18th International Conference on
RF Superconductivity
Lanzhou China
July 17-21, 2017

The Commissioning of the European XFEL Linac and its Performance

Detlef Reschke
Winfried Decking, Nick Walker, Hans Weise - DESY
for the European XFEL Accelerator Consortium and Commissioning Team

SRF 2017, Lanzhou

European XFEL

First Lasing

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FIRST LASING.

World's largest X-ray laser generates first laser light

1 2 3 4 5

European XFEL

Light of the future »
DESY is the main shareholder of the next generation X-ray laser

17/05/04 · Press-Release

Biggest X-ray laser in the world generates its first laser light

In the metropolitan region of Hamburg, the European XFEL, the biggest X-ray laser in the world, has reached the last major milestone before the official opening in September. The 3.4 km long facility,...

The super X-ray laser »
More about the European XFEL in DESY's research magazine!

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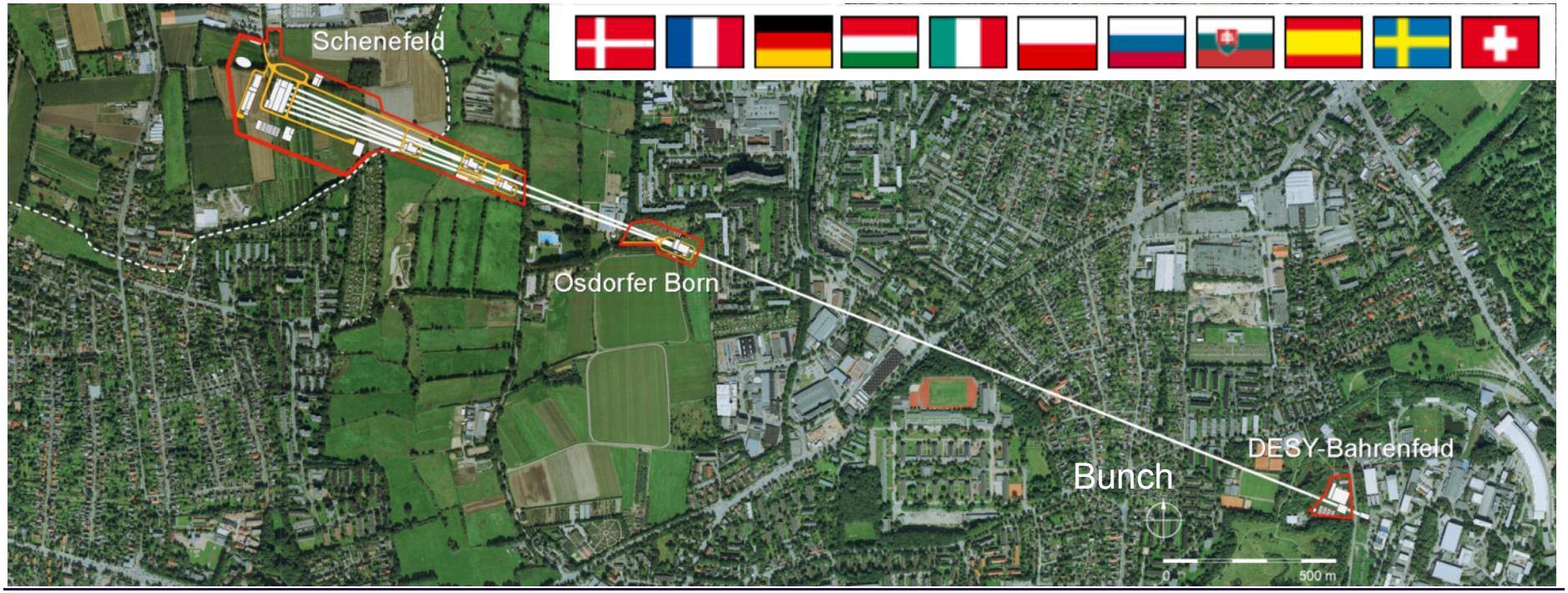
European XFEL at a Glance

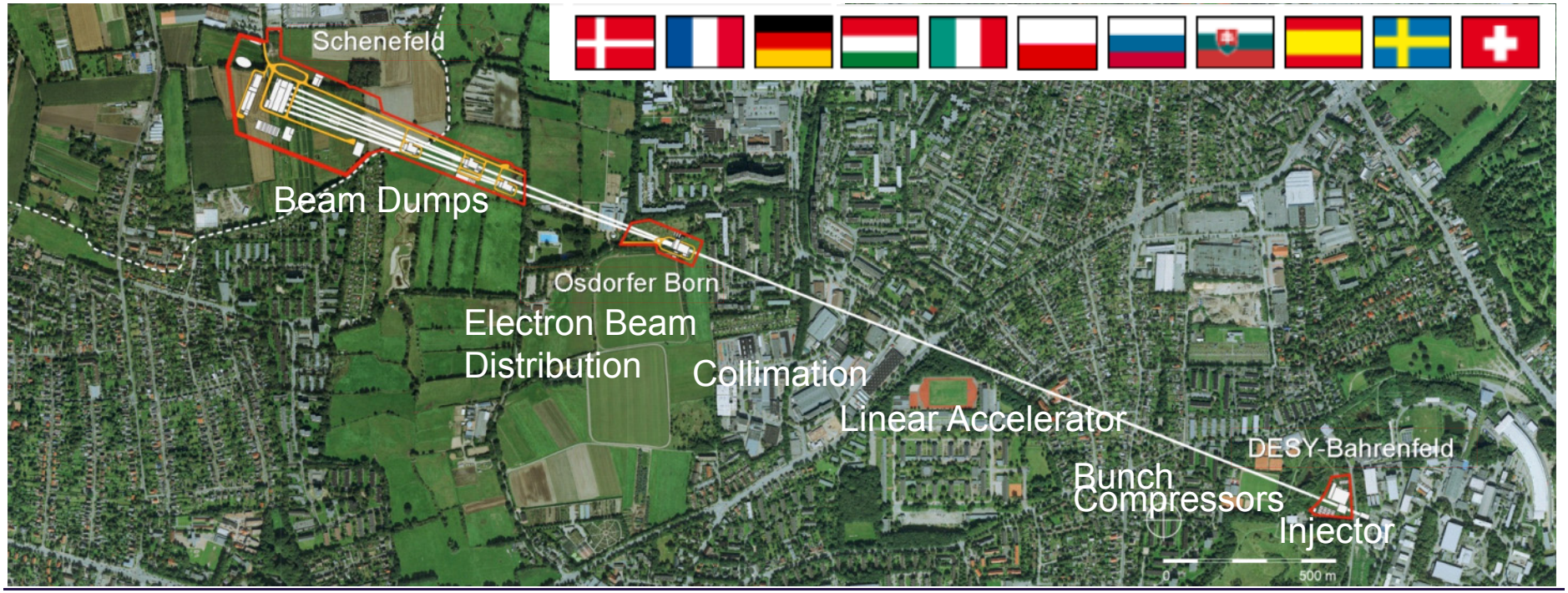
- International project realised in Hamburg area, Germany



European XFEL

European XFEL at a Glance

- International project realised in Hamburg area, Germany
- 17.5 GeV superconducting linac, 500 kW beam power
- 27000 pulses per second in 10 Hz operation



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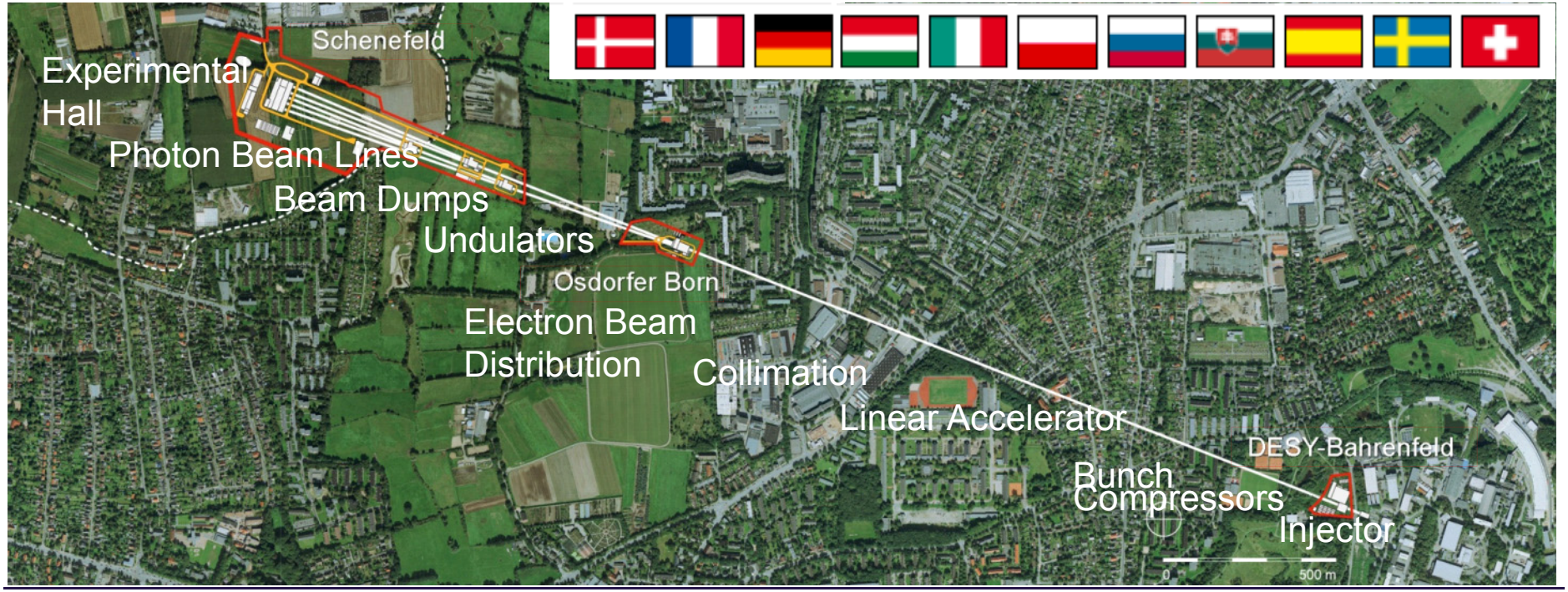
- Initially 6 equipped experiments



