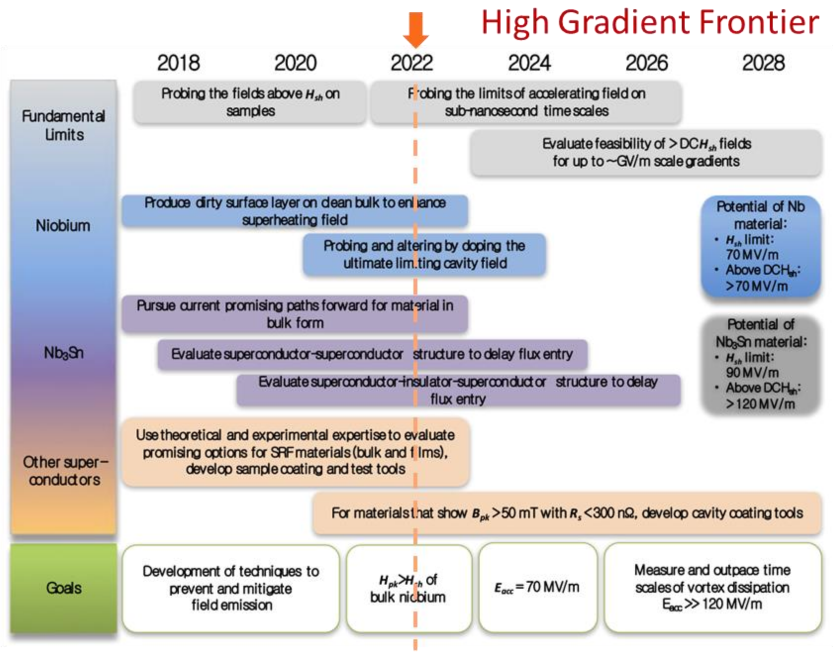


General Accelerator R&D RF Research Roadmap Workshop Report

https://www.osti.gov/servlets/purl/1631119/

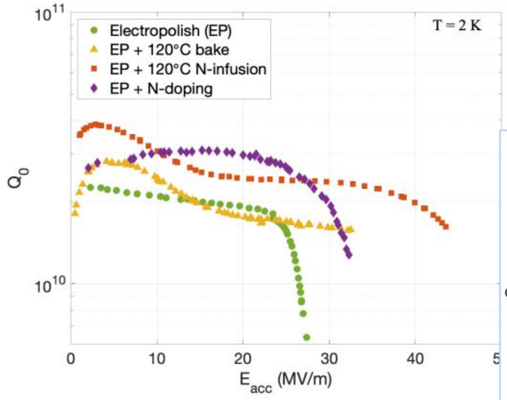
- It reflected the P5 strategy and the subsequent HEPAP Accelerator Subpanel recommendations
- The roadmap incorporated the most promising research directions for advances that enable future experimental high energy physics programs
- We anticipate that the roadmaps will be updated after *SnowMass2021* and subsequent P5 process





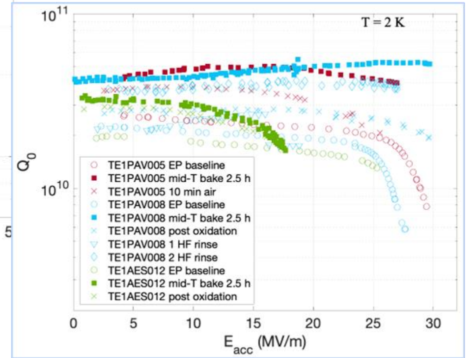
High Q & High Gradient SRF Frontier - Main Directions

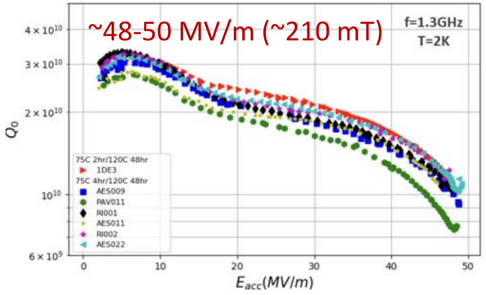
- Continue exploration of the effect of interstitial impurities on bulk Nb surface resistance
- Study the effect of doping on *Q* of cavities at different frequencies (650 MHz – 3.9 GHz)
- Develop fundamental understanding of the reverse field dependence of the BCS surface resistance and devise experiments towards validation of different theories



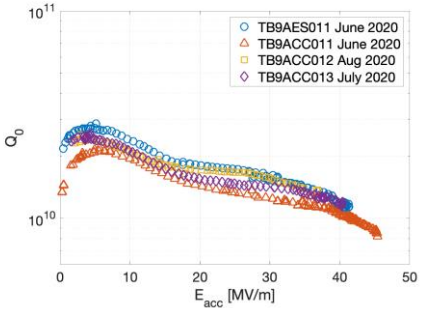
N doping & infusion

Mid-T bake





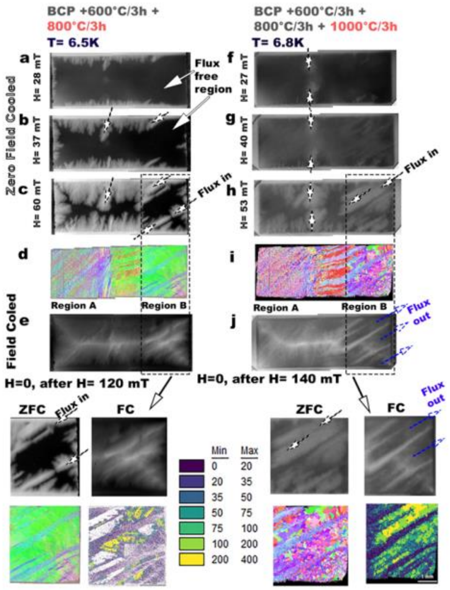
High gradient cryomodule

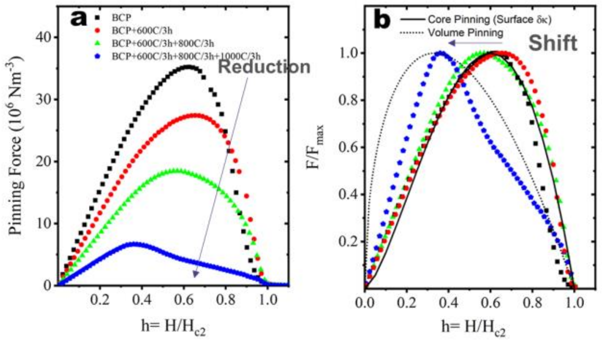


- ❑ Develop understanding of mechanisms of trapping magnetic vortices and their contribution to the RF losses
- ❑ Develop understanding of 'intrinsic' residual resistance and its field dependence
- ❑ Ameliorate trapped vortices via innovative ideas
- ❑ Develop Nb_3Sn coating on single and multi-cell cavities of different frequencies
- ❑ Investigate feasibility of other materials for high *Q*

- ❑ Furthering our understanding of RF losses and ultimate quench fields of niobium via experimental and theoretical investigations;
- ❑ developing methods for nano-engineering the niobium surface layer and tailoring it for specific applications;
- ❑ studying new SRF materials beyond niobium via advanced deposition techniques and bringing these materials to practical applications;
- ❑ developing advanced cavity geometries to push accelerating gradients of bulk niobium cavities to ~ 70 MV/m and pursuing R&D on companion RF technologies to mitigate field emission, provide precise resonance control, etc.;
- ❑ investigating application of SRF technology to dark sector searches.

Basic materials research community for the accelerated development of SRF materials.

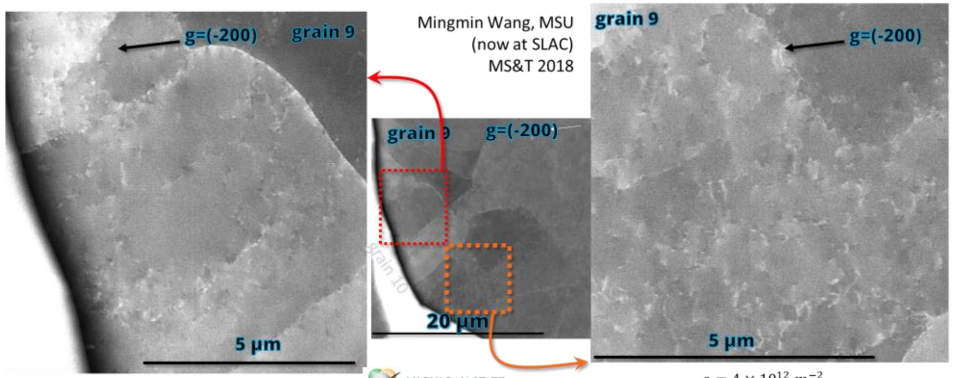




ECCI imaging developed for Nb by MSU for SRF applications (ρ~ 10^{12} to 10^{13} m^{-2})- A TEM alternative, applicable to other SRF materials?

This is a lower bound of dislocation density estimation since:

- Not all dislocations are visible in a single ECCI image due to invisibility criteria
- Dislocation lines that are not perpendicular lead to underestimate of dislocation density



Mingmin Wang, MSU (now at SLAC) MS&T 2018

Dislocation density: $\rho = 2 \times 10^{13}$ $\rho = 4 \times 10^{12}$ m^{-2}

- **Fundamental medium-term R&D needs to be supported for current Nb material to produce consistent high Q cavities.**
  - Up stream process variables for current high RRR Nb can be tuned.
  - Coupon samples are efficient in tuning metallurgical variables.
  - Specification of material would likely change.
- **Long term support from GARD University Grants for materials research is essential**
  - Accelerator Stewardship has contributed additional support, and synergies between ARDAP and GARD should be exploited.
  - Possibilities exist for material research synergies with the magnet development program for new SRF materials
  - Approaches to evaluate microwave properties on coupon (20-50mm) samples needs development.
- **Engage academic research for long term sustainability**
  - Provides man-power for future projects.
  - Also forms a broad base to draw from during mission critical emergencies.
  - Possibilities exist for couplings between different areas of expertise when focused on long term R&D.
  - Engaging subject experts from outside the SRF community has been and will continue to be valuable

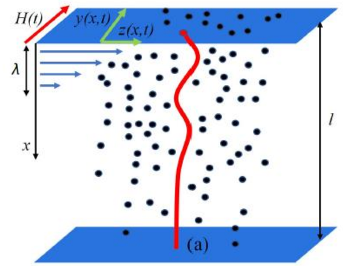
SRF theory for next generation particle accelerators

Field limit

- The widely used GL theory of dc superheating field $H_s(T)$ is applicable near T_c but not at $T << T_c$.
- Only $H_s(0) = 0.84H_c$ at $\kappa = \lambda/\xi \gg 1$ was calculated (Galaiko 1966, Catelani and Sethna, 2008; Lin and Gurevich, 2012).
  $H_s(T,\kappa)$ at $T << T_c$ and arbitrary GL parameter has not yet been calculated.
- Dynamic superheating field $H_d(T,f)$. How different can it be from the static $H_s(T)$ at GHz frequencies?
  Recent result: $H_d(T,f) \to \sqrt{2}H_s(T), \quad T \approx T_c$ (Sheikhzada and Gurevich, 2020)

Q limit

- BCS surface resistance $R_s(T)$ vanishes at T=0. How far can the residual resistance be decreased?
  Trapped vortices, subgap quasiparticles and two-level states, proximity-coupled suboxide layers.



