The European XFEL

Presented at the

CERN Accelerator School (CAS)

Free Electron Lasers and Energy Recovery Linacs

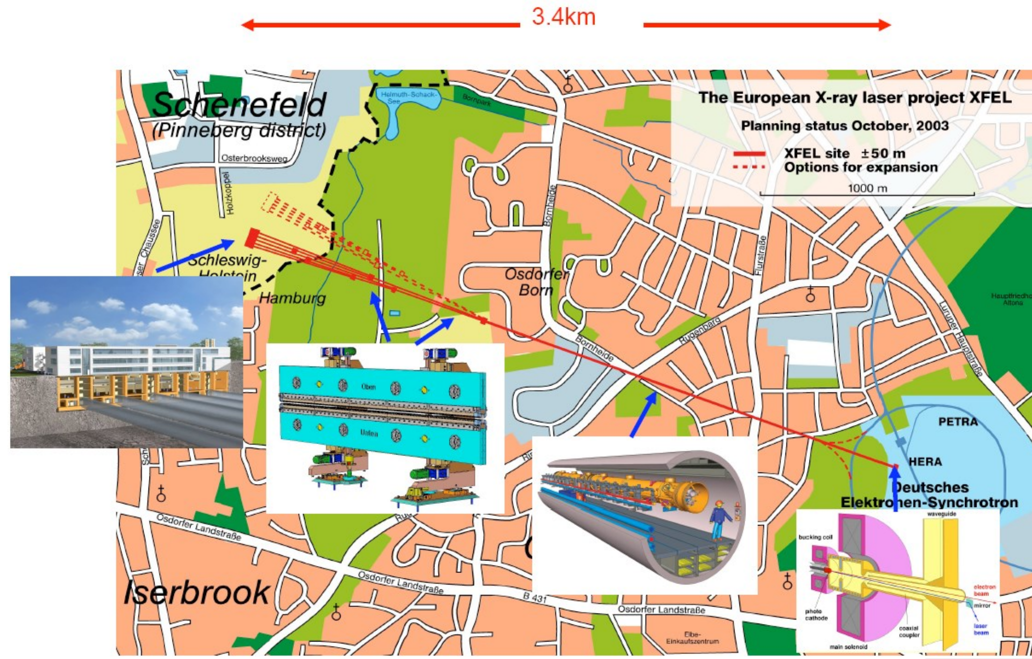
June 7th , 2016

Hans Weise

with many pictures from Dirk Noelle

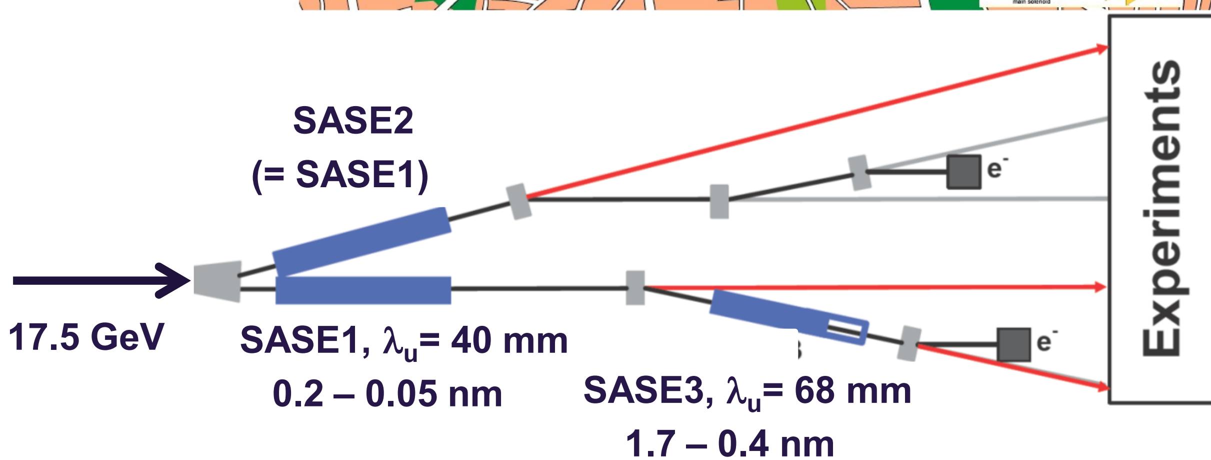
Superconducting Cavities

The European XFEL
Built by Research Institutes from 12 European Nations



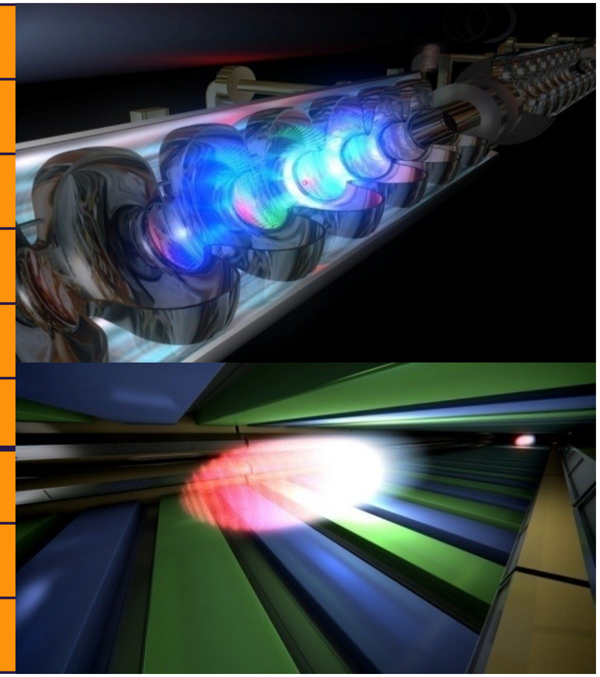
Some specifications

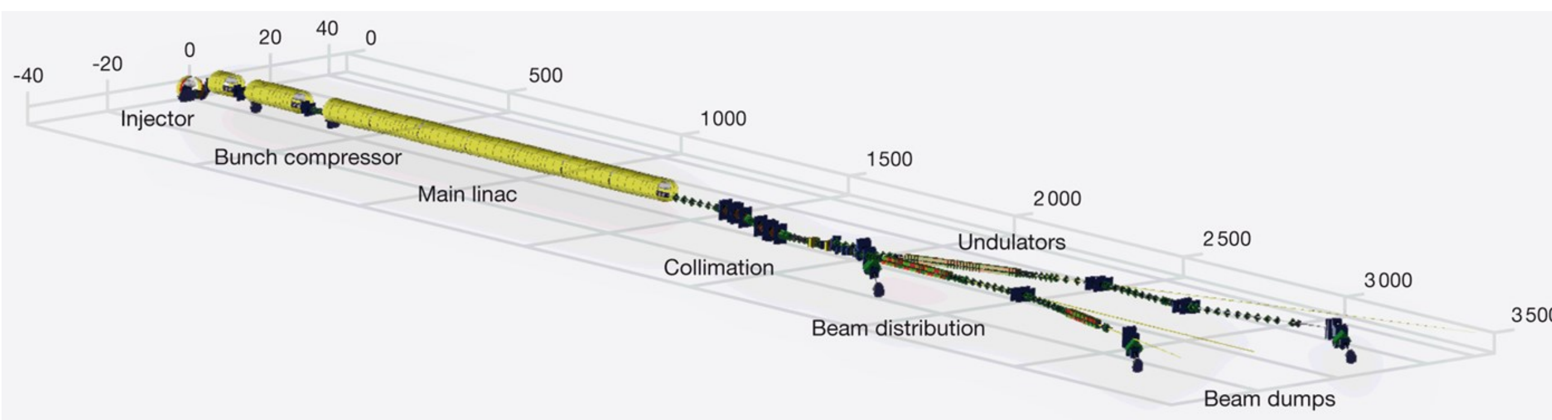
- Photon energy 0.3 - 24 keV
- Pulse duration ~ 10 - 100 fs
- Pulse energy few mJ
- Superconducting linac 17.5 GeV
- 10 Hz (27 000 b/s)
- 5 beam lines / 10 instruments
  - Start version with 3 beam lines and 6 instruments
- Several extensions possible:
  - More undulators
  - More instruments
  - …….
  - Variable polarization
  - Self-Seeding
  - CW operation



Accelerator Complex with Challenging Parameter Set

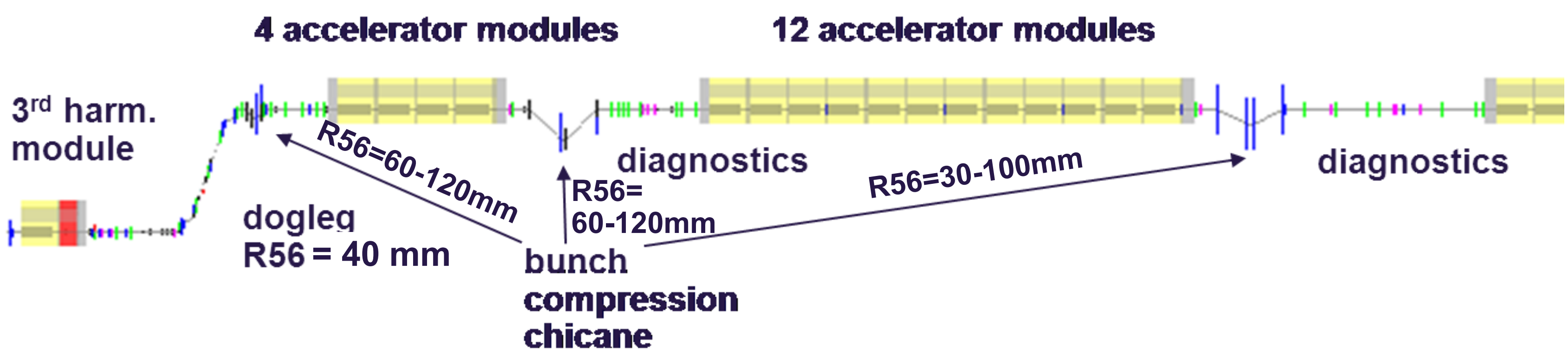
Electron beam energy	17.5 GeV
Bunch charge	**0.02 - 1 nC**
Peak current	2 - 5 kA
Slice emittance	**0.4 - 1.0 mm mrad**
Slice energy spread	4 - 2 MeV
Shortest SASE wavelength	**0.05 nm**
Pulse repetition rate	10 Hz
Bunches per pulse	2700
Pulse length	600 μs





3 Stage Bunch Compression

3 stage bunch compression: flexible and less sensitive to noise from RF system



σ_σ = 2 mm
I_{peak} = 50 A
σ_E = 0 %
E = 130 MeV

→

σ_σ = 1 mm
I_{peak} = 100 A
σ_E = 1.5 %
E = 130 MeV

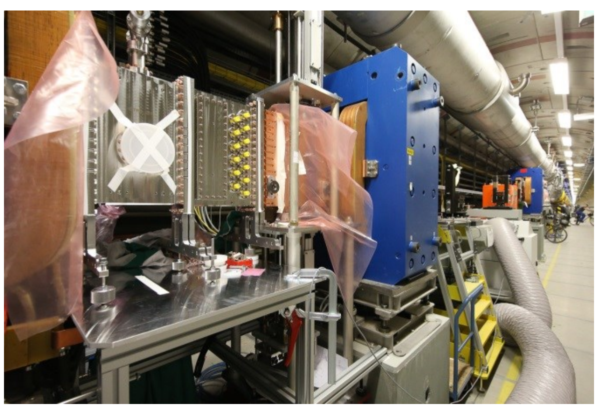
→

σ_σ = 0.1 mm
I_{peak} = 1 kA
σ_E = 1 %
E = 600 MeV

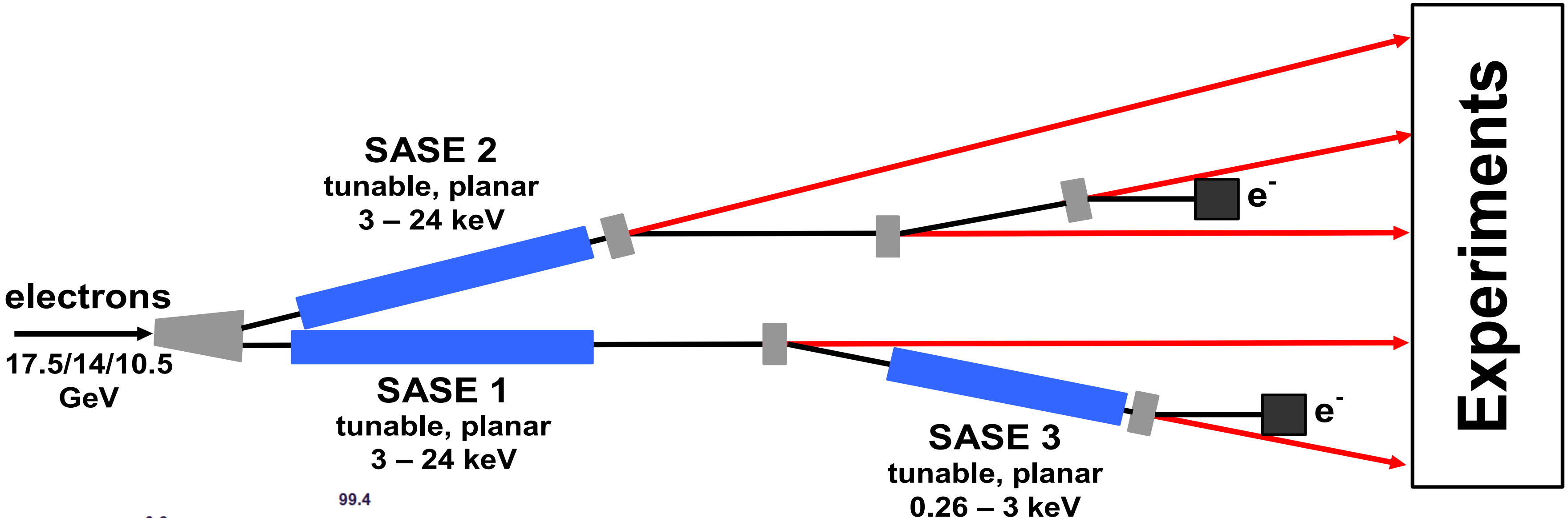
→

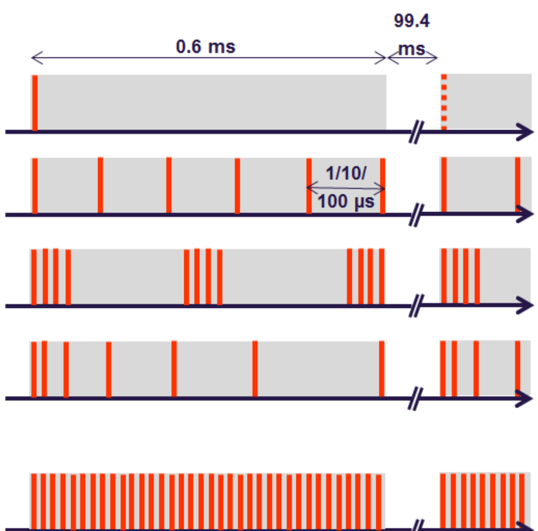
σ_σ = 0.02 mm
I_{peak} = 5 kA
σ_E = 0.3 %
E = 2400 MeV

→

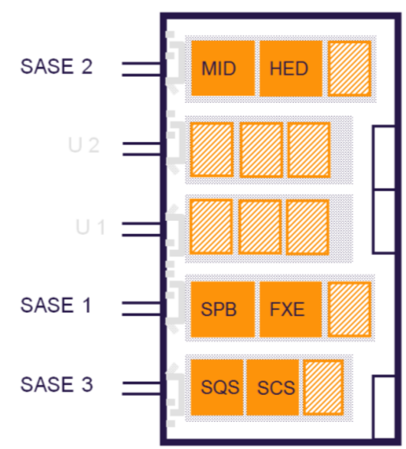


X-ray Beamlines for Different Wavelengths with Different Time Structures



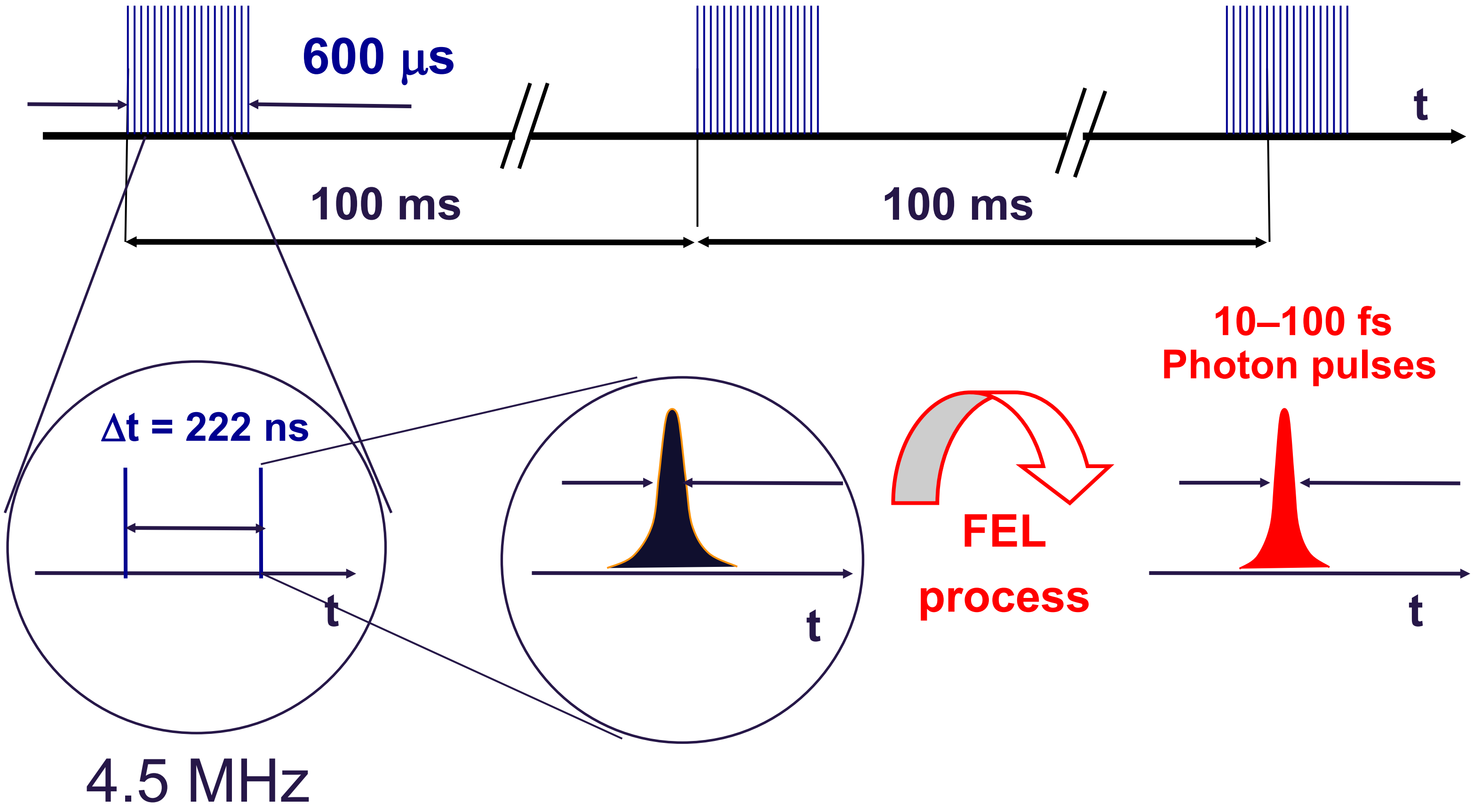


- 2 hard x-ray undulators and beam transport with 4 instruments
- 1 soft x-ray undulators and beam transport with 2 instruments

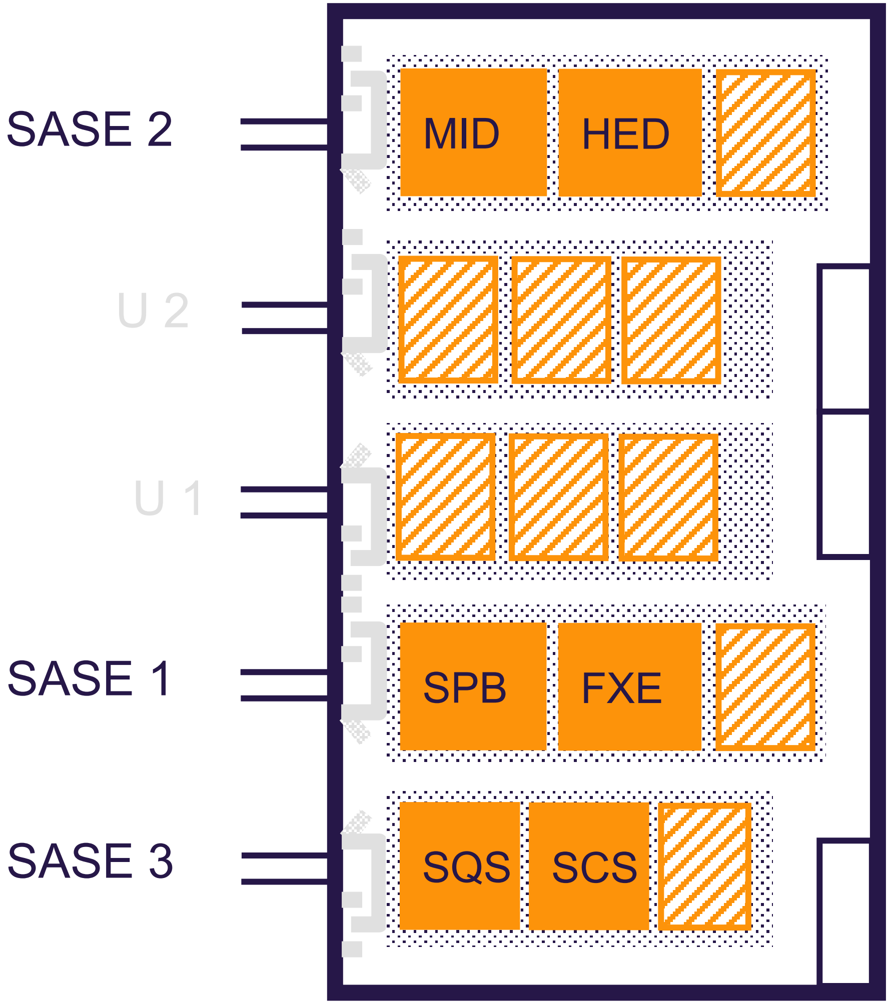


Time Structure of the European XFEL

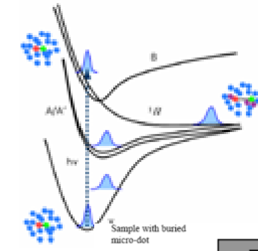
Electron bunch trains at 10 Hz repetition rate (with up to 2700 bunches per train, 0.1–1 nC)



