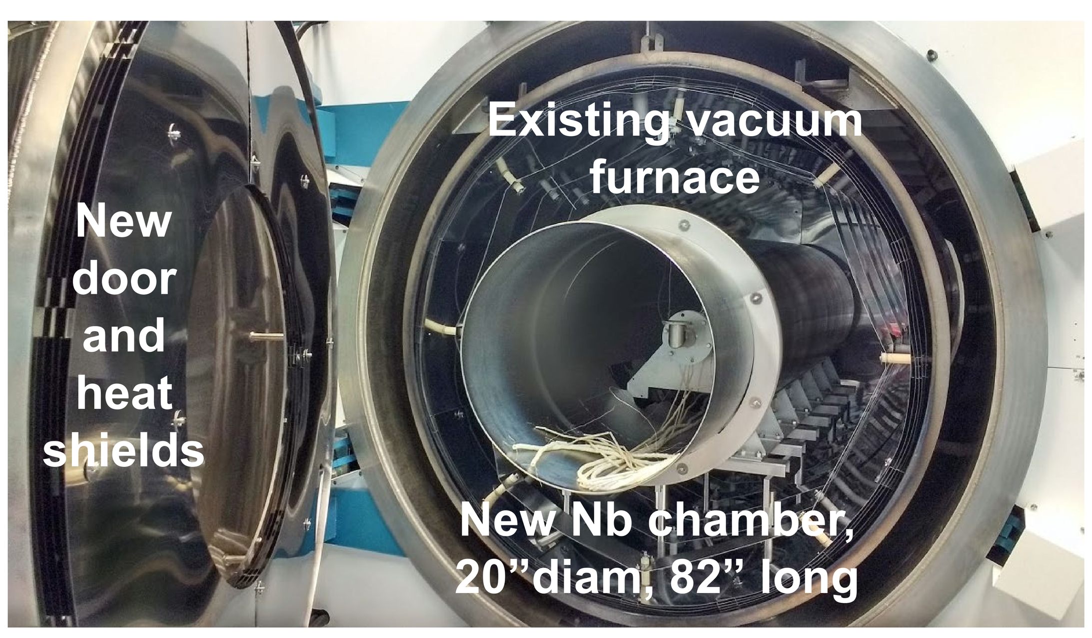
# $Nb_3Sn$ Superconducting RF Cavities: R&D Progress at Fermilab and Opportunities

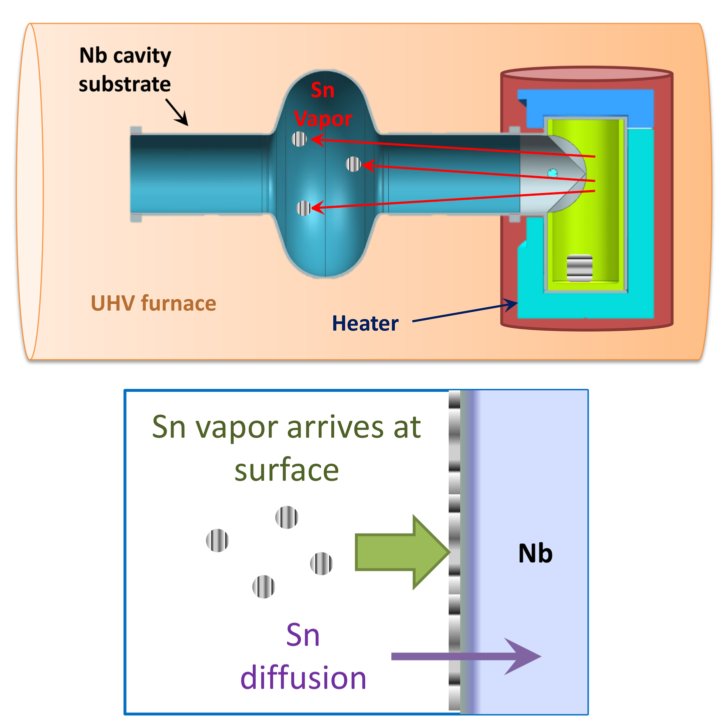
FERMILAB-CONF-20-044-

## Why $Nb_3Sn$? Advantages of Advanced SRF Material

$Nb_3Sn$ becomes superconducting at twice as high temperature as our standard SRF material niobium. This allows us to efficiently operate $Nb_3Sn$ cavities at 4.4 K instead of the usual 2 K. This reduces cryogenic costs and even makes it possible to use a cryocooler instead of a large, complex cryogenic plant.