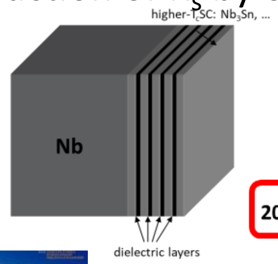
Pathirana and Gurevich, PRB 101, 064504 (2020) and unpublished

Nonequilibrium superconductivity

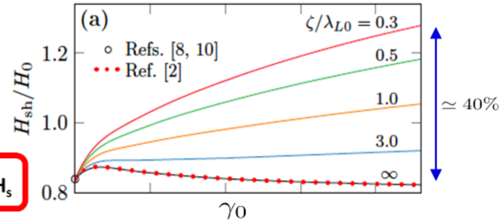
- Nonlinear BCS surface resistance in a nonequilibrium SC under strong rf current. Negative Q(H) slope.
- Extreme dynamics and nonlinear losses of trapped vortices driven by strong rf current

Tuning SRF performance by surface nanostructuring

- Increase of H_s and vortex penetration field by SIS multilayers and impurity gradients at the surface
- Reduction of R_s by optimizing proximity-coupled layers and transparency of grain boundaries

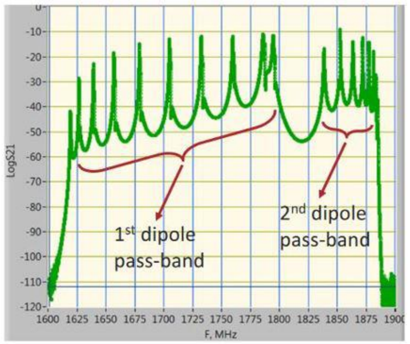


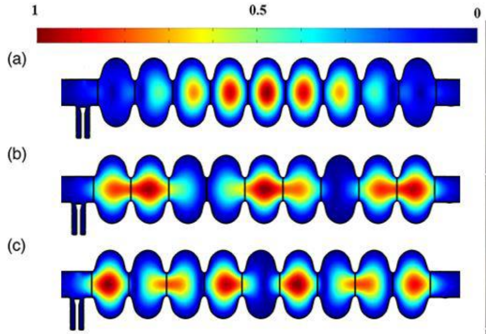
20-40% increase of H_s

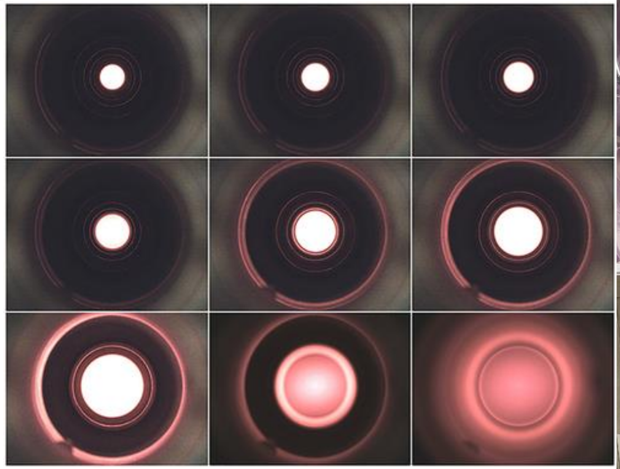


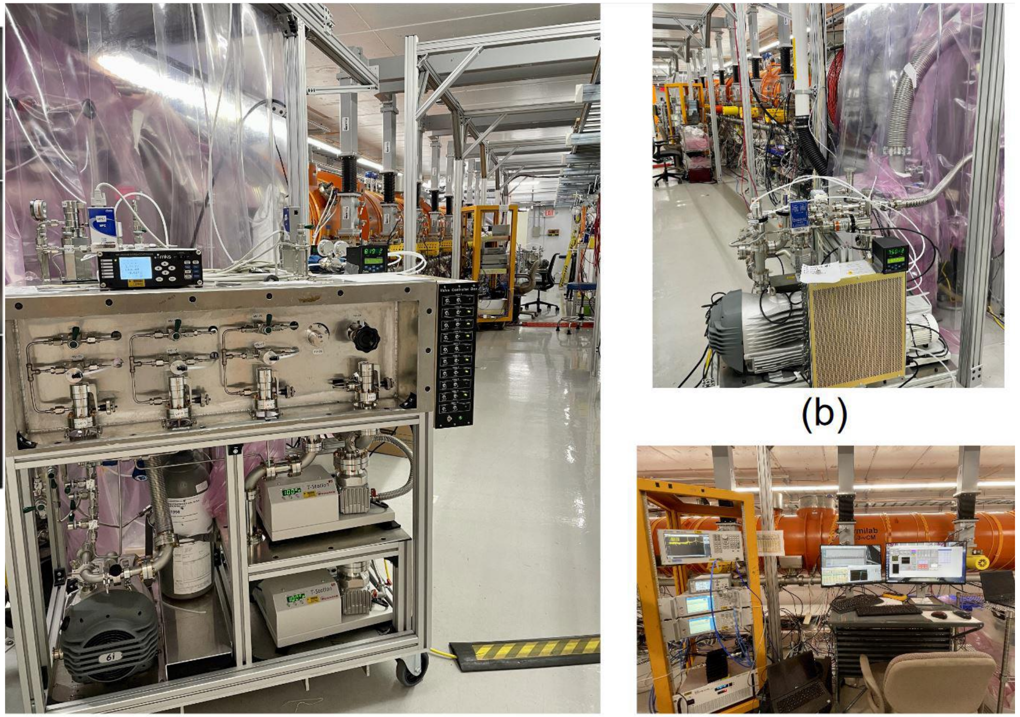
Alex Gurevich, Takayuki Kubo, James A. Sauls
"Challenges and opportunities of SRF theory for next generation particle accelerators"
https://arxiv.org/pdf/2203.08315

Plasma Processing for In-Situ Field Emission Mitigation





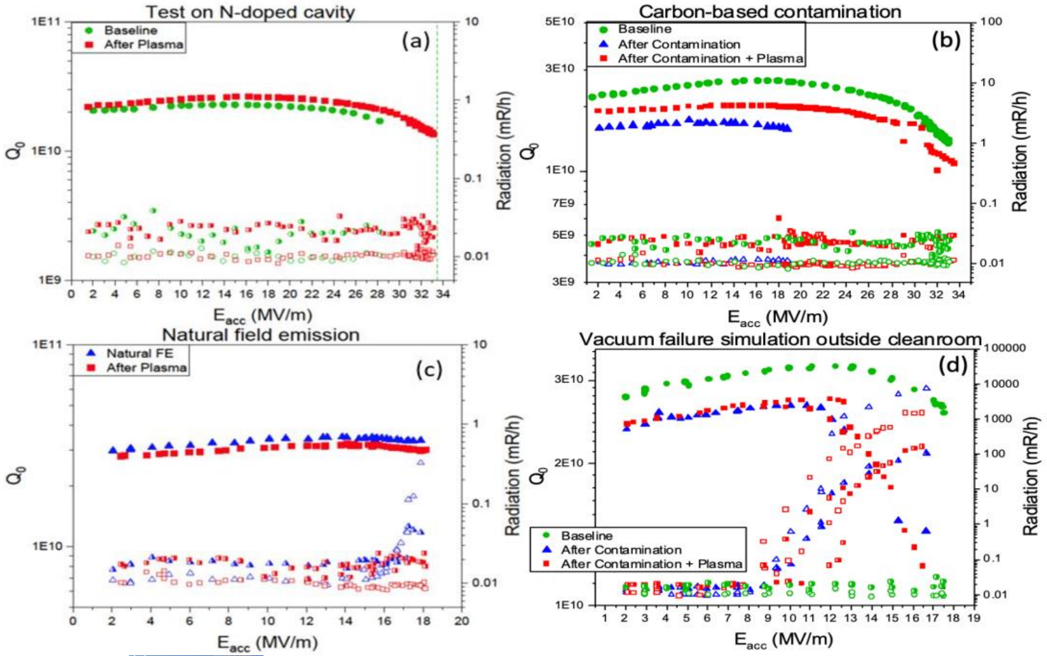




(b)

(a)

(c)



M. Martinello, P. Berrutti, B. Giaccone, S. Belomestnykh, M. Checchin, et al.
Plasma Processing for In-Situ Field Emission Mitigation of Superconducting Radiofrequency (SRF) Cryomodules
https://arxiv.org/pdf/arXiv:2203.12442

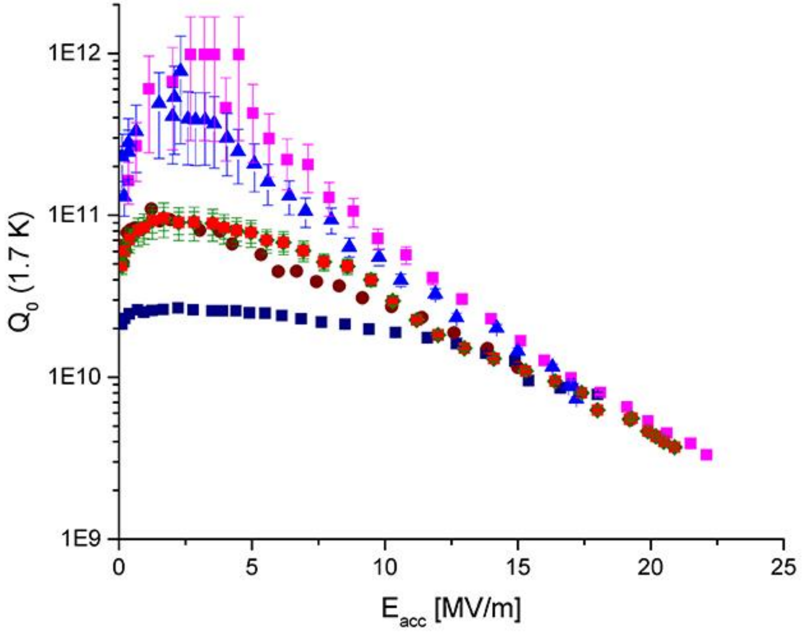
G. Myneni, Hani E. Elsayed-Ali, Md Obidul Islam, Md Nizam Sayeed, G. Ciovati, et al.
”Medium-Grain Niobium SRF Cavity Production Technology for Science Frontiers and Accelerator Applications”
, https://arxiv.org/pdf/2203.07371].”

