

THE PATH TO HIGH DUTY CYCLE AT EuXFEL.

Cryomodule developments

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DESY MKS group

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HELMHOLTZ



Outline

The EuXFEL High Duty Cycle (HDC) upgrade

- 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



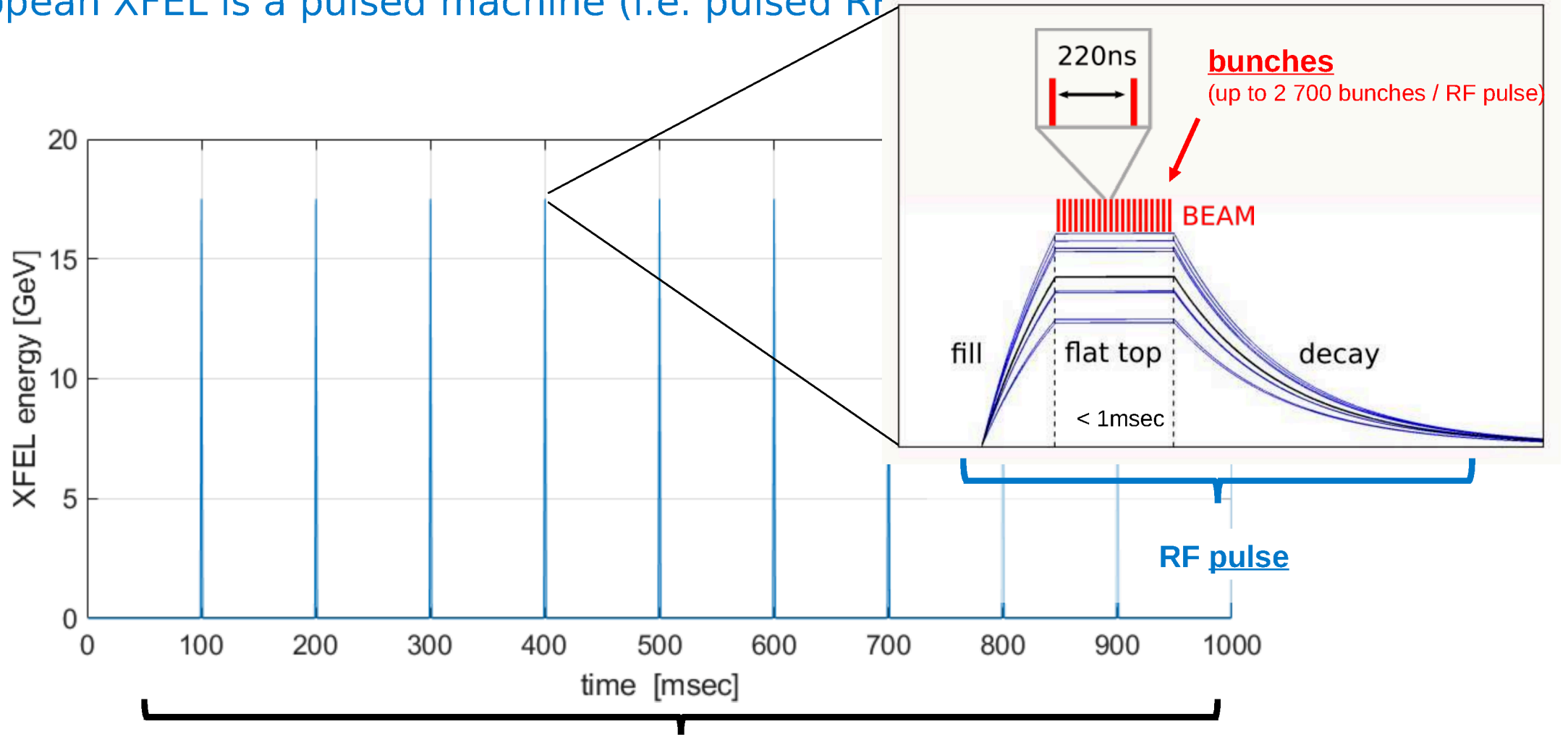
The EuXFEL High Duty Cycle upgrade

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)

