R&D on Large Grain Niobium Materials for SCRF-Cavity Applications

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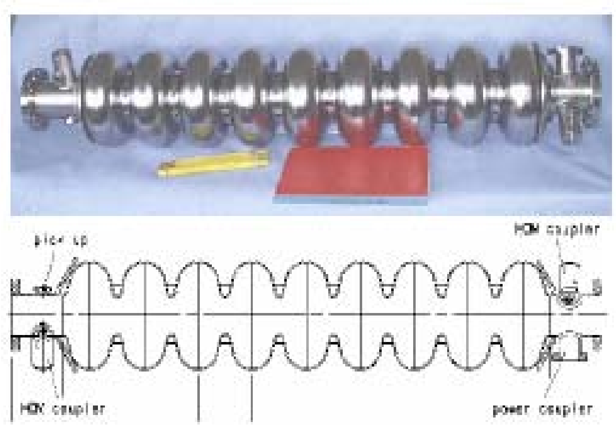
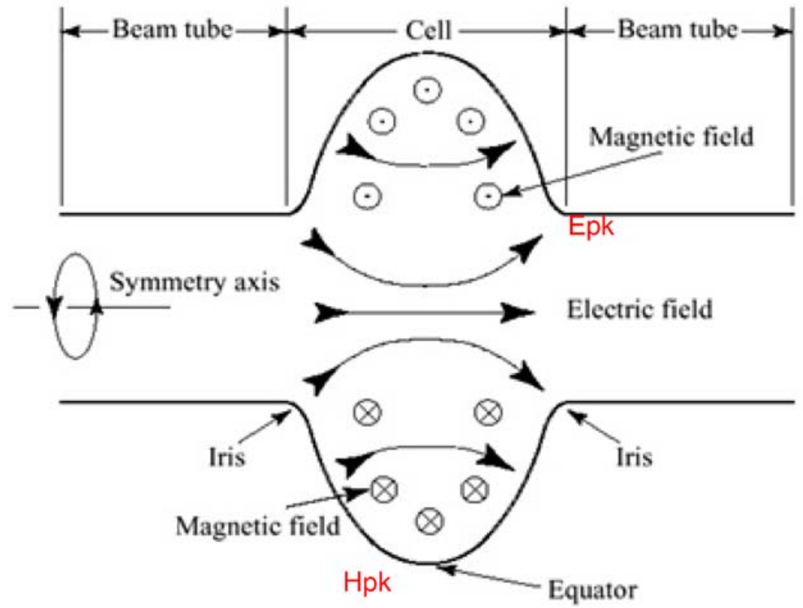
Radio Frequency (RF) Cavity



‘An RF power source’ fills the RF cavity via a ‘coupler’.



EM field will accelerate & impart energy to the charge particles if they are in phase with the electric field.

What do we want from a good RF cavity ?

High Quality Factor: **Q = (Stored energy)/(Dissipated power)** **&**

As high a gradient as possible

Dissipated power: $P_d = \frac{R_s}{2} \int |\vec{H}|^2 dS$

$$R_{s\ normal} = \sqrt{\frac{\omega \mu_o}{2\sigma}}$$ → For copper at 300 K 1.3 GHz, $R_{s\ Copper}$ = 9.4 mΩ

$$R_{BCS} \propto \lambda_L^3 \omega^2 \ell \exp(-1.76\, T_c/T)\,.$$ → For bulk Nb at 2K R_{BCS} ~ 10 nΩ

Superconducting RF cavities excel in applications where one needs 'continuous wave or long-pulse' acceleration with gradients above a few million volts per meter (MV m^{-1})

Superconducting Materials R&D for SCRF Technology: Overall Aim

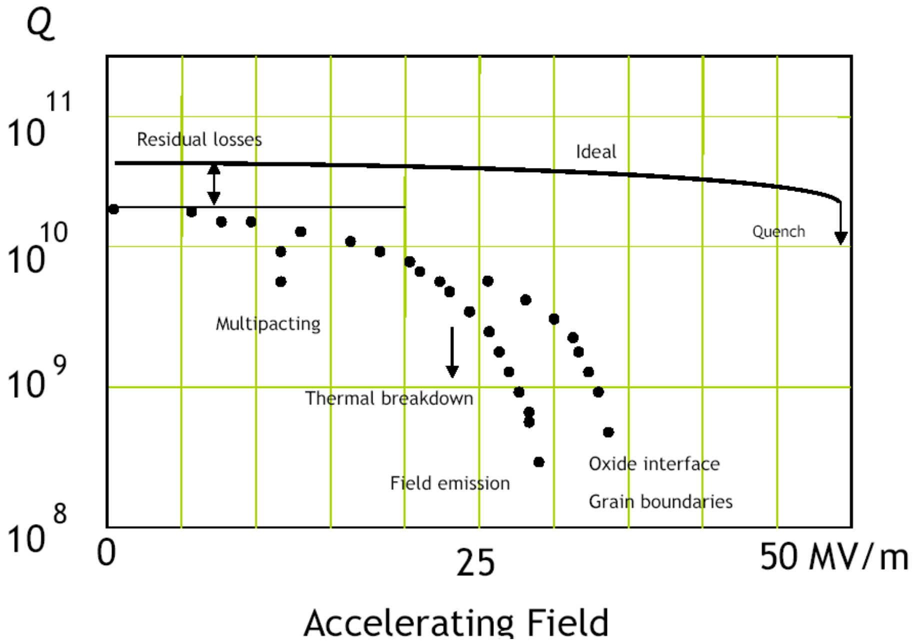
- Tuning superconducting properties of a suitable material for fabrication of an energy efficient and cost effective SCRF accelerator structure.
- Achieving reliability and reproducibility in the SCRF cavity performance.
- Gain knowledge and experience to venture into newer energy efficient and superior materials.
- Elemental Niobium with superconducting transition temperature of ~9.2 K is currently the material of choice for SCRF cavity fabrication.

Niobium SCRF Cavities: Limit of their performance

Materials and surface issues in Niobium SCRF cavities

Extrinsic effects

- Surface roughness, grain boundaries → Electrical break down; ↓Gradient
- Impurities → Depress superconductivity, increase $R_{residual}$.
- Surface Oxides → Suspected to degraded SC response?? NO
- Field emission and multipacting → Quenching of the Cavity.



