The 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

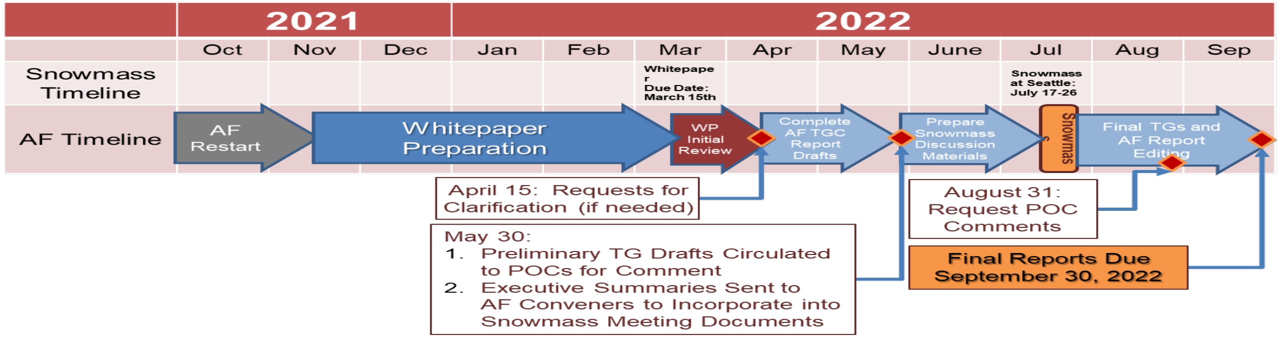
- ❑ Sponsored by APD DPF, DPB…
- ❑ Define the most important questions in the field of particle physics and identify promising opportunities to address them.
- ❑ Assess the future of elementary particle physics, to explore the limits of our technological capabilities, and to consider the nature of future major facilities for particle physics in the US.

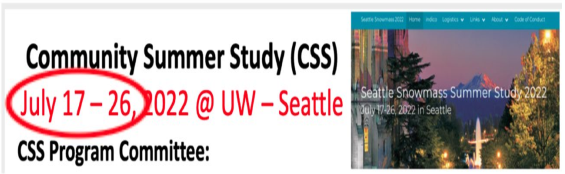
https://www.snowmass21.org/

- ❑ Provides scientific input to DOE's P5 (Particle Physics Project Prioritization Panel) that develops a strategy for the US HEP program that can be executed over a 10 year timescale, in the context of a 20-year global vision for the field.
- ❑ Planning for 2025-2035 with a view toward 2050

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





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 Accelerator Frontier

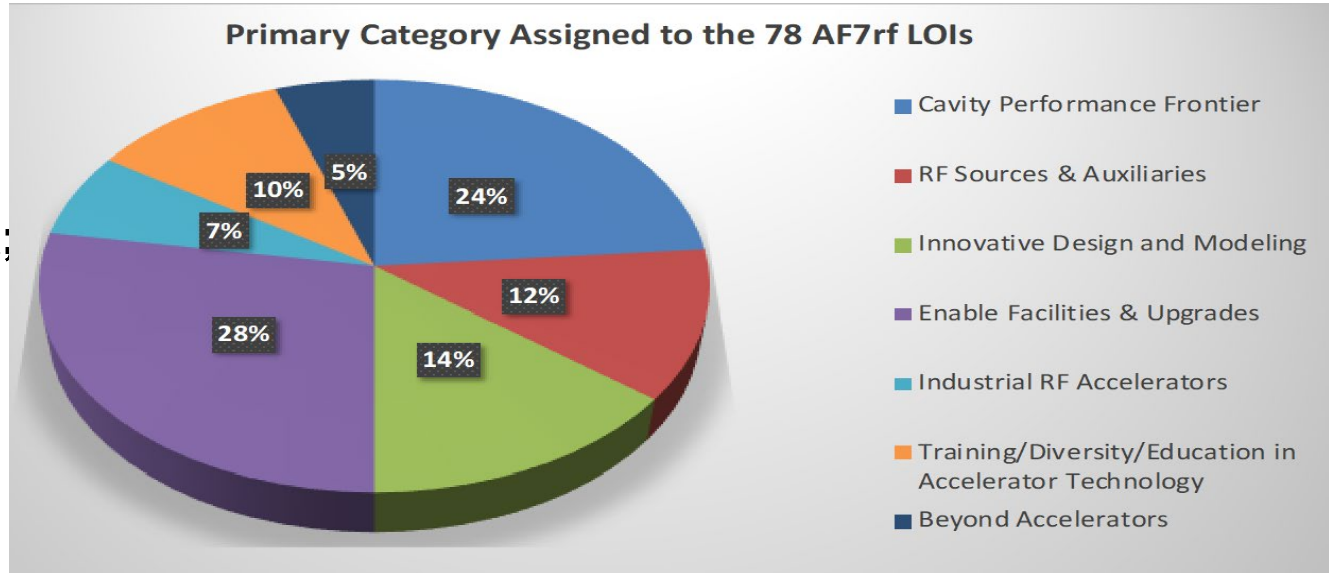
The Accelerator Frontier activities include discussions on high-energy hadron and lepton colliders, high-intensity beams for neutrino research and for the “Physics Beyond Colliders”, accelerator technologies, science, education and outreach as well as the progress of core accelerator technology, including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

Participants submitted Letters of Intent, contributed papers, took part in corresponding workshops and events, contributed to writing summaries and took 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

Sergey Belomestnykh, Emilio Nanni, Hans Weise



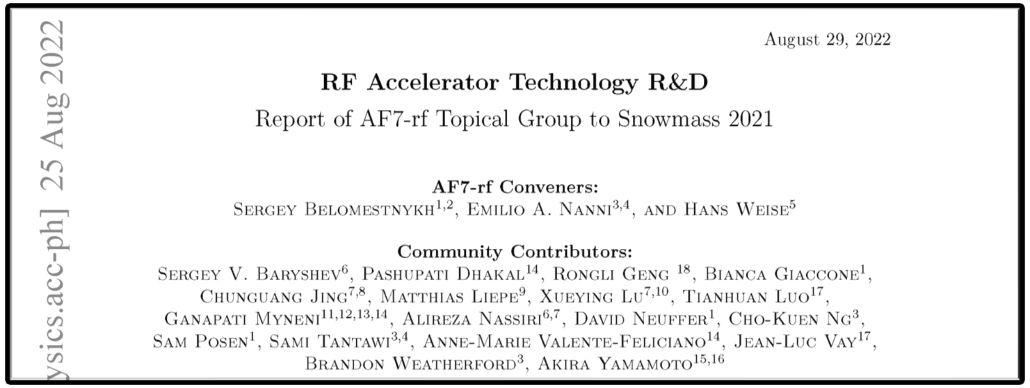
- ❑ **78 LOIs submitted**
- ❑ **18 WP submitted to AF-RF (additional 9 relevant; probably more)**

https://snowmass21.org/submissions/start

- ❑ ***3 mini Workshops***

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

AF7-rf report presented at July Meting; structure informed from submissions & community events


ysics.acc-ph] 25 Aug 2022

August 29, 2022

RF Accelerator Technology R&D

Report of AF7-rf Topical Group to Snowmass 2021

AF7-rf Conveners:

Sergey Belomestnykh[1,2], Emilio A. Nanni[3,4], and Hans Weise[5]

Community Contributors:

Sergey V. Baryshev[6], Pashupati Dhakal[14], Rongli Geng [18], Bianca Giaccone[1], Chunguang Jing[7,8], Matthias Liepe[9], Xueying Lu[7,10], Tianhuan Luo[17], Ganapati Myneni[11,12,13,14], Alireza Nassiri[6,7], David Neuffer[1], Cho-Kuen Ng[3], Sam Posen[1], Sami Tantawi[3,4], Anne-Marie Valente-Feliciano[14], Jean-Luc Vay[17], Brandon Weatherford[3], Akira Yamamoto[15,16]

Jefferson Lab

SRF Performance Frontier - Contributions

miniWorkshop on Cavity Performance Frontier

Snowmass 2021

19 Workshop presentations

Three groups

- Structure wakefield accelerators
- Normal conducting high-gradient structures
- SRF R&D

Welcome and Introduction: Welcome and Introduction		09:00 - 09:10
Structure Wakefield Acceleration (SWFA) Development for an Energy Frontier Machine	John Power	09:10 - 09:25
SWFA demonstrators with integrated technologies for future large-scale machines	Jiahang Shao	09:25 - 09:40
Short-pulse wakefield structure R&D for high gradient and high efficiency acceleration in future large-scale machines	Jiahang Shao	
Open Floor - Discussion on SWFA		09:55 - 10:15
A model of rf vacuum arcs	Jim Norem	10:15 - 10:30
High-Gradient Accelerators at THz Frequencies	Emilio Nanni	10:30 - 10:45
High-gradient RF structures for C3	Prof. Sami Tantawi	10:45 - 11:00
Open Floor – Discussion on Normal conducting high-gradient structures		11:00 - 11:20
Key Directions for Research and Development of Superconducting Radiofrequency (SRF) Cavities	Sergey Belomestnykh	
Challenges and opportunities of SRF theory for particle accelerators	Alex Gurevich	11:35 - 11:50
Normal and super conducting RF R&D for muon collider	Alexey Grudiev	11:50 - 12:05
Plasma Processing for In-Situ Field Emission Mitigation of Superconducting Radiofrequency (SRF) Cryomodules	Marina Martinello	
Field Emission Suppression in High-Gradient SRF Cavity Systems	Rongli Geng et al.	12:20 - 12:35
Open Floor - Discussion on general SRF topics		12:35 - 12:55

55

Welcome		09:00 - 09:05
Traveling wave SRF for ILC Energy Upgrade	Prof. Hasan Padamsee	09:05 - 09:20
Development of High-efficiency and Cost-effective Forged Ingot Niobium Technology for Science Frontiers and Accelerator Applications	Ganapati Myneni et al.	
Open Floor - Discussion on general SRF topics		09:35 - 09:55
Nb3Sn Superconducting Radiofrequency Cavities	Ryan Porter	09:55 - 10:10
An Impartial Perspective for Superconducting Nb3Sn coated Copper RF Cavities for Future Linear Accelerators	Emanuela Barzi	
Open Floor - Discussion on Nb3Sn cavities		10:25 - 10:45
Next-Generation Superconducting RF Technology based on Advanced Thin Film Technologies and Innovative Materials for Accelerator Enhanced Performance & ...	Anne-Marie Valente-Feliciano	
Innovative Materials and Surface Treatments for SRF applications	Mattia Checchin	11:00 - 11:15
The necessity of a basic materials research community for the accelerated development of SRF materials	Shreyas Balachandran	
Development of MgB2 Coated Superconducting Cavities	Dr Tsuyoshi Tajima	11:30 - 11:45
Open Floor - Discussion on Thin films, new materials		11:45 - 12:05
General discussion, Closing remarks		12:05 - 12:35

