# Strategy for cavity R&D towards an upgrade of the European XFEL - current performance and the need for a new specification

**LCWS 2024**

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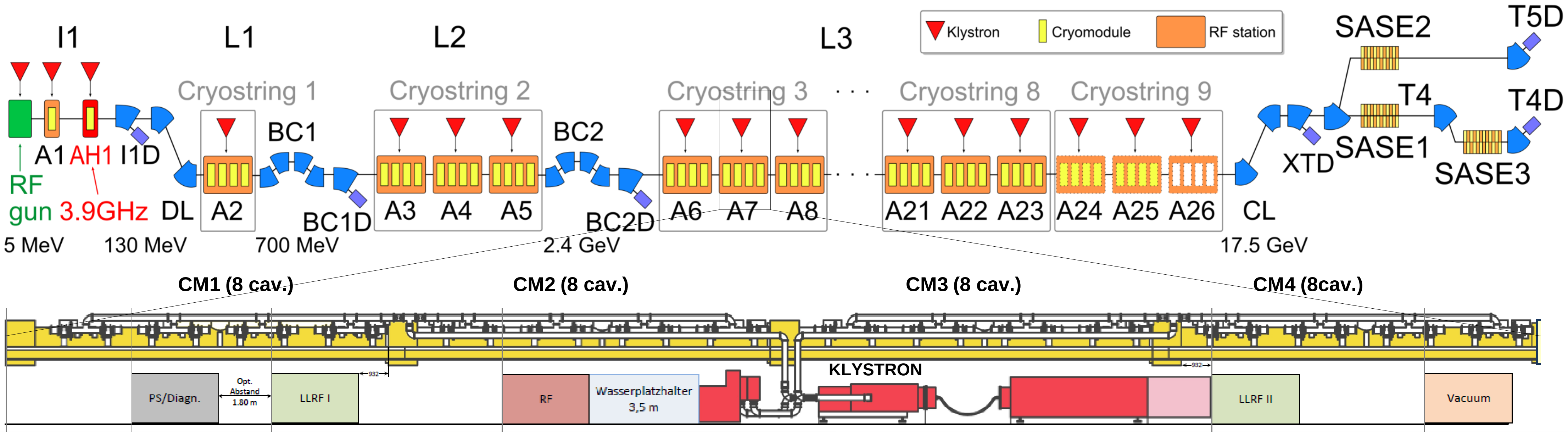
with slides / input from Hans Weise, Julien Branlard, Nick Walker, ….
for the DESY SRF team

July 10th, 2024

HELMHOLTZ

# Introduction

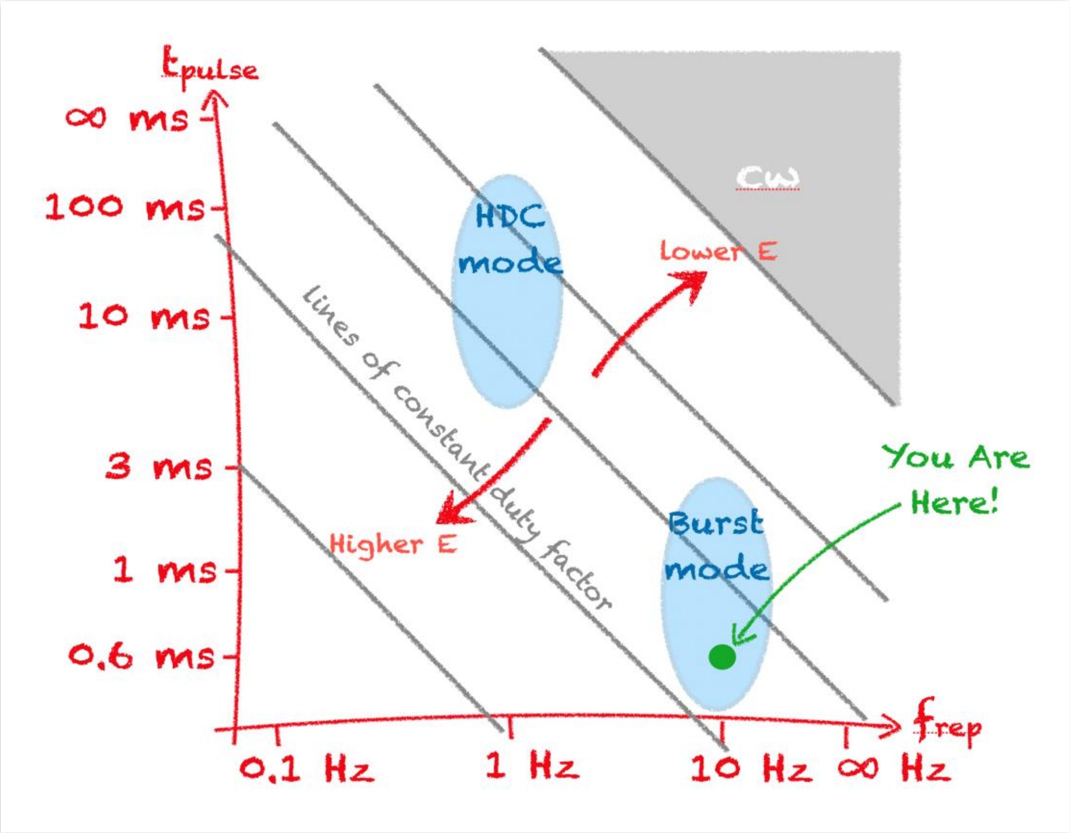
## The European XFEL Accelerator : one RF station




- 10 MW klystron to power 32 cavities
- one accelerating field RF control FB loop
- remote frequency tuning (motor / piezo) / cavity
- remote phase and external coupling tuning / cavity

