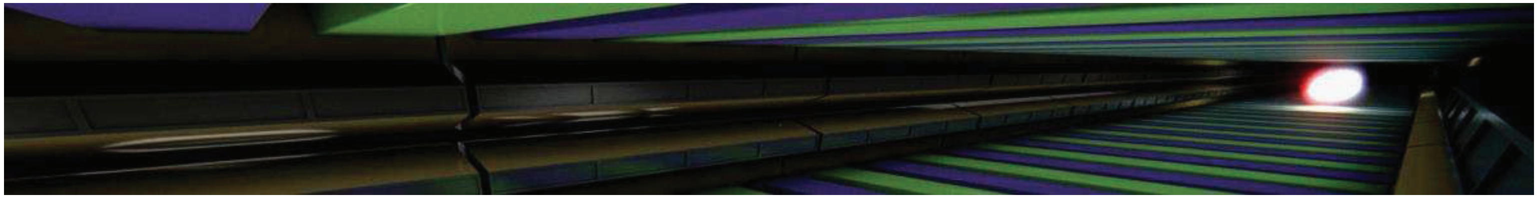
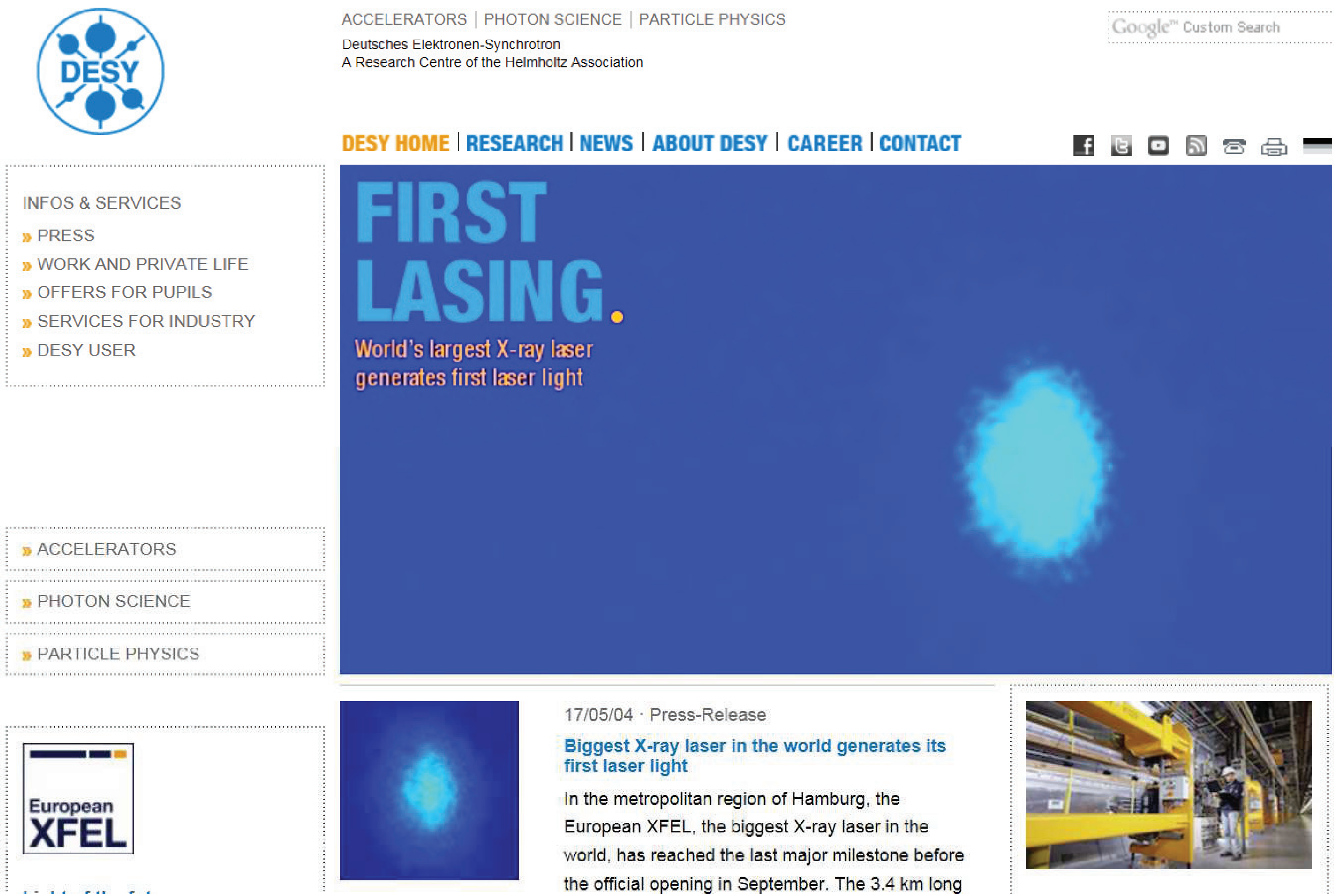


Commissioning of the European XFEL Accelerator

Winfried Decking, Hans Weise - DESY

for the European XFEL Accelerator Consortium and Commissioning Team

IPAC 2017, Copenhagen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FIRST LASING.
World's largest X-ray laser generates first laser light
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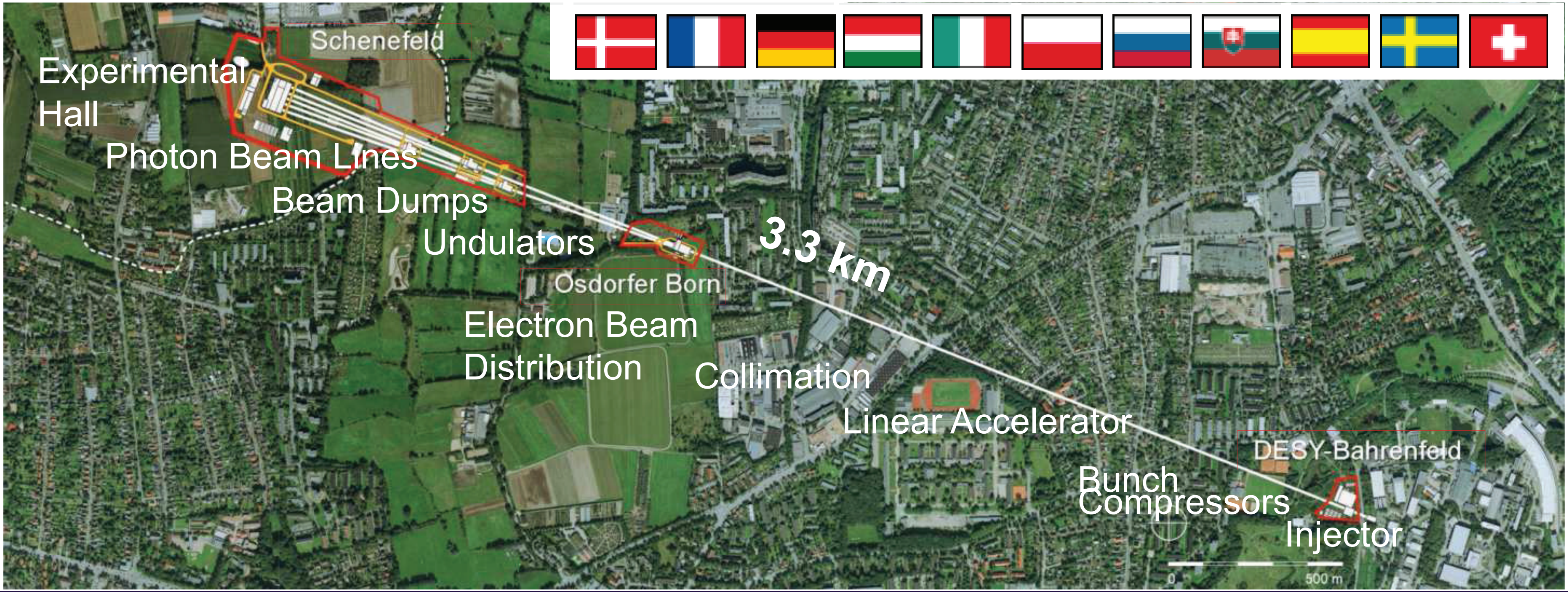
» PARTICLE PHYSICS
European XFEL
17/05/04 · Press-Release
Biggest X-ray laser in the world generates its first laser light
In the metropolitan region of Hamburg, the European XFEL, the biggest X-ray laser in the world, has reached the last major milestone before the official opening in September. The 3.4 km long

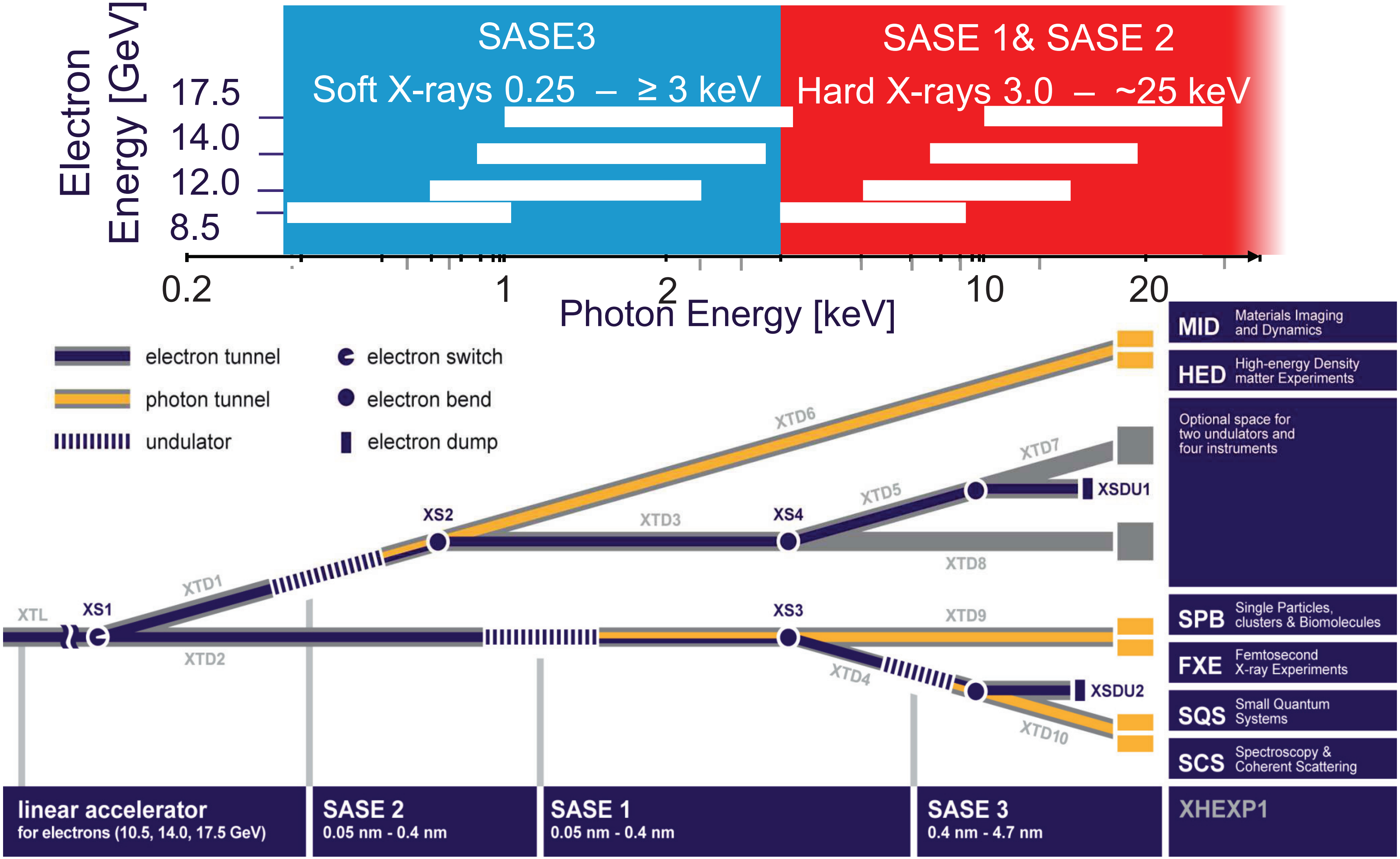
European XFEL at a Glance

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



European XFEL

Covers photon energies from 0.25 keV to 25 keV



Project History

2000: First lasing at 109 nm at the Tesla Test Facility (TTF), now FLASH

2001: TESLA Linear Collider TDR with XFEL appendix

2002: TESLA TDR supplement with stand-alone XFEL

2006: European XFEL TDR

2009: Foundation of the European XFEL GmbH

Start of underground construction

2010: Formation of the Accelerator Consortium:

