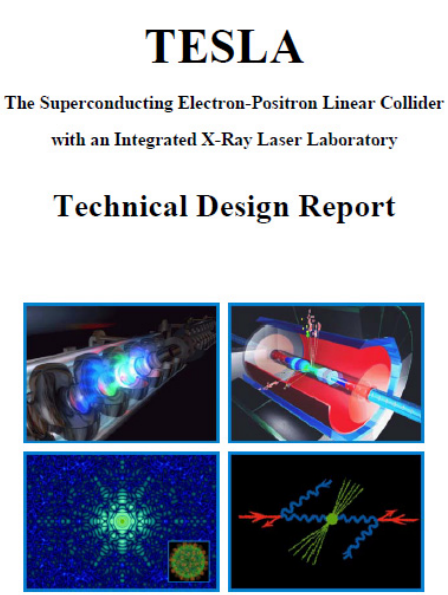
The High Power RF System for the European XFEL

Stefan Choroba, DESY
for the XFEL WP HPRF

LINAC2018
Beijing, China, 19/09/2018

Descent of the XFEL HPRF

- Early 1990s start of the TESLA Collaboration
- In 1990s Tesla Test Facility (TTF) setup at DESY
- 2001 TESLA TDR of a Linear Collider with integrated XFEL
- 2002 Supplement to the TDR on a dedicated linac for the XFEL, negotiations started to build the XFEL as European project at DESY
- 2006 TDR of the European XFEL
- June 5, 2007 official launch European XFEL
- First beam 2017
- 2004 ITRP recommended superconducting technology for a future Linear Collider => ILC

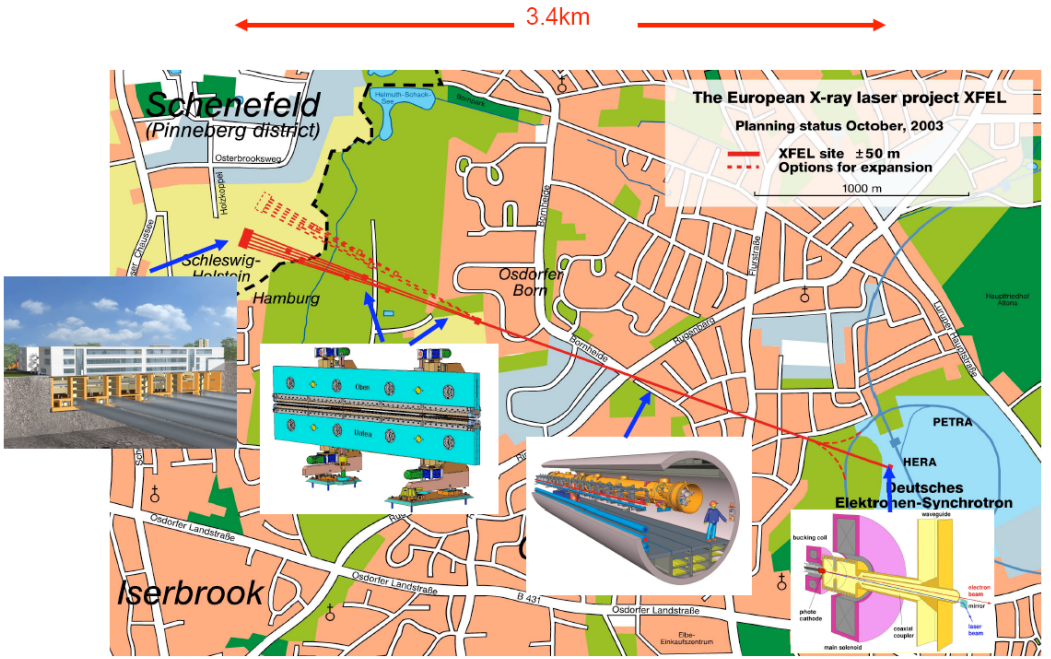


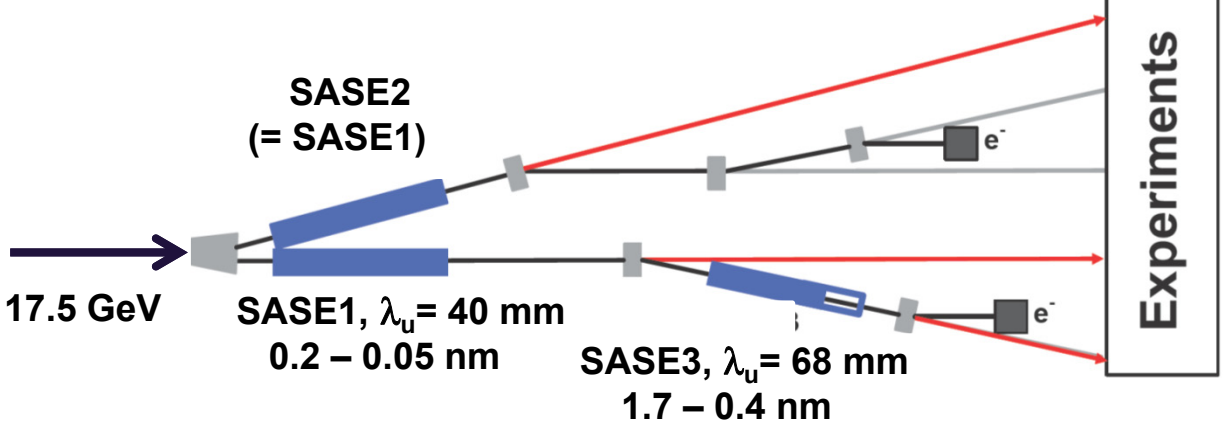
European XFEL

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

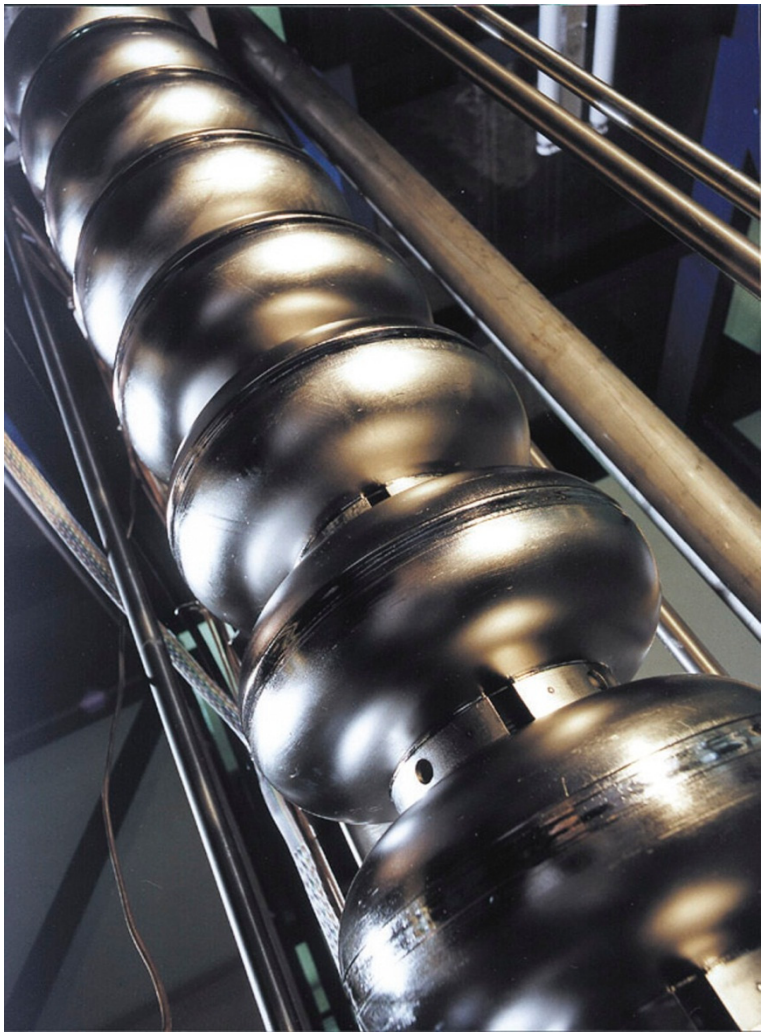




Presentation by Dirk Nölle FR2A02

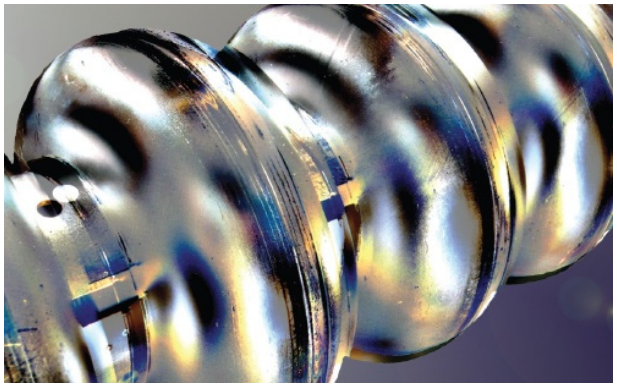
1.3GHz superconducting cavities

- 1.3GHz 9-cell Tesla type
- Average gradient 23.6MV/m
- Coaxial input coupler
- 8 cavities per cryo modules

