WG5 Superconducting cavities and couplers

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4 Processing & Testing

General Requirements - Overview

The preparation of the cavities should finally result in fully assembled cavities (incl. power coupler) which are ready for string assembly. After delivery from the welder, several things are to be done:

a) Leak check, mechanical checks, inspection
b) Frequency tuning
c) Cleaning
d) Damage layer removal
e) Furnace treatments
f) Final frequency tuning
g) Final surface preparation
h) Final cleaning
i) Bake-out at 120-130°C
j) Low-power acceptance test
k) Tank-welding
l) Assembly for high power operation
m) High-power test

Although all these steps need improvements in QA/QC for a mass production, the most challenging one is to define final (electro-)chemical surface preparation to deliver a reliable and reproducible performance. Today, highest cavity performance has been achieved with electropolishing as main damage layer removal and final surface preparation.

Therefore the **BCD recommendation** for this process is:

- Electropolishing for damage layer removal (~120-150 μm)
- 800°C furnace treatment
- Electropolishing for final preparation (~20-50 μm)
- High pressure rinsing for final cleaning

There is no data on multi-cell cavities which suggests that this procedure can be avoided. Initial results on single-cell cavities with other material (see section Materials R&D) need to be confirmed by multi-cell R&D.

The major risk in the cavity preparation is the contamination of the inner cavity surface which will then lead to enhanced field emission and to performance degradation. In most series productions of cavities field emission is the reason for performance limitation. Therefore, it is highly desirable to further improve quality control of the processes applied to the cavity. Moreover, any development on cavity shapes with an increased ratio of electric surface peak field to accelerating gradient (E_{peak}/E_{acc}) requires a continuing effort to reduce field emission.

Quite some experience has been accumulated on cavity preparation systems. Still, most of the facilities in operation are laboratory scale systems. Most of them differ from each other in more or less obvious ways. The R&D on the cavity preparation should result finally in improved preparation facilities of a second generation which are designed for improved quality control.

There are three main areas in the cavity preparation process where a strong R&D plan is needed:

- **Electropolishing (EP) system**: A generic parameter set for niobium cavity EP was developed at KEK. So far the experience on multi-cell cavities is not as reproducible as desired. Several improvements are suggested.
    - Improved parameter control:
        - Development of efficient heat exchangers to improve temperature stability
        - Compensation for losses of hydrofluouric acid (HF) from evaporation and chemical reaction with the niobium by actively adding HF during the process.
        - Optimization of the current distribution for homogenous material removal
    - Contamination control:
        - Avoidance of sulphur by either improved post-EP rinsing methods (e.g. alcohol rinse) or changed EP parameters (e.g. bath composition)
        - Definition of measurement techniques for contamination and quality control (e.g. Nb and HF content of the electrolyte)
    - Quality control
        - Development of a roughness measurement of the inner cavity surface as it might be insufficient to look at witness samples

- **High pressure rinsing (HPR)**: Currently, the rinse of cavities with high pressure water is the only effective means of removing particles from the cavity inside. Still, further R&D is required to reduce performance spread and increase the onset level field emission.
    - Improved parameter control
        - Optimization of the cleaning force by proper adjustment of
            - Nozzle geometry, material and size.
            - Impact angle and flow rates
    - Contamination control
        - Online particulate monitoring on both the high pressure input side and on the drain water from the cavity
        - Reliable online TOC (total organic carbon) monitoring of input and output water.
        - Understanding of what specification is needed on other contaminants (e.g. dissolved solids).

- **Assembly procedures**: Currently, the assembly and cleaning of components is not streamlined to fit into a mass production environment. To facilitate this some development is needed to simplify procedures and reduce the amount of parts used during assembly. An investigation on improved tooling and (semi-) automation seems necessary.
    - Assembly of components
        - For the quality control of assembly procedures it is desirable to develop a technology to assess particle contaminations of the inner cavity surface.
        - Methods for mass production need to be developed (e.g. cleaning of screws, gaskets etc.)
        - The assembly of the cavity string needs a further improved quality control procedure as it is currently not possible to clean the full string after assembly.
        - The overall workflow during inspection, preparation, assembly and testing needs optimization to avoid contamination and be cost effective.
        -
    - Drying
        - An evaluation on drying procedures after HPR is needed to avoid re-contamination of the surface
        - An integration of the drying with the ‘in-situ’ bake-out seems desirable and should be developed

Without improvements on these critical R&D issues a cost efficient production with a high yield is endangered as too many cavities might not achieve the specified accelerating gradient and quality factor. It is recommended that any new R&D infrastructure for the ILC takes into account the enhanced need for quality control.