The superheating field $H_{sh}$ of $Nb_3Sn$ is twice that of niobium. $H_{sh}$ is thought to be the ultimate limit for a defect-free superconductor. $Nb_3Sn$ cavities being made today are still about a factor of 4 away from this ultimate limit, but R&D has been leading to substantial progress towards this goal.

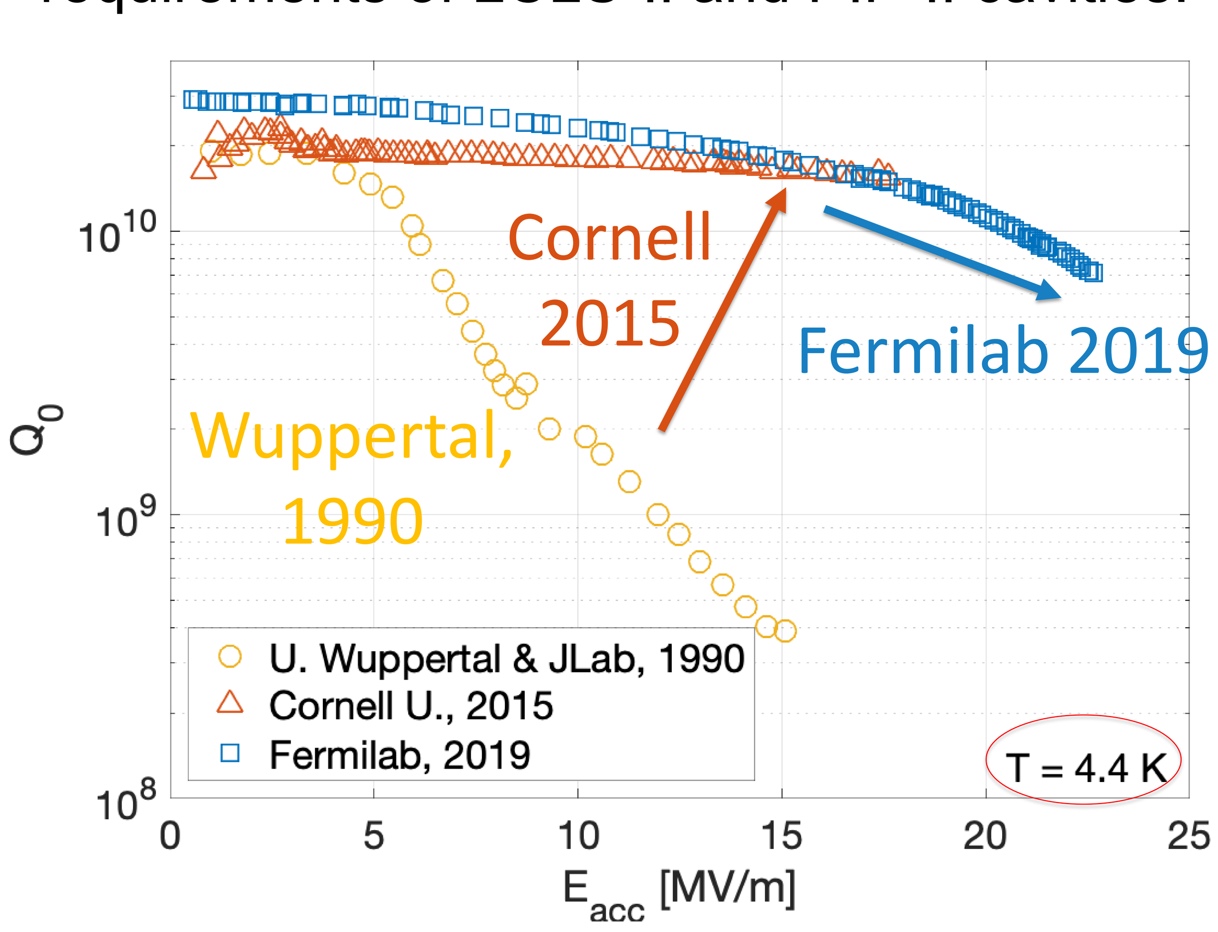


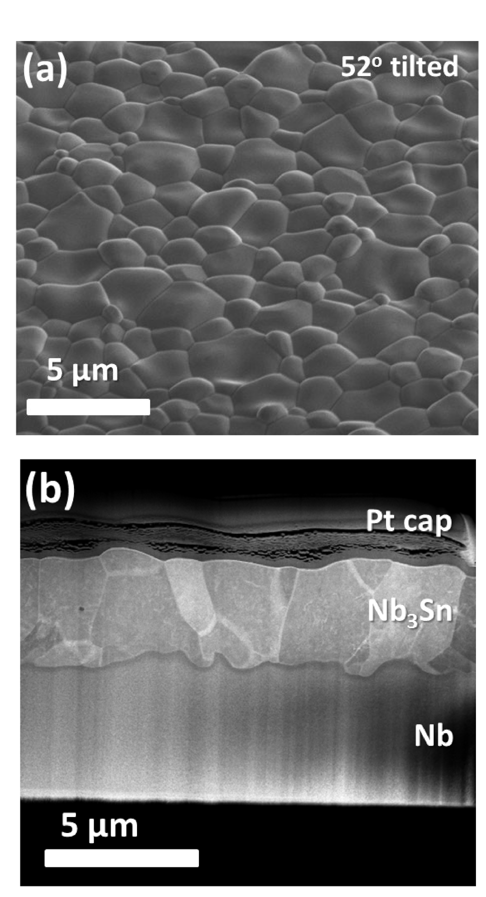




Fermilab's $Nb_3Sn$ coating system in MP9 uses the vapor diffusion process: tin is evaporated and the vapor reaches niobium cavities at 1100 C. The Nb-Sn phase diagram favors the growth of stoichiometric $Nb_3Sn$ at this very high temperature.

## Record $Nb_3Sn$ Accelerating Gradients at Fermilab

If $Nb_3Sn$ cavities can reach $H_{sh}$, this would correspond to a gradient of nearly 100 MV/m, which would be extremely beneficial for high energy accelerators. This field has not yet been reached, and experiments suggest that defects in the film are the limitation. Improvements in film quality has led to steady progress in maximum gradient. In 2019, a Fermilab cavity reached a new record gradient of 24 MV/m. This is already useful in many applications. For example, this exceeds the operating gradient requirements of LCLS-II and PIP-II cavities.

