THE PATH TO HIGH DUTY CYCLE AT EuXFEL.

Cryomodule developments

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DESY MKS group

23/09/2025

HELMHOLTZ

SRF2025 TOKYO

European XFEL

DESY.

Outline

The EuXFEL High Duty Cycle (HDC) upg

- Reasons
- Overview

HDC for the EuXFEL cryomodules

- Main challenges

R&D activities on cryomodules

- For new HDC cryomodules in L1-L2
- For existing modules in L3

Conclusions

The EuXFEL High Duty Cycle upgrade

Why a HDC upgrade?

- **EuXFEL** is the **world leading FEL facility** since its first **user operation** in 2017

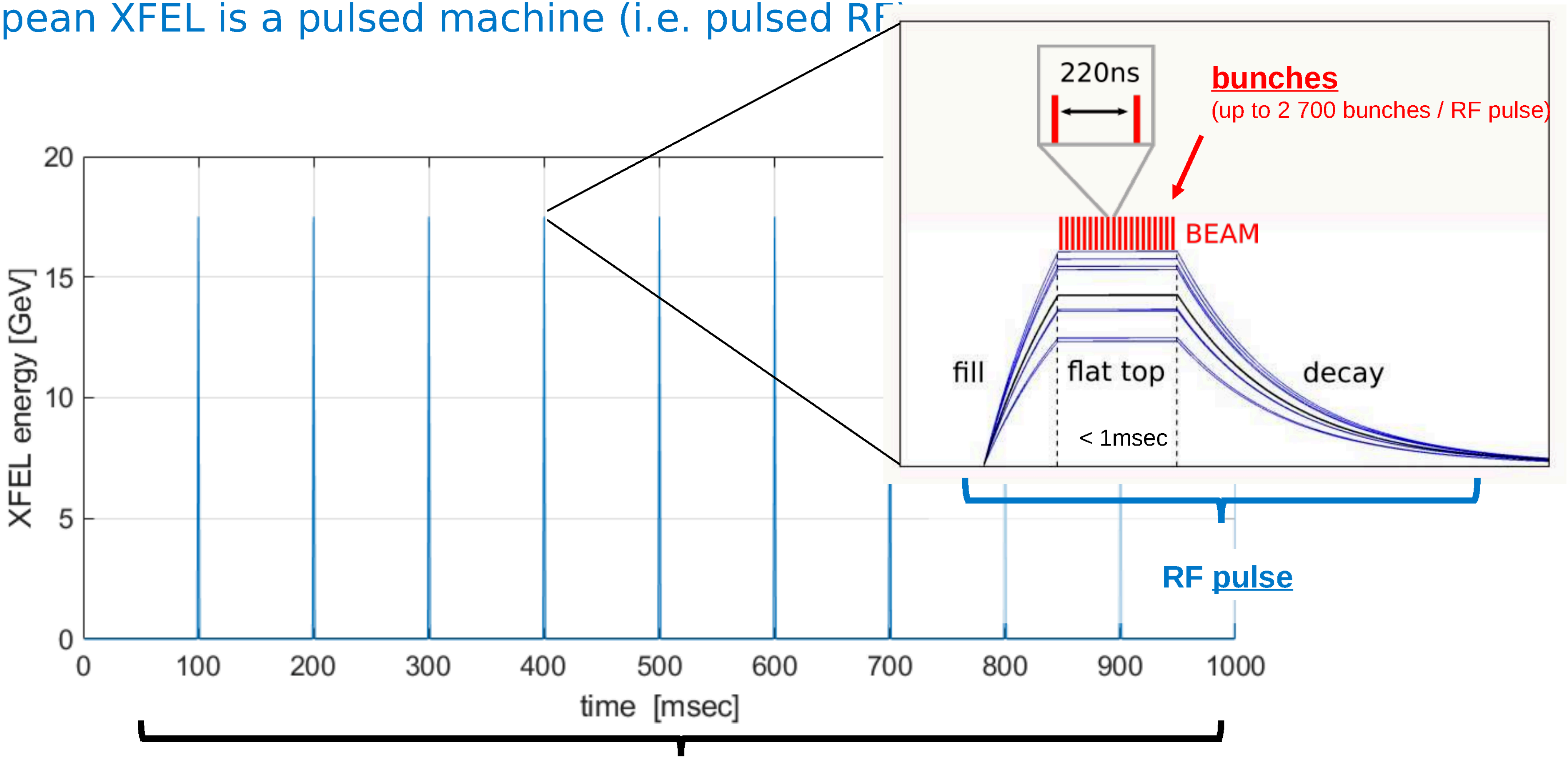
- **Key features**
  - peak brilliance X-rays 17.5 GeV
  - high photon energy 30 keV
  - burst mode beam 4.5 MHz
  - parallel user operation SASE1/2/3
  - SRF linac availability > 98%

- Currently in the **"harvesting phase",** but the **competition is catching up**

  we need to **upgrade** (next decade) **if we want to stay on top**

Current operating mode

The European XFEL is a pulsed machine (i.e. pulsed RF)



10x RF pulses / sec (i.e. 10 Hz repetition rate)

Currently, XFEL offers max 27000 bunches / sec (i.e. 27 kHz)

Where to improve ?