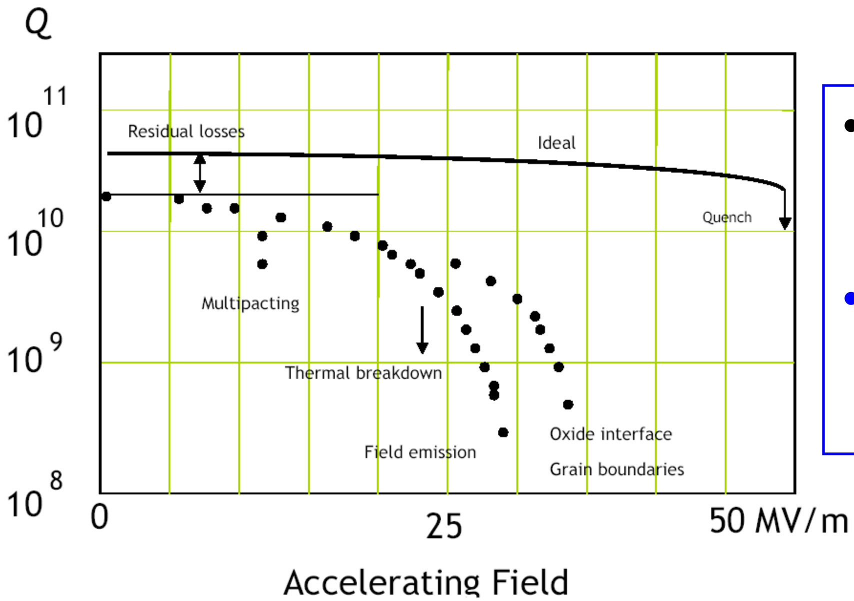
Most of these problems are solved with proper cavity shape, and chemical treatment and cleaning of cavity surface. **Field emission free 1.3 GHz Tesla type cavities reaching up to 30-35 MV m^{-1} are obtained regularly in various labs.**

Is it the upper limit of achievable gradient ?
Answer is No!

Two fundamental limits for Niobium SCRF cavities

1. A critical RF magnetic field above which the perfect SC state is destroyed
   -- limits the Accelerating Field or Gradient.

2. The surface resistance as predicted by the microscopic BCS theory.
   -- limits Quality Factor Q.



- For good quality Nb material H_{C1} ~ 1.8-1.9 kOe at 2K.
- For a 1.3 GHz Tesla type elliptical cavity operating at 2K, this will correspond to a maximum gradient of ~ 50 MV/m

But Nb elliptical 1.3 GHz SCRF cavities operating at 2K seldom reaches > 40 MV/m?!

Puzzles and Open Issues in Niobium SCRF cavities

Puzzles:

- All cavities fabricated in the same way do not give high gradients.
- Cavity gradient seldom reaches above 40 MV/m.
- Recent report of a 9 Cell Tesla type cavity reaching 45 MV/m

Open Issues:

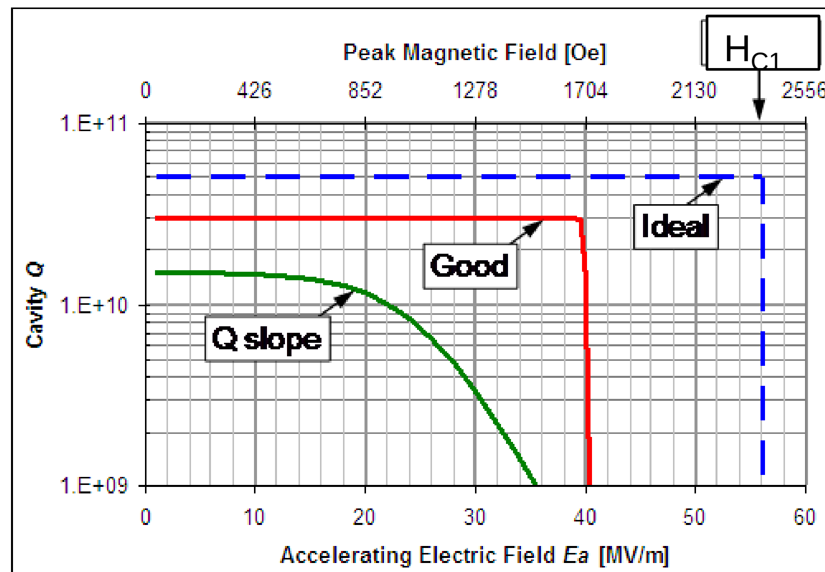
(1) What is the RF critical magnetic field in Niobium? Is it

– Thermodynamical critical field-H_c or field for first flux line penetration-H_P?

– How does it depend on temperature?

(2) Why does the RF surface resistance of niobium increase sharply at high RF magnetic field?

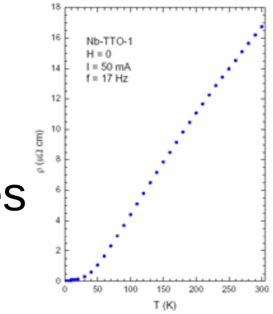
-- High-field slope in the quality factor-Q-slope



Nb for SCRF cavity fabrication: Material qualifying criterion

- Current approach mainly relies on improving the residual resistivity ratio (RRR) of the Nb. Involves expensive Niobium refinement process.

- High RRR Nb + right cavity shape + chemical treatment
$\Rightarrow$ Low extrinsic (+ surface) defects, so cavity loss reduces



RRR = R_{300K}/R_{10K}

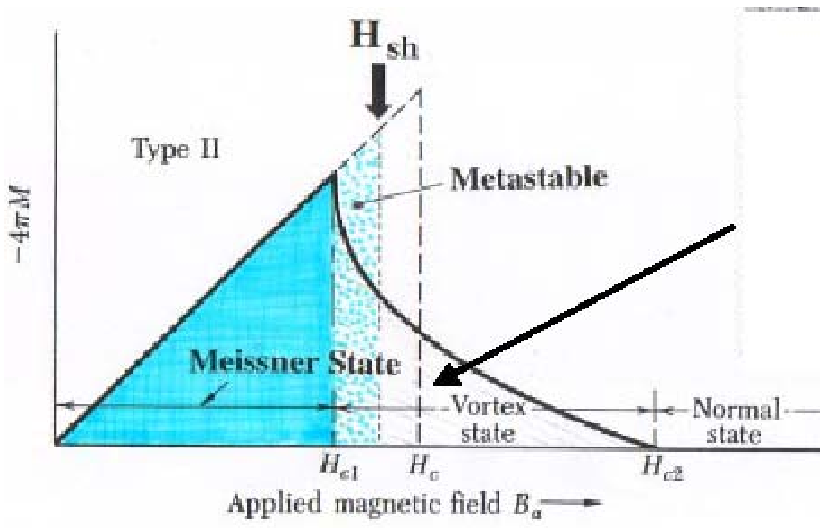
- High RRR, however, does not necessarily say how good are the superconducting properties of Niobium & at best gives indirect information on thermal conductivity.

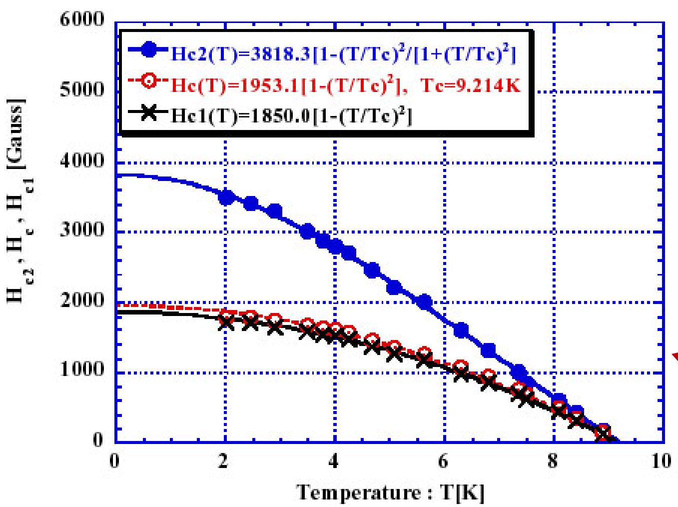
- RRR of Nb material in the formed SCRF cavity will be significantly different from the RRR of starting Nb-sheet metal. So will be the thermal conductivity !