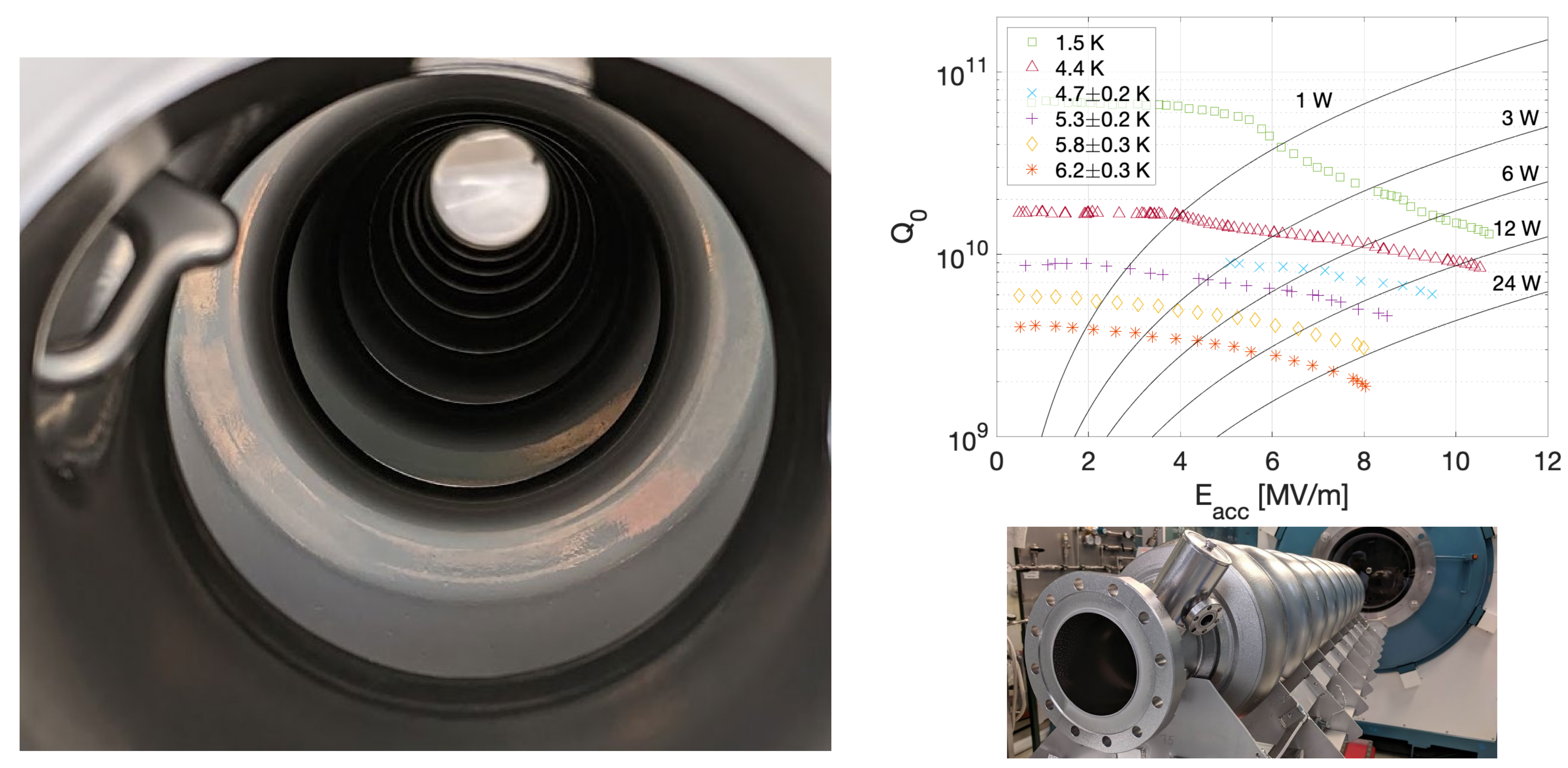



Left: Improvement in maximum accelerating gradient of Nb3Sn cavities over time. Fermilab R&D recently led to reaching 24 MV/m in a single cell 1.3 GHz cavities. Right: Microscopic images of a $Nb_3Sn$ film from above (a) and cross section (b).

## First Ever 9-cell $Nb_3Sn$ Cavity

9-cell 1.3 GHz cavities are practical accelerator structures ~1 m in length used in state-of-the-art facilities such as the European XFEL and LCLS-II. They