9 WP

Direct Cavity Performance Frontier White Papers

Snowmass 2021

1. Medium-Grain Niobium SRF Cavity Production Technology For Science Frontiers and Accelerator Applications https://arxiv.org/abs/2203.07371
2. Understanding Vacuum Arcs and Gradient Limits https://arxiv.org/abs/2203.01847
3. Advanced RF Structures for Wakefield Acceleration and High-Gradient Research https://arxiv.org/abs/2203.08374
4. Key Directions for Research and Development of Superconducting Radiofrequency (SRF) Cavities http://arxiv.org/abs/2204.01178
5. Next-Generation Superconducting RF Technology based on Advanced Thin Film Technologies and Innovative Materials for Accelerator Enhanced Performance & Energy Reach https://arxiv.org/abs/2204.02536
6. Nb_3Sn Superconducting Radiofrequency Cavities: a Maturing Technology for Particle Accelerators and Detectors https://arxiv.org/abs/2203.06752
7. An Impartial Perspective for Superconducting Nb_3Sn coated Copper RF Cavities for Future Linear Accelerators https://arxiv.org/abs/2203.09718
8. Plasma Processing for In-Situ Field Emission Mitigation of Superconducting Radiofrequency (SRF) Cryomodules https://arxiv.org/abs/2203.12442
9. Challenges and opportunities of SRF theory for next generation particle accelerators https://arxiv.org/abs/2203.08315

Improve SRF Cavity Performance (Gradient and Q), Study New Superconductors
Advanced SWFA Strytuctures; Understanding Vacuum Arc and RF Breakdown

Facility White Papers with Strong Need for Cavity Performance

Snowmass 2021

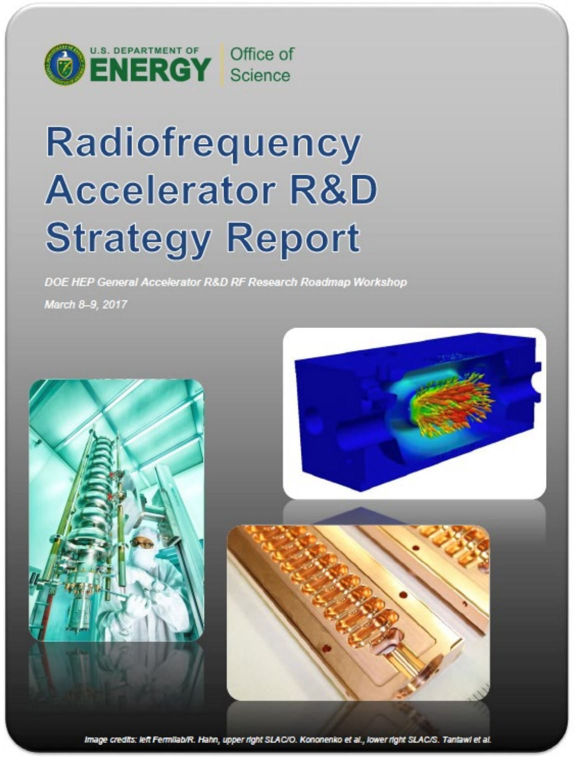
- The International Linear Collider: Report to Snowmass 2021 https://arxiv.org/abs/2203.07622
- Higgs-Energy LEptoN (HELEN) Collider based on advanced superconducting radio frequency technology https://arxiv.org/abs/2203.08211
- Continuous and Coordinated Efforts of Structure Wakefield Acceleration (SWFA) Development for an Energy Frontier Machine https://arxiv.org/abs/2203.08275
- C^3: A 'Cool' Route to the Higgs Boson and Beyond https://arxiv.org/abs/2110.15800
- C^3 Demonstration Research and Development Plan https://arxiv.org/abs/2203.09076
- An 8 GeV Linac as the Booster Replacement in the Fermilab Power Upgrade: a Snowmass 2021 White Paper https://arxiv.org/abs/2203.05052
- The CLIC Project https://arxiv.org/abs/2203.09186
- The Future Circular Collider: a Summary for the US 2021 Snowmass Process https://arxiv.org/abs/2203.06520
- Searches for new particles, dark matter, and gravitational waves with SRF cavities https://arxiv.org/abs/2204.01178
- Snowmass2021 White Paper AF3- CEPC
- A Muon Collider Facility for Physics Discovery
- CERC - Circular e+e- Collider using Energy-Recovery Linac
- The ReLiC– Recycling Linear e+e- Collider

High-gradient SRF and NCRF for Future Accelerators and Dark Matter Searches
SWFA for Energy Frontier

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

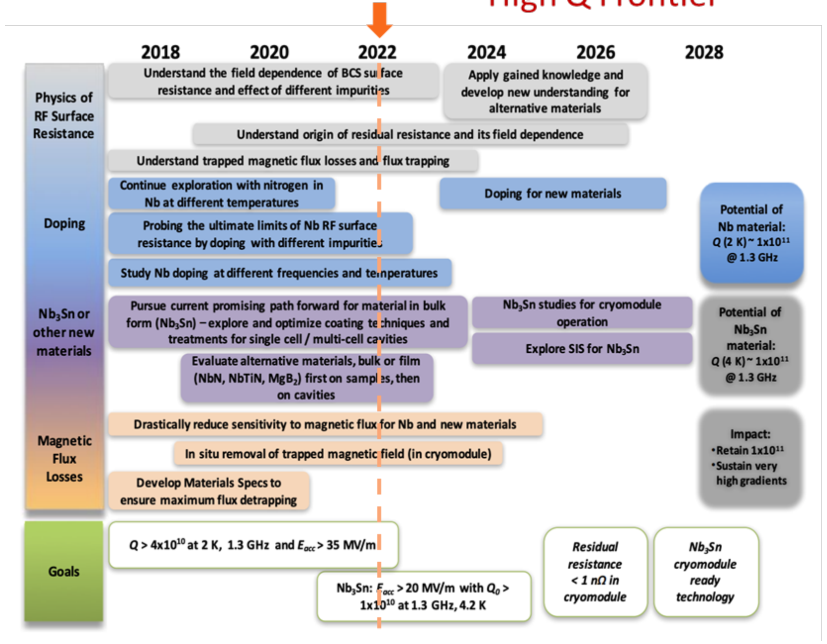


General Accelerator R&D RF Research Roadmap Workshop Report

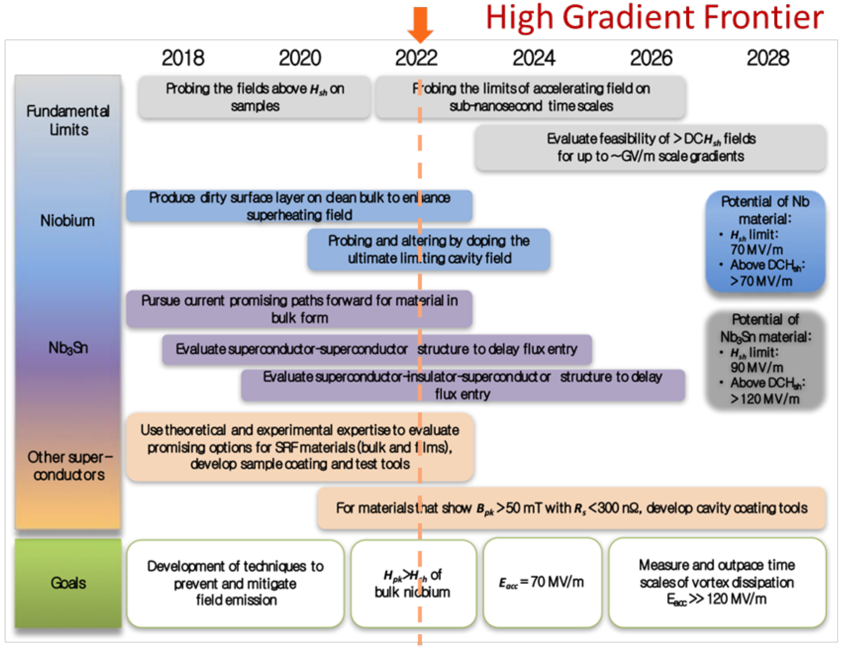
https://www.osti.gov/servlets/purl/1631119/

- 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
- Anticipated that the roadmaps will be updated after *SnowMass2021* and subsequent P5 process

High Q Frontier

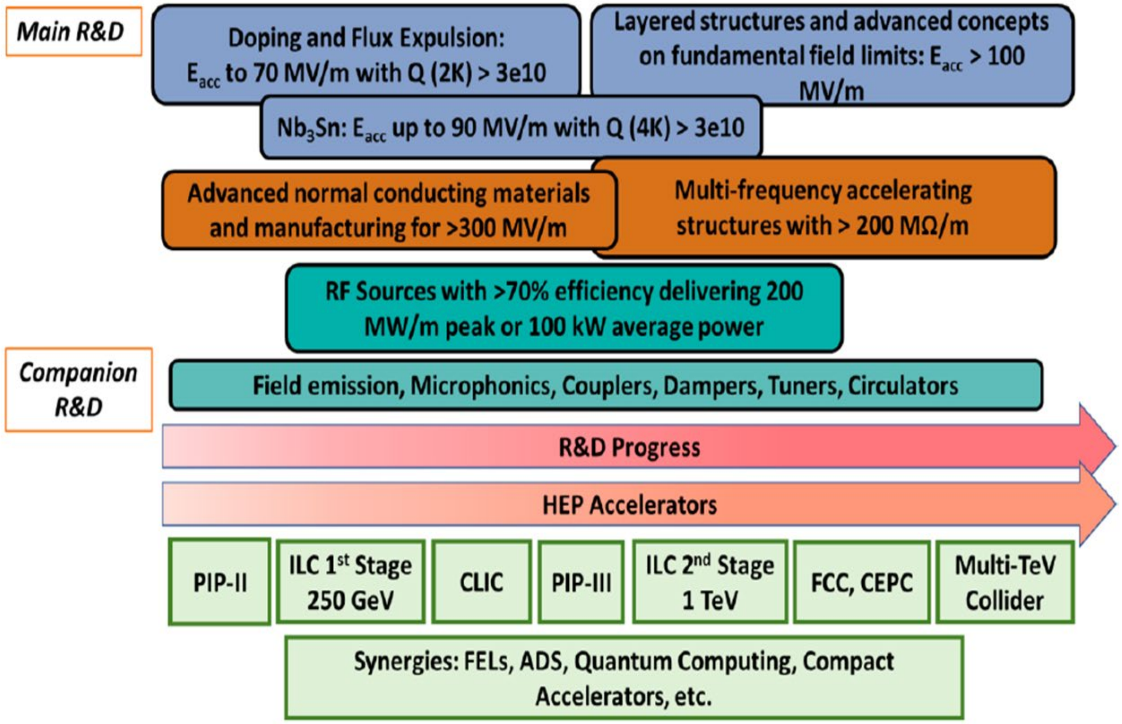


High Gradient Frontier



Key directions for R&D of SRF cavities

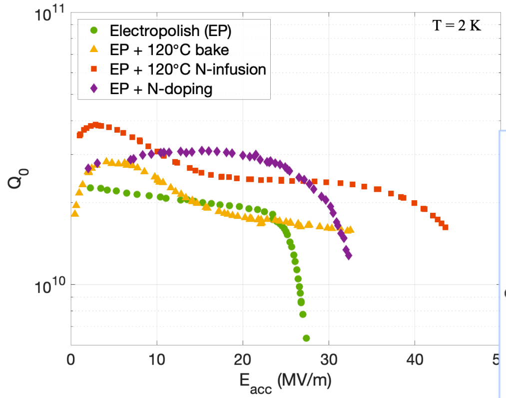
- SRF is a critical technology for several accelerator-based frontier HEP facilities:
  - HL-LHC (crab cavities)
  - LBNF/DUNE/PIP-II
  - Future linear (ILC) and circular (FCC-ee, CEPC) colliders
  - Muon collider
- Other potential applications:
  - Next generation dark sector searches (axions, dark 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