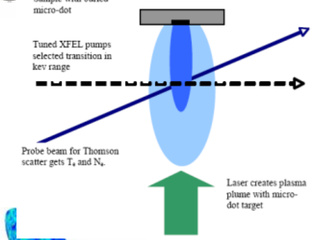
The Suite of Instruments



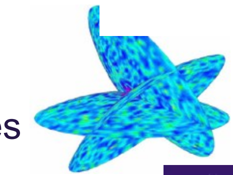
FXE Femtosecond X-ray Experiments



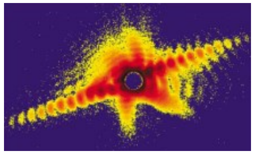
HED High Energy Density Science



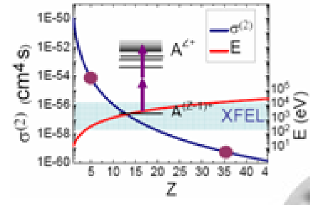
SPB Single Particle & Biomolecules



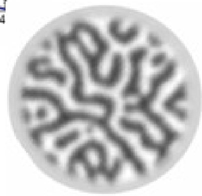
MID Materials Imaging & Dynamics



SQS Small Quantum Systems

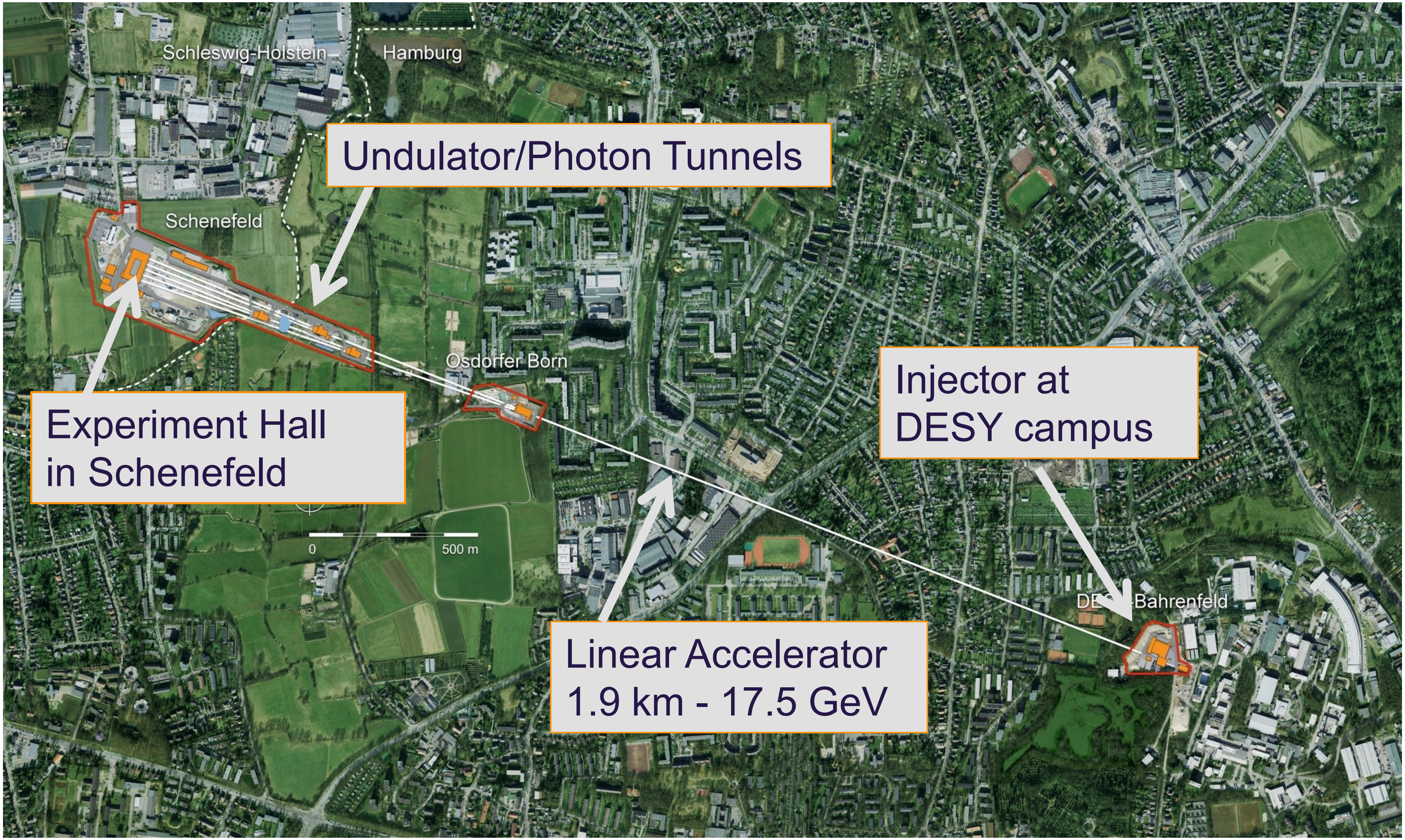


SCS Spectroscopy & Coherent Scattering



More about experiments: http://www.xfel.eu

European XFEL Layout



Organization of the European XFEL Project

In-kind Contributions

Accelerator Consortium

Institutes from D, F, I, CH, PL, ES, RU, CN, SE…

Coordinator: DESY

Other In-kind Contributors

European XFEL GmbH

Council

Management Board

Managing Directors

M. Altarelli, Chair

C. Burger, Admin. Director

Scientific Directors

S. Molodtsov

A. Schwarz

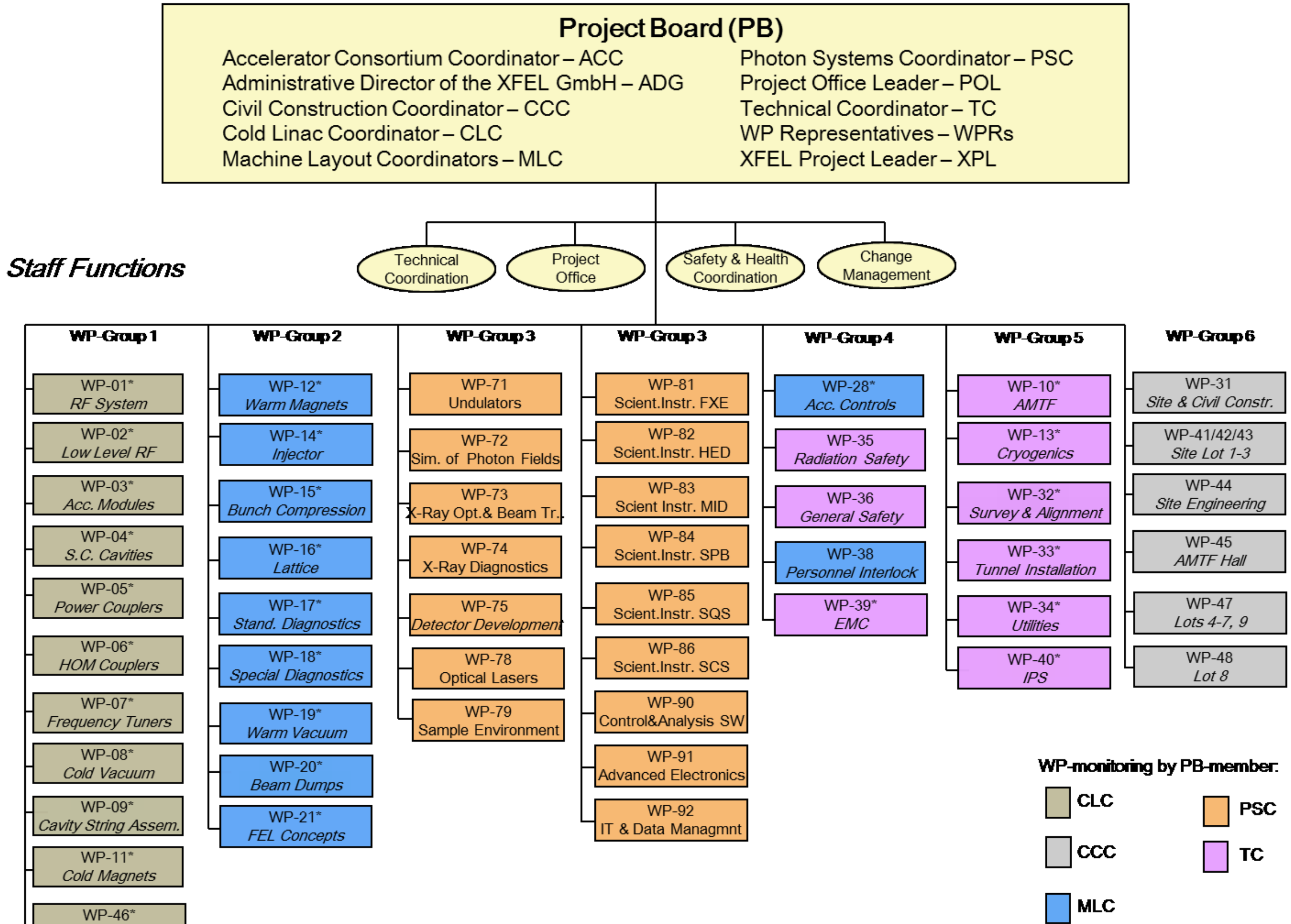
T. Tschentscher

Advisory Committees

- SAC
- MAC
- AFC
- IKRC +
- *Det. AC*
- *Lasers AC*

European XFEL

Organigram of the XFEL Construction Project



* Work Packages, which are covered by the Accelerator Construction Consortium

Figures and Facts

- 1.22 billion euro (price level 2005)
- Approx. 50% in-kind

  http://www.xfel.eu/project/in_kind_contributions/
- 11 countries
- XFEL company founded in 9/2009

- Construction time 2009 to 2016

- First electron beam / start injector operation in 12/2015
- Technical commissioning starts in 2016
- User operation with first beamline and two experiments starts in 2017

Milestones

starting 1992	TESLA R&D aiming for large scale SRF electron beam accelerators TESLA Test Facility (TTF) located at DESY
2/2000	first lasing at TTF (today FLASH)
10/2002	XFEL TDR as supplement to TESLA TDR
2/2003	Fundamental decision of the German Federal Ministry of Education and Research: *The X-ray laser laboratory is to be realized as a European project at DESY, and Germany will bear approximately half of the costs because of the advantage of location.*
2003	TESLA Test Facility (TTF) is extended to a total length of 260 m and modified into the new VUV-FEL (later renamed FLASH).
2/2004	An international steering committee is established to concretize the participation of European countries in the project.
9/2004	MoU signed by first countries; and a state treaty provides a legal basis for the construction and operation of the X-ray laser

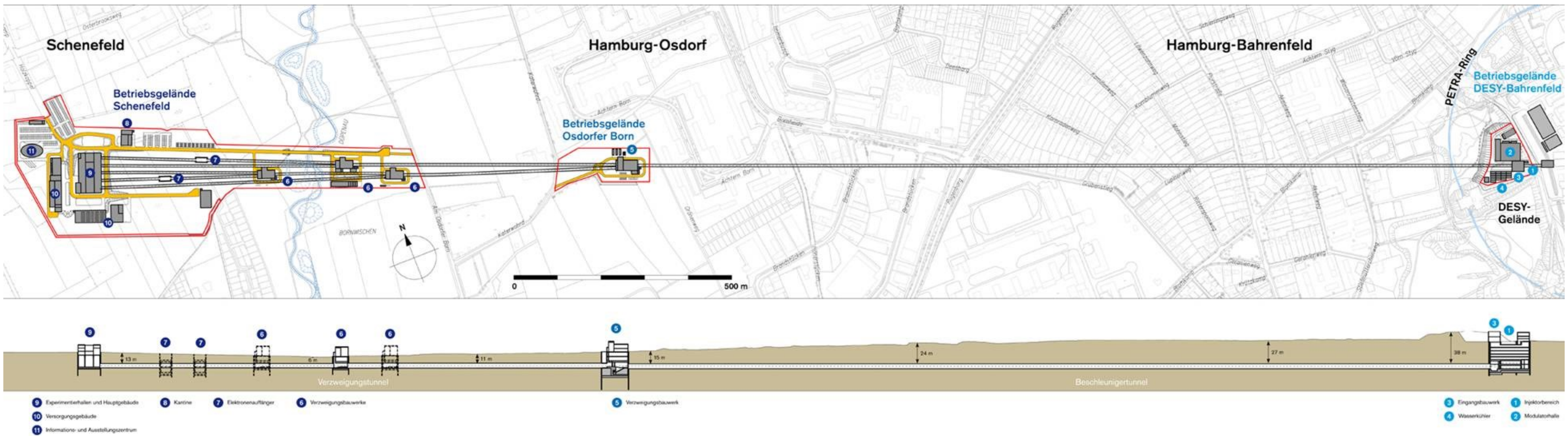
- **for further details see http://www.xfel.eu/overview/milestones/**

Milestones

1/2005	The free-electron laser VUV-FEL (today known as FLASH) generates high-intensity, ultrashort laser pulses with a wavelength of 32 nm for the first time • shortest wavelength ever produced at a free-electron laser • properties of the radiation perfectly match the theoretical predictions
4/2005	Application for the XFEL public planning approval procedure
7/2006	approval resolution (”Planfeststellungsbeschluss”) for the construction and operation of the European XFEL
6/2007	The German Federal Minister of Education and Research Dr. Annette Schavan officially launches the European XFEL
1/2009	Start of construction
11/2009	Signing ceremony of the international convention in Hamburg. Five shareholders from the non-German partner countries join the European XFEL company (founded 9/2009)
2017	Start of user operation with first beamline and first 2 experiments

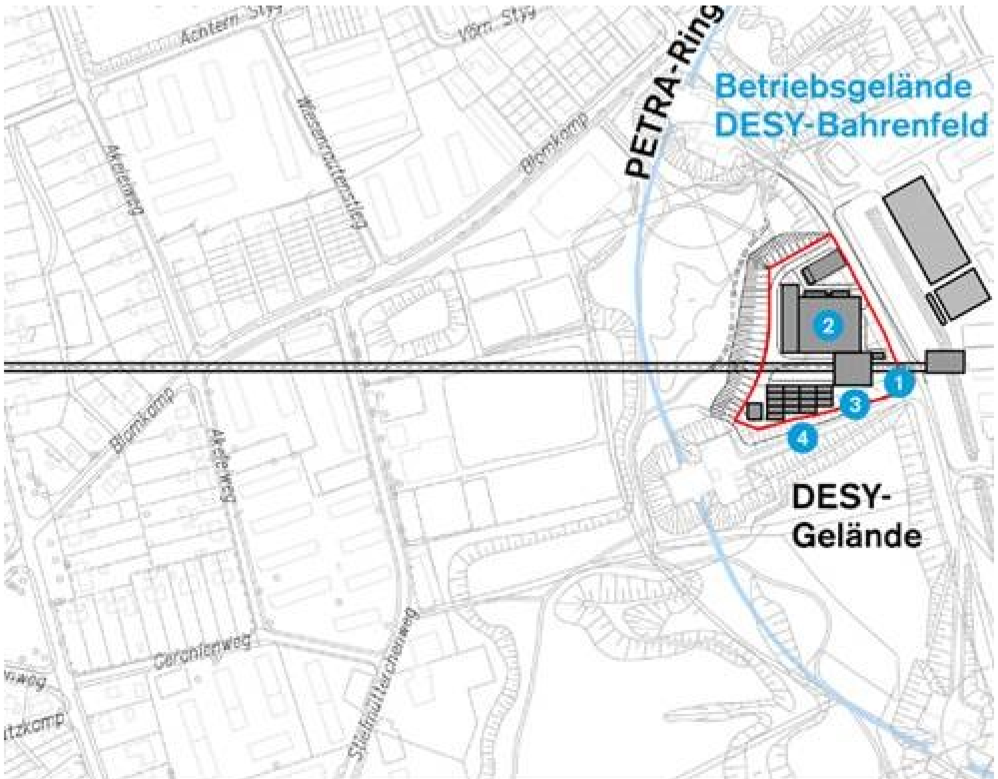
XFEL Facility Largely Underground

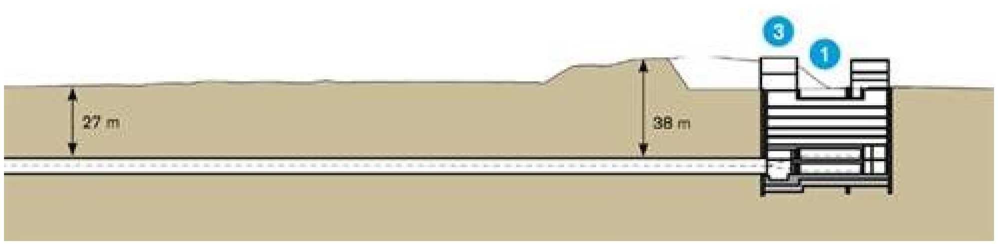
Schenefeld Osdorfer Born Bahrenfeld

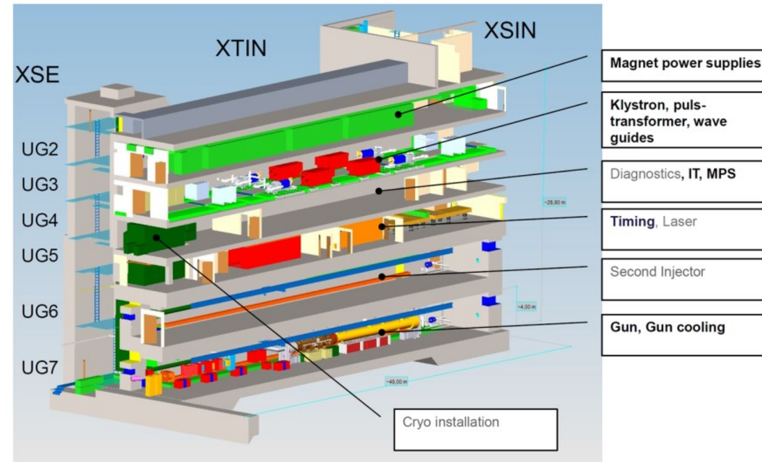


- Three construction sites
- 5.8 km tunnels (approx. 6 to 38 m below surface)
- 12,000 m² surface buildings
- 150,000 m³ of underground building volume

