THREE TRANSVERSE DEFLECTING SYSTEMS FOR ELECTRON BEAM DIAGNOSTICS IN THE EUROPEAN FREE-ELECTRON LASER XFEL*

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Abstract

In frames of Russian in-kind contribution to European XFEL, INR in cooperation with DESY is responsible for Transverse Deflecting Systems (TDS) for special beam diagnostic in the XFEL linac. Three TDS have been developed: TDS INJ in the Injector, TDS BC1 in the Accelerator tunnel after Bunch Compressor 1 and TDS BC1 after Bunch Compressor 2. Each system includes S-band disk-loaded deflecting structure (DLS), waveguide system, klystron, pulse transformer, modulator and control system. TDS INJ has been built, assembled in the Injector building and tested. It is used to monitor the bunch length, longitudinal phase space and slice emittance now. Exceptionally small, exceeding expectations, slice emittance of electron bunch was measured using TDS INJ during the XFEL Injector commissioning. Three structures for TDS BC1 and TDS BC2 as well as the waveguide systems have been built, tested and TDS BC2 part installed in the XFEL tunnel.

INTRODUCTION

Tree Transverse Deflecting Systems operating at frequency 2998 MHz have been designed, built and installed (partially) for longitudinal electron beam diagnostics in the European XFEL at three locations: in the Injector, after BC1 and after BC2. The TDS location and corresponding electron energies are shown in the XFEL block-diagram (Figure 1).

The full scale prototype of the TDS INJ has been developed, designed, built and commissioned at DESY PITZ, Zeuthen facility [1]. It operates successfully now [2].

TRANSVERSE DEFLECTING STRUCTURE

Several travelling wave DLS operating at a hybrid mode have been considered for the XFEL TDS at the stage of development (Figure 2). These structures have been considered in details in [3] and [4]. Azimuthal inhomogeneity in these structures is used for stabilization of the azimuthal position of the deflecting field and for increasing frequency difference of two perpendicular polarizations of the hybrid mode.

All variants have very similar RF efficiency. The frequency separation of two perpendicular modes is about 40 MHz for variants A, B and D, 150 MHz for variant C and 900 MHz for variant E.

Basing on similar RF efficiency of these structures, taking into account the level of development and proven experience of high power operation at LOLA, the DLS of variant A was accepted for XFEL TDS.

The DLS of variant A has been developed in details. TDS systems include 16 cell structure for TDS INJ, 46 cell structure for TDS BC1 and two 46 cell structures for TDS BC2, so the lengths of these structures are 0.7 m and 1.7 m correspondingly. The same shape and the geometry dimensions have been chosen for all four structures to meet all requirements optimally. Therefore, the cells are the same and the couplers are the same for all structures. It simplifies the production and the tuning of the structures significantly [5].

The group velocity of the structure has been minimised to β_g=-0.018 choosing the shape of the cell. It allows us to use the TDS System for single bunch measurement.

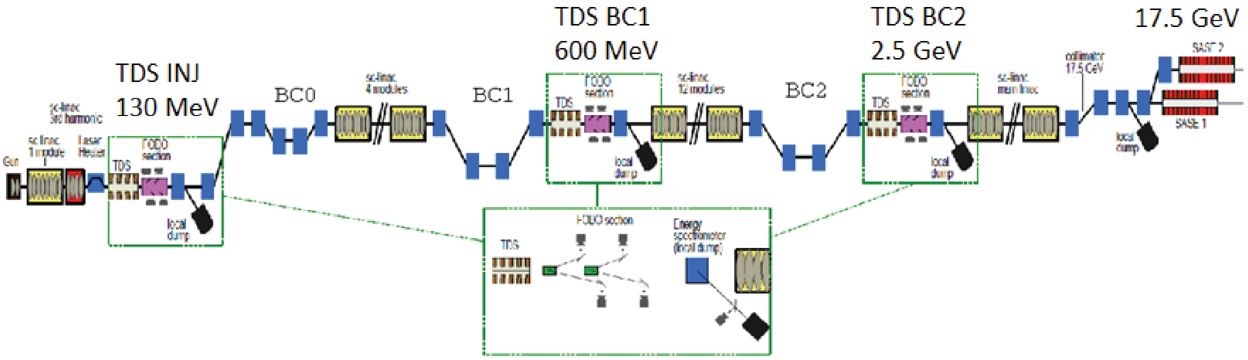

Figure 1: TDS Systems at the XFEL block-diagram.

