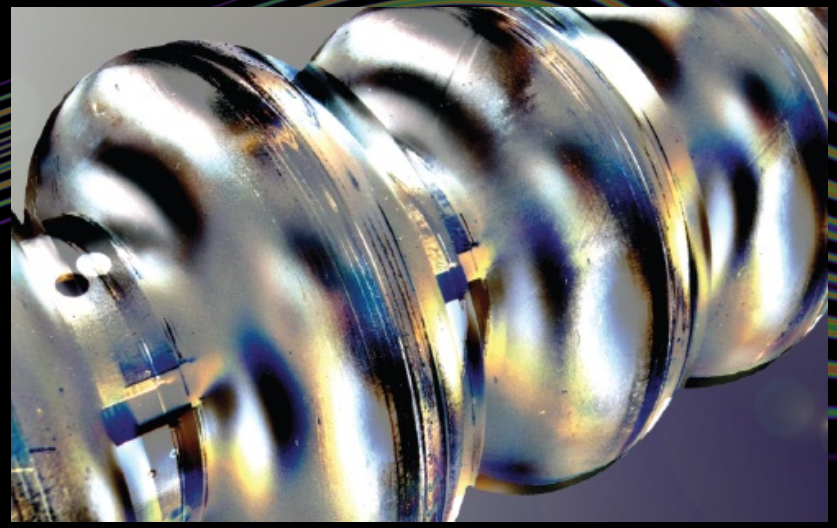
superconducting cavity R&D @ DESY

towards continuous wave operation of the European XFEL



Lea Steder on behalf of the SRF team at DESY
4th Annual MT Meeting, HZB
12 – 14 June 2018

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

MT
MATTER AND TECHNOLOGIES

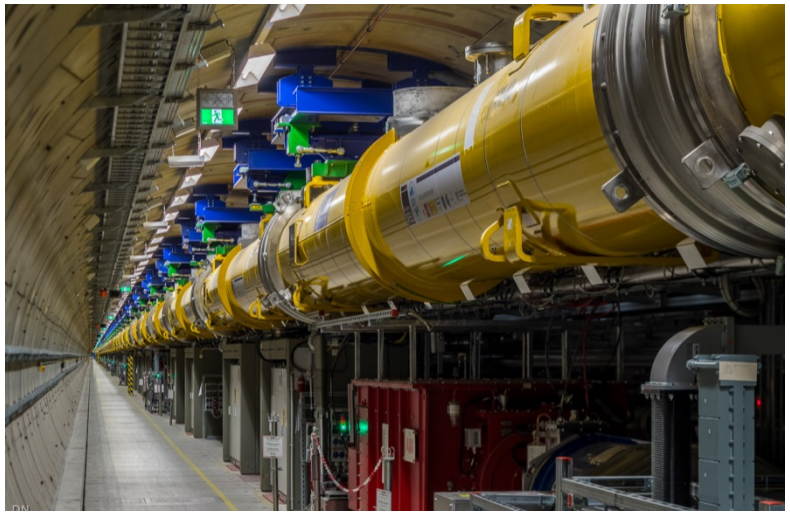
DESY.

superconducting radiofrequency technology

European XFEL defining the standard

- superconducting radiofrequency (SRF) cavities are figurehead of DESY's engagement for accelerator science
- other projects like LCLS-II, ESS, new SRF based FELs e.g. @ SINAP are profiting from successful technology transfer to industry
- European XFEL is longest SRF linear accelerator worldwide ~ 800 cavities
  - average accelerating gradient 30 MV/m (design: 23.6 MV/m)
  - average quality factor 1.4 x 10^{10} (design 1.0 x 10^{10})

[D. Reschke et al., PhysRevAccelBeams.20.042004 (2017)]



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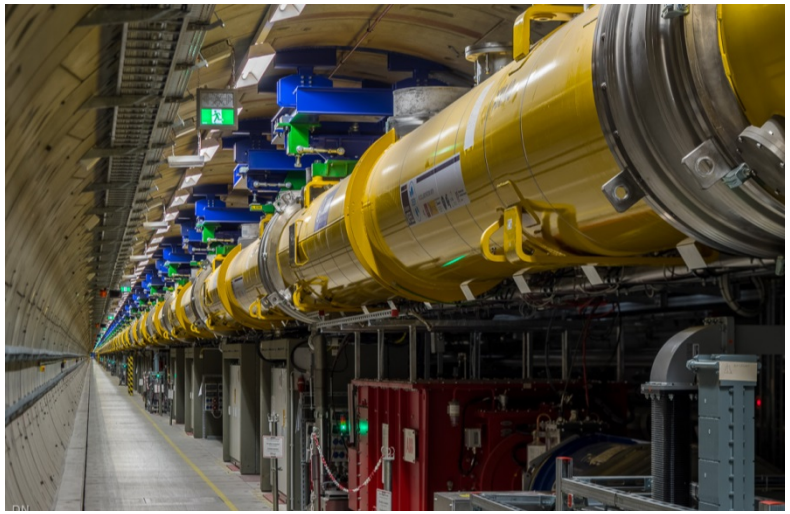
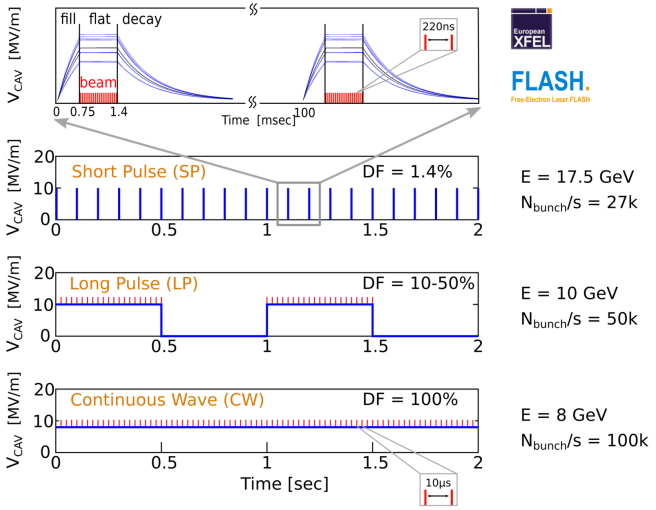
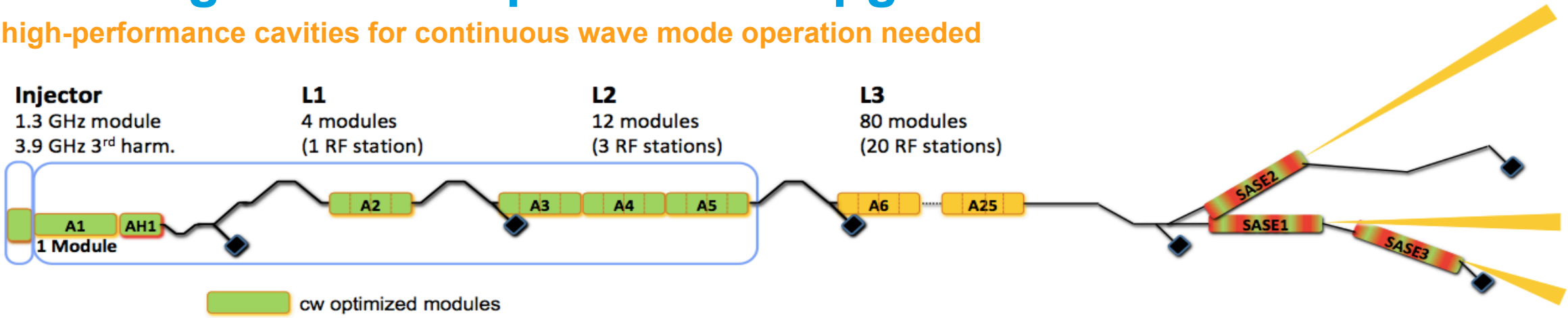