European XFEL

European XFEL at a Glance

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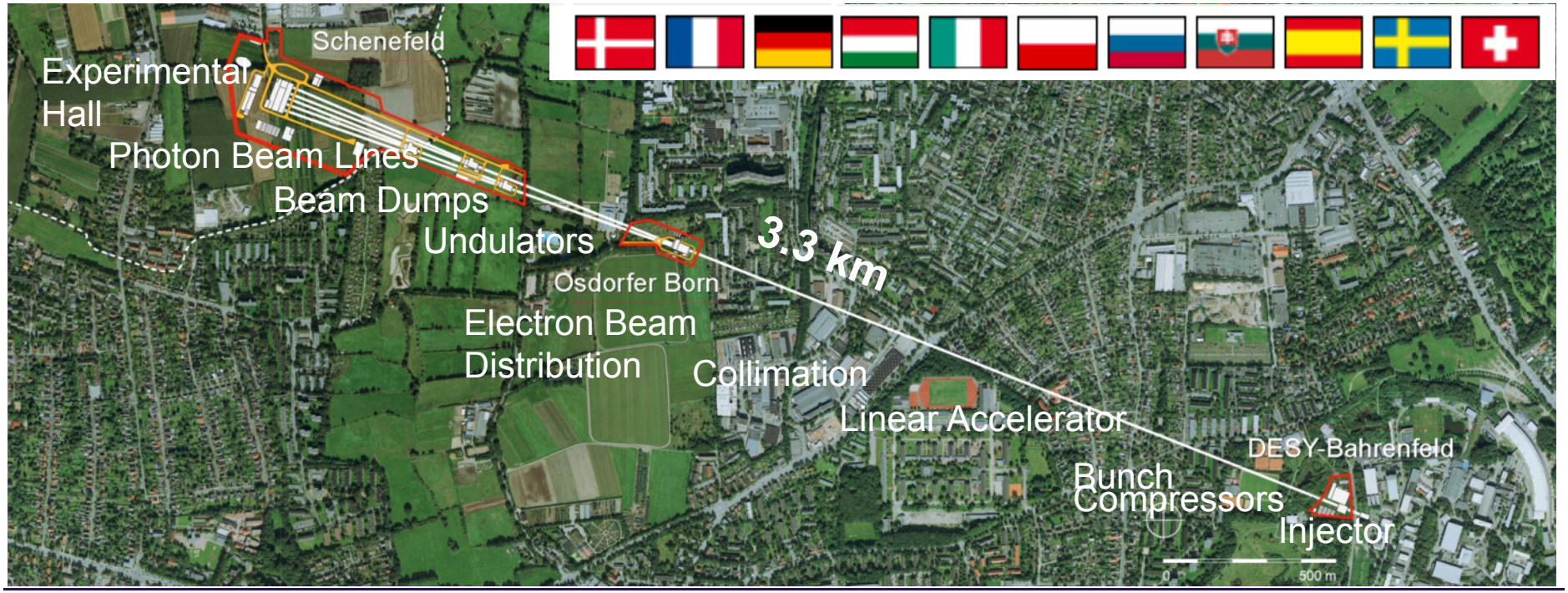
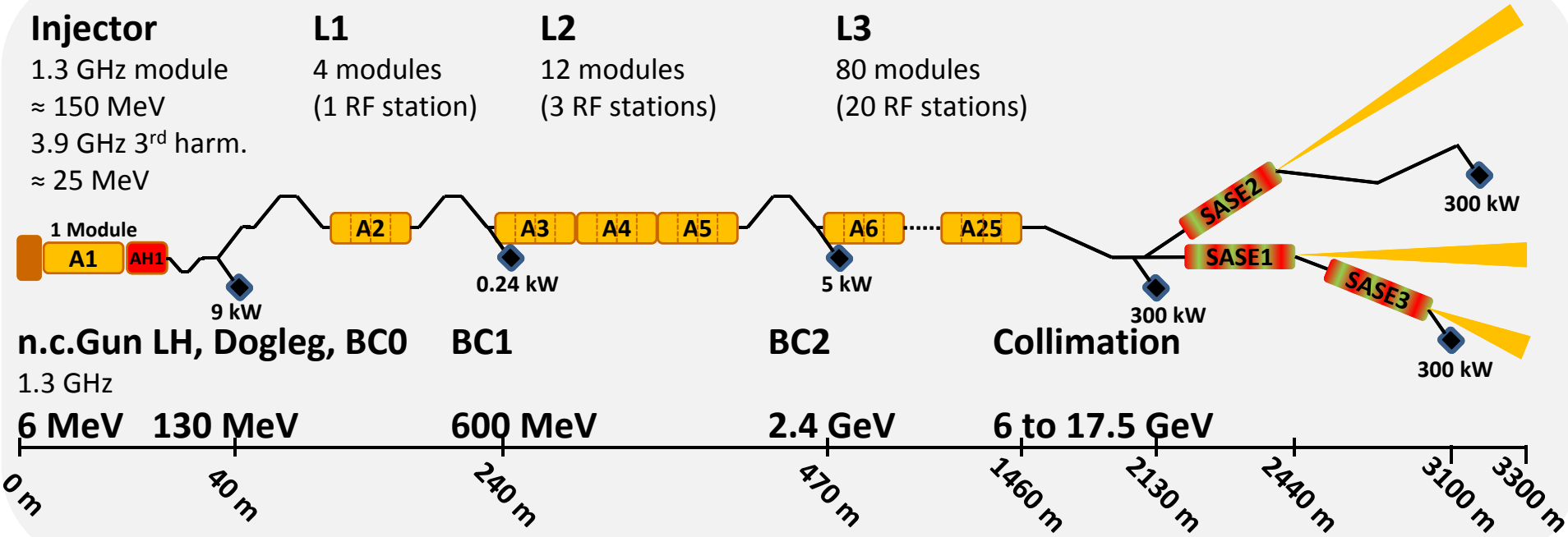
- 17.5 GeV superconducting linac, 500 kW beam power
- 27000 pulses per second in 10 Hz operation
- Three variable gap undulators for hard and soft X-rays
- Initially 6 equipped experiments
- All accelerator and beamlines in tunnels 6 -25 m below surface



SRF Accelerator Overview



- s.c. linac with 97 1.3 GHz superconducting modules + 1 third harmonic module
- design gradient: 23.6 MV/m; pulsed with 1.3 ms rf pulse length
- 4 modules / 32 s.c. cavities are connected to one 10 MW klystron (“RF station”)
- 12 modules form a cryogenic string
- down to app. 50m behind the last module the complete beam vacuum is “particle free”

SRF Project History

1990's: Construction of the Tesla Test Facility (TTF) based on 1.3 GHz cavities (**TESLA type cavity**) and cryomodules

2000: First lasing at 109 nm at TTF, now FLASH

2002: TESLA TDR supplement with stand-alone XFEL

2006: European XFEL TDR + preparation of industrial cavity production

2007: Preparation of cryomodule assembly at CEA Saclay

2010: Orders placed for 800 series cavities + first prototype module assembly at CEA Saclay + Accelerator Consortium formed

2012: **First cavities delivered** "ready for test" + test at AMTF

2013: **First series modules assembled at CEA Saclay** + test at AMTF

2014: First modules installed to the accelerator tunnel

2016: **Last series modules assembled + installed to the tunnel**
Start of commissioning

