Path Forward for Economic and High Performance SRF Accelerator Structures

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Outline

- State of the art of SRF Technology ~1970
  - Ingot niobium to polycrystalline niobium
- Specifications and sources of niobium
  - Low tantalum to high tantalum
- State of the art of SRF Technology 2004
  - Polycrystalline niobium to ingot niobium
- New directions of cavity production
  - Streamlined to reduce costs
- Summary

Ingot niobium SRF technology 1970's

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.

B_{pk}~ 108 mT with BCP
After 1800° C heat treatment

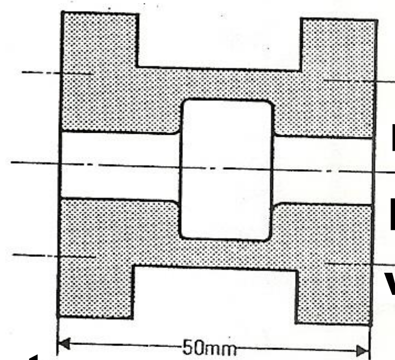


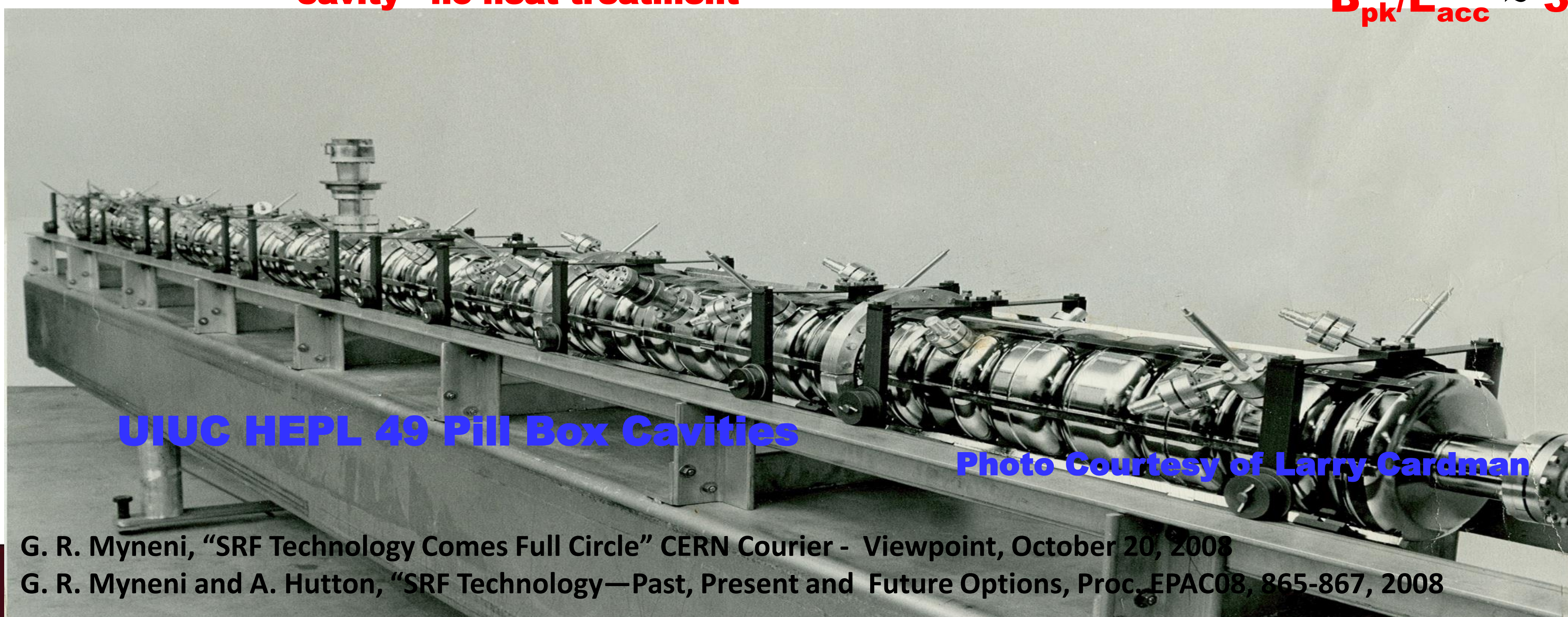
Fig. 1. Single piece TM_{010}-niobium cavity with a resonant frequency of 9.5 GHz.

B_{pk}~ 109 mT with BCP

B_{pk}~ 130 mT with EP
with heat treatments

Note:
B_{pk} ~ 159 mT with EP for reactor grade polycrystalline cavity - no heat treatment

B_{pk}/E_{acc} ~ 3



UIUC HEPL 49 Pill Box Cavities

Photo Courtesy of Larry Cardman

G. R. Myneni, "SRF Technology Comes Full Circle" CERN Courier - Viewpoint, October 20, 2008
G. R. Myneni and A. Hutton, "SRF Technology—Past, Present and Future Options, Proc. EPAC08, 865-867, 2008

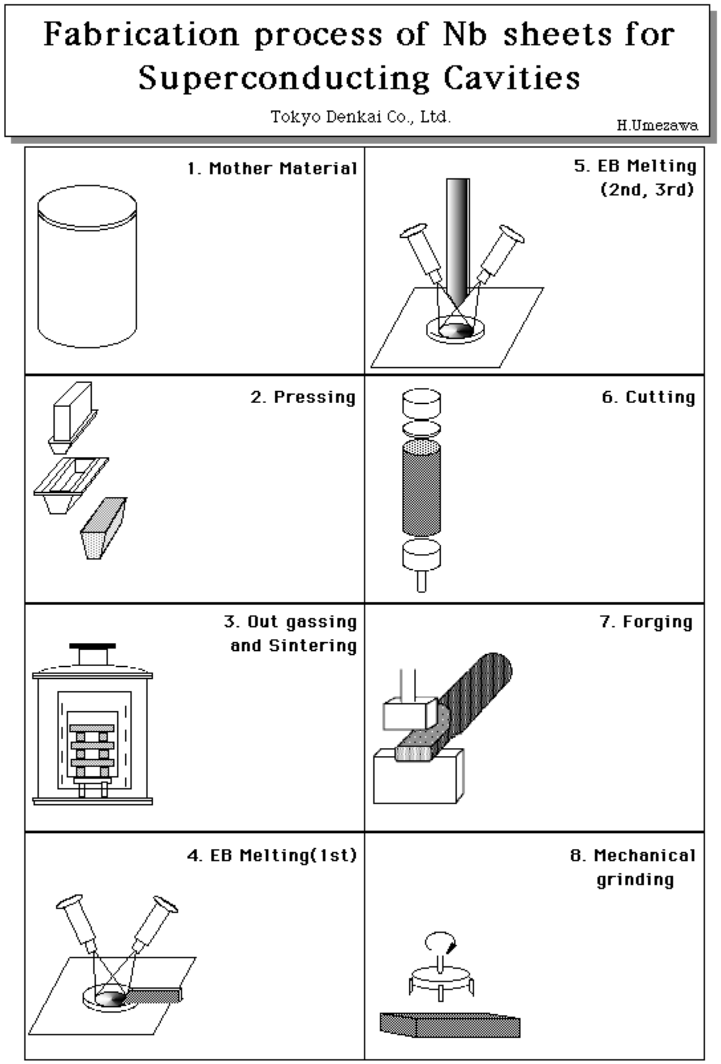
Current Niobium Specifications ("TESLA Spec")