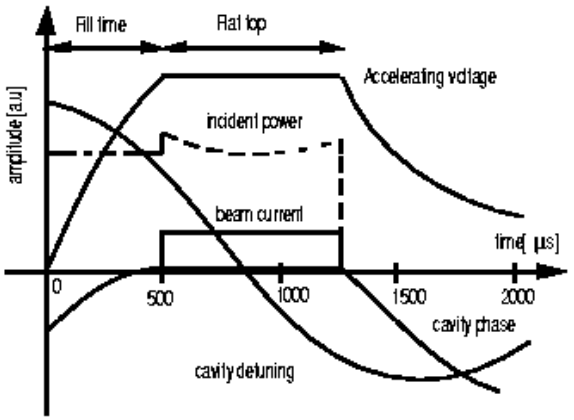


XFEL Cold Linac

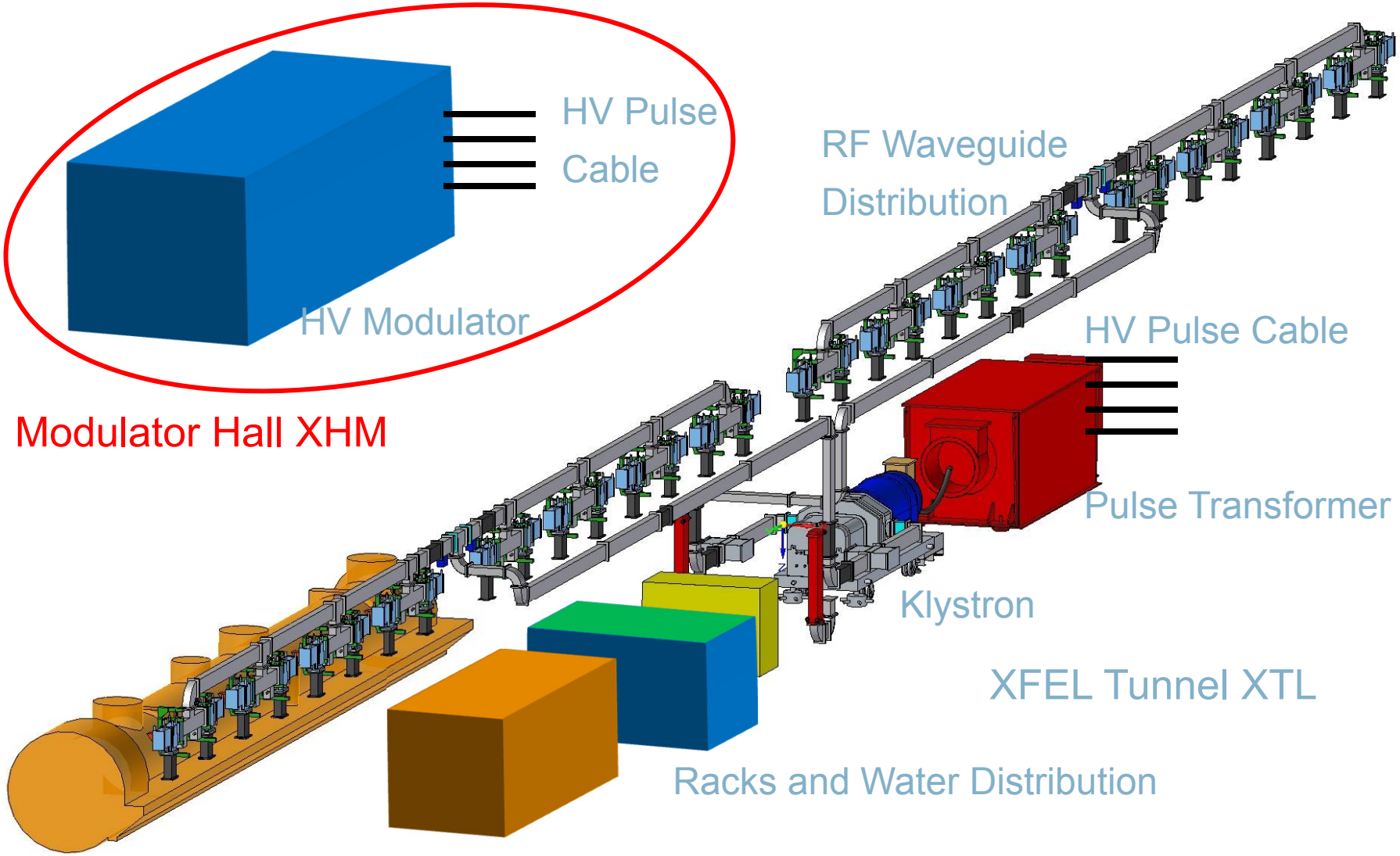
XFEL High Power RF Requirements



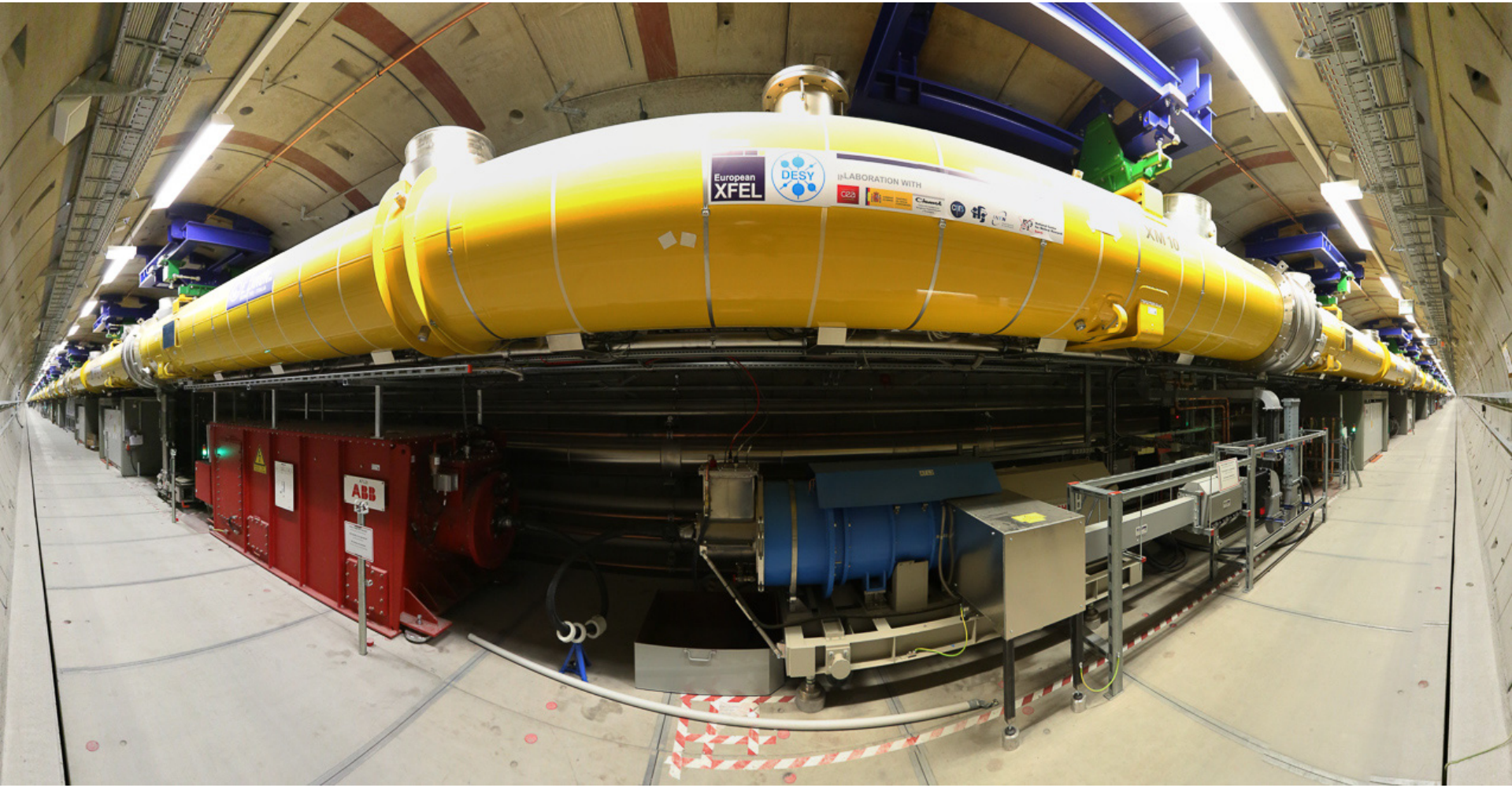
- Number of sc cavities: 776 total for **17.5GeV**
- Power per cavity: **122 kW**
- Gradient at 17.5GeV: **23.6 MV/m**
- Power per 32 cavities (4 cryo modules): 3.9MW
- Power per RF station: **5.2MW** (including 10% losses in waveguides and circulators and a regulation reserve of 15%)
- Number of RF stations: **26** 24 main linac, 2 injector
- Macro beam pulse duration: 600µs
- RF pulse duration: **1.38ms**
- Repetition rate: **10Hz (25Hz)**
- Average RF power per station: **72kW (150kW)**