- future goal for European XFEL: **flexible beam patterns** for experiments
  - short pulses with high energy of 17.5 GeV
  - long pulses (duty factor 10-50 %) with medium energy of 10 GeV
  - continuous wave (cw) mode at 8 GeV



challenges for European XFEL upgrade

high-performance cavities for continuous wave mode operation needed



- second injector for continuous wave operation *talk E. Vogel*
- first 17 cryo-modules to be exchanged: 136 new cavities
- L3 remains untouched but old modules can lengthen L3
- cw-mode capable RF sources (1 IOT per station, + 4 stations in L3)
- cryo plant needs twice the power: 2.5 ➔ 5 kW *poster A. Bellandi*

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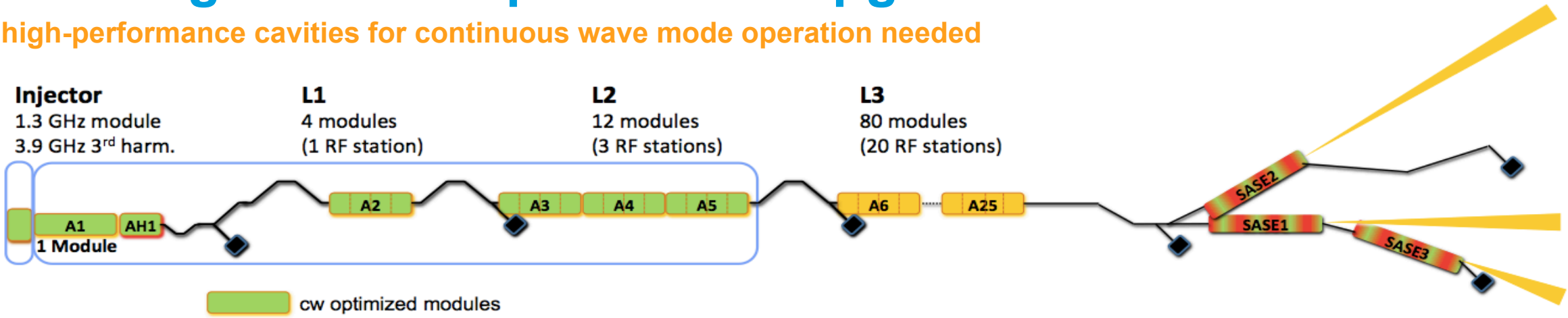

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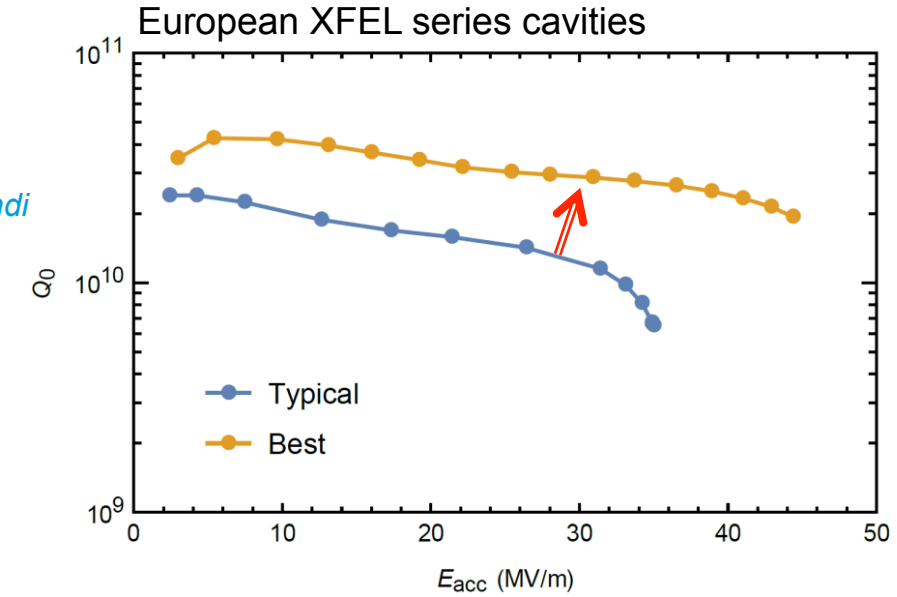
poster A. Bellandi