DESY Bahrenfeld – Injector Complex

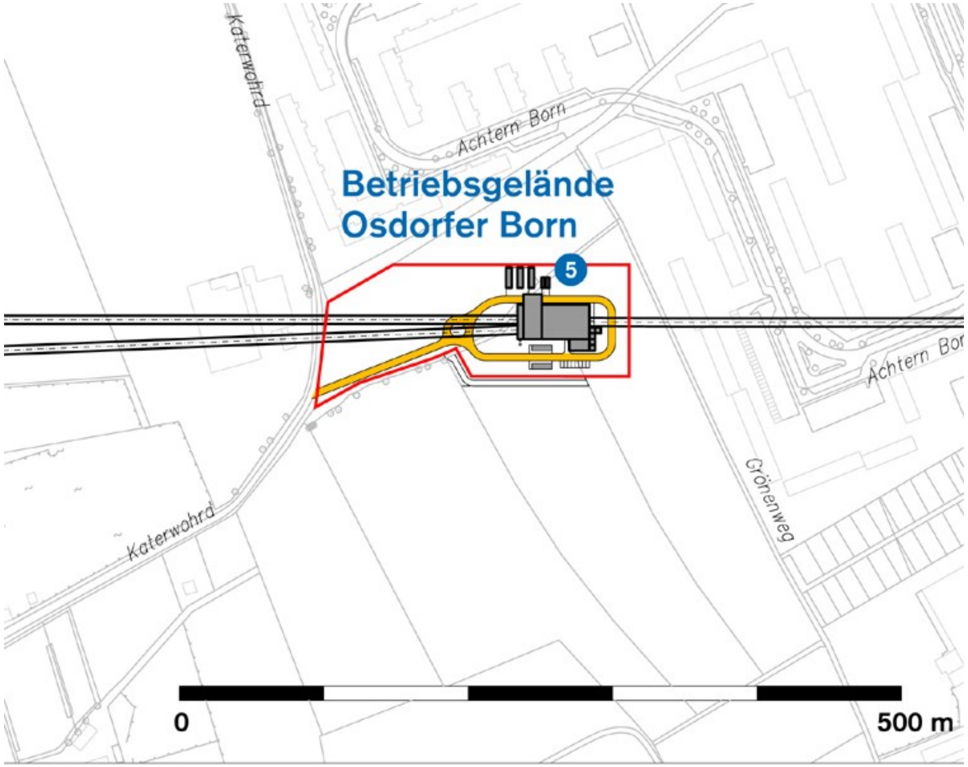


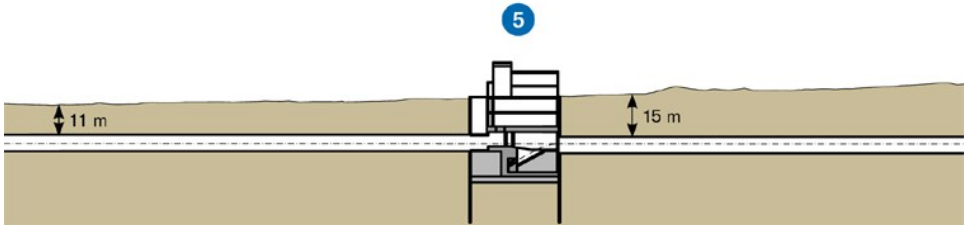




Two injector tunnels and main transport shaft

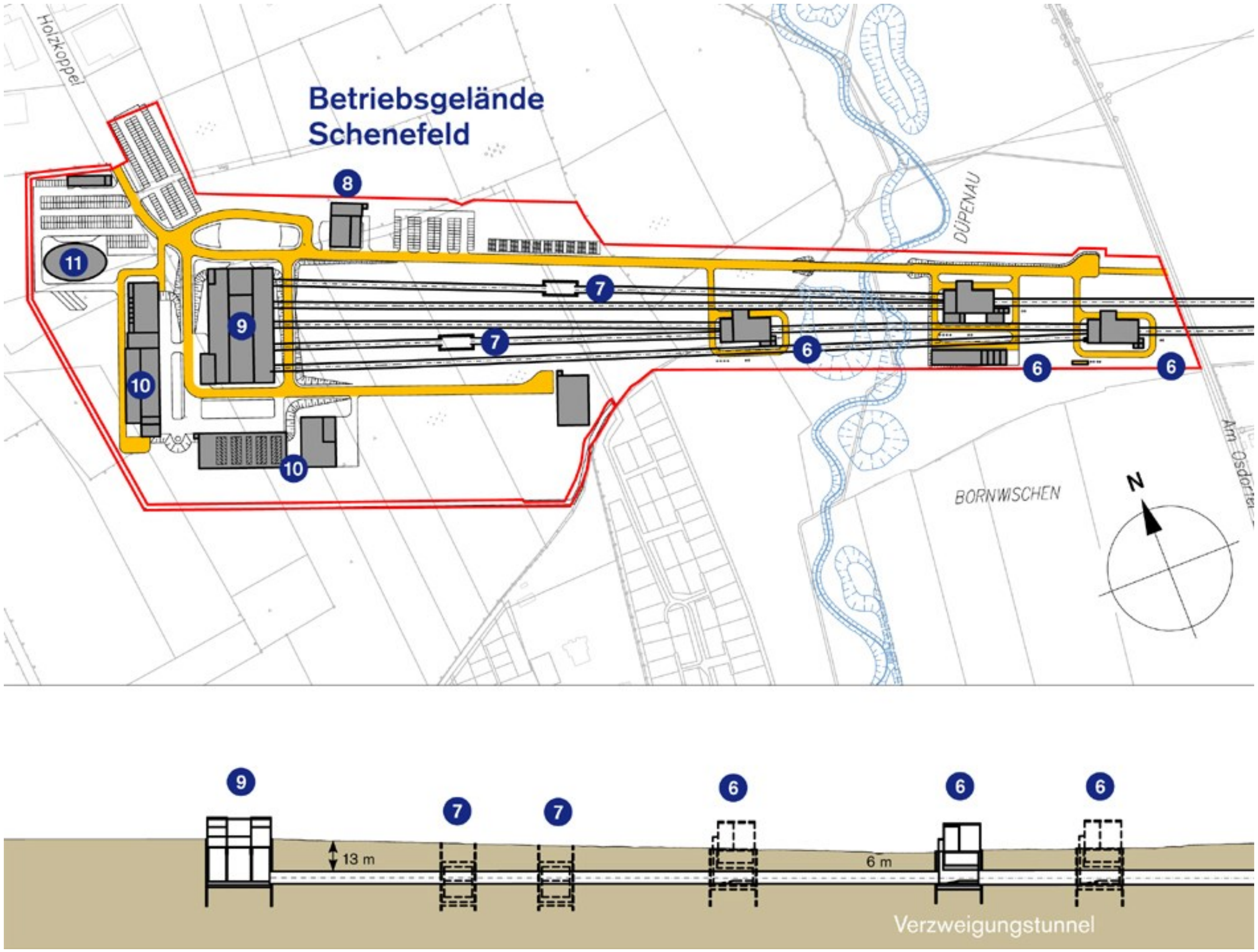
Osdorfer Born Site





Distribution shaft from linac tunnel to undulator tunnels

Schenefeld Site



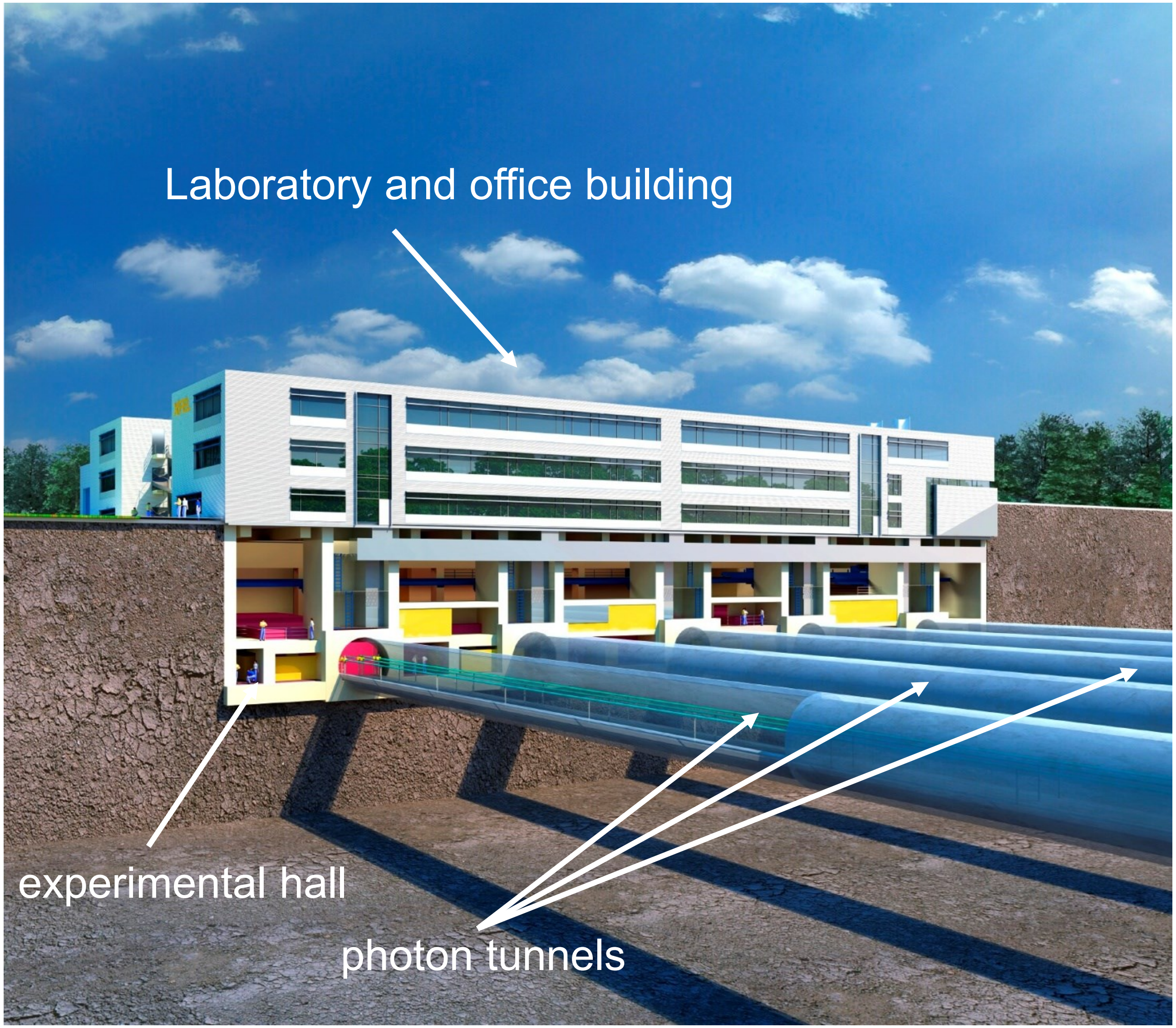
Distribution Shafts

Power, Water, Cooling Supplies

Experimental Hall

Office Building

Schenefeld Site – Experiment Complex

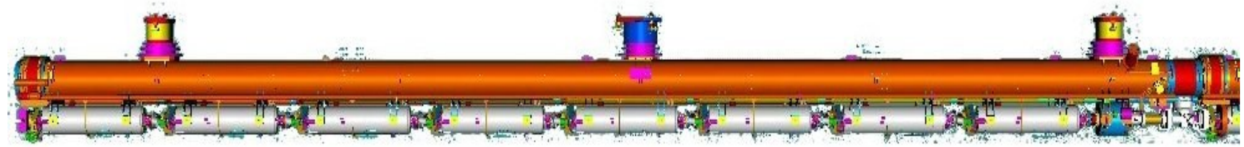


Schenefeld Site

Inauguration of main building 6/2016
Laboratories and offices

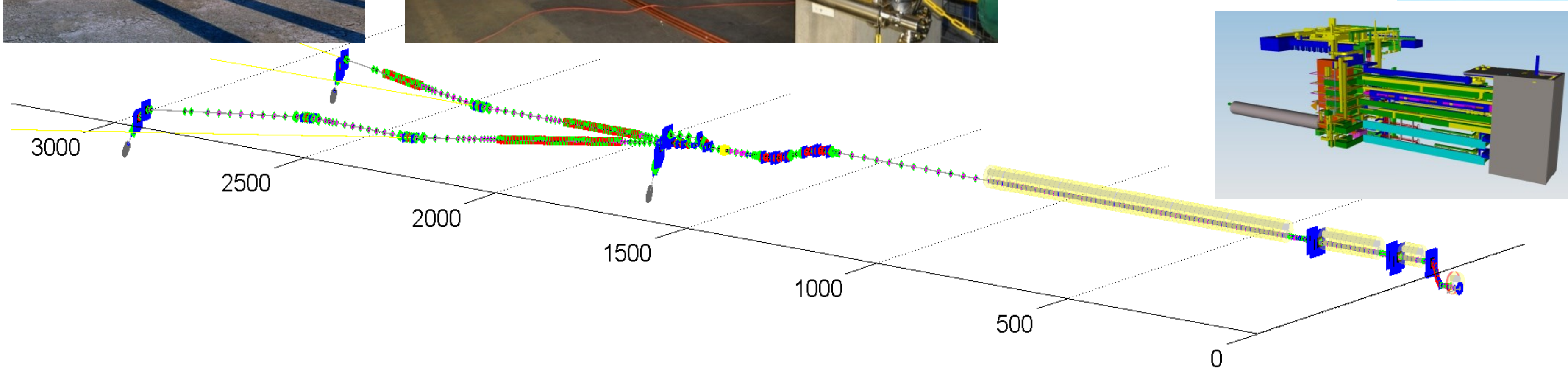
An Accelerator Complex for 17.5 GeV

100 accelerator modules



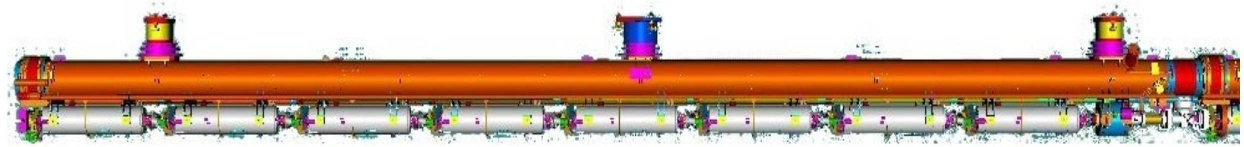
800 accelerating cavities
1.3 GHz / 23.6 MV/m

25 RF stations
5.2 MW each



Contributors to the XFEL Accelerator

100 accelerator modules



800 accelerating cavities

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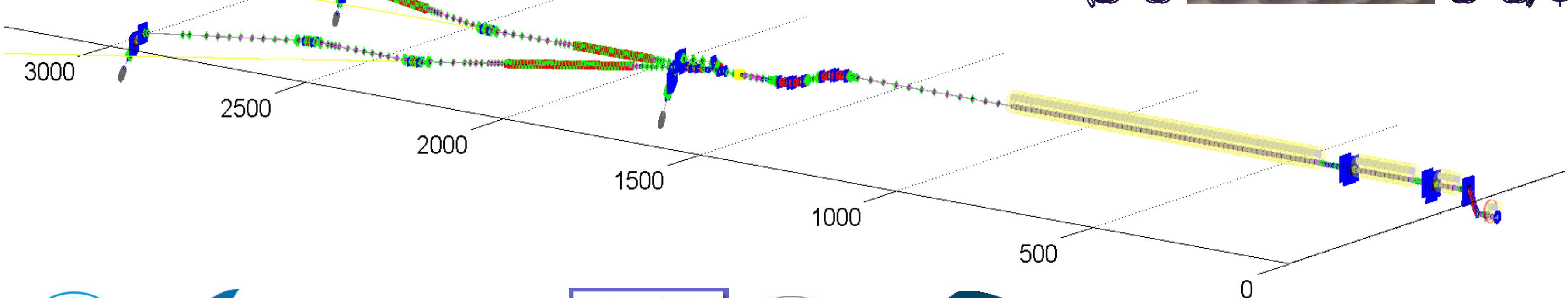
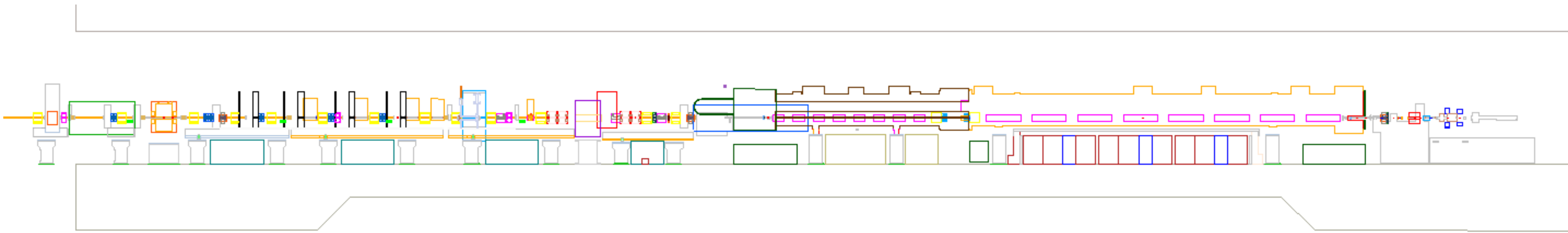
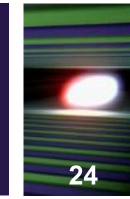


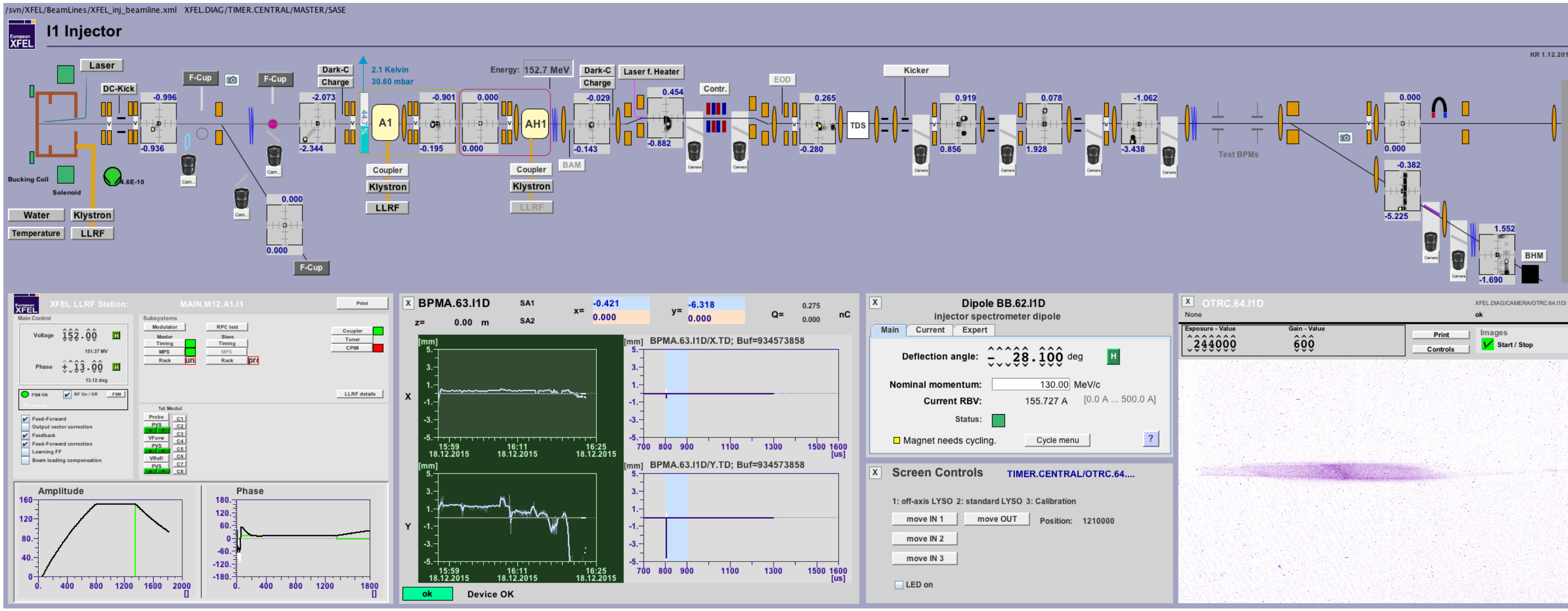
Injector in Operation – First Beam in 12/2015



Dump Spectrometer Diagnostic Section Transverse Deflecting Structure Laser Heater 3.9 GHz Module 1.3 GHz Module **Gun**



18.12.2015 - First Beam into the Injector Dump



The first injector beam represented only …

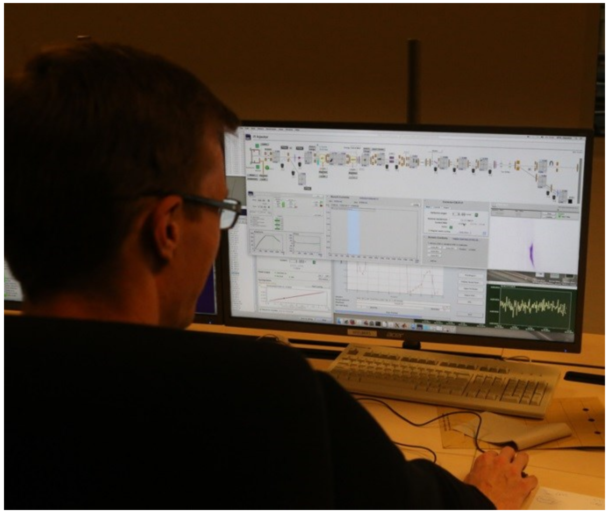
≈ 1% of the total accelerator length

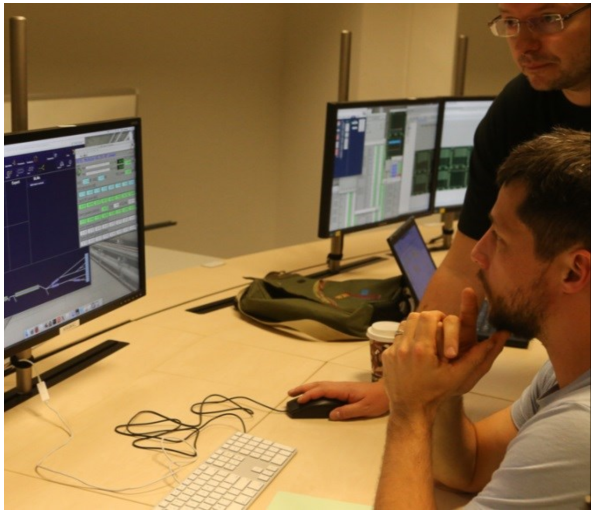
≈ 1% of the final energy

≈ 1% of the electrons/second

… but all accelerator sub-systems were needed and functional.