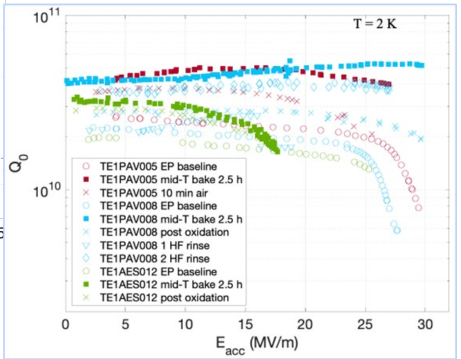
High Q & High Gradient SRF Frontier - Main Directions

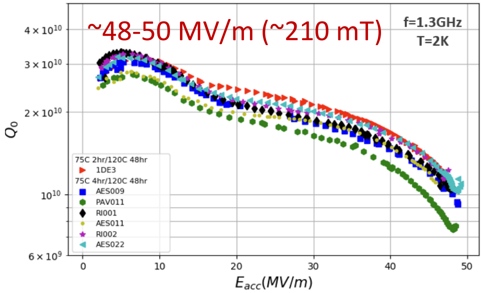
- Continue exploration of the effect of interstitial impurities on bulk Nb surface resistance
- Study the effect of doping on *Q* of cavities at different frequencies (650 MHz – 3.9 GHz)
- Develop fundamental understanding of the reverse field dependence of the BCS surface resistance and devise experiments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



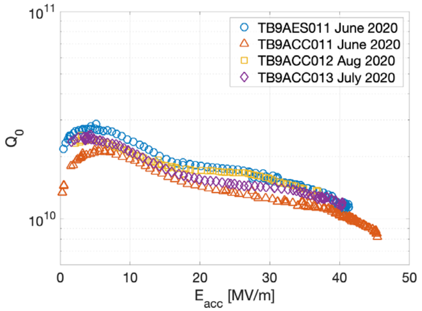
N doping & infusion

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.

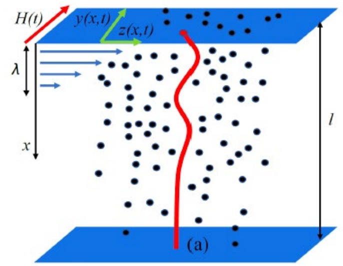
SRF theory for next generation particle accelerators

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.



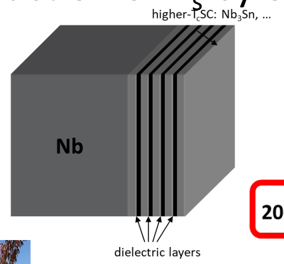
Pathirana and Gurevich, PRB 101, 064504 (2020) and unpublished

Nonequilibrium superconductivity

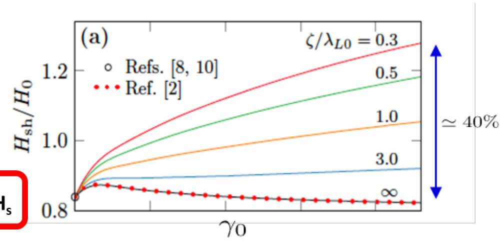
- Nonlinear BCS surface resistance in a nonequilibrium SC under strong rf current. Negative Q(H) slope.
- Extreme dynamics and nonlinear losses of trapped vortices driven by strong rf current

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

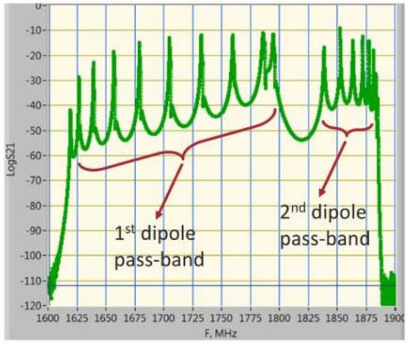


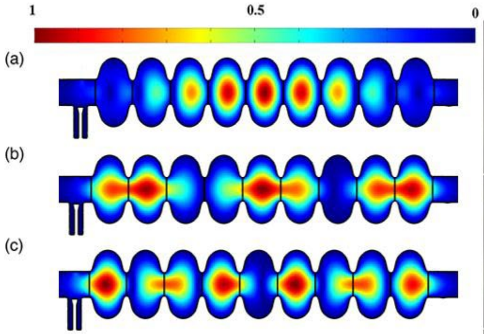
20-40% increase of H_s

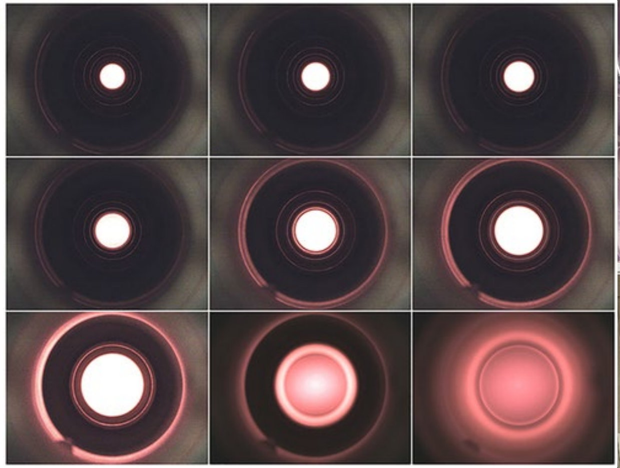


Alex Gurevich, Takayuki Kubo, James A. Sauls
"Challenges and opportunities of SRF theory for next generation particle accelerators"
https://arxiv.org/pdf/2203.08315

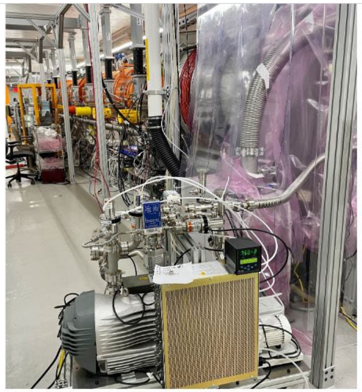
Plasma Processing for In-Situ Field Emission Mitigation





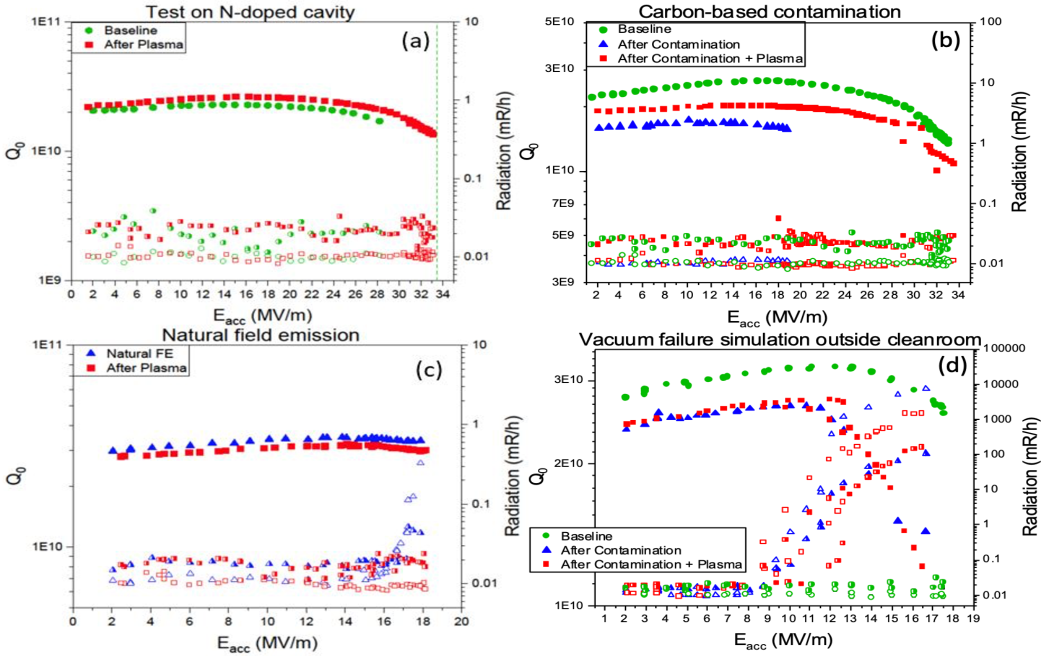


(a)



(b)

(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

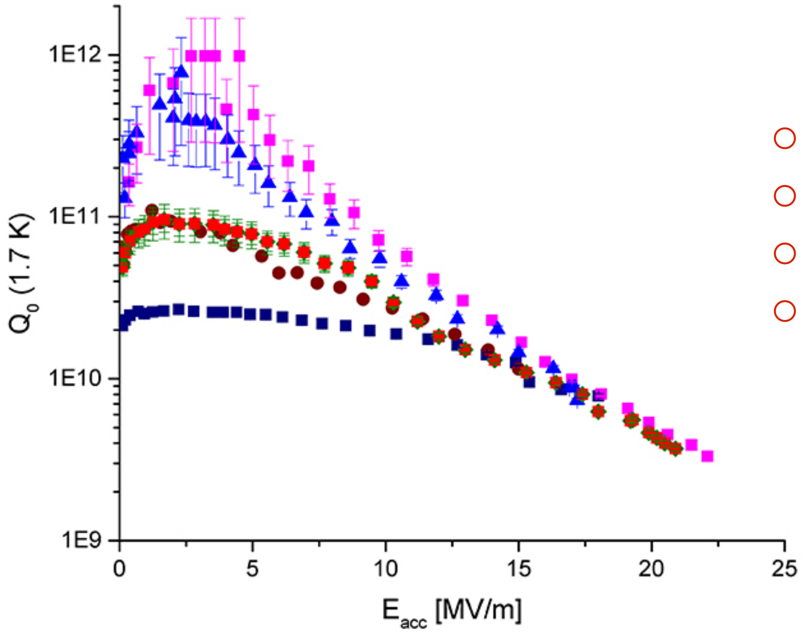
G. Myneni, Hani E. Elsayed-Ali, Md Obidul Islam, Md Nizam Sayeed, G. Ciovati, et al.
”Medium-Grain Niobium SRF Cavity Production Technology for Science Frontiers and Accelerator Applications”
, https://arxiv.org/pdf/2203.07371].”

