Low RRR Materials for ILC

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Outline

Early History

Present Status

Future Prospects

Summary

Historical Example of Ingot Niobium 1

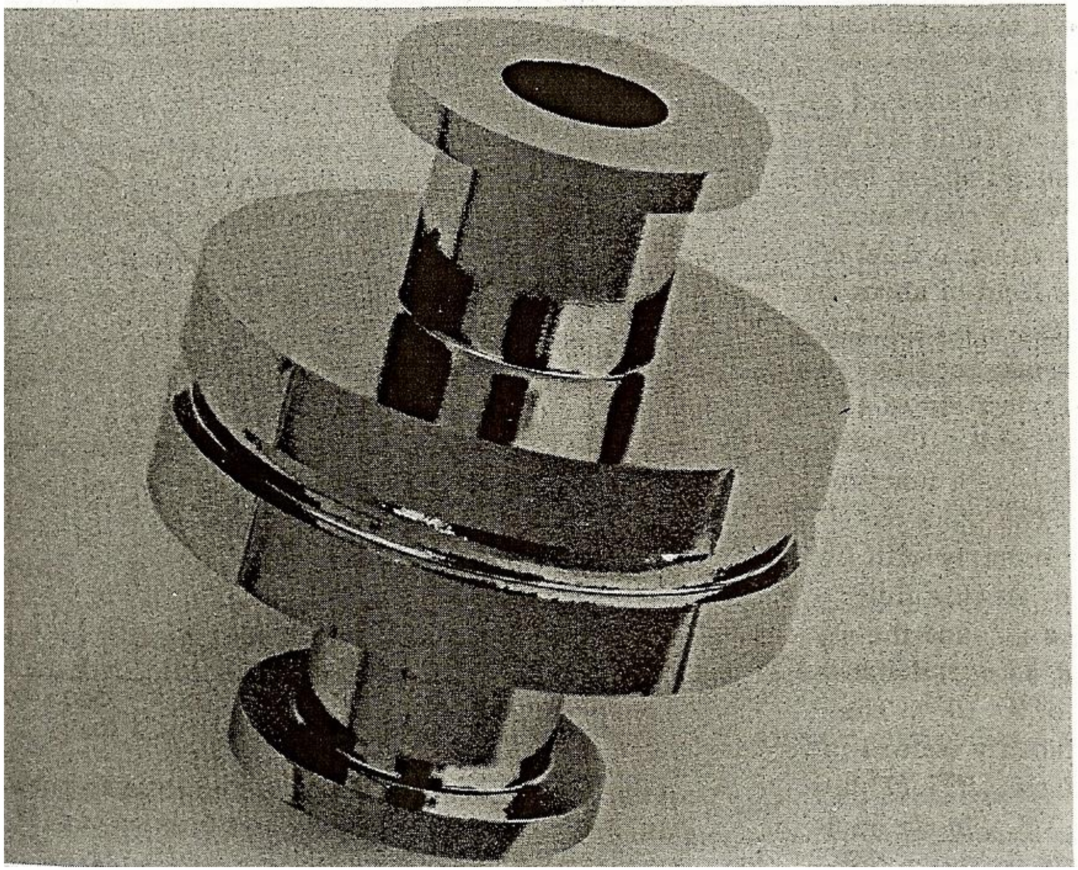


FIG. 1. An electron-beam welded TM_{010} mode Nb cavity. The cavity is resonant at 8.6 GHz and is 3.6 cm in overall length.

