Review of heat treatments for low beta cavities: what's so different from elliptical cavities

D. Longuevergne

SRF2017 – July 2017 - Lanzhou
OUTLINE

- Introduction

- Heat treatments
  - Hydrogen degassing
  - Low temperature baking
  - Perspectives on nitrogen doping… is there one?

- Conclusion

SPECIAL THANKS TO :
- Z. Conway, ANL
- W. Yue, IMP
- E. Cenni, CEA
- Z. Yao, TRIUMF
- R. Laxdal, TRIUMF
ACCELERATING STRUCTURES

Quarter-Wave

Half-wave resonator (150-400 MHz)

Elliptical cavity (700-3000 MHz)

IAP $\beta=0.07$, 215MHz

RISP $\beta=0.12$, 162.5MHz

SPIRAL2, $\beta=0.12$, 88 MHz

D. Longuevergne, SRF2017, Lanzhou, 17th-21st July 2017
ACCELERATING STRUCTURES

ESS $\beta = 0.67$, 700 MHz

XFEL $\beta = 1$, 1.3 GHz

ESS $\beta = 0.5$, 352 MHz

MYRRHA $\beta = 0.37$, 352 MHz

SPIRAL2, $\beta = 0.12$, 88 MHz

RISP, $\beta = 0.12$, 162.5 MHz

IAP $\beta = 0.07$, 215 MHz

Elliptical cavity (700-3000 MHz)

Quarter-Wave resonators (80-150 MHz)

Half-wave resonator (150-400 MHz)

CH resonator (200-350 MHz)
ACCELERATING STRUCTURES

In this talk:
LOW BETA = everything below 1 GHz

ESS $\beta=0.67$, 700 MHz
ESS $\beta=0.5$, 352 MHz
IAP $\beta=0.07$, 215 MHz
SPIRAL2, $\beta=0.12$, 88 MHz
RISP, $\beta=0.12$, 162.5 MHz
MYRRHA $\beta=0.37$, 352 MHz

Quarter-Wave
Half-wave resonator (150-400 MHz)
Elliptical cavity (700-3000 MHz)

0.03 0.15 0.3 0.65 1
OUTLINE

- Introduction
- Heat treatments
  - Hydrogen degassing
  - Low temperature baking
  - Perspectives on nitrogen doping… is there one?
- Conclusion
- Aims at degassing hydrogen out of Niobium
  - Avoids Q-disease and irreversible degradation due to Q-disease
  - Decreases residual resistance and Q-slope
  - Releases mechanical stresses, recristalization

- But:
  - Require expensive dedicated furnace
  - Pollution of surface
    - Re-absorption of residual gas because oxide layer has been dissolved
  - Post chemical etching « required » to remove contaminated layer

---

**HYDROGEN DEGASSING history**

- Test results on high gradient L-band superconducting cavities », E. Kako et al., Proceedings of the 6th SRF workshop, Newport News, USA, 1993

1.3 GHz elliptical cavity
- Compulsory
  - Irreversible degradation observed.
- Done in standard preparation
- Done with bare cavity
- Typically at 800°C during 2-3h.
  - Temperature limitation to limit recrystalization and softening

Low beta resonators
- Not compulsory for QWR up to 170 MHz.
  - Accelerators with non degassed cavities (ISAC2, ALPI, Saraf, Spiral2).
  - Accelerators with degassed cavities (ATLAS, FRIB, C-ADS, IFMIF).
- Looks compulsory for Spoke resonators at 352 MHz.
  - Irreversible degradation observed in VT
- Done with/without dressed cavity
- Typically at 600°C - 650°C during 10h.
  - Temperature limitation due to brazed stainless steel parts
HYDROGEN DEGASSING OF LOW BETA

08/06/2013

IMP-HWR-S-04 VTA Results

Field Emission

Quench

Radiation before con
Radiation after condi
#04 before condi
#04 after condi
#04 after condi

Heavy BCP 1:1:2 120min 125.5um
Annealing 680°C, 1E-3Pa, 10h
Slight BCP 30 min, ~25um
HPR 84bar 8h
Baking 120°C, 46h
Cool down 300K-150K 80min, 150K 88min, 150K-4K 40min
Results Succeed with FE or MP