Jefferson Lab

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

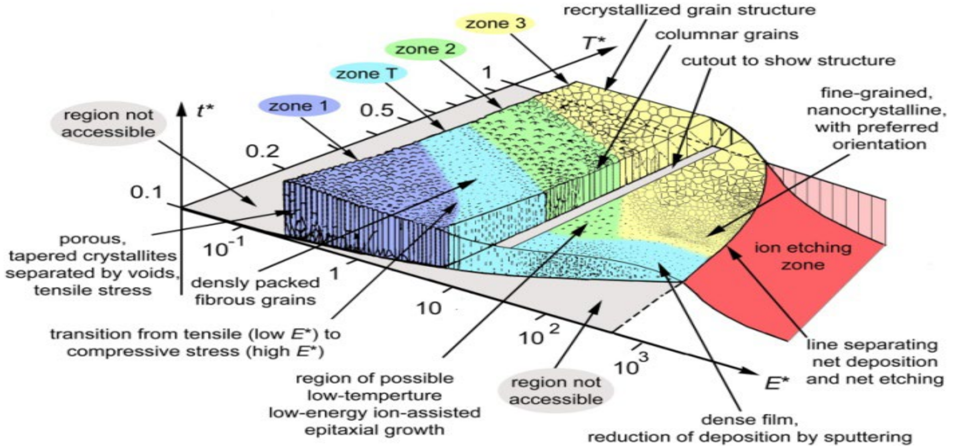


high current storage ring colliders : FCC, EIC and CEPC

- 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.

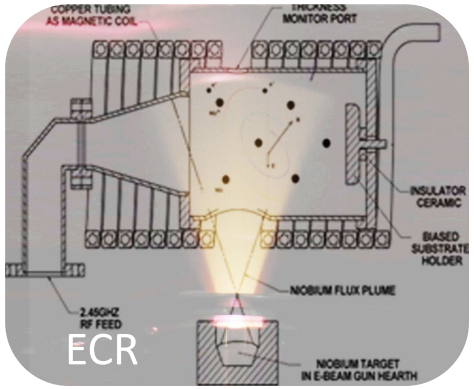
Novel deposition techniques exploiting species energetics offer opportunities to improve and manipulate film structure and performance

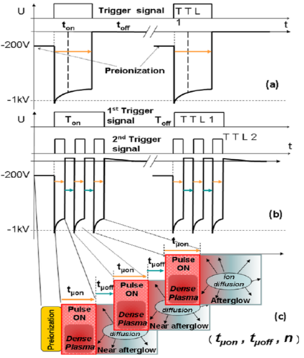


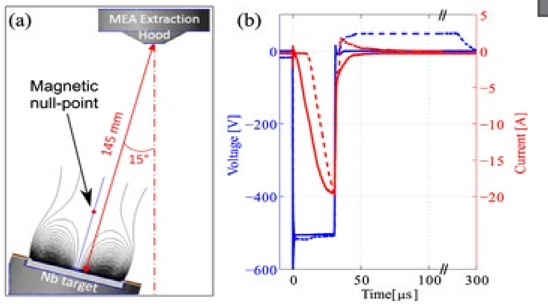
Anders, André. "A structure zone diagram including plasma-based deposition and ion etching." *Thin Solid Films* 518.15 (2010): 4087-4090.

Advances in Thin Film Nb on Cu Technology

Energetic condensation

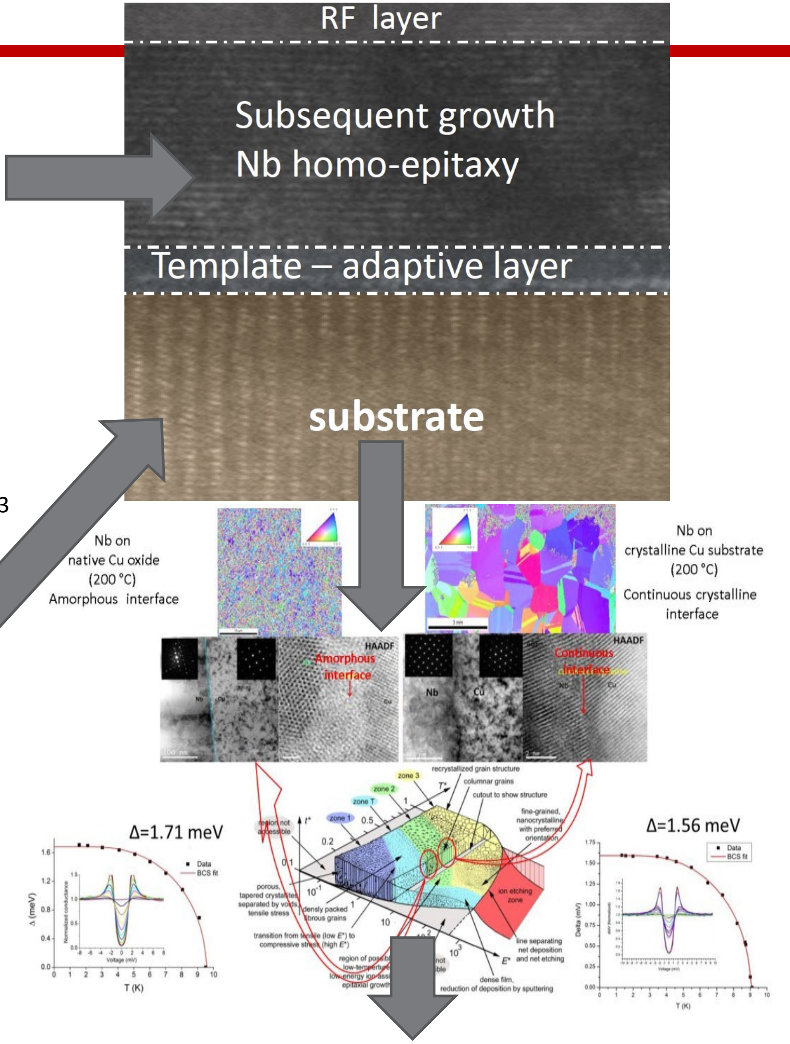






F Avino *et al* 2019 *Plasma Sources Sci. Technol.* **28** 01LT03

HiPIMS + kick pulse

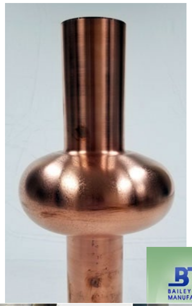


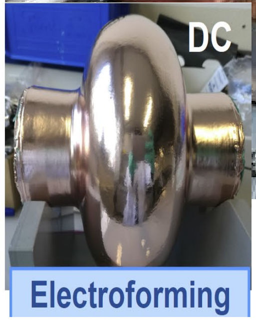
Full control over final SRF performance with strict process protocols

Further tailoring opportunities:

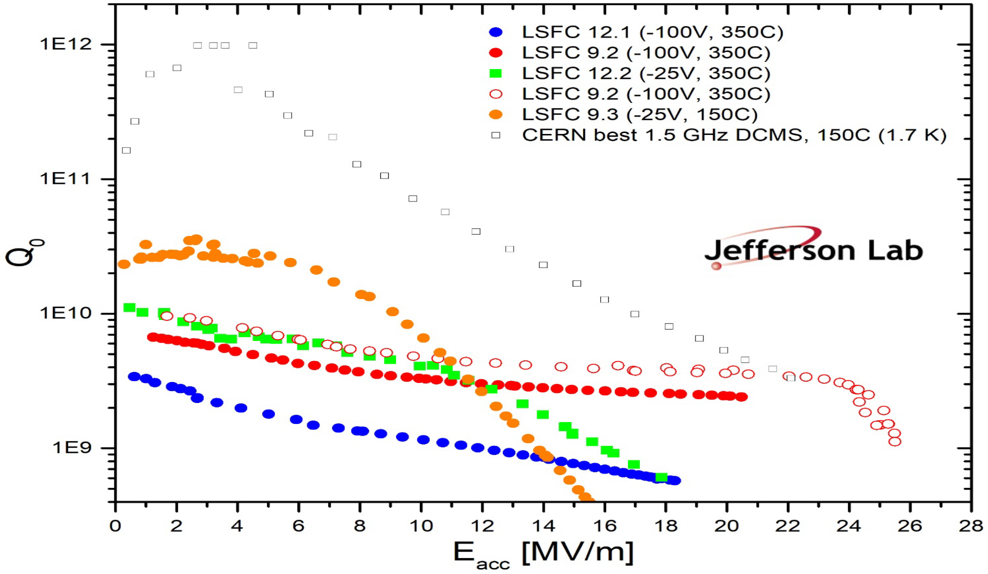
N doping on films

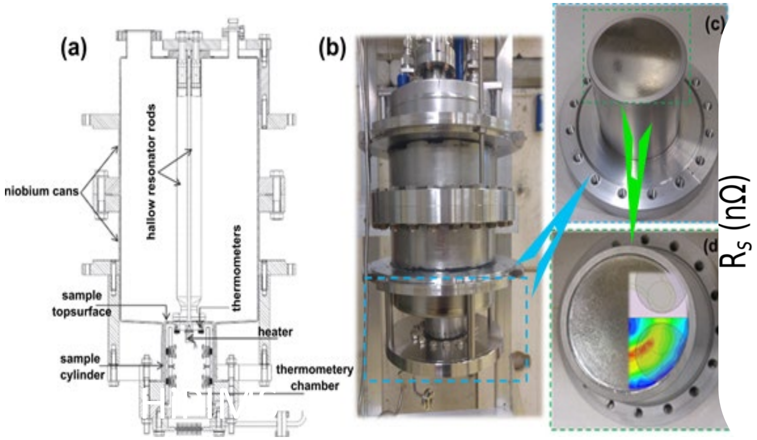
Substrate Fabrication & Processing

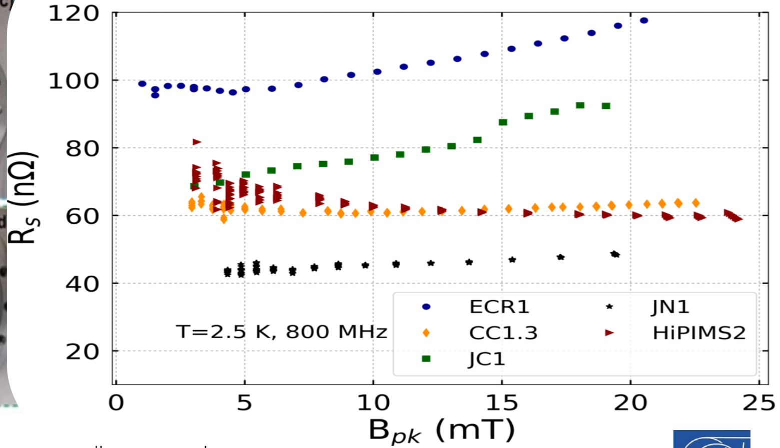




Advances in Thin Film Nb on Cu Technology

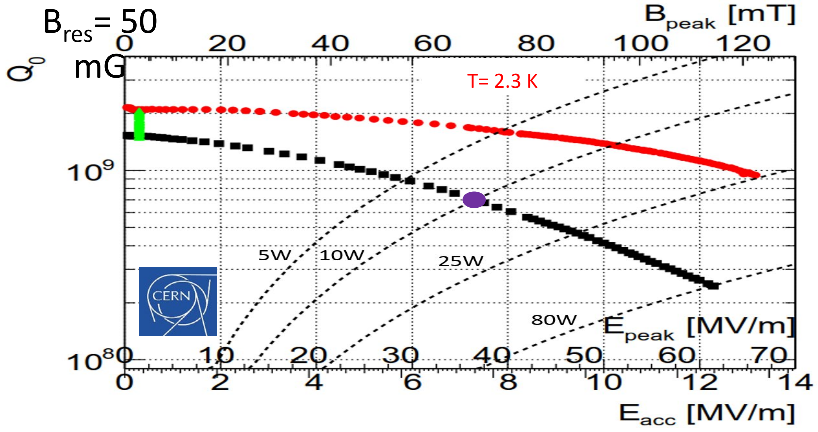




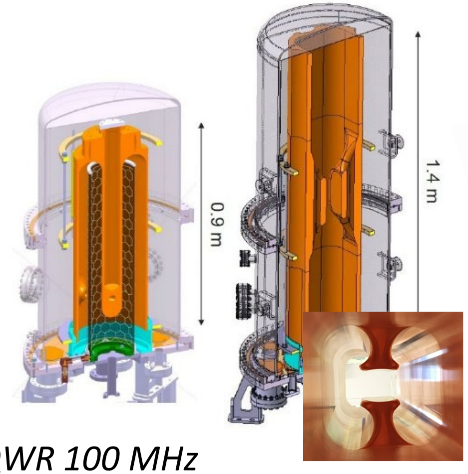


Sample	400 MHz R_{s0} (nΩ)	R_{s1} (nΩ/mT)	800 MHz R_{s0} (nΩ)	R_{s1} (nΩ/mT)	1200 MHz R_{s0} (nΩ)	R_{s1} (nΩ/mT)
ECR	19.7	0.84	65.8	1.14	126.2	1.35
HiPIMS	19.8	0.11	n/a*	n/a*	100.9	0.3
bulk Nb	21.2	0.13	42.1	0.32	120.1	0.69

Jefferson Lab



Developments across shapes & frequencies



QWR 100 MHz

LHC 400 MHz

FCC 800 MHz

956.2 MHz / 1.3 GHz

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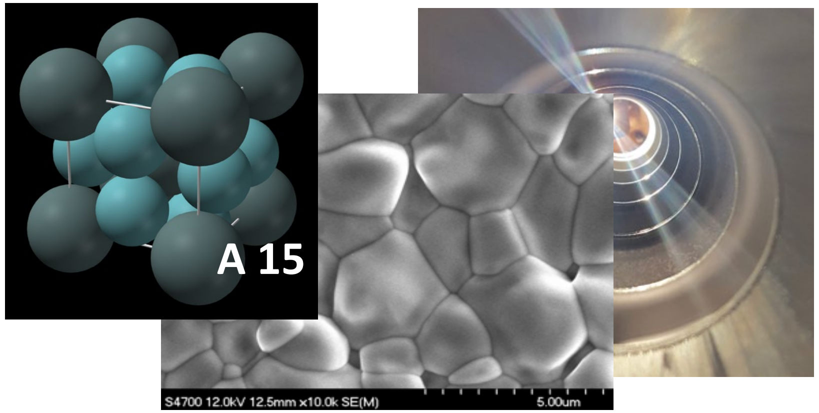
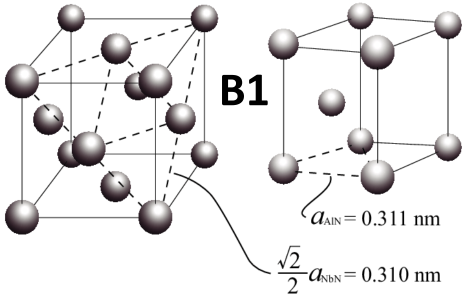
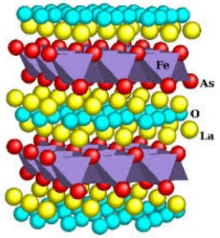
Explore alternative materials with higher critical temperature and critical fields

Alternate Materials and Advanced Structures for Higher Gradients and High Q

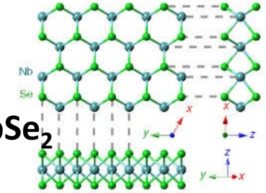
Alternative materials with higher critical temperature and critical field are the prime candidates to disrupt the established bulk Nb technology.



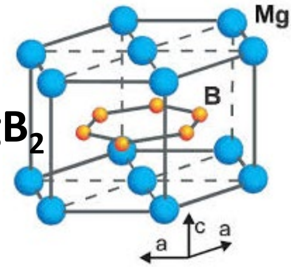




Pnictides

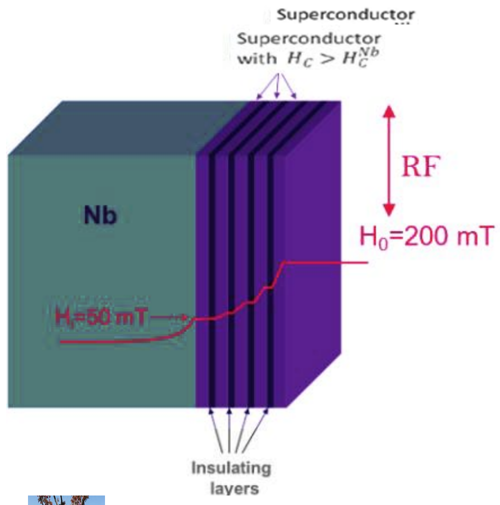


2D-NbSe$_2$

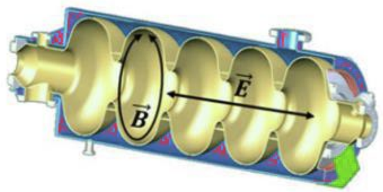


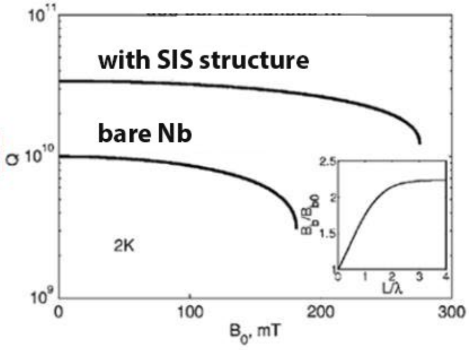
MgB$_2$

Material	T_c [K]	ρ_n(μΩcm)	H_c(0) [mT]	H_{c1}(0) [T]	H_{c2}(0) [T]	H_{SH} [T]	λ(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

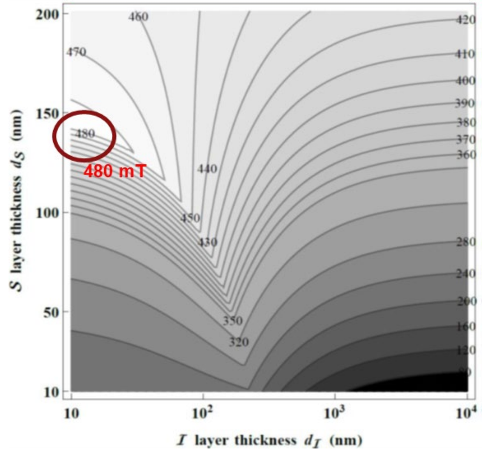


Multicell cavity





Nb$_3$Sn Enhancement



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

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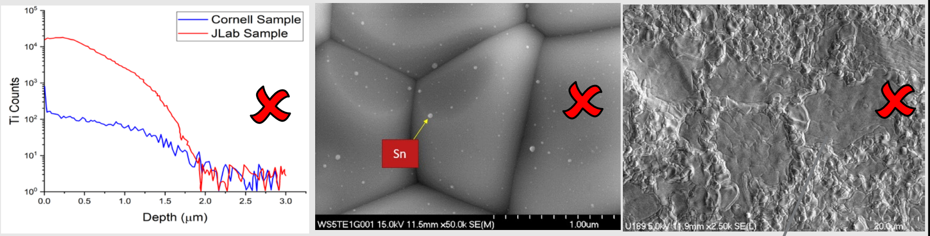
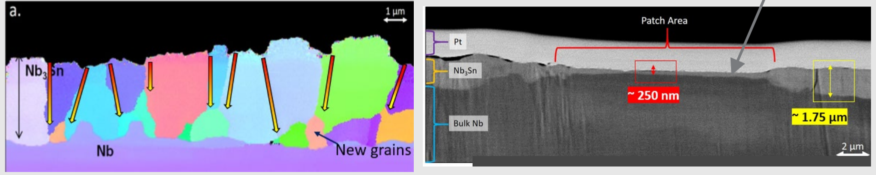
A15 Materials for SRF cavities - Nb_3Sn Development

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

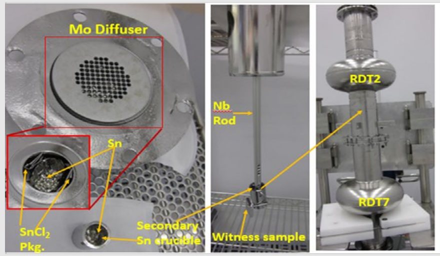


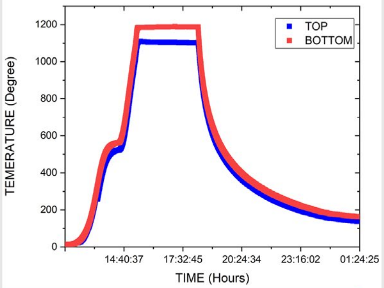
Potential factors contributing to recurrent Q-slopes in Nb_3Sn cavities

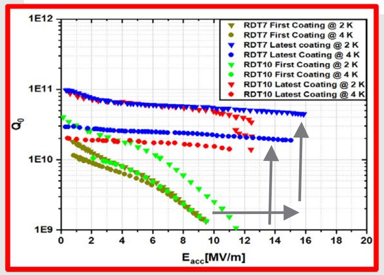


Grain-boundary diffusion primarily controls thin-film growth. Patchy regions lack grain boundaries resulting in RF-affecting thin regions.

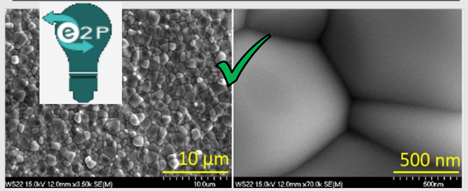
Process Development







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.

