SRF activities discussed within Snowmass and European HEP strategy process

TESLA Technology Meeting, Aomori, Japan

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http://seattlesnowmass2021.net/

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Aomori, Oct 11^{th}, 2022

- The **Strategy Report** was published bei CERN in 3/2022.
- It is also known as **LDG Report** with LDG eq. Lab Directors Group.
- **The SRF related part can be found also via https://doi.org/10.23731/CYRM-2022-001.61**
- The assembly of Chapter 3: High-gradient RF structures and systems was chaired by S. Bousson and H. Weise.
- The author team was S. Bousson, H. Weise, G. Burt, G. Devanz, A. Gallo, F. Gerigk, A. Grudiev, D. Longuevergne, T. Proslier, and R. Ruber

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Vol. 1 (2022): European Strategy for Particle Physics - Accelerator R&D Roadmap

European Strategy Update | Laboratory Directors Group

Editor: Nicolas Mounet

The 2020 update of the European Strategy for Particle Physics emphasised the importance of an intensified and well-coordinated programme of accelerator R&D, supporting the design and delivery of future particle accelerators in a timely, affordable and sustainable way. This report sets out a roadmap for European accelerator R&D for the next five to ten years, covering five topical areas identified in the Strategy update. The R&D objectives include: improvement of the performance and cost-performance of magnet and radio frequency acceleration systems; investigations of the potential of laser/plasma acceleration and energy-recovery linac techniques; and development of new concepts for muon beams and muon colliders. The goal of the roadmap is to document the collective view of the field on the next steps for the R&D programme, and to provide the evidence base to support subsequent decisions on prioritisation, resourcing and implementation.

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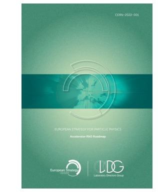
LDG RF Systems - Abstract

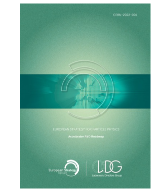


Abstract

Radio frequency (RF) systems are the workhorse of most particle accelerators and achieve high levels of performance and reliability. Despite five decades of improvement the community is still advancing RF performance with several novel developments. The next generation of particle accelerators will likely be still based on RF technology, but will require operational parameters in excess of state of the art, requiring an advanced R&D program. The R&D covers superconducting RF (SRF), normal conducting RF (NC RF) and ancillary systems such as RF sources, couplers, tuners and the systems that control them.

- we are still advancing cavity RF performance
- operational parameters in excess of state of the art
- advanced R&D program
- superconducting RF (SRF) and normal conducting RF (NC RF)
- and ancillary systems such as RF sources, couplers, tuners and the systems that control them

LDG RF Systems – Excerpt from Executive Summary

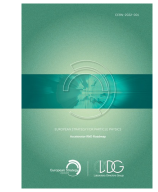


In SRF the development is focused in two areas, bulk niobium and thin-film (including high-T_c) superconductors. In bulk SRF new treatments are allowing niobium cavities to exceed previous record Q factors and avoiding degradation with increasing gradients. This includes nitrogen infusion and doping, and two-step baking processes. There is also an emphasis on limiting field emission. For thin-films the community is investigating creating coated cavities that perform as good as or better than bulk niobium (but with reduced cost and better thermal stability), as well as developing cavities coated with materials that can operate at higher temperatures or sustain higher fields. One method of achieving this is to use multi-layer coatings. Innovative cooling schemes for coated cavities are also being developed. Coupled to the cavity development is improvement in the cost and complexity of power couplers for SRF cavities.

- two areas, **bulk niobium** and **thin-film** (including high-T_c)
  - exceed previous record Q factors and avoiding degradation with increasing gradients
  - includes nitrogen infusion and doping, and two-step baking processes
  - create coated cavities that perform as good as or better than bulk niobium (but with reduced cost and better thermal stability
  - materials that can operate at higher temperatures or sustain higher fields
  - multi-layer coatings
- innovative cooling schemes for coated cavities
- RF power couplers

SRF challenges and R&D objectives

Bulk niobium and the path towards high quality factors at high gradients

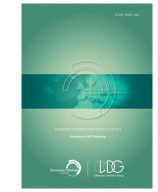


Even though the hard fundamental limit of niobium has been close to being reached for the past 10 years, very specific and alternative surface and heat treatments have been investigated to tune the cavity performance to the very stringent specifications required by new projects and thus improve very specifically the driving parameters (Q_0, E_{max}, fabrication cost and reliability among others). Bulk niobium technology is still expected to be competitive for years to come, compared to the new alternative thin-film superconductors under investigation. Still many technical and technological challenges have to be tackled to allow their industrialization.