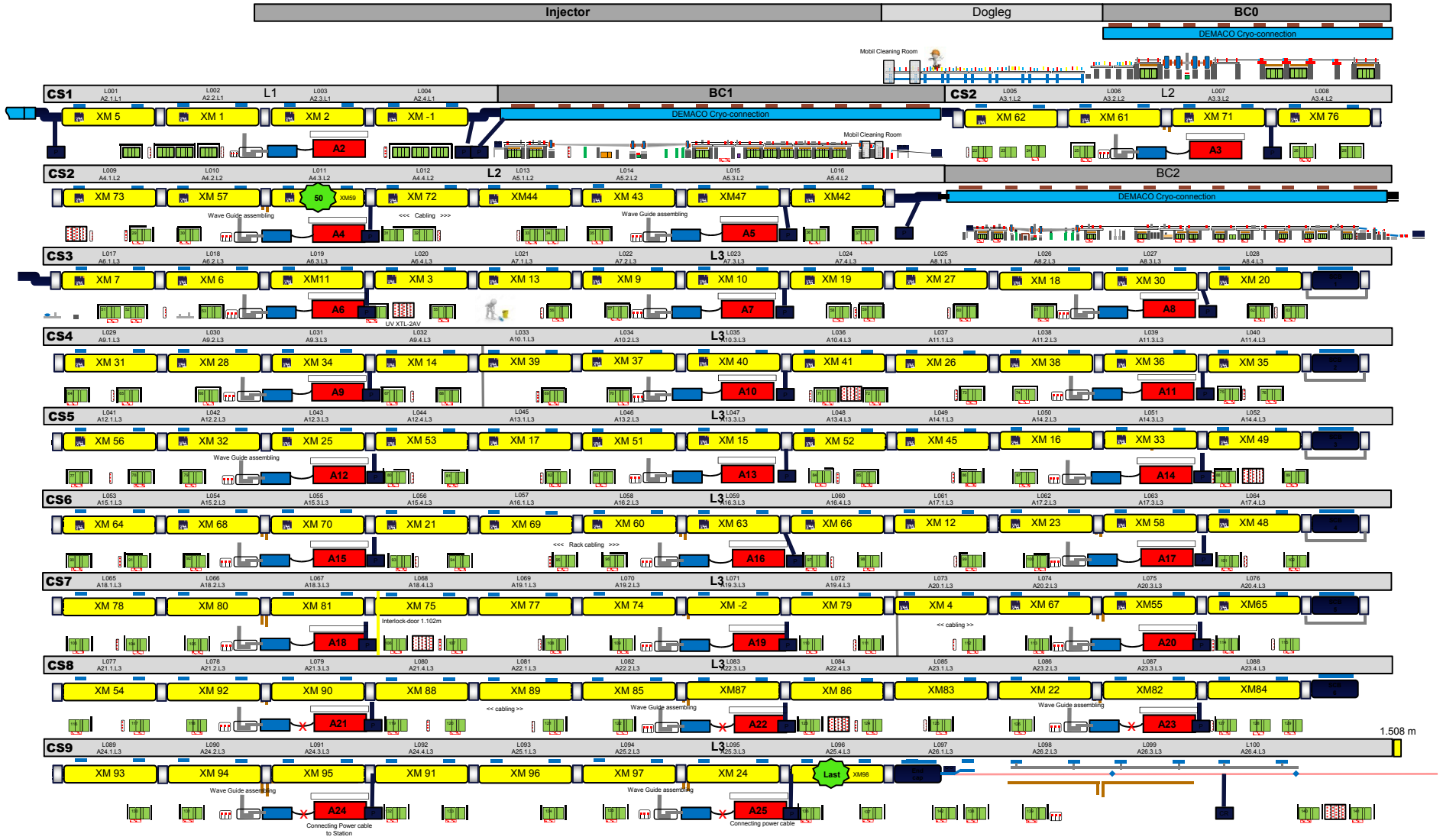
XTL RF Station Overview



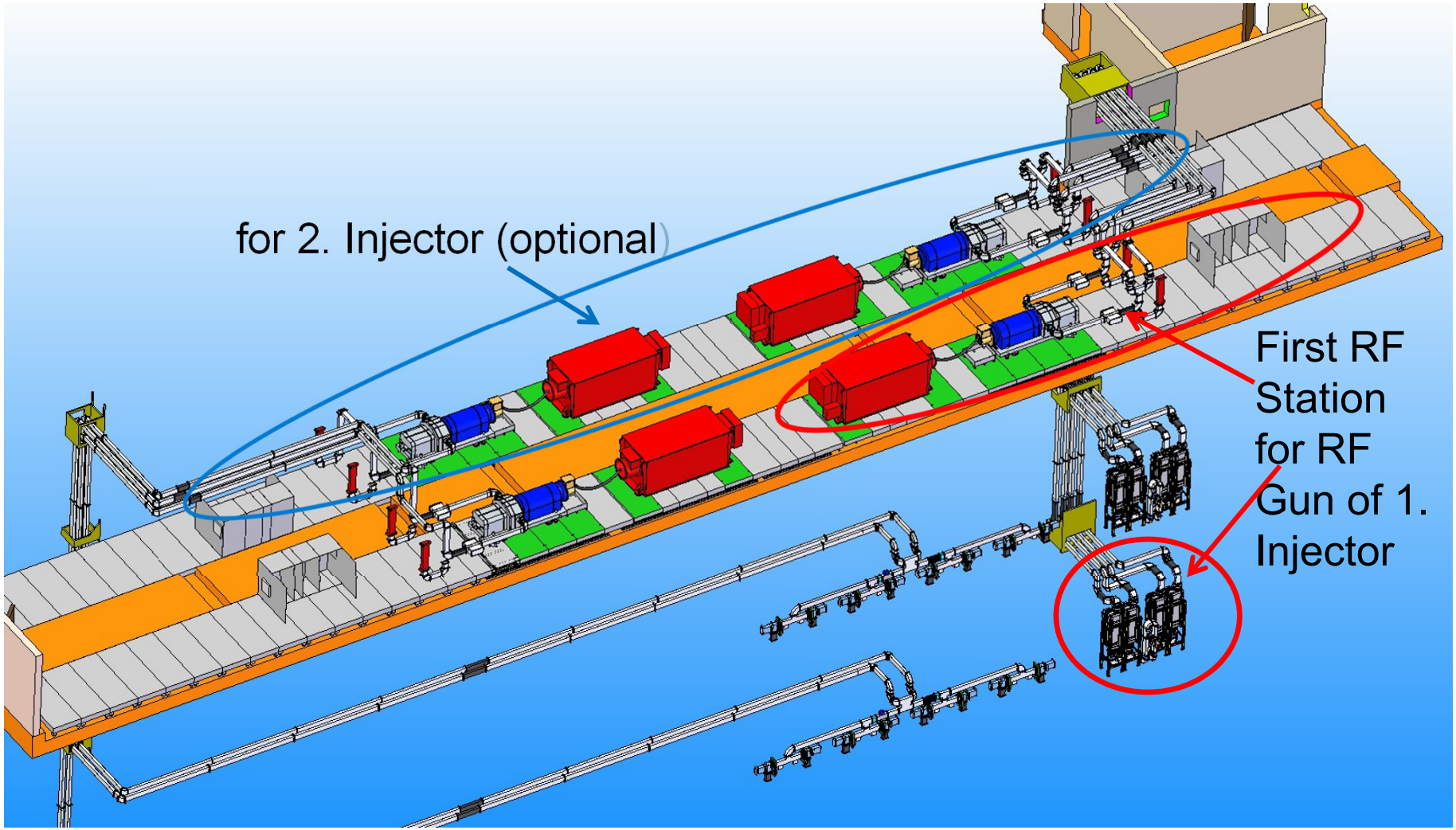
XFEL RF Station in Main Linac



XFEL Linac


Injector
Dogleg
BC0
DEMACO Cryo-connection
Mobil Cleaning Room
CS1
L1
BC1
CS2
L2
DEMACO Cryo-connection
XM 5
XM 1
XM 2
XM -1
XM 62
XM 61
XM 71
XM 76
A2
A3
CS2
L2
BC2
DEMACO Cryo-connection
XM 73
XM 57
50
XM59
XM 72
XM44
XM 43
XM47
XM42
Wave Guide assembling
<<< Cabling >>>
A4
A5
CS3
L3
XM 7
XM 6
XM11
XM 3
XM 13
XM 9
XM 10
XM 19
XM 27
XM 18
XM 30
XM 20
A6
A7
A8
UV XTL-2AV
CS4
L3
XM 31
XM 28
XM 34
XM 14
XM 39
XM 37
XM 40
XM 41
XM 26
XM 38
XM 36
XM 35
A9
A10
A11
CS5
L3
XM 56
XM 32
XM 25
XM 53
XM 17
XM 51
XM 15
XM 52
XM 45
XM 16
XM 33
XM 49
Wave Guide assembling
A12
A13
A14
CS6
L3
XM 64
XM 68
XM 70
XM 21
XM 69
XM 60
XM 63
XM 66
XM 12
XM 23
XM 58
XM 48
<<< Rack cabling >>>
A15
A16
A17
CS7
L3
XM 78
XM 80
XM 81
XM 75
XM 77
XM 74
XM -2
XM 79
XM 4
XM 67
XM55
XM65
interlock-door 1.102m
<< cabling >>
A18
A19
A20
CS8
L3
XM 54
XM 92
XM 90
XM 88
XM 89
XM 85
XM87
XM 86
XM83
XM 22
XM82
XM84
<< cabling >>
Wave Guide assembling
Wave Guide assembling
A21
A22
A23
CS9
L3
XM 93
XM 94
XM 95
XM 91
XM 96
XM 97
XM 24
Last
XM98
Wave Guide assembling
Wave Guide assembling
A24
A25
Connecting Power cable to Station
Connecting power cable
1.508 m
European XFEL

Injector RF Station Overview

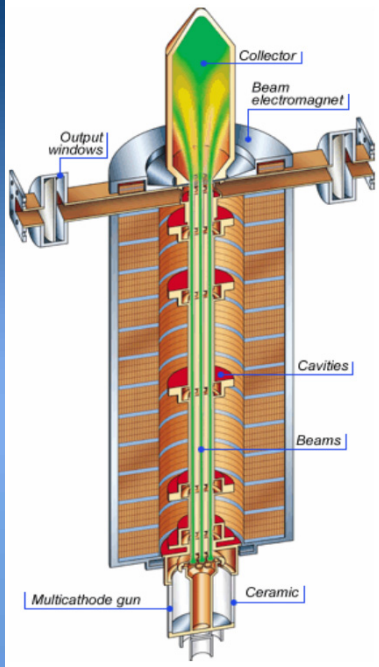


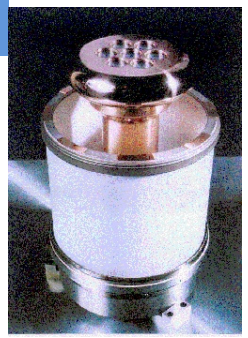
XFEL Injector RF Station

- RF Gun RF station: typ. **5MW** up to **6.5MW at RF Gun (~7MW generated by the Klystron max. 10MW), 650μs, 10Hz** (taking into account losses in waveguide distribution system)
- Cryomodule RF station: **1.3MW, 1.38ms, 10Hz** (as for main linac, but one quarter of RF power)
- Klystrons, pulse transformers, racks for the injector are on the 3rd underground floor of the injector building. RF power is transmitted in waveguides to the 7th underground floor.

Multi Beam Klystron as RF Power Source

RF Frequency:	1.3GHz	
Cathode Voltage:	< 120kV	**low high voltage**
Beam Current:	< 140A	
µperveance:	< 3.5	
Max. RF Peak Power:	10MW	**high power**
RF Pulse Duration:	1.5ms	**long pulse**
Repetition Rate:	10Hz	
RF Average Power:	150kW	
Efficiency:	65%	**high efficiency**
Gain:	48.2dB	
Solenoid Power:	6kW	
Length:	2.5m	
Lifetime (goal):	~40000h	