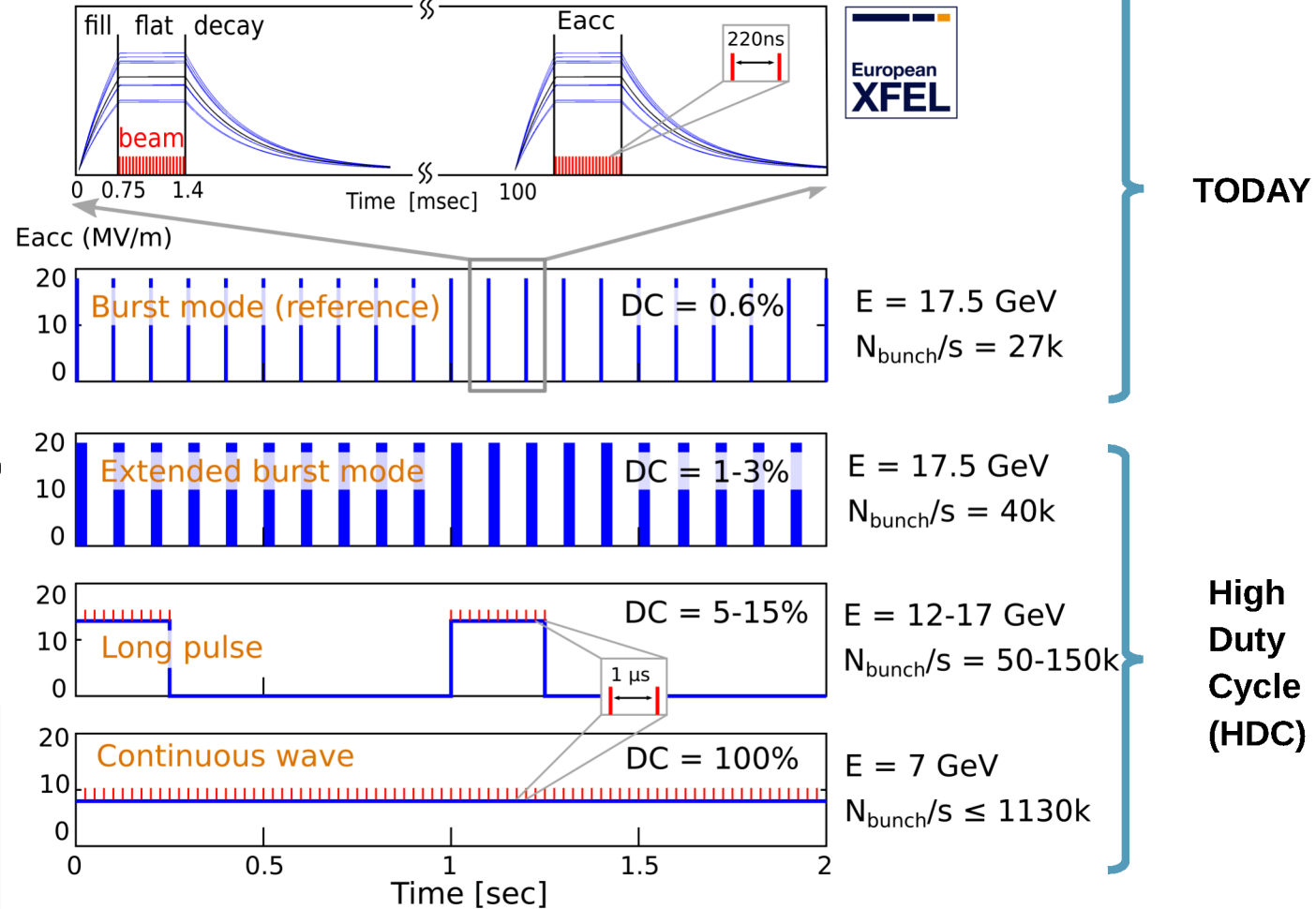
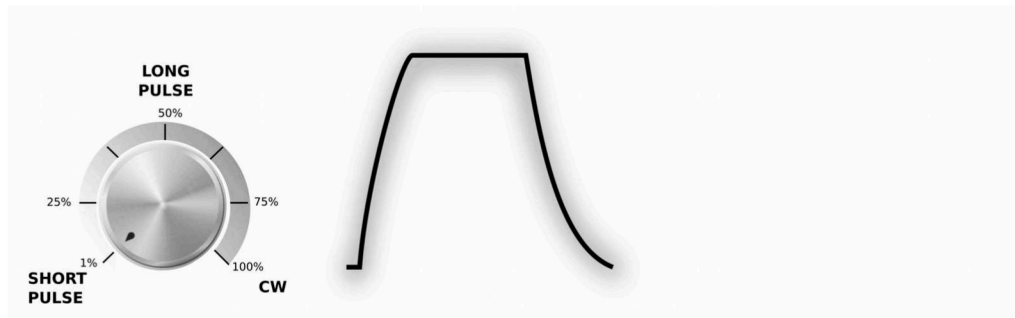
Where to improve ?

User feedback driven by science case

EuXFEL users wish to have

- **Everything they have now**
- **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

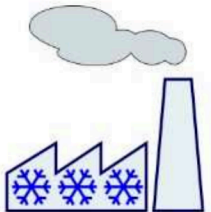
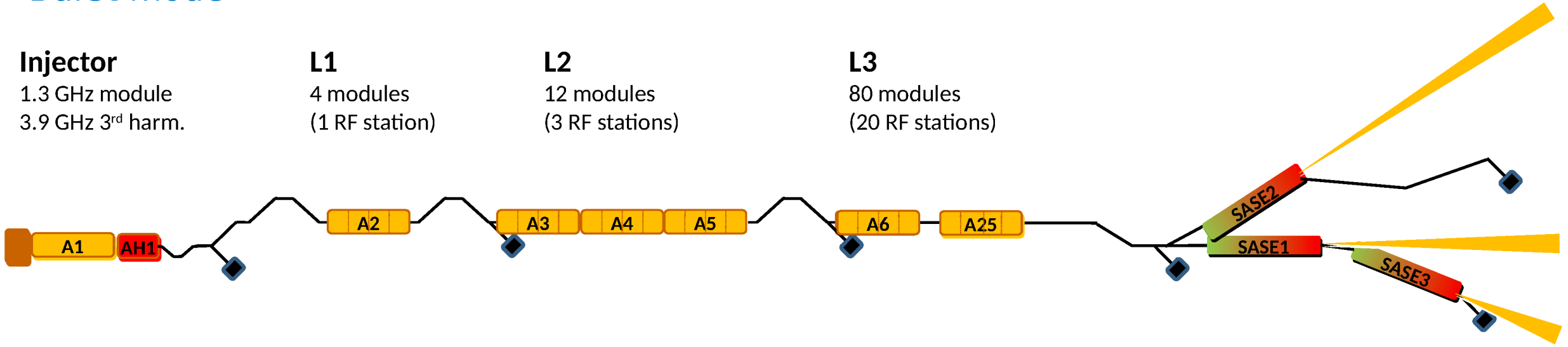
Burst mode

Injector
1.3 GHz module
3.9 GHz 3rd harm.