User feedback driven by science case

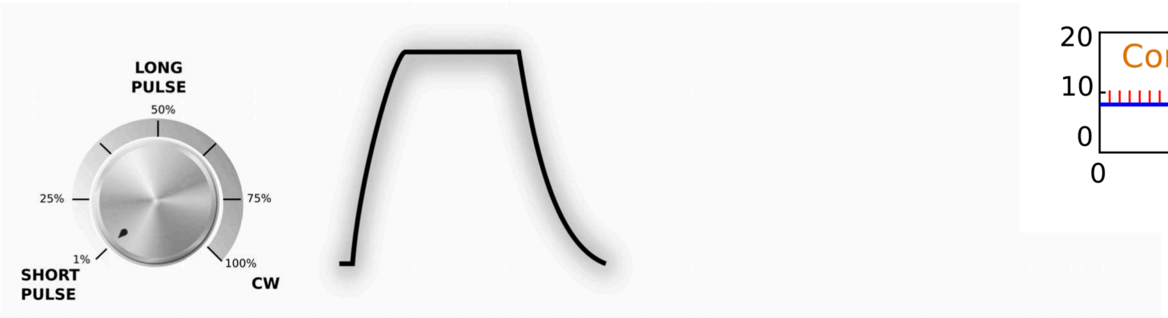
EuXFEL users wish to have

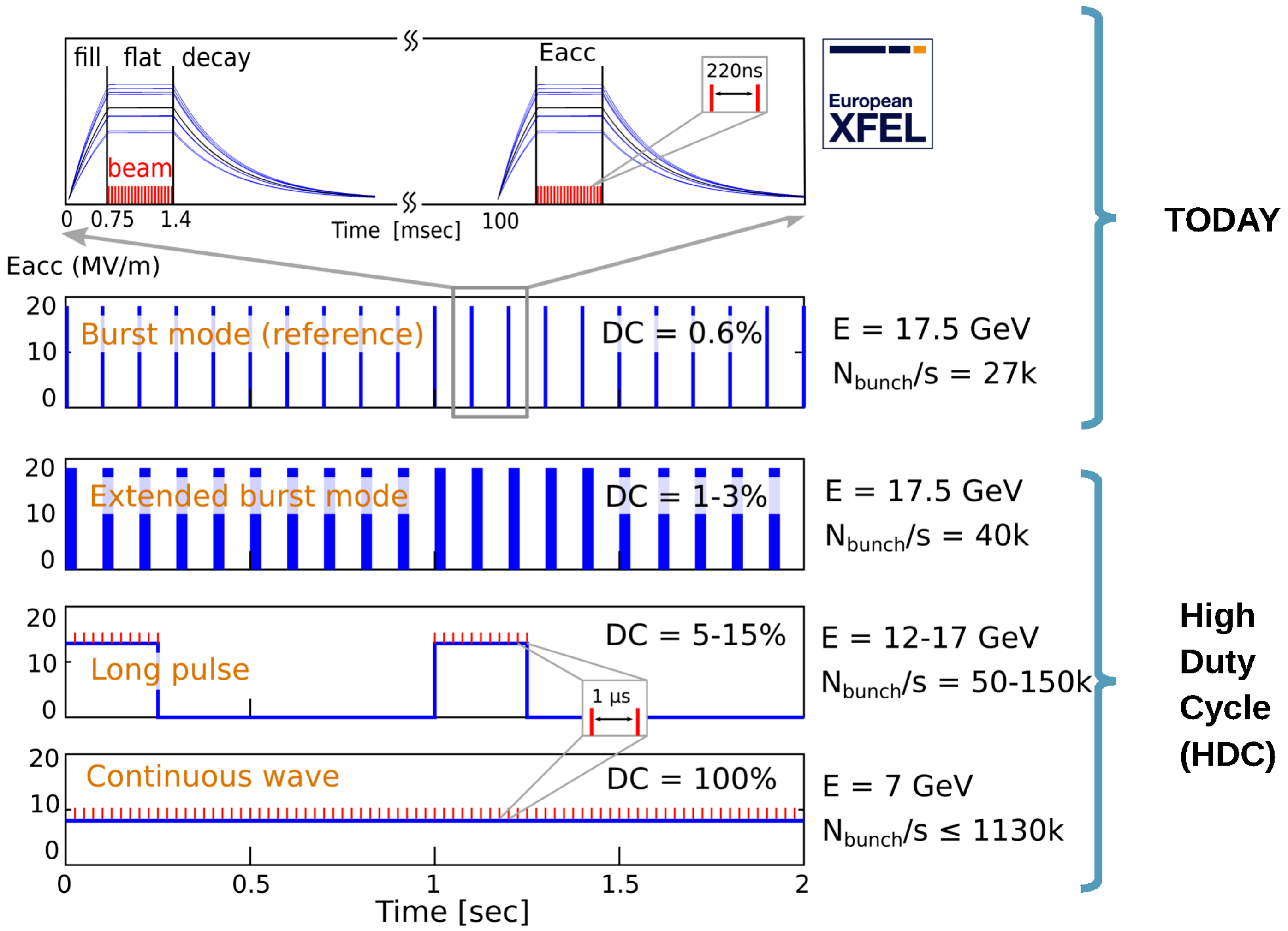
- **Everything they have now**

and

- **More bunches per second**
- **More time separation between bunch**

we need **longer RF pulses**
(i.e. more time for more bunches)





High Duty Cycle Upgrade

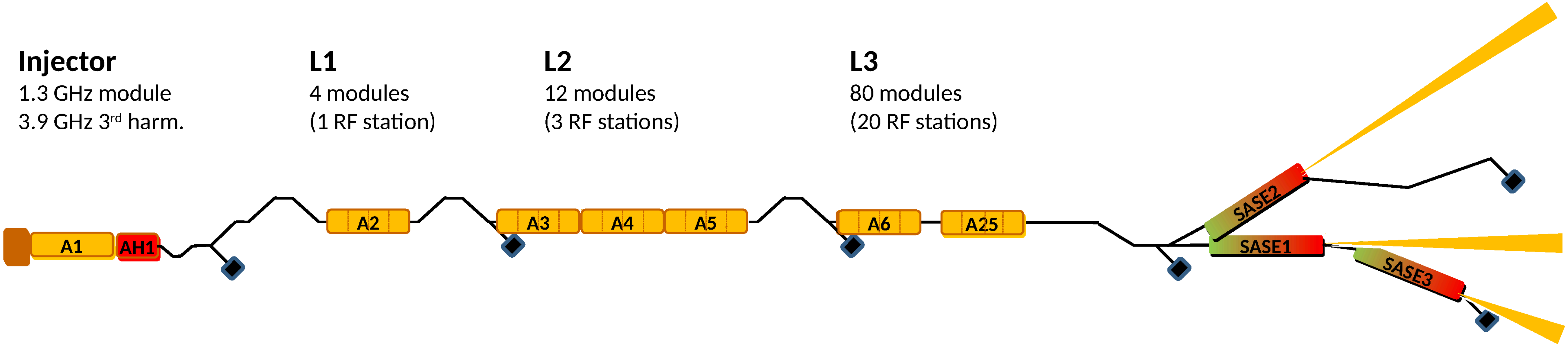
Burst mode

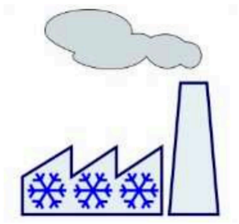
Injector
1.3 GHz module
3.9 GHz 3rd harm.

