CAVITY FABRICATION

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Thomas Jefferson National Accelerator Facility
Outline

• Nb production for SRF cavities fabrication

• Standard cavity fabrication:
  – Deep drawing
  – Electron beam welding

• Cavity fabrication R&D:
  – Large-grain/single crystal Nb
  – Hydroforming
  – Spinning
• Niobium is the material of choice to fabricate SRF cavities:
  – High critical temperature ($T_c = 9.25K$)
  – High critical field ($H_c(0K) \approx 200mT$)
  – Chemically inert (surface covered by oxide layer)
  – Easily machined and deep drawn
  – Available as bulk and sheet material in any size
Niobium, Brief History

- Named after *Niobe* (daughter of Tantalus, Greek mythology)

- Discovered in 1801 by Charles Hatchett in England from a columbite ore from Connecticut. He called it *Columbium*
Niobium, Brief History

• It was confused with tantalum until 1846, when it was re-discovered by Heinrich Rose and Jean Charles Galissard de Marignac, who called it Niobium

• “Niobium” was officially adopted as the name for the element 41 in 1950

• It was found to be a superconductor (zero electrical resistance) in the 1920s
Niobium Production

Niobium is mostly obtained from mineral known as **pyrochlore** (NaCaNb$_2$O$_6$F). The pyrochlore mineral is processed to give a concentrate ranging from 55 to about 60% niobium oxide (Brazil, CBMM).

**Columbite** ((Fe, Mn)(Nb,Ta)$_2$O$_6$), a mineral with a ratio of Nb$_2$O$_5$:Ta$_2$O$_5$ ranging from 10:1 to 13:1, occurs in Brazil, Nigeria, and Australia, also other countries in central Africa. Niobium is recovered when the ores are processed for tantalum.
The world's largest niobium deposits are located in Araxá, Brazil owned by Companhia Brasileira de Metalurgia e Mineração (CBMM). The reserves are enough to supply current world demand for about 500 years, about 460 million tons. The mining of weathered ore, running between 2.5 and 3.0% $\text{Nb}_2\text{O}_5$, is carried out by open pit mining without the need for drilling and explosives. Approximately 85 to 90% of the niobium industry obtains its niobium ores.
Niobium Processing Plant

• CBMM Plant

• CBMM hosted the International Workshop on Single Crystal Niobium Technology in 2006
Nb Production (CBMM)

- Niobium Ore in Araxa mine (open air pit) is pyrochlor with 2.5% Nb₂O₅
- The ore is crushed and magnetite is magnetically separated from the pyrochlor.
- By chemical processes the ore is concentrated in Nb contents (50 –60 % of Nb₂O₅)
- A mixture of Nb₂O₅ and aluminum powder is being reacted to reduce the oxide to Nb
- This Nb is the feedstock for the EBM processes

Fig. 3: Production flow chart at CBMM.

Jefferson Lab
Thomas Jefferson National Accelerator Facility
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Electron Beam Melting

- Molten metal globules fall into a pool on the ingot which is contained in a water cooled copper cylinder (sleeve).
- Impurities are evaporated and pumped away.
- The pool is molten out to within a few mm of the crucible wall.
- During melting the ingot formed is continuously withdrawn through the sleeve.
- The rate of withdrawal has to be carefully coordinated with the rate of the material to insure complete melting of the feed material and proper outgassing.

Electron beam melting of Nb
Electron Beam Melting

• As a result of the increasing demand for refractory metals in the last few decades, the electron-beam furnace has been developed to a reliable, efficient apparatus for melting and purification.

