Present status and possible upgrade of the XFEL cryomodules

From TTF to CW-EuXFEL

Kay Jensch

European Cryogenic Days, 07/10/2019 Lund

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Outlook

01 The cryogenic of the EuXFEL accelerator

- General layout of the accelerator
- Components: modules and more

02 The EuXFEL cryomodule

- Short history
- Main components

03 EuXFEL-CW

- Scope and requirements
- Main challenges for the cryogenic

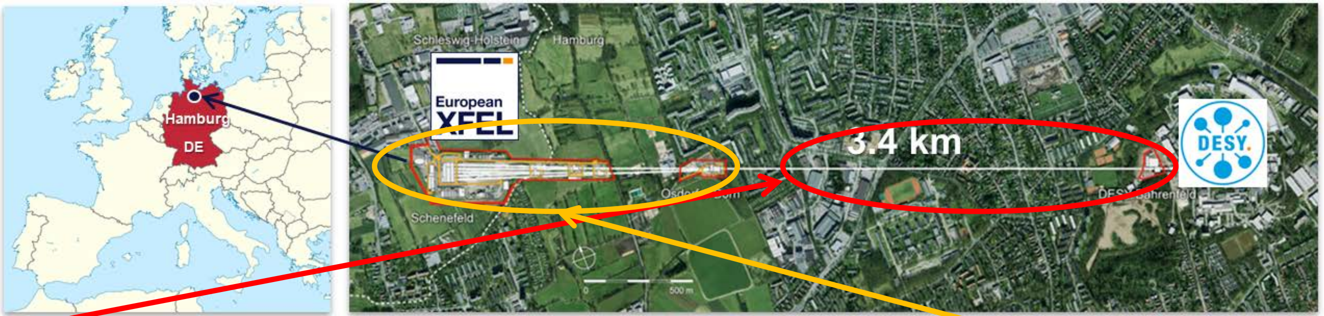
The cryogenic of the European XFEL accelerator

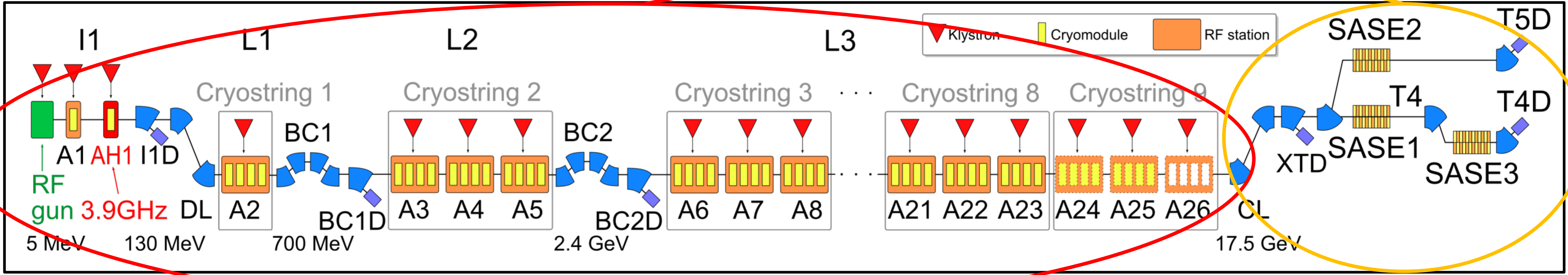
Courtesy J. Branlard

The European X-ray Free Electron Laser (EuXFEL)

The complete facility

- Soft and hard X-ray light experiments
- Design energy 17.5 GeV, typical SASE user runs at 14 -14.5 GeV
- Pulsed operation at 10 Hz
- ~800 TESLA-type cavities
- Resonance frequency 1.3 GHz
- 32 cavities per XTL RF station
- Typical 3 RF stations for a cryogenic string





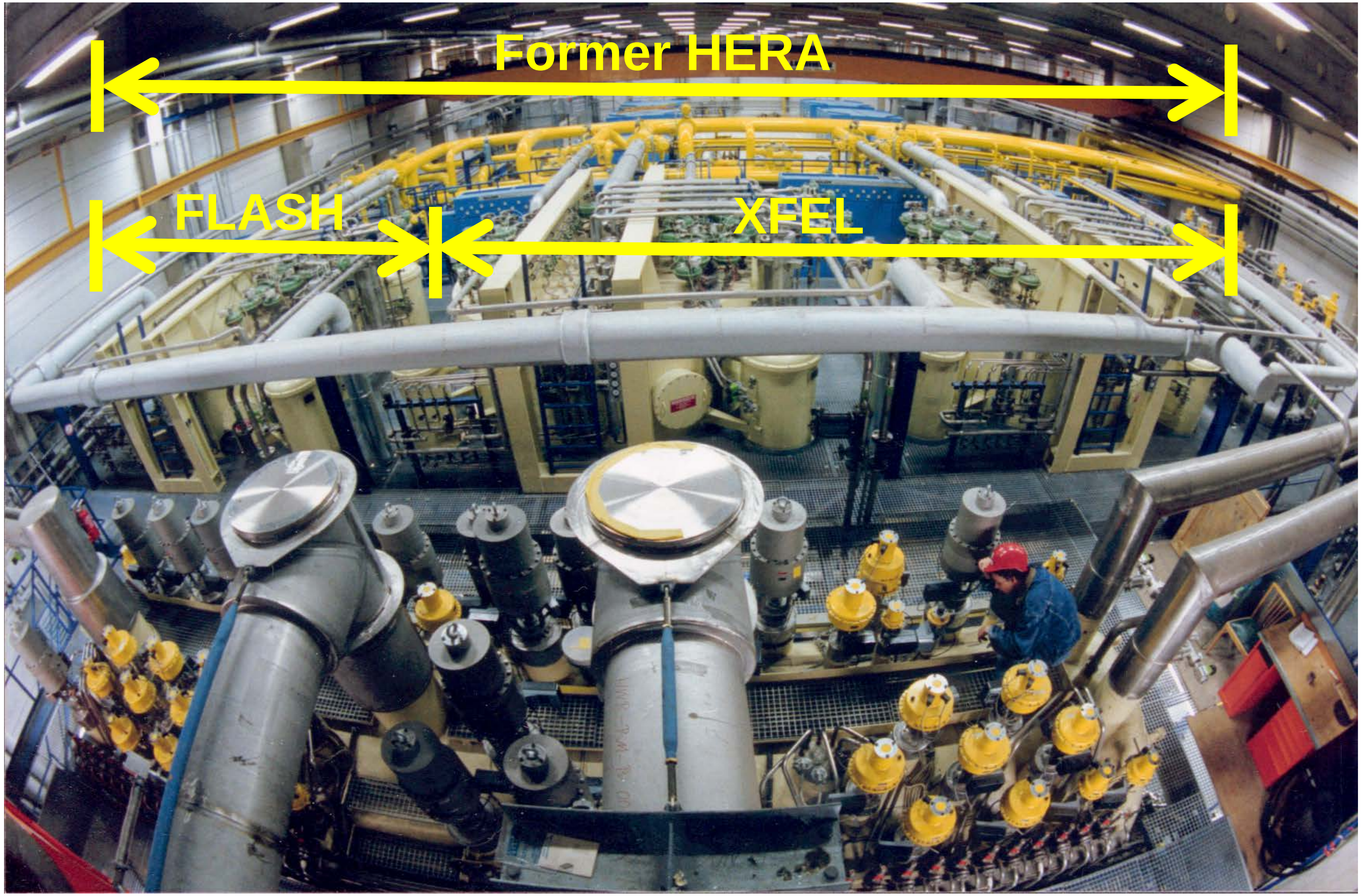
The European X-ray Free Electron Laser (EuXFEL)

The cryogenic facility

- 2 cryoplants (2 refurbished of 3 former HERA plants)
- 1 new 2K Coldbox with 4 stage cold compressors
- 1 distribution system (4 main boxes, >300 m of transfer lines, …)
- 14 cryogenic caps/boxes for cryomodule connections
- 98 cryomodules
- Test facility (AMTF) :
  - 3 cryomodule test benches @ 2K (1.8K)
  - 2 cavity vertical test cryostat @ 2K (1.8K)

