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

Overview on DESY mid-T campaign

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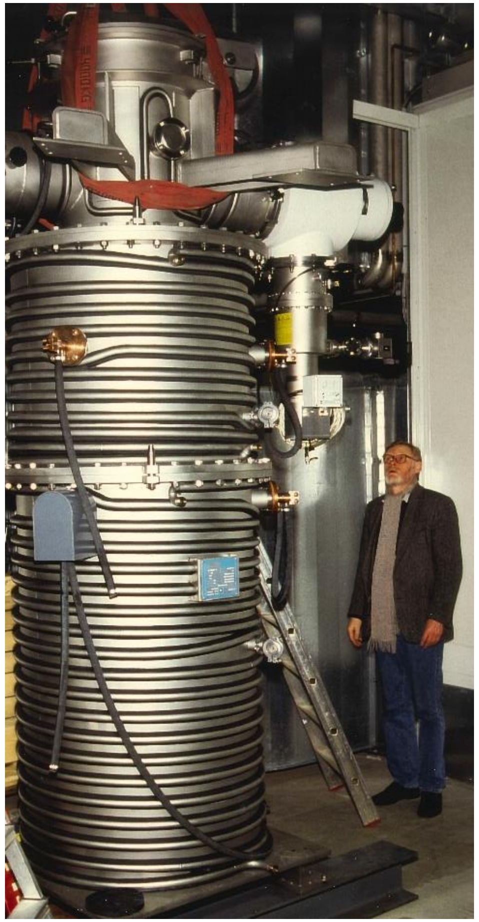
Medium temperature (mid-T) treatments at DESY

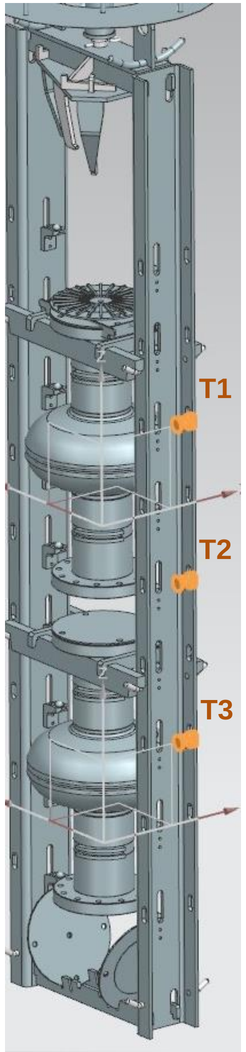
DESY mid-T campaign started in 2021

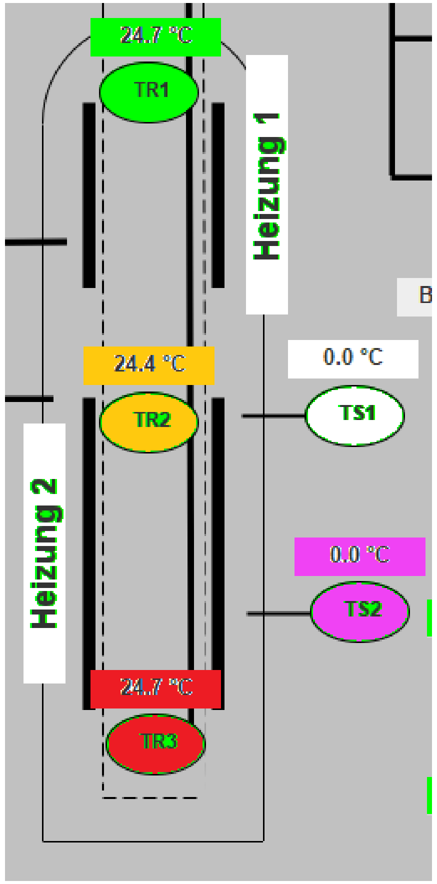
- Refurbished furnace infrastructure at DESY
  - Nb retort furnace attached to ISO4 cleanroom
  - Vertical assembly of 2x single-cell or 1x nine-cell
  - Separate inner vac system; 2x cryo pumps
  - Start pressure ~ $2x10^{-8}$ mbar; clean vac system
  - Pressure at 300°C ~ $1x10^{-7}$ mbar
- Total of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

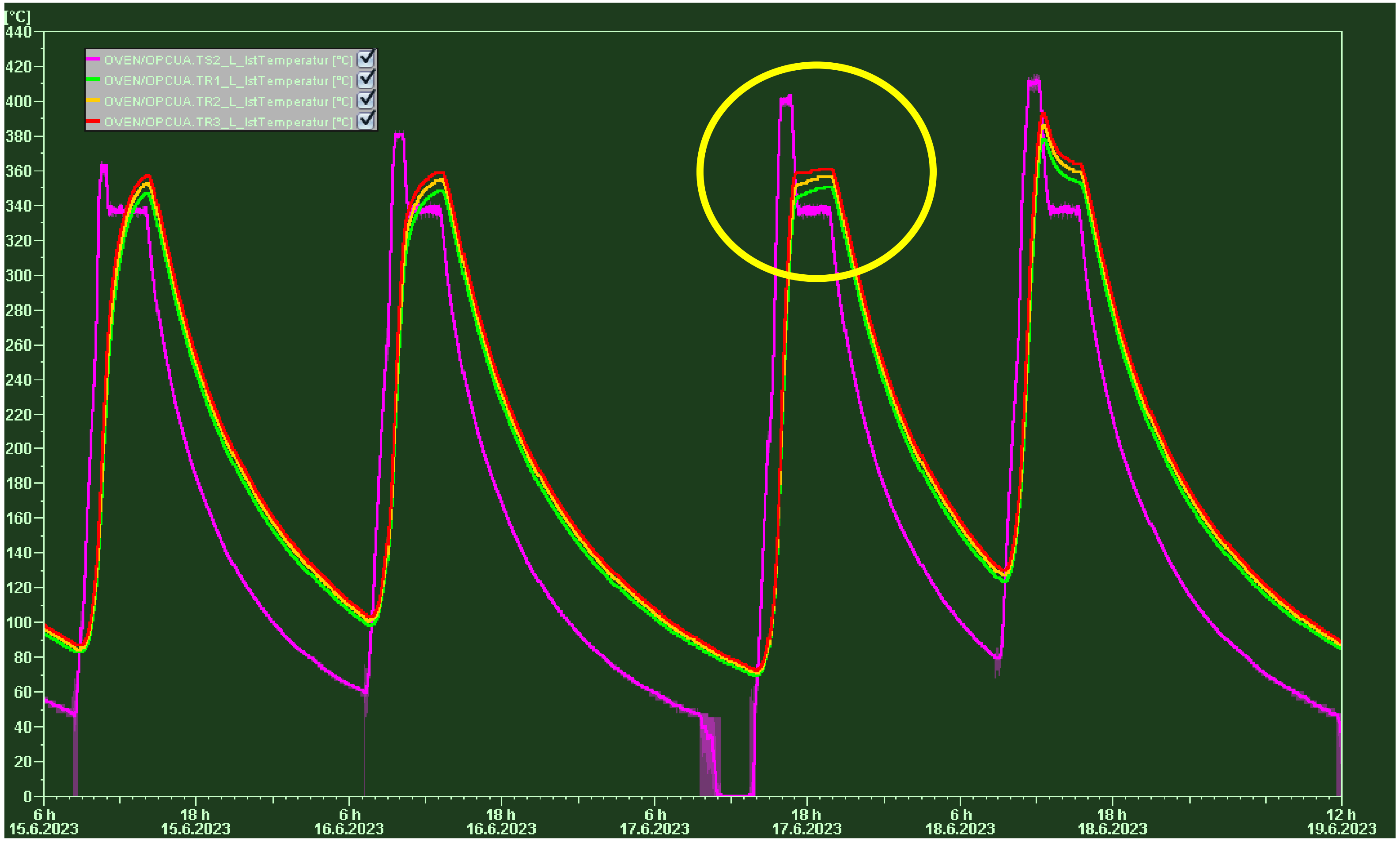


Commissioning and fine-tuning the furnace

Delayed temperature control solved by overshooting

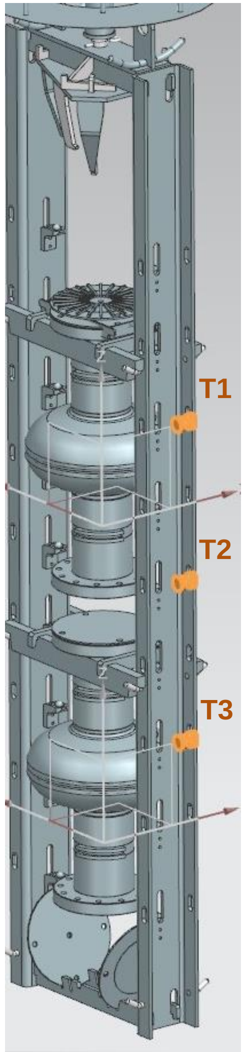


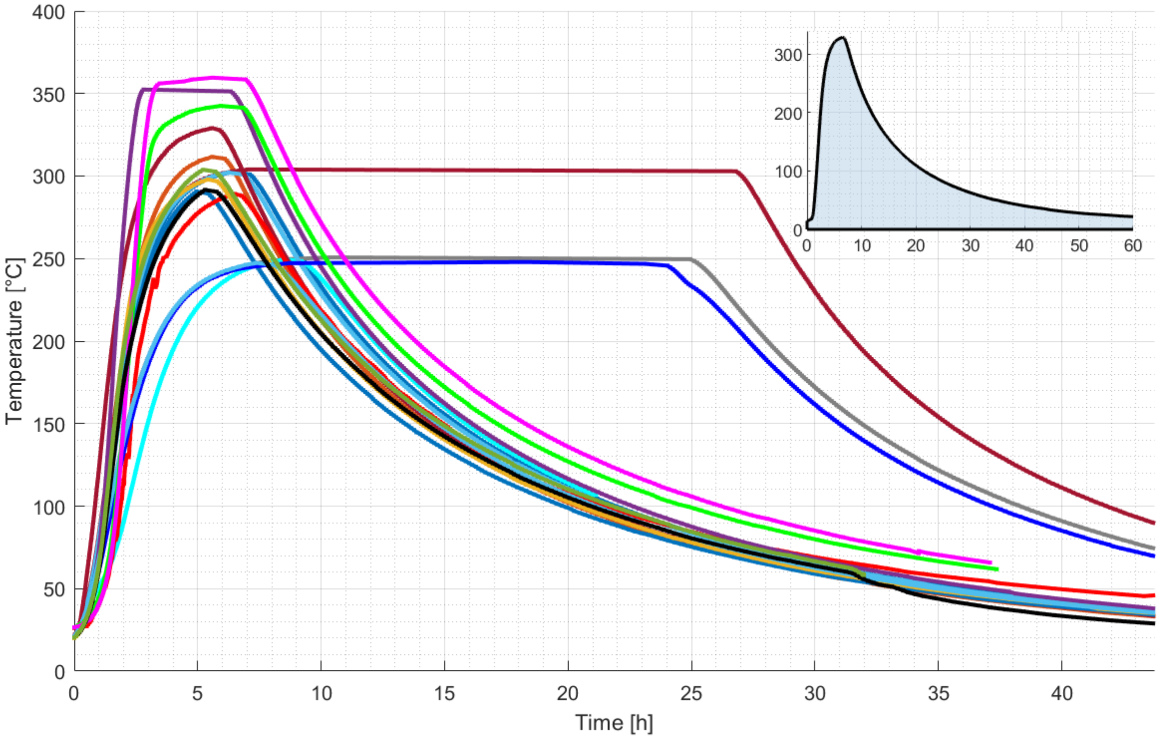




Improved oxygen diffusion length calculation

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





Temperature profiles of all mid-T treatments

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

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

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

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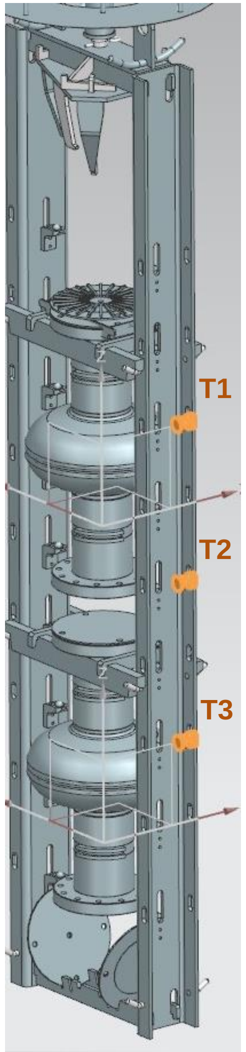

