CW SRF Systems with Ingot Niobium* and their Applications

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*CBMM – JLab Technology

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Overview

- ✓Brief introduction to the largest SRF CW Accelerator
- ✓Fine grain and ingot niobium technologies
- ✓Qo Improvement Program
- ✓Ingot niobium CW Applications

Glossary 1

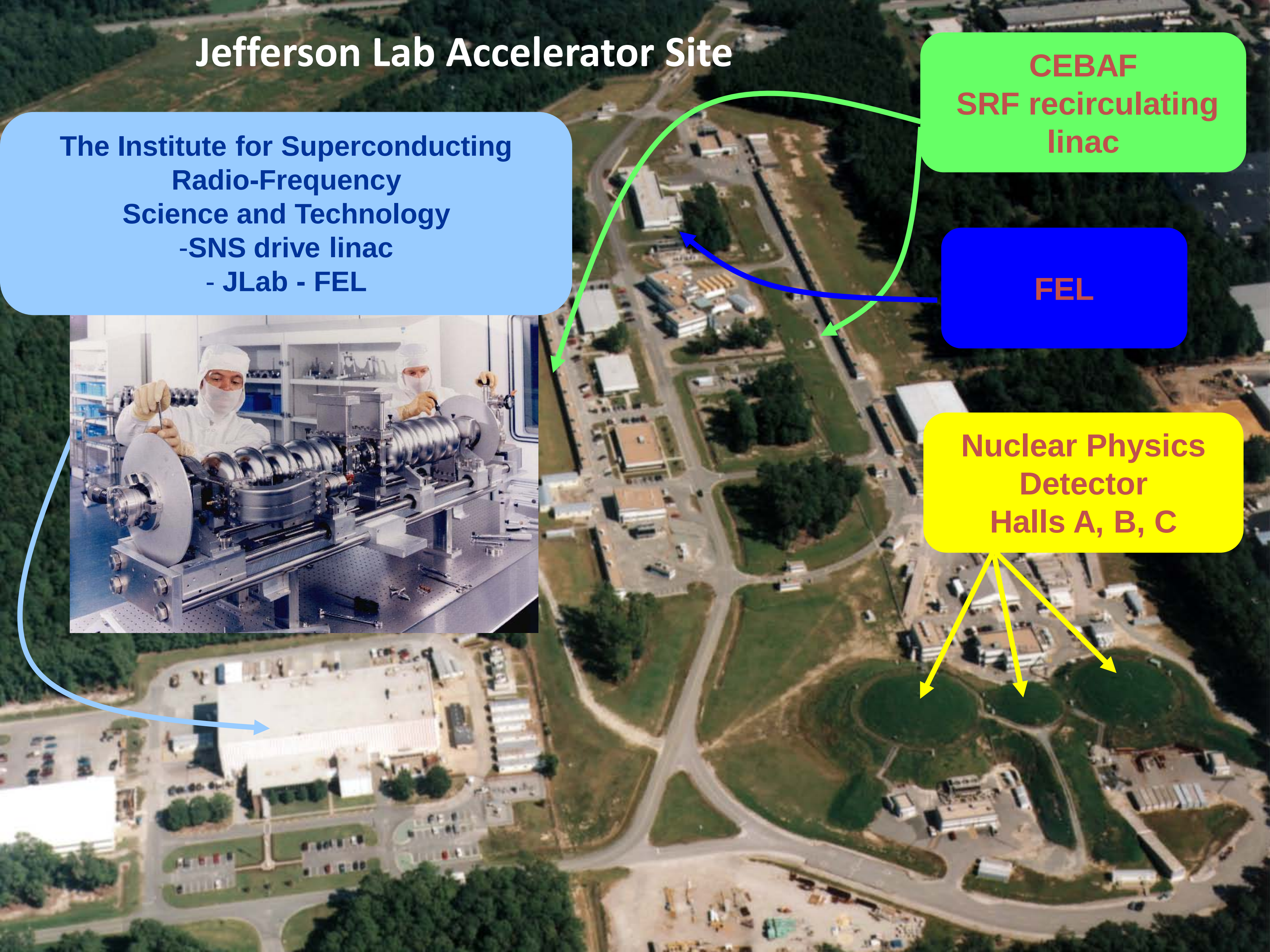
- Niobium – highly ductile refractory metal with highest superconducting transition temperature (T_C ~ 9.25 K) at which the electrical resistance drops to Zero, highest peak magnetic field H_{pk} & high melting temperature T_m
- RRR – Residual Resistance Ratio ~ R300/R4.2
- Important Interstitials H, C, N and O that contribute to RRR significantly
  - and tantalum, substitutional impurity does not significantly contribute
- Surface Resistance $R_s = R_{BCS} + R_0$

  R_{BCS} depends on surface magnetic field, temperature and frequency

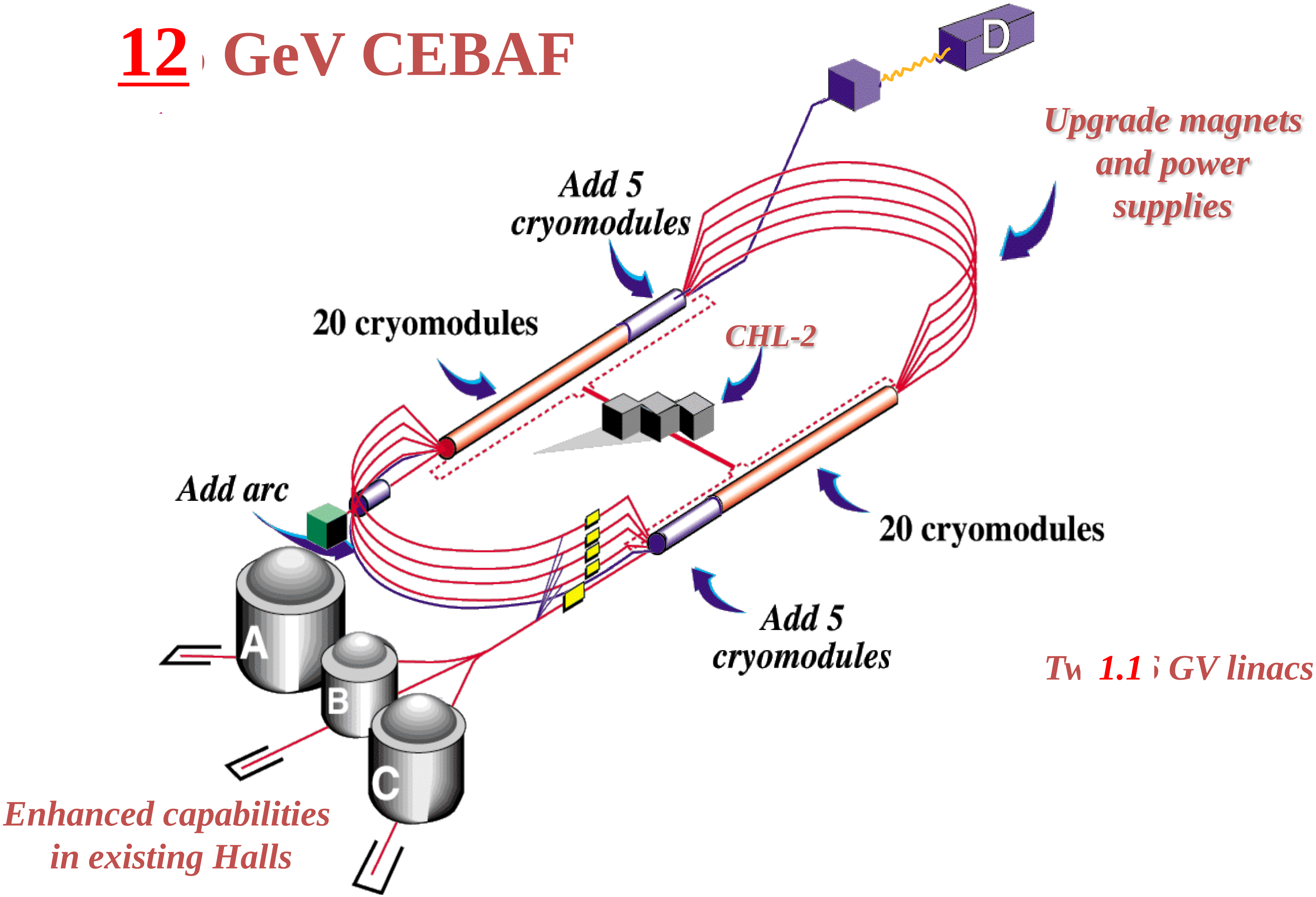
Glossary 2

- Quality Factor $Q_0 = G/R_{s,}$ where G is the geometry factor and it is independent of the cavity frequency (ideal ~ 2×10^{11})
- H_{pk} Surface peak magnetic field (mT)
- E_{acc} Accelerating gradient (MV/m)
- Optimized Processes and procedures: forming cells, cleaning, welding, surface treatments and stress relieving processes and final contamination free evacuation

Jefferson Lab Accelerator Site



12 GeV CEBAF


D
Upgrade magnets and power supplies
Add 5 cryomodules
20 cryomodules
CHL-2
Add arc
A
B
C
20 cryomodules
Add 5 cryomodules
Tw 1.1 GV linacs
Enhanced capabilities in existing Halls

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 (nΩ) was not well understood
  - Still the case
- At highest frequencies (Electropolished fine grain, X-band) Hpk ~ 159 mT Q0 ~5x109
- (BCP'd ingot Nb, 1970's) Hpk ~ 108 mT & Q0 ~1 × 1011 @ 1.2 K CW
- For comparison (CEBAF upgrade spec.) Hpk ~ 76 mT Q0 ~ 7 × 109 @ 2 K CW (2008)