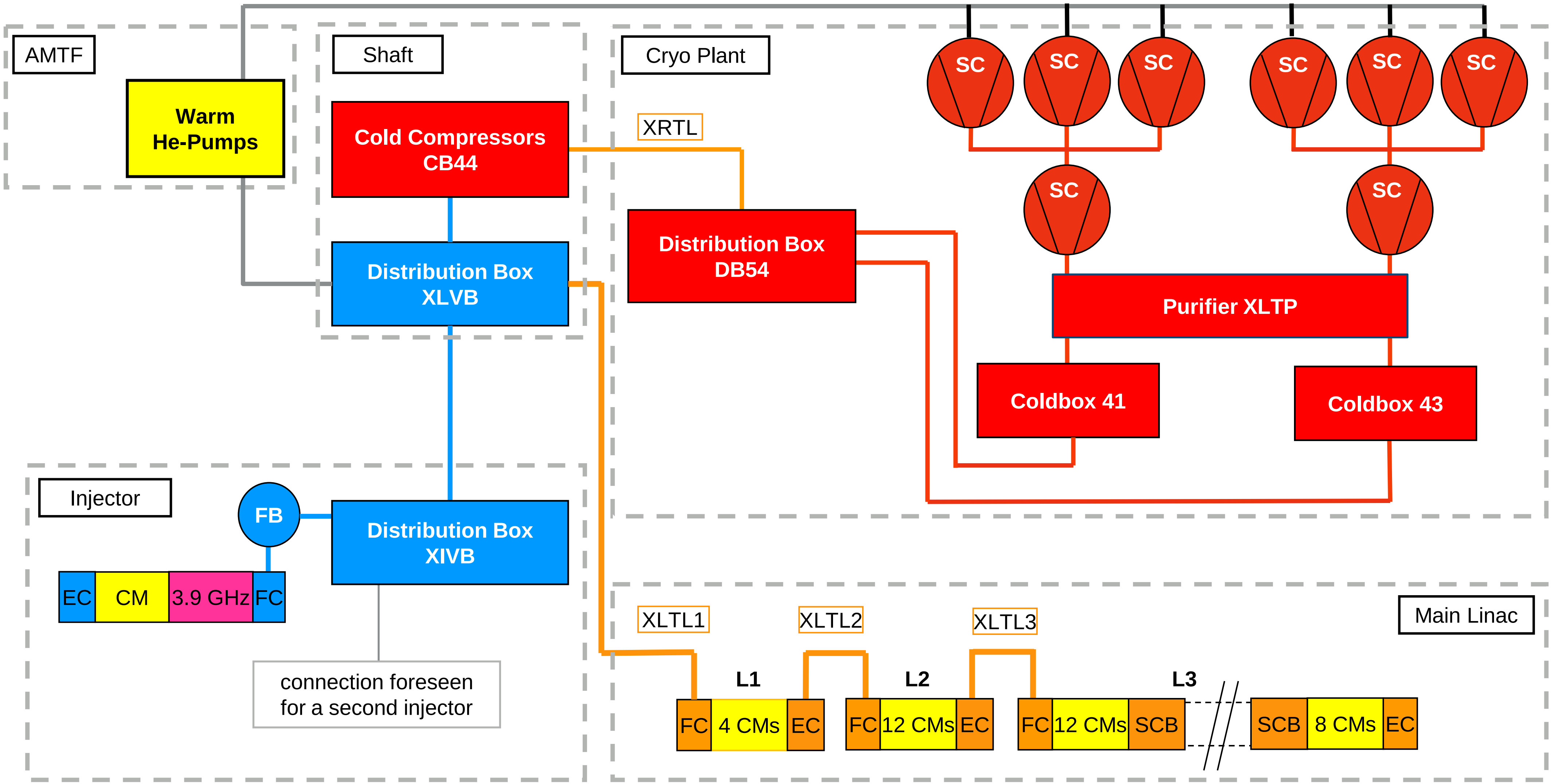
Cryo plant

2 cold boxes for the XFEL-Linac and 1 for FLASH, AMTF and CMTB operation



The EuXFEL cryogenic system

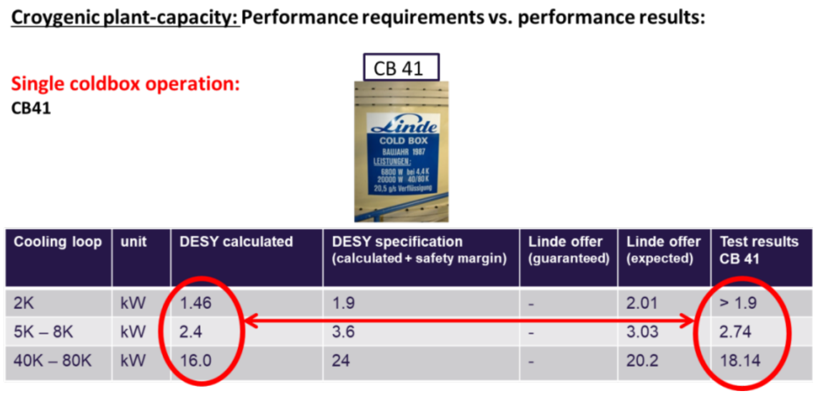
At 2K since December 2016



EuXFEL 2K philosophy

Cold and warm compressors

- Up to 17,5 GeV operation - only one cryo-plant necessary
- Coldbox and Cold Compressors for standard 2K operation
- Warm compressors only as backup -> can cover only static losses
    - AMTF Test Benches and FLASH operated only with the warm compressors

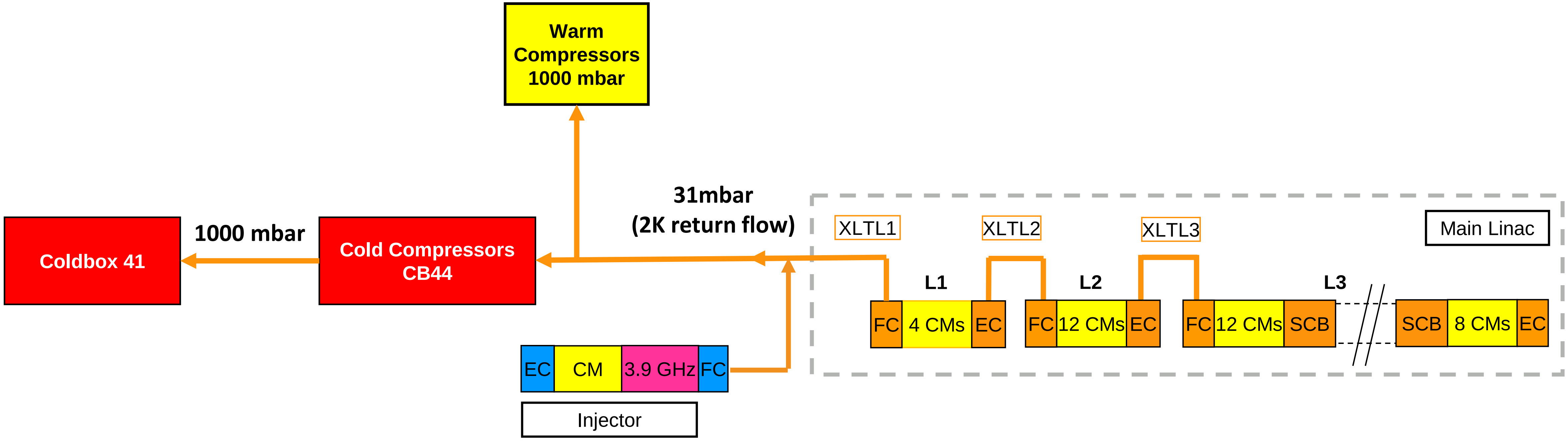


Croygenic plant-capacity: Performance requirements vs. performance results:

Single coldbox operation:
CB41

CB 41

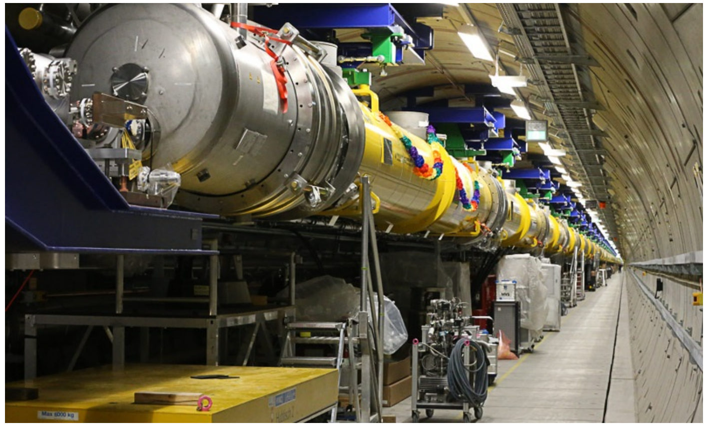
Cooling loop	unit	DESY calculated	DESY specification (calculated + safety margin)	Linde offer (guaranteed)	Linde offer (expected)	Test results CB 41
2K	kW	1.46	1.9	-	2.01	> 1.9
5K – 8K	kW	2.4	3.6	-	3.03	2.74
40K – 80K	kW	16.0	24	-	20.2	18.14

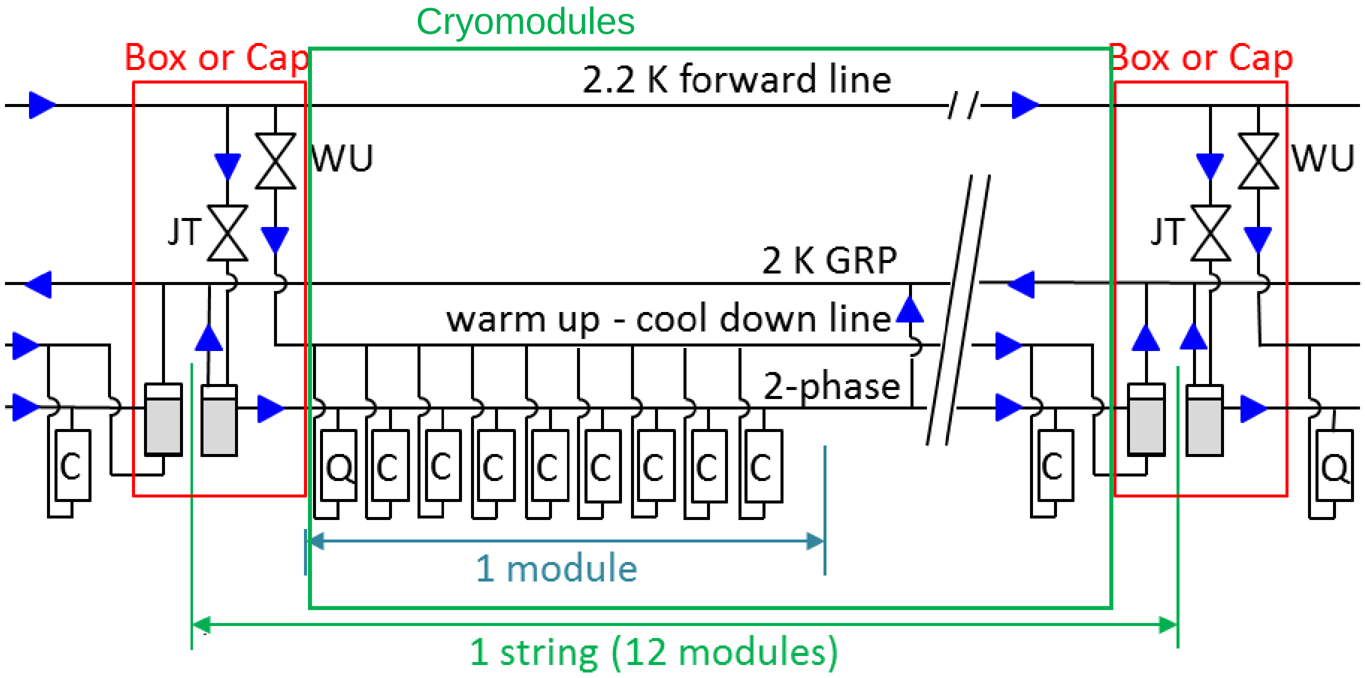


Helium distribution in the linac

Flow scheme for one cold string

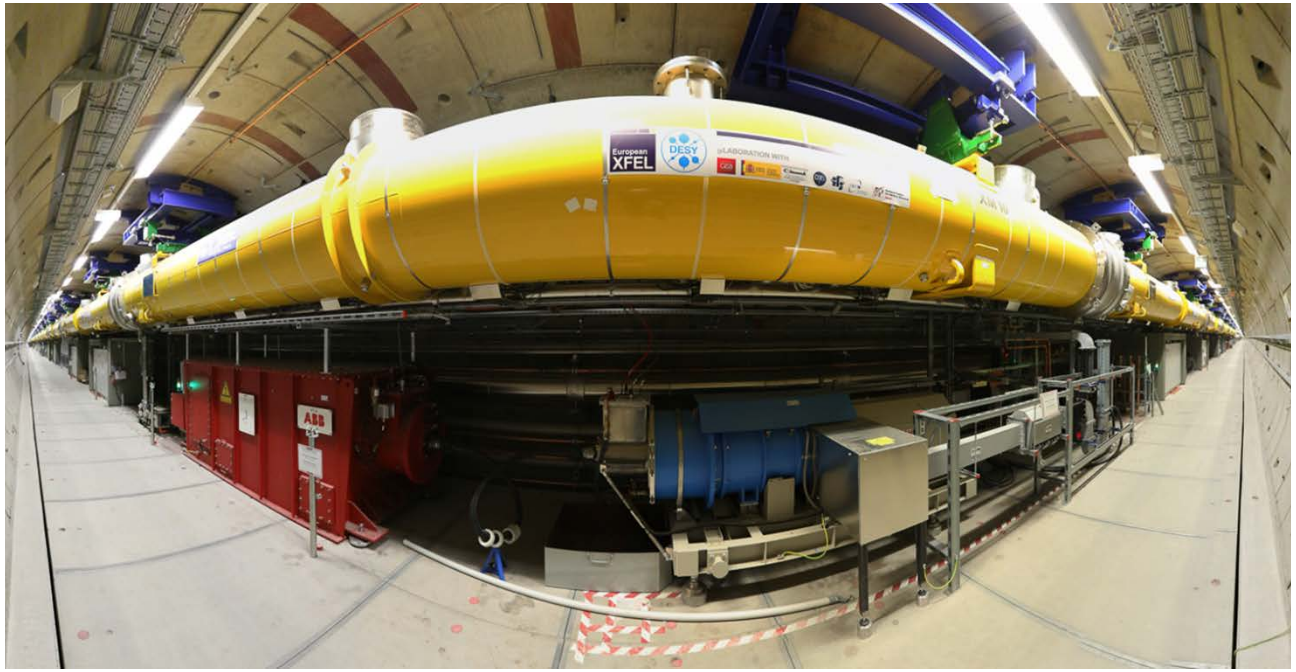
- 2 indipendent sections: injector and main linac
- Main linac divided in 3 parts L1, L2, L3, but one big cryosection (cool down as one)
- 2K helium divided in smaller strings (CS1 to CS9)
  → end, feed and string connection boxes
- JT-valves only in the boxes
- Boxes directly attached to the modules