L1
4 modules
(1 RF station)

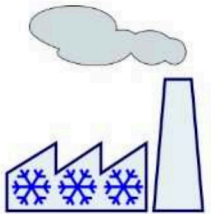
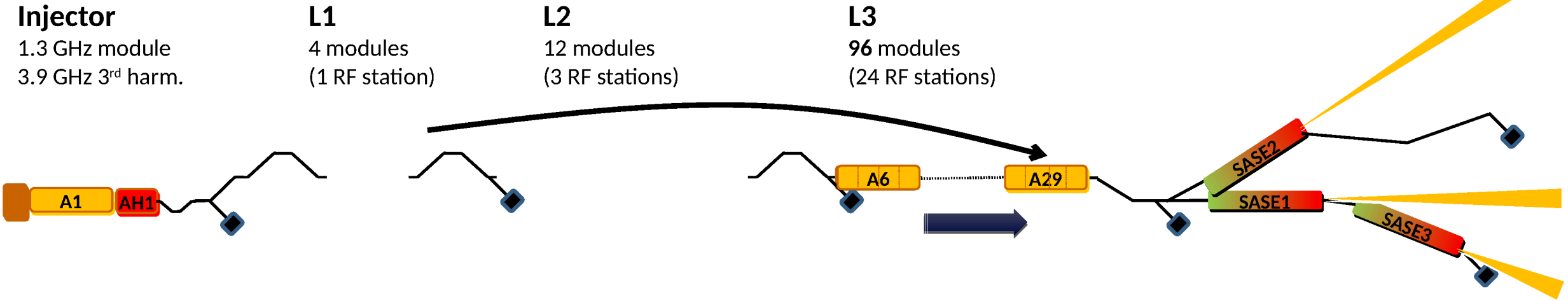
L2
12 modules
(3 RF stations)

L3
80 modules
(20 RF stations)



High Duty Cycle Upgrade

Current proposal baseline



High Duty Cycle Upgrade

Current proposal baseline

Injector

1.3 GHz module
3.9 GHz 3rd harm.

L1

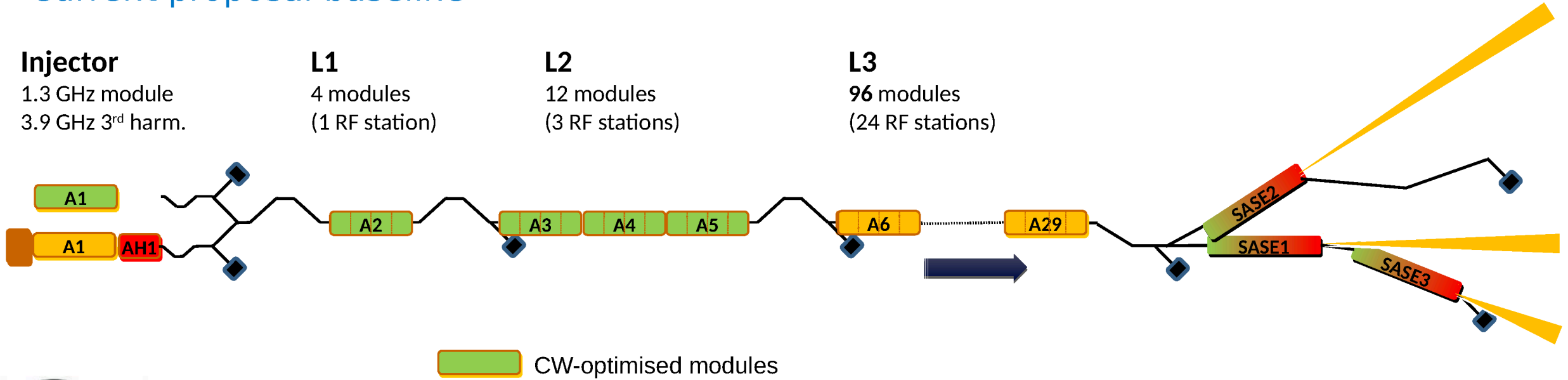
4 modules
(1 RF station)

L2

12 modules
(3 RF stations)

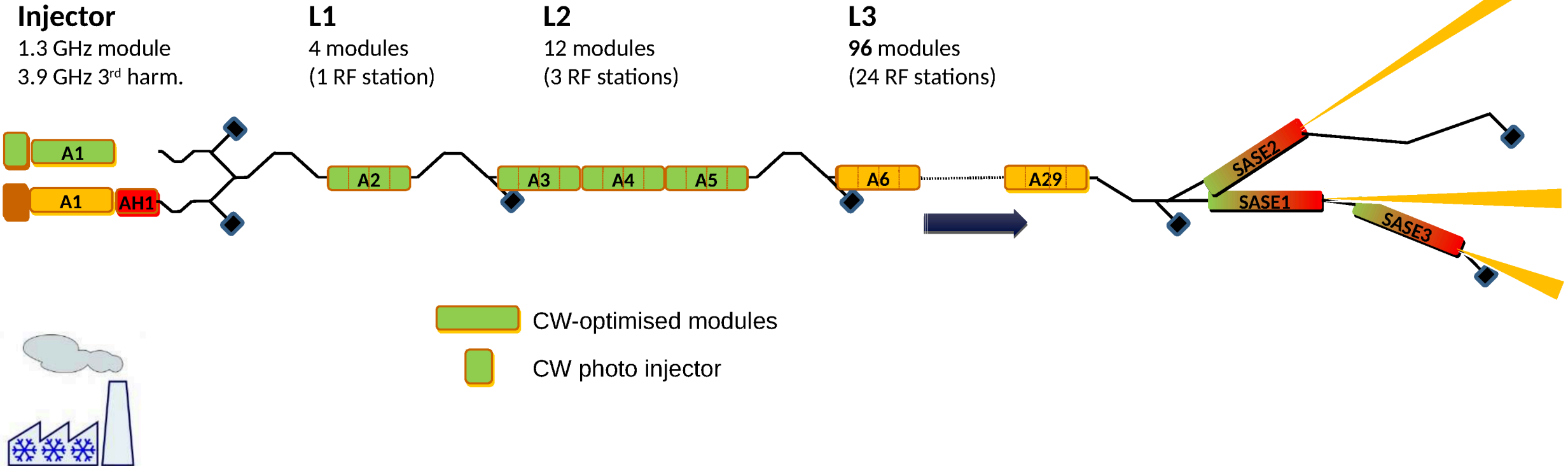
L3

96 modules
(24 RF stations)