D. Longuevergne, SRF2017, Lanzhou, 17th-21st July 2017
Hydrogen degassing at ANL : Courtesy of Z. Conway

Results for 345 MHz Beta = 0.63 Triple Spoke Resonator
After Hydrogen Degassing, Performance Indicated that Cavities Should be Operated at 2 Kelvin

345 MHz $\beta = 0.63$ Resonator
Before (Left) and After (Right) 600°C H-Degassing

Material : Bulk Niobium
$\beta = 0.63$
$F_0 = 345$ MHz
$T = 2K$
$Bpk/Eacc = 9$ mT/MV/m
$Epk/Eacc = 2.93$
$G = 93$

M. Kelly, SRF2005
K. Shepard, SRF2005
Hydrogen degassing at IPNO:

- **Material:** Bulk Niobium
- **$\beta = 0.5$**
- **$F_0 = 352$ MHz**
- **$T : 2K$**
- **$E_{acc} : 9$ MV/m**
- **$B_{pk}/E_{acc} = 6.9$ mT/MV/m**
- **$E_{pk}/E_{acc} = 4.3$**
- **$r/Q = 426$**
- **$G = 130$**

- **Material:** Bulk Niobium
- **$\beta = 0.37$**
- **$F_0 = 352$ MHz**
- **$T : 2K$**
- **$E_{acc} : 6.4$ MV/m**
- **$B_{pk}/E_{acc} = 7.3$ mT/MV/m**
- **$E_{pk}/E_{acc} = 4.3$**
- **$r/Q = 217$**
- **$G = 109$**

*Furnace commissioned in 2016*

Q degradation after 300K thermal cycle

**Graphs**

- **$\delta$ vs. $E_{acc}$ (MV/m)**
- **$E_{acc}$ vs. $\delta$**
- **$E_{acc}$ vs. $Q$ degradation**

**Cavity**

D. Longuevergne, SRF2017, Lanzhou, 17th-21st July 2017
Hydrogen degassing at IPNO:

- Material: Bulk Niobium
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Furnace commissioned in 2016

D. Longuevrgne, SRF2017, Lanzhou, 17th-21st July 2017
Hydrogen degassing at IPNO:

- Residual resistance decreasing: $6 \Omega \rightarrow 3.5 \Omega$
- BCS resistance decreasing (4.2K): $64 \Omega \rightarrow 51 \Omega$
- After degassing at $650^\circ C$ 10h + BCP
- Baseline additional cold BCP
- Baseline warm BCP

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HYDROGEN DEGASSING OF LOW BETA

Baseline warm BCP
After degassing at 650°C 10h + 4 um BCP
After degassing at 650°C 10h (no post-BCP)
Baseline warm BCP

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HYDROGEN DEGASSING OF LOW BETA

- **Material**: Bulk Niobium
- **$\beta$**: 0.67
- **$F_0$**: 704 MHz
- **$T$**: 2K
- **$B_{pk}/E_{acc}$**: 4.8 mT/MV/m
- **$E_{pk}/E_{acc}$**: 3.8
- **$G$**: 197

Treated at Zanon facility

COURTESY OF E. CENNI, CEA

D. Longuevergne, SRF2017, Lanzhou, 17th-21st July 2017
HYDROGEN DEGASSING OF LOW BETA

- FRIB example after degassing
- Unfortunately no data before hydrogen degassing for comparison

Residual resistance between 1.5nΩ and 3nΩ

Residual resistance between 2nΩ and 5nΩ

K. Saito, February 2017 TTC201702

D. Longuevergne, SRF2017, Lanzhou, 17th-21st July 2017
Degassing with Niobium caps very interesting
- No post etching required
- Allow alternative treatment like N2 infusion

Residual resistance is decreased \(\rightarrow\) No hydrogen precipitation

Linear dependence of Q-slope is eliminated
\(\rightarrow\) Disparition of Josephson weak links [*]

BCS resistance is decreased as well \(\rightarrow\) «doping of Niobium», RRR \(\downarrow\)

Magnetic sensitivity is decreased
\(\rightarrow\) Observed on elliptical cavities
\(\rightarrow\) And also on Spoke cavities at 352 MHz
Degassing with Niobium caps is very interesting:

- No post-etching required.
- Allows alternative treatments like N2 infusion.
- Residual resistance is decreased, implying no hydrogen precipitation.
- Linear dependence of $Q$-slope is eliminated, leading to the disappearance of Josephson weak links.
- BCS resistance is decreased as well, indicating "doping of Niobium" and an increased RRR.
- Magnetic sensitivity is decreased, observed on elliptical cavities and also on Spoke cavities at 352 MHz.

