Cooldown and thermal budget dependencies of mid-T treated cavity performance

Overview on DESY mid-T campaign

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Medium temperature (mid-T) treatments at DESY

DESY mid-T campaign started in 2021

- Refurbished furnace infrastructure at DESY
  - Nb retort furnace attached to ISO4 cleanroom
  - Vertical assembly of 2x single-cell or 1x nine-cell
  - Separate inner vac system; 2x cryo pumps
  - Start pressure ~ 2x10^-8 mbar; clean vac system
  - Pressure at 300°C ~ 1x10^-7 mbar
- Total of 18 Mid-T treatments were conducted!
  - On 16 cavities
  - Only on 1.3 GHz single cell cavities so far
Commissioning and fine-tuning the furnace

Delayed temperature control solved by overshooting
Improved oxygen diffusion length calculation

Temperature profile used to calculate the oxygen diffusion length („thermal budget“)

\[ D(T) = D_0 \cdot e^{-\frac{E_a}{kT(t)}} \]

Diffusion length: \[ l = 2 \sqrt{\int D(t) \, dt} \]

- \[ \int D(T(t)) \, dt \rightarrow „\text{thermal budget}“ \]
- Diffusion coefficient \( D(T) \) is temperature dependent
- Higher thermal budget \( \rightarrow \) larger diffusion length
- Temperature beats time!
  - 20h @ 250°C \( \rightarrow \) ~500-550 nm
  - 3h @ 300°C \( \rightarrow \) ~550-800 nm

Temperature profiles of all mid-T treatments
Improved oxygen diffusion length calculation

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Mid-T treatments sorted by diffusion length „thermal budget“
Nominal treatment against calculated diffusion length as classification attempt

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Nominal treatment</th>
<th>Calculated diff. Length (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1RI04</td>
<td>3h @ 250</td>
<td>234</td>
</tr>
<tr>
<td>1DE12</td>
<td>3h @ 250</td>
<td>249</td>
</tr>
<tr>
<td>1DE26</td>
<td>3h @ 300</td>
<td>501</td>
</tr>
<tr>
<td>1RI02</td>
<td>20 h @ 250</td>
<td>512</td>
</tr>
<tr>
<td>1DE04</td>
<td>3h @ 300</td>
<td>528</td>
</tr>
<tr>
<td>1DE03</td>
<td>3h @ 300</td>
<td>537</td>
</tr>
<tr>
<td>1DE07</td>
<td>20h @ 250</td>
<td>560</td>
</tr>
<tr>
<td>1DE07 18x HPR</td>
<td>3h @ 300</td>
<td>641</td>
</tr>
<tr>
<td>1AC07</td>
<td>3h @ 300</td>
<td>697</td>
</tr>
<tr>
<td>1DE10 coated</td>
<td>3h @ 300</td>
<td>749</td>
</tr>
<tr>
<td>1DE18 coated</td>
<td>3h @ 300</td>
<td>773</td>
</tr>
<tr>
<td>1AC03</td>
<td>3h @ 300</td>
<td>789</td>
</tr>
<tr>
<td>1AC02</td>
<td>3.25h @ 325</td>
<td>865</td>
</tr>
<tr>
<td>1DE19</td>
<td>4.5h @ 335</td>
<td>1248</td>
</tr>
<tr>
<td>1DE11</td>
<td>3h @ 350</td>
<td>1839</td>
</tr>
<tr>
<td>1DE17</td>
<td>20h @ 300</td>
<td>2039</td>
</tr>
<tr>
<td>1RI01</td>
<td>3h @ 350</td>
<td>2354</td>
</tr>
<tr>
<td>1DE12</td>
<td>3h @ 350</td>
<td>2655</td>
</tr>
</tbody>
</table>

- First cavity (1DE19) with two caps; others top cap only as dust protection
- final HPR & assembly, only
- 3x large grain cavity
- 2x coated cavity
- 2x tandem runs (2 cavities simultaneously)
Collected lots of data

$Q_0$ vs $E_{acc}$ & $R_{BCS}$ of 18 single cell cavity treatments

- Multitude of treatments with very high reproducibility and characteristic features
- 7 of 18 cavities degraded in $Q_0$ after quench
Short 250°C leads to reduced $Q_0$

$Q_0$ vs $E_{acc}$ & $R_{BCS}$ - thermal budget similar to 3h 250°C

- 250°C exhibits behavior similar to mid-T but with inferior performance
- But lowest $R_{BCS}$!
- $Q_0$ degraded after a quench
300°C treatments lead to best results

$Q_0$ vs $E_{acc}$ & $R_{BCS}$ - thermal budget similar to 3h 300°C

- Typical 300°C treatment demonstrates very high $Q_0$ with an anti-$Q$-slope and good $R_{BCS}$
- In three cases, the values have shown inferior results
  - Two 20h 250°C treatment (long treatment but low thermal budget) → deteriorates performance?
  - One with additional 18 HPRs
  - Same thermal budget but very different $R_{BCS}$
    → presentation by Marc
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300°C treatments lead to best results