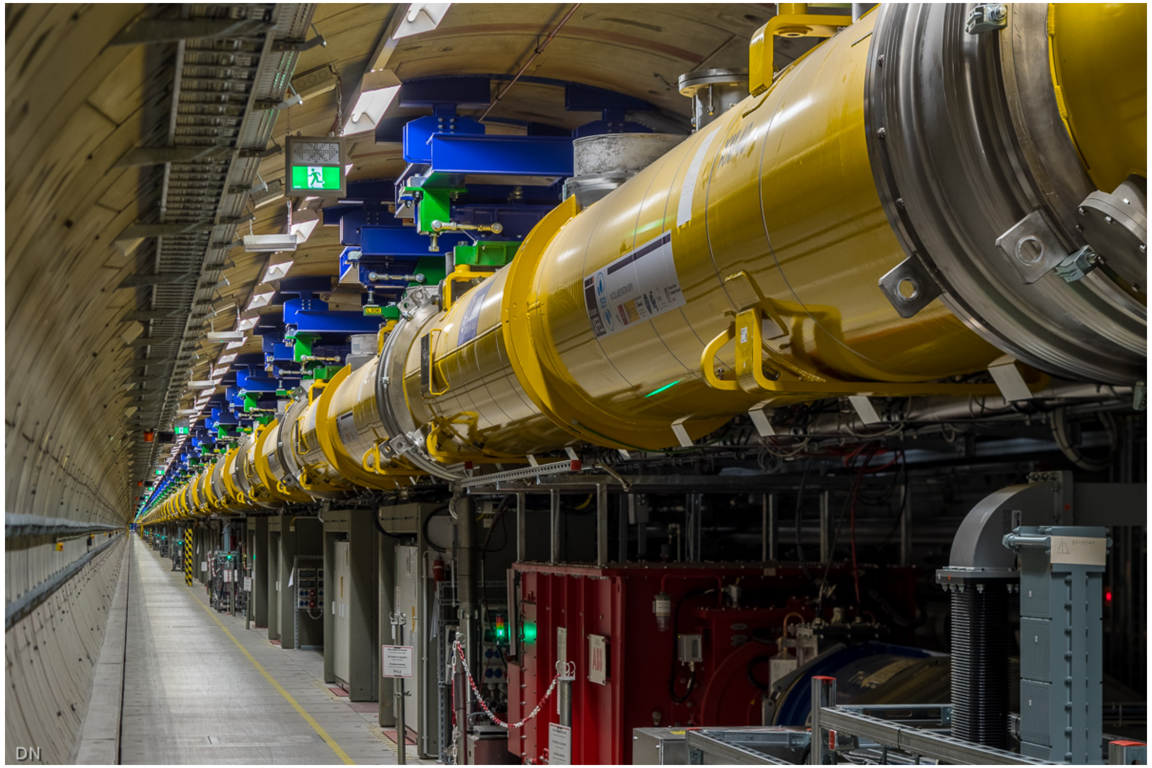




It means “roughly one Kilometer of Cold Linac”

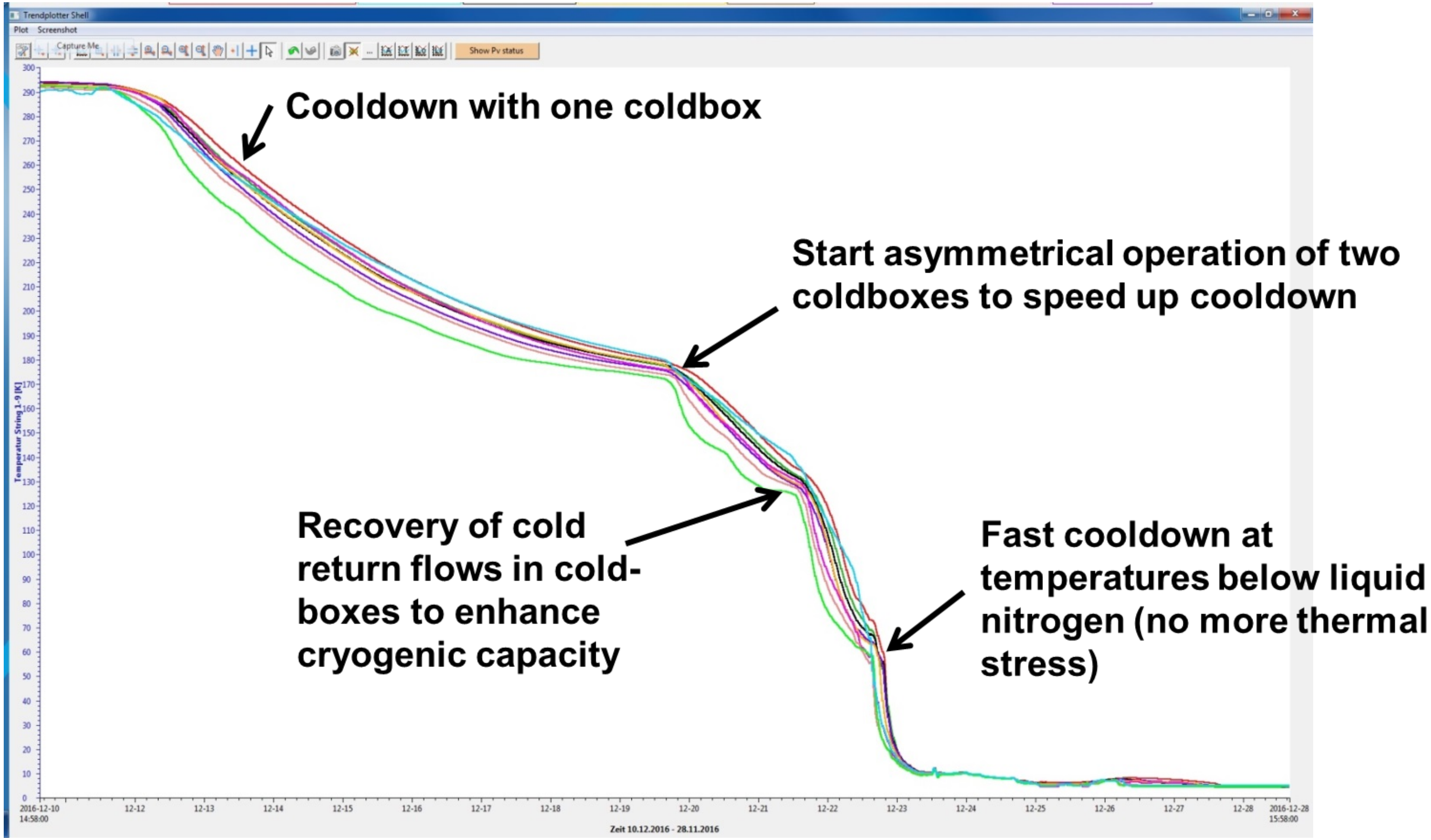
Linear Accelerator (XTL)





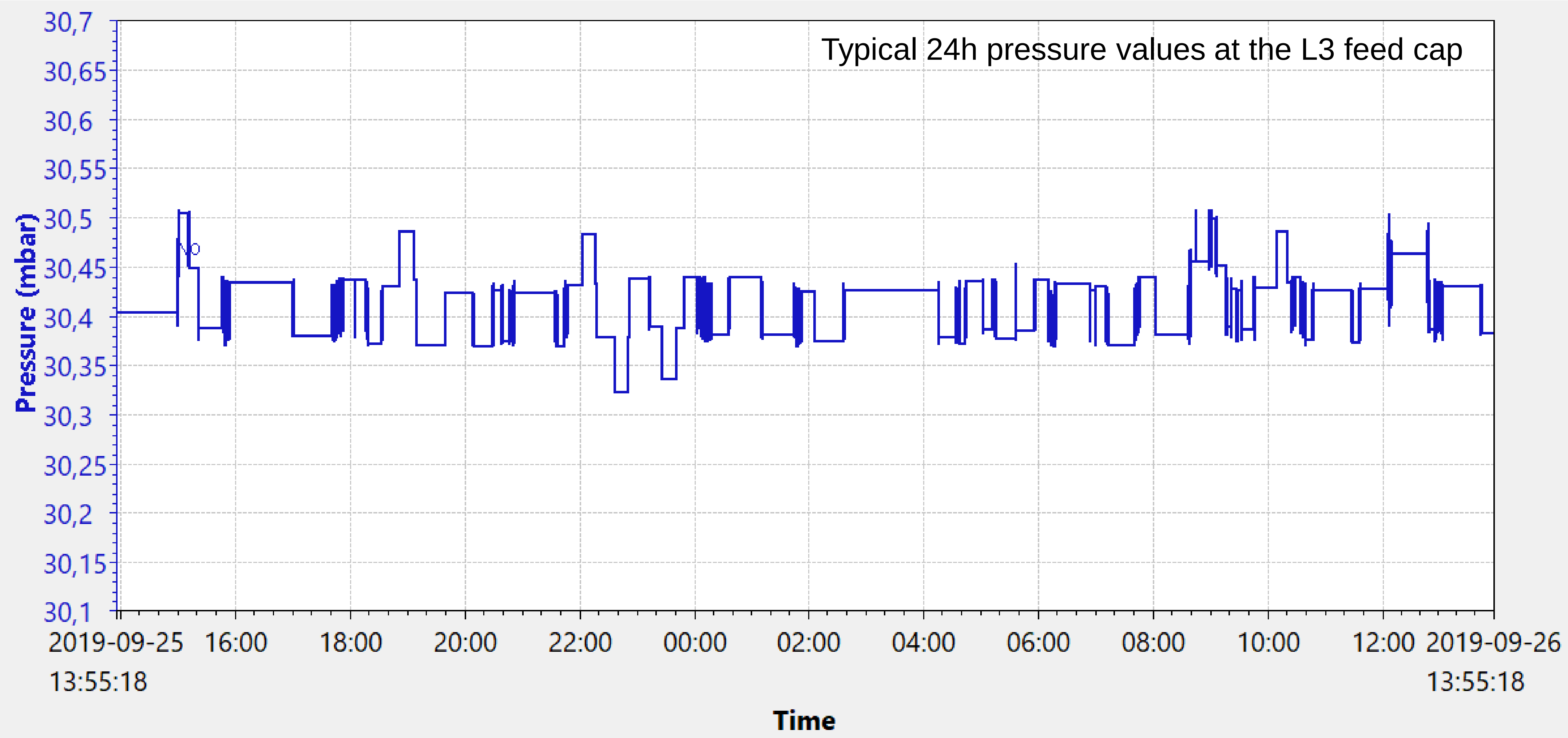
Cool Down curve EuXFEL

First EuXFEL Linac cool down 10.12. – 27.12.2016 -> since then continuously cold



2K Helium pressure stability

Required: +- 1% (0.3 mbar), typically achieved better than +-0.5% (0.15 mbar)

