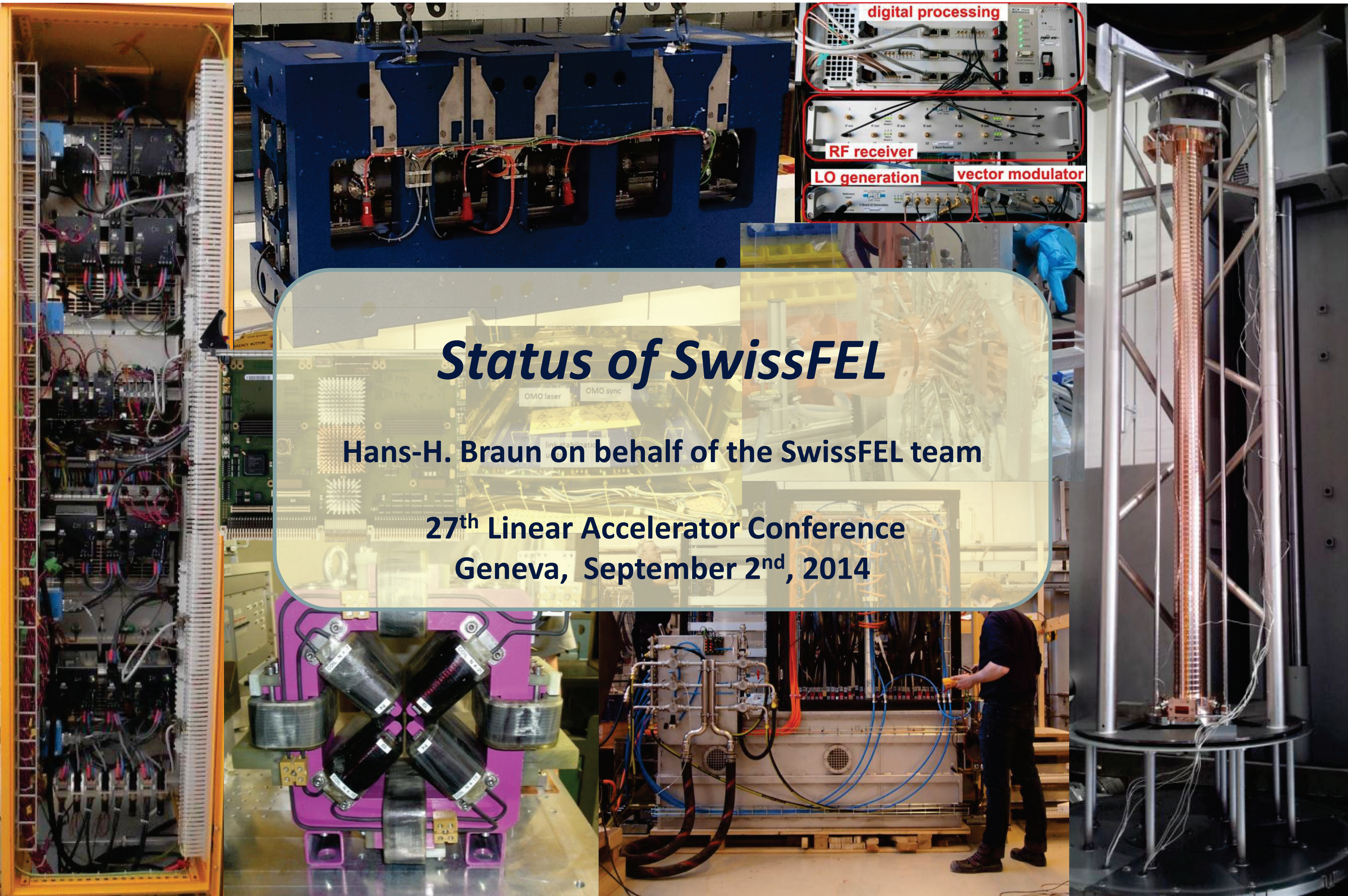
Status of SwissFEL

Hans-H. Braun on behalf of the SwissFEL team

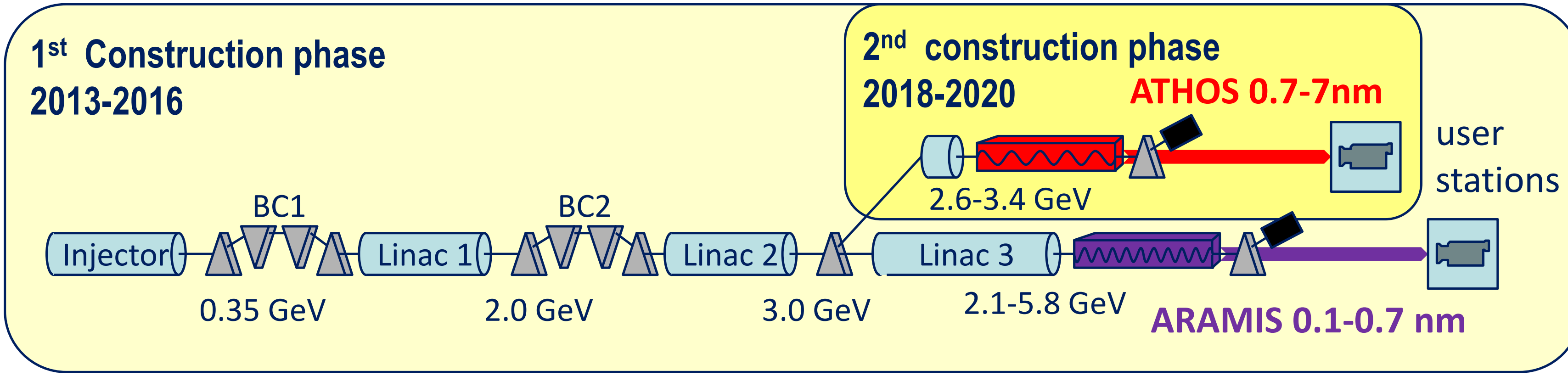
27th Linear Accelerator Conference
Geneva, September 2nd, 2014



Outline

- Overview
- Injector
- Main Linac

SwissFEL in a nutshell



ARAMIS

- Hard X-ray FEL, λ=0.1-0.7 nm
- Linear polarization, variable gap, in-vacuum Undulators
- First users 2017
- Operation modes: SASE & self seeded

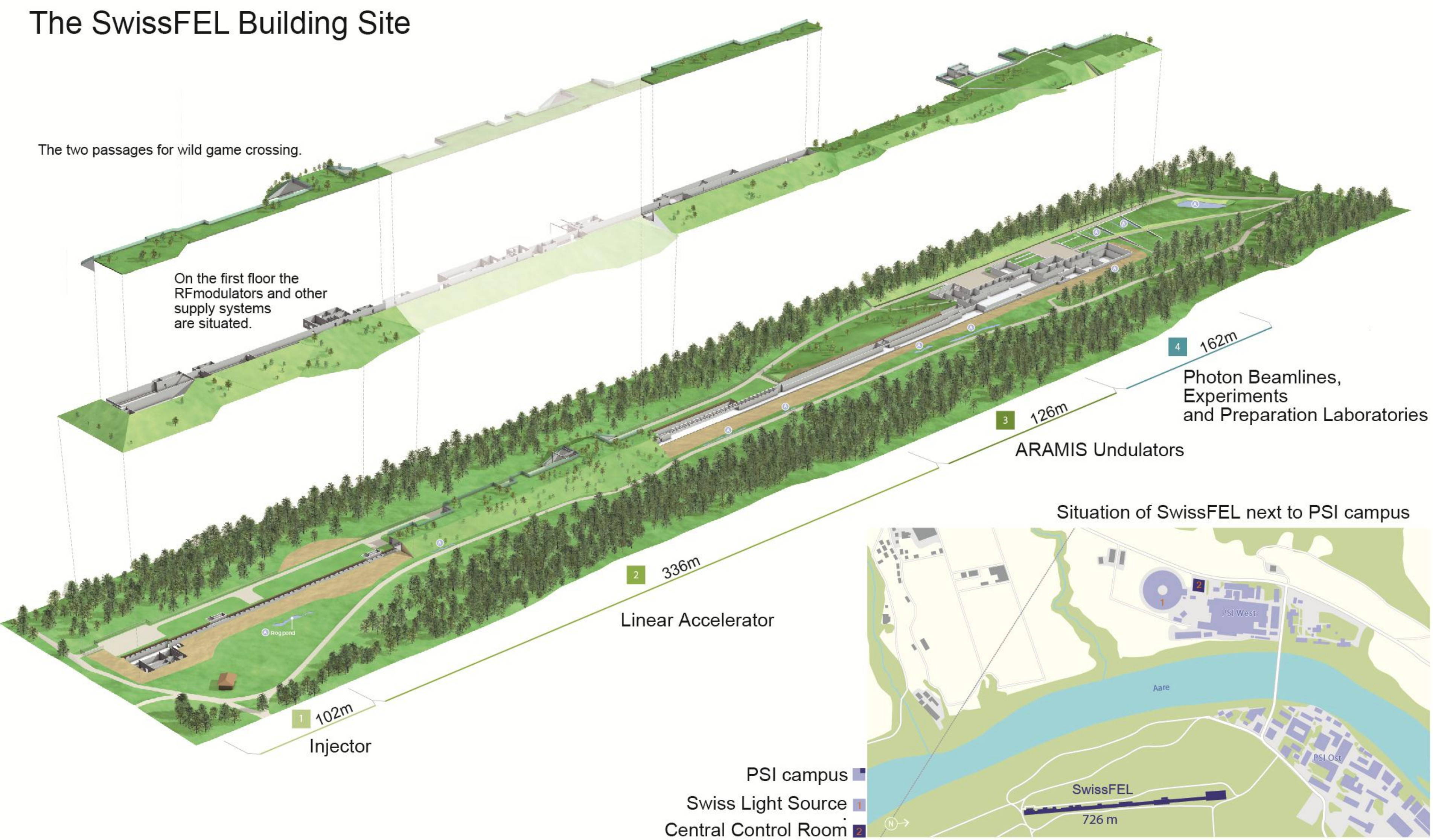
ATHOS

- Soft X-ray FEL, λ=0.7-7.0 nm
- Variable polarization, Apple II undulators
- First users 2020
- Operation modes: SASE & self seeded

Main parameters

Wavelength from	0.1nm–7nm
Photon energy	0.2-12 keV
Pulse duration	1 fs - 20 fs
e^- Energy	5.8 GeV
e^- Bunch charge	10-200 pC
Repetition rate	100 Hz

SwissFEL building



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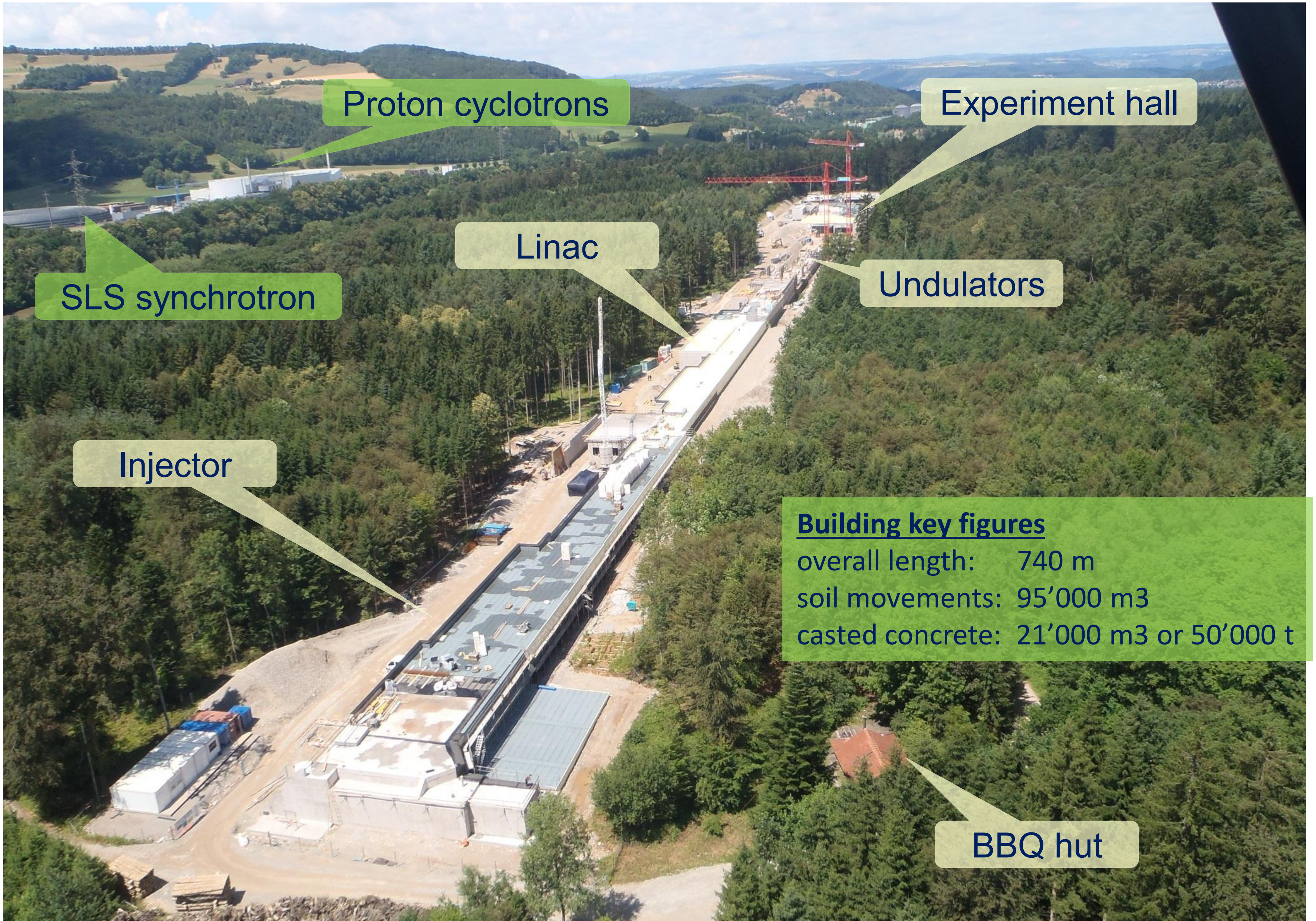
Building location (picture May 2013)

SwissFEL construction site, (picture July 2014)