SCRF Materials R&D:
Approach of a Condensed Matter Physicist

Superconducting Critical Fields and Surface Resistance

Critical Fields in a Superconductor





- External magnetic field is expelled below a lower critical field limit H_{C1}.
- In a type-I superconductor above H_{c1} normal state is reached.
- In a type-II superconductor magnetic field penetrates the materials above H_{C1} in the form of quantized flux lines; the material remains superconductor until a upper critical field H_{C2}
- $H_{C1} < H < H_{C2}$ => Abrikosov lattice or Vortex state => important for high critical current (J_c) applications e.g. SC magnets.
- $H < H_{C1}$ => Meissner state, important for RF superconductivity applications.

Niobium is a type-II superconductor

Surface Resistance in a Superconductor

Response of a superconductor in ac field is described by two fluid model:

- Cooper pairs form superfluid.
- Unpaired electrons form normal fluid. Source of power dissipation in ac field.

BCS Surface resistance

$$R_{BCS} \propto \lambda_L^3 \, \omega^2 \, \ell \, \exp(-1.76 \, T_c/T)$$

- Surface resistance depends exponentially on temperature.
- Surface resistance depends to the square of frequency.

Points to be examined (in Niobium & other Sc materials)

Role of the field of first flux-line penetration H_P and surface resistance R_{BCS} and how they may be varying with,

(1) the methods of Nb materials preparation, grain size ?

(2) the surface chemical treatment of Nb: Electro-polishing versus Buffer Chemical Polishing ?

(3) thermal treatment -- annealing temperature and time ?

What is our Aim ?

- Through an understanding of the microscopic properties of the materials treated differently we can possibly identify SC materials, which will give best performance.

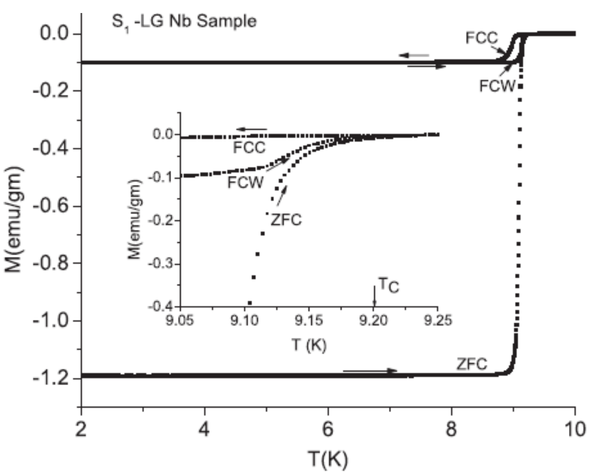
- An effective SCRF materials qualification scheme using H_{C1} or H_p and R_{BCS} since those set limits on achievable SC-RF accelerating gradients and Quality factor.

Materials R&D on large grain Niobium: Some results

Comparison of Superconducting Transition Temperature in Large grain and Fine Grain Niobium-Materials

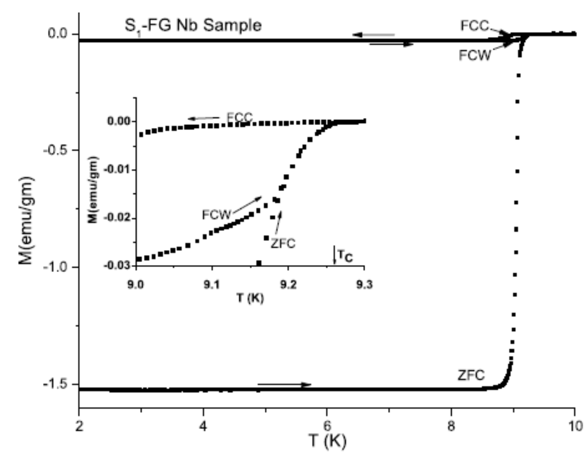
- Superconducting transition temperature of fine grain and large grain samples of Niobium in pristine conditions has been determined through magnetization measurements.

- Average grain size: Large grain (> 1 mm) ; Fine grain (~ 50 micron)



- T_C of pristine large grain Niobium ~ 9.2K, measured in H= 100 Oe.

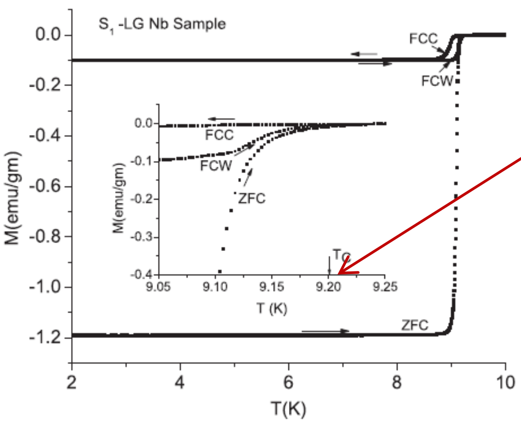
- T_C of pristine fine grain Niobium ~ 9.25 K, measured in H= 100 Oe.



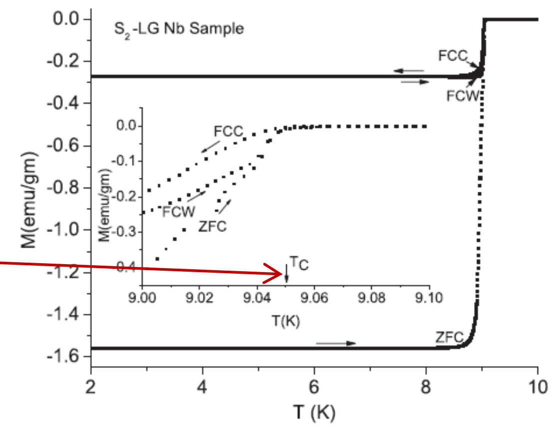
Supercond. Sci. Tech. **Vol. 21** 065002 (2008); **Vol. 22** 105014 (2009)

Effect of Chemical Treatment on Superconducting Transition Temperature of Niobium-Materials

Superconducting transition temperature of large grain samples of Niobium in pristine conditions as well as after chemical and thermal treatments has been determined through magnetization.