Historical Example of Ingot Niobium 1

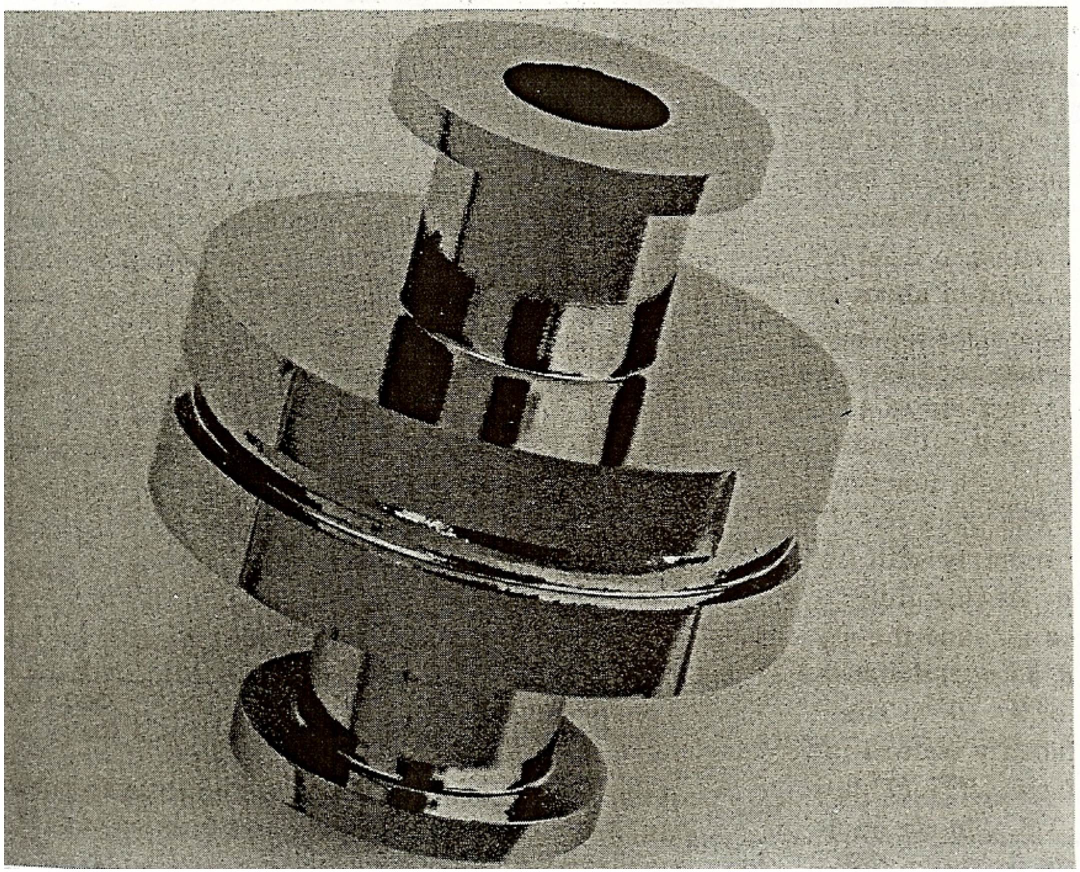


FIG. 1. An electron-beam welded TM_{010} mode Nb cavity. The cavity is resonant at 8.6 GHz and is 3.6 cm in overall length.

H_{pk}~ 108 mT with BCP

Stanford solid niobium cavity 1970

Historical Example of Ingot Niobium 2

Siemens solid niobium cavity 1973

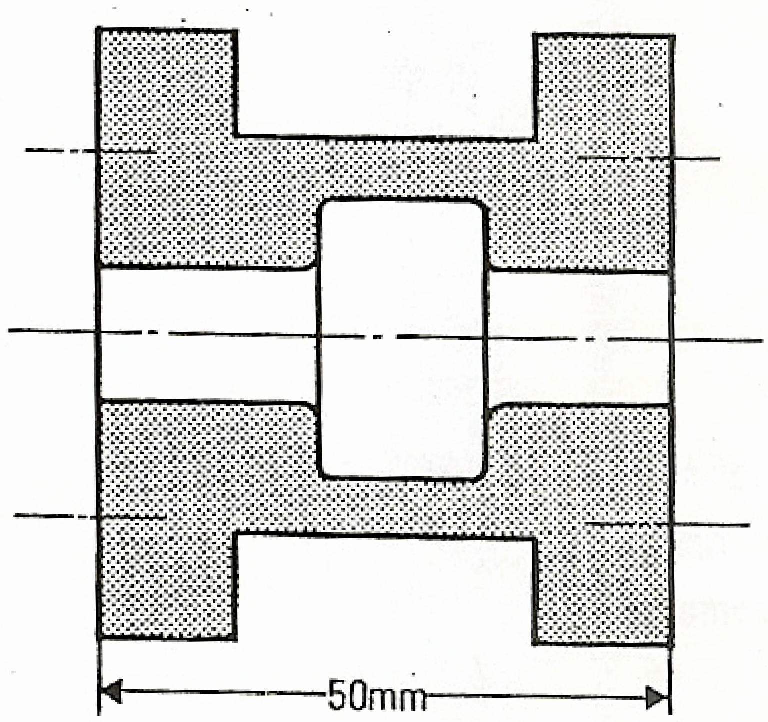


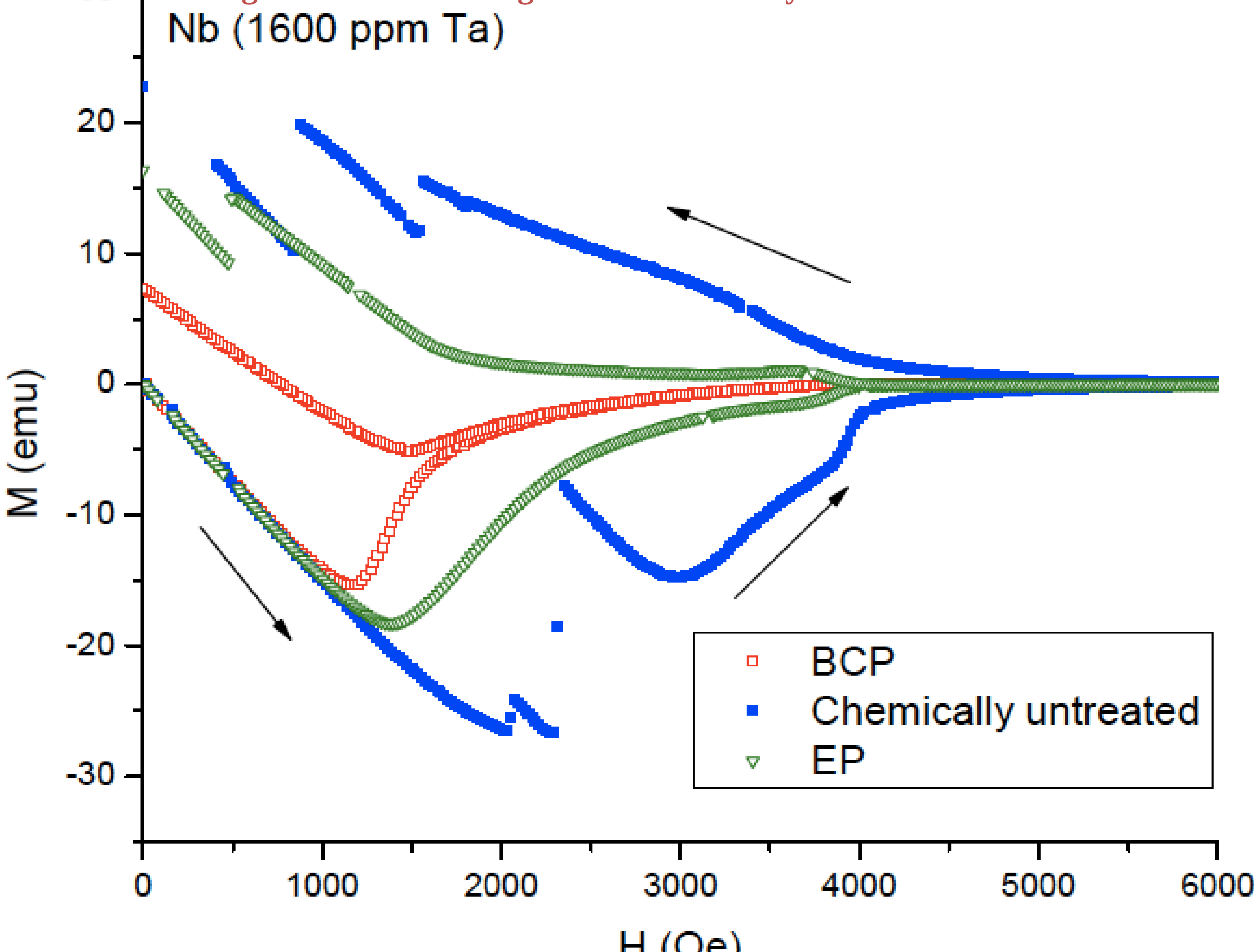
Fig. 1. Single piece TM_{010}-niobium cavity with a resonant frequency of 9.5 GHz.