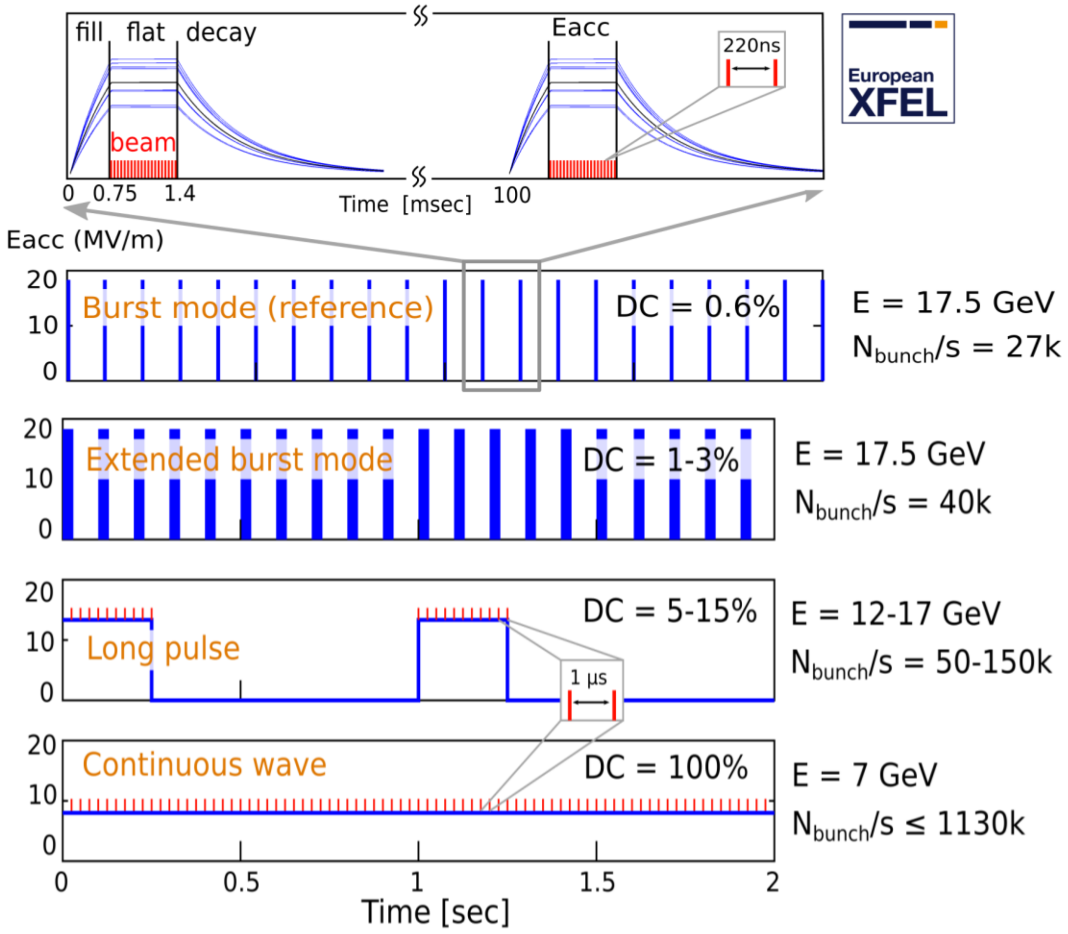
- average coupler peak power 102 kW (140 kW) for low (high) runs
- average gradient 18.5 MV/m (22.5 MV/m) for low (high) runs
- average detuning +/- 10 Hz
- average $Q_{ext}$ = 4.6e6 average $Q_0$ = 1e10

# R&D towards HDC



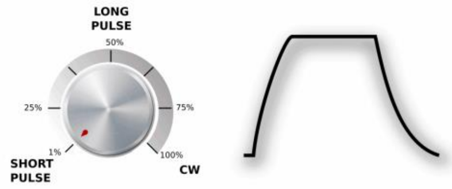
# R&D for the High Duty-Cycle program (i.e. cw and long pulse)

## Motivation




TODAY

High Duty Cycle (HDC)



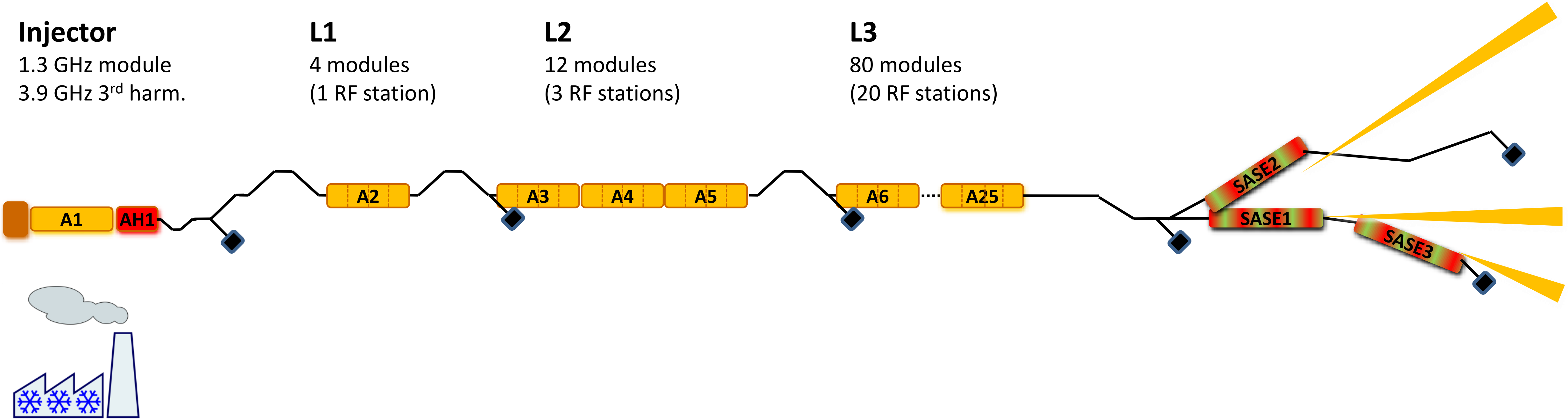
# original CW upgrade proposal (canonical upgrade)

**Injector**
1.3 GHz module
3.9 GHz 3rd harm.

**L1**
4 modules
(1 RF station)

**L2**
12 modules
(3 RF stations)

**L3**
80 modules
(20 RF stations)



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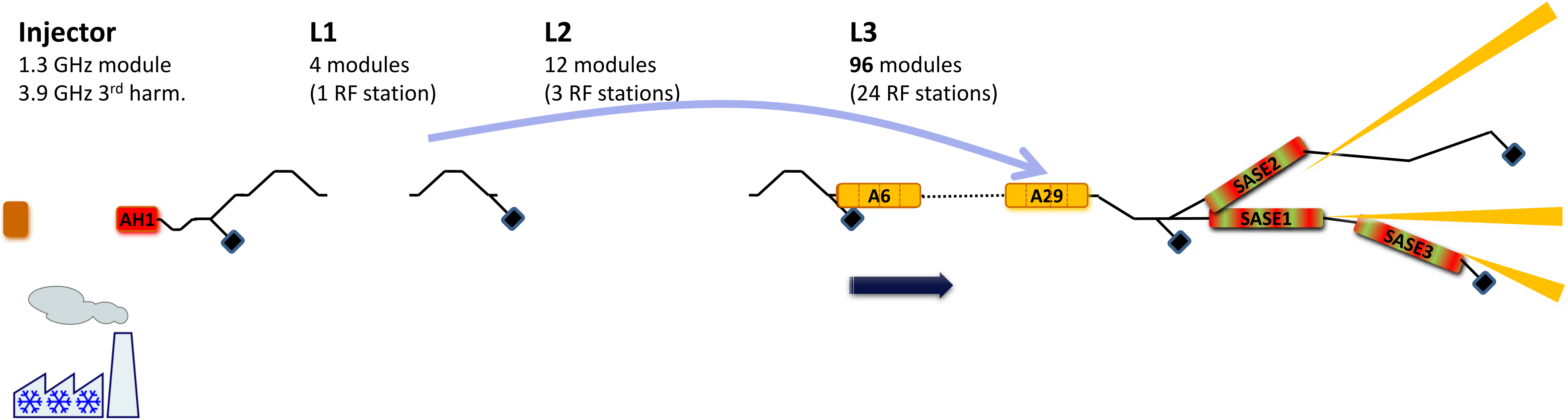
**96** modules
(24 RF stations)