L1
4 modules
(1 RF station)

L2
12 modules
(3 RF stations)

L3
80 modules
(20 RF stations)





High Duty Cycle Upgrade

Current proposal baseline

Injector
1.3 GHz module
3.9 GHz 3rd harm.

L1
4 modules
(1 RF station)

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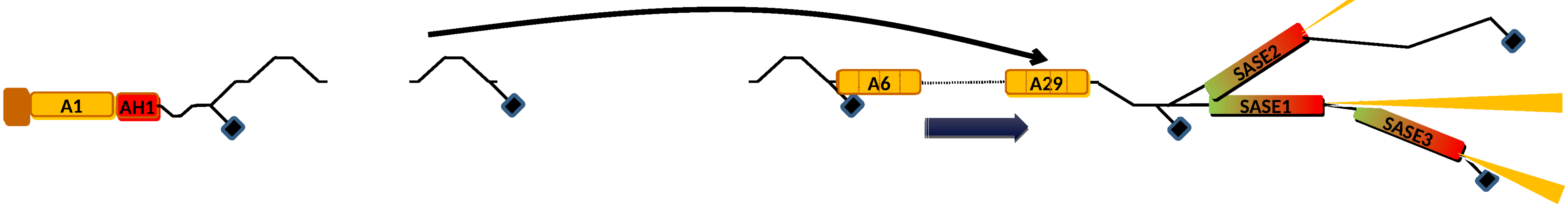
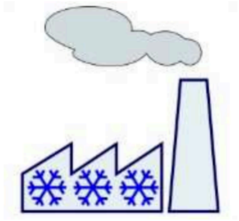
L3
96 modules
(24 RF stations)





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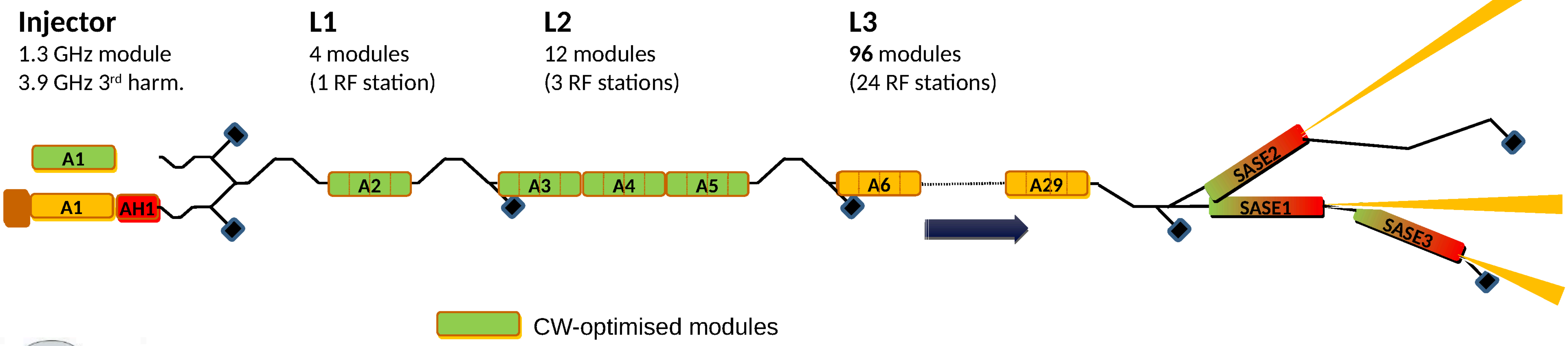

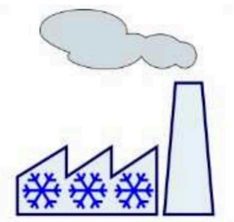

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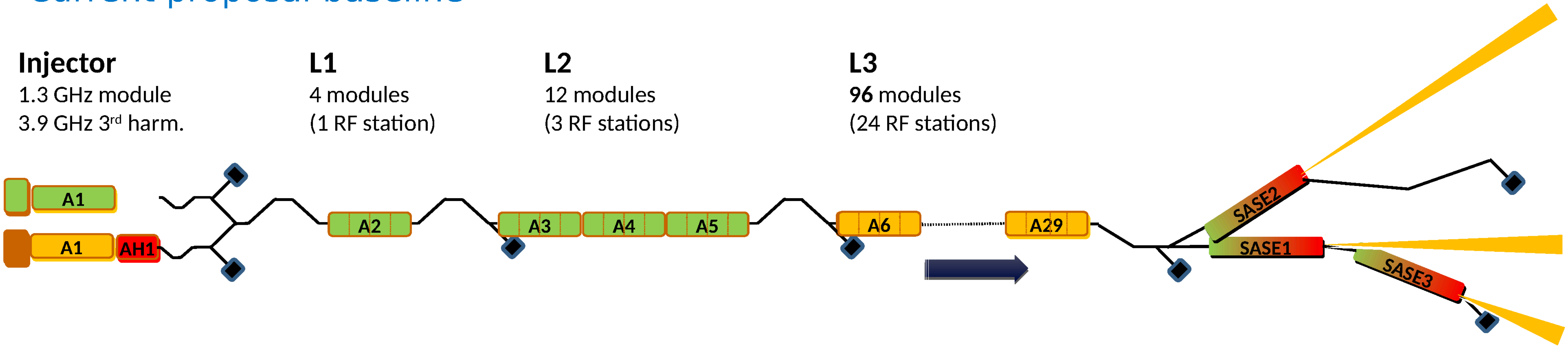
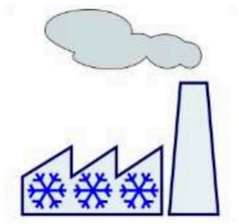