16 accelerator institutes under the coordination of DESY

2012: End of tunnel construction

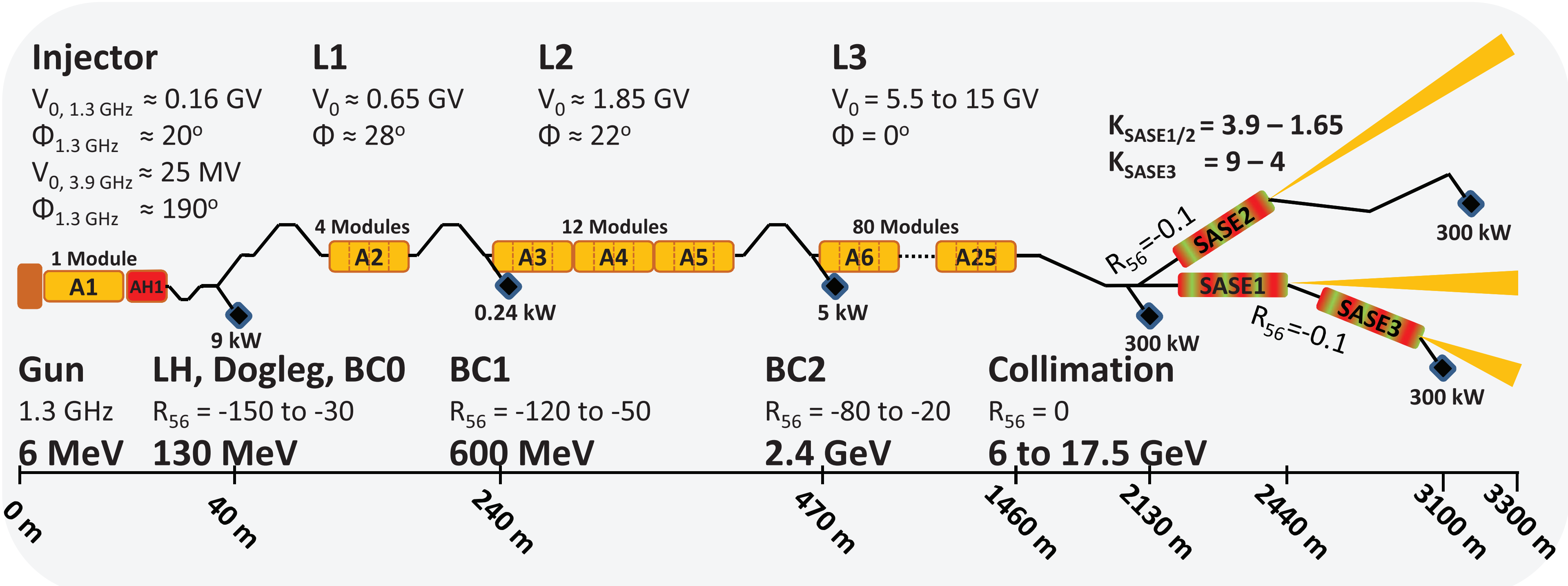
Start of underground installation

2016: Finish of accelerator installation

Start of commissioning

M. Bousonville, TUPAB039
J. Kreutzkamp, WEPAB018, THPAB104

Accelerator Overview



- Superconducting linac with 97 1.3 GHz superconducting modules
- 10 Hz pulsed mode with 600 μs flat-top, 2700 bunches/pulse
- Variation of bunch charges between 20-1000 pC foreseen to vary final pulse length
- Fast distribution of bunches into beam distribution lines

Commissioning Plan

Strategy: get as many systems in the game as soon as possible

12/16	Start: Cooldown
01/17	Injector at 130 MeV (3 RF stations)
01/17	L1 commissioning (+1 RF station)
02/17	L2 commissioning (+3 RF stations)
02-04/17	L3 commissioning (+15 RF stations)
05/17	Beam through SASE1 & SASE3 undulator sections
End 05/17	Milestone “First Lasing Possible”
06-08/17	Commission SASE1 photon beamline and experiment Consolidate FEL operation at 8-10 keV photon energy
09/17	First user experiments (total 800 hours)
2018	Continue facility commissioning + 2000 user hours
2019	Routine operation with 6 experiments + 4000 user hours

European XFEL

Final E-beam parameters

Quantity	Value
electron energy	8/12.5/14/17.5 GeV
macro pulse repetition rate	10 Hz
RF pulse length (flat top)	600 µs
# of bunches/second	27000
bunch charge	0.02 – 1 nC
electron bunch length after compression (FWHM)	2 – 180 fs
normalized slice emittance*	0.4 - 1.0 mm mrad
beam power	500 kW
simultaneously operated SASE undulators	3

* normalized emittance: $\varepsilon_n = \gamma\varepsilon = \gamma\sqrt{\langle x^2\rangle\langle p^2\rangle + \langle xp_x\rangle^2}$

DESY HELMHOLTZ ASSOCIATION

Commissioning E-beam parameters

Quantity	Value
electron energy	~~8/12.5/~~14/~~17.5~~ GeV
macro pulse repetition rate	10 Hz
RF pulse length (flat top)	600 µs
# of bunches/second	~~27000~~ 600
bunch charge	~~0.02 – 1 nC~~ 0.5 nC
electron bunch length after compression (FWHM)	~~2 – 180 fs~~ 90 fs
normalized slice emittance	~~0.4 -~~ 1.0 mm mrad
beam power	~~500 kW~~ 5 kW
simultaneously operated SASE undulators	~~3~~ 1

Injector in Operation 2015/2016

- Photoinjector conditioned and characterized at PITZ, DESY-Zeuthen
- Injector cool-down 12/2015
- First Beam on 18/12/2015- commissioning till Q2/2016
- 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
- 3.9 GHz system operational from day 2
- Laser heater commissioned (but not in routine operation)

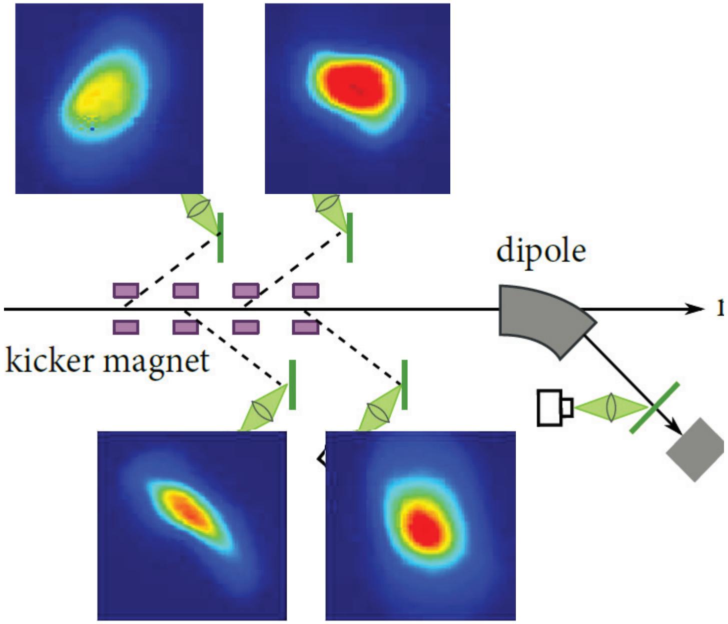
Y. Renier, TUPIK051/TUPIK052

C. Maiano, MOPVA058/MOPVA059
P. Pierini, MOPVA067

M. Hamberg, WEPAB024

Emittance Measurements

Scheme of the XFEL injector diagnostic section



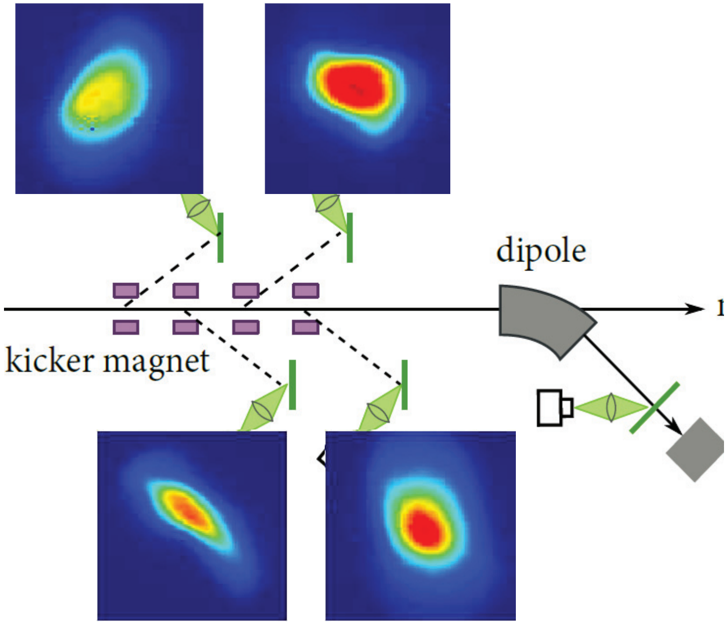
Emittance optimization mainly at 500 pC and reduced gun gradient (≈ 52 MV/m)

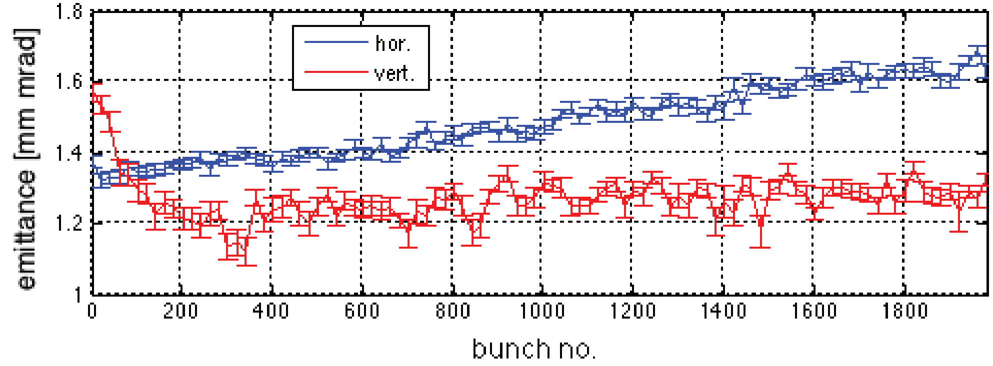
	Design	Achieved
Normalized proj. emittance [mm mrad]	> 1.5	1.2
Normalized slice emittance [mm mrad]	0.6	0.6

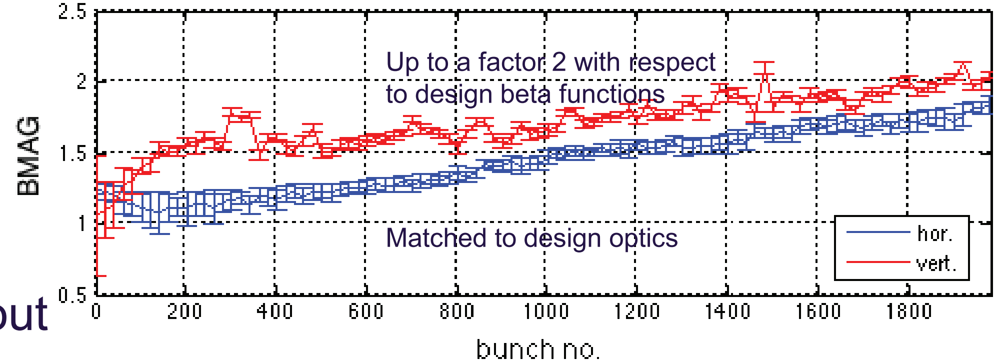
- Fast kickers kick single bunches out of the trains to off-axis screens
- "Semi-parasitic" diagnostics during beam delivery
- Together with transverse deflecting system also used for slice diagnostics