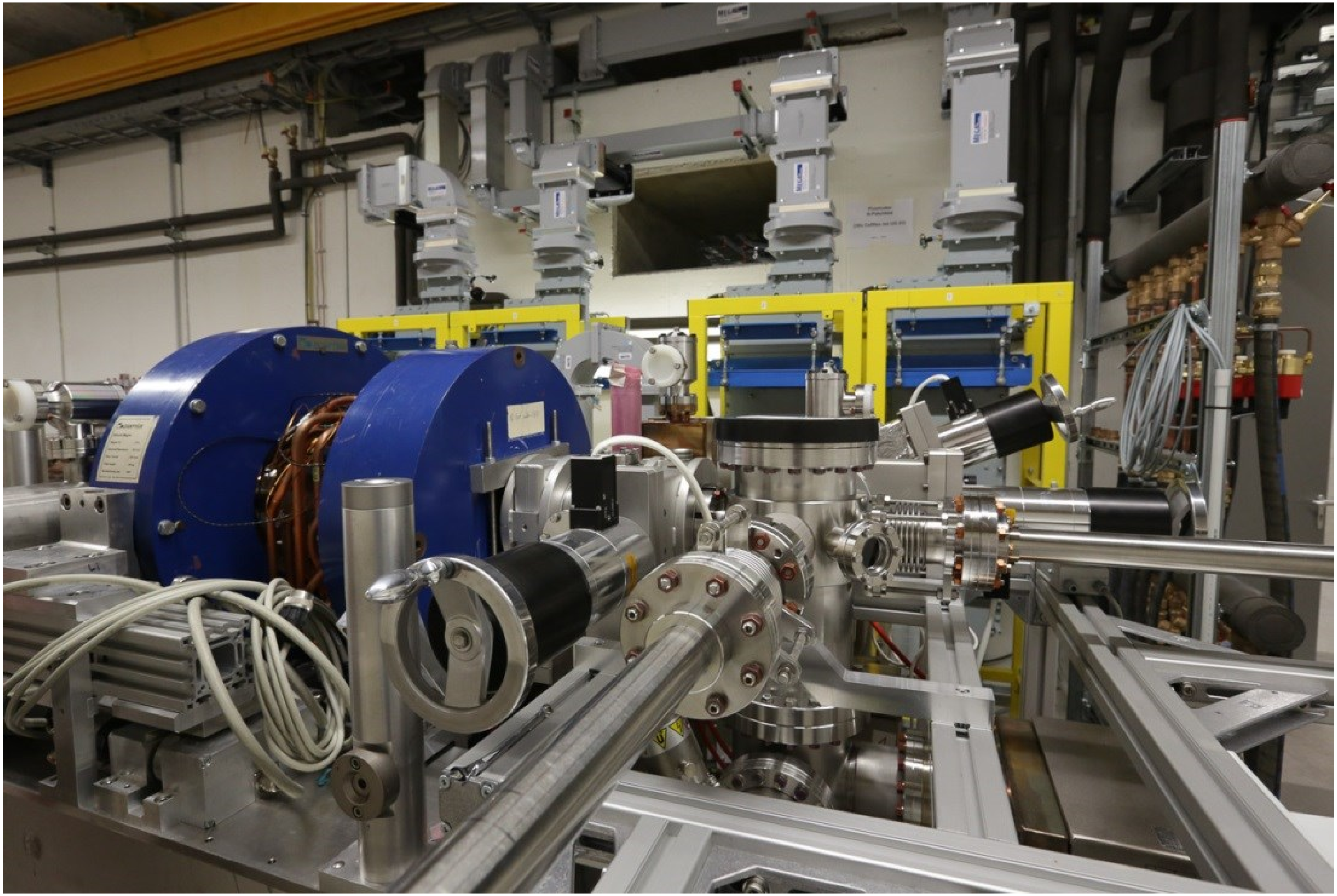
Before and after Getting the First Injector Beam



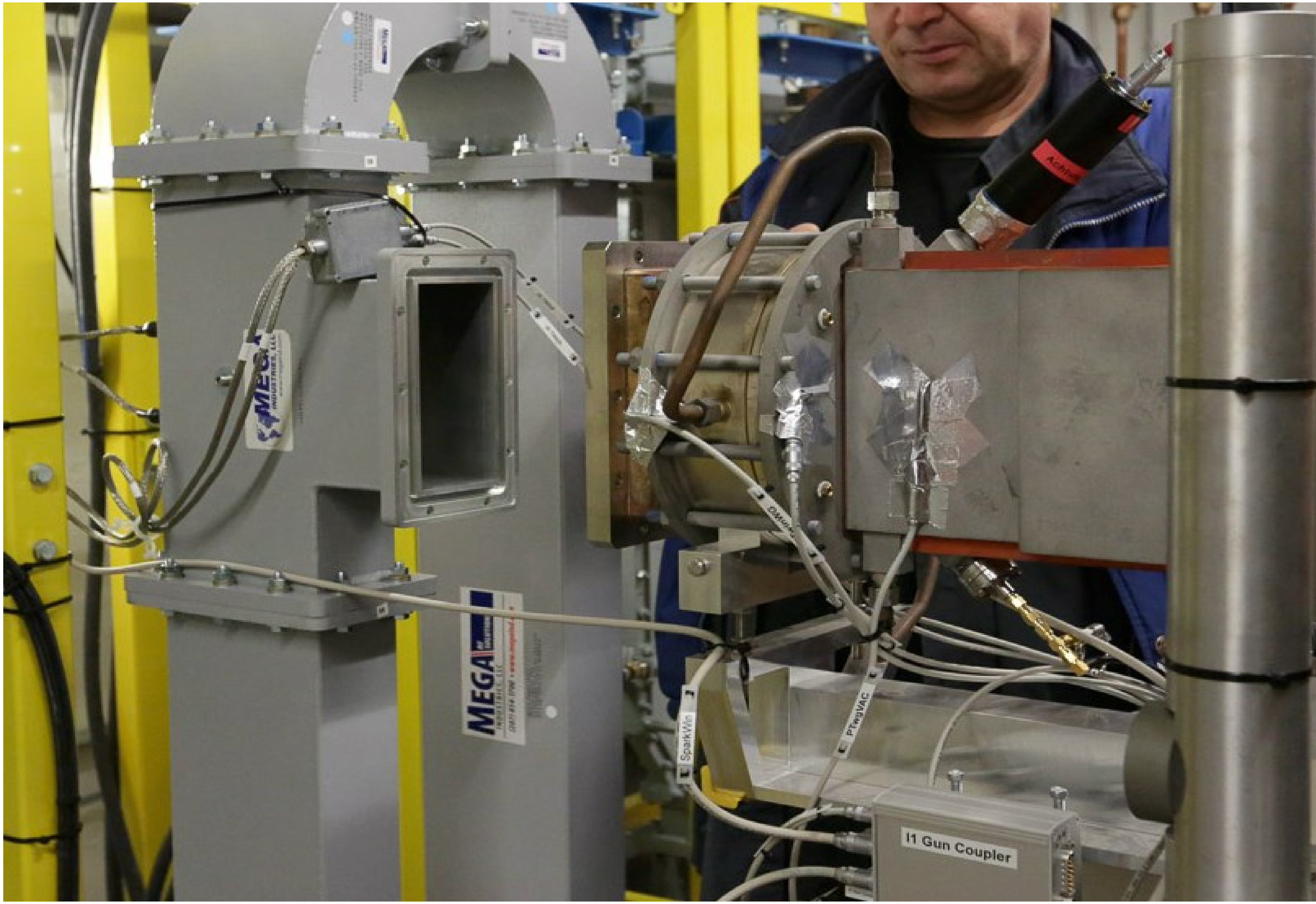


XFEL RF Gun Installed in XTIN

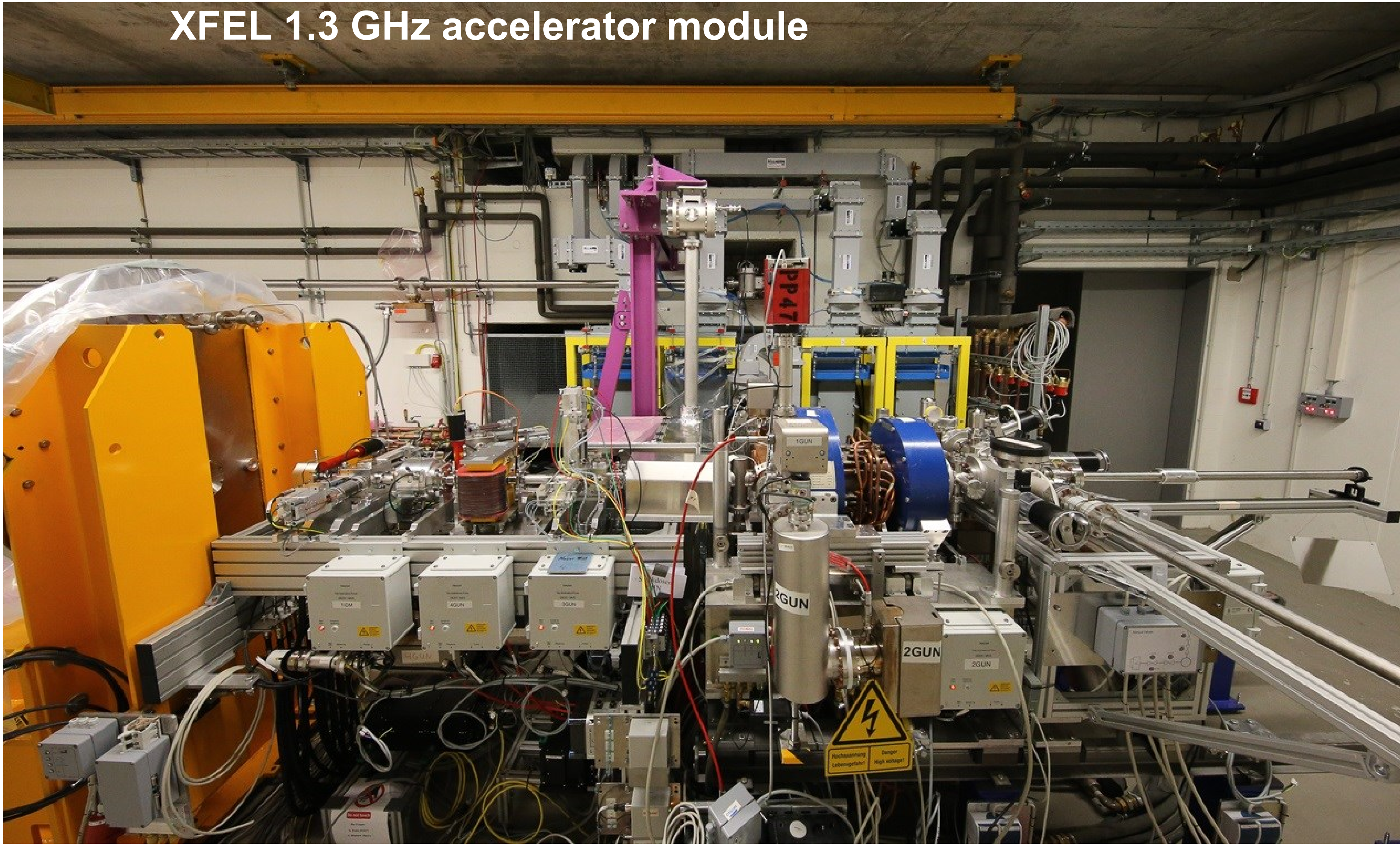
4 waveguides connect to one 10 MW multi-beam klystron



RF Gun Waveguide Installation
one single RF window connects to the rf gun

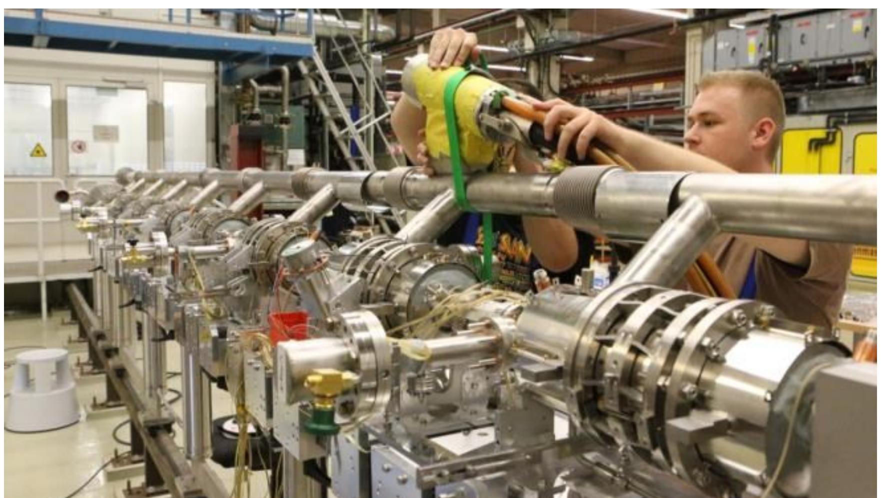


RF Gun Commissioning
a short beam diagnostics section upstream of a standard XFEL 1.3 GHz accelerator module



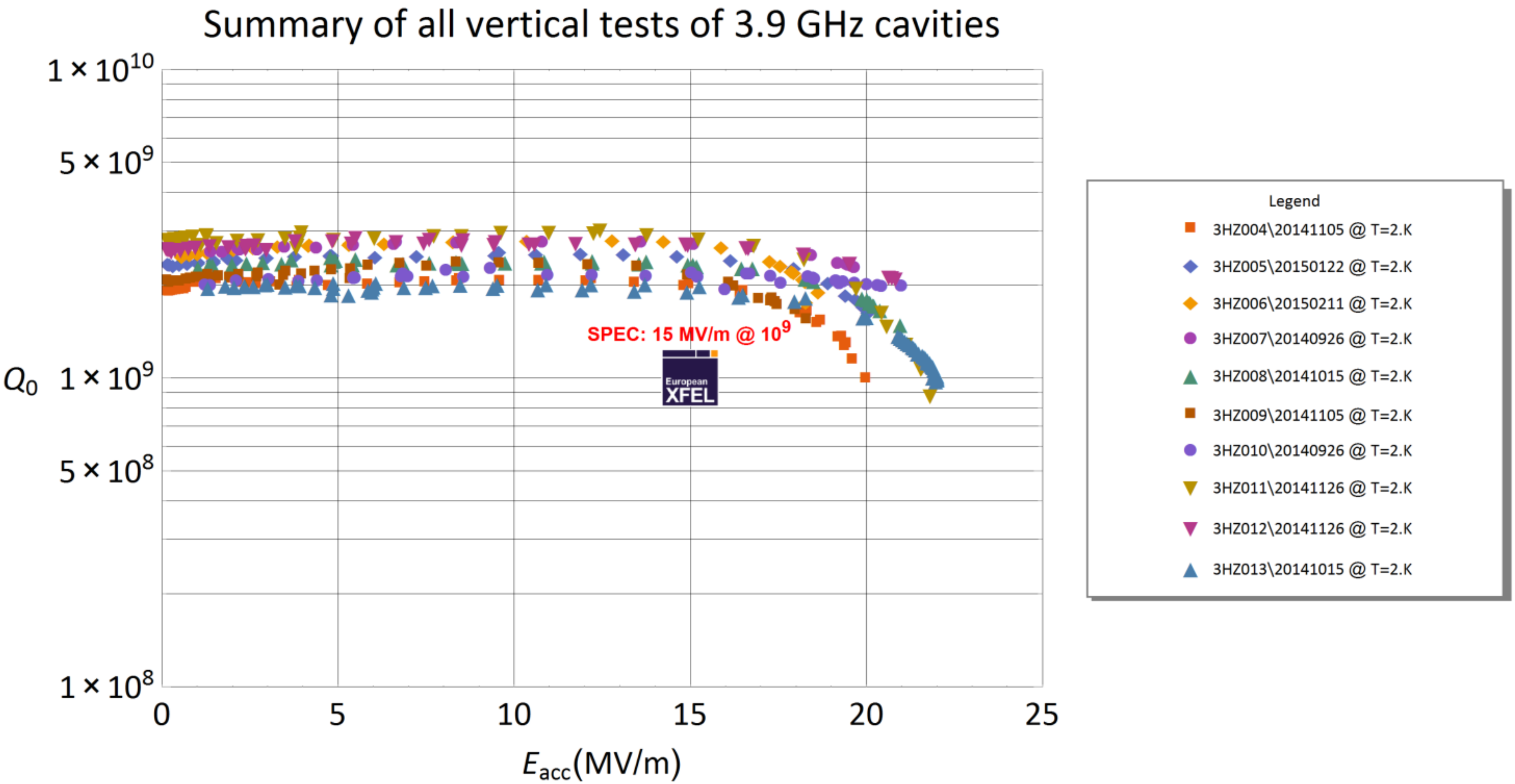
3.9 GHz Module
supporting the longitudinal phase space gymnastics

- 3.9 GHz cavity string and module was assembled at DESY
- Common effort of INFN and DESY based on multitude of expertise like Ti welding, X-ray certification, frequency tuners, couplers, super insulation, vacuum… i.e. full expertise in s.c. cavities and modules was required

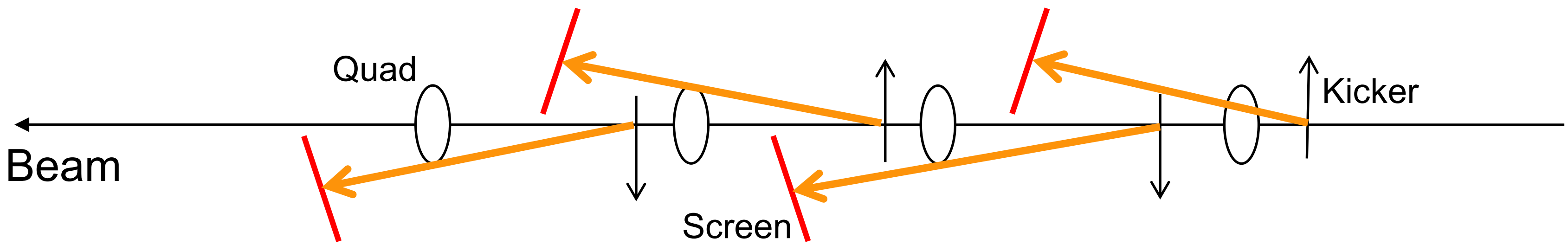


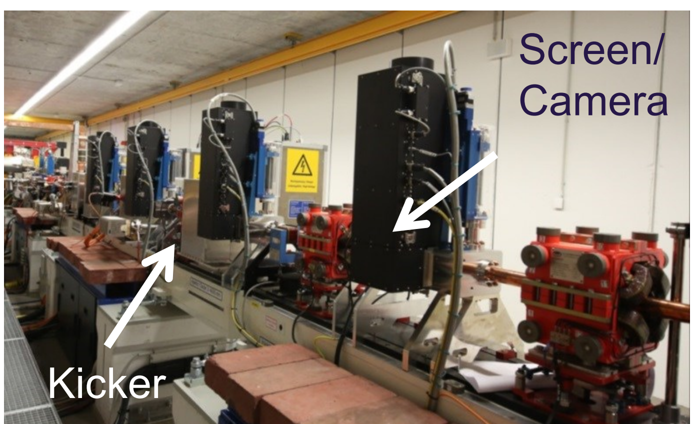
Cavity Vertical Tests at INFN/LASA

First cavity vertical test 26-Sep-14 and last 11-Feb-2015

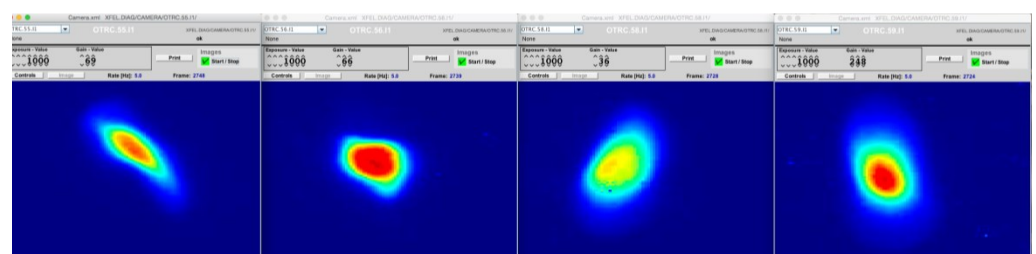


Kickers and off-axis screens allow to measure emittances of single bunches during operation with long bunch trains

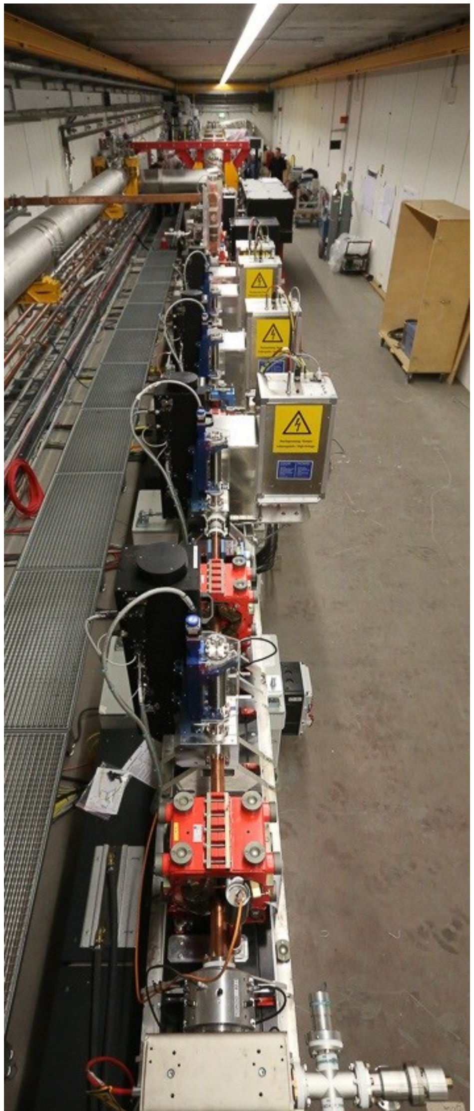




- These measurements are fast and allow also to measure the emittance and mismatch evolution over the bunch train.