H_{pk}~ 108 mT with BCP

Stanford solid niobium cavity 1970

Historical Example of Ingot Niobium 2

Siemens solid niobium cavity 1973

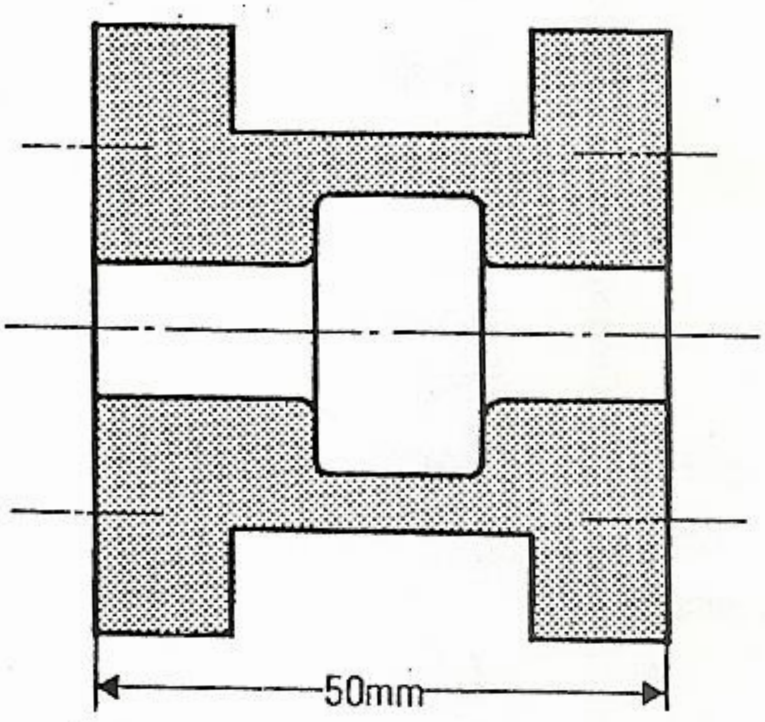


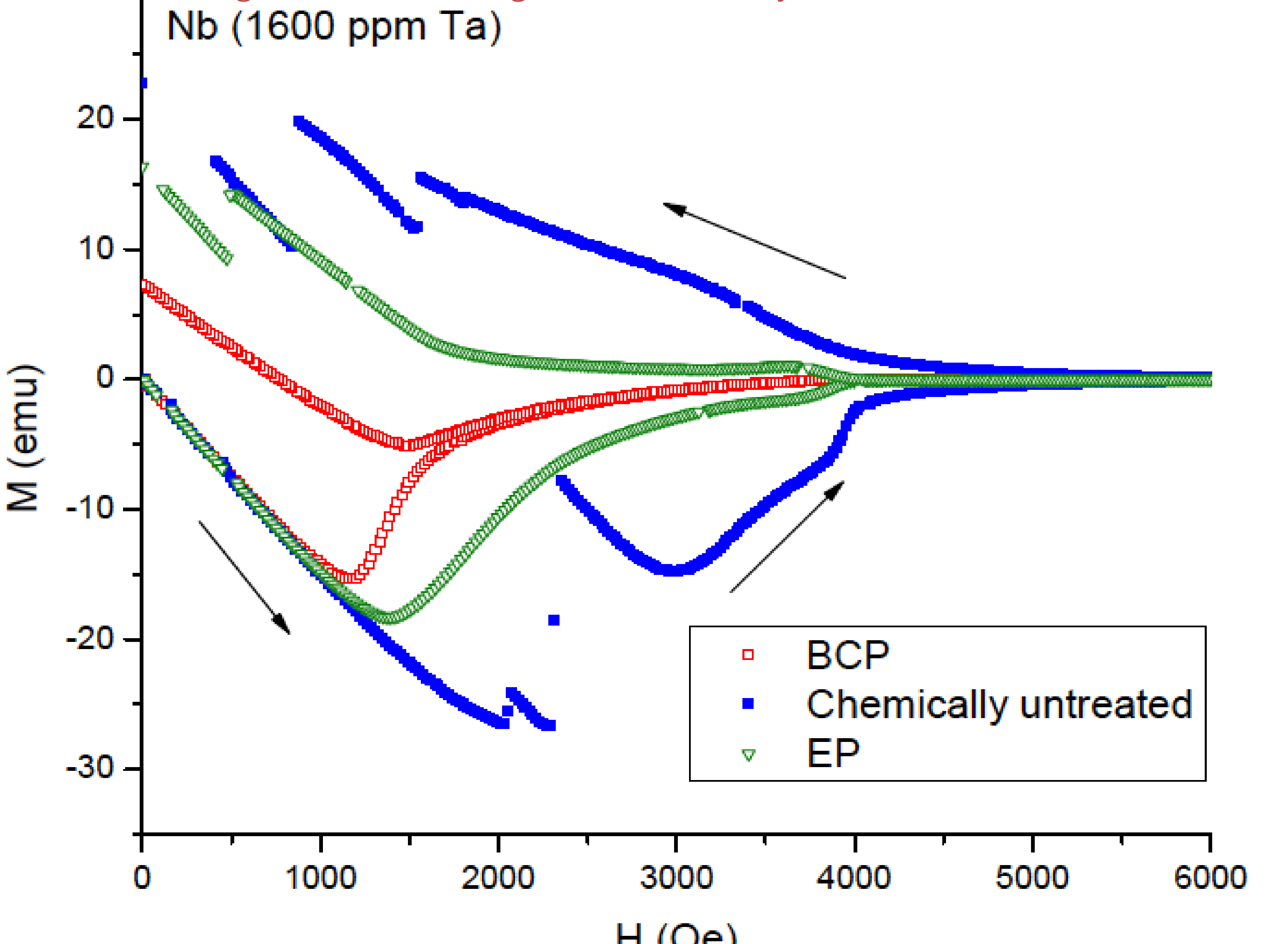
Fig. 1. Single piece TM_{010}-niobium cavity with a resonant frequency of 9.5 GHz.

H_{pk}~ 109 mT with BCP

H_{pk}~ 130 mT with EP

EP' d reactor grade fine grain niobium cavity set a record Hpk of 159 mT

Ingot niobium DC magnetization S.B. Roy/RRCAT 10/6/2011



Highlights of Early SRF Technology

- Cavities were mostly made from ingot niobium
  - Process and procedures were similar and as varied as today
- Reactor grade Niobium material in ingot, bar, plate sheet and tube form was available
- Achievable gradient limited by multipacting and/or field emission
- Residual surface resistance (~ 1nΩ) was not well understood
  - Still the case
- At highest frequencies (Electropolished fine grain, X-band) Hpk ~ 159 mT Q0 ~5×10^9
- (BCP'd ingot Nb, 1970's) Hpk ~ 108 mT & Q0 ~1×10^{11} @ 1.2 K CW

- For comparison (CEBAF upgrade spec.) Hpk ~ 76 mT Q0 ~ 7×10^9 @ 2 K CW (2008)

Extrinsic and intrinsic contamination of Nb determines the performance of the cavities

Extrinsic

- Surface contamination
  - Molecular and particulate

Intrinsic

- Niobium is a prolific hydrogen absorber in the absence of the natural surface oxide
  - Hydride formation
  - Dislocations

Niobium Specifications – Past & Present @JLab

- Polycrystalline Niobium with ASTM #5 Grain Size or finer ~ 50 micro meters & 90% recrystallized
- Percentage of elongation > 25
- Yield Strength > 10.7 KSI (~75 MPa) (7 KSI for SNS)
- RRR > 250
- Tantalum < 1000 wt ppm

Note:
Recrystallization and high yield strength (YS) are mutually exclusive, the "kiss pass" used for increasin the YS introduces significant surface damage

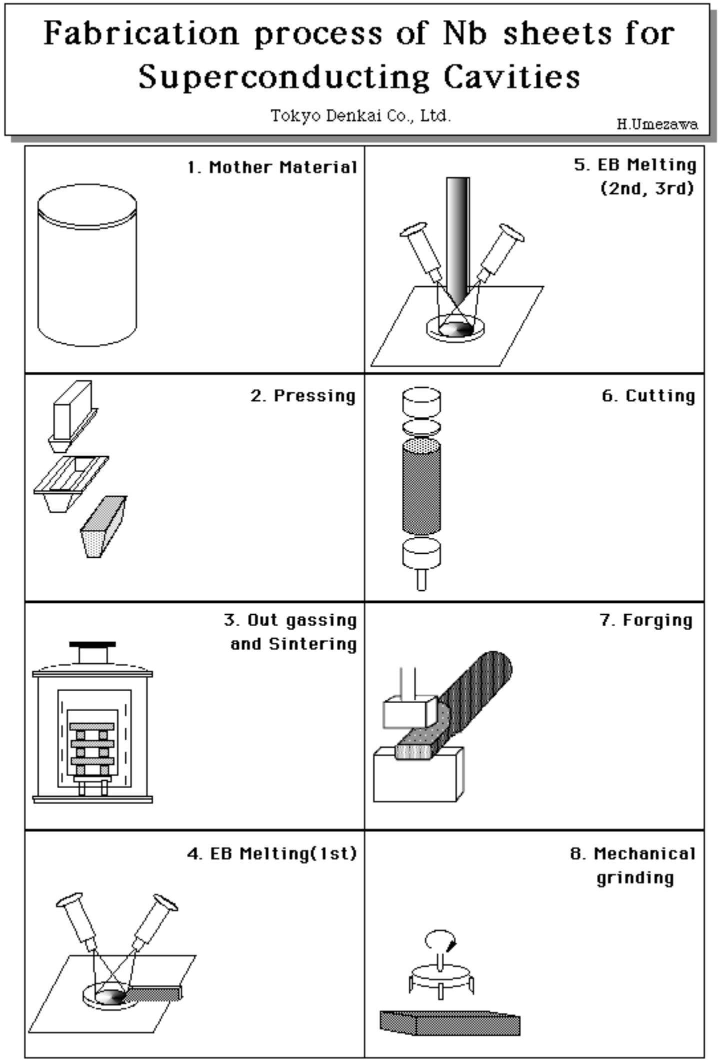
Note: These specifications are wrt the physical structure only & do not include SC properties