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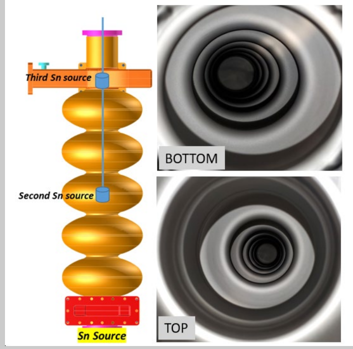
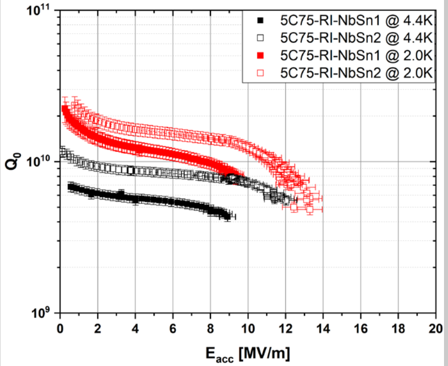
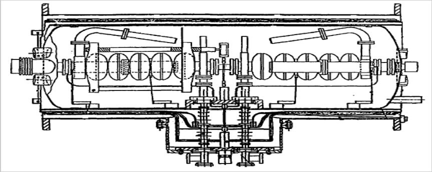
Multi-cell cavity coating for accelerator application

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

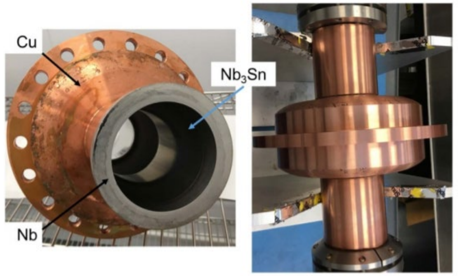


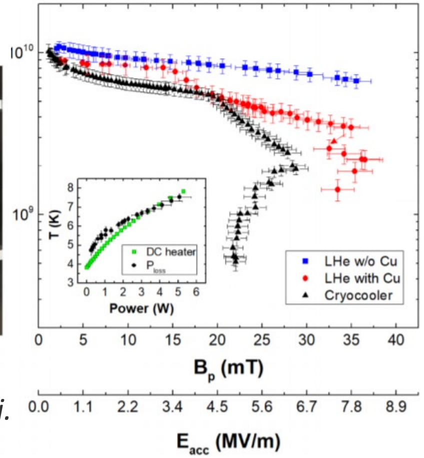




These cavities progress to quarter cryomodule for the first-ever beam test.

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.

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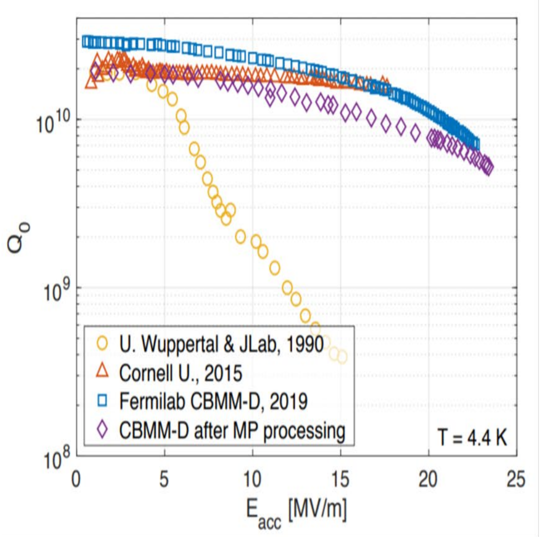
A15 Materials for SRF cavities - Nb_3Sn Development



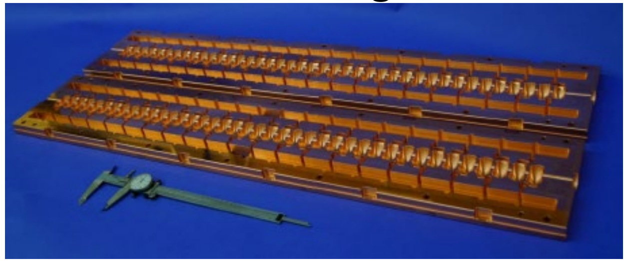
- Can reach **24 MV/m** E_{acc}
  - Meets spec for many machines!
  - Could read **100 MV/m**

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 ???

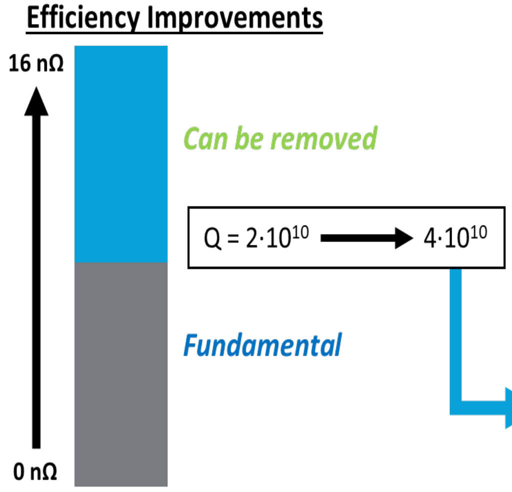
Alternative coating methods for Nb_3Sn/Cu or Nb/CuSn



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 ???



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/

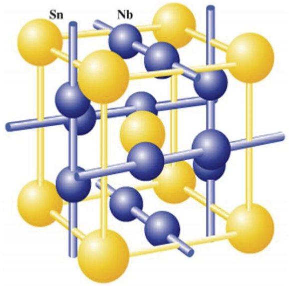
Alternative Materials to Nb & Multilayered Structures

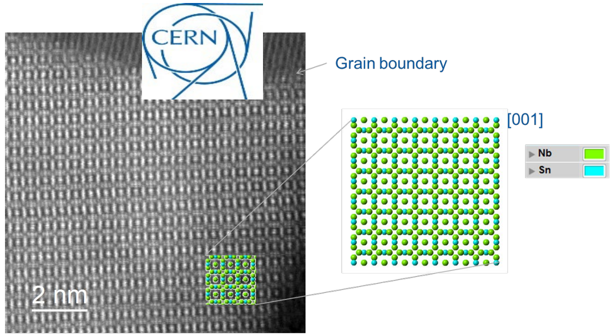
- Develop alternative materials such as NbTiN, NbN, Nb_3Sn Va_3Si, ... with advanced coating techniques.

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

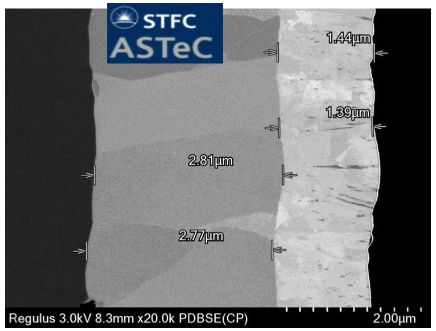
- Newly discovered high temperature superconducting (HTS) materials (pnictides …) would be particularly interesting if any of them turns out to have favorable microwave properties

- Advanced coating techniques

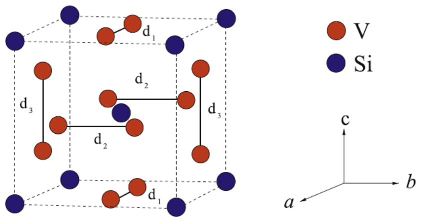


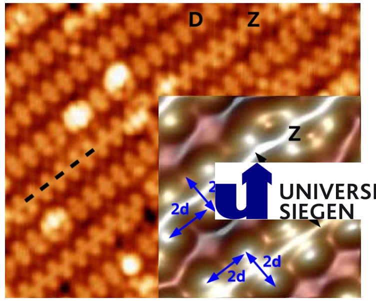


HAADF STEM image of Nb3Sn grain in [001] zone axis and grain boundary



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

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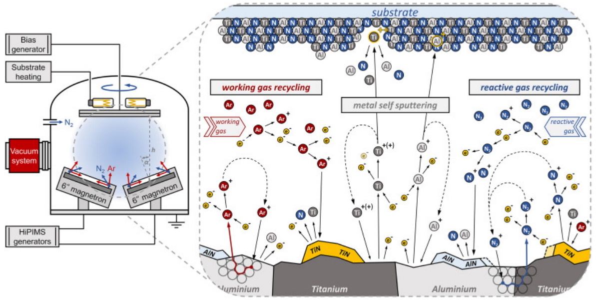
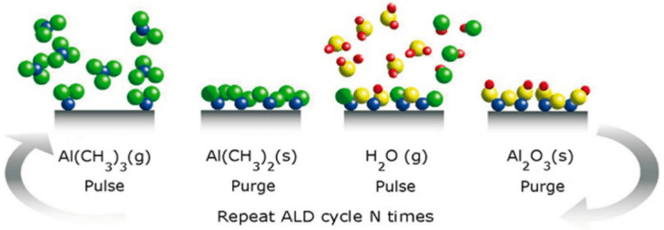
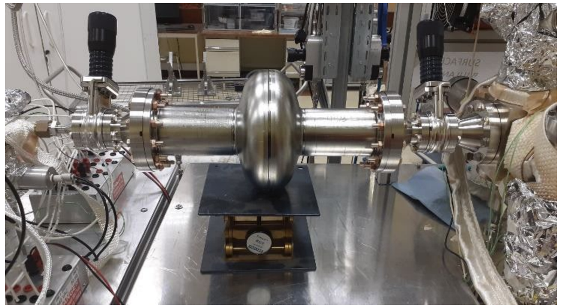
Re-HiPIMS



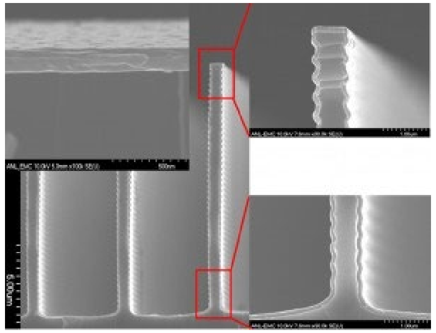
High quality dense films
Improved conformality

ALD



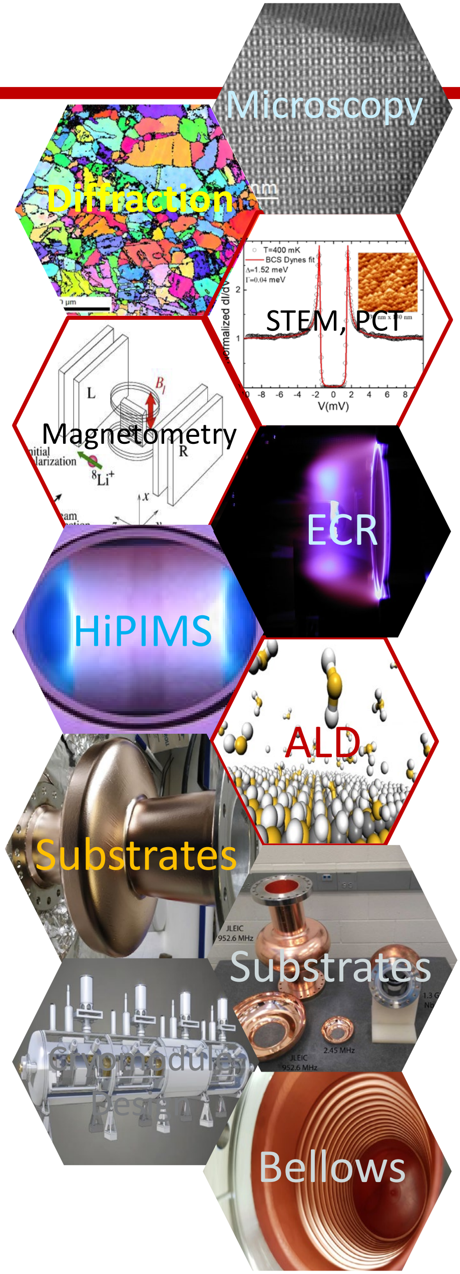


Conformal, self-limiting
nm precision
Precursors difficult



Institut national de physique nucléaire et de physique des particules · cnrs · IJCLab Irène Joliot-Curie · cea · Irfu CEA Saclay · UHH · DESY · Fermilab · Jefferson Lab