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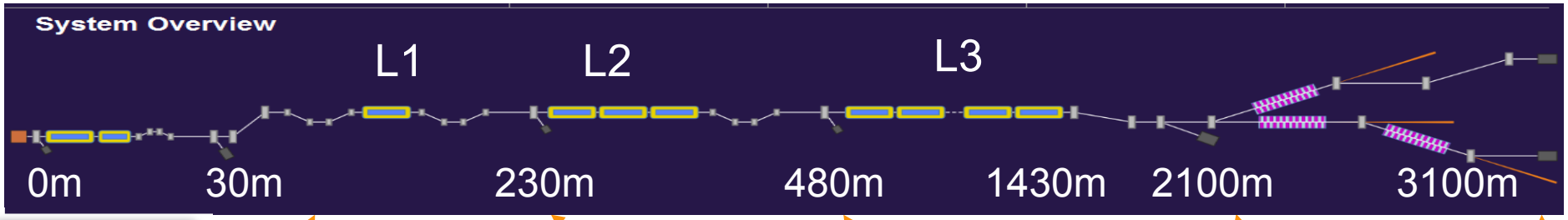
Beam Commissioning Progress



Dec.16: cooldown

13/01

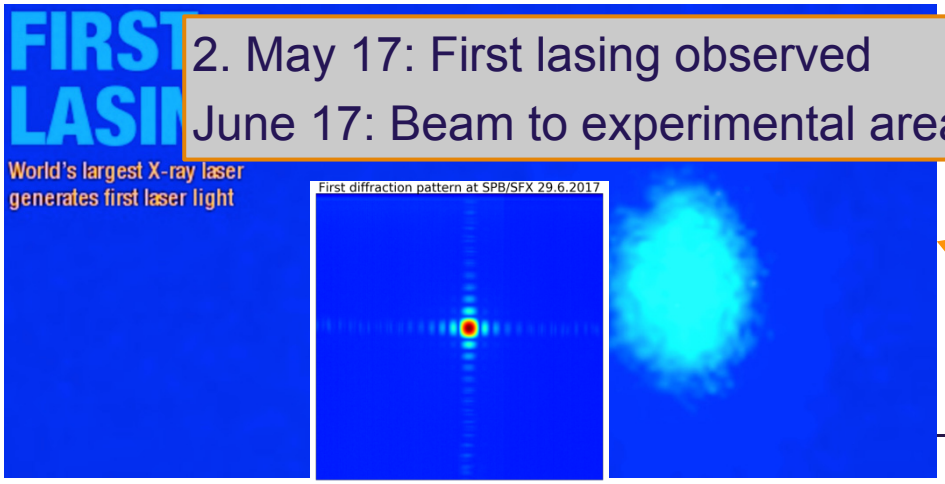
15/01 @ 130 MeV
19/01 @ 600 MeV

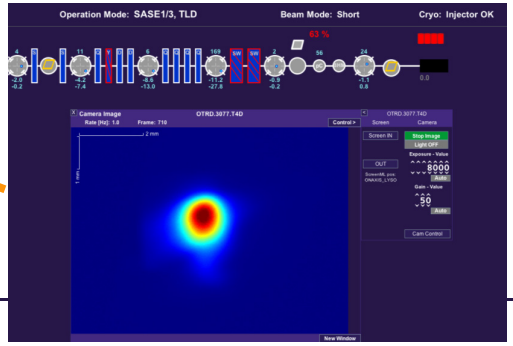
02/02 @ 600 MeV
22/02 @ 2.5 GeV

25/02 @ 2.5 GeV
19/03 @ 6 GeV
08/04 @ 12 GeV
(22/06 @ 14 GeV)

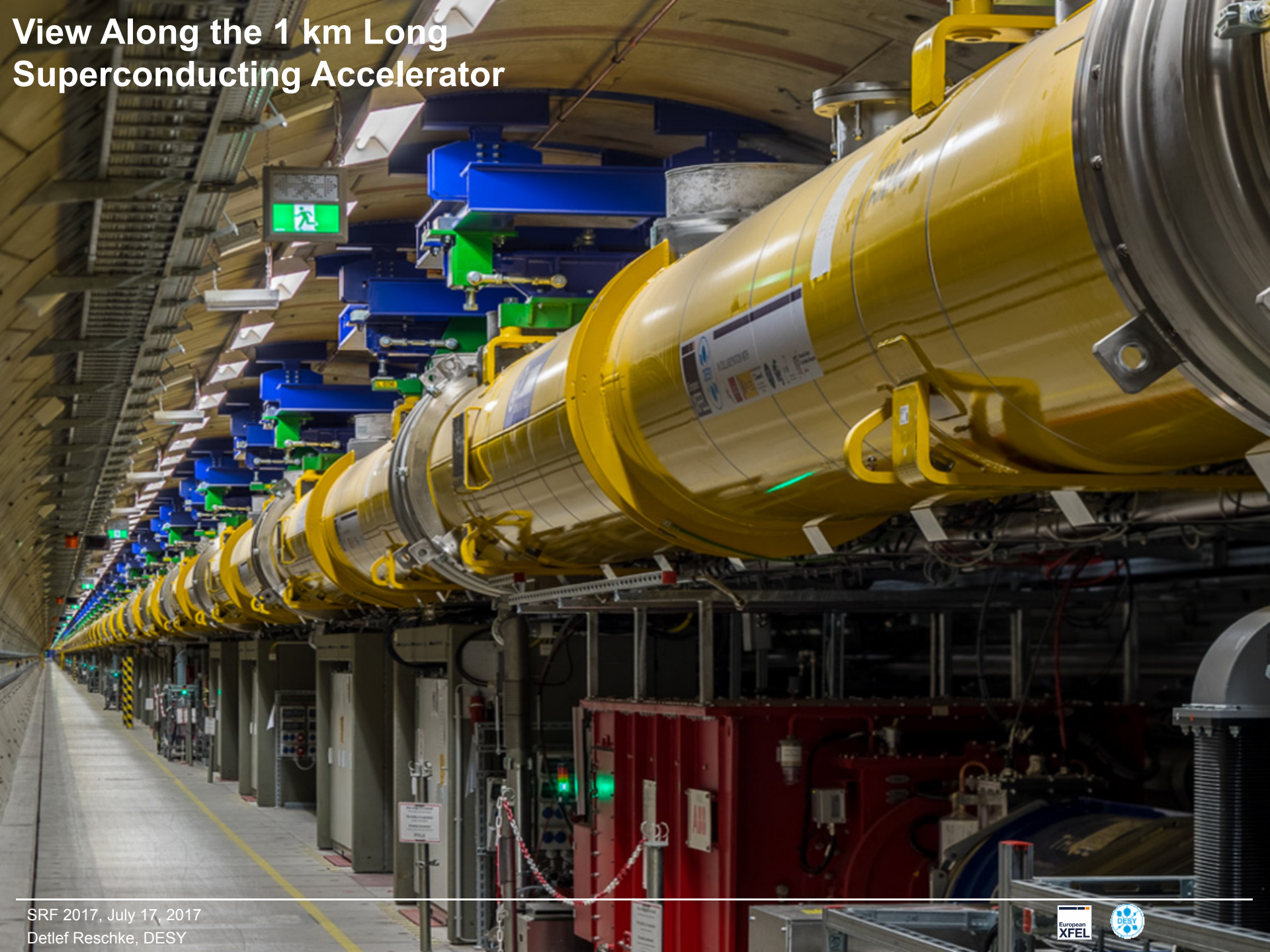
27/04/17

2. May 17: First lasing observed
June 17: Beam to experimental area





View Along the 1 km Long Superconducting Accelerator



European XFEL

Injector in Operation since 2015/2016

- N.c. photoinjector conditioned and characterized at PITZ, DESY-Zeuthen
- Injector cool-down 12/2015
- First Beam on 18/12/2015 - commissioning till Q2/2016
- 3.9 GHz system operational from day 2
- 1.3 GHz module w/o cavity limitation up to 160 MeV
- Full bunch train length (27000 bunches/s) reached for 20pC-1000pC bunch charges
- Photocathode laser (Yb:YAG laser from Max-Born Institute Berlin 257 nm ≤ 4 µJ; 3 ps) with excellent up-time
- Laser heater commissioned (but not in routine operation)

P. Pierini, MOPPB100
M. Schmökel, MOPB088
INFN Milano, MOPB077

DESY HELMHOLTZ ASSOCIATION

European XFEL

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Talk by Paolo Pierini on Friday