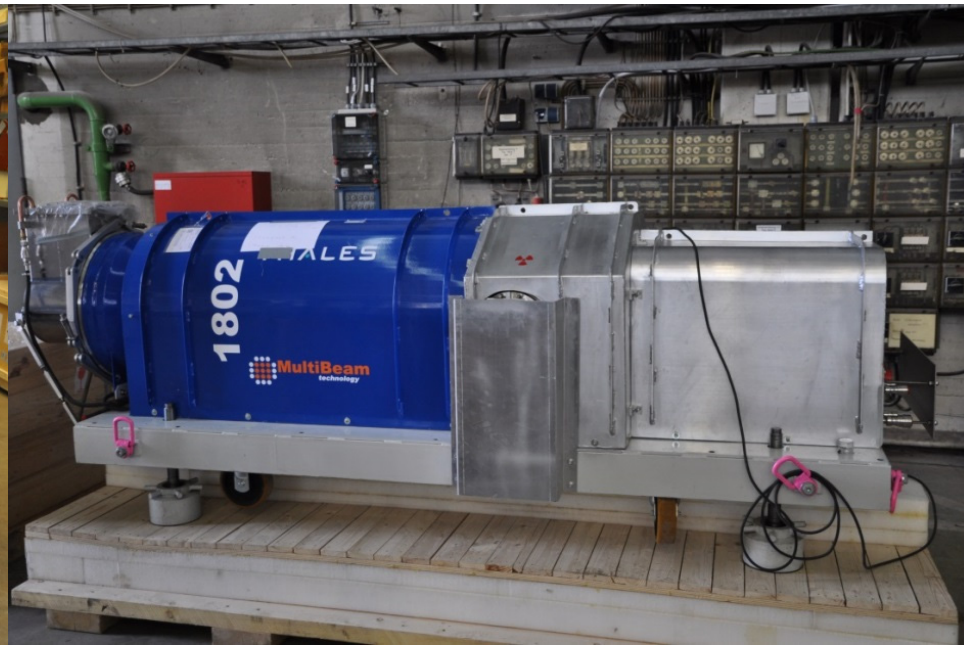


Multi Beam Klystron

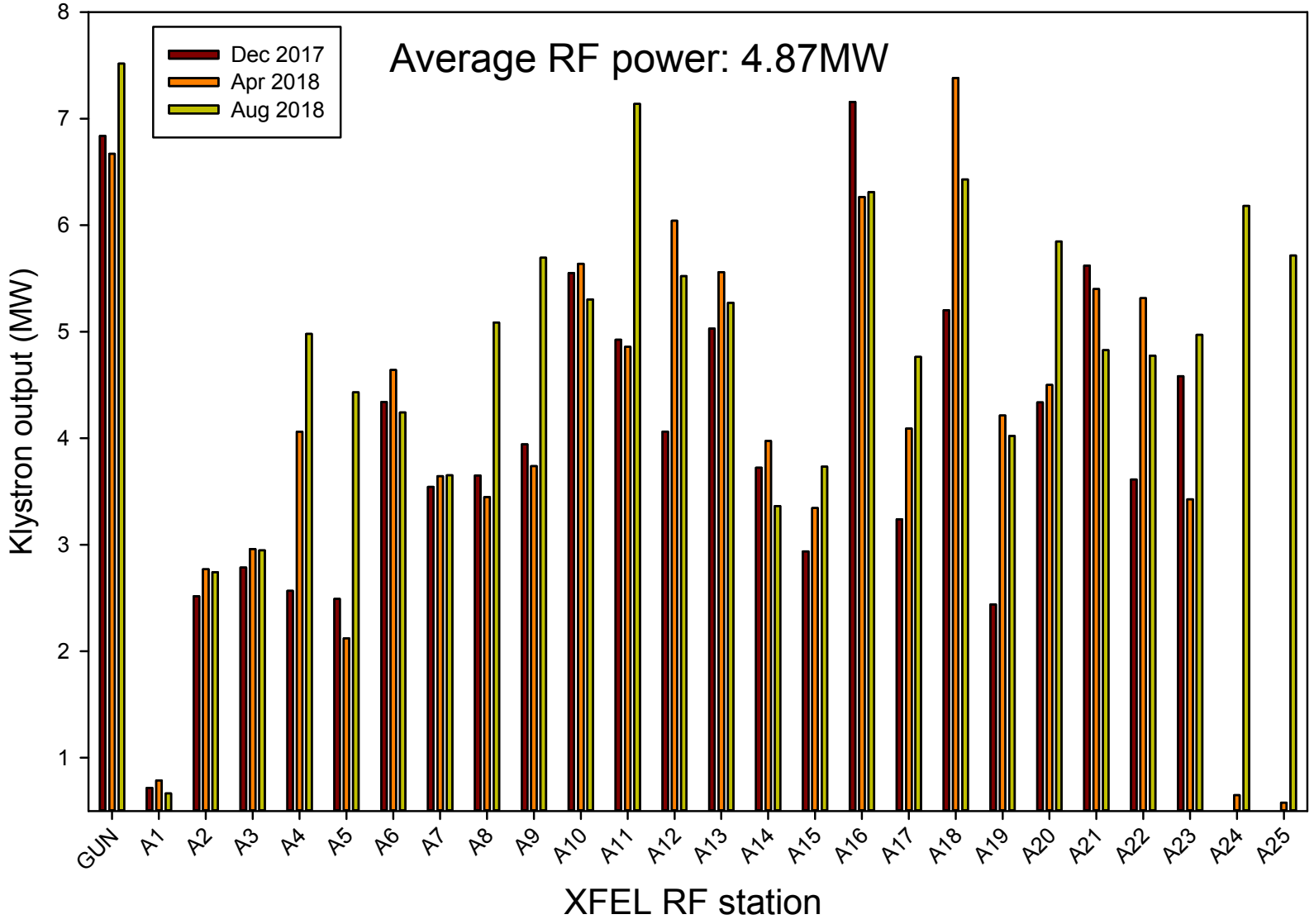
3 vendors developed MBKs meeting the requirements, 2 have been selected as suppliers