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

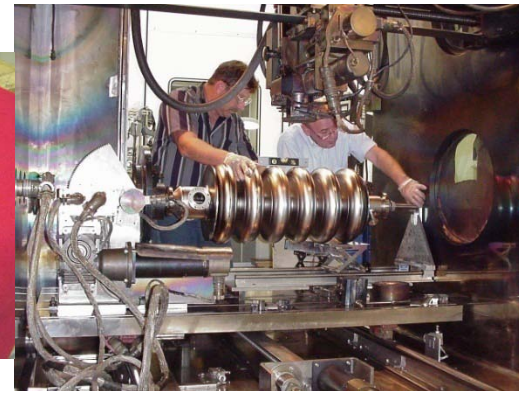


Multi cell cavity fabrication

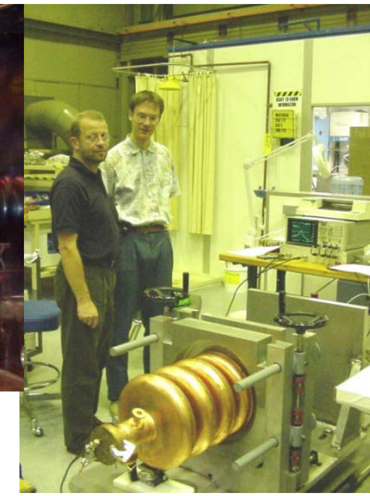
Forming

Machining

Welding

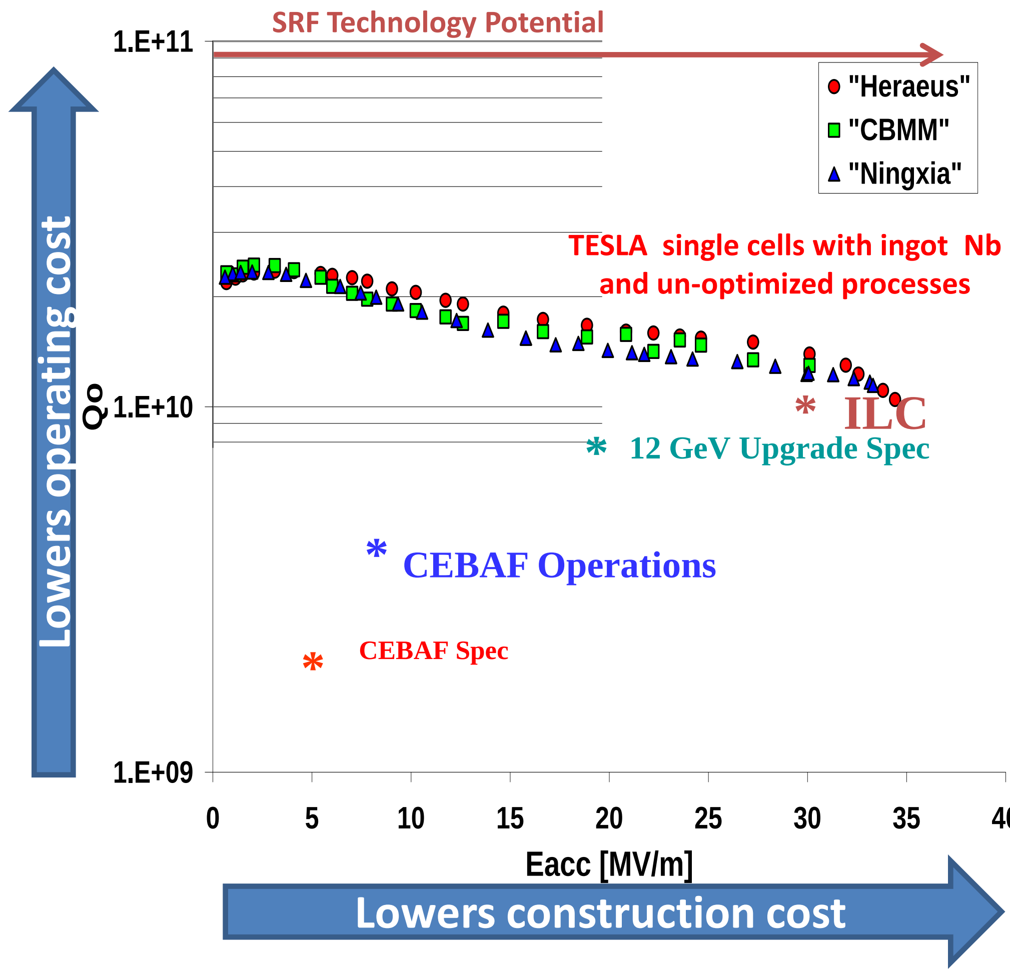


Tuning



>80% 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, now DOE NP and JLab working to improve Q_0 by a factor of ~3

Comparison of fine grain and ingot niobium

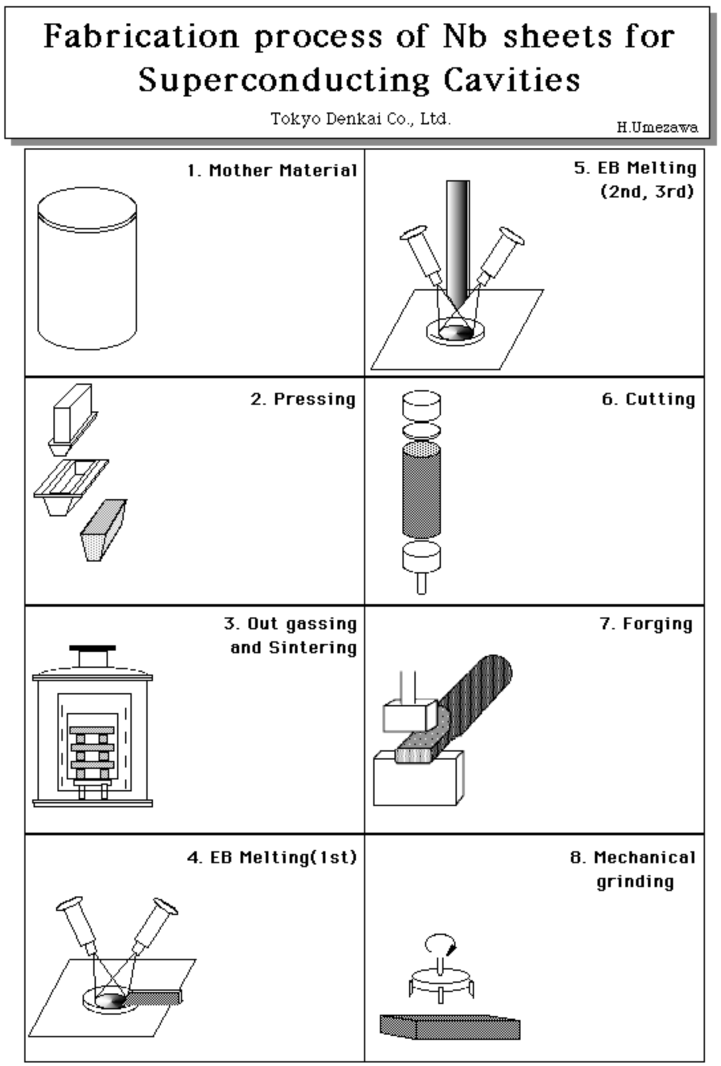
Niobium Specifications – Past & Present (@JLab)

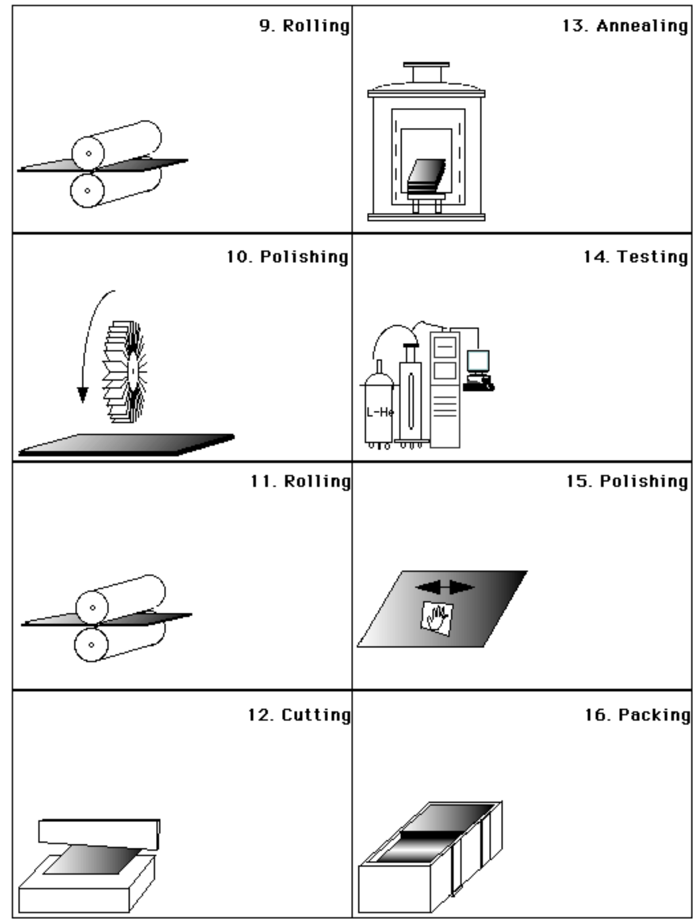
- Polycrystalline Niobium with ASTM #5 Grain Size or finer ~ 50 micro meters & 90% recrystallized
- Percentage of elongation > 25
- Yield Strength > 10.7 KSI (~75 MPa) (7 KSI for SNS)
- RRR > 250
- Tantalum < 1000 wt ppm