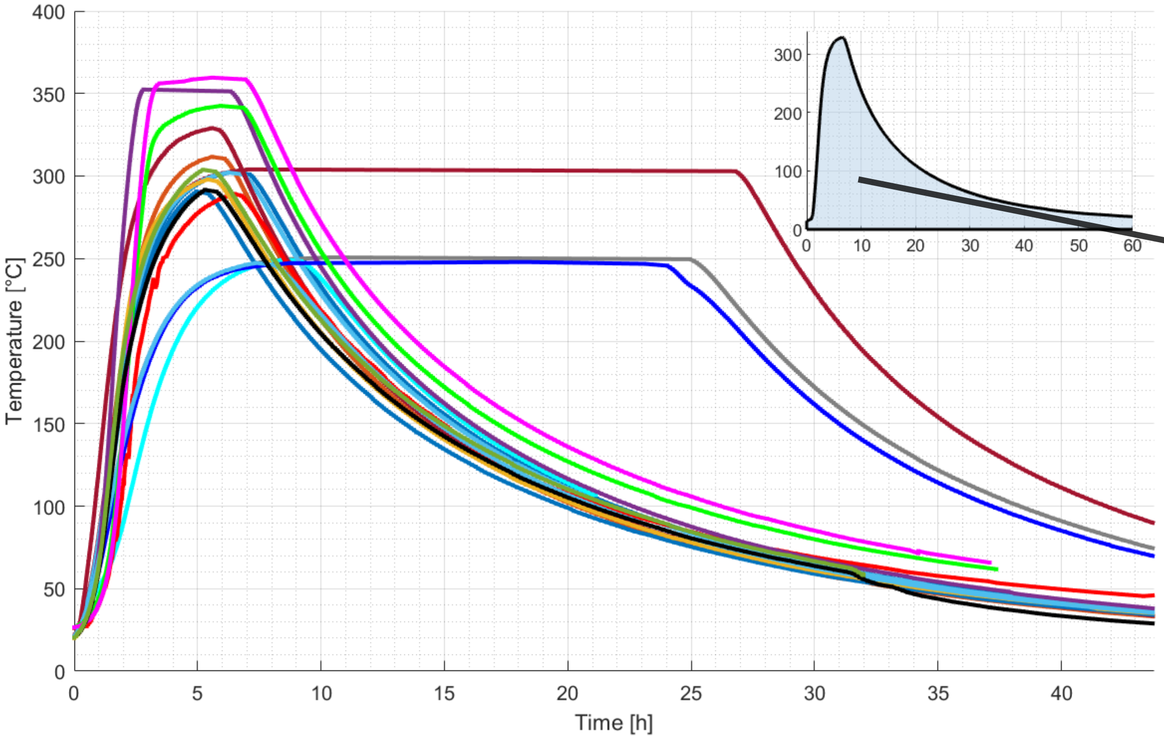

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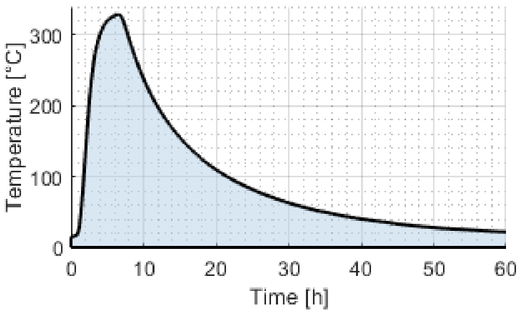
Mid-T treatments sorted by diffusion length „thermal budget“

Nominal treatment against calculated diffusion length as classification attempt

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

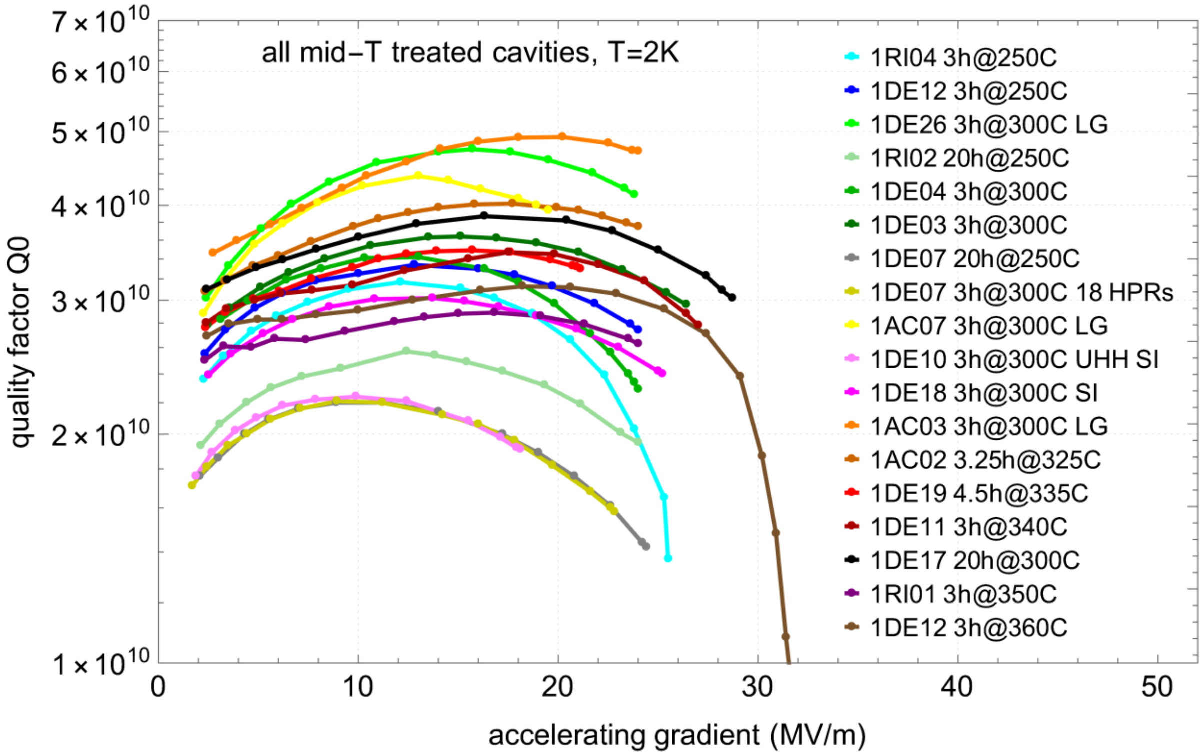
- First cavity (1DE19) with two caps; others **top cap** only as dust protection
- final HPR & assembly, only

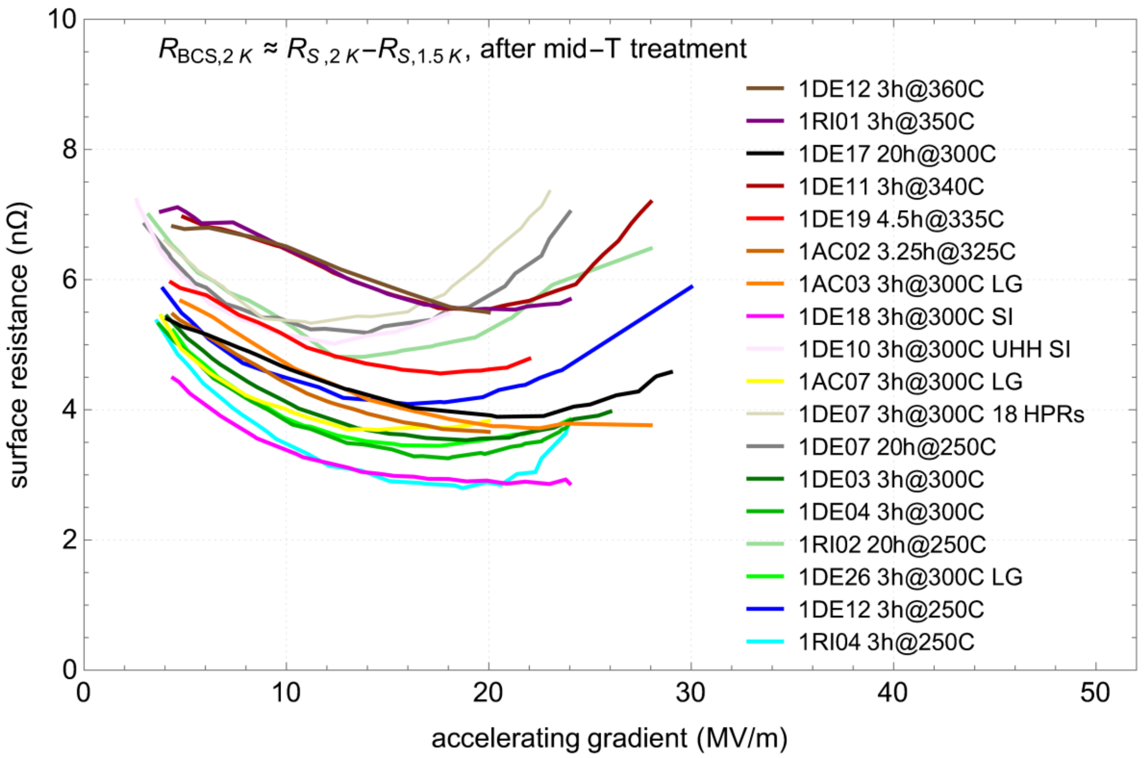
- 3x large grain cavity
- 2x coated cavity
- 2x tandem runs (2 cavities simultaneously)



Collected lots of data

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

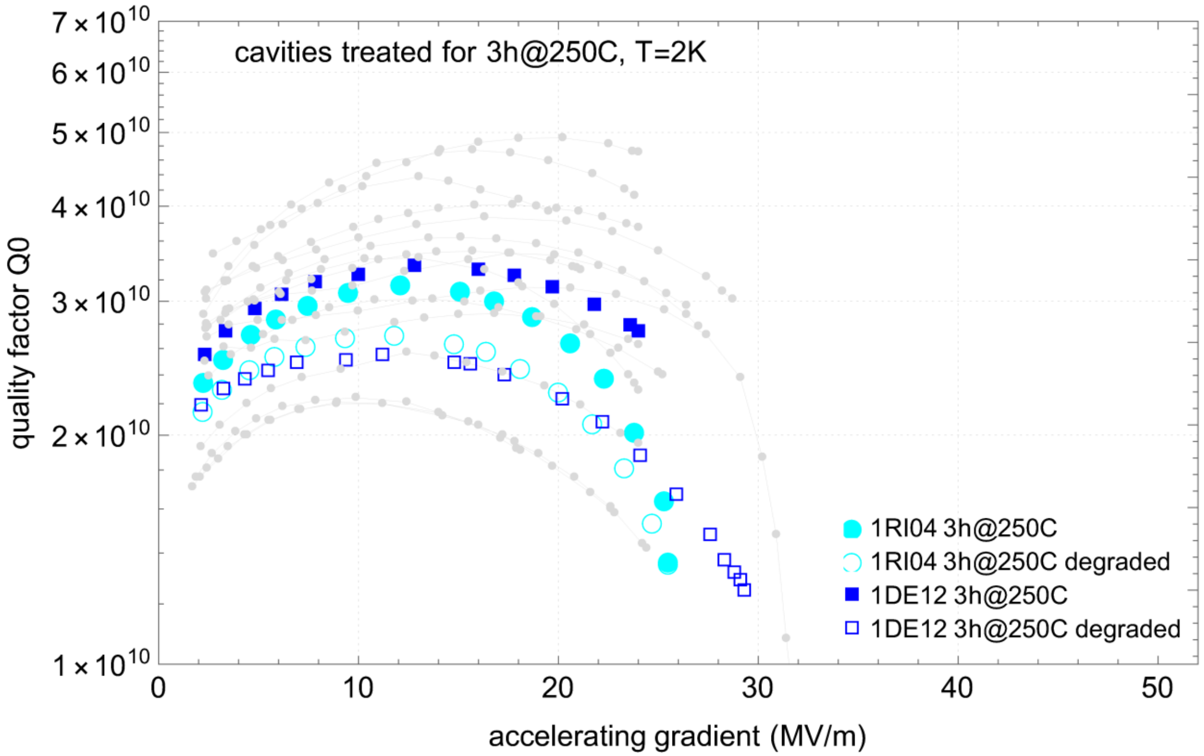


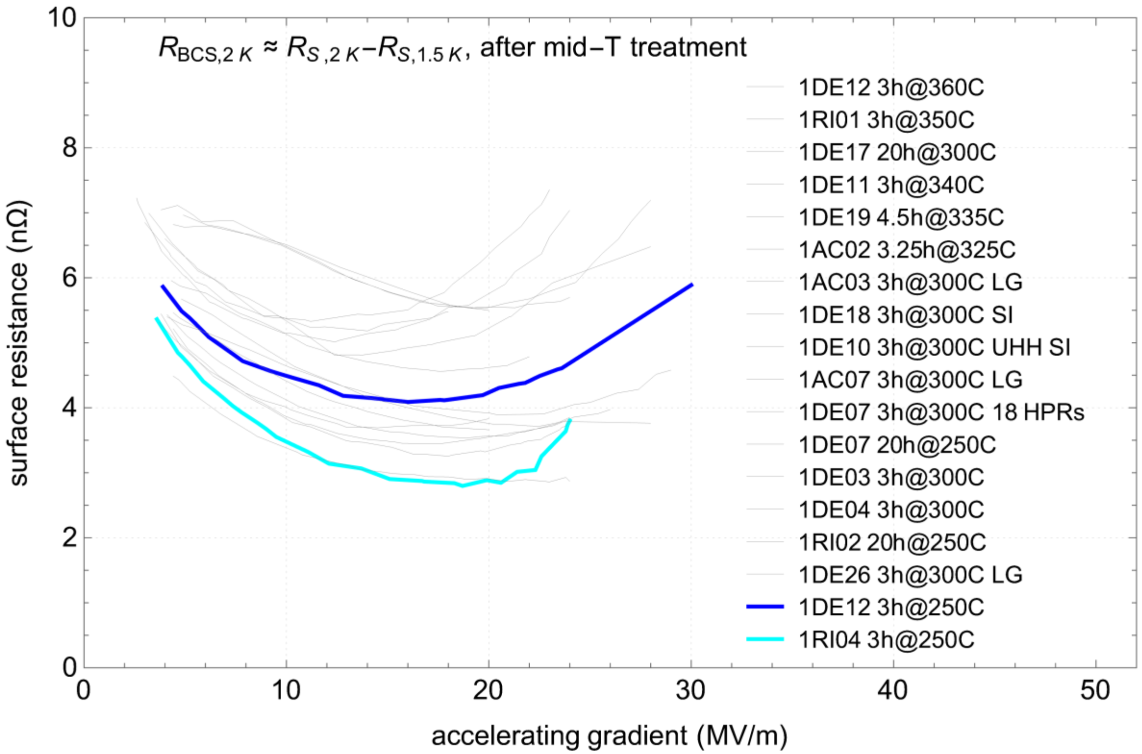


- Multitude of treatments with very high reproducibility and characteristic features
- 7 of 18 cavities degraded in Q_0 after quench