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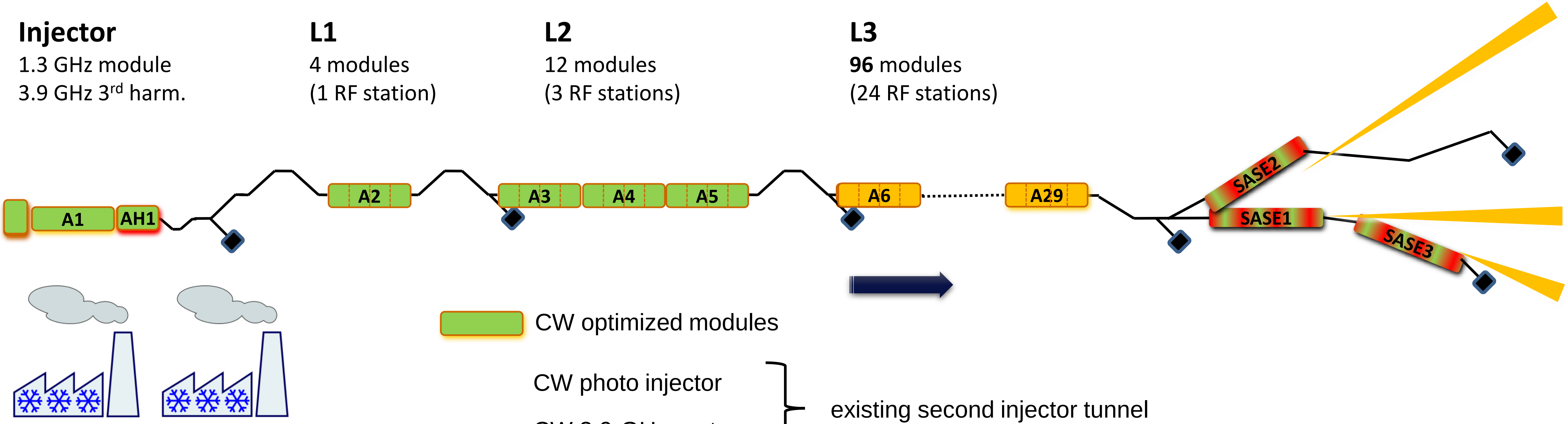



CW optimized modules

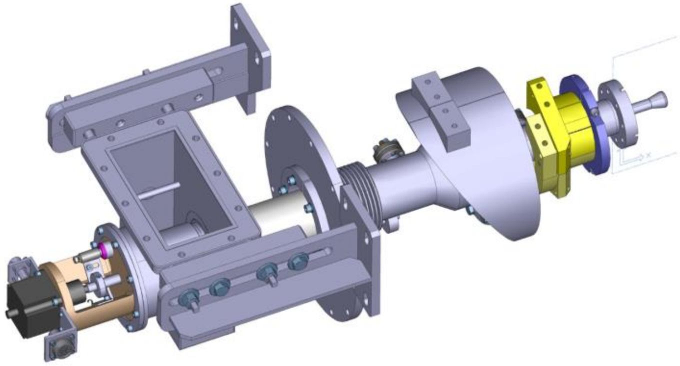
CW photo injector
CW 3.9-GHz system
} existing second injector tunnel

2nd cryo plant (2.5 kW ➔ 5 kW)

# requirements for hdc optimized modules: HDC and pulsed

## Preliminary list

- to be emphasized:
  requirement for **high energy (pulsed) mode and hdc/cw mode in one linac**
- performance requirements:
  - gradient **$E_{acc}$ > 20 MV/m**
  - quality factor **$Q_0$(~20 MV/m) ≥ 3 · $10^{10}$**
  - significantly **lower (no) field emission** than existing cryomodules
  - PED conformity: no annealing above 800 °C
- as **less as practicable modifications** to EuXFEL cavity and cryomodule
  → first ideas, but design not started
- preliminary: Use existing EuXFEL-coupler design with thicker Cu coating
- **new cw** compatible **3.9 GHz cavities** required
  → preliminary base: follow available $3^{rd}$ harmonic cavity and module designs



# R&D for the High Duty-Cycle program (i.e. CW and long pulse)

**accelerator modules**

- high $Q_L$ operation
- cw diagnostics and resonance control
- studies towards operating series cryomodules in CW

**s.c. cavities**

- renewal of DESY XFEL cavity specification incl. PED
- extensive R&D using a large number of single cell cavs
- new/optimized treatment recipes

**s.c. electron gun**

- SRF gun as the source
- SRF injector design
- Ts4i

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W. Singer

VALID DOCUMENTS
FOR THE
SERIES MECHANICAL
FABRICATION
OF
SUPERCONDUCTING 1.3GHZ
CAVITIES
FOR THE
EUROPEAN XFEL

(XFEL/001)

REVISION B / JUNE 23, 2009

SERIES SURFACE AND
ACCEPTANCE TEST PREPARATION
OF SUPERCONDUCTING CAVITIES
FOR THE EUROPEAN XFEL

(XFEL/A - D)

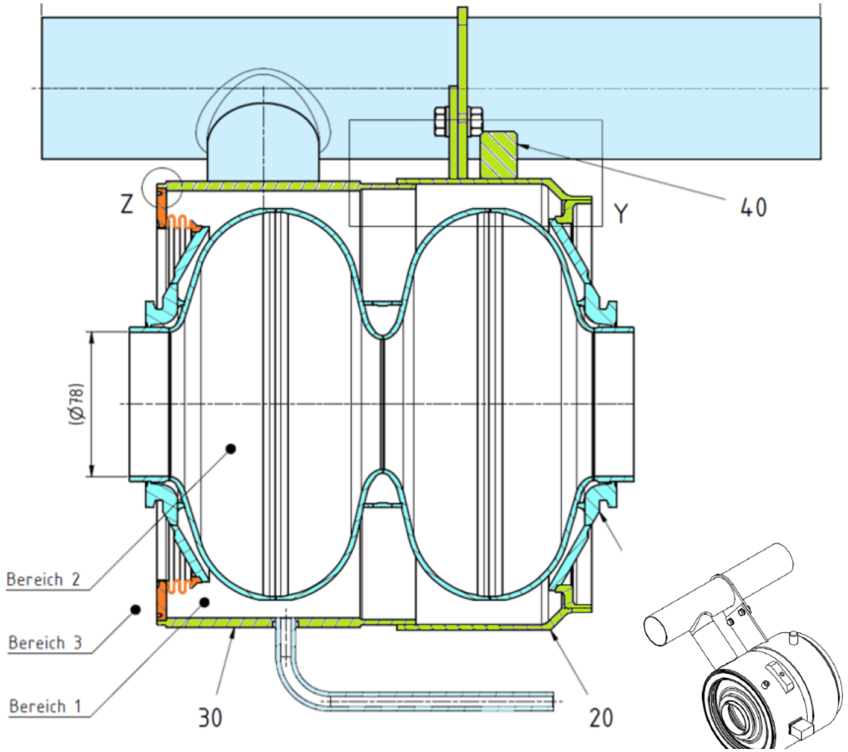
REVISION B / JUNE 30, 2009

1 / 71

# towards an updated DESY XFEL spec

## European XFEL uses 800 cavities ordered in 2010; the tendering started 15+ years ago

- the often-called DESY specs were the **role model** for LCLS-II (HE), SHINE et al.
- **PED certification** was/is a major issue for DESY, a renewal is a must in order to prepare for an EuXFEL upgrade cavity ordering
- basis for tendering of **ten new nine-cells** (early 2025)
- **lessons learned** from EuXFEL, LCLS-II (-HE), SHINE production to be included
- **company experience** counts
- **next generation of experts** to be trained
(mix of new and experienced colleagues; new roles)
- new and **optimized surface treatment** recipes to be finalized; decision for next EuXFEL ordering




