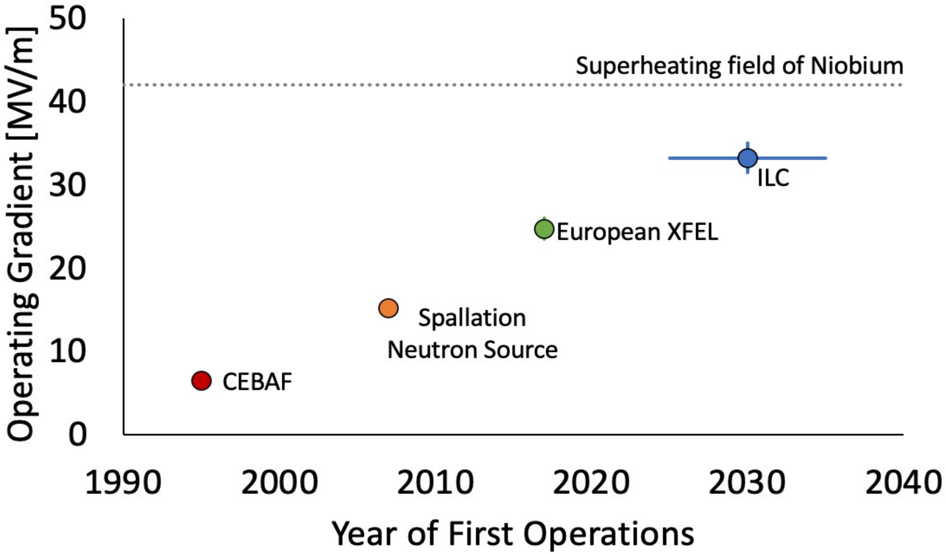
High Gradient and Nb_3Sn SRF Technology

Sam Posen

Muon Community Meeting 2021
20 May 2021

Progress in Maximum Operating Gradient of SRF Linacs

- SRF R&D has led to substantial progress in accelerating gradient
- Mitigations developed for many non-fundamental limitations, such as:
  - Field emission
  - Multipacting
  - High Field Q-slope (HFQS)
- Still working on making field emission more fully mitigated
- Best Nb cavities today are limited by quench close to the superheating field – theoretical maximum field of flux penetration for Nb



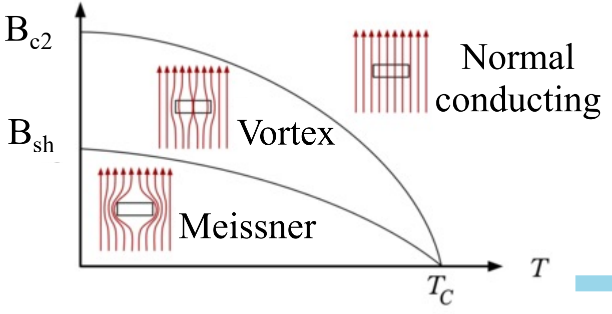
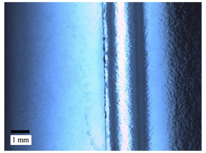


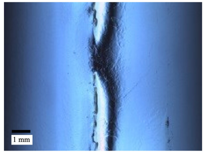
Image: Wikipedia

Meissner state required for $Q\sim10^{10}$ in Nb – See Sergio Calatroni's talk for (lower Q) SRF in the vortex state!

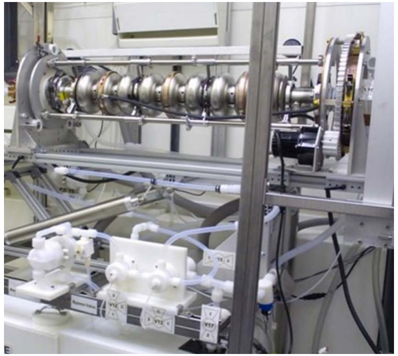
SRF Processing For ILC – 4 Key Steps for Gradients >30 MV/m

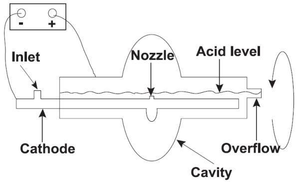
Carefully Quality Controlled Cavity Fabrication using High Purity Niobium



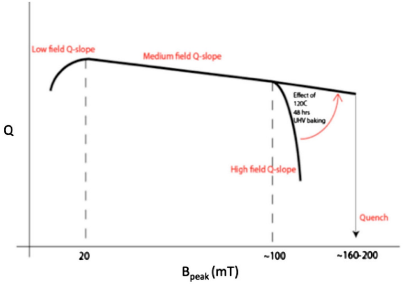


Electropolishing

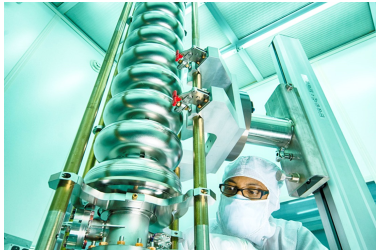




120 C Bake



High Pressure Water Rinsing (HPR) & Clean Assembly



Today we benefit from and build on the work of the international community of pioneering SRF researchers who developed these techniques (and more)!