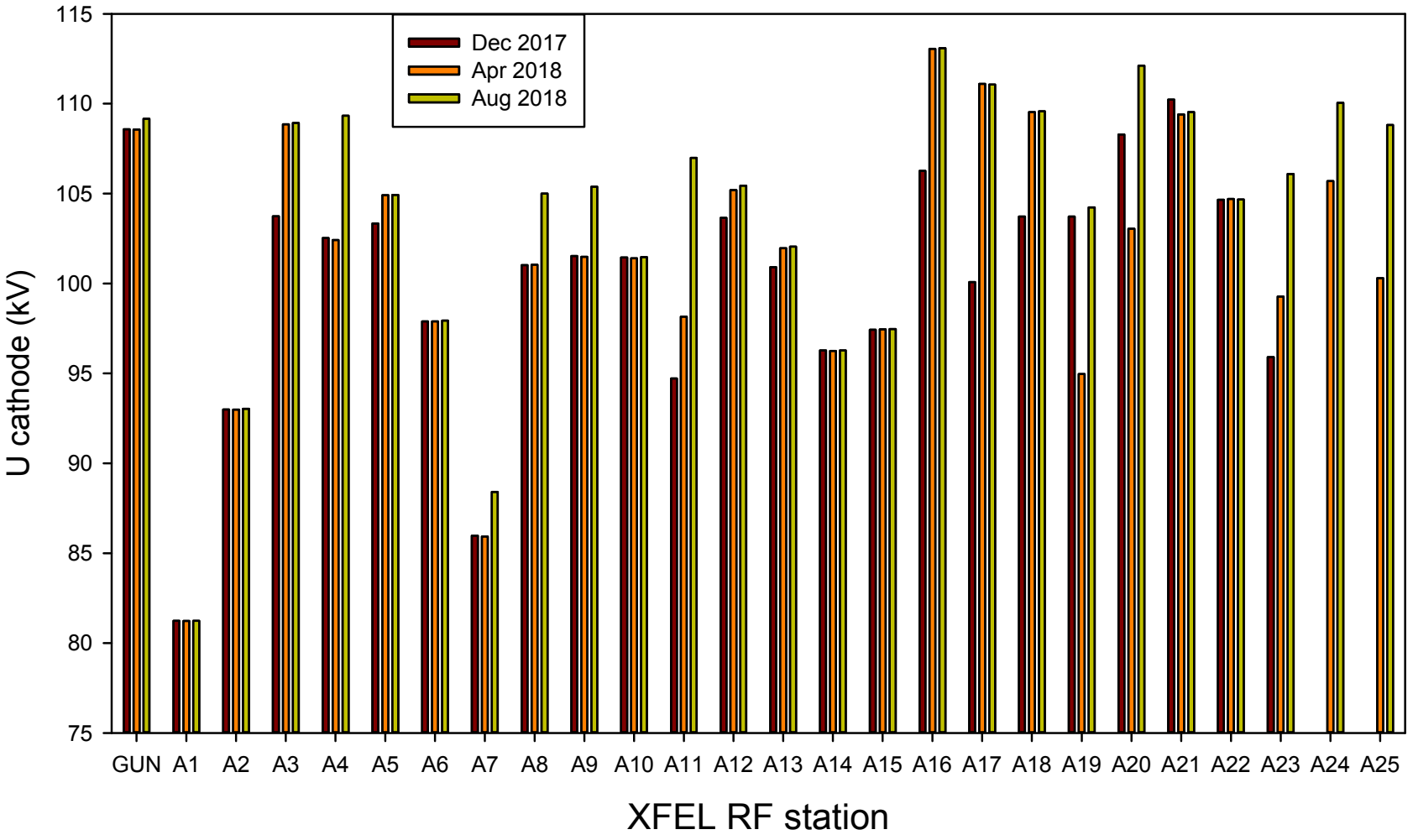
Presentation by Vladimir Vogel MOPO036

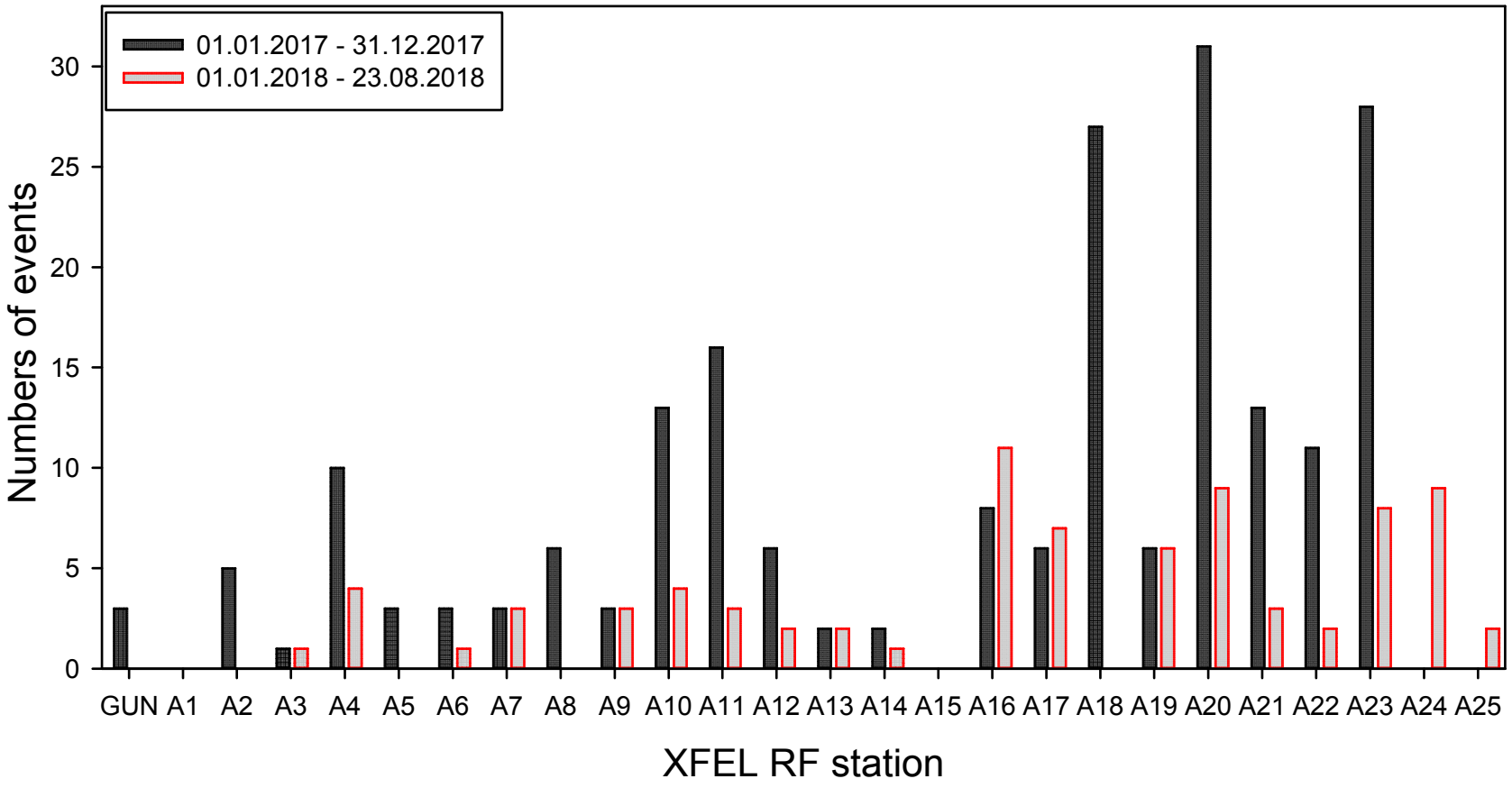
7 (6) pcs Toshiba E3736H



22 (20) pcs Thales TH1802

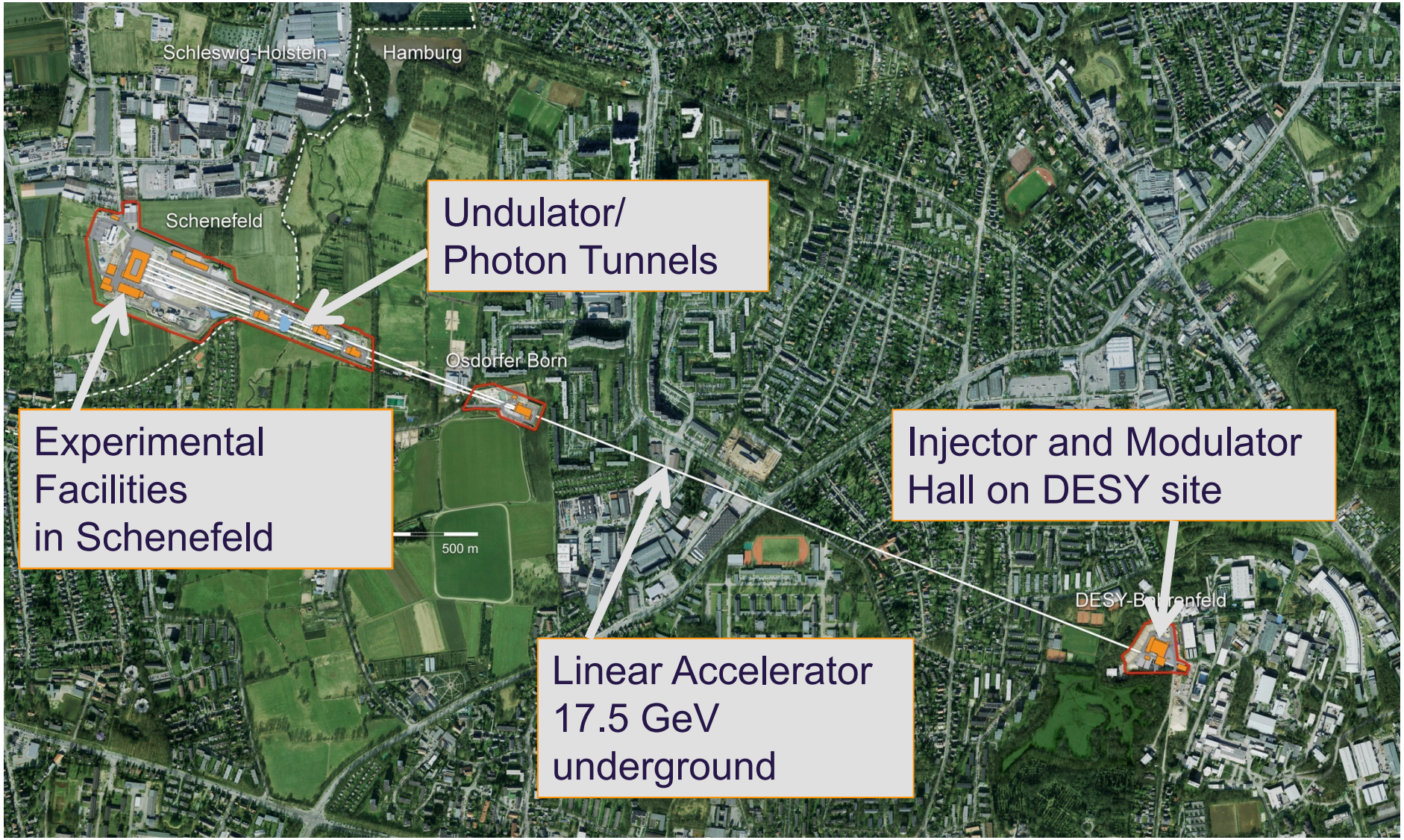

Average RF power: 4.87MW
Dec 2017
Apr 2018
Aug 2018
Klystron output (MW)
XFEL RF station
8
7
6
5
4
3
2
1
GUN
A1
A2
A3
A4
A5
A6
A7
A8
A9
A10
A11
A12
A13
A14
A15
A16
A17
A18
A19
A20
A21
A22
A23
A24
A25


Dec 2017
Apr 2018
Aug 2018
U cathode (kV)
115
110
105
100
95
90
85
80
75
GUN A1 A2 A3 A4 A5 A6 A7 A8 A9 A10 A11 A12 A13 A14 A15 A16 A17 A18 A19 A20 A21 A22 A23 A24 A25
XFEL RF station



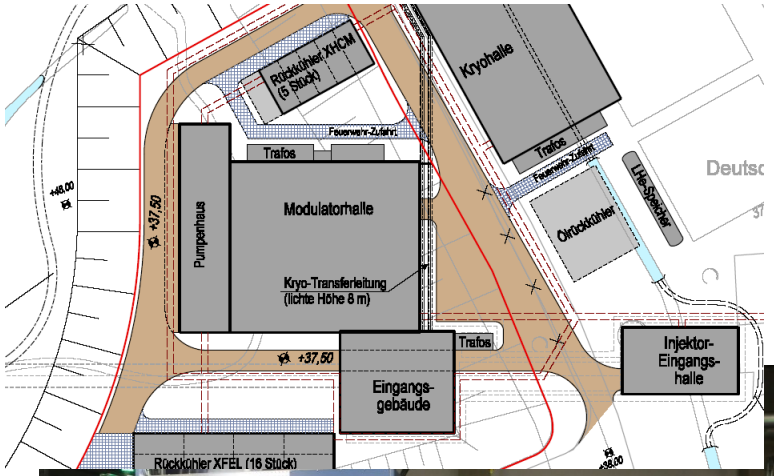
Average trip rate 0.443 klystron trip per day

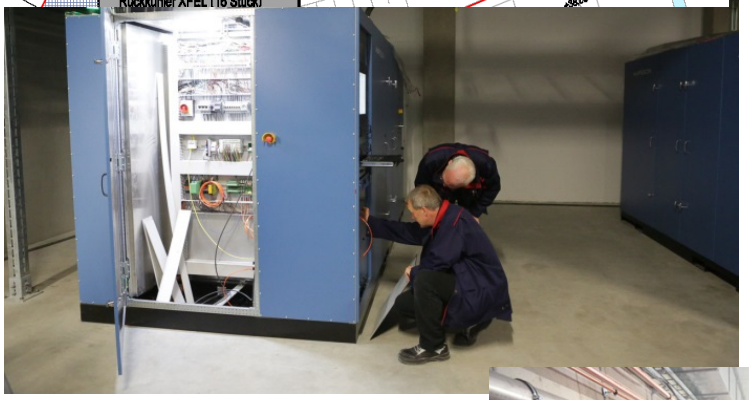
European XFEL Layout

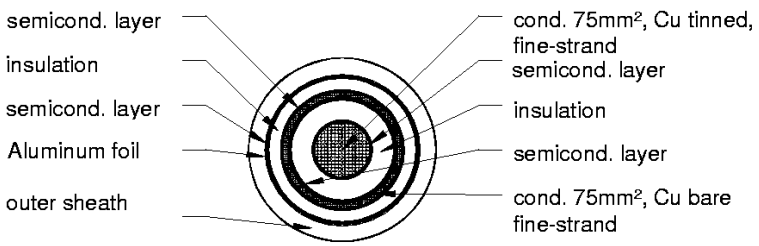


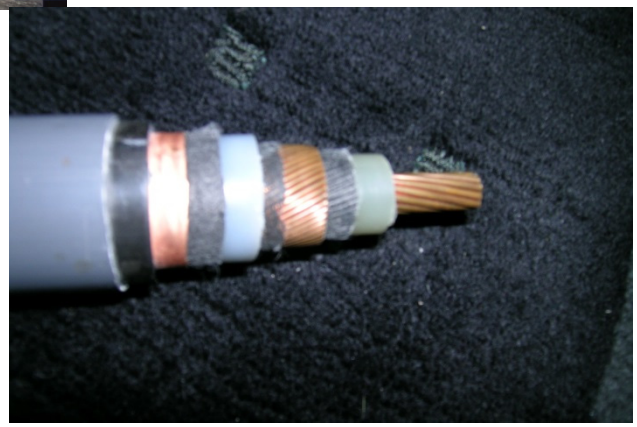
Modulators

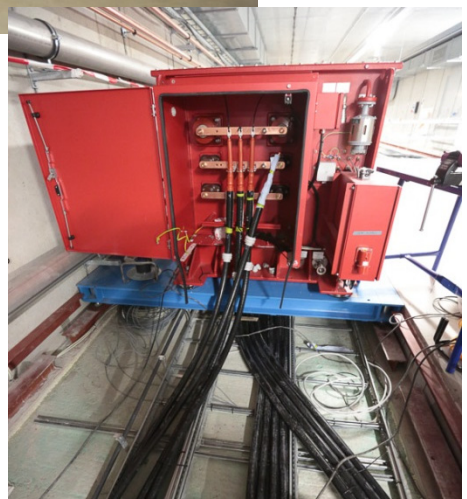
- HV Pulsers Modulator are located in a separate hall near the injector and each modulator is connected to a pulse transformer in the tunnel or injector by 4 triaxial pulse cables up to 1.5km long.





