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CONSOLIDATION AND EXTENSION OF THE HIGH-GRADIENT LINAC RF TECHNOLOGY AT PSI

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Abstract

For SwissFEL a novel production process for high-gradient, high-precision C-band accelerating structures had been developed at PSI and was implemented for series production in collaboration with industry. The copper parts of the structures are machined and brazed relying on a ultra-high precision manufacturing process and tight mechanical tolerances; no RF tuning methods are applied during or after production. So far none of the structures of the series production failed during RF power conditioning and operation in the SwissFEL facility. After completing the series production for SwissFEL PSI started collaborations with CERN, ELETTRA and DESY for applying the production process and related know-how to other frequencies, namely S-band (3 GHz) and X-band (12 GHz). This paper gives an overview on the ongoing and planned R&D activities and results obtained so far.

INTRODUCTION

The SwissFEL project [1], presently under commissioning at the Paul Scherrer Institut (PSI), produces FEL radiation for hard X-rays with pulse durations ranging from a few to several tens of femtoseconds. The SwissFEL accelerator consists of an electron source, an S-band (3 GHz) booster Linac and a C-band (5.7 GHz) main Linac. A total of 26 C-band modules are installed in the C-band Linac and each module consists of four 2-m long C-band structures that are mounted onto two granite girders (see [2] for a schematic and [3] for further information). The C-band structures [4] are stacked and brazed at PSI out of copper cells that were produced at VDL ETG (J-couplers) and VDL ETG Switzerland (regular cells) with micrometer precision using ultra-precision diamond milling and turning. These structures do not undergo any tuning steps from cup production to installation into the bunker. The target precision of a single copper cup is less than ±2 μm with a surface finish Ra of 25 nm and concentricity of less than 50 μm before and after brazing of a stack of 111 copper regular cells and two couplers. Bead pull measurements have confirmed the high precision machining of the cups and couplers and thus validated the choice to produce the structures without implementing mechanical tuning on the cups, i.e., any push-pull technique. Furthermore, the measurement of the Q-factor was within 1% of the simulated one and the rms phase advance error was less than 2° over the whole structure which has a negligible effect on the energy gain. The manufacturing process of the individual cup was developed and tested at PSI before transferring the technology to the industry for the series production. It consists of an initial raw-cut and then pre-turned on a conventional and numerical lathe to a precision of about 10 μm while the finishing of the cups is performed on a sturdy and pneumatically stabilized slanted bed lathe using poly and mono-crystalline diamond (PCD, MCD) tools in a temperature and humidity controlled machining compartment of the lathe itself. Metrology measurements on the copper cells have shown a turning precision better than ±0.5 μm. The copper is oxygen free, high-conductivity and forged in three dimensions to have a homogeneous distribution of the small pores, a stress-free and intrinsically stable material. In order to assure the required concentricity, a robot with an action radius of 2 m and a tridimensional accuracy of 5 μm is used for the stacking of the cups before brazing [5]. This production process allows one to avoid any tuning steps while still achieving excellent field flatness and phase advance errors. In addition to the four structures, each Linac module also comprises a barrel open cavity (BOC) pulse compressor [6], and these were machined and brazed at PSI [7]. A picture of the C-band module is shown in Figure 1. A module is fed by a single RF source with up to 50 MW. The achieved straightness of the structures is excellent, the maximum measured deviations from a straight line are typically below 25 μm. The RF properties of the C-band structures have been measured using the bead-pull technique and an example result is shown in Fig. 2. All structures achieved an excellent electric field profile along the longitudinal coordinate of the

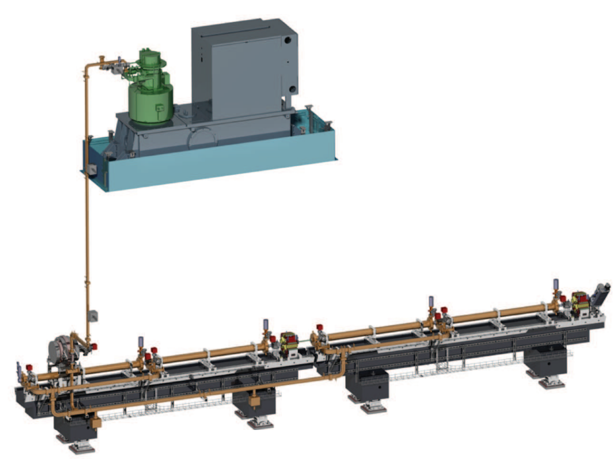

Figure 1: C-band module composed from four C-band accelerating structures, a pulse compressor and 50 MW Toshiba klystron.