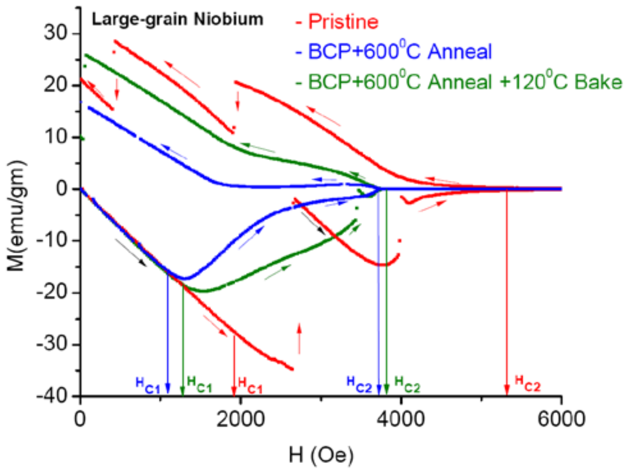
- T_C of pristine large grain Niobium ~ 9.2K, measured in H= 100 Oe.
- T_C of chemically treated large grain Niobium~9.05K, measured in H= 100 Oe.



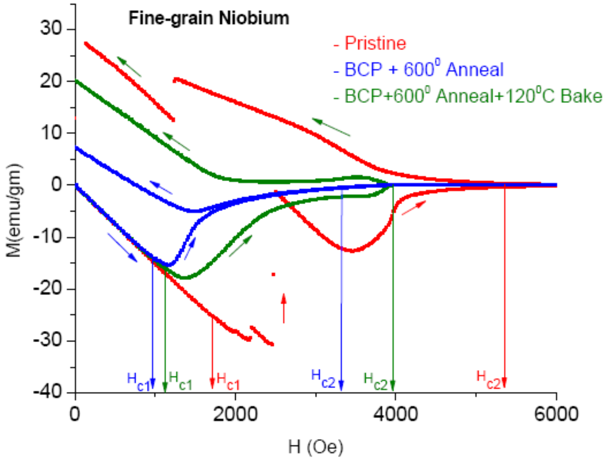
Supercond. Sci. Tech. **Vol. 21** 065002 (2008); **Vol. 22** 105014 (2009)

Effect of Chemical Treatment on Critical Fields of Niobium-Materials used in SCRF Cavity Fabrication

H_{C1} and H_{C2} of fine grain, large grain samples of Niobium in pristine conditions as well as after chemical and thermal treatments has been determined through magnetization measurements.



- H_{C1} of pristine Nb ~ 1800 Oe at 2K.
- H_{C1} of buffer chemical polished (BCP) Nb is reduced to ~ 1200 Oe.
- H_{C1} recovers to ~ 1400 Oe with 120^0 C bake.
- SCRF cavity prepared with such BCP Nb would reach maximum 30-35 MV/m.



Supercond. Sci. Tech. **Vol. 21** 065002 (2008); **Vol. 22** 105014 (2009)

Possible causes of degradation of superconducting properties of Niobium due to chemical treatment

- Chemical reactions during chemical treatment release gaseous atoms of O and H, which diffuse into bulk of Niobium and resides in the interstitial positions or defect structures.

- There exist experimental evidence that such interstitial atoms causes degradation of superconducting properties of Nb.

- If bulk superconducting properties get affected, the surface superconducting properties are likely to be even more vulnerable.

PHYSICAL REVIEW B VOLUME 9, NUMBER 3 1 FEBRUARY 1974

Effects of interstitial oxygen on the superconductivity of niobium*

C. C. Koch, J. O. Scarbrough, and D. M. Kroeger
Metals and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830
(Received 14 May 1973)

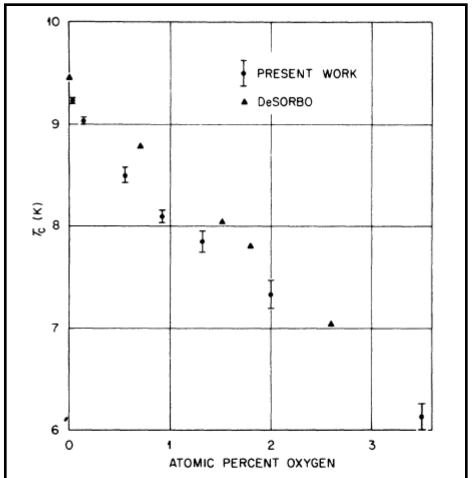
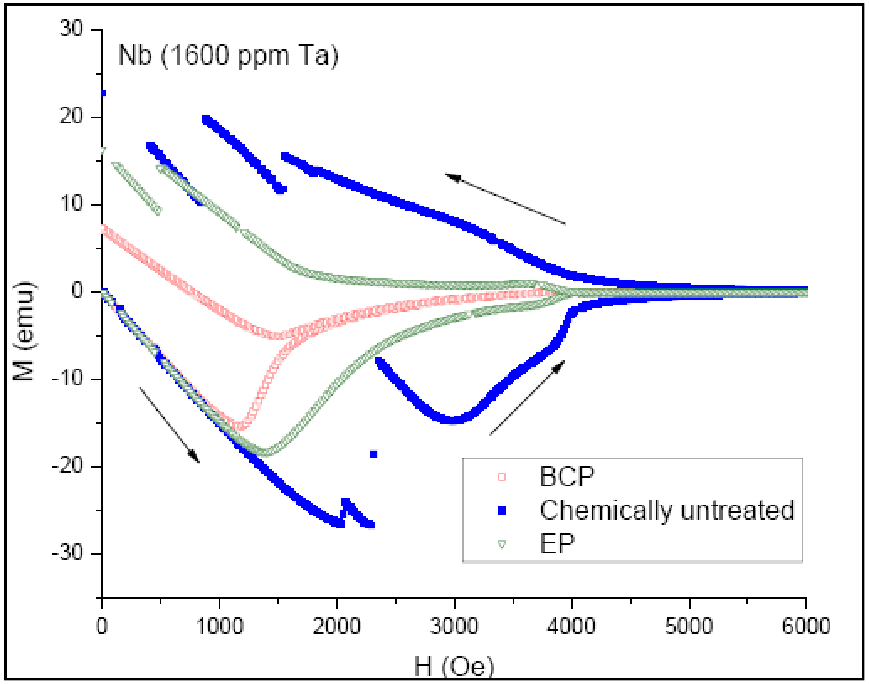


FIG. 4. Superconducting-normal transition temperature T_c vs atomic-percent oxygen.

Comparison of superconducting properties of electropolished and buffer chemical polished Niobium-Materials.

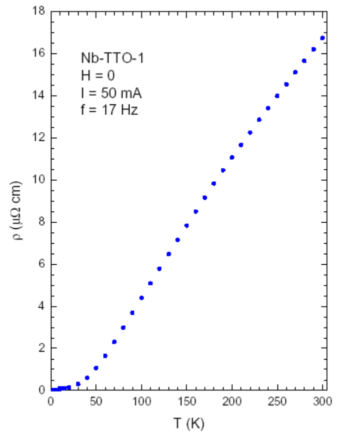


- H_{C1} of EP-Nb material is higher than that of BCP-Nb material.
- This is in consonance with the fact that accelerating gradient achieved in EP-Niobium SCRF cavities are > 35 MV/m.
- Electropolishing seems to be less harsh on Nb than Buffer Chemical polishing!