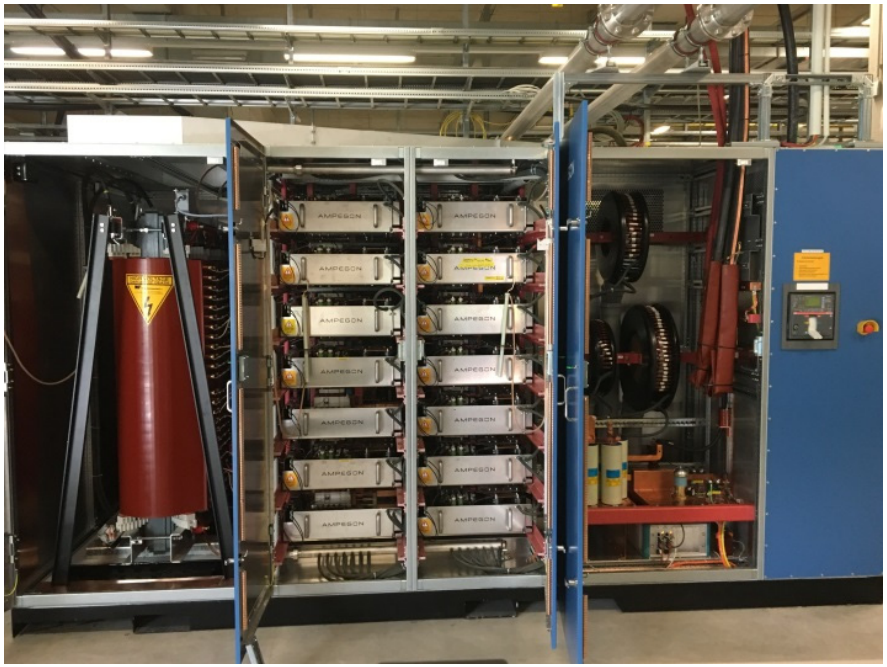


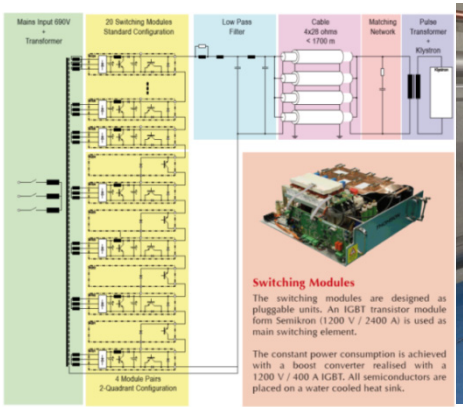




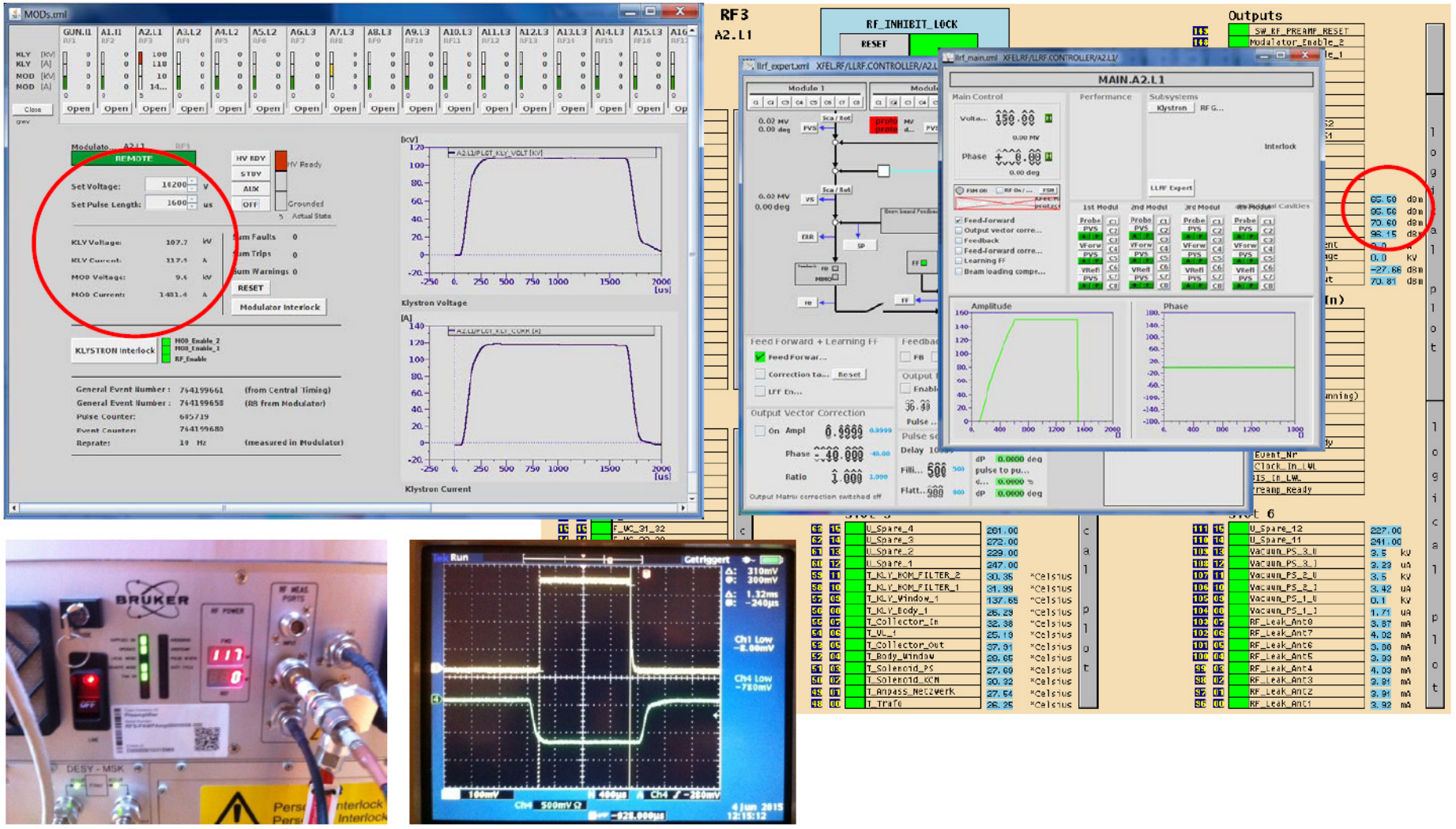
HV Pulse Modulator

	typical	max.
Modulator Pulse Voltage	9.6kV	12kV
Modulator Pulse Current	1.62kA	1.8kA
Klystron Gun Voltage	115kV	132kV
Klystron Gun Current	135A	150A
High Voltage Pulse Duration (70% to 70%)	1.57ms	1.7ms
High Voltage Rise and Fall Time (0 to 99%)	0.15ms	0.2ms
High Voltage Flat Top (99% to 99%)	1.37ms	1.5ms
Pulse Flatness during Flat Top	±0.2%	±0.3%
Pulse-to-Pulse Voltage fluctuation	±0.1%	±0.1%
Energy Deposit in Klystron in Case of Gun Spark	<20J	20J
Pulse Repetition Rate	10Hz	10Hz (30Hz)
Pulse Transformer Ratio	1 :12	1 :12



