
Paolo Craievich on behalf of RF group - Paul Scherrer Institut

# RF activities for SwissFEL

High-Gradient applications outside particle physics, CLIC Workshop, 6-10 March 2017

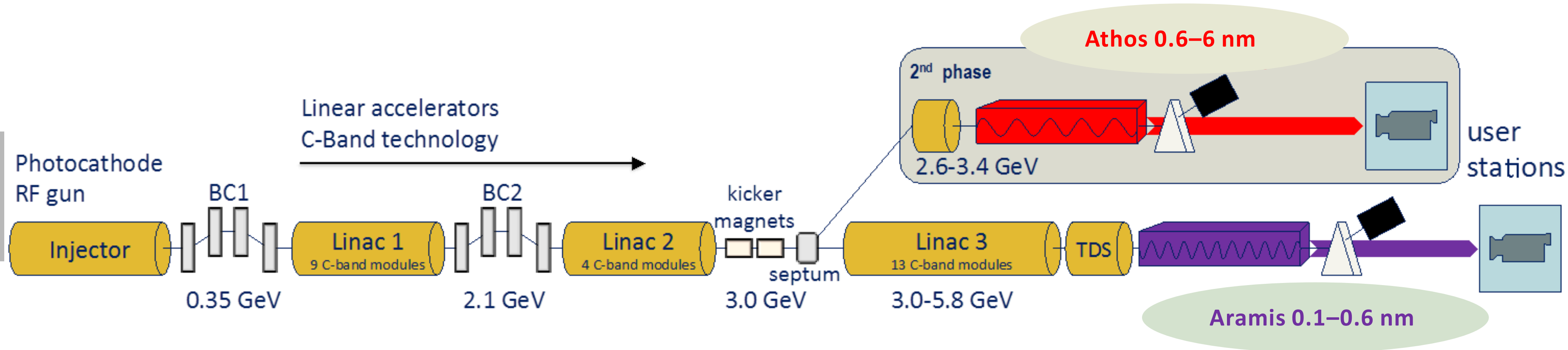
PAUL SCHERRER INSTITUT

# Outline

- Some RF activities in SwissFEL
  - 2.5 cell S-band RF gun
  - Status of C-band linac
- Consolidation of the RF technology at PSI
  - CERN-PSI X-band accelerating structures
  - Post-undulator X-band Transverse Deflecting Structures

    → ongoing collaboration between CERN-PSI-DESY
- RF Travelling-Wave Electron Guns

# SwissFEL overview




**Main parameters**

| | |
|---|---|
| Wavelength from | 0.1 nm–6 nm |
| Photon energy | 0.2-12 keV |
| Pulse duration (rms) | 2 fs - 30 fs |
| $e^-$ Energy (0.1 nm) | 5.8 GeV |
| $e^-$ Bunch charge | 10-200 pC |
| Repetition rate | 100 Hz |

**ARAMIS**

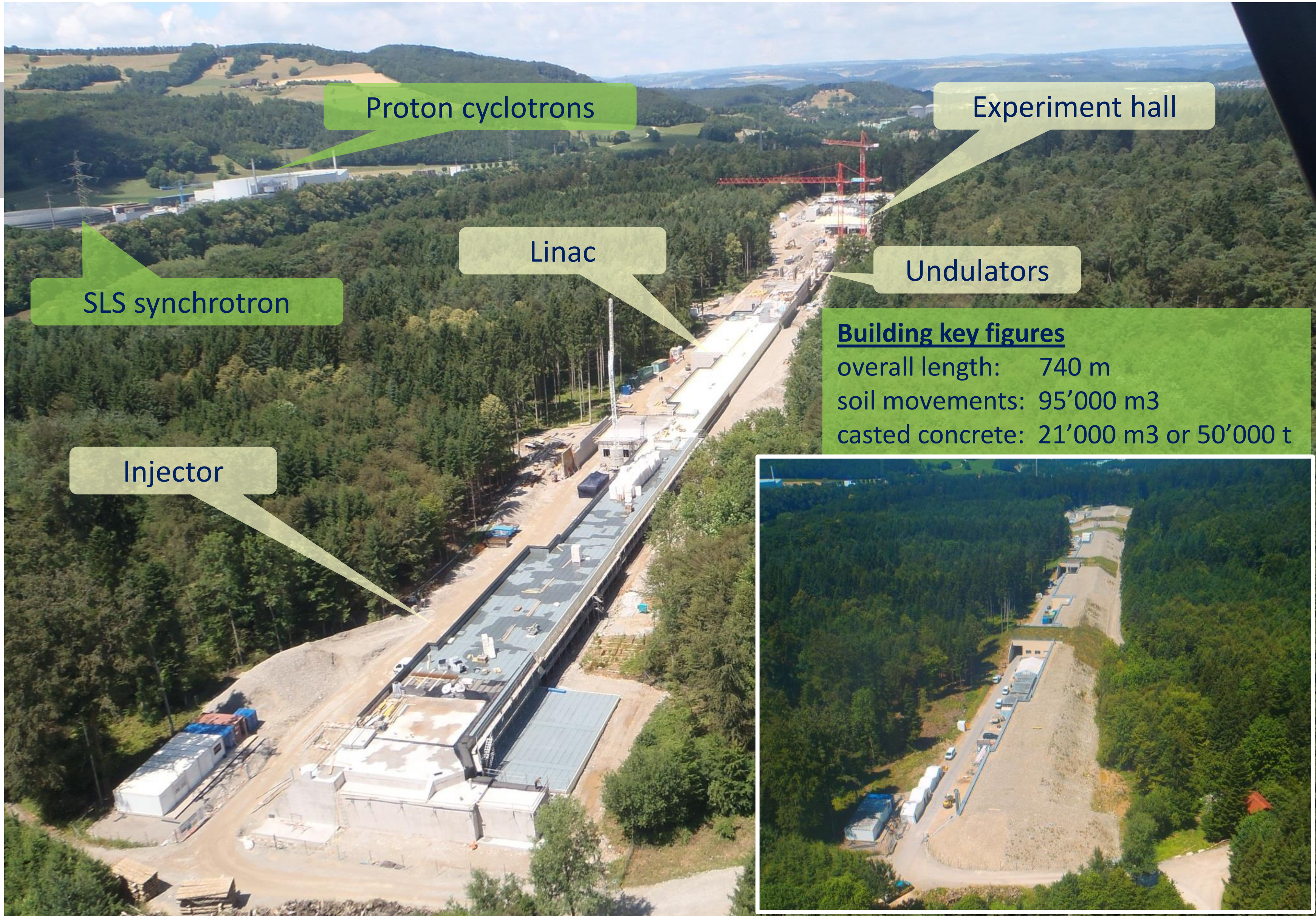
- Hard X-ray FEL, λ=0.1 - 0.6 nm (12-2 keV)
- Linear polarization, variable gap, in-vacuum undulators
- First Pilot Experiment by End 2017 (SASE)
- Operation modes: SASE & self seeded

**ATHOS – Beam Energy 2.78 – 3.22 GeV**

- Soft X-ray FEL, λ=0.6 - 6.0 nm (2-0.2 keV)
- Variable polarization with Apple-X undulators (2 m length)
- 2nd construction phase 2017 – 2020
- Operation modes: SASE & self seeded & many more

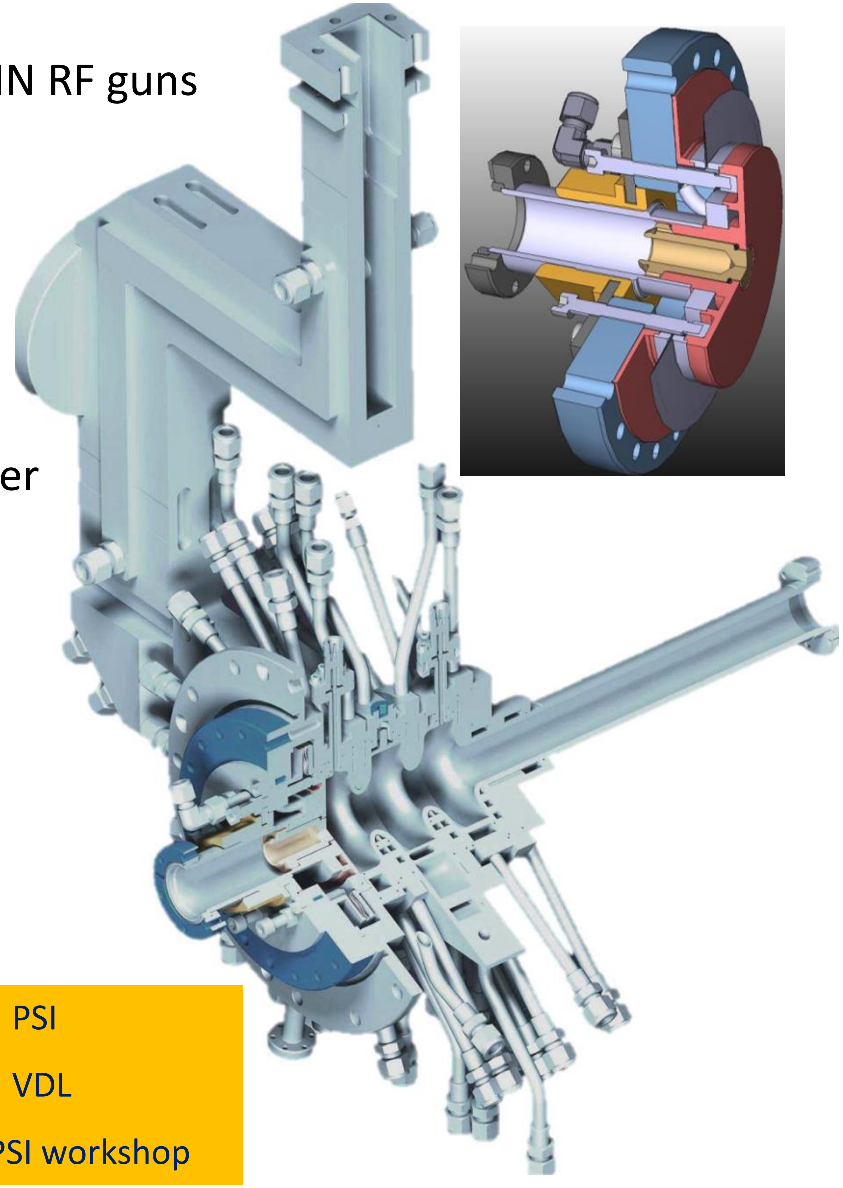
PAUL SCHERRER INSTITUT PSI

# SwissFEL site



# 2.5 cell S-band RF gun

- Best design features from LCLS and CTF/PHIN RF guns adopted
- Machined "on tune" according to HFSS
- No tuning plungers
- No tuning step during machining
- Quadrupole compensated symmetric coupler
- Load lock chamber
- β=2



**SwissFEL Gun 1**

| | | |
|---|---|---|
| $f$ | [GHz] | 2.9988 |
| $\Delta f$ | [MHz] | 15 |
| $E_{acc,0}$ | [MV/m] | 100 |
| $E_{max}$ | [MV/m] | 100 |
| $P_{in}$ | [MW] | 18 |
| $\Delta t_{RF}$ | [ns] | 1000 |
| $P_{diss}$ | [kW] | 0.9 |

