STATUS OF THE SwissFEL C-BAND LINAC

F. Loehl, J. Alex, H. Blumer, M. Bopp, H. Braun, A. Citterio, U. Ellenberger, H. Fitze,
H. Joehri, T. Kleeb, L. Paly, J.-Y. Raguin, L. Schulz, R. Zennaro, C. Zumbach,
Paul Scherrer Institut, Villigen PSI, Switzerland

Abstract

The linear accelerator of SwissFEL will be based on C-band technology. This paper summarizes the latest results that were achieved with the first prototype components. Furthermore, the progress and plans of the series production are discussed.

INTRODUCTION

The hard x-ray free-electron laser facility SwissFEL [1] is currently under construction at the Paul Scherrer Institute. In the main linear accelerator (Linac) of SwissFEL, the electron bunches are accelerated from an energy of 350 MeV to a final energy of up to 5.8 GeV. For this, the Linac is divided into three segments (see Fig. 1): Linac 1, Linac 2, and Linac 3. After Linac 1, the electron bunches are compressed in a magnetic bunch compressor chicane BC2 at an intermediate energy of 2.1 GeV - the first bunch compressor BC1 is located within the injector at an energy of ~350MeV. After Linac 2, at an energy of 3.0 GeV, a switch-yard [2] is installed with which electron bunches can be sent either straight into Linac 3 and consequently the hard x-ray Aramis line, or into a future soft x-ray line called Athos. At the end of Linac 3, transversely deflecting structures will be located that will allow for measurements of the longitudinal charge profile with a resolution of a few femtoseconds.

C-BAND MODULE

The C-band modules for SwissFEL consists of four C-band structures that are installed onto two granite girders (see [3] for a schematic). A module is fed by a single RF source with up to 50 MW of RF power. The RF pulse is compressed using a barrel open cavity (BOC) pulse compressor [4], and the compressed pulse is distributed to the four accelerating structures using a wave-guide network that is installed on the side of the girders. That way, the entire linac module can be pre-assembled and complete modules can be brought into the SwissFEL facility, which simplifies the assembly procedure of the 26 modules.

The accelerating modules can be operated in two different modes that are defined by how the pulse compressor is operated. In mode I, a 180° phase jump is applied towards the end of the RF pulse, yielding an RF pulse with more than 300 MW of peak power. The pulse is, however, not flat (see [4]). In mode II, a phase modulation is applied that yields a flat RF pulse at the cost of a significantly reduced RF power.

At an RF power from the klystron of 50 MW, the expected on-crest energy gain of a module is around 220 MeV when a flat RF pulse is applied and 275 MeV with the phase jump mode. In SwissFEL, it is planned to operated the klystrons at up to 40 MW which yields on-crest energy gains of close to 200 MeV and 250 MeV in both modes. When two or more bunches are accelerated within the same RF bunch, as planned for the parallel operation of the hard and soft x-ray lines Aramis and Athos, a flat RF pulse might provide better stability and simplify the operation in Linac 1, where the beam is accelerated off-crest. In Linacs 2 & 3, where the beam is accelerated on-crest, it is planned to operate in the phase jump mode in order to maximize the energy gain.

C-band High Power Test Stand

In order to test RF components, PSI operates a C-band test stand that provides two test benches: a component test bench and a test bench for a complete linac module. All test results that are discussed here are obtained within the component test bench. The second test bench with a complete Linac module is currently being setup and expected to become operational end of this year. The current state of the first prototype module is depicted in Fig. 2. The picture shows the module in beam direction with the accelerating structures and the wave-guide network already in place. On top of the linac module, the water distribution is visible that is also prototyped. The pulse compressor is not yet installed but the support is already visible right at the beginning of the module.

RF Source

The C-band RF pulses with a power of up to 50 MW and a duration of 3 μs are generated by Toshiba klystrons of type E37212 that are driven by solid-state pre-amplifiers and solid-state modulators. In order to save energy, the collectors of the klystrons will be operated at a temperature of 80 °C so that part of the energy can be recovered to heat buildings on the PSI campus. This scheme was successfully tested in the high power test stand. The first klystrons for SwissFEL are already delivered to PSI, and the delivery of the complete set of klystrons will be completed ahead of schedule.

In order to validate their performance, different pre-amplifiers have been characterized in the test stand, showing that the required phase and amplitude stability can be reached. The tender process for the SwissFEL series will start end of this year.