P. Pierini, MOPPB100
M. Schmökel, MOPB088
INFN Milano, MOPB077

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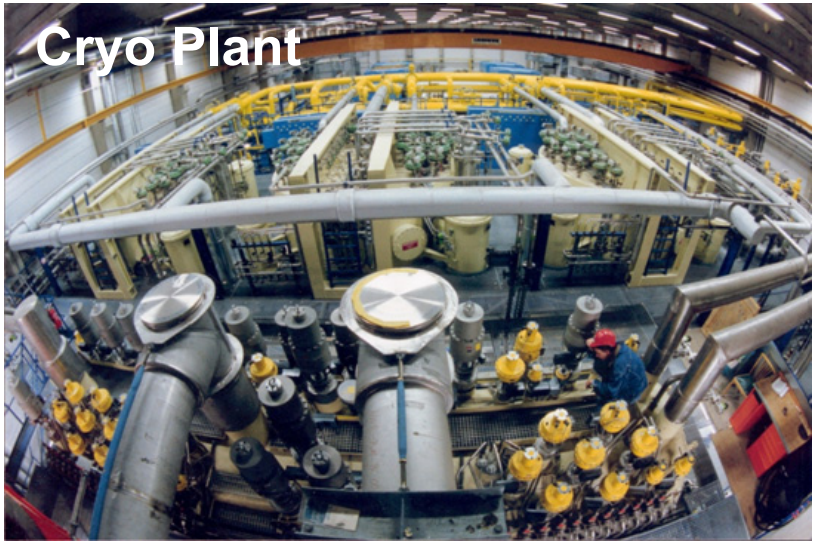
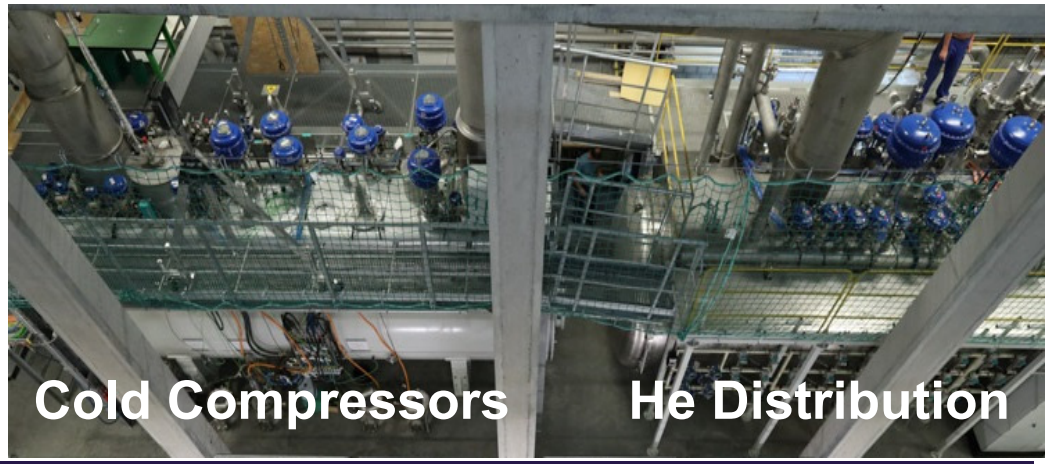
Overview of XFEL Cryogenic Equipment



- Upgraded HERA cryo plant with new 2K **cold compressors** (CC)
- Cooling capacity
  - 2K : >1.9 kW
  - 5/8K : 4 kW
  - 40/80K : 26 kW
- Linac is **one 1.5 km long cryo-string** (300t)
- 671 control valves, >3,800 sensors, 433 regulation loops, > 22,000 records, …
- Problem with lifetime of CC-engines (bearings) => close to solution!



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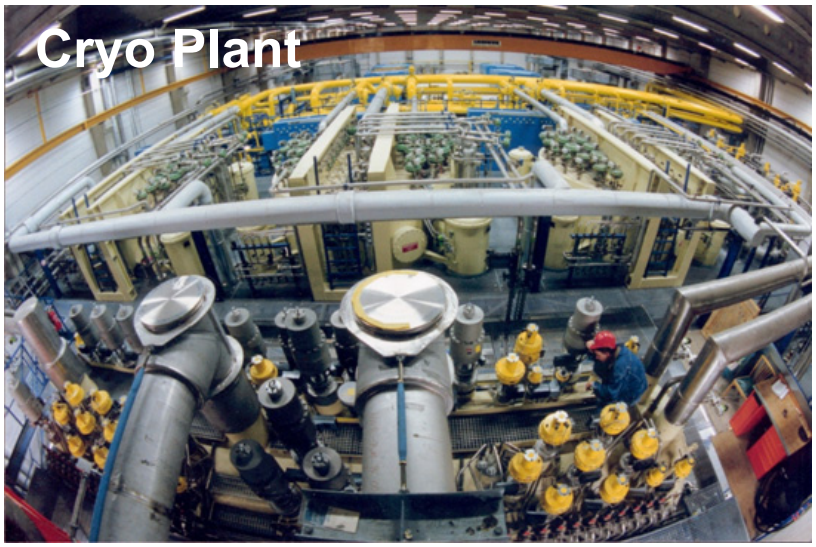

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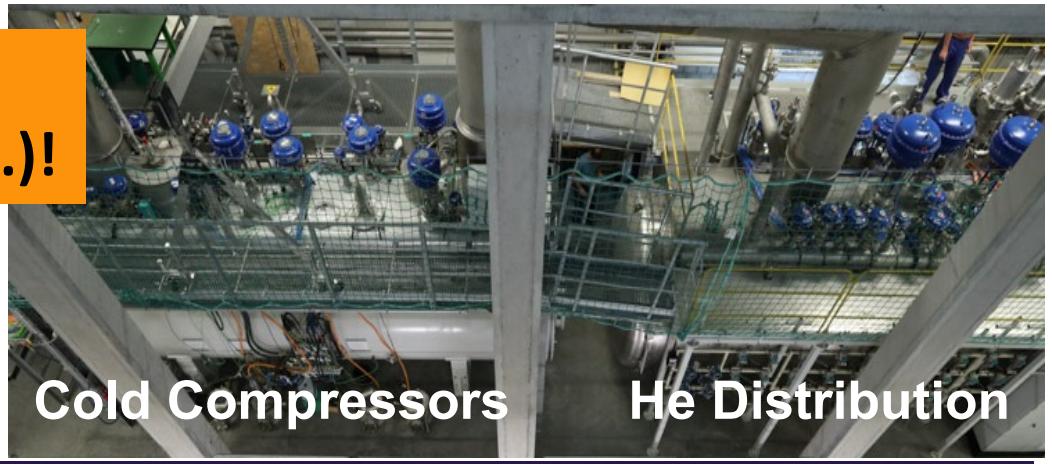
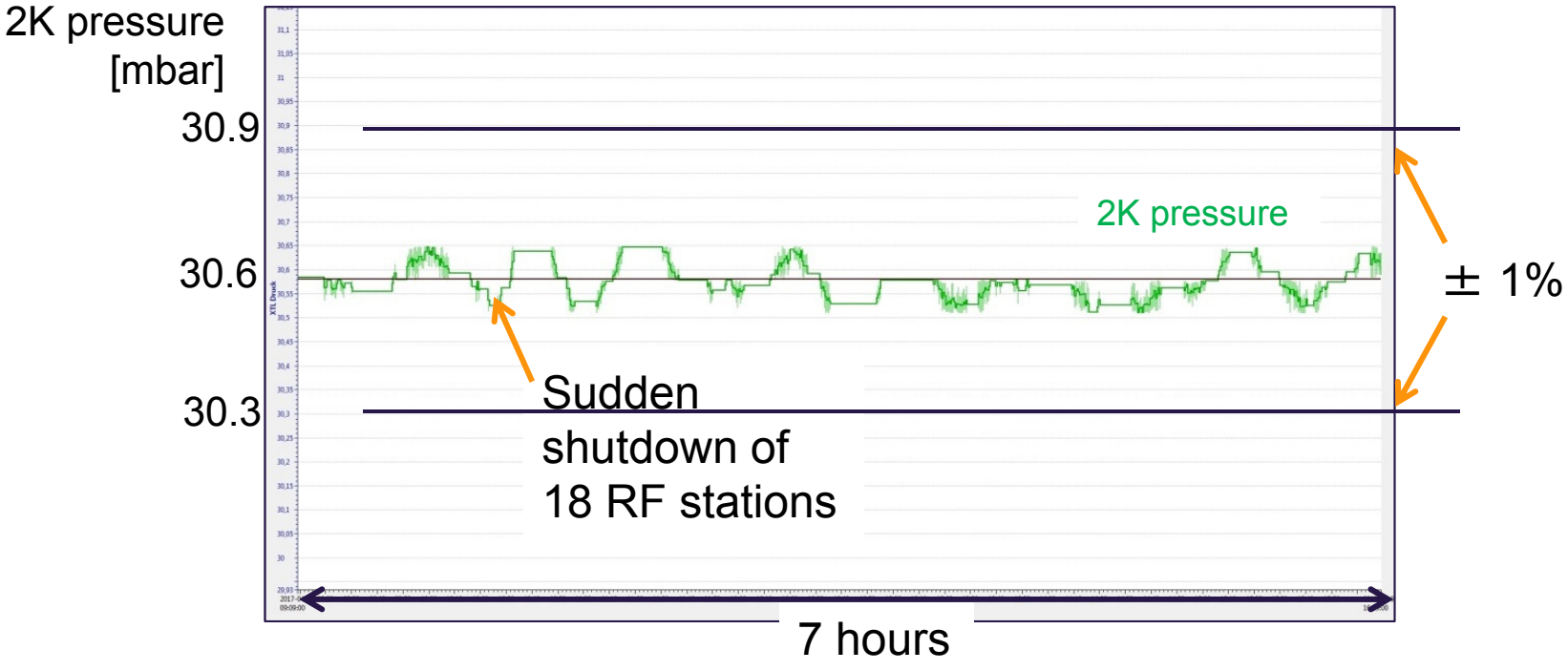
No cold leaks !
All static losses in budget (prel.)!