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structures. The RF conditioning of the first C-band module was mainly performed without issue and Fig. 3 shows the progress. The maximum power from the klystron, 50 MW, was reached, yielding beyond 300 MW of power after the pulse compressor. Counting the number of arcs produced by the extraction of electrons from the metallic surface, the breakdown rate (BDR) can be estimated as a function of the accelerating gradient. Figure 4 shows an example of a BDR measurement where an accelerating gradient of approximately 52 MV/m was reached on the C-band prototype [8].

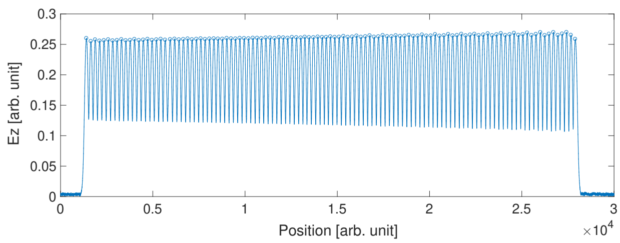

Figure 2: Example of the bead-pull measurements. Measured on-axis electric field along the longitudinal coordinate of the 2-m long C-band structure.

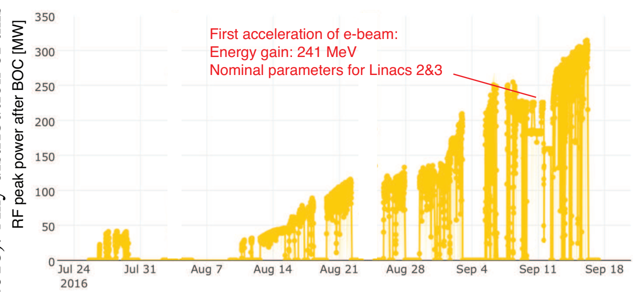

Figure 3: Conditioning progress for first C-band RF module.

PSI is interested in extending, consolidating and broadening

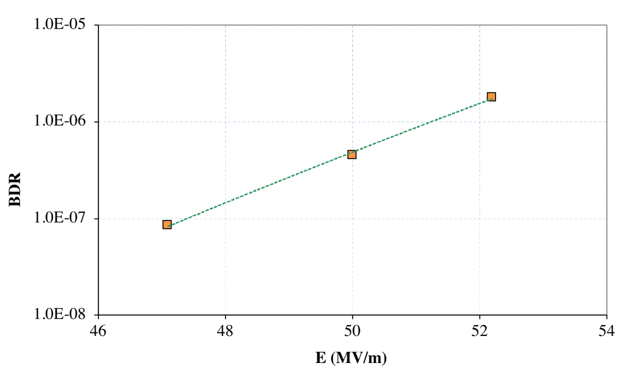

Figure 4: Example of the breakdown rate (BDR) as a function of the accelerating gradient for the C-band structure.

its know-how to other frequency ranges, as for instance in the S-band (3 GHz) and X-band (12 GHz) range. Our research group is presently involved in the following projects:

- development of an X-Band tune-free T24 prototype for CLIC [9];
- development of a high-gradient S-Band tuning-free prototype for the FERMI Linac at ELETTRA [10];
- development, in collaboration with DESY and CERN, of POLARIX, an X-band tune-free deflector with variable polarization [11].