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

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

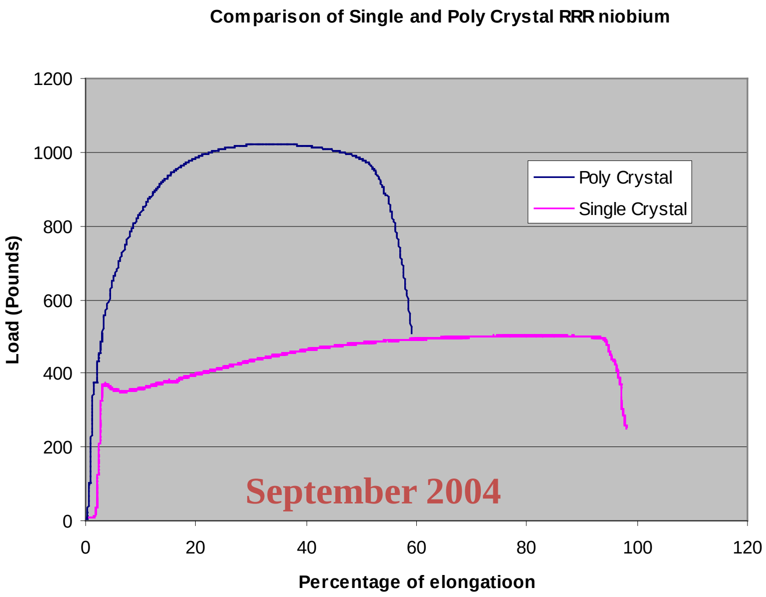
Process steps - fine grain Niobium





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

Birth of Ingot Niobium Technology
CBMM-JLab CRADA, August 2004



Chosen for Excellent Ductility and Surface Smoothness with just BCP

First CBMM/JLab International Patents were applied for in April, 2005

Araxá Mine in Brazil & RRR Ni

From ore to oxide to large grain ingots

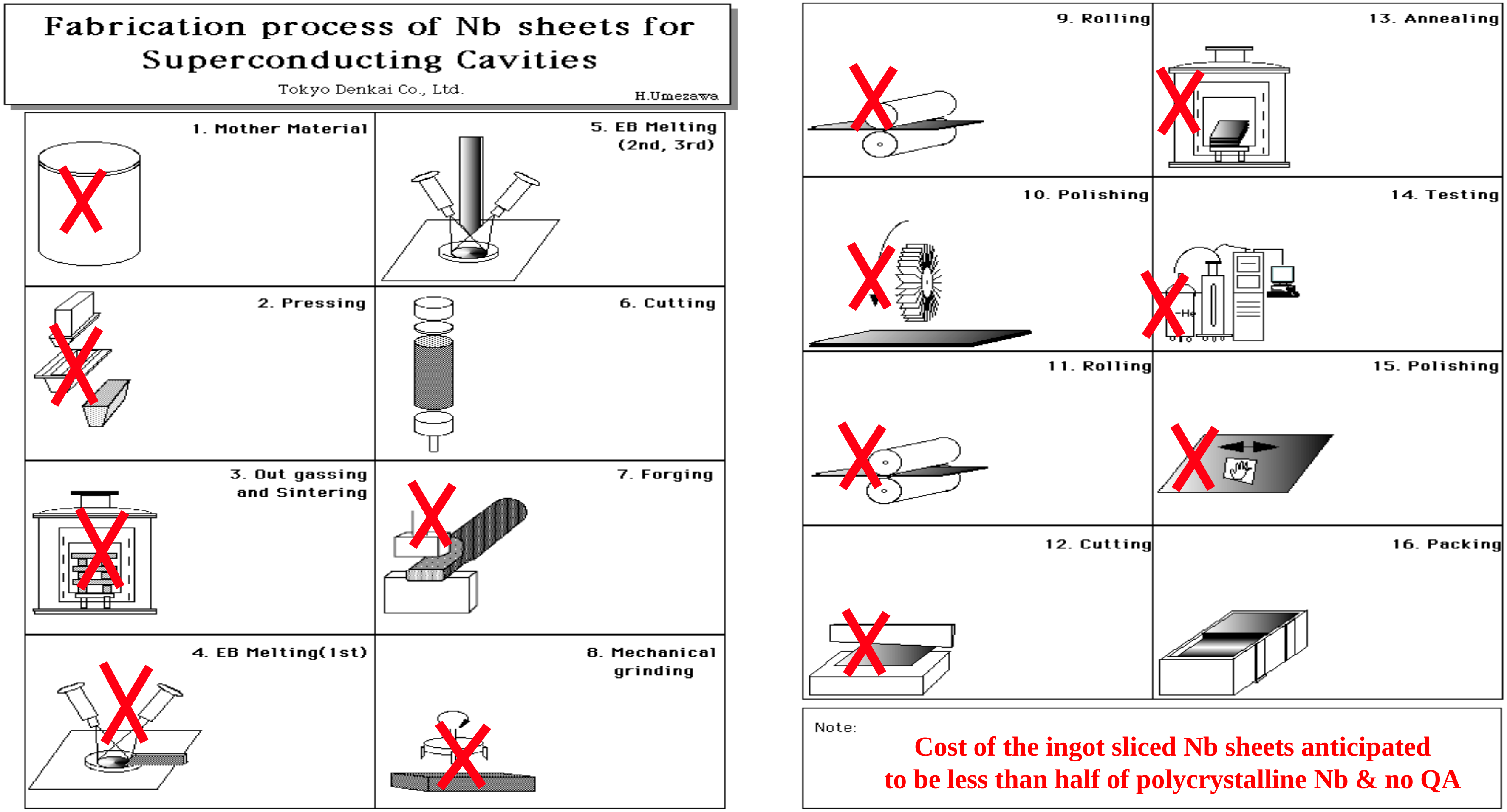
The CBMM open cast mine

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

Economic path for CW applications



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

Vacuum Contamination Work Shop at JLab 1997

Minimizing organic and particulate recontamination addressed

Re-contamination prevention courses were organized at JLab in 2000 and 2005

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

Q_0, hydrogen & cavity performance

- **Q-disease in the cavities is an example of a gross manifestation of hydrogen effect similar to gross air leak in high vacuum systems**
- **As we are looking to improve the cavity performance (Q) further we need to understand the effects of proton in niobium and take steps to minimize the solid-solution of protons, similar to eliminating smaller air leaks in UHV systems**
- **Hydrogen is difficult to measure quantitatively at the concentration levels that we have to in materials in general and greatly in niobium**
- **Like vacuum leak standards, we need to develop Nb-hydrogen standards**

Goals of the Qo Improvement Program

1. Scientific Understanding

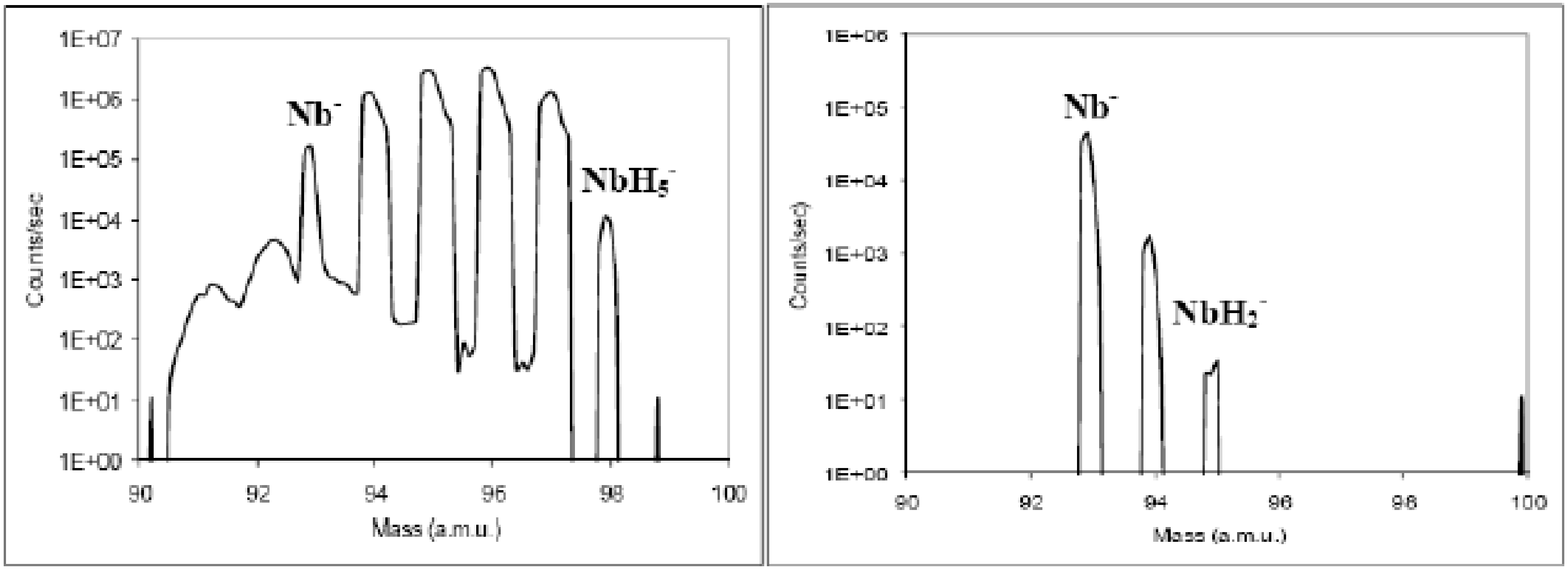
Hydrogen absorption with BCP and EP

- **Very high equilibrium hydrogen activities (fugacity) have been estimated when Nb metal is in contact with water or BCP solution**
- **Hydrogen is readily absorbed into Nb when the protective oxide layer is removed**
- **Lower H fugacity's are obtained due to an anodic polarization of Nb during EP and hence lower hydrogen absorption**

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

NIST/JLab

High temperature annealing removes gross hydrogen

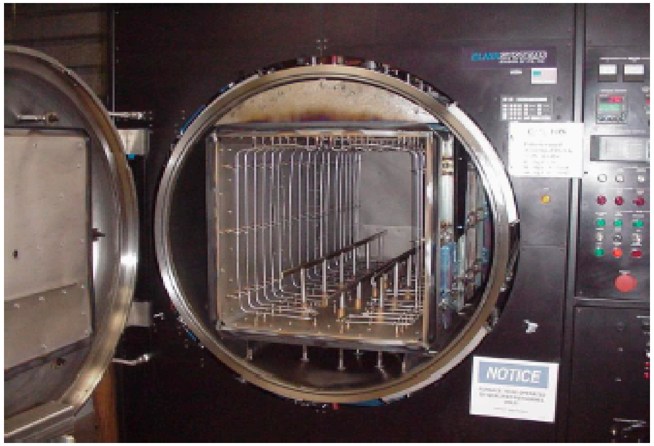


(a) (b)

FIGURE 1. SIMS mass spectra showing difference in H between (a) non-heat treated and (b) heat treated sample.

NbH (Beta Phase) very much in existence after anneals

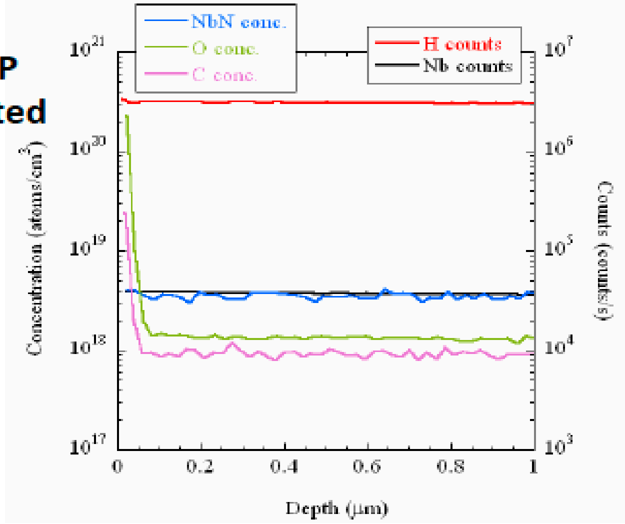
Heat treatment to remove hydrogen



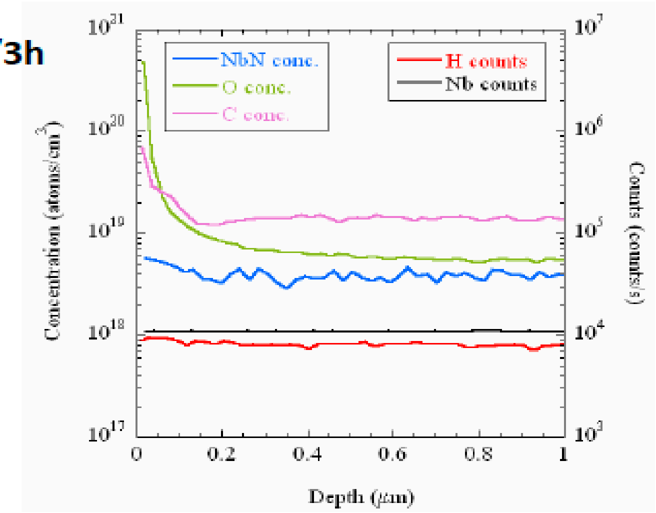
- 800°C/3h, pressure ~ 10^{-6} mbar
- **No chemical etching afterwards!**
- Nb samples were treated with the cavities and depth profiling of the impurities was done at NCSU