European XFEL – >800 cavities, 100 cryomodules

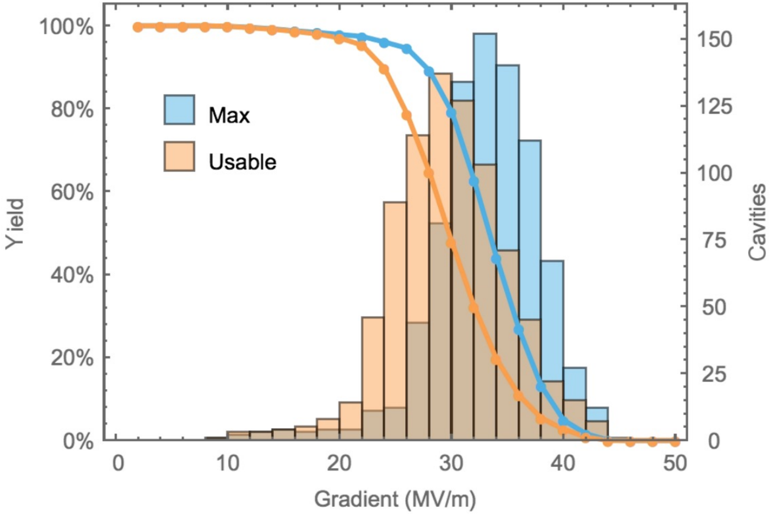
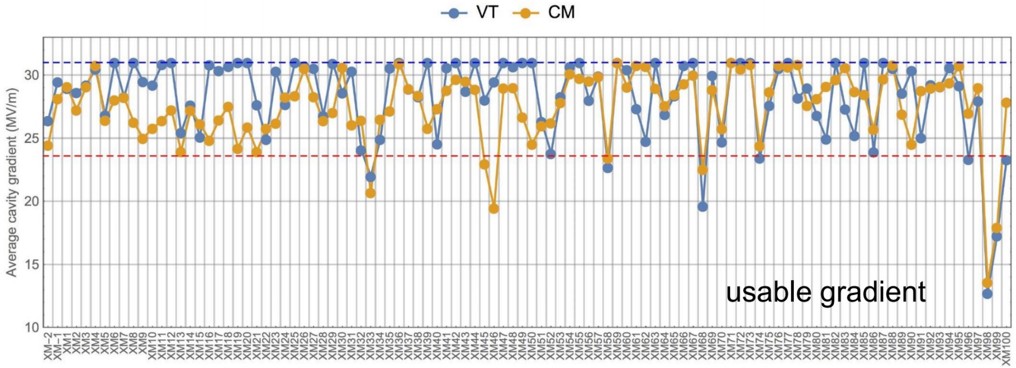


FIG. 28. Final maximum and usable gradient distributions of cavities accepted for string assembly (including retreatments).

D. RESCHKE *et al.*

PHYS. REV. ACCEL. BEAMS **20,** 042004 (2017)



Nick Walker (DESY)