- Material structure: Fine Grain -> Large Grain or Mid Grain?
- Heat treatment at different temperatures, or in the presence of Nitrogen (or others?)
- Surface polishing: established Electro-Polishing; new ideas: metallographic polishing (MP) and more recently electrolytic plasma polishing (EPP)
- Field emission reduction is a must for all accelerators
  - clean room preparation: Improvement in manipulation, pumping/venting procedures and automation, introduction of robots
  - diagnostics to support analyzing X- and γ-ray patterns emerging from the cryomodule
  - mitigation and recovery: plasma cleaning and dry-ice rinsing are very promising

SRF challenges and R&D objectives

Thin superconducting films for superconducting radiofrequency cavities

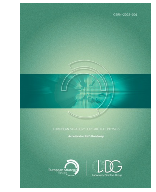


SRF cavities are one of the cornerstone infrastructures of particle accelerators… for the past 50 years great advances have been made with bulk niobium technology which is now reaching with a high level of reproducibility~35 MV/m, Q~2–5x10^{10} at 2 K. Nibbling on the last cavity performance improvements to reproducibly reach the intrinsic limits of niobium will become increasingly difficult and exponentially expensive. In order to overcome this roadblock, a technological leap is needed to produce next generation SRF cavities with cost-effective means and reliable production methods scalable to mass industrialization.

- Reduced amount of superconducting materials: Recent remarkable results obtained at CERN with Nb/Cu
- Increased operation temperature
  - Higher T_c materials such as A15 compounds(Nb_3Sn, Nb_3Al, V_3Si) and MgB_2
  - results obtained at Cornell and Fermilab with Nb3Sn synthesized on bulk niobium
  - the major challenge is now to reproduce these results on Cu substrates and cavities
- Increased maximum operation gradient (E_{max})
  - new multilayer hetero-structures with higher critical fields than niobium have been proposed
  - complementary deposition techniques and efforts must be pursued in Europe
    - Vapor phase – CVD, atomic layer deposition (ALD) and physical vapor deposition (PVD), plasma-assisted deposition (HIP-IMS, custom DC/AC sputtering) and electro deposition are promising methods

SRF R&D plan

A nominal plan, roughly based on the actual effort of European labs in generic R&D

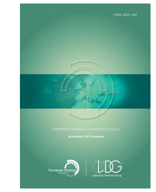


The proposed plan is addressing a generic R&D program for RF acceleration. The corresponding estimated cost is the required budget to develop technologies and solutions that could be later adapted to targeted HEP projects which could benefit from the scientific and technological outcomes. The required budget for the specific adaptation or optimization for a given facility is not accounted for here, as we consider it as direct project funding. The generic R&D budget is to support development of new concepts, new ideas and to prove their feasibility…

3.6.1.1 Bulk niobium and the path towards high quality factors at high gradients

1. Push forward the development and validation of large/medium grain material.
   (a) Milestones at five years:
      i. Operational CW cryomodule at gradients > 20 MV/m.
      ii. Develop new vendors of LG/MG ingots to allow mass production.
   (b) Milestone at ten years: scale to lower frequencies than 1.3 GHz (larger cavities).
2. Continue R&D on vacuum heat treatment and doping.
   (a) Milestones at five years:
      i. Push further investigation of the so-called mid-T baking (300–600°C) and doping.
      ii. Fine tuning of parameters of advanced heat treatments as mid-T baking, doping, etc.
      iii. Demonstrate improvements and applicability of these advanced heat treatment for other frequencies than 1.3 GHz.
   (b) Milestone at ten years: apply advanced heat treatments as standard treatment for new accelerator projects.
3. Improvement of surface polishing and characterisation techniques: standard techniques (EP, BCP) and developing new techniques (EPP, MP, etc.).
   (a) Milestones at five years:
      i. Develop new infrastructures for large cavities (multicells, low beta, etc.): extra-cold EP, rotational BCP.
      ii. Investigate and identify new polishing techniques compatible with SRF requirements and industrialisation.
   (b) Milestone at ten years: new and advanced polishing techniques mature for new accelerator projects.