Short 250°C leads to reduced Q_0

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

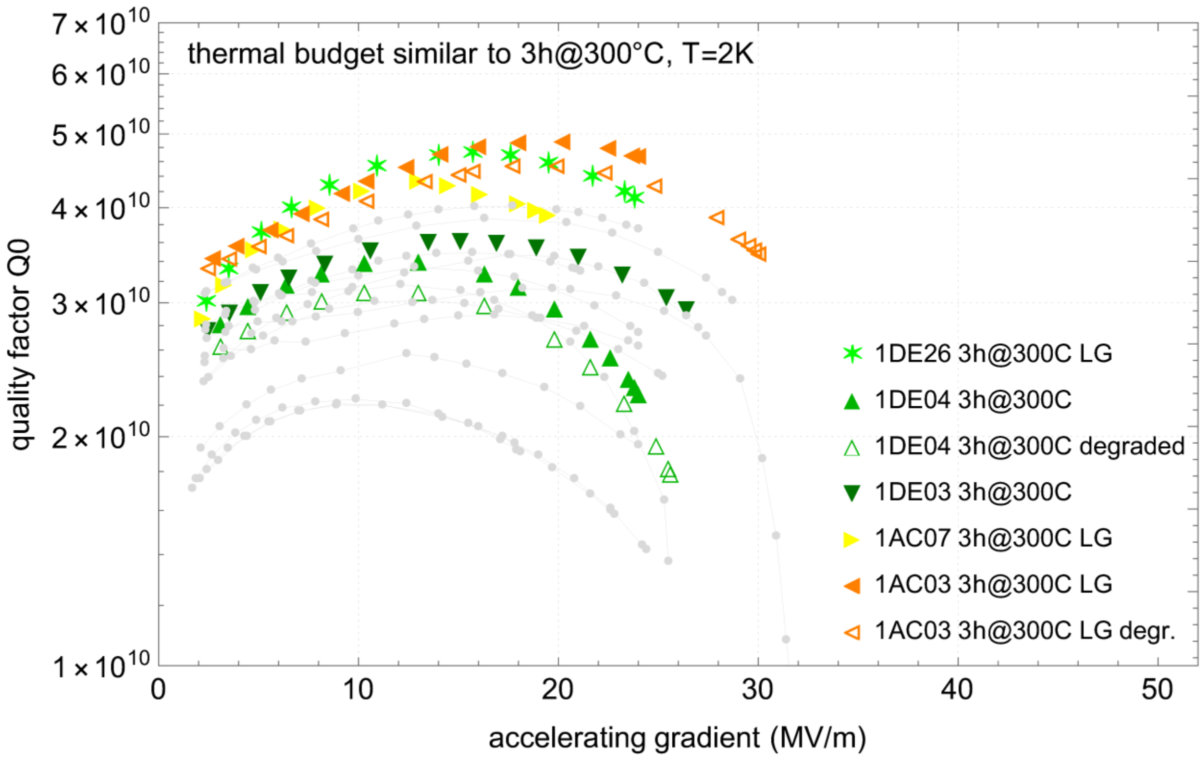


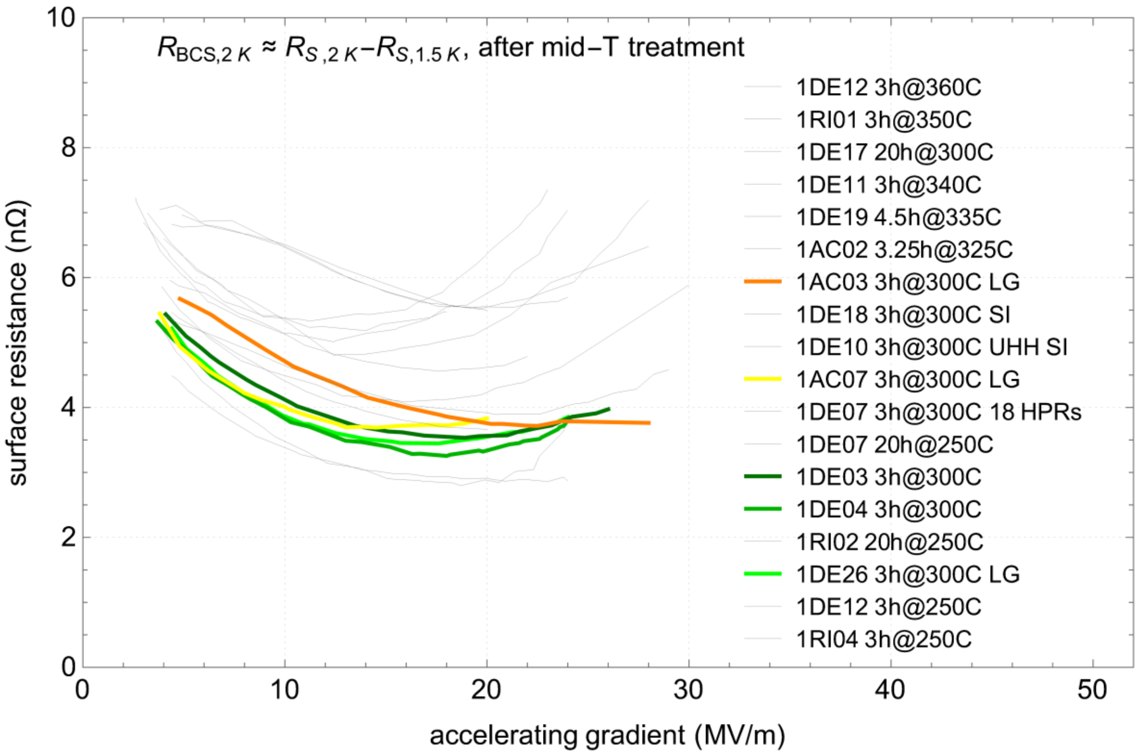


- 250°C exhibits behavior similar to mid-T but with inferior performance
- But lowest R_{BCS} !
- Q_0 degraded after a quench

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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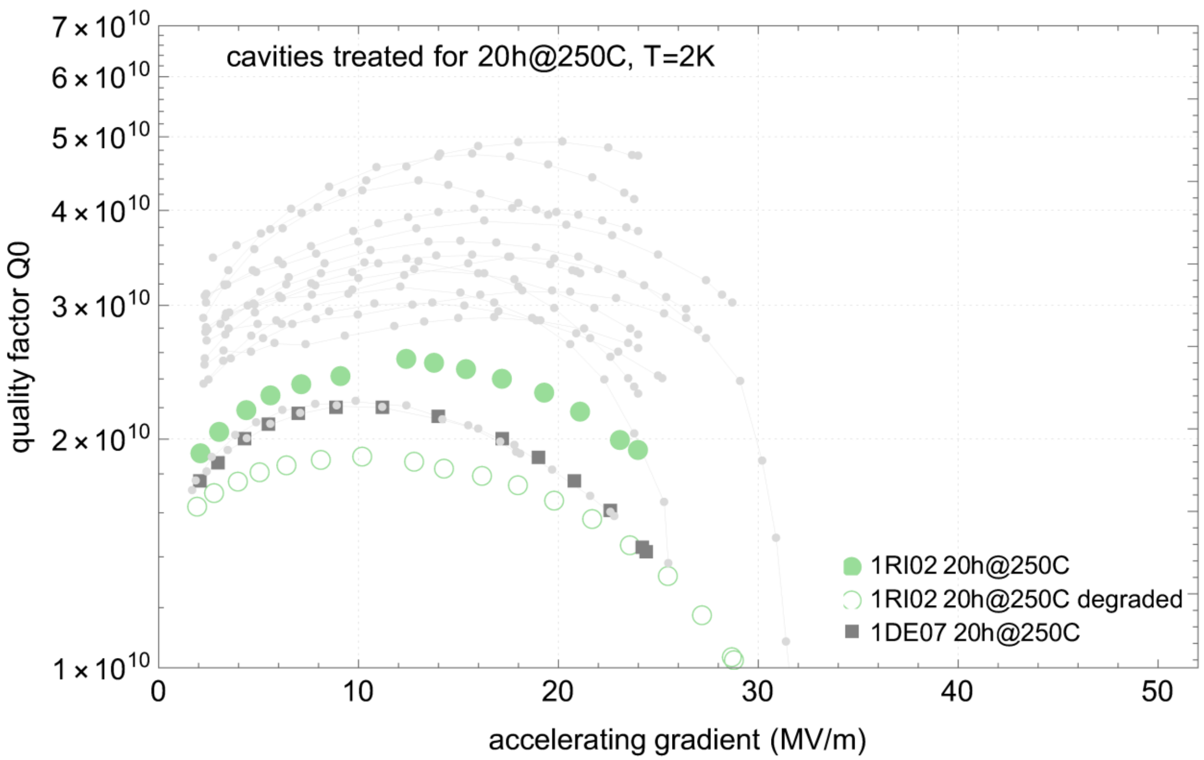

