Update Cavity Fabrication Process and Recipe; Redefinition of Production Yield

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Proposed Changes

- Allow second pass re-processing
  - **Replace the RDR "over production" scheme by the "second pass re-processing" scheme**
  - **Why?**
    - One-pass production yield and average gradient too low
    - Lower average gradient leaves smaller gradient margin
    - Lower yield requires at least 25% "over production"
  - **Supporting R&D results**
    - Higher average gradient if second pass re-processing is allowed
    - Hence more gradient margin
    - Significant cost saving (on order of 10-20% in cavity production)
      - See analysis presented at December 2011 TTC meeting
    - More in Camille's talk

Proposed Changes

- Optical inspection of cavity RF surface at key time points: as built and after main EP
- Mechanical polishing to remove defects determined by optical inspection prior to cryogenic RF test
- Why?
  - Fabrication flaw/defect has "permanent" nature and can not be effectively removed by EP
  - Fabrication flaw/defect causes reduced first pass yield as well as second pass yield and average gradient
  - Permanent defects need to removed prior to helium tank welding
- Supporting R&D results
  - Positive correlation between quench & fab defects (sub mm size)
  - Positive experience of quench-causing mechanical flaw by mechanical polishing (CBP or local grinding)

Cavity Production Recipe

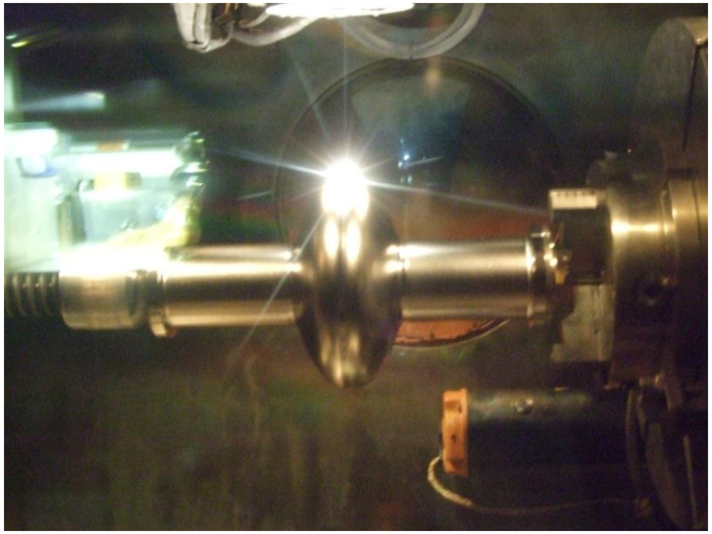
- TESLA cavity shape
  - **Small shape variation can be accepted under the condition of cavity flange design meeting the "plug compatible" requirements**
- 1300 MHz in Pi mode
- 9 cells
- 70 mm aperture
- Antenna-type HOM damper

Cavity Production Recipe

- Cavity cell material and specification
  - **Sheet fine-grain niobium of high purity**
  - **Specification to be compatible with the most recent large-scale (on the order of 100 to 1000 multi-cell cavities) niobium procurements for SRF accelerators**
- Sheet niobium QA/QC
  - **Niobium sheets inspection by eddy current scanning**
  - **Spot checking**