D. Reschke, J. Schaffran, L. Steder, M. Wenskat, DESY

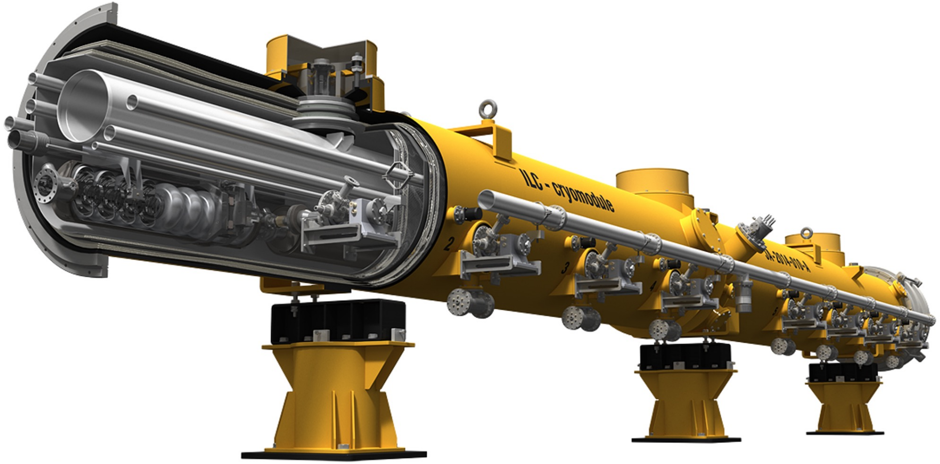
L. Monaco, INFN Milano

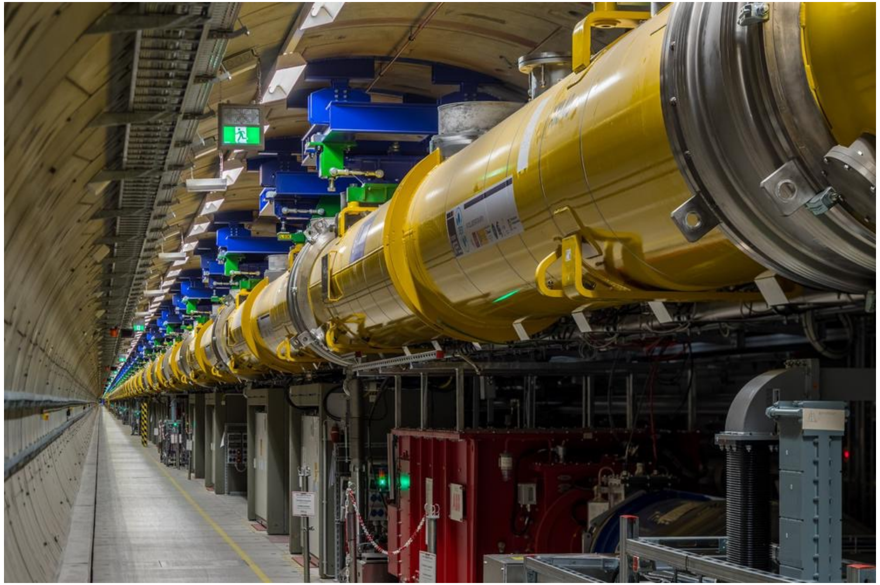
Performance Analysis of the European XFEL SRF Cavities, From Vertical Test to Operation in Modules

Fermilab

Mass Production of State-of-the-Art SRF Linac Modules

- Now very well-established techniques thanks in part to ILC R&D
- Now implemented in 100 cryomodules for European XFEL
- Technology adapted to cw SRF for LCLS-II and LCLS-II-HE





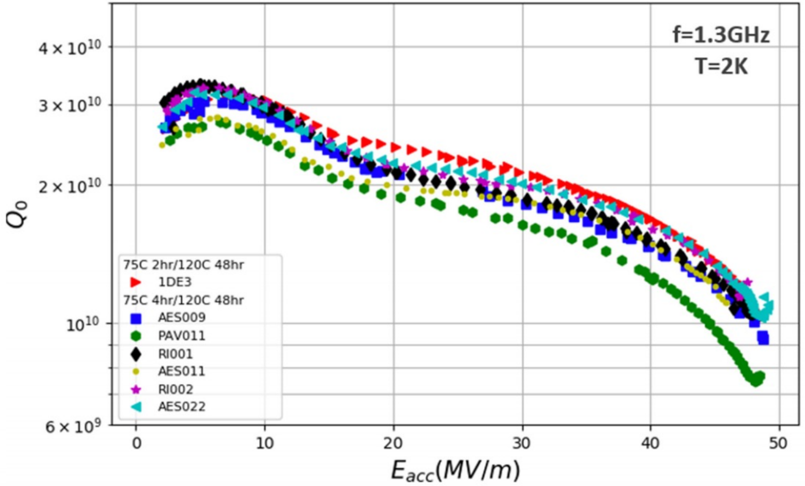
Images: Rey Hori (linearcollider.org) and European XFEL

Fermilab Cryomodule Assembly Timelapse

Fermilab

Recent SRF High Gradient R&D: 75/120 C Bake

- Single cell cavities treated with 75/120 C bake have reached unprecedented accelerating gradients ~48-50 MV/m (~ 210 mT, TESLA shape)
- 75 C for ~4 hours, plus standard 48 hour 120 C bake – consistent results in single cells, still studying origin, possibly linked to hydrides
- 50 MV/m cavity sent around for confirmation studies: Cornell, JLab, KEK, DESY