RF and mechanical design: PSI

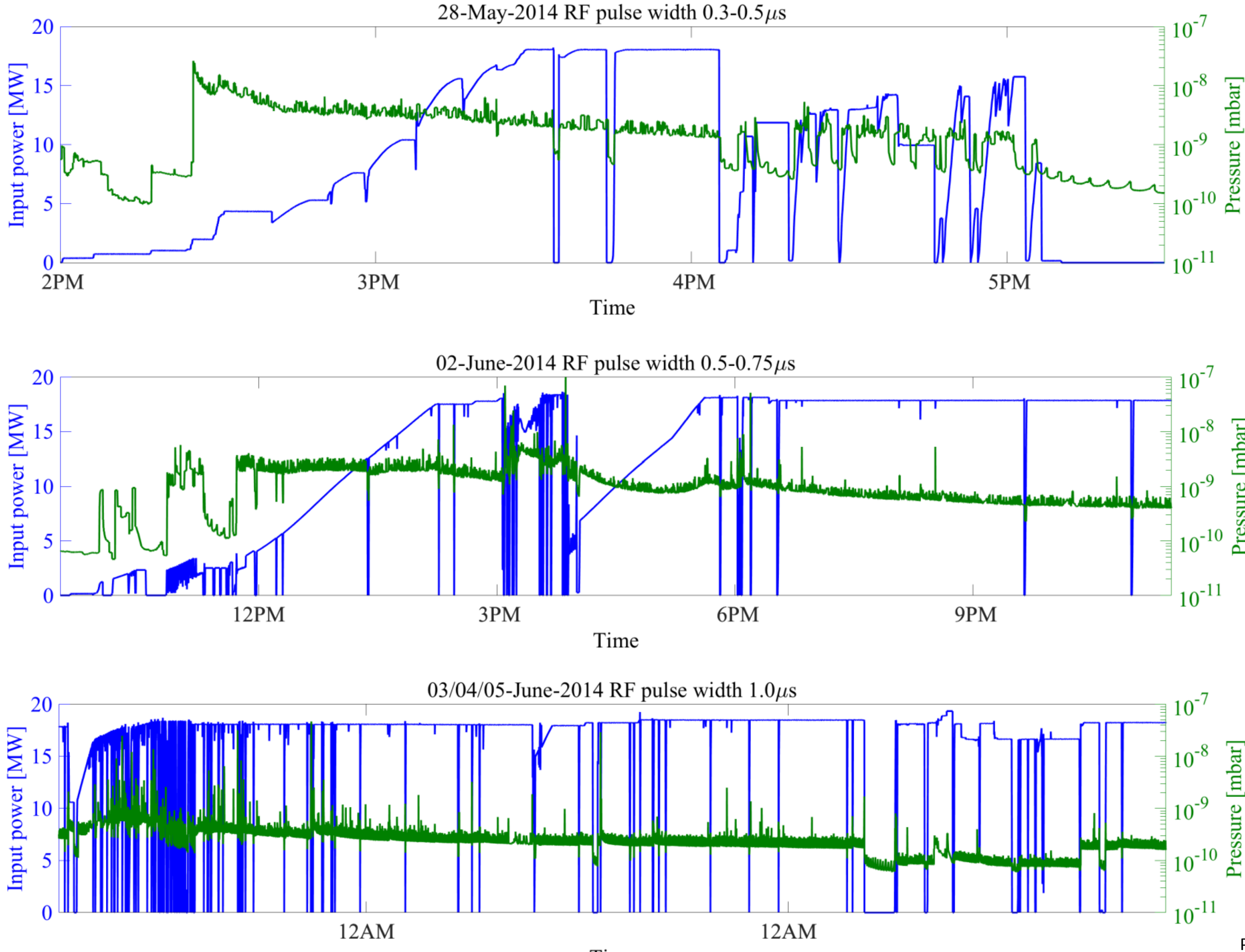
Fine machining cavities : VDL

Pre-machining & brazing: PSI workshop

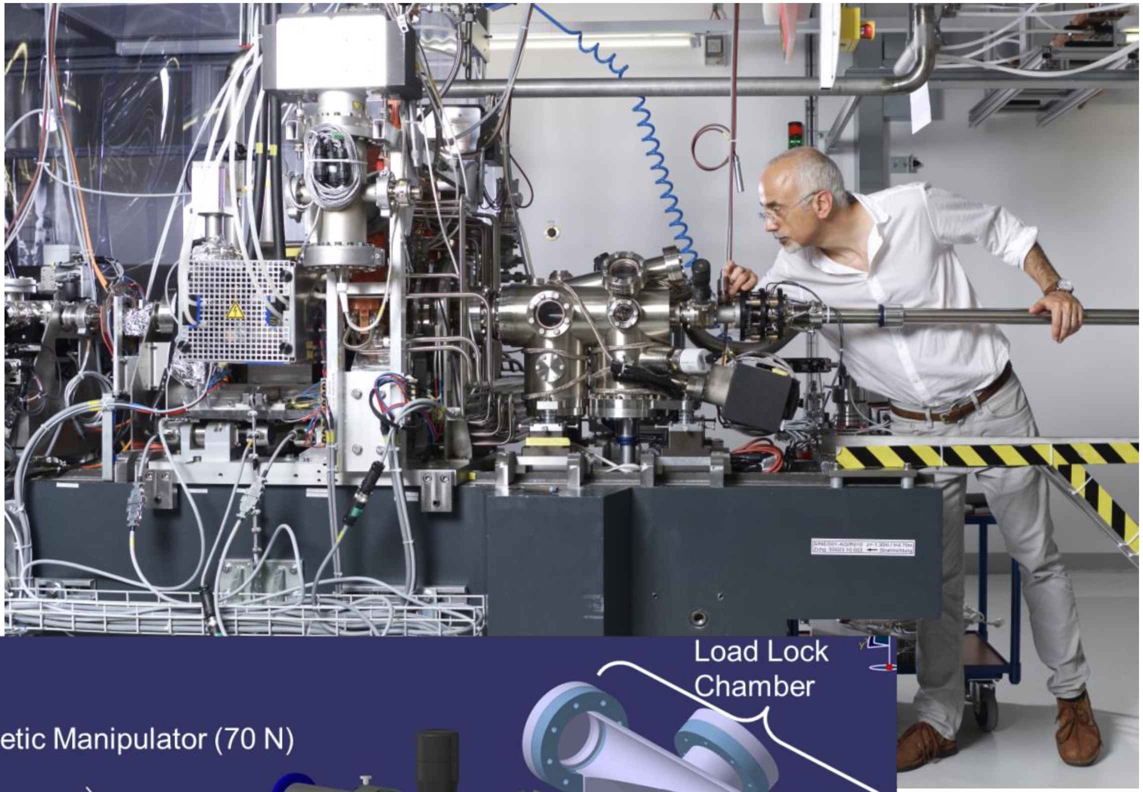
# RF conditioning at SITF

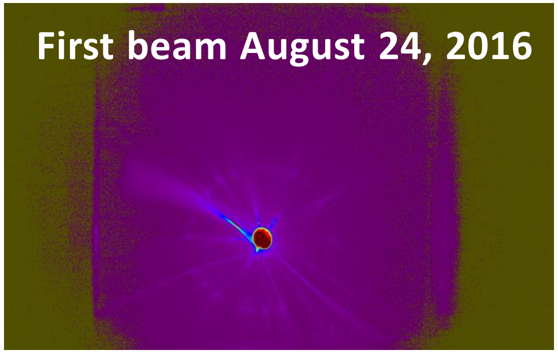
Blue lines: RF power

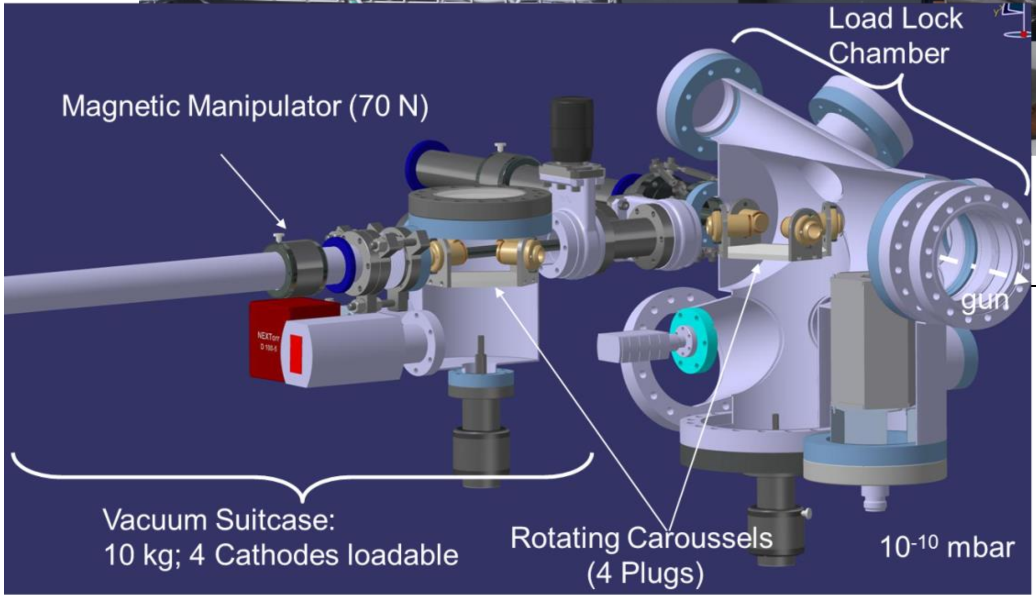
Green: vacuum pressure



# Gun installed in SwissFEL






Vacuum suitcase connected to the load-lock, showing the cathode transfer principle and the storage carroussels..

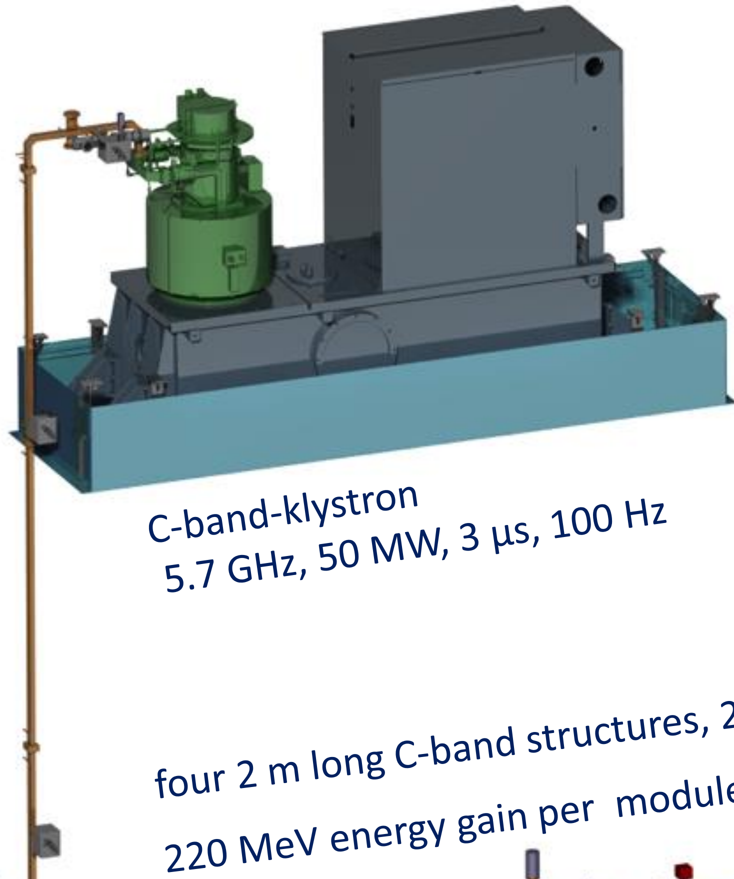
## Reference performances

(Q = 200 pC and $E_{cath}$=100MV/m)