Cavity Production Recipe

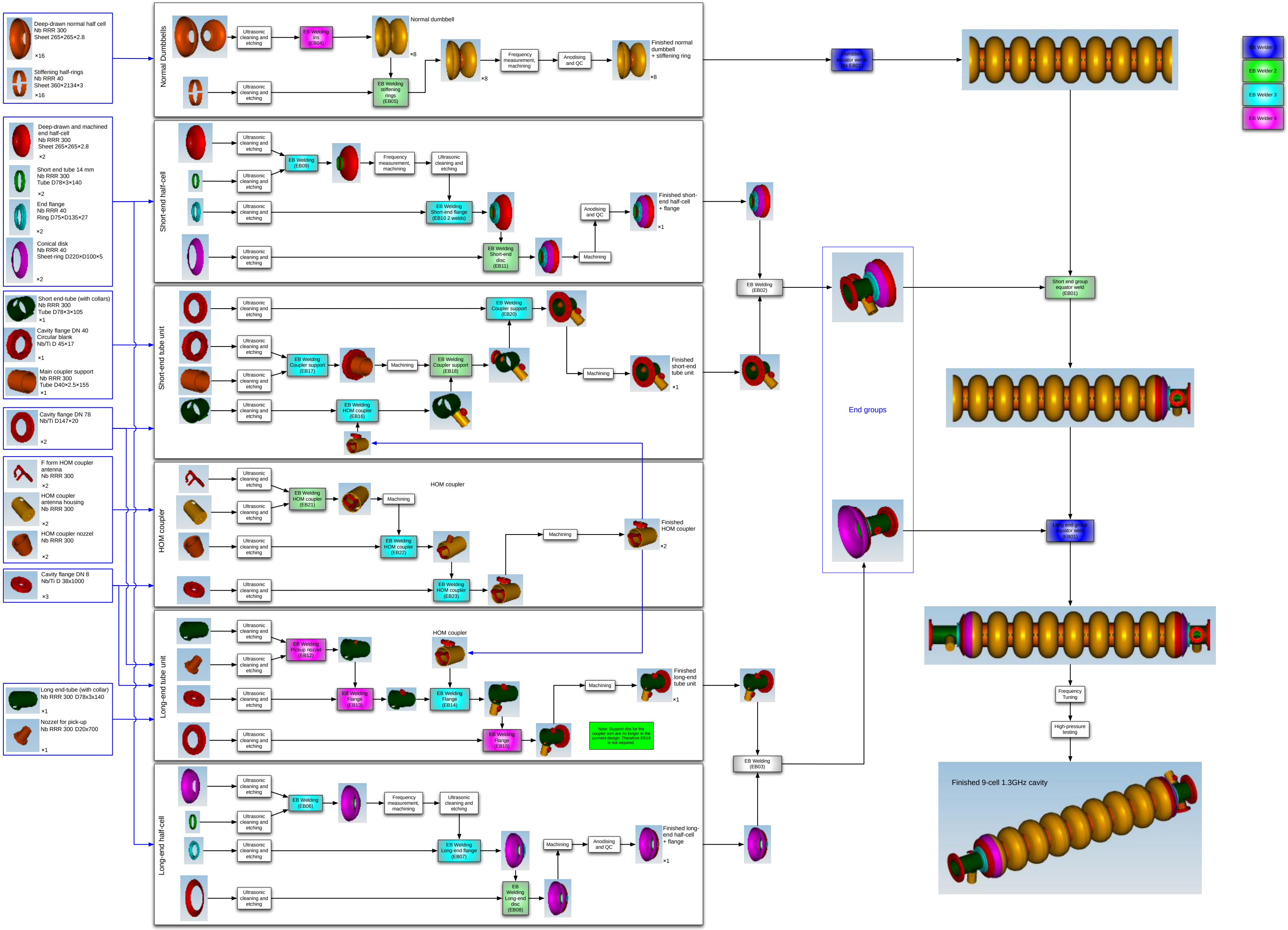
- Cavity fabrication
  - **Center-cell sub-assembly**
    - Sheets forming into cups (deep drawing)
    - Iris weld prep machining
    - Half-cell cleaning and chemical etching
    - Iris EBW
    - Stiffening ring forming
    - Stiffening ring cleaning and etching
    - Stiffening ring EBW
    - Dumb-bell frequency tuning
    - Dumb-bell equator weld prep machining
    - Dumb-bell RF surface QA
    - Dumb-bell weld cleaning and etching
    - Dumb-bell equator EBW



Cavity Production Recipe

- Cavity fabrication
  - **End group sub-assembly (repeated twice)**
    - Sheets forming into cups (deep drawing)
    - Iris weld prep machining
    - End half-cell cleaning and etching
    - End flange and conical disk machining
    - End flange and conical disk cleaning and etching
    - End flange and conical disk EBW
    - End half-cell frequency check and machining
    - End-half cell QA
    - End tube and HOM coupler machining and EBW
    - End half-cell and end tube weld prep cleaning and etching
    - End half-cell and end tube EBW

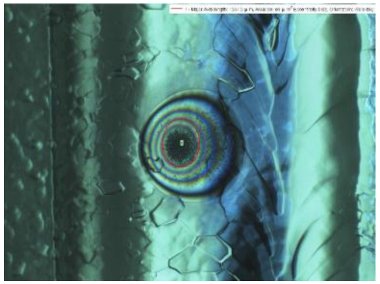
  - **Completed 9-cell cavity with end groups**
    - Weld prep etching
    - Final equator EBW between center-cell sub-assm and end group sub-assm