Emittance Measurements along Bunch Trains

Scheme of the XFEL injector diagnostic section





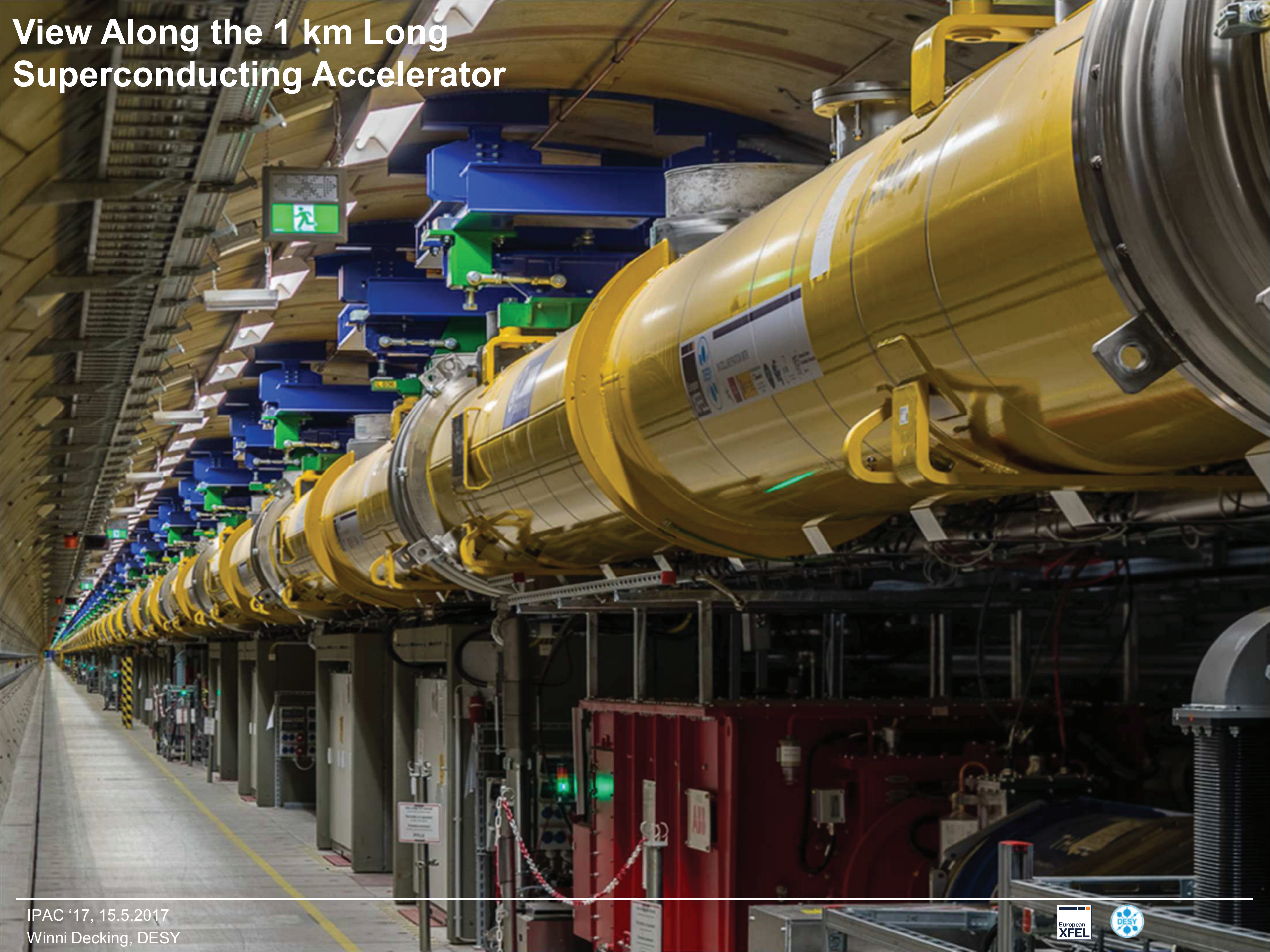


- Fast kickers kick single bunches out of the trains to off-axis screens
- "Semi-parasitic" diagnostics during beam delivery
- Together with transverse deflecting system also used for slice diagnostics

- Variations along the train can be monitored
- Corrections to provide uniform conditions along train

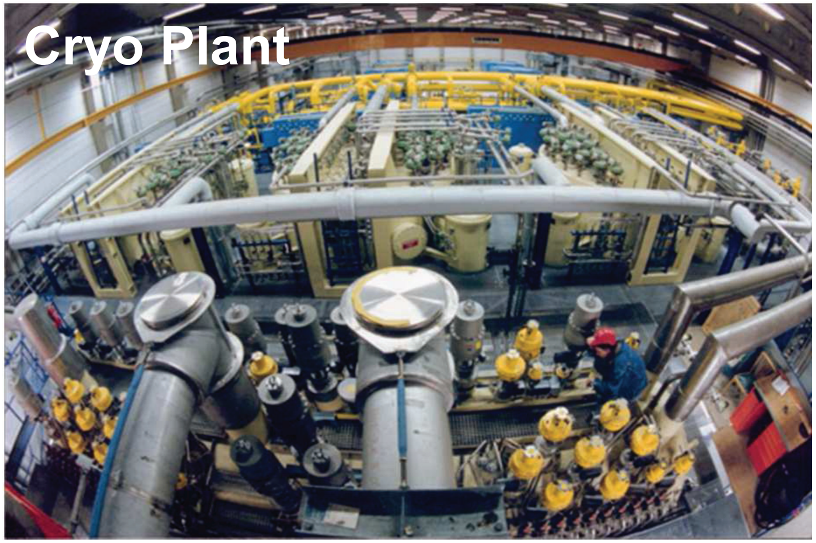
B. Beutner, WEPAB013
M. Scholz, MOPAB047

View Along the 1 km Long Superconducting Accelerator



European XFEL

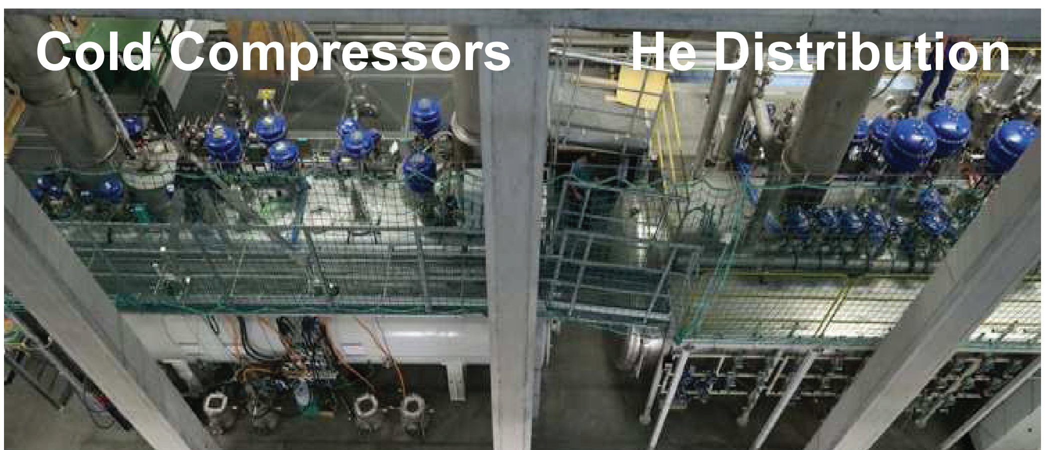
Overview of XFEL Cryogenic Equipment

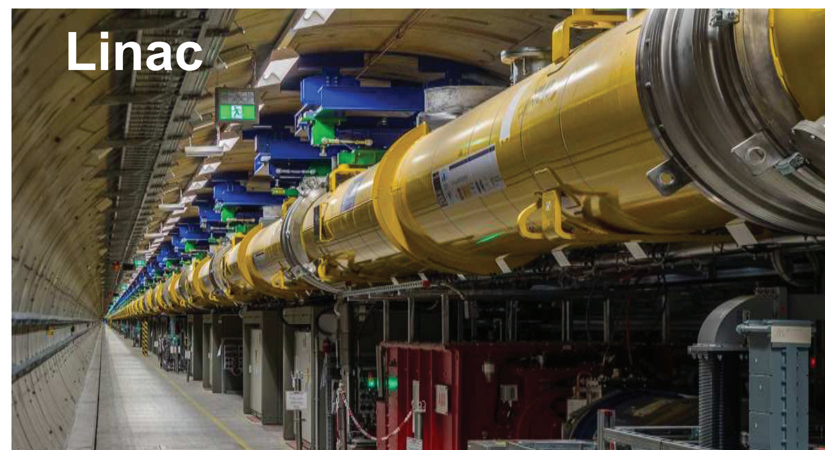


- Cryo plant with cold compressors and extended distribution system
- Cooling capacity:

2K	: >1.9 kW
5/8K	: 4 kW
40/80K	: 24 kW

- Linac is one 1.5 km long cryo-string

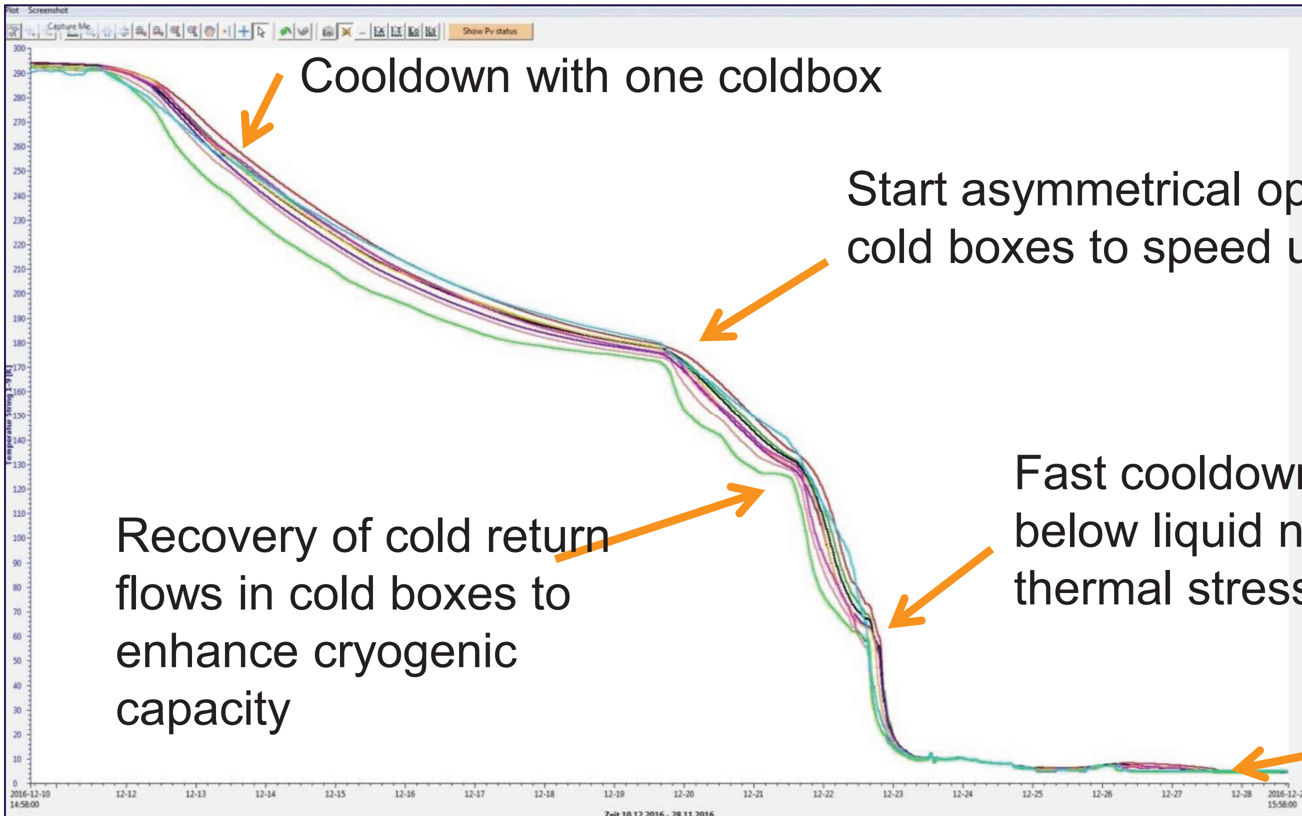




European XFEL

First Cooldown of XFEL Linac (>300 t)