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

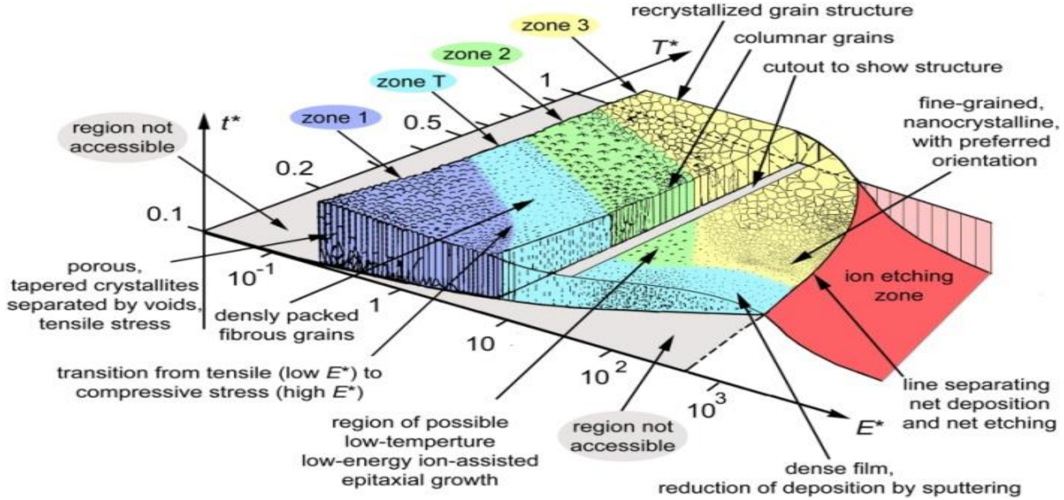
high current storage ring colliders : FCC, EIC and CEPC



- 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.

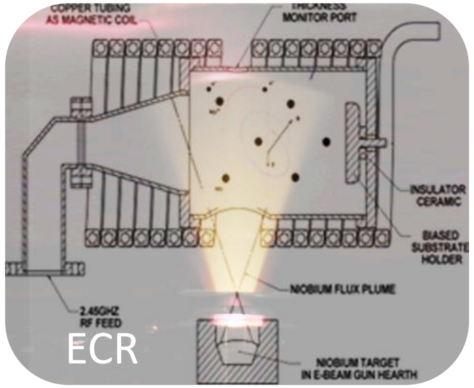
Novel deposition techniques exploiting species energetics offer opportunities to improve and manipulate film structure and performance

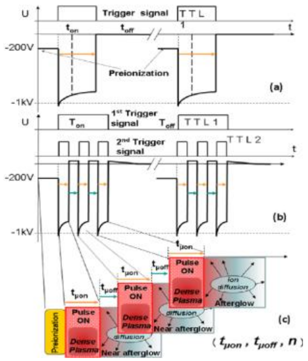


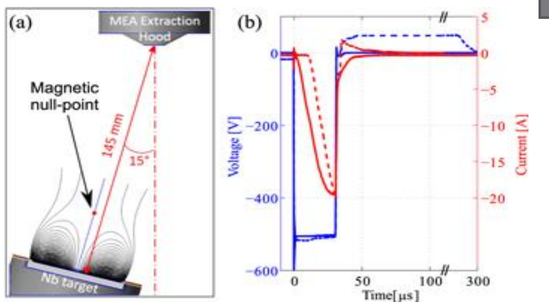
Anders, André. "A structure zone diagram including plasma-based deposition and ion etching." *Thin Solid Films* 518.15 (2010): 4087-4090.

Advances in Thin Film Nb on Cu Technology

Energetic condensation

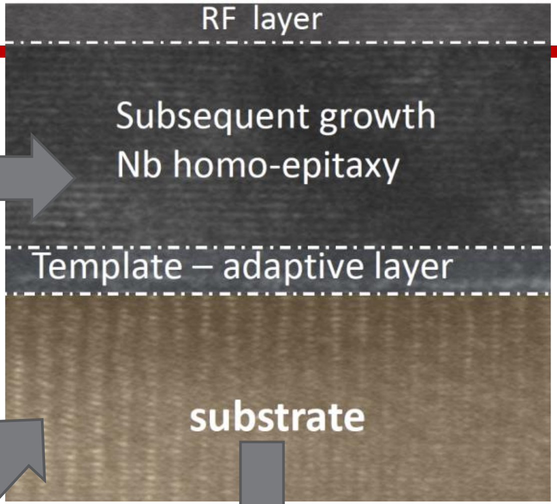


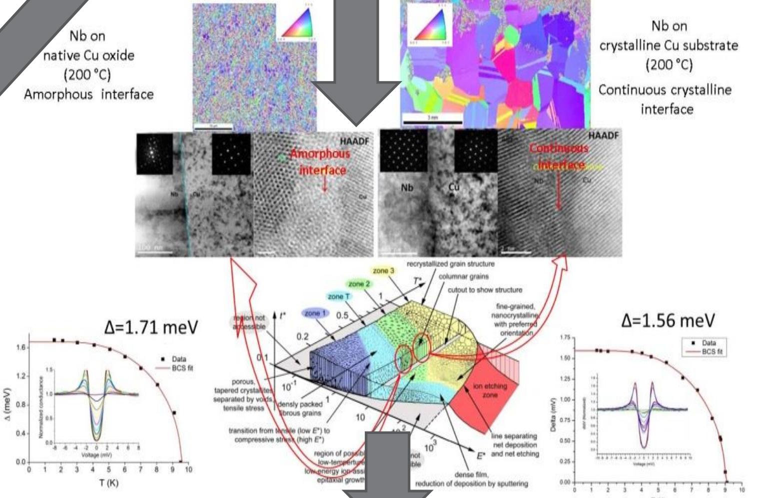




F Avino *et al* 2019 *Plasma Sources Sci. Technol.* **28** 01LT03

HiPIMS + kick pulse



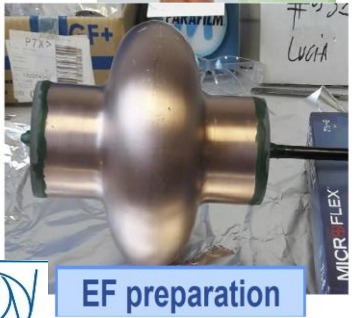


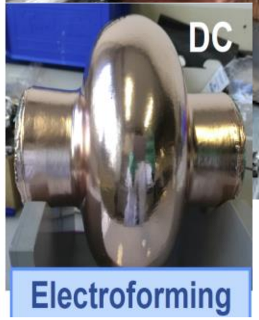
Full control over final SRF performance with strict process protocols

Further tailoring opportunities:

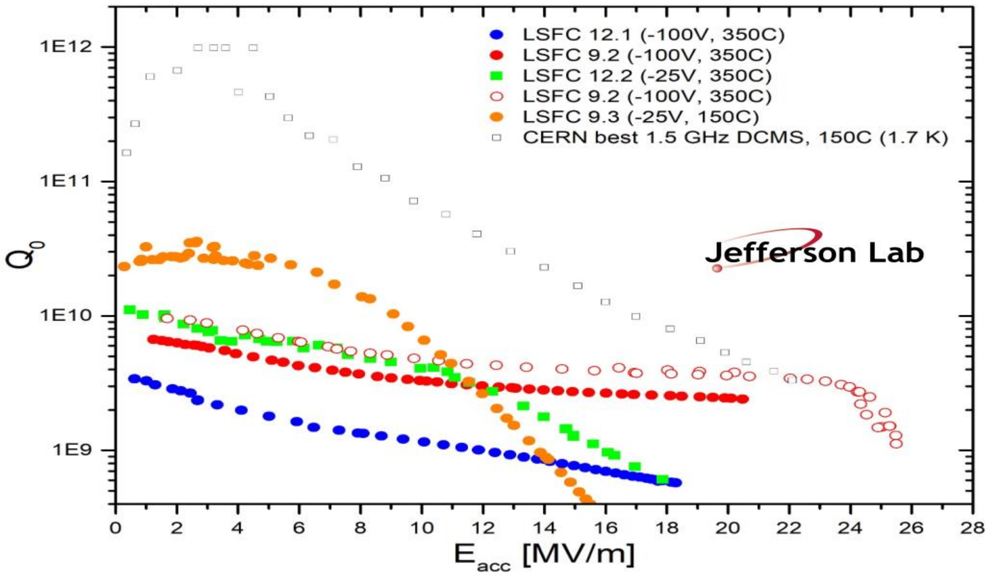
N doping on films

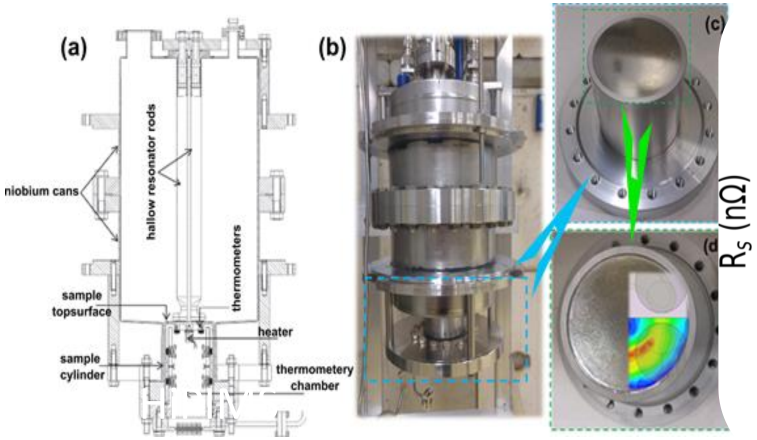
Substrate Fabrication & Processing

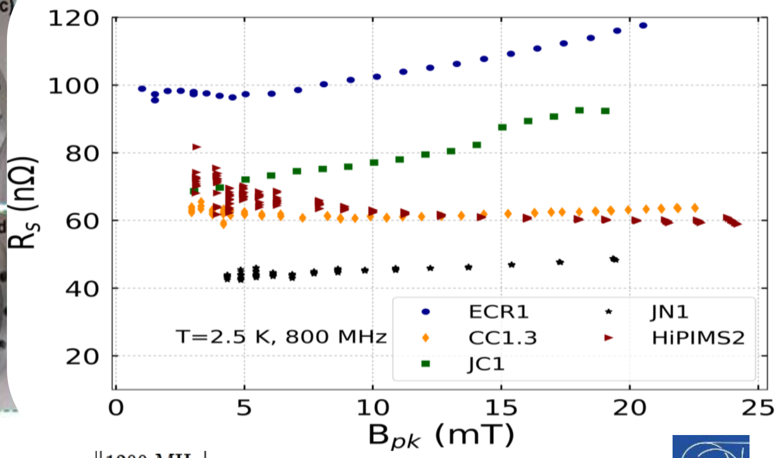




Advances in Thin Film Nb on Cu Technology



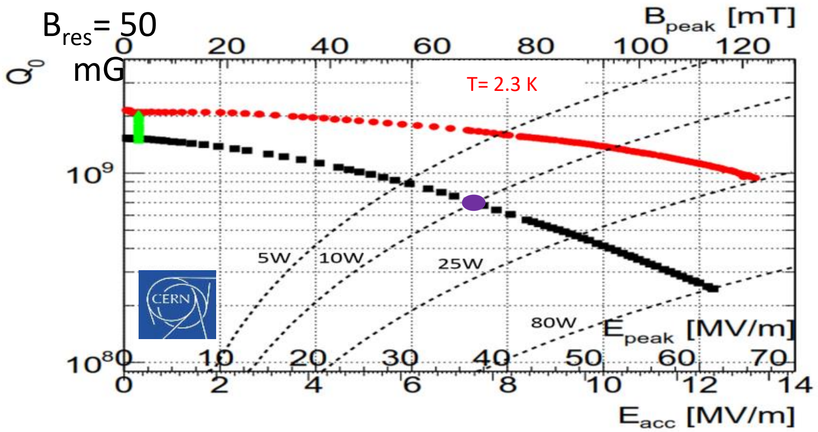




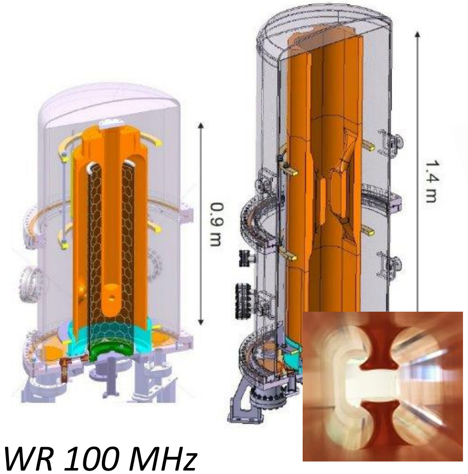
Sample	400 MHz R_{s0} (nΩ)	R_{s1} (nΩ/mT)	800 MHz R_{s0} (nΩ)	R_{s1} (nΩ/mT)	1200 MHz R_{s0} (nΩ)	R_{s1} (nΩ/mT)
ECR	19.7	0.84	65.8	1.14	126.2	1.35
HiPIMS	19.8	0.11	n/a*	n/a*	100.9	0.3
bulk Nb	21.2	0.13	42.1	0.32	120.1	0.69

Jefferson Lab

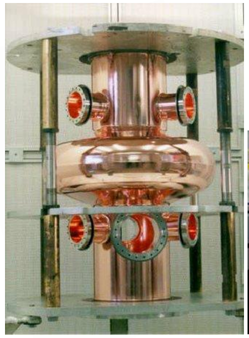
B_{res}= 50 mG



Developments across shapes & frequencies



QWR 100 MHz



LHC 400 MHz

FCC 800 MHz

956.2 MHz / 1.3 GHz

Jefferson Lab

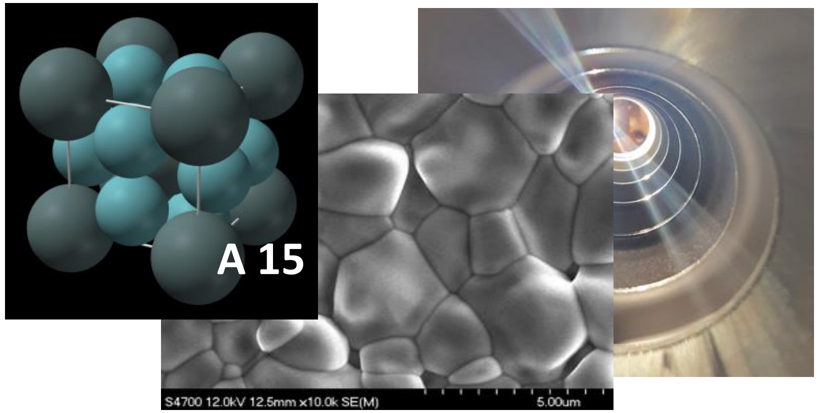
Jefferson Lab

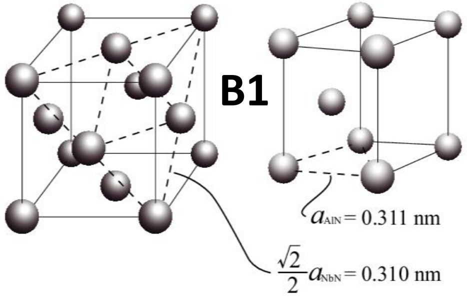
Explore alternative materials with higher critical temperature and critical fields

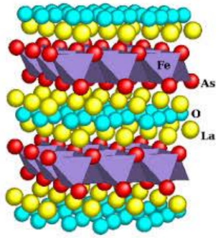
Alternate Materials and Advanced Structures for Higher Gradients and High Q

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

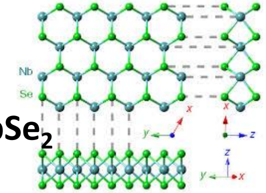
Material	T_c [K]	ρ_n(μΩcm)	$H_c(0)$ [mT]	$H_{c1}(0)$ [T]	$H_{c2}(0)$ [T]	H_{SH} [T]	$\lambda(0)$ [nm]	Δ [meV]	ξ [nm]	Type
Nb	9.23	2	200	0.17	0.28	0.219	40	1.5	28	II
Pb	7.2		80	N/A	N/A		48			I
NbN	16.2	70	230	0.02	15	0.214	200-350	2.6	<5	II, B1 comp.
NbTiN	17.3	35		0.03			150-200		<5	II, B1 comp.
Nb_3Sn	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



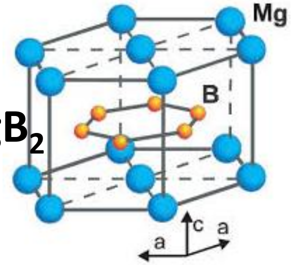




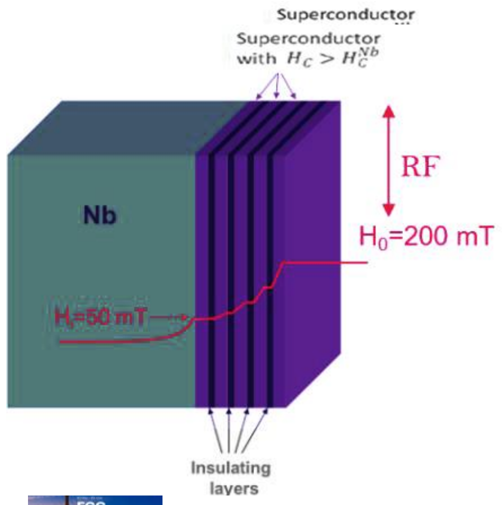
Pnictides



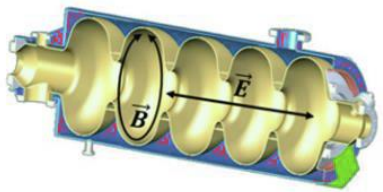
2D-$NbSe_2$

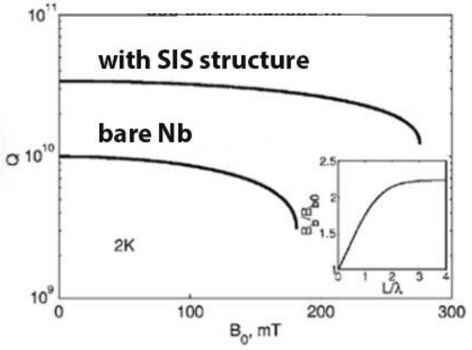


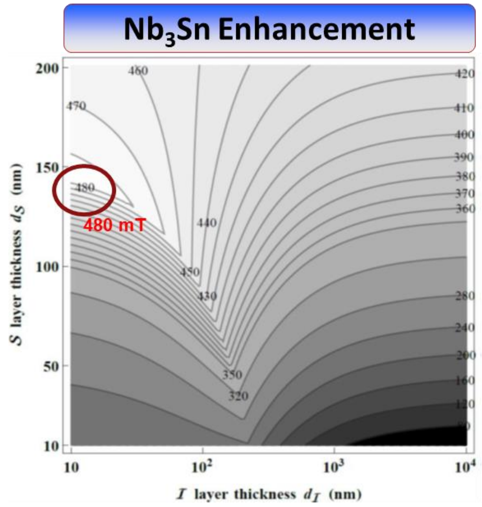
MgB_2



Multicell cavity



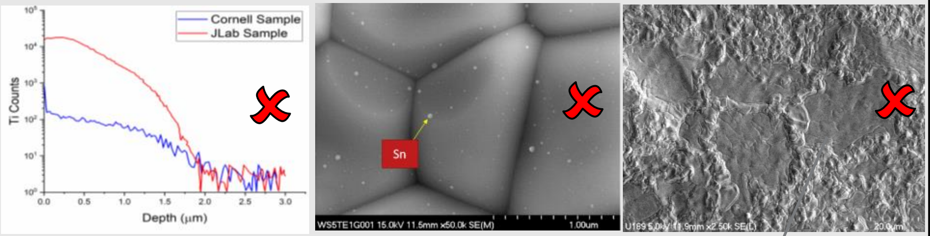




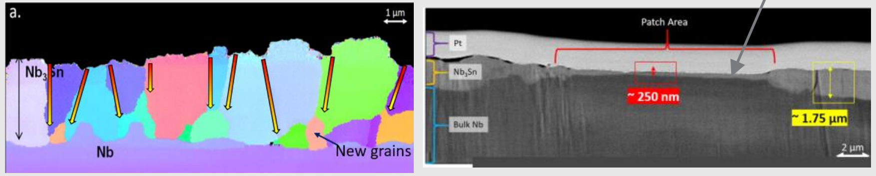
Alex Gurevich, Appl. Phys. Lett. 88, 012511 (2006)
Alex Gurevich, AIP ADVANCES 5, 017112 (2015)
T. Kubo, Applied Physics Letters 104, 032603 (2014)

Nb_3Sn Development

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

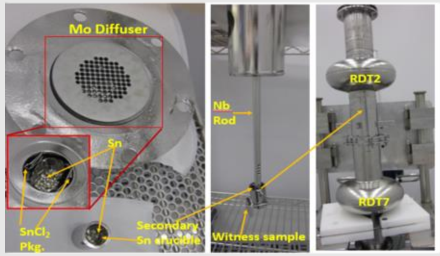


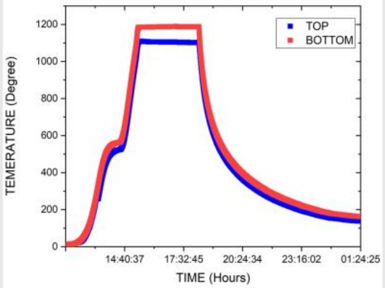
Potential factors contributing to recurrent Q-slopes in Nb_3Sn cavities



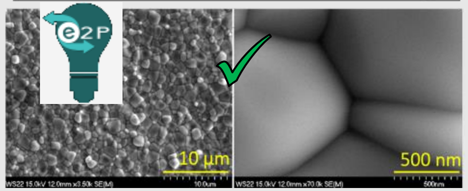
Grain-boundary diffusion primarily controls thin-film growth. Patchy regions lack grain boundaries resulting in RF-affecting thin regions.