SRF R&D plan



Further milestones are given for a large number of R&D goals

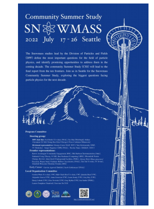
- Develop robotization/cobotisation (human-robot collaboration) for surface processing/cleaning of SRF components
- Pursue R&D effort on particle counting in clean room and X-rays diagnostics capabilities
- Intensify R&D on field emission mitigation/in-situ recovery techniques (dry-ice, plasma)
- Continue R&D niobium on copper – construction cost saving and securing supply
- Intensify R&D of new superconductors on Cu – 4.2 K operational cost saving
- Pursue multilayers – push for high gradient
- Intensify Cu cavity production and surface preparation
- Develop 3D printing and innovative cooling techniques.
- Infrastructures and manpower – high-throughput testing

For each topic five-year as well as ten-year milestones can be found in the LDG report chapter 3.6.1.

5 year cost estimate (see the several disclaimers given in the report!!!)		
bulk Nb	4M CHF	75 FTEy
FE related R&D	4M CHF	40 FTEy
thin film	15M CHF	100 FTEy
Key technologies	5M CHF	15 FTEy
RF couplers	4M CHF	16 FTEy

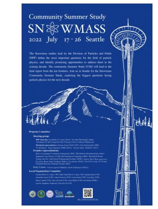
Snowmass

Introduction



- The **Particle Physics Community Planning Exercise** (a.k.a. “**Snowmass**”) is organized by the Division of Particles and Fields (DPF) of the American Physical Society
- Snowmass is a **scientific study**. It provides an opportunity for the entire particle physics community to come together to identify and document a scientific vision for the future of particle physics in the U.S. and its international partners
- Snowmass goal is to **define the most important questions** for the field of particle physics and **identify promising opportunities** to address them
- The **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
- The previous Snowmass was in 2013 and P5 in 2014
- Snowmass 2021 (https://snowmass21.org/start) was delayed by one year by COVID-19 but retained its 2021 designation

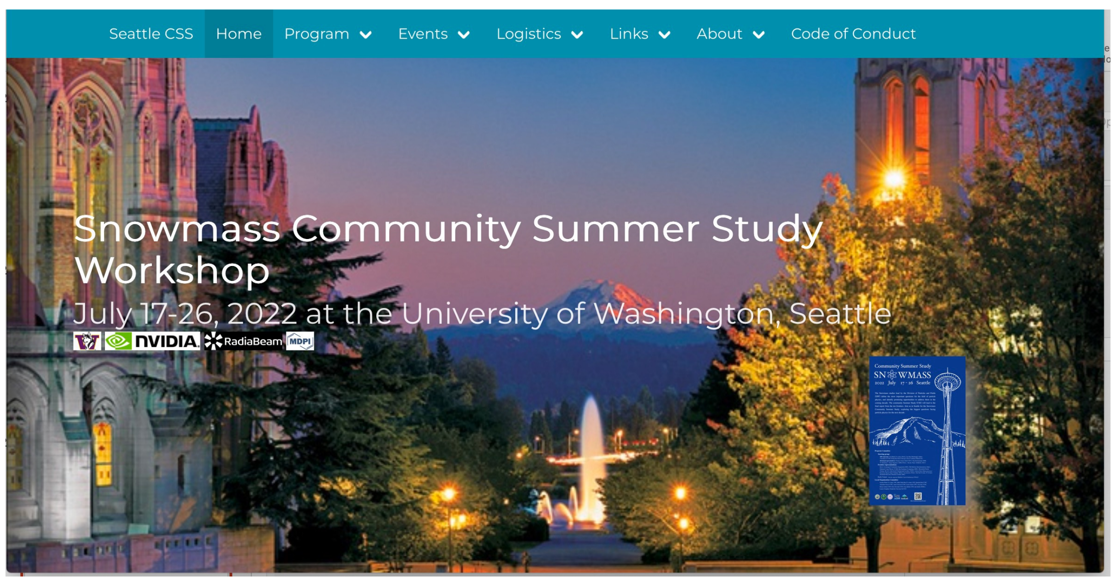
Snowmass 2021



Snowmass 2021

Introduction

- Snowmass 2021 was **divided into 10 Frontiers**, e.g., Energy Frontier, Neutrino Physics Frontier, Rare Processes, etc.
- The community was encouraged to submit **Letters Of Interest** (LOIs) and then **White Papers** based on those LOIs
- The Exercise culminated in the **Community Summer Study (CSS) and Workshop** in Seattle (July 17-26, 2022), https://seattlesnowmass2021.net/
- Due to COVID, it was a hybrid meeting with 1397 total number of participants (743 in person)