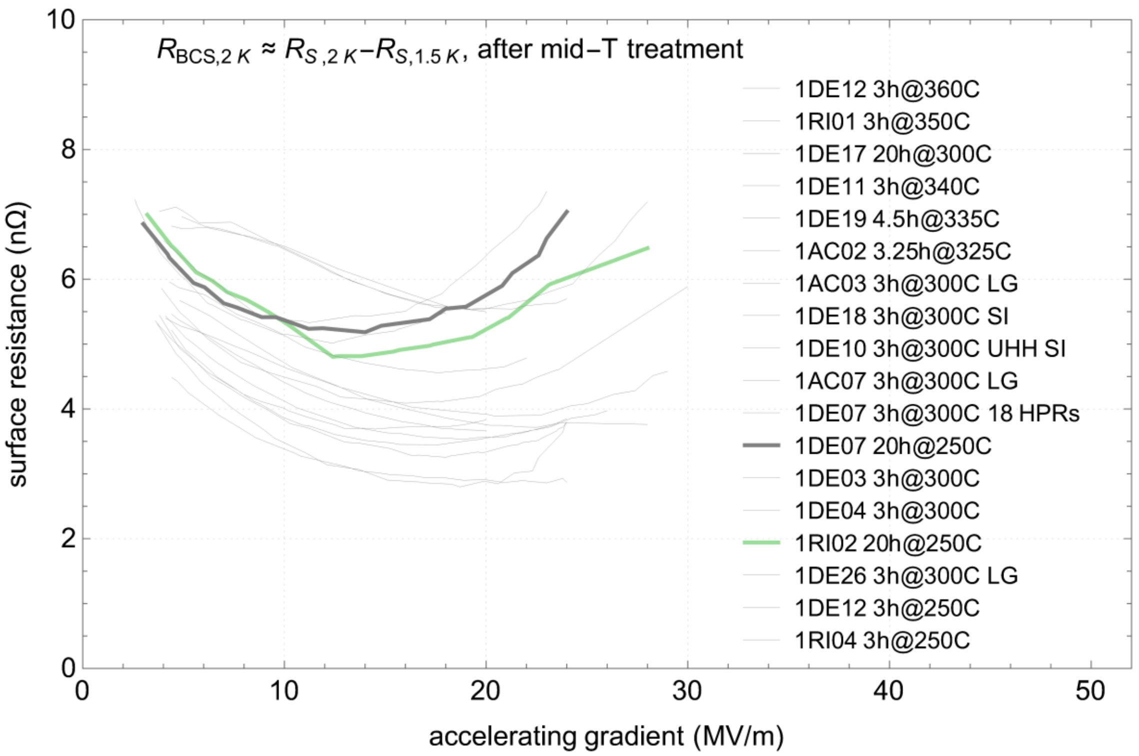

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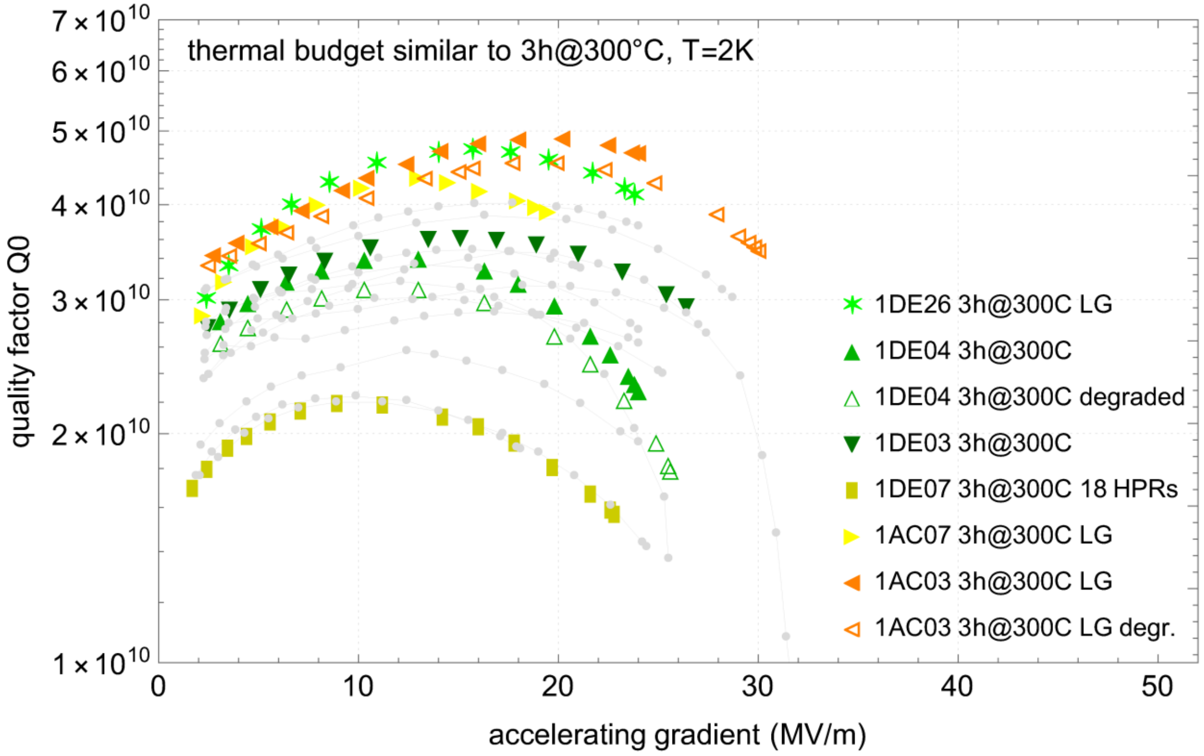

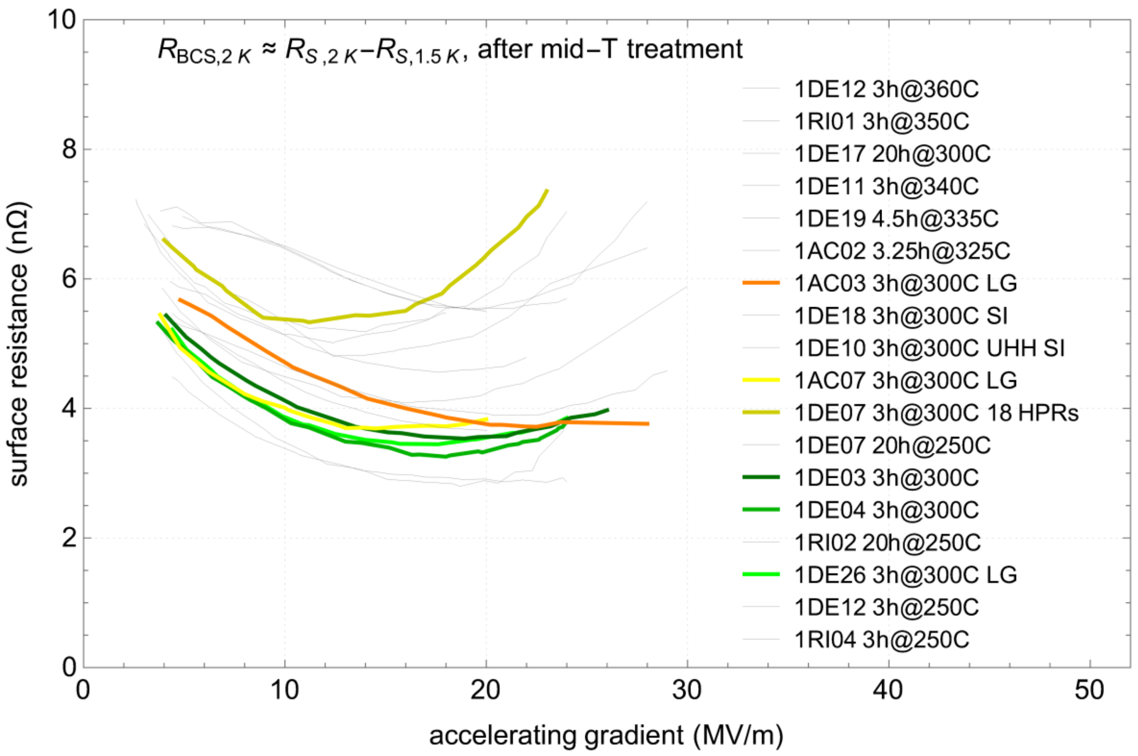

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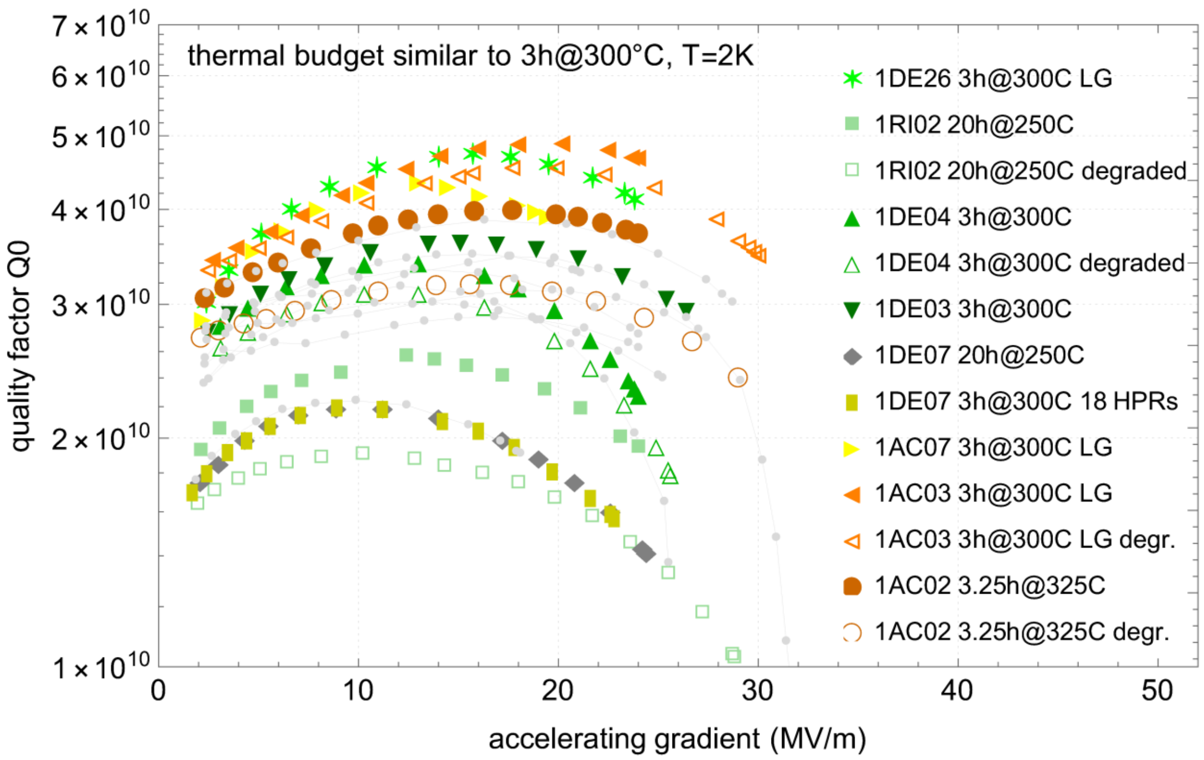