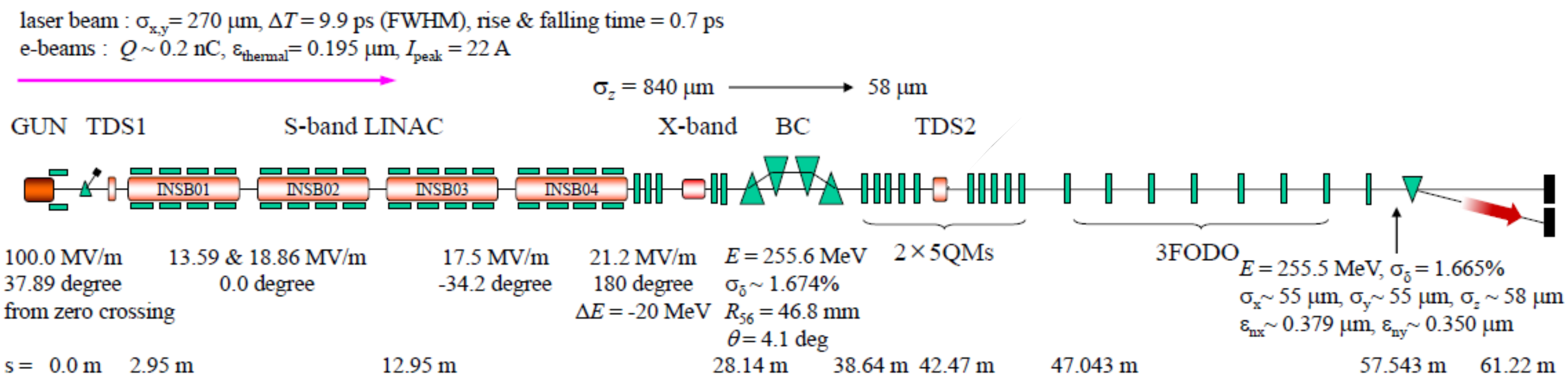
Building key figures

overall length: 740 m

soil movements: 95’000 m3

casted concrete: 21’000 m3 or 50’000 t

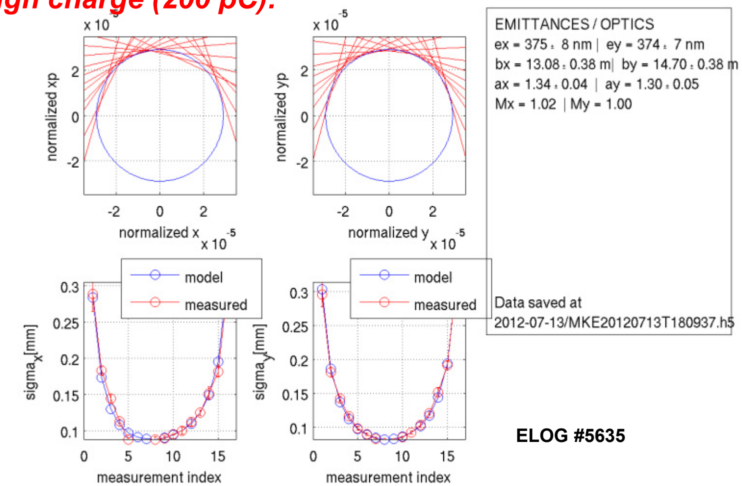
SwissFEL Injector Test-Facility



Injector Emittance Achievements
(uncompressed beam)

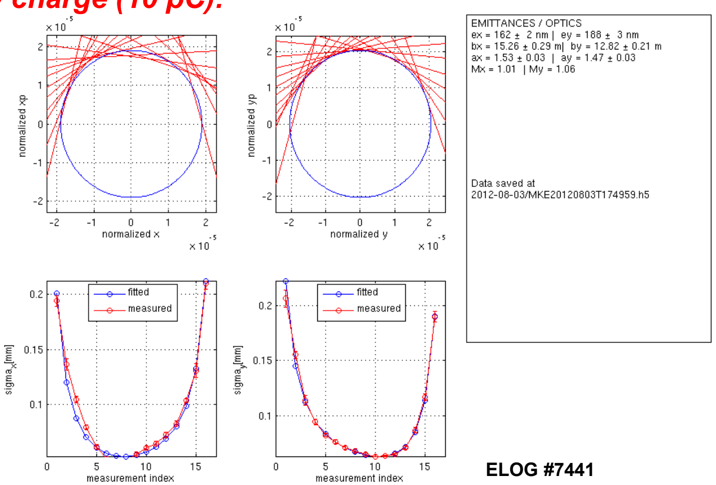
Example measurements projected emittance

High charge (200 pC):



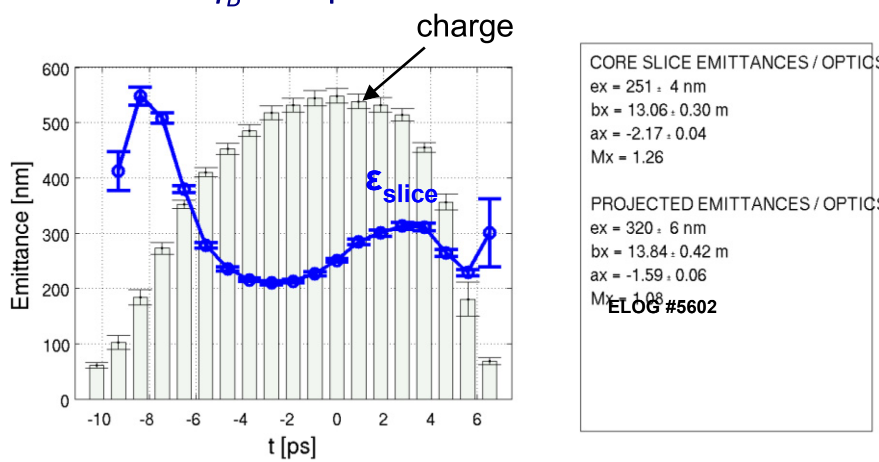
ELOG #5635

Low charge (10 pC):



ELOG #7441

Example slice emittance measurement at q_B=200pC

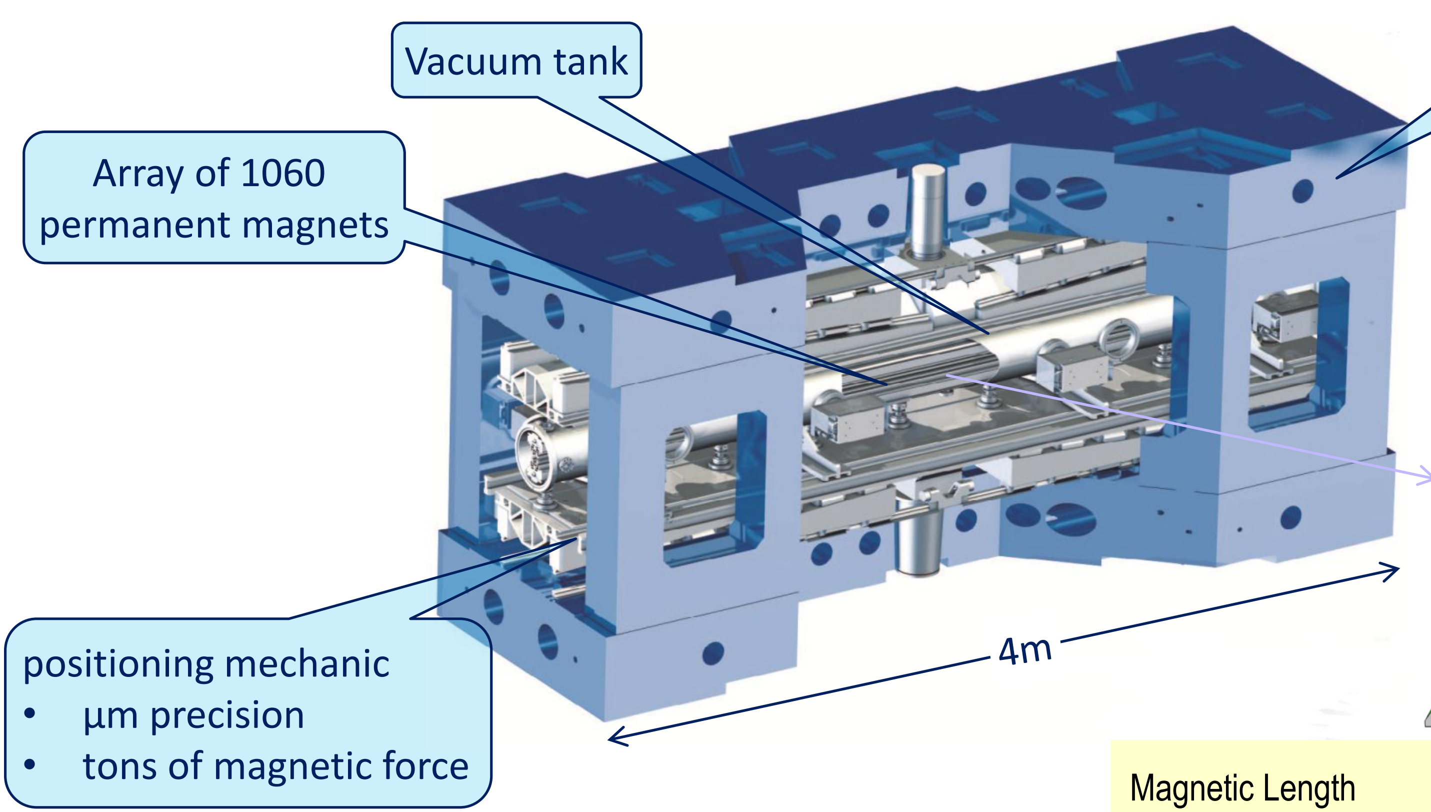


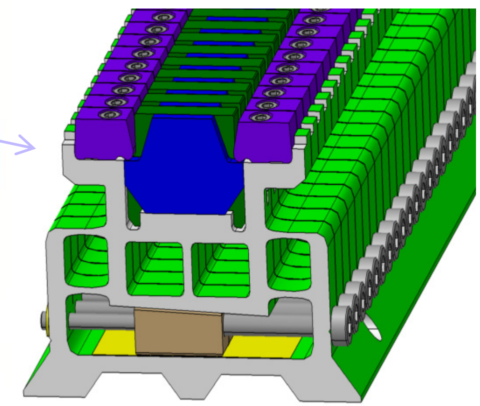
Summary emittance measurements (for uncompressed beam):

Measurement	σ_{laser} [mm]	$\varepsilon_{n,x}$ [µm]	$\varepsilon_{n,y}$ [µm]	$\varepsilon_{n,simulated}$ [µm]	$\varepsilon_{n,required}$ @undulator [µm]
High-charge mode (~200 pC):					
projected:	0.21	0.38	0.37	0.350	0.65
core slice:	0.21	0.25	–	0.330	0.43
Low-charge mode (~10 pC):					
projected:	0.10	0.16	0.18	0.096	0.25
core slice:	0.10	≤ 0.15*	–	0.080	0.18

*measurement limited by signal-to-noise ratio

U15 Undulator for ARAMIS beamline





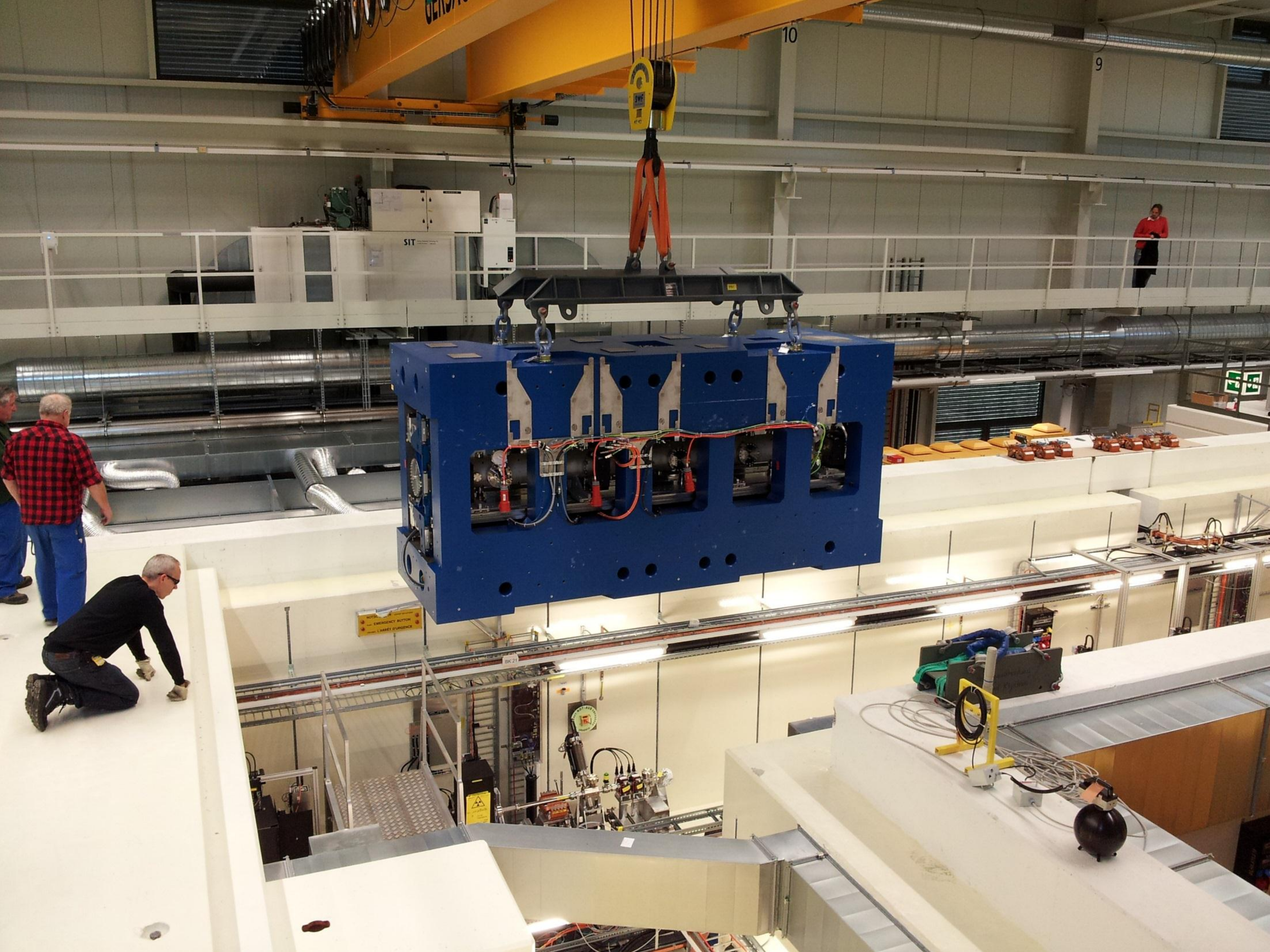
Magnetic Length	3990 mm
Period λ_u	15 mm
Gap	3.2 4.2 4.7 5.5 mm
Undulator K value	1.8 1.4 1.2 1.0
Magnetic Field Bz on axis	1.3 1.0 0.9 0.7 T
Magnetic Material	NdFeB-Dy
Pole Material	Permendur (CoFeVa)

M= 17t

12 x U15 for ARAMIS

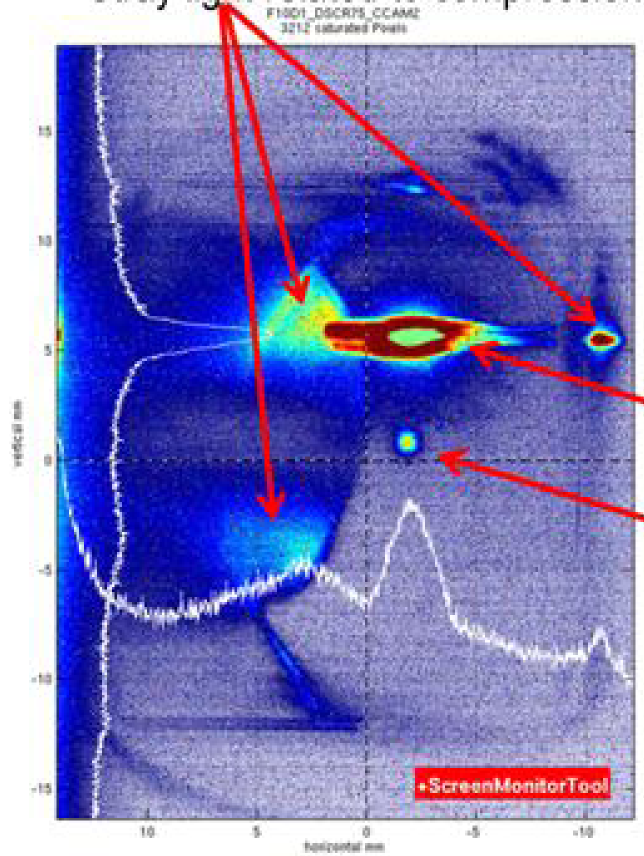
Key industry partners:

- MDC Daetwyler Industries (CH)
- Bruker (D)
- Hitachi (Jp)
- Vakuumschmelze (D)


10
9
SIT
EMERGENCY BUTTON

SASE lasing in in SwissFEL Injector Test Facility

Stray light related to compression ...???