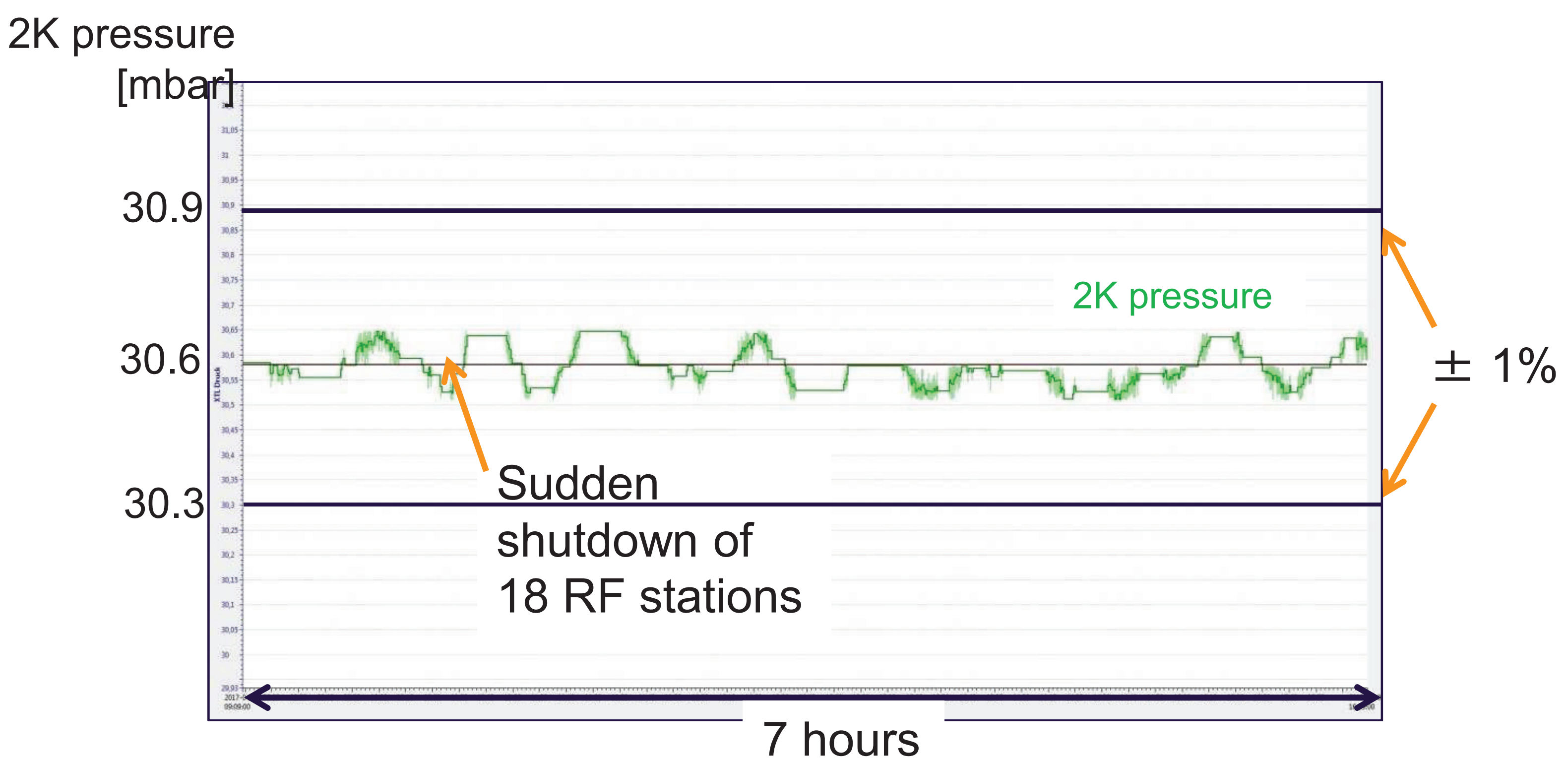
Temperature at 9 positions along the linac versus time



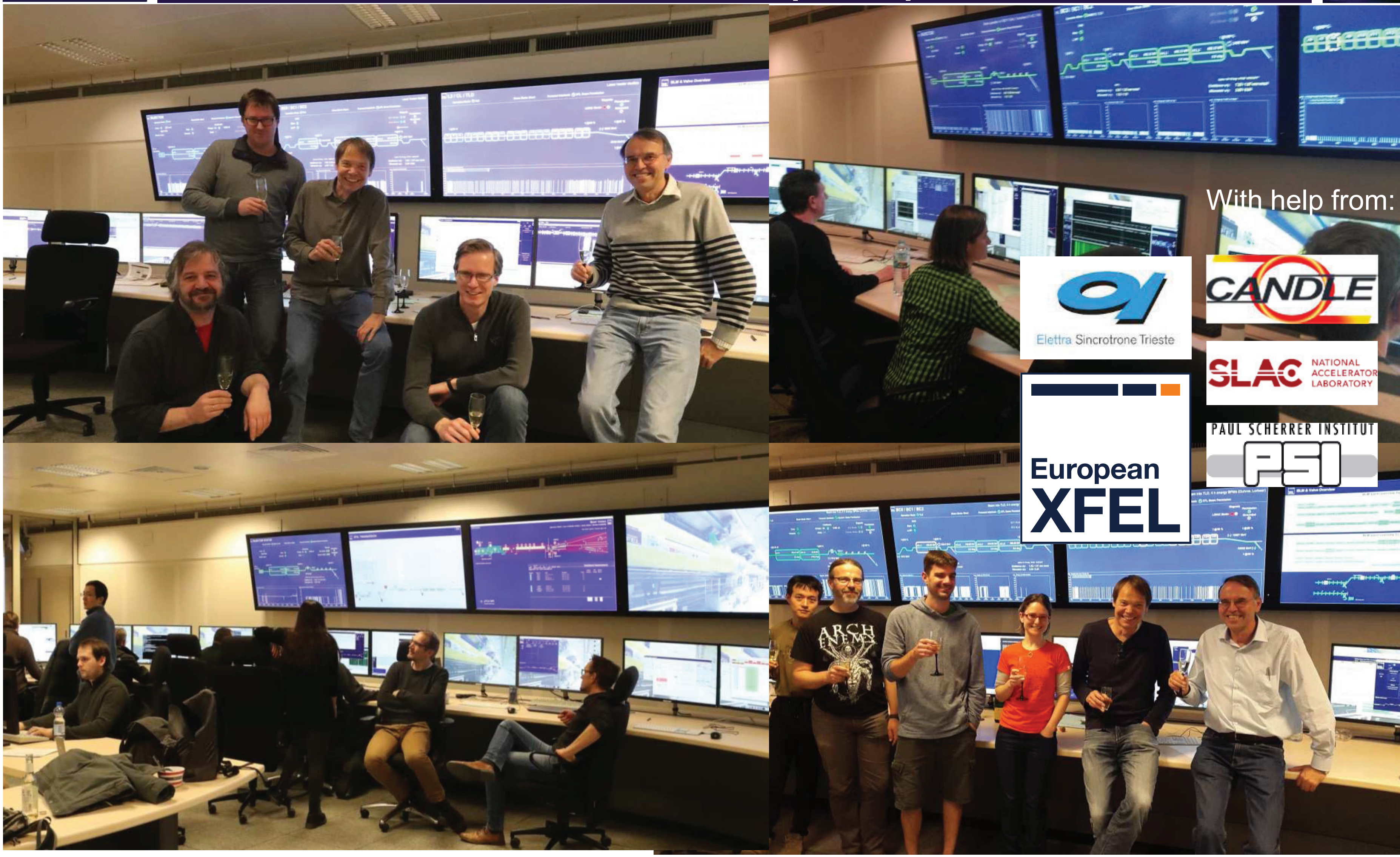
No cold leaks !

Pressure Stability in 2K Circuit

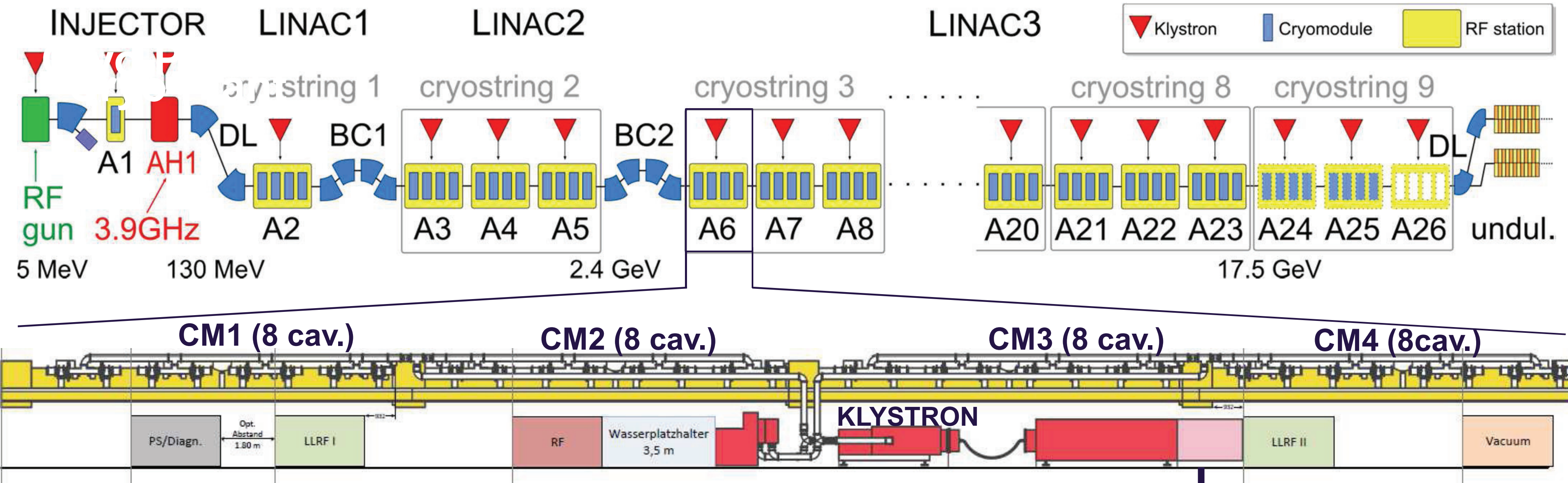
- Requirement on 2K pressure stability: 2% peak from LLRF requirements (cavity detuning)
- Tedious adjustment of regulation loops
- Inner-system heaters to counteract dynamic processes



Linac Commissioning started from Accelerator Control Room (BKR)