“test piece” production for vendor qualification

# progress of the updated DESY XFEL spec

## a team effort

- **one consistent document**
- includes lessons-learnt of XFEL-production (e.g. not well-defined dimensions for He-tank brackets)
- **vendor independent workflow** description
- **bellow unit at He-tank simplified**
- additional **acceptance level for a R&D phase** before He-tank integration
- surface treatment:
  - **“final EP“ as initial surface treatment** only
  - **cold EP** process adopted
  - Mid-T treatment during R&D phase at DESY
- emphasis kept on **well-defined processes** during whole production incl. **on-site visits**

**EuXFEL specification 2009**

- several separate documents (fabrication, treatments, …)
- modifications during the tender process, adaption to infrastructure at vendor and during series fabrication
- delivery of tank-integrated cavities
- no experience in industry with large-scale cavity surface treatment
- included “Flash-BCP“ as final surface treatment

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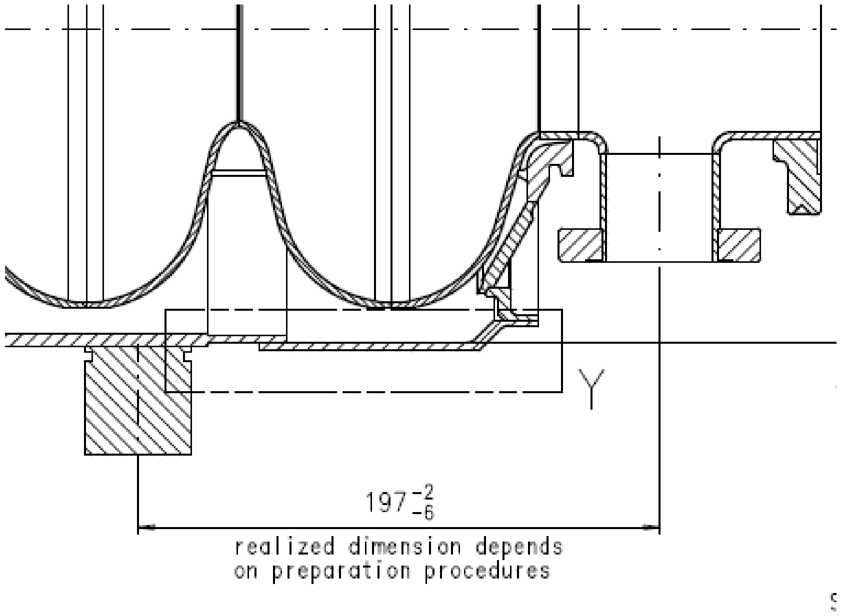

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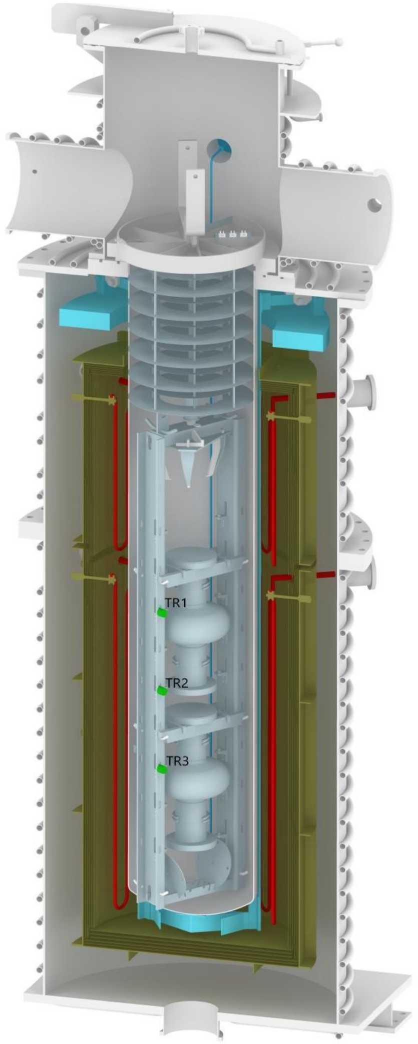
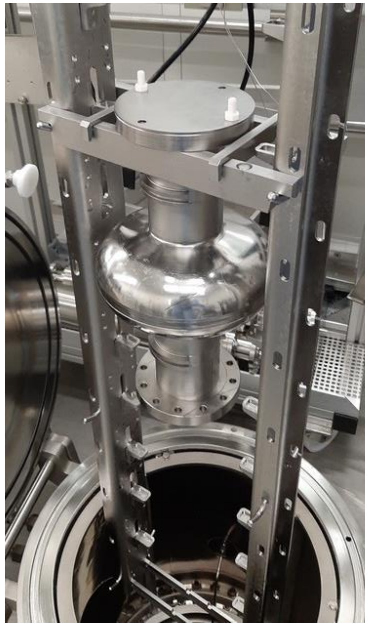
# cavity treatment towards hdc operation

## focus on mid-T heat treatment

- **refurbished UHV niobium retort furnace** is used to anneal cavities up to 800°C.
- loading of the furnace is done directly in the DESY ISO4 clean room i.e. **extremely clean** environment
- single-cell cavities / **pairs of single-cell** / 9-cell cavities can be treated.
- mid-T treatment in UHV at 250-350°C
(rem.: so far all studies without additional gas inlet - which is possible)



# oxygen diffusion length as key parameter

## huge DESY mid-T campaign

### mid-T campaign

- all 19 treatments on single-cell cavities after ”reset”
- 5 treatments on large grain (LG) cavities
- wide range for T: 250°C to 350°C and t: 3h to 20h
- use of calculated oxygen diffusion length ℓ for classification