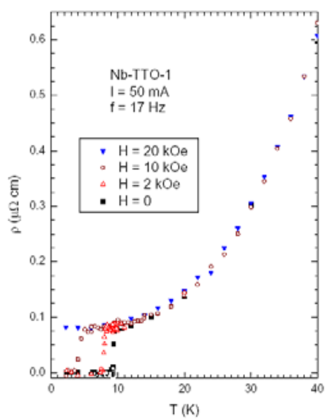
–"By now there exists compelling evidence that the BCP process limits the attainable accelerating fields of multicell cavities to about 30 MV/m **even if niobium of excellent thermal conductivity is used**." L. Lilje et al (DESY) arXiv Physics:0401134v1

Electrical resistivity and thermal conductivity of large grain Niobium

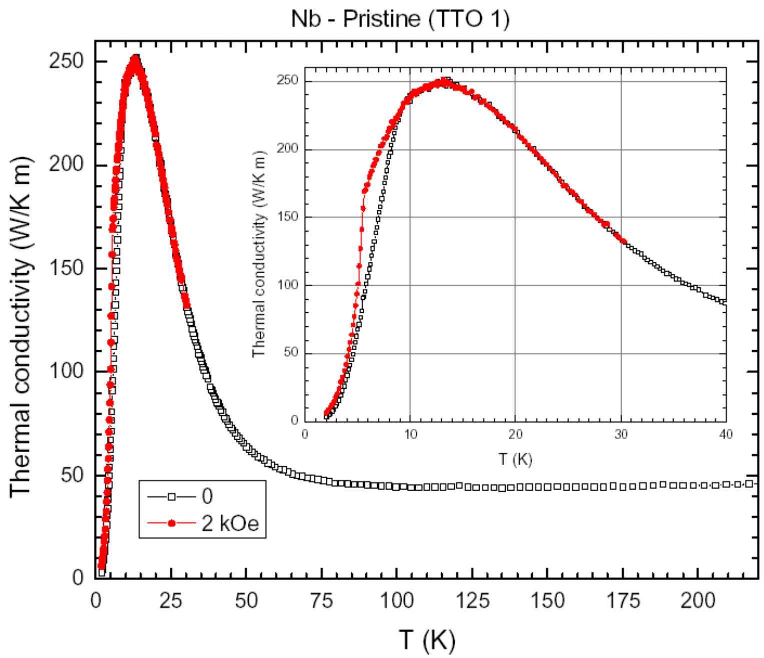
Chemically untreated sample of Large Grain Nb



Residual resistivity ratio RRR ~ 200



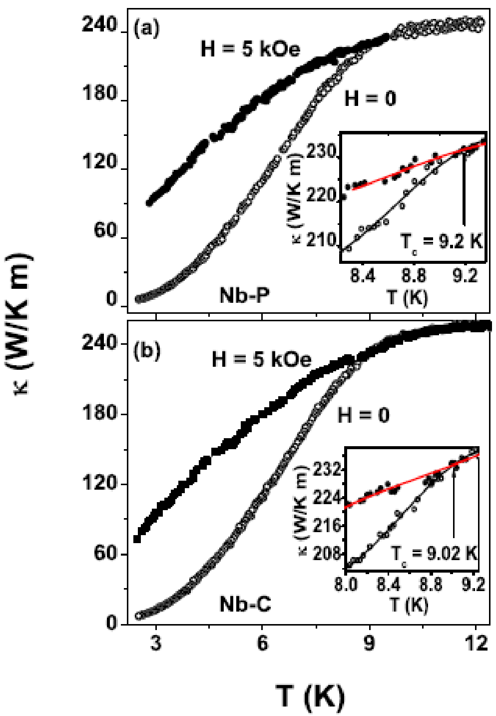
Resistivity vs Temperature plot



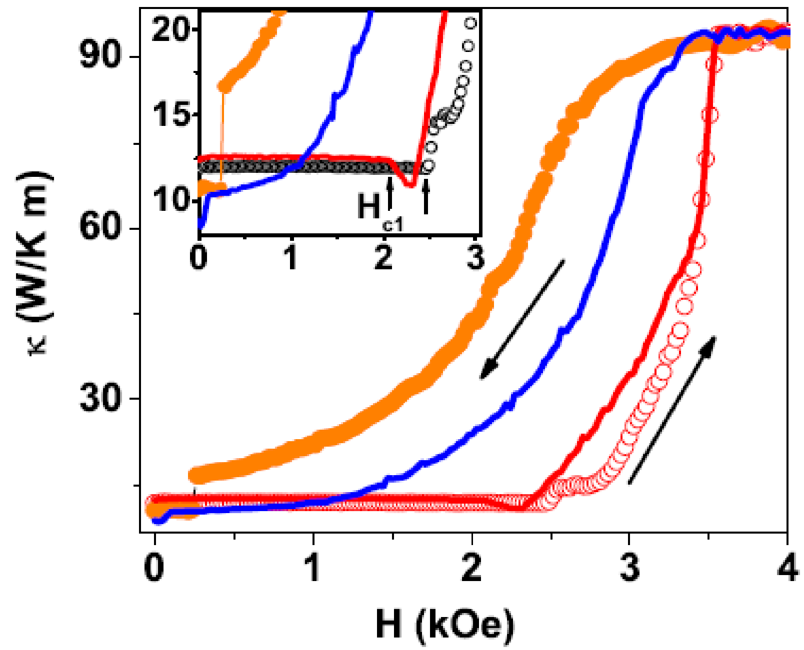
Thermal Conductivity vs Temperature plot

Temperature and magnetic field dependence of thermal conductivity of superconducting large grain Niobium

- Normal state κ (T) of BCP treated Nb is lower (by 10%) than that of pristine Nb.
- Both Tc and H_{C1} of BCP treated Nb is lower than the pristine Nb.
- A small but distinct dip in κ (T) is observed at H_{C1}