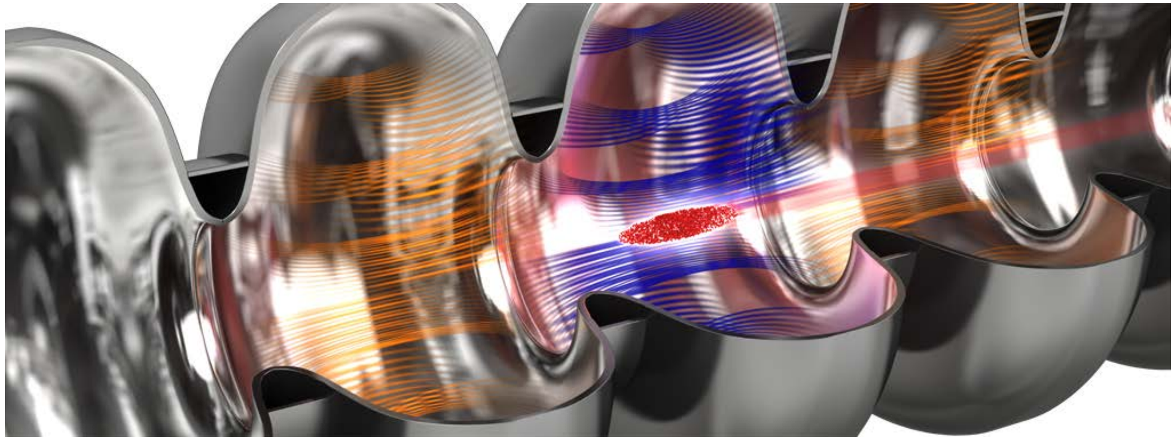


The EuXFEL cryomodule

The accelerating cavity

How does it work

- The 1.7 km-long particle accelerator brings bunches of electrons to high energies at nearly the speed of light.
- The electrons are accelerated in special cavities, the so-called resonators, where an oscillating microwave transfers its energy to the electrons.
- The resonators are made of the niobium and are superconducting, i.e. nearly the entire electrical power is transferred to the particles.
- The electron bunches are generated by knocking the particles out of a piece of metal using a conventional laser.

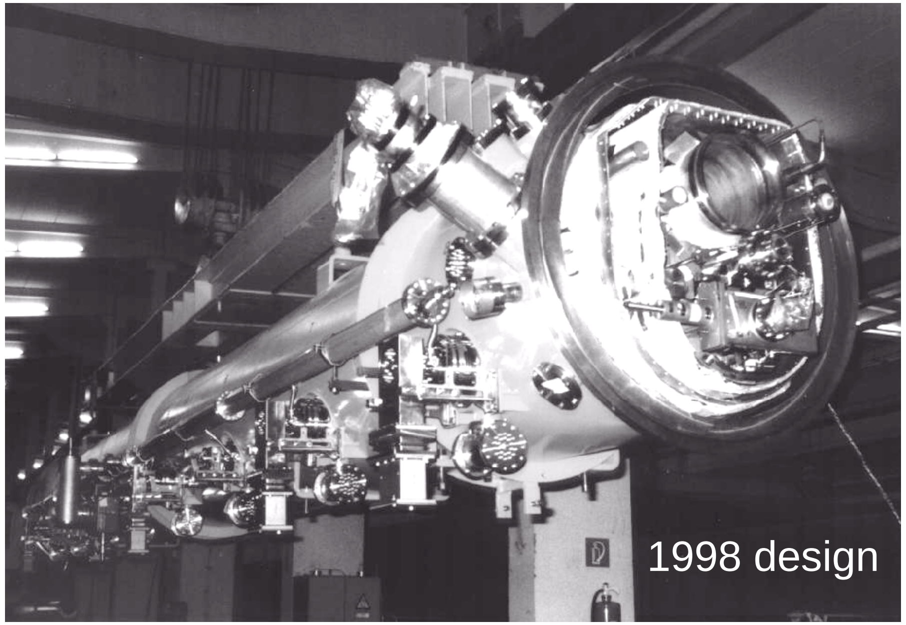


Source (text and upper picture): https://www.xfel.eu/facility/overview/how_it_works/index_eng.html

Cryomodules: a short history

Where do we come from

- Design based on the TTF cryomodule
  - Components developed in a wide international collaboration (DESY, Saclay, Fermilab, INFN-LASA, …)
    - “Construction, Commissioning and Cryogenic Performances of the first Tesla Test Facility (TTF) Cryomodule”, C. Pagani, J.G. Weisend et al., **1998”**
  - 3 generations of cryomodules (simplification and optimization for mass production)
  - Different stages of the design are installed in FLASH (the **F**ree-Electron **LAS**er in **H**amburg)
- 3 prototypes and 3 pre-series finalized the design for the XFEL
- Production and assembly of the different XFEL components around the world:
  - Cavities (IT, DE), Cold Mass and Vacuum Vessel (IT, China), Magnet (Spain), Vacuum components (Poland, DE, Russia), Couplers (DE, FR, USA), …
  - Assembly in France (CEA Saclay)
  - Test and installation in Germany (DESY)



Main features of a cryomodule

What are they for?

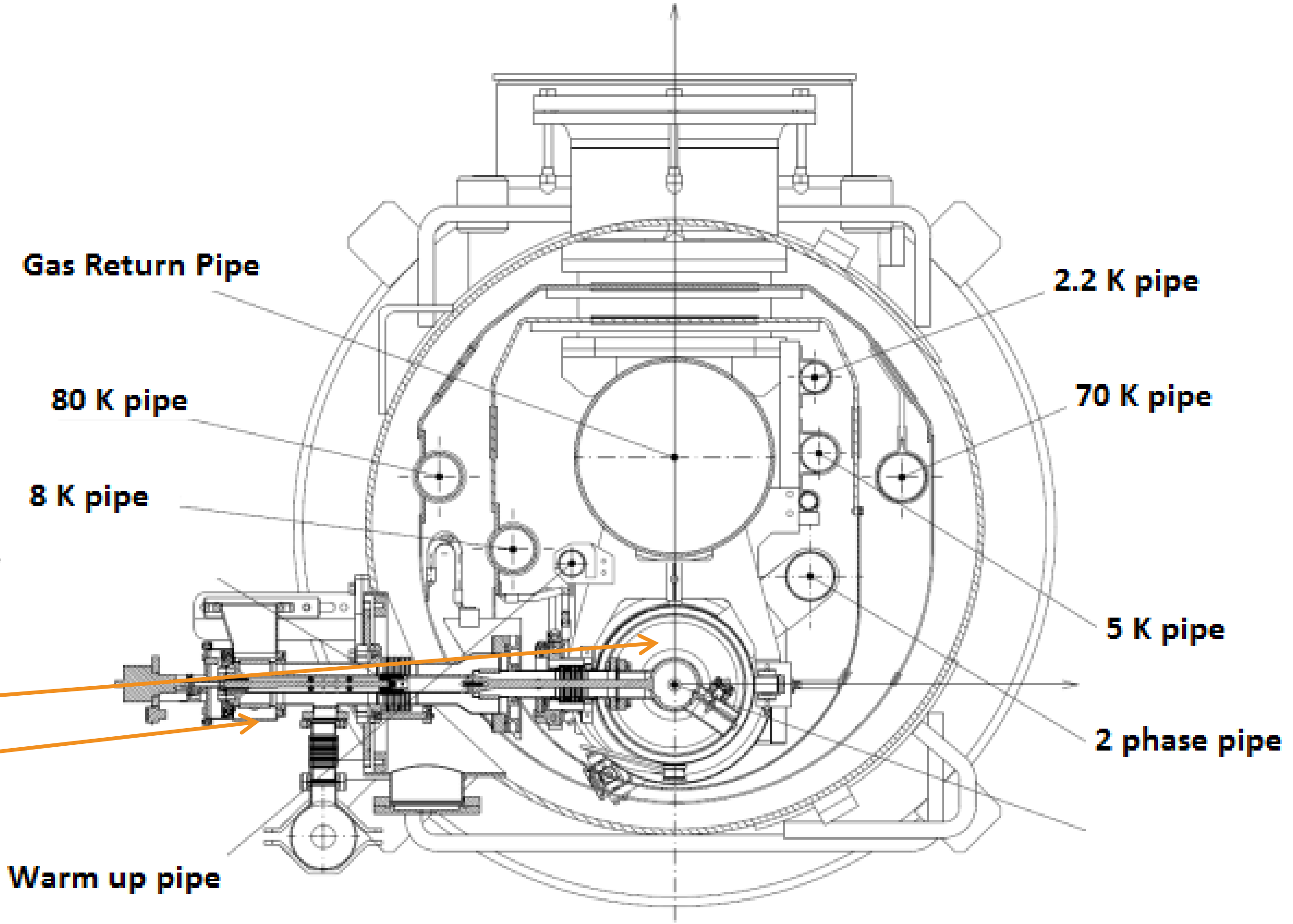
- Supply the cavity string with 2 K liquid helium
- Multi-transfer line for the 2.2 – 80K circuits -> no separate transferlines in the Linac
- Mechanically support the cavity string, allowing thermal shrinkage of parts from 300 K to 2 K without introducing stresses during cool down and warm up
- Guarantee the cavity string alignment with a precision better than 0.5 mm
- Thermally isolate the cavity string at 2K from the 300 K environment
- Bring high power RF to the cavity string (coupler)

