superconducting cavity R&D @ DESY

towards continuous wave operation of the European XFEL

Lea Steder on behalf of the SRF team at DESY
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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 $1.4 \times 10^{10}$ (design $1.0 \times 10^{10}$)

[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 $\rightarrow$ 5 kW  poster A. Bellandi
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- 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

27 cm
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

[A. Ermakov et al., 2008 J. Phys.: Conf. Ser. 97 012014]
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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

[A. Ermakov et al., 2008 J. Phys.: Conf. Ser. 97 012014]
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 $2.3 \times 10^{10}$ 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

$\Rightarrow$ goal: definition of stable recipe for high-performance cavities
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➔ goal: definition of stable recipe for high-performance cavities

• 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
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
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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
evolution of infusion process at DESY

large parameter space to be controlled

• first tests couldn’t reproduce Fermilab results
evolution of infusion process at DESY

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- star-like structures found on samples
- possible hydro-carbon contamination of furnace
- process parameters compared to setups at other labs
- close collaboration with Fermilab
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- furnace environment improved, studies for further optimization ongoing
- precipitates depending on grain orientation observable
  - hexagonal $\beta$-Nb$_2$C phase?
- correlation to cavity performance?

SEM after heat treatment

TEM-EDS: Carbon

‘star-like’ precipitates identified as carbon using advanced surface analysis techniques
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
summary and outlook

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→ production process for high-performance cavities

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

thanks to the complete DESY and Nanolab SRF team, I gave this talk on their behalf
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only collaboration with many partners allows for complex R&D work