The TDS Deflector INJ at the test stand is shown in Figure 3. The precision of the cell machining ensures the cell eigen frequency tolerance, which is equivalent to the cell

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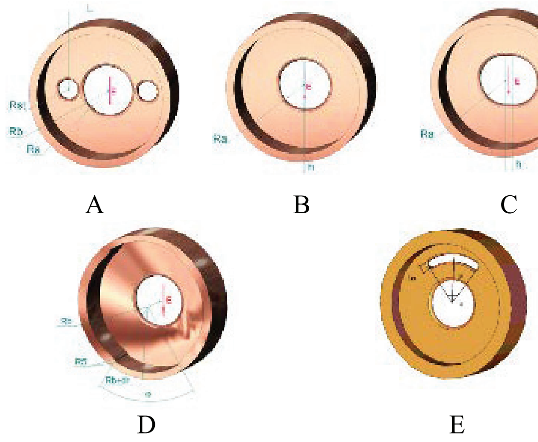

Figure 2: DLS deflecting structures.

radius tolerance of 3-5 μm. Nevertheless, each cell has been provided with two tools for tuning after brazing allowing both to increase and to decrease the frequency via the cell wall bending inside or outside the cell. The tuning tool is shown in Figure 3. The max frequency tuning range of the cell is 4 MHz at 2 mm wall bulge of two tools.

Figure 3: TDS INJ at test stand and tuning tool.

The TDS Systems BC1 and BC2 includes three the same deflecting structures 1.7 m long each. It is shown in Figure 4, including also measured amplitude and phase of the deflecting electric field.

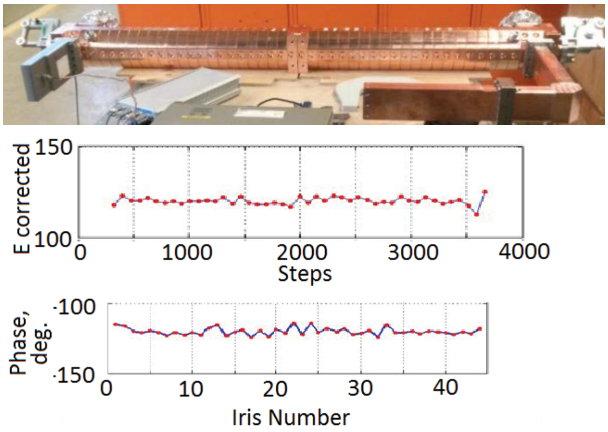

Figure 4: One of three structures for TDS BC1 and TDS BC2 at the test stand and measured amplitude and phase of deflecting electric field.

HIGH POWER RF SYSTEM

High Power RF System (HPRF) includes modulator, RF generator (pulse transformer, klystron, solenoid and local shielding) and waveguide system.

Modulator

Arkadiev type modulator is used both for TDS INJ and for TDS BC1/BC2. The capacitors are charged in parallel and discharged in series. The voltage in the load is a sum of the capacitor voltages. IGBT is used as a switch in these modulators. The modulator for TDS INJ includes six 10 kV modules. The modulator for TDS BC1 includes two dual 22 kV modules. The load of the modulator is the primary winding of the pulse transformer.

The modulator for TDS INJ is shown in Figure 5. It is assembled in the standard cabinet and includes 6 modules, 3 power supplies, 2 safety earthing units, control module, bias power supply for the pulse transformer, and low voltage filament power supply for the klystron. The control module is coupled with the modules via fiber optic lines.

Three modules produce negative voltage -24 kV with respect to the ground. Another three modules produce positive voltage +24 kV. Differential voltage 48 kV is transmitted to the primary winding of the pulse transformer via HV cables.

Table 1: Modulator Parameters

Parameter	Unit	INJ	BC1/BC2
Number of modules		6	2
Voltage of the module	kV	8	22
Voltage of the modulator	kV	48	44
Voltage in the modulator with respect to the ground	kV	24	22
Current of the modulator	A	166	1420
Ratio of pulse transformer		2.3	5.7
Max klystron voltage	kV	110	250
Nom klystron voltage	kV	101	230/232
Max klystron current	A	72	250
Nom klystron current	A	66.4	214/219

Test of the modulator with equivalent resistive load shown following results:

- output differential voltage U=50kV,
- current I=170A,
- pulse length up to τ=6 μsec,
- repetition rate F=10 Hz,
- pulse flat-top length τ_{ft}=0.1-5.5 μsec,
- pulse flat-top voltage uniformity <1%,
- pulse rise time is τ_r=0.2 μsec,
- pulse fall time is τ_f=0.2 μsec.

The modulator, developed for TDS BC1 and TDS BC2, includes two dual modules producing -22 kV and +22 kV with respect to the ground. So differential voltage of 44 kV is transmitted to the primary winding of the pulse transformer.

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Figure 5: Modulator and RF generator of the TDS INJ.

Pulse Transformer

The pulse transformers for the TDS INJ and the TDS BC1/BC2 have been simulated, designed and manufactured. Figure 5 shows RF generator of the TDS INJ, including the pulse transformer, low voltage filter, bias filter, high voltage filament power supply, voltage&current monitor, located in oil tank, and klystron, solenoid, and oil circulating system, located on the top of the oil tank.

Pulse transformer of the TDS BC1 is shown in Figure 6.

Figure 6: Pulse transformer of the TDS BC1.

Klystron

CPI VKS-8262HS klystron is used for the TDS INJ, and THALES TV2002DoD klystron is used for the TDS BC1/BC2.