XFEL RF System

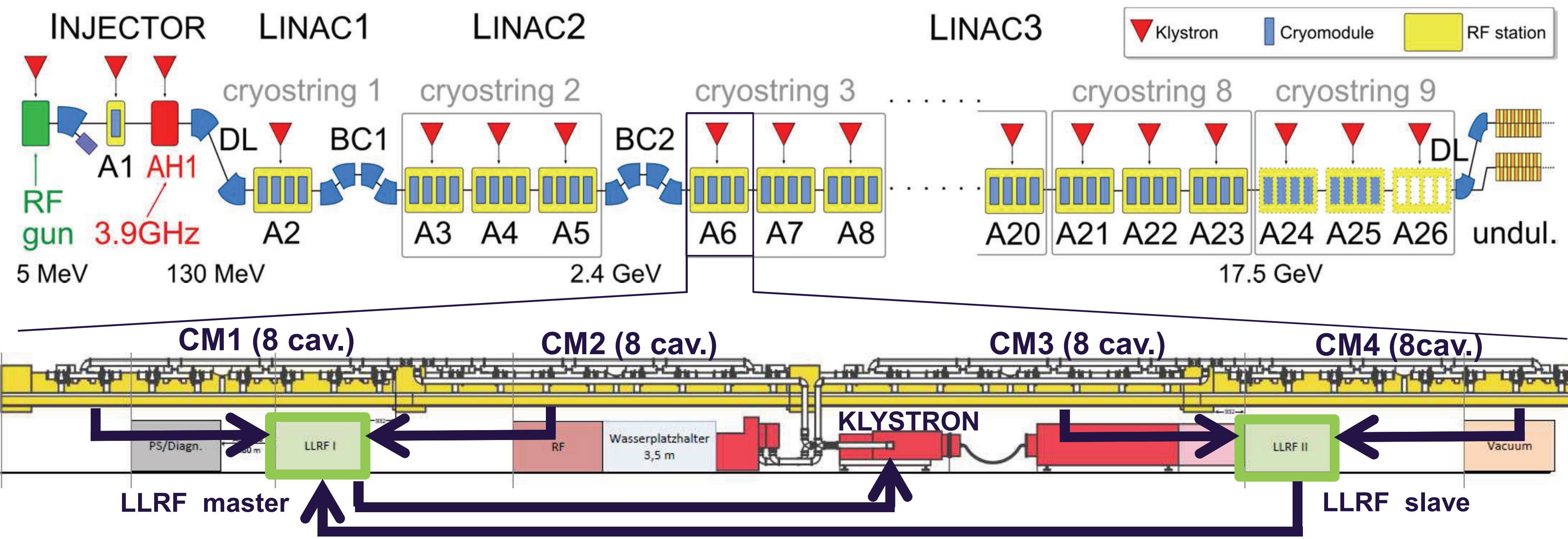


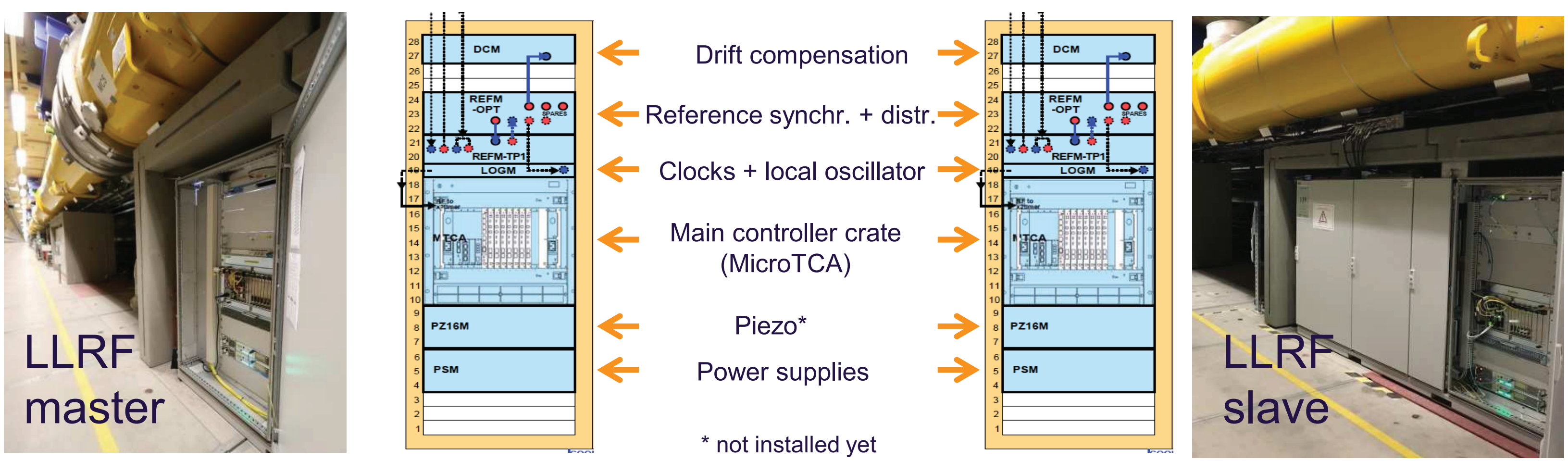
- HV Modulators in surface hall
- Connected to pulse transformer via up to 2km long pulse cables

Klystron and modulator below module

European XFEL

XFEL LLRF System





European XFEL

MicroTCA.4 for Accelerator Controls

- MicroTCA.4-based components used as standard hardware platform (LLRF, Diagnostics, Vacuum, HPRF, Magnets, Timing, ….)
- About 200 systems installed, serving more than 7.000.000 control parameters
- Operational from day 1 of deployment

- Key benefits:
  - Fully automated and standardized installation procedure allows rapid deployment and recovery
  - Enhanced remote management via IPMI and Ethernet allow for simplified maintenance
  - Extended monitoring and management of module ensure reliable crate operation

T. Walter, THOAB2

European XFEL

LLRF commissioning

J. Branlard, THOAA3

Commissioning milestones

RF ONLY

- **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)

BEAM REQUIRIED

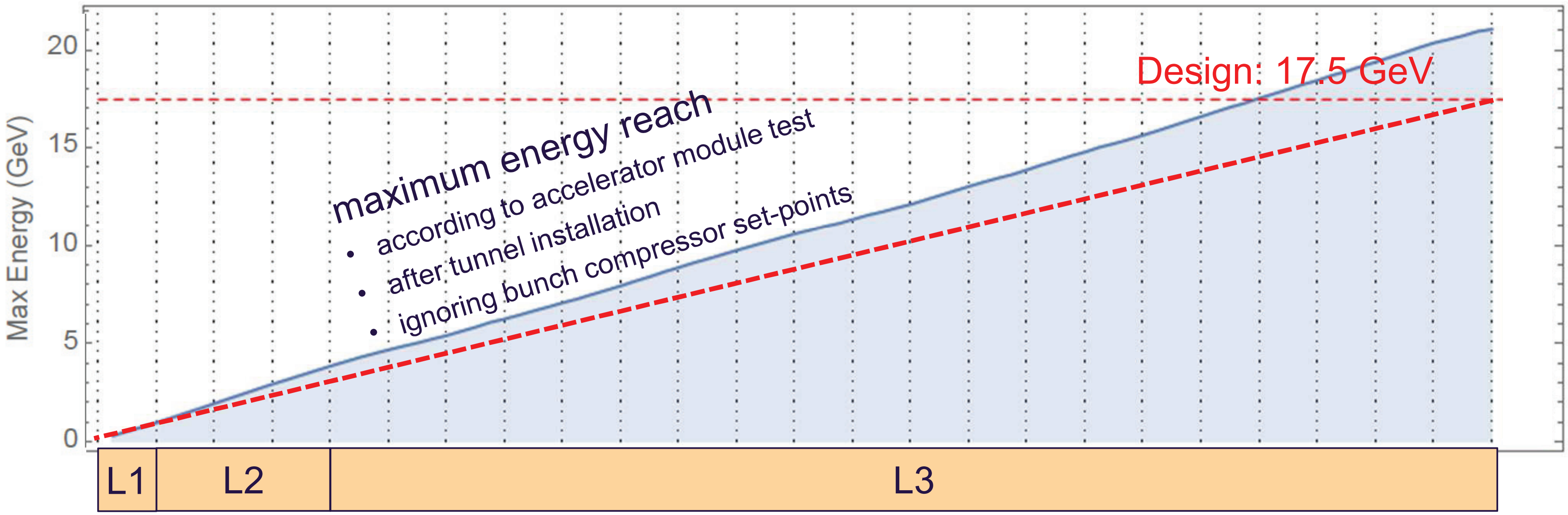
- **Establish beam transport (0.5 nC, 30 bunches)**
- **Cavity phasing** (moving waveguide phase shifters)
- **Beam-based gradient calibration** (fine)

Estimated schedule

- **Injector** (gun, A1, AH1) 2 weeks ✓
- **L1** (1 RF station) 2 weeks ✓
- **L2** (3 RF stations) 2 weeks ✓
- **L3** (15 RF stations) 2 months ✓

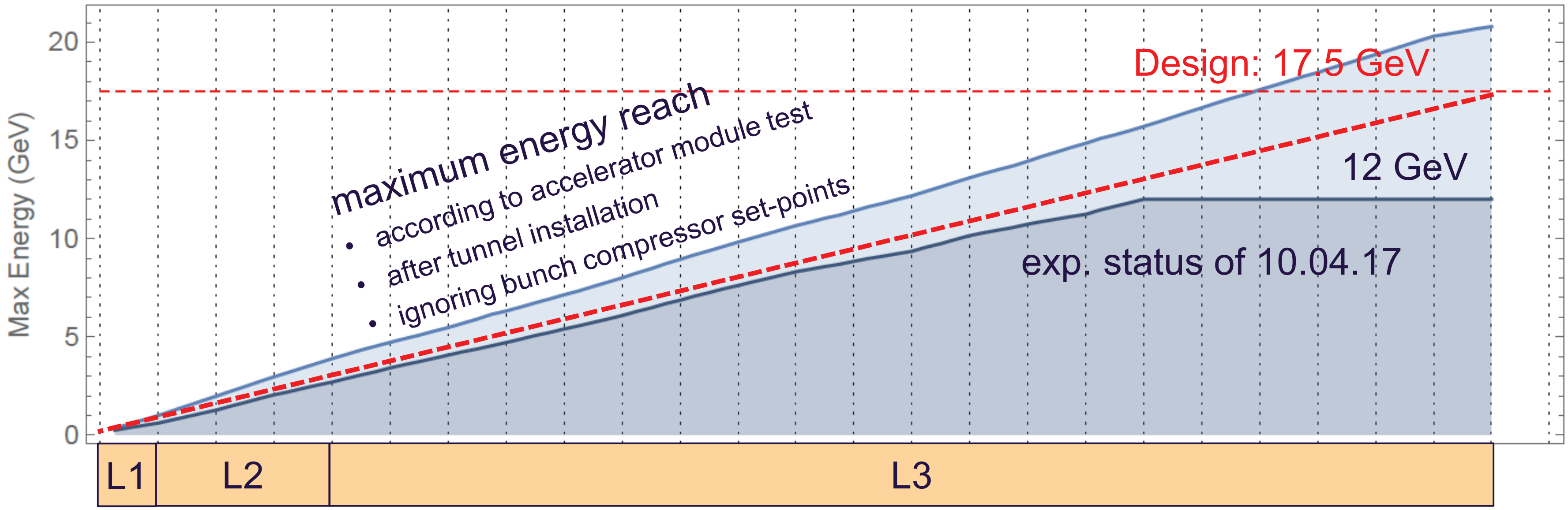
Operation of RF stations time shifted “off-beam” allowed for parallel beam commissioning in L3

Energy Reach of European XFEL Modules



- Average accelerating gradient after module test and waveguide tailoring
  - 26 MV/m, (design 23.5 MV/m)
- Some additional gradient “loss” due to tunnel waveguide distribution
- Excess energy reach will enhance operation reliability

Operating Gradients used so far



- After initial commissioning design gradient almost reached
- Operation of RF stations "off beam" allows final commissioning of single stations parallel to XFEL operation