are much larger than the single cell cavities typically used in R&D. For the first time ever, we coated a 9-cell cavity, which had good performance. While not as strongly performing as the single cell cavities, it shows significant progress towards making $Nb_3Sn$ coatings practical for applications.



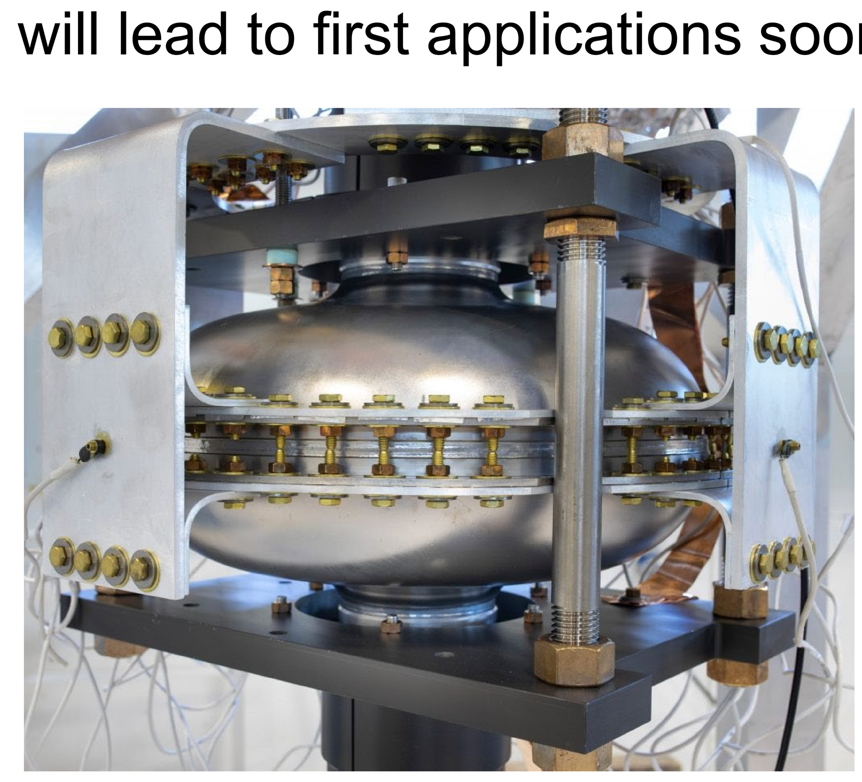

Inner surface of the 9-cell cavity after coating, performance, and view of the cavity after coating outside the MP9 furnace.