CW-optimised modules

CW photo injector



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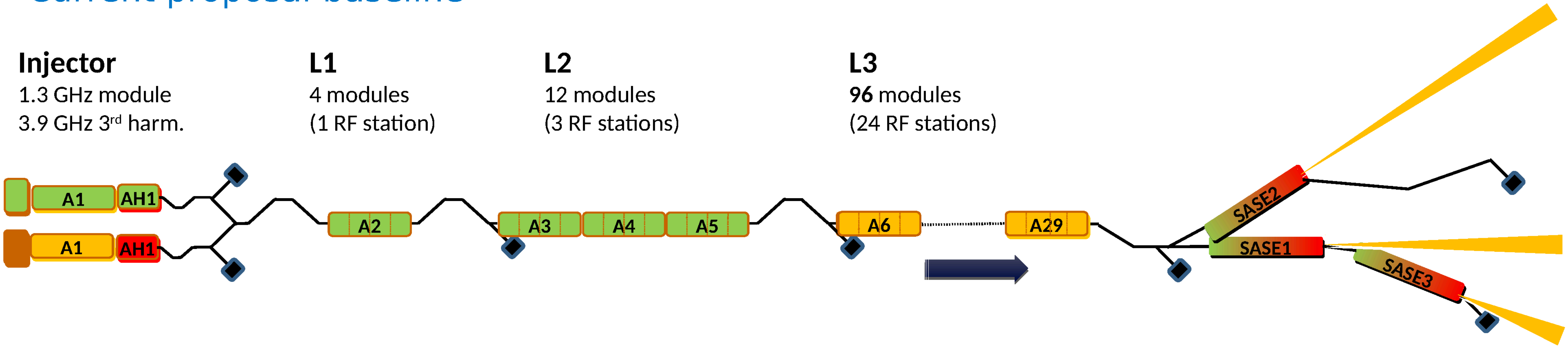

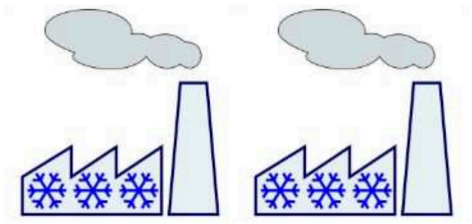

CW-optimised modules

CW photo injector

AH1 CW 3.9-GHz system

2nd cryo plant (2.5 kW ➔ 5 kW)

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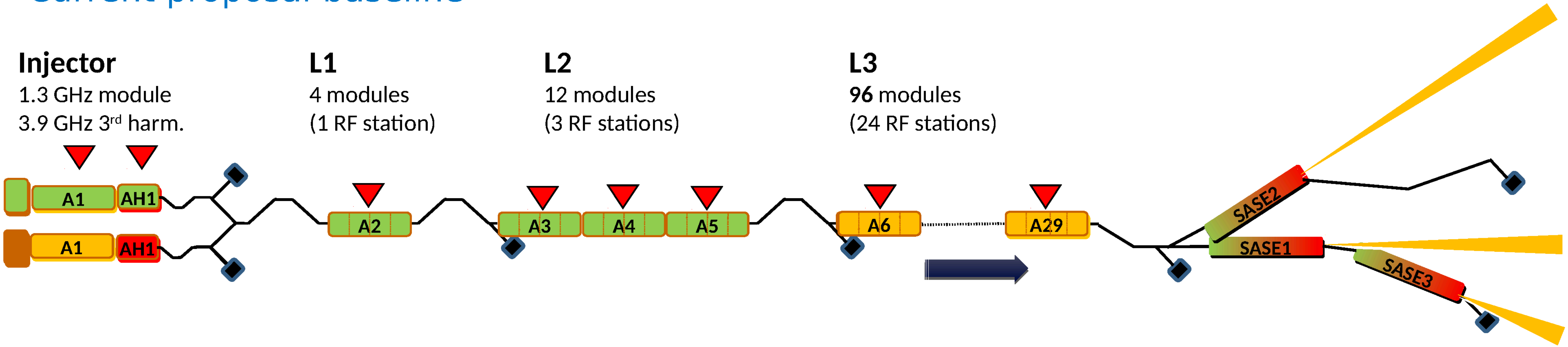
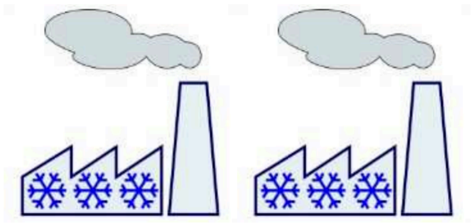




CW-optimised modules

CW photo injector

AH1 CW 3.9-GHz system

2nd cryo plant (2.5 kW ➔ 5 kW)

Low peak power rf system
(does not permit 17.5 GeV at low d.c.)

The **performance of our existing linac** is a key constraint of the upgrade

A dual R&D scope for the HDC upgrade

New <u>front-end</u> (Inj, L1, L2) combined with <u>legacy linac</u> (L3)

New accelerator front-end (Inj, L1, L2)

- New **CW-optimised cavities & cryomodules**, build on experience from LCLS-II and SH
- Develop an **SRF CW injector**, starting with test stand
- Develop next generation **beam controls and diagnostics**

This talk and talk TUA05

Talk THB05 and poster TUP65 (cath

Key challenges for the legacy linac

- Understanding the **cryogenic performance** (dynamic heat loac
- Assessing **RF couplers limitations** in CW (temperature, power)
- Exploring and finding **optimal** $\mathbf{Q_{ext}}$ range (efficiency)
- Choice of CW and long-pulse capable **power source**