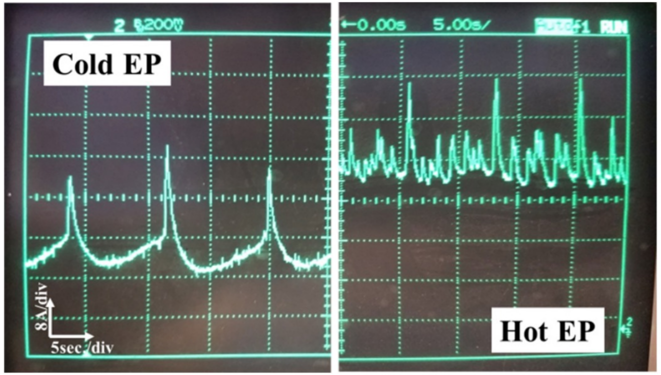
See Grassellino et al. arXiv:1806.09824

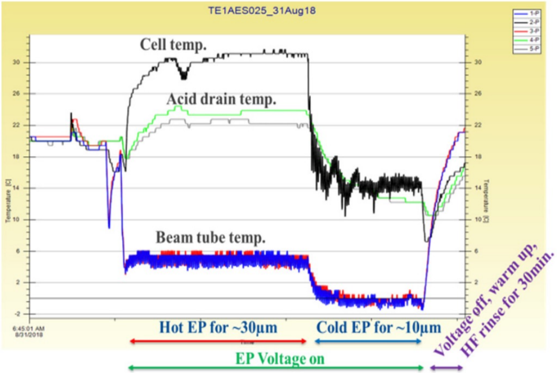
Fermilab

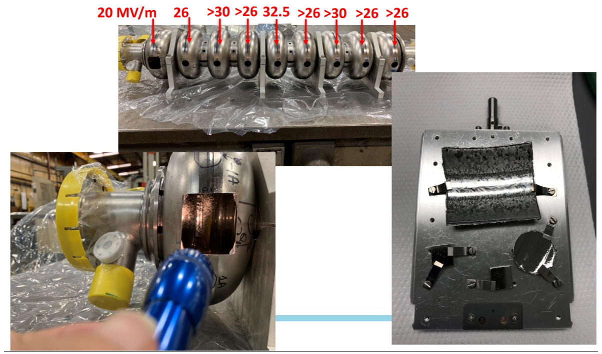
Recent SRF High Gradient R&D: Cold Electropolishing

- In Fermilab's single cell EP facility, it was found that keeping the electrolyte cold (~12°C) would result in less heating, lower flow, and strong current oscillations
- When rough surfaces were found in nitrogen doped cavities, cold EP was implemented, and found to substantially improve surface quality
- Does cold EP improve also non-doped cavity surfaces?
- Studies needed to evaluate and improve understanding

See Furuta et al. TUP022, SRF 2019







See Grassellino et al. TUFUA2, SRF 2019 and Palczewski et al. TUFUA3, SRF 2019

Fermilab

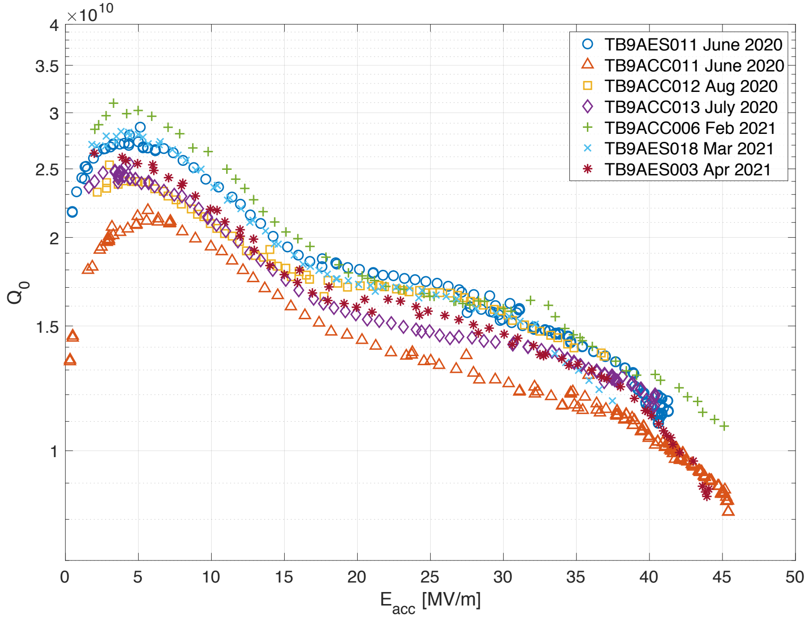
High gradient/high Q cryomodule – ILC cost reduction

- High gradient – high Q cryomodule collaboration work ongoing, goal $E_{acc} > 38$ MV/m with $Q > 1e10$
  - 7 cavities qualified for the cryomodule with $E_{acc} > 35$ MV/m, 5 of which are >40 MV/m
  - Cavity treatment based on recent high gradient SRF R&D (cold EP, 2-step bake)
  - Rebuild of first SRF module assembled at FNAL in ~2007 (disassembly has started – see image)
- Collaboration includes FNAL, JLab, Cornell, KEK, DESY, Saclay, TRIUMF…
  - Contributing in-kind on different aspects, from cavity treatment, to magnetic shielding, to cryomodule and components design

Fermilab Jefferson Lab DESY. cea
Cornell University Founded A.D. 1865 KEK-JAPAN Argonne National Laboratory TRIUMF

VTS Testing of Cavities for HGC @ FNAL

- Cavity results so far >35 MV/m:
  - TB9AES011 – 41.3 MV/m (max x-rays ~1000 mR/hr)
  - TB9ACC011 – 45.5 MV/m (max x-rays ~background)
  - TB9ACC013 – 40.4 MV/m (max x-rays ~100 mR/hr)
  - TB9ACC006 – 44.7 MV/m (max x-rays ~100 mR/hr)
  - TB9ACC012 – 36.9 MV/m (max x-rays ~1 mR/hr)
  - TB9AES018 – 37.6 MV/m (max x-rays ~3000 mR/hr)
  - TB9AES003 – 43.9 MV/m (max x-rays ~3000 mR/hr)



