ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-WEP040

SUB-FEMTOSECOND TIME-RESOLVED MEASUREMENTS BASED ON A VARIABLE POLARIZATION X-BAND TRANSVERSE DEFLECTION STRUCTURE FOR SwissFEL

P. Craievich*, M. Bopp, H.-H. Braun, R. Ganter, M. Pedrozzi, E. Prat,
S. Reiche, R. Zennaro, Paul Scherrer Institut, Villigen-PSI, Switzerland
A. Grudiev, N. Catalan Lasheras, G. Mcmonagle, W. Wuensch, CERN, Geneve, Switzerland
B. Marchetti, R. Assmann, F. Christie, R. D'Arcy, D. Marx, DESY, Germany

Abstract

The SwissFEL project, under commissioning at the Paul Scherrer Institut (PSI), will produce FEL radiation for soft and hard X-rays with pulse durations ranging from a few to several tens of femtoseconds. A collaboration between DESY, PSI and CERN has been established with the aim of developing and building an advanced X-Band transverse deflection structure (TDS) with the new feature of providing variable polarization of the deflecting force. As this innovative CERN design requires very high manufacturing precision to guarantee highest azimuthal symmetry of the structure to avoid the deterioration of the polarization of the streaking field, the high-precision tuning-free assembly procedures developed at PSI for the SwissFEL C-band accelerating structures will be used for the manufacturing. Such a TDS will be installed downstream of the undulators of the soft X-ray beamline of SwissFEL and thanks to the variable polarization of the TDS it will be possible to perform a complete characterization of the 6D phase space. We summarize in this work the status of the project and its main technical parameters.

INTRODUCTION

The SwissFEL project at PSI consists out of a 6 GeV accelerator complex and two undulator beam lines. The Aramis beam line, presently under commissioning, covers the energy photon ranges from 12.4 to 1.8 keV [1], while the Athos beam line the range from 1.9 to 0.25 keV [2]. The Athos line will operate in parallel to the Aramis line and, actually consists of a fast-kicker magnet, a dog-leg transfer line, a small linac and 16 APPLE undulators. It is designed to operate in advanced modes of operation slightly different to standard SASE operation and will produce soft X-rays FEL radiation with pulse durations ranging from a few to several tens of femtoseconds [3]. Electron beam diagnostic based on a transverse deflection structure (TDS) placed downstream of the undulators (post-undulator TDS) in conjunction with an electron beam energy spectrometer can indirectly measure the pulse length of these ultra-short photon beam analysing the induced energy spread on the electron bunch due to the FEL process [4, 5]. Furthermore, a complete characterization of the electron beam 6D phase space by means of measurements of the bunch length, energy and of the transverse slice emittances (vertical and horizontal) are important tasks for commissioning and optimization of FEL process [6–9]. In this context, the design of an innovative X-band TDS structure, including a novel variable polarisation feature, has been proposed by CERN [10, 11]. In order to avoid the rotation of the polarization of the dipole fields along the structure, a high-precision tuning-free assembly procedure developed for the C-band linac at PSI will be used for the fabrication of the TDSs [12]. This procedure has been used to fabricate 120 cavities for the SwissFEL linac and it is currently being used for the fabrication of the tuning free X-band structure prototypes for CLIC [13]. Several experiments at DESY (FLASH2, FLASHForward, SINBAD) and PSI (Athos) are interested in the utilization of high gradient X-band TDS systems for high resolution longitudinal diagnostics. In this context a collaboration between DESY, PSI and CERN has been established with the aim of developing and building an advanced X-Band transverse deflection structure (TDS) with the new feature of providing variable polarization of the deflecting field [14]. In this paper we summarize the specifications of the TDS system for the Athos line and we also introduce some details of the mechanical design of the first prototype that will be compatible with the requests from DESY and PSI [14].

* paolo.craievich@psi.ch

TDS DIAGNOSTIC LINE

Table 1 contains the electron beam parameters at Athos post-undulator diagnostic section that have been used for the following calculations. Layout and more details on the Athos line are in [2].

Table 1: Beam and optical parameters involved in the streaking process at ATHOS post-undulator diagnostic section.

Parameter	Sy.		Unit
Beam energy	E	2.9-3.4	GeV
Charge	Q	10-200	pC
Bunch length	σ_t	2-30	fs
β@TDS	$\beta_x = \beta_y$	50	m
Emittance	$\gamma\varepsilon_x = \gamma\varepsilon_y$	0.1-0.3	µm
Rep. rate		100	Hz

Figure 1 shows a schematic layout of the post-undulator diagnostic section. Beam slice emittance in both transverse planes will be investigated by a multi-quadrupole scan technique combined with the TDS. By means of the TDS, the

ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-WEP040

beam is vertically and horizontally streaked and a multi-quadrupole scan is performed in the horizontal or vertical direction, respectively, with the constraint of keeping the vertical/horizontal beam size constant over the whole scan [15]. For this purpose, five quadrupoles are foreseen to be placed downstream of the TDS. Reconstruction of the longitudinal phase space will be performed by means of the spectrometer line.