HEAT TREATMENTS

HYDROGEN DEGASSING OF LOW BETA

D. Longuevergne, SRF2017, Lanzhou, 17th-21st July 2017
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  - Hydrogen degassing
  - Low temperature baking
  - Perspectives on nitrogen doping… is there one?
- Conclusion
Most of labs converged toward 120°C during 48h

Aims at removing the high field Q-slope
- First reported by B. Visentin in 1998.
- Decreases BCS resistance
- Decreases (for BCP cavity) or eliminates (for EP cavity) the high field Q-slope
- Could be used to accelerate drying of cavity

But:
- Increases residual resistance

«Improvements of superconducting cavity performances at high accelerating gradients », B. Visentin et al., Proc EPAC 1998, p. 1885
Most of labs converged toward 120°C during 48h

Aims at removing the high-field Q-slope

First reported by B. Visentin in 1998.

Decreases BCS resistance

Decreases (for BCP cavity) or eliminates (for EP cavity) the high-field Q-slope

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But:

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«Improvements of superconducting cavity performances at high accelerating gradients», B. Visentin et al., Proc EPAC 1998, p. 1885

«Q-slope at high gradients : review of experiments and high gradient », B. Visentin, Proceedings of the 11th SRF workshop, Lübeck, Germany, 2003
Low temperature baking of low beta

- **Baking for RISP**:
  - 81.25MHz QWR and 162.5MHz HWR designed by RISP.
  - **Cavity treatments**
    - 120µm BCP (+15µm for HWR)
    - HPR
    - 48hr 120°C bake
  - Cavities were tested before and after bake.

<table>
<thead>
<tr>
<th></th>
<th>QWR</th>
<th>HWR</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency y</td>
<td>81.25</td>
<td>162.5</td>
<td>MHz</td>
</tr>
<tr>
<td>β</td>
<td>0.047</td>
<td>0.12</td>
<td>1</td>
</tr>
<tr>
<td>$L_{\text{eff}} = \beta \lambda$</td>
<td>0.173</td>
<td>0.221</td>
<td>m</td>
</tr>
<tr>
<td>$E_{\text{peak}} / E_{\text{acc}}$</td>
<td>5.3</td>
<td>5.6</td>
<td>1</td>
</tr>
<tr>
<td>$B_{\text{peak}} / E_{\text{acc}}$</td>
<td>9.5</td>
<td>8.2</td>
<td>mT/MV/m</td>
</tr>
<tr>
<td>$G$</td>
<td>21</td>
<td>40</td>
<td>Ω</td>
</tr>
<tr>
<td>$U/E_{\text{acc}}^2$</td>
<td>0.126</td>
<td>0.159</td>
<td>J/(MV/m$^2$)</td>
</tr>
</tbody>
</table>
Low temperature baking of low beta

Baking for RISP : 81 MHz QWR

2K : $R_{BCS} \sim 0.1 \, \text{n}\Omega$

4.2K : $R_{BCS} \sim 2.5 \, \text{n}\Omega$

COURTESY OF Z. Yao

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Low temperature baking of low beta

- Baking for RISP: 162 MHz HWR

4.2K: $R_{BCS} \sim 2.5$ nΩ

2K: $R_{BCS} \sim 0.1$ nΩ

COURTESY OF Z. Yao
Low temperature baking of low beta

- Baking at 120°C during 48h at FRIB : 80.5 MHz QWR

Effect of baking or indium seal re-tightening?