- requirements for **new cavities**
  - high Q_0 since $1/Q \sim P_{RF,loss} \sim P_{cryo,dyn}$
  - high gradient for short pulse operation



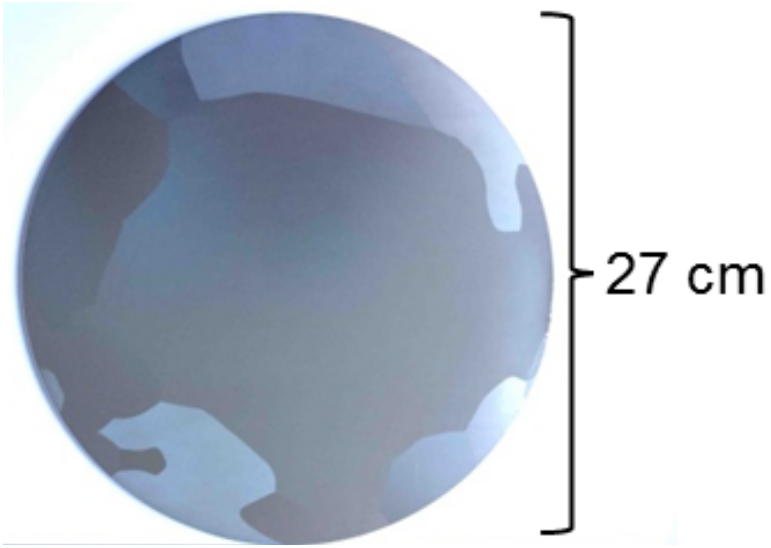
cavity R&D topics within ARD ST1

improved niobium material and new surface treatments

- two SRF R&D topics identified
  - **large grain niobium**

    disks for cavity production based on the existing world-leading experience at DESY
  - **nitrogen infusion**

    a novel surface treatment applying a partial pressure of nitrogen during heat treatment developed at Fermilab



large grain cavity R&D

engineering and surface physics towards high-performance cavities

- fine grain (FG) niobium: typical grain size of ~ 50 µm
  - well-known mechanical & physical properties, commercially available, used for all recent SRF accelerator projects (XFEL, LCLS-2, ESS, MESA)
- large grain (LG) niobium: typical grain size of ~ cm
  - first R&D during preparation phase for European XFEL

[W. Singer et al., PhysRevSTAB.16.012003 (2013)]
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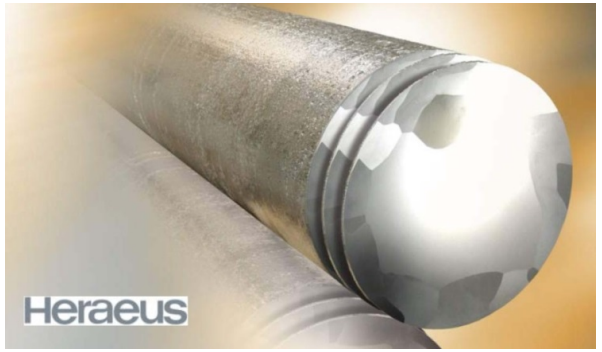

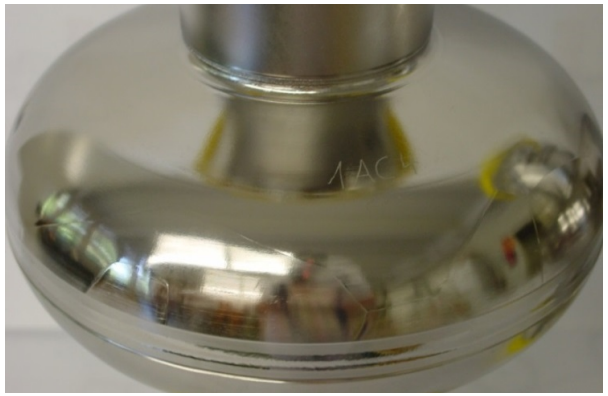

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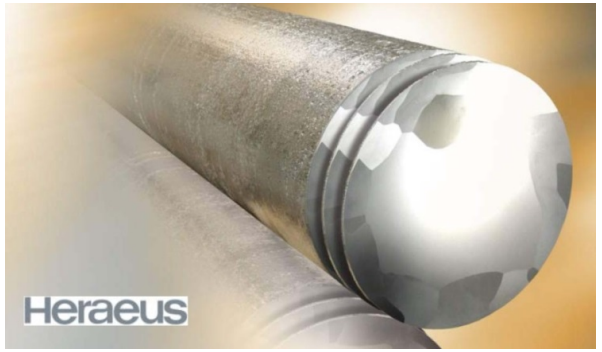

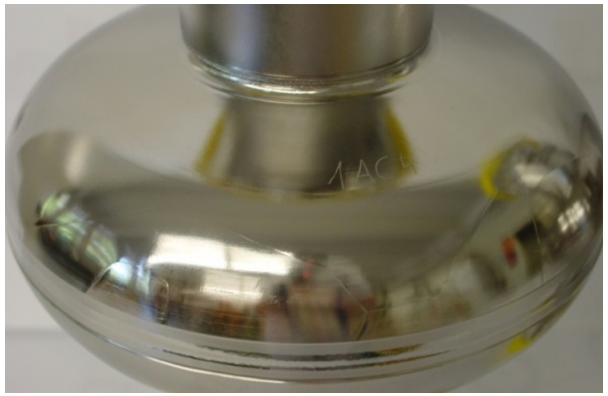

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- specification for material, mechanical forming and welding process to be defined
  - compatibility with pressure equipment directive (PED)
    → investigation of mechanical properties LG disks from different vendors