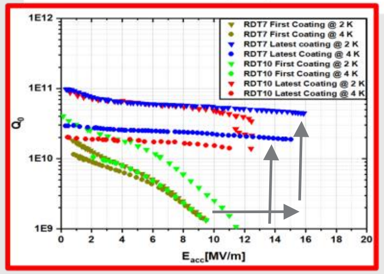
Process Development





No Sn-residues and uniform coating

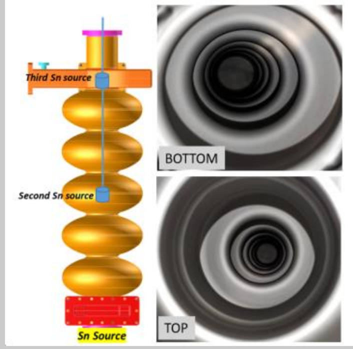


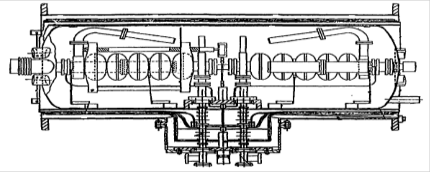


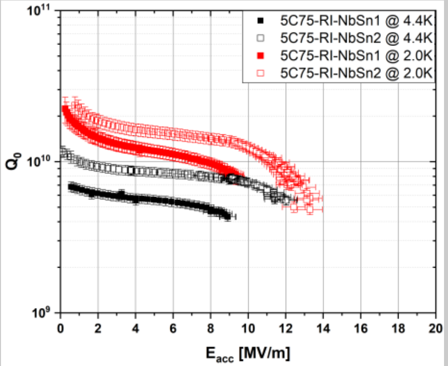
Modification of coating process based on learnings from correlated material and RF studies of Nb_3Sn samples resulted in the removal of recurrent Q-slopes.

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.

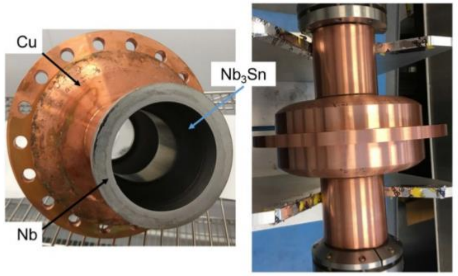


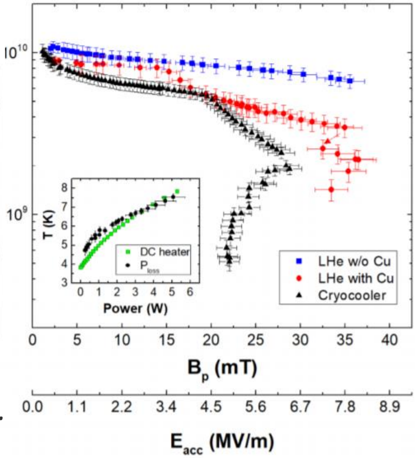




These cavities progress to quarter cryomodule for the first-ever beam test.

Multi-metallic conduction cooled Nb3Sn-coated cavity

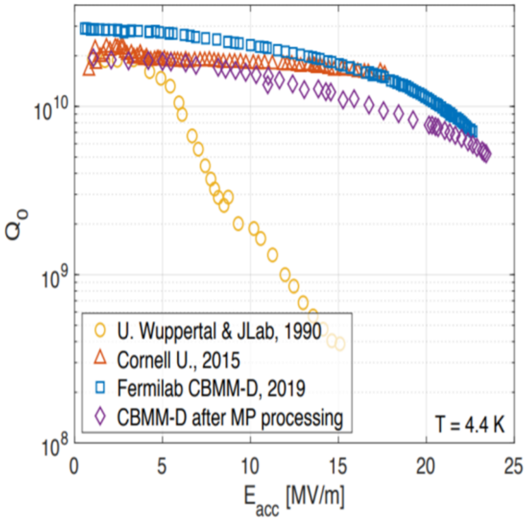




G. Ciovati *et al* 2020 *Supercond. Sci. Technol.* **33** 07LT01

- 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.

A15 Materials for SRF cavities



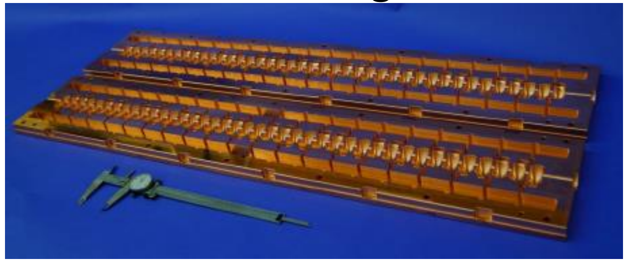
- Can reach **24 MV/m** E_{acc}
  - Meets spec for many machines!
  - Could read **100 MV/m**

Current 24 MV/m → Future 100 MV/m

Steady advancement over last 10 years:

Before 2013 ~5 MV/m → 2013 15 MV/m → 2015 18 MV/m → 2020 24 MV/m → 2030 50 MV/m ???

Alternative coating methods for Nb_3Sn/Cu or Nb/CuSn

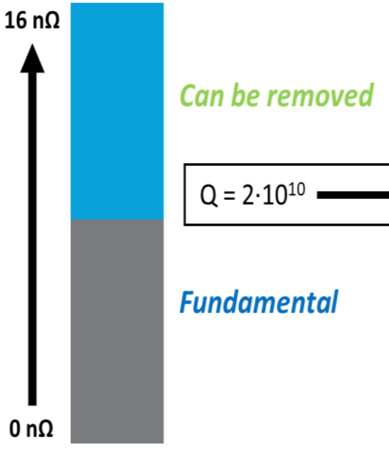


Electrodeposition, Nb/CuSn+annealing, magnetron sputtering

Meter-scale prototype C^3 structure

Before 2013 < 5 MV/m → 2013 15 MV/m → 2015 18 MV/m → 2020 24 MV/m → 2030 50 MV/m ???

Efficiency Improvements



$Q = 2\cdot10^{10} \longrightarrow 4\cdot10^{10}$

Higher Energy

- ~2 x higher potential maximum gradients
- Nb_3Sn + Traveling Wave + Improved cell shape → **E_{acc} > 140 MV/m (?)**

Higher Luminosity

- Lower cryogenics loses
- Lower cost
- Longer pulse lengths/bunch train length
- And/or higher rep. rate

S. Posen, M. Liepe, G. Eremeev, U. Pudasaini, C.E. Reece
"Nb3Sn Superconducting Radiofrequency Cavities: a Maturing Technology for Particle Accelerators and Detectors"
https://arxiv.org/pdf/2203.06752

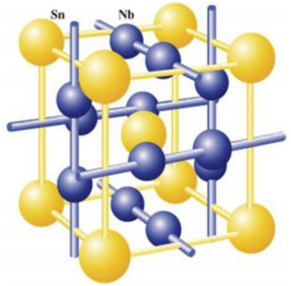
E. Barzi et al.
An Impartial Perspective on Superconducting Nb3Sn coated Cu RF Cavities for Future Accelerators
https://indico.cern.ch/event/656491/contributions/2932254/

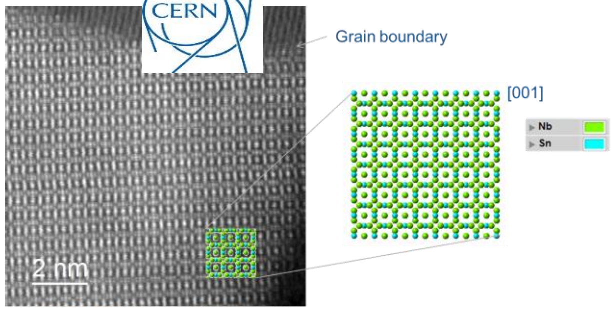
Alternative Materials to Nb & Multilayered Structures

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

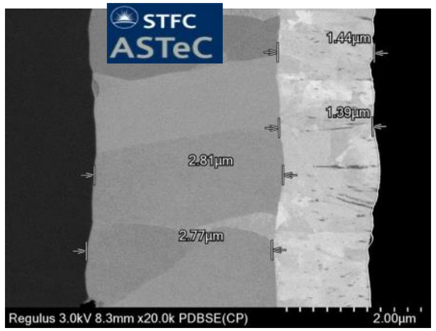
Especially for low melting temperature substrates (Cu, CuSn, Al…)

- 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

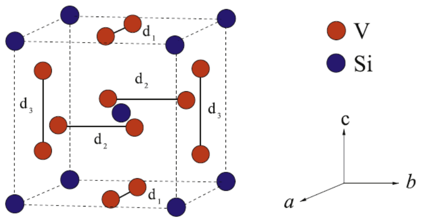


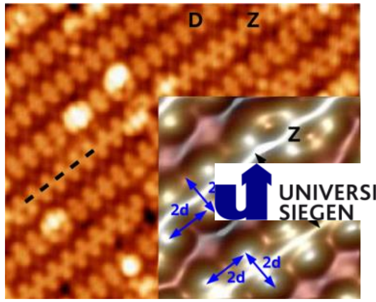


HAADF STEM image of Nb3Sn grain in [001] zone axis and grain boundary



Cubic Phase (a = b =c)



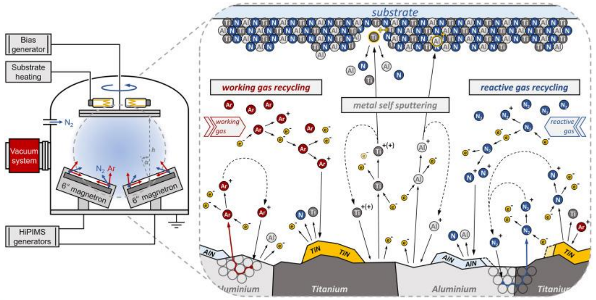


Hauptmann, N., M. Becker, J. Kröger and R. Berndt. "Surface reconstruction and energy gap of superconducting V (001)." Physical Review B 79 (2009): 144522.