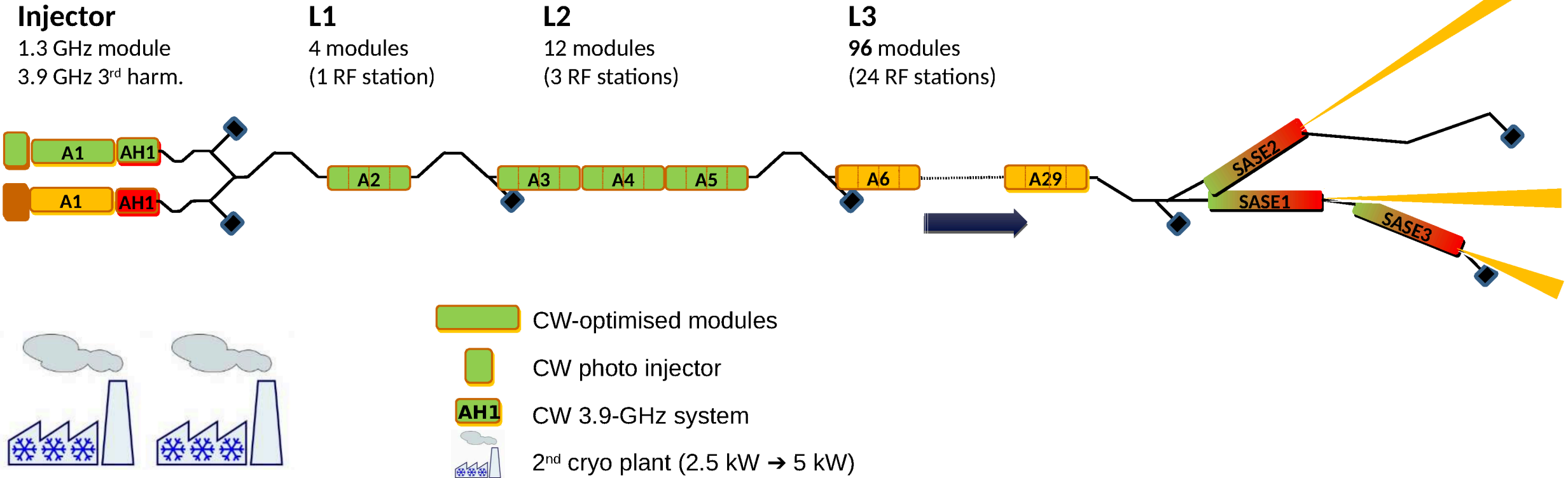
High Duty Cycle Upgrade

Current proposal baseline



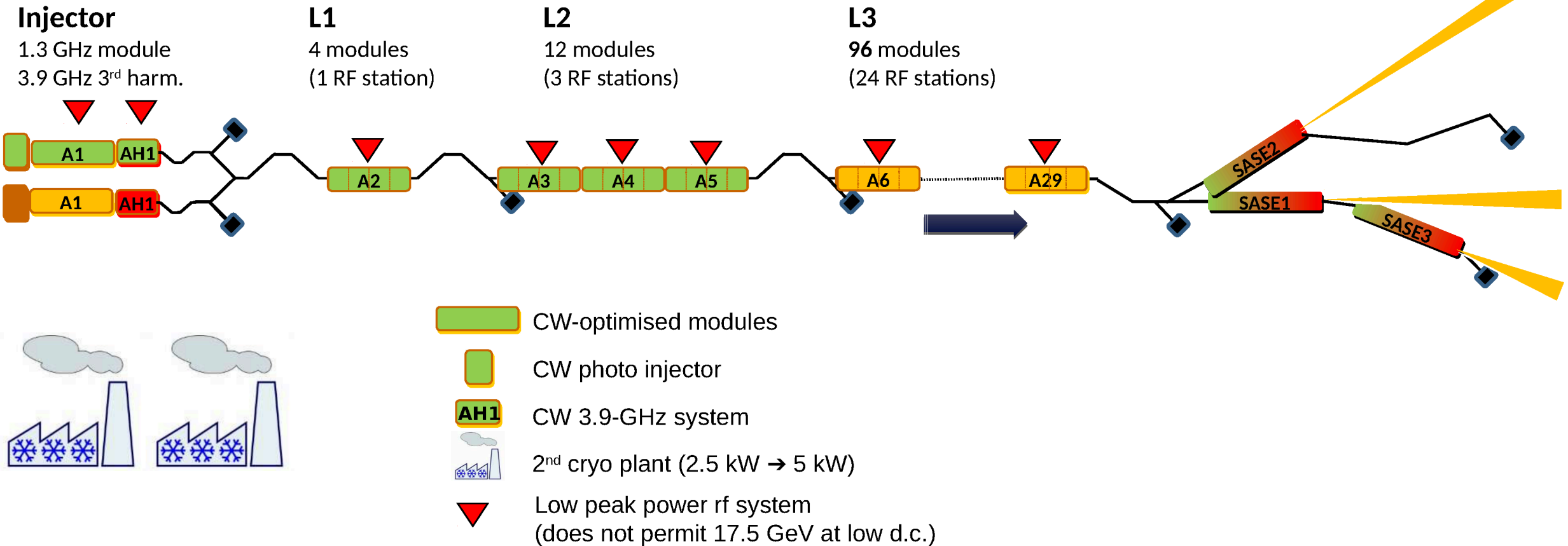
High Duty Cycle Upgrade

Current proposal baseline



High Duty Cycle Upgrade

Current proposal baseline



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

A dual R&D scope for the HDC upgrade

New front-end (Inj, L1, L2) combined with legacy linac (L3)