Of major importance for SwissFEL are the modulators that drive the klystrons. The C-band test stand was operated until now with a ScandiNova K2 modulator. Since this modulator does not fulfill the requirements for SwissFEL in terms of reliability and stability, two prototype solid-state modulators were ordered at two companies last year. The first modulator is built by Scandinova, the second one by

ISBN 978-3-95450-133-5

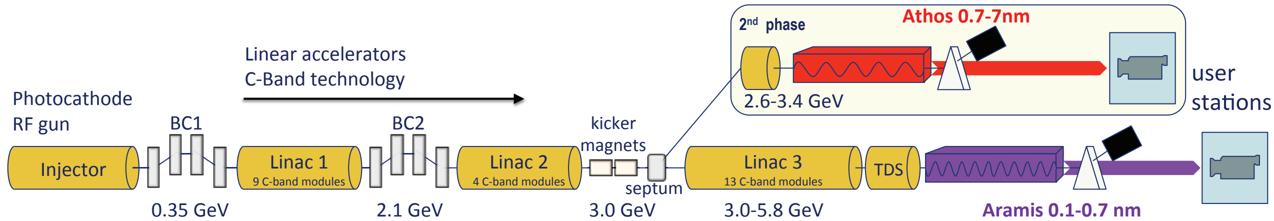

Figure 1: Schematic layout of the SwissFEL facility. It consists of an S-band injector, a C-band linear accelerator, and two undulator lines.

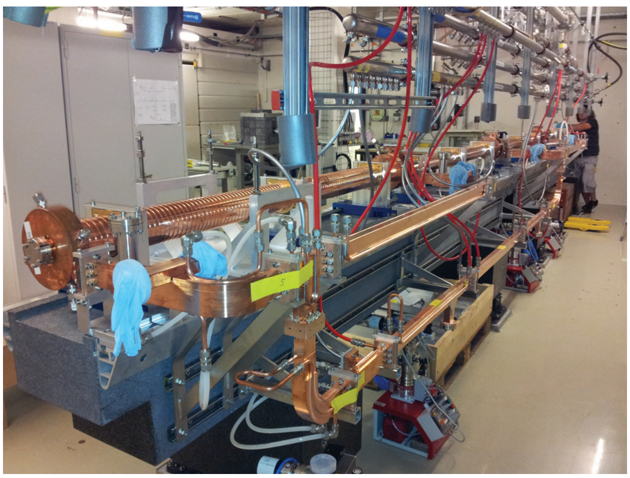

Figure 2: Picture of the first C-band prototype module in the high power test stand.

Ampegon. PSI is in close contact with both companies to support these developments. The delivery of both modulators is expected later this year and it is planned to extensively test both modulator types in the C-band test stand before the order for the SwissFEL series will be placed.

Waveguide Network

There are two main challenge for the waveguide network of the C-band modules. The first one is the length tolerance on the entire horizontal network of only ±0.2 mm due to the fact that the waveguides are attached directly to the girders. The second challenge is the high RF power of up to 300 MW after the pulse compressor.

Many waveguide components from various manufactures as well as in-house developments of directional couplers, H-splitters, and E-splitter were tested in the C-band test stand prior to a tender process for the SwissFEL series. The winner of this tender is Mitsubishi Heavy Industries (MHI) and MHI already started with the manufacturing of a prototype waveguide network that will be delivered in December this year and consequently tested in the C-band test stand. Another prototype waveguide network was built by TEL Mechatronics based on PSI designs. This waveguide network is currently installed at the prototype C-band module and used to test assembly and tuning procedures. The RF loads were also part of the tender process, and we decided to use water loads manufactured by CML.

Pulse Compressor

The first results that were obtained with the barrel open cavity (BOC) type pulse compressor that was designed at PSI were already presented in [3, 4]. The prototype used during the previously presented measurements was built by VDL. The series for SwissFEL – a total of 26 BOCs are needed for the C-band linac and another one for the transversely deflecting C-band structures at the end of Linac 3 – will be built in house at PSI. The first four BOCs were already completed, and BOCs 5-8 are currently under production (see [5]).

We conducted first measurements of the break-down rates for the BOC manufactured by VDL and for the first BOC from PSI. The VDL BOC was operated in both the phase jump mode at an RF power of 35 MW from the klystron and the phase modulation mode with 40 MW of power from the klystron. The measured break-down rates were $3 \cdot 10^{-8}$ and $2 \cdot 10^{-8}$, respectively. For SwissFEL, a break-down rate of below $4 \cdot 10^{-8}$ is desired under nominal conditions, and with the presently assumed energy gains of the C-band modules, an RF power of 40 MW will be required for Linac 1 (phase modulation) and less than 35 MW for Linac 2 & 3. The measured break-down rates are therefore already in the region that is envisioned for SwissFEL. Recently, initial break-down measurements were performed with the first BOC thas was manufactured at PSI, and these yielded a break down rate of $1 \cdot 10^{-7}$ in phase jump mode for 40 MW of RF power. This is an even better result than the one obtained for the VDL prototype. After the excellent break-down results that were obtained for the first C-band structure (see [3]), however, the BOCs still remain the most critical components in terms of break-downs.