E- beam

200 pC; 130 MeV

SASE scintillation

λ=210 nm

YAG screen

Z=54.191m

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Layout and main RF systems

Injector

2.6 cell S-band RF gun
Cu or Cs_2Te cathodes
fed by 1 S-Band RF station

6 x 4m S-band travelling wave,
const. gradient, 2π/3
acc. structures
fed by 4 S-Band RF stations

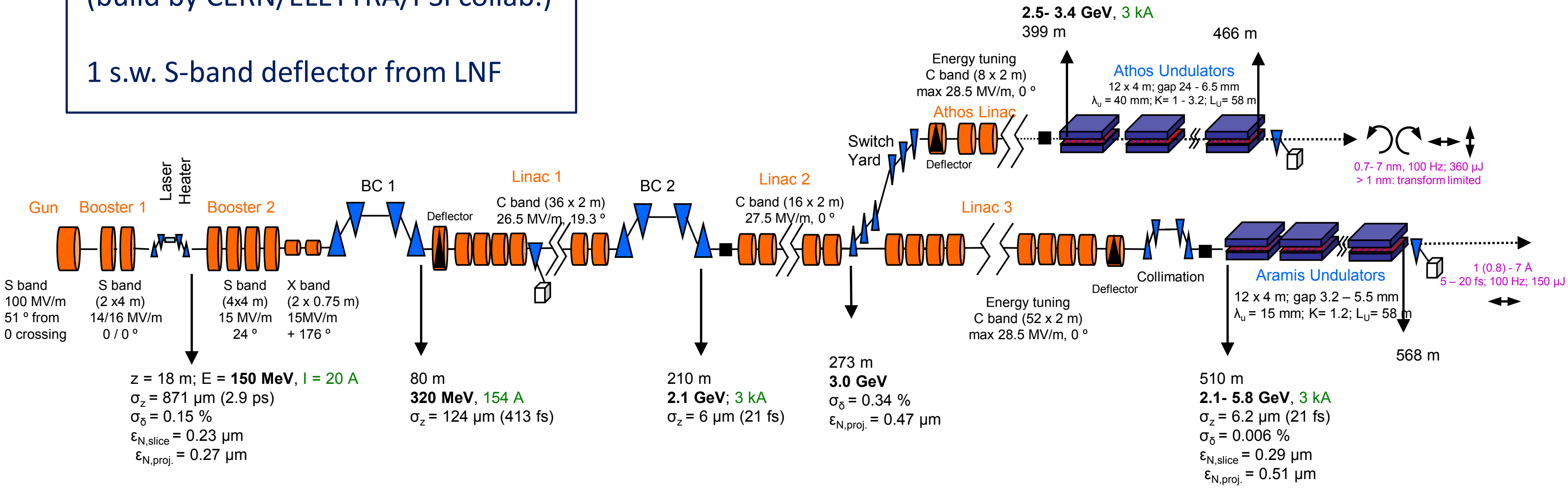
1 x 1m X-band travelling wave,
const. grad. harmonic linearizer
fed by 1 X-band RF station
(build by CERN/ELETTRA/PSI collab.)

1 s.w. S-band deflector from LNF

Linacs

104 (+8) x 2m
C-band travelling wave, const. gradient, 2π/3
acc. structures with BOC RF pulse compression
fed by 26 (+2) C-band RF station

2 x 2m
C-band transverse deflecting structures
fed by RF switch from last C-band station

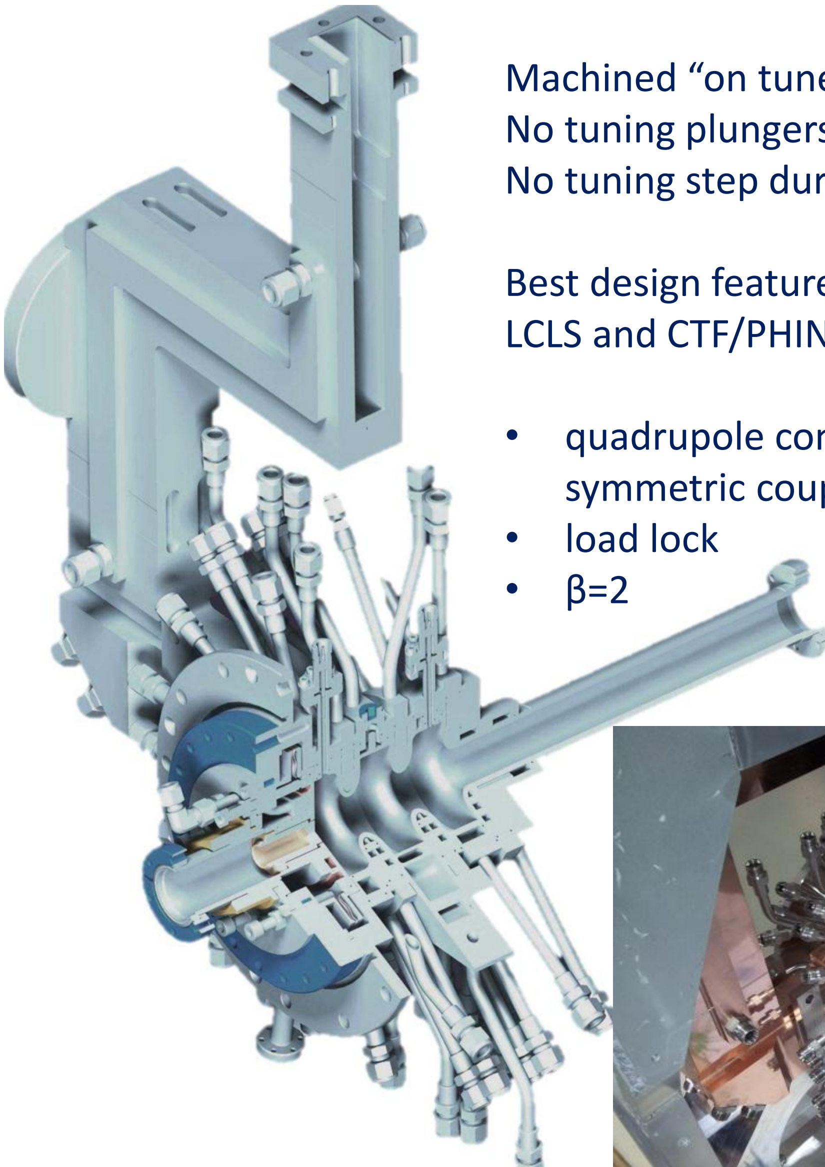


Overview RF cavities

(without TDS)

	Unit	S-band photogun	S-band cavities (injector)	X-band cavities (injector)	C-band cavities (Linacs 1)	C-band cavities (Linacs 2)	C-band cavities (Linacs 3)	C-band cavities (Athos linac)
Frequency (MHz) – f_b=142.8 MHz		2998.8 (21 x f_b)	2998.8 (21 x f_b)	11995.2 (84 x f_b)	5712 (40 X f_b)			
Phase Advance		π	2π/3	5π/6	2π/3			
Active Length	mm	162	4070	750	1978			
Total Length	mm		4150	965	2050			
Number of Cells		2.5	122	72	113			
Operating Temperature	°C	40	40	31	40			
Maximum Gradient	MV/m	120	25	34	28	28	30	30
Operating Gradient	MV/m	100	14.8	25	27	27.5	28.5	28.5
Required Input Peak Power per structure		19 MW for 100 MV/m	24 MW for 16 MV/m	7 MW for 20 MV/m	27.2 MW for 27.5 MV/m			
Klystron maximum performance		35 MW – 4.5 μs	45 MW – 4.5 μs	50 MW – 1.5 μs	50 MW – 2.5 μs 40 MW – 3 μs			
Filling Time	ns	490	1000	105	322			
Number of structures		1	6	2	36	16	52	8
Number of structures per klystron		1	1 or 2	2	4			

RF gun

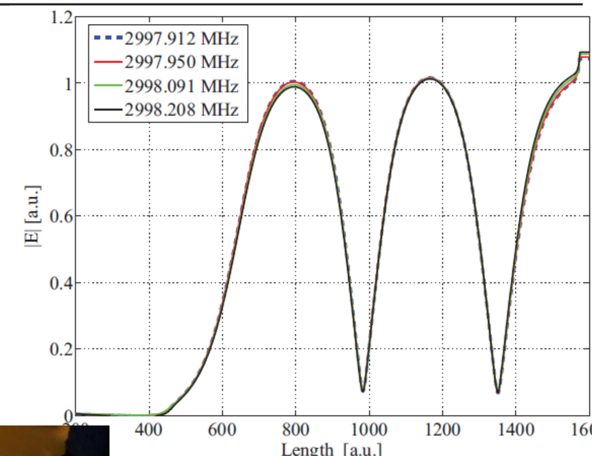


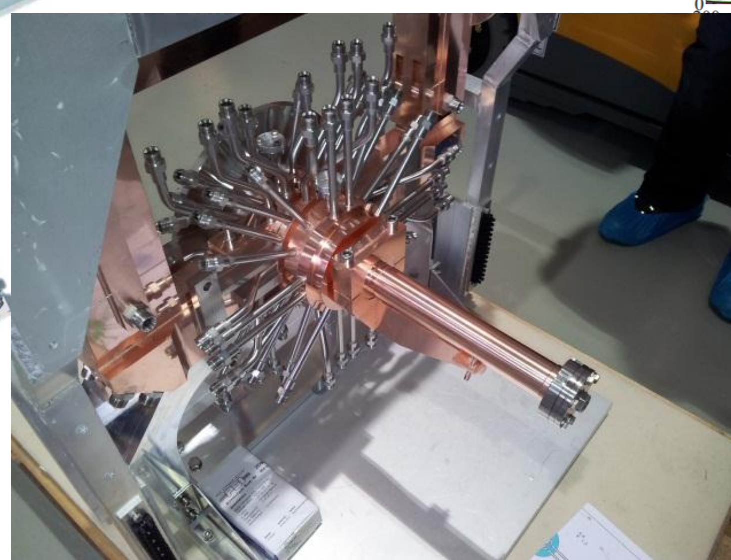
Machined "on tune" according to HFSS
No tuning plungers
No tuning step during machining

Best design features from
LCLS and CTF/PHIN RF guns adopted

- quadrupole compensated symmetric coupler
- load lock
- β=2

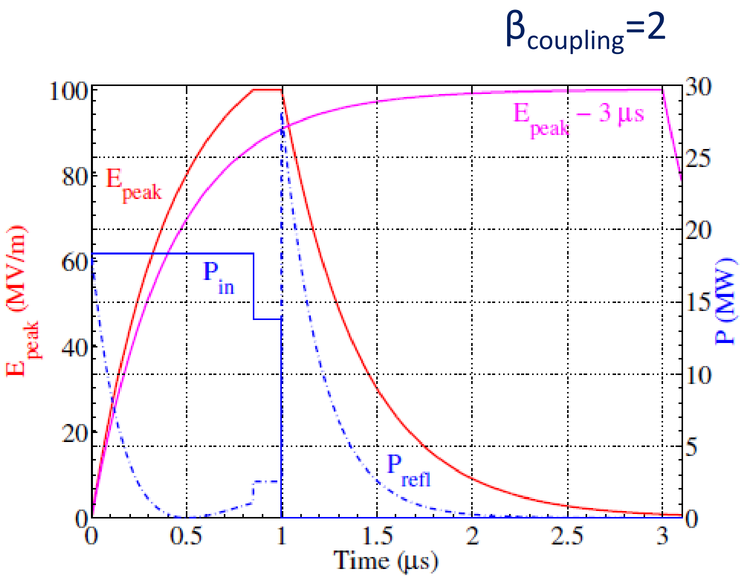
Parameter	HFSS	Measured	unit
π-mode freq.	2997.912	2997.912	*MHz*
β-coupling	1.98	2.02	
Q_0	13630	13690±100	
Filling time	485	481	*ns*
Mode sep.	16.36	16.20	*MHz*
Field balance	>98	>98	%
Operational temp.	57.7	53.0	°C



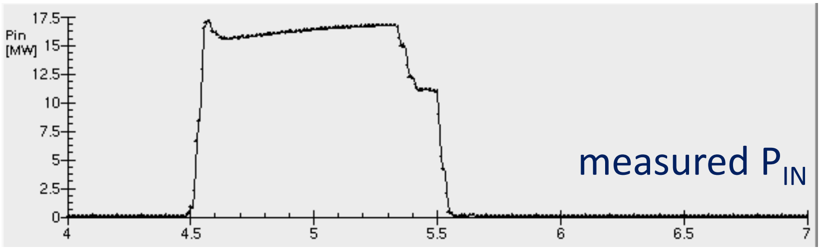


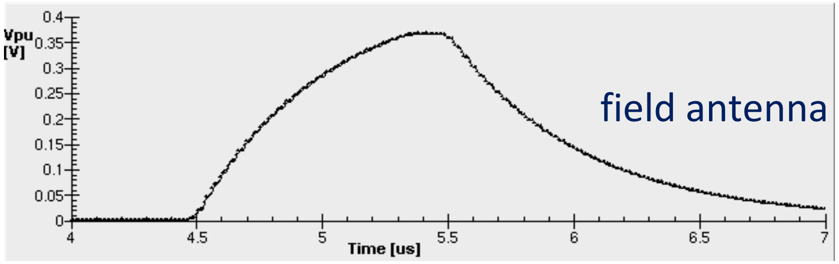
Machining: VDL
Brazing: PSI workshop

Programmed RF Amplitude for RF Gun to minimize heat load and dark current



Amplitude modulation scheme with 150 ns flattop - fast filling and two bunch operation.