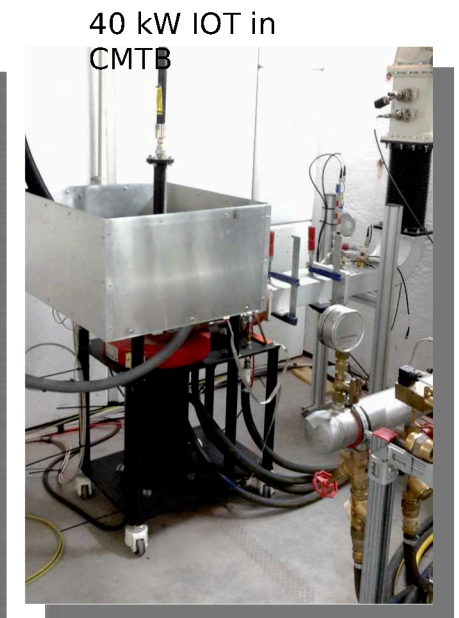
New accelerator front-end (Inj, L1, L2)

- New **CW-optimised cavities & cryomodules**, build on experience from LCLS-II and ST This talk and talk TUA05
- Develop an **SRF CW injector**, starting with test stand T44i Talk THB05 and poster TUP65 (cath)
- Develop next generation **beam controls and diagnostics**

Key challenges for the legacy linac

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

Entire HDC R&D program devoted to answering these questions



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..

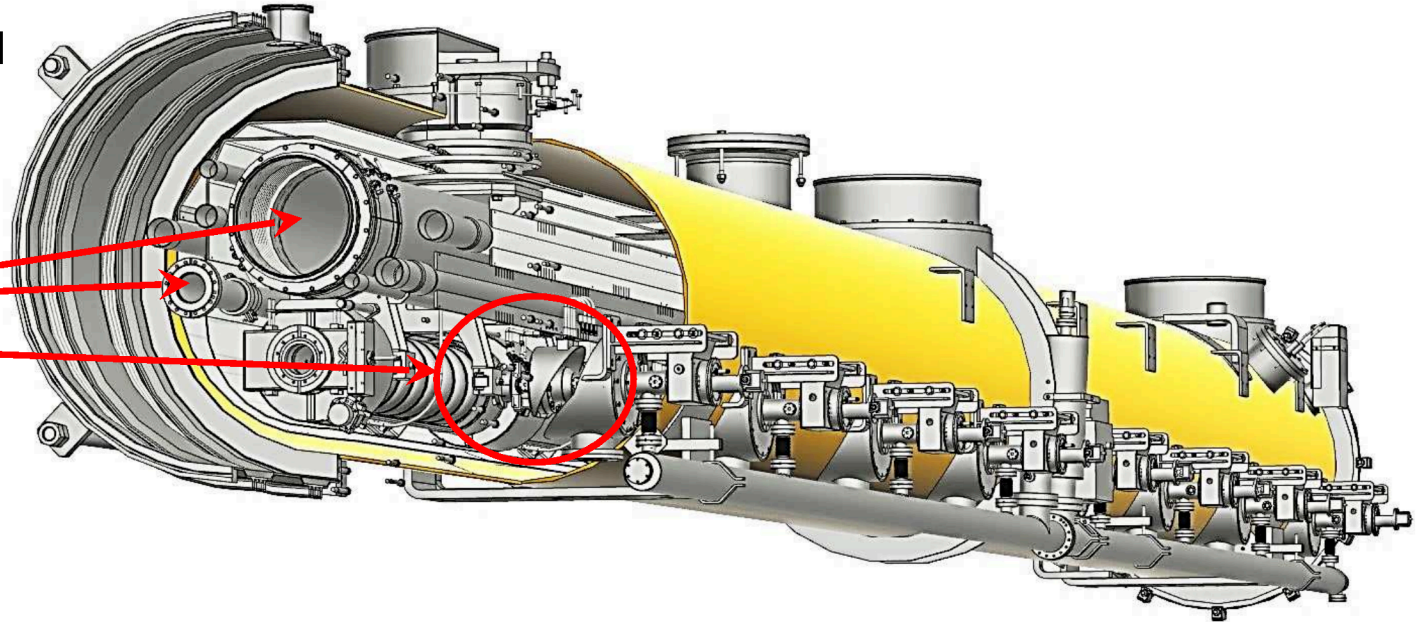
Solutions for new cryomodules (L1-L2)