Deep-drawn normal half cell
Nb RRR 300
Sheet 265×265×2.8
×16
Stiffening half-rings
Nb RRR 40
Sheet 360×2134×3
×16
Normal Dumbbells
Ultrasonic cleaning and etching
EB Welding iris (EB04)
Normal dumbbell
×8
EB Welding stiffening rings (EB05)
Frequency measurement, machining
Anodising and QC
Finished normal dumbbell + stiffening ring
Dumbbell equator welds 8x (EB01)
Deep-drawn and machined end half-cell
Nb RRR 300
Sheet 265×265×2.8
×2
Short end tube 14 mm
Nb RRR 300
Tube D78×3×140
×2
End flange
Nb RRR 40
Ring D75×D135×27
×2
Conical disk
Nb RRR 40
Sheet-ring D220×D100×5
×2
Short-end half-cell
EB Welding (EB09)
Ultrasonic cleaning and etching
EB Welding Short-end flange (EB10 2 welds)
EB Welding Short-end disc (EB11)
Machining
Finished short-end half-cell + flange
×1
EB Welding (EB02)
Short end group equator weld (EB01)
Short end-tube (with collars)
Nb RRR 300
Tube D78×3×105
×1
Cavity flange DN 40
Circular blank
Nb/Ti D 45×17
×1
Main coupler support
Nb RRR 300
Tube D40×2.5×155
×1
Short-end tube unit
EB Welding Coupler support (EB20)
EB Welding Coupler support (EB17)
EB Welding Coupler support (EB18)
EB Welding HOM coupler (EB16)
Finished short-end tube unit
Cavity flange DN 78
Nb/Ti D147×20
×2
End groups
F form HOM coupler antenna
Nb RRR 300
×2
HOM coupler antenna housing
Nb RRR 300
×2
HOM coupler nozzel
Nb RRR 300
×2
HOM coupler
EB Welding HOM coupler (EB21)
EB Welding HOM coupler (EB22)
EB Welding HOM coupler (EB23)
Finished HOM coupler
Cavity flange DN 8
Nb/Ti D 38x1000
×3
Long-end tube unit
EB Welding Pickup nozzel (EB12)
EB Welding Flange (EB13)
EB Welding Flange (EB14)
EB Welding Flange (EB15)
Finished long-end tube unit
Long end-tube (with collar)
Nb RRR 300 D78x3x140
×1
Nozzel for pick-up
Nb RRR 300 D20x700
×1
Long end group equator weld (EB01)
EB Welding (EB03)
Long-end half-cell
EB Welding (EB06)
EB Welding Long-end flange (EB07)
EB Welding Long-end disc (EB08)
Finished long-end half-cell + flange
Frequency Tuning
High-pressure testing
Finished 9-cell 1.3GHz cavity
EB Welder 1
EB Welder 2
EB Welder 3
EB Welder 4

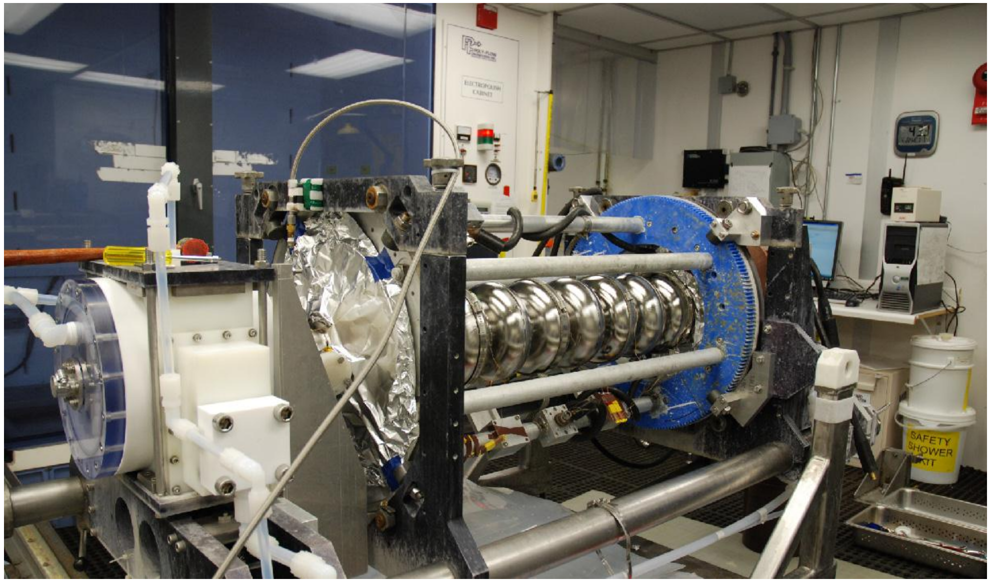
Cavity Production Recipe

- Cavity fabrication
  - **Optical inspection of RF surface of completed cavity**
    - All cavities during initial production; spot checking during full production
    - Cavity with surface defect (sub-mm in size) to be treated by mechanical polishing
  - **Completed cavity mechanical, vacuum and RF inspection**
    - Check for mechanical dimensions
    - Vacuum leak check
    - Tune for RF frequency, field flatness



Cavity Processing Recipe

- Cavity processing
  - **Pre-chemistry**
    - Light Buffered Chemical Polishing (BCP) etching of inner surface (10 µm)
    - No outer surface BCP etching
  - **Main RF surface removal**
    - Inner surface removal by electropolishing (EP) for 120 µm
    - Post-EP low pressure water rinsing, end group wiping, ultrasonic cleaning
    - High pressure water rinse (HPR)
    - Ethanol rinsing
    - Vacuum furnace heat treatment 800 C 2 hour