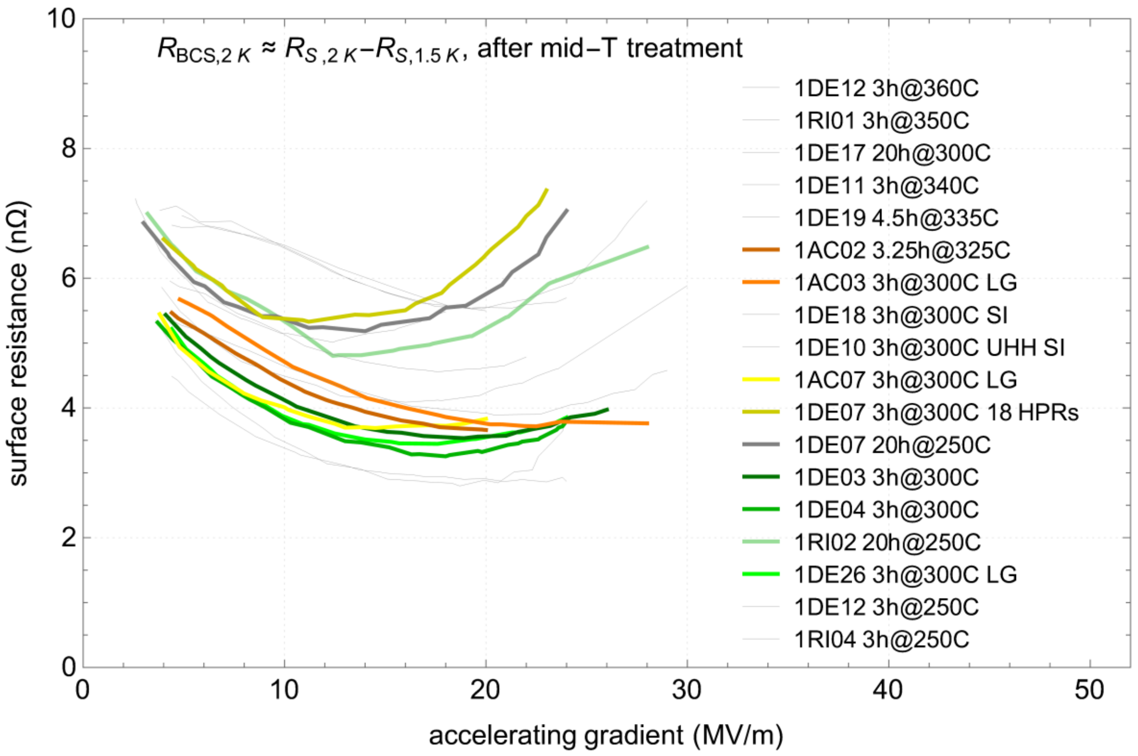

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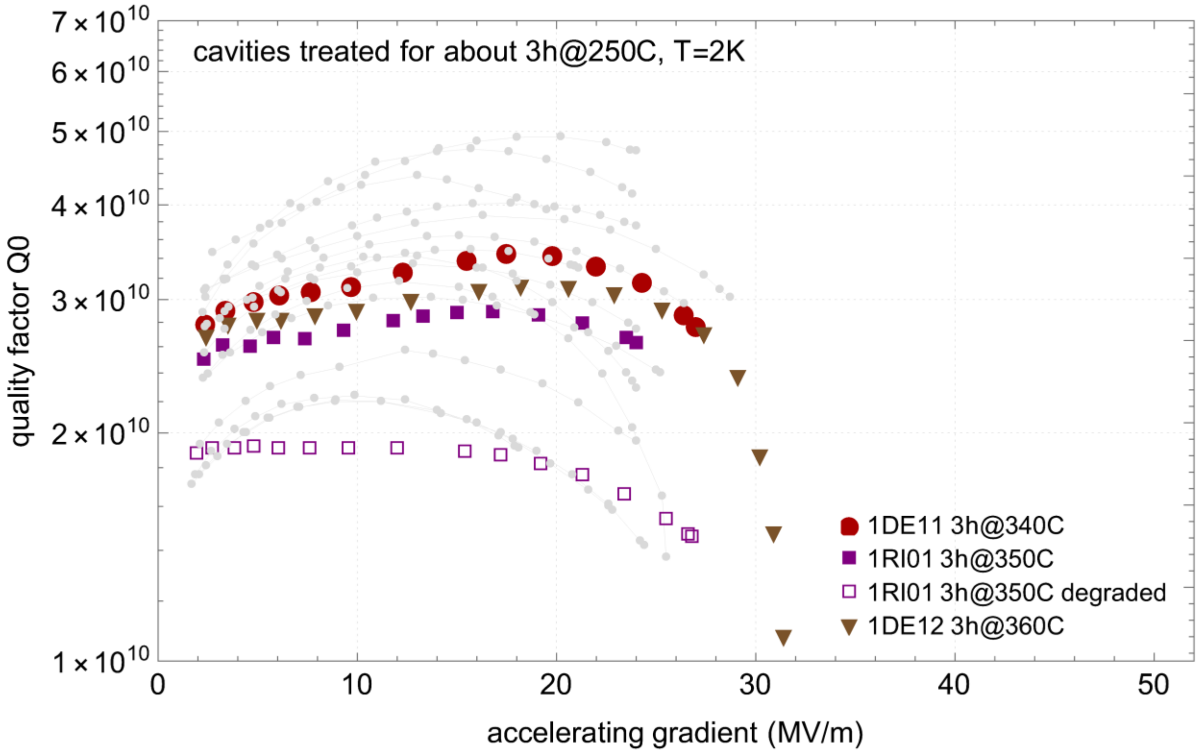
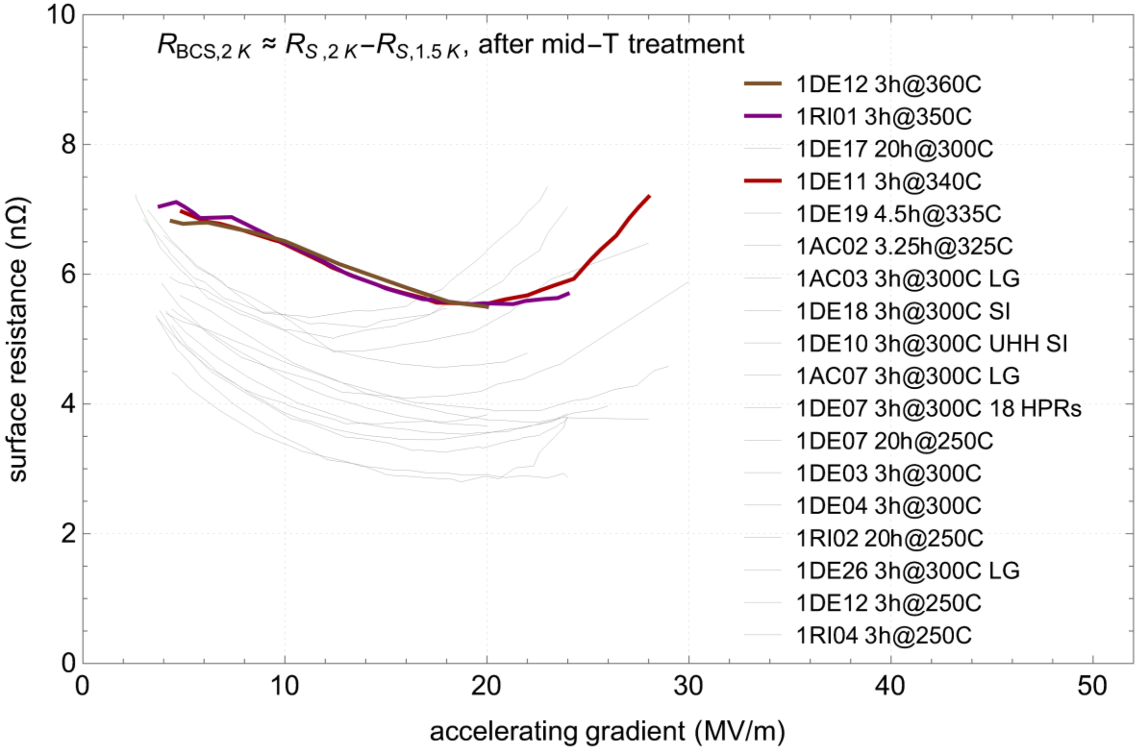
On the edge of Mid-T - 350°C lead to HFQS

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

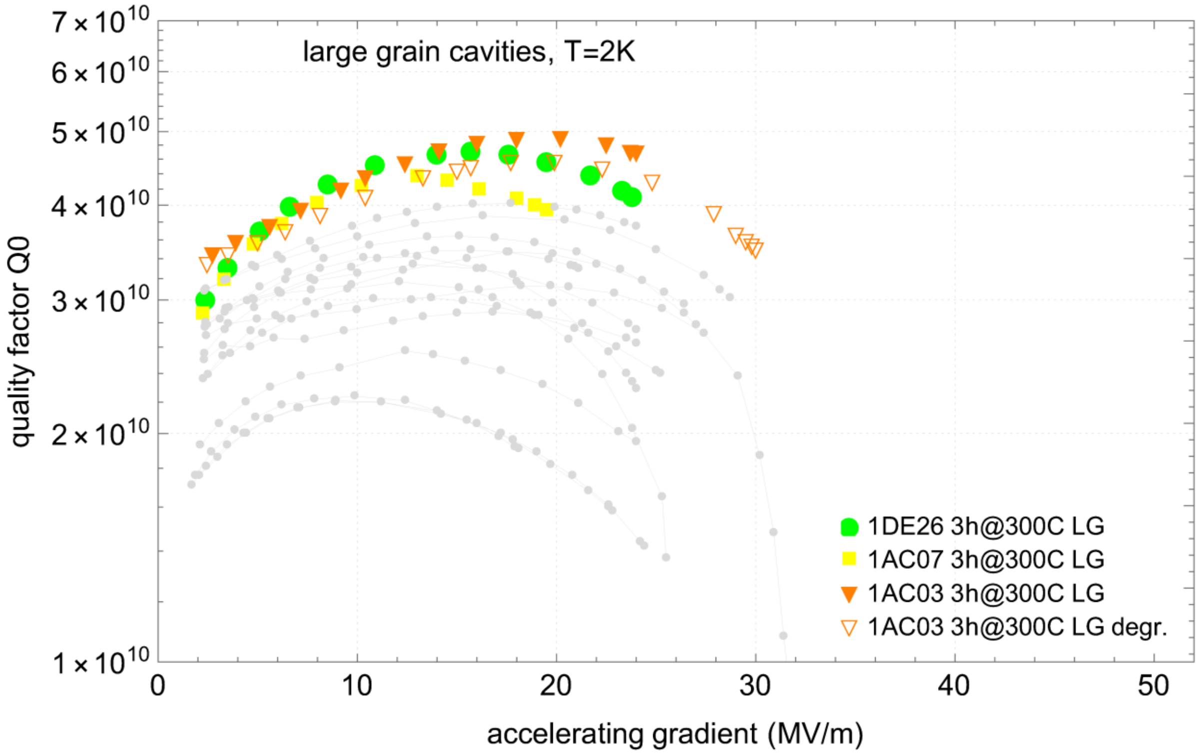


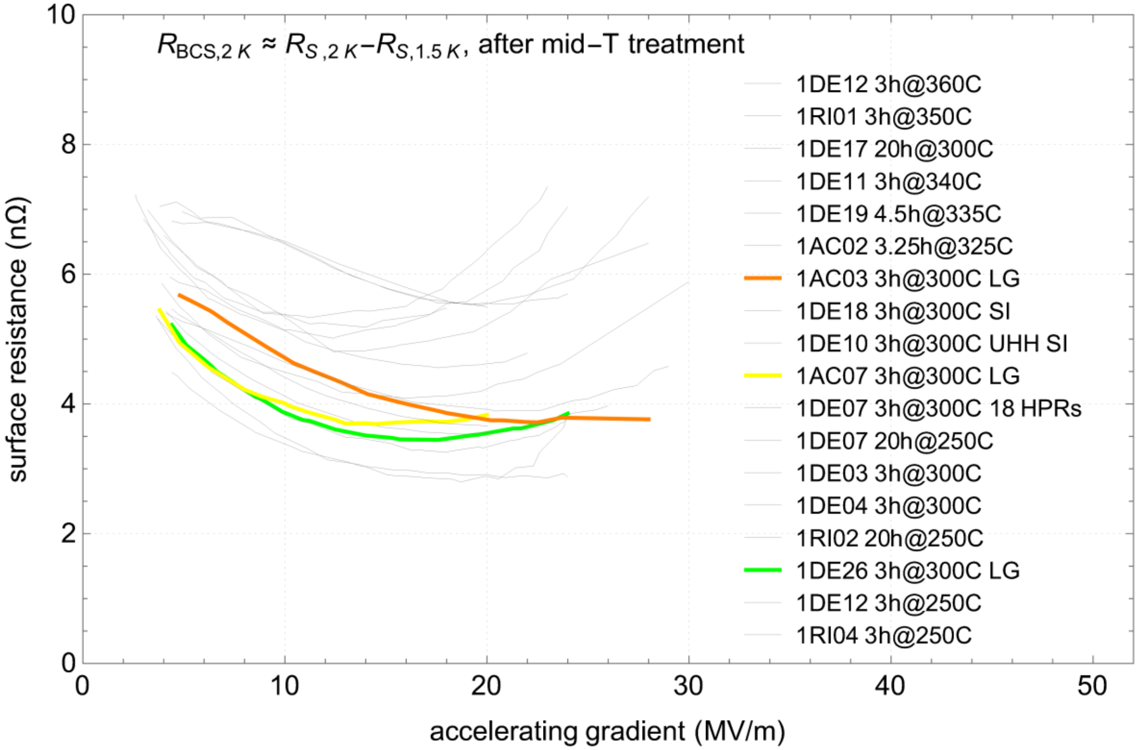


- Slightly lower Q_0 for gradients in region of 25-30 MV/m
- High field Q-Slope!
  - 350°C lowest temperature to cause this?! → At 350°C Pentoxides are gone!
- Differences are particularly reflected in R_{BCS}!

Large grain cavities are high performer!

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

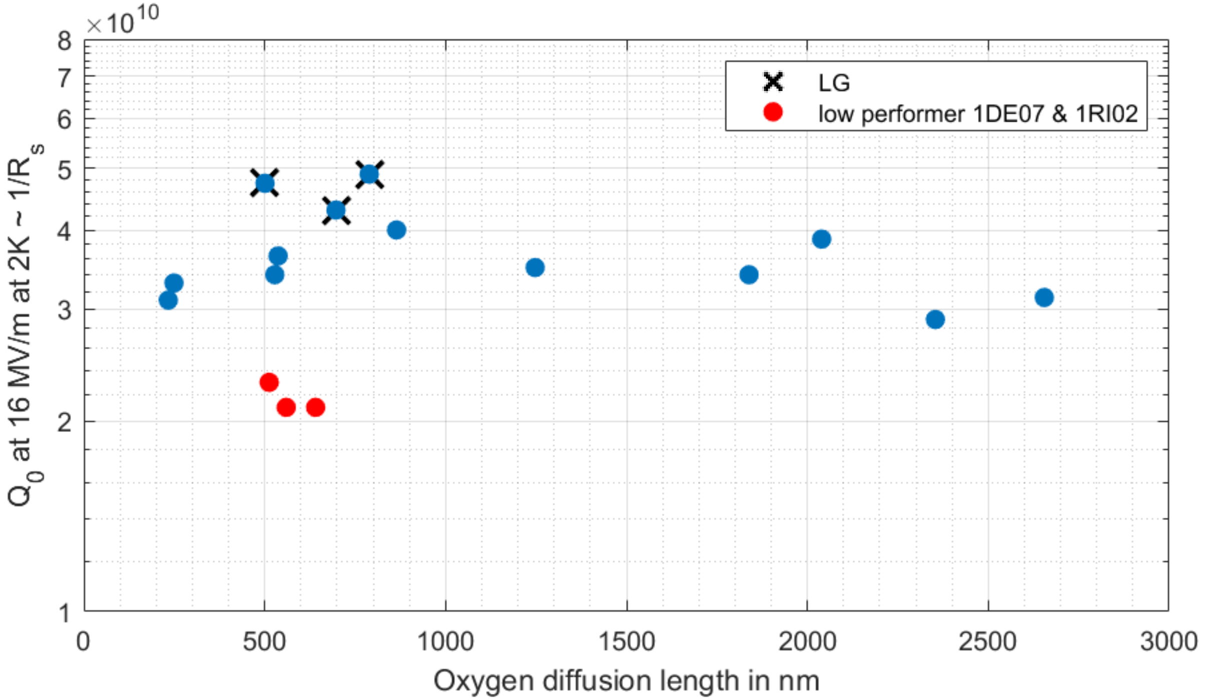


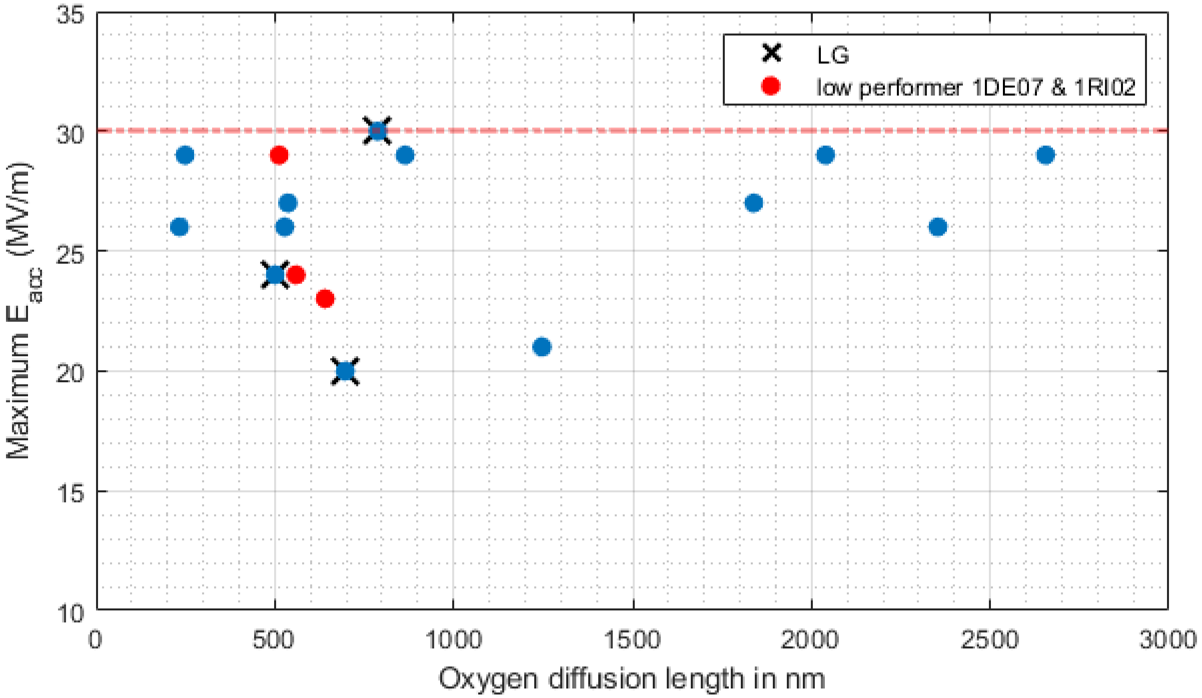


- Mid-T treatments works very well with LG cavities
- R_{BCS} values similar to FG → main improvement comes from R_{res}!