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

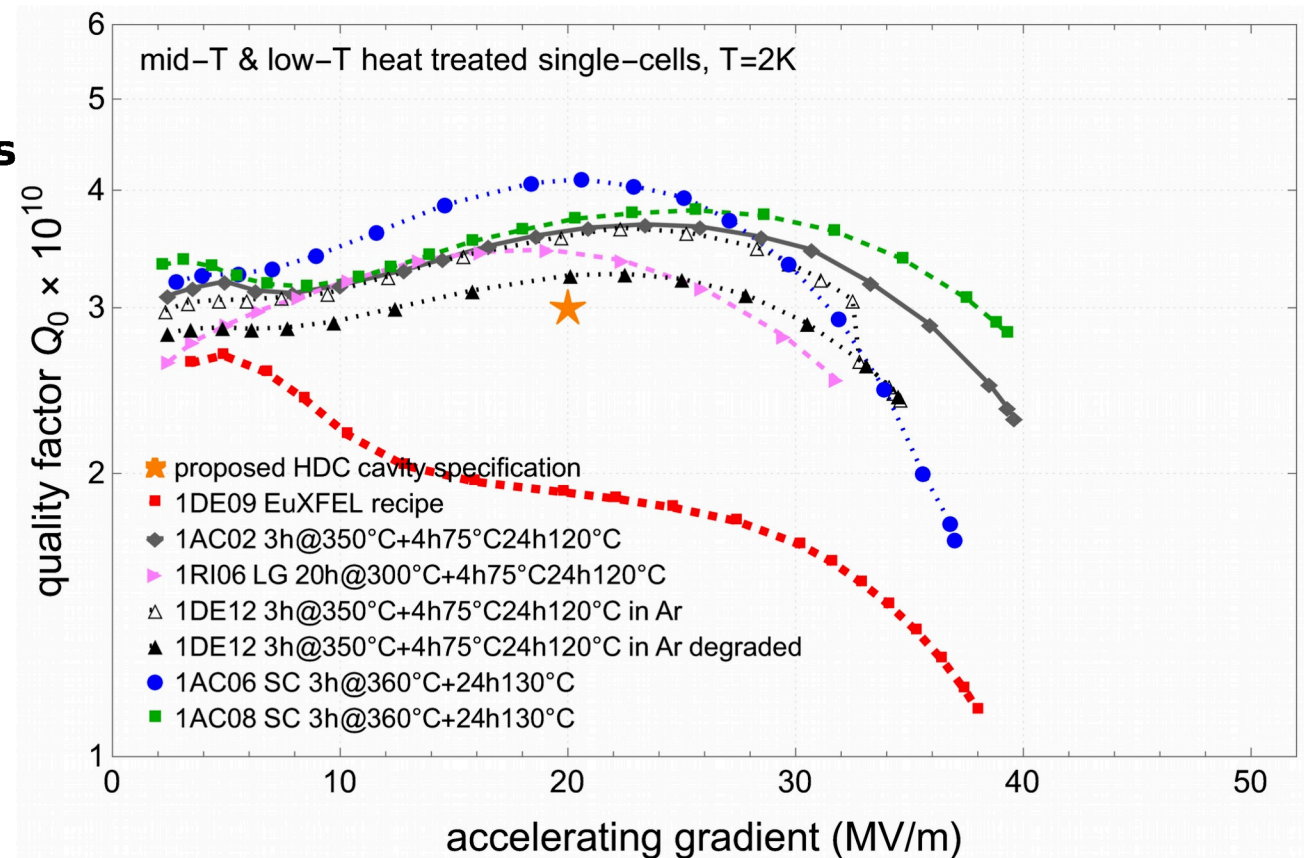
- flux trapping sensitivity

- 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

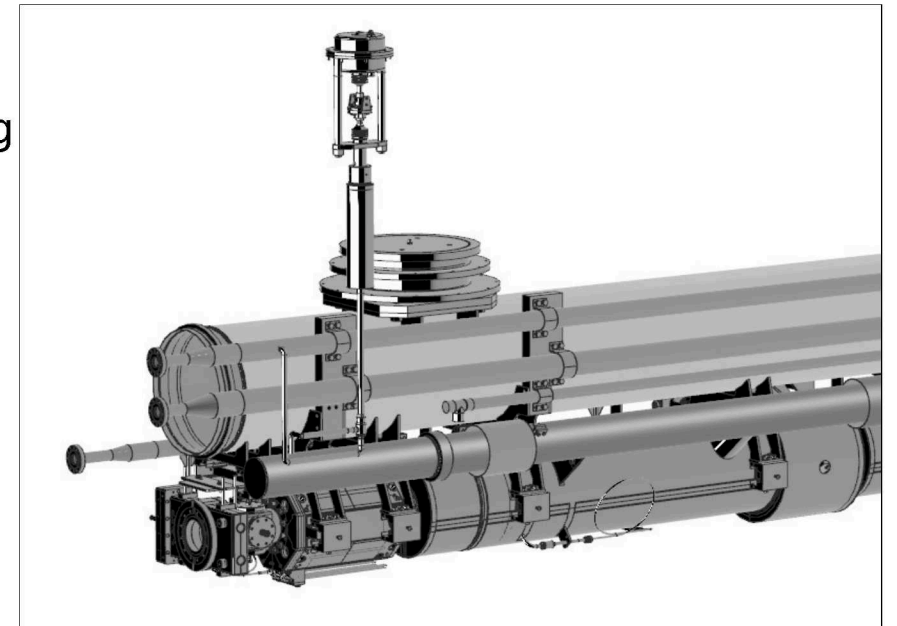
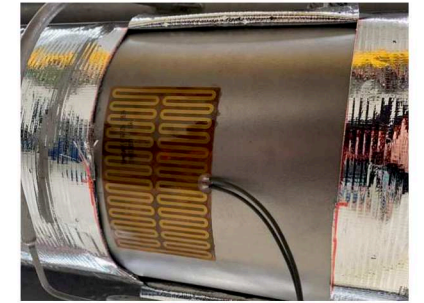
- New coupler cooling connection
- Additional instrumentation: heaters, P/T and vibration sensors
- 5-8 K thermal shield removed