The testing sequence during the cavity preparation process must include at least one accelerating mode $Q(E_{acc})$ curve in a low power test potentially using fixed antennas, with many cavities being inserted in vertical test dewars. This procedure would allow to potentially sort cavities during production with some benefit in overall performance.

High-power tests on individual cavities seem to be necessary in an initial production phase where the critical assembly steps (e.g. high-power coupler mounting) are set up and where sub-components are qualified (e.g. tuners).

Full tests on all modules are mandatory in the first phase of the production. When the production process is well enough established, a statistical approach on testing might be feasible as in the linear collider a cool-down of linac sections might be envisaged, so that major problems (e.g. vacuum leaks) could be detected before machine operation starts. A risk analysis of different scenarios by qualified “non-cavity” experts might be desirable.

BCD/ACD List of Recommendations

Brief summary on the discussions at Snowmass

The rest of the document reflects the state of the discussions at Snowmass. The BCD/ACD recommendations have been discussed in the working group and agreed upon. The list of R&D items related is being regarded as the most important ones and should be taken as a starting point for the work on a detailed R&D plan with avoidance of duplication of effort.

So far only the interest of laboratories is identified. This means the names of laboratories reflect that a lab is working or intents to work on a topic. The list makes no attempt whether sufficient funding is available or enough resources are allocated to attack the problems. The level of detail is not yet sufficient to address these issues.

4. a) Mechanical checks, optical inspection

Options under consideration

1. Mechanical measurements (Eccentricity, etc.), Optical inspection (EB welds etc.)
2. Integration of mechanical measurements (Eccentricity, etc.), optical inspection (EB welds etc.) into the cleanroom area

BCD choice

Mechanical measurements (Eccentricity, etc.), Optical inspection (EB welds etc.)

Pros & Cons of BCD (technical, cost, reliability/risk)

Pros

- Concept exists.

Cons

R&D necessary (at different levels)

- Is a roughness measurement of the inner cavity surface needed?
  - If so: At which steps in the preparation process?
- Is it possible to assess the particle contamination of the inner cavity surface?
- Mass production issues need work

ACDs choices prioritized

Priority 1 ACD

Integration of mechanical measurements (Eccentricity, etc.), optical inspection (EB welds etc.) into the cleanroom area

Pros

- Reduction of contaminations of inner cavity surface

Cons

Technical advantages, increased tech potential

Potential cost impacts

- Enlargement of cleanroom facility

Risk and Reliability impacts

R&D necessary (at different levels)

- As above.

Time scales for R&D

4. b) Frequency tuning

- Principle clear.

R&D necessary (at different levels)

- Mass production issues need to be solved.
- Integration into clean room seems desirable (see above).

4. c) Cleaning

- Principle clear.
    - Ultrasound cleaning of components
    - Resistivity rinse with ultra-pure water
    - Ionized nitrogen blowing of components (e.g. screws).

R&D necessary (at different levels)

- Mass production issues need to be solved.
- Is an outside etching of the full cavity required?
- Is hot ultra-pure water rinsing desirable?
- Improved quality control at all levels seems desirable.
- Can the number of parts to be assembled be reduced?

4. d) Damage layer removal (100-150 um)

Options under consideration

1. Electropolishing (EP)
2. Tumbling / Barrel polishing + small (electro-)chemistry
3. Etching (BCP)

BCD choice

Electropolishing

Pros & Cons of BCD (technical, cost, reliability/risk)

Pros

- Only preparation method that has proven gradients of more than 35 MV/m on multi-cell cavities.

Cons

- Potential of hydrogen contamination of the niobium material.
- Slower material removal rate than BCP.
- Up to now process seems to be more manpower intensive than BCP or tumbling (more sophisticated assembly to setup).
- Safety issues related to strong acids.

Potential Mods to BCD with impact (tech, cost, difficulity/time scale).