Path Forward



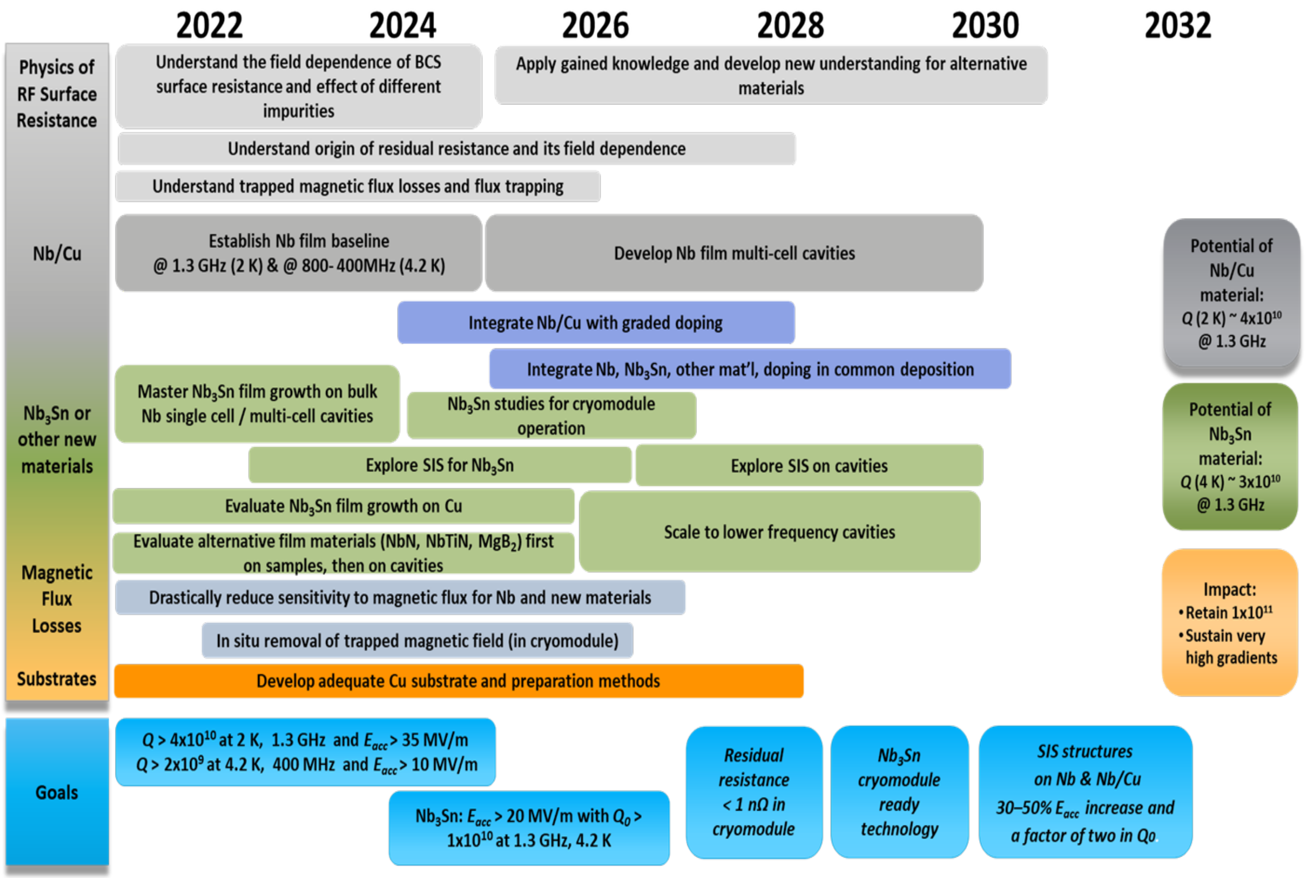
Already well-established and fruitful international R&D collaborations
JLab, SLAC, ODU, CORNELL, FNAL, FSU, W&M, ANL, Temple U. …
&
CEA Saclay, CERN, DESY, HZB, INFN-LNL, KEK, STFC, TRIUMF and other institutions

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…

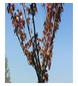
SRFTF Development

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

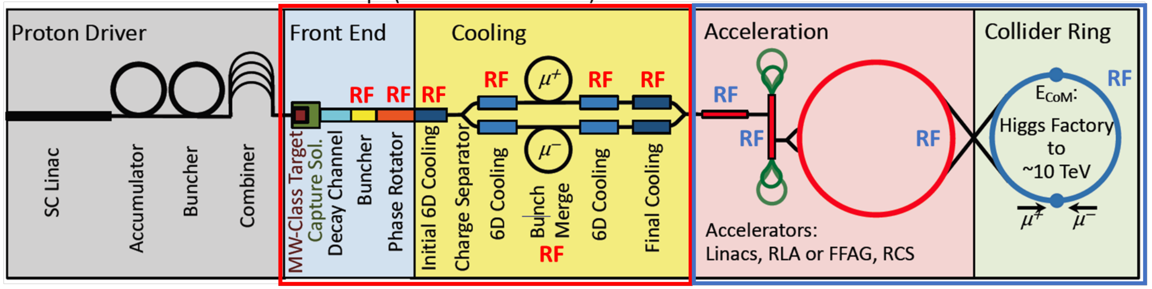
Asher Berlin, Sergey Belomestnykh, Diego Blas, et al.
Searches for New Particles, Dark Matter, and Gravitational Waves with SRF Cavities
https://arxiv.org/pdf/2203.12714.pdf

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

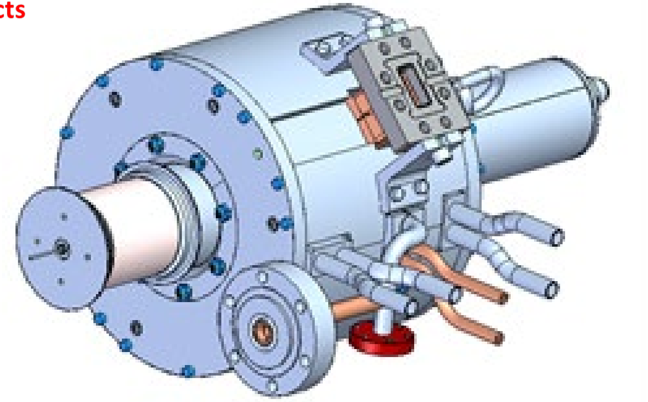
Proton driven Muon Collider Concept (MAP collaboration)



Normal conducting RF for capture and cooling

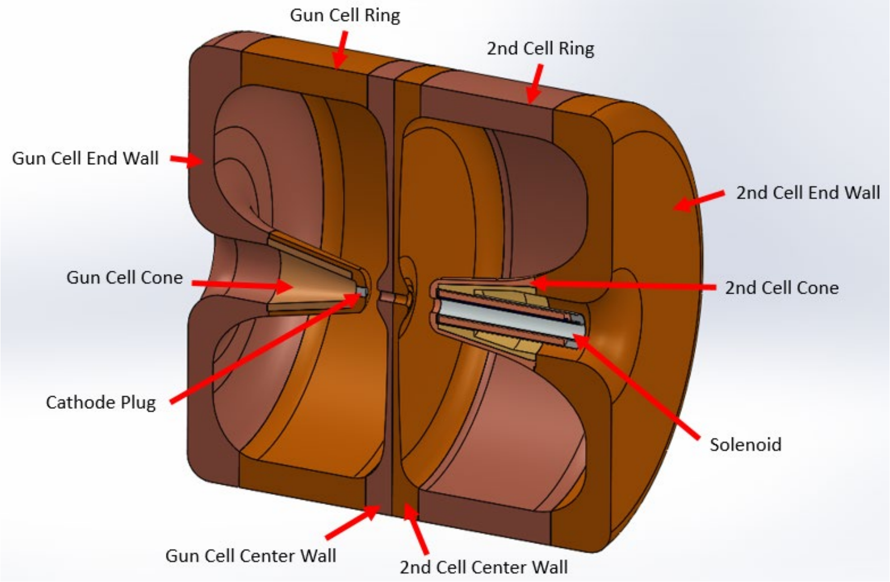
- **High-gradient cavities in high magnetic field**
- **High charge, Huge beam size, Important beam losses**
- **Peak RF power**
- **Little synergy with other projects**

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



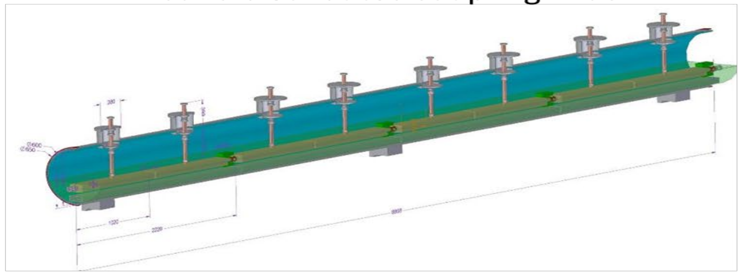
Thomas Roser.
"Sustainability Considerations for Accelerator and Collider Facilities"
https://arxiv.org/pdf/2203.07423 (also under CommF07)

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

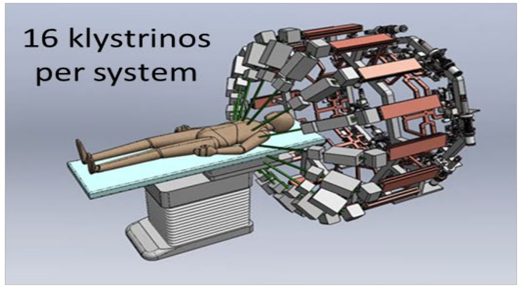


Compact SRF Accelerators for Societal Applications

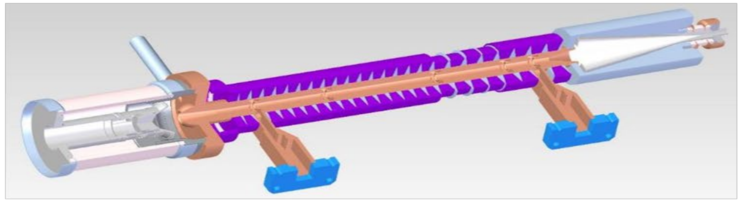
Cool Copper Collider (C^3) – Liquid N_2-cooled C-band distributed coupling linac



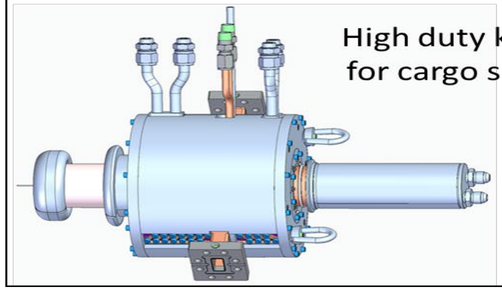
Next-generation radiation therapy



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.