Cryo: Operational Stability at 2K

- Requirement on 2K pressure stability: 2% peak to avoid cavity detuning
- Complex system requires operation experience (= commissioning time)
- Inner-system heaters to counteract dynamic processes
  => **Automation of heat load compensation and "compromise" adjustment of control parameters successful**



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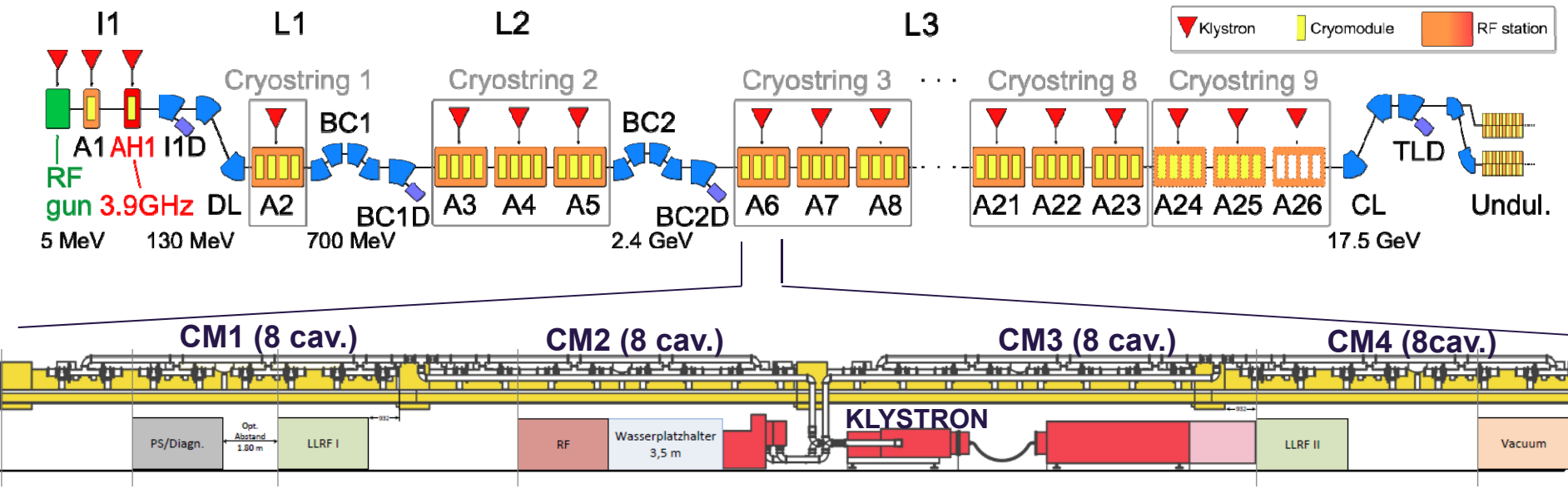
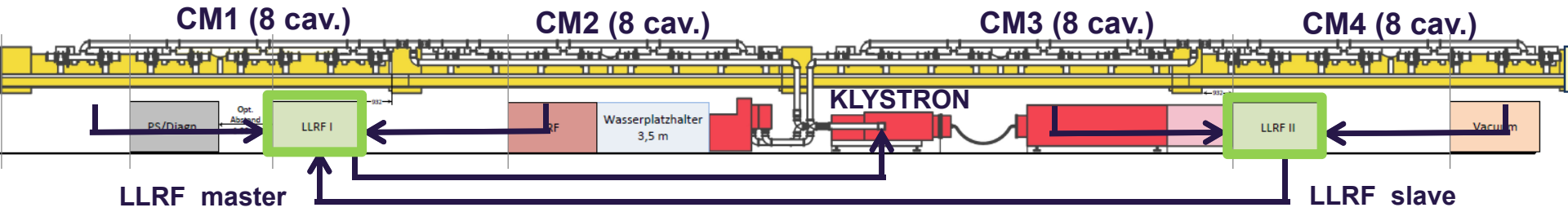
High Power RF System



- HV Modulators in surface hall
- Connected to pulse transformer via up to 2km long pulse cables
- Absolute RF power measurement at Klystron, only !
  (One power meter per Klystron arm)

XFEL LLRF System

- Each RF station with its own LLRF system in “master-slave” configuration



- Commissioning
  - Cold coupler conditioning (when needed)
  - Frequency tuning (from parking position)
  - Coupler tuning (target QL)
  - Power-based gradient calibration (coarse)
  - Closed-loop operation (feedback, learning feedforward)

RF ONLY

  - Cavities: “Multipacting” processing (if necessary)
  - Couplers: 4 couplers shorted due to 70K window overheating

D. Kostin, MOPB111

  - Establish beam transport (0.5 nC, 30 bunches)
  - Cavity phasing (moving waveguide phase shifters)
  - Beam-based gradient calibration (fine)

BEAM REQUIRIED

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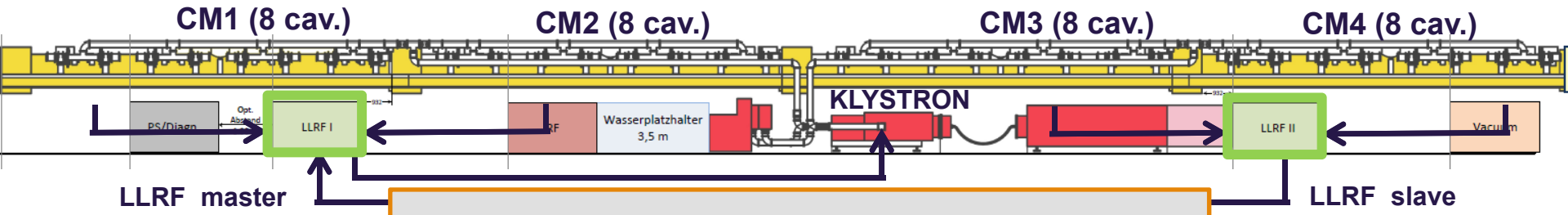

- Commissioning

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  - Frequency tun
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  - Power-based
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RF ONLY

Talk by Mathieu Omet on Friday

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BEAM REQUIRIED

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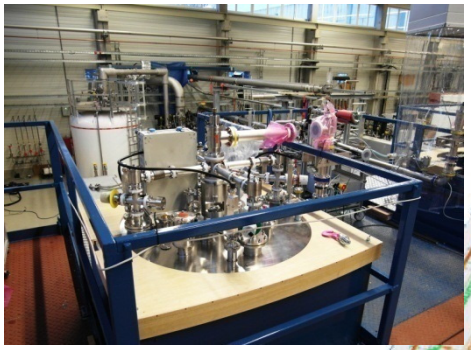
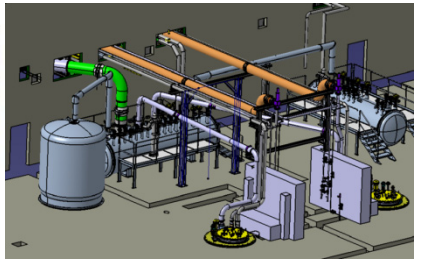
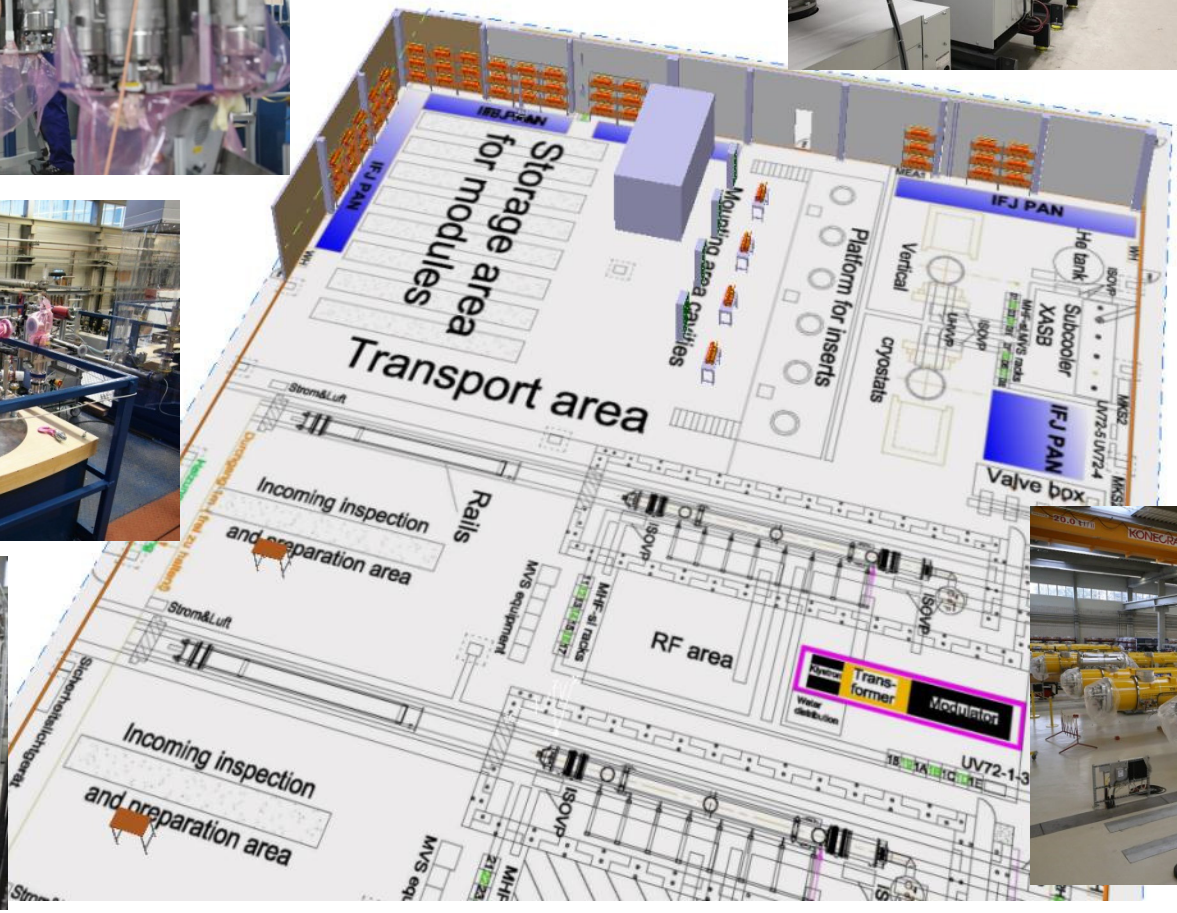
AMTF Test Stand Infrastructure at DESY