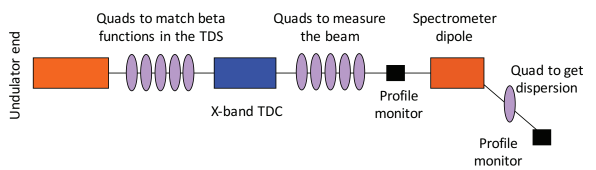

Figure 1: Concept of the post-undulator diagnostic section.

Figure 2 shows the β-functions of the beam lattice optics in the post-undulator diagnostic section. The locations of the deflectors are highlighted with a green circle and the β-functions are the same for the two polarization ($\beta_x = \beta_y = 50$ m). The rms energy spread resolution at the spectrometer is less than 180 keV. Moreover, if we also consider the minimum rms beam size that can be measured at the screen, corresponding to150 keV, then adding the two contributions in quadrature we obtain a resolution of less than 234 keV.

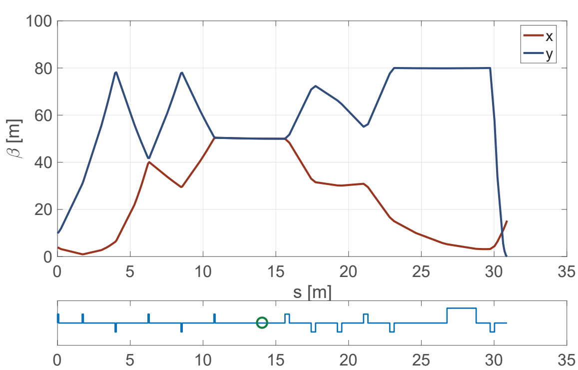

Figure 2: (Top) The β-function of the beam lattice optics for the post-undulator diagnostic section. s=0 corresponds to the end of the last Athos undulator. (Bottom) Locations of the quadrupoles and dipole are indicated with vertical lines while the TDS are highlighted with a green circle where $\beta_x = \beta_y = 50$ m.

The well-known formulas, i.e. contained in [9], describing the dynamics of the bunch deflection as a function of the TDS parameters and of the optical Twiss parameters are used here. Figure 3 shows the time resolution (up), the induced energy spread (middle) and the rms centroid jitter induced by the RF jitter (bottom) as a function of the integrated deflecting voltage. The time resolution is on sub-fs scale if the deflecting voltage is more than 45 MV with a $\beta_d = 50$ m. Such time resolutions allow the characterization of the shortest beam profile pulse indicated in Table 1 with approximately 2-3 slices. The uncorrelated energy spread induced by the TDS is 500 keV with $\beta_d = 50$ m. Considering the RF phase jitters indicated in Fig. 3 (bottom) and a deflecting voltage of 45 M, the expected shot-to-shot centroid jitter of the streaked beam is approximately 200-700 µm (rms). This is in the same order of magnitude as the beam size of the streaked beam on the screen for the longer pulse ($\sigma_y = 450$ µm) while it is an order of magnitude higher for the shortest pulse ($\sigma_y = 30$ µm).

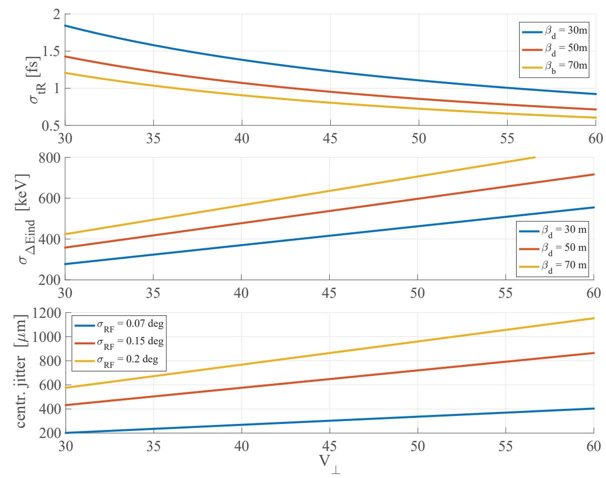

Figure 3: Time resolution (up) and rms induced energy spread (middle) as a function of the integrated deflecting voltage. Sub-fs resolution with $V_\perp > 45$ MV and $\beta_d = 50$ m in both transverse planes. Centroid jitter (bottom) as a function of the integrated deflecting voltage. Centroid jitter is estimated considering three different values of the RF phase jitters for $\beta_d = 50$ m.