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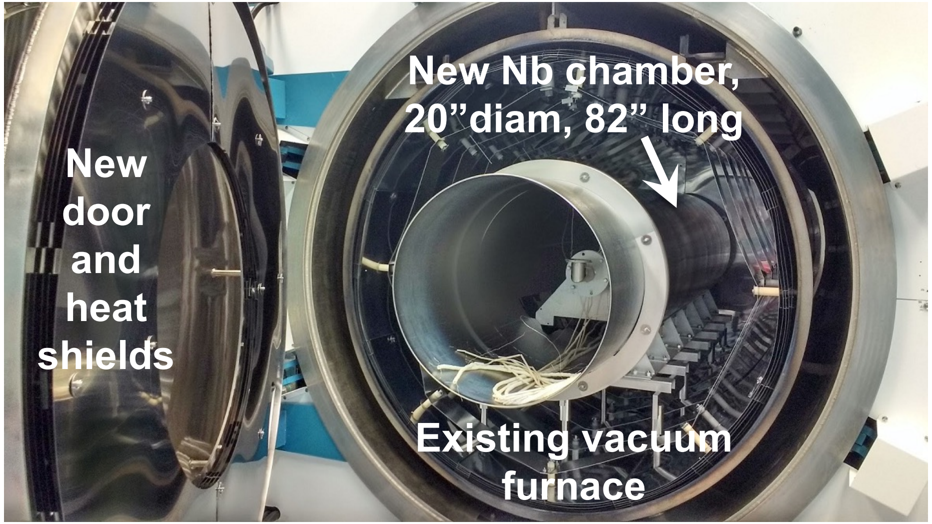
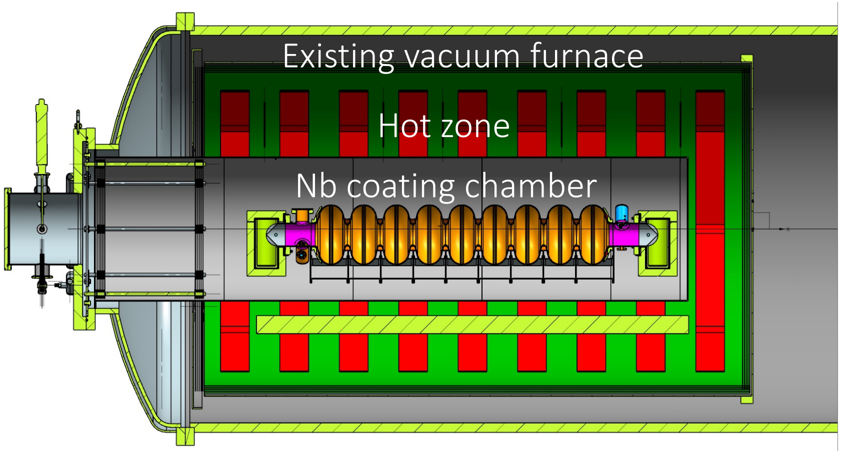
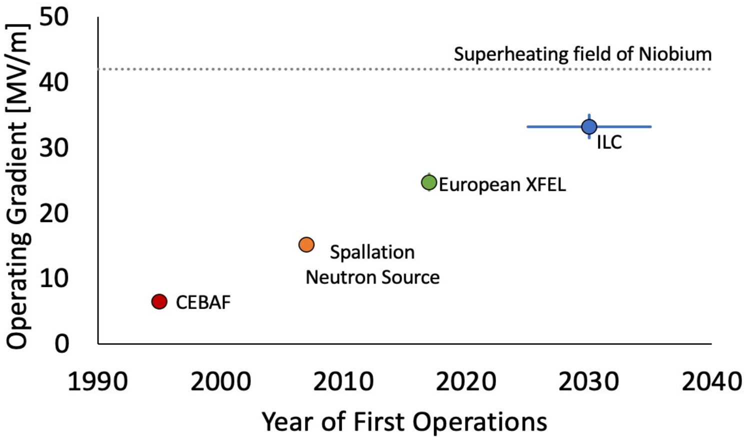
Example of a Nb_3Sn Coating System - Fermilab