Shorter RF pulses

→Thermal load reduction from 3 to 0.9 KW

→ Dark current reduction

→ Less RF breakdown

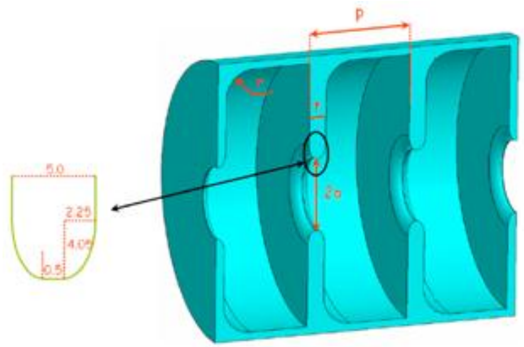
J.-Y. Raguin et al., "The Swiss FEL RF Gun: RF Design and Thermal Analysis", in Proc. LINAC 2012, Tel-Aviv

U.Ellenberger et al., “The SwissFEL RF Gun: Manufacturing and Proof of Precision by Field ProfileMeasurements”, THPP114, this conference

P. Craievich et al., “High Power RF Test and Analysis of Dark Current in the SwissFEL-GUN”, proc. FEL 2014, Basel

M. Schaer et al., “Study of a C-Band Hybrid Electron Gun for SwissFEL”, TUPP112, this conference

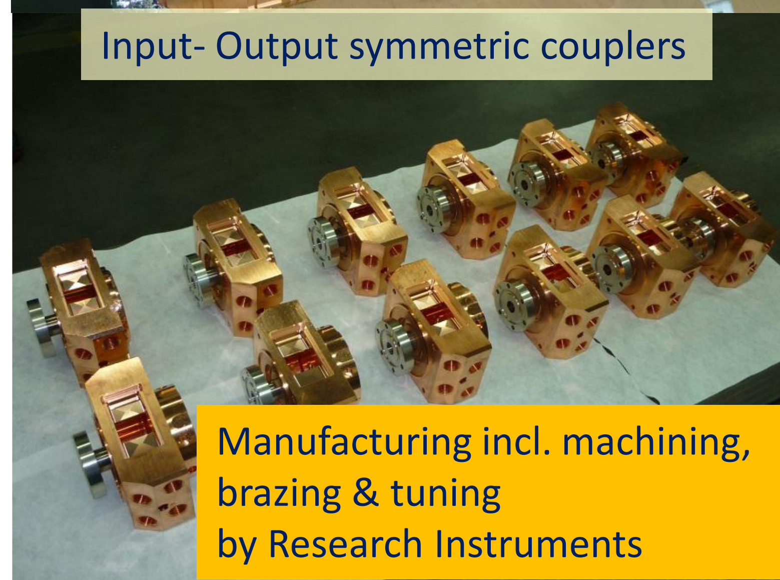
S-band Structures for Injector



Parameter	Value
Operating frequency	2998.8 MHz
Phase advance per cell	$2\pi/3$
Total number of cells	122
Accelerating gradient	20 MV/m
Maximum pulse repetition frequency	100 Hz

	v_g/c (%)	r/Q (kΩ/m)	Q
First cell	2.91	3.85	11688
Middle cell	1.87	4.23	11640
Last cell	0.79	4.81	11589

J.-Y. Raguin, "The Swiss FEL S-Band Accelerating Structure: RF Design", Proc. LINAC 2012, Tel-Aviv, Israel, 2012



Main Linac Design Requirements

- Minimize investment + operation cost
- Preserve emittance for one or two bunches
- Longitudinal wake of Linac 3 has to compensate residual energy chirp from bunch compression
- Transverse wakefield must allow for two bunches spaced by 28 ns
- Design should facilitate assembly and installation
- Minimize sources of transverse and longitudinal jitter

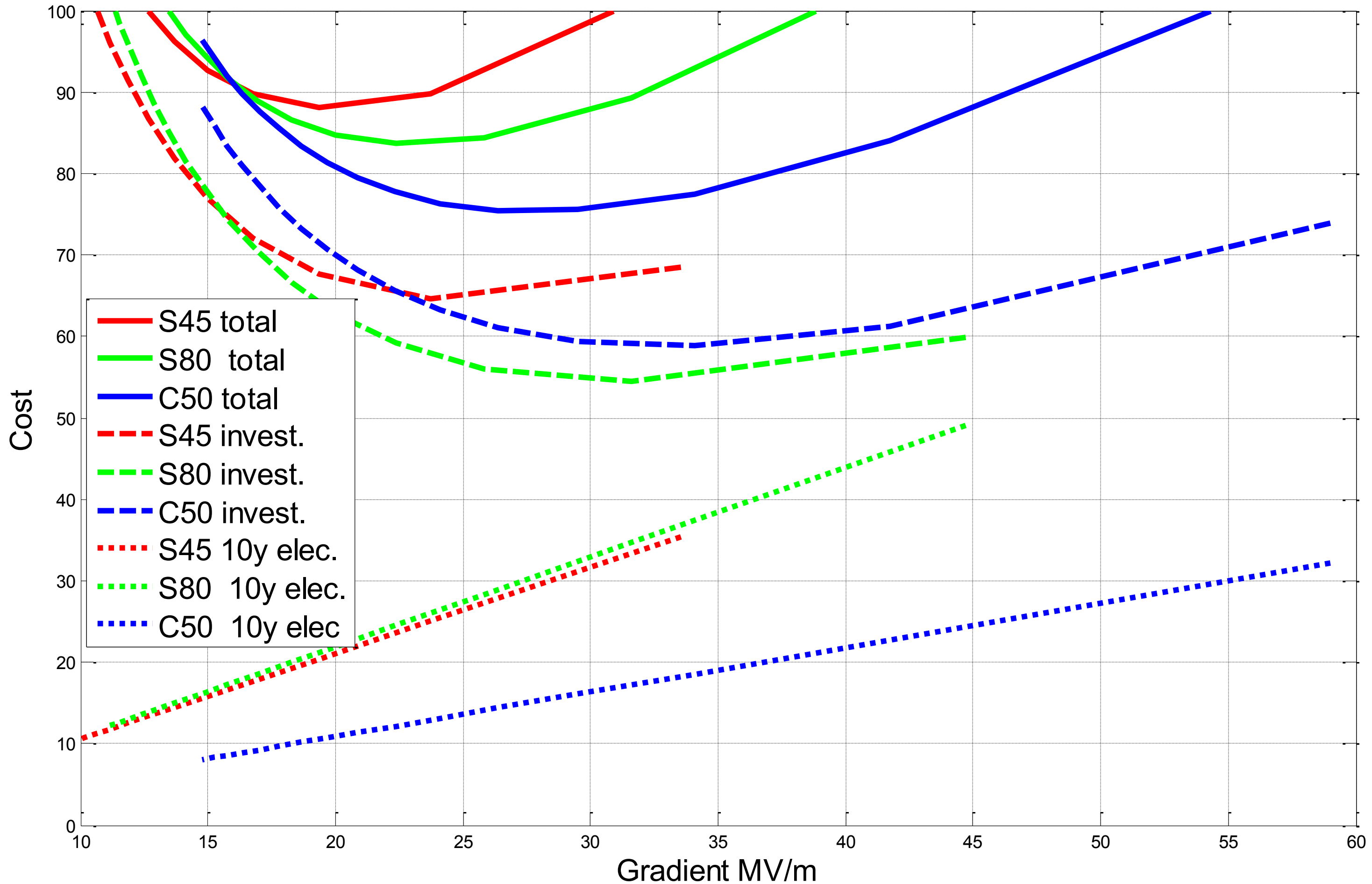
Linac design choices

Choices

- Normal conducting, C-band frequency, profit from KEK-JLC-C & Spring8/SACLA development
- High shunt impedance structure design with moderate gradient of 28MV/m
- Structure manufacturing tolerances tight enough to allow “on tune” fabrication,
  → no tuning provisions, no tuning step in production process
- High Q BOC (=barrel open cavity) RF pulse compressor
- Waveguide distribution and BOC mounted on girder
  → pre-assembly with most components before transport in tunnel
- Klystron modulator with solid state HV switches
  → compact design, very good pulse flatness, small pulse to pulse jitters
- Optical fiber reference distribution, high performance digital LLRF
- Precise cooling water temperature regulation with local smart controllers incl. LLRF as T sensor
- ∅16mm vacuum pipe → low power, air-cooled quadrupoles; high resolution cavity BPMs

cost optimization pulsed n.c. linac for SwissFEL

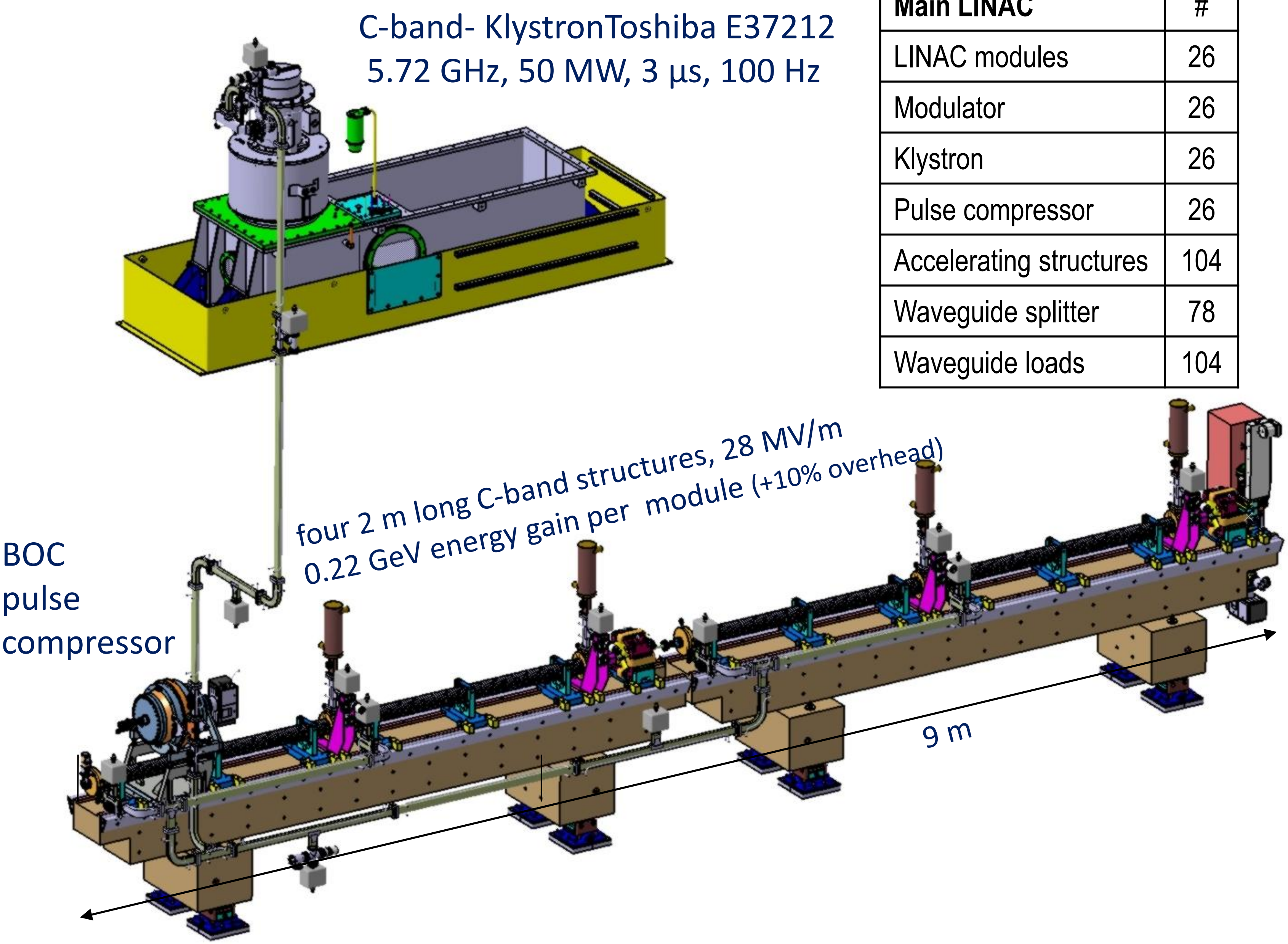
Cost vs. gradient for S-band with 45 MW klystron, S-band with 80MW klystron and C-band with 50 MW klystron



Advantage of C-band is in real-estate needs and electricity consumption

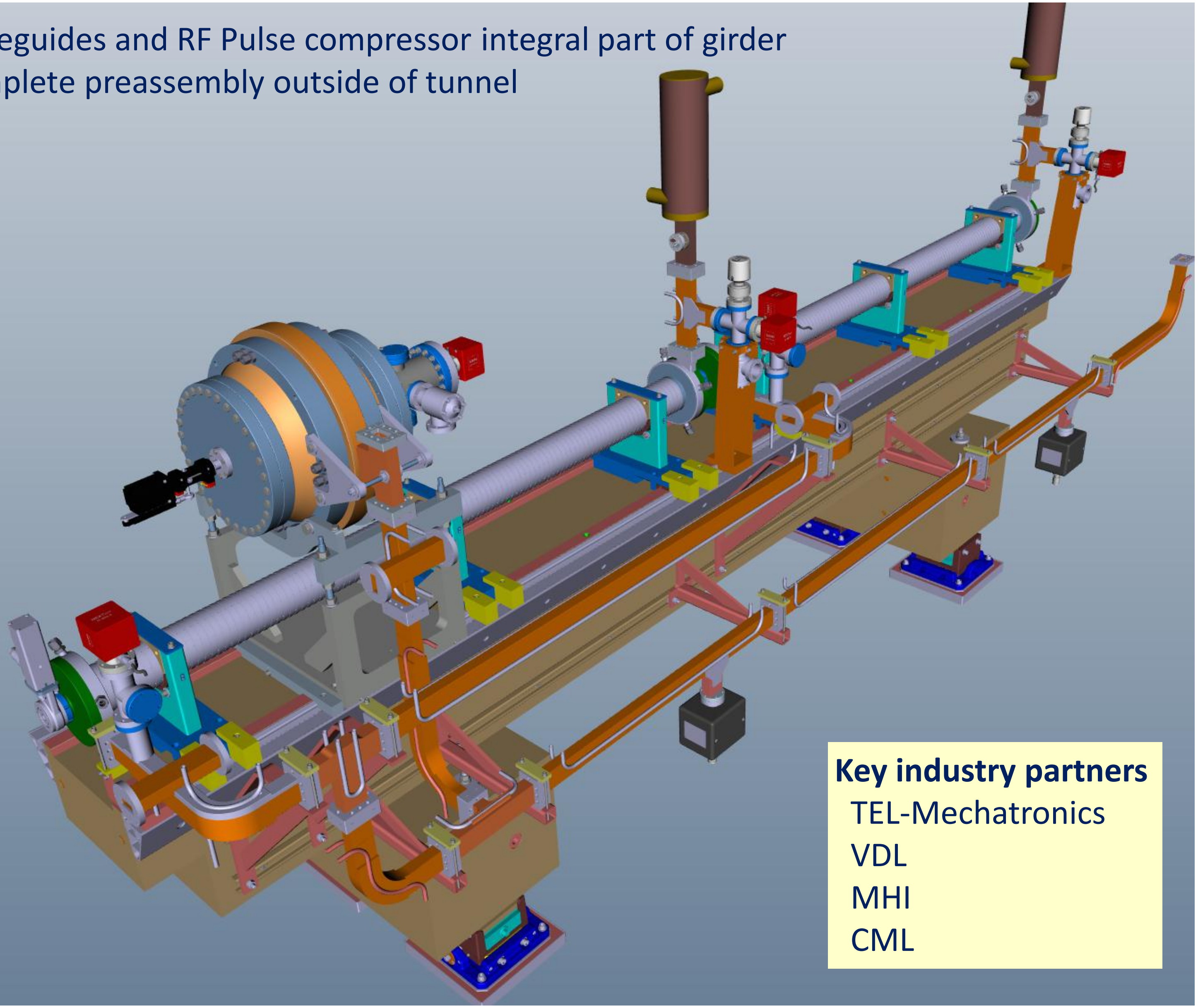
SwissFEL Main Linac building block

Main LINAC	#
LINAC modules	26
Modulator	26
Klystron	26
Pulse compressor	26
Accelerating structures	104
Waveguide splitter	78
Waveguide loads	104