Presented at TTC meeting by J. Popielarski, December 2011

D. Longuevergne, SRF2017, Lanzhou, 17th-21st July 2017
Low temperature baking of low beta

- Baking at 120°C at IPNO: 88 MHz QWR

Presented at SRF15, Whistler

D. Longuevergne, SRF2017, Lanzhou, 17th-21st July 2017
Low temperature baking of low beta

- **Baking at 120°C at IPNO : 88 MHz QWR**

![Graph showing the effects of baking on resistance and magnetic beta](image)

- **Baked 24h**
  - $R_{BCS}(B=0) = 3 \, \text{n}\Omega$
  - $R_{res0} = 1.9 \, \text{n}\Omega$
  - $R_{res1} = 0.65 \, \text{n}\Omega/\text{MV/m}$
  - $\beta_{mag} = 1.5$

- **Baked 55h**
  - $R_{BCS}(B=0) = 2.4 \, \text{n}\Omega$
  - $R_{res0} = 4.3 \, \text{n}\Omega$
  - $R_{res1} = 0.2 \, \text{n}\Omega/\text{MV/m}$
  - $\beta_{mag} = 1.55$

- **No baking**
  - $R_{BCS}(B=0) = 3.5 \, \text{n}\Omega$
  - $R_{res0} = 1.9 \, \text{n}\Omega$
  - $R_{res1} = 0.65 \, \text{n}\Omega/\text{MV/m}$
  - $\beta_{mag} = 1.55$


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Residual resistance is increased $\rightarrow$ diffusion of surface impurities

- BCS resistance is decreased $\rightarrow$ reduction of electron mean free path

- 4.2 K Q-slope is decreased $\rightarrow$ origin of Q-slope is BCS

Difference between elliptical and low beta:

- **For elliptical cavities**: baking affects only the high field Q-slope (>20 MV/m)
- **For low beta cavities**: Q-slope impacted at low field

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Frequency</th>
<th>Pre-treatment</th>
<th>Residual resistance</th>
<th>BCS resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>QWR RISP</td>
<td>81.25 MHz</td>
<td>BCP</td>
<td>$\uparrow$</td>
<td>$\downarrow$</td>
</tr>
<tr>
<td>HWR RISP</td>
<td>162.5 MHz</td>
<td>BCP</td>
<td>$\uparrow$</td>
<td>$\downarrow$</td>
</tr>
<tr>
<td>QWR ReA3</td>
<td>80.5 MHz</td>
<td>BCP + 600°C degassing</td>
<td>$\downarrow$ ??</td>
<td>$\downarrow$</td>
</tr>
<tr>
<td>QWR Spiral2</td>
<td>88 MHz</td>
<td>BCP</td>
<td>$\uparrow$</td>
<td>$\downarrow$</td>
</tr>
</tbody>
</table>
OUTLINE

- Introduction
- Heat treatments
  - Hydrogen degassing
  - Low temperature baking
  - Perspectives on nitrogen doping… is there one?
- Conclusion
Nitrogen doping reported in 2013 at Fermilab
- Cavity exposed to nitrogen gas at the end of thermal cycle at 800° C
- Small chemical etching required to remove over-doped layer

Positive effects:
- Decrease of BCS resistance
- BCS resistance is improving with accelerating gradient (anti Q-slope)

Negative effects:
- Quenching gradient is reduced
- Magnetic sensitivity is drastically increased

Heat treatment (300° C to 800° C) with N₂/Ar refill already tried by B. Visentin in 2001
- Anomalously low BCS resistance observed. No mention of anti Q-slope

G. Ciovatti reported nitridization treatment at 400° C following a 800° C treatment in 2010
- Improvement of residual resistance
Nitrogen doping reported in 2013 at Fermilab.

Cavity exposed to nitrogen gas at the end of thermal cycle at 800 °C.

Small chemical etching required to remove overdoped layer.

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G. Ciovatti reported nitridization treatment at 400 °C following a 800 °C treatment in 2010.

Perspectives on nitrogen doping:
- Improvements of residual resistance

N$_2$ « doping » for low beta

- Only one example at 650 MHz

CAVITY PROCESSING AND PREPARATION OF 650 MHz ELLIPTICAL CELL CAVITIES FOR PIP-II®, A. M. Rowe et al., Proceedings of LINAC2016, East Lansing, US.
Nitrogen doping keeps residual resistance low and decreases BCS resistance.

To be beneficial, residual resistance has to be low compared to BCS resistance.