A major source of contamination of the copper surface within the first BOCs resulted from the fact that the BOCs had to be tuned after the final brazing step. This involved the application of grease during the machining process, and it is difficult to clean the BOCs afterwards. Due to the good results with the first BOCs that were machined, the manufacturing process was meanwhile adapted such that the BOCs are machined on-frequency without involving an additional tuning step. This way, the BOCs will stay clean after the final brazing step, and it is expected that this will improve the break-down rate further. The first of these BOCs that involves this manufacturing procedure will be tested together with the linac module prototype beginning of next year.

ISBN 978-3-95450-133-5

Figure 3: New clean area to perform vacuum leak tests and RF bead-pull measurements. The space is next to the stacking and brazing area.

Figure 4: Transport girder for the transfer of structures from the brazing area on the PSI campus to the external storage area.

Accelerating Structures

The 2 m long accelerating structures have been designed at PSI [6], and meanwhile a total of 5 structures was successfully brazed. The manufacturing process is described in detail in [7].

The structures consist out of 108 copper discs and a J-coupler at both ends. Since the structures are built on-frequency without the possibility for tuning, the parts have to be machined with micrometer precision.

For the J-couplers, various companies were qualified before the tender process for the SwissFEL series was launched. The winner of this tender process is VDL, and the production process has already started. The first batch of coupler parts will be delivered to PSI in October. The brazing of the couplers takes place at PSI.

The main provider for the copper discs is TEL Mechatronics. PSI qualified TEL Mechatronics to build the discs according to a production scheme developed at PSI. Earlier this year, TEL Mechatronics delivered the cups for a first structure to PSI, and after brazing the structure delivered excellent RF bead-pull results. The series production has meanwhile started at TEL Mechatronics, and the delivery of discs will start beginning of September this year.

Since the production of the C-band structures is delayed with respect to the project schedule, PSI ordered C-band discs also from VDL, and the discs for one structure were already delivered earlier this month. The orders foresee a delivery of cups for a total of 4 structures from VDL and of 13 structures from TEL Mechatronics until the end of this year.

The structures are stacked and brazed at PSI (see [3, 5]). In order to be able to deal with the amount of structures that will be brazed at PSI – a total of 104 structures are required for SwissFEL – the area in which the stacking and brazing takes place was meanwhile extended by a new clean area. This space will be used to perform leak-tests of the brazed structures as well as bead-pull measurements to characterize the RF performance. Figure 3 shows a picture of the new clean area.

The following issue in the manufacturing process is still not entirely understood: Out of the five structures that were brazed so far, 3 had a vacuum leak after they were brazed. In a second repair-brazing step, all three structures could be repaired, but we aim to prevent these repair steps during series production. From the five structures that were brazed, the first two had an initial vacuum leak. For the next three structures, the amount of brazing alloy was increased, and structure 3 & 4 were vacuum tight after they were brazed the first time. The same procedure, however, was applied to structure 5, and this structure required a repair step. There are various possible sources for this that we are looking at. Two of them are the fact that the copper discs for structure 5 were stored a long time under normal atmosphere, and some of the discs were stored on latex rubber mats, and it appears that the discs that came into contact with the latex material showed color changes near the contact areas. These two aspects will be taken care of in the series production by storing the discs under nitrogen atmosphere and by removing the latex material. In order to understand better the amount of brazing alloy that is optimum, additional brazing tests with different amounts of brazing alloy will be performed.

Production of C-band Modules

Once the structures are brazed, leak-checked, and a bead-pull measurement was performed, the structures are transported into a storage hall that PSI has rented for the duration of the SwissFEL project. This happens using special transport girders as shown in Fig. 4. In the storage hall, depicted in Fig. 5, an area is reserved in which the structures can be transferred onto the final granite girders. A set of multiple granite girders will be used as a buffer before the assembly of a linac module takes place. This allows to sort the structures by frequency. Since the structures are fine-tuned in frequency using the temperature of the cooling water, and in