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)

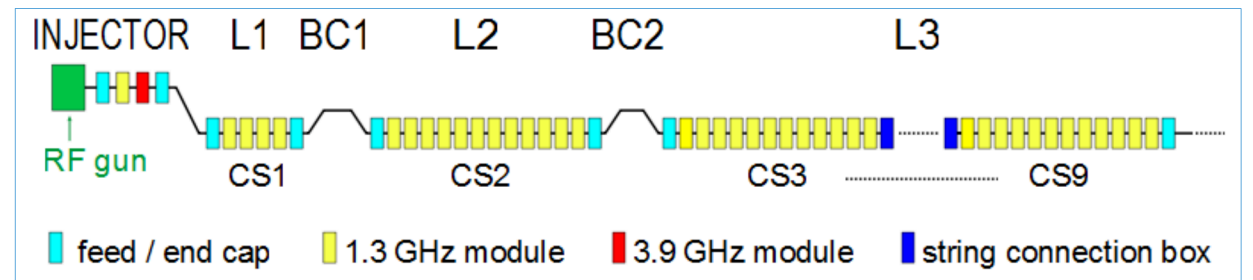
HDC R&D scope for L3

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 existing cryomodules (L3)

1. Calculation of optimised 2K distribution ongoing

- First configuration available: **20 additional 2K** Joule-Thompson valves 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

Hausmitteilung MKS Deutsches Elektronen-Synchrotron

Author: Y. Bozhko Subject: Necessary number of JT valves in

1. Background and aims
Influence of the number of the JT valves in L3 string, the parallel and serial LHe II supply schemes. The optimum ones since these do assume zero pressure connections. The assumed zero pressure drop results ZPP of one CM which is a favourable one from the as pointed in [2], real pressure drop across the GRP, the symmetrical distribution of the boil-off gas, the appearance of a bypass flow across the ZPP. This HM aims to examine how pressure drop across LHe II supply scheme in L3. The serial LHe II requires much greater number of JT valves in comparison to 4W per cavity) is assumed to be a target value as req. Only 2K (2Joule) operation for v_0 filled L3 23402 Joules/kg, $\rho_0 = 145.65 \text{ kg/m}^3$, $\rho_v = 0.78$

2. Flow rate across the GRP
In order to calculate the pressure drop across the GRP rate in GRP in each location of XTL. One should compare within L3 - the closer the CM to the CC, the number N_{JT} , the flow rate across the GRP of this CM. This component is relatively easy to calculate. Flow gas. Its fraction in the flow rate across the GRP will 2.KF pipe. In turn, the 2.KF temperature in any XTL to solve the problem in general, it is necessary to solve




Fig.1 T and GRP flow along XTL.

In order to get rid of counter-streams, the follow-up of the 2.KF temperature and the GRP flow. It was if pressure and temperature of helium entering XTL are set known, the GRP flow and T distribution along XTL.

3. Symmetric and asymmetric vapor flow
Let's consider the case of one JT valve per one L3 GRP (Fig. 3). One can note that the first CM in the maximal flow rates of LHe II and the boil-off gas are heat load of the concerned string.

Hausmitteilung MKS Deutsches Elektronen-Synchrotron

Author: Y. Bozhko Subject: Transition to wavy flow in the

1. Background and aims
The cryomodules in XTL are arranged into strings of their own. Flow maps in the ZPPs for the CMs are to investigate these differences and draw conclusions.

2. Arrangement of the ZPP-GRP

FC	01	02	03	04	05
Location					

Fig.1 The ZPP-GRP arrangement of the ZPP-GRP and EC valve is placed at a highest place of the connection between FC. This concern also is placed. The connection box (or the correct referred as EC. One string consists therefore of

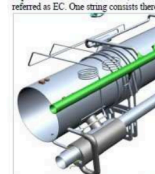


Fig.2 The LHe II vessel in FCs 1, 2 and 3

FC and EC contain each a LHe II vessel. The vessel has available one ZPP-GRP connection between two neighbouring CMs. Such connection. The ZPP-GRP connections are also above the ZPP-GRP connections in the LHe II vessel. All JT valves in XTL are DN10 ones. The DN of a DN10-DN15 reducer. The length of the different for the linac connection boxes. It is SCB 5.4. Flash gas resulting from the JT valve led away into the GRP in the LHe II vessel. Discharge of the boil-off gas looks identical: connections located at opposite ends of the 2K GRP connection, this results in no net vapor

Hausmitteilung MKS Deutsches Elektronen-Synchrotron

Author: Y. Bozhko Subject: Analytical prediction of the transition to wavy flow in two-phase pipe of XFEL-like CMs on CMTB/AMTF

Hamburg, 07.12.2023

1. Background and aims
The heat load limits as regards transition to the wavy flow were obtained in [1] using numerical calculations. This HM aims to provide simple equations allowing to predict the heat load at which the transition to wavy flow occurs as well as the position within the ZPP where the transition takes place. The equations are applicable to such ZPPs where the JT valve and the connection between the ZPP and GRP are located at opposite sides of the ZPP.