~ 2 orders of magnitude lower hydrogen content after HT

BCP treated

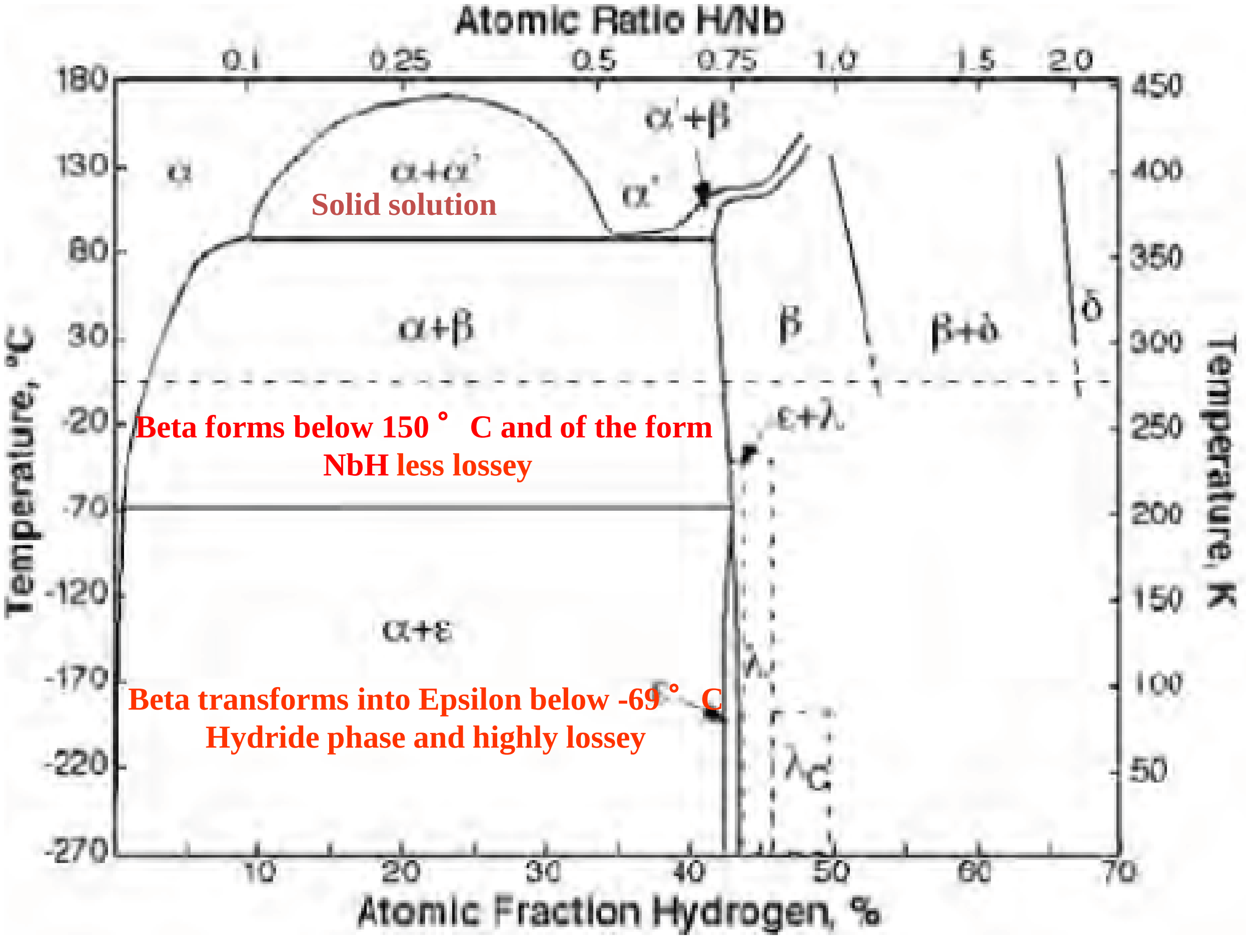


800C/3h

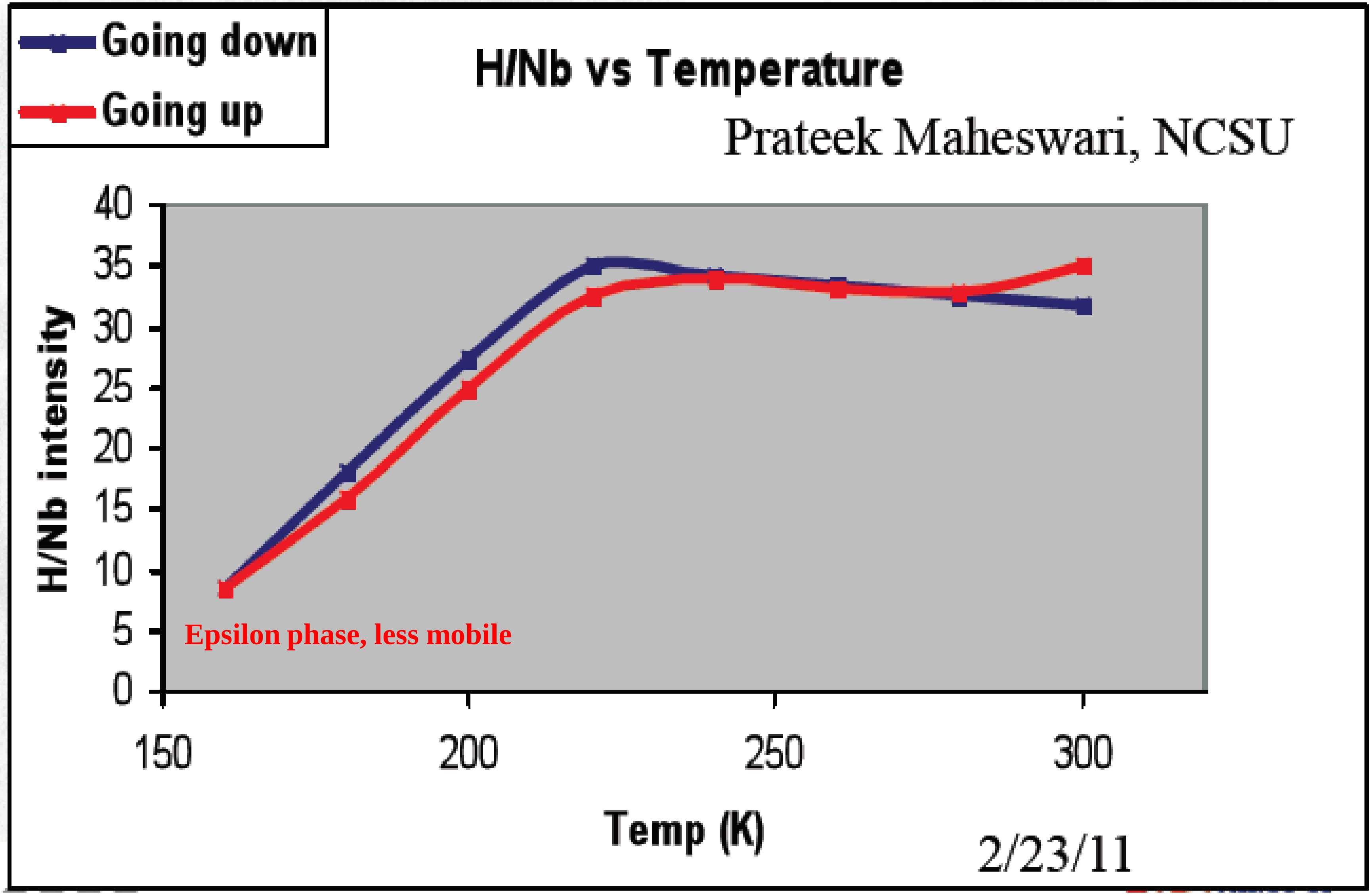


Currently used furnaces contaminate the cavity surfaces, chemical re-etching reintroduces H

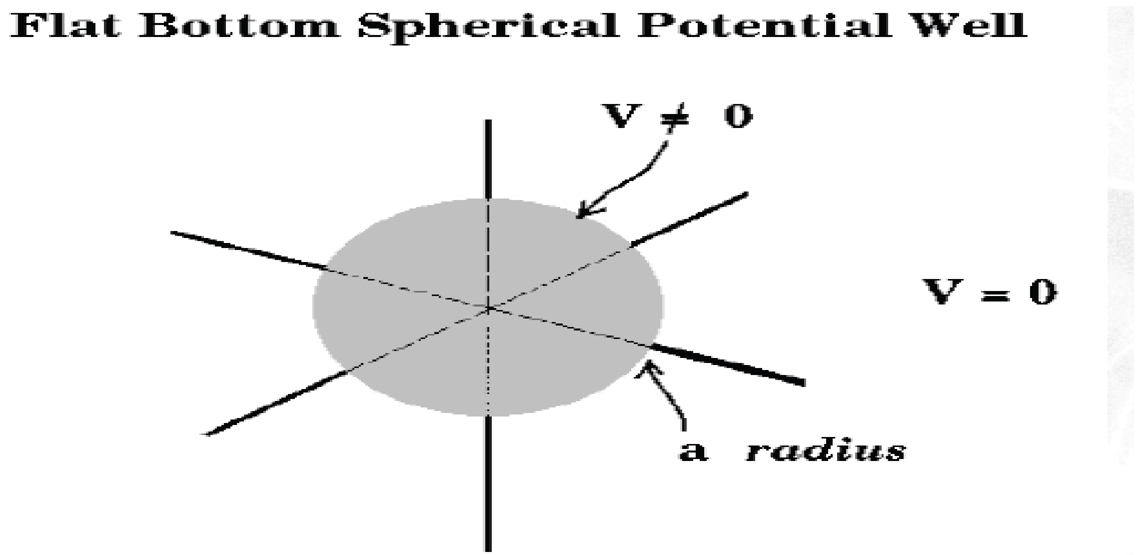
Niobium – hydrogen phase diagram



Hydrogen phase change



Atomic model of proton in niobium



•The proton at an interstitial site is represented by a wave function in a spherical potential well of radius a and depth V

•The proton's bound states will strongly interact with one another leading to more complex electronic properties