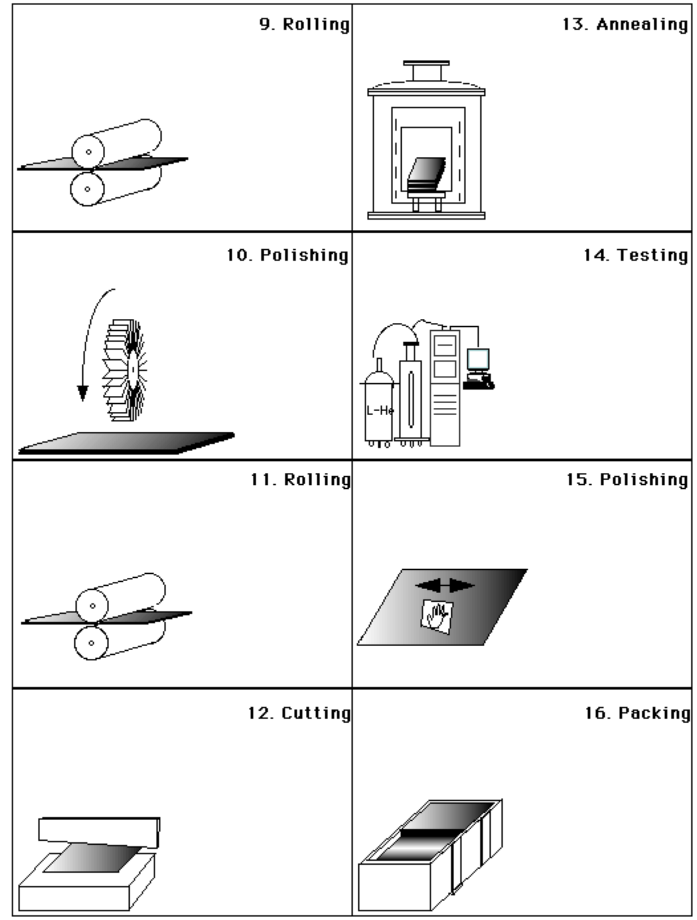
- The currently accepted specifications for niobium are:

Material parameter	TESLA/XFEL/LCLS Pulsed/CW
Type	Polycrystalline
RRR	> 300
Grain Size	~ 50 µm
Yield Strength	> 50 N/mm^2
Tensile Strength	> 100 N/mm^2
Elongation	≥30%
Tantalum wt. ppm	Ta ≤ 500
Impurities wt. ppm	O ≤ 10, N ≤ 10, C ≤ 10, H ≤ 2
Vickers Hardness	≤ 50

- *We believe that these specifications are too restrictive, adding cost, and for CW applications are sub-optimal*

Process steps of fine grain Niobium with potential foreign material embedment





Note:

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

Present Polycrystalline Nb Cavity processing steps

- Electron Beam welding of the cavities
- 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
- High pressure ultra pure water rinse
- Vacuum bake ~120 °C for up to 48 hours
- RF test

Sources of Niobium

- Niobium is produced from one of two sources:
  - Columbite/tantalite - niobium with tantalum in similar proportions
    - Niobium is produced as a by-product of the process of refining the ore to produce tantalum
    - Niobium is purified by electron beam refining in a series of “melts”
    - Successive melts (>3) mostly reduce the interstitials
  - Pyrochlore - predominantly niobium with tantalum as an “impurity”
    - Successive melts (>3) mostly reduce the interstitials
      - Tantalum content is mostly unaffected
- Over 90% of the world’s niobium comes from pyrochlore ore
  - CBMM is the major producer
  - Jefferson Lab has had a CRADA with CBMM 2004–2015 to develop ingot niobium technology

Niobium Impurities

- Niobium impurities can be categorized in three classes
  - Tantalum
  - Other metallic impurities
    - Iron, copper, tungsten, titanium, etc.
      - Silicon behaves similarly
  - Interstitial impurities
    - Hydrogen, carbon, oxygen, nitrogen
- Residual Resistivity Ratio (RRR) is commonly employed as a measure of niobium purity
  - In fact, interstitials have the biggest impact on RRR

G. R. Myneni and H. Umezewa, "Variation of Mechanical Properties of High RRR Niobium and Reactor Grade Niobium with Heat Treatments" Materiaux & Techniques No 7-8-9 2003 19-22

Properties of Interstitials

- Hydrogen, carbon, nitrogen and oxygen tend to move along grain boundaries to defect sites where they are immobilized
- Hydrogen also diffuses through the bulk material
  - Diffusion velocity is 7 x 10^{-6} cm^2/sec at room temperature
  - 6 orders of magnitude greater than the other interstitials
- Hydrogen interacts with defects and other interstitials
- Hydrogen diffusion is influenced by gradient of residual stress
- Hydrogen affects the magnetic properties
- Hydrogen diffusion into bulk niobium can be blocked by niobium nitride and niobium oxides on the surface
  - Depends on surface processing

A. Magerl, J. J. Rush, J. M. Rowe, D. Richter, and H. Wipf, Phys. Rev. B 27, 927 (1983). Hydride prevention by Ti and N_2

Tantalum

- Tantalum content of columbite niobium is <500 ppm
  - Specification adopted for SRF cavities was <500
  - Tantalum content of pyrochlore is ~1300
    - Specification precluded pyrochlore niobium from consideration
- Tantalum inclusions are unacceptable
  - Inclusions have occurred when processing columbite because tantalum and niobium metals were being handled in the same facility (not all manufacturers)
  - Requires quality control measures (additional cost)
  - Inclusions are extremely unlikely with pyrochlore niobium
- *Experimental data from labs worldwide shows that the specification is overly restrictive for uniformly distributed tantalum*

Tantalum Effect on SRF Cavity Performance

Material # Sheet #	Tantalum Content [wt. ppm]	Average Eacc MV/m] before post purification	Average Bp [mT] before post purification	Eacc [MV/m] post purification + 100 µm BCP
1164_12-12	1300	18.1	80	29
1164_11_14	1300	22.2	98	24.8
1161_33_34	~600	23.1	103	31,5
1161_31_34	~150	21.9	97	27.8
1161_32_33	~150	23.2	103	27.3