- damage layer removal on cups with EP

R&D necessary (at different levels)

- Reproducibility of the process needs improvement.
    - Control of HF concentrations during processing e.g. to avoid sulphur contamination and compensate the loss of HF due to evaporation
        - Sample measurements exist (Saclay)
        - Automated addition of HF during process with relation to current density monitor (Jlab)
        - Monitor the current density, improved heat exchanger, addition of HF (DESY)
    - Control of Nb content during processing other contaminants?
        - Some sample measurements exist (Saclay, KEK)
        - On EP system
            - Calculated (KEK,JLAB,DESY)
            - Measurement (online, offline)
    - Monitoring removal rate
        - Online (Cornell ?)
        - Offline:
            - Witness Samples (DESY,JLAB)
            - Weight (KEK,JLAB,DESY)
            - Ultrasonic (KEK,CORNELL, JLAB, DESY)
    - Are we working in the right part of the I-V curve?
        - Dc (DESY, KEK, JLAB)
            - Voltage control (DESY,KEK,JLAB)
            - Current (JLAB, HENKEL)

            - Feedback (INFN Legnaro)
        - pulsed
    - Can we get the right current distributions for uniform etching?
        - Measurement off the removal dependent on position, then calculate (KEK)
        - Grooved in equator region (JLAB bench)
        - Software for calculation (DESY)
        - Fluxgate magnetometer (INFN Legnaro)
    - Measure surface roughness as process QA - can we do it?
        - Witness samples might be insufficient
        - Measure inside the cavity ?????
        - Gloss measurement at Saclay??
    - Orientation
        - Horizontal (KEK,DESY,JLAB, HENKEL, INFN)
        - Vertical (CORNELL)
    - Other acid compositions
        - Increase HF (KEK, Saclay)
        - Buffering
        - Lactic (JLAB, half cells, test bench)
        - add water plus HF (Saclay)
        - Nitric acid (KEK)
    - Develop a technique to EP cavities in helium vessels (understand and minimize voltage drop along cavity)
    - Mass production
        - Quick connect (DESY, JLAB?)
        - Acid recycling (KEK)
            - Cost and environmental issues
    - Determination of optimum post-etching rinse processes
        - Rinse fluid
            - Water (DESY, JLAB, KEK, ….)
            - Hydrogen peroxide (KEK, CORNELL)
            - Ozonated water (KEK)
            - Alcohol (DESY, JLAB?)
        - Duration? Output water quality parameters?
        - Rinse & dump? Steady flow?
    - Post-rinse handling
        - Manipulation
            - Cleaning of the outside of the cavity
                - Ultra-sound (DESY, JLAB?)
                - HPR (KEK)
        - Storage until HPR
            - baseline is to keep it full of water
- Fundamental R&D:
    - Is the smoothness the important parameter for good performance ?
    - If not: Is a long EP (100 um) needed for damage layer removal?
        - If yes: What is the best way to avoid hydrogen contamination?

4. **d) Damage layer removal (100-150 um)**

ACDs choices prioritized

Priority 1 ACD

Tumbling / Barrel polishing + small (electro-)chemistry

Pros

- Simple process.
- Less evironmental impact.

Cons

- Proven for high gradients only for single-cells.

Technical advantages, increased tech potential

Potential cost impacts

- Cost reduction compared to EP seems likely.

Risk and Reliability impacts

R&D necessary (at different levels)

- Removal of abrasive material: BCP or EP?
- Multi-cell issues need to be solved.

Time scales for R&D

e) Furnace treatment

Options under consideration

1. 800°C
2. 1400 °C
3. No furnace

BCD choice

800°C

Pros & Cons of BCD (technical, cost, reliability/risk)

Pros

- 35 MV/m cavity performace has been demonstrated.

Cons

- Cavity results are not yet as reproducible as desired.

Potential cost impact

Potential Mods to BCD with impact (tech, cost, difficulity/time scale).

R&D necessary (at different levels)

- Optimise temperature and duration
- Attach furnaces to cleanroom
- Cavity under separate vacuum

4 e) Furnace treatment

ACDs choices prioritized

Priority 1 ACD
1400° C

Pros

- Higher thermal conductivity of niobium material might improve reproducibility.

Cons

- Cavities become mechanically soft.
- More difficult handling.
- More sophisticated furnaces needed.

Technical advantages, increased tech potential

Potential cost impacts

Risk and Reliability impacts

R&D necessary (at different levels)

- High RRR needed?
  - Check E_{acc}/RRR for many cells
- Can High-RRR sheets be used, if necessary

Time scales for R&D

No Priority ACD
No furnace treatment.

Pros

Cons

- Increased risk of hydrogen contamination.
- Cost reduction marginal

4 f) Final frequency tuning

See 4 b)

4 g) Final surface preparation (20-30um)

Options under consideration
Electropolishing (EP)

BCD choice
Electropolishing

Pros & Cons of BCD (technical, cost, reliability/risk)

Pros

- Only preparation method that has proven gradients of more than 35 MV/m.