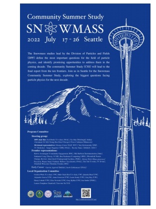


Snowmass AF7-rf

RF Technology Topical Group

- The Snowmass **Accelerator Frontier (AF)** consisted of several topical groups including **AF7-rf**, which covered **RF Systems and Sources**, **Innovative Design and Modeling**, and **Cavity Performance Frontier**
- The AF7-rf co-conveners were Emilio Nanni (SLAC), Hans Weise (DESY), and Sergey Belomestnykh (FNAL)
- **SRF technology** was discussed under the Cavity Performance Frontier topic
- To facilitate the process, AF7-rf held miniWorkshops and seminars
- AF7-rf discussion were structured around **DOE RF Accelerator Roadmap** (developed in 2017)
- In addition, we explored new or overlooked topics and concepts
- All White Papers were submitted to **arXiv** as part of **Snowmass Proceedings** (to be finalized soon)

SRF-related White Papers



SRF Cavity Performance (Gradient and Q), Studies of New Superconductors, Other Topics

Overview papers

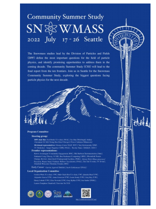
- Key Directions for Research and Development of Superconducting Radiofrequency (SRF) Cavities
  http://arxiv.org/abs/2204.01178
- Challenges and opportunities of SRF theory for next generation particle accelerators
  https://arxiv.org/abs/2203.08315
- Next-Generation Superconducting RF Technology based on Advanced Thin Film Technologies and Innovative Materials for Accelerator Enhanced Performance & Energy Reach
  https://arxiv.org/abs/2204.02536

Specific topics

- Medium-Grain Niobium SRF Cavity Production Technology for Science Frontiers and Accelerator Applications https://arxiv.org/abs/2203.07371
- Nb_3Sn Superconducting Radiofrequency Cavities: a Maturing Technology for Particle Accelerators and Detectors https://arxiv.org/abs/2203.06752
- An Impartial Perspective for Superconducting Nb_3Sn coated Copper RF Cavities for Future Linear Accelerators https://arxiv.org/abs/2203.09718
- Plasma Processing for In-Situ Field Emission Mitigation of Superconducting Radiofrequency (SRF) Cryomodules https://arxiv.org/abs/2203.12442

SRF-related White Papers

White Papers for Proposed Facilities with Strong Need for High-gradient / High-Q SRF Technology



Colliders

- 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
- The ReLiC – Recycling Linear e+e- Collider https://arxiv.org/abs/2203.06476
- The Future Circular Collider: a Summary for the US 2021 Snowmass Process https://arxiv.org/abs/2203.06520
- Snowmass2021 White Paper AF3-CEPC https://arxiv.org/abs/2203.09451
- CERC – Circular e+e- Collider using Energy-Recovery Linac https://arxiv.org/abs/2203.07358
- A Muon Collider Facility for Physics Discovery https://arxiv.org/abs/2203.08033

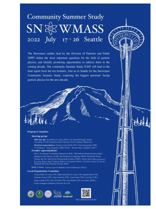
Neutrino experiments

- An 8 GeV Linac as the Booster Replacement in the Fermilab Power Upgrade: a Snowmass 2021 White Paper https://arxiv.org/abs/2203.05052

Dark matter searches

- Searches for new particles, dark matter, and gravitational waves with SRF cavities https://arxiv.org/abs/2204.01178

AF7-rf Topical Group Report



- The AF7-rf discussions and submitted White Papers and LOIs are summarized in the topical group report, which was discussed at the Snowmass Community Summer Study Workshop in Seattle and then published in arXiv: https://arxiv.org/abs/2208.12368