• There are several companies, which can produce high purity refractory metals in larger quantities: WahChang (USA), Cabot (USA), W.C.Heraeus (Germany), Tokyo Denkai (Japan), OTIC (China), CBMM (Brasil), H.C. Starck (Germany, USA)
Electron Beam Refining Furnace

Furnace “S10” at ATI Wah Chang

- 4 900 mm diffusion pumps
- 200,000 l/sec
- $10^{-4}$ Torr
- 2,250 kW
- 3 EB guns
- Crucible diameter: 25-48 cm
- Ingot length: 2.9 m
• The heating temperature is a compromise between the maximization of purification and minimization of the material losses by evaporation.
• RRR=300-500 are reachable currently.
 Nb EB Refining

- One problem sometimes observed with e-beam melted ingots is the nonhomogeneous distribution of impurities.
- The skin of the ingot has been found to contain more impurities than the inside.
- Top to bottom inhomogeneity has also been observed. The first part of the melt which usually ends up at the bottom getters impurities in the early stages of the melt.
- Machining away the skin and cutting away a short section from the bottom are recommended for a purer final product.
Niobium Ingot

Crucibles

Intermediate Ingot

2.75 m
35 cm
Fabrication of Fine-Grain Nb Sheets

1. Mother Material
2. Pressing
3. Outgassing and Sintering
4. EB Melting (1st)
5. EB Melting (2nd, 3rd)
6. Cutting
7. Forging
8. Mechanical grinding
9. Rolling
10. Polishing
11. Rolling
12. Cutting
13. Annealing
14. Testing
15. Polishing
16. Packing
Forging

2000 ton open die forge (Wah Chang)
Rolling

700 mm wide cold rolling mill (Wah Chang)

800 mm wide hot rolling mill (Wah Chang)

Hot rolling, used mainly to produce sheet metal is when industrial metal is passed or deformed between a set of work rolls and the temperature of the metal is generally above its recrystallization temperature. Cold rolling takes place below recrystallization temperature.
Damage Layer by Rolling

Finite element simulation of 2% reduction of 3.5 mm sheet with 1 cm diameter rolls. Strain is concentrated in the near-surface region.

As-received RRR Nb Sheet, 20 μm below surface (ion milled thin foil)

High dislocation density.

Transmission electron microscopy image (BFTEM)
Annealing: recrystallization

Choosing the proper annealing conditions is important to produce the correct grain size near 100% recrystallization and keep the highest possible purity (RRR).

**Recovery**: removing point defects, decrease and change direction of dislocations

**Recrystallization**: nucleation of new grains and growing of new crystals

**Grain growth**: increase in grain size
Recrystallization

- deformation > 65% =>
  - uniform nucleation
  - small grains
- if purity ↑, T_{recryst} ↓
  - RRR ≤ 100 => T_{recryst} ≥ 900°C
  - RRR 300 => T_{recryst} ~ 800°C
  - RRR 400 => T_{recryst} ~ 750°C?

Recrystallization

We need recrystallized material

Not completely recrystallized Nb

Completely recrystallized Nb
Recrystallization

The grain structure influences the formability

Therefore the yield strength, $\sigma_{0.2}$ is specified for XFEL as

$50 < \sigma_{0.2} < 100$ N/mm$^2$ (Mpa)
Nb Mechanical Properties at Low T

- Yield strength ↑↑ when T ↓
- Ductility ↓ (T < 20 K => Nb is brittle)
# Nb Sheets: Technical Specifications

<table>
<thead>
<tr>
<th>Concentration of impurities in wt.ppm</th>
<th>Mechanical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ta* ≤ 500</td>
<td>Yield strength**, ( \sigma_{0.2} )</td>
</tr>
<tr>
<td>W* ≤ 70</td>
<td>Tensile strength**</td>
</tr>
<tr>
<td>Ti* ≤ 50</td>
<td>Elongation at break**</td>
</tr>
<tr>
<td>Fe* ≤ 30</td>
<td>Vickers hardness**, HV 10</td>
</tr>
<tr>
<td>Mo* ≤ 50</td>
<td>Absence of foreign material inclusions*</td>
</tr>
<tr>
<td>Ni* ≤ 30</td>
<td>Texture *, **</td>
</tr>
</tbody>
</table>

* - relevant for performance
** - relevant for successful fabrication

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* - relevant for performance
** - relevant for successful fabrication
Nb Sheets Quality Control

RRR measurement

Tensile test

Gas analysis

Tokyo Denkay (Japan)

Gas analysis (Hydrogen, Oxygen, Nitrogen) : HORIBA
Nb Purity: RRR

Electrical resistivity of metals at low temperatures is related to the impurity concentrations. The residual resistivity at T=0K is caused mainly by scattering of electrons by impurities.