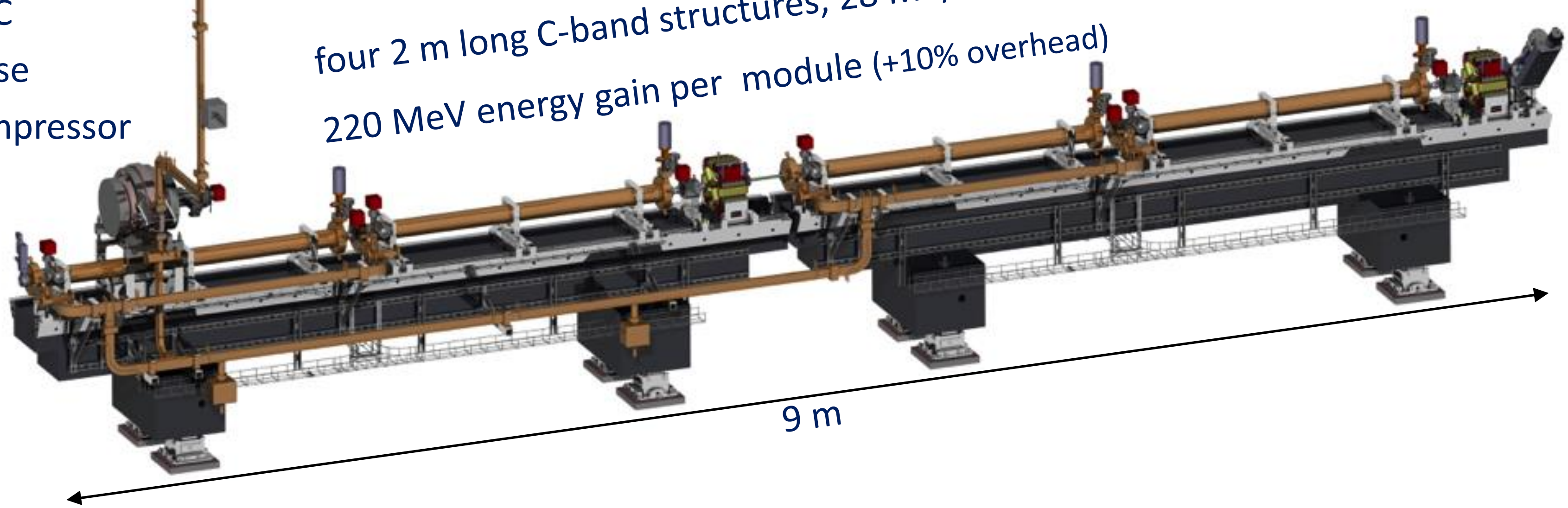
| | | SwissFEL Sim. | SITF Sim. | SITF Meas. |
|---|---|---|---|---|
| $E_{kin}$ | [MeV] | 6.6 | 6.6 | 6.6 |
| $I_{peak}$ | [A] | 20 | 20 | 20 |
| $\varepsilon_{x,n}$ | [μm] | 0.21 | 0.26 | 0.28 |
| $\bar{\varepsilon}_{x,n}$ | [μm] | 0.144 | 0.18 | 0.20 |
| $B_n$ | [TA/m$^2$] | 450 | 300 | 260 |
| $\bar{B}_n$ | [TA/m$^2$] | 965 | 620 | 500 |

PAUL SCHERRER INSTITUT

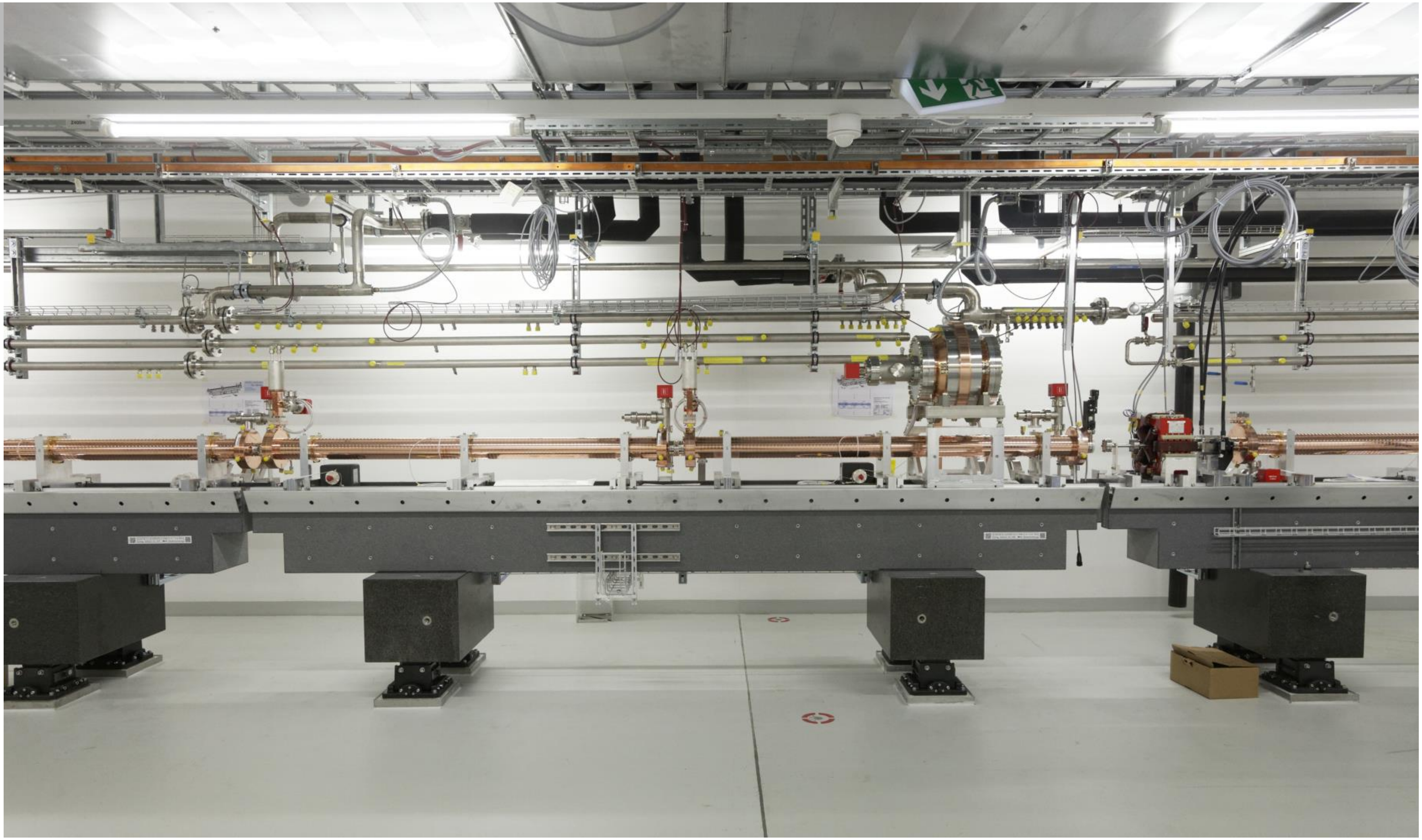
# SwissFEL C-Band module



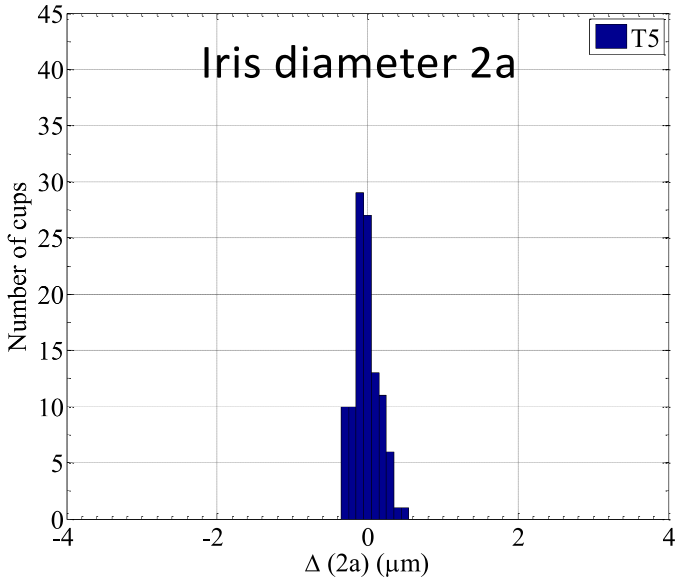

| Main LINAC | # |
|---|---|
| LINAC module | 26 |
| Modulator | 26 |
| Klystron | 26 |
| Pulse compressor | 26 |
| Accelerating structure | 104 |
| Waveguide splitter | 78 |
| Waveguide load | 104 |

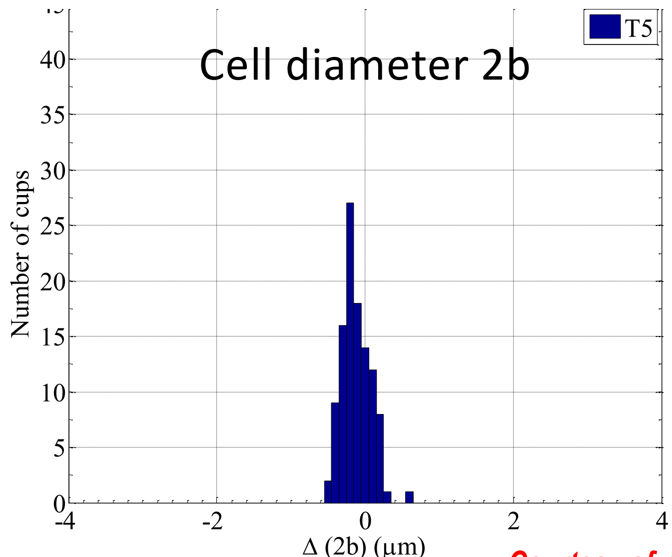


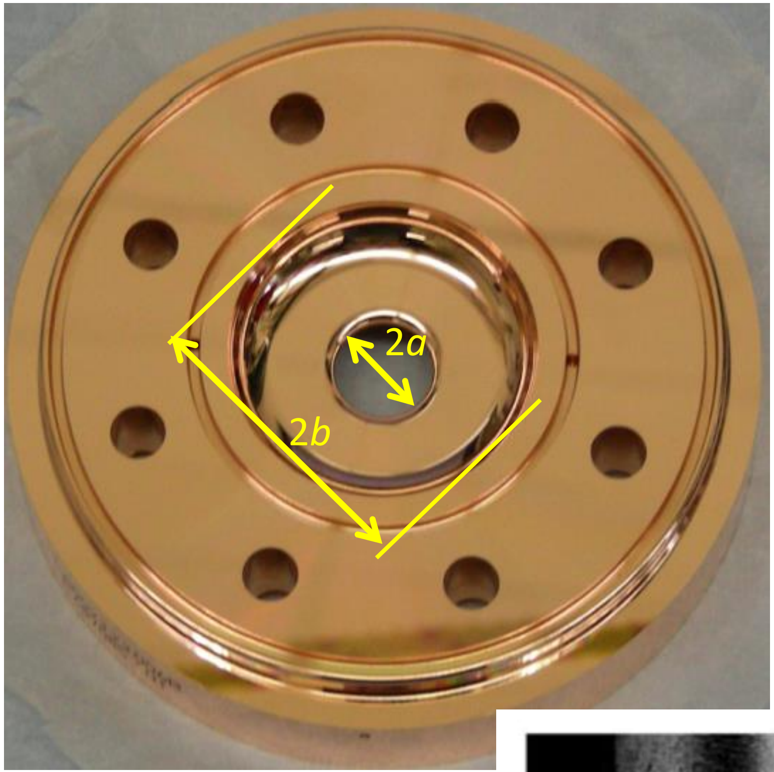
# Installation of last Linac girder: Sept. 13, 2016