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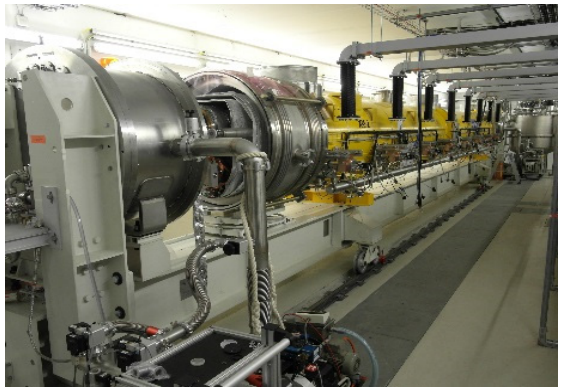
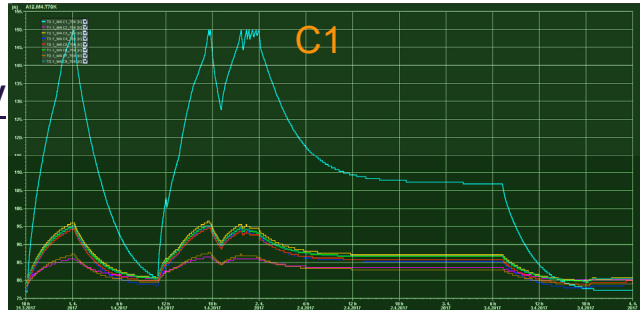
Cryomodules: From AMTF to XTL

- The initially projected rate of module assembly, testing and installation to XTL was one cryomodule per week.
- Variation in coupler availability was compensated by additional efforts at CEA Saclay wrt. assembly rate.
- Gained experience with module testing was used to shorten test duration of module XM40+ .
- During the end of production the major non-conformity was overheating at the 70K coupler window; all necessary warm coupler parts were exchanged.
- Repaired modules were retested at AMTF only when needed.
- Individual waveguide tailoring was done for all modules depending on the cavity performance





M. Schmökel, MOPB088
E. Vogel, MOPB015
F. Hoffmann, MOPB013
K. Kasprzak, MOBP106

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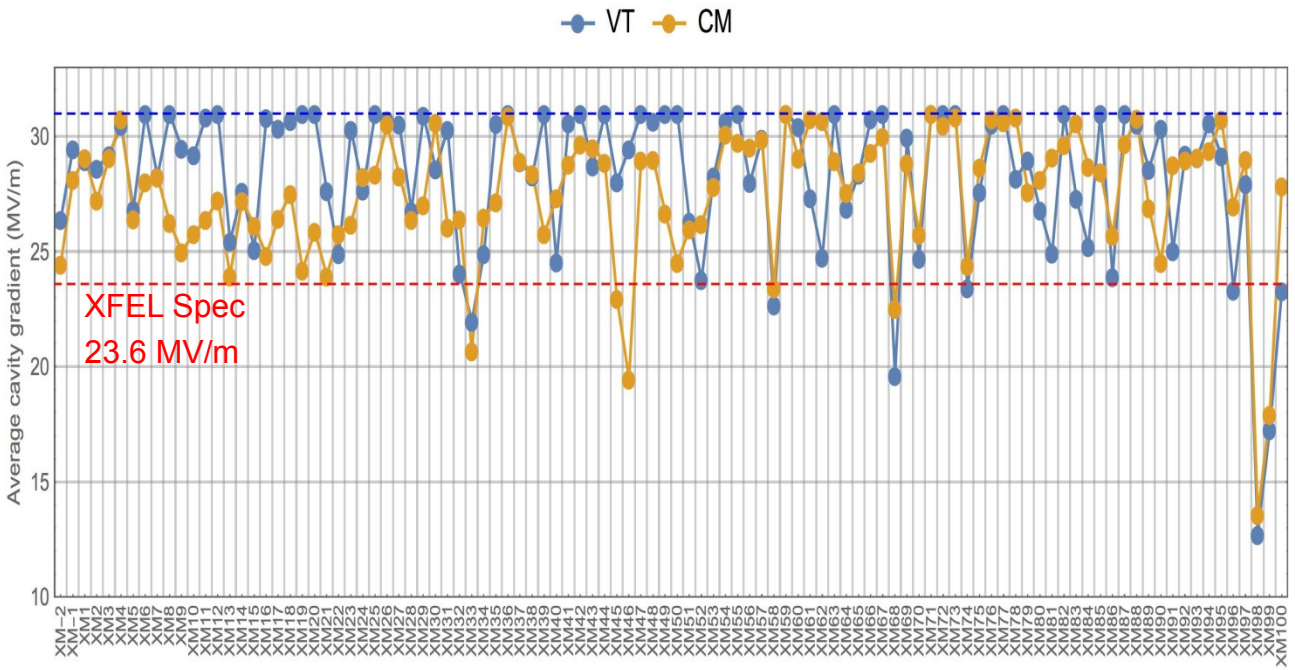
Cryomodule counting

- 103 modules (XM-3 to XM100) assembled at CEA Saclay and tested at AMTF
  - 1 module in the injector
  - 96 modules in 103 working weeks assembled to XTL
  - 5 modules not installed yet
    - XM8 (leaky cryogenic line)
    - XM46 & XM50 (inacceptable cavity performance)
    - XM99 (leaky beam line)
    - XM100 now spare module (XM-2 used in tunnel)
  - XM-3 used for cw-tests (non PED certified cavities)
- In XTL one RF station (A26) not installed yet
- Two RF stations require final installation work (A24,A25)

89 modules / 712 cavities for operation so far
– 5 cav. (shorted due to poor performance)
– 4 cav. (shorted due to coupler heating)
= 703 cavities accelerating

AMTF Cryomodule Test: Average Gradient Performance



vertical test (clipped at 31 MV/m)
cryomodule performance

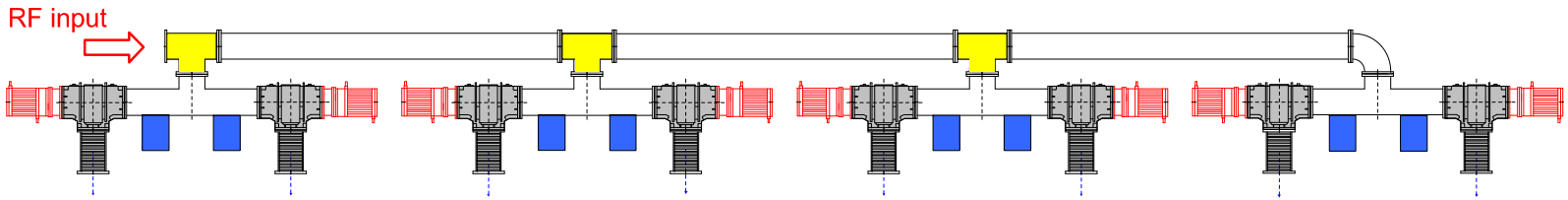
- Module performance well above specs. and visible improvement with time
- Tunnel installation used sorting of modules based on AMTF performance
- XM98 as scavenger module

	N_{cavs}	Average	RMS
VT	815	28.3 MV/m	3.5
CM	815	27.5 MV/m	4.8

Remark:

Clipping at 31 MV/m is done due to max. available RF power; limit given by waveguide distribution.