➔ **stable industrial high-performance cavity production**

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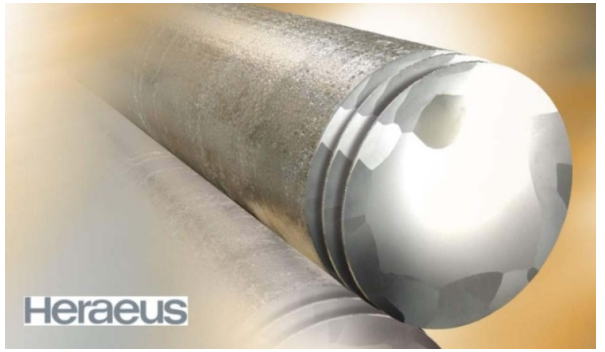
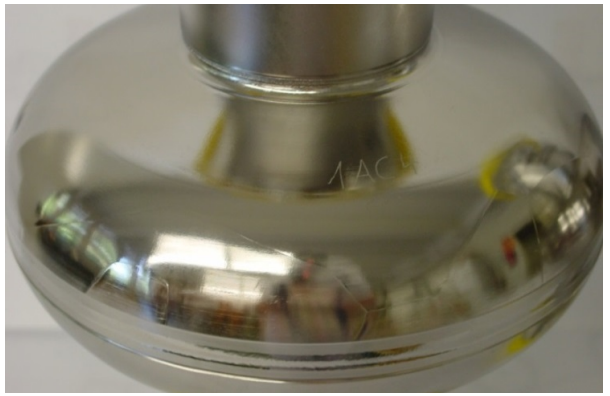
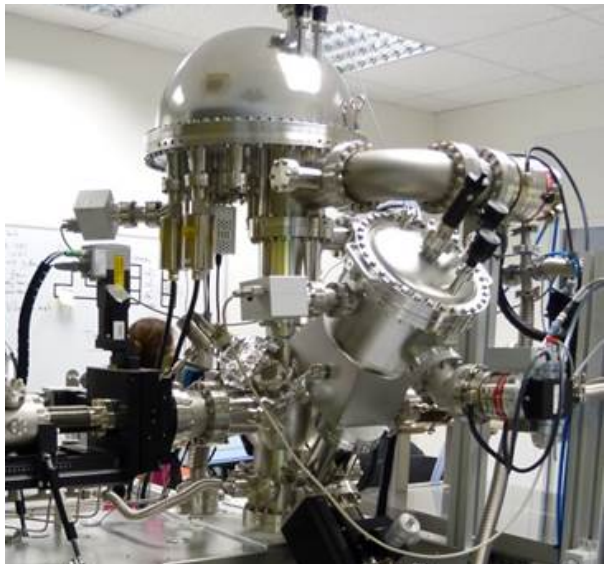
➔ **stable industrial high-performance cavity production**

- surface-sensitive characterization techniques and analysis of existing cavity test data
  - investigation of grain boundaries (less than in FG) - responsible for RF losses?
  - systematic studies of correlations between cavity treatment and performance

➔ **identification of surface properties correlating with cavity performance**





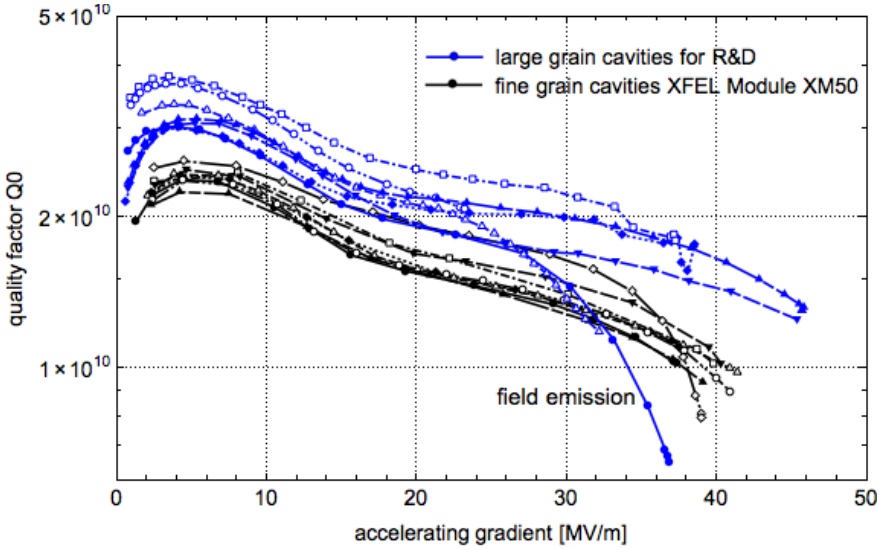


performance of large grain niobium cavities

promising Q_0 values in vertical and module tests

- 11 nine-cell, several three- and single-cell large grain **cavities** fabricated
  ➔ world class performance

- vertical test comparison to fine grain cavities
  - for standard EP surface treatment about 25 % higher Q_0
  - same reach for high accelerating gradients