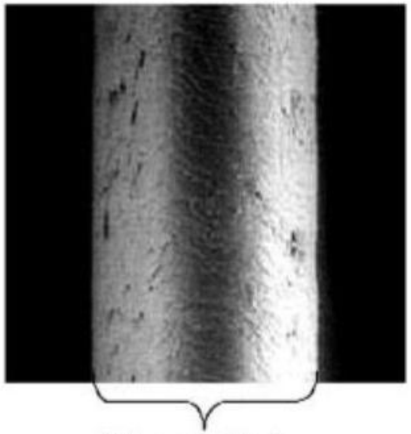


# C-band structures: ultra-precision machining



Human Hair
(60 μm diameter)

**Courtesy of J.Y. Raguin**

Typical examples of metrology on a structure:
top histogram iris diameter, bottom histogram iris cell diameter

# C-band structures

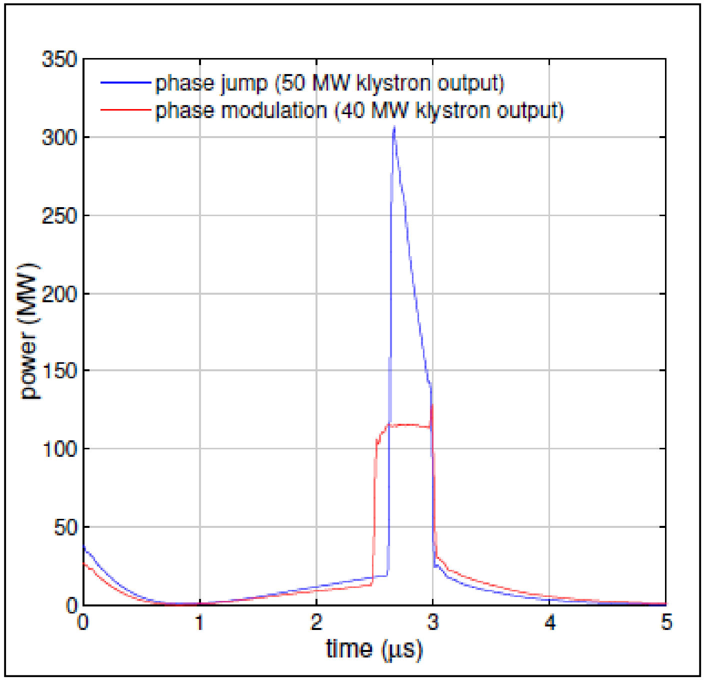
- Structures are machined "on tune", no provisions for dimple tuning!
- Cup manufacturing with micron precision at VDL ETG Switzerland
- Coupler manufacturing at VDL ETG
- Stacked by robot at PSI
- Vacuum-brazed at PSI
- Production rate: 1-2 / week
- Production finished August 2016

- **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 negligible (well below the specified threshold of $10^{-8}$)

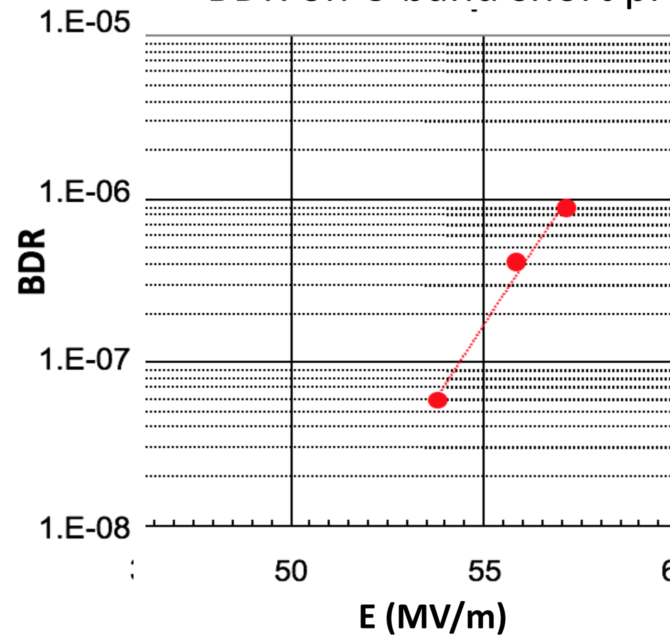
R. Zennaro et al.,

"Measurement and High Power Test of the First C-Band Accelerating Structure for SwissFEL", Proceedings of LINAC2014, Geneva, Switzerland

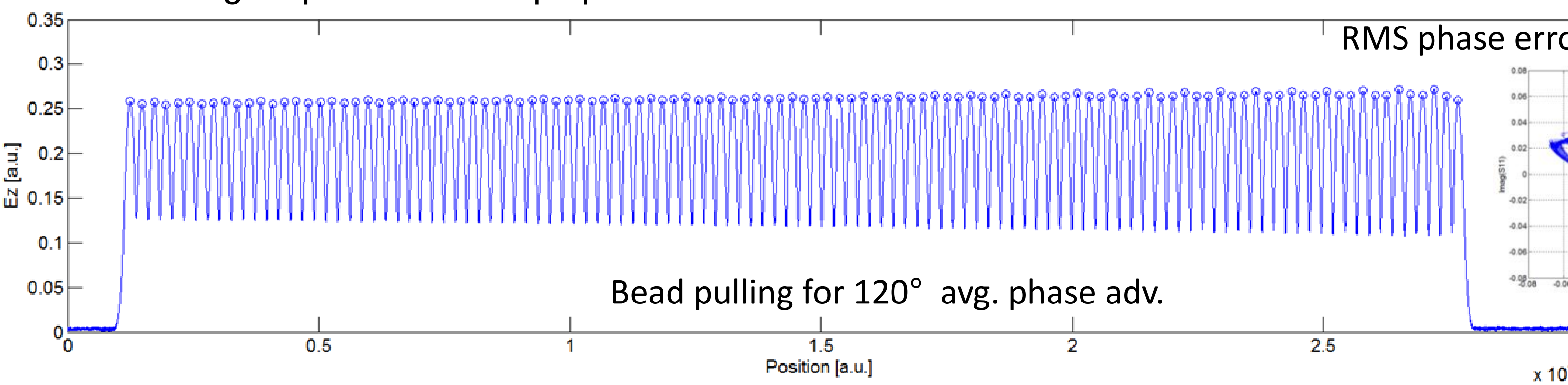
# Pulse compressor, max. gradient and bead-pull



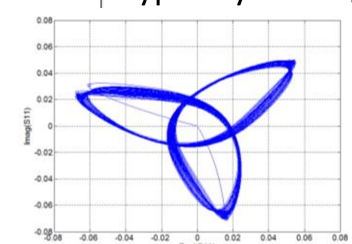

BDR on C-band short prototype




No tuning steps from the cups production to the installation into the bunker.



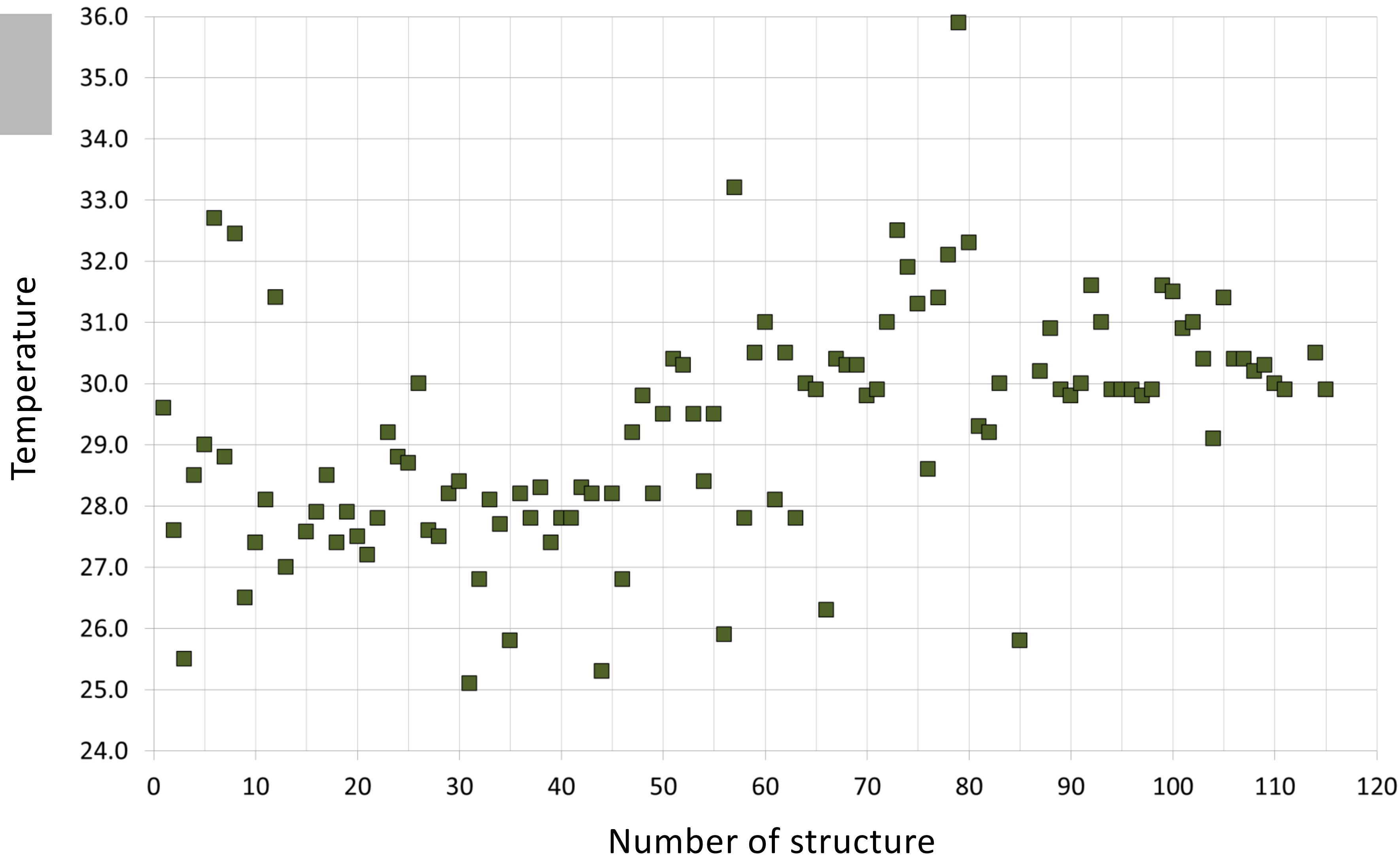

RMS phase error typically < 1 deg



*References: R. Zennaro and A. Citterio*

# Temperature distribution @5712 MHz

Δ1°C = 0.75 µm @ ~44mm cell diameter



PAUL SCHERRER INSTITUT PSI

# Solid-state modulators for C-band linac

- ✓ Two prototypes were tested at PSI for evaluation of the series.
- ✓ **50 MW / 3µs RF, 370kV / 344A / <20 ppm voltage stability pulse to pulse @ 100 Hz**

AMPEGON

**Type-µ modulator prot. for PSI C-band**

- 13 modulators (Linac 1, Linac 2)