**Residual Resistivity Ratio:**

\[
RRR = \frac{\rho(295K)}{\rho(4.2K)}
\]

\[
\rho(T) = \rho_{res} + \rho_{ideal}(T)
\]
RRR Measurement

Temperature dependence of resistivity for superconducting Nb at temperatures close to Tc

DC method: extrapolation of U(T) curve

RRR determination by magnetic field extrapolation method
Influence of Impurities on RRR

Contribution of different defects in the scattering mechanism:

\[
RRR = \frac{\rho(300K)}{\rho_{\text{ideal}}(4.2K) + \sum_i \frac{\partial \rho_i}{\partial C_i} C_i}
\]

\[\rho(300K) = 14.6 \ \mu\Omega \ \text{cm}\]

\[RRR_{\text{ideal}} \approx 35,000\]

Relationship between RRR and nonmetallic impurities measured by Tokyo Denkai

Expected RRR contribution for Nb for 1 wt ppm of impurities

<table>
<thead>
<tr>
<th>Element</th>
<th>RRR</th>
<th>Element</th>
<th>RRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>2640</td>
<td>Zr</td>
<td>102 000–239 000</td>
</tr>
<tr>
<td>N</td>
<td>4230</td>
<td>Hf</td>
<td>200 000</td>
</tr>
<tr>
<td>C</td>
<td>4380</td>
<td>W</td>
<td>262 000–721 000</td>
</tr>
<tr>
<td>O</td>
<td>5580</td>
<td>Mo</td>
<td>717 000</td>
</tr>
<tr>
<td>Ti</td>
<td>53 700</td>
<td>Ta</td>
<td>1 140 000</td>
</tr>
</tbody>
</table>
Nb Thermal Conductivity

Rule of thumb:
\[ \lambda(4.2\text{K}) = C \cdot \text{RRR} \]
\[ C \sim 0.25 \text{ W/(m K)} \]
Nb Thermal Conductivity

Phonon peak is clearly observed for single crystals/large grain samples.

\[ \lambda(T, RRRG) = R(y) \left[ \frac{\rho_{29K}}{L \cdot RRR T} + a \cdot T^2 \right]^{-1} + \left[ \frac{1}{D \cdot \exp(y) \cdot T^2} + \frac{1}{B \cdot G \cdot T^3} \right]^{-1} \]

Electron term

Lattice term

\[ y = \frac{\Delta}{k_B T} \]

\[ R(y) = \frac{\lambda_{es}}{\lambda_{en}} \]

\[ L \approx 2.45 \times 10^{-8} \text{ W/K}^2 \]

\[ G: \text{phonon mean free path} \sim \text{grain size} \]
Texture

Microstructure of the three grains of Nb after proper etching (optical microscope). The crystal lattice in neighboring grains is the same (bcc) but has a different orientation.

Niobium sheet after annealing. Colors refers to crystal orientations (orientation image).
Price

- High RRR Nb (RRR ~ 300): ~ $ 530/kg
- Reactor grade Nb (RRR ~ 30): ~ $ 130/kg
Quality Control of Nb Sheets

DESY eddy current scanning apparatus for niobium discs. 100% Nb sheets for TTF scanned and sorted out. Feedback to manufacturer was very important.