### DESY mid-T workflow

- “reset”: 800°C anneal / short, cold EP (20 µm)
- HPR & assembly
- baseline vertical test
- mid-T treatment with different temperatures and durations (T, t)
- HPR & assembly
- vertical test (VT)

| Cavity | Nominal treatm. | $l$ (nm) | |
|---|---|---|---|
| 1RI04 | <3h <250°C | 234 | Fig. 9 |
| 1DE12 | <3h 250°C | 249 | short $l$ |
| 1DE26 (LG) | <3h <300°C | 501 | |
| 1RI02 | 20h 250°C | 512 | |
| 1DE04 | <3h <300°C | 528 | |
| 1DE03 | <3h <300°C | 537 | Fig. 10 |
| 1DE07 | 20h 250°C | 560 | medium $l$ |
| 1DE07 18xHPR | <3h <300°C | 641 | |
| 1AC07 (LG) | <3h <300°C | 697 | |
| 1AC03 (LG) | <3h <300°C | 789 | |
| 1AC02 | 3.25h <325°C | 865 | |
| 1DE19 | 4.5h <335°C | 1248 | Fig. 4 |
| 1RI06 (LG) | 20h 300°C | 1735 | |
| 1RI07 (LG) | 3h <350°C | 1806 | |
| 1DE11 | 3h <350°C | 1839 | Fig. 11 |
| 1DE17 | 20h 300°C | 2039 | long $l$ |
| 1RI01 | 3h 350°C | 2354 | |
| 1AC02 | 3h ≥350°C | 2568 | |
| 1DE12 | 3h >350°C | 2655 | |

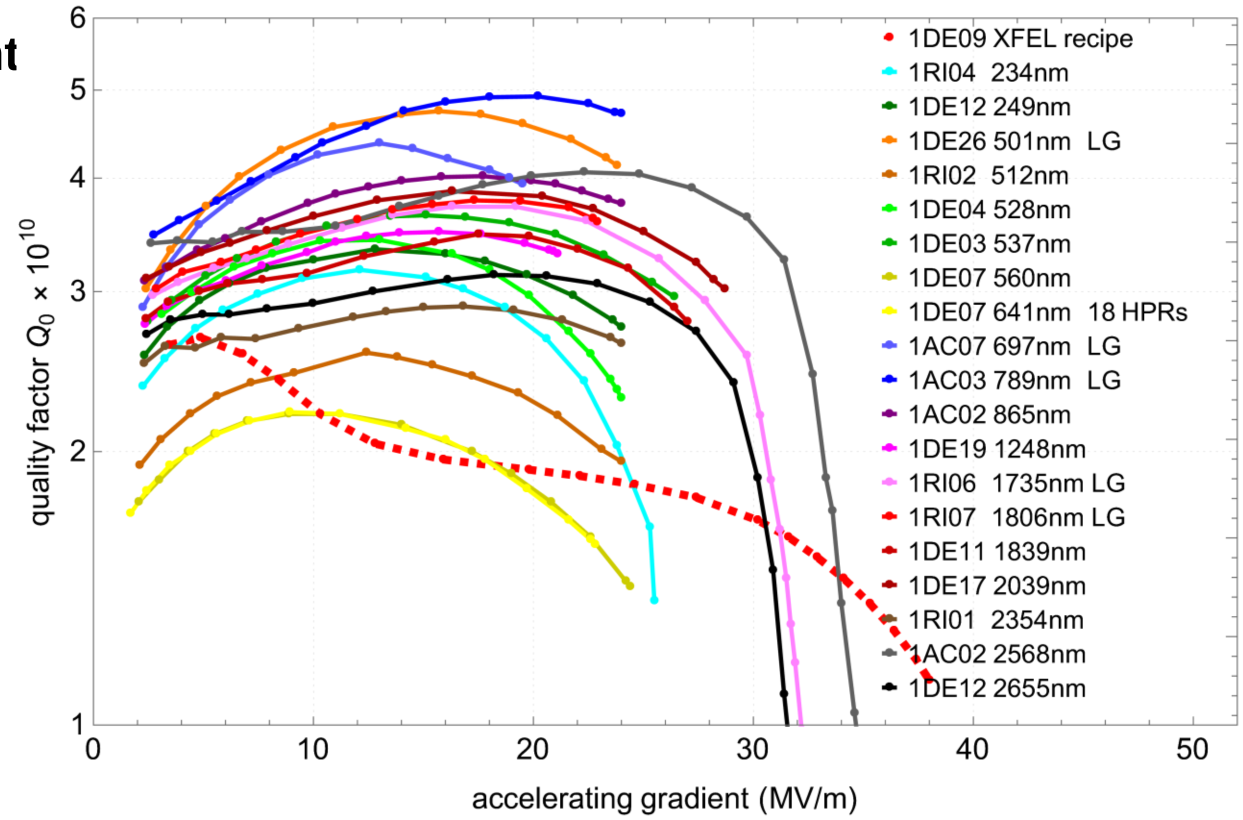
Table 1: Cavity treatments sorted by calculated diffusion length $l$ and grouped according to $l$.

# quality factor enhancement and anti-$Q_0$-slope

## special characteristics of mid-T heat treated cavities

**standard EuXFEL recipe vs mid-T heat treatment**

- significantly enhanced quality factors
- **anti-Q-slope**
- lower gradients
  - **partially stopped** to avoid quenching