TDS RF PARAMETERS

Two versions of constant-impedance and backward traveling wave TDS are under study. A short version, 960-mm long, and a longer and more efficient structure about 1.2 m long. Table 2 lists the RF parameters for both versions. The shortest version, matching the space constraints at FLASH2 at DESY [14, 16], will be fabricated as first prototype. Table 2 also lists the RF parameters if a RF pulse compressor, as a Barrel Open Cavity (BOC) or SLED systems, will be adopted. It is worthwhile noting that the iris aperture was fixed at 8 mm based on some considerations about the photon beam transmission through the TDS system on one side and based on the maximisation of the cell shut impedance on the other side. The distance between the first undulator stage and the TDS system is about 40 m and the worst case is the two color operation with the first undulator stage tuned to the longest wavelength of 5 nm [3]. In this case, the divergence is approximately 25 µrad providing an rms photon beam radius of 1 mm at the TDS location that is enough for the photon beam transmission.

Mechanical design

The mechanical design is very similar to that of the SwissFEL C-band structure [12], with the main difference in the

ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-WEP040

input/output couplers. They are E-Rotator-type in order to provide a linearly polarized mode out of the two circularly polarized input waves [10]. The orientation of the linearly polarized mode can be varied by changing the phase between the two input waveguide, as shown in Fig. 4 (left and middle).

Table 2: RF parameters for short and long X-band TDS. Both structures are constant impedance and backward traveling wave structures. t_k is the klystron pulse width.

Cell parameter		**Unit**	
Frequency	11995.2	MHz	
Phase advance/cell	120	°	
Iris radius	4	mm	
Iris thickness	2.6	mm	
Group velocity	-2.666	‰c	
Quality factor	6490		
Shunt impedance	50	MΩ/m	
TDS parameter	**Short**	**Long**	**Unit**
n. cells	96	120	
Filling time	104.5	129.5	ns
Active length	800	1000	mm
Total length	960	1160	mm
Power-to-voltage	5.225	6.124	$\mathrm{MV/MW^{0.5}}$
TDS + BOC	**Short**	**Long**	**Unit**
BOC Q_0	150000	150000	
BOC β@t_k=1.5 µs	8.7	8	
Power-to-voltage	11.958	13.528	$\mathrm{MV/MW^{0.5}}$

Figure 4 (right) also shows the basic disk in copper which has a T-shape. Thanks to the absence of any tuning feature, machining of the half cell will be subsequently performed on both side with the aim of having the brazing plane in the middle of the cell. An important advantage of this solution is to have a double rounding of the cells and to thus avoid that the braze alloy can flow into the structure through capillary action. The brazing alloy in copper-silver will be placed in two brazing grooves. Furthermore, sharp edges are foreseen in the cells in order to eventually hold the melted brazing material back from flowing into the cells. However, the size of the brazing groove has been experimentally optimized to provide the best reproducibility of the brazing material distribution. The cooling circuits are integrated in the cups as shown in Fig. 4. From the tolerance study [18], the inner profiles of the cups should be within the tolerance of ±3 m with an average surface roughness R_a below 25 nm.

WAVEGUIDE NETWORK (CONCEPT)

The linearizer system at the SwissFEL injector is equipped with a Scandinova K2-3X solid state modulator and a 50 MW, 100 Hz X-band klystron. A first preliminary idea is to reproduce a similar RF plant for the TDS system in order to eventually use it as spare parts for the injector plant. Figure 5 shows a preliminary sketch of the X-band TDS power

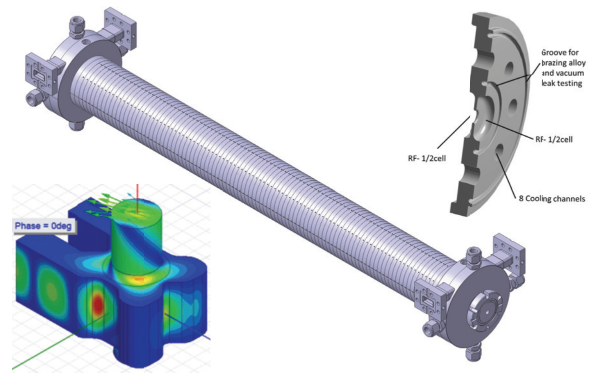

Figure 4: Left: detail of the input/ouput coupler. Middle: whole TDS prototype. Right: basic disk.

distribution system. The main RF parameters of the TDS and pulse compressor are summarized in Table 2.