What does that mean for low beta cavities:

- If operated at 2K
  - No point to dope up to 500 MHz, as BCS resistance is low and MFQS is negligible.
- If operated at 4.2K
  - Worth doing it especially if Q-slope is from BCS and not residual resistance.

Could nitrogen doping allow 4.2K operation of Spoke cavities at 352 MHz?

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>$R_{\text{BCS}}$ (n(\Omega))</th>
<th>4.2K</th>
<th>2K</th>
<th>1.8K</th>
<th>1.5K</th>
</tr>
</thead>
<tbody>
<tr>
<td>1300 MHz</td>
<td>585</td>
<td>15</td>
<td>6.5</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>700 MHz</td>
<td>174</td>
<td>4.3</td>
<td>1.9</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>352 MHz</td>
<td><strong>44</strong></td>
<td><strong>1</strong></td>
<td>0.5</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>176 MHz</td>
<td>11</td>
<td>0.3</td>
<td>0.1</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>88 MHz</td>
<td>3</td>
<td>0.07</td>
<td>0.03</td>
<td>0.006</td>
<td></td>
</tr>
</tbody>
</table>
## CONCLUSION

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<thead>
<tr>
<th>1.3 GHz Elliptical</th>
<th>Observed improvements</th>
<th>Low beta cavities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen degassing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Compulsory</td>
<td>- Improvement of Residual</td>
<td>- Not compulsory below 300 MHz</td>
</tr>
<tr>
<td>- Done without tank</td>
<td>- Improvement of BCS</td>
<td>- Done with/without tank</td>
</tr>
<tr>
<td>- Done at 800°C</td>
<td>- Improvement of Q-slope</td>
<td>- Brazed parts → done at 600°C</td>
</tr>
<tr>
<td>- Done during 3h</td>
<td>- Q-disease disappears</td>
<td>- Done during 10h</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>120°C baking</th>
<th></th>
<th></th>
</tr>
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<tbody>
<tr>
<td>- Done during 48h</td>
<td>- Improvement of BCS</td>
<td>- Done during 48h</td>
</tr>
<tr>
<td>- Hot air/nitrogen blown around cavity</td>
<td>- Degradation of Residual</td>
<td>- Hot air blown in helium tank</td>
</tr>
<tr>
<td>-</td>
<td>- Improves HFQS</td>
<td>- Heating wires</td>
</tr>
<tr>
<td>-</td>
<td>- Improves MFQS</td>
<td></td>
</tr>
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<th>Nitrogen doping</th>
<th></th>
<th></th>
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<tr>
<td>- 800°C 3h + 2 min at 25 mtorr N₂ + 6 min in UHV + EP</td>
<td>- Improvement of BCS resistance</td>
<td>- Tried on 650 MHz only</td>
</tr>
<tr>
<td>- 800°C 3h + 160°C at 25 mtorr N₂ during 48h</td>
<td>- Residual resistance stays constant</td>
<td>- Will be tried on Spoke at 352 MHz</td>
</tr>
<tr>
<td>- Anti Q-slope</td>
<td>- No anti Q-slope</td>
<td></td>
</tr>
</tbody>
</table>

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D. Longuevergne, SRF2017, Lanzhou, 17th-21st July 2017
THANKS A LOT FOR YOUR ATTENTION

AND MANY THANKS FOR PROVIDING MATERIAL TO:

- Zack Conway, ANL
- Zhongyuan Yao, TRIUMF/RISP
- Yue Weiming, IMP
- Enrico Cenni, CEA
THE BCS RESISTANCE

\[ R_{BCS} = \frac{8 \cdot 10^{-5}}{T} \cdot f^2 \cdot \exp\left( -\frac{1.83 \cdot T_c}{T} \right) \]

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<tr>
<td>Cavity</td>
<td>Frequency</td>
<td>Residual (nΩ)</td>
<td>A (10⁻⁵ nΩ K/s⁻²)</td>
<td></td>
</tr>
<tr>
<td>----------------</td>
<td>-----------</td>
<td>---------------</td>
<td>-------------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Before HT</td>
<td>After HT</td>
<td>Before HT</td>
<td>After HT</td>
</tr>
<tr>
<td>QWR FRIB</td>
<td>80.5 MHz</td>
<td>1.5</td>
<td>X</td>
<td>7</td>
</tr>
<tr>
<td>Spoke ANL</td>
<td>345 MHz</td>
<td>4.5</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Spoke IPNO</td>
<td>352 MHz</td>
<td>1.3</td>
<td>9.5</td>
<td>8</td>
</tr>
<tr>
<td>Elliptical ESS</td>
<td>704 MHz</td>
<td>6</td>
<td>15</td>
<td>12.5</td>
</tr>
<tr>
<td>Elliptical KEK</td>
<td>1.3 GHz</td>
<td>10</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