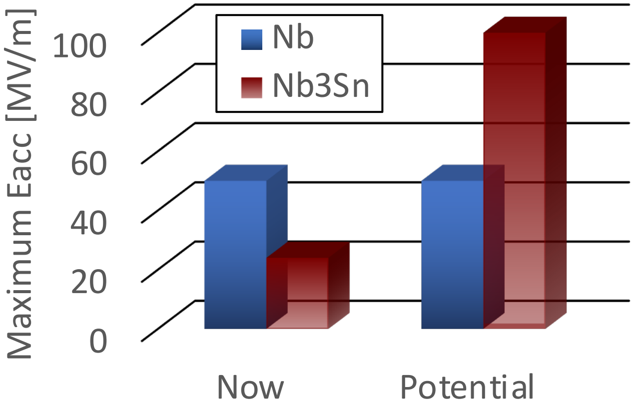




Advantages of Nb_3Sn Cavities: Higher Superheating Field

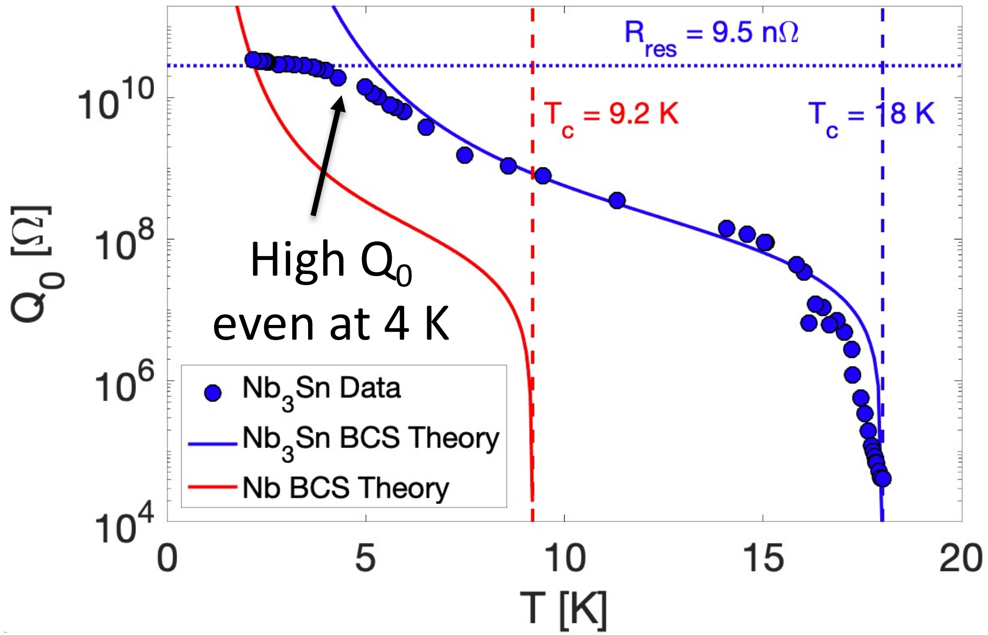
- Decades of R&D have made it possible to operate Nb cavities at higher and higher accelerating gradients, enabling new accelerator-based science over the years
- Developed mitigation methods for many limitation mechanisms
- State-of-the-art Nb cavities are limited very close to the superheating field H_{sh} of Nb
- *Predicted* H_{sh} of Nb_3Sn ~2x that of niobium
- Reaching H_{sh} would correspond to ~100 MV/m – currently far from this, but substantial progress





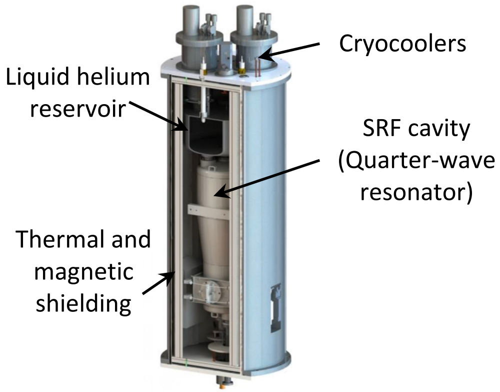
Advantages of Nb_3Sn Cavities: Higher Q_0 at High Temperature

- Nb_3Sn has substantially higher T_c than Nb (18 K vs 9 K)
- High Q_0 at relatively high temperatures
  - Potential for ~4.5 K operation in liquid helium
  - Potential for replacing cryoplant with cryocoolers
  - Even eliminating liquid helium via conduction cooling
- Impacts for CW applications, especially small and medium-scale