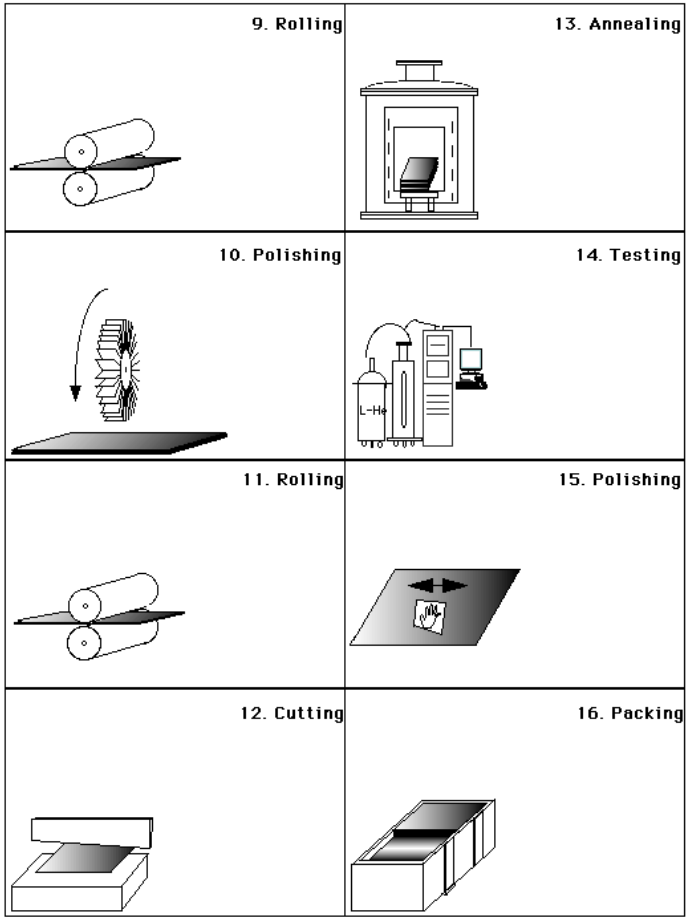
Niobium For SRF Cavities

- At present, Niobium for SRF cavities comes from Columbite/Tantalite ore
  - Niobium is present as "impurity"
  - Niobium is produced as a by-product

- Primary reason – the Tantalum content is lower
  - Tantalum is generally believed to negatively impact SRF properties of Niobium
  - JLab data shows reducing Tantalum content below 1000 ppm has no advantage for Superconducting RF cavities
  - Low Tantalum niobium is relatively expensive

Process steps - fine grain Niobium

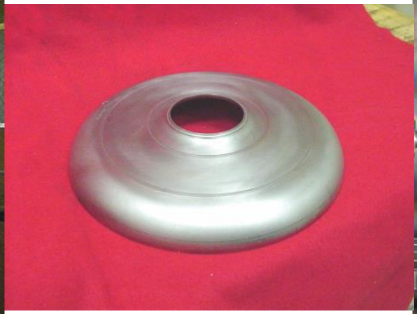


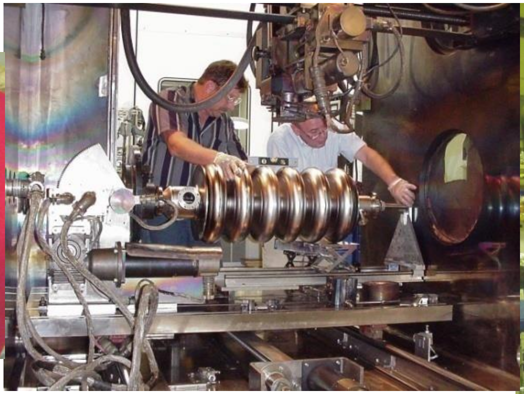


Note:
During this process foreign materials can be embedded so QA is required

Multi cell cavity fabrication

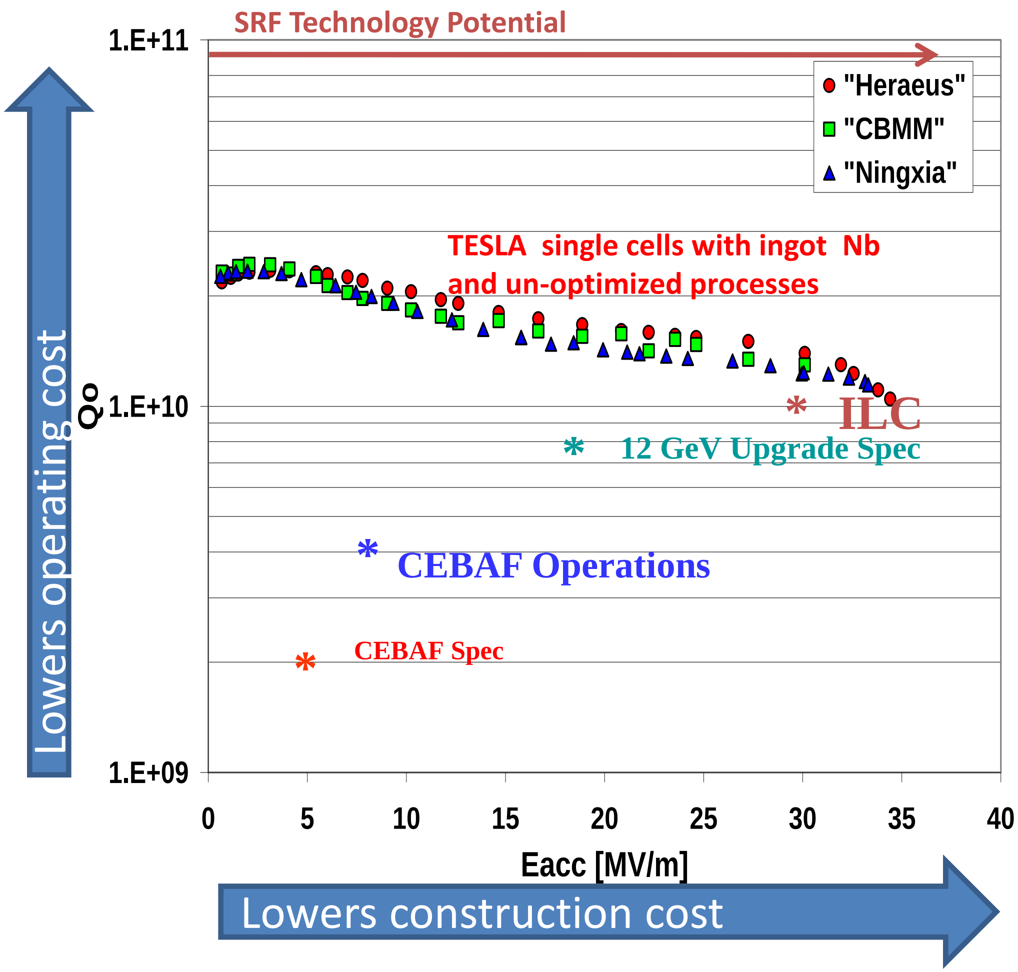
Forming Machining Welding Tuning





~90% of CEBAF cavities were made with CBMM Pyrochlore ore based niobium
In comparison to present day use of Tantalite/Columbite ore based niobium