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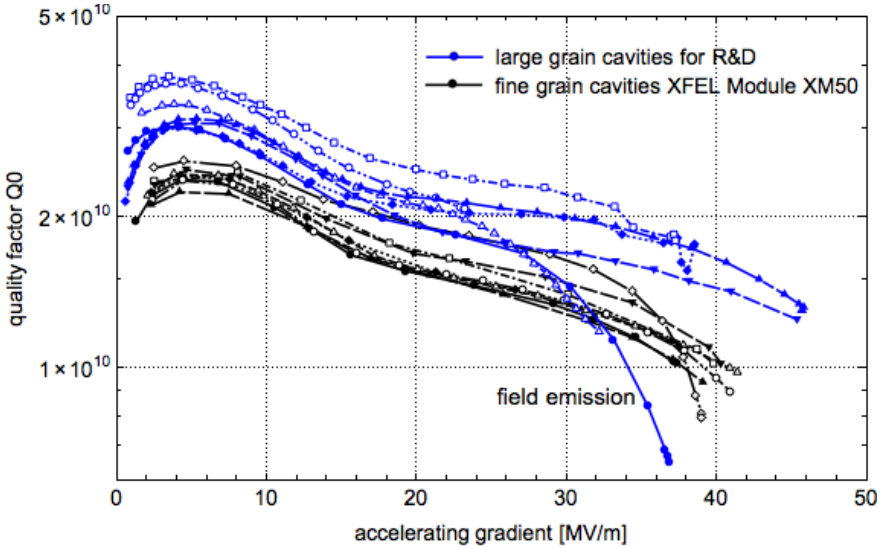
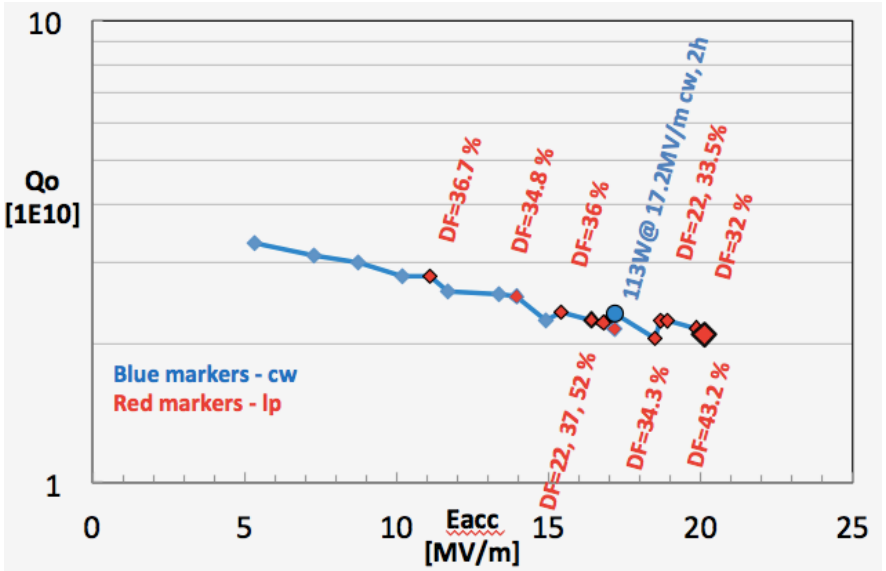
- European XFEL pre-series **cryo-module** XM-3 with 7 LG + 1 FG cavities
  ➔ cw operation with excellent results and stability

- module test in continuous wave and long pulse mode
  - stable operation at 17 MV/m and Q_0 of 2.3 x 10^{10} at 2K
  - long pulse operation with duty factors (DF) from 22-43 %
- long term (>7y) operation of two further LG cavities in FLASH modules



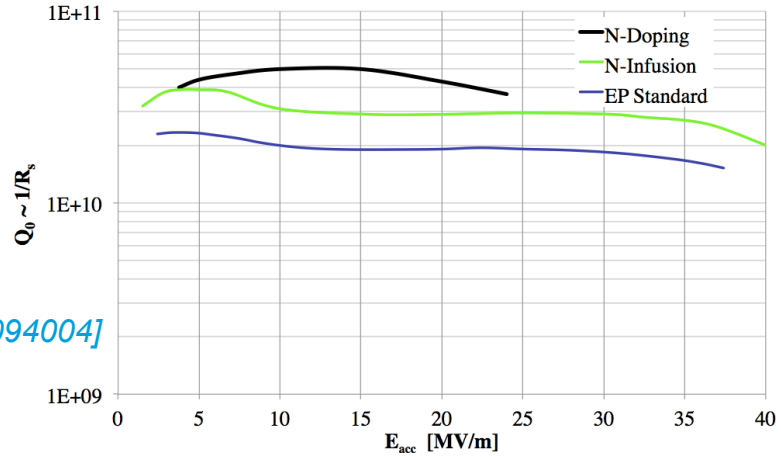


heat treatments in a partial pressure of nitrogen

nitrogen infusion as promising approach

- nitrogen infusion yields significant development of quality factors
  - baseline recipe: 3 hours heat treatment at 800°C, then 48 hours 120°C in UHV with nitrogen – partial pressure of 25 mTorr
  - no additional final EP treatment (as in standard surface treatment) necessary
  - high Q_0 and high gradients reported, *[A. Grasselino et al. 2017 Supercond. Sci. Technol. 30 094004]* but process still not reproducible in every attempt

➔ **goal: definition of stable recipe for high-performance cavities**



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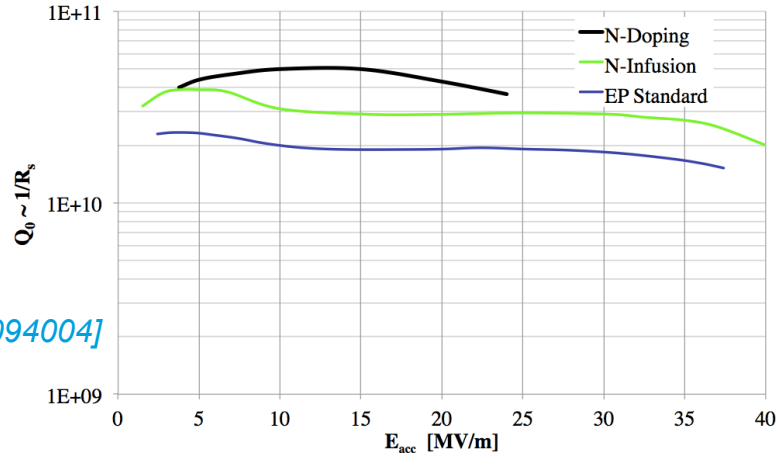

- two R&D approaches at DESY
  - in-situ infusion of samples followed by surface characterization techniques
    - ➔ understanding from surface physics point of view
  - heat treatment of cavities and samples
    - vertical tests of cavities
    - surface analysis of samples
    - ➔ correlation of surface and RF properties

poster G. Dalla Lana Semione

nitrogen infusion at Nanolab

surface characterization shows no nitrides

- to understand role of nitrogen in infusion process
  - sample treatment in UHV chamber on high-purity, UHV-annealed single crystal Nb (100) – as a model system
  - surface analysis wrt. oxides, nitrides, hydrides and interstitials
    - in-situ XRR and GIXRD experiments, XPS, SEM, AFM

[Dangwal Pandey, A., Dalla Lana Semione, G., Prudnikava, A. et al. J Mater Sci (2018) 53: 10411]