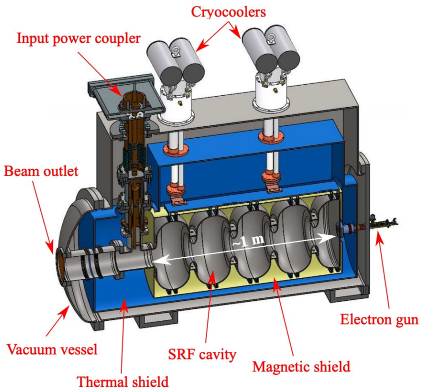


Potential Near-Term Applications of Nb_3Sn Cavities

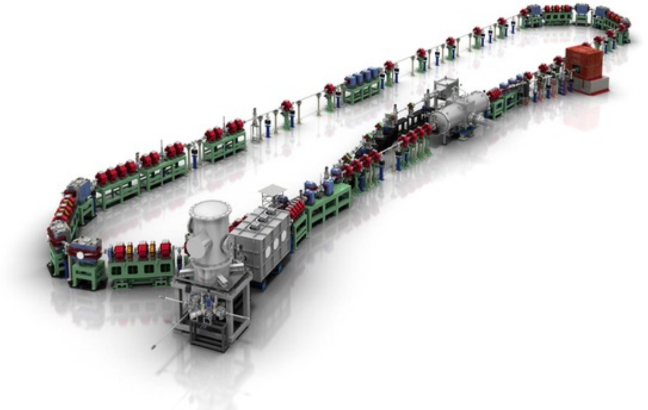
- Nb_3Sn is a potentially enabling technology for CW accelerator applications that could be realized in the near future:
  - Stand-alone cryomodules (e.g. isotope separator, harmonic cavities)
  - Compact high power accelerators (e.g. water treatment)
  - Turnkey/high MTBF energy recovery linacs (e.g. isotope production, EUV sources)



S. Kutsaev et al, *IEEE Trans. App. Superc.* 30, 8, 2020



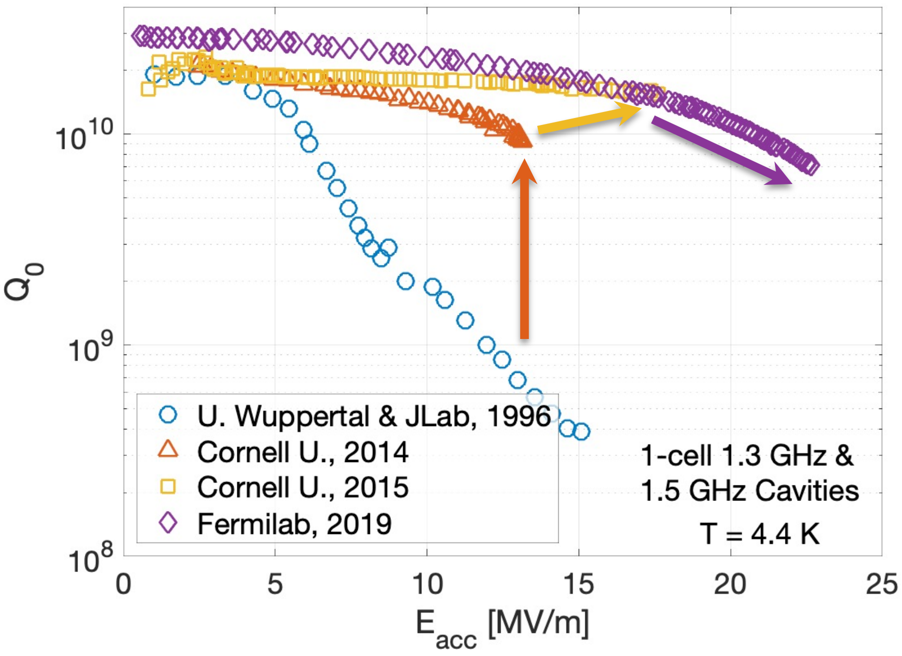
R.C. Dhuley et al, *Supercond. Sci. Technol.* 33 06LT01 (2020).



Y. Morikawa et al, New industrial application beamline for the cERL in KEK, IPAC’19, THPMP012

Evolution of Single Cell Nb_3Sn Cavity Accelerating Gradient

- Substantial progress in maximum gradient with high $Q \sim 10^{10}$
  - 1990: 7 MV/m
  - 2014: 13 MV/m
  - 2015: 17 MV/m
  - 2019: 24 MV/m
- Working up towards higher gradients, learning a lot about materials science of Nb_3Sn RF superconductivity
- Concurrently performing studies of practical considerations for Nb_3Sn operation, e.g. cavity tuning



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Advances in Nb_3Sn superconducting radiofrequency cavities towards first practical accelerator applications

S Posen[1], J Lee[1,2], D N Seidman[2,3], A Romanenko[1], B Tennis[1], O S Melnychuk[1] and D A Sergatskov[1]