Principle of eddy current measurement
Defects in Nb Sheets

Iron particles, probably imbedded during rolling T17

Iron signal distribution in one of the locations of the Nb sheet T17 measured Synchrotron Radiation Fluorescence Analysis (SURFA) and defects image.
Feedback Example: Final Rolling

Example of the feedback to companies: Tokyo Denkai improved the cleanliness around of the rolling equipment
Overview of Cavity Components (ILC)

Cavity
(9 cell TTF/XFEL/ILC design)

Dumb-bell

End group 1

End group 2

HOM - Koppler
kurze Seite

HOM - Koppler
lange Seite

Flansch (Endflansch)

Antennenflansch NW 12
HOM - Koppler DESY

End - kurz - lang

Formteil F

Antennenstutzen lang

Flansch (end - kurz - lang)

HOM - Koppler lange Seite

Formteil F

Endrohr lang

HOM - Koppler
kurze Seite

Hauptkoppler - stutzen

Endrohr kurz

Cavity

Normalhalblelle Nb - Blech

Normalhalelle Nb - Blech

Dumb - bell

Overview of Cavity Components (ILC)
Dumb-bell Fabrication

1. Deep drawing
2. Mechanical measurement
3. Cleaning (by ultra sonic cleaning + rinsing)
4. Trimming of iris region and reshaping of cups if needed
5. Cleaning
6. RF measurement of cups
7. Buffered chemical polishing + Rinsing (for welding of Iris)
8. Welding of Iris
9. Welding of stiffening rings
10. Mechanical measurement of dumb-bells
11. Reshaping of dumb-bell if needed
12. Cleaning
13. RF measurement of dumb-bell
14. Trimming of dumb-bells (Equator regions)
15. Cleaning
16. Intermediate chemical etching (BCP, 20-40 µm) + Rinsing
17. Visual Inspection of the inner surface of the dumb-bell, local grinding if needed + (second chemical treatment + inspection)

Dumb-bell ready for cavity
Deep Drawing

- Deep drawing with hydraulic press
  - 100 tons + 25 tons for iris coining for 10.25” discs (ILC)
  - 400 tons + 50 tons for iris coining for 15.5-16.5” discs (SNS)
Deep Drawing
Shape Measurement

Shape accuracy: optical and mechanical 3D measurement of the half cell shape
Mechanical grinding of visible local defects with aluminum oxide grinding discs
RF Measurements of Dumb-bells and Middle-Cups

Measure frequency and length to determine how much to trim at the equator to obtain target frequency and length of the cavity fully welded.
Cavity Parts

- Welding sequence:
  - Two cups form a dumb bell
  - Stiffening ring at iris
  - Welding together two dumb-bells
  - Add next dumb bell
  - Add end group
  - For mass production: weld all dumb bells at once
Cavity Welding Preparation Steps

1. Degreasing and rinsing of parts
2. Drying under clean condition
3. Chemical etching at the welding area (Equator)
4. Careful and intensive rinsing with ultra pure water
5. Dry under clean conditions
6. Install parts to fixture under clean conditions
7. Install parts into electron beam (eb) welding chamber
   (no contamination on the weld area allowed)
8. Pump down to vacuum in the EBW chamber E^{-5} mbar
9. Welding and cool down of Nb to T < 150° C, venting
10. Leak check of weld
Electron Beam Welding

- Welding under good vacuum, $10^{-5}$ mbar range
- Broad welding seam
  - Operate with defocussed beam
  - Smooth underbead
- Overlap at end of welding to avoid accumulation of impurities
- Wait to cool down before opening chamber
Electron Beam Welding

Rhombic raster pattern for the beam during EBW. This rastering produces a well-defined and reproducibly defocused beam.

Welding Scheme (circular raster)
1-Electron beam (P₀-power of the beam, r-spot radius on the surface, L-scanning amplitude, V-velocity of the beam movement)
2-Nb sheet
3-melting zone (z-depth of the melting zone).
Microstructure of Nb EBW Joint

Microstructure of the EB welding area. The grain size is 50 ÷ 2000 µm
EBW Machine (JLab)

- **Tack- Welding:** 4 tacks, focused beam
- **Voltage:** 50 kV
- **Current:** 15 mA
- **Rotational Speed:** 20 inches/min
- **Distance of gun to work:** 6"
- **Final weld Current:** 33 mA
- **Rotational speed:** 18”/min
- **Focussing:** elliptical pattern
**EBW Machine (DESY)**