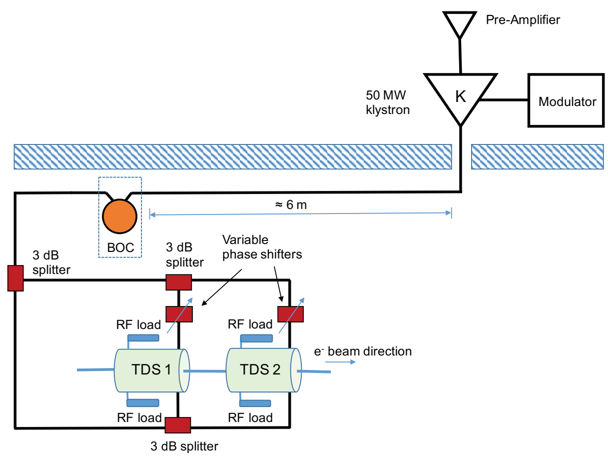

Figure 5: First concept for RF power feeding scheme with a 50 MW CPI klystron for two long TDS. If a pulse compressor will be adopted then a short TDS can be just used.

Considering the waveguide attenuation and insertion losses of the waveguide components then for Athos a deflecting voltage of 45 MV can be achieved with a RF power from the klystron of 36 MW and a set of two long TDSs without pulse compressor. On the other hand, a Barrel Open Cavity (BOC) pulse compressor scaled from the C-band linac may be adopted to increase RF power for the TDS [17]. Thus, for Athos a deflecting voltage of 45 MV can be also achieved with a RF power from the klystron of 19 MW and only a single TDS.

CONCLUSION

In this paper we have presented the X-band TDS system for the Athos diagnostic line. We also introduced some details of the mechanical design of the first prototype that will be compatible with the requests from DESY and PSI.

ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-WEP040

REFERENCES

[1] C. J. Milne *et al.*, "SwissFEL: The Swiss X-ray Free Electron Laser", *Appl. Sci.*, vol. 7, no. 720, July 2017.

[2] R. Ganter *et al.*, "Overview of the soft X-ray line ATHOS at SwissFEL", presented at the 38th Int. Free Electron Laser Conf. (FEL2017), Santa Fe, USA, August 2017, paper MOP038, this conference.

[3] J. Alex *et al.*, "Athos Conceptual Design Report", PSI Report, in press, 2017.

[4] V. A. Dolgashev *et al.*, *Phys. Rev. ST Accel. Beams*, vol. 17, p. 102801, October 2014.

[5] C. Behrens *et al.*, *Nature Communications*, vol. 5, no. 3762, April 2014.

[6] D. Alesini *et al.*, *Nucl. Instrum. Meth. Phys. Res.*, A 568 (2006), pp. 488–502.

[7] R. Akre *et al.*, in *Proc. PAC'01*, Chicago, IL, USA, 2001, pp. 2353-2355.

[8] H. Ego *et al.*, *Nucl. Instrum. Meth. Phys. Res.*, A 795 (2015), pp. 381–388.

[9] P. Craievich *et al.*, *IEEE Transact.on Nucl. Science*, vol. 62, no. 1, 2015.

[10] A. Grudiev, "Design of compact high power rf components at X-band", CERN, Geneva, Switzerland, Rep. CLIC Note 1067, May 2016.

[11] A. Grudiev, "RF Design of X-band TDS with variable polarization", presented at *CLIC Workshop 2017*, CERN, Geneva, Switzerland, March 2017.

[12] U. Ellenberger *et al.*, "Status of the manufacturing process for the SwissFEL C-band accelerating structures", in *Proc. FEL'13*, New York, USA, paper TUPSO17, pp. 246–249.

[13] R. Zennaro *et al.*, "High power tests of a prototype X-band accelerating structure for CLIC", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, paper THPIK097, pp. 4318–4320.

[14] B. Marchetti *et al.*, "X-Band TDS project", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, paper MOPAB044, pp. 184–187.

[15] E. Prat and M. Aiba, *Phys. Rev. ST Accel. Beams*, vol. 17, p. 052801 (2014).

[16] F. Christie, J. Roensch-Schulenburg, S. Schreiber, and M. Vogt, "Generation of ultra-short electron bunches and FEL pulses and characterization of their longitudinal properties at FLASH2", in *Proc. IPAC2017*, Copenhagen, Denmark, May 2017, paper WEPAB017, pp. 2600–2603.

[17] R. Zennaro *et al.*, in *Proc. IPAC'13*, Shanghai, China, paper WEPFI059, pp. 2827–2829.

[18] A. Grudiev, P. Craievich, and B. Marchetti, Internal note, to be published.