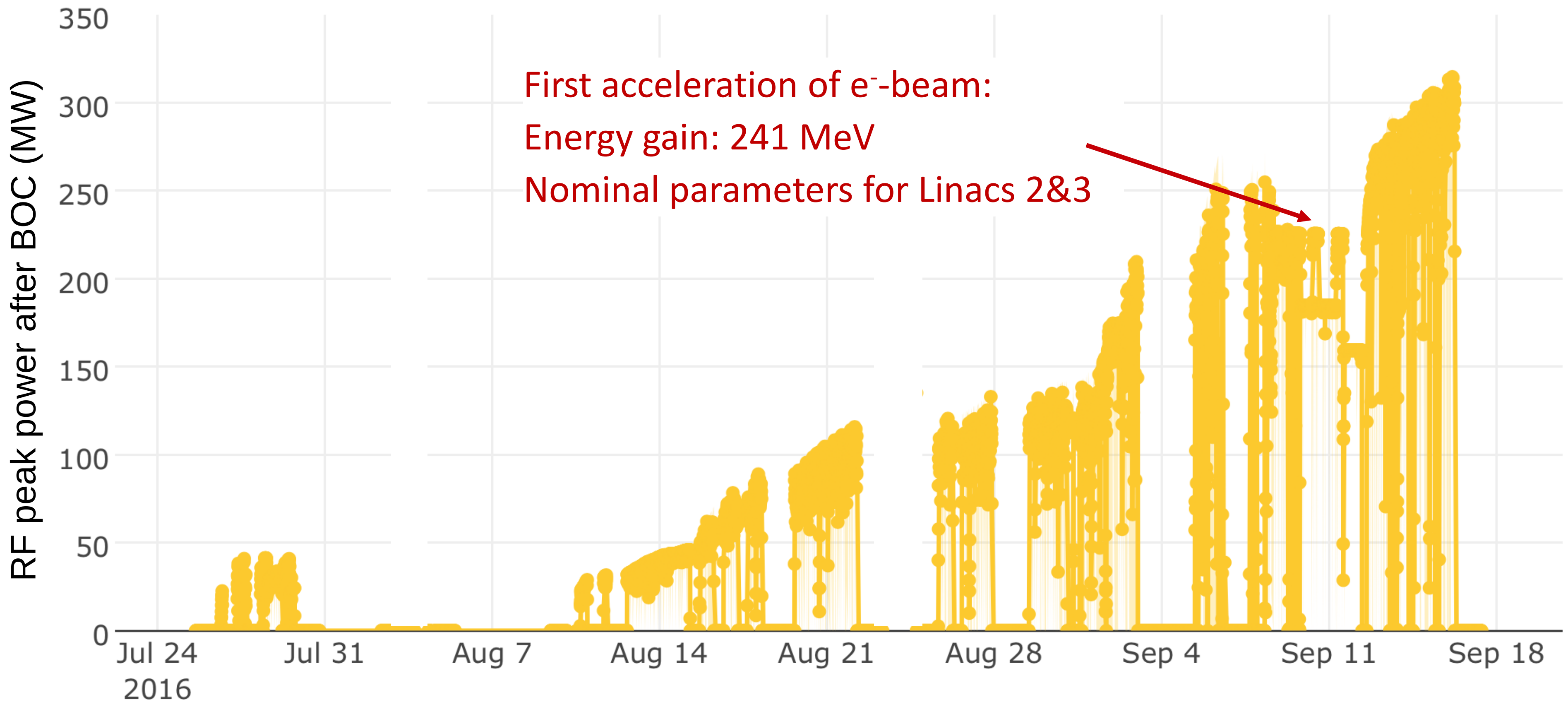
ScandiNova

**K2-3 proto. for PSI C-band**


- 13 modulators (Linac 3)

- ✓ Progressive increase of beam energy to final energy of 5.8 GeV
- ✓ First Pilot Experiments by End 2017 (requested 3 GeV beam)

# Conditioning of first C-band module




Module conditioning: Reached almost maximum available RF power (50 MW, 3 μs, full compression)

**SwissFEL energy gain scheme based on BOC performances:**

- **Linac 1 with phase modulation operation**: on-crest energy gain of 52 MeV/structure (~26 MV/m) @40 MW from klystron.
- **Linac 2 and 3 with phase jump operation**: on-crest energy gain of 58 MeV/structure (~29 MV/m) @36 MW from klystron.

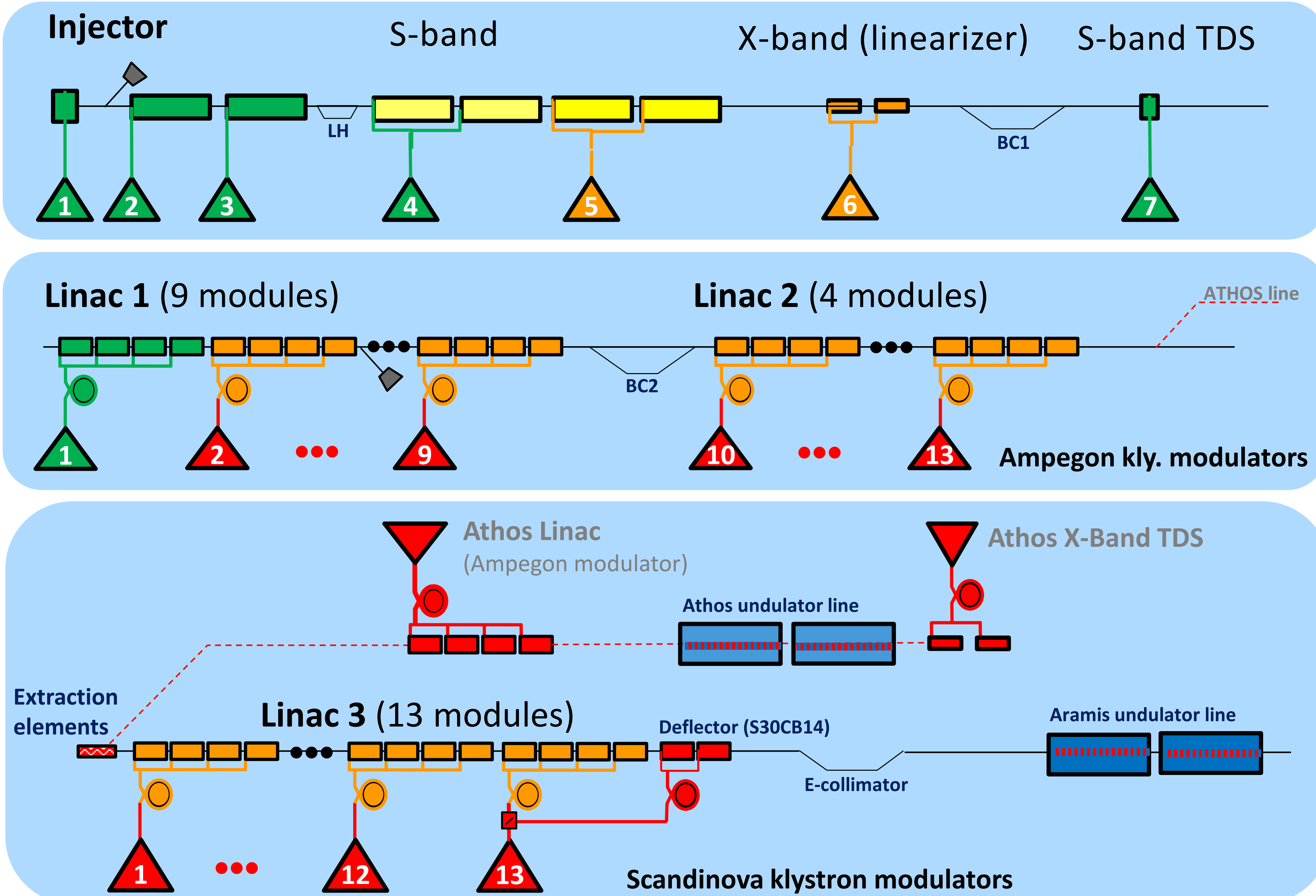
*References: R. Zennaro, F. Löhl et al.*

PAUL SCHERRER INSTITUT

# Overview SwissFEL RF

*Present status*

- operational
- Operational but not fully conditioned
- Installed but not commissioned
- To be installed and commissioned



# Consolidation of the RF technology at PSI

- PSI has developed a production line of high technological content for high-quality, high-gradient C-band accelerating structures for the SwissFEL project.

- PSI is interested in extending, consolidating and broadening its know-how to S-band and X-band frequencies

  → RF group is establishing international collaborations on different topics:

  - CERN-PSI: development of X-Band high-gradient accelerating structures structures in tuning-free C-band design;

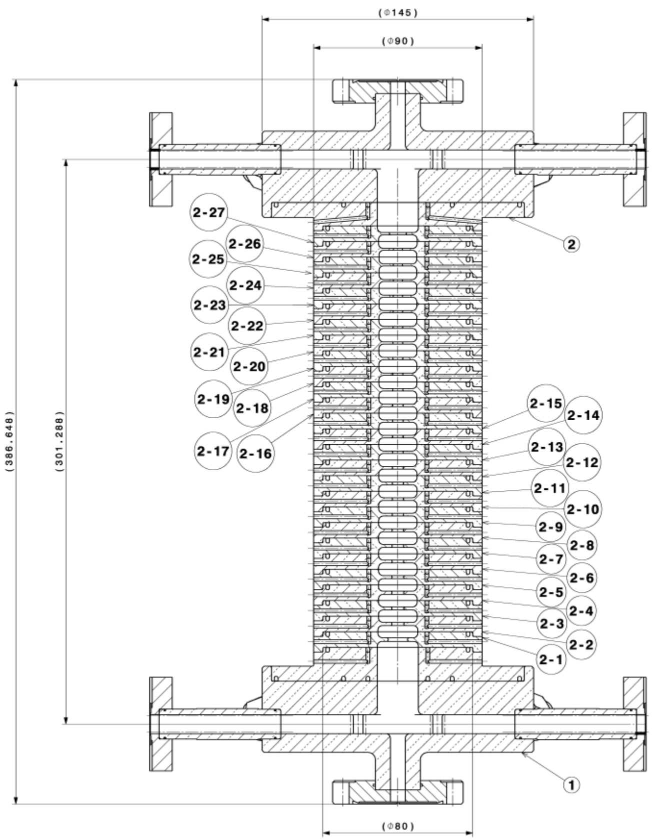
  - CERN-DESY-PSI: development of innovative X-band tuning-free transverse deflecting structure with a novel variable polarization feature, *also see B. Marchetti's talk.*

  - FERMI@Elettra-PSI: development of S-band high-gradient accelerating in tuning-free C-band design, *see C. Serpico's talk held on Monday.*

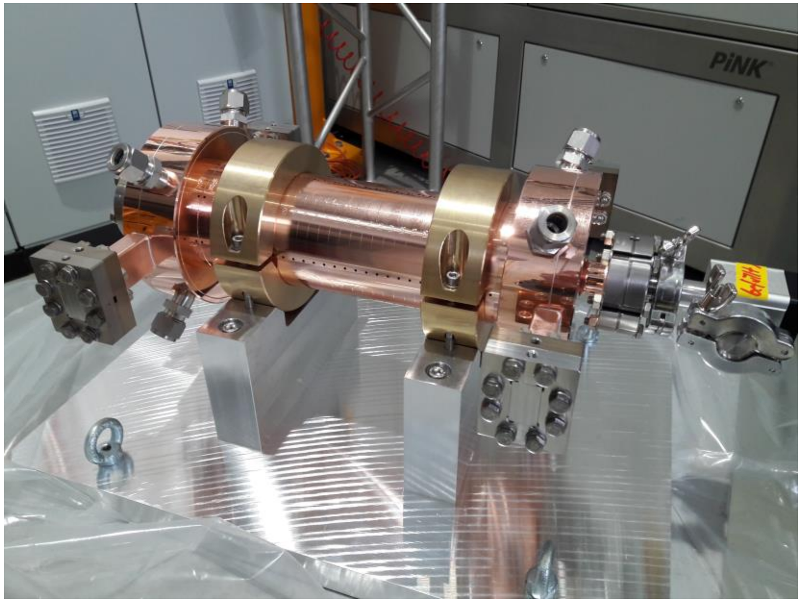
- *Consolidation of the exiting C- band technology in accelerators applications: development of C-band traveling-wave photo guns for the SwissFEL project and for a multipurpose photo-injectors.*