[***]: « Additional losses in high purity niobium cavities related to slow cooldown and hydrogen segregation », J. Halbritter et al., Proceedings of the 6th SRF workshop, Newport News, USA, 1993

Field distribution very different depending on the geometry
Niobium samples have been installed in cavity

SIMS (Secondary Ion Mass Spectrometer) analysis to know what is on the surface after heat treatment

Compact SIMS from Hiden Analytical
A cavity not shielded during heat treatment:

![Graph showing mass spectra and hits per seconds for different samples.](image-url)
A cavity not shielded during heat treatment:

```
<table>
<thead>
<tr>
<th>Masses (uma)</th>
<th>SD01-650° C-10h</th>
<th>ZA01-650° C-10h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NbO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NbO2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Na</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

Sample study

D. Longuevergne, SRF2017, Lanzhou, 17th-21st July 2017
A cavity shielded during heat treatment:

- Masses (uma)
  - Ti
  - Ca
  - Nb
  - NbO
  - NbO2
  - Fe
  - Na
  - O
  - O2
  - H

A bit of Iron because of stainless steel wire

D. Longuevergne, SRF2017, Lanzhou, 17th-21st July 2017
A cavity shielded during heat treatment:

```
<table>
<thead>
<tr>
<th>Masses (uma)</th>
<th>f1-650° C-10h</th>
<th>c1-650° C-10h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NbO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe - f1 - beam tube</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

D. Longuevergne, SRF2017, Lanzhou, 17th-21st July 2017
How to compare elliptical and low beta

<table>
<thead>
<tr>
<th>Cavity type</th>
<th>β</th>
<th>T° (K)</th>
<th>G (Ω)</th>
<th>Qo at 1 nΩ res</th>
<th>F (MHz)</th>
<th>Eacc (MV/m)</th>
<th>Bpk/Eacc (mT/MV/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QWR (FRIB)</td>
<td>0.041</td>
<td>2</td>
<td>15</td>
<td>1.4E10</td>
<td>80.5</td>
<td>5.3 (54.6)</td>
<td>10.3</td>
</tr>
<tr>
<td>QWR (SPIRAL2)</td>
<td>0.12</td>
<td>4.2</td>
<td>33</td>
<td>8.2E9</td>
<td>88</td>
<td>6.5 (61.7)</td>
<td>9.5</td>
</tr>
<tr>
<td>HWR (RISP)</td>
<td>0.12</td>
<td>2</td>
<td>40</td>
<td>3.2E10</td>
<td>162</td>
<td>5.9 (48.4)</td>
<td>8.2</td>
</tr>
<tr>
<td>HWR (FRIB)</td>
<td>0.53</td>
<td>2</td>
<td>107</td>
<td>5.3E10</td>
<td>322</td>
<td>7.5 (63)</td>
<td>8.4</td>
</tr>
<tr>
<td>SPOKE (ESS)</td>
<td>0.5</td>
<td>2</td>
<td>133</td>
<td>6E10</td>
<td>352</td>
<td>9 (63)</td>
<td>7</td>
</tr>
<tr>
<td>Elliptical (ESS)</td>
<td>0.67</td>
<td>2</td>
<td>197</td>
<td>3.4E10</td>
<td>704</td>
<td>16.7 (83.5)</td>
<td>4.8</td>
</tr>
<tr>
<td>Elliptical (XFEL)</td>
<td>1</td>
<td>2</td>
<td>271</td>
<td>1.5E10</td>
<td>1300</td>
<td>23.6 (99)</td>
<td>4.2</td>
</tr>
</tbody>
</table>
IMPROVEMENT OF Q CONSIDERING BCS IS DIVIDED BY 2


D. Longuevergne, SRF2017, Lanzhou, 17th-21st July 2017