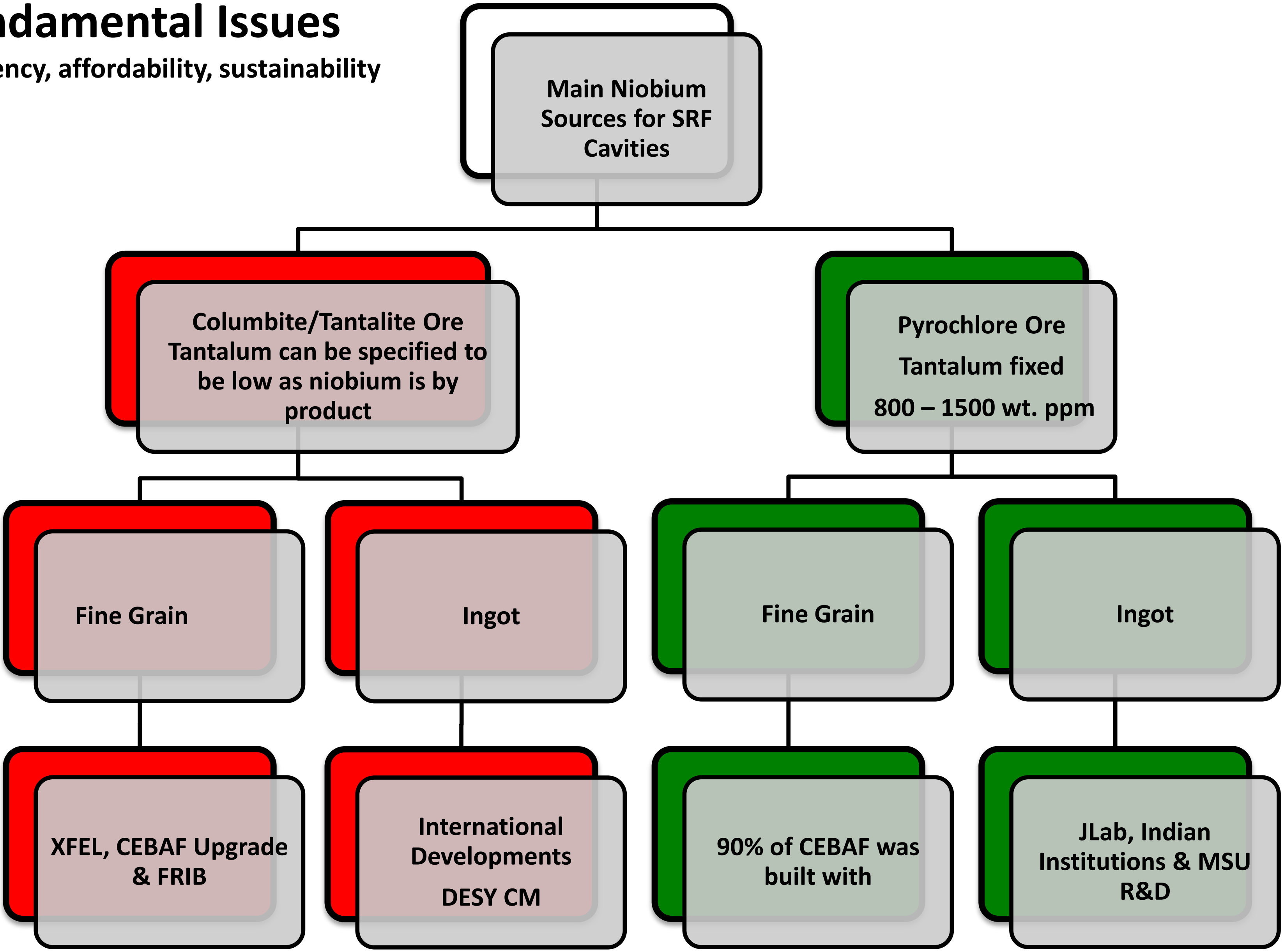
Niobium cavity – performance (CW)



In nearly 40 years E_{acc} improved by a factor of 5, DOE NP and Jlab improved Q_0 by a factor of ~4 Ti doping (2011) FNAL ~ 4 N doping(2012)