Correlation of performance with oxygen diffusion length

Q_0 & E_{acc}

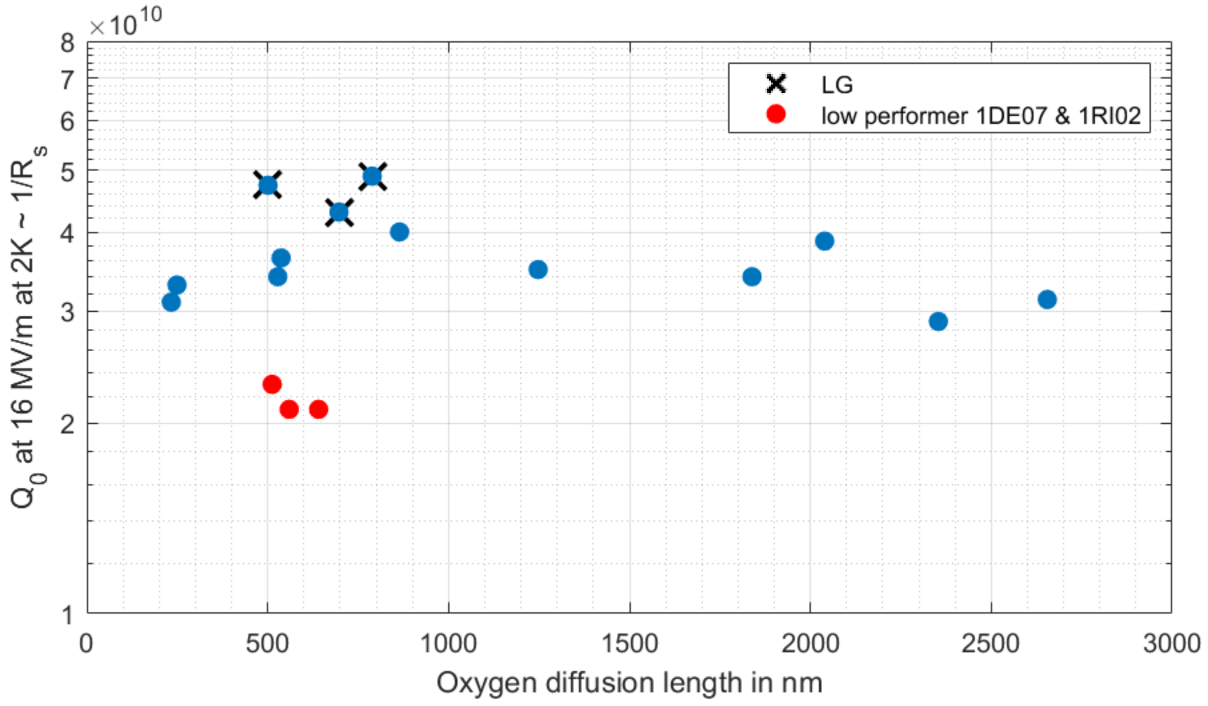


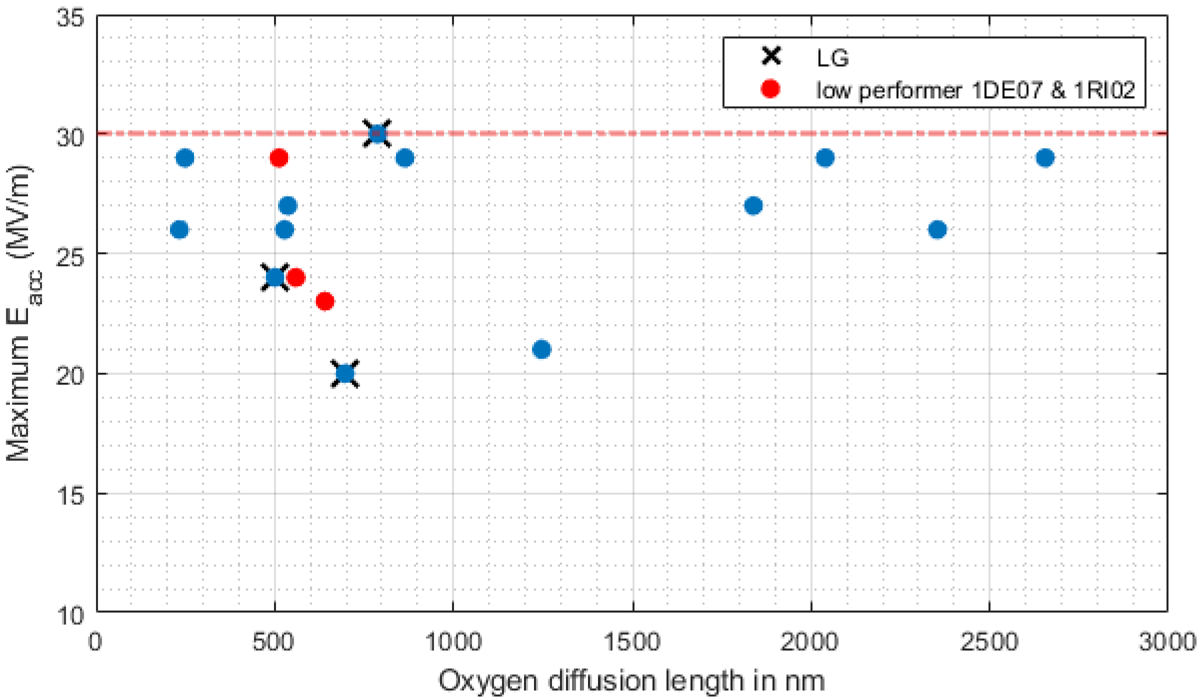


- **No clear trend** for Q_0 or E_{acc} against diffusion length (thermal budget)

Correlation of performance with oxygen diffusion length

Q_0 & E_{acc}

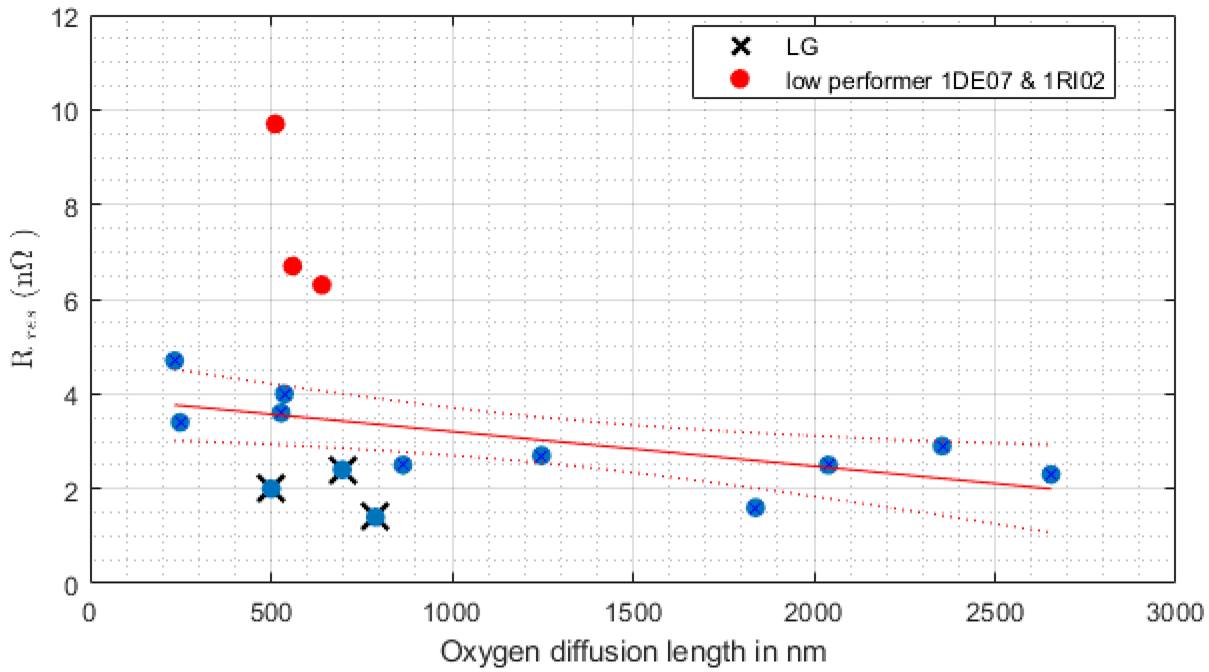


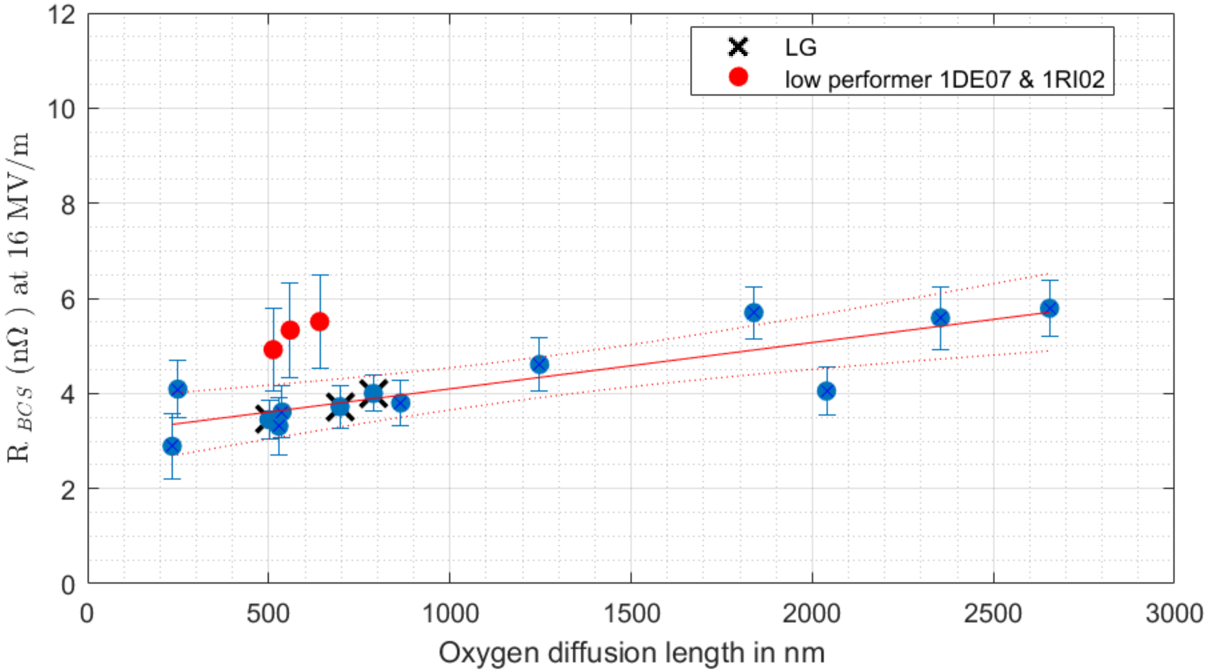


- **No clear trend** for Q_0 or E_{acc} against diffusion length (thermal budget)
  - Or maybe for Q0?