**Specification of DESY Electron Beam Welding Machine**

- **Voltage**: 70 - 150 kV
- **Beam power**: max. 15 kW
- **Beam current**: 0 bis 100 mA

  Chamber size: 3300mm x 1400mm x 1600mm (ca. 7.4 m³)

- **Vacuum**: > 5x10⁻⁶ mbar (ca. 2x10⁻⁸ mbar)
- **Pumping time**: ca. 20 min =3x10⁻⁶ mbar
- **2 Cryogenic - Pumps**: ca. 2 x 10,000 l/s
- **Displacement along the X-Axes**: ca. 1400 mm
The RRR degradation at welding seam started since pressure of ca. $10^{-5}$ mbar.

RRR in the welding seam versus pressure in the welding chamber.
RRR Variation After EBW

RRR in the EB welding area versus distance from the welding seam at different pressures of DESY EBW facility

The RRR degradation can take place in the welding seam itself, but also in the thermally affected area and overlapping region.
RRR Variation After EBW

- Water decomposition during welding
- Hydrogen from water and due to degassing
- Oxygen uptake

Partial pressure in the EB chamber during welding of Nb300 sample
RRR Variation After EBW

Absorption of hydrogen can take place at the area with moderate temperatures.

Comparison of RRR and hydrogen content in welding area (pressure $2.3 \times 10^{-8}$ mbar)
Nb Contamination After EBW

Where the carbon come from?
- Diffusion pump
- Dirty EB chamber
- Not sufficient cleaning prior to weld…

Surface inclusion (mainly carbon) found in the sample extracted from one of XFEL prototype cavity
Nb Contamination After EBW

Example Fe (iron)

Where the Iron come from?

- Nb sheet fabrication
- Deep drawing
- Handling

Clean conditions are essential

Surface inclusion (mainly iron) found in the sample extracted from one of XFEL prototype cavity
Welded Cavity Parts
Welded Cavity Parts
Cavity Inspection

- Check of all mechanical tolerances
  - Take care with sealing surfaces
- Inspection of inner cavity surface
- Measure and adjust frequency and electrical field profile
Cavity Tuning

Set-up for field profile measurements: a metallic needle is perturbing the RF fields while it is pulled through the cavity along its axis; the stored energy in each cell is recorded.
Cavity Tuning

- Small mechanical adjustments to the cavity’s cells to obtain flat field profile and desired frequency
Cavity Tuning

Computerized tuning machine at DESY

- Equalizing stored energy in each cell by squeezing or pulling
- Straightening of cavity
Industrialization of Cavity Fabrication

Engineering Data Management System at DESY
Low-\(\beta\) Cavity Fabrication

Cavity components prior to EBW (AES)

The ANL 345 MHz Triple-spoke cavities
Low-\( \beta \) Cavity Fabrication

- Work out frequency tuning sequence to arrive at final frequency – build into parts initial sizing
- Plastic deformation can be used after manufacture to achieve the final frequency
- Somewhat risky in jacketed cavity since pressure is put on the welds
- Flexible tuning plate can be deformed safely over some limited range without risk to cavity
Cavity Fabrication R&D

- Large-grain/Single-crystal cavities
- Hydroforming
- Spinning
Large-Grain Nb

CBMM Large-grain Nb disc
RRR value: ~300
Ta content: ~500 ppm
Large-Grain/Single-Crystal Nb Advantages

- Cost effective
- Reduced risk of contamination during sheet fabrication
- Simplified quality control
- Higher thermal conductivity at low temperatures (phonon peak)
- Smooth surfaces, comparable to EP, can be achieved by standard BCP
- Baking at 120°C works to reach high-fields
Material Suppliers

- **Fine-Grain:**
  - Tokyo Denkay (Japan)
  - ATI Wah Chang (USA)

- **Large-Grain:**
  - Tokyo Denkay (Japan)
  - ATI Wah Chang (USA)
  - OTIC (China)
  - CBMM (Brazil)
  - WC Heraeus (Germany)
Ingot Slicing