ISBN 978-3-95450-133-5

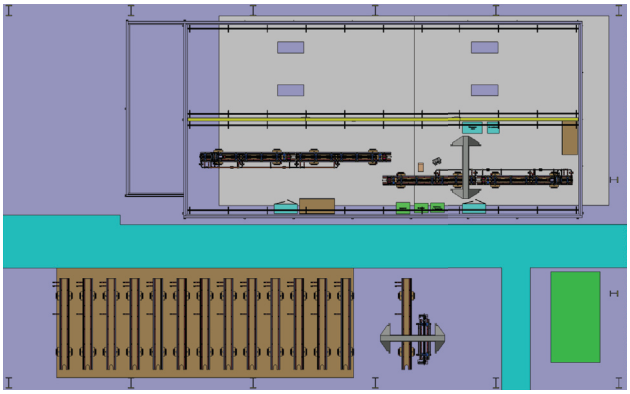

Figure 5: Schematic showing the storage area for the C-band structures (bottom) and the clean room (top) in which the module assembly will take place. Up to two modules can be assembled in parallel.

Figure 6: Clean room that will be used for the assembly of the C-band modules as well as for other girders for SwissFEL.

SwissFEL all four structures of a linac module share a common cooling system, this is a way to increase the efficiency of the linac modules.

When a matching pair of two girders with four structures is available, the girders are transferred into a big clean room (see Fig. 6), where the module assembly takes place. This includes the installation of the pulse compressors, the wave-guide network including its tuning, and components such as quadrupole magnets and diagnostics (BPMs, wire-scanners). The assembled linac modules are then either stored again outside of the clean room, or transported directly into the SwissFEL accelerator tunnel (see Fig. 7).

Temperature Regulation

In reference [3], a first prototype for the BOC temperature regulation system was presented. With this system, a temperature stability of 3 mK was reached. A disadvantage of the presented system was that the time required to reach a steady-state after a distortion happened was rather long with around 4 to 5 minutes. In order to speed up the regulation, a number of steps were taken. The most important ones

Figure 7: Picture of the empty SwissFEL accelerator tunnel.

were the replacement of the heater against a model with an increased heat transfer, the installation of the heater very close to the pulse compressor in order to reduce the dead-time, and the adaption of the regulation algorithm. Besides several other additions, the new algorithm now has a very large gain when the BOC temperature deviation exceeds a desired temperature band. With all these changes, it now takes around 40 seconds until the BOC temperature is stable again when a distortion happens or a step in the temperature set-point is applied.

As a prototype for SwissFEL, the C-band module in the test stand is equipped with a complete SwissFEL cooling station. This station will regulate the temperature of the modulator body, the klystron collector, the BOC, and the four accelerating structures, and we will use it to test and optimize the SwissFEL cooling stations.

SUMMARY AND OUTLOOK

Many prototypes for the SwissFEL C-band Linac have been built and tested, and most of them show the desired performance. Meanwhile, we launched the series production for many components including the C-band structures, the BOC RF pulse compressors, and the wave-guide network. Two prototype solid-state modulators are ordered and will be delivered to PSI in the second half of this year. The next steps include validating the performance of the two modulators before the SwissFEL series can be ordered, and the test of a complete C-band module in the high power RF test stand.

REFERENCES

[1] R.Ganter (ed.), "SwissFELConceptualDesignReport," „PSI Bericht, 10-04, 2010."

[2] M. Paraliev *et al.*, "High stability resonant kicker development for the SwissFEL switch yard," in *These Proceedings: Proc. 36th Int. Free-Electron Laser Conf.*, Basel, 2014, MOP039.

[3] F. Loehl *et al.*, "Status of the SwissFEL C-band linear accelerator," in *Proc. 35th Int. Free-Electron Laser Conf.*, New York, USA, 2013, pp. 317–321.

ISBN 978-3-95450-133-5

[4] R. Zennaro *et al.*, "C-band RF pulse compressor for SwissFEL," in *Proc. of the IPAC 2013 Conf.*, Shanghai, China., 2013, pp. 2827–2829.

[5] U. Ellenberger *et al.*, "The SwissFEL pulse compressor BOC: manufacturing and proof of precision by RF measurements," in *These Proceedings: Proc. 36th Int. Free-Electron Laser Conf.*, Basel, 2014, THP056.

[6] J.-Y. Raguin and M. Bopp, "The SwissFEL C-band accelerating structure: RF design and thermal analysis," in *Proc. of the Linac 2012 Conf.*, Tel-Aviv, Israel, 2012, pp. 501–503.

[7] U. Ellenberger *et al.*, "Status of the manufacturing process for the SwissFEL C-band accelerating structures," in *Proc. 35th Int. Free-Electron Laser Conf.*, New York, USA, 2013, pp. 245–249.

ISBN 978-3-95450-133-5