LLRF in operation

in operation

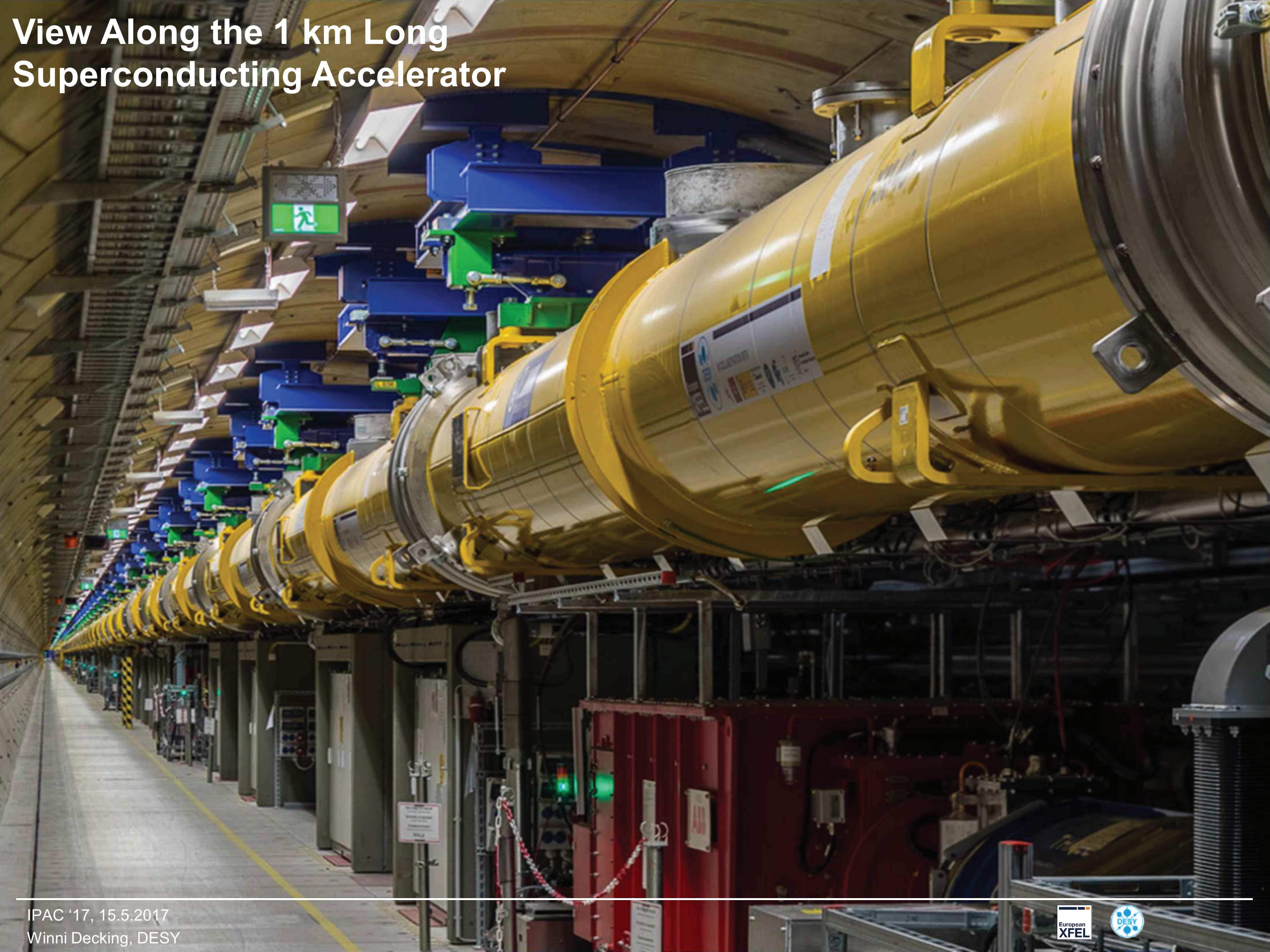
dito. but shifted off beam

off

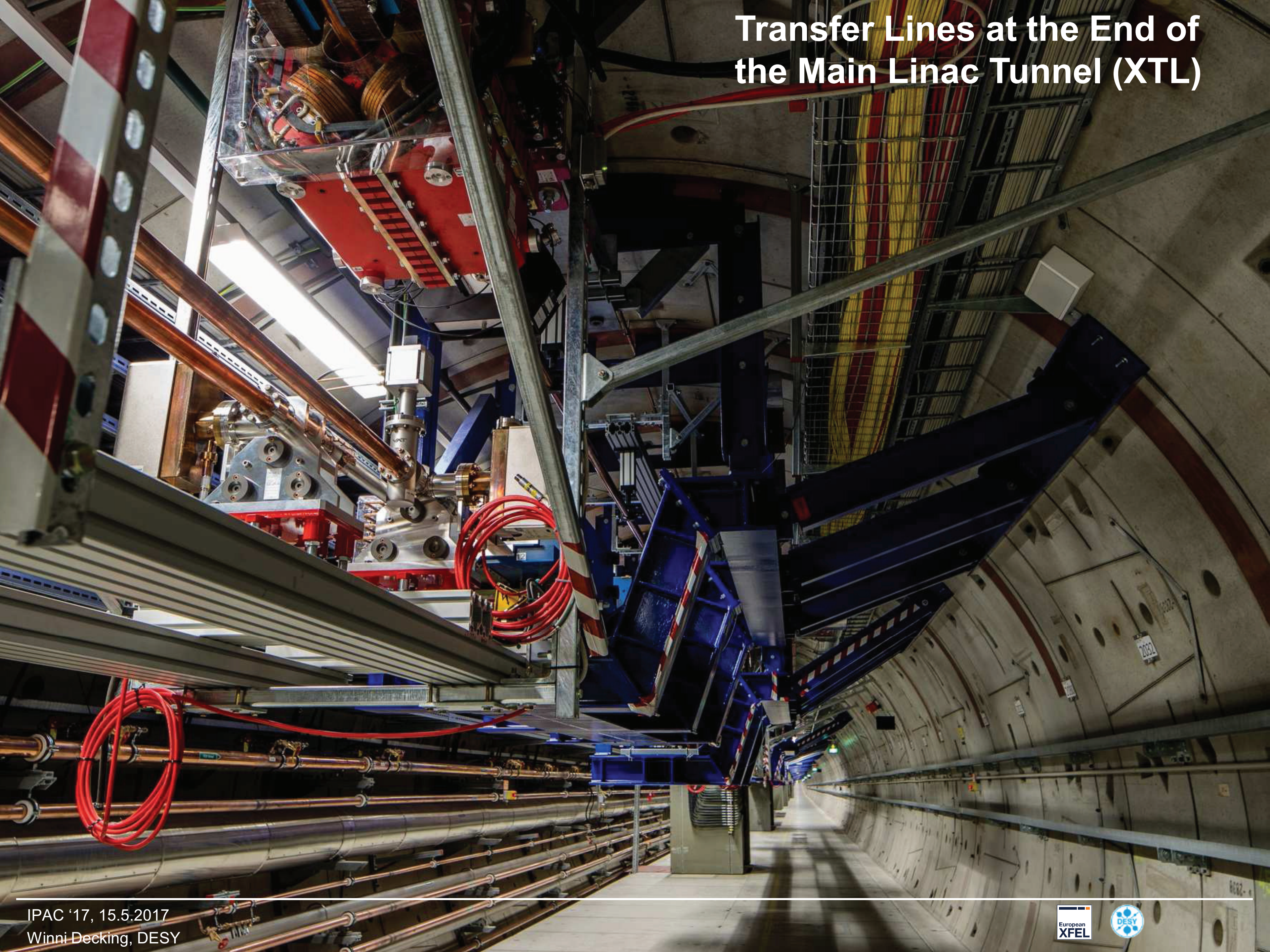
- 20 out of 25 RF stations are commissioned
- Handed over to operations and controlled via FSM
- Inner loop RF stability <0.01 deg, < 0.01%
- Preliminary measurements of beam energy jitter ≈ 10^{-4}

First Bunch Compressor Chicane (BC0)

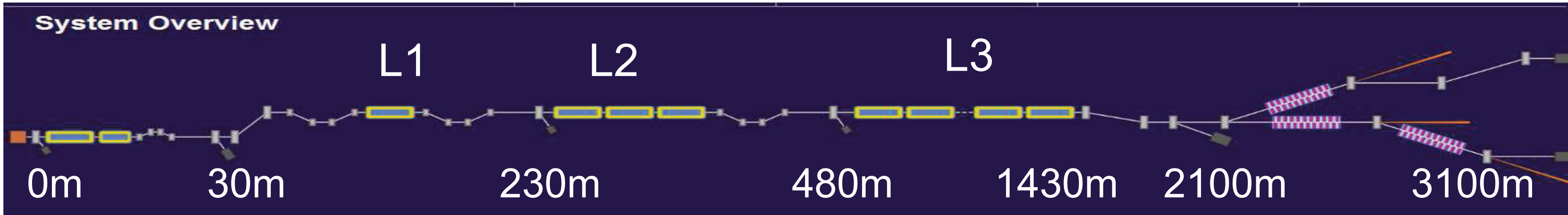
View Along the 1 km Long Superconducting Accelerator



Transfer Lines at the End of the Main Linac Tunnel (XTL)



Beamline Commissioning Progress



13/01*

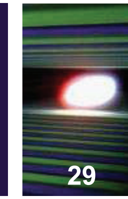
15/01 @ 130 MeV
19/01 @ 600 MeV

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

25/02 @ 2.5 GeV
19/03 @ 6 GeV
08/04 @ 12 GeV

* Beam permission on 13/01

Achieved E-beam parameters



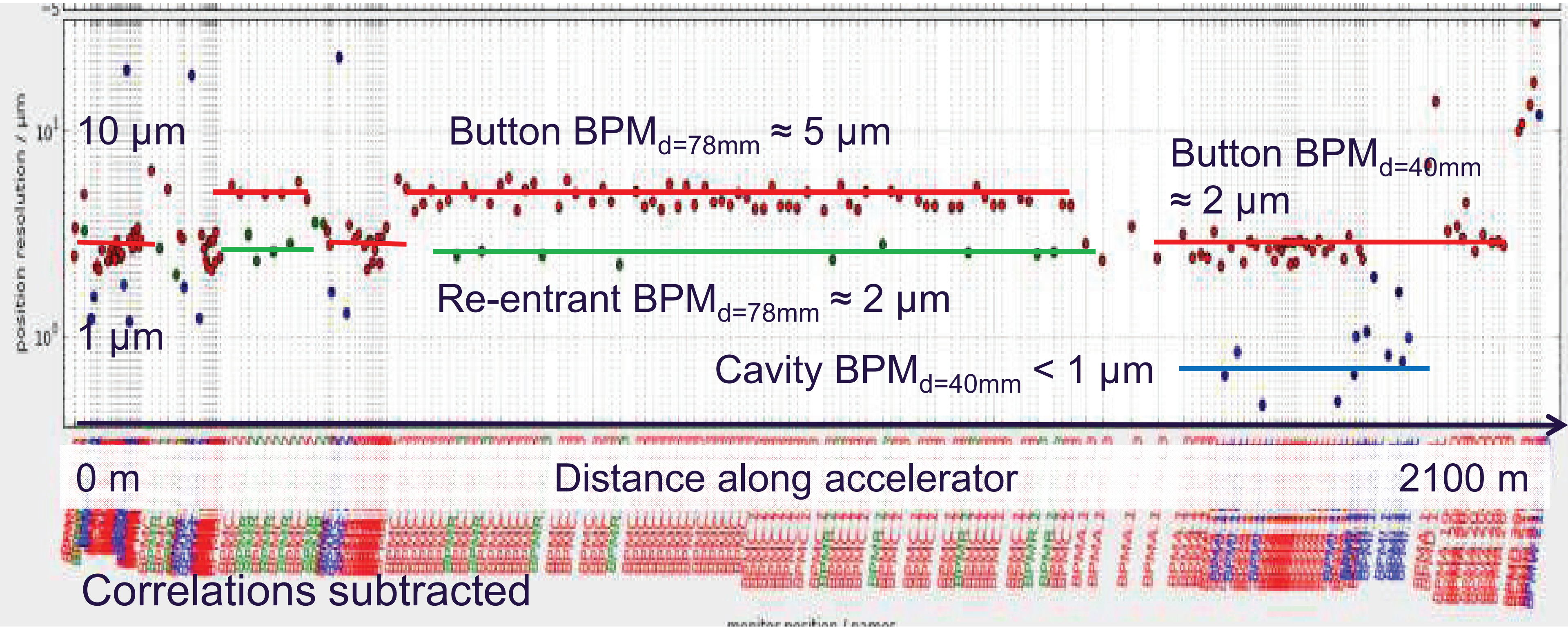
Quantity	Target	Achieved
electron energy	14 GeV	12 GeV[%]
macro pulse repetition rate	10 Hz	**10 Hz**
RF pulse length (flat top)	600 µs	**600 µs**
# bunches / second	600	**300**[$]
bunch charge	0.5 nC	**0.1, 0.5 nC**
electron bunch length after compression (FWHM)	90 fs	**90 fs**
Normalized slice emittance	1 mm mrad	**0.6 mm mrad**[$]
beam power	4.2 kW	1.8 kW