Fundamental Issues

Efficiency, affordability, sustainability

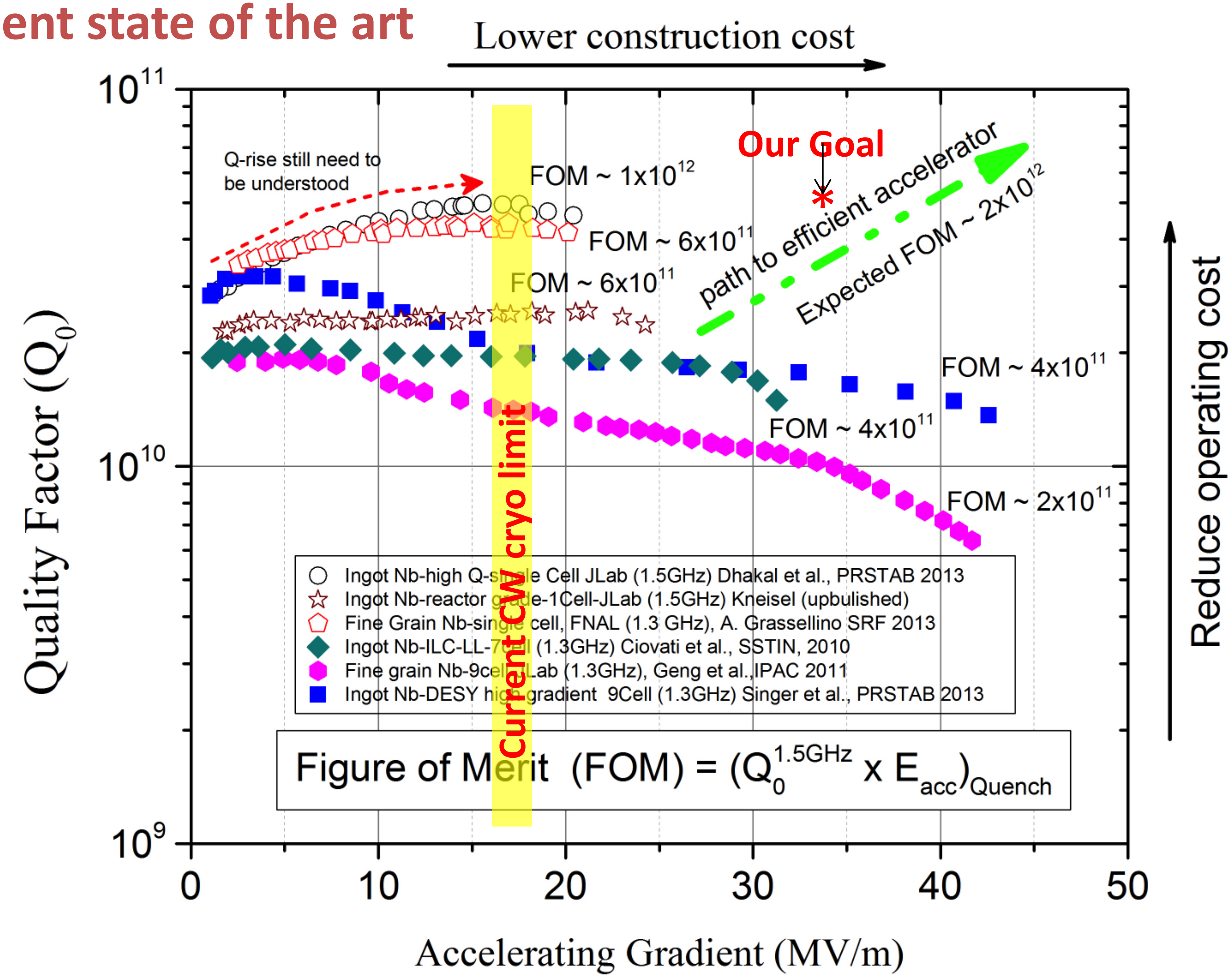


Purity specification determines no of E-beam melting cycles and cost

Cavity ILC processing steps

- Buffer chemical polishing (BCP) ~ 150 micro meters
- Electro polishing (EP) ~ 50 micro meters
- High pressure ultra pure water rinse
- ~ 600 – 900 °C heat treatment
- Light EP/Flash BCP
- High pressure ultra pure water rinse
- Vacuum bake ~120 °C for up to 48 hours
- RF test

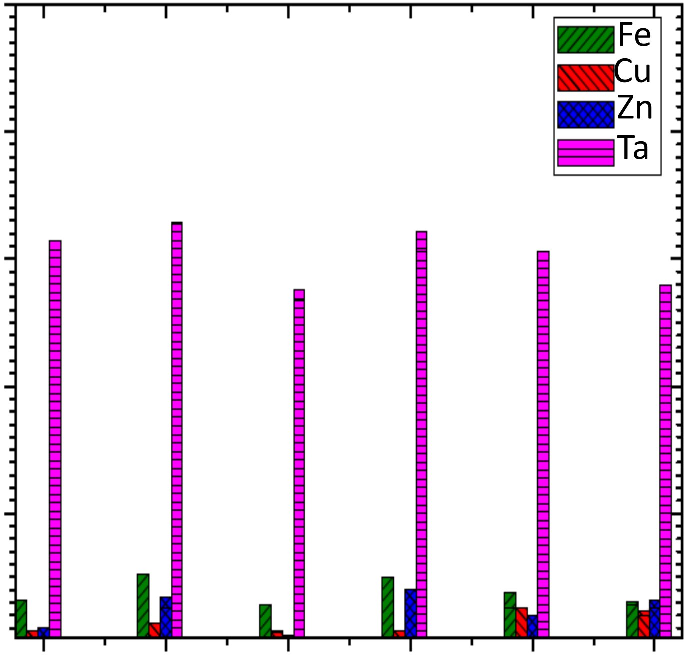
Present state of the art



Ingot niobium Rs is low and phonon peak improves thermal stability

Our goal is to improve both Q_0 and E_{acc}

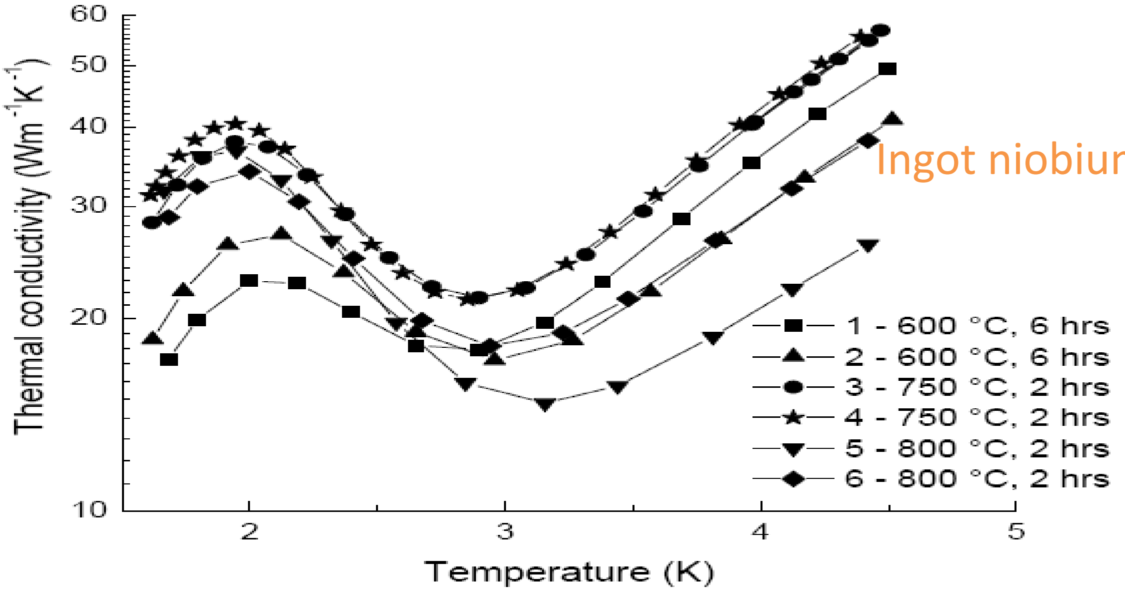
Uniform distribution of Ta has no effect on SC Parameters, BCP has



Sample	Ta-Content (ppm)	T_C at 100 Oe (K)	H_P (Oe)	H_{C2} (Oe)	H'_{C2} (Oe)
Technical-Niobium-1P	1339±36	9.18	1700	4150	7500
Technical-Niobium-2P	800 ±80	9.18	1600	4125	7500
Technical-Niobium-3P	243±10	9.2	1600	4090	7500
Technical-Niobium-1CT	1285±35	9.05	1150	3930	-
Technical-Niobium-2CT	684±54	9.05	1290	3735	-
Technical-Niobium-3CT	149±11	9.06	1350	3820	-