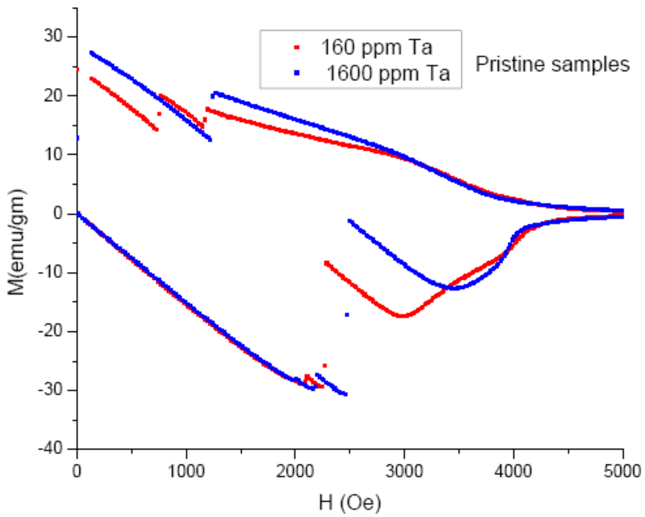
κ vs T Plot

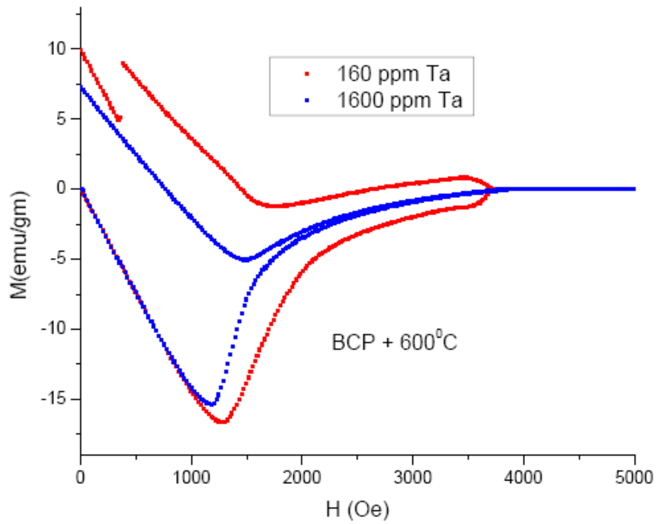


κ vs H Plot

Effect of Ta Impurities on the SC Properties of Nb

Significant amount of money and resources are being spent in Nb refinement.





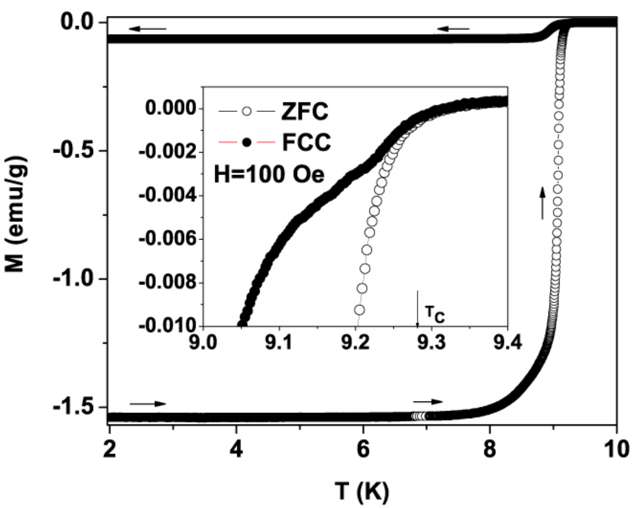
- Higher Ta impurity only marginally affects SC properties both in pristine and chemically treated Nb samples. This effect is much less than the chemical treatment.
- A less refined Nb material may be deployable for cavity applications, provided the inclusions of Ta does not influence the surface conductivity of Nb significantly.

AIP Conf. Proc. **Vol 1352** 56 (2011)

Correlation between microscopic superconducting properties and the performance of superconducting resonator

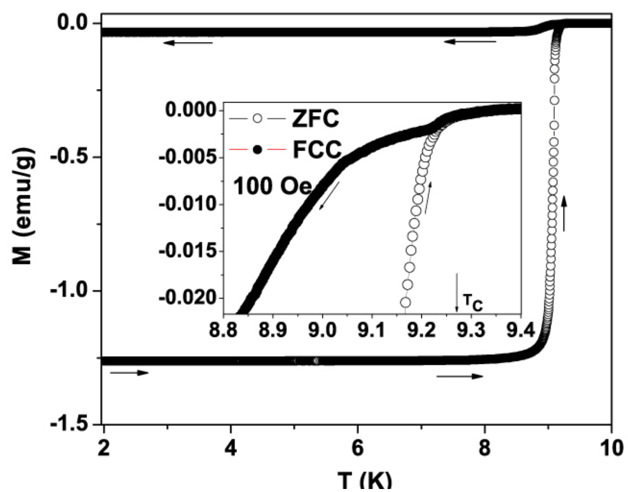
Temperature dependence of the superconducting properties of the e-beam welded part of fine grain Niobium

- Electron beam welded (EBW) joints are part and parcel of the SCRF cavities.
- EBW regions are often exposed to high magnetic field in a SCRF cavity.
- Our study shows that the superconducting onset temperature of Niobium does not get affected by EBW process.
- SC response of NB does not depend significantly on the types of EBW process.



M vs T plot of Step-joint Nb

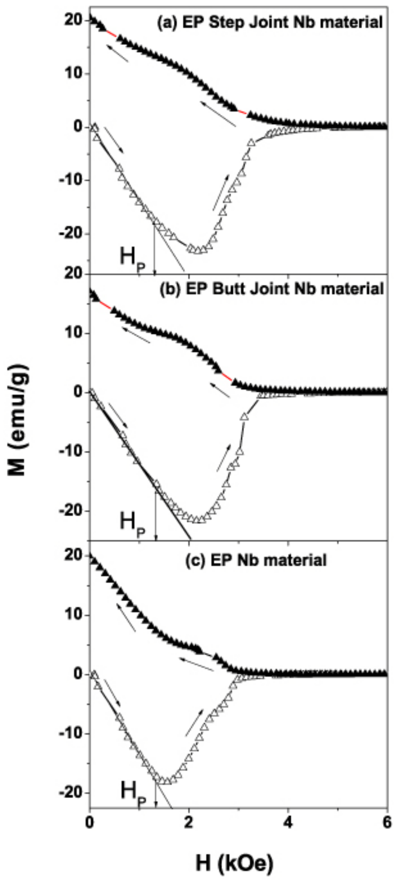
Average grain size:
50 micron



M vs T plot of Butt-joint Nb

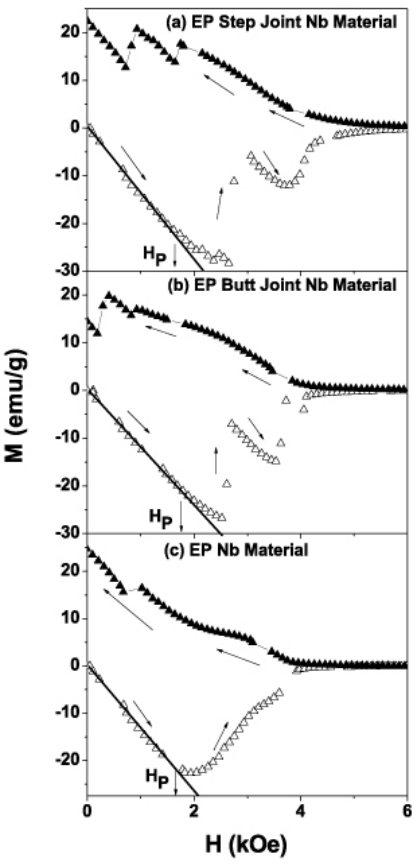
Phys. Rev. ST Accel. Beams **Vol 14** 12201 (2011)

Isothermal magnetic field dependence of the superconducting properties of the e-beam welded part of fine grain Niobium