$: in the injector

% Initial commissioning at reduced gradients & 3 more stations ready

$ Machine protection system ‘soft’ limit

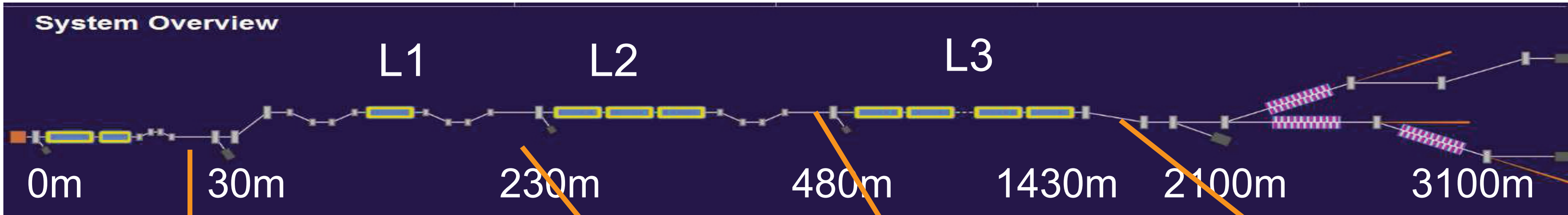
Subsytems: Example BPM Resolution

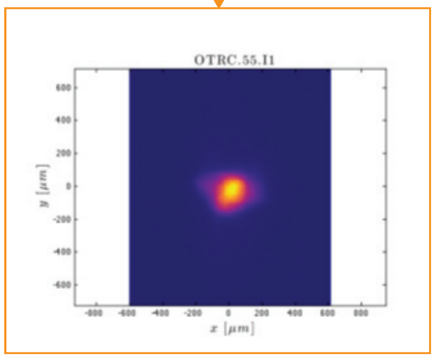


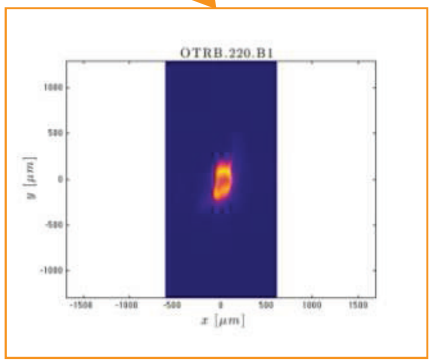
"All systems perform better than specification"

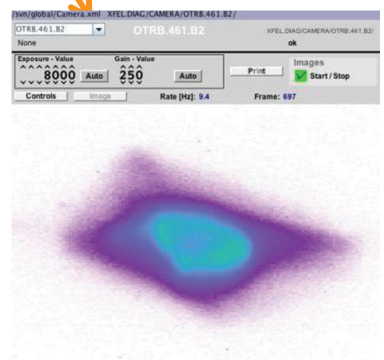
D. Lipka, MOPAB043

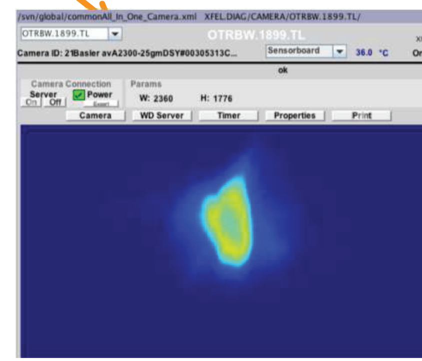
Open Question: Transverse Beam Distribution







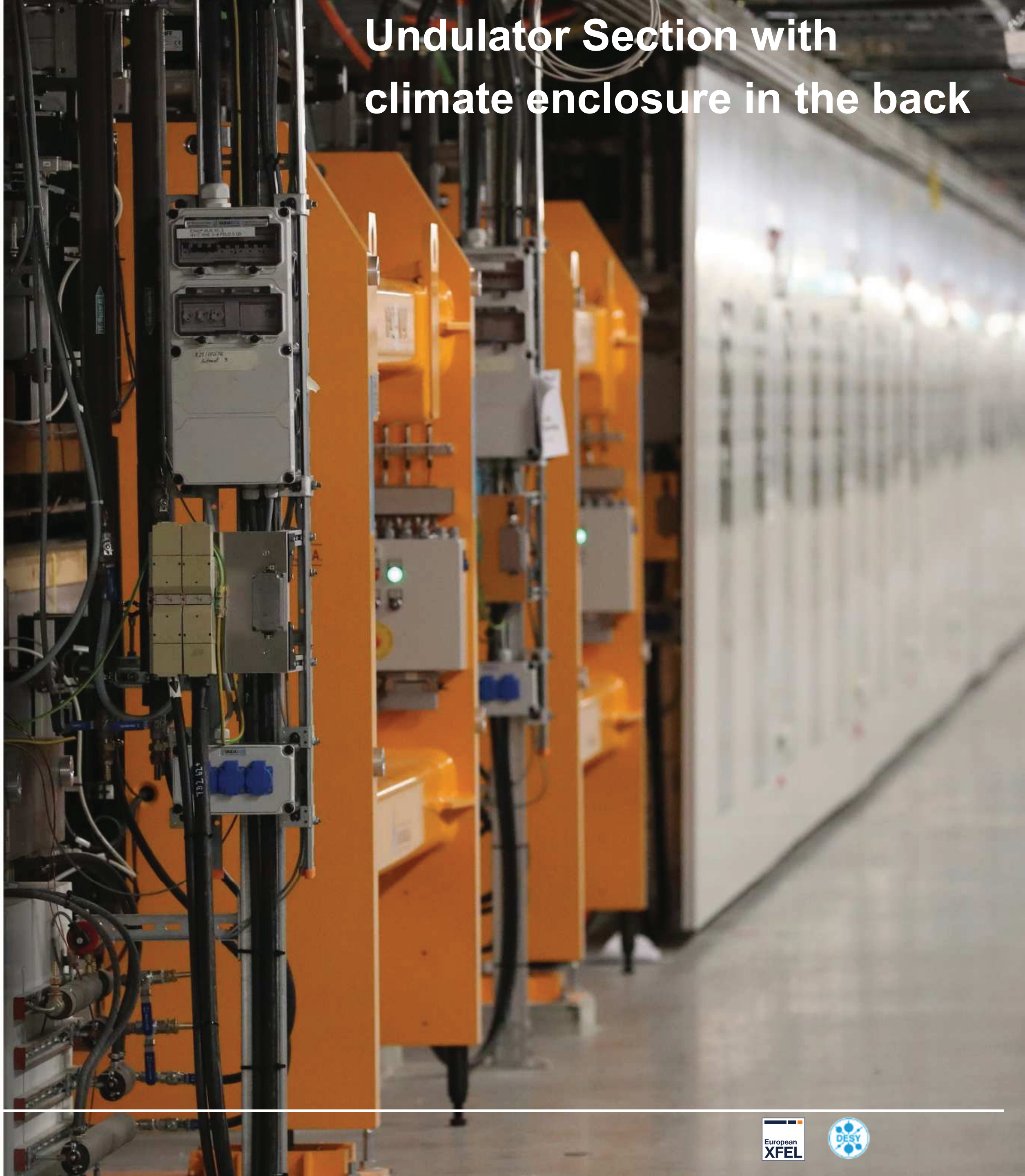




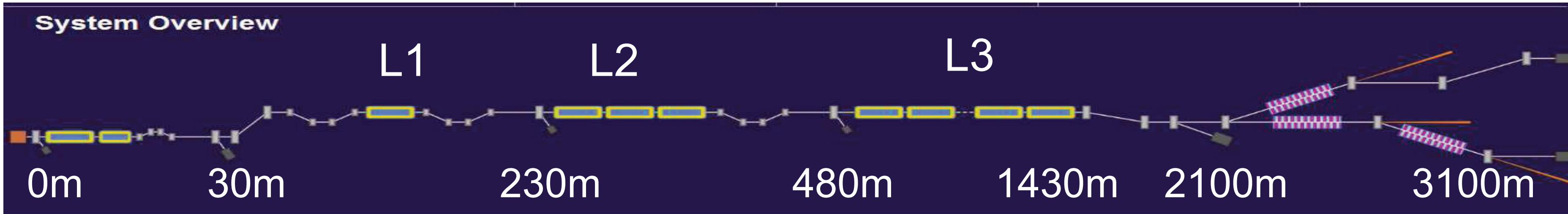
- Images of scintillating screens along the beam line
- Structure is present even after acceleration and compression
- Can be observed in simulations (non-linear space charge effect), but should be more sensitive to phase-advance …