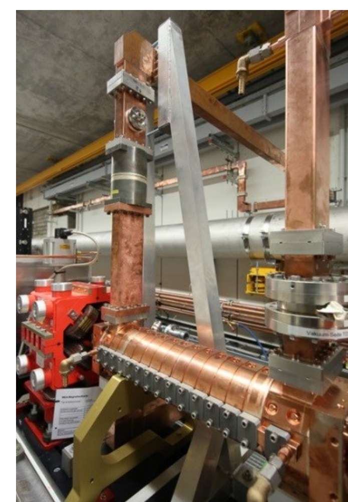
XFEL Injector Status as of 6/2016



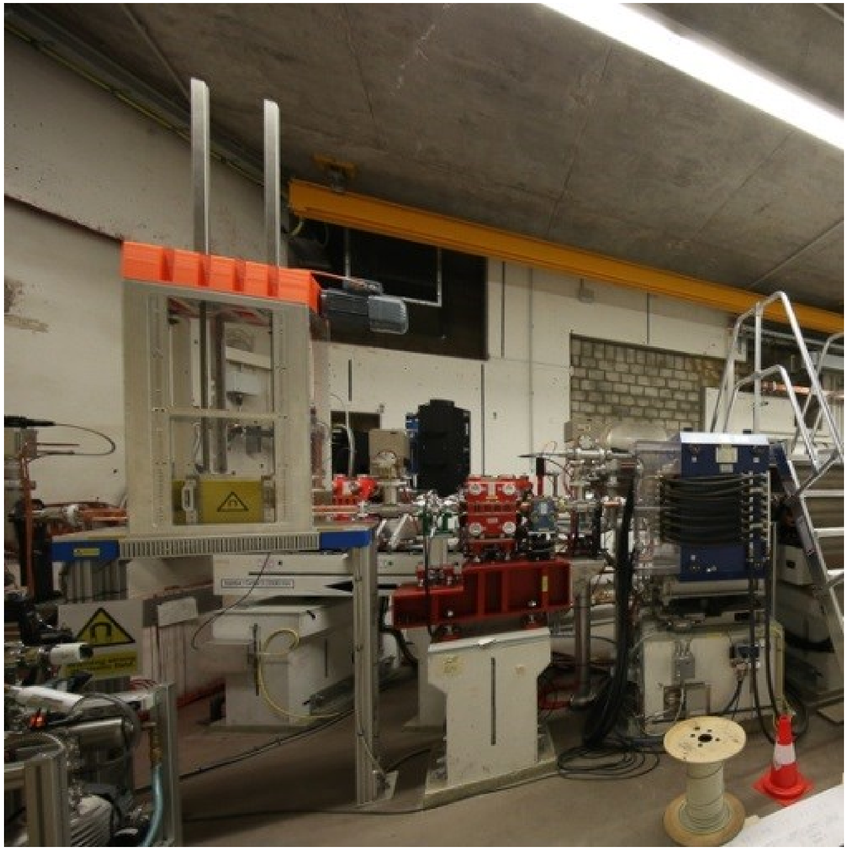
- Injector installation finalized in Q4/2015
- 3.9 GHz module installed in 9/2015
- Injector cool-down started beginning of 12/2015
- First Beam on December 18th , 2015
- Successful commissioning during Q1/2016

- Emittance measurements done on a routine basis;
- Projected emittance as expected (1...1.5 mm mrad)
- Full bunch train length (2700 bunches) reached and beam stopped in injector beam dump

- Commissioning of Transverse Deflecting System started
- First slice emittance measurement showed 0.5 mm mrad for 500 pC
- Laser heater commissioning started

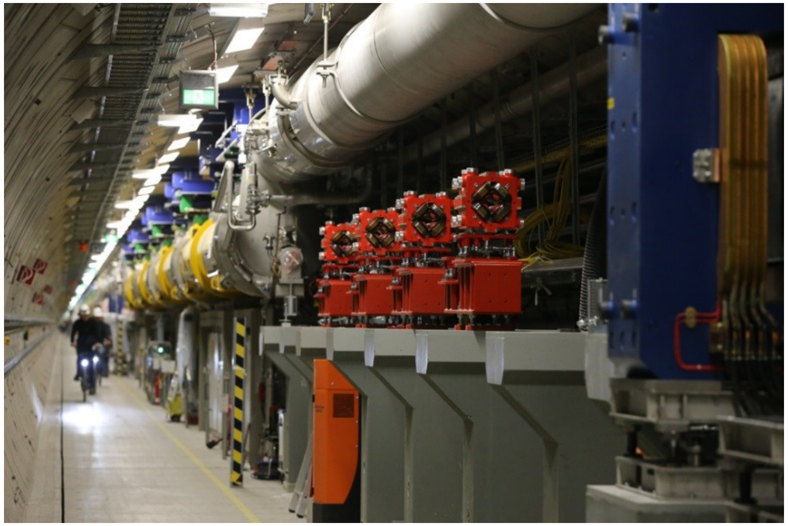


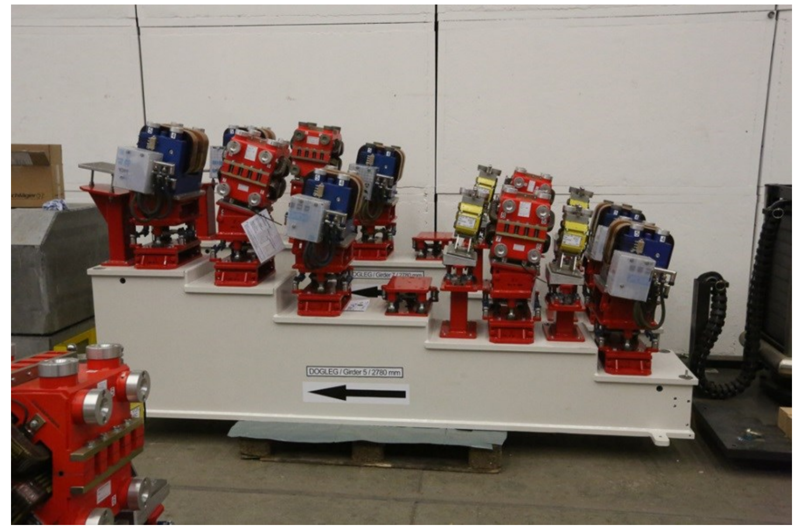
Full Bunch Train Operation

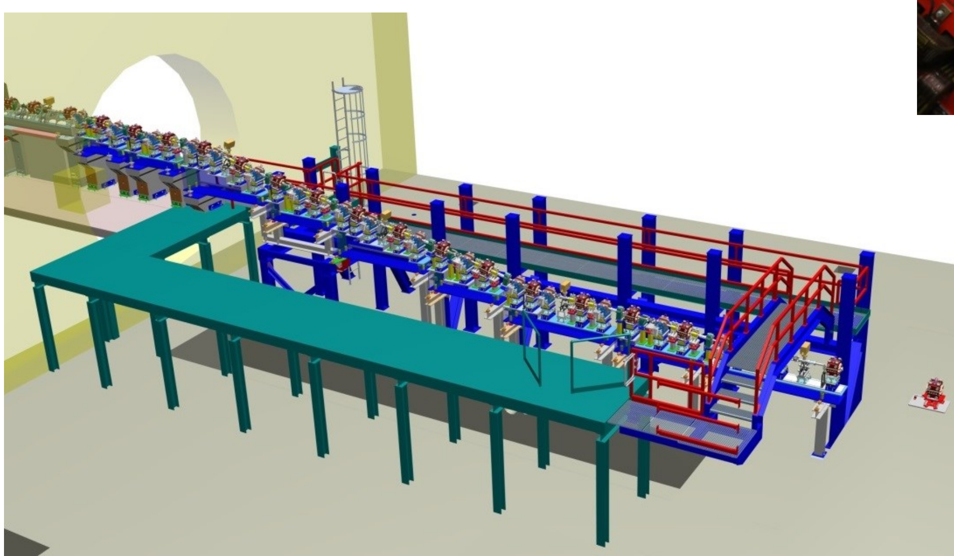


- A dedicated injector beam dump system allows for full bunch train operation
- **24/7 operation** is used to test many operation procedures
- **Operation crew** is getting trained

Warm Beam Line Sections
Dogleg & BC0 in Front of Linac L1

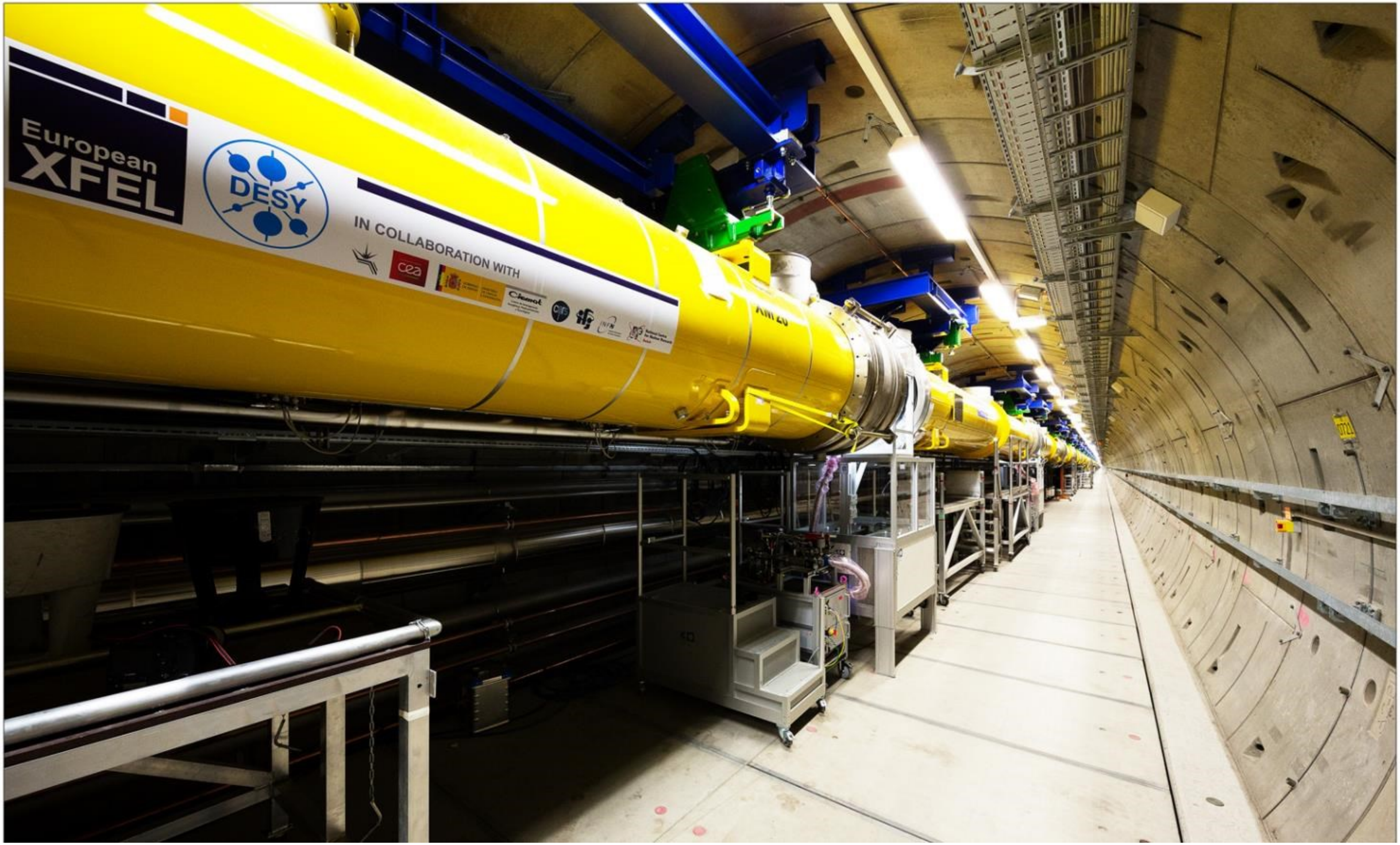






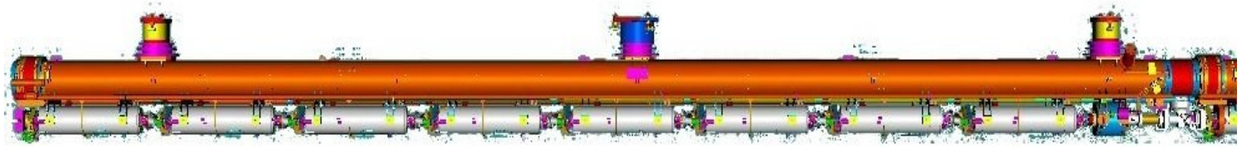
- installation started
- some remaining girders to be assembled in clean rooms

Linear Accelerator



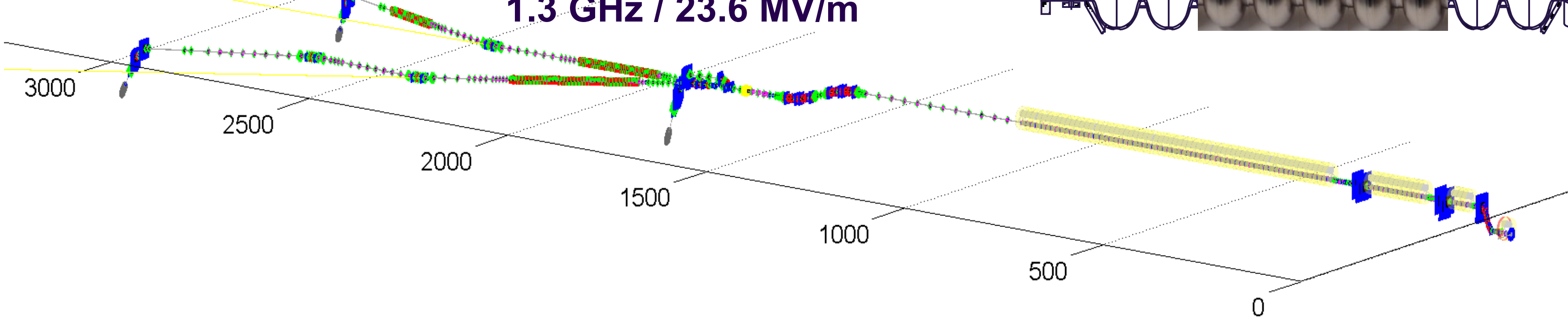
Accelerator Modules

100 accelerator modules



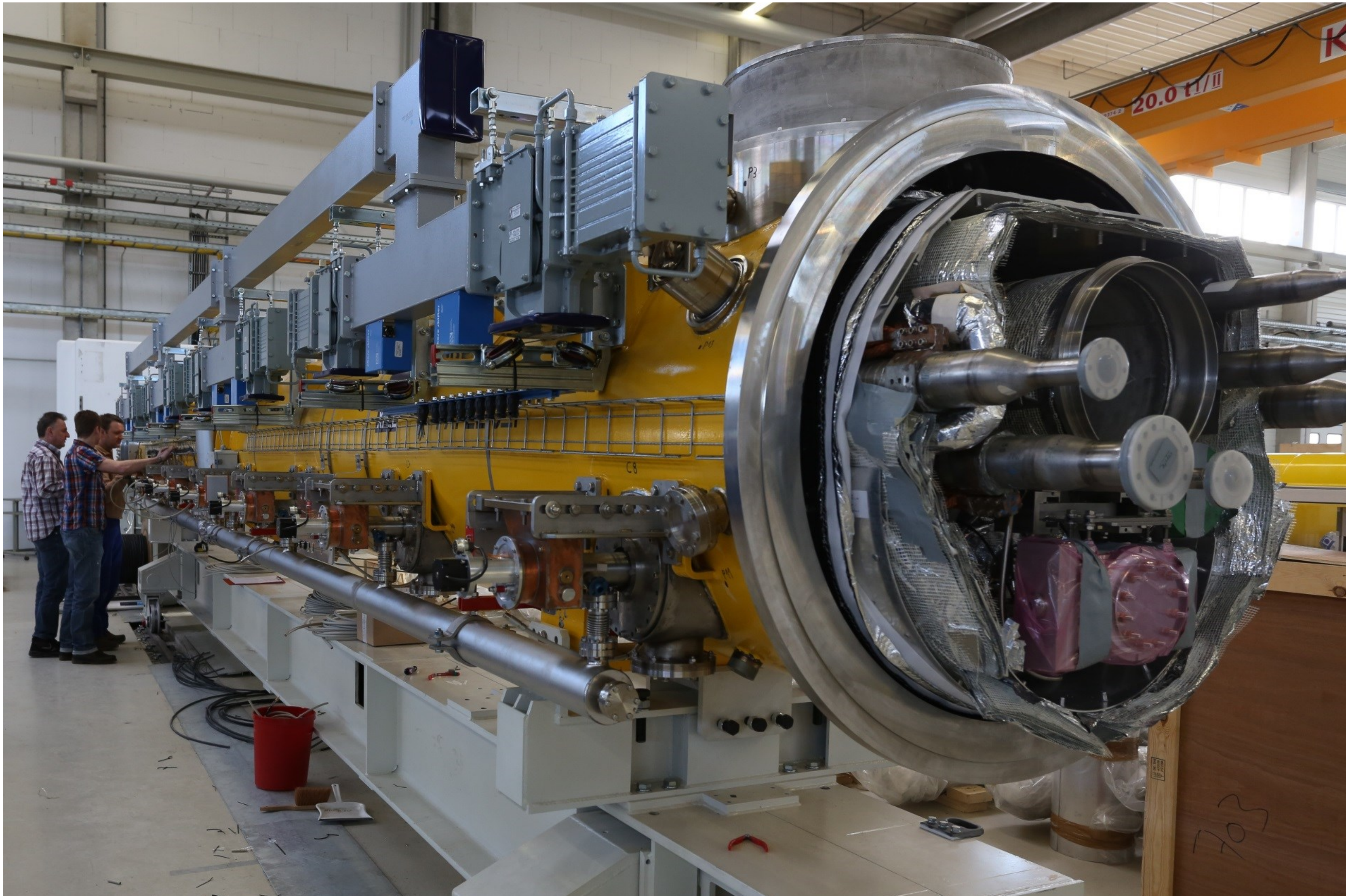
800 accelerating cavities

1.3 GHz / 23.6 MV/m



- The accelerator tunnel (XTL) houses three cold linac sections separated by bunch compressors.
- Down to the end of module XM100 the complete beam vacuum system is particle free.
- 4 modules / 32 s.c. cavities are connected to one 10 MW klystron.
- 12 modules form a cryogenic string.
- At the XTL end a collimation and separation system is installed.

XFEL Accelerator Module with Tailored Waveguide System



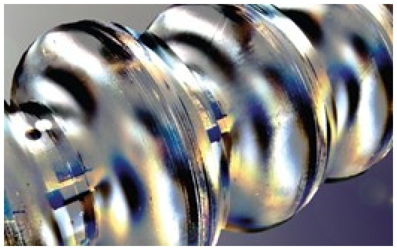
Contributions to the European XFEL Modules

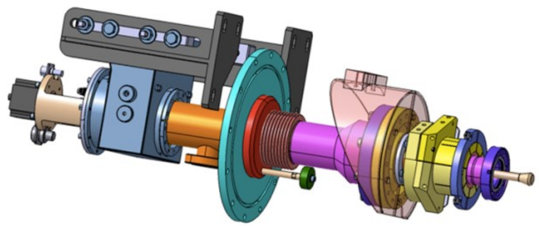
BINP Novosibirsk, Russia	• cold vacuum bellows • coupler vacuum line
CEA Saclay / Irfu, France	• cavity string and module assembly • cold beam position monitors • magnetic shields, superinsulation blankets
CIEMAT, Spain	• Superconducting magnets
CNRS / LAL Orsay, France	• RF main input coupler incl. RF conditioning
DESY, Germany	• cavities & cryostats • contributions to string & module assembly • coupler interlock • frequency tuner • cold vacuum system • integration of superconducting magnets / current leads • cold beam position monitors
INFN Milano, Italy	• cavities & cryostats • contributions to frequency tuners
Soltan Institute, Poland	• Higher Order Mode coupler & absorber