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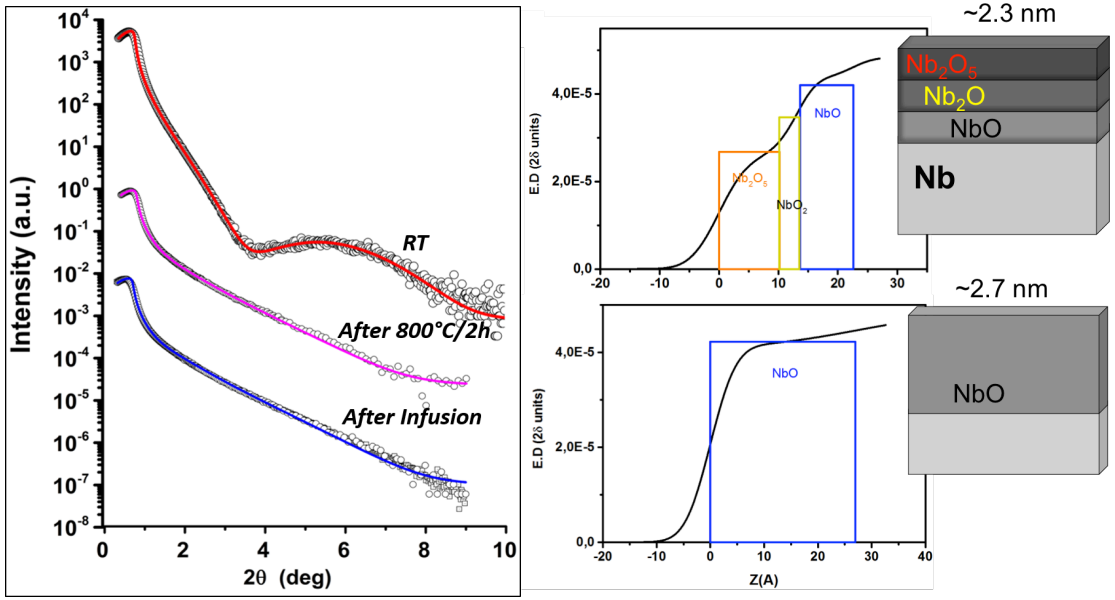
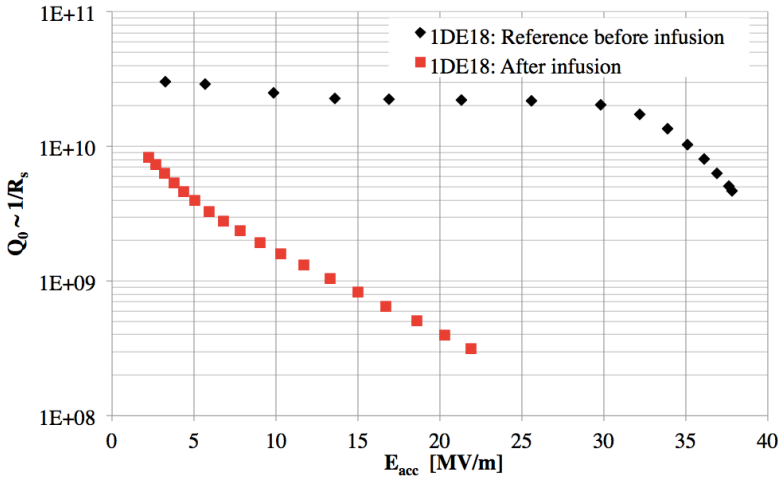
- results of in-situ XRR & XPS:
  - NbO phase present
  - but **no nitride phase** identified after nitrogen infusion process
  - no other unexpected layers
  - natural oxides re-grow after venting



poster C. Bate

evolution of infusion process at DESY

large parameter space to be controlled



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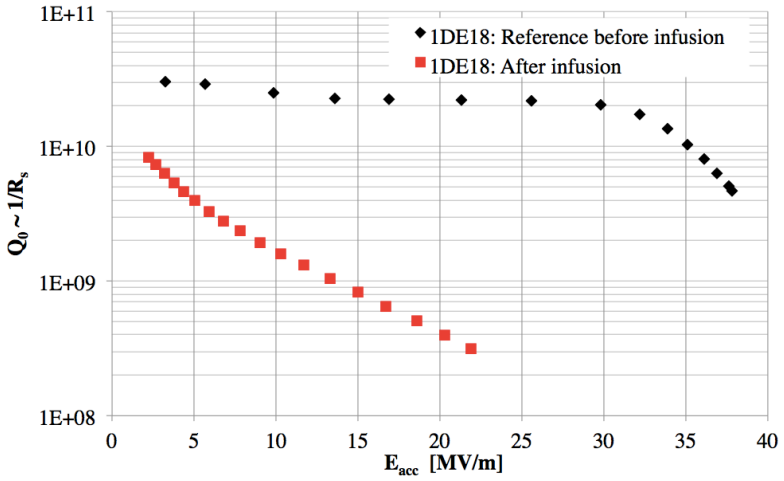
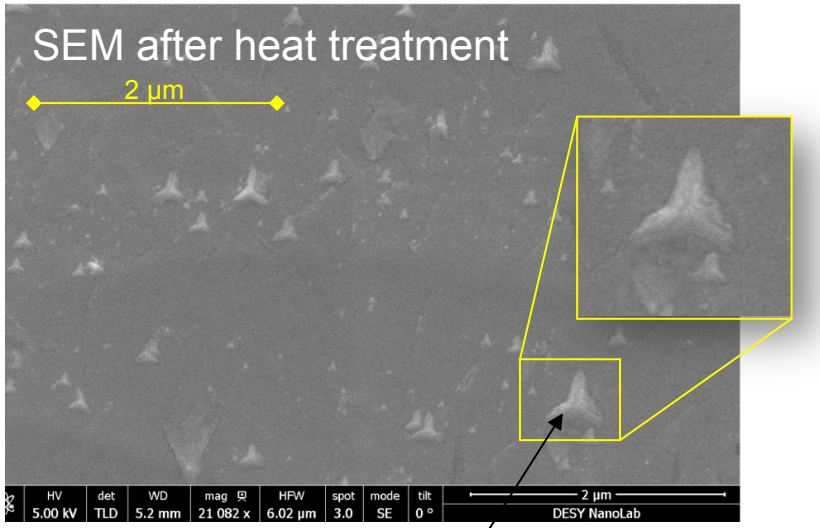
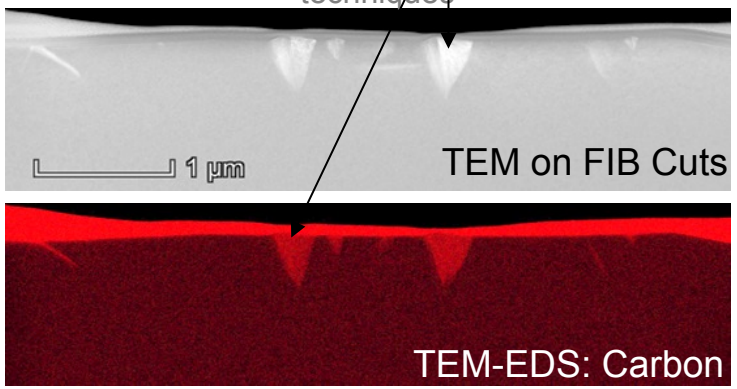