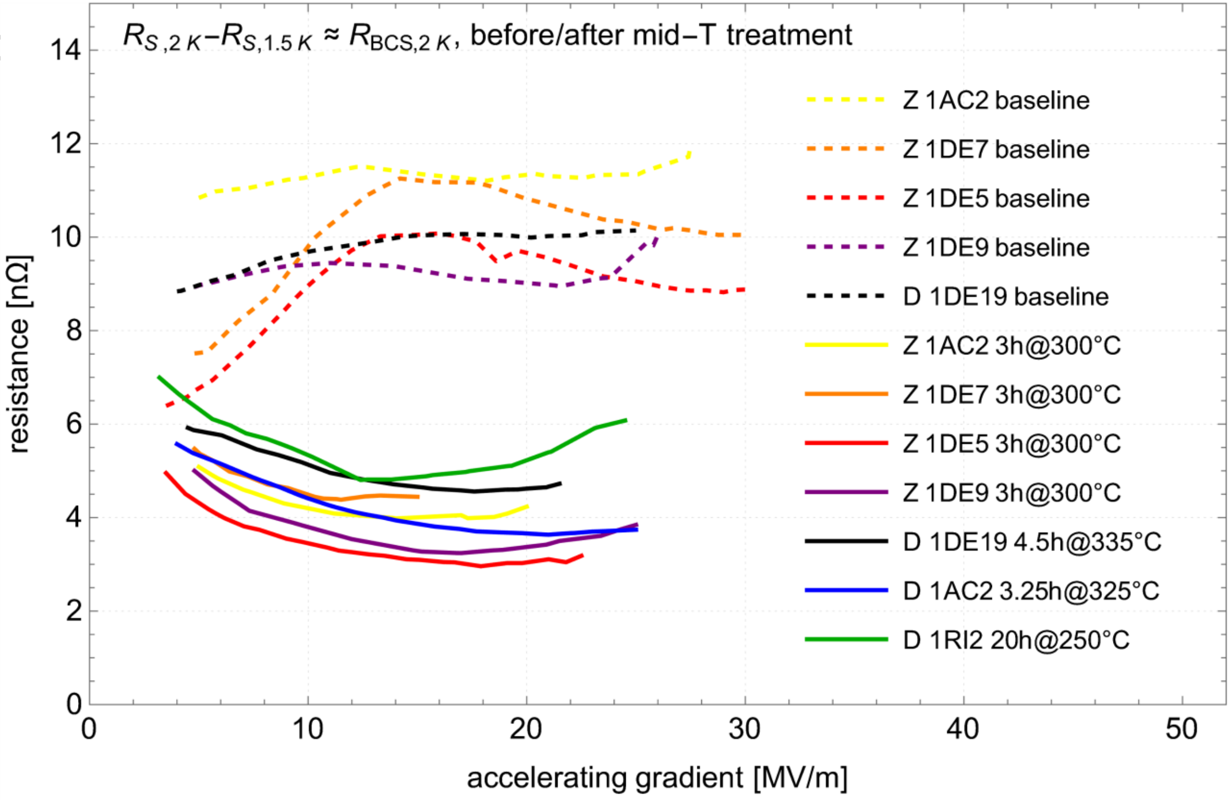


# very low BCS surface resistance

## special characteristics of mid-T heat treated cavities

**standard EuXFEL recipe vs mid-T heat treatment**

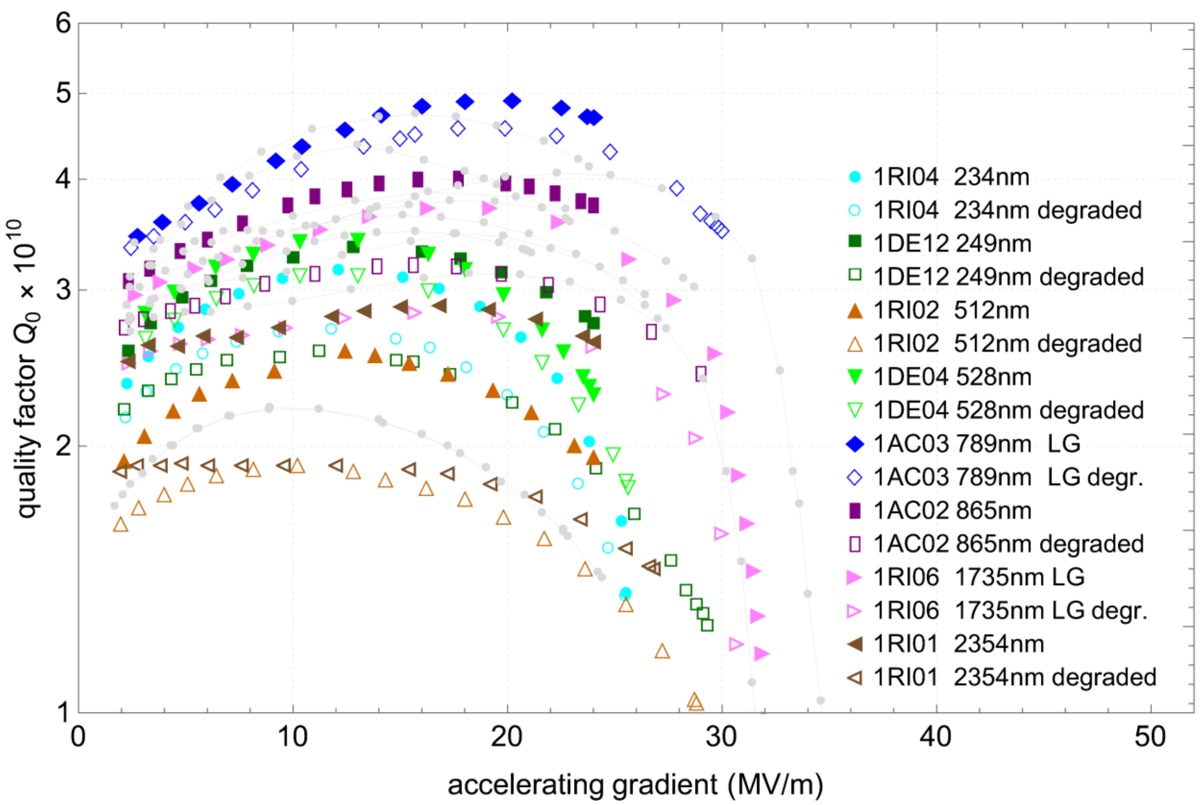
- significantly enhanced quality factors
- anti-Q-slope
- lower gradients
- $R_S(T,B)$ = $\mathbf{R_{BCS}(T)}$ + $\underbrace{R_{res} + R_{flux}(B)}$
- **lower $R_{BCS}$**
- **but** partially higher $R_{const}$



# sometimes degradation after quenches

## special characteristics of mid-T heat treated cavities

- significantly enhanced quality factors
- anti-Q-slope
- lower gradients
- $R_S(T,B) = R_{BCS}(T) + R_{res} + R_{flux}(B)$
- lower $R_{BCS}$
- **but** partially higher $R_{const}$
- 8 of 19 cavities **degrade after first quench**
  - unclear origin
  - **healing** via thermal cycling to 30 K