S. B. Roy et al Supercond. Sci. Technol. 25 (2012) 115020

Tantalum and RRR have minimal influence on phonon peak

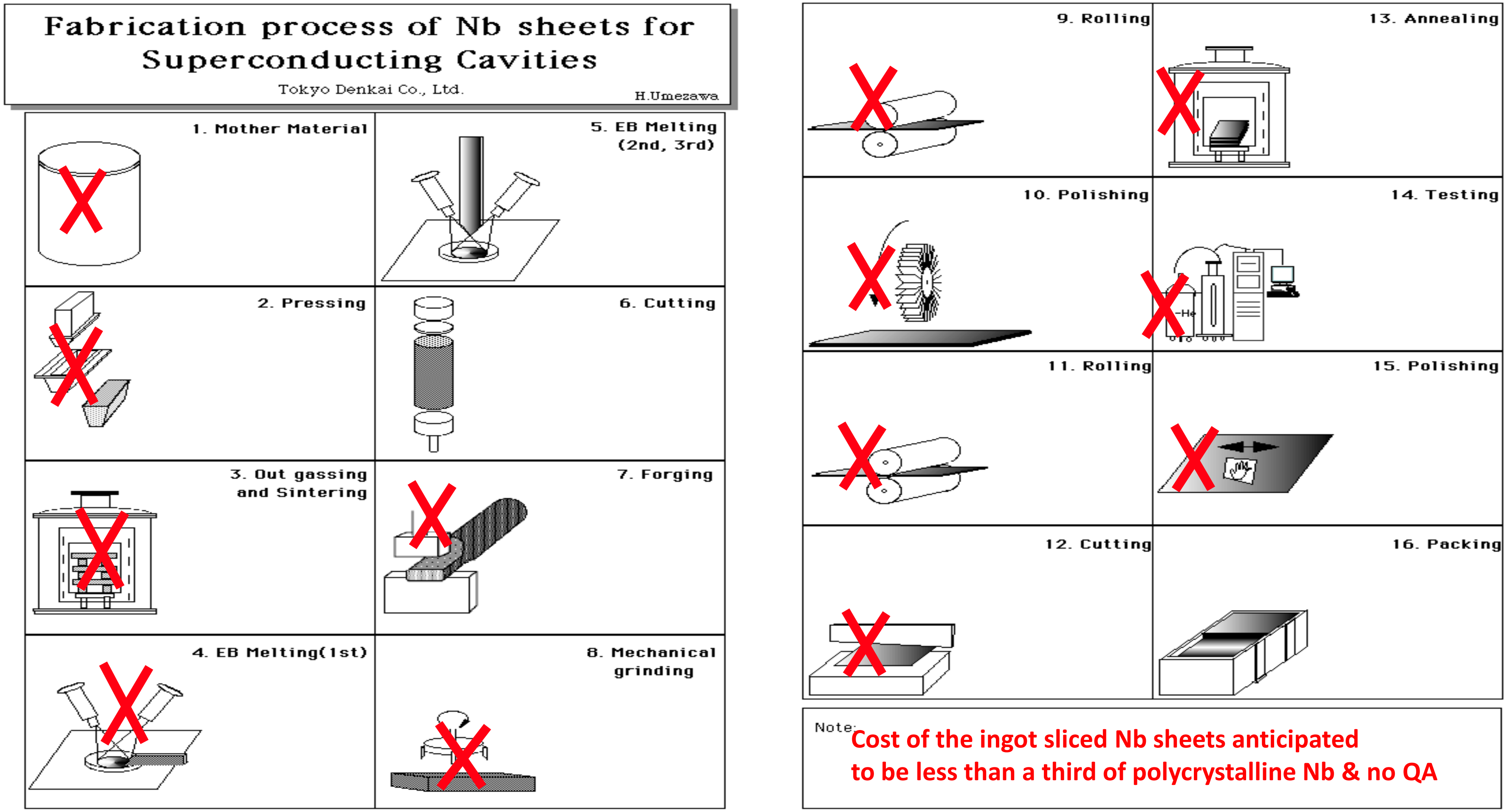


Ingot niobium

Specimen	Estimated RRR	Tantalum content (ppm) [3]	Heat Treatment	Titanium getter
1	191	1275	600 °C, 6 hrs	No
2	131	668	600 °C, 6 hrs	No
3	190	756	750 °C, 2 hrs	Yes
4	196	756	750 °C, 2 hrs	Yes
5	104	1322	800 °C, 2 hrs	No
6	143	523	800 °C, 2 hrs	No

PhD thesis at MSU

Economic path for future SRF systems



Note: Cost of the ingot sliced Nb sheets anticipated to be less than a third of polycrystalline Nb & no QA