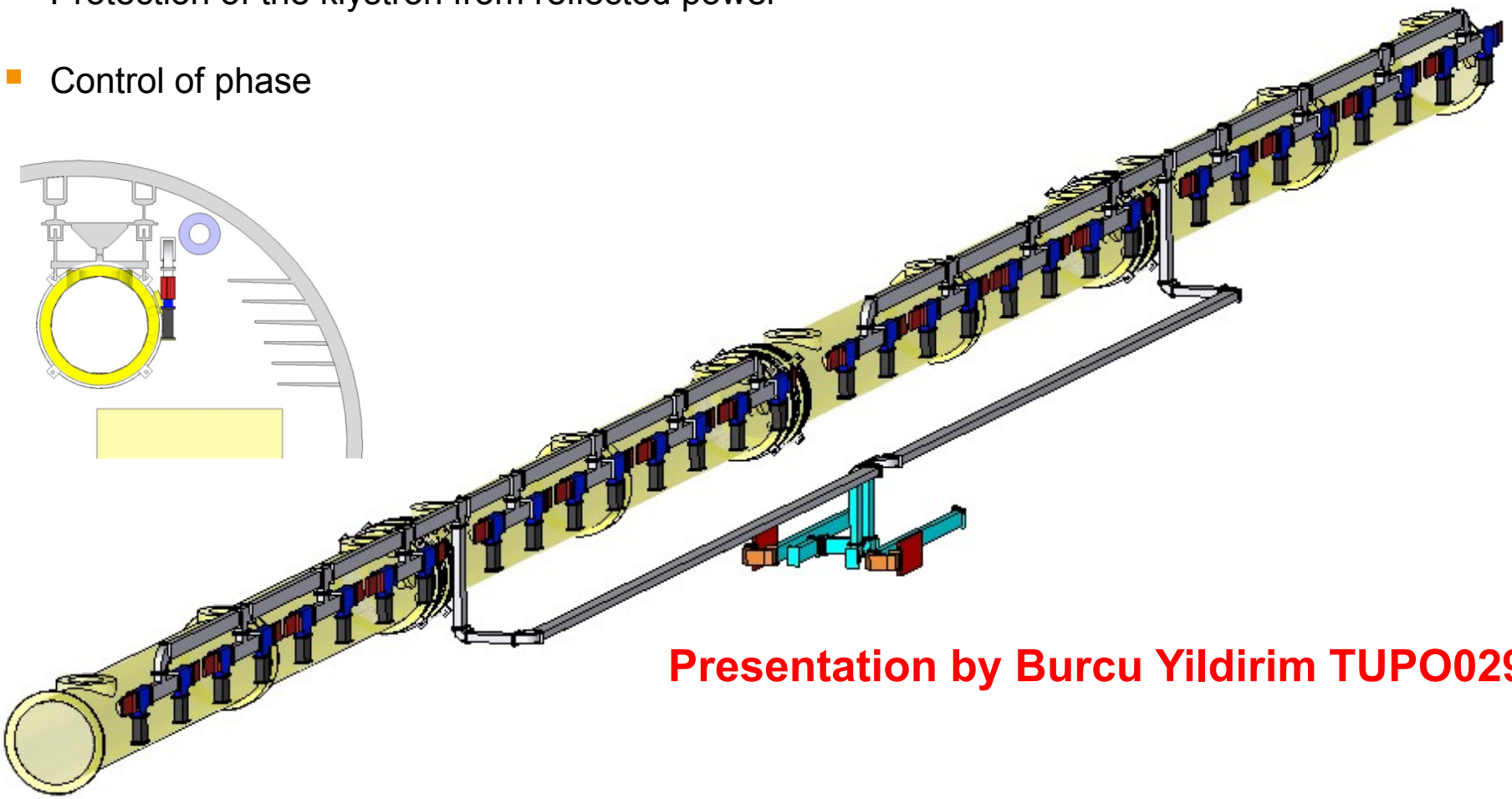


RF Station Signals and Diagnostics



RF Power Distribution

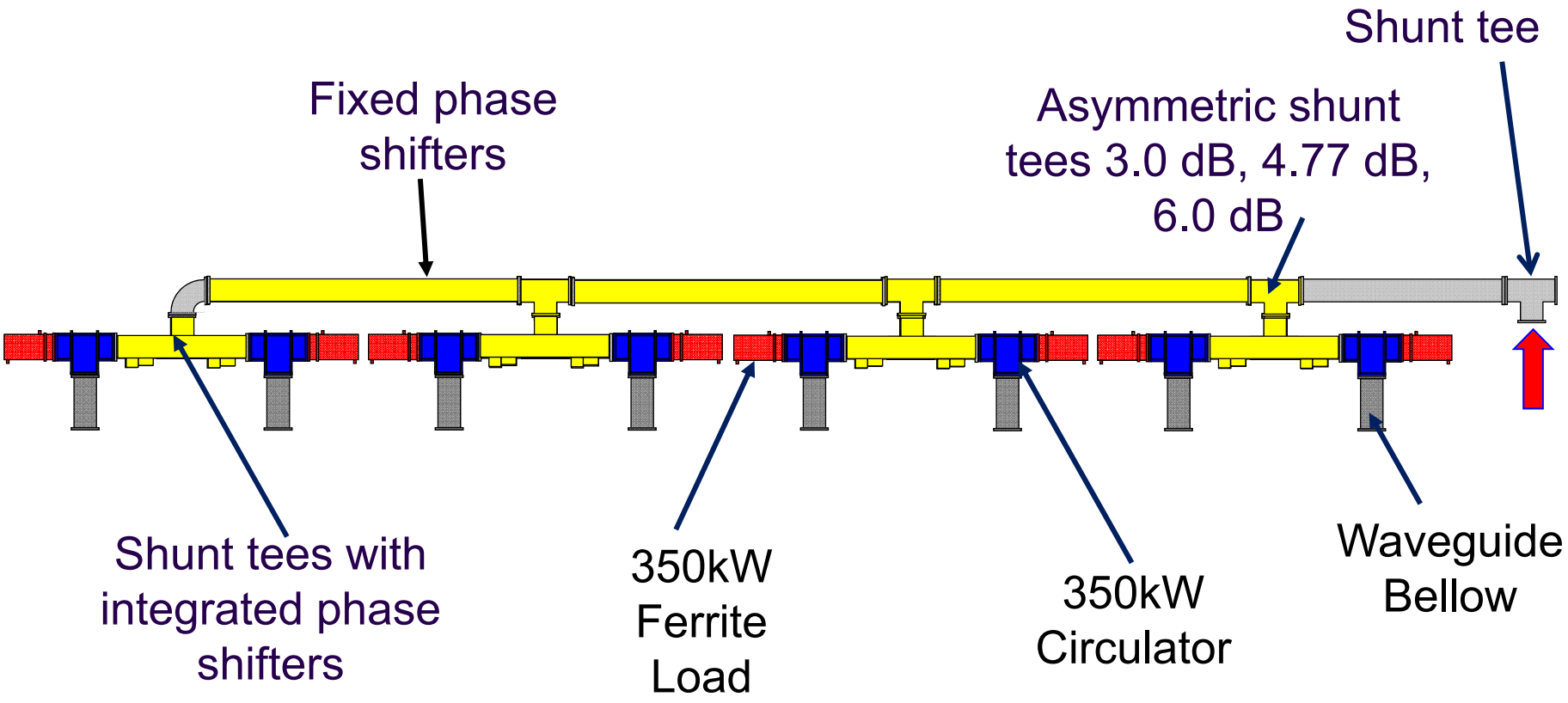
- Distribution of klystron output power to the superconducting cavities
- Protection of the klystron from reflected power
- Control of phase



Presentation by Burcu Yildirim TUPO029

Module Waveguide Distribution

5.2MW, 1.37ms, 10Hz per RF station, equal power to 32 cavities.



Example for Module Measurement Results

Specification for Waveguide Distribution (WD) production

WD number	063
WD type[1]	*Left*
Cryomodule name	*XM70*

Cavity number[2]	1	2	3	4	5	6	7	8
Cavity gradient[3], MV/m	15.7	22.2	30.7	23.0	23.8	26.8	31.0	27.3
Cavity power[4], kW	59	118	225	127	136	172	230	178

P_{WD} [5] ≈ 1.2 MW

1 *WD position in the RF station* L(1) R(2) L(3) R(4)
2 *Cavity number in the beam direction*
3 *The smaller number for a pair of cavities will used*
4 *Cavity power is calculated by MHF-p based on accelerator parameters from XFEL TDR*
5 *Preliminary estimation of waveguide distribution power*

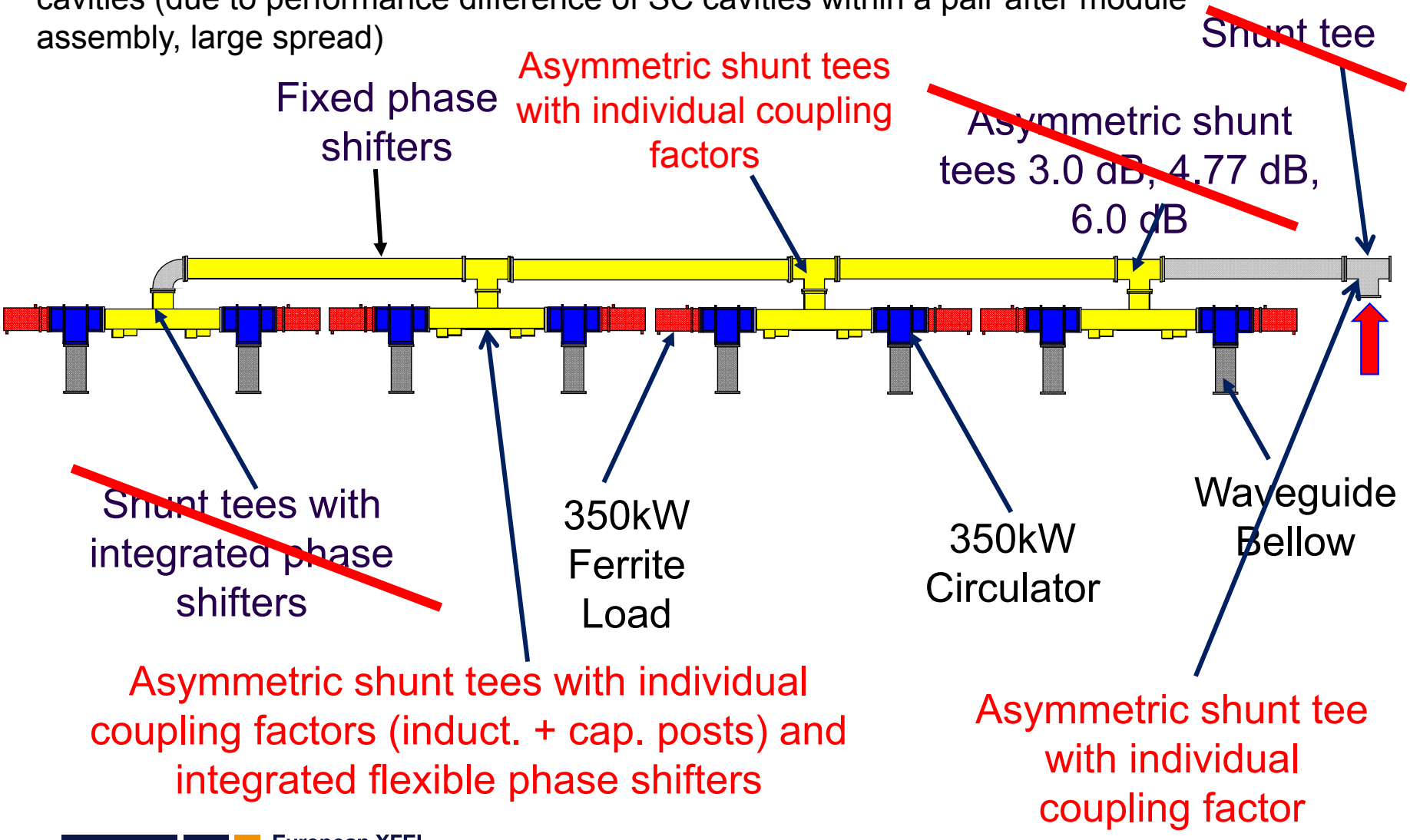
Signed for and behalf of WP01

B. Yildirim

Data 08.12.2015

Module Waveguide Distribution, updated Requirements

Allow for adjustment of power for individual cavities and modules and for large spread of cavities (due to performance difference of SC cavities within a pair after module assembly, large spread)



WATF (Waveguide Assembly and Test Facility)

- Acceptance, test and preparation of subsystems (waveguide components, cables, cooling system, supports), specification, assembly, test of waveguide distributions and connection
- 4 working places – Binary cell assembly and tuning, WD assembly and mechanical adjustment, LLRF and HPRF stand
- 12 specific test stands for tuning and adjustment of WD component (input geometrical control, air tightness test, step motor test, WG cleaning and drying, shunt tee tuning etc.)
- Measurement process is automated
- Storage place for 6 WD components plus 7 complete WD
- Production rate – 2 tailored WD per week
- Connection to modules in AMTF area

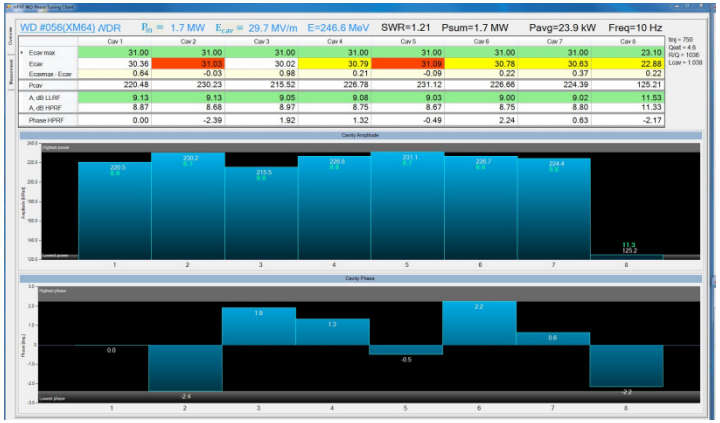
WD and Cryomodule at AMTF

- WD connection to cryomodule with special 6 DoF (degree of freedom) setup at AMTF
- precision: +/-1.5mm, 0.2 degree at each coupler to avoid stress
- The cryomodule itself is the support for the WD
- WD Installation at cryomodule took about 7 hours