UNIVERSITÄT SIEGEN

TECHNISCHE UNIVERSITÄT DARMSTADT

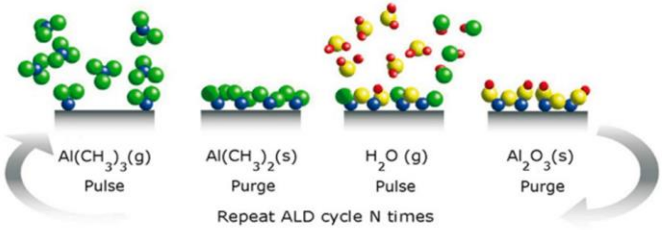
Re-HiPIMS

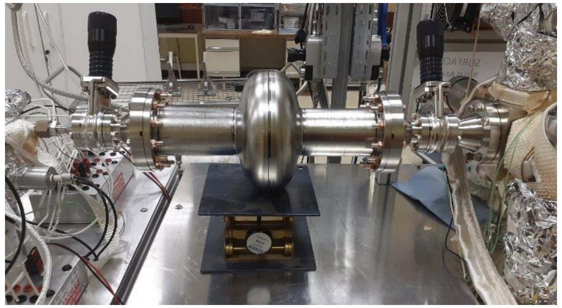


High quality dense films

Improved conformality

ALD

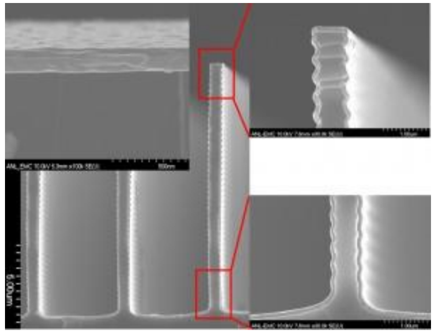




Conformal, self-limiting

nm precision

Precursors difficult

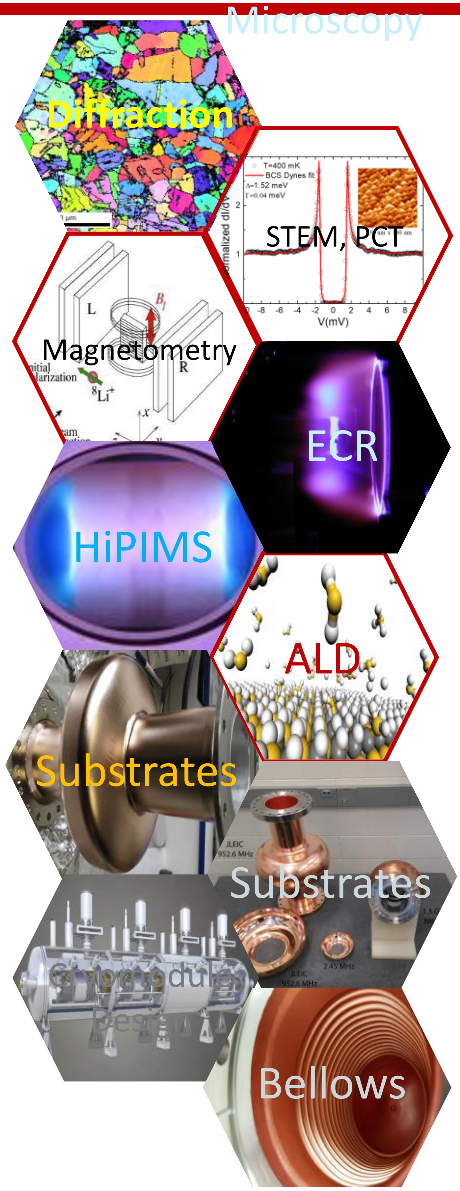


Institut national de physique nucléaire et de physique des particules

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

Irfu - CEA Saclay

Path Forward



Already well-established and fruitful international R&D collaborations

JLab, SLAC, ODU, CORNELL, FNAL, FSU, W&M, ANL, Temple U. …

&

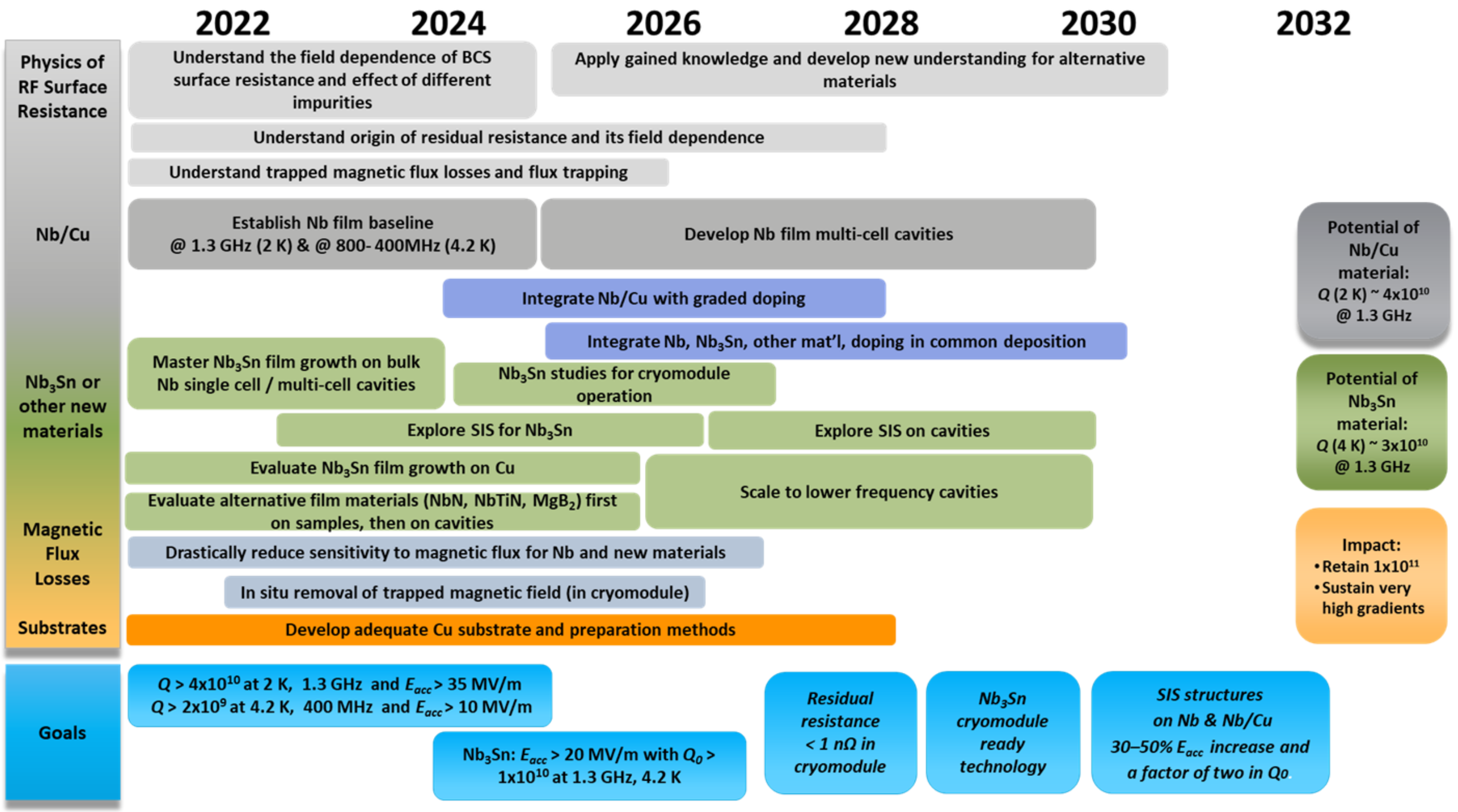
CEA Saclay, CERN, DESY, HZB, INFN-LNL, KEK, STFC, TRIUMF and other institutions

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…

SRFTF Development

F. Marhauser, R. A. Rimmer et al.



- 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.
- Developments 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

A.- M. Valente-Feliciano, C. Antoine, S. Anlage, G. Ciovati, J. Delayen, et al.
"Next-Generation Superconducting RF Technology based on Advanced Thin Film Technologies and Innovative Materials for Accelerator Enhanced Performance and Energy Reach"
https://arxiv.org/pdf/arXiv:2204.02536

Machine Developments Based on Advanced SRF Systems

incorporate recent improvements in SRF technology

- 650 MHz: higher Q (>6×10^{10}) at 2 K and 20.9 MV/m – using nitrogen doping recipe improvement.
- 1300 MHz: high Q (>2×10^{10}) at 2 K and higher gradient of >33.7 MV/m – using a new 2-step low temperature bake or some other recipe.
- Resonance control R&D for microphonics suppression (CW) and Lorentz Force Detuning (LFD) compensation (pulsed).
- Ferroelectric tuner for both resonance control and coupling adjustment – will improve efficiency of the SRF systems.
- Robotic assembly of the SRF cavity strings in clean rooms – essential for achieving high gradients.

S. Belomestnykh, M. Checchin, D. Johnson, D. Neuffer, S. Posen, E. Pozdeyev, V. Pronskikh, N. Solyak, V. Yakovlev.
"An 8 GeV Linac as the Booster Replacement in the Fermilab Power Upgrade
https://arxiv.org/pdf/2203.05052 (also under NF09)

S. Belomestnykh, P.C. Bhat, A. Grassellino, M. Checchin, D. Denisovet al.
Higgs-Energy LEptoN (HELEN) Collider based on advanced superconducting radio frequency technology
https://arxiv.org/pdf/2203.05052

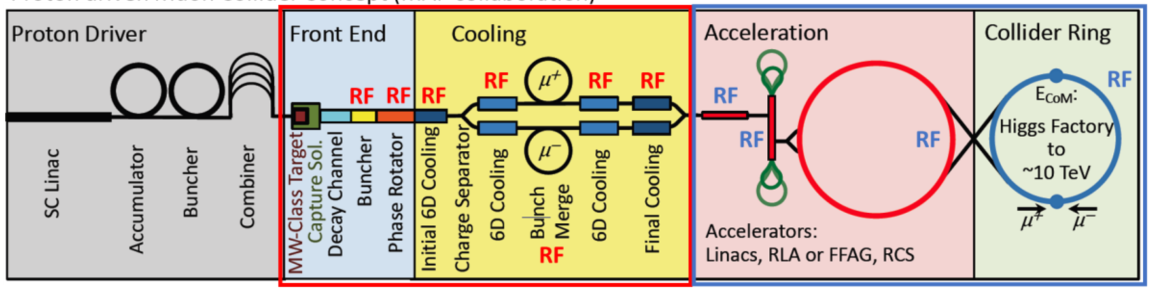
Asher Berlin, Sergey Belomestnykh, Diego Blas, et al.
Searches for New Particles, Dark Matter, and Gravitational Waves with SRF Cavities
https://arxiv.org/pdf/2203.12714.pdf

Alexander Scheinker, Spencer Gessner
"Adaptive Machine Learning for Time-Varying Systems: Towards 6D Phase Space Diagnostics of Short Intense Charged Particle Beams"
https://arxiv.org/pdf/2203.04391 (also under CompF03)

SRF for muon acceleration

Muon collider and RF system challenges

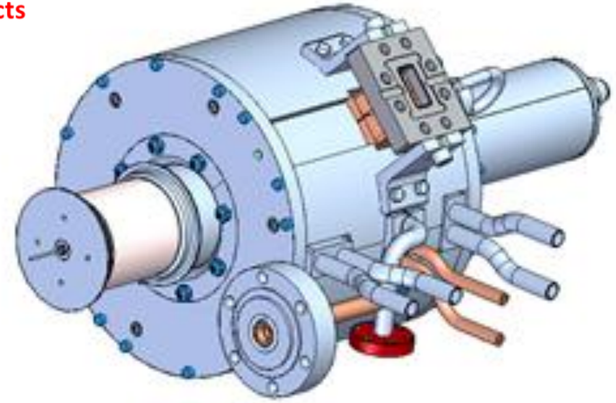
Proton driven Muon Collider Concept (MAP collaboration)



Normal conducting RF for capture and cooling

- **High-gradient cavities in high magnetic field**
- **High charge, Huge beam size, Important beam losses**
- **Peak RF power**
- **Little synergy with other projects**