Entire HDC R&D program devoted to answering these questions

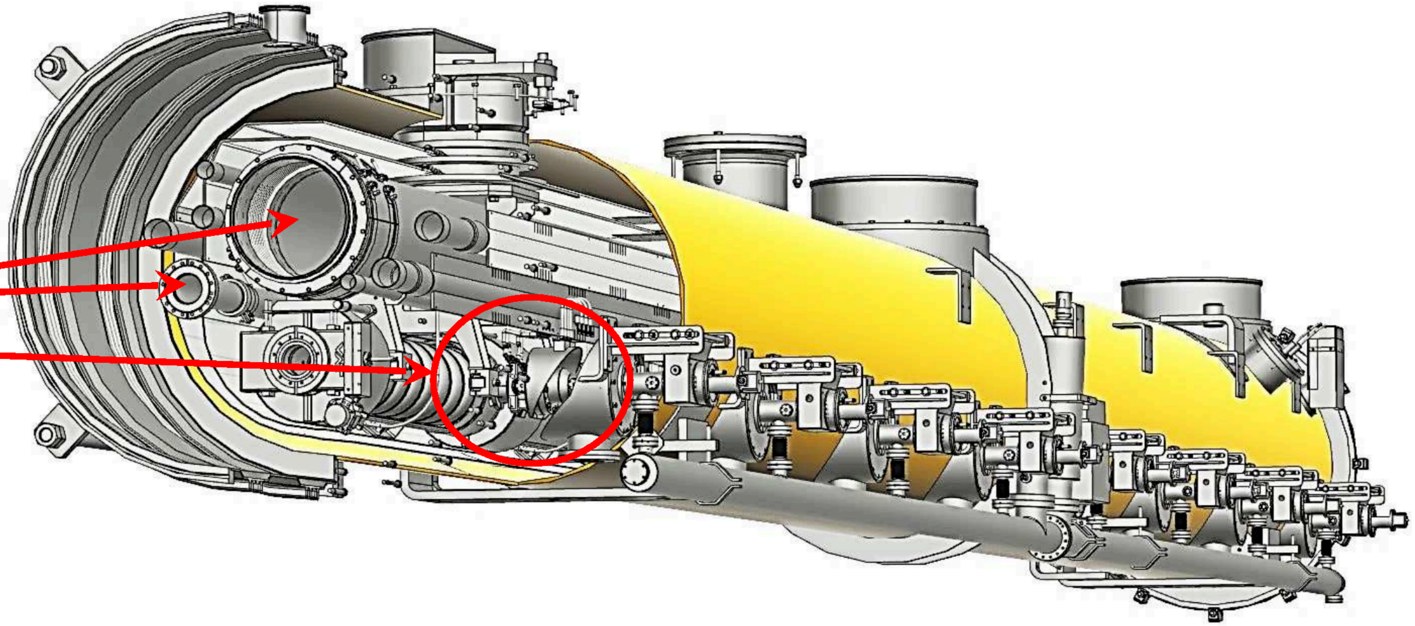
4 kW SSA in AMTF

40 kW IOT in CMTB

EuXFEL HDC for cryomodules

Main impact of changing operation mode

For the cryomodules



Increased 2K dynamic heat load / cryomod

Present: 5 W / module

HDC L1-L2: up to 130 W / module **in CW**

L3: > 25 W / module **in CW**

- → Increased flow through 2K piping
- → Heating of coupler, HOM, end groups..

Solutions for new cryomodules (L1-L2)

New cavity recipe for higher Q_0

Modifications of the 2K piping

Modifications of couplers (thicker copper plating), HOMs (better cooling), …

BUT, these solutions can not be applied to the existing 96 cryomodules (L3)

Towards CW-optimised cryomodules (L1-L2)

Starting point

New CW-optimized cryomodules (L1-L2)

Cavity parameters

- $Q_0 = 3 \times 10^{10}$ at gradient 20 MV/m

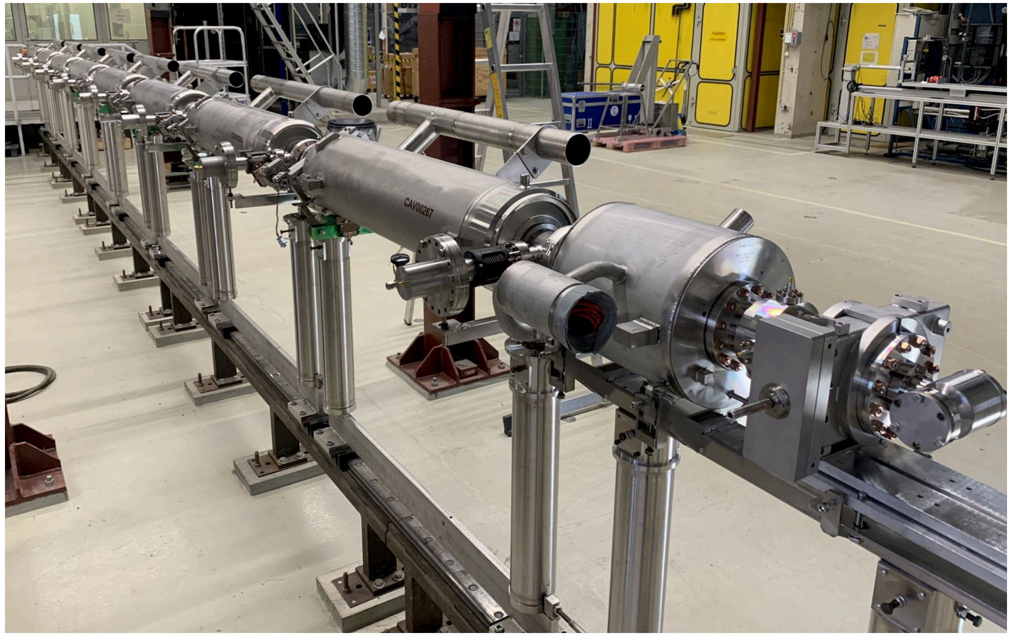
  ✉ dynamic heat load ~130 W / module **in CW**

All **17 HDC cryomodules** should be **identical** (one design)