- first tests couldn't reproduce Fermilab results
- star-like structures found on samples
- possible hydro-carbon contamination of furnace
- process parameters compared to setups at other labs
- close collaboration with Fermilab



'star-like' precipitates identified as carbon using advanced surface analysis techniques



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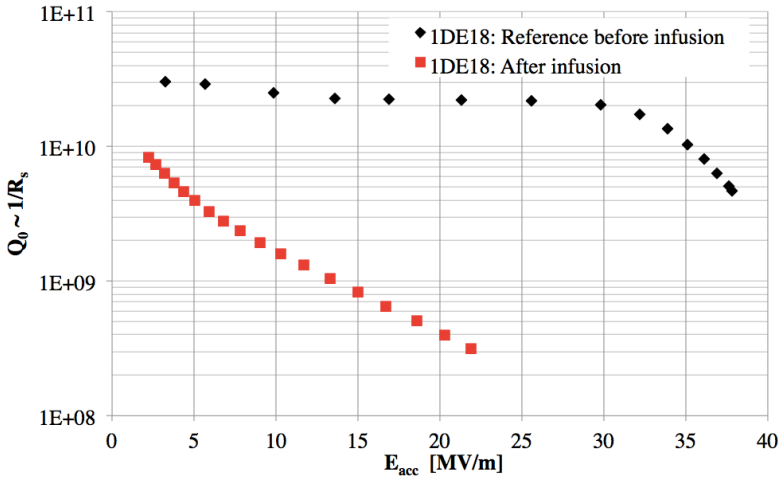

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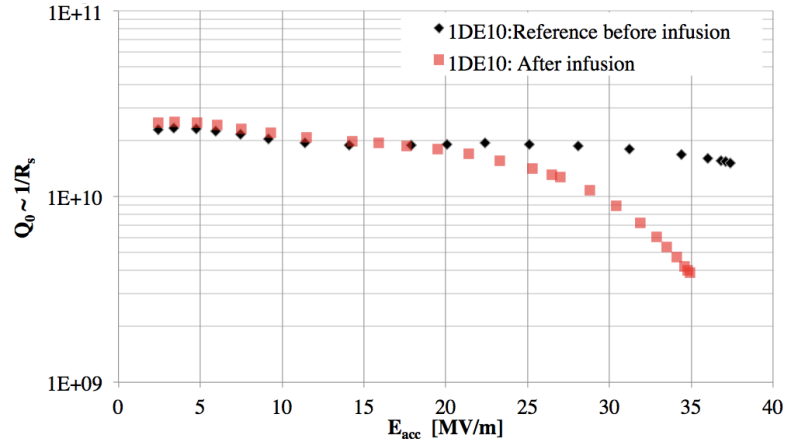
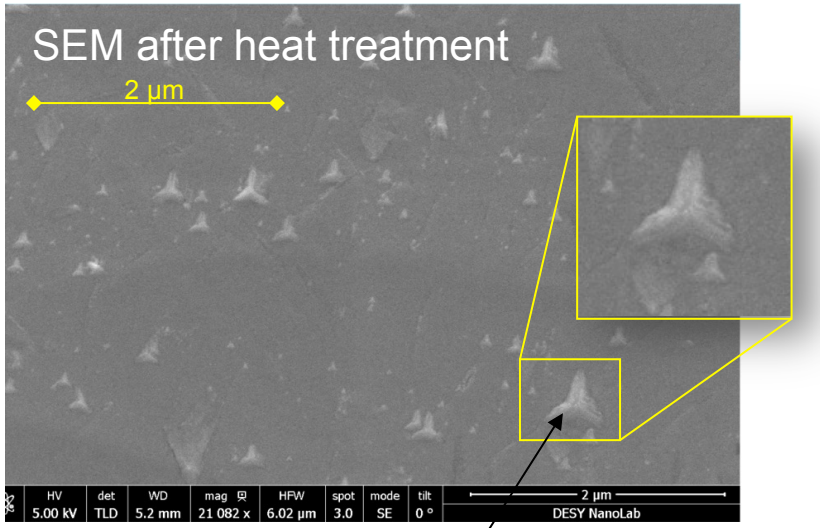


- furnace environment improved, studies for further optimization ongoing
- precipitates depending on grain orientation observable

  ➔ hexagonal β-Nb_2C phase?
- correlation to cavity performance?