Supply helium

Cryo module cross section

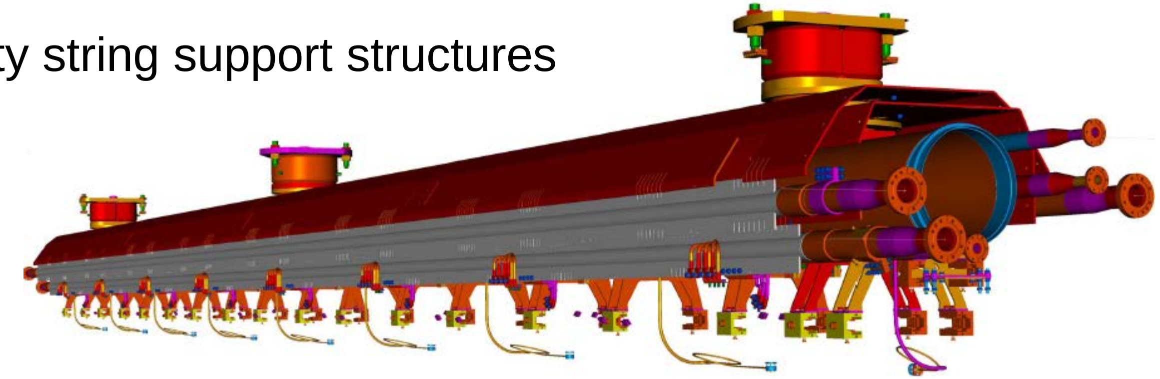
- 3 main circuits:
  - 40-80 K thermal shield
  - 5-8 K thermal shield
  - 2 K circuit
    - Warm up / cool down
    - 2.2K supply
    - 2 phase pipe - LHe/GHe supply/return
    - GRP GHe return

- Cavity-String
  - 8x 1.3 GHz cavities @2K
  - 8x main RF-coupler (FPC)
  - 1x Q-pole magnet @2K
  - 1x Beam Position Monitor (BPM)

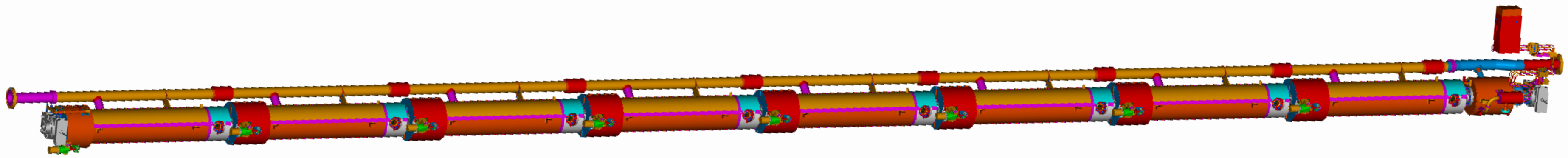


Support of the cavity string 1/2

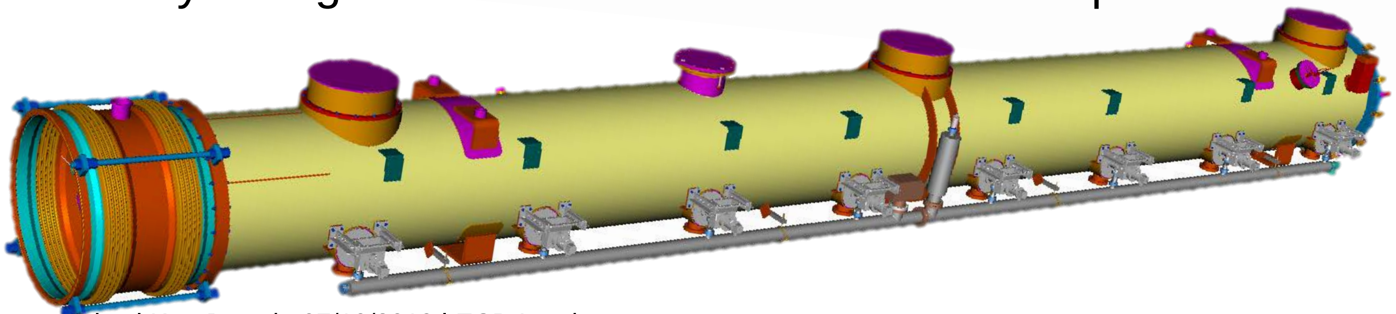
- Cold Mass: includes all service pipes and the cavity string support structures



- Cavity-String: 8 SCRF cavities (with helium tank, 2 phase line, tuner with piezos,…, 1 quadrupole and 8 RF-cold couplers



- Vacuum Vessel: Cold Mass with Cavity-String and on the outside 8 RF-warm couplers and the whole wave guide system



Support of the cavity string 2/2

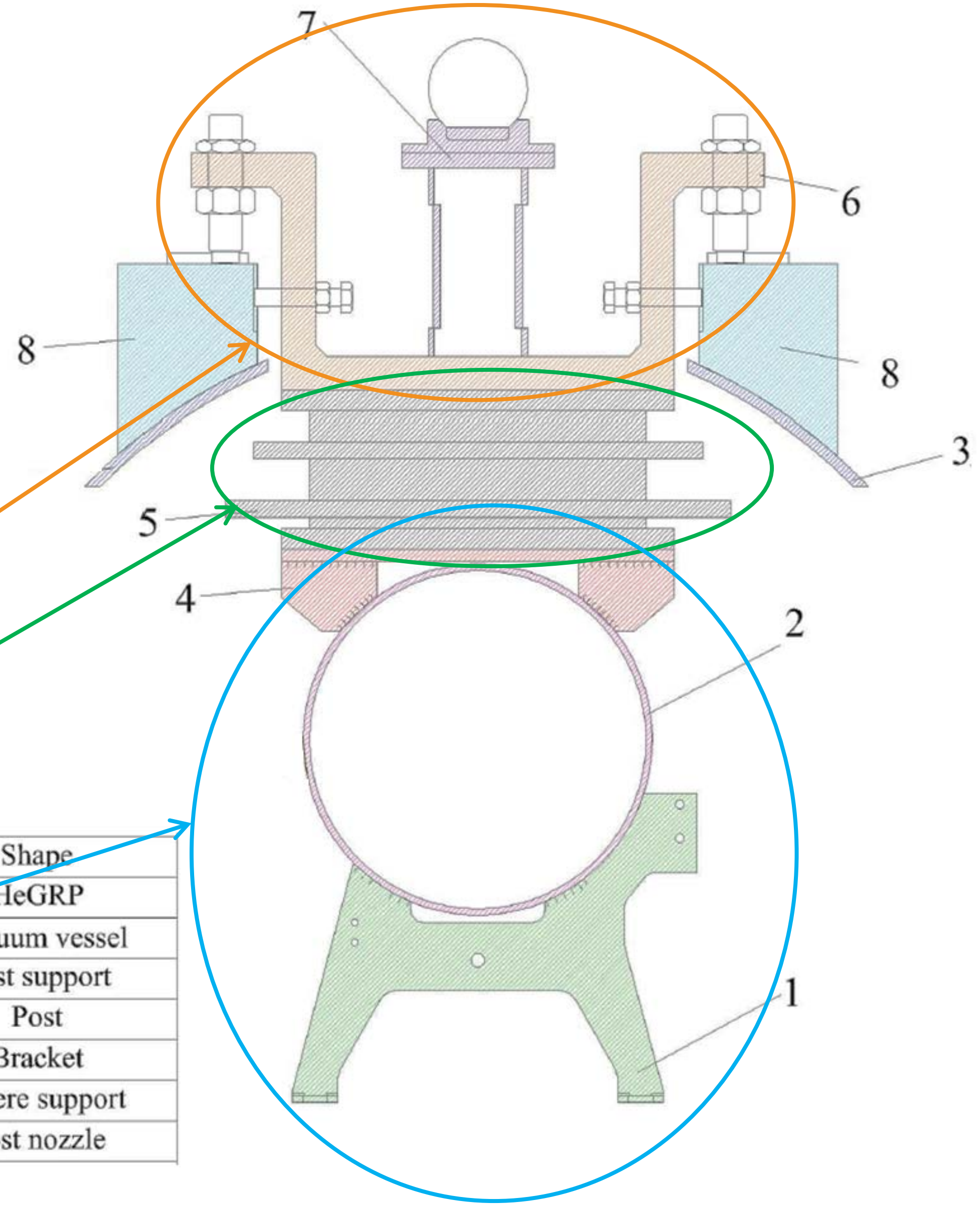
- The vacuum vessel is either hanging from the ceiling of the XFEL tunnel or supported on the floor in the AMTF, CMTB and FLASH
- The cold mass is supported via the bracket + post assembly to the vacuum vessel. The center bracket is fixed to the vacuum vessel, while the 2 lateral ones are free to slide longitudinally, to allow the thermal shrinkage of the cold mass without introducing stresses.

Thermal sections:

300K

300 – 2K

2K



1	Shape
2	HeGRP
3	Vacuum vessel
4	Post support
5	Post
6	Bracket
7	Sphere support
8	Post nozzle

Thermally isolate the cavity string

Image courtesy N. Ohuchi

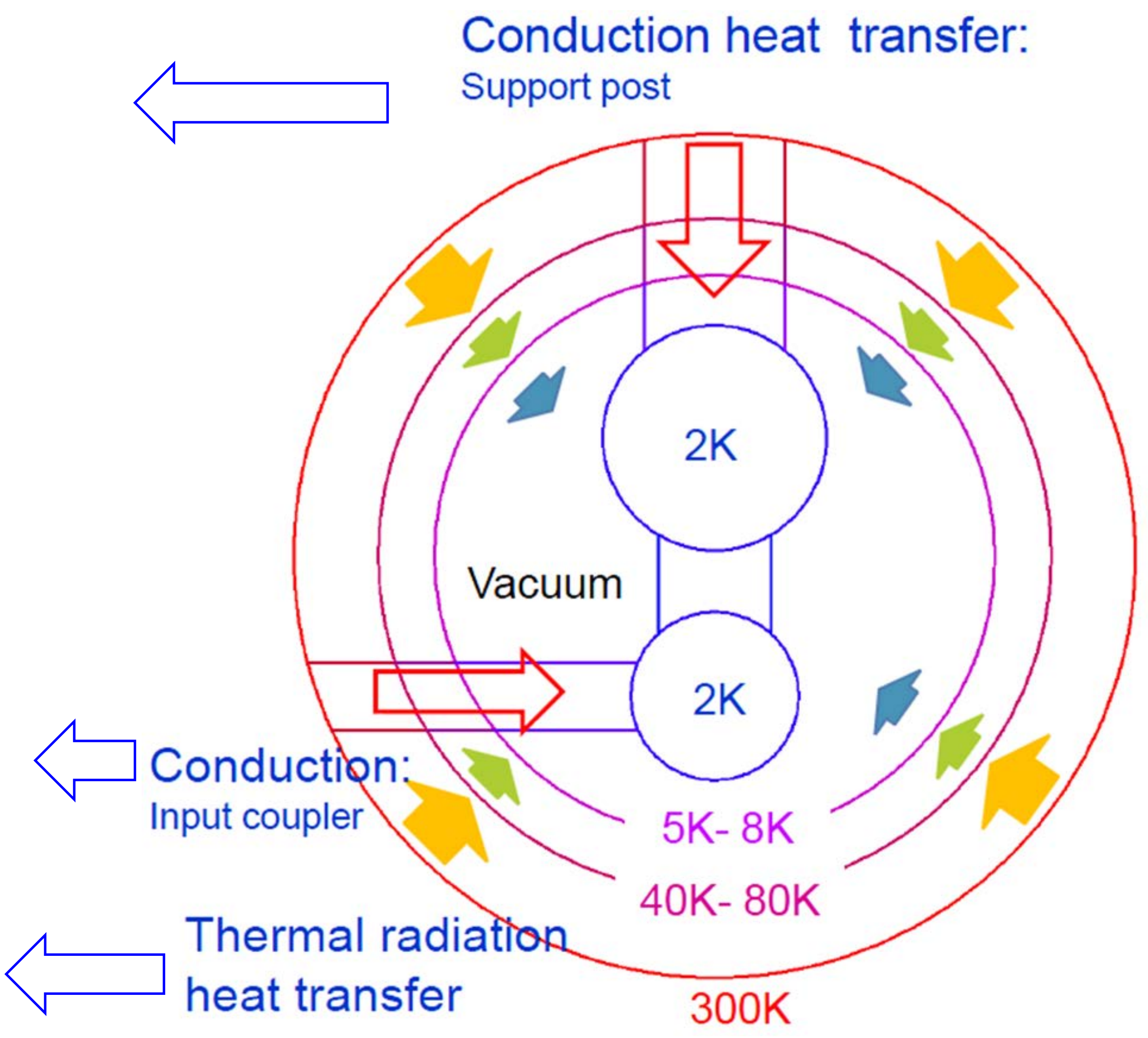
From 300 k to 2K

- Design of the support post:
  thin pipe of G10 material to reduce conduction;
  shirink-fit assembly tecnique to guarantee strength

- Thermal shields at 5-8 K and 40-80 K

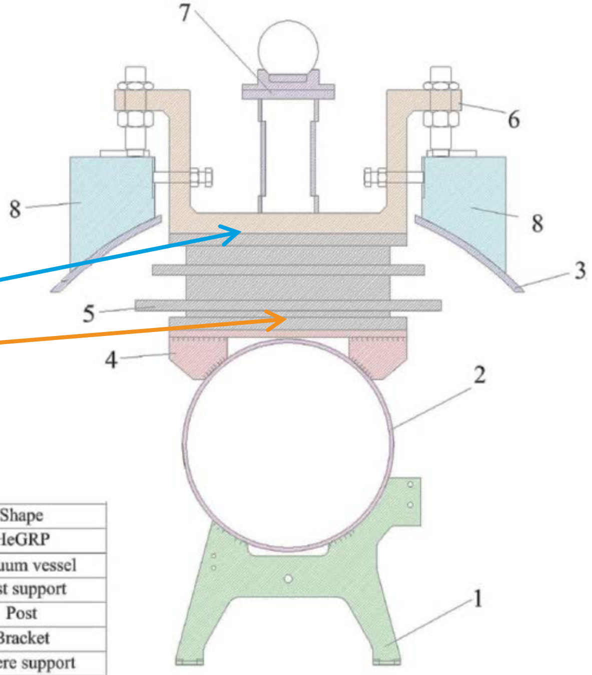
- Thermal intercepts at 4K and 80K to readuce direct conduction 2 K -> 300 K

- Isolation vacuum with Multi Layer Insulation (MLI)



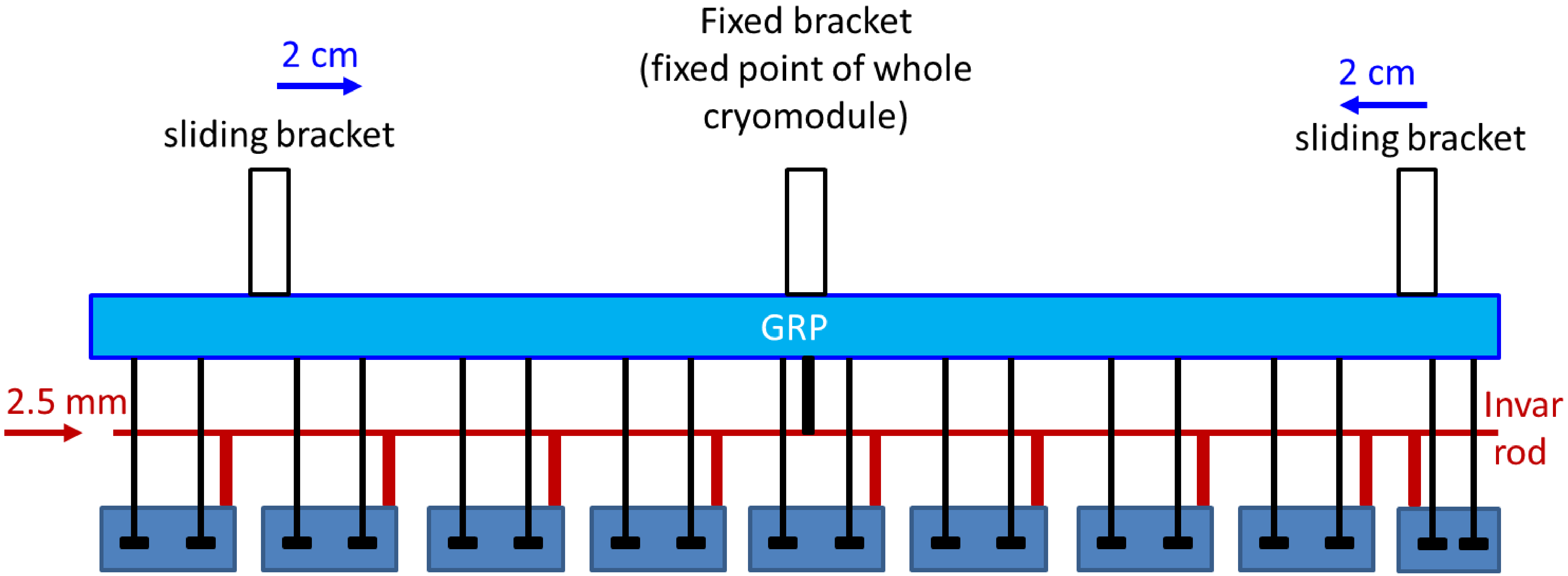
Guarantee string alignment (1/2)

- Only one fixed point: the middle post (no stresses due to shrinkage)
- Coupler longitudinal flexibility (in the mm range)
- Cavity string fixed to an invar bar
  (integral shrinking coefficient 300 K – 2 K = 0.04 mm/m)
- Cavity string support system with rollers: very low friction
- Pins between **GRP and post** and **post and brackets**,
  to reproduce exact position after multiple assemblies



1	Shape
2	HeGRP
3	Vacuum vessel
4	Post support
5	Post
6	Bracket
7	Sphere support
8	Post nozzle

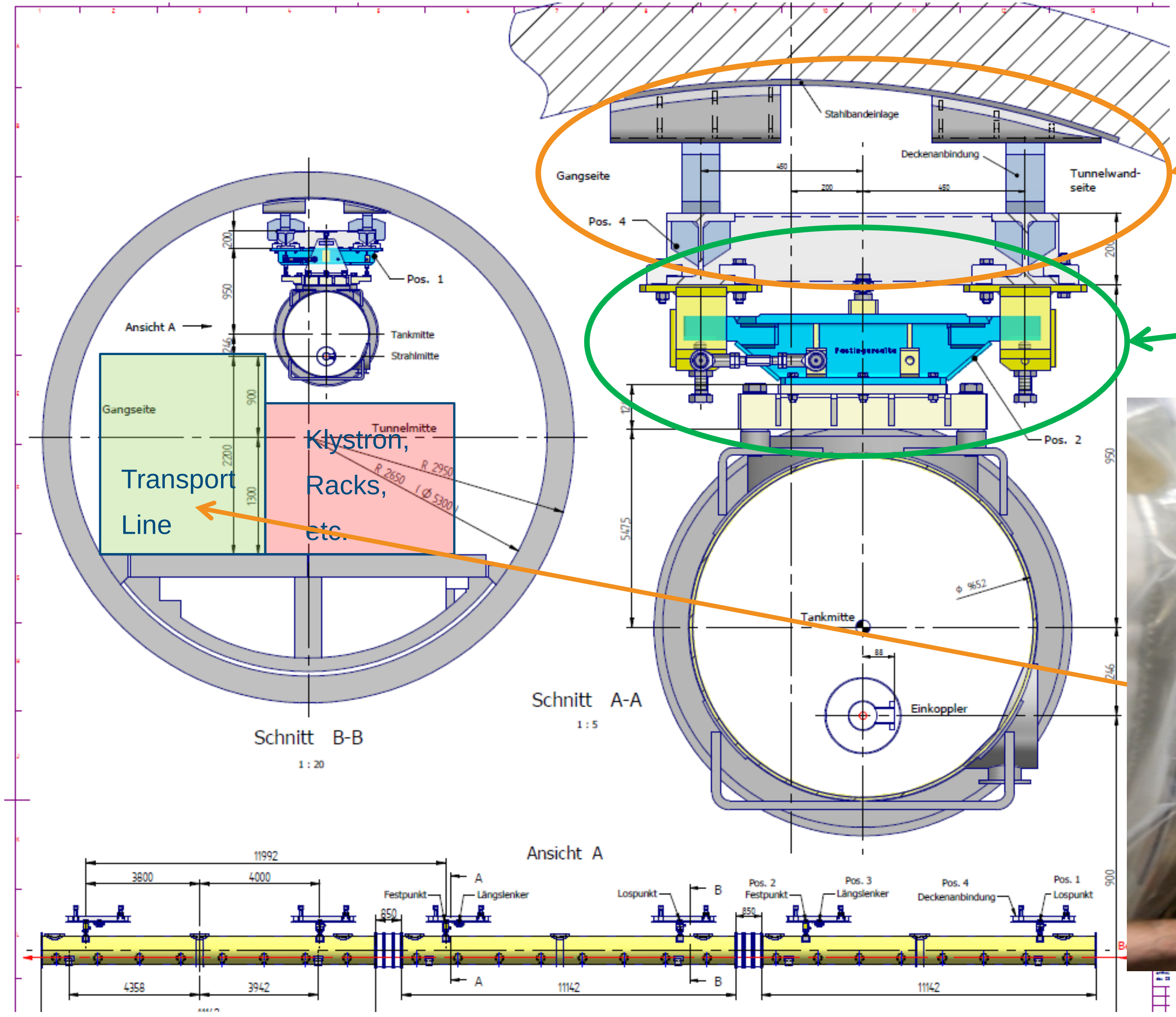
Guarantee string alignment (2/2)