Cavity and cryomodule modifications only if necessary

- EuXFEL very robust and reliable design

  ✉ keep original XFEL design as much as possible
- Compatibility with existing piping, components (end and feed caps) and support configuration
- Compatibility with existing tooling for assembly and installation in tunnel



Currently assuming cryomodule assembly for the 17 modules at DESY

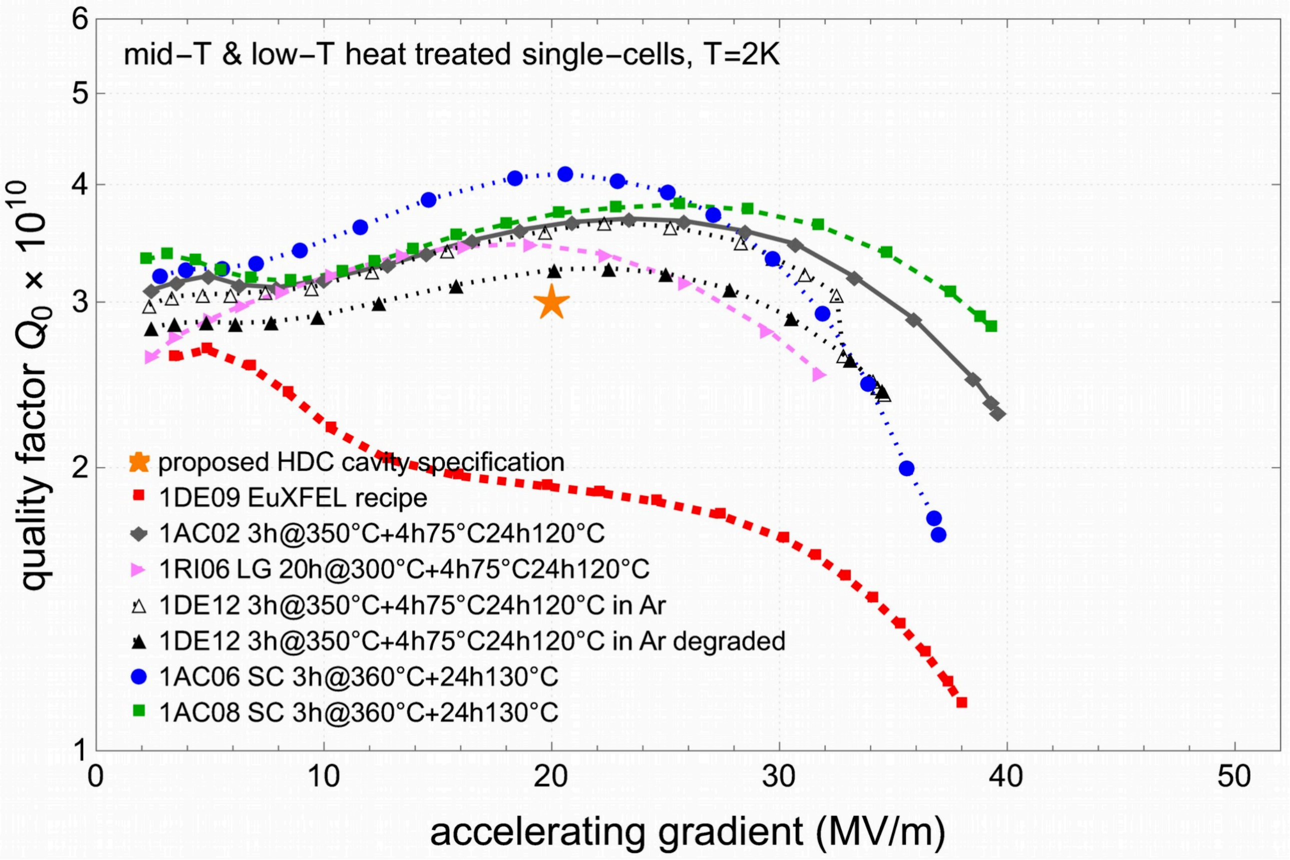
R&D towards CW-optimised cavities

Mid-T/low-T combination for even better gradients

Goal: **high Q_0** at moderate **accelerating gradients**

- $3 \cdot 10^{10}$ @ 20 MV/m

- Actual choice: new **mid-T/low-T recipe**
  - **high Q_0** and gradients up to **40 MV/m**
  - **established** on single-cells, more **statistics** being collected
- Open questions tackled by **actual R&D** projects
  - flux trapping sensitivity
  - sometimes degradation of Q_0 after quenches
- Transition to **nine-cell cavities** ongoing
  - first treatments done
  - **specification** & qualification of new nine-cell cavities started



More details: talk TUA05

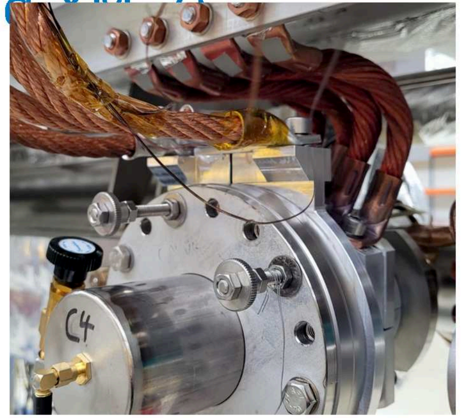
R&D towards CW-optimised cryomodules

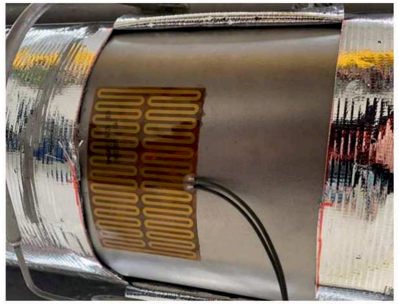
New CW-optimised cryomodules (L1-L2)