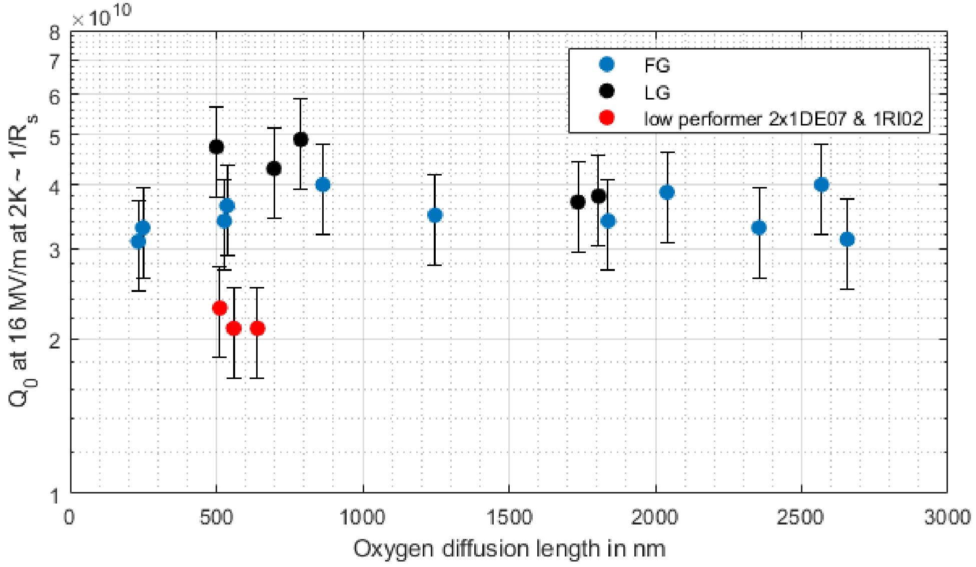


# correlation of performance to oxygen diffusion length missing

## gap between 900 and 1700 nm to be filled

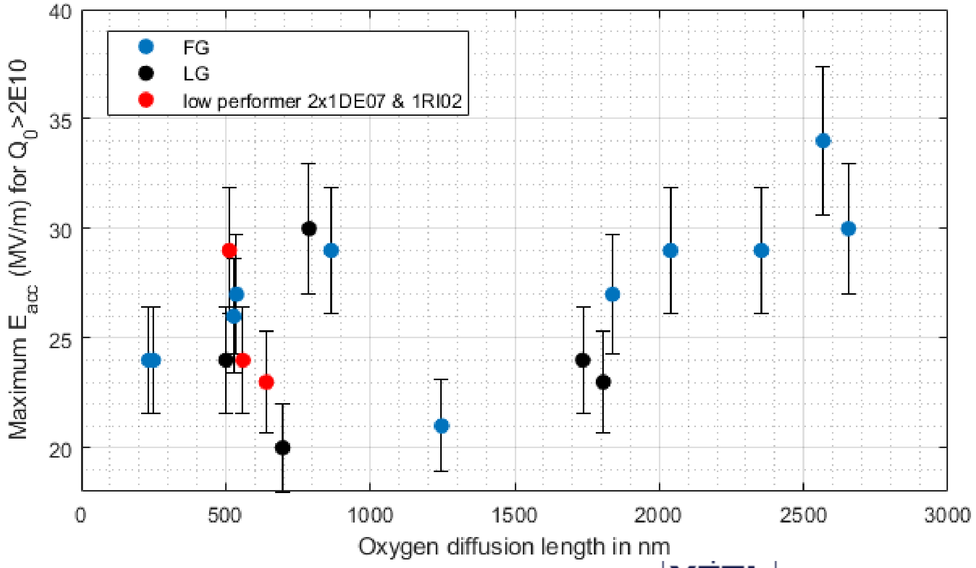
**quality factor $Q_0$**

- flat distribution over diffusion length
- only low performer deviating
- LG cavities on upper edge




**maximal $E_{acc}$**

- spread between 20 and 35 MV/m
  - tendency at higher length towards larger gradients?

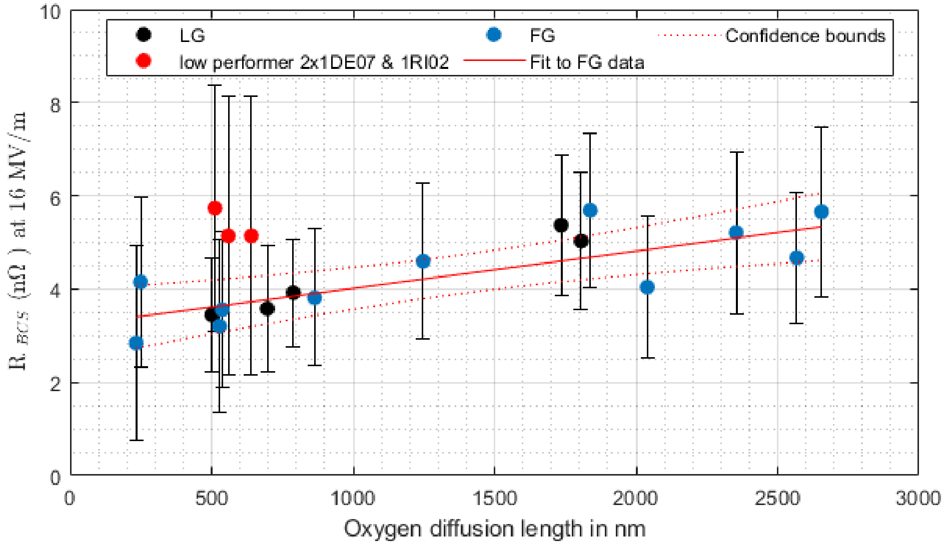


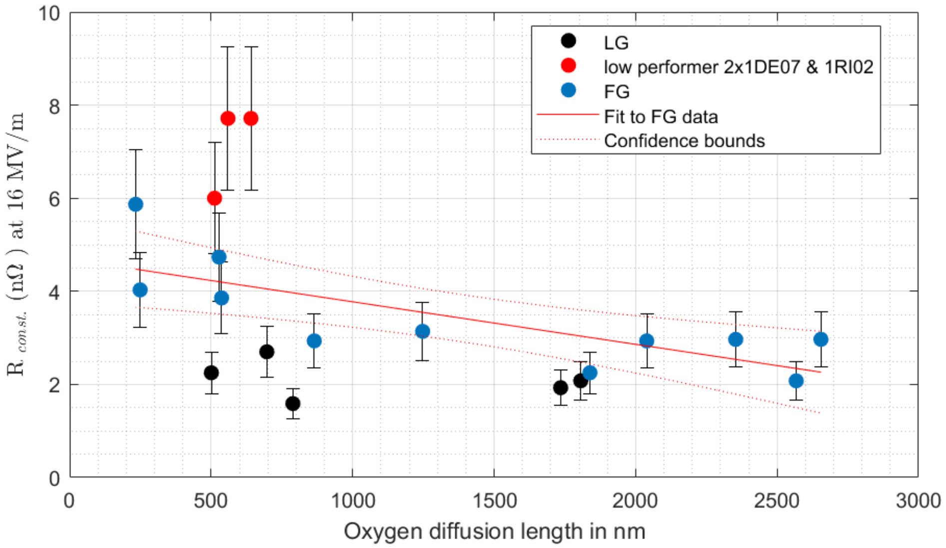
# not much room for optimization

## trends in resistances cancel each other

**$R_{BCS}$ and $R_{const}$**

- LG and low performer excluded
- opposing trends
- LG cavities profit from low $R_{const}$