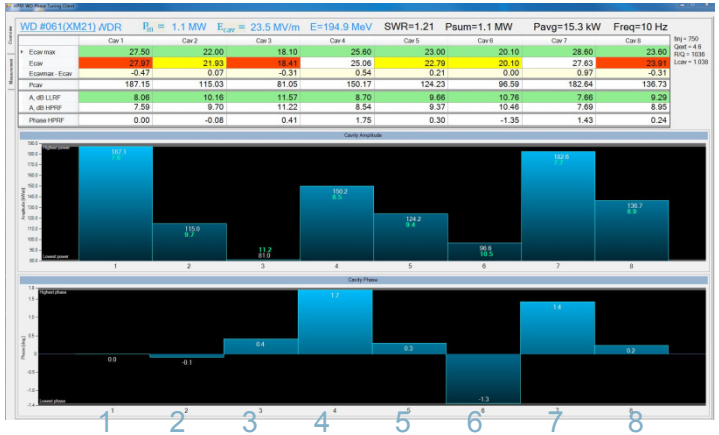
Power pattern for different WDs

High Power RF Test Results Δ = +250 MeV ⇨ 4 new ACC = 5 standard ACC
Tailoring of waveguide distributions allows to reach nominal gradient with less RF stations

WD#56 EXFEL WD = 247 MeV Estandard = 192 MeV



WD#61 EXFEL WD = 195 MeV Estandard = 150 MeV

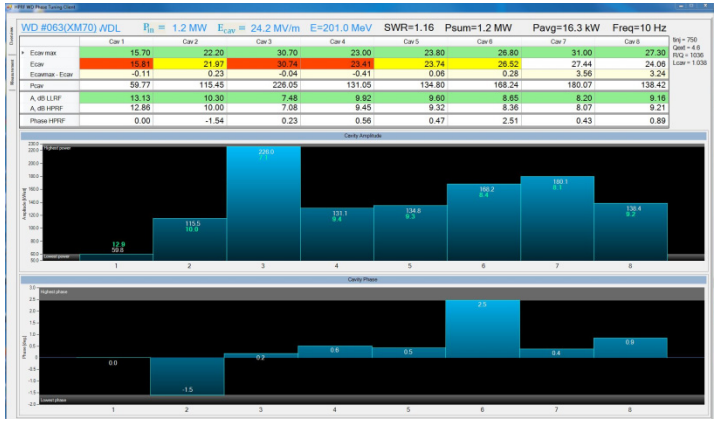


RF Power
Zero supressed

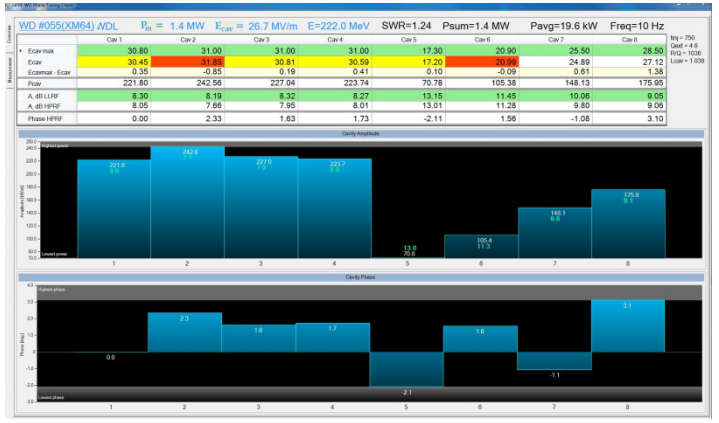
Phase

1 2 3 4 5 6 7 8

WD#63 EXFEL WD = 201 MeV Estandard = 130 MeV



WD#55 EXFEL WD = 222 MeV Estandard = 143 MeV



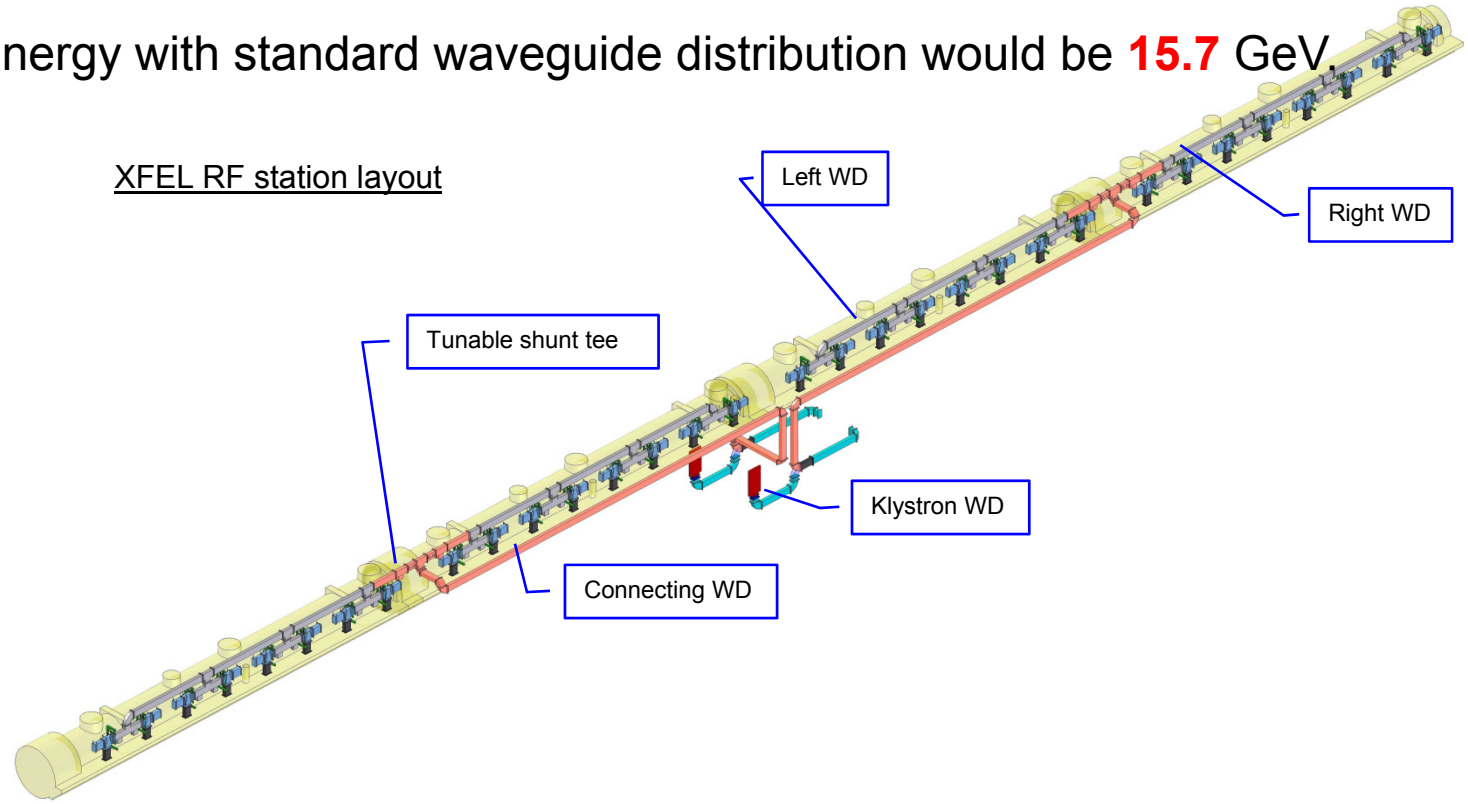
XFEL Waveguide Distribution

Max achievable linac energy is **22.2** GeV (from module test).

Linac energy with specific waveguide distribution is **21.1** GeV (installed) / **19.5** GeV (BC2 energy 2.4GeV).

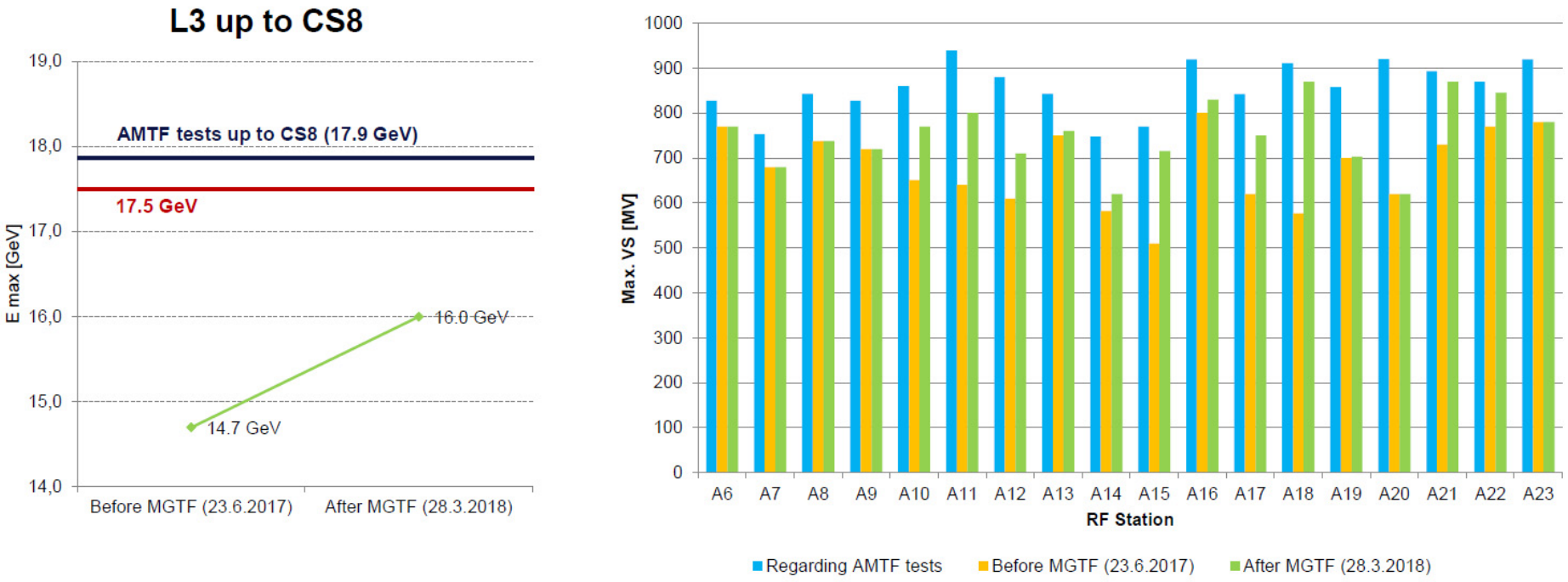
Linac energy with standard waveguide distribution would be **15.7** GeV.

XFEL RF station layout



RF Performance

Courtesy of M. Omet, DESY



Presentation by Julian Branlard MOPO038

Summary

- Installation of RF stations was done until end of 2016.
- Commissioning and operation of RF gun started already in 2014.
- Main linac commissioning and operation started beginning of 2017.
- XFEL is in operation for users.
- Last 2 stations (CS9) were commissioned in spring 2018.
- XFEL reached 17.5GeV in July 2018.
- All 26 RF stations are in operation, minor but no severe problems were detected during commissioning.
- Waveguides might be re-tailoired between modules and at klystron output because of changed cavity performance.

Thank you for your attention