- **Design an optimised 2K distribution** for new cryomodules
  - bigger 2-phase pipe
  - one 2K Joule-Thompson valve per module
- **Study coupler, HOM and end groups heating**, define needed modifications
- **Study 5-8K thermal** shield heat load
  - keep the shield if possible (unlike LCLS-II and SHINE)
- Verify **tuner, magnetic shield**, ... for HDC
- Define requirements and verify feasibility for **fast cooldown** in case needed
- **Reduce venting cycles of string vacuum** during assembly to minimize risk of field emission

Towards a prototype cryomodule

Modifications of existing cryomodules (XM99, XM50.1 and XM-3)





XM99, under test

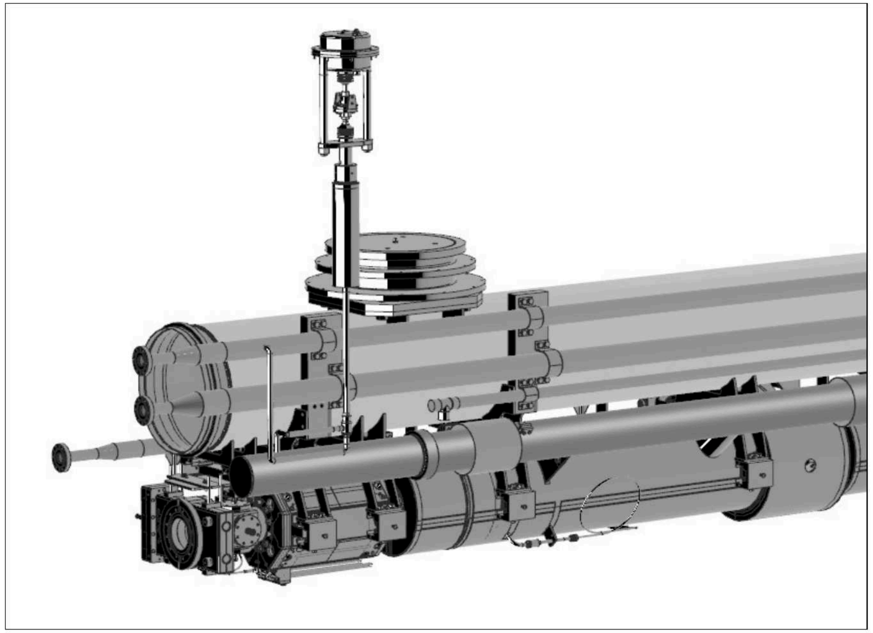
- New coupler cooling connection
- Additional instrumentation: heaters, P/T and vibration sensors
- 5-8 K thermal shield removed

Preliminary results

- Improvement in temperature distribution at coupler with new cooling
- Demonstrated stable cryogenic operation with dynamic heat load up to 15 W (limited by power source)

XM50.1, XM-3 coming next

- Test assembly of couplers and tuners with beam pipe under vacuum
- Use for testing cryogenic modifications: additional 2K valve, bigger 2-phase pipe, new level vessel, …

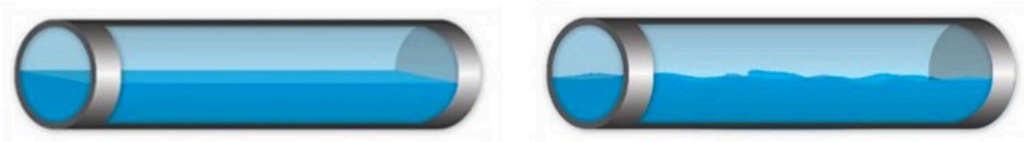


Activities for L3 cryomodules

R&D activities at L3 cryomodules

96 existing cryomodules (L3)

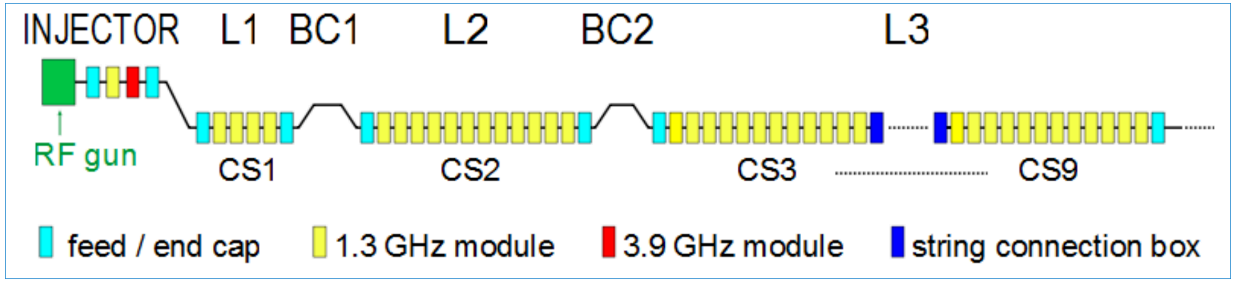
HDC R&D scope for L3



1. Look for the maximal heat load for stable RF operation to avoid oscillations, instabilities due to cryogenic: higher heat load means higher gas and liquid velocity in the 2-phase pipe ✉ possible instabilities
2. Evaluate heat load of existing cryomodules at gradients ~10 MV/m

Present design

- In L3 has one 2K supply valve and one continuous 2-phase pipe for string of 12 cryomodules