Successfully Multi-sliced 59 sheets (3.2t) from 201 mm long Nb Ingot

- Wire EDM (slow)
- Diamond saw
- Multi-wire

Large-grain Nb sheets are available up to 18” diameter
Deep Drawing Large-Grain Nb

- Non-uniformity in the equator area
- Visible steps at grain boundaries
- Thinning at iris region if there is no large single crystal at the center
Large-Grain Nb Cavity Fabrication

- Same procedures as fine-grain Nb
- Assembly for equator welds a bit more complicated as cells are not as round as fine grain cells
Large-Grain Single-Cell Studies

OTIC, RRR ~ 330

\[ \langle B_p \rangle = 141 \text{ mT} \pm 10\% \]

WC Heraeus, RRR ~ 500

\[ \langle B_p \rangle = 147 \text{ mT} \pm 13\% \]

CBMM, RRR ~ 280
Large-Grain 9-Cell Results

- 11 Large-Grain 9-cell cavities at RI from Heraeus material

After 120 μm BCP & baking

After additional EP & baking
Single-Crystal Nb Cavity Fabrication

1. Take out central single crystal of definite thickness
2. Cutting through the disc
3. Increasing of diameter by special rolling with an intermediate annealing
4. Deep drawing
5. EB welding by matching the crystal orientation

Single Crystal Cavities with three different crystal orientation
### Single-Crystal Nb Cavity Results

<table>
<thead>
<tr>
<th>Cavity #</th>
<th>$E_{\text{acc, max}}$ (MV/m)</th>
<th>$B_{\text{peak, max}}$ (mT)</th>
<th>$Q_0(B_{\text{peak, max}})$</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38</td>
<td>162</td>
<td>$4 \times 10^9$</td>
<td>200μm BCP, 800°C 3h, HPR, 120°C 48h</td>
</tr>
<tr>
<td>2</td>
<td>45</td>
<td>160</td>
<td>$7 \times 10^9$</td>
<td>200μm BCP, 800°C 3h, HPR, 120°C 24h</td>
</tr>
<tr>
<td>3 (1AC6)</td>
<td>41</td>
<td>177</td>
<td>$1.2 \times 10^{10}$</td>
<td>250μm BCP, 750°C 2h, 120μm EP, HPR, 135°C 12h</td>
</tr>
<tr>
<td>4 (1AC8)</td>
<td>38.9</td>
<td>168</td>
<td>$1.8 \times 10^{10}$</td>
<td>216μm BCP, 600°C 10h, HPR, 120°C 12h</td>
</tr>
<tr>
<td>5</td>
<td>38.5</td>
<td>166</td>
<td>$7.6 \times 10^9$</td>
<td>170μm BCP, HPR, 120°C 12h</td>
</tr>
</tbody>
</table>
Single-Crystal Nb Cavities

- Scaled Low Loss shape
- Scaled High Gradient shape

$T = 2 \text{ K}$

$B_{p,max} = 160 \text{ mT}$

$B_{p,max} = 150 \text{ mT}$
Seamless Cavities

- Eliminate equator welds and associated problems
- Cost effective

- Hydroforming
- Spinning

Example of welding connection of EP treated cavity. Up to 75 µm steps
Hydroforming

- Tube of intermediate diameter between iris and equator
- Necking to form iris area
- Hydroforming (hydraulic expansion)
Tube Forming: Fine-Grain Nb

Flow forming over a cylindrical mandrel with three work rollers allows to produce long and very precise tubes from thick walled cylindrical part. After optimization of several parameters shiny Nb surface and small wall thickness variations (less than +/-0.1 mm) have been achieved.
Tube Forming: Fine-Grain Nb

- Small and uniform grains
- Elongation at break > 30%
Tube Forming: Single-Crystal Nb

Seamless single-crystal tube by back extrusion

- Welded single-crystal tube:
  - Rolling of single-crystal with intermediate annealing
  - EBW with matching of the orientation
Necking