Cavity Processing Recipe

- Cavity processing
  - **Optical inspection**
    - Cavity with surface defect (sub-mm size) to be treated by mechanical polishing
  - **Tuning for frequency and field flatness (no-touch bead-pull)**
  - **Final RF surface removal**
    - Inner surface removal by EP 25 µm
    - Post-EP low pressure water rinsing, end group wiping, ultrasonic cleaning
  - **Helium tank welding**
  - **Final clean room cleaning and assembly**
    - First clean room HPR
    - First clean room assembly
    - Final clean room HPR
    - Final clean room assembly
    - Slow pump down
    - Leak check
  - **In-situ bake 120 °C 48 hour**

The inter-cavity connection is done in class 10 cleanrooms

Cavity Processing Recipe

- Cavity processing: re-processing strategy
  - **Cryogenic RF testing at 2 K**
  - **First pass test results drive second pass re-processing**
    - If gradient ≥ 35 MV/m and Q0 ≥ 8×109, cavity is then accepted
      - 60% yield is expected to pass
    - If gradient < 35 MV/m, cavity then proceed for second pass re-processing
      - Re-HPR if field emission limited
      - Re-EP (including post-EP cleaning, clean room HPR, assembly, 120 °C bake) if quench limited
    - Cryogenic RF testing at 2 K after second pass re-processing
      - If gradient ≥ 28 MV/m and Q0 ≥ 8×109, cavity is then accepted
      - 80% yield is expected to pass among the re-processed cavities
      - Accumulative yield of 92% expected combining two passes
      - The average gradient of all accepted cavities expected to reach 38 MV/m
  - **“Rejected” cavities, expected to reach average gradient 24 MV/m, still have a value. They might be used for positron source or polarized electron source – to further improve cost effectiveness.**

Documentation

- TDR Part I Section 3.3.1.2

As a quality assurance check prior to the expensive cavity processing and testing, the RF surface of a completed 9-cell cavity is optically inspected for irregularities. Over the past few years, high-resolution optical inspection devices suitable for checking 9-cell cavities have been routinely used in major labs in all regions. It has been shown that most quench-causing defects are located in the fusion zone or the heat-affected zone of the equator weld. Many of these defects can be traced back to fabrication process. Typically, the fusion zone is a few mm in width. The heat-affected zone is a narrow region outside the fusion zone, where the grain-growth is apparent due to heat deposited during the welding. The two heat-affected zones (one each on both sides of the weld) plus the fusion zone covers a total zone typically 40-50 mm in width. Due to the high surface magnetic field in this region, quenches can be initiated through either thermal process (such as strong resistive heating of a normal-conducting inclusion) or magneto-thermal process (such as strong magnetic field enhancement at sharp edges of pure geometric defects). There is a growing database on the optically identifiable defects, which are correlated to quench during the ultimate cavity qualification test [7][8][9][10]. The optical inspection is very effective in identifying sub-mm sized geometrical defects in the equator region, such as sharp edges, exposed welding pores/holes, unclosed weld prep, rough under-bead and weld spatters etc. This not only provides rapid feedback for production but also allows informed decisions for defect removal by suitable methods, such as local grinding at a distinctive defect area [11] and mechanical polishing over the entire RF surface of a completed cavity [12]. Overall, the QA/QC of the completed cavity by optical inspection is an important step for improved production yield. Ultimately, this will lead to cost-effective mass production of niobium cavities.

Documentation

3.3.3.2 Second-pass re-processing strategy

The first-pass test results drive the second-pass re-processing. If gradient $\geq$ 35 MV/m and $Q_0 \geq 8\times10^9$, the cavity is then accepted. If gradient $<$ 35 MV/m, the cavity then will need a second-pass re-processing. In case it is limited by field emission during the first-pass testing, the cavity will be high-pressure water rinsed one more time and proceed for the second RF testing (without 120 °C baking). In case it is limited by quench during the first-pass testing, the cavity will go through one more time of the final surface processing (including a light EP, post-EP cleaning and 120 °C baking). The cavity will be accepted if a gradient of $\geq$ 28 MV/m is obtained during the second-pass RF testing. A small fraction ($<$10%) of cavities will be rejected according to this criterion. The average gradient of the rejected cavities is expected to reach 24 MV/m or more. These cavities might be used for positron source or polarized electron source.

Allowing a second-pass re-treatment or re-processing, a significant cost saving benefit can be expected as compared to the "over production" model. Another important benefit is that a higher average gradient can be expected by allowing the second-pass processing, providing valuable gradient margins.