2. Deriving the analytical expression
As described in [1], the flow rates of LHe II and vapor change along the ZPP towards the connection between the ZPP and GRP—the flow rate of liquid decreases while the flow rate of vapor increases. The changes occur in steps—after having passed a chimney the flow rate of liquid is decreased by a certain value while the flow rate of vapor is increased by exactly the same value. Such view can however be simplified by replacing the stepwise change of flow rates by corresponding linear functions. If a CM installed at CMTB/AMTF needs to cope with the total heat load Q , the total flow rate of liquid m_l to be produced by the JT valve will amount to $m_l = Q/23398$. Assuming that the total heat load is evenly distributed along the whole length of the ZPP, the flow rate of liquid at the pipe end opposite to the JT valve will be equal to zero. Assuming also the pipe length equal to unity, then the function describing the dependence of the flow rate of liquid from the distance l from the JT valve will look as

$$m_l(l) = \frac{Q}{23398} \cdot (1-l) \quad (1)$$

Correspondingly, the dependence of linear velocity of liquid from the distance l will be defined as

$$U_l(l) = \frac{m_l(l)}{\rho_l \cdot A} = \frac{Q}{23398 \cdot A} \cdot (1-l) \quad (2)$$

If equality of the liquid-vapor mixture after the JT expansion is equal to 1, then the total flow after the JT valve will be

$$m_{tot}(l) = \frac{Q}{23398 \cdot A} \cdot (1-l) \quad (3)$$

The total flow rate is constant along the ZPP, i.e. independent on the distance l and consists of the sum of liquid and vapor flow rates in any section of the ZPP. Therefore, the dependence of flow rate of vapor from the distance l will be defined as

$$m_v(l) = \frac{Q}{23398 \cdot A} \cdot (1-l) - \frac{Q}{23398 \cdot A} \cdot (1-l) \cdot \left[\frac{1}{1-\beta} - (1-\beta) \right] \quad (4)$$

The linear velocity of vapor will then be

$$U_v(l) = \frac{m_v(l)}{\rho_v \cdot A} = \frac{Q}{23398 \cdot A} \cdot (1-l) \cdot \left[\frac{1}{1-\beta} - (1-\beta) \right] \quad (5)$$

The factor defining transition to wavy flow according to [1] will look here as

$$[U_l(l)]^2 \cdot U_v(l) = \frac{Q^3}{23398^3 \cdot A^3} \cdot (1-l)^3 \cdot \left[\frac{1}{1-\beta} - (1-\beta) \right]^2 \quad (6)$$

This factor shall exceed a certain value also defined in [1]. The right side of the equation (6) depends on the distance l . Therefore, it is necessary to find the maximum value of the function $F = (1-l) \cdot \left[\frac{1}{1-\beta} - (1-\beta) \right]^2$ (6) by taking the derivative of the function with respect to the distance l and equating the result to zero.

$$\frac{\partial F}{\partial l} = -(1-l) \cdot \left[\frac{1}{1-\beta} - (1-\beta) \right] + (1-l)^2 \cdot \left[\frac{1}{1-\beta} - (1-\beta) \right]^{-1} \cdot 1 = \left[\frac{1}{1-\beta} - (1-\beta) \right] \cdot \left\{ (-1) \cdot \left[\frac{1}{1-\beta} - (1-\beta) \right] + 2 \cdot (1-l) \right\} = \left[\frac{1}{1-\beta} - (1-\beta) \right] \cdot \left[2 \cdot (1-l) - \frac{1}{1-\beta} + (1-\beta) \right] = 0 \quad (7)$$

Testing the heat load limit for L3 cryomodules

06 existing cryomodules (L3)

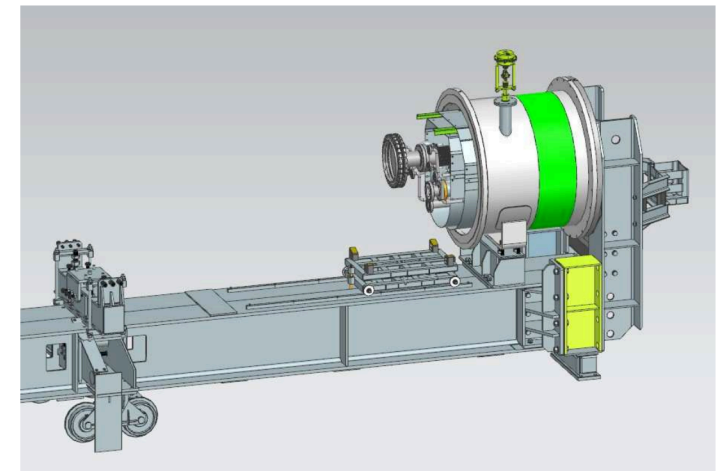
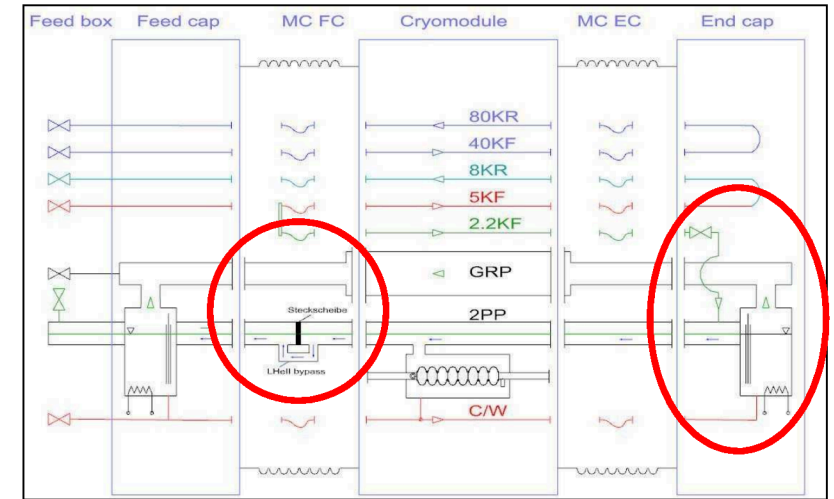
No possibilities to test higher flow rate in existing strings (XTL)

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 planned
 - 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 attendance



DESY HDC workshop, April 2025