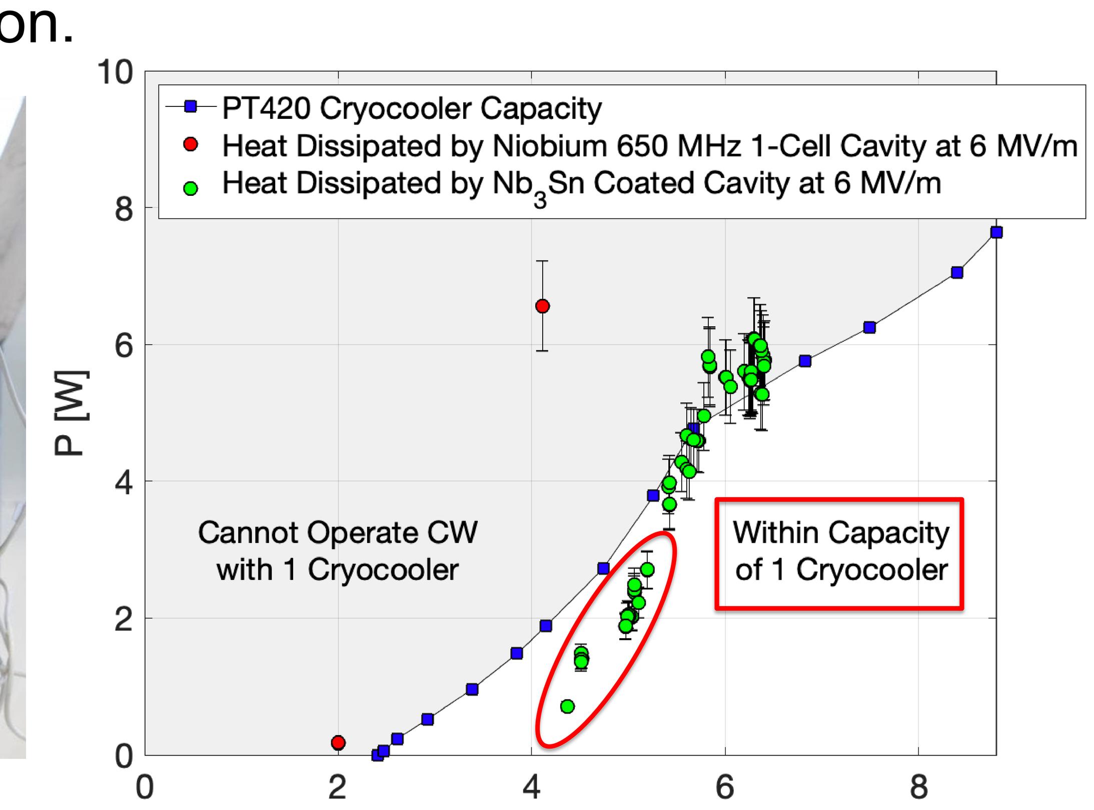
## Conduction Cooled $Nb_3Sn$ Cavity

Compared to cryogenic plants, cryocoolers are inexpensive, have a very small footprint, and require minimal operator attention and maintenance. If cavities could be cooled by cryocooler, it could enable compact SRF accelerators for industrial applications.

Cryocoolers can provide only a tiny amount of cooling at ~2 K, but a few watts at ~4 K. This makes them incompatible with typical niobium cavities, but compatible with $Nb_3Sn$ cavities thanks to its higher superconducting critical temperature.

Working with IARC, APSTD SRF researchers coated a cavity that was specially fabricated with conduction cooling links with $Nb_3Sn$. The cavity was then tested in a conduction cooling setup with a cryocooler, showing a successful proof-of-principle that we hope will lead to first applications soon.






Cavity with conduction cooling links (left, photo courtesy IARC) and plot showing the small heat dissipation measured in a Nb3Sn in the temperature range relevant for cryocooler-based cooling (right).

Fermi National Accelerator Laboratory

Fermilab U.S. DEPARTMENT OF ENERGY

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.