Araxá Mine in Brazil & Ingot Niobium

From ore to oxide to large grain ingots

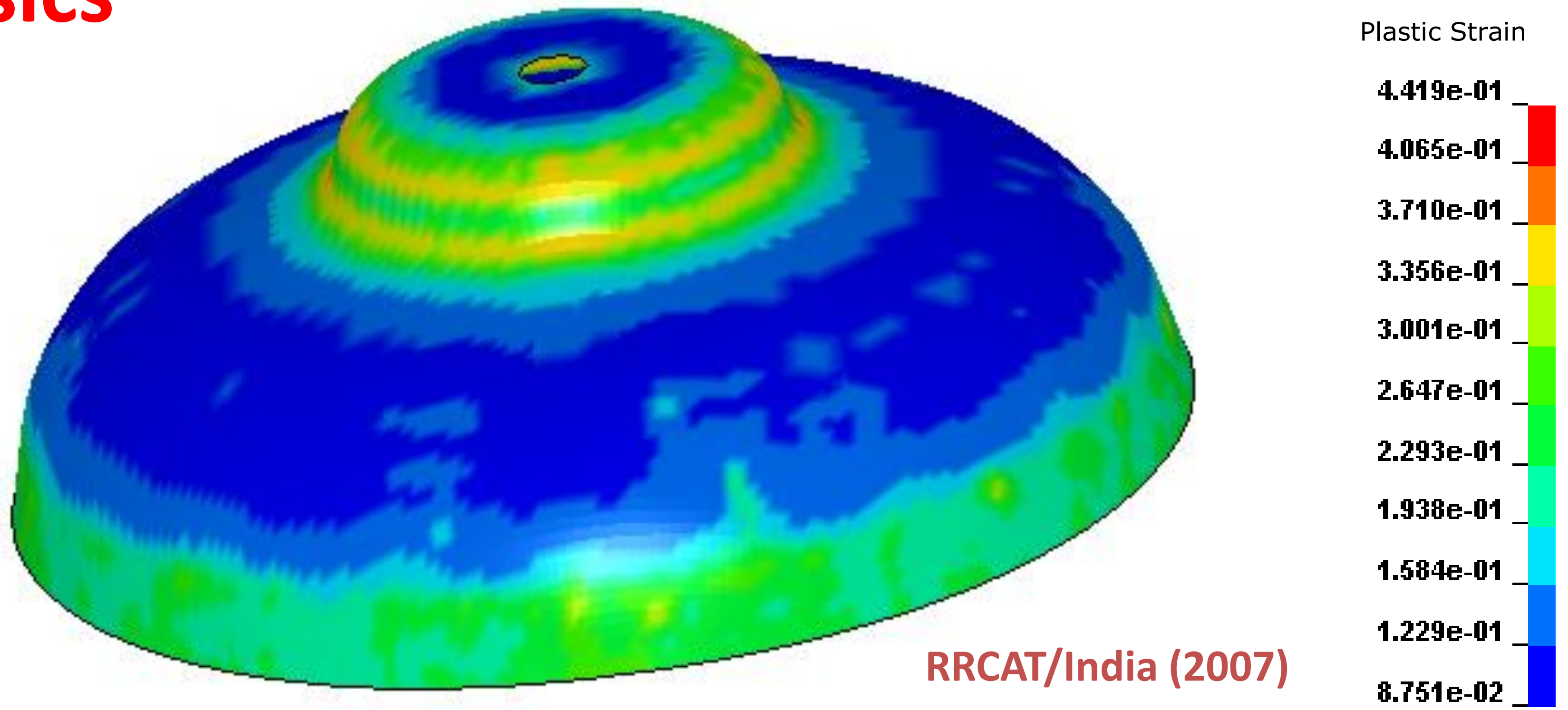
The CBMM open cast mine

Conveyor belt bringing the ore to concentration plant

Electron beam furnace for the refinement of Niobium metal, producing 210 tonnes per annum

Finished RRR Nb ingot from the Pyrochlore ore

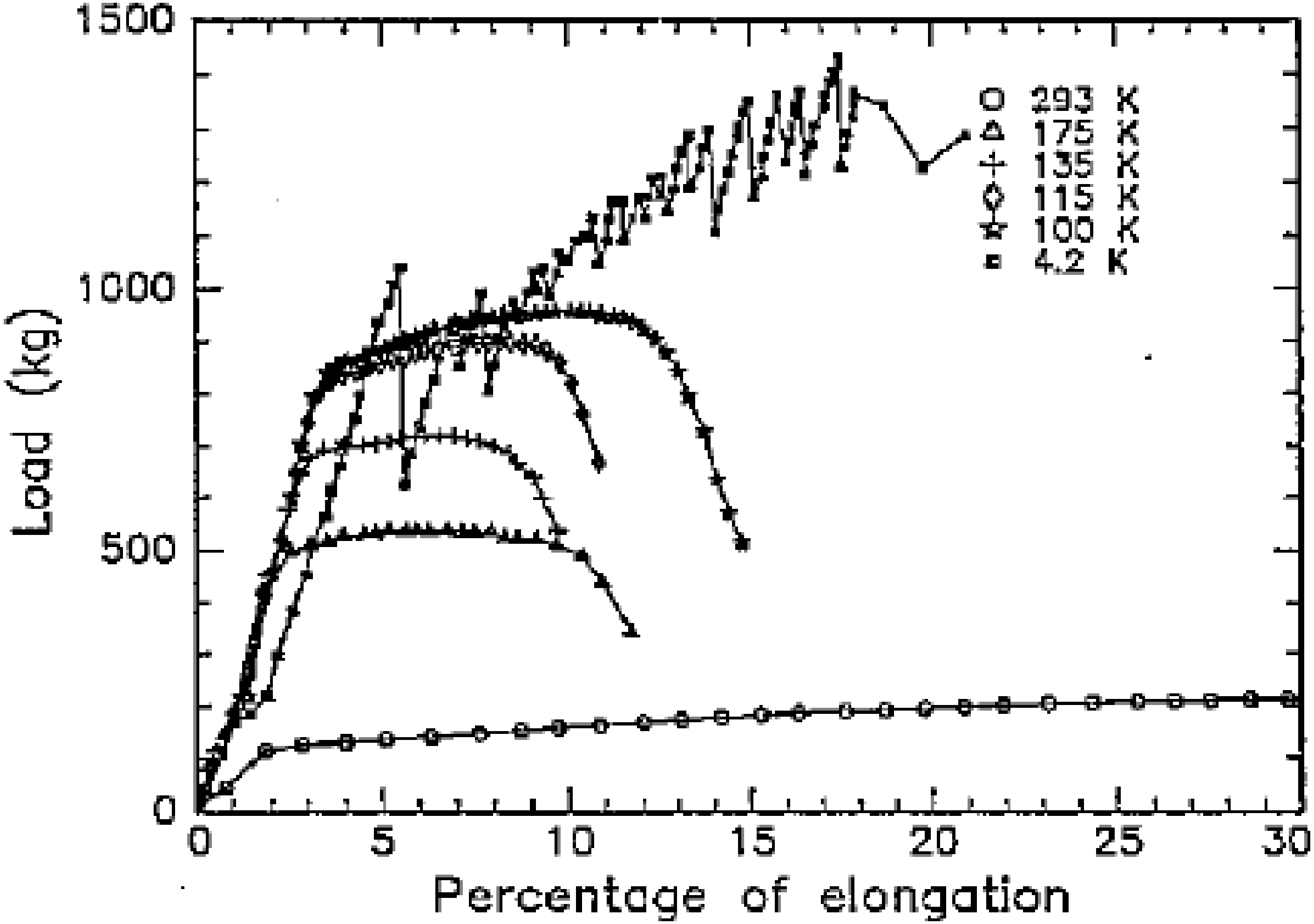
Basics



Residual stress is largest near the equator and Iris
Peak surface magnetic filed is highest near the equator, where quenches originate, etch pits seen and is the bed for hydrogen-dislocation interactions

Hydrogen-dislocation interactions

The samples were annealed at 1400 °C for 3 hours



M. G. Rao and P. Kneisel, Mechanical properties of high RRR niobium at cryogenic temperatures, Adv. in Cryogenic Engineering Vol. 40 1383-1390, 1994

We would like to further investigate this phenomena

Intrinsic contamination of Nb & proton-dislocation interaction appear to determine the performance of the cavities

- **Niobium is a prolific hydrogen absorber in the absence of the natural surface oxide***
  - **Hydride formation**
  - **Dislocations-proton interaction**