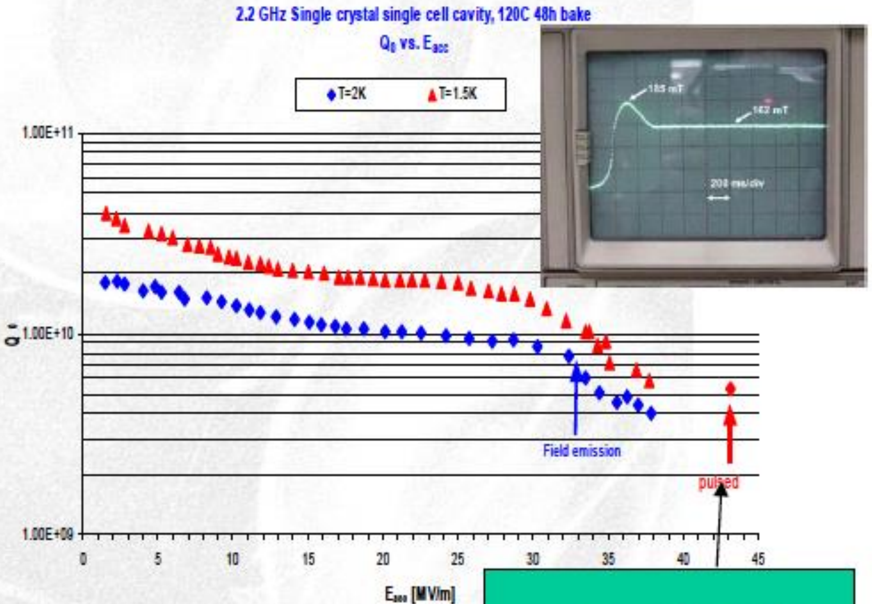
- Performance of cavities is unaffected by tantalum content up to ~1300 wt. ppm

P. Kneisel, G. Myneni, G. Ciovati, D. Proch, W. Singer, T. Carneiro et al in Proceedings of PAC 2005

State of the art SRF Technology 2004

First Single Crystal Cavity

2.2 GHz



Hc ~ 185 mT

Highest reached at that time

8 Years of Ingot Niobium Material Studies

Mechanical Properties	Yield strength, tensile strength, elongation for different grain orientation, bulging, residual strain, formability
Thermal properties	Thermal conductivity, phonon peak, effect of annealing and impurities, effect of strain
Magnetic/electrical properties	Hc1, Hc2, Hc3 for different crystal orientations, temperature dependences, penetration depth
Crystal orientation, recrystallization	Grain orientation in different materials, dislocation density, dependence of etch rate on orientation and residual strain
Flux penetration	Magneto-optical investigations, influence of grain boundaries on flux penetration
Oxidation / Hydrides	Oxide composition for different crystal orientations, sealing of surface, hydrides
Field emission	Emitter density, grain boundary segregation, cleaning
Fabrication	Forming issues, EBW, enlargement of single crystal, avoiding recrystallization, recovery
Surface topography	Influence of polishing conditions, replica technique, pits, roughness, field enhancement
Hot spots, cold spots	Hydrogen depth profile
SIMS analysis	Point contact tunneling, vacancies, dislocations

105 References

The Rise of Ingot Niobium as a Material for Superconducting Radiofrequency Accelerating Cavities, Peter Kneisel, Gianluigi Ciovati, Pashupati Dhakal, Kenji Saito, W. Singer, X. Singer, Ganapati Rao Myneni, Nuclear Instruments & Methods in Physics Research, Section A (2015)


Ingot niobium summary workshop
Jefferson Lab December 4, 2015

Summary of the workshop

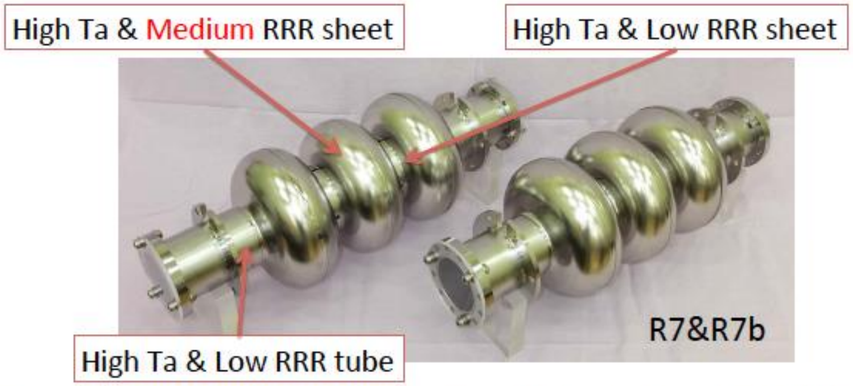
- Tantalum specifications should be relaxed to >1300 wt. ppm
- Ingot niobium technology is mature for CW applications
- Process procedures need to be optimized to reach high gradients with enhanced Q_0's
- Thermal diffusivity aspects should be investigated

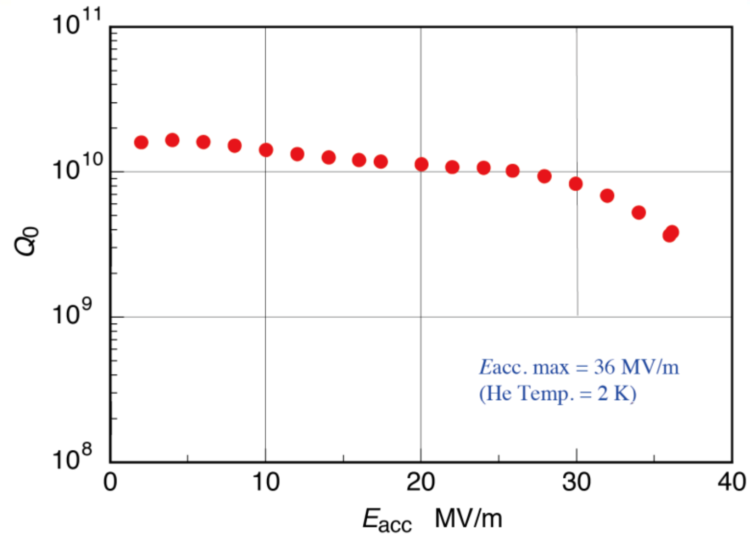
Proposed Technical Niobium Specifications for future SRF Cavities

Material parameter	TESLA/XFEL/LCLS Pulsed/CW	CW/Pulsed SRF Linac (proposed)
Type	Polycrystalline	Ingot
RRR	> 300	> 150
Grain Size	~ 50 µm	> 1 cm
Yield Strength	> 50 N/mm^2	> 50 N/mm^2
Tensile Strength	> 100 N/mm^2	> 100 N/mm^2
Elongation	≥30%	≥30%
Tantalum wt.ppm	Ta ≤ 500	Ta ≤ 1300
Impurities wt. ppm	O ≤ 10, N ≤ 10, C ≤ 10, H ≤ 2	O ≤ 30, N ≤ 30, C ≤ 40, H ≤ 5
Vickers Hardness	≤ 50	≤ 55

**G. Myneni, P. Kneisel, G. Ciovati, S. B. Roy, "Ingot niobium material specifications for continuous wave superconducting radio frequency cavities" JLab-TN-14-009*