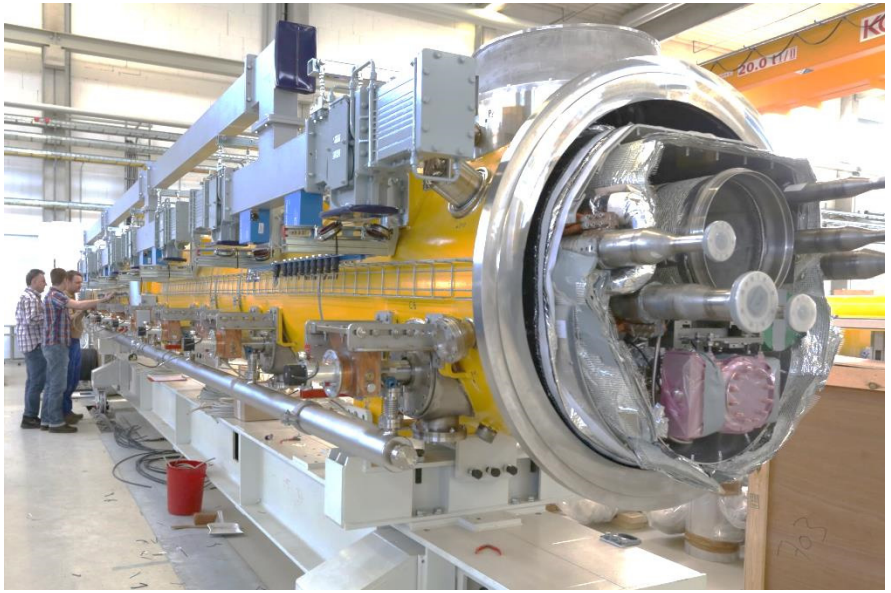
Impact of Waveguide Distribution (WD) system (Installed Gradient)



courtesy V. Katelev

- One 10-MW klystron drives four modules (32 cavities)
- WD of each module tailored according to AMTF test results:
  - maximising voltage
  - up to 3dB difference between cavity pairs allowed
- Allow up to 3dB split between adjacent cryomodule pairs
- Assumption: Equal power output from two klystron arms

=> Reduction in installed gradient



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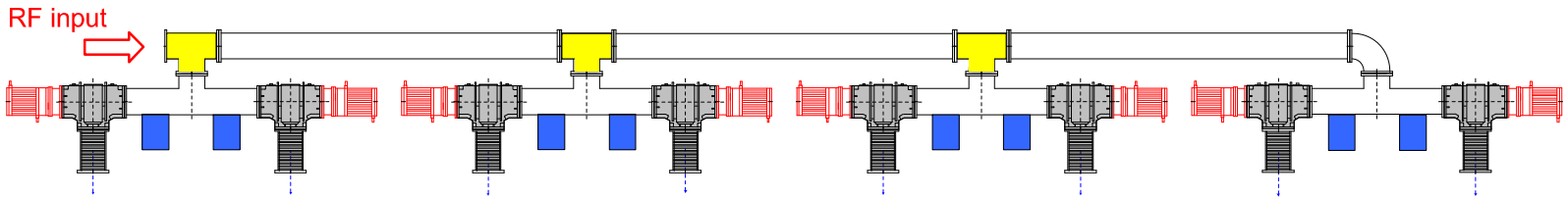

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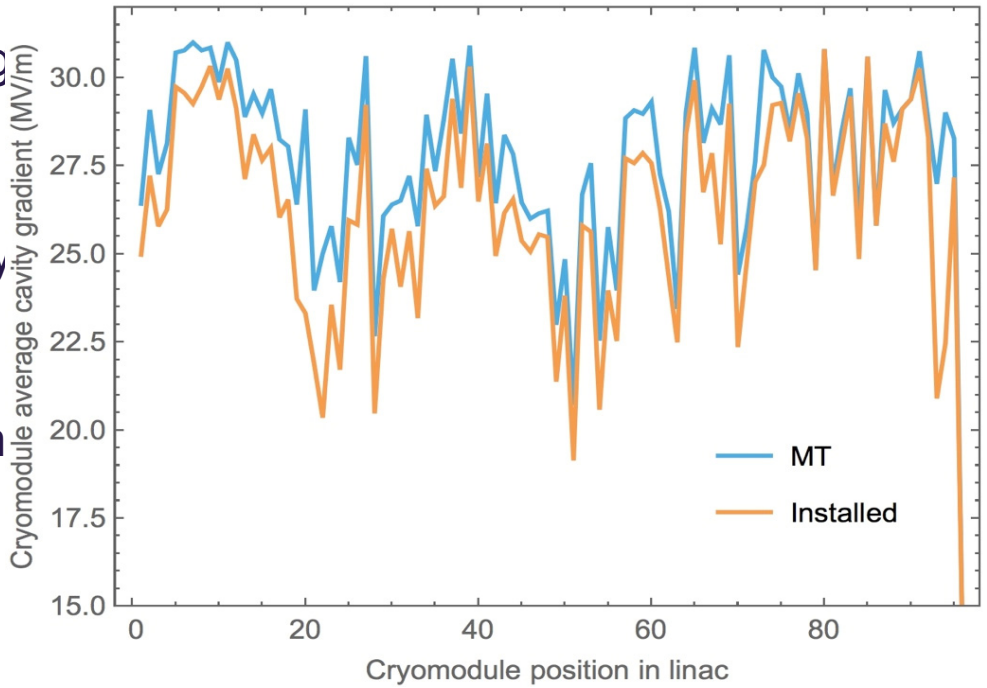
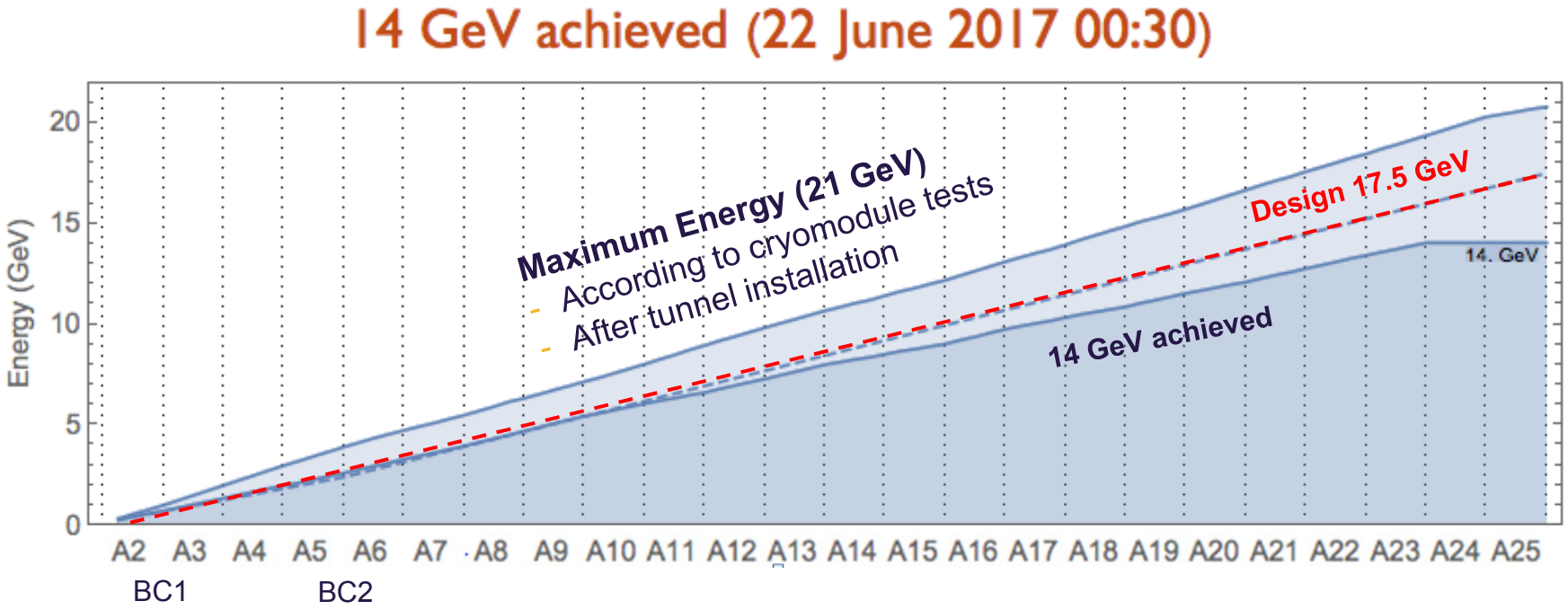