Correlation of performance with oxygen diffusion length

R_{res} & R_{BCS}





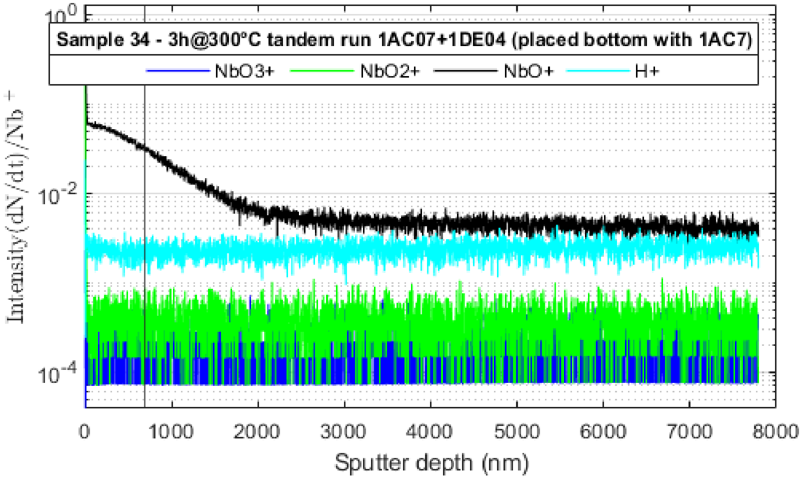
- Neglecting outliers, **a trend is observable**
- Data suggests the possibility of an optimization issue related to diffusion length (thermal budget)
- More data needed to fill the gaps

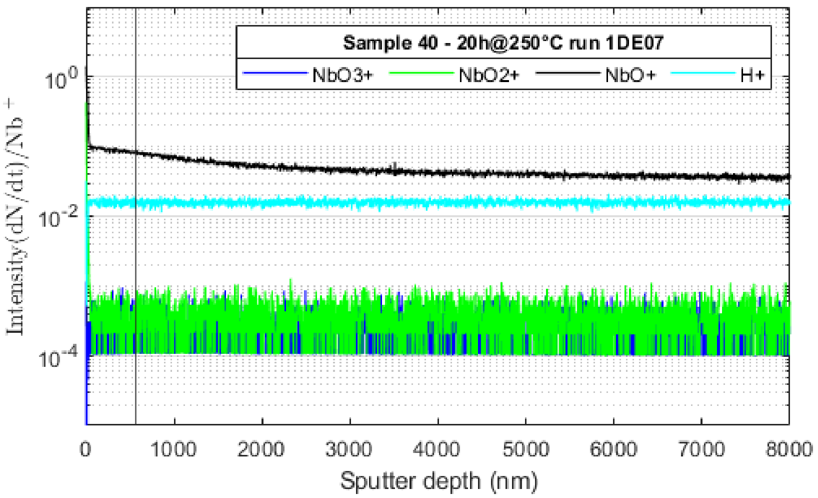
Oxygen diffusion length measurements on samples

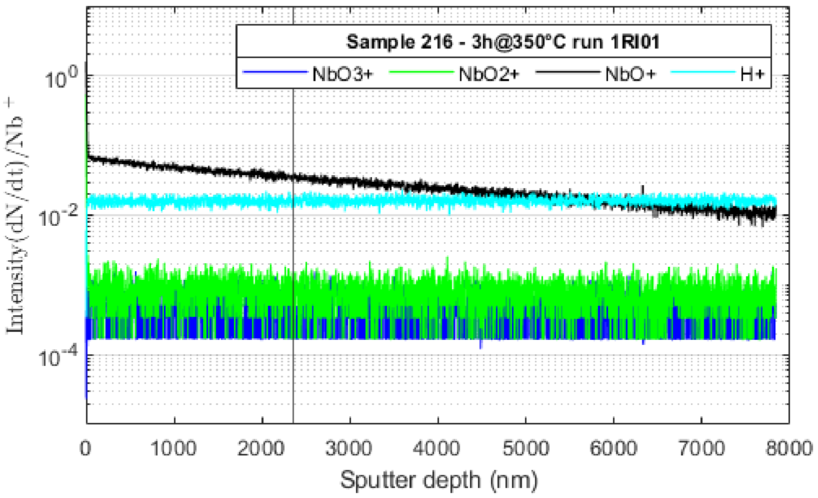
SIMS profiles - deep sputtering

Calculated diffusion length from temperature profile:

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





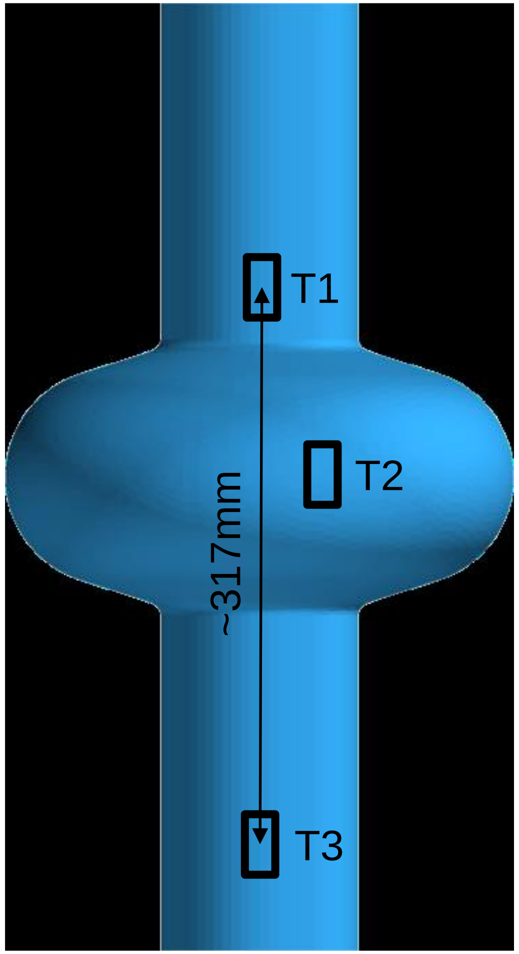


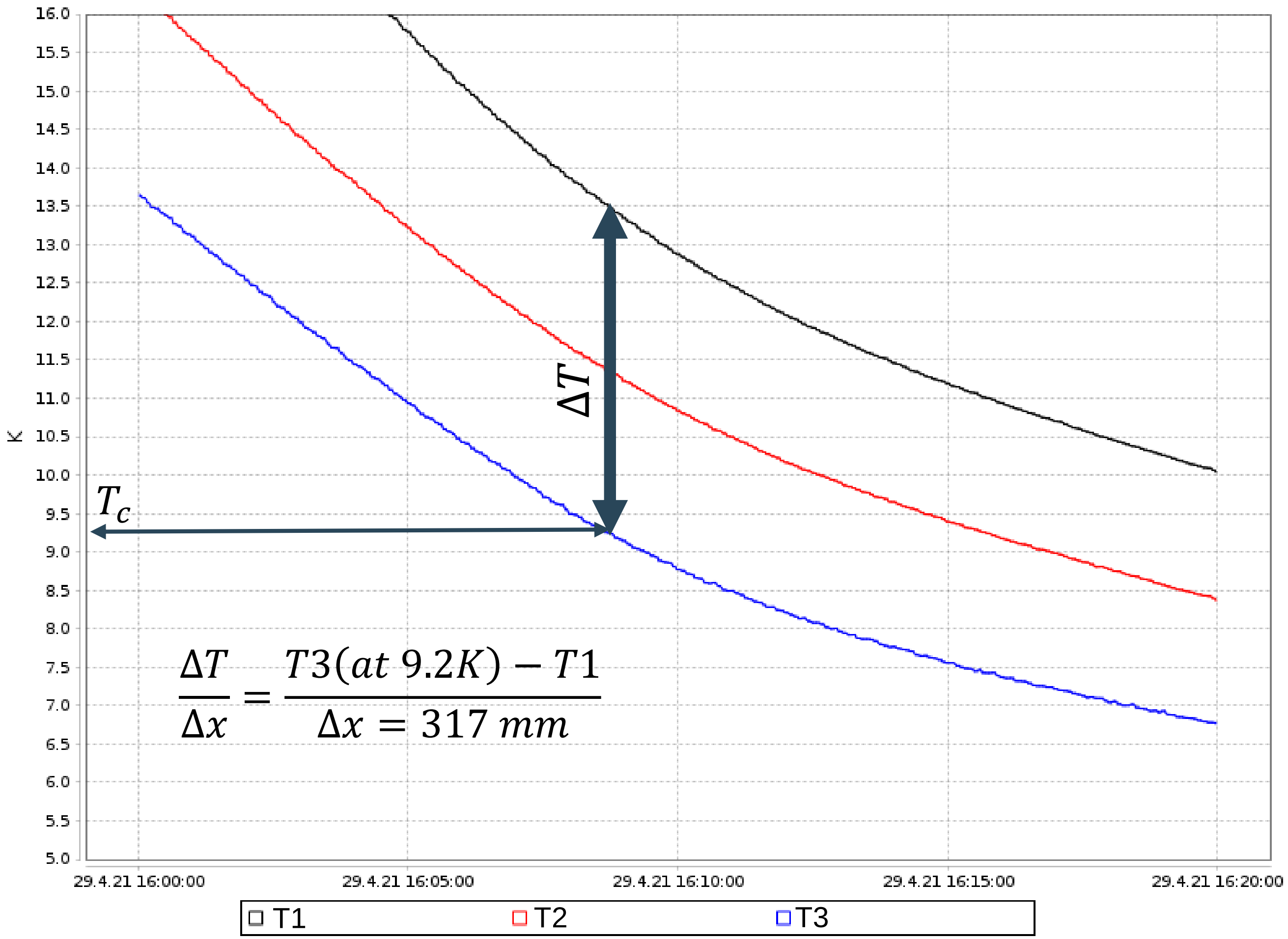
Measurement conducted at IFAM, Bremen, Germany

- 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

Spatial temperature gradient of cooldown

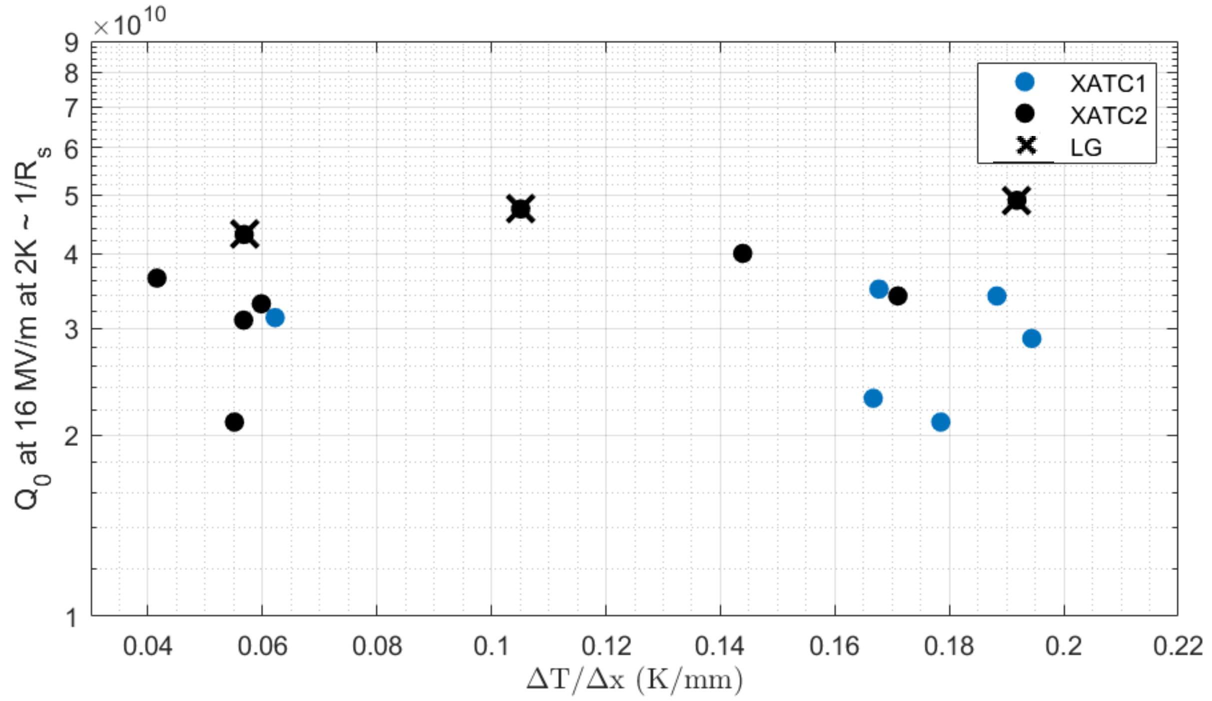
Determined by temperature sensors at cavity