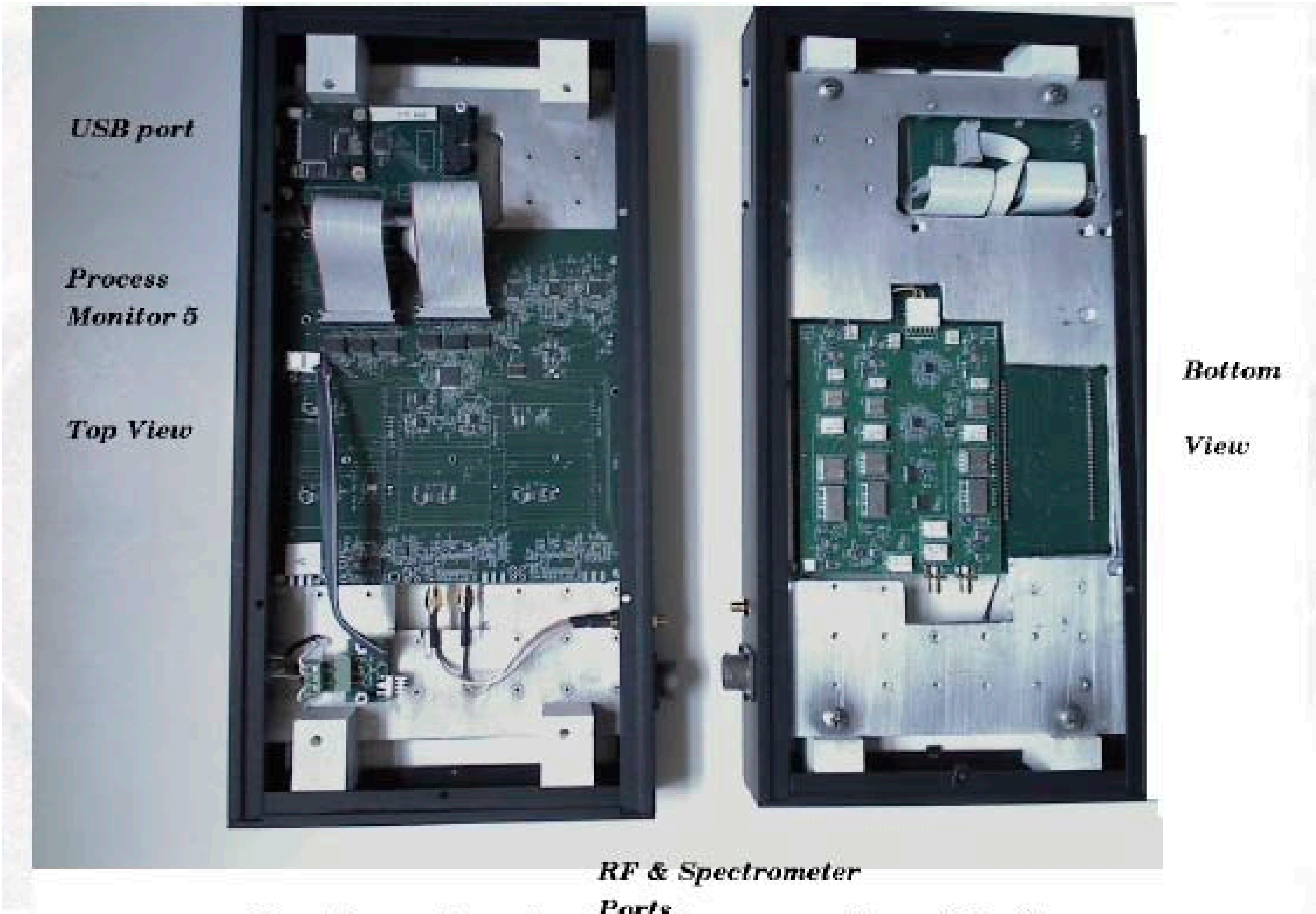
•Formation of a "proton band structure" within the metal will also affect mechanical and superconducting properties

John Wallace, Casting Analysis Corporation

Goals of the Qo Improvement Program

2. Technology Development

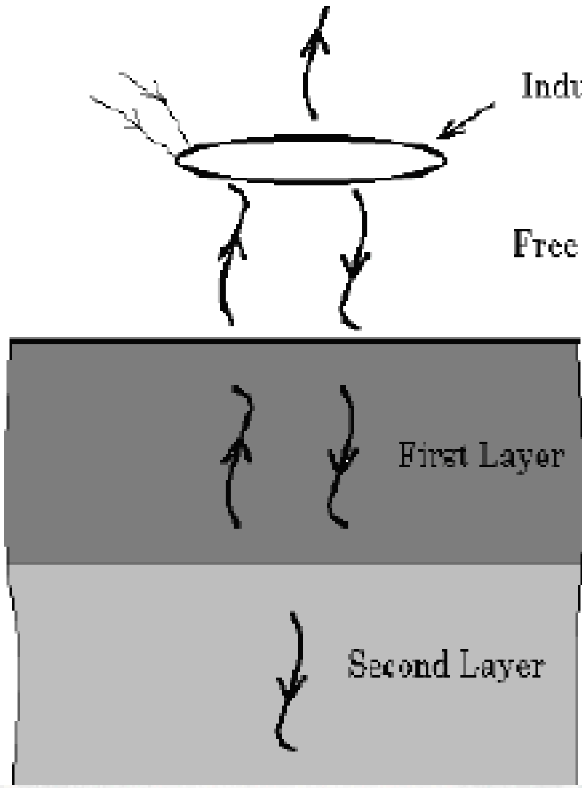
Eddy current (0.1 to 2 GHz) & Optical measurement system