Energy Reach of European XFEL



- For 14 GeV: 23 RF stations (89 modules) in operation
- At present the bunch compressor working point of BC2 (2.4 GeV) leads to maximum energy of 19.5 GeV

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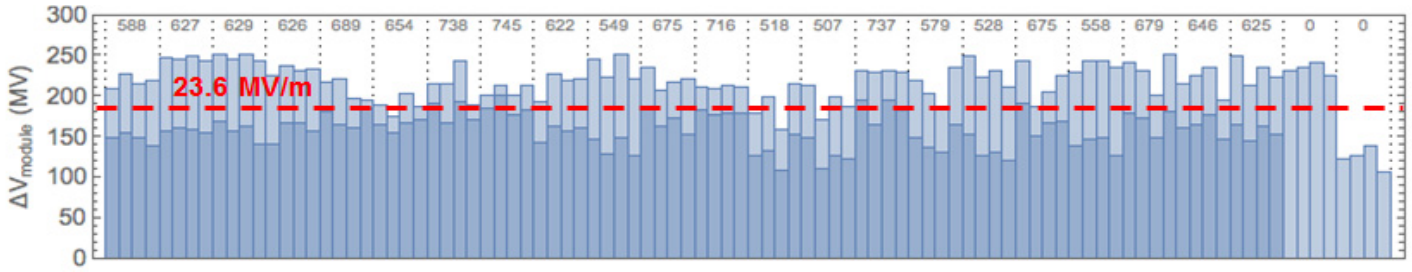
Operating so far

- **No significant degradation** of individual cavities / modules observed so far

- Some gradient reduction in tunnel configuration observed
  => Tunnel waveguide distribution and calibrations under investigation



- Operation of RF stations “off beam” allows commissioning/investigation of single RF stations parallel to lasing operation
- More cavities needed short Multipacting processing than in AMTF test

- Preliminary:
  Average Q-value is >10^{10} estimated from the dynamic cryo losses at 12-14 GeV

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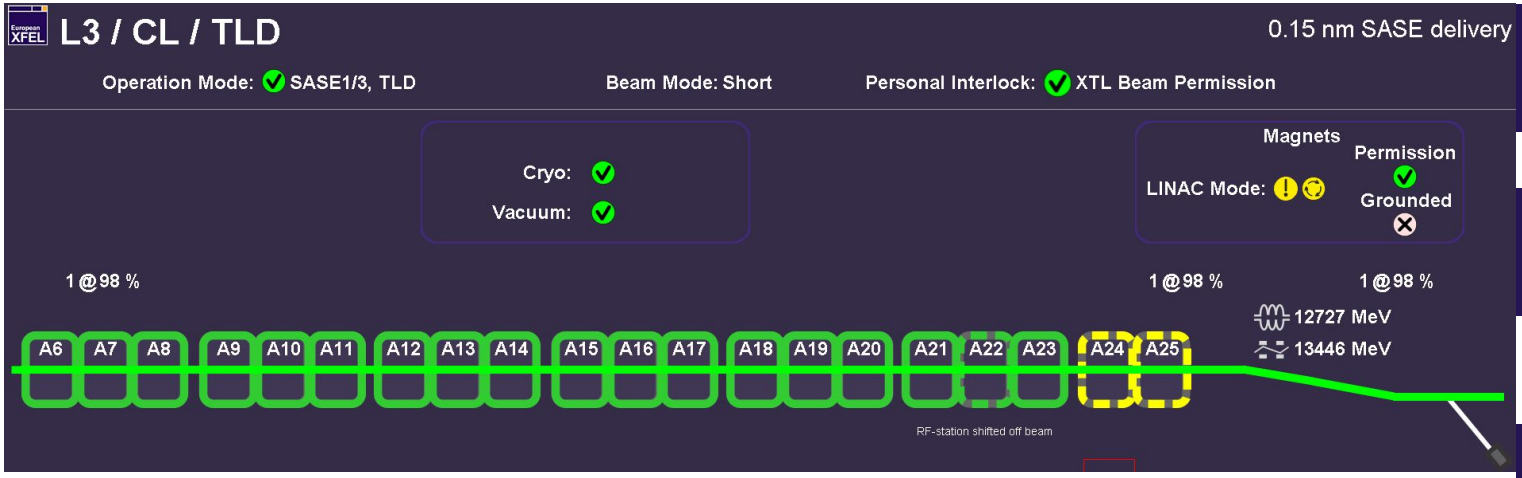
Summary (or "Linac in operation")

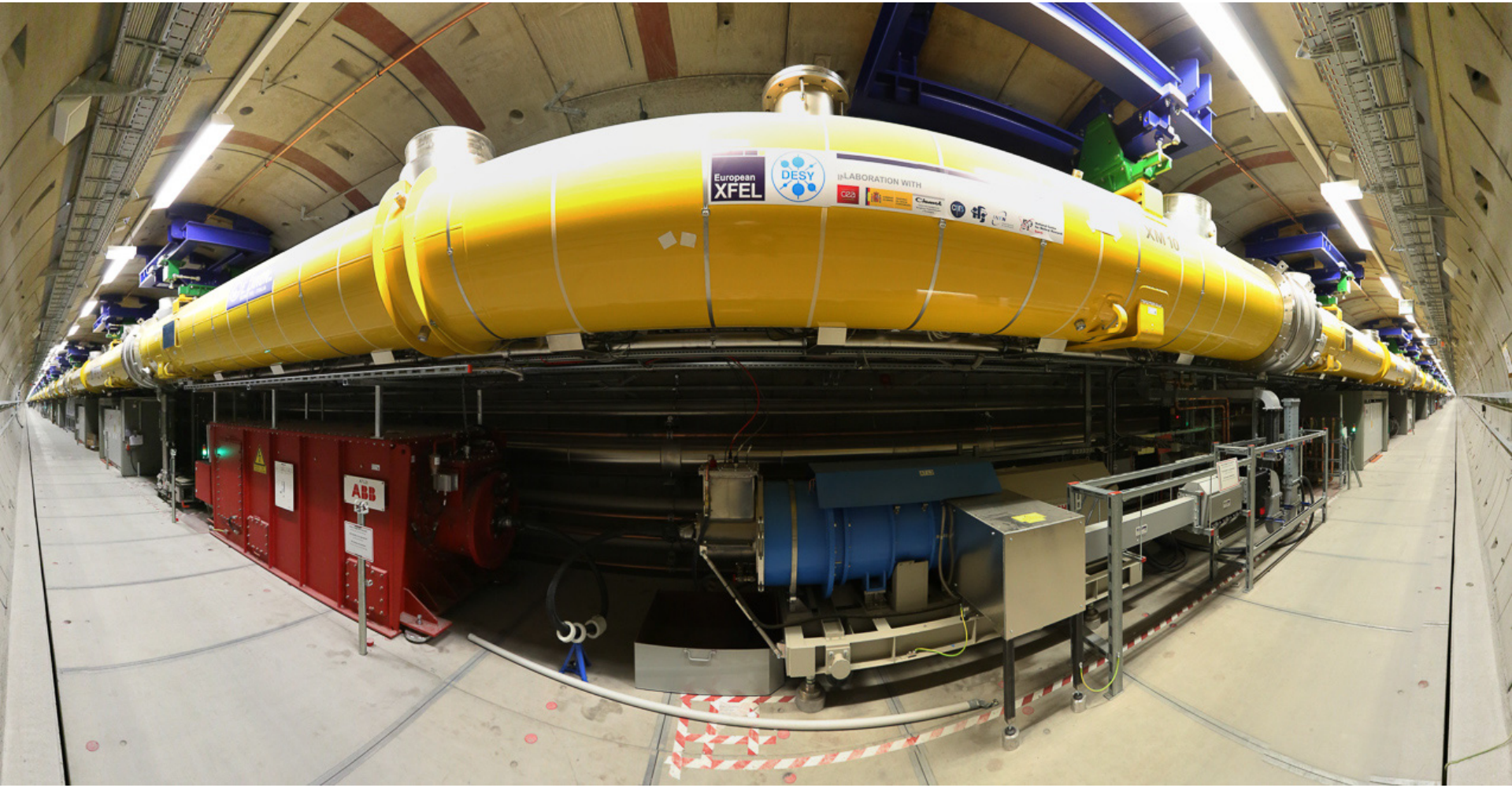


- 23 out of 25 RF stations are commissioned at moderate gradients and with cryo losses in budget
- Handed over to operations and controlled via FSM
- Detailed measurements will show the path towards higher beam energies A1

- Inner loop RF stability <0.01 deg, < 0.01%
- Preliminary measurements of beam energy jitter ≈ 10^{-4}
- 0.15nm SASE delivered to experimental area

- The last two RF stations still require longer tunnel access

One Kilometer of Cold Linac



General Assembly of the European
XFEL Accelerator Consortium
04.05.2017

THANK YOU TO ALL CONTRIBUTORS TO THE EUROPEAN XFEL