# CERN-PSI X-band accelerating structures

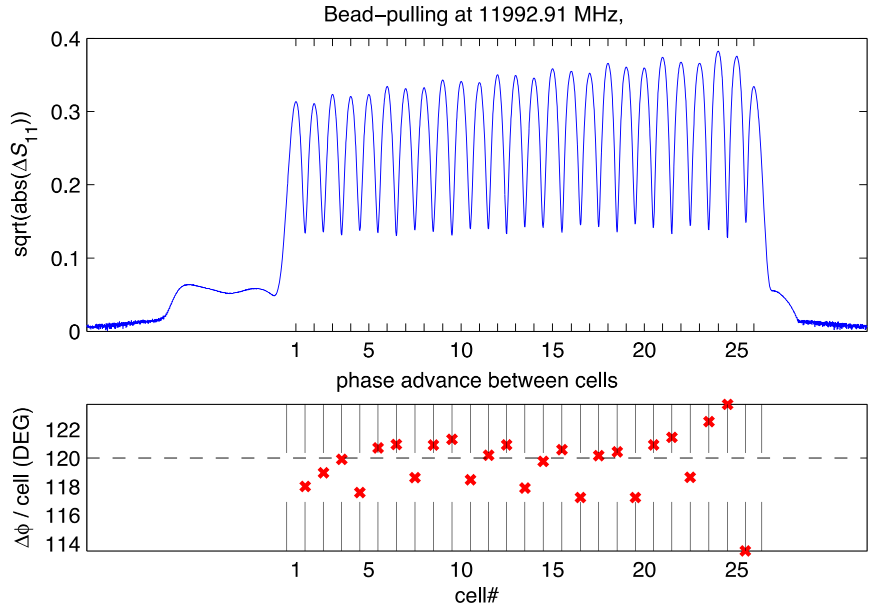
27 cells + input couplers (2π/3)




- Tolerances on the drawing is ±2 μm (iris aperture and cell diameter ($R_a$ = 25 nm).
- Parts are all fabricated (by VDL)
- Assembling and brazing at PSI
- 2 structures:
  - ✓ first one ready for high-power tests at CERN
  - ✓ second one is brazed and vacuum tight and ready for bead-pull measurements at CERN.

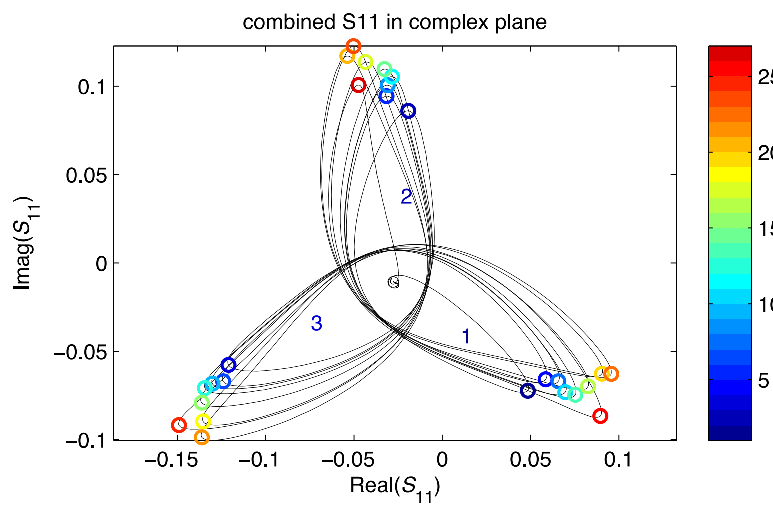


# First X-band accelerating structure




Working frequency is 29°C (design 30°C)

Matching is at -30 dB level.



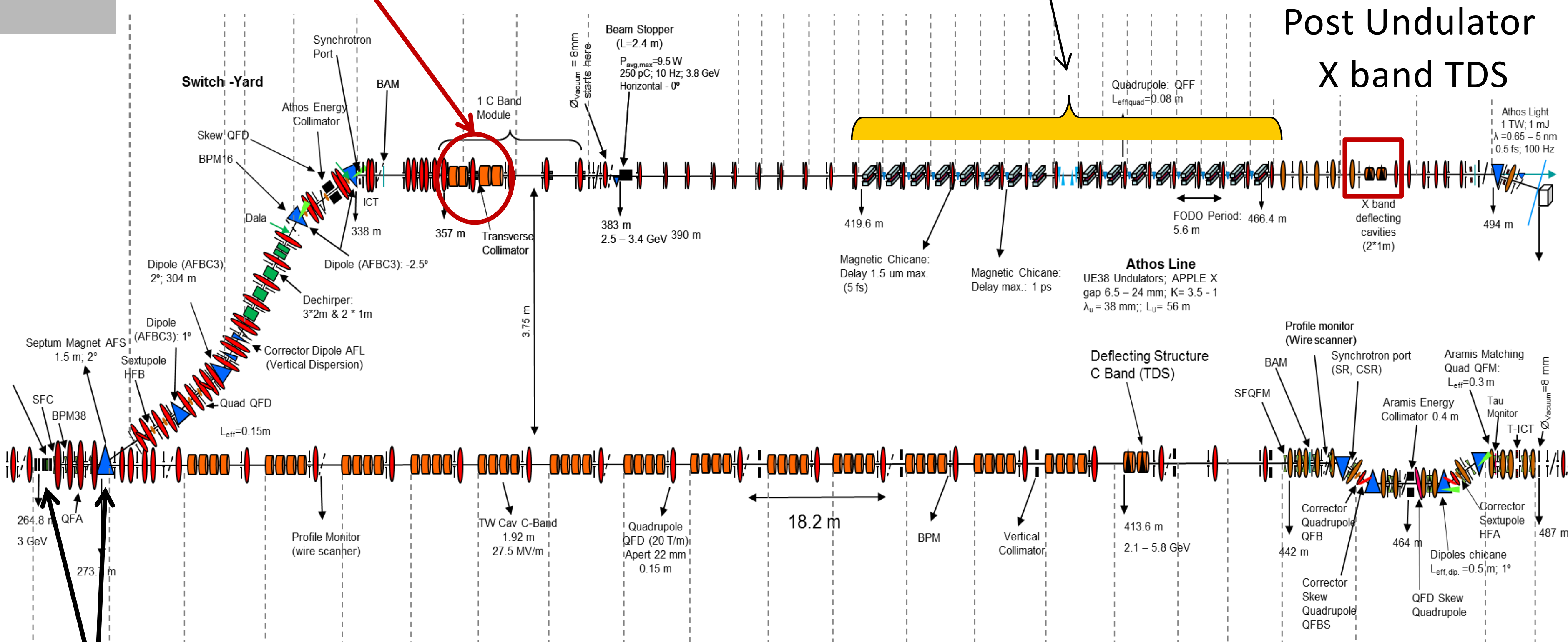

*Courtesy of Rolf Wagner (CERN)*

# Post-undulator X-band TDS for Athos beamline

Athos Linac
(one C band module)

16 Apple X Undulator UE38 (module 2 m long)
15 Magnetic chicane: delay, compress and shift bunches

Post Undulator
X band TDS




Courtesy R. Ganter

Resonant kicker
Septum (28 ns)

*Reference for post-undulator TDS: C. Behrens et al., „Few-femtosecond time-resolved measurements of X-ray free electron laser“ , Nat. Comm. 4762 (2014).*

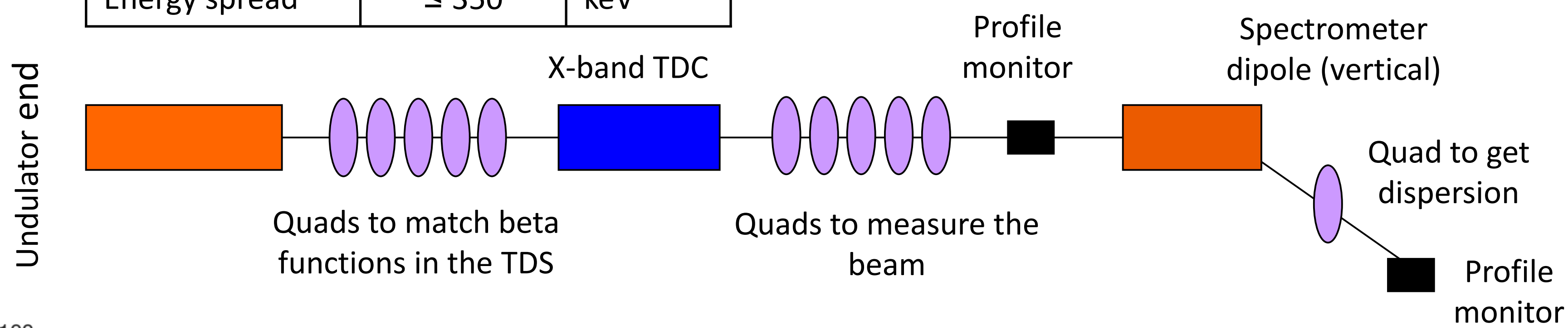
PAUL SCHERRER INSTITUT PSI

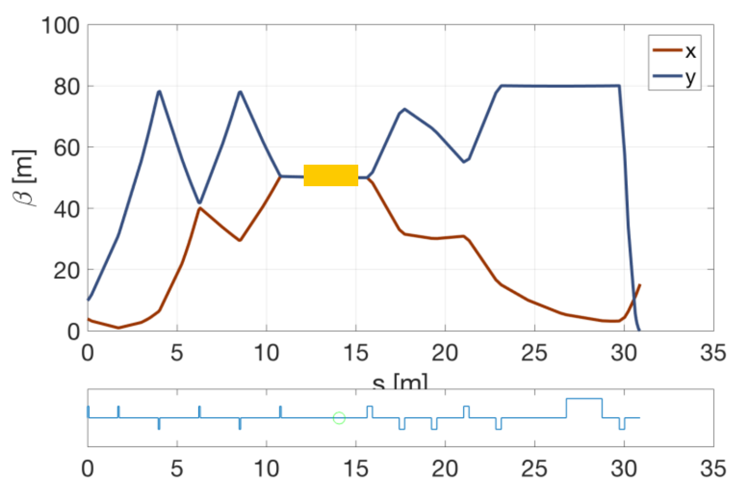
# Beam parameters and measurement concept

| Parameter | Value | Unit |
|---|---|---|
| $e^-$ charge | 10 - 200 | pC |
| Peak current | 2-3 | kA |
| Pulse duration | 2 - 30 | fs (rms) |
| $e^-$ Energy | ≤ 3.5 | GeV |
| Emittance | ≤ 300 | nm |
| Energy spread | ≤ 350 | keV |

**Beam measurements:**

- ❑ Slice emittance on both planes
- ❑ Projected emittance on both planes
- ❑ Electron and photon pulse length
- ❑ Energy spread induced by FEL process

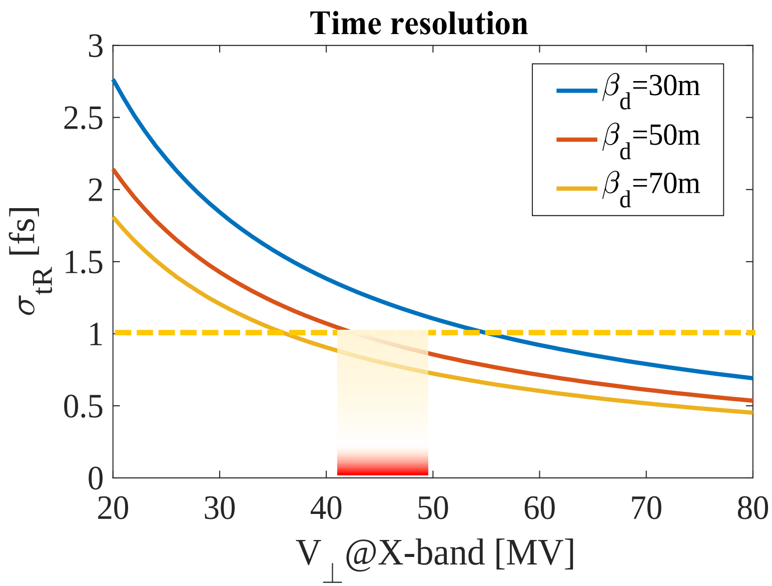



- ❑ $\beta_x = \beta_y = 50$ m → **optics for both polarizations**
- ❑ Energy resolution
  - ❑ Due to betatronic effect < 180 keV (beam size)
  - ❑ Due to screen resolution = 150 keV
  - ❑ But TDC induces energy spread!