Principle of diameter reduction in the tube end and in the tube middle.
Hydroforming

Relies on the correct relationship between applied internal pressure and axial displacement (strain rate) to remain below the plastic limit.
Hydroforming

DESY hydroforming machine
Hydroforming: Cavity Results

Hydroformed single cell Nb cavity 1K2

Hydroformed 9-cell cavity Z145

1K2, Nb100 Heraeus, HT1400°C, BCP 250 μm, EP 100μm

EP170μm; 800°C, 2h; EP48μm add. baking 120°C, 48 h
Spinning

- Starting from discs or seamless tubes
- Collapsible mandrels
- Very rough surface after fabrication
Spinning

The problem of excessive thinning at the terminal iris
Spinning: Cavity Test Results

1.3 GHz single-cell cavity

1.3 GHz 9-cell cavity. Damaged after CBP, no test
Spinning: Cheap Sample Cavities

6 GHz
Nb/Cu Clad Material

**Advantages**

- cost effective: allows saving a lot of Nb (ca. 4 mm cavity wall has only ca. 1 mm of Nb and 3 mm Cu). Especially significant for large projects like ILC
- bulk Nb microstructure and properties (the competing sputtering technique does not have such advantages)
- the treatment of the bulk Nb BCP, EP, annealing at 800°C, bake out at 150°C, HPR, HPP can be applied (excluding only post purification at 1400°C).
- high thermal conductivity of Cu helps for thermal stabilization
- stiffening against Lorentz - force detuning and microphonics can be easily done by increasing of the thickness of Cu layer.
- fabrication by seamless technique allows elimination of the critical for the performance welds especially on equator
Nb/Cu Clad Cavity Fabrication

• Nb/Cu laminated material is formed into a tube by:
  – Explosion bonding
  – Back extrusion
  – Hot bonding

• Nb/Cu clad cavity if formed from the tube by hydroforming

• Beam tubes/End groups are welded to the thin Nb layer by EBW. The Cu backing must be removed and cleaned at the weld joints
Nb/Cu Tubes: Explosion Bonding

- Explosion bonding of seamless Nb tube 4 mm thick with Cu tube 12 mm thick
- Flow forming into Nb/Cu tube, wall thickness 1 mm Nb, 3 mm Cu

The bonding takes place by an explosively driven, high-velocity angular impact of two metal surfaces.
Nb/Cu Clad Cavities

NbCu single cell cavity 1NC2 produced at DESY by hydroforming from explosively bonded tube. Preparation and HF tests at Jeff. Lab: 180 µm BCP, annealing at 800°C, baking at 140°C for 30 hours, HPR (P. Kneisel).

40 MV/m without EP

W. Singer SRF 2005

NbCu cavities hydroformed from explosively bonded tubes at DESY.

Difficult to get reproducibly high bonding quality. Hot bonding fabrication procedure of NbCu tubes seems to be more promising.
Nb/Cu Tubes: Hot Bonding

Fabrication principle of sandwiched hot rolled Cu-Nb-Cu tube (KEK and Nippon Steel Co.)

Hot roll bonded Cu-Nb-Cu tube produced at Nippon Steel Co.
**Nb/Cu Clad Cavities**

Single-cell Nb/Cu cavities from “sandwiched” tube

Four double cell NbCu clad cavities produced at DESY from KEK tubes (no cracks on the inside surface)

Hot roll bonded tube fabrication at Nippon Steel Co., hydroforming at DESY, Preparation and RF tests at KEK

**NSC-3 Cavity (Nb/Cu Clad)**

NSC-3: Barrel polishing, CP(10 μm), Annealing 750°C x 3h, EP(70 μm) K. Saito
Nb/Cu Clad Cavities Issues

- Possibility of leaky welds because of Cu contamination
- Nb/Cu cavities still quench, resulting in Q-degradations
- Cooldown needs to be very uniform because of thermo–currents
- Cooldown of cryomodules would need modification
- Cracks sometimes appear in iris region during fabrication