KEK 3 cell high Ta TESLA-like cavity





1.3 GHz three-cell cavities manufactured by CFF at KEK
Cell shape: TESLA-like

Chemical compositions and RRR

unit: wt ppm except RRR

	C	N	O	H	Zr	Ta	Fe	Si	W	Ni	Mo	Hf	Ti	S	RRR*4
Spec. ASTM B391*1	100	100	250	15	200	3000	100	50	500	50	200	200	300	N/A	N/A
Ingot*2	<30	33	26	<2	<1	1194	3	<20	<5	<1	<1	<2	7	<10	60~ 103
Ingot*3	<10	30	<10	1	<10	1210	<10	<10	<10	10	<10		<5		277~ 298

*1 R04210-Type 2, Commercial grade unalloyed niobium
*2 Start material, measured by CBMM
*3 After 2-time EB melting, measured by ULVAC
*4 RRR was measured by KEK

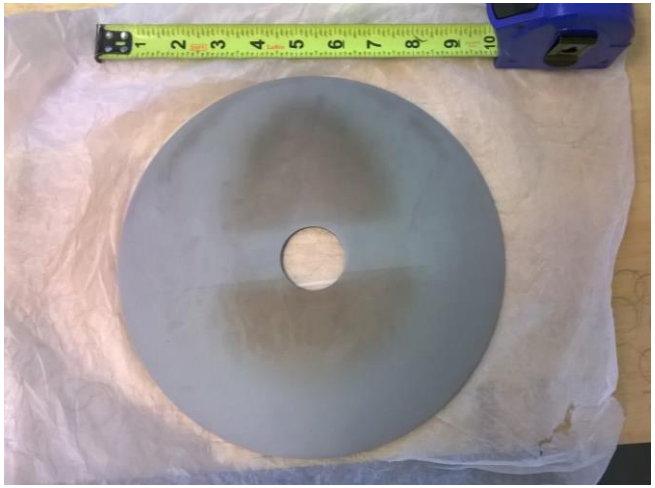
SRF2017: 2017.7.17

Acknowledgements: Niobium ingot was provided by **CBMM**.
Secondary processes (EB melting, manufacturing to sheet and tube) was provided by **ULVAC**

Masashi YAMANAKA, T. DOHMAE, Y. WATANABE, H. INOUE,
K. UMEMORI, S. MICHIZONO (KEK)

Multi-wire slicing in the USA

- We have qualified a US vendor for multi-wire slicing of Nb ingots ($R_a \leq 1.6$ μm, thickness tolerance ± 0.1 mm, as per DESY X-FEL spec.)