Contents

arXiv:2208.12368v1 [physics.acc-ph] 25 Aug 2022

August 29, 2022

RF Accelerator Technology R&D

Report of AF7-rf Topical Group to Snowmass 2021

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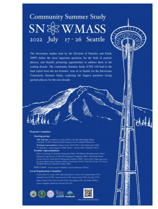
Key Directions for SRF R&D (1)



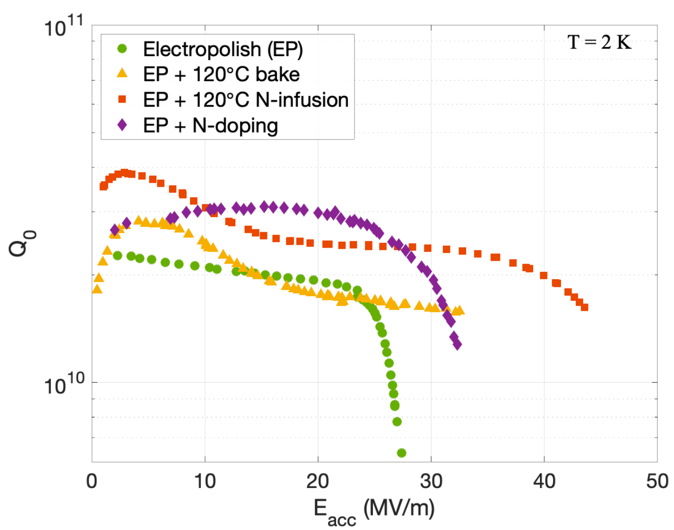
From AF7-rf Topical Group Report, White Papers, and Presenttaions

The **key directions for SRF technology R&D** are outlined in the AF7-rf Topical Group Report to be pursued during the next decade. In the next slides we list these directions and show some examples.

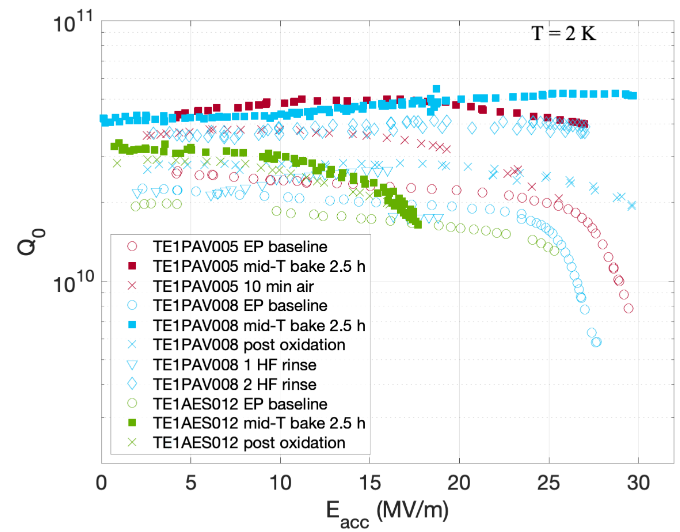
- Studies to **push performance of niobium** and improve our understanding of SRF losses and ultimate quench fields via experimental and theoretical investigations
- Developing **methods for nano-engineering the niobium surface layer** and tailoring SRF cavity performance to a specific application, e.g., a linear collider, a circular collider, or a high-intensity proton linac

Examples of new cavity treatment methods:

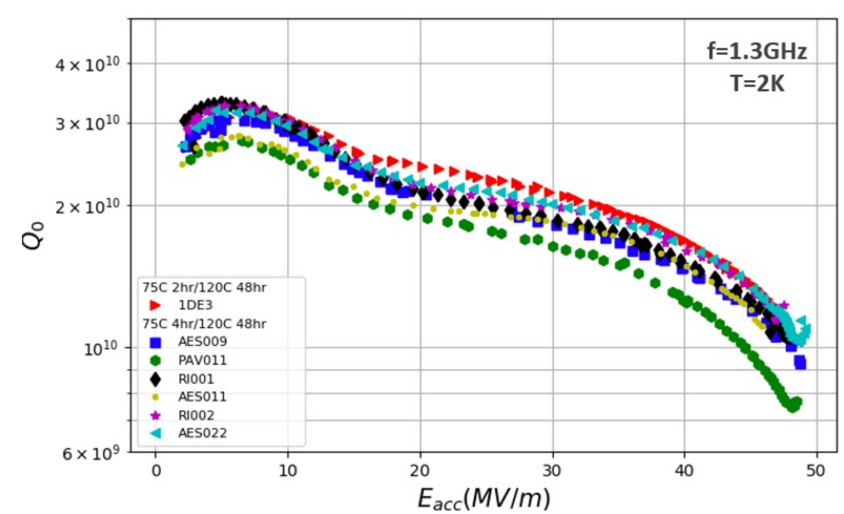
Nitrogen doping and infusion



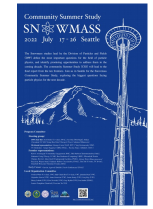
Mid-T baking



2-step low-temperature baking



Key Directions for SRF R&D (2)

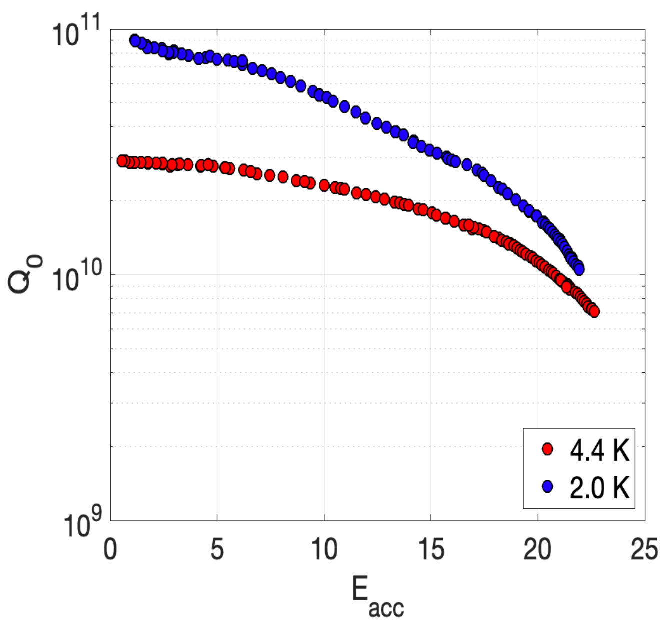


From AF7-rf Topical Group Report, White Papers, and Presentations

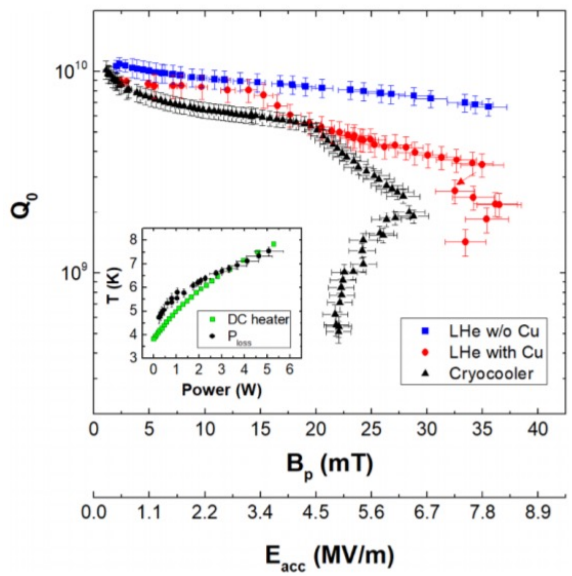
- Investigations of **new SRF materials beyond niobium** via advanced deposition techniques and bringing these materials to practical applications
- Developing **advanced SRF cavity geometries** to push accelerating gradients of bulk niobium cavities to ~70 MV/m for either upgrade of the ILC or compact SRF linear collider

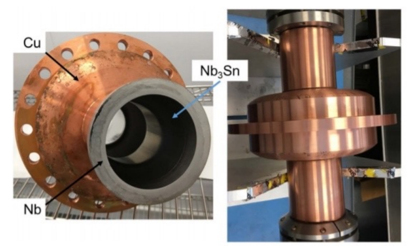
Examples:

Record performing Nb_3Sn cavity

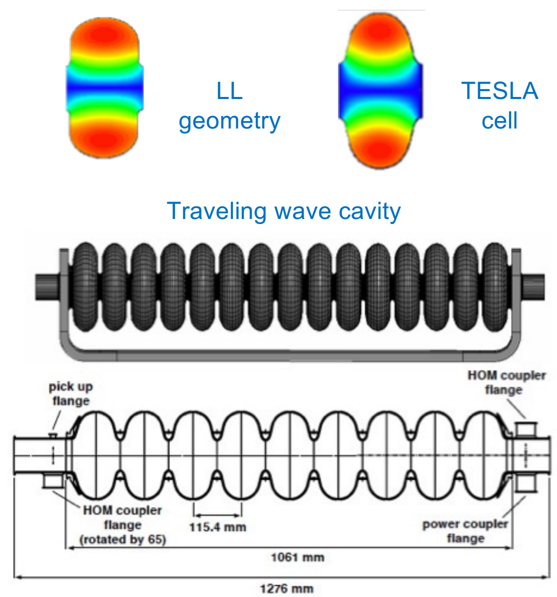


Multi-metallic conduction cooled Nb_3Sn cavity



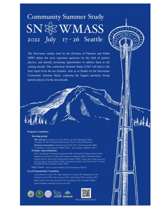


Advanced SRF cavity geometries



Key Directions for SRF R&D (3)

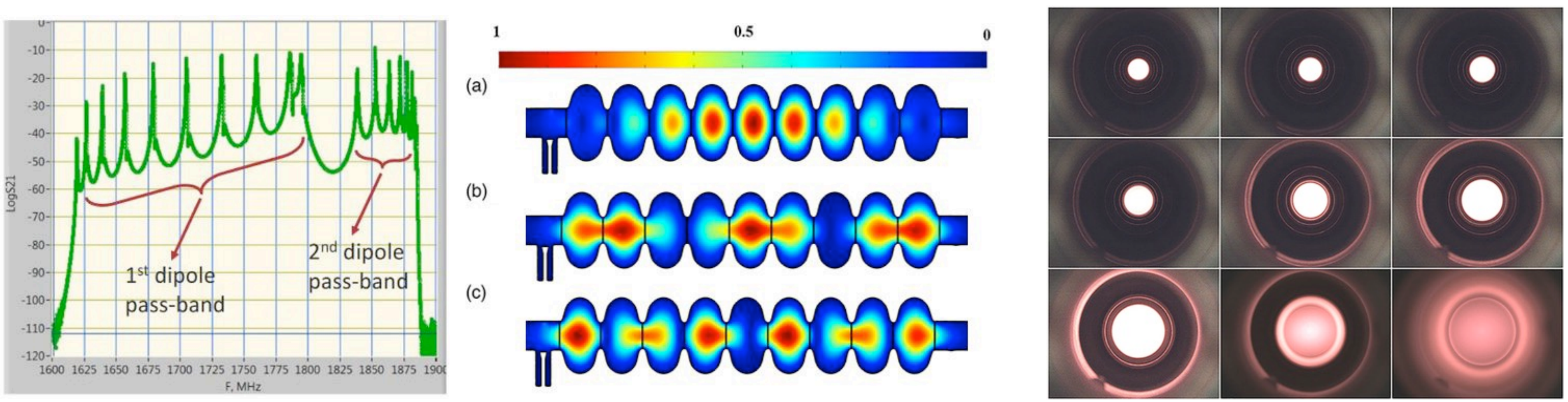
From AF7-rf Topical Group Report, White Papers, and Presentations



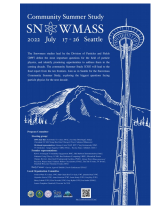
- Research on application of **SRF technology to dark sector searches**
- Pursuing R&D on **companion RF technologies** to mitigate field emission, provide precise resonance control, enable robust low level RF systems for high gradient and high Q accelerators, develop high efficiency, low-cost RF sources, etc.

Example:

Plasma processing for in-situ field emission mitigation



Summary



- The U.S. DOE Radiofrequency Accelerator R&D Roadmap and the European Accelerator R&D Roadmap cover similar SRF technology topics
- The Snowmass discussions, White Papers, and reports confirmed that the DOE Roadmap remains valid, highlighted recent progress, and outlined the key directions for the SRF technology
- There are many opportunities for collaboration between the European and U.S. institutions on many topics discussed during the European HEP Strategy Process and Snowmass
- Some key direction are among WG topics of this TTC Meeting