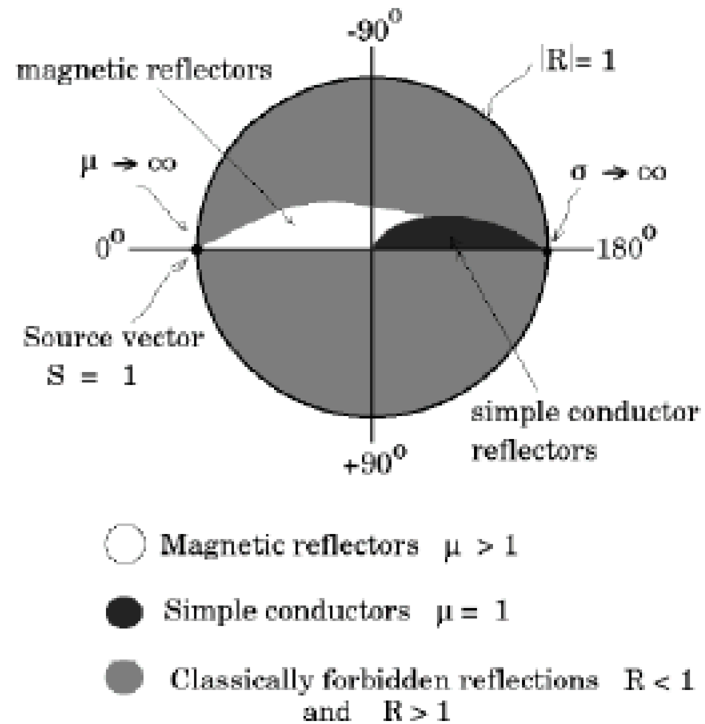


Casting Analysis Corporation/JLab

Niobium-hydrogen measurement cells

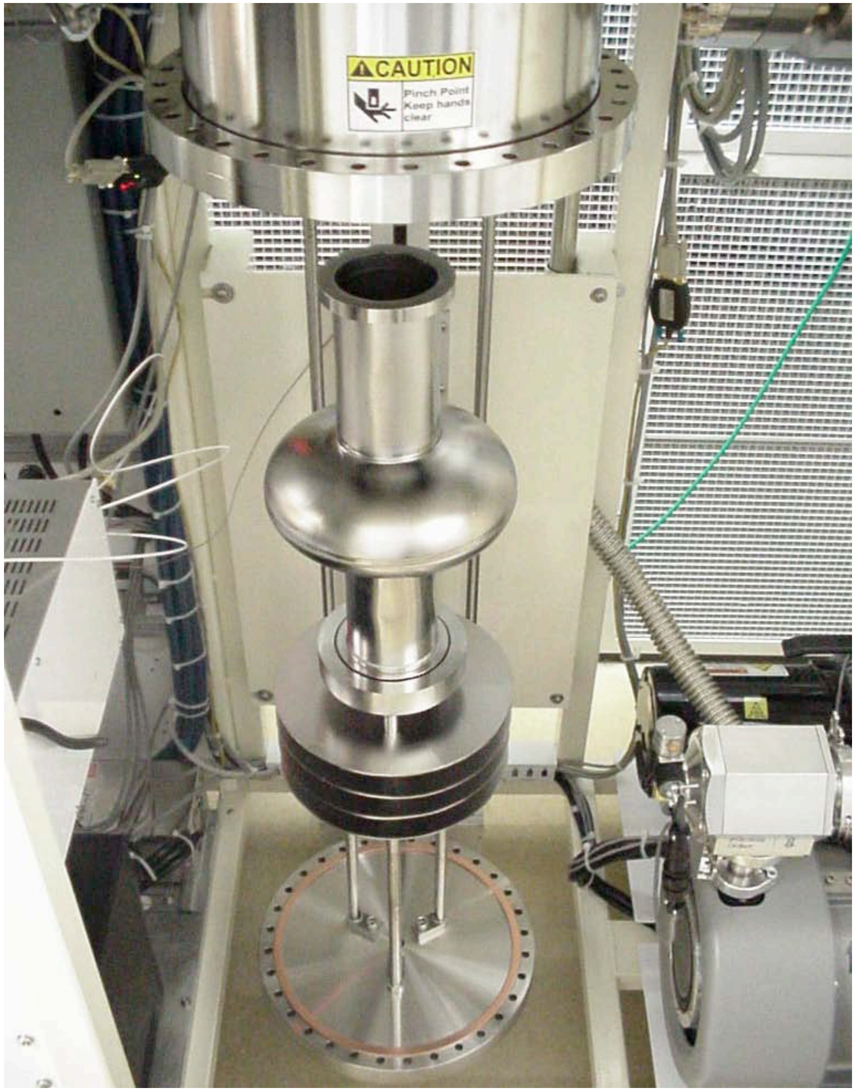
RF reflection measurement principle





Proton in SRF niobium, J. P. Wallace, SSTIN10 AIP CP 1352, 2011

Clean UHV furnace - patents applied for

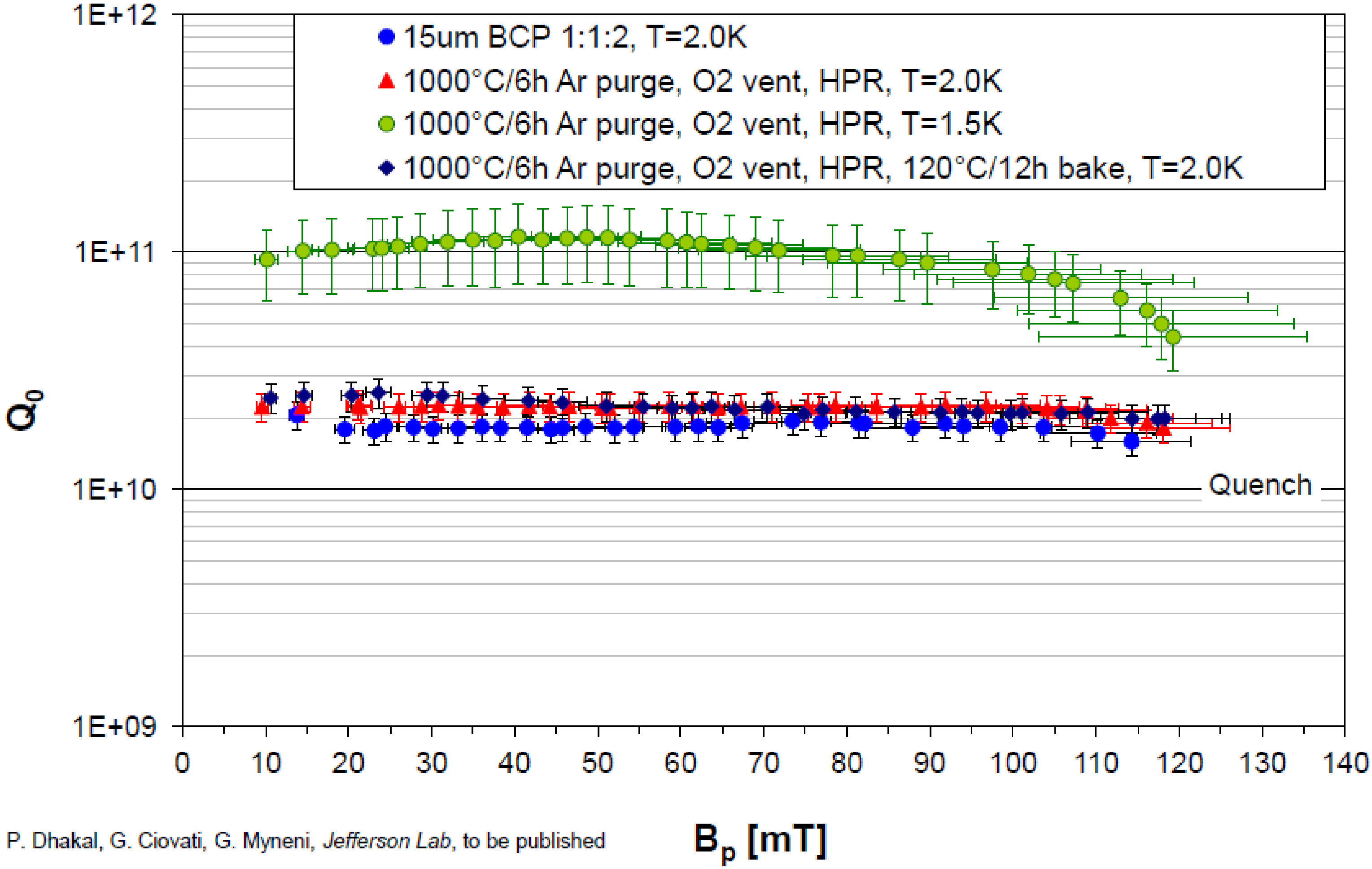


Cavity material and preparation

- CBMM ingot niobium, RRR ~ 200 (>350), Ta ~ 1350 (<500) wt ppm, inexpensive 50% to 60% less than conventional Nb
- Barrel polishing 73µm, BCP 65µm , a total of 138 µm removal and high pressure UHP water (~200 µm for fine grain)

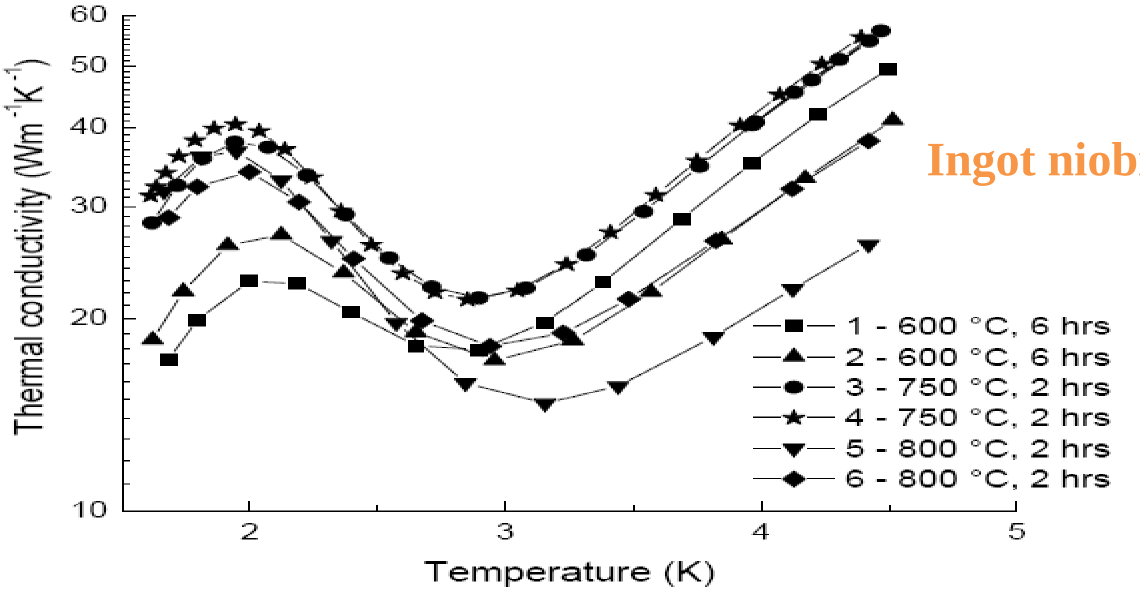
High and flat Qo – characteristic of ingot niobium

Large grain RRR ~ 200 Ta ~ 1375 CEBAF OC shape 1474 MHz cavity



P. Dhakal, G. Ciovati, G. Myneni, *Jefferson Lab*, to be published

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

MSU

Cryogenic Refrigeration Cost Reduction with improved Qo (~factor of 3) CW SRF Cavities

- A 10 kW 2 K refrigerator costs ~ 100 M$
- A factor of 3 improvement in Qo will lower this to ~ 45 M$
- The power consumption and hence the operating costs will be reduced by a third

SSTIN10

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Myneni
Ciovati
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Symposium on the Superconducting Science & Technology of Ingot Niobium

2010
AIP Conference Proceedings
AIP

10th International Symposium On Hydrogen In Matter (ISOHIM)

Jefferson Lab

CBMM

SSTIN10

Symposium on the Superconducting Science & Technology of Ingot Niobium

Jefferson Lab • Newport News, Virginia, USA
September 22-24, 2010

Editors:
Ganapati Rao Myneni
Gianluigi Ciovati
Marcos Stuart

AMERICAN INSTITUTE OF PHYSICS

CP 1352

AIP CONFERENCE PROCEEDINGS

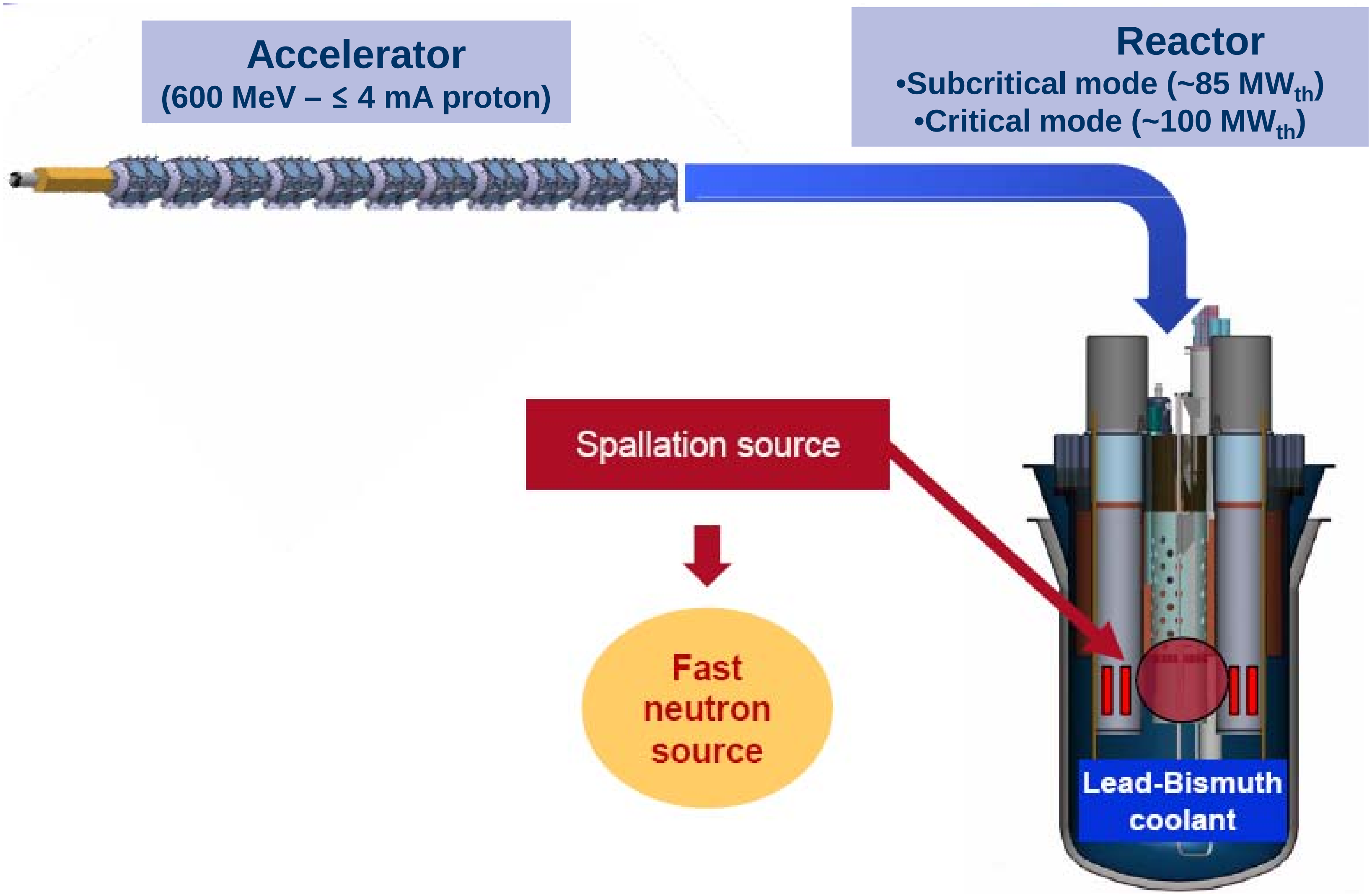
Ingot niobium CW Applications

- Accelerator Driven Systems
- Energy Recovery Linacs for future light sources
- Compact Electron Linacs for Industrial and Medical Applications