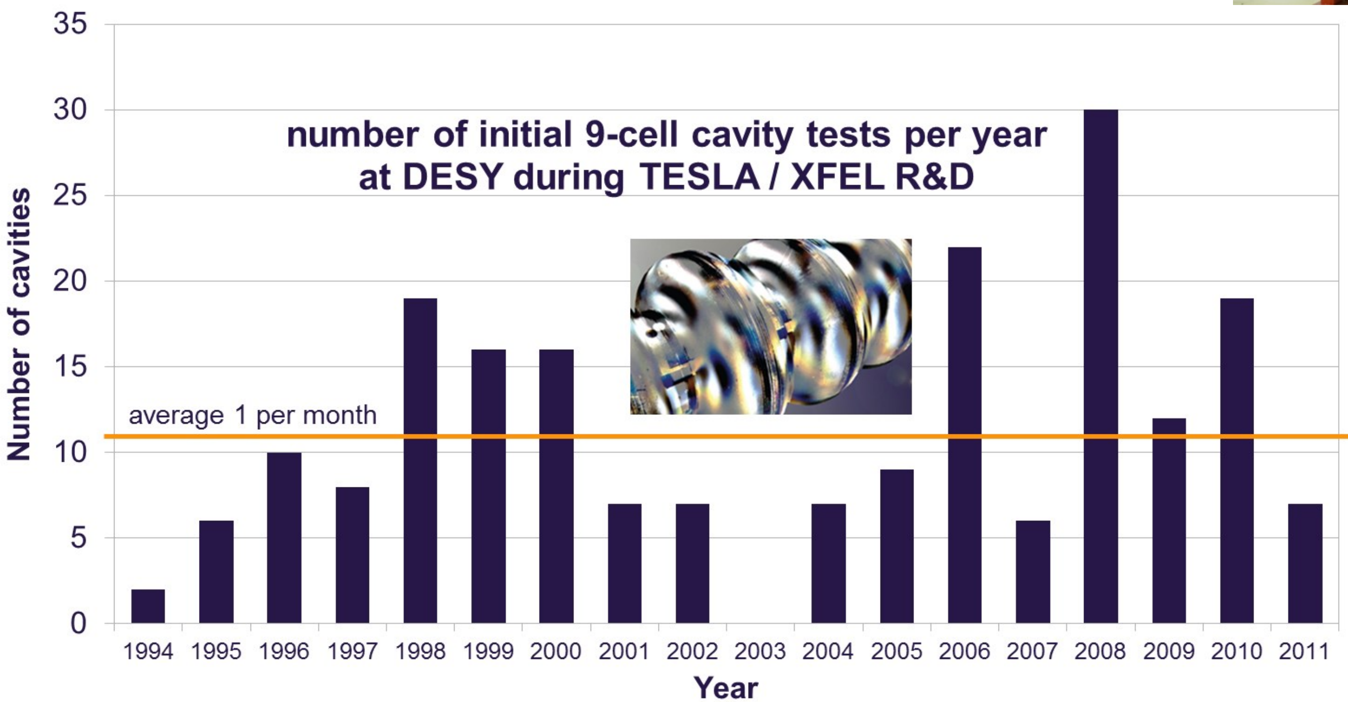
European XFEL

Production Rate of Key Components

European XFEL requires **8 cavities & couplers** to build **1 module per week**



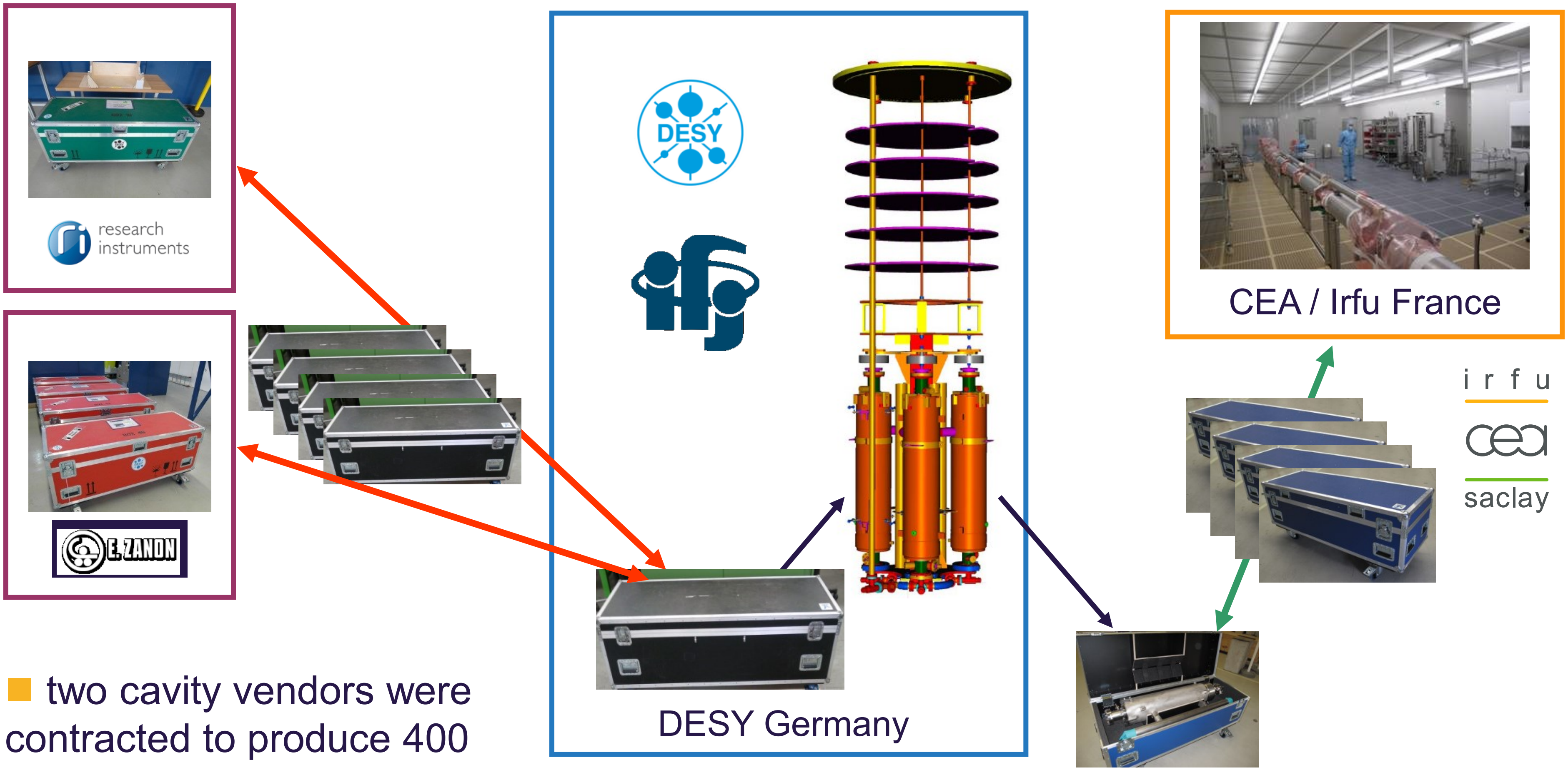




monthly average was to increased by approximately

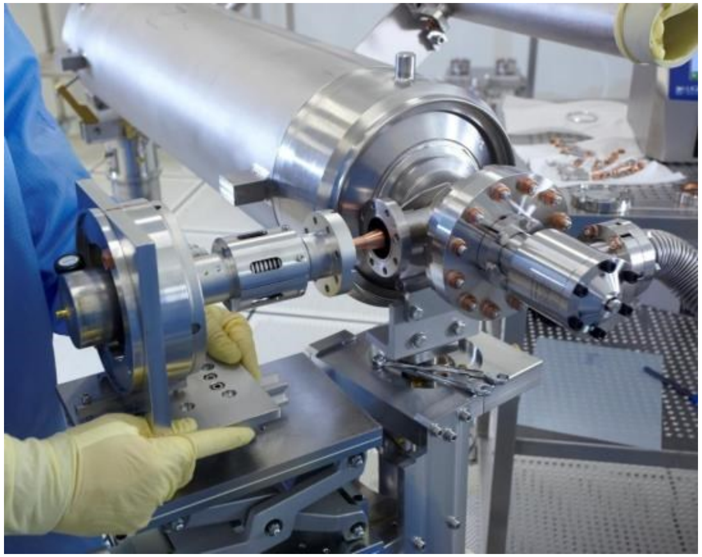
x 30

800 XFEL Cavities Travel Through Europe



- two cavity vendors were contracted to produce 400 cavities each
- slight variation in final surface treatment
- all cavities are tested and partly re-treated / re-tested in collaboration of IFJ / DESY
- further assembly takes place at CEA Saclay / Irfu

Linear Accelerator
Buffer for all Sub-Components Established

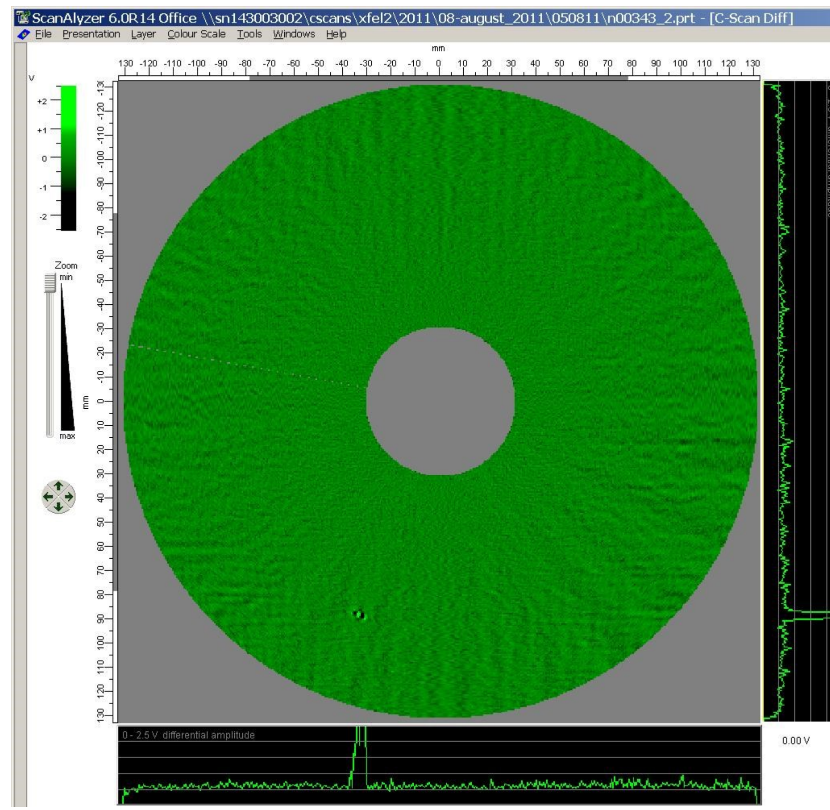


string and module assembly relies on sufficiently filled buffers for all parts

- Cavities
- Couplers
- BQU (beam position monitor & quadrupole
- Vacuum parts (bellows / gate valves)
- Cryostats
- Magnetic shielding
- Tuner

Niobium Material Bought and QC-ed by DESY

- All Nb / NbTi material (24,420 single parts!) was procured by DESY.
- Detailed quality inspection was developed and carried out.
- All material made available to cavity vendors.



Industrial Cavity Production Relies on DESY & INFN Supervision

- Special CE certified machines were developed and given to industry.
- Since accelerator cavities are delivered without performance guarantee, very detailed specifications are used.
- Many productions steps were supported and partly supervised by DESY & INFN.
- Several QC steps are established. Very detailed documentation.

Cavity Production (here at Company RI)

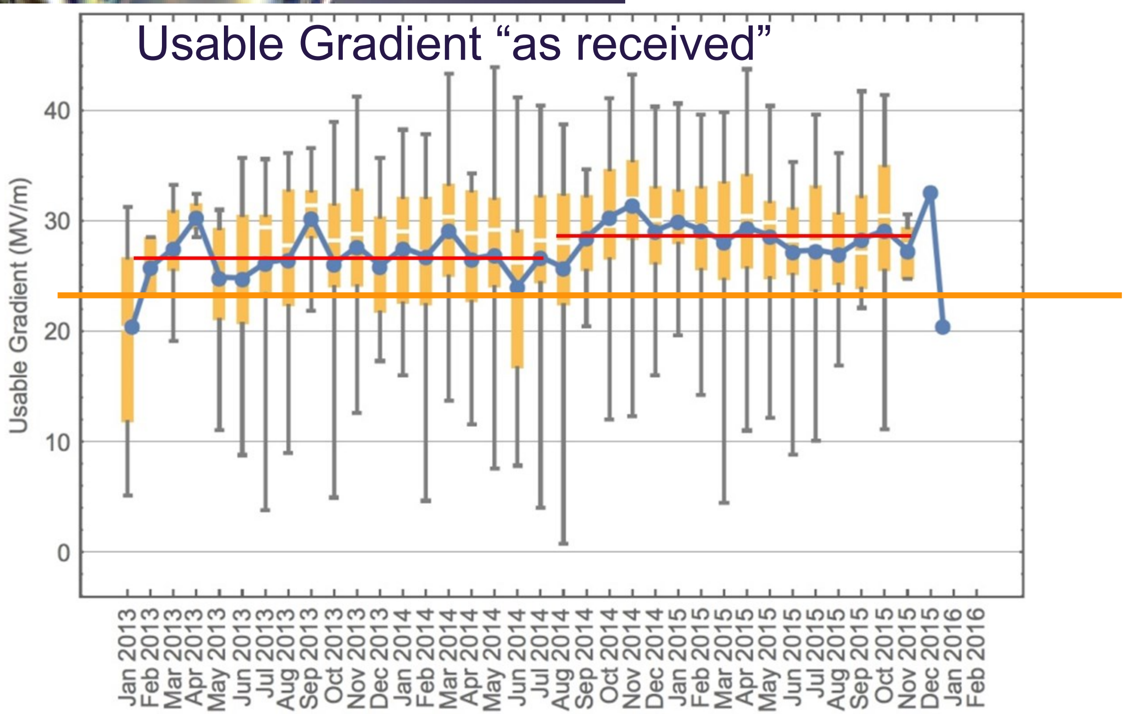
- all pictures courtesy Research Instruments

XFEL Cavities Ready for Testing at DESY

Vertical Test Cryostat at DESY

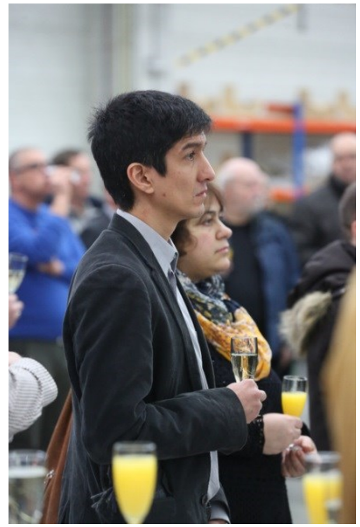
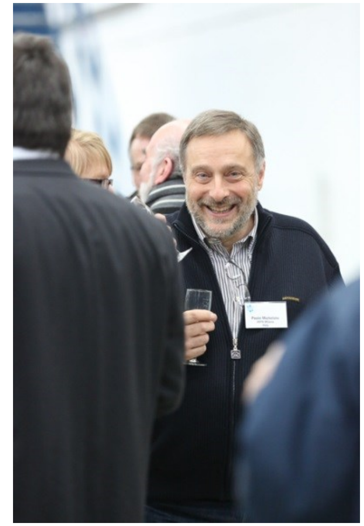
Module Components: Cavities

Production, Delivery and Test of > 800 cavities finished



- usable gradient well above specifications of 23.6 MV/m
- good stability of usable gradient over full production period
- the world-wide largest cavity production was finished 1/2016

800 Cavity Production Ended 1/2016

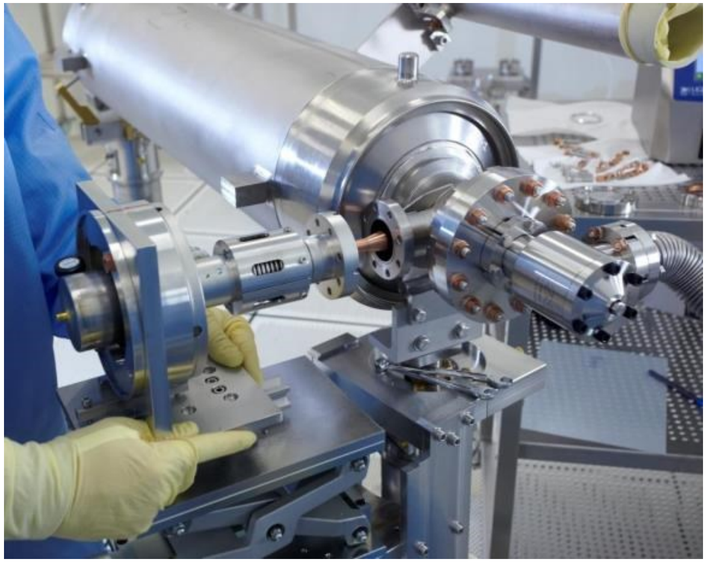








Module Components: Couplers

- A total of 800 RF power couplers was produced at three different vendors
- The largest fraction was procured by LAL Orsay and produced by Thales / RI
- Approx. 20% were procured from CPI
- RF conditioning of all couplers was done at LAL Orsay at a rate of 10+ couplers/week
- **Couplers were the by far the most challenging single items in the supply chain of the accelerator modules**
- Continuing quality and delivery issues needed to be addressed
- **Coupler delivery rate did not match the module assembly rate**



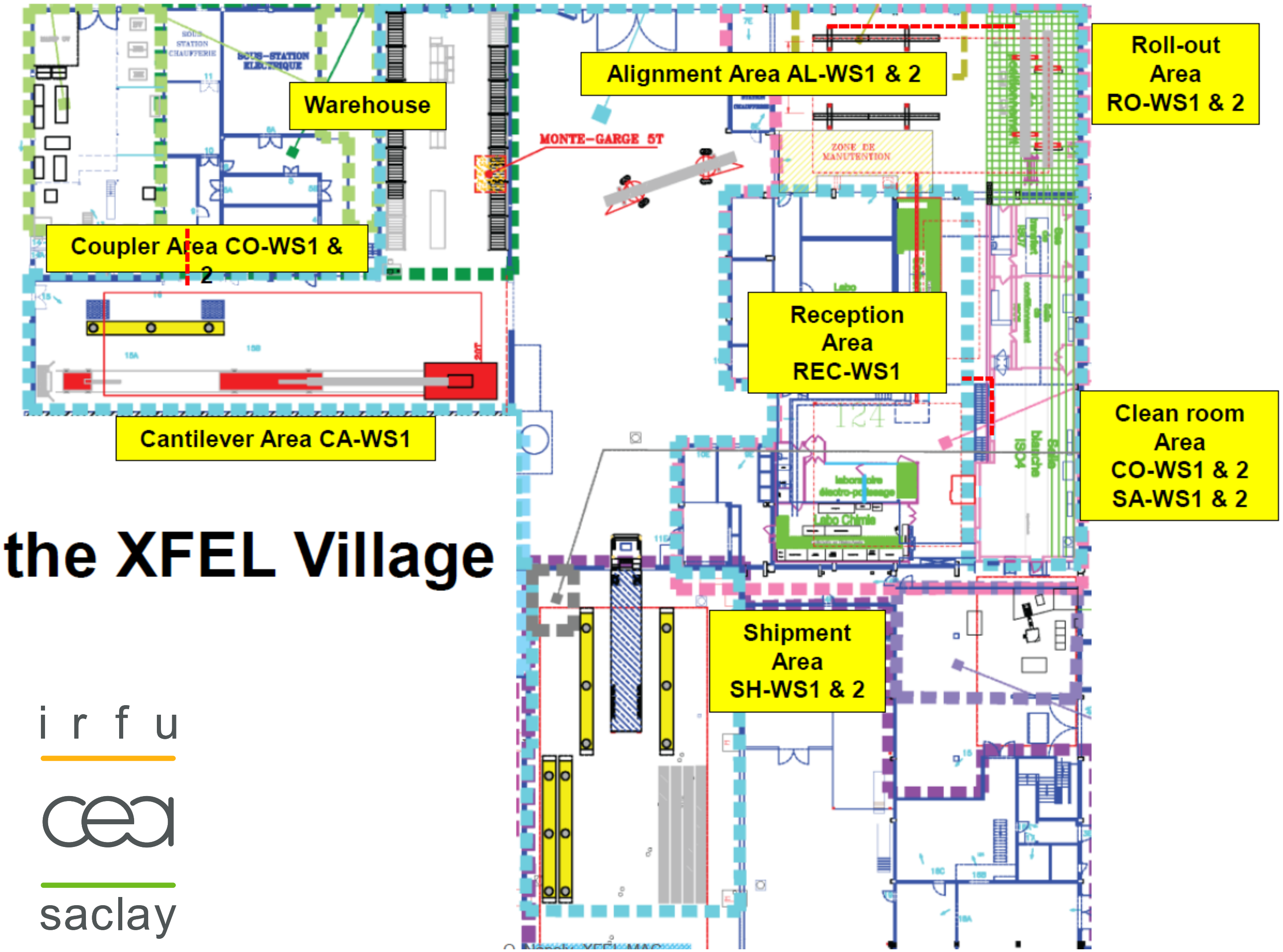
Module Assembly at IRFU / Saclay

- We have seen an assembly at a rate 1+/week
- XM 97 started as of May 24th , 2016
- We are **still waiting for the last couplers**

- Based on extensive quality checks and test results, almost all accelerator modules were accepted for linac installation
- Number of non-conform modules steadily decreased; repair work of those modules (5%) was organized with the goal to repair as many as possible before the last delivery