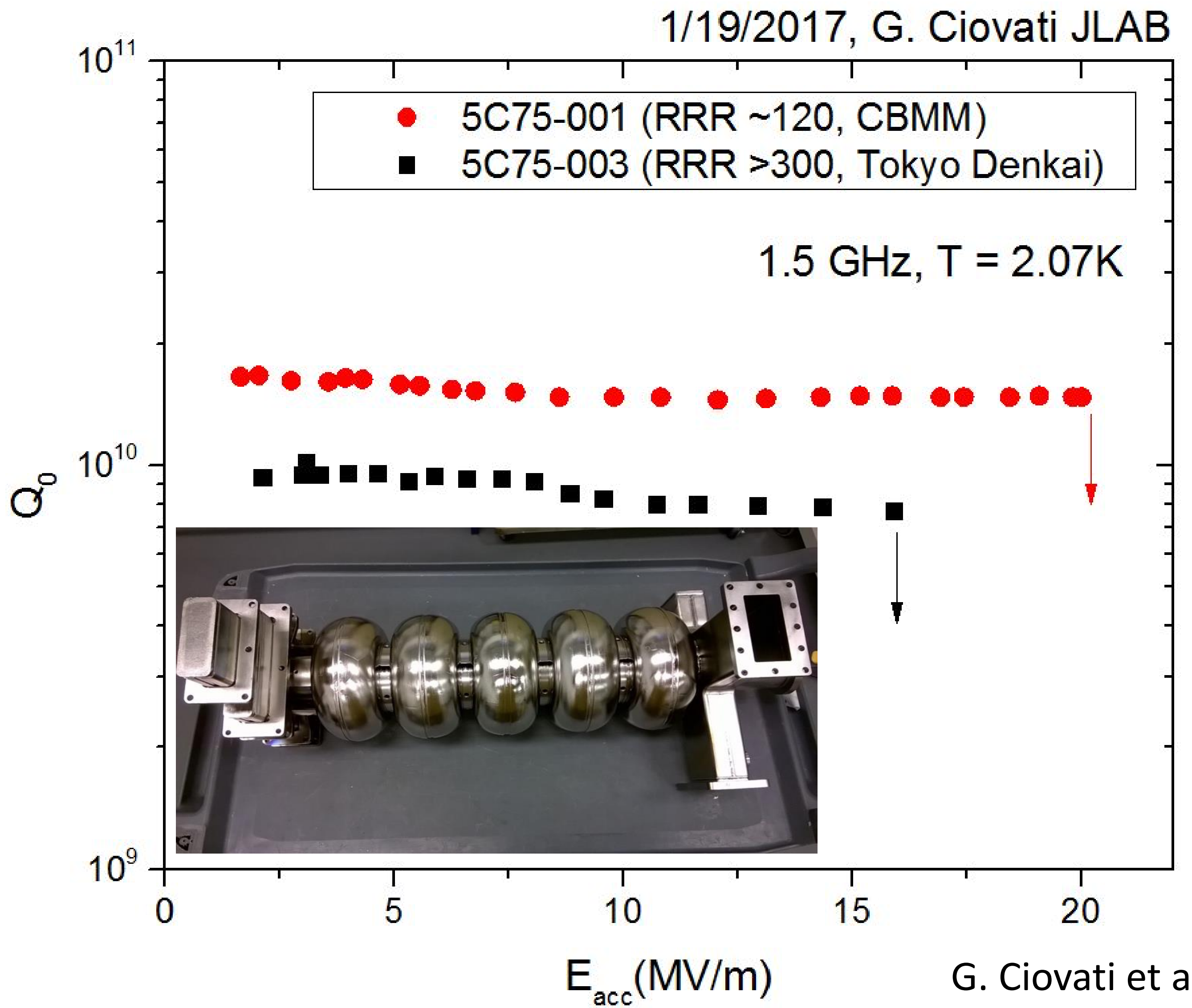


∅ 9.5”, 1/8” thick disc, as cut

∅ 9.5”, 1/8” thick disc, after 10μm BCP

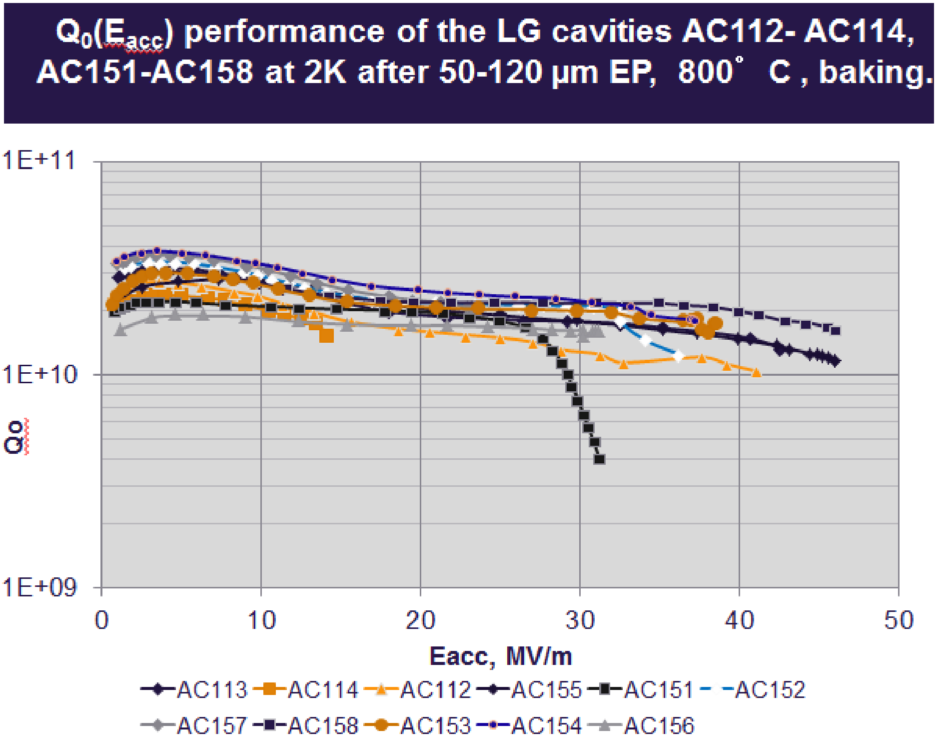
Slicing Technology, Bangor, PA

CEBAF C75 upgrade 5 cell ingot niobium cavities

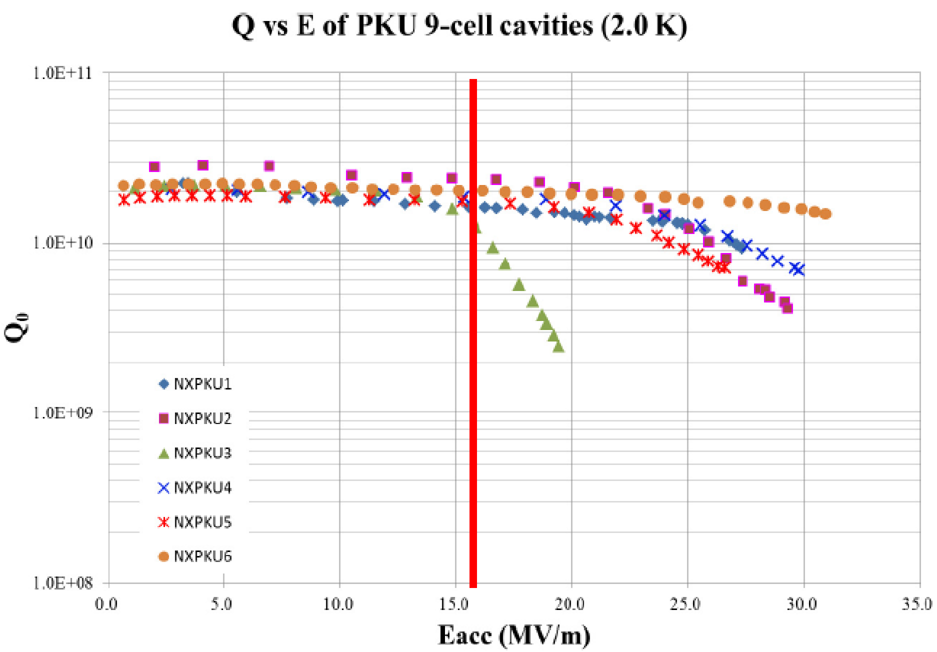


G. Ciovati et al to be published

Ingot niobium 9 cell cavities performance

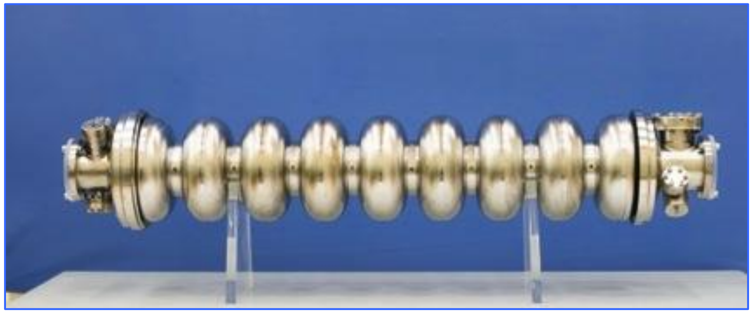


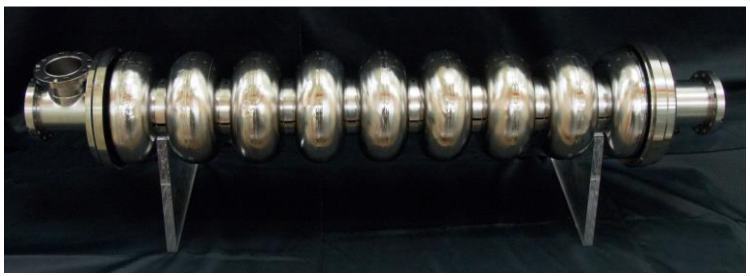