M vs H plot of Nb at 4K

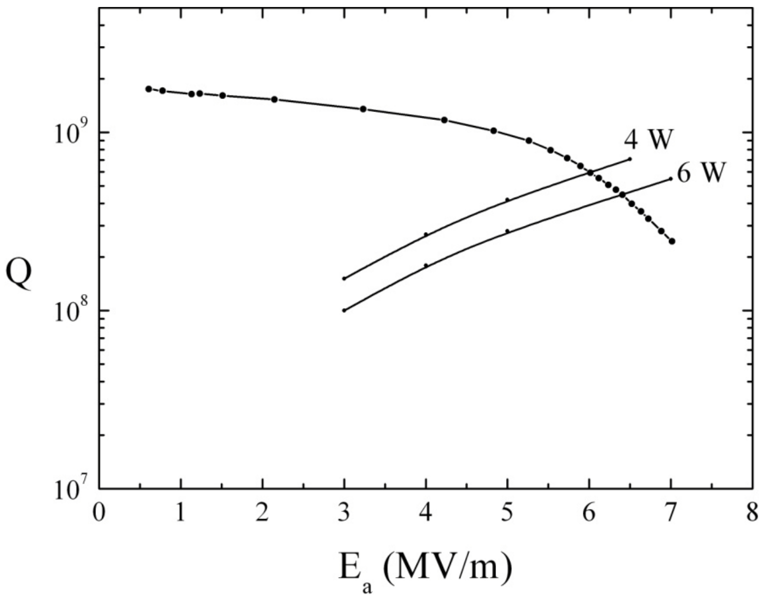
- Critical magnetic fields of Nb does not change by EBW process.
- Superconducting response of Nb does not depend significantly on the different types of EBW process.



M vs H plot of Nb at 2K

Phys. Rev. ST Accel. Beams **Vol 14** 12201 (2011)

Comparison with the performance of a Quarter Wave Resonator



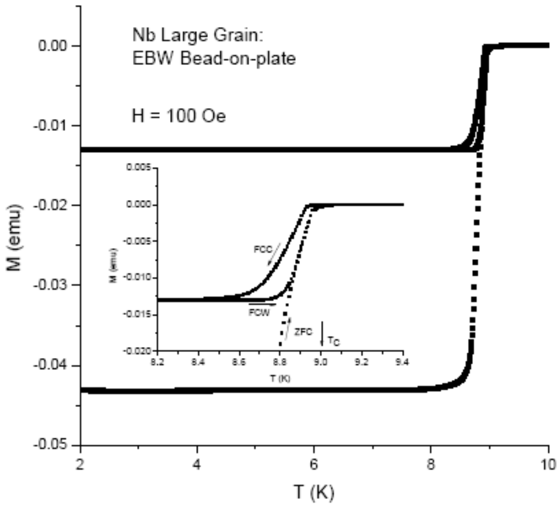
Q vs Accelerating Gradient plot

- QWR fabricated with the same Nb materials at IUAC, New Delhi and installed in the superconducting LINAC.
- The resonator has more than 30 EBW joints.
- Limiting accelerating gradient is close to the intrinsic limit of accelerating gradient as predicted from the measured value of Hp in the EBW and elctropolished samples of Nb.

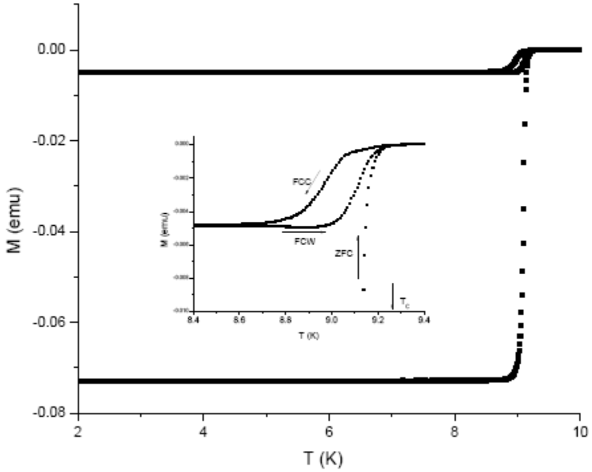
Phys. Rev. ST Accel. Beams **Vol 14** 12201 (2011)

Superconducting properties of the e-beam welded joint of large grain Niobium

- Bead-on-plate has been made on a flat plate of large grain Nb.
- Temperature and magnetic field dependence of the superconducting properties of this EBW joint have been studied.
- Comparison has been made with a similar bead-on-plate of fine grain Nb material.

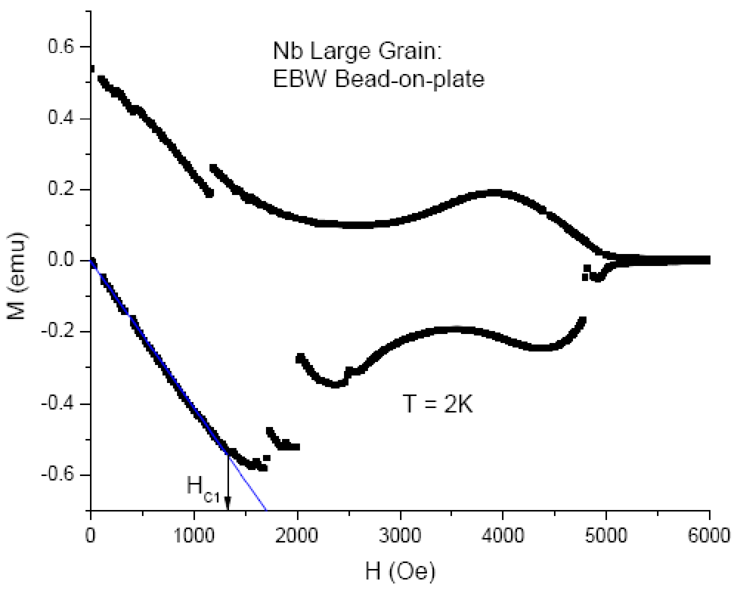


M vs T plot: Large grain Nb

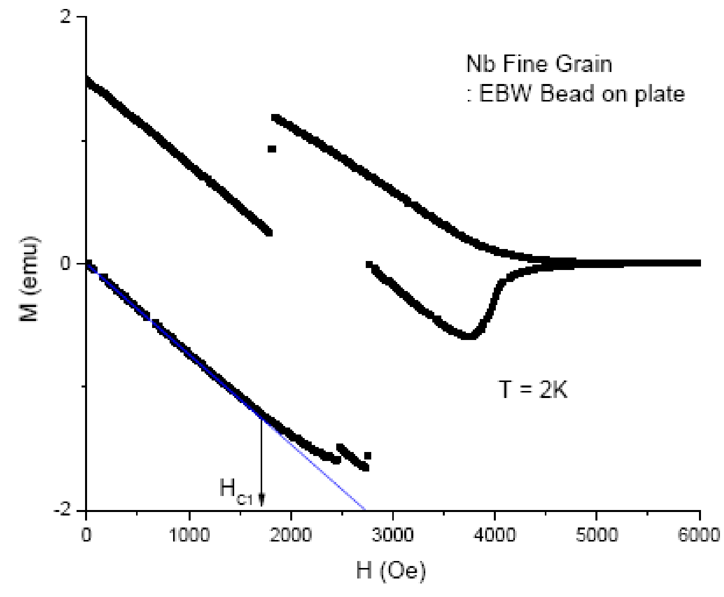


M vs T plot: Fine grain Nb

Superconducting properties of the e-beam welded joint of large grain Niobium :Contd.