Cons

- Potential of hydrogen contamination of the niobium material.

Potential cost impact

Potential Mods to BCD with impact (tech, cost, difficulity/time scale).

R&D necessary (at different levels)

See section 4 d)

4 h) Final cleaning

Options under consideration

1. High-pressure rinsing with ultra-pure water.
2. Dry-ice cleaning

BCD choice

High-pressure rinsing with ultra-pure water.

Pros & Cons of BCD (technical, cost, reliability/risk)

Pros

- Only preparation method that has proven gradients of more than 35 MV/m.

Cons

- Reproducibility for multi-cell cavities needs improvement.

Potential cost impact

Potential Mods to BCD with impact (tech, cost, difficulity/time scale).

R&D necessary (at different levels)

- Improve water quality with additional/better monitoring
  - Particulates
    - Input
      - Online (High Pressure side: Jlab; Low pressure: DESY)
    - Output
      - Online (Jlab?)
      - Offline (DESY)
  - Total organic carbon
    - Need reliable system (Specification? Oil contamination?)
    - Online (High Pressure side: Jlab; Low pressure: DESY)
    - Active carbon filter (KEK)
    - Degassing of oxygen against bacteria (KEK)
    - Sanitizing procedures (1x year JLAB, DESY)
  - Dissolved solids
    - Full water analysis (JLAB 1x year)
  - Resistivity (all)
- Improve cleaning power
  - Optimize nozzle material, geometry, size (JLAB)
  - Optimize flow rates, impact angles (JLAB, INFN Milano)
  - Optimize pressure (JLAB)
  - Investigate electrostatic charging
    - Change of oxide structure, monitoring needed
- Optimize duration of rinse
- Quantify water quality needed

- Post-HPR handling:
  - Drying procedures
    - Laminar flow in clean room (DESY, KEK, JLab)
    - Vacuum (DESY, KEK, JLab)
      - Understanding of the best Vacuum system needed (JLAB ?)
      - Oil-free (DESY)
      - No particulate contamination
    - Hot nitrogen drying (JLAB) (with in-situ bake???)
    - Heating
      - With evacuated cavity (KEK): 'In-situ' bake
      - Air bake (SACLAY)
    - Alcohol rinse
- Storage until test
  - air, vacuum, clean nitrogen, argon, ????
- Assembly
  - Standardisation of cleaning methods for sub-components
  - Cf. Mass production
  - QA of particle counts etc.
  - Main power coupler:
    - Can it be cleaned like the other components (before processing)?
  - Documentation of assembly procedures
  - QA of particle counts etc.
  - Training of people
- Bakeout at ~120° C
  - Optimize low-T bakeout temperature and time (Saclay)
  - Part of the drying process (KEK)
  - Air bakeout (Saclay)
- Backfill
  - Argon
    - Avoid nitride formation during tank welding (DESY)
    - KEK: After RF test only Argon
  - Nitrogen
    - Jlab, DESY (single-cells), CEA ?
    - KEK: Before RF test

ACDs choices prioritized

Priority 1 ACD

Dry-ice cleaning

Pros

- Could be applied in horizontal position.

Cons

- More sophisticated setup.
- Very preliminary results available

Technical advantages, increased tech potential

Potential cost impacts

Risk and Reliability impacts

R&D necessary (at different levels)

- Need Proof-of-Principle on horizontal cleaning process
- Multi-cell issues need to be solved.

Time scales for R&D

4 i) Bake-out at 120 - 130°C

Options under consideration
'In-situ' bakeout of the evacuated cavity
Air bakeout as part of drying process

BCD choice
'In-situ' bakeout of the evacuated cavity

Pros & Cons of BCD (technical, cost, reliability/risk)

Pros
- Process has shown up to 40 MV/m in multi-cell cavities.

Cons

Potential cost impact

Potential Mods to BCD with impact (tech, cost, difficulity/time scale).

R&D necessary (at different levels)
- Optimum bakeout temperature and time need investigation.
  Standard today: 120-135C for 48 hours
- Mass production issues.

ACDs choices prioritized

Priority 1 ACD
Air bakeout as part of drying process
Pros
- Could significantly simplify process.
- Less risk of leaks.

Cons
- Not proven yet.

Technical advantages, increased tech potential
- together with drying after final HPR (vacuum, nitrogen)

Potential cost impacts

Risk and Reliability impacts

R&D necessary (at different levels)
- Single-cell R&D necessary.
- Multi-cell issues need work.

Time scales for R&D