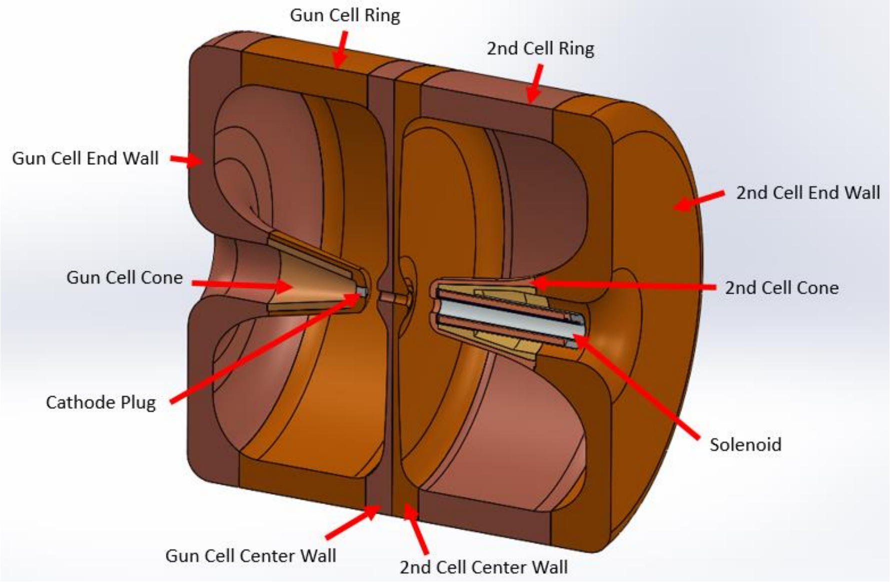
- **Super conducting RF for acceleration**
  - **High charge, short bunch, low current**
  - **High efficiency at high gradient**
  - **Maintain beam quality**
  - **Longitudinal and transverse stability**



Thomas Roser.
"Sustainability Considerations for Accelerator and Collider Facilities"
https://arxiv.org/pdf/2203.07423 (also under CommF07)

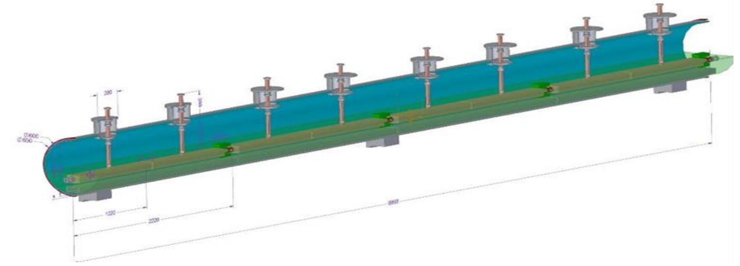
Highest possible gradient
Pulsed operation of ~1ms (linac) -> ~10ms (RCS) may help
Resilience to beam losses and (stray) magnetic field
Design of the cavity considering

- High gradient
- High efficiency
- Longitudinal & transverse beam dynamic requirements

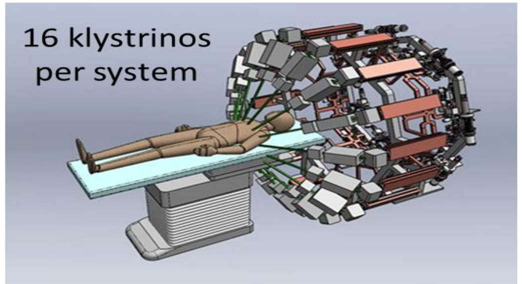


Compact SRF Accelerators for Societal Applications

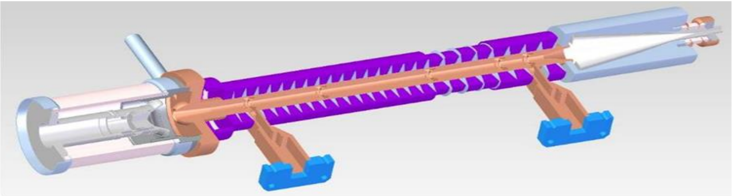
Cool Copper Collider (C^3) – Liquid N_2-cooled C-band distributed coupling linac



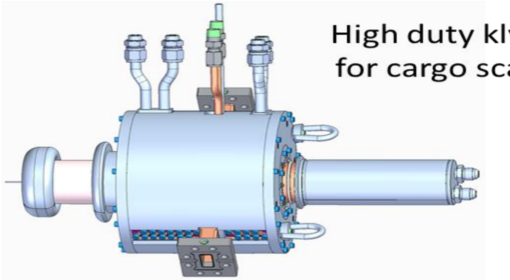
Next-generation radiation therapy



Compact PPM-focused klystrinos – Portable radiography for emergency response



High duty klystrino for cargo scanning



Salime Boucher, Eric Esarey, Cameron Geddes, Carol Johnstone, Sergey Kutsaev, Billy W. Loo Jr et al
"Transformative Technology for FLASH Radiation Therapy"
https://arxiv.org/pdf/arXiv:2203.11047, also under CommF01

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

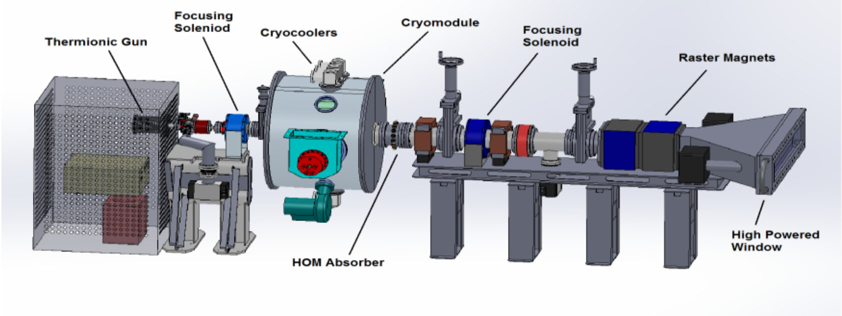
Cost effective compact superconducting accelerators will reduce the footprint and capital investment of

- *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

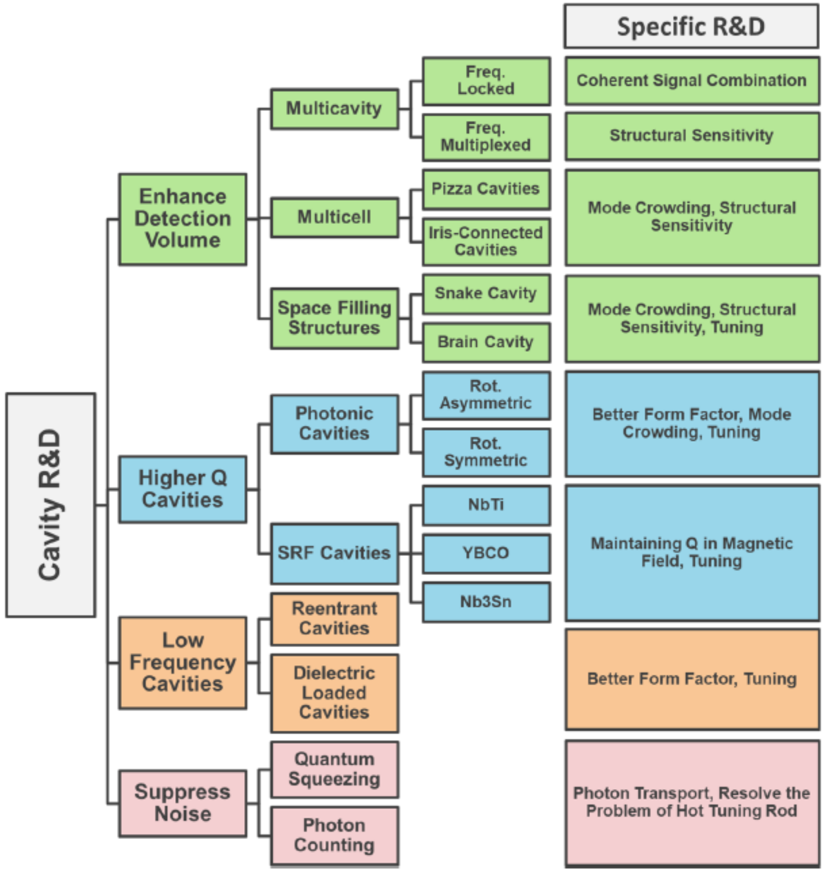
Compact cavity cooled by cryocoolers for environmental applications



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.

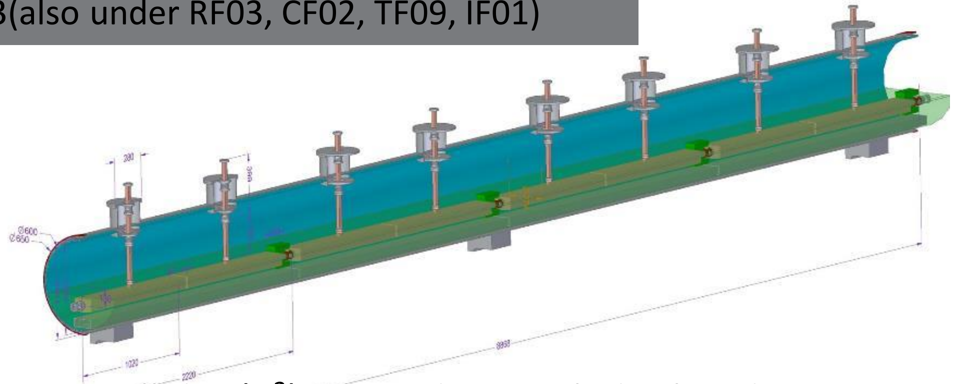
Stilin, Neil et al. "Stable CW Operation of Nb_3Sn SRF Cavity at 10 MV/m using Conduction Cooling." arXiv: 2002.11755: Accelerator Physics (2020).
R C Dhuley et al 2020 Supercond. Sci. Technol. 33 06LT01

Advanced RF Structures



- ❑ Cavities with sophisticated geometry and tuning mechanisms required to allow large volume experiments to be operated at high frequencies.
- ❑ Microwave cavities for axion searches leverage new ideas from both accelerators and quantum information sciences.
- ❑ Moving to higher frequencies cavity volumes run into rapidly degrading volumes and lower quality factors for ordinary metals. There are several methods to recover this:
  - •Increase volume by coherently adding multiple cavities in phase at the same frequency to take advantage of the axion coherence
  - •Increase search scan rate but building an array of cavities with complementary frequencies and small tuning range to perform a frequency comb search. Does not take advantage of axion coherence but may be simpler to implement

J. Jaeckel, G. Rybka, L. Winslow, for the Axion Prospects Collaboration
"Axion Dark Matter"
https://arxiv.org/pdf/arXiv:2203.14923(also under RF03, CF02, TF09, IF01)



Cool Copper Collider (C^3) – Liquid N_2-cooled C-band distributed coupling linac
For compact Higgs Factory

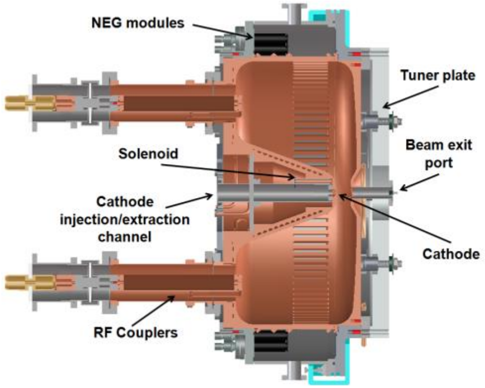
Emilio A. Nanni, Martin Breidenbach, Caterina Vernieri, Sergey Belomestnykh, et al.
"C^3 Demonstration Research and Development Plan"
https://arxiv.org/pdf/arXiv:2203.09076, also under CommF01)