Backside view

Undulator Section with climate enclosure in the back



Beamline Commissioning Progress



13/01*

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

* Beam permission on 13/01

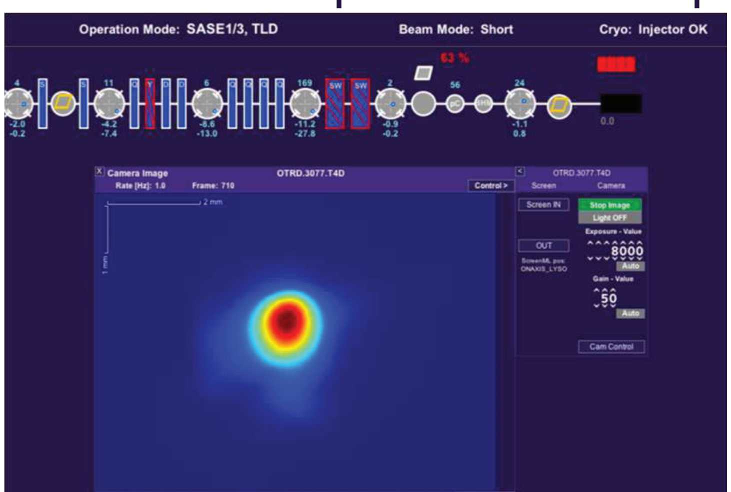
02/02 @ 600 MeV
22/02 @ 2.5 GeV

25/02 @ 2.5 GeV
19/03 @ 6 GeV
08/04 @ 12 GeV

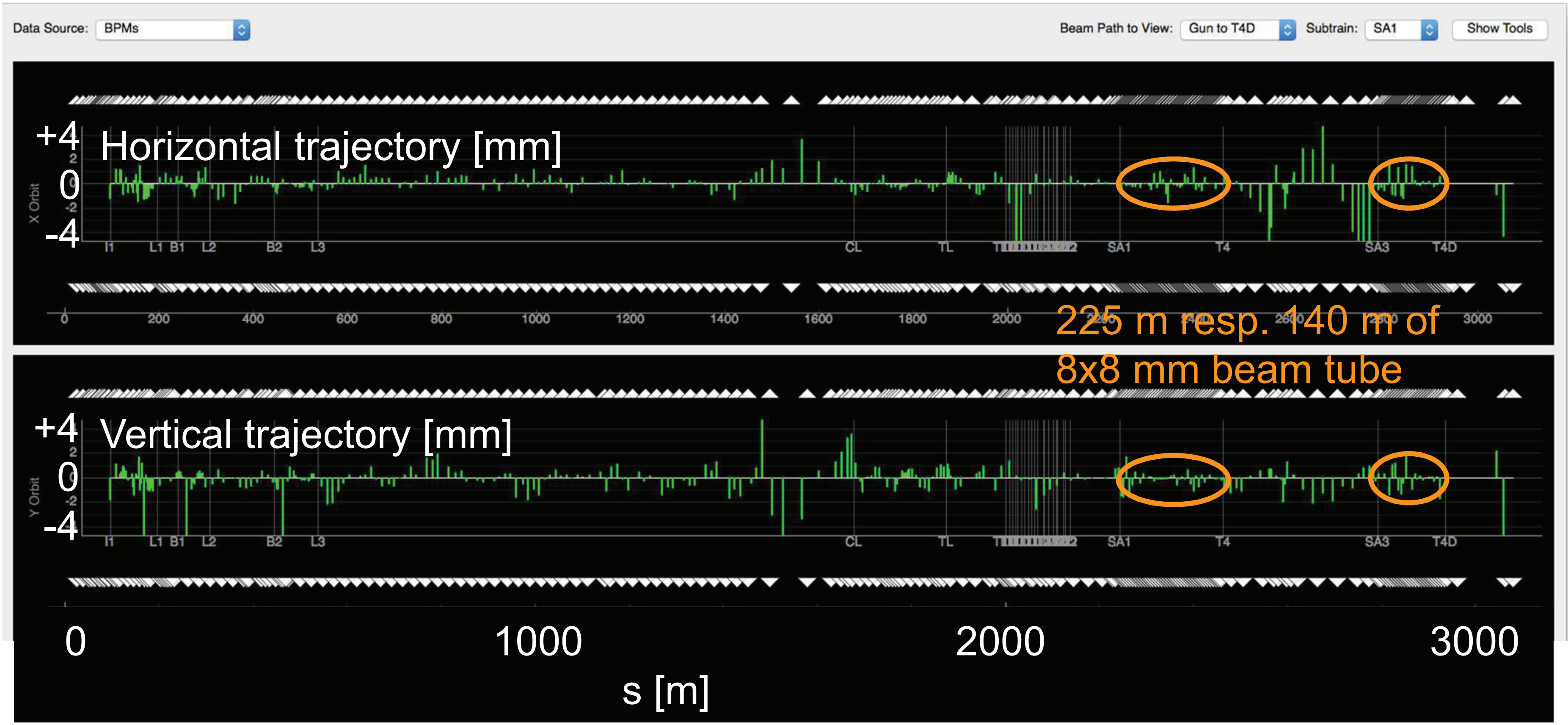
27/04*

* Beam permission on 26/04

27/04 Beam spot before dump

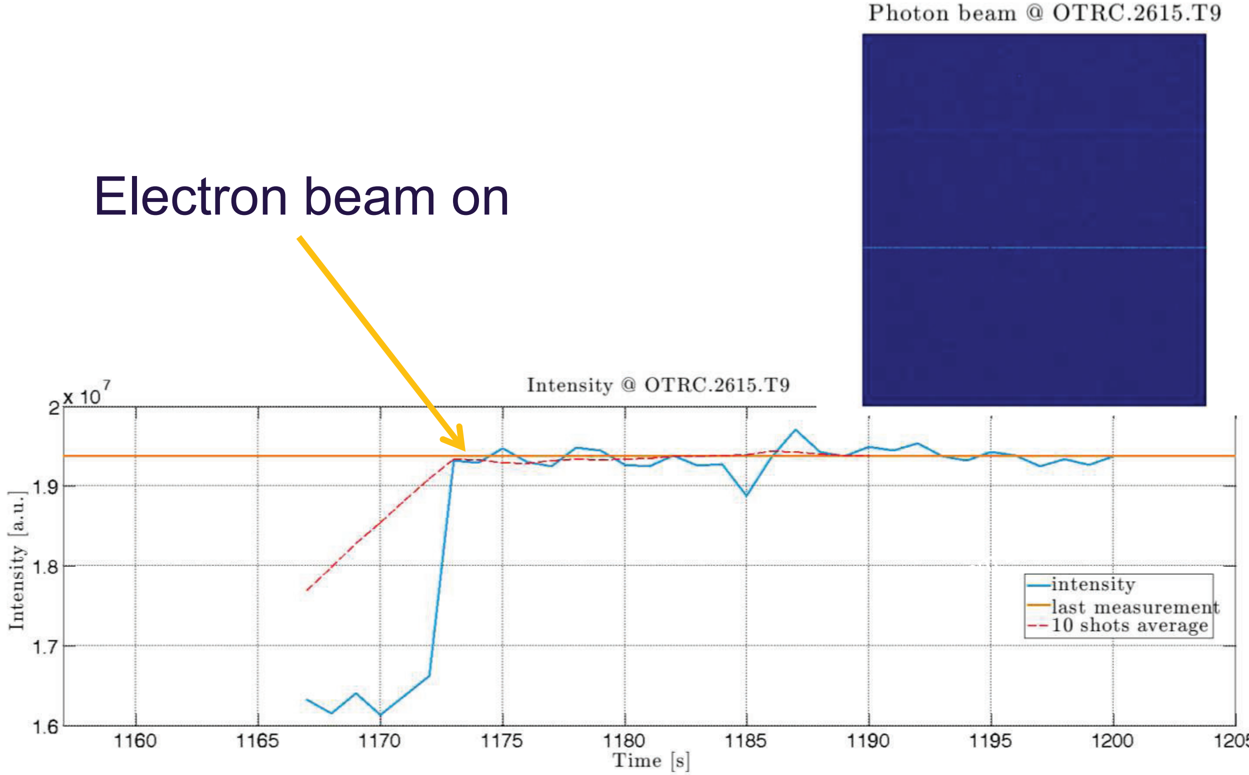


Undulators passed with no steering



‘First lasing possible’ 29.04.2017

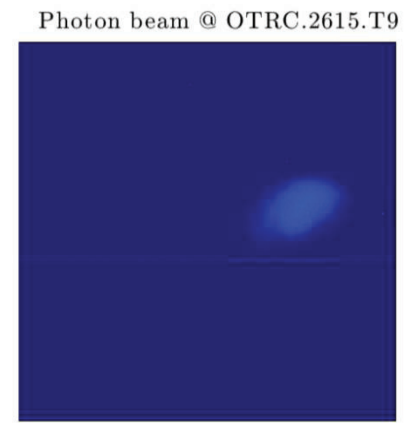
- Closed all (35) SASE undulators to 11 mm gap (K=3.5)
- Observed spontaneous radiation on scintillator screen about 170 m downstream of undulator
- Radiation fills complete screen and is visible as increase of intensity only



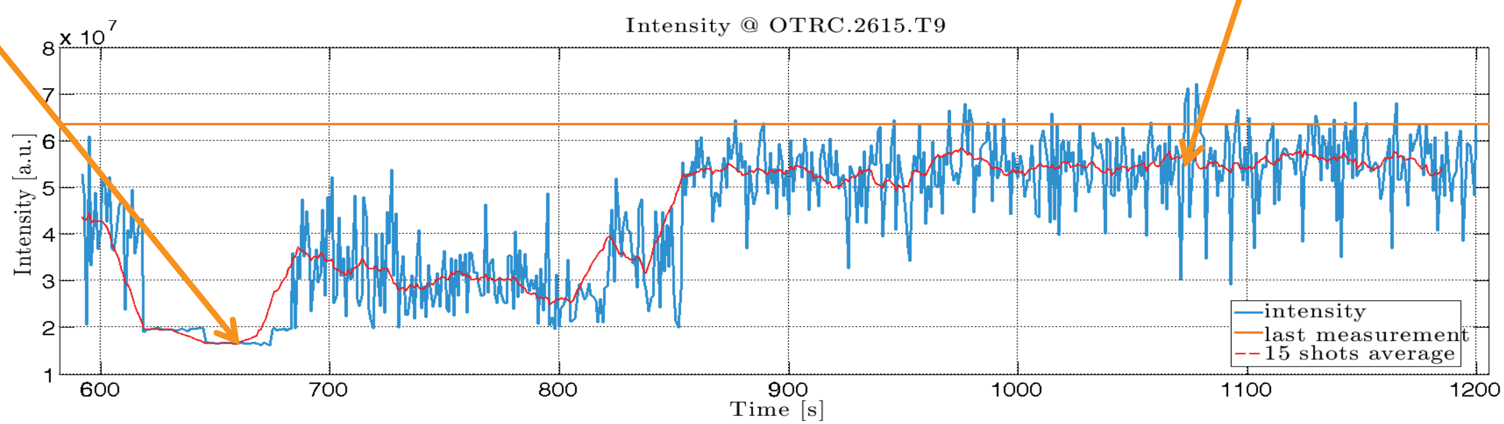
First signal from FEL radiation 02.05.17-03.05.17

- low energy 6.4 GeV working point for beam based alignment
- no undulator beam based alignment yet, no laser heater

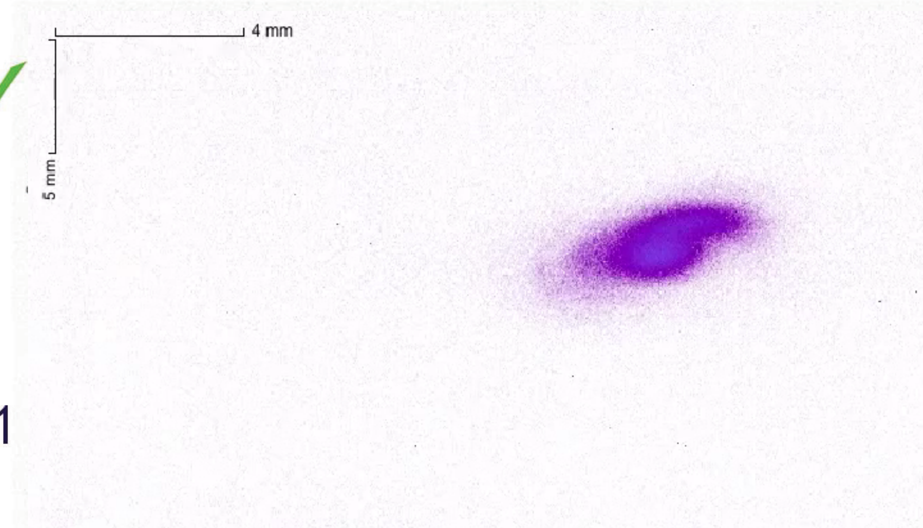
some tweaking of compression and trajectory



E = 6.4 GeV
K = 3.5
1.3 keV



Commissioning Timeline



12/16 Cooldown ✓

01/17 Injector at 130 MeV ✓

01/17 L1 commissioning ✓

02/17 L2 commissioning ✓

02-04/17 L3 commissioning ✓

04/17 Beam through SASE1 undulator sections ✓

End 04/17 Milestone "First Lasing Possible" ✓

2-3/5/17 FEL radiation observed

05-08/17 Commission SASE1 photon beamline and experiment
Consolidate FEL operation at 8-10 keV photon energy

09/17 First user experiments (total 800 hours)

2018 Continue facility commissioning + 2000 user hours

2019 Routine operation with 6 experiments + 4000 user hours


General Assembly of the European
XFEL Accelerator Consortium
04.05.2017
THANK YOU TO ALL CONTRIBUTORS TO THE
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