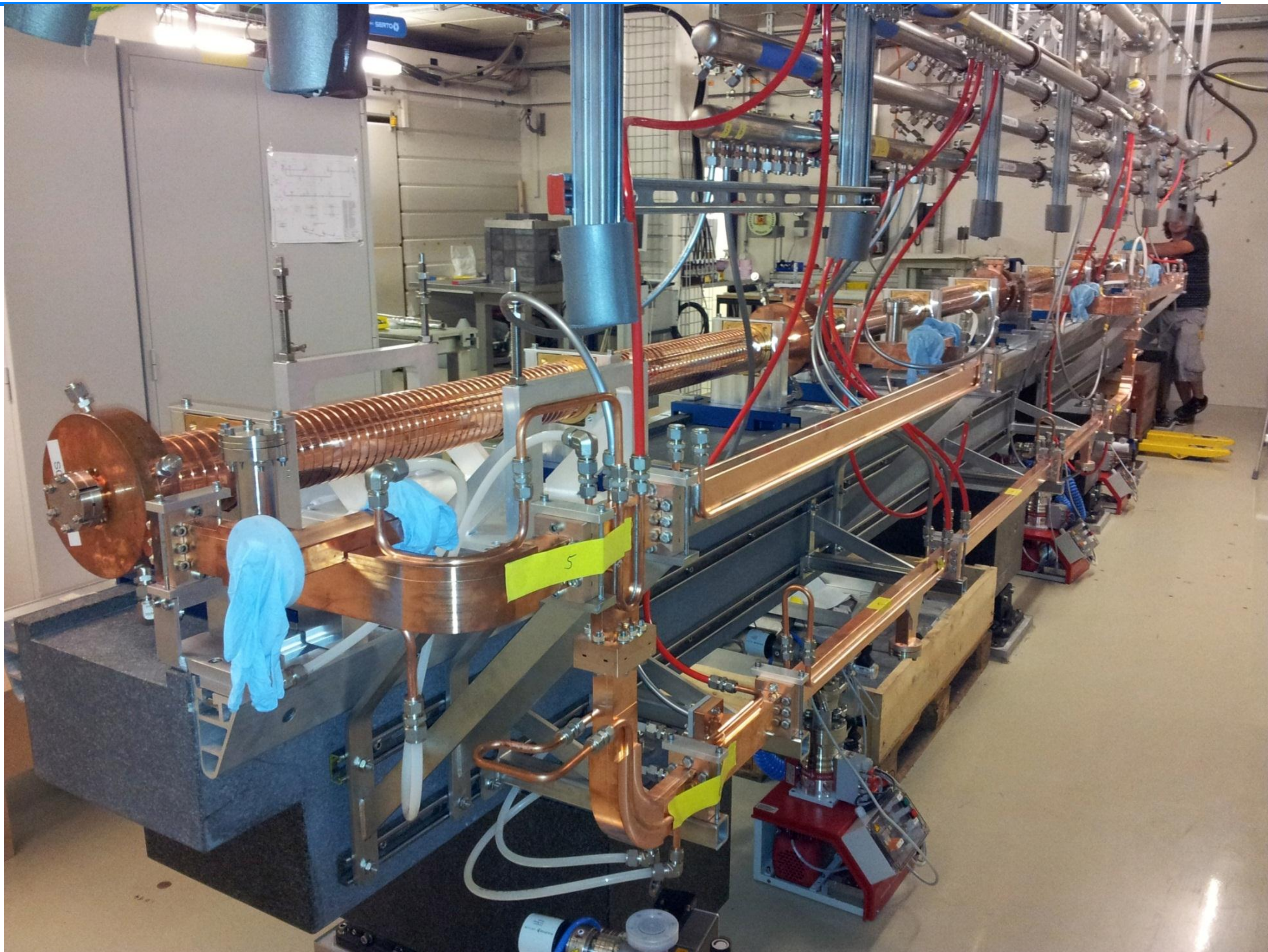
Linac girder

Waveguides and RF Pulse compressor integral part of girder
⇨ complete preassembly outside of tunnel



Key industry partners
- TEL-Mechatronics
- VDL
- MHI
- CML

Assembly of First Linac Module

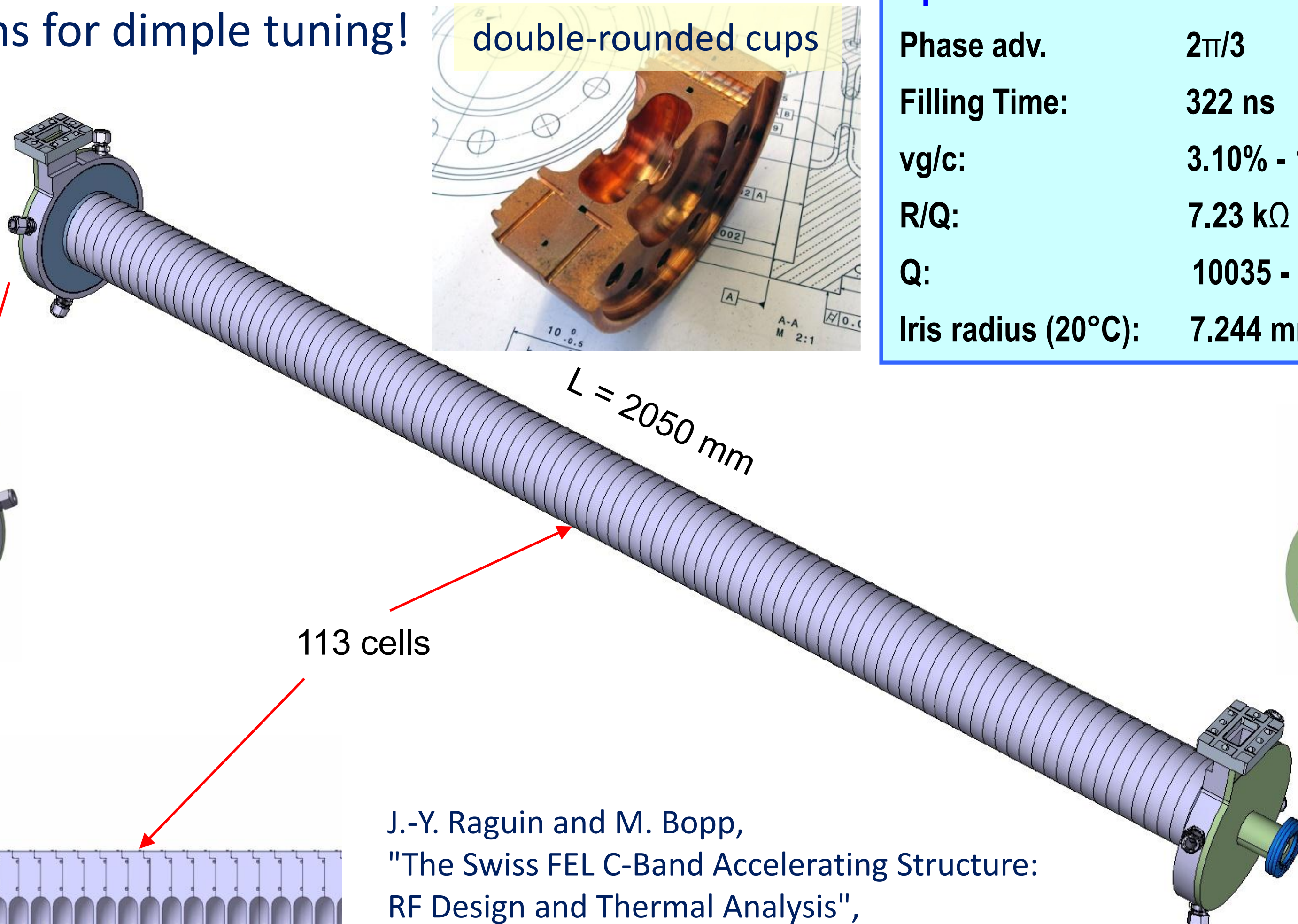


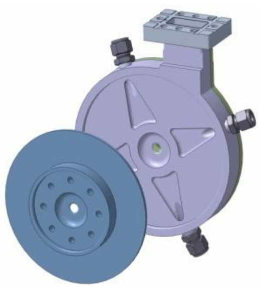
C-band structure

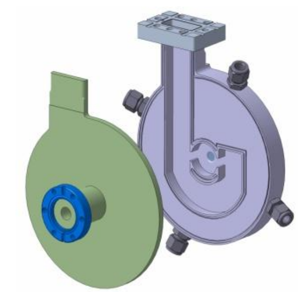
Structures are machined “on tune”
no provisions for dimple tuning!

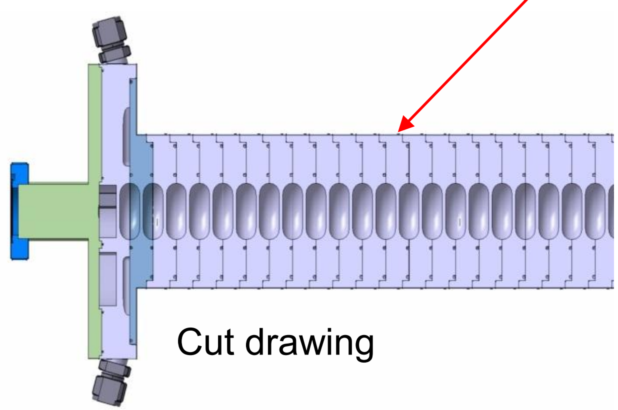
Specifications:

Phase adv.	$2\pi/3$
Filling Time:	322 ns
vg/c:	3.10% - 1.19%
R/Q:	7.23 kΩ – 8.70 kΩ
Q:	10035 - 9950
Iris radius (20°C):	7.244 mm – 5.436 mm









J.-Y. Raguin and M. Bopp,
"The Swiss FEL C-Band Accelerating Structure: RF Design and Thermal Analysis",
proc. LINAC 2012, Tel-Aviv

First 2 m C-band structures

- **5 structures have been brazed so far**
- **High power results for first structure:**

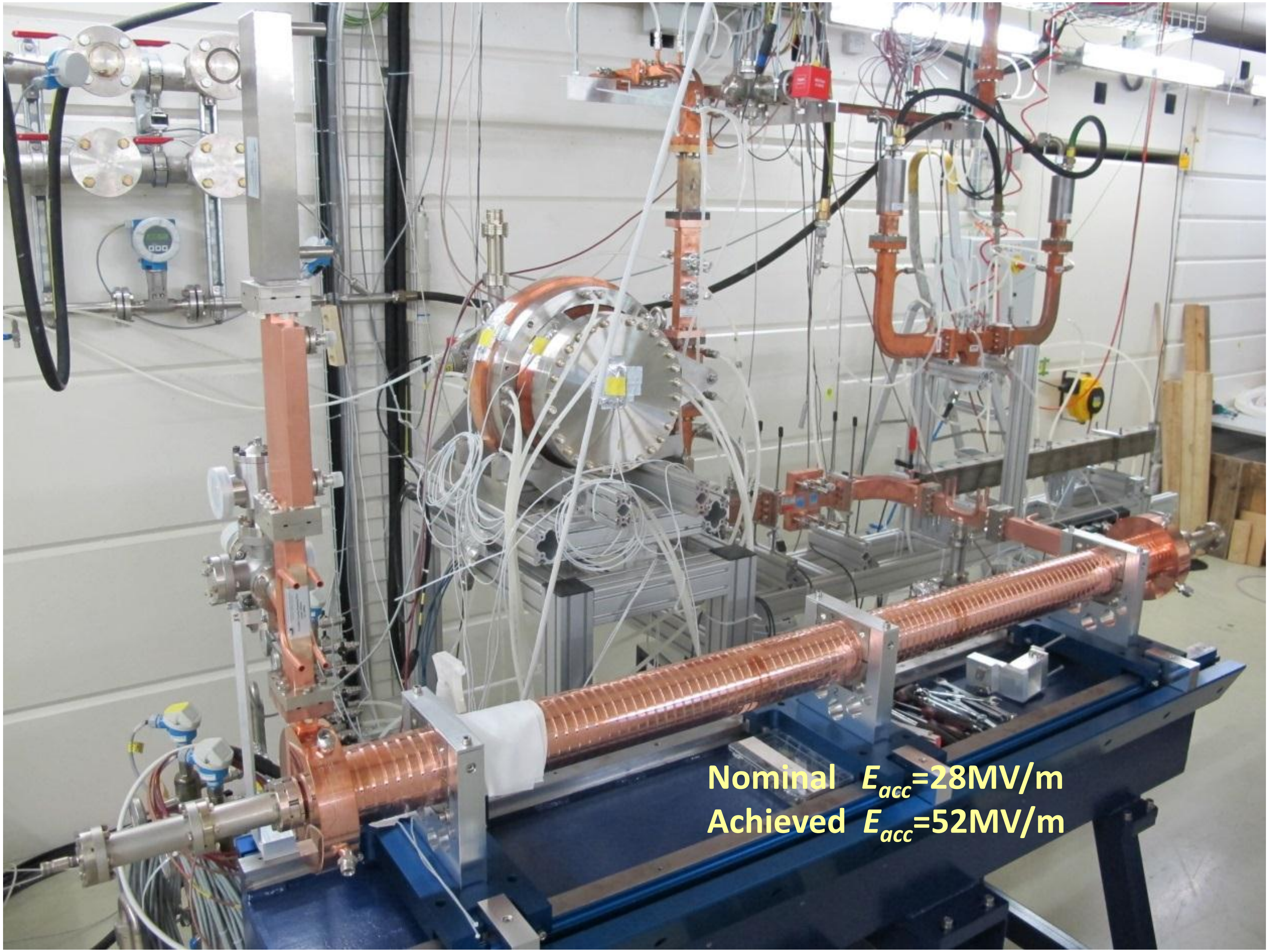
  → conditioned to 52 MV / m

  → Break-down rate at 52 MV / m ≈2 x 10^{-6}

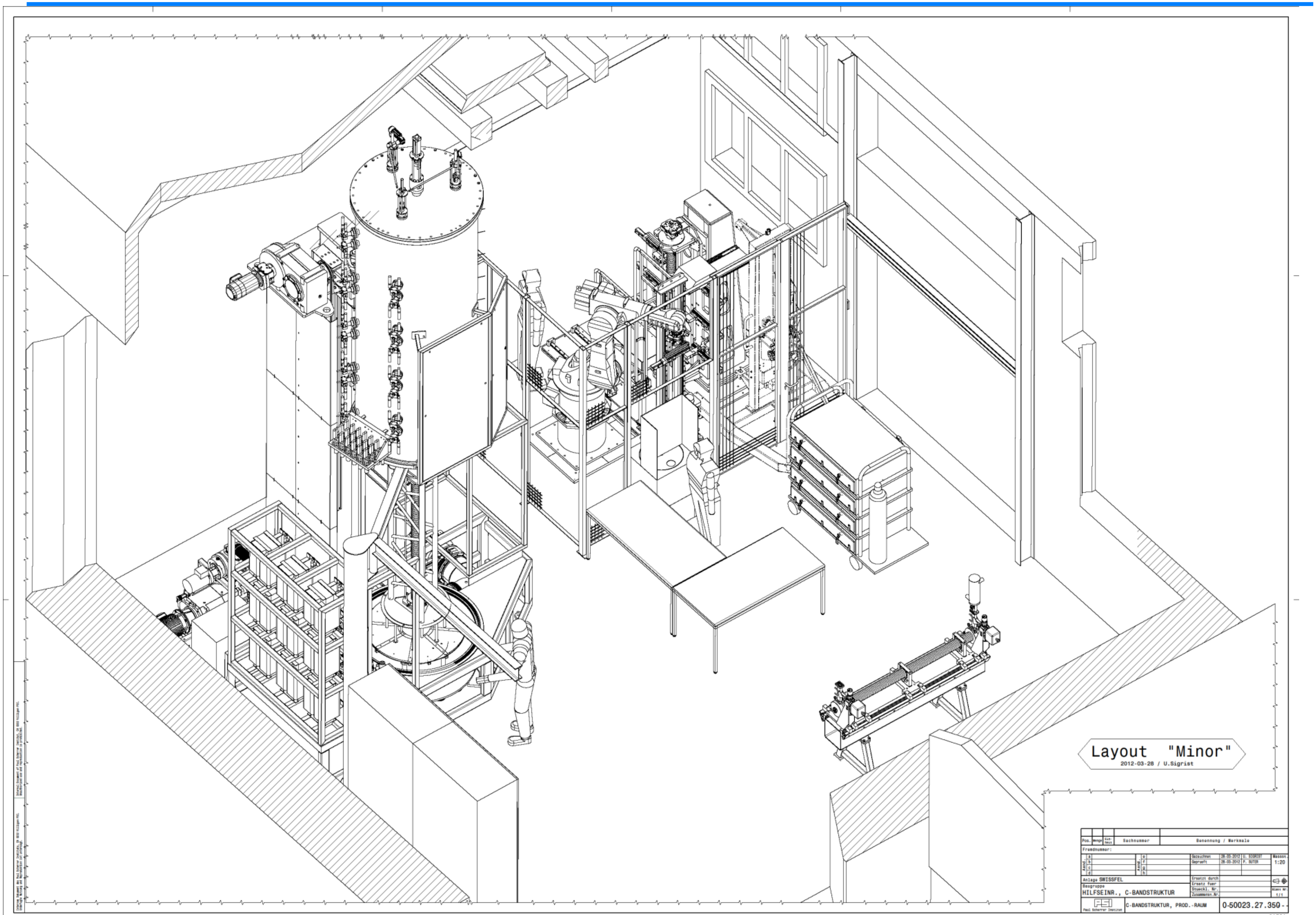
  → At nominal 28MV/m, break-down rate negilible