High Efficiency RF Sources

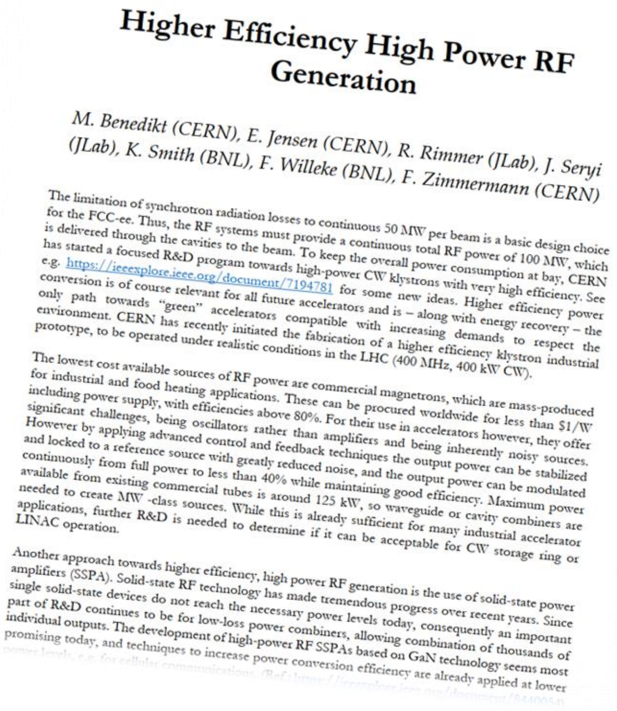
Thomas Kroc, Vyacheslav Yakovlev, Charles Thangaraj, Brian Chase, Ram Dhuley.
"The Need for Further Development of Magnetrons as RF Sources for HEP"
https://arxiv.org/pdf/arXiv:2203.07888

Xueying Lu, Jiahang Shao, John Power, Chunguang Jing, Gwanghui Ha, et al.
"Advanced RF Structures for Wakefield Acceleration and High-Gradient Research"
https://arxiv.org/pdf/arXiv:2203.08374

R&D areas



- ❑ **Higher efficiency klystron** development involving modern concepts like "BAC", "COM", "CSM" and others. Application also to Inductive Output Tubes (IOTs),
- ❑ Investigate stabilization, phase control and combination of **magnetron** RF sources for possible accelerator use.
- ❑ Development of scalable **power combiners** to combine thousands of inputs (of kW level) in few stages to reach power levels necessary to operate large particle accelerators,
- ❑ Development, jointly with industry, GaN-based **SSPA modules**, applying techniques to increase efficiency at high power levels (Class F, multi-harmonic terminations …)



Higher Efficiency High Power RF Generation

M. Benedikt (CERN), E. Jensen (CERN), R. Rimmer (JLab), J. Seryi (JLab), K. Smith (BNL), F. Willeke (BNL), F. Zimmermann (CERN)

The limitation of synchrotron radiation losses to continuous 50 MW per beam is a basic design choice for the FCC-ee. Thus, the RF systems must provide a continuous total RF power of 100 MW, which is delivered through the cavities to the beam. To keep the overall power consumption at bay, CERN has started a focused R&D program towards high-power CW klystrons with very high efficiency. See e.g. https://ieeexplore.ieee.org/document/7194781 for some new ideas. Higher efficiency power conversion is of course relevant for all future accelerators and is – along with energy recovery – the only path towards "green" accelerators compatible with increasing demands to respect the environment. CERN has recently initiated the fabrication of a higher efficiency klystron industrial prototype, to be operated under realistic conditions in the LHC (400 MHz, 400 kW CW).

The lowest cost available sources of RF power are commercial magnetrons, which are mass-produced for industrial and food heating applications. These can be procured worldwide for less than $1/W including power supply, with efficiencies above 80%. For their use in accelerators however, they offer significant challenges, being oscillators rather than amplifiers and being inherently noisy sources. However by applying advanced control and feedback techniques the output power can be stabilized and locked to a reference source with greatly reduced noise, and the output power can be modulated continuously from full power to less than 40% while maintaining good efficiency. Maximum power available from existing commercial tubes is around 125 kW, so waveguide or cavity combiners are needed to create MW -class sources. While this is already sufficient for many industrial accelerator applications, further R&D is needed to determine if it can be acceptable for CW storage ring or LINAC operation.

Another approach towards higher efficiency, high power RF generation is the use of solid-state power amplifiers (SSPA). Solid-state RF technology has made tremendous progress over recent years. Since single solid-state devices do not reach the necessary power levels today, consequently an important part of R&D continues to be for low-loss power combiners, allowing combination of thousands of individual outputs. The development of high-power RF SSPAs based on GaN technology seems most promising today, and techniques to increase power conversion efficiency are already applied at lower

Sustainability for SRF Systems

R. Lawrence Ives, Michael Read, Thuc Bui, David Marsden, et al
. **”High Efficiency, Low Cost, RF Sources for Accelerators an Colliders”**
https://arxiv.org/pdf/arXiv:2203.12043 (also under EF0, RF0, AF03)

Brandon Weatherford, Emilio A. Nanni, Sami Tantawi
”Advanced RF Sources R&D for Economical Future Colliders”,
https://arxiv.org/pdf/2203.15984

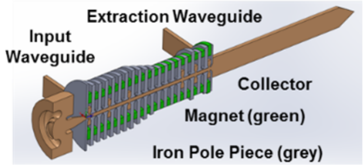
Xueying Lu, Jiahang Shao, John Power, Chunguang Jing, Gwanghui Ha, et al.
”Advanced RF Structures for Wakefield Acceleration and High-Gradient Research”
https://arxiv.org/pdf/arXiv:2203.08374

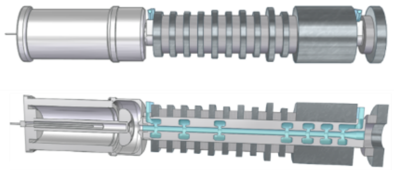
The Modular Array Multi-Beam Klystron (MA-MBK) – High volume RF sources with several uses

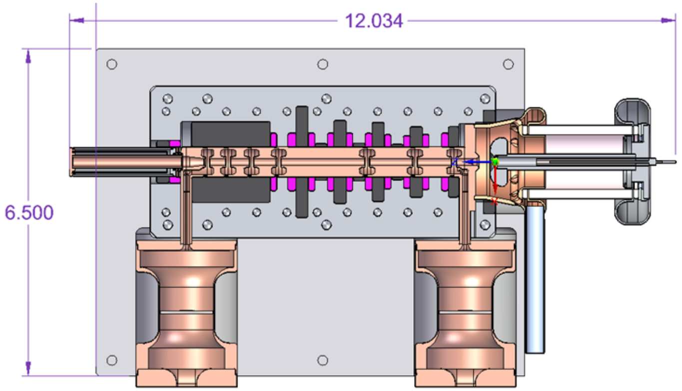
Compact, low-voltage “klystrinos” – one RF source topology for many situations:

- Stand-alone RF sources for low power, compact and portable systems
- High volume, distributed linac feeding
- Passive combining for higher peak power

Integrated Pole Pieces/
Long Period Halbach Arrays

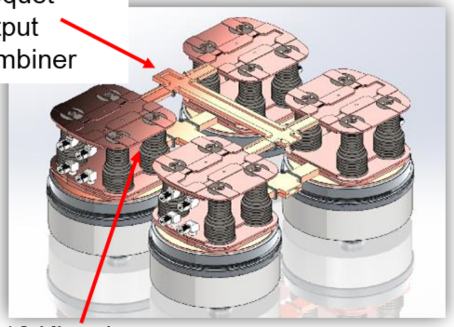






A. Jensen, “A Modular 5 MW X-Band Multi-Beam Klystron”, SLAC-PUB-15877.
Franzi, Gamzina, Jensen, Kowalczyk, Tantawi

Floquet output combiner



16 Klystrinos

Jefferson Lab

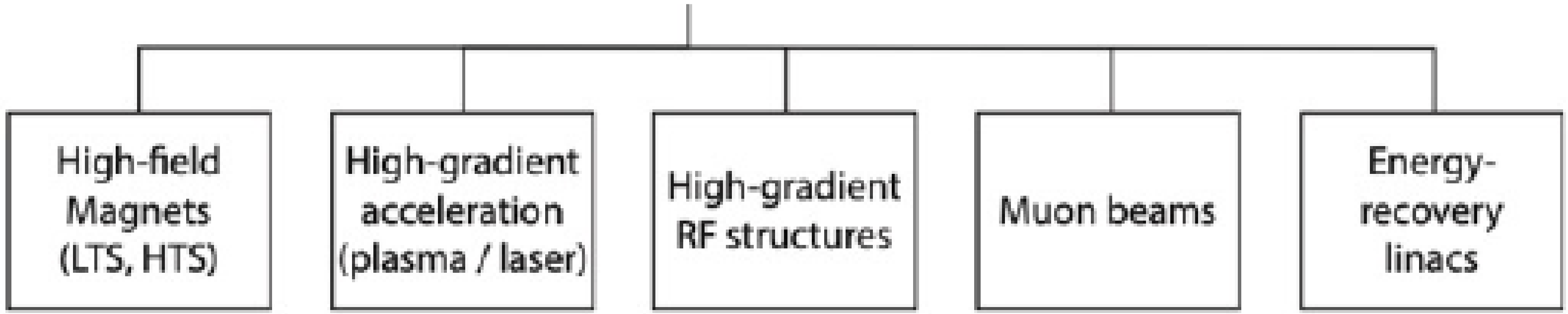
What is needed?

- 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

Synergy with European Strategy

- ❑ European Strategy for Particle Physics (ESPP) describes strategy for particle physics in Europe and their contributions world-wide (June 19, 2020)
- ❑ European National Laboratories Directors Group (LDG) – July 2 (Chaired by Lenny Rivkin)
- ❑ Immediate outcome àAccelerator R&D Task Forces reporting to Lab Directors Group(LDG) and CERN Council
- ❑ Address the question of what are the most promising Accelerator R&D activities for HEP

5 Targetted Accelerator R&D Expert Panels



Snowmass AF participants are active on all the LDG panels

Efforts in the United States for SRF research and development are in synergy with other regions, Europe and Asia coherent with the European Strategy for particle physics document published January 2022

CONCLUSIONS

The next 5-40 years will be an exciting time in Accelerator Physics & SRF

Snowmass process is well advanced and offer opportunities to advocate to

The scientific community

the public

our funding agencies and governments

Will lead to a comprehensive international program for US participation in future colliders that welcomes all with know-how and interest, and at all levels of innovation and R&D

http://seattlesnowmass2021.net/

MERCI

THANK YOU