M vs H plot: Large grain Nb



M vs H plot: Fine grain Nb

Concluding Remarks

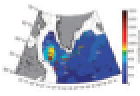
- Initial studies of superconducting properties of large grain Nb materials indicate that they are at least as good as the fine grain Nb materials currently employed in SCRF cavity fabrication.

- There exist indications that relatively impure ($RRR < 200$) large grain Nb may be deployed to achieve large accelerating gradient in Nb SCRF cavities.

- Superconducting surface resistance properties of large grain Nb needs to be investigated for the upper limit of achievable Q.

Ongoing and future works : Fundamental physics & newer SCRF materials

- Which one is most influential: H_C or H_P ?
- Does upper critical field H_{C2} (or H_{C3}) play any role in the SCRF cavity ?
- Thermal instability in superconducting properties of Nb
  – flux jump in Nb → role of thermal conductivity
- Detailed study of surface resistance of superconductors R_{BCS} in applied magnetic fields.
- Nb thin films → Nb-coated Copper cavities.
- Newer materials : MgB_2 ,Nb-Zr, Nb-Al, Mo-Re alloys etc.



OCEAN MIXING
North Atlantic overturning restarts after stagnant decade.
www.nature.com/news

Can triniobium tin shrink accelerators?

The superconducting cavities that drive most of the world's particle accelerators are running out of room for improvement. But new theoretical work suggests that overlooked superconducting materials could be used to make cavities that accelerate particles to higher energies over shorter distances — thereby doing the job more cheaply.

Still, it would take years to develop and test new accelerator components made of materials such as triniobium tin.

For decades, researchers have worked to improve the performance of superconducting cavities. When stacked in a row and pumped with microwave pulses, they build up large electromagnetic fields that accelerate the charged particles used in particle-physics experiments, or in synchrotrons working as high-intensity light sources. The cavities are typically made of niobium, a metal that superconducts when cooled to a few degrees above absolute zero.

C. SCHMID/DESY

Particle-accelerator cavities are currently made from niobium.

Slow and steady

Scientists have also grappled to improve the performance of the metal, working with different welds, rolls, cavity shapes and surface treatments to make steady but slow gains to the accelerating gradients. The gradients, measured in megaelectronvolts (MeV) per metre, are a measure of how quickly cavities can push particles up to a particular speed. The best laboratory performance of a single cavity is 59 MeV per metre; full machines rely on strings of hundreds of the cavities and would be hard-pressed, under real-world conditions, to achieve gradients half as good.

Other superconducting metals, such as magnesium diboride and triniobium tin, have been discovered, but there have been few efforts to make cavities with them. "People have been assuming that these new materials would be much worse, or not much better than niobium," says James Sethna, a condensed-matter theorist at Cornell University in Ithaca, New York. "Our estimates suggest that you could do dramatically better."

Sethna's work, done with Gianluigi Catelani of Rutgers University in Piscataway, New Jersey, will appear in *Physical Review B* and is available on the physics preprint server arXiv (G. Catelani and J. P. Sethna http://arXiv.org/abs/0810.4720; 2008). Sethna says that the peak gradient for triniobium tin is 120 MeV per metre and magnesium diboride could reach 200 MeV per metre.

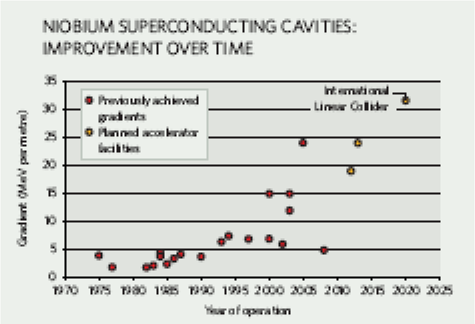
Although a distant goal, achieving such gradients could result in huge savings for future accelerators. For example, the US$7-billion International Linear Collider (ILC) — a wished for next-generation particle accelerator — will need thousands of cavities, stretching along a tunnel 31 kilometres long, to help it produce energies of 500 gigaelectronvolts. And that's if its niobium cavities can reach ambitious target gradients of a bit more than 30 MeV per metre (see graph). Ramping up the gradients to a theoretically possible peak of 200 MeV per metre could significantly reduce the length of the ILC, therefore also reducing costs of most of its physical parts such as tunnels and beamlines.

Breaking the limits

According to Sethna, old theories describing the limits of superconducting materials didn't correctly account for ultracold operating temperatures or vortices in the superconductors, which, in creating barriers to the magnetic field lines, allow the cavities to operate at higher gradients. "The excuse has been, 'We've worked so hard on niobium, why try these other materials?'" says Sethna. "All of a sudden, we're telling them, 'you've been listening to the wrong theorists'."

Hasan Padamsee, a superconductivity expert at Cornell University, is excited by Sethna's work. In the late 1990s he made a test cavity out of triniobium tin, and it performed less well than niobium alone. But the new work gives Padamsee confidence that the result was due to a problem with the particular sample rather than a fundamental quality of the material.

He says a good working cavity with the new materials would take at least five years to perfect. That's too long to help the ILC in the near term, but perhaps soon enough to be incorporated into upgrades to it.

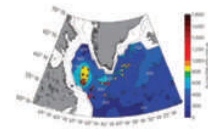


SOURCE: H. PADAMSEE

Peter Kneisel, a senior staff scientist at the Thomas Jefferson National Accelerator Facility in Newport News, Virginia, is less optimistic. He would prefer to wring incremental advances out of niobium cavities, and accept their limitations.

"The grass on the other side of the fence is always greener," says Kneisel, who has spent 40 years working to improve niobium. "It will take, I don't know, 40 years again to bring it to some practical use in accelerators."

Eric Hand



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Can triniobium tin shrink accelerators?

The superconducting cavities that drive most of the world's particle accelerators are running out of room for improvement. But new theoretical work suggests that overlooked superconducting materials could be used to make cavities that accelerate particles to higher energies over shorter distances — thereby doing the job more cheaply.

Still, it would take years to develop and test new accelerator components made of materials such as triniobium tin.

Breaking the limits

According to Sethna, old theories describing the limits of superconducting materials didn't correctly account for ultracold operating temperatures or vortices in the superconductors, which, in creating barriers to the magnetic field lines, allow the cavities to operate at higher gradients. "The excuse has been, 'We've worked so hard on niobium, why try these other materials?'" says Sethna. "All of a sudden, we're telling them, 'you've been listening to the wrong theorists.'"

THANK YOU