R. Zennaro et al.,
"Measurement and High Power Test of the First C-Band Accelerating Structure for SwissFEL",
MOPP119, this conference

C-band structure with BOC pulse compression in RF power test area



Assembly & brazing set-up for series production



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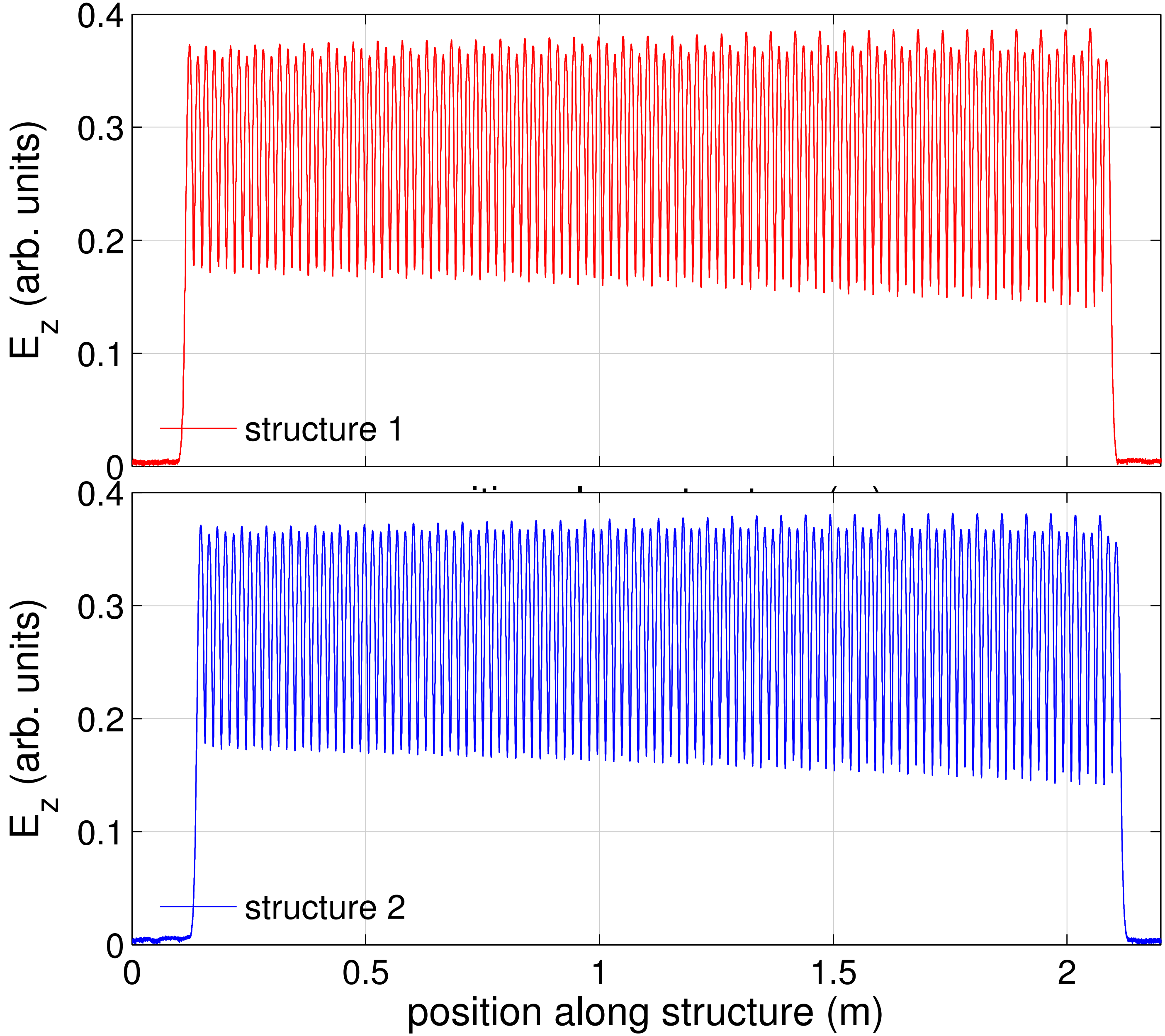
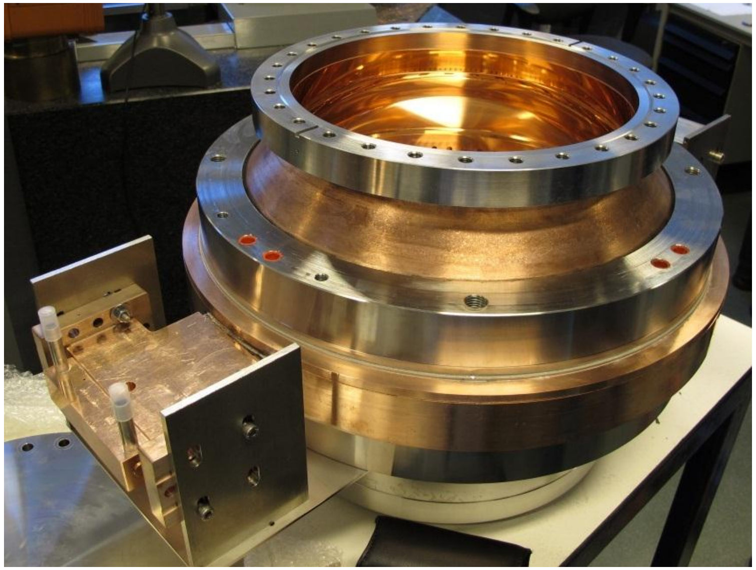
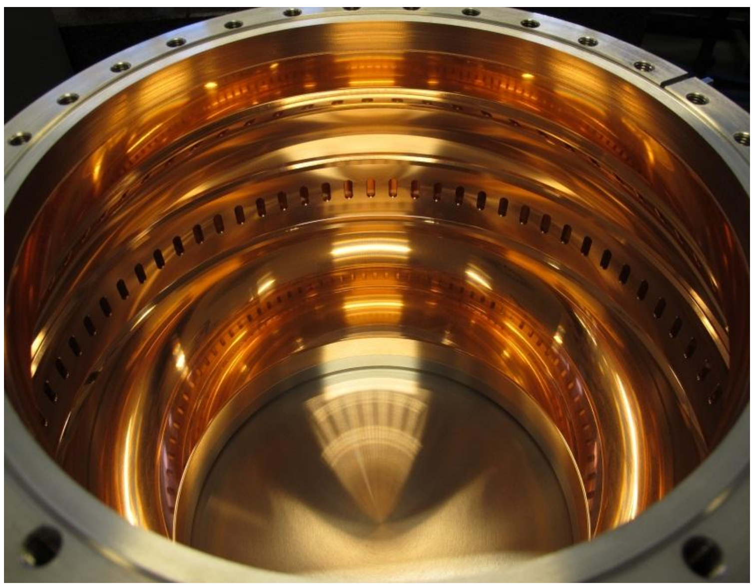
2 m C-band structure: longitudinal field distribution



BOC Pulse compressor

whispering gallery mode





RF design:

- ✓ Single cavity
- ✓ Whispering gallery mode with analytical solution
- ✓ intrinsic high Q>200000

Mechanical design:

Simple and robust design:

- ✓ Inner body from a single piece
- ✓ Two brazing steps
- ✓ Machined on tune

R. Zennaro et al., "C-band RF pulse compressor for the SwissFEL", Proc. IPAC 2013, Shanghai

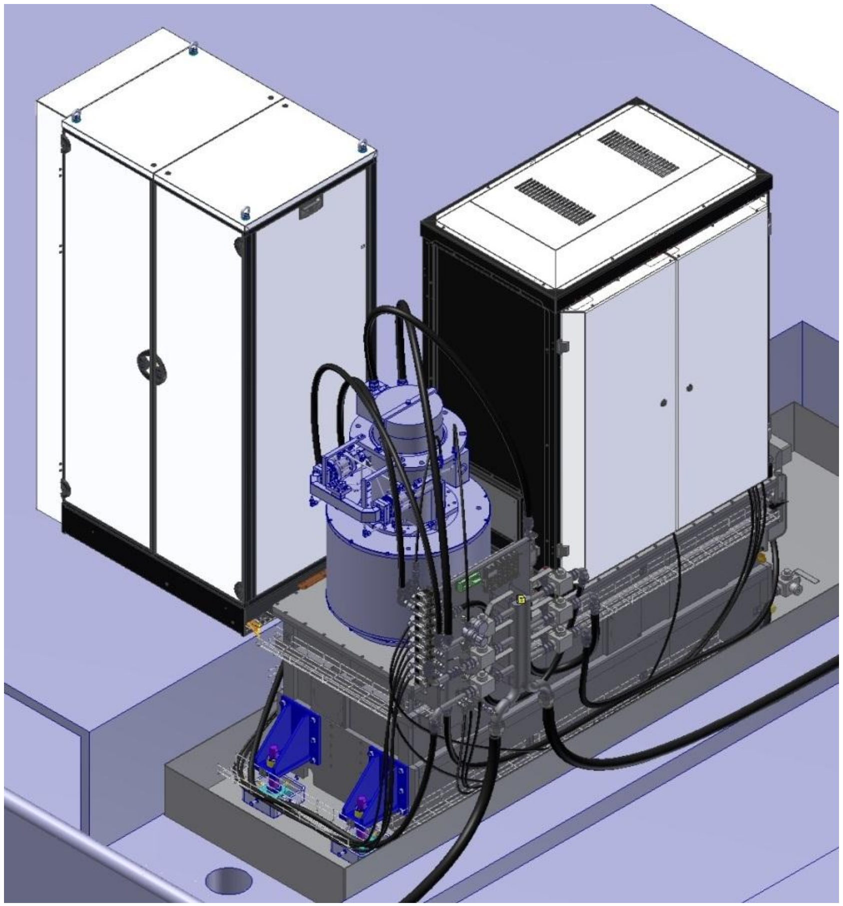
U. Ellenberger et al., "The SwissFEL C-Band RF Pulse Compressor: Manufacturing and Proof of Precision by RF Measurements", FEL 2014, Basel

A. Citterio et al., “C-band Load Development for the High Power Test of the SwissFEL RF Pulse Compressor”, this conf. MOPP118

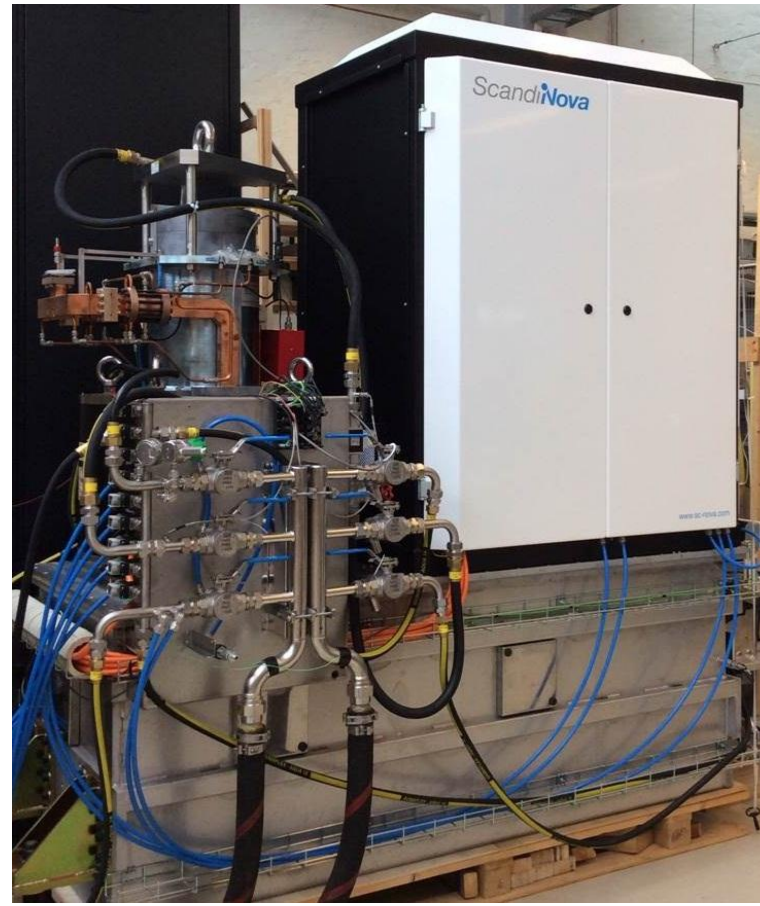
Prototype modulator from Scandinova

ScandiNova

K2-3 for PSI C-band:
50 MW, 370kV / 344A / 3µs / 100 Hz



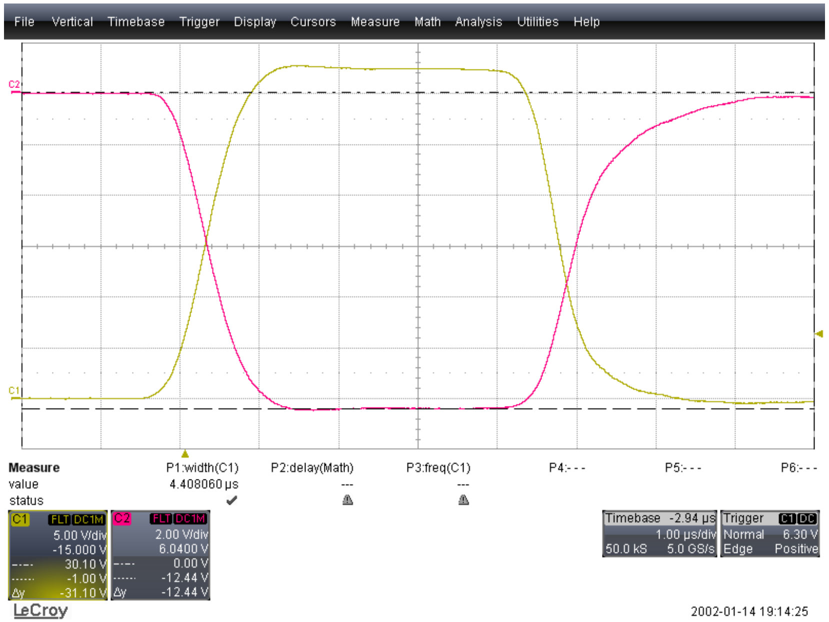
Design of C-Band K2-3 Modulator



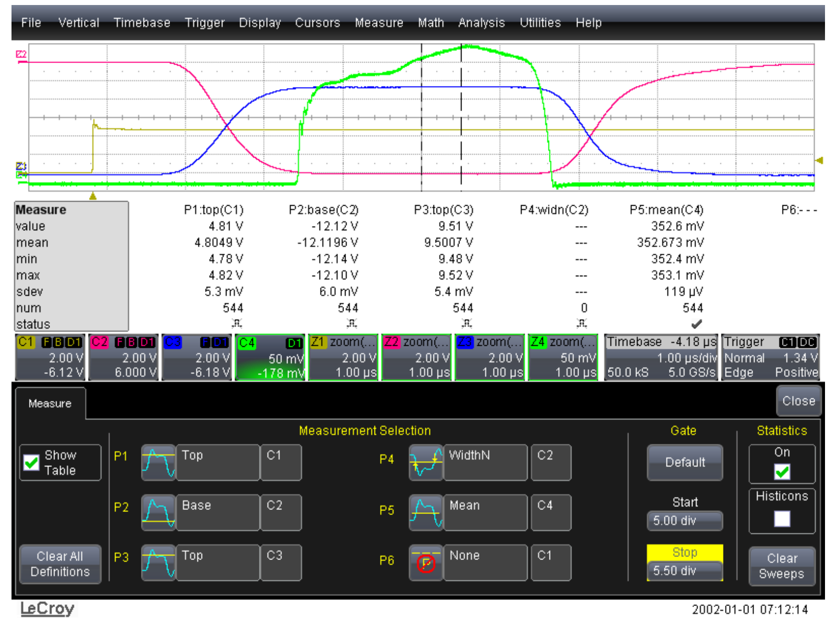
50MW Klystron and K2-3 Modulator

Based on K2-series: new control system, new mechanical layout.
Achieves excellent pulse shape and an rms stability of 13 ppm.