Design modifications

- no disassembly foreseen for the cryomodules, limited modifications possible

R&D activities at L3 cryomodules

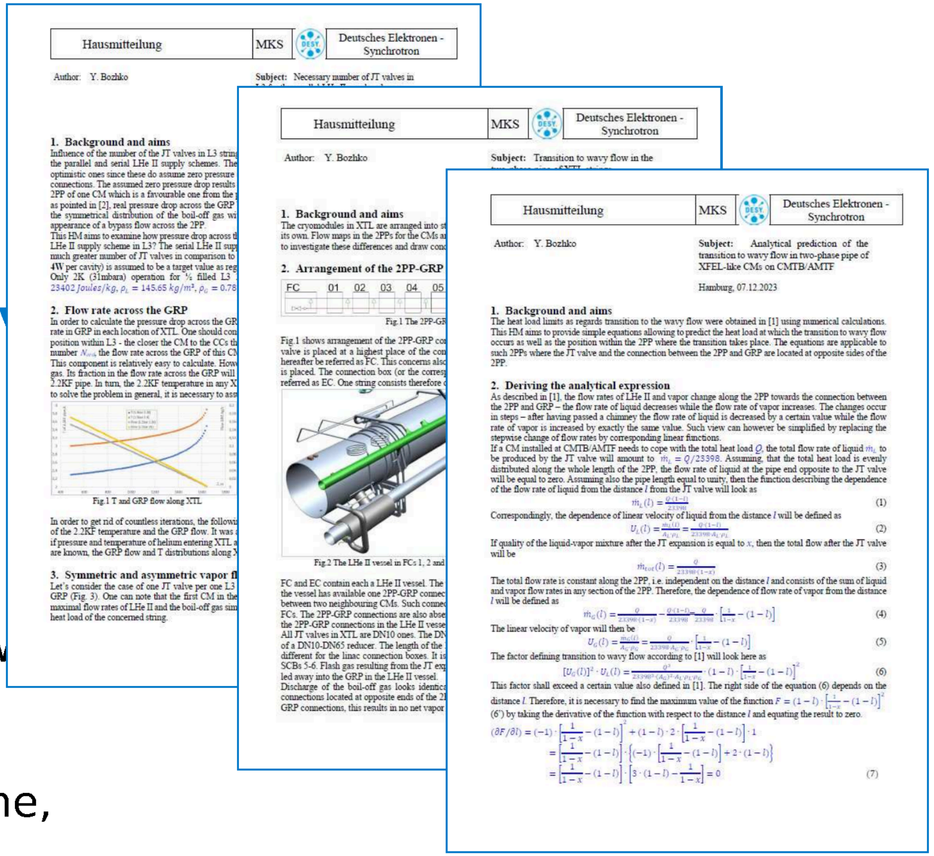
96 <u>existing</u> cryomodules (L3)

1. Calculation of optimised 2K distribution ongoing

- First configuration available: **20 additional 2K** Joule-Thompson **valv** needed at module connections to reach ~**32 W /module**
- Design needs to be implemented and assembly tested

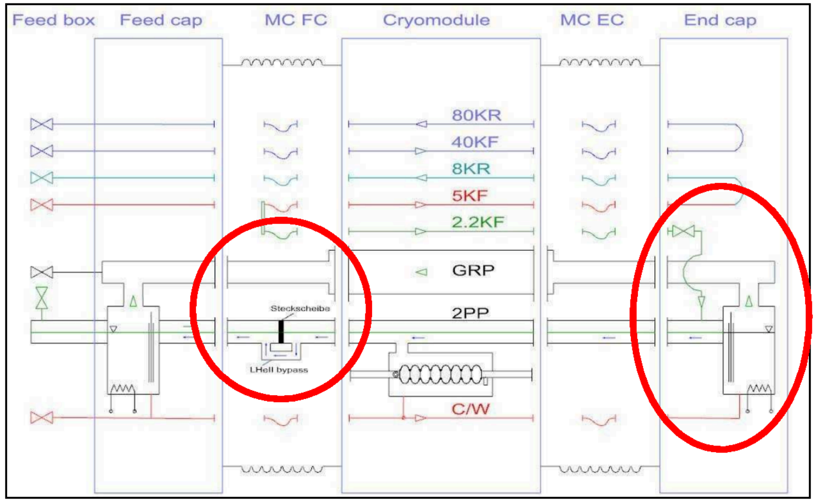
2. Heat load measurement of existing XFEL cryomodules at low

- Plan to use evaporation method for installed cryomodule
- Procedure under optimization: delta level, how many strings at a time, at which gradient, …
- First test on a string in the EuXFEL tunnel (XTL) performed in summer 2025, further tests in 2026



Testing the heat load limit for L3 cryomodules

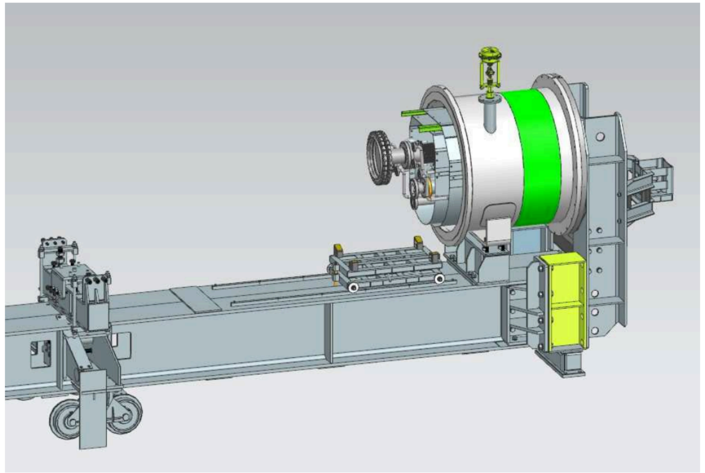
96 existing cryomodules (L3)



No possibilities to test higher flow rate in existing strings (XTL)

We need to **simulate the different flow conditions** at the horizontal **module test stands**

- Bypass flow at the 2-phase pipe
- Higher flow from neighboring cryomodules



Design available, some modifications of the test stand needed

- Special adapters at the module connection
- Connection of JT valve and level vessel at the end cap

Summary

Summary

- **High Duty Cycle** upgrade for EuXFEL **in development**
  - Extensive R&D ongoing
    - New CW-optimised cryomodules needed
- Basis is **existing EuXFEL cryomodule**
  - **No failure** of cold components during first operation period of 8 y

- **Activities** towards a HDC prototype ongoing and planed
  - New cavity recipe verified for 1-cell cavities, transfer to 9-cell ongoing
  - First modifications at a cryomodule implemented and under test
- Plan for the next 2-3 years includes **upgrade of test stands**
  - Modify test stand for HDC cryogenic tests and start verifying proposed design for L3
  - Finish assembly and commissioning of new horizontal cavity test stand XATB

Thank you for your atte

DESY HDC workshop, April 2025