X-BAND T24 PROTOTYPES FOR CLIC

The mechanical topology is very similar to that of the SwissFEL C-band structure with the main difference being the input/output couplers which are of the mode launcher type as for many CLIC test prototypes. All cups and the two couplers were produced by the company VDL. The inner profiles of the cups are all well within the specified tolerances (±2 µm) and the average surface roughness (Ra) is below 20 nm. The cups have been vacuum fired at 400 °C for two hours before brazing to remove residual oxidation. The final straightness after brazing is better than 10 µm. The classical RF design had to be slightly modified to adapt it to the PSI mechanical design which is based on double rounded copper disks with one half cell machined on each side in order to have the brazing plane in the middle of the cell [9]. As an example of the excellent high power performances, Figure 5 demonstrates the second PSI structure conditioning history to date. The extrapolated BDR at the nominal gradient (100 MV/m) is $2{\cdot}10^{-7}$. It is worthwhile noting that the results are only provisional and that the test is not completed yet.

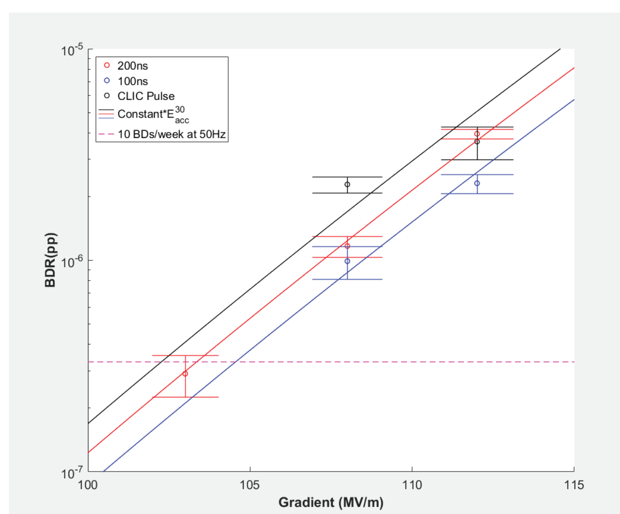

Figure 5: BDR for the second PSI structure manufactured for CERN (courtesy of CERN).

S-BAND HIGH GRADIENT STRUCTURES FOR FERMI

An upgrade of the FERMI Linac is currently under study and it foresees that each 6-m long Backward Travelling Wave structure equipping the high energy section of the Linac would be replaced by two, 3-m long, high gradient structures fed by the same power source. This upgrade would ensure a reliable accelerating gradient of 30 MV/m at 50 Hz and increase in beam energy from 1.5 GeV to 1.8 GeV [10].

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The technology applied to the present prototype of S band cavity is also very similar to that of the SwissFEL C-Band structures. A first step is the production at PSI of a short test structure that should confirm the validity of the PSI technology also at S band. The cold measurements of this prototype, i.e., bead pulling and S-parameter confirmed the possibility to produce without tuning. The operating temperature is 36.4 °C, only 1.4 °C higher than the design value (35 °C). This deviation may be reduced during the production of the series. The field along the structure, as shown in Fig. 6 is perfectly flat and the mismatch is below −30 dB at both couplers [10]. The structure is under high power test at ELETTRA Trieste. Preliminary results are very encouraging, reaching the nominal operating condition of 30 MV/m with a pulse length of 600 ns after only 295 breakdown events.

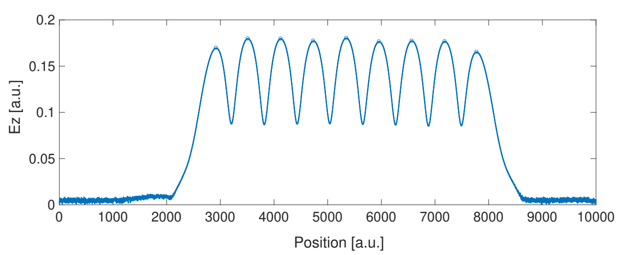

Figure 6: Results of a bead pull test at PSI.