Invar rod, 300 K -> 2 K shrinkage 0.4 mm/m: 6 m -> about 2.5 mm

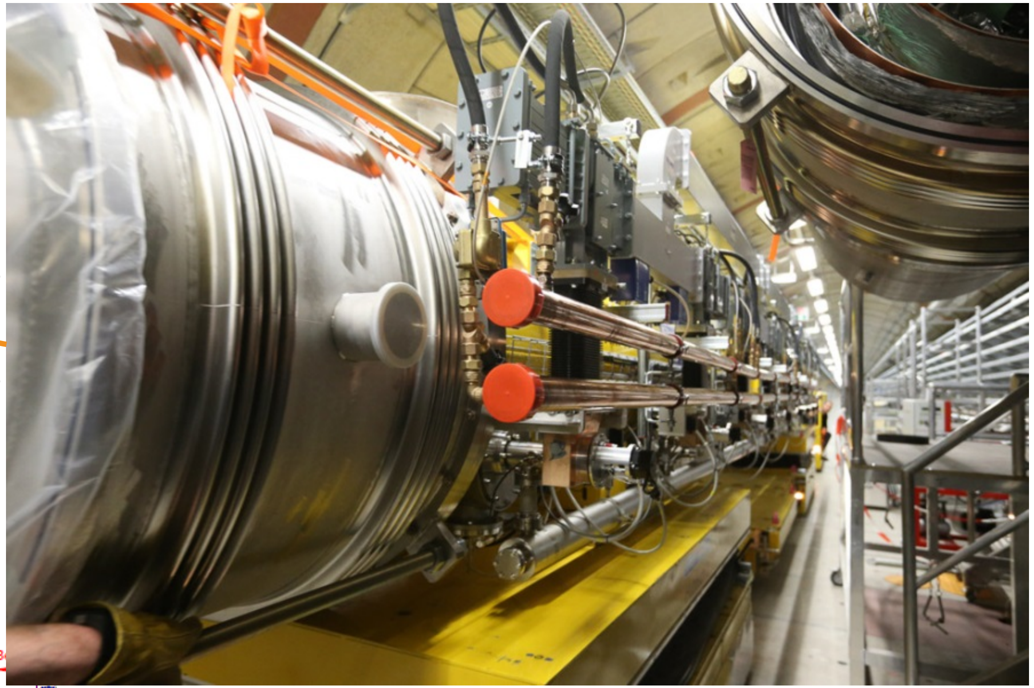
GRP, stainless steel, 300 K -> 2 K shrinkage 3.1 mm/m: 6 m -> about 2 cm

Modules supports @ XFEL



Welded roof frame

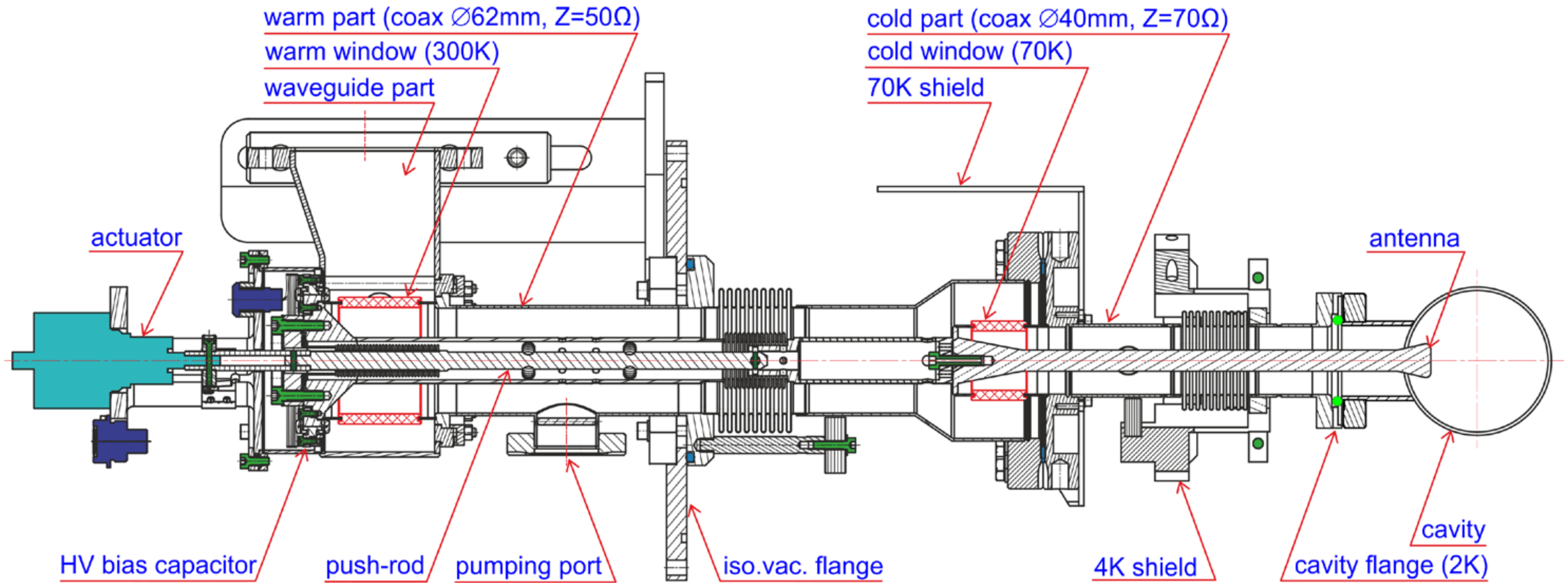
Alignment frame (adjustable)



Bring RF to the cavities

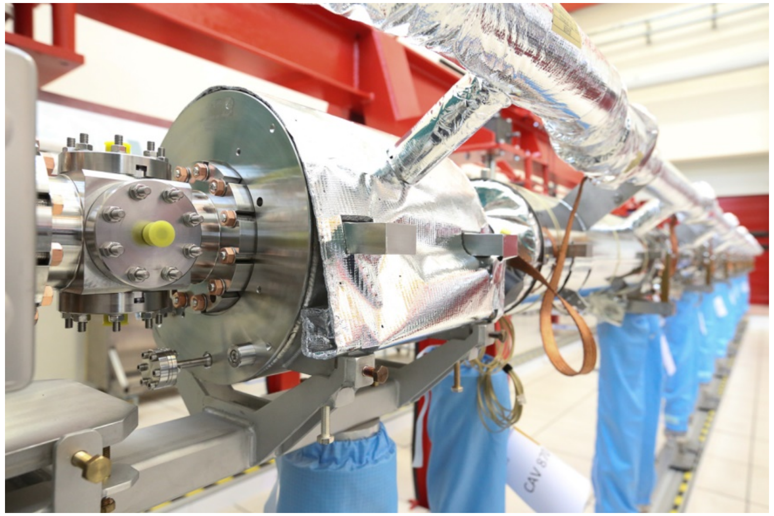
The XFEL input RF power coupler

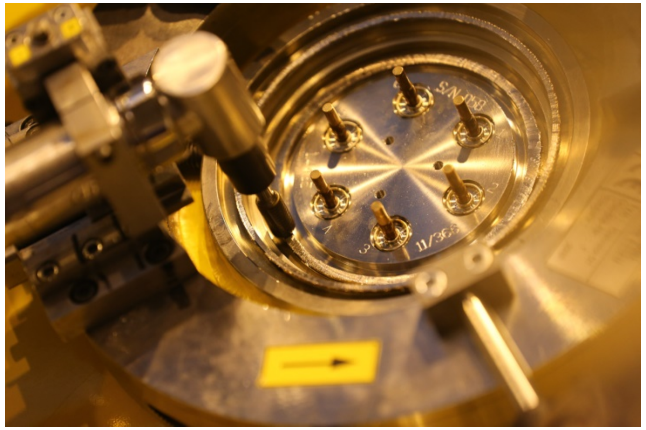
- The XFEL coupler consists of warm, cold and waveguide main parts. Coaxial coupler is made of copper and copper plated (10/30µm) stainless steel with 2 alumina TiN coated ceramic windows.
- Motorized antenna tuning (±10mm) allows for Qext adjustment ($10^6..10^7$).
- All FPCs are pre-conditioned up to 1 MW pulsed RF power up to 400 µs, repetition rate is 10Hz

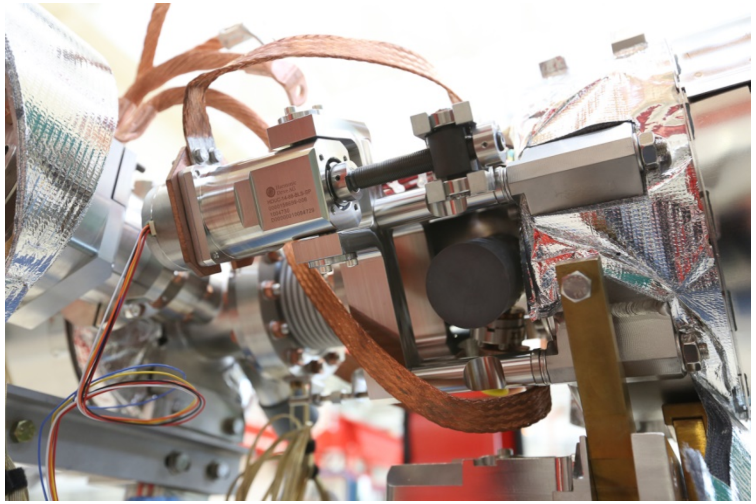


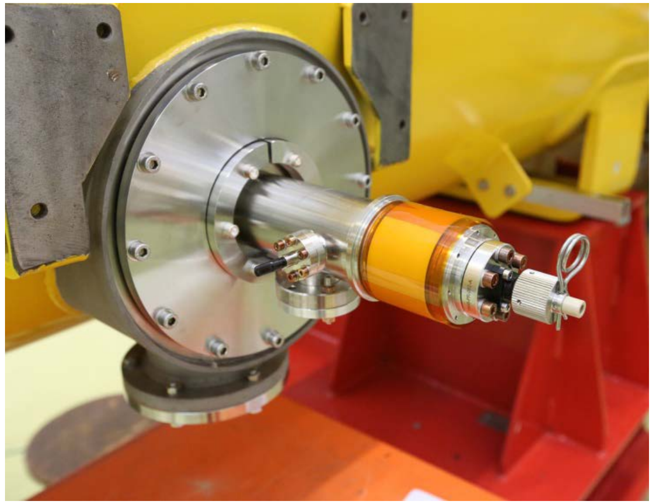
Some cryomodule components

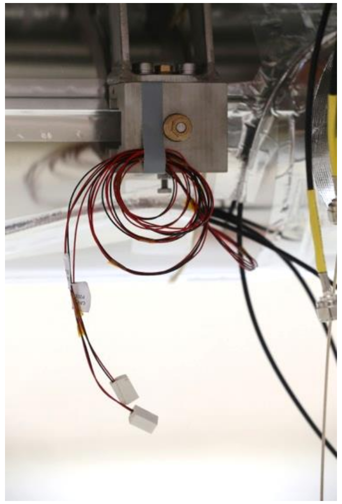
Cavity, magnet and CL, coupler, tuner, HOM, WG, magnetic shielding … only to mention a few











Some additional remarks

Related to cryomodules

Tunnel “inclination”

- The tunnel itself is laser straight
  - -> therefore all components inside the tunnel (modules) have a slight slope (gravity), i.e. the liquid helium level is different at the beginning and at the end of a string of 12 modules
  - -> after ~two-thirds of the main accelerator the He supply (JT-valves) is shifted to end of the cryo-string to keep the liquid Helium level lower at the JT-valve than at the end-cap

TÜV / PED, manufacturing

- The accelerator was constructed by DESY but handed over for operation to the XFEL-company (i.e. marketing)
  - -> all components has to be build according to the PED and be CE-certified

Transport

- The modules were assembled about 1000 km from Hamburg at CEA-Saclay -> therefore a “closed and tested transport scenario” was necessary
- No transported XFEL module showed transport damages or performance degradations related to the transport.