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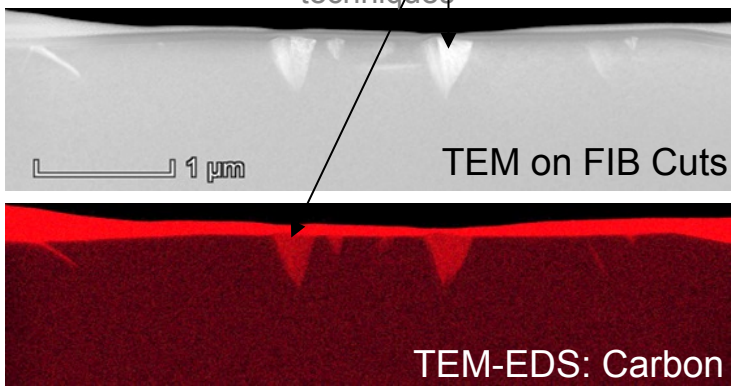
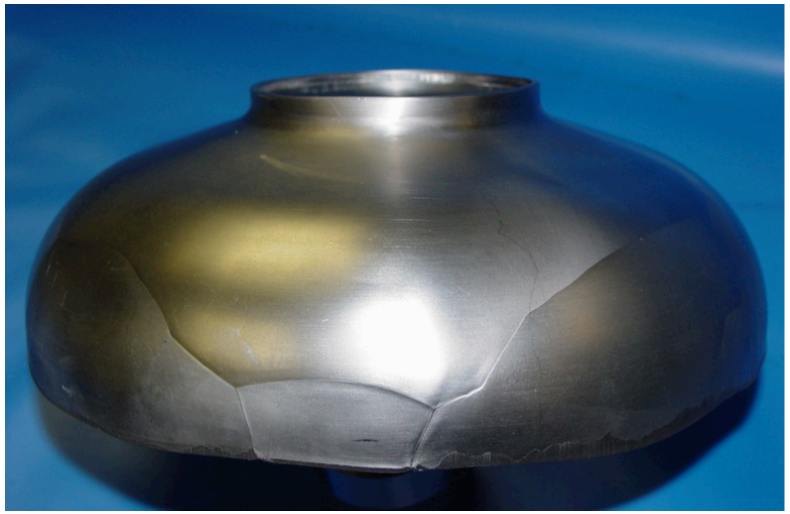


summary and outlook

answers raise more questions

- large grain cavities very promising
  - vertical / module test
- preparation serial cavity production: specification for material, mechanical forming and welding process started
- vertical and module tests ongoing
- systematic re-analyzing of older test

➔ **production process for high-performance cavities**



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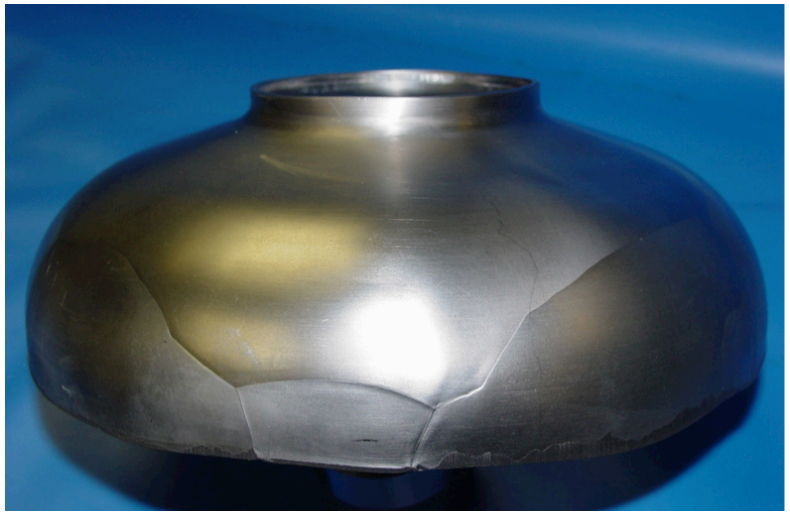
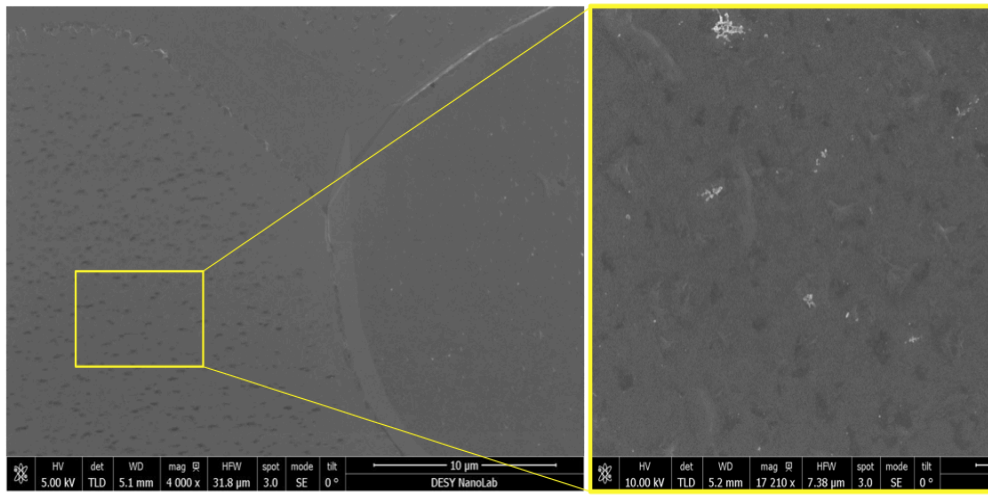


- no nitride phase on surface found
- effects on grain boundaries and due to grain orientation under study
- impact of infusion temperature will be analyzed
- correlation of sample surface to cavity performance
  - cutting of cavity for direct surface investigation
- analysis of other interstitial gases planned

➔ **stable and reproducible recipe for nitrogen infusion**



SRF R&D at DESY in full swing

closing remarks

- two aspects of SRF R&D towards and continuous wave upgrade of E-XFEL
  - large grain R&D shall provide cavities with naturally high Q_0 and large accelerating gradients
  - nitrogen infusion R&D shall allow for a surface treatment improving standard cavities to high-performance cavities with high Q_0 at large gradients

➔ **goal of SRF R&D @ DESY:**
136 high-performance cavities for low energy section of European XFEL

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- thanks to the complete DESY and Nanolab SRF team,
  I gave this talk on their behalf
- special thanks to Detlef Reschke, Julien Branlard, Christopher Bate and Guilherme Dalla Lana Semione for providing material from their talks and posters
- only collaboration with many partners allows for complex R&D work