- **XM100 expected for July 2016**

The XFEL Village at IRFU / CEA Saclay

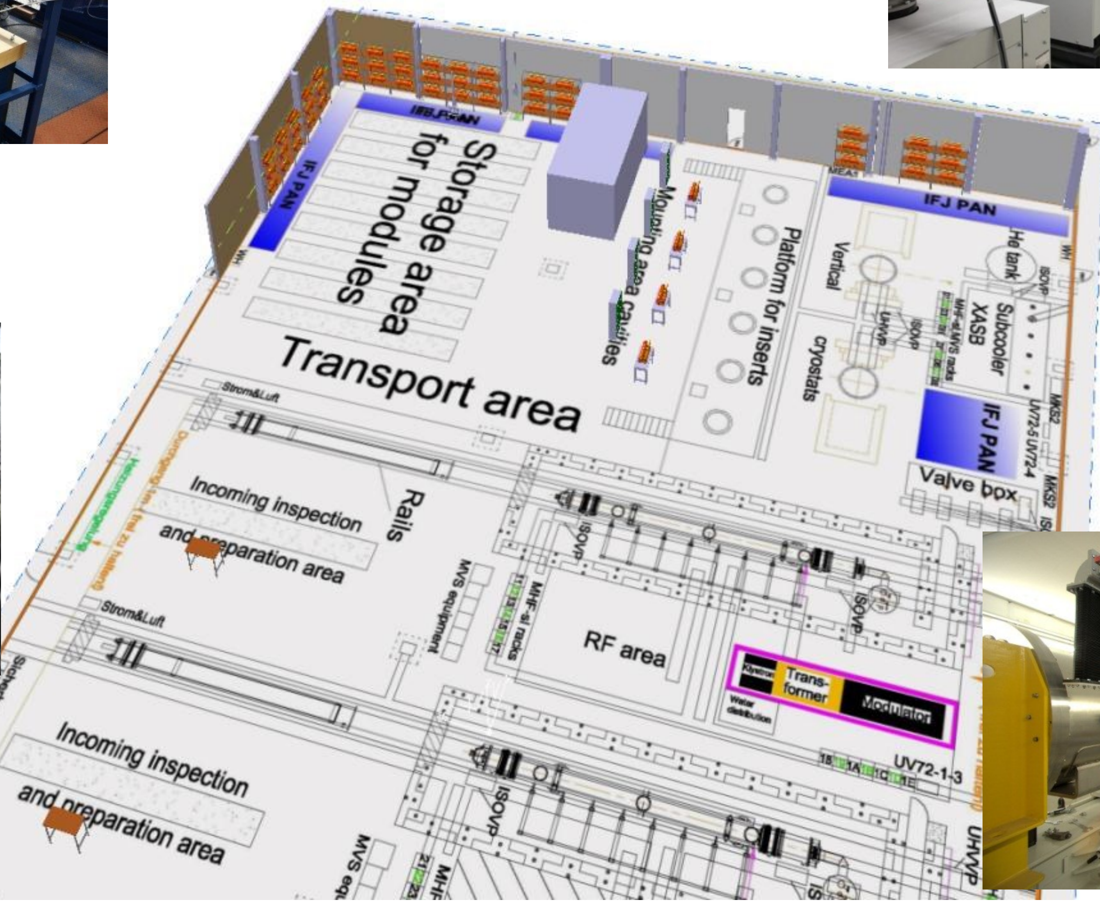


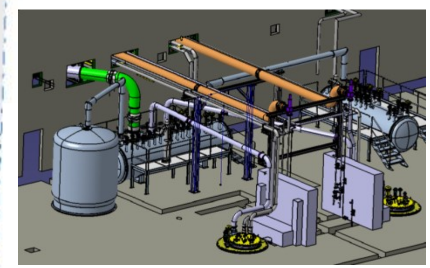
the XFEL Village

irfu

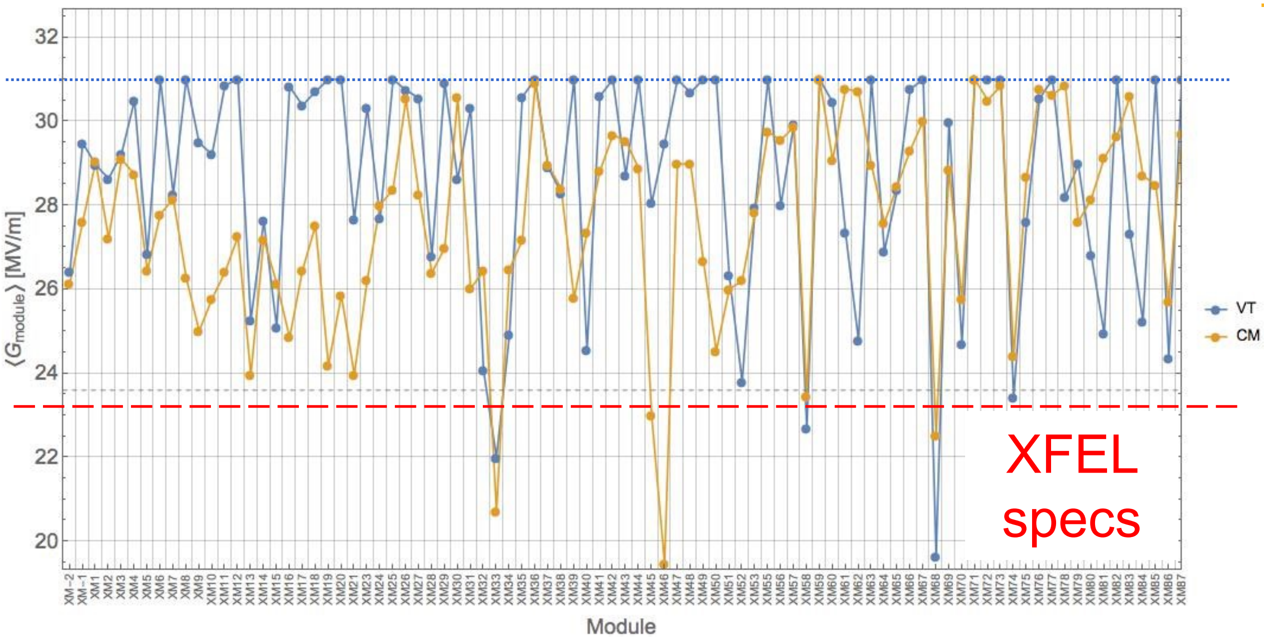
saclay

AMTF Test Stand Infrastructure





XFEL Module Performance



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

- Module performance well above specs. and visible improvement with time
- Tunnel installation uses sorting of modules based on AMTF performance
- **Ramp-down impact to be avoided**

<u>Remark</u>:

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

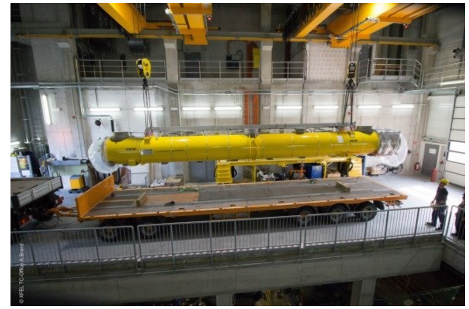
	N_{cavs}	Average	RMS
VT	695	28.7 MV/m	2.9
CM	695	27.6 MV/m	4.5

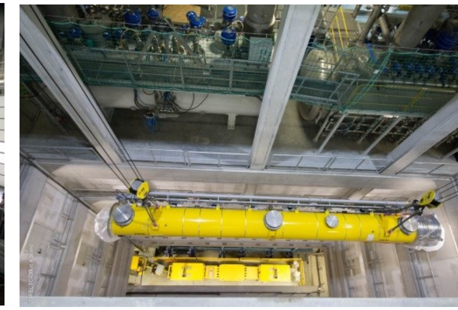
Accelerator Modules at AMTF & WATF

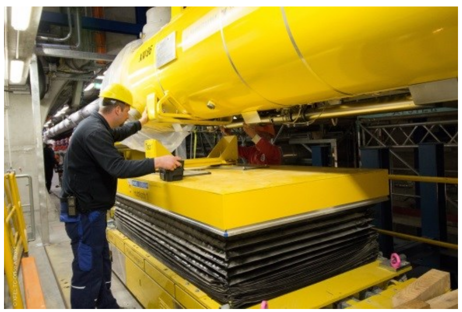
- Three test benches were built to cope with 1 module per week
- Experience gained allowed for optimized procedures.
- Testing rate drastically increased (10-12 days instead of >21 days).
- All delivered modules can be immediately tested on one of the three benches.

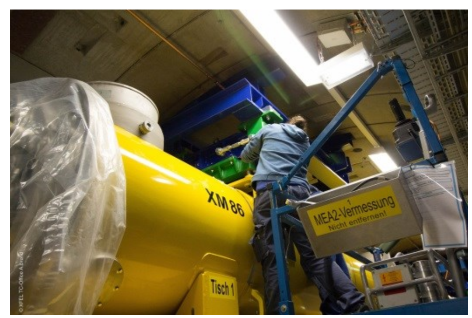
- Tailored waveguide distributions incl. cooling and cables are assembled, tested and connected.
- Assembly rate increased to 1.5 per week by adding resources.

Accelerator Module on its Way to the Tunnel





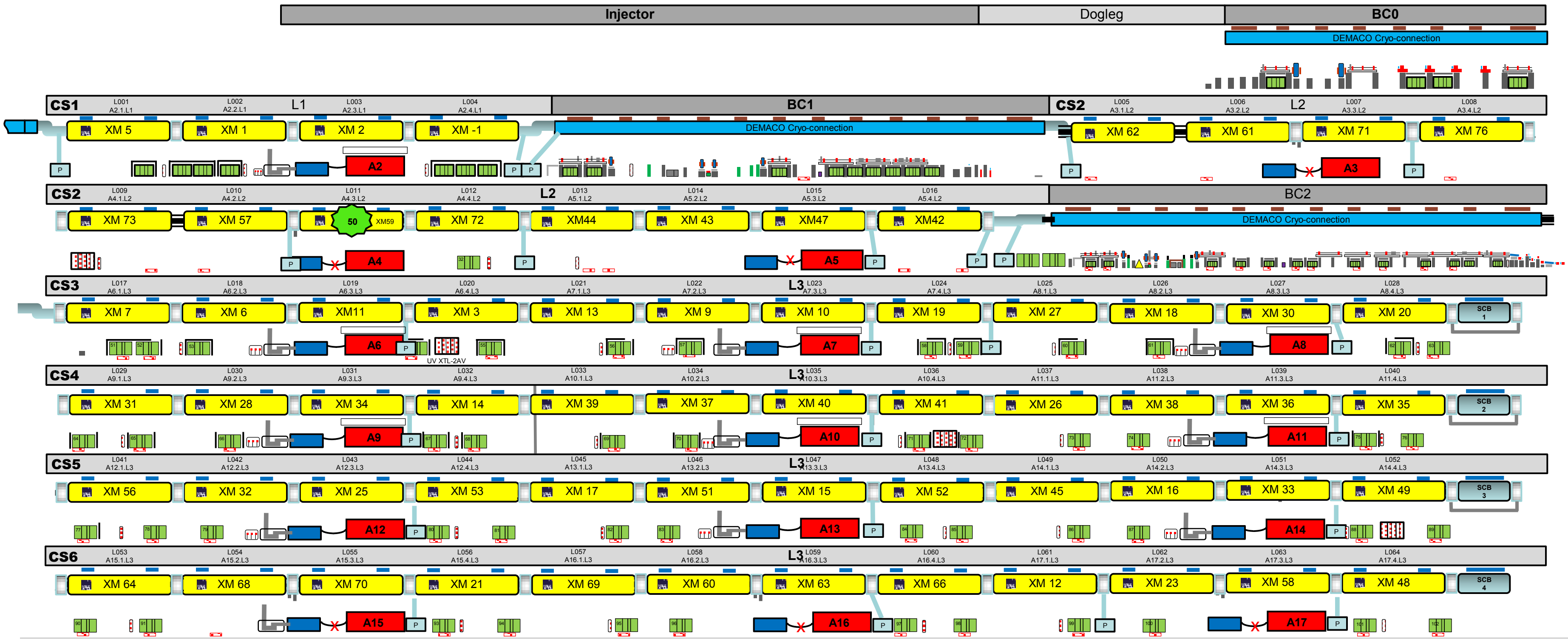




Module to Module Connection

- With time module to module connection rate was ramped up to approx. 1.5 connections per week

Installation Status Linac Tunnel



Status 30.06.2016

84 Modules installed

next 5 Modules in prep.

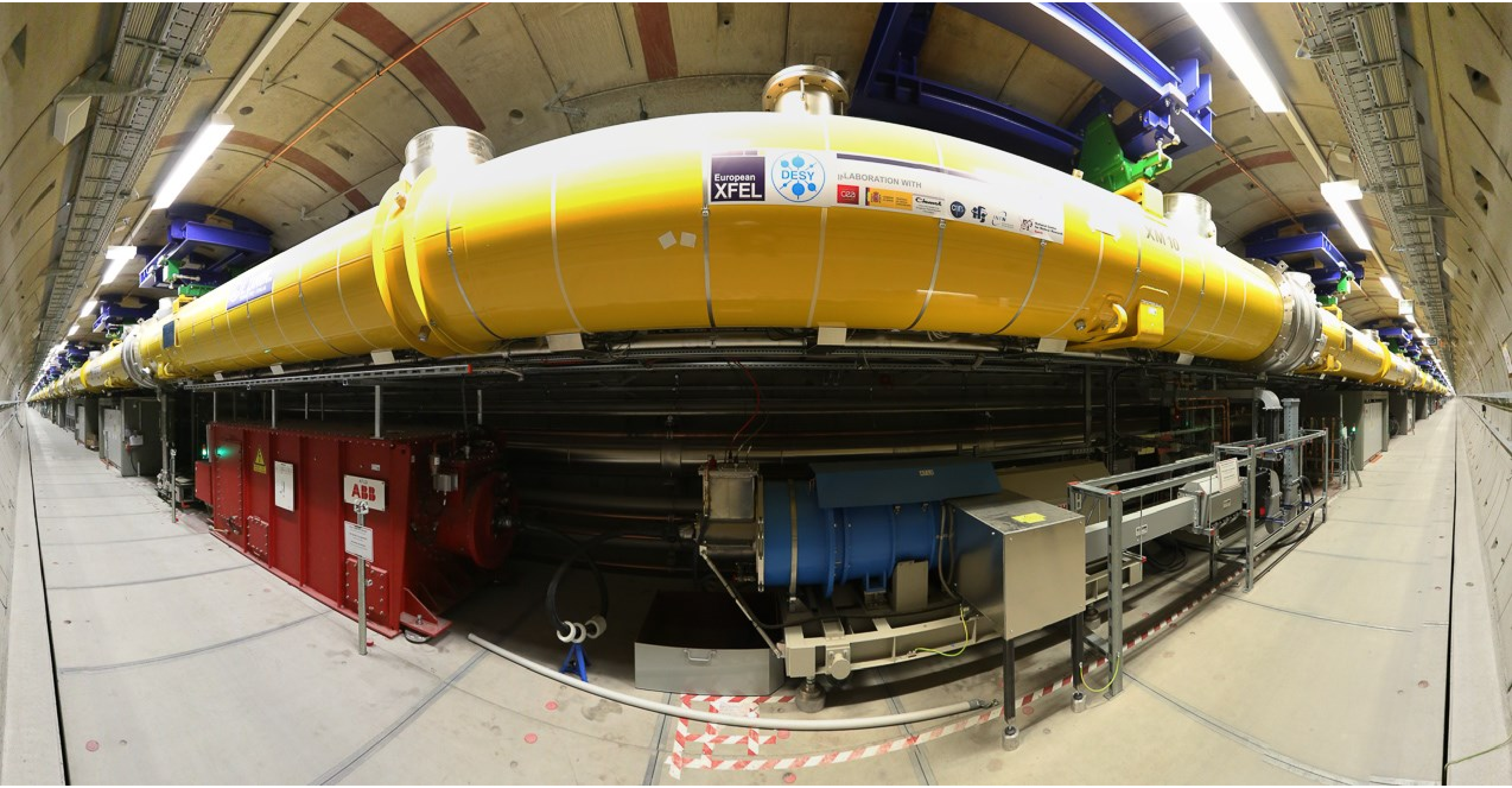
add. 6 Modules during assembly

1 RF-Station ready

6 RF-Stations commissioning

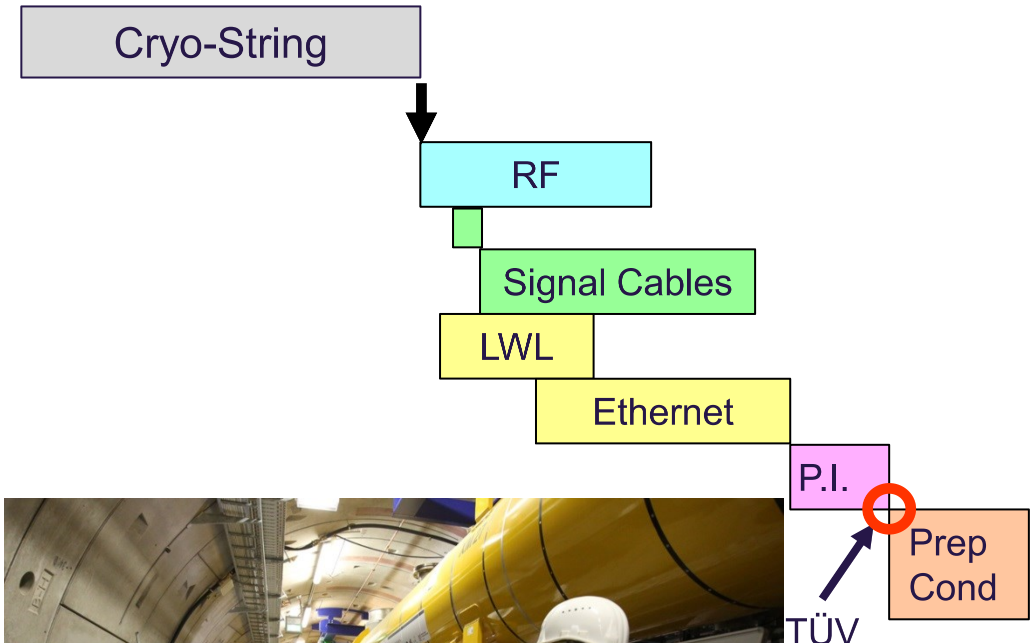
9 RF-Stations in preparation

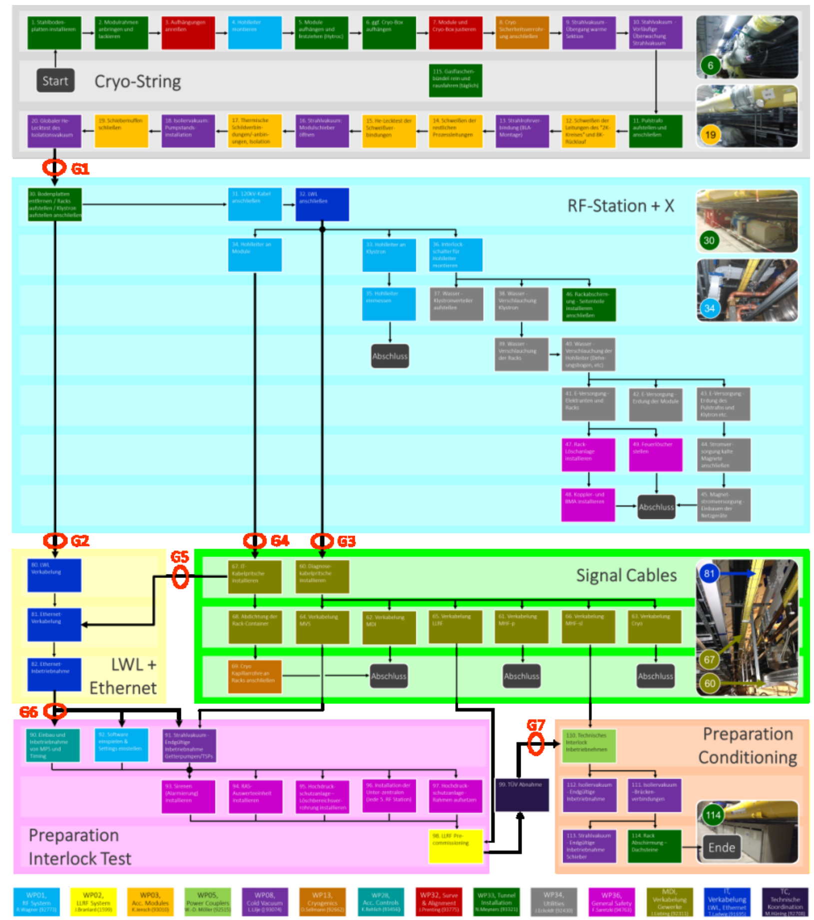
One Kilometer of Cold Linac



Tunnel Installation Process

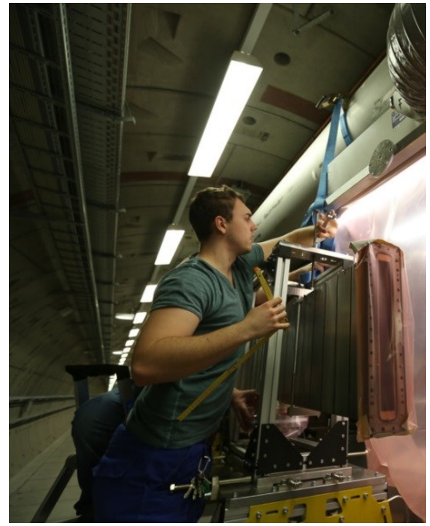
- Optimized global process steps and sequence & daily improvements

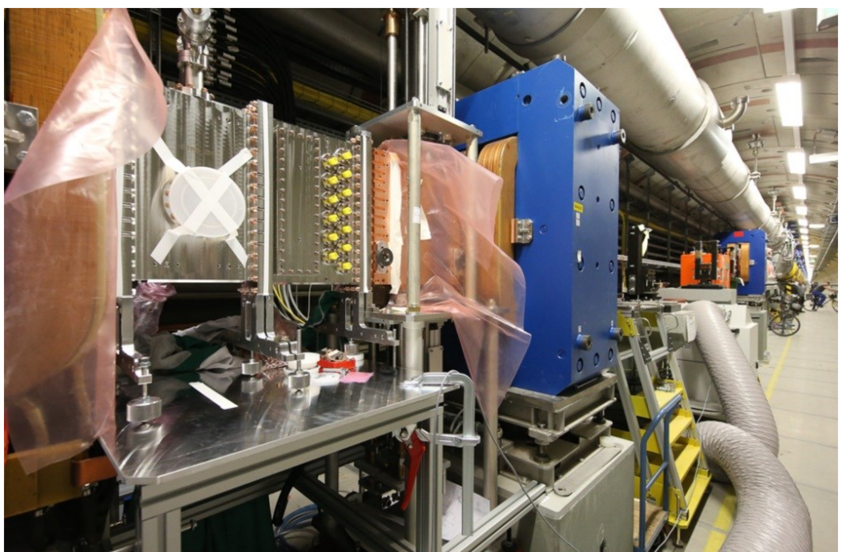




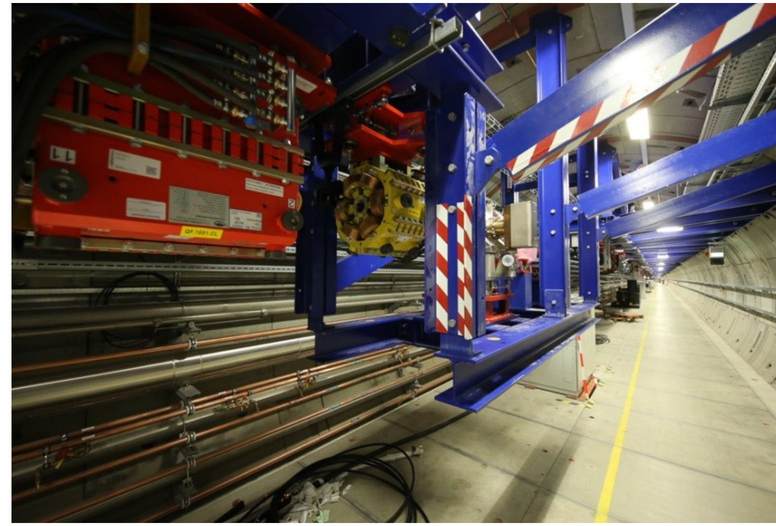
European XFEL

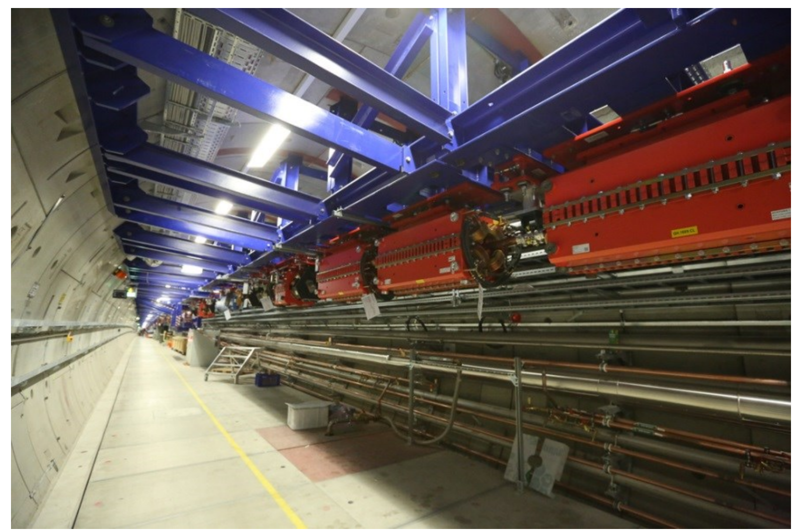
Warm Beam Line Sections
Bunch Compressor Section