DESY 167 mT

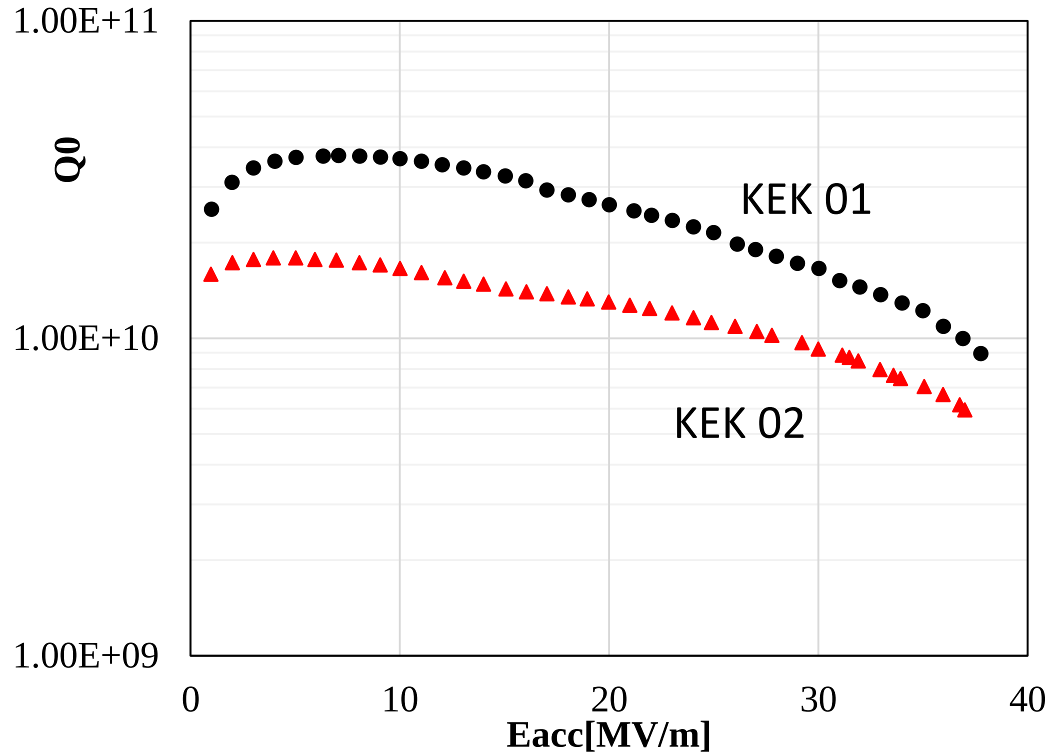


PKU just BCP 110 mT

KEK 9-Cell Cavity (KEK-01/02)reached 36/38 MV/m

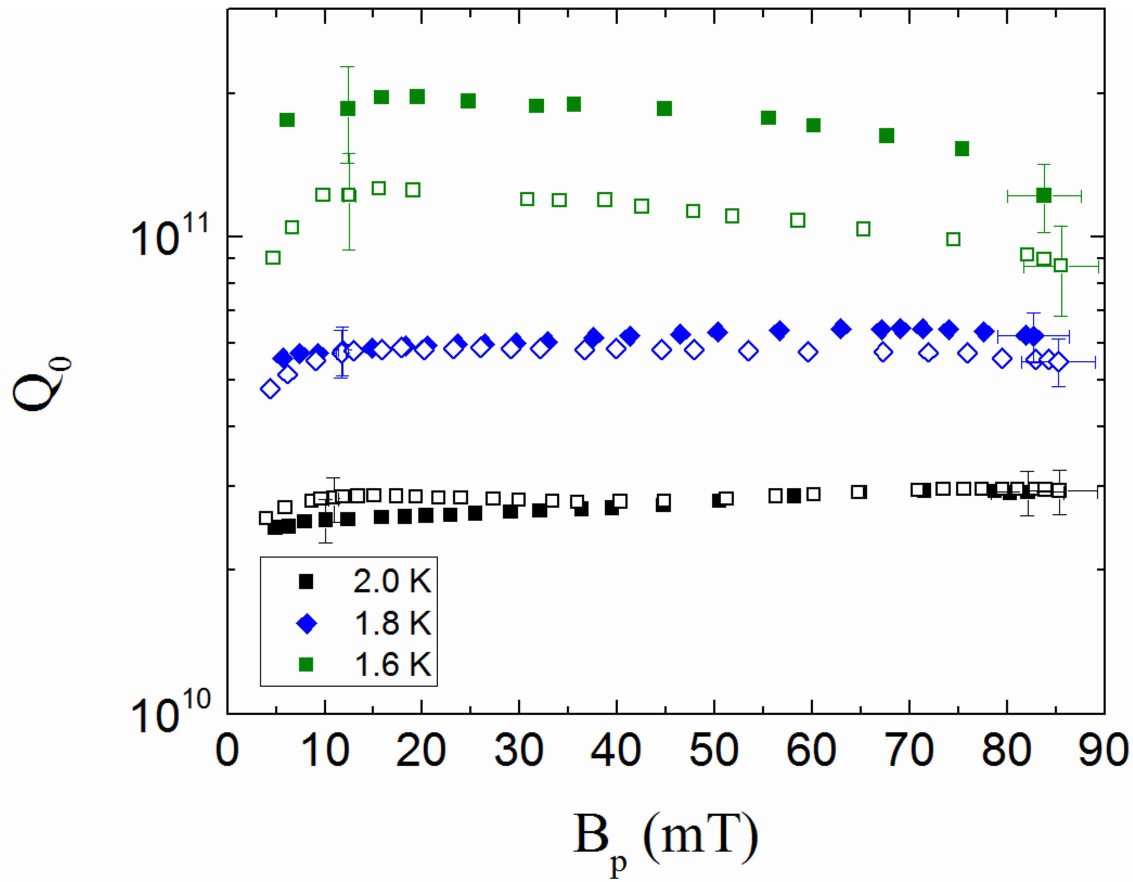






KEK-01 (Ingot-sliced, LG, 2016): Reached 38 MV/m
KEK-02 (Rolled, FG, 2014): Reached 36 MV/m

Enhanced Q_0 with no N_2 doping/infusion



1.5 GHz Single-cell "F3F4", ingot Nb of RRR~120

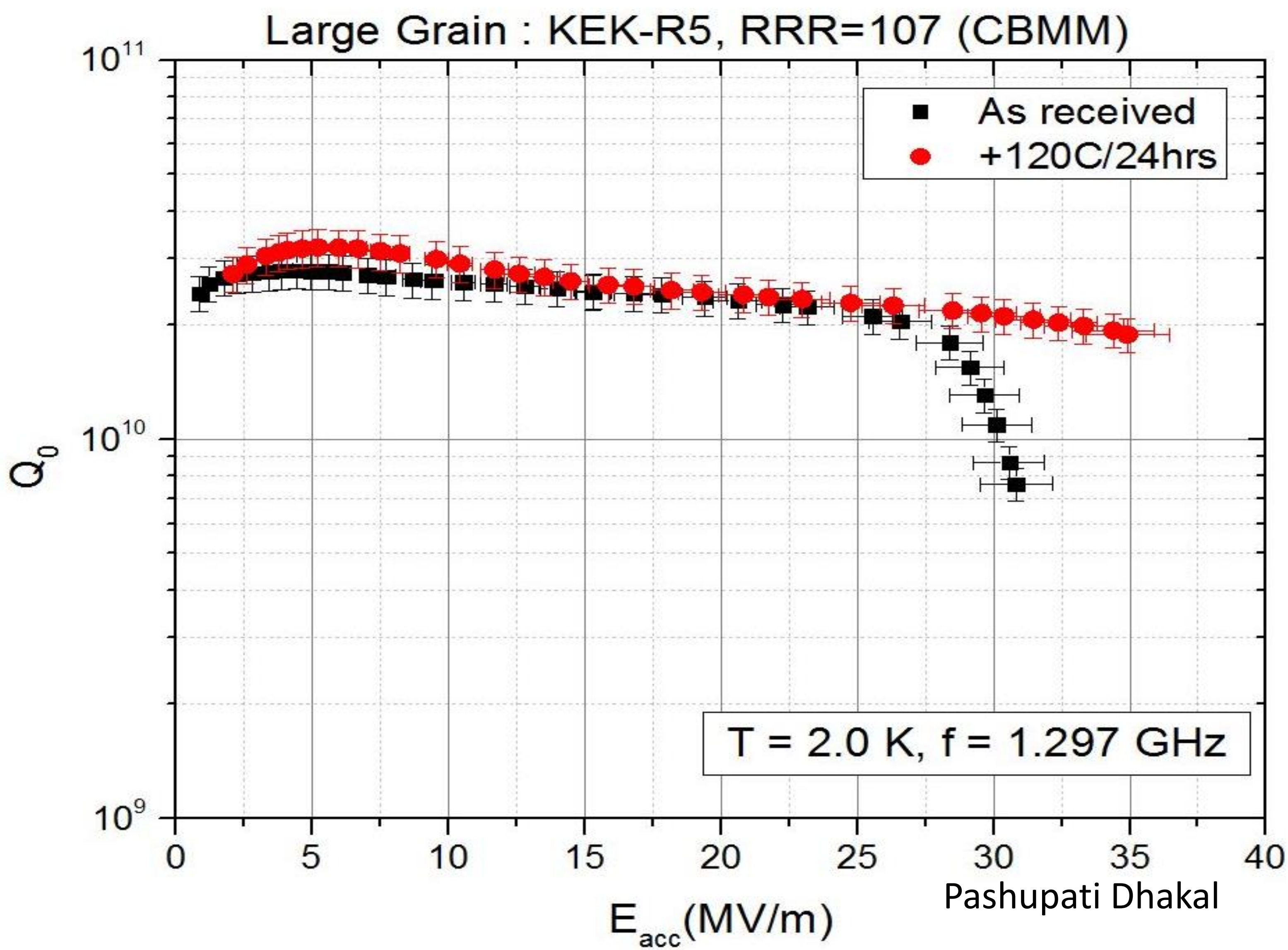
Treatments:

- 100 μm CBP + 50 μm BCP + 800°C/2h + 20 μm BCP (solid symbols)
- 120°C/12h bake (empty symbols)

The equivalent Q_0(2 K) at 1.3 GHz is ~3.8×10^{10} with no doping!

G. Ciovati, P. Dhakal, G. Myneni, Supercond. Sci. Technol. 29 (2016) 064002

KEK CBMM ingot niobium (RRR~100) single cell cavity

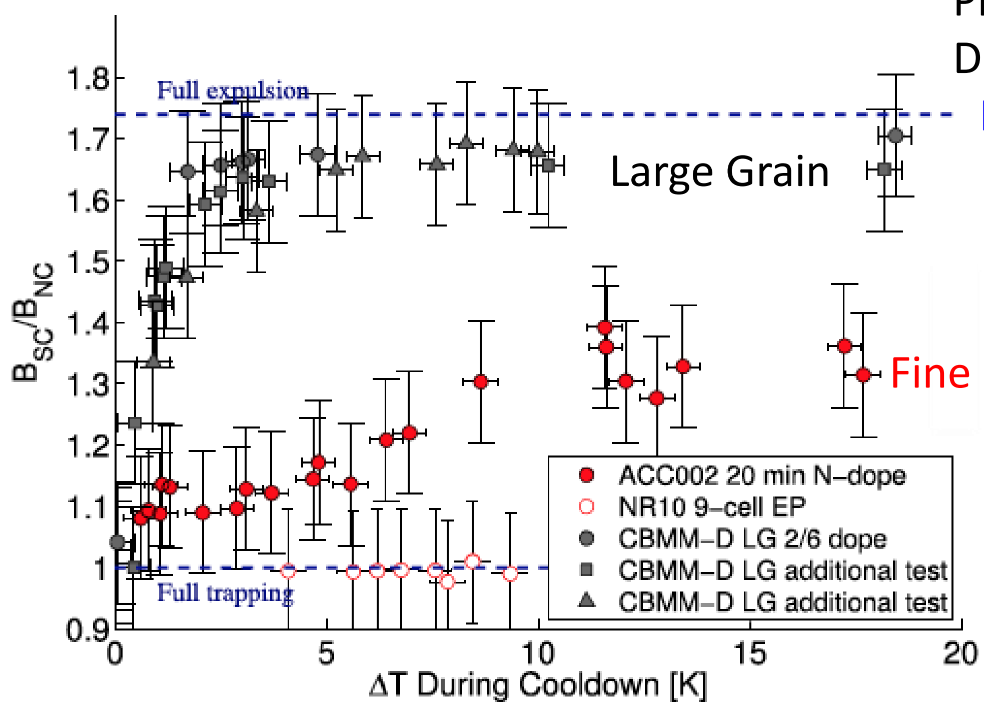


Pashupati Dhakal

Magnetic Flux Expulsion

- Magnetic flux trapped in superconducting niobium increases RF losses, decreasing the Q_0
  - Nitrogen doping/infusion exacerbates this problem
- Ingot material is less susceptible to this effect

Please see 4LP5-16 poster for latest data Dhakal et al



S. Posen et al, Journal of Applied Physics 119 , 213903 (2016)

Fermilab results, Jefferson Lab has measured similar results

High Efficiency and Affordable SRF Accelerator structures

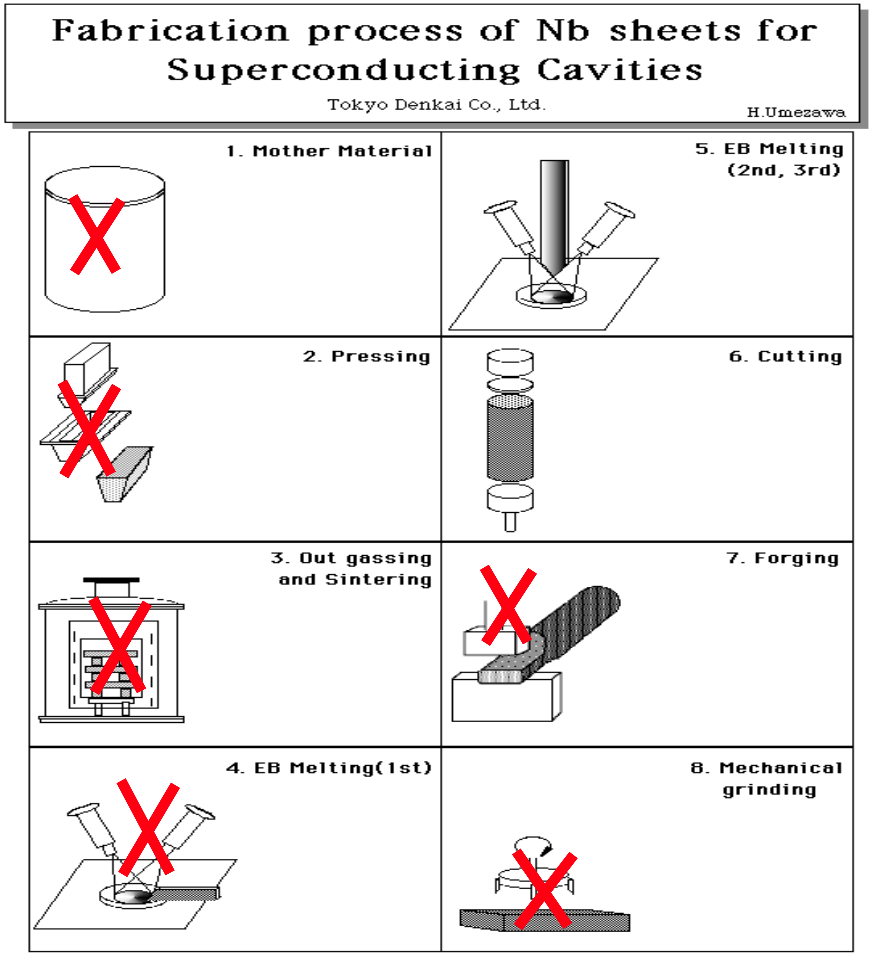
- Present SRF accelerator structures are produced with expensive high purity polycrystalline niobium which has limited availability when multiple SRF linac projects are to be built simultaneously