*courtesy of E. Prat*

# Resolution, induced energy spread and jitter

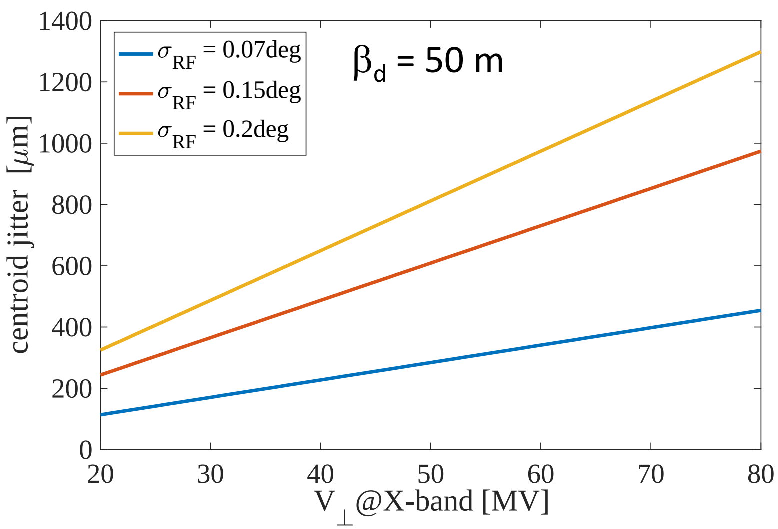


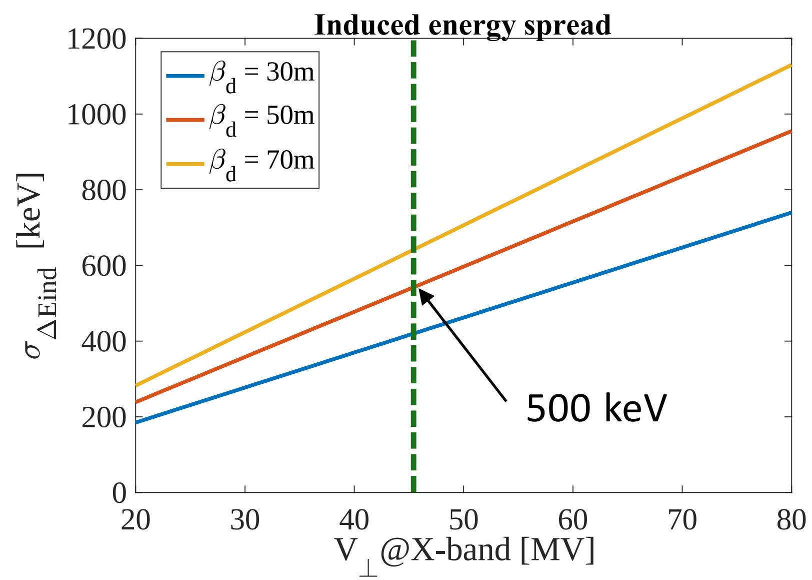

$$\sigma_{t,res} = \frac{\sqrt{\varepsilon_N} \cdot E_0 \cdot \sqrt{\gamma}}{\sqrt{\beta_y} \cdot \sin \Delta\psi_{ds} \cdot eV_\perp \cdot c \cdot k_{rf}}$$

Resolution 0.95 fs @45MV and $\beta_d$ = 50 m

Resolution 0.71 fs @60MV and $\beta_d$ = 50 m

$$\sigma_{\Delta Eind} = \frac{E_0 \cdot \varepsilon_N}{c \cdot \sigma_{t,res}}$$



# RF stability – X-band linearizer

Typical rf stability figures (rms values) over one hour of operation for all rf stations operated at the SITF [1]:

| rf station | Amplitude | | Phase | |
|---|---|---|---|---|
| *S-band:* | | | | |
| FINSS (rf gun) | $1.3 \times 10^{-4}$ | 1.8e-4 | 0.020° | 0.018° |
| FINSB01 | $1.4 \times 10^{-4}$ | | 0.030° | |
| FINSB02 | $1.2 \times 10^{-4}$ | | 0.027° | |
| FINSB03/04 | $2.1 \times 10^{-4}$ | | 0.032° | |
| *X-band:* | | | | |
| FINXB[a] | $2.1 \times 10^{-3}$ | | 0.17° | 0.072° |

[a] Limited by klystron pre-amplifier stability.

Pre-amplifier: Advance System Engineering, Model 174 X TWT

## Specifications for the SwissFEL:

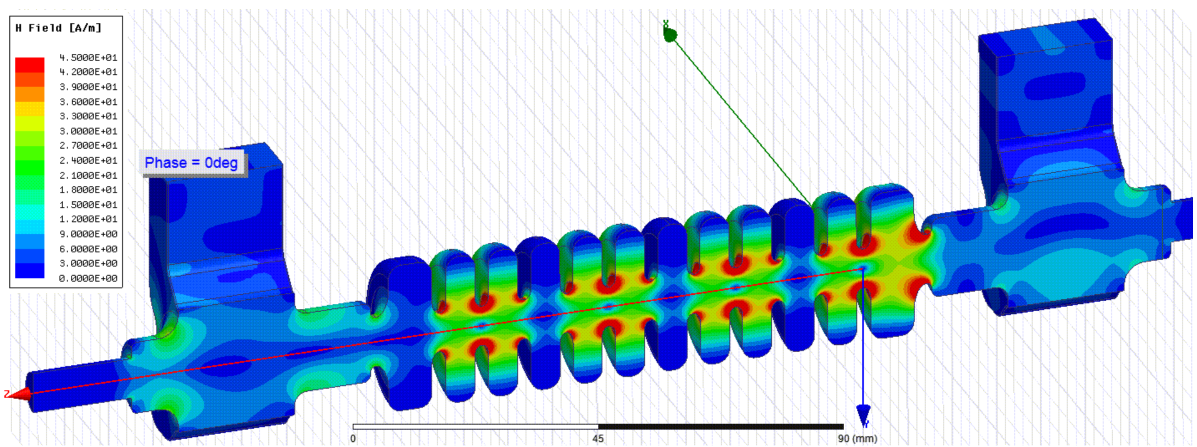
| Frequency band | Frequency [MHz] | RF tolerance / phase noise (rms) [fs] / [°] | ref. distr. phase noise performance (rms) [fs] / [°] | max. added phase noise vec. mod. (rms) [fs] / [°] | max. allowed added phase noise pre-amplifier / (klystron/HV mod.) (rms) [fs] / [°] | required HV modulator stability (rms) |
|---|---|---|---|---|---|---|
| X-band | 11995.2 | 16.7 fs / 0.072° | 3.5 fs / 0.015° | 6.1 fs / 0.026° | 10.7 fs / 0.046° | < 29 ppm |

[1] T. Schietinger et al., "Commissioning experience and beam physics measurements at the SwissFEL Injector Test Facility ", PR AB (2016)

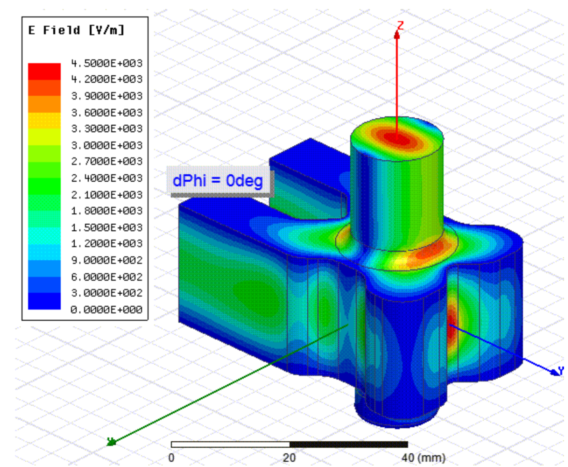
*Ref.: T. Schilcher*

# Ongoing collaboration for X-band TDS

- Establishing a collaboration between CERN, PSI and DESY
- TDS with a novel variable polarization feature
  → tuning may be difficult because a tight symmetry is required!
- RF design by A. Grudiev in CLIC-note-1067 (2016)
- First prototype with tuning-free assembly procedure developed at PSI
- Eventually starting with the series for PSI and DESY applications



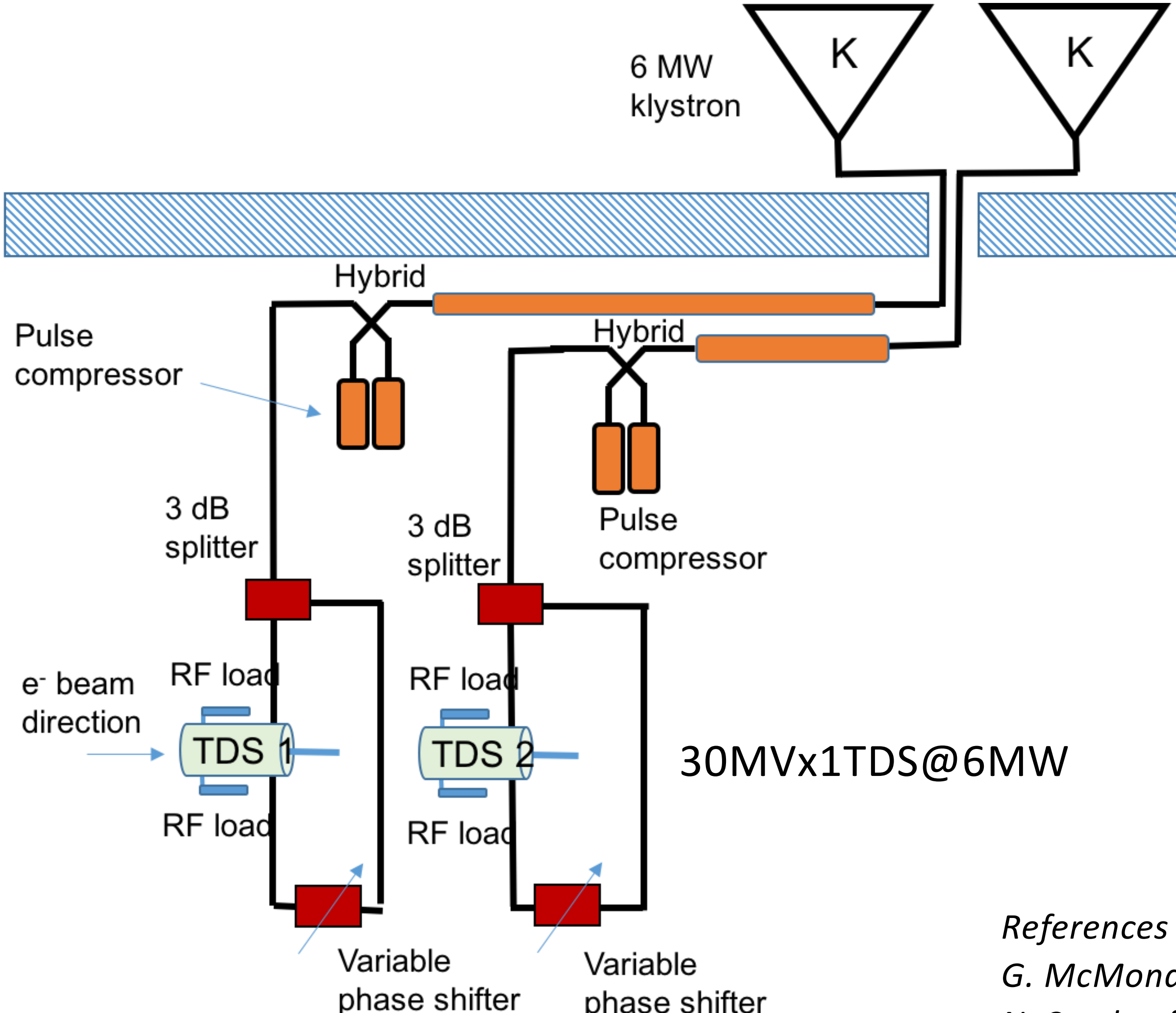

*Courtesy of A. Grudiev*




Variable Polarization
Circular TE11 Mode Launcher

# RF waveguide network (first concept)

First concept based on CERN Xbox3 system with a 6 MW Toshiba klystron, Scandinova K200-type modulator (1.6mx1.3m), SLED system and waveguide components