K2-3 FOR C-BAND AT 50 MW-LEVEL, DESIGNED FOR 20 PPM STABILITY



Klystron Voltage & Current Pulses
366kV / 325A / 3.5µs / 100Hz



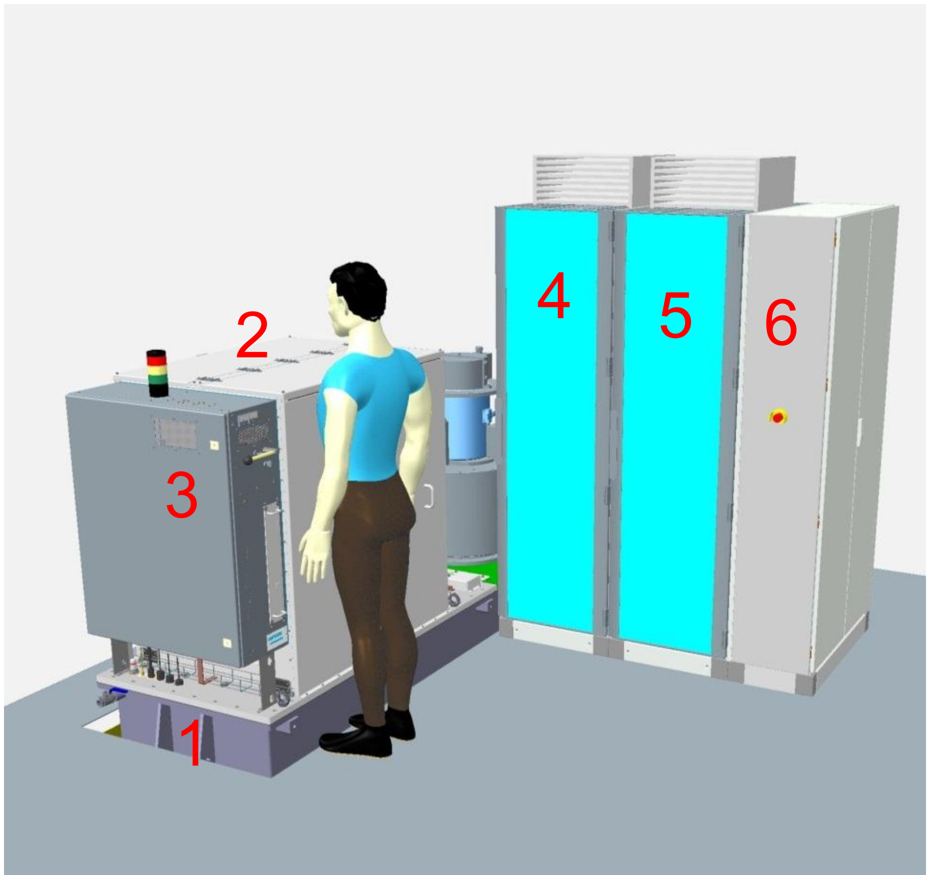
Recorded Stability on Pulse Middle section
Avgerage over 0.5 µs

Stab = 119 uV / 9.51 V
= 13 ppm RMS

Peak to Peak 74 ppm

AMPEGON

Mechanical Layout of the new prototype Modulator



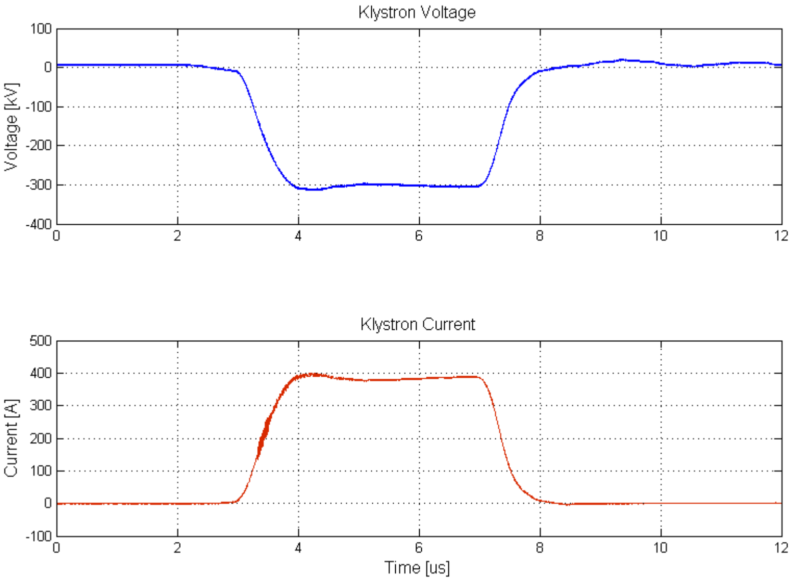
The Modulator consists of the following mechanical units:

1. Modulator tank, housing the oil immersed pulse transformer, HV divider and current measurement
2. 12 Pulse Power Modules (IGBT modules), including pre-magnetisation circuits
3. Modulator control, HV earthing, cap bank discharge, oil supervision and water manifold
4. 19” rack housing the active PFC power supplies and focus power supplies
5. 19” rack housing the precision boost converter, control system, klystron auxiliary power supplies
6. 400VAC / 50Hz Mains input and distribution cabinet

AMPEGON

Type-µ modulator prototype for PSI C-band

Measured pulses on demonstrator modulator



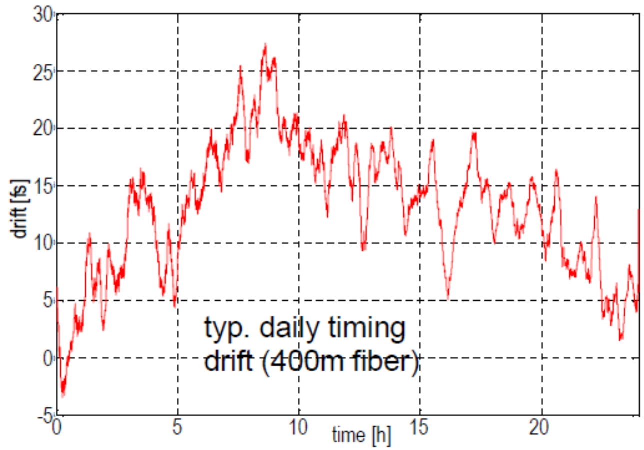
(Resistive load, no perveance;
pulse parameters like overshoot not optimized)

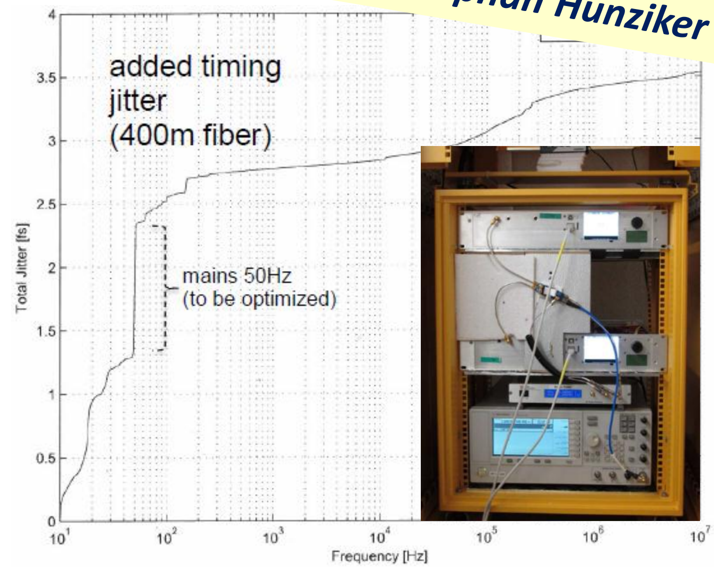
Reference distribution and LLRF

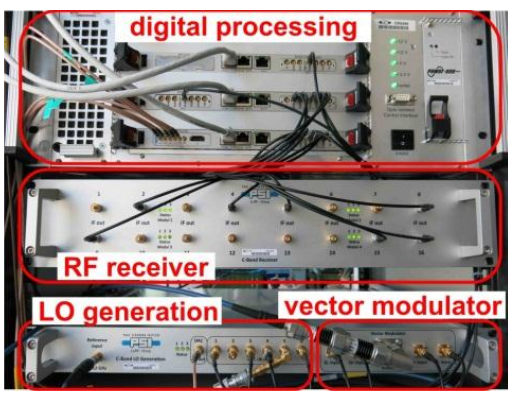
First results with I-Tech/PSI s-band (2.9988GHz) link prototype

courtesy Stephan Hunziker

Influence of temperature, humidity variations and mechanical vibrations are compensated by group delay control.
Further drift reduction expected.







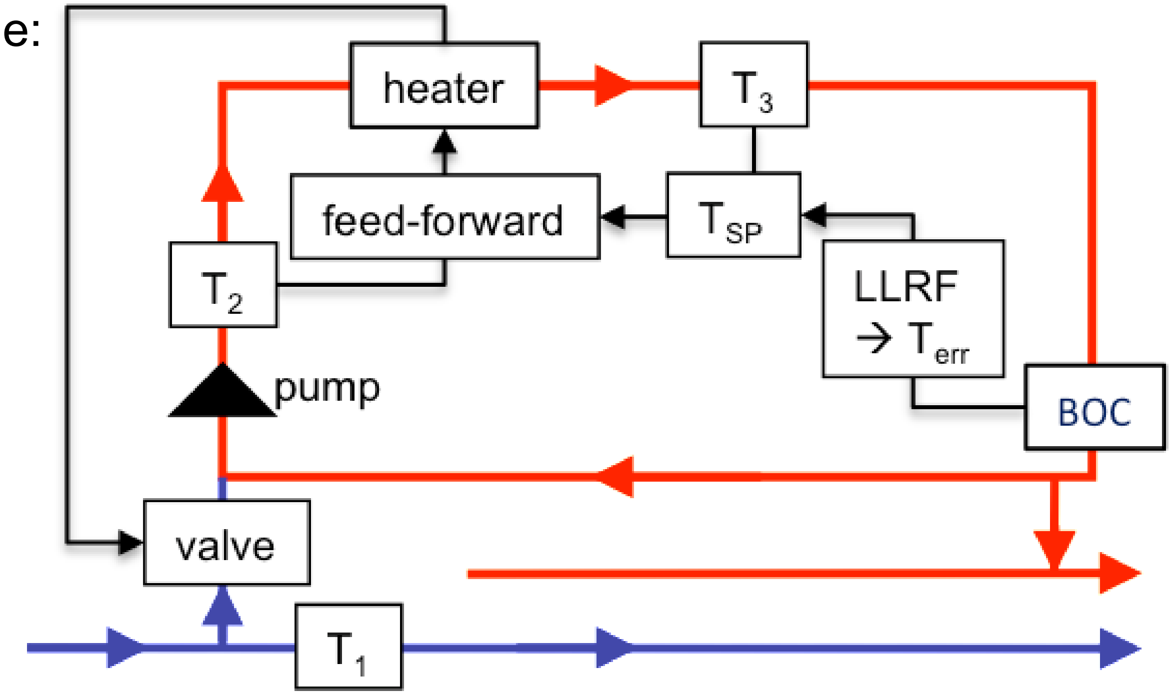
C-band LLRF prototype system

A. Hauff et al.,"SwissFEL C-band LLRF Prototype System", this conf. TUPP111

Z. Geng et al., "Architecture Design for the SwissFEL LLRF System", this conf. THPP113

Principle of the temperature regulation units

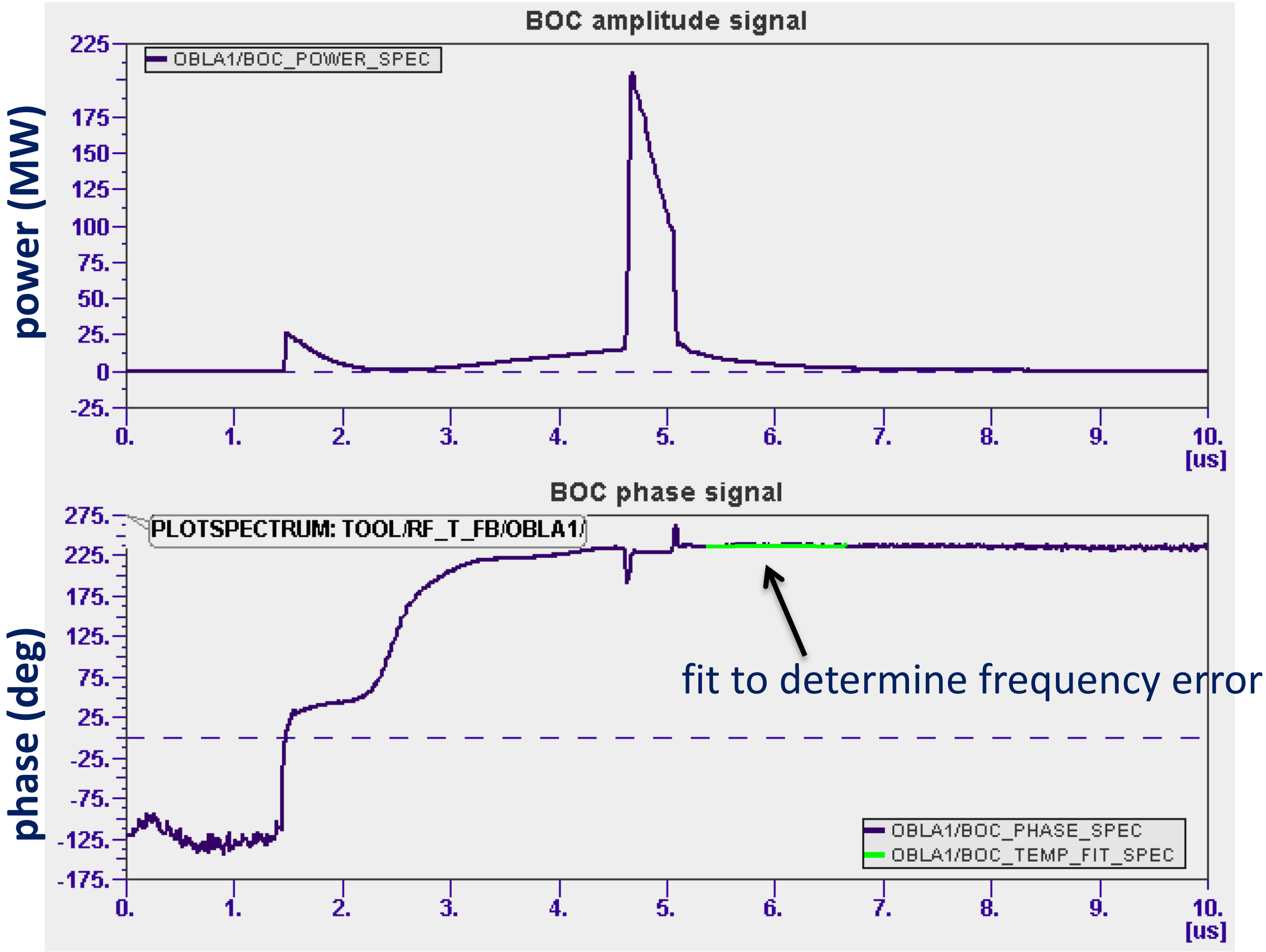
Principle:



Prototype system commissioned in spring 2013

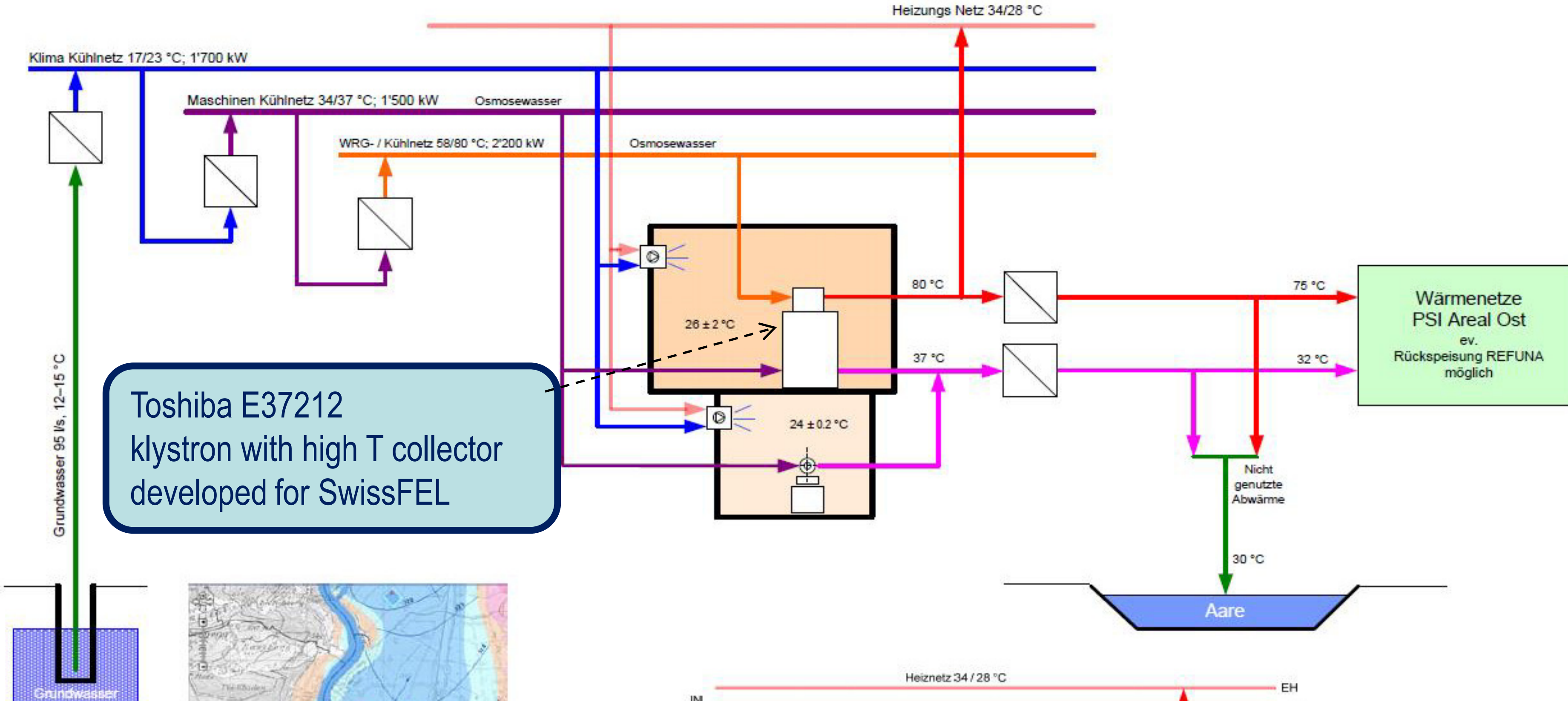
- Mixing ratio of ~ 1:10 improves temperature stability in stabilized circuit by factor of 10 compared to supply water
- A linearly regulated heater is used in a regulation loop to improve the stability further
- Temperature sensors are used as monitors when RF is turned off
- LLRF-based temperature measurement is used as an additional monitor during RF operation

BOC temperature stabilization

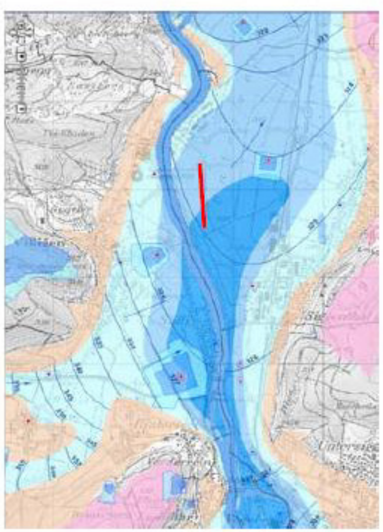


Temperature stability (T-sensor based):	≈3 mK rms
BOC frequency stability (LLRF based):	≈ 300 Hz
BOC temperature stability (LLRF based):	≈ 3 mK rms

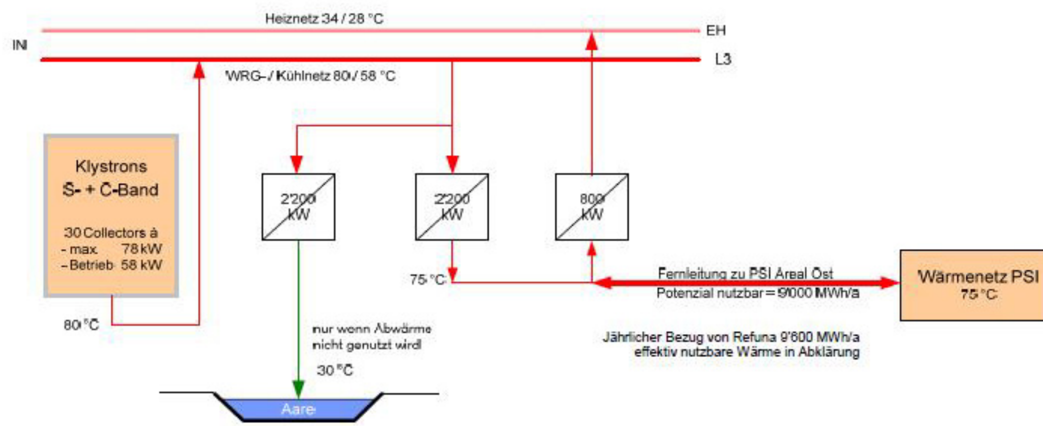
Energy recovery for SwissFEL



Toshiba E37212
klystron with high T collector
developed for SwissFEL

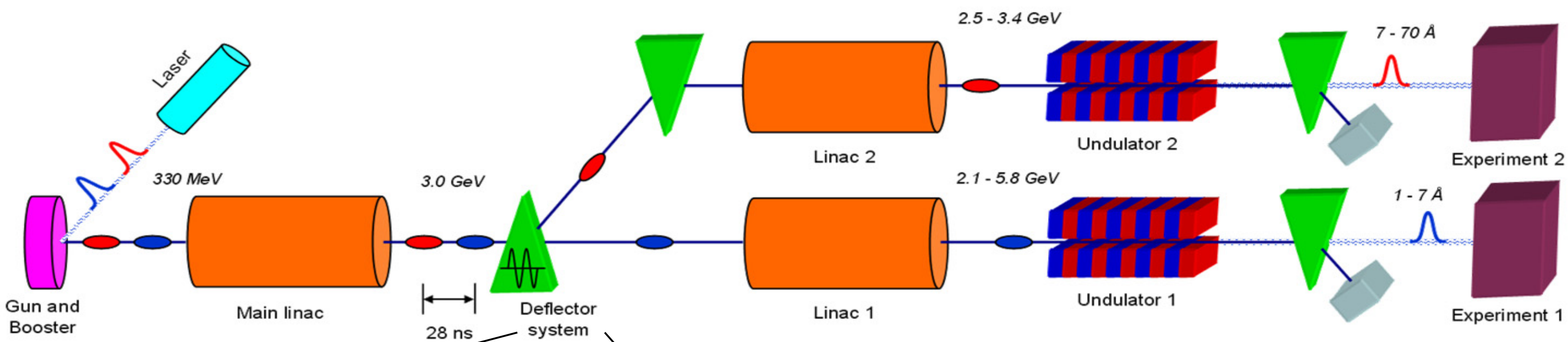


Grundwasserkarte

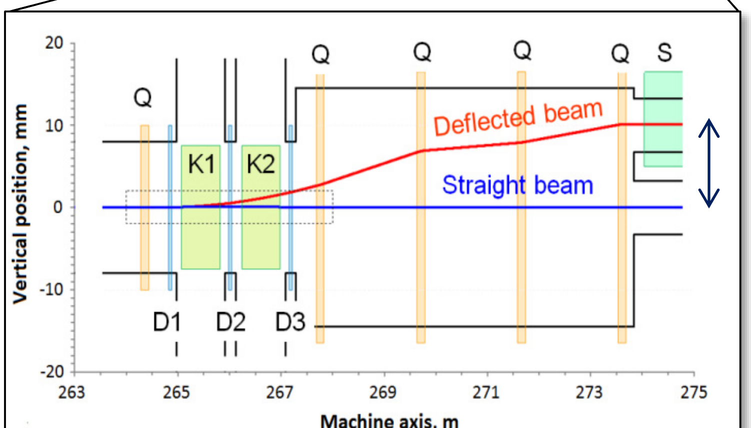


Wärmerückgewinnung

Two bunch operation



SwissFEL layout



Beam separation at the septum entrance – 10 mm

Beam trajectories of the straight and deflected beam. The color rectangles represent the corresponding magnet's field region: Kx – Kicker magnet, Dx – Dipole magnet, S – Septum magnet, Q – Quadrupole magnet.

<u>Kicker system</u>

Number of kickers	– 2
Kickers type	– In vacuum, resonant
Total deflection angle	– 1 mrad (vertical)
Deflection stability	– ±80 ppm pk-pk
Total magnetic length	– 1.5 m
Line field integral	– 10 mT.m
Deflecting current	– 500 A pk-pk

<u>Septum</u>

Number of septa	– 1
Septum type	– Lambertson, DC
Total deflection angle	– 35 mrad (horizontal)
Deflection stability	– ±10 ppm pk-pk
Total magnetic length	– 1.0 m
Line field integral	– 350 mT.m

Resonant Kicker Concept

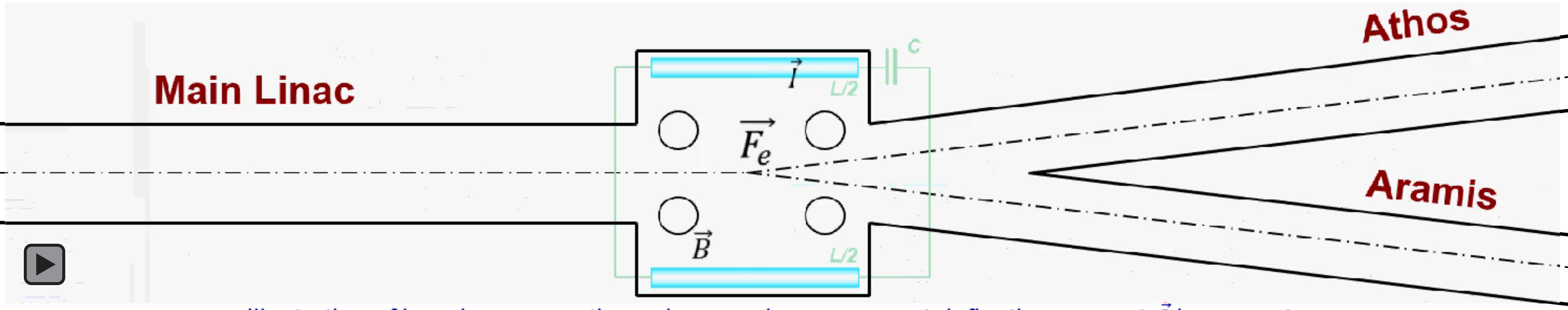
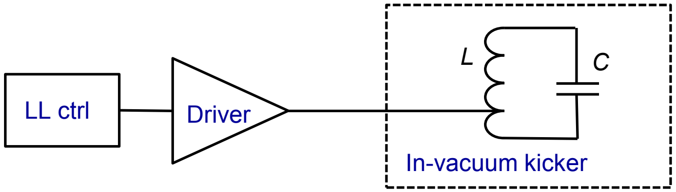
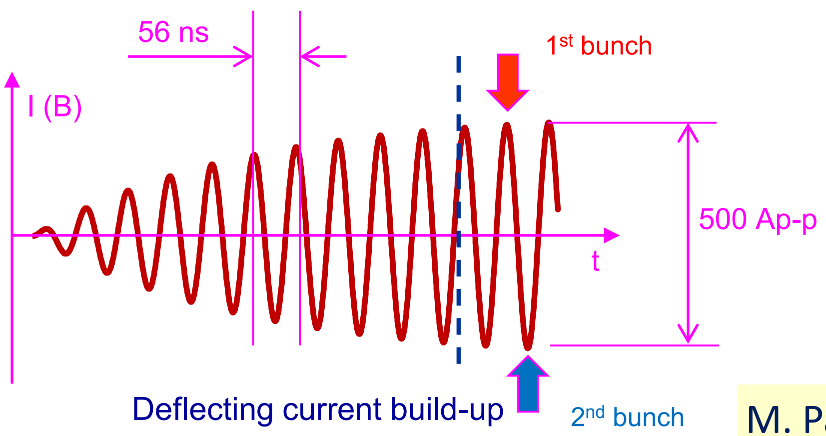


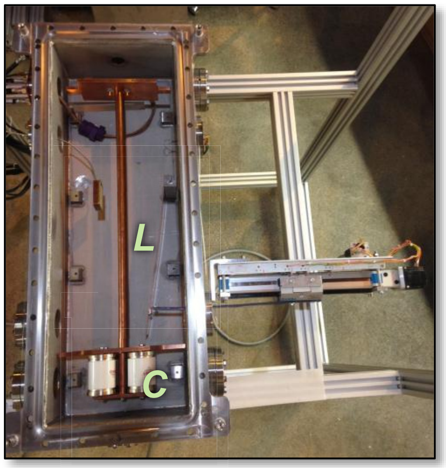
Illustration of bunches separation scheme using a resonant deflecting magnet. $\vec{I}$ is magnet current, $\vec{B}$ is the magnetic field and $\vec{F_e}$ is the deflecting force.



Simplified electrical circuit



Deflecting current build-up



Prototype kicker resonator in the vacuum tank.

Achieved kicker (prototype) stability – < ±15 ppm pk-pk

M. Paraliev et al., “High Stability Resonant Kicker Development for the SwissFEL Switch Yard”, proc. FEL2014, Basel


Challenge:
get 6 GeV of Linac put here until
LINAC 2016 conference