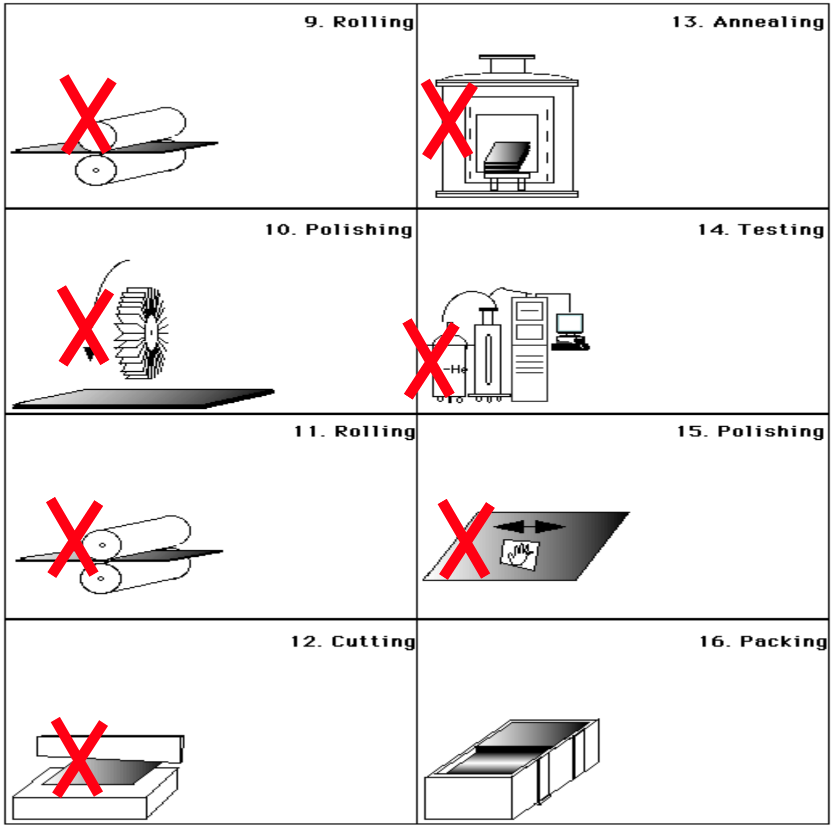
- Additionally the production of these accelerator cavities are based on recipes and yet need to develop scientific understanding for obtaining reproducible performance due to many process steps and complex procedures

- II – VI Corporation, in collaboration with Jefferson Lab & KEK, has embarked on economically producing the required high performance accelerators with simplified & state of the art processes and streamlined procedures

- Such high performance accelerator structures will be based on the ingot niobium technology and they will be very cost effective even when a large number of discovery science programs and new nuclear energy systems based on ADS and MSR's are to be built simultaneously

Economic, efficient and sustainable path for SRF applications
Ingot Niobium Technology





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

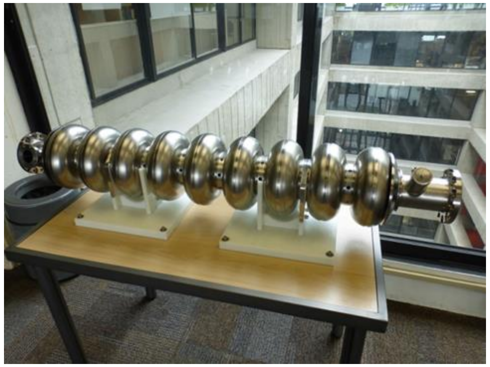
Expected material cost savings up to 75%

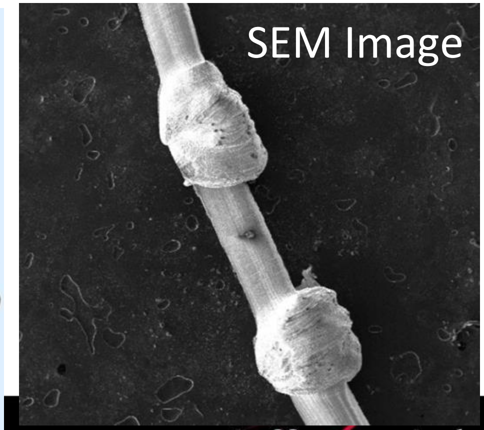
New Simplified Process Steps

- Minimize the process steps
  - 3 D Machining ~ 100 micro meters (II – VI Corporation)
  - Laser welding
  - High pressure ultra pure water rinse/megasonic rinsing
  - RF test

II-VI Infrared Precision Niobium Machining

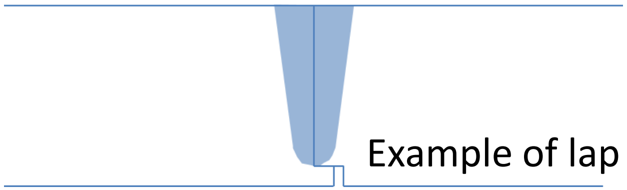
- State of the art diamond turning facility with >20 machines in USA
- Multi-axis diamond machining technology ideal platform for Nb surfacing and shaping
- Hydrostatic B-Axis provides 3D machining for dumb-bell geometry
- High torque air bearing spindle can be retrofitted for stiffness if needed
- Flood coolant compatible machines available if needed
- Room temperature trials show that Nb will stick to the cutting tool
- Machine modifications added to enable cryo-cooling of Nb and tool
- Technology improvements identified to improve surface roughness





II-VI Infrared Laser Processing

- **II-VI Highyag located in Berlin, Germany is a market leader in the manufacture of 1 micron laser cutting and welding heads**
- **Partnering with US based System Integrator, II-VI will develop and own processes to provide reliable weld quality**
- **Laser Beam welding**
  - Faster than EB welding
  - Full penetration of shell thickness possible Partial penetration also available -- full penetration weld from OD would likely cause splatter inside dumb-bell
  - Laser welding from inside dumb-bell is achievable if necessary
  - Lap weld could yield high quality with gap as small as 20 microns
  - Impact of shielding gas and atmosphere on Nb oxidation and contamination to be evaluated



Example of lap welding

Summary

- JLab, KEK and RRCAT-India have relaxed tantalum specifications to ~ 1300 wt. ppm and also lowered the RRR (100 – 250)
- Ingot niobium SRF accelerator structures are not prone to flux trapping in comparison to high purity polycrystalline niobium cavities of today
- II-VI is a global manufacturer with extensive experience in setting up facilities in the USA & around the world and has embarked on producing economic & efficient accelerator structures in collaboration with KEK and JLab