30MVx1TDS@6MW

K200 modulator

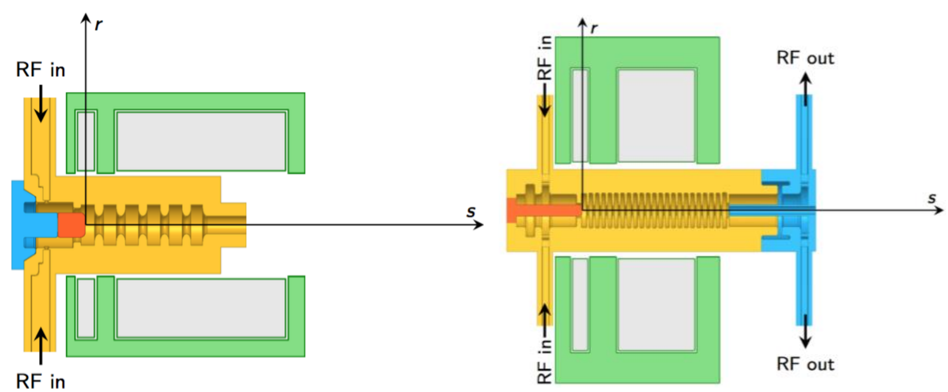
*References at CERN:*
*G. McMonagle for klystron and modulator*
*N. Catalan for waveguide components*

# RF Travelling-Wave Electron Gun

- Motivation: exploring new designs of electron source at C-band frequency that could represent a future upgrade of the SwissFEL injector.
- Constrains: possible beam dynamics improvements were investigated by substituting only the electron gun and the relative solenoid while leaving the rest of the injector (downstream of the first booster structure) almost unchanged.

| Setup | | SwissFEL Gun 1 reference | C-Band SW Gun | C-Band TW Gun 60° | C-Band TW Gun 120° |
|---|---|---|---|---|---|
| $E_{kin}$ | [MeV] | 6.6 | 9.8 | 12.0 | 12.7 |
| $I_{peak}$ | [A] | 20 | 41 | 48 | 41 |
| $\varepsilon_{x,n}$ | [μm] | 0.21 | 0.22 | 0.21 | 0.22 |
| $\bar{\varepsilon}_{x,n}$ | [μm] | 0.14 | 0.17 | 0.13 | 0.15 |
| $\bar{\zeta}$ | | 1.14 | 1.03 | 1.13 | 1.09 |
| $B_n$ | [TA/m²] | 450 | 850 | 1050 | 870 |
| $\bar{B}_n$ | [TA/m²] | 965 | 1480 | 2940 | 1840 |
| $f_p$ | | −1 | −1.5 | −2.0 | −1.4 |

- Brightness a **factor 3** higher than the SwissFEL
- Peak current a **factor 2** higher than SwissFEL gun
- Very conservative value of the field at cathode (**135 MV/m** with a filling time **< 100 ns**)



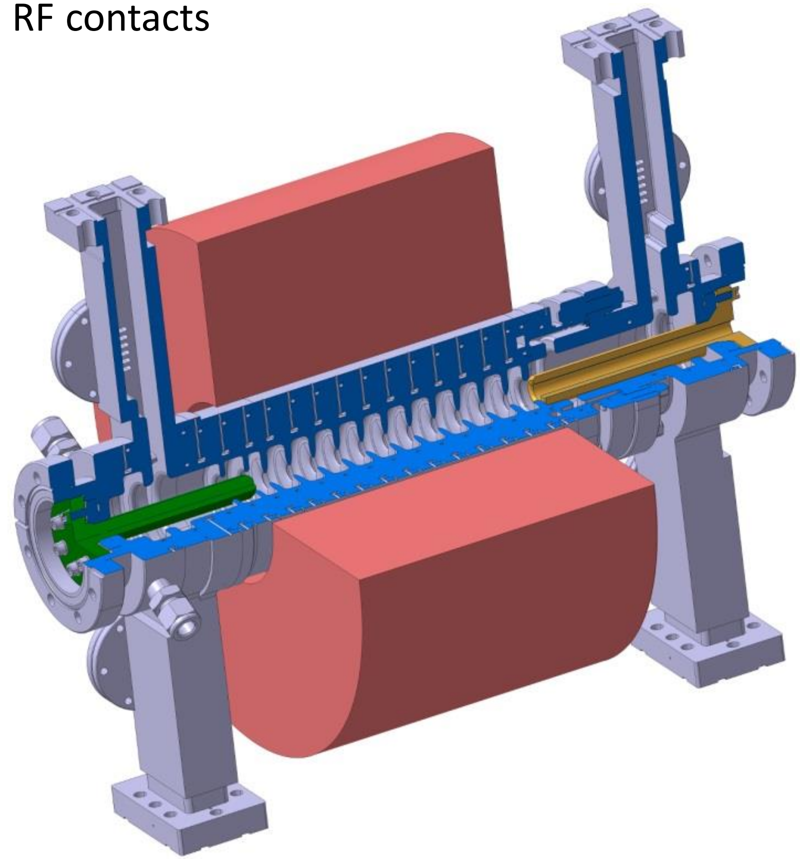

*M. Schaer et al., PR AB 19, 072001 (2016).*

# C-band RF Travelling-Wave Electron Gun

An innovative coaxial RF coupling from the cathode side enables

- the placement of the focusing solenoid around the cathode with a simplified magnet design that integrates main and bucking coil
- the elimination of the quadrupole components of the RF fields in the region where the beam is accelerated
- the introduction of gaps with vanishing RF fields, making the gun compatible with the load-lock system without the need of special RF contacts

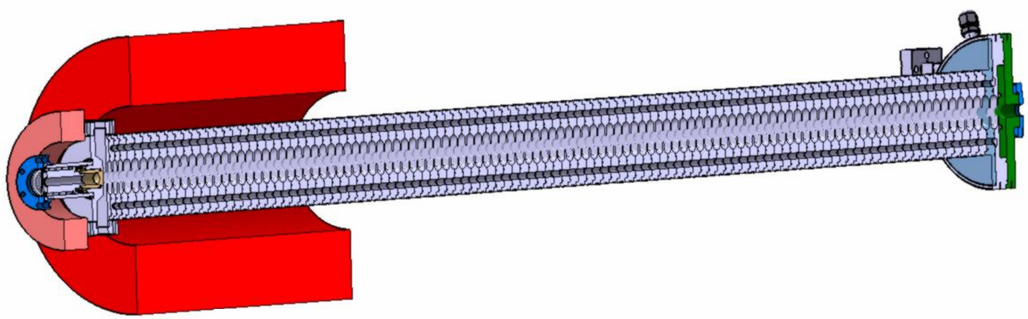
| **C-band TW Gun** | |
|---|---|
| **Frequency** | 5.712 GHz |
| **Phase advance per cell** | 60 deg/120 deg |
| **# cells** | 21/10 |
| **Structure length** | 215/220 mm |
| **Q** | 4700/10000 |
| **Filling time** | 73/90 ns |
| **Iris radius** | 5.5 mm |
| **Group velocity** | 0.95/079 % of [c] |
| **Nominal gradient** | 135 MV/m |
| **Nominal power** | 57.9/37.4 MW |
| **Repetition rate** | 100 Hz |



*M. Schaer et al., PR AB 19, 072001 (2016).*

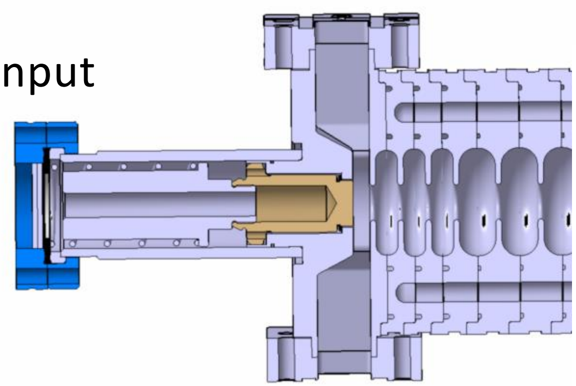
# Multipurpose C-band TW photo-injector

- Development of an innovative and compact C-band traveling-wave photo injector based on the C-band accelerating structures 2-m long
- This project is part of the consolidation of the exiting C- band technology in accelerators applications (RF photo-injectors for free-electron lasers, synchrotron light source, time-resolved electron diffraction, and advanced accelerator concepts)



| | |
|---|---|
| Length (m) | 2.108 |
| Number of accelerating cells | 113 |
| Phase advance/cell  (deg) | 120 |
| Frequency (GHz) | 5.712 |
| Repetition rate (Hz) | 100 |
| Filling time (ns) | 330 |
| Gradient (MV/m) | 20 |
| Max. field at cathode (MV/m) | 80 |
| Output beam energy (MeV) | 42 |
| Input power (MW) | 20 |

Details of the input coupler and cathode plug



Preliminary simulations:

| Bunch charge | 0.1pC | 15pC | 150pC |
|---|---|---|---|
| Bunch Length | <20fs | 4ps | 5 ps |
| Energy spread | 15keV | 30keV | 70keV |
| Emittance | <0.1urad | <0.1urad | <2.5uad |

*Ref.: R. Zennaro and L. Stingelin*

PAUL SCHERRER INSTITUT

# Conclusions

- **Status of the SwissFEL linac**
  - Progressive increase of beam energy to final energy of 5.8 GeV
  - First Pilot Experiments by End 2017 (requested 3 GeV beam)
- **Pathway towards a consolidation of the RF technology at PSI**
  - X-band high-gradient accelerating structures (CERN-PSI)
  - X-band TDS for the characterization of ultra-short bunches (CERN-PSI-DESY)
  - S-band high-gradient accelerating structures (FERMI-PSI)
  - C-band Travelling-wave photo-guns

# Acknowledgements


- Special thanks to the colleagues at PSI:
  - ✓ *R. Zennaro, A. Citterio, L. Stingelin, M. Pedrozzi, F. Löhl, M. Bopp, E. Prat, S. Reiche et al.*
- and to the colleagues from **CERN** and **DESY** working on X-band TDS collaboration, in particular:
  - ✓ *A. Grudiev, W. Wuensch, N. Catalan Lasheras, G. Mcmonagle (CERN)*
  - ✓ *B. Marchetti, F. Christie, R. D'Arcy, D. Marx (DESY)*


Thank you for the attention!!