The EuXFEL CW upgrade

Courtesy J. Branlard

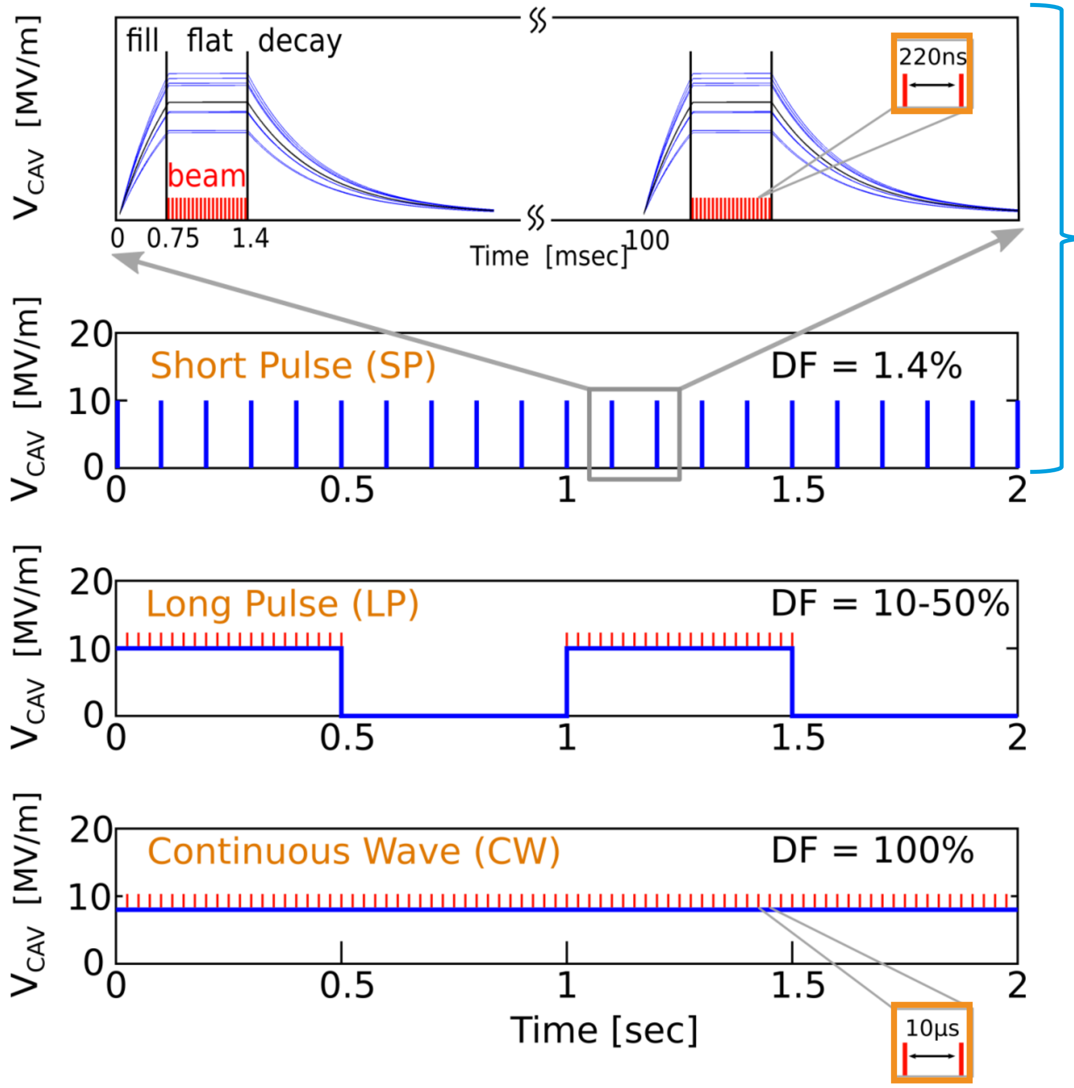
Motivation for Continuous Wave (CW) Operation

Benefits of Continuous Wave (CW) operation

- Flexible beam patterns for detectors
  Almost any macro pulse structure can be offered
- Slower repetition rate lasers
- Fill-transients no longer an issue

Benefits of Long Pulse (LP) operation

- Still high duty factor (DF = 10-50%)
- Higher gradients than CW with same heat load



European XFEL

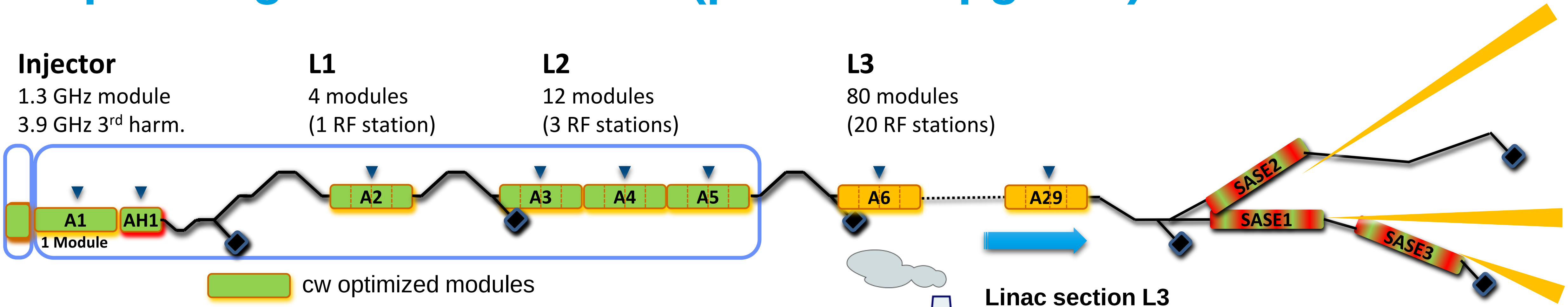
FLASH. Free-Electron Laser FLASH

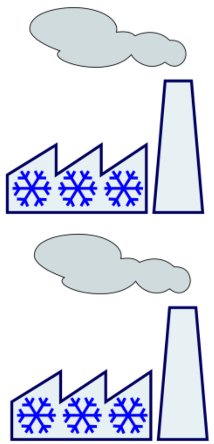
$E = 17.5$ GeV
$N_{bunch}/s = 27k$

$E = 10$ GeV
$N_{bunch}/s = 50k^*$
*up to 500 kHz for 20pC

$E = 8$ GeV
$N_{bunch}/s = 100k^*$
*up to 1 MHz for 20pC

Operating the XFEL in CW (possible upgrade)





Linac section L3

- operated at moderate CW gradients
- lengthened by former A2 … A5

  80 + 12 modules

  24 RF stations

➔ **Expected energy 8 GeV !**

1 – Replace the front-end cryomodules (17x)

- CW cavities higher Q0 / lower cryo-losses

2 – Install CW capable RF sources

- 1x IOT per RF station

3 – Double the cryo plant (cost driver)

- 2.5 → 5kW

4 – Install CW capable gun:

- RF gun upgrade

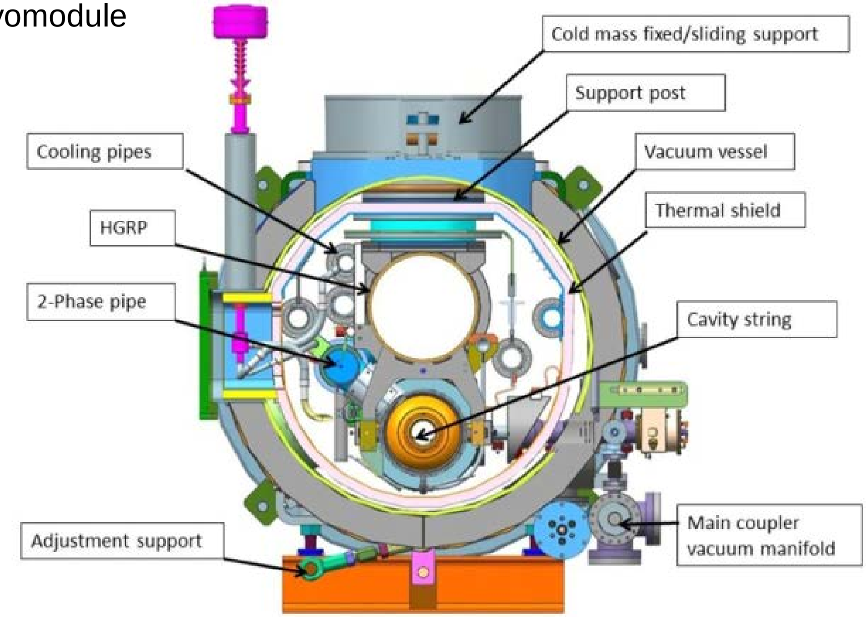
- **The former front-end cryomodules can be installed at the end of the linac to lengthen L3 (+4 RF stations)**
- **No further action required in L3 (>1km)**
- **The upgraded XFEL would be capable of short pulse long pulse <u>AND</u> continuous wave operation**

What does it mean for cryogenic and cryomodules

Our first thoughts…

- Much higher Heat loads!
  - New cryoplant needed
  - New cryo-distribution needed
- New modules for high gradient CW (e.g. LCLSII)
  - Bigger 2-phase pipe
  - JT and LHe level control in the module?
  - Modifications at the RF Power Coupler possible
  - Design changes of the tuner system inc. piezos
  - Microphonics vs Lorentz Force Detuning compensation
  - Better thermalisation
  - Fast cool down capabilities
- Thermoacoustic oscillations in modules and cryo system
- Test stand upgrade / modifications
  - Different He distribution
  - Fast cool down capabilities
  - Inductive Output Tube (IOT) in AMTF
  - New test environment for SC GUN in AMTF
- Injector: NC vs SC gun -> R&D ongoing @DESY

LCLSII cryomodule



Thank you