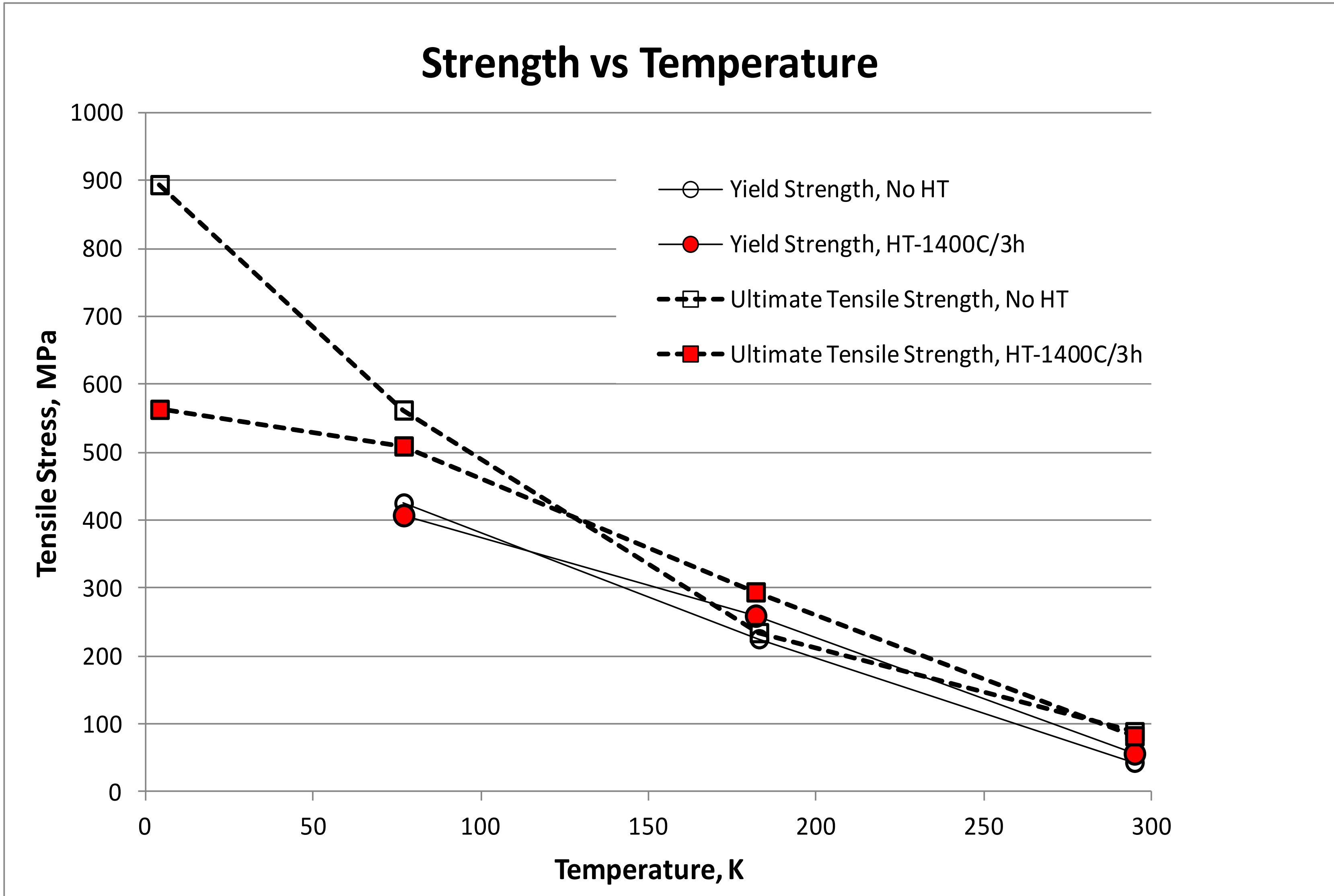
*** R.E. Ricker, G. R. Myneni, J. Res. Natl. Inst. Stand. Technol. 115, 353-371 (2010)**

Our goal is to Simplify process steps

- Minimize the process steps
  - H-free mechanical polishing ~ 100 micro meters *
  - High pressure ultra pure water rinse
  - High temperature heat treatment
  - Megasonic cleaning
  - RF test
- These simple steps reduce proton-dislocation interactions and hence expected unparalleled high performance delivery

* T. Higuchi and K. Saito, "Hydrogen Absorption in Electropolishing of Niobium", CP 671 Hydrogen in Materials and Vacuum Systems pp 203-219 2002 Edited by G. R. Myneni and S. Chattopadhyay

Improved mechanical properties with 1400 C HT



R.P Walsh and D. M. McRae NHMFL 2012

Future Outlook

- Ingot niobium technology (low RRR, high tantalum content) has proven to be ideal for CW SRF applications
- We expect that this technology will be the preferred choice for future superconducting CW linacs world-wide
- Several Labs from the three continents are discussing a joint program to optimize the ingot niobium multi cell cavity processes for high efficiency & high intensity CW linac applications

JLab's worldwide network of collaborators

Tadeu Carneiro, Marcos Stuart – CBMM	ingot niobium technology
F. Stevie, P. Maheswari, D. Griffis – NCSU	niobium surface science
R. Ricker – NIST	hydrogen-niobium system
J. Wallace – Casting Analysis Corporation	co-PI DOE ONP ARRA Q_0 improvement program
Björgvin Hjörvarsson – Uppsala University	hydrogen-niobium system
B. Lanford – UNY, Albany	nuclear reaction analysis
R. Pike and summer student interns – W&M	XRD analysis of niobium
Hani Elsayed-Ali, Ashraf Hassan Farha – ODU	niobium nitride
Asavari Dhavale & J. Mondal – BARC/HBNI	ingot niobium properties
Sindhunil Roy – RRCAT	SC properties of niobium
Saravan Chandrasekaran – MSU	ingot niobium properties

International Symposium On Hydrogen In Matter (ISOHIM) non profit organization for education/training

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International Symposium On Hydrogen In Matter (ISOHIM) Publications

Hydrogen in Materials and Vacuum Systems AIP CP 671
http://www.virtualjournals.org/dbt/dbt.jsp?KEY=APCPCS&Volume=671&Issue=1

Hydrogen in Matter AIP CP 837
http://www.virtualjournals.org/dbt/dbt.jsp?KEY=APCPCS&Volume=837&Issue=1

Single Crystal Large Grain Niobium AIP CP 927
http://www.virtualjournals.org/dbt/dbt.jsp?KEY=APCPCS&Volume=927&Issue=1

Superconducting Science and Technology of Ingot Niobium AIP CP 1352
http://scitation.aip.org/dbt/dbt.jsp?KEY=APCPCS&Volume=1352&Issue=1