Warm Beam Line Sections
XTL Tunnel Downstream of Linac L3

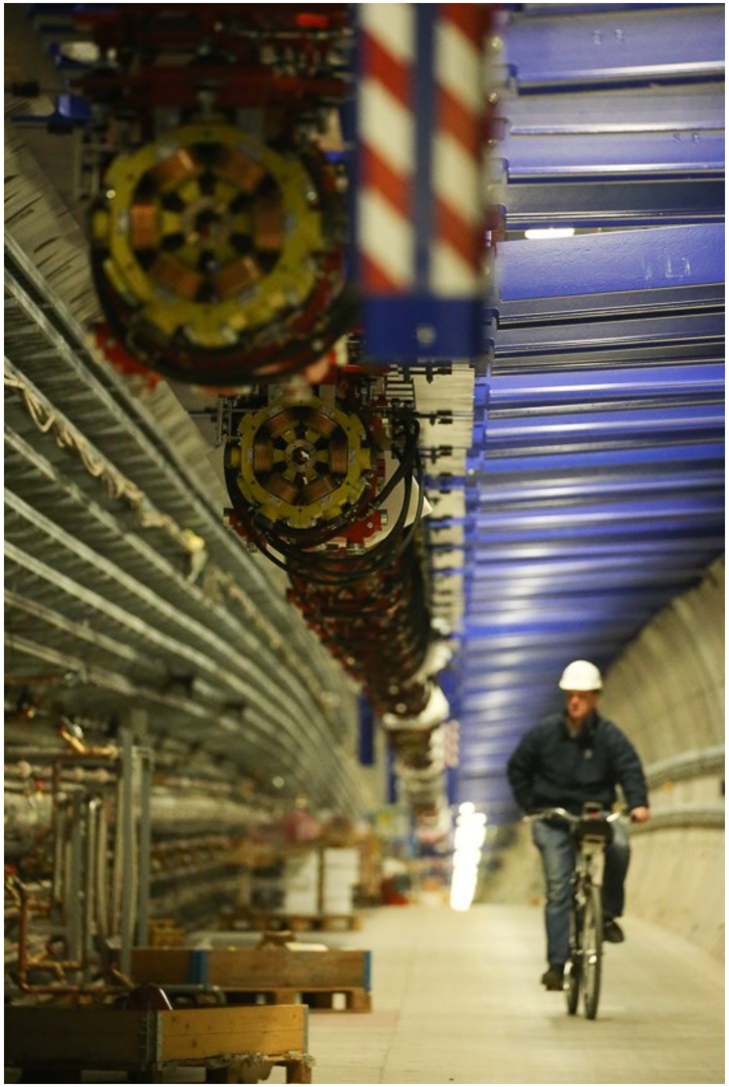




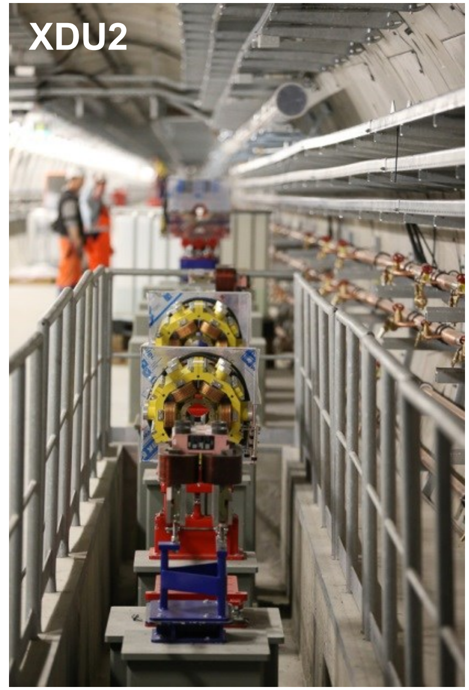
Warm Beam Line Sections
XTL Tunnel Downstream of Linac L3

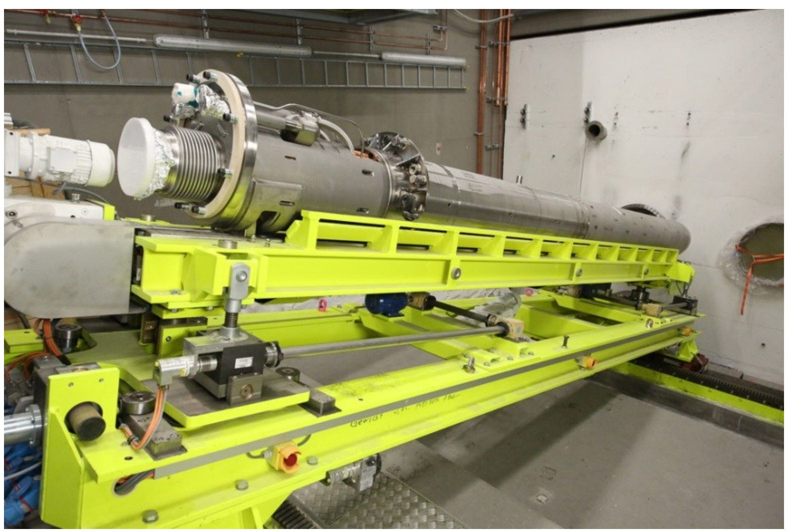
- Many beam line section are suspended from the ceiling
- Engineering of 'hanging' system took longer than anticipated, but very satisfying result
- Installation of supports / mounts finished
- Installation of magnets and vacuum components is ongoing at quite some pace
- Planned to be finished mid 2016

- Temporary beam line replacing 4 / 8 modules is in production



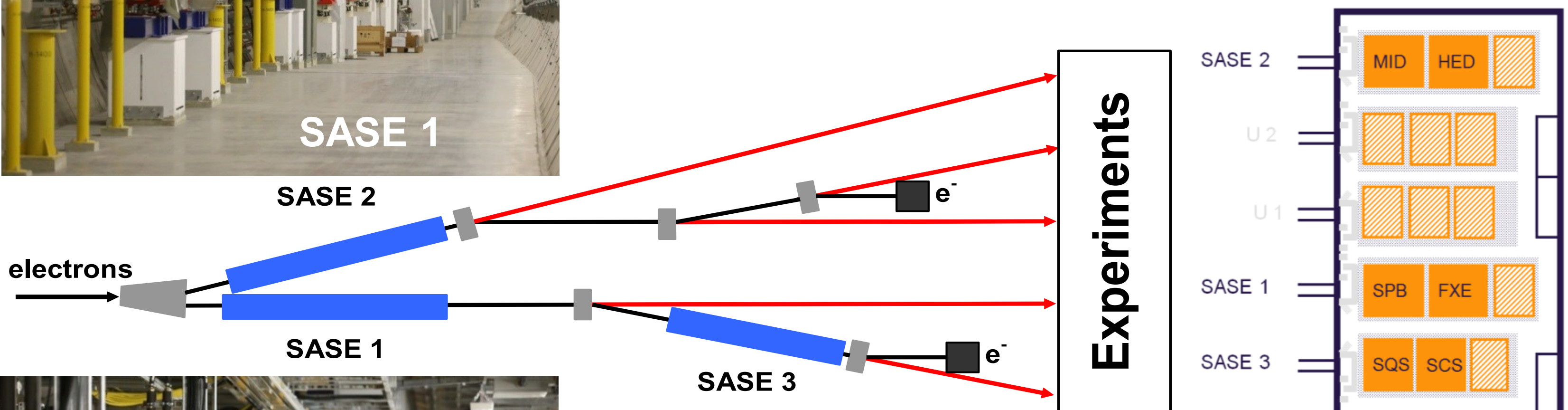
Warm Beam Line Sections
Transport Line to XS1 Beam Dump





- Several beam dumps
- Special vehicle to exchange activated dumps

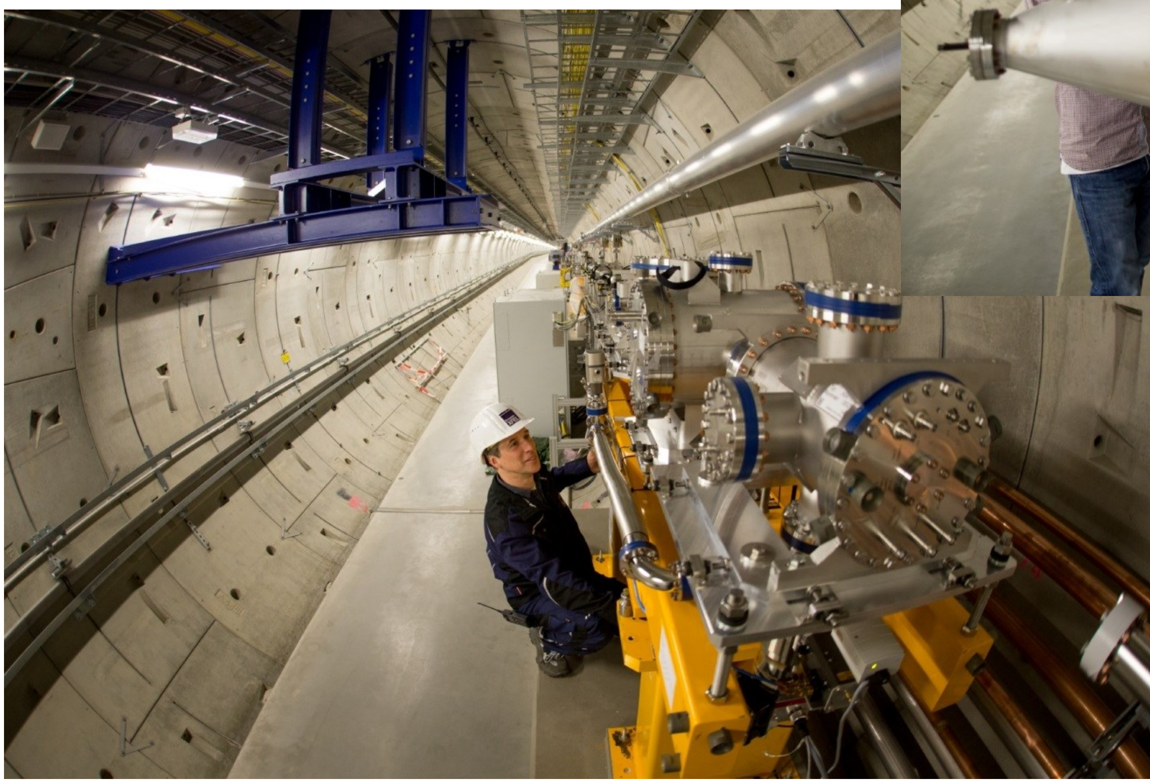
X-ray Beamlines



courtesy of XFEL.EU

35 Undulator Segments in SASE1

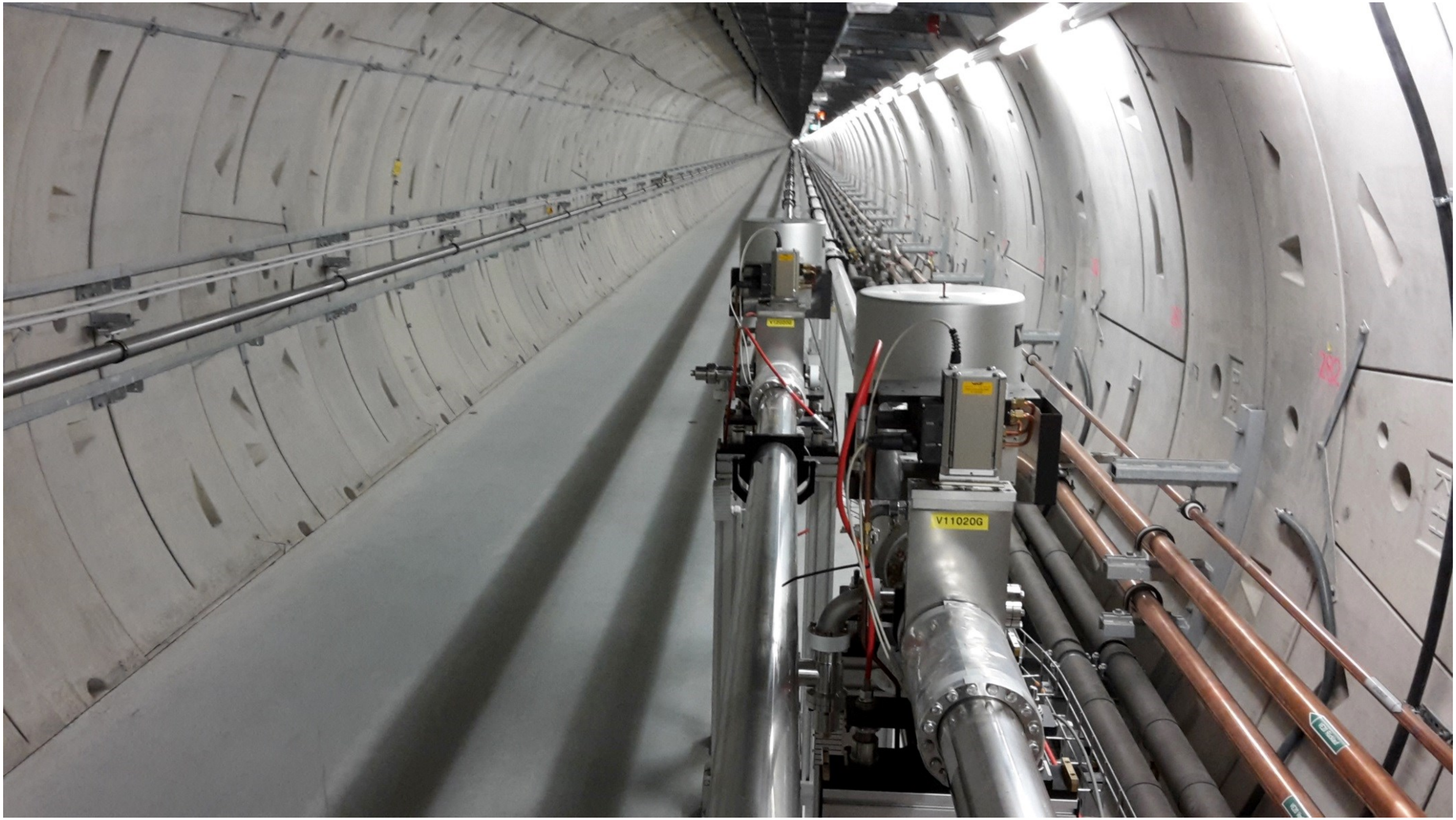
Optical Elements and Photon Diagnostics of the SASE1 Beamline



courtesy of XFEL.EU

Installation Activities Photon Beam Lines

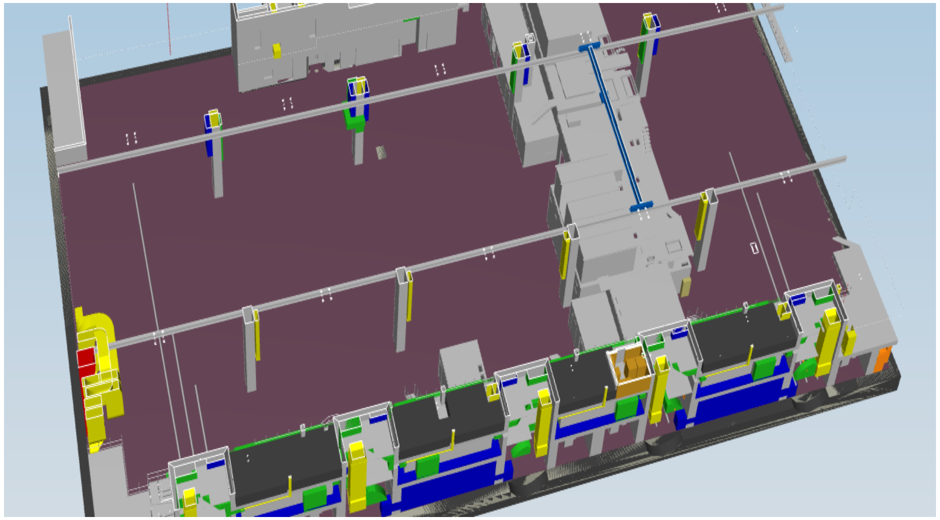
Installation Activities Photon Beam Lines

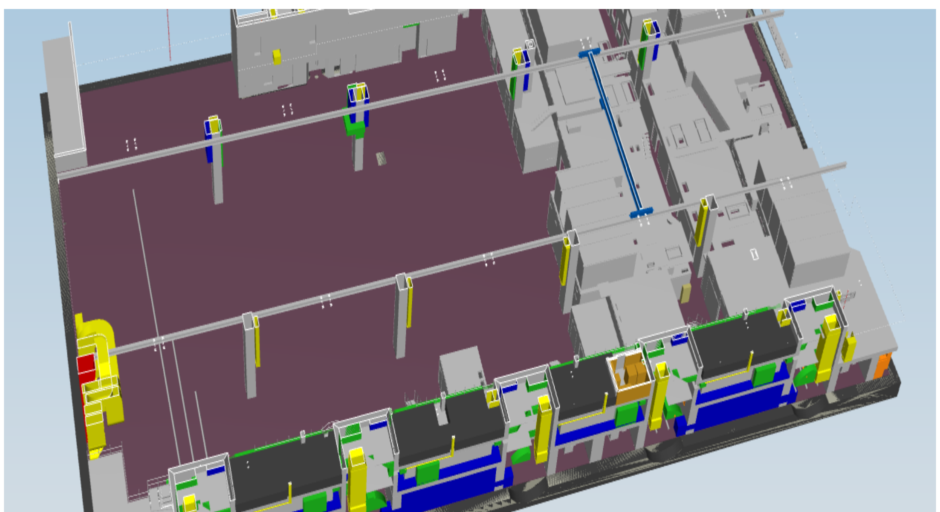


courtesy of XFEL.EU

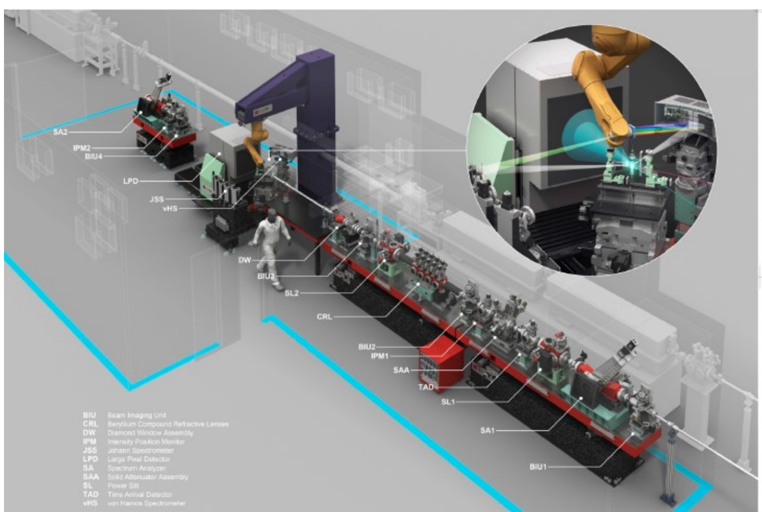
Installation Activities
Photon Beam Lines

SASE1 and SASE3 Hutches Installation





SASE1 stations FXE and SPB/SFX just prior to instrument installation



Courtesy by European XFEL/Rey.Hori

Summary and Outlook

- Accelerator module production / testing / installation comes to an end
- Based on injector experience and accelerator module performance we are looking forward to reaching all design parameters
- Tunnel closure is expected for end Q3/2016
- Technical commissioning continues after first cool-down
- **The milestone ‚first lasing possible' is scheduled 6 months after ‚tunnel closure'**
- User operation will start in 2017
- Full performance is expected approx. 1.5 years after first lasing

more than 1000 participants
at the 2016 users' meeting