POLARIX TDS

A collaboration between DESY, PSI and CERN has been established to develop and build an advanced modular X-band transverse deflection structure (TDS) system with the new feature of providing variable polarization of the deflecting force [12]. This innovative CERN design requires very high manufacturing precision to guarantee the highest azimuthal symmetry of the structure for avoiding accidental rotations of the polarization of the streaking field along the cavity. Therefore, the high-precision tune-free production process developed at PSI for the C-band and X-band accelerating structures will be used for the manufacturing. Several experiments at DESY (FLASH2, FLASHForward, SINBAD) and PSI (ATHOS at SwissFEL) are interested in the utilization of such high-gradient X-band TDS systems for high resolution longitudinal diagnostics [13]. The prototype of this novel X-band TDS [11], the Polarizable X-band (PolariX) TDS, is under production at PSI and bead-pull RF measurements will be performed in October. Figure 7 shows the detail of the input and output couplers (left), the whole TDS prototype (middle) and the basic disk geometry (right).

CONCLUSION

Developments in Ultra Precision (UP) turning and innovative vacuum brazing procedures at PSI for SwissFEL have led to a production technique for new structures. The strong motivation to improve the cavity technology at PSI was that the fabrication of traveling-wave accelerating structures had

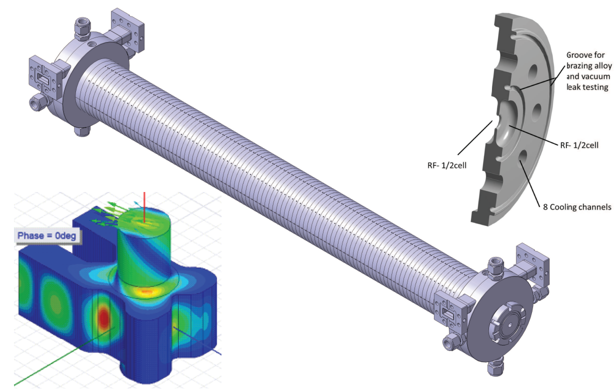

Figure 7: Left: detail of the input/output coupler. Middle: whole TDS prototype. Right: basic disk.

to meet the stringent RF requirement while minimizing the cost and achieving a stable process for an economical industrial series production. In that case the mass production foresaw the construction of 120 structures. PSI is now interested in extending, consolidating and broadening its know-how to other frequency ranges, obtaining already encouraging results at S- and X-Band frequencies.

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REFERENCES

[1] C. J. Milne *et al.*, *Appl. Sci.*, vol. 7, p. 720, 2017.

[2] F. Loehl *et al.*, in *Proc. FEL'13*, New York, USA, 2013, pp. 317-321.

[3] F. Loehl *et al.*, in *Proc. FEL'14*, Basel, Switzerland, 2014, pp. 322-326.

[4] J.-Y. Raguin and M. Bopp, in *Proc. LINAC'12*, Tel-Aviv, Israel, 2012, pp. 501-503.

[5] U. Ellenberger *et al.*, in *Proc. FEL'13*, New York, USA, 2013, pp. 245-249.

[6] R. Zennaro *et al.*, in *Proc. IPAC'13*, Shanghai, China., 2013, pp. 2827-2829.

[7] U. Ellenberger *et al.*, in *Proc. FEL'14*, Basel, Switzerland, Aug 2014, pp. 859-863.

[8] R. Zennaro *et al.*, in *Proc. LINAC'14*, Geneva, Switzerland, 2014, pp. 333-335.

[9] R. Zennaro *et al.*, in *Proc. IPAC'17*, Kopenhagen, Danmark, 2017, pp. 4318-4320.

[10] C. Serpico *et al.*, in *Proc. IPAC'18*, Vancouver, BC, Canada, 2018, WEPMF067.

[11] P. Craievich *et al.*, in *Proc. IPAC'18*, Vancouver, Canada, 2018, pp. 3808-3811.

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[12] A. Grudiev, CLIC-Note -1067, CERN, Geneva, Switzerland, May 2016.

[13] B. Marchetti *et al.*, in *Proc. IPAC'17*, Copenhagen, Denmark, 2017, pp. 184-187.