Q₀ vs E_{acc} & R_{BCS} - thermal budget similar to 3h 300°C

- Typical 300°C treatment demonstrates very high Q₀ with an anti-Q-slope and good R_{BCS}
- In three cases, the values have shown inferior results
  - Two 20h 250°C treatment (long treatment but low thermal budget) → deteriorates performance?
  - One with additional 18 HPRs
  - Same thermal budget but very different R_{BCS} → presentation by Marc
300°C treatments lead to best results

$Q_0$ vs $E_{acc}$ & $R_{BCS}$ - thermal budget similar to 3h 300°C

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    → presentation by Marc
On the edge of Mid-T - 350°C lead to HFQS

$Q_0$ vs $E_{\text{acc}}$ & $R_{\text{BCS}}$ – thermal budget similar to 3h 350°C

- Slightly lower $Q_0$ for gradients in region of 25-30 MV/m
- High field $Q$-Slope!
  - 350°C lowest temperature to cause this?! → At 350°C Pentoxides are gone!
- Differences are particularly reflected in $R_{\text{BCS}}$!
Large grain cavities are high performer!

\( Q_0 \) vs \( E_{\text{acc}} \) & \( R_{\text{BCS}} \) – large grain cavities treated with typical mid-T 3h 300°C

- Mid-T treatments works very well with LG cavities
- \( R_{\text{BCS}} \) values similar to FG → main improvement comes from \( R_{\text{res}} \)!
Correlation of performance with oxygen diffusion length

$Q_0$ & $E_{\text{acc}}$

- **No clear trend** for $Q_0$ or $E_{\text{acc}}$ against diffusion length (thermal budget)
Correlation of performance with oxygen diffusion length

\( Q_0 \) & \( E_{acc} \)

- **No clear trend** for \( Q_0 \) or \( E_{acc} \) against diffusion length (thermal budget)
  - Or maybe for \( Q_0 \)?
Correlation of performance with oxygen diffusion length

$R_{res}$ & $R_{BCS}$

- Neglecting outliers, a trend is observable
- Data suggests the possibility of an optimization issue related to diffusion length (thermal budget)
- More data needed to fill the gaps
Oxygen diffusion length measurements on samples

SIMS profiles - deep sputtering

Calculated diffusion length from temperature profile:

- 697 nm for 3h@300°C
- 560 nm for 20h@250°C
- 2354 nm for 3h@350°C

- Calculated diffusion length same order of magnitude as measured value for the 3h 300°C treatment
- The increased treatment duration appears to flatten the profile
- The 350°C treatment also exhibits a relatively flat and deep profile, making it challenging to compare with the diffusion model

Measurement conducted at IFAM, Bremen, Germany
Spatial temperature gradient of cooldown

Determined by temperature sensors at cavity

\[ \Delta x = 317 \text{ mm} \]

\[ \Delta T = \frac{T3(9.2K) - T1}{\Delta x} \]

\[ \Delta T = \frac{T3 - T1}{317 \text{ mm}} \]
Spatial cooldown gradient dependency to performance

$Q_0$ & $E_{\text{acc}}$ - divided into two cryo test setups

- No correlation to performance observed
- Two ranges of $\Delta T/\Delta x$ observable $\rightarrow$ attributed to our two test setups
Spatial cooldown gradient dependency to performance

$R_{\text{res}}$ & $R_{\text{BCS}}$ - divided into two cryo test setups

- No correlation to $R_{\text{res}}$ and $R_{\text{BCS}}$
- Lower limit of $\sim2n\Omega$ for $R_{\text{res}}$ observed (without magnetic field compensation)
- We can exclude the impact of different cryostats and inserts
- Observable difference between the test setups exists for $R_{\text{BCS}}$ (?)
Summary and outlook for the mid-T campaign at DESY

The amount of data has increased and we are filling the gaps

- Very high reproducibility of characteristic results
  - The 30 MV/m is still an unbreakable wall
  - 7 out of 18 cavities degrade after quenching (restorable by $T_c$ cycling)
- LG cavities show best performances
- Sorting by thermal budget appears to provide insights
- 350°C edge to new characteristic regime
- SIMS measurements only partially conclusive
- Additional diagnostics & studies ongoing
  - flux trapping sensitivity via new B-mapping system
  - frequency vs. temperature measurements
    => presentation by Marc

- Optimisation potential
  - New/alternative recipes necessary?
  - Role of caps?
- Transfer to 9-cell cavity Mid-T treatments ongoing
- 18 new single cell cavities produced to increase the statistics even further
Thank you
Some cavities exhibit the phenomenon of degrading in quality after quenching. Not attributable to any specific treatment group → not yet understood the cause.