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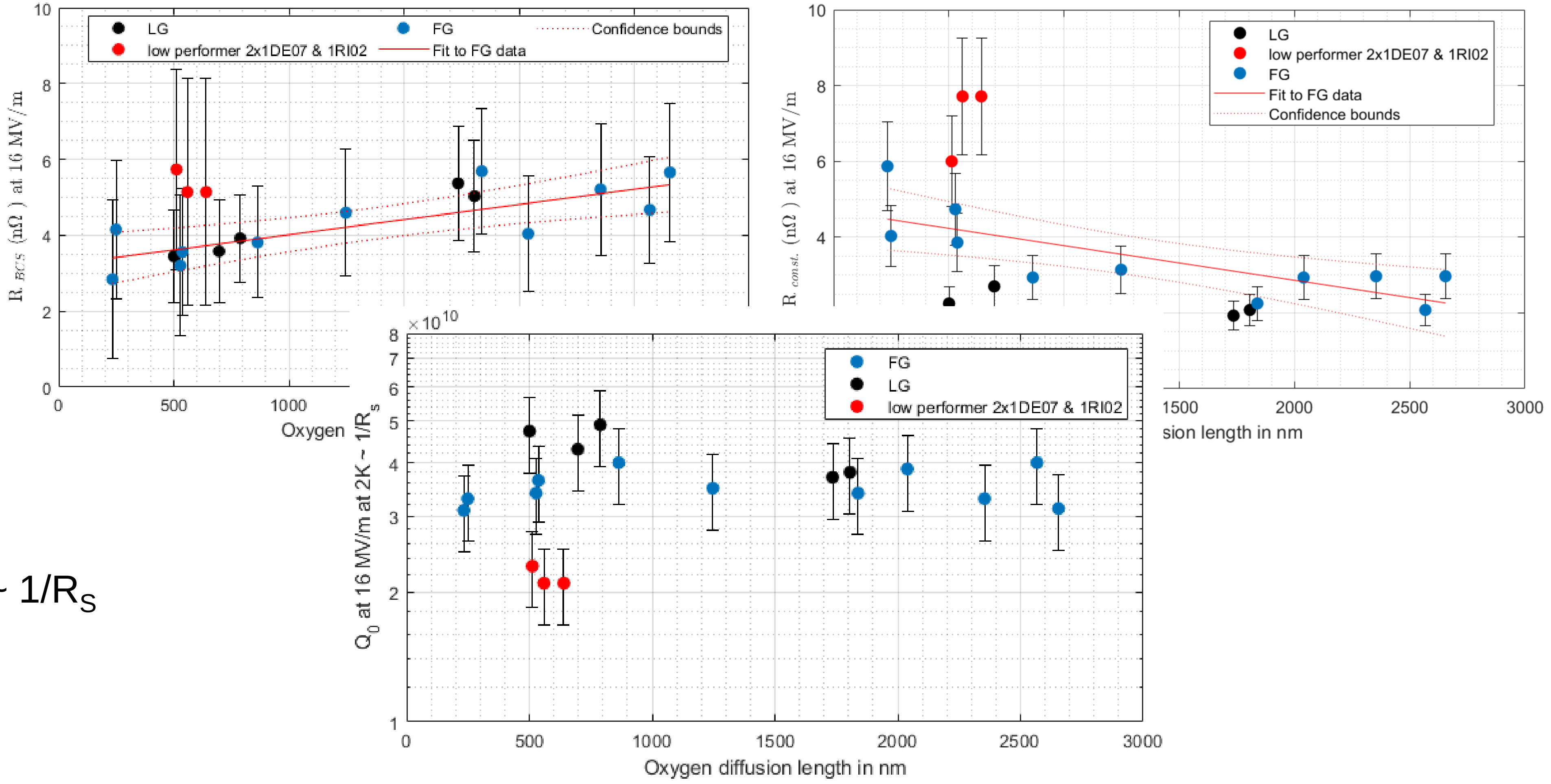


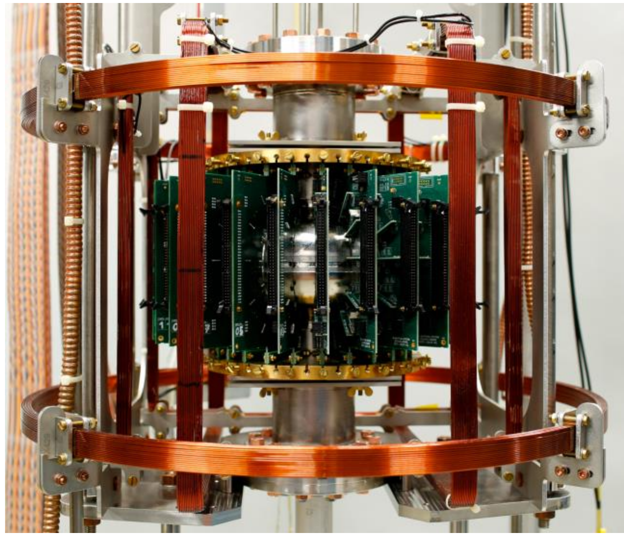

**reminder**

- $R_S = R_{BCS} + R_{const}$, $Q_0 \sim 1/R_S$

# sensitivity to magnetic flux trapping is a challenge

## B-mapping studies show large impact of mid-T heat treatment

- definition: $S = \frac{\Delta R_S}{B_{trap}}$
- $R_S$ measured via $Q_0$ with and w/o applied magnetic field (10 µT)
- $B_{trap}$ obtained via B-mapping system
  - FG (1DE03) and LG (1DE26) cavity with medium I (< 3h, < 300°C)
  - measurements at KEK



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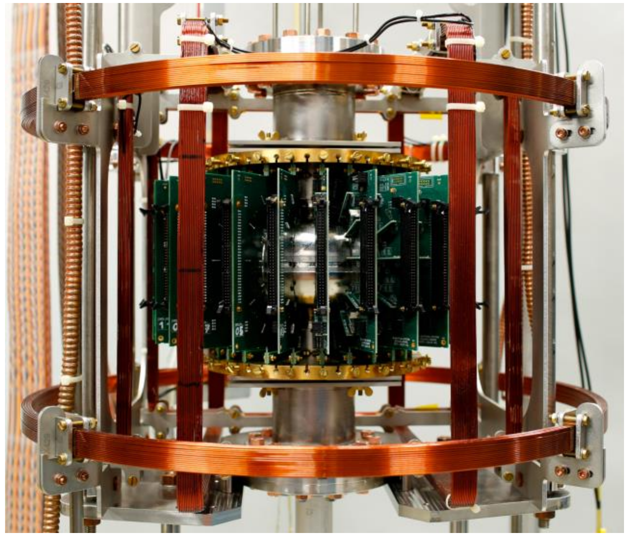
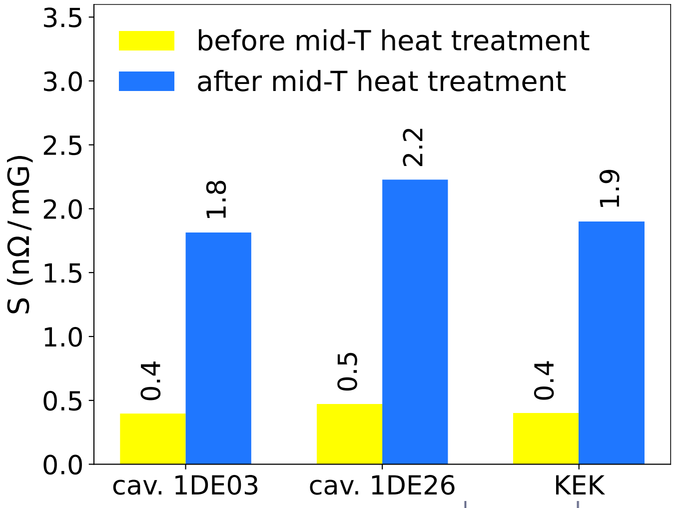
- increase in sensitivity: factor 4 - 5!
  - independent of cavity material
- magnetic environment - also in accelerator - very important
  - flux trapping has to be avoided
  - otherwise $Q_0$ will drop significantly
- more studies to come for better statistics with wider range of ℓ





# summary

- (smooth EuXFEL linac operation => aiming for three 9s linac availability)
- **broad R&D towards** an hdc upgrade of the European XFEL started – **pulsed and hdc operation**
- good progress of **reworked spec** for cavity production
- **excellent furnace and cleanroom** infrastructure as well as sufficient single-cells available
- R&D focus on **mid-T treatment**: **Arxiv publication** with more details this week
  - **reproducible and very promising results** on single-cells
  - **high sensitivity S** to magnetic flux is a challenge
  - next: transfer to nine-cells

Funding by the European XFEL R&D program and the Helmholtz MT ARD program acknowledged

# thank you for your attention

**Many thanks to all colleagues from different groups at DESY who have contributed to these results.**

**Contact**

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