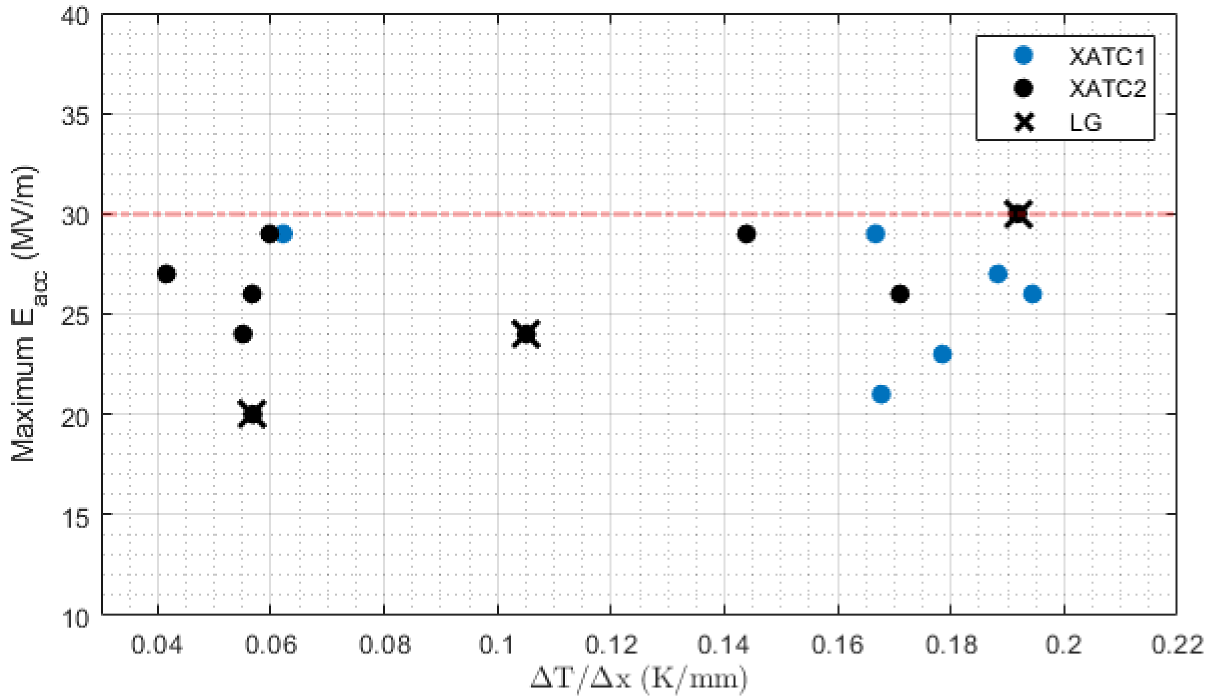




Spatial cooldown gradient dependency to performance

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

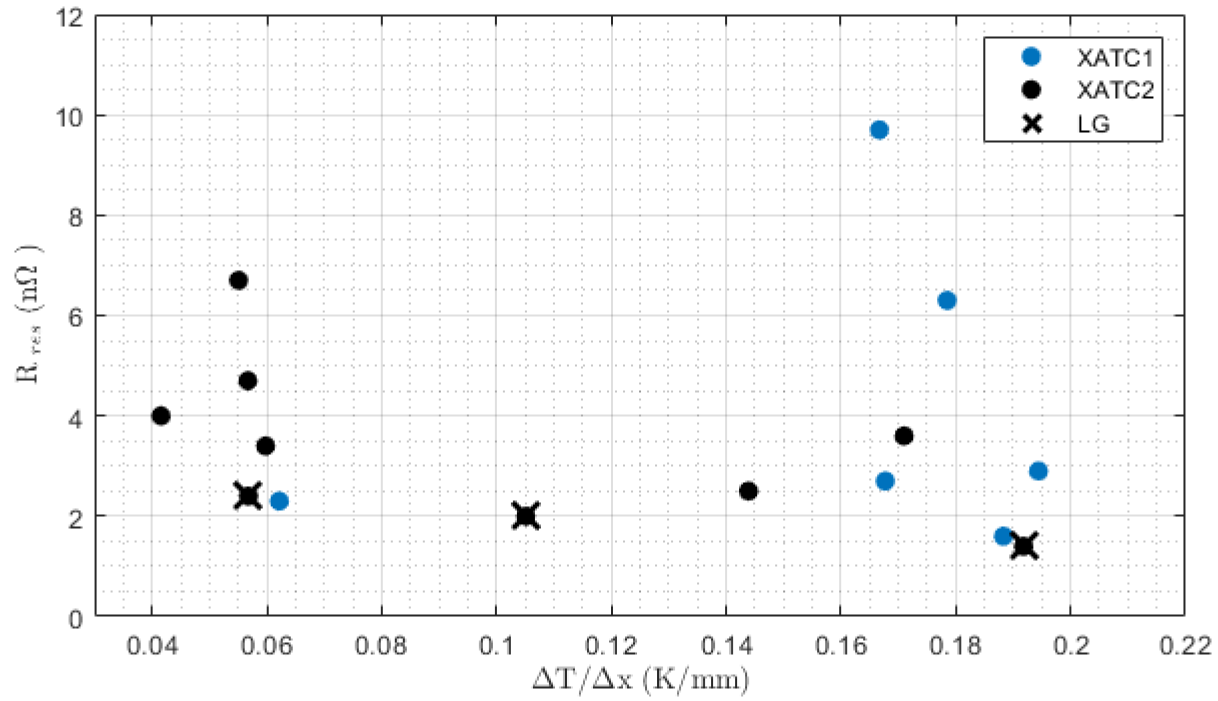


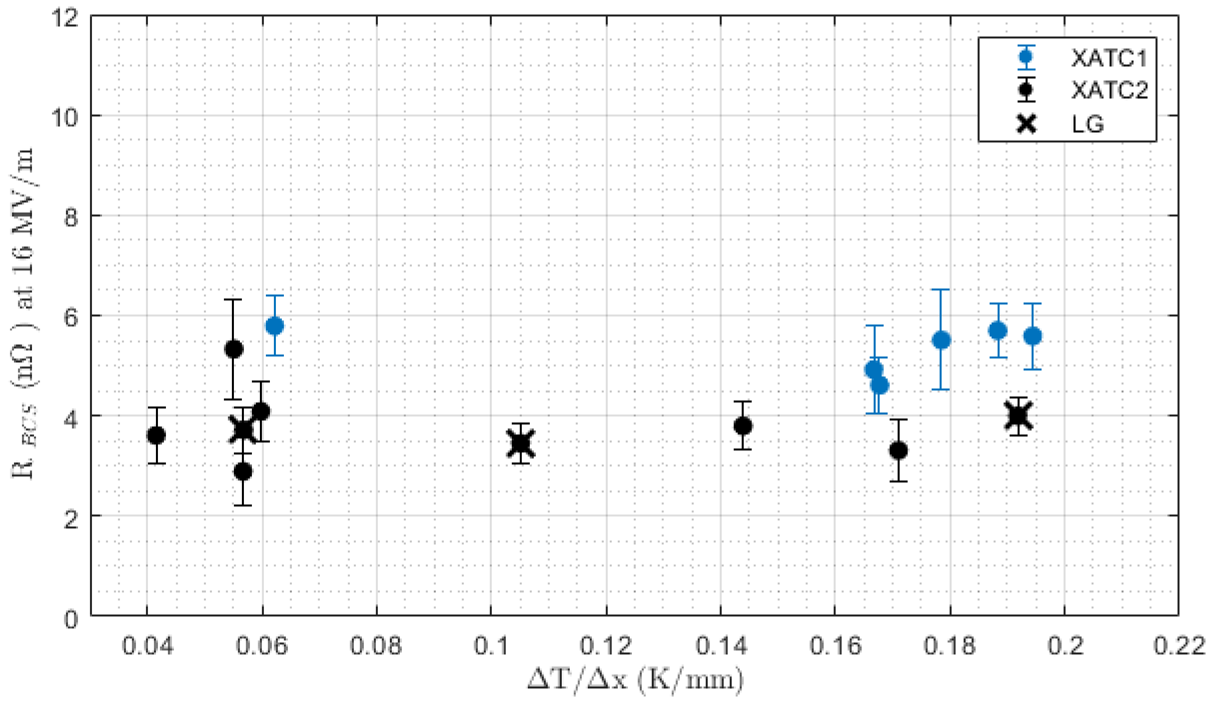


- **No correlation to performance observed**
- Two ranges of $^{\Delta T}/_{\Delta x}$ observable → attributed to our two test setups

Spatial cooldown gradient dependency to performance

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





- **No correlation to to R_{res} and R_{BCS}**
- Lower limit of ~2nΩ for R_{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_{BCS} (?!)

Summary and outlook for the mid-T campaign at DESY

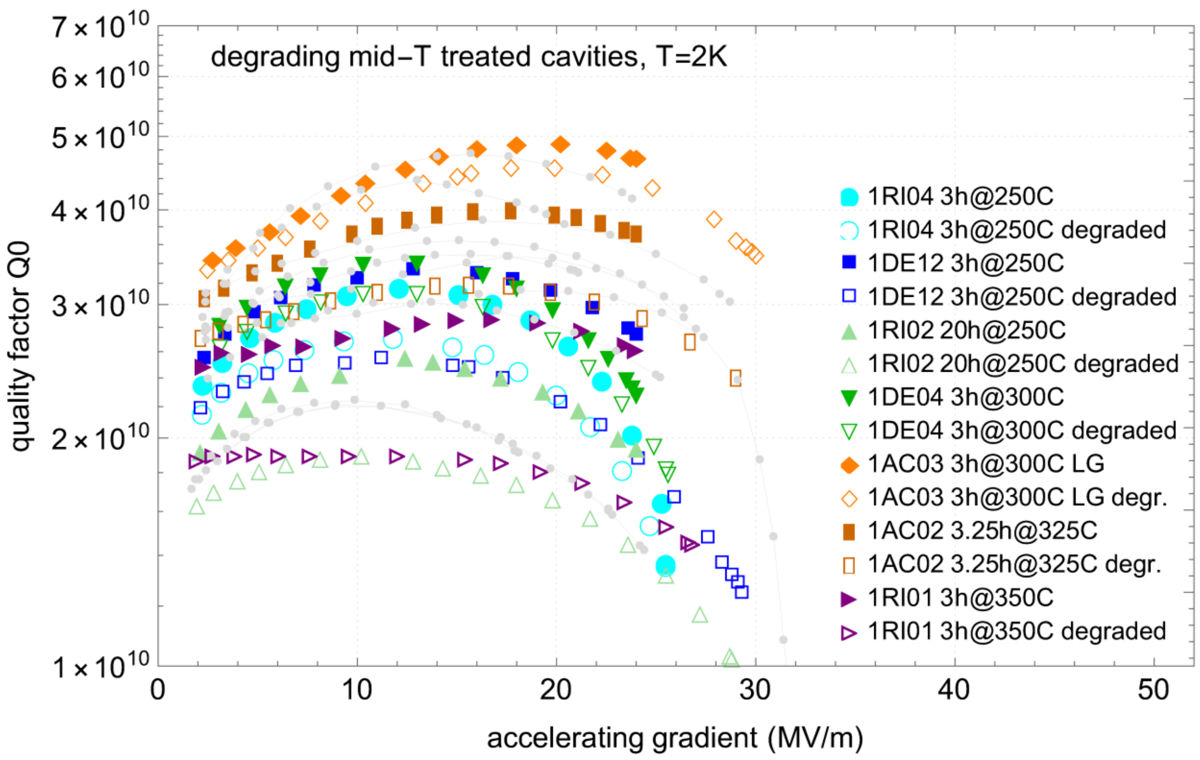
The amount of data has increased and we are filling the gaps

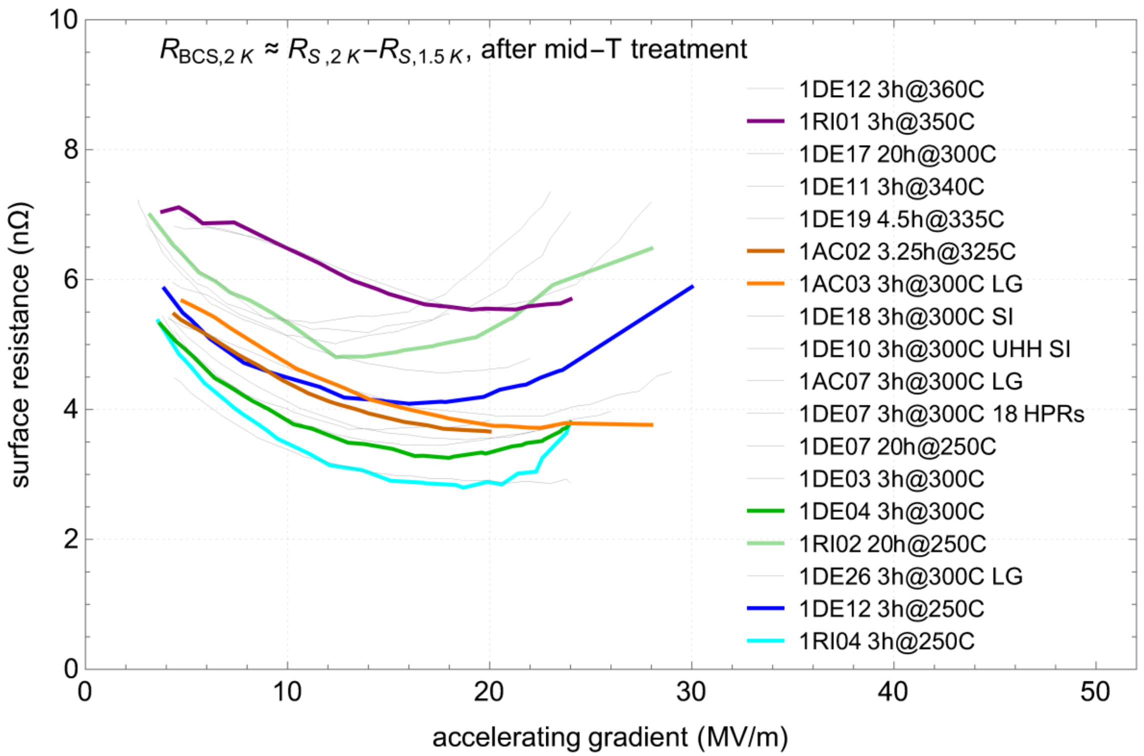
- Very high reproducibility of characteristic results
  - The 30 MV/m is still an unbreakable wall
  - 7 out of 18 cavities degrade after quenching (restorable by T_c cycling)
- LG cavities show best performances
- Sorting by thermal budget appears to provide insights
- 350°C edge to new characteristic 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

Q_0 Degradation after quench

Some cavities degrade in Q_0 after a quench





- Some cavities exhibit the phenomenon of degrading in quality after quenching
- Not attributable to any specific treatment group → not yet understood the cause