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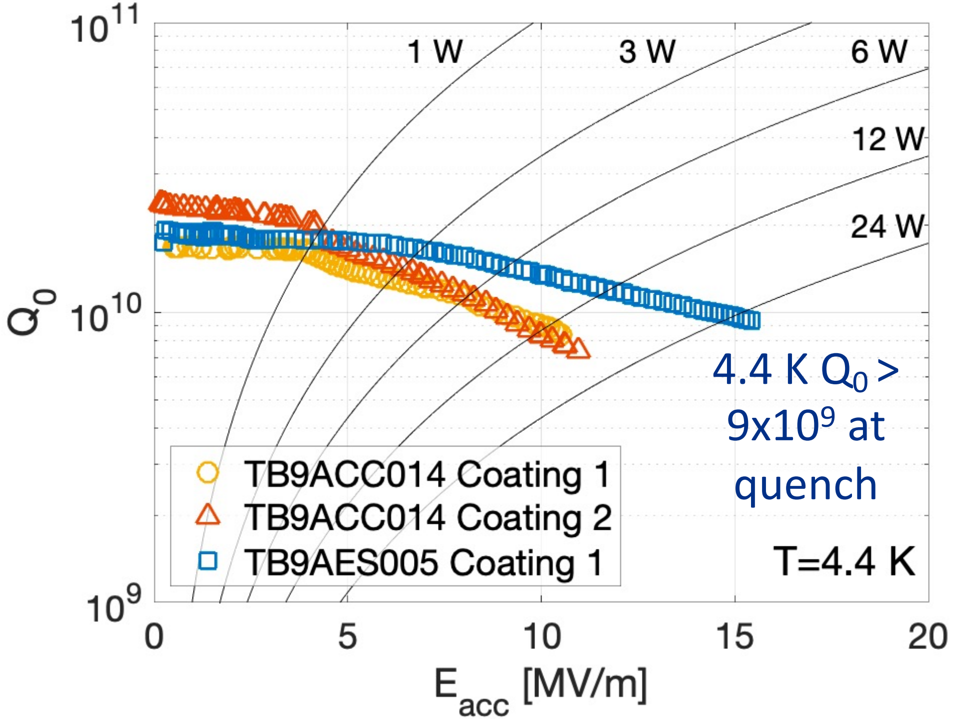
Superconductor Science and Technology, Volume 34, Number 2

Citation S Posen *et al* 2021 *Supercond. Sci. Technol.* **34** 025007

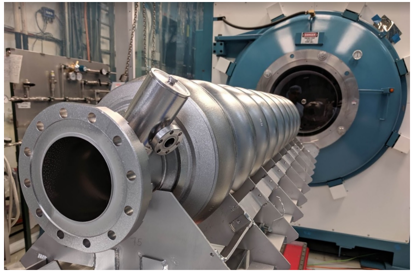
Coating Practical Accelerator Structures

Coating Practical Accelerator Structures

Nb_3Sn-coated 9-cell cavities TB9ACC014 and TB9AES005



4.4 K Q_0 > 9×10^9 at quench



Includes correction for stainless steel flanges 2x0.8 nΩ

Prospects for Continued Gradient Increase in Nb_3Sn Cavities

- Would be excellent to to realize full potential of Nb_3Sn. We have come a long way in the last 10 years and will continue R&D focus, hope to make substantial progress on time scales relevant for a muon collider
- Many ideas being pursued actively in labs across the world to push gradient
  - Smoother/thinner films from coating optimization
  - Post-coating treatment
  - New coating methods
  - Layered structures
- Supporting fundamental materials science efforts

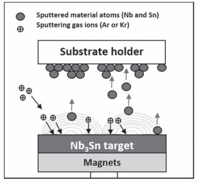


Figure 1. Schematic image of the sputtering setup.

IOP Publishing Superconductor Science and Technology

Supercond. Sci. Technol. **32** (2019) 035002 (10pp) https://doi.org/10.1088/1361-6668/aaf61f

Development of sputtered Nb_3Sn films on copper substrates for superconducting radiofrequency applications

E A Ilyina, G Rosaz[1], J B Descarrega, W Vollenberg, A J G Lunt, F Leaux, S Calatroni, W Venturini-Delsolaro and M Taborelli

European Organization for Nuclear Research (CERN), 1211 Geneva 23, Switzerland

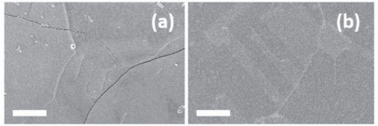
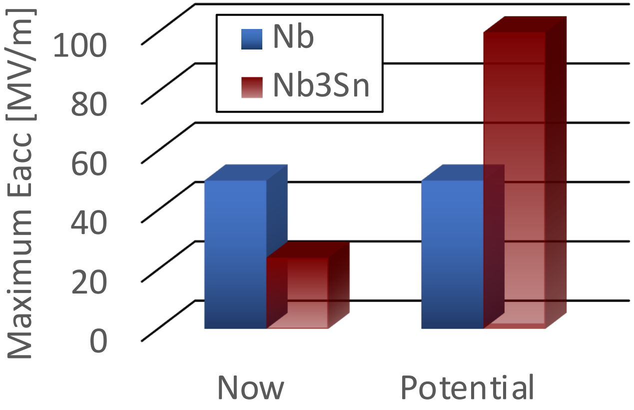


Figure 5. Surface morphology of Nb_3Sn coated under 1×10^{-3} mbar of (a) Ar and (b) Kr atmosphere after high-temperature treatment. Scale bars represent 400 nm.



Summary

- Sustained SRF R&D has led to enormous gains in performance, enabling new accelerator-based science that previously had not been feasible
- Innovations in processing made it possible to reach >30 MV/m accelerating gradients needed for ILC
- Progress continues, including recent developments leading towards >40 MV/m gradients in multicell Nb cavities
- Nb_3Sn has great potential but is currently limited to significantly below Nb
- There has been substantial progress recently in Nb_3Sn R&D and hope sustained efforts will lead to continued improvements in maximum accelerating field