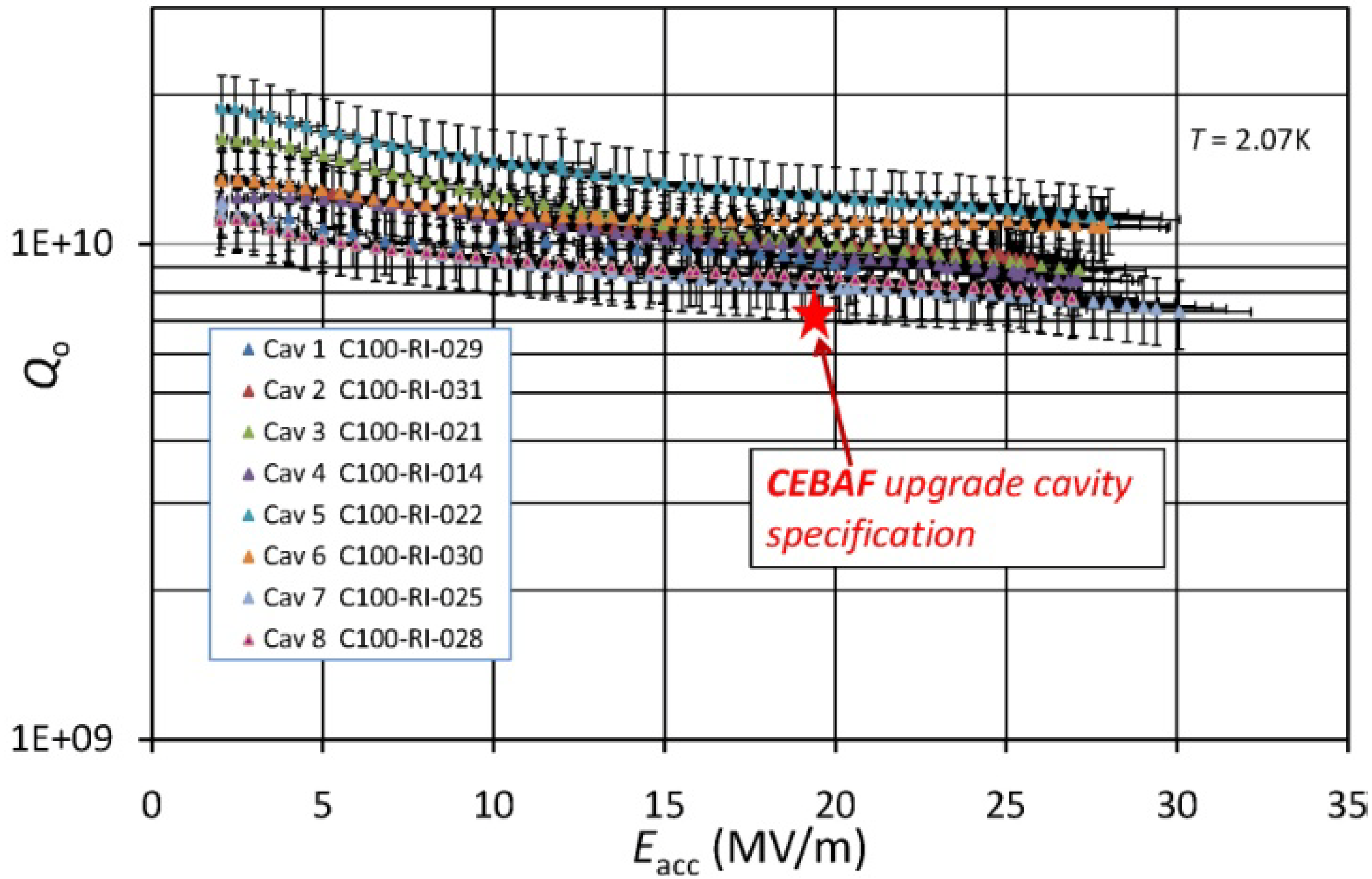
Accelerator Driven Systems

- Nuclear Waste Transmutation
- New nuclear fuel cycle material studies
- Energy Sustainability
- Carbon foot print reduction

MYRRHA Concept

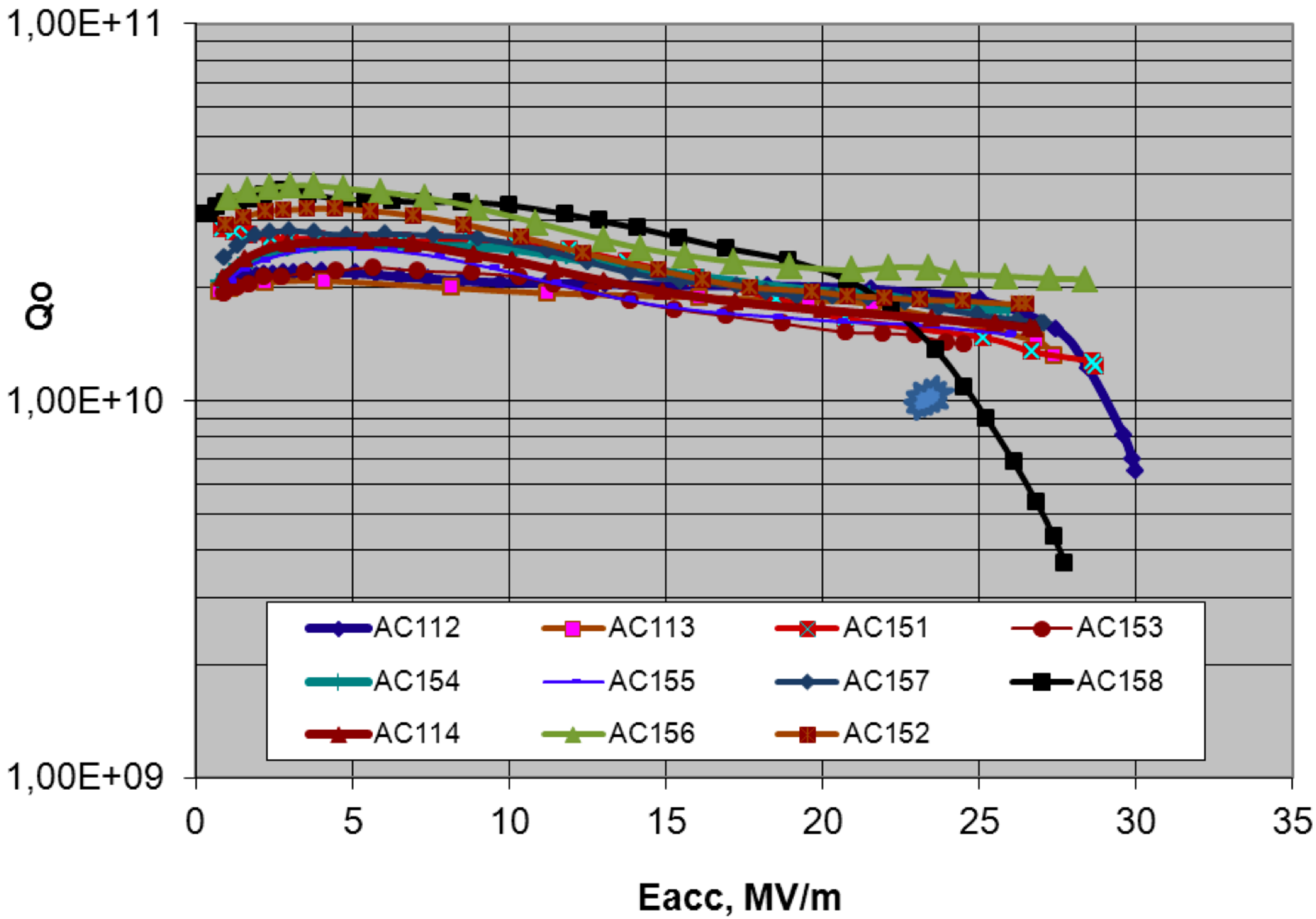


CEBAF Upgrade cavities performance with the state of the art processes (EP)

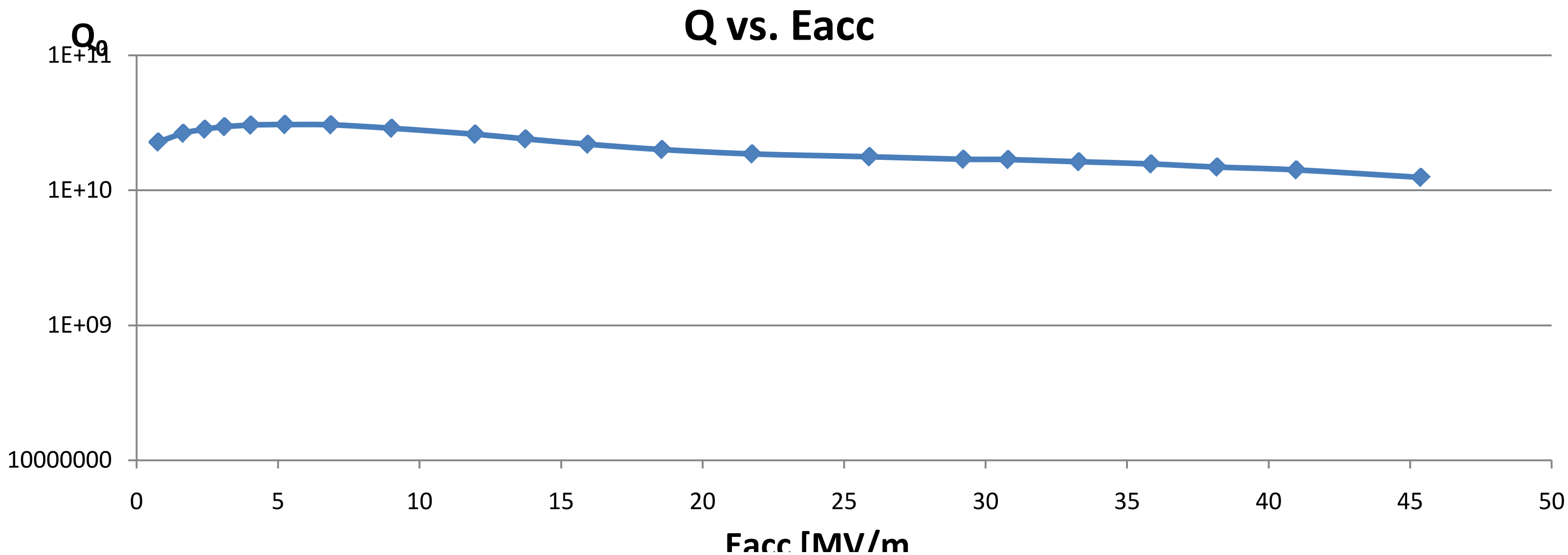


Oliver Napoly

First Saclay built XFEL cryommodule will have all the ingot Nb cavities developed at DESY (Just BCP)



DESY 9 Cell ingot XFEL cavity sets the world record



Waldemar Singer

Summary

* **Ingot niobium with high tantalum content meets CW SRF applications with minimum processing, lower cost and enhanced performance**

* **Let us jointly work in implementing this cutting edge technology for energy sustainability at reduced carbon foot print**

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Asavari Dhavale (grad student) – BARC/HBNI

Sindhunil Roy – RRCAT