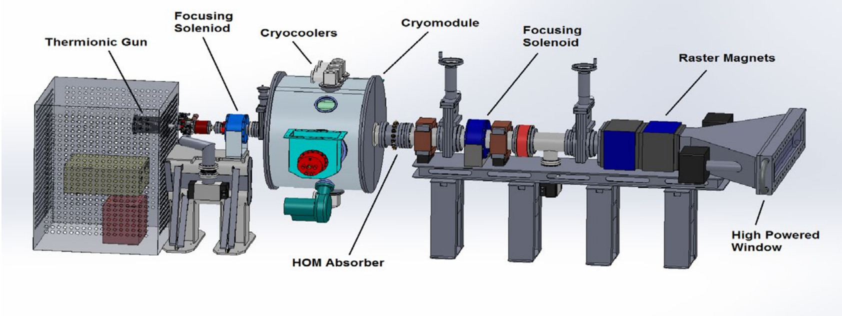
Cost effective compact superconducting accelerators will reduce the footprint and capital investment of

- *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

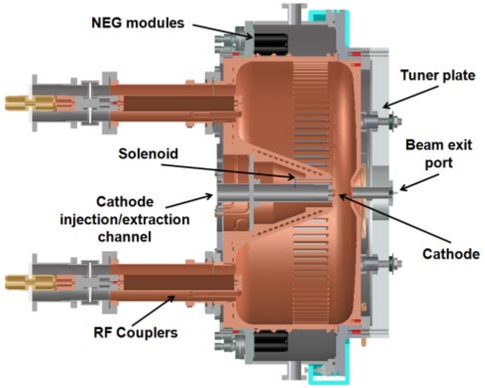
Jefferson Lab

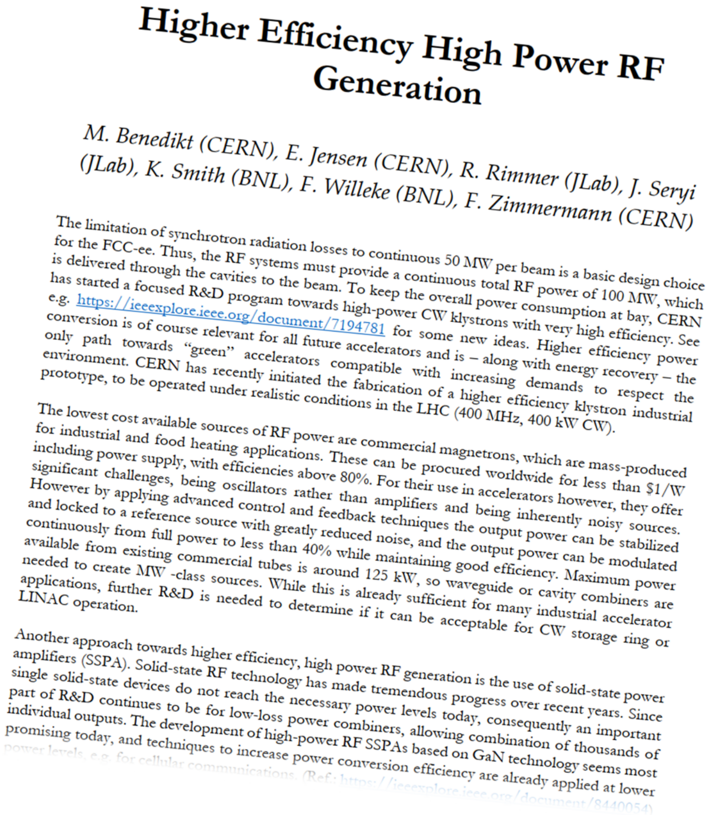
High Efficiency RF Sources

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 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
power levels, e.g. for cellular communications. (Ref.: https://ieeexplore.ieee.org/document/8440054)

- ❑ **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 …)

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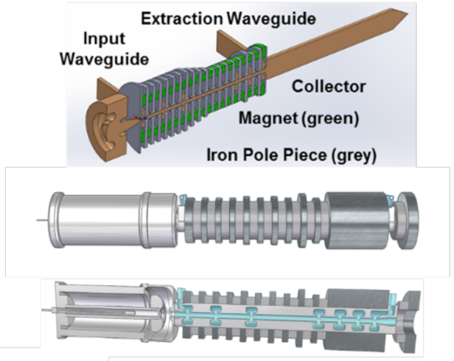
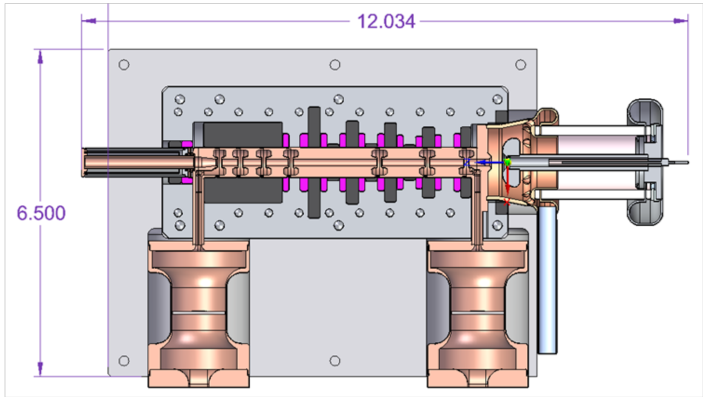
The Modular Array Multi-Beam Klystron (MA-MBK) – High volume RF sources with several uses

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

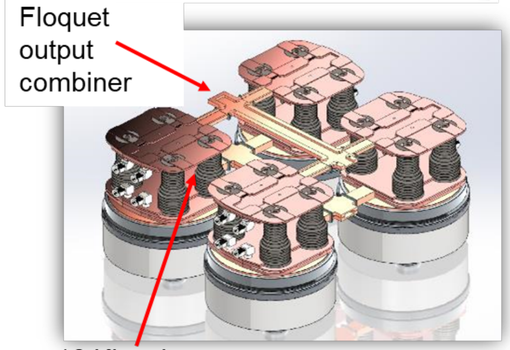
- Stand-alone RF sources for low power, compact and portable systems
- High volume, distributed linac feeding
- Passive combining for higher peak power

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



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

AF7 Recommendations

https://docs.google.com/document/d/1E3NrtnSKeS8XkaBwqoCZO3XQOQC2HRd5t5RiDd34LTk/edit

Key Directions (1)

While the **GARD roadmap continues to serve as a community-developed guidance** for the RF technology R&D, it would benefit from some **mid-course corrections**. Based on the discussions and submitted White Papers, we present the following key directions that should be pursued during the next decade

SRF

- Studies to **push performance of niobium** and improve our understanding of SRF losses and ultimate quench fields via experimental and theoretical investigations;
- Developing **methods for nano-engineering the niobium surface** layer and tailoring SRF cavity performance to a specific application, e.g., a linear collider, a circular collider, or a high-intensity proton linac;
- Investigations of **new SRF materials beyond niobium** via advanced deposition techniques and bringing these materials to practical applications;
- Developing **advanced SRF cavity geometries** to push accelerating gradients of bulk niobium cavities to ~ 70 MV/m for either upgrade of the ILC or compact SRF linear collider;
- Research on application of **SRF technology to dark sector searches**;

Auxiliaries

- Pursuing R&D on **companion RF technologies** to mitigate field emission, provide precise resonance control, enable robust low level RF systems for high gradient and high Q accelerators, etc.;

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https://docs.google.com/document/d/1E3NrtnSKeS8XkaBwqoCZO3XQOQC2HRd5t5RiDd34LTk/edit

Facilities and Workforce

R&D Facilities

To support these key research directions, there is a **need to upgrade and add new capabilities** to the existing R&D and test **facilities to investigate the new concepts** and help integrate them into systems with ready access to researchers. Collaborative efforts at National Laboratories and universities have provided a broad spectrum of sources and manufacturing facilities that has enabled this progress. However, **much of this infrastructure is aging and in need of rejuvenation**. Without **adequate investment** in the facilities, further progress in advancing RF technologies will be hindered.

Workforce

The **workforce** that supports the existing capabilities and facilities **is currently insufficient**. A significant portion of this workforce is approaching the end of their career. **Bringing the next generation of staff into these facilities is a struggle. Additional resources and a strategy are urgently needed for education, training and knowledge transfer**.

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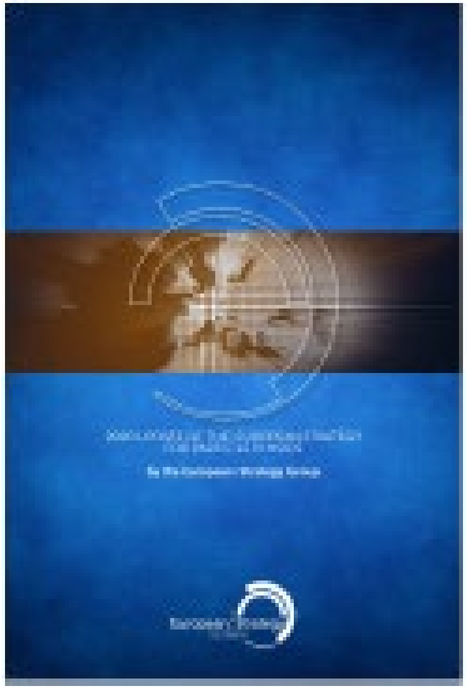
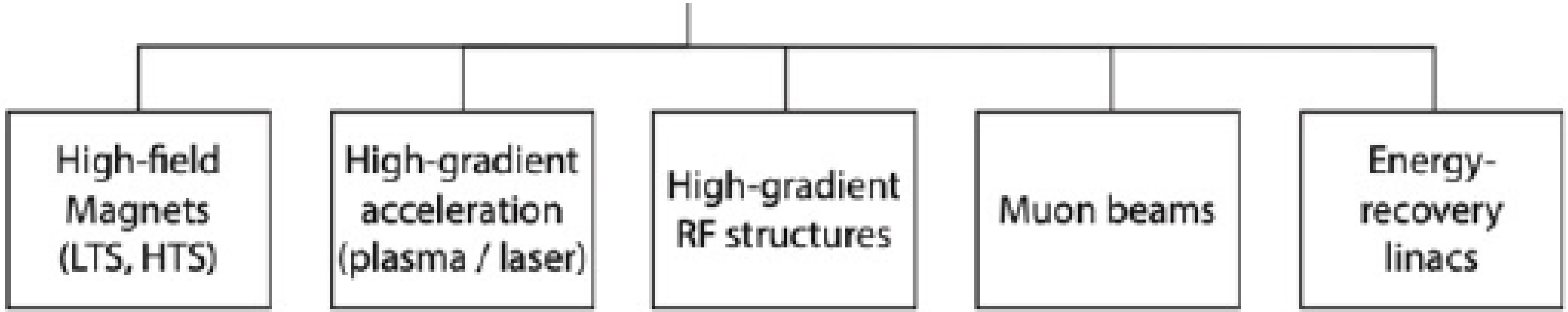
Synergy with European Strategy



- 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
The Snowmass process offers 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/

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

August 29, 2022

RF Accelerator Technology R&D

Report of AF7-rf Topical Group to Snowmass 2021

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THANK YOU