Table 2: Klystron Parameters

Parameter	Unit	INJ	BC1/2
Klystron		VKS-8262HS	TV2002DoD
Frequency	GHz	2.998	2.998
Peak power	MW	3	24
Voltage	kV	110	250
Current	A	72	250
Pulse length	µsec	12	6.5
Drive power	W	80	240

The test of the HPRF INJ with waveguide load shown following results:

- klystron voltage ***U***=0…110 kV
- klystron current ***I***=0…82 A
- pulse length τ=6 µsec
- repetition rate ***F***=10 Hz
- pulse-to-pulse output voltage instability (peak-to-peak) 0.19%
- RMS voltage fluctuation 0.03%
- flat-top voltage non-uniformity <1%

Measured oscillograms are shown in Figure 7: in normal operation and in the fast interlock event (high voltage breakdown - high voltage interrupts within the pulse, and current is limited).

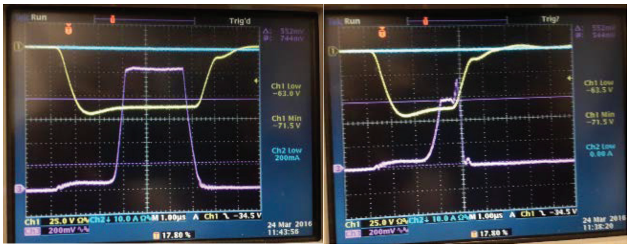

Figure 7: Measured pulses at HPRF INJ: yellow is the klystron voltage, pink is RF power in the klystron waveguide.

Waveguide System

The waveguide system connects the klystron and the deflecting structure [6]. It includes:

- directional coupler,
- waveguide window,
- waveguide load,
- spark detectors,
- waveguide adapters for ion pumps,
- E-bends,
- H-bends,
- straight waveguides.

Each directional coupler includes two channels: for forward and for reflected power. Typical parameters of the directional coupler are presented in Table 3: coupling ***S13***, isolation ***S14*** and directivity ***D***. The directional coupler is shown in Figure 8.

Table 3: Directional Coupler Parameters

Channel	***S13***, dB	***S14***, dB	***D***, dB
Forward	-65.9	-103	37
Reflected	-65.6	-100	34

Figure 8: Directional coupler.

The UHV dual mode waveguide window with ALUMINA flat disk has been developed and built for TDS Systems. It is shown in Figure 9. Measured reflection is ***S11***=-37 dB at operating frequency. The frequency band is 60 MHz at ***S11***<-20 dB.

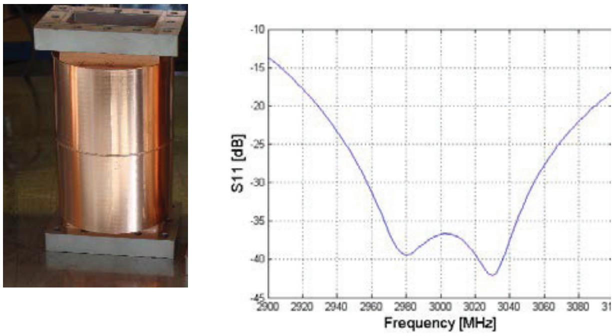

Figure 9: UHV dual mode waveguide window.

The UHV waveguide load has been developed and built. It consists of rectangular waveguide with decreasing of the height on special function covered by Sendust inside. The test of the Sundust coating, performed by DESY, confirmed its UHV compatibility. The load is shown in Figure 10. Reflection is ***S11***=-36 dB at operating frequency and ***S11***<-33 dB in frequency band 200 MHz.

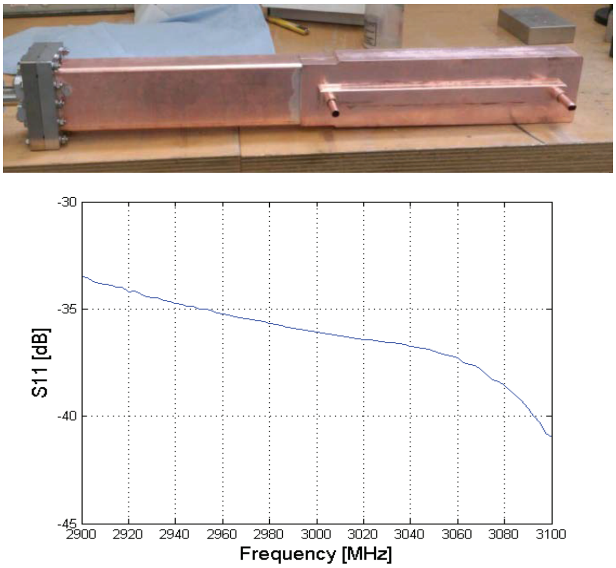

Figure 10: UHV waveguide load.

55 m long waveguide system of XFEL TDS INJ has been assembled in in XFEL Injector building. It is shown in Figure 11. Reflection from the waveguide line is ***S11***=-42 dB at operating frequency.

TDS SYSTEM DESIGN

3D design of the TDS System INJ is shown in Figures 12 and 13.

RF generator and control cabinet of the TDS INJ are located at -5 floor of the Injector building, and the deflecting structure is located in the Injector tunnel at -7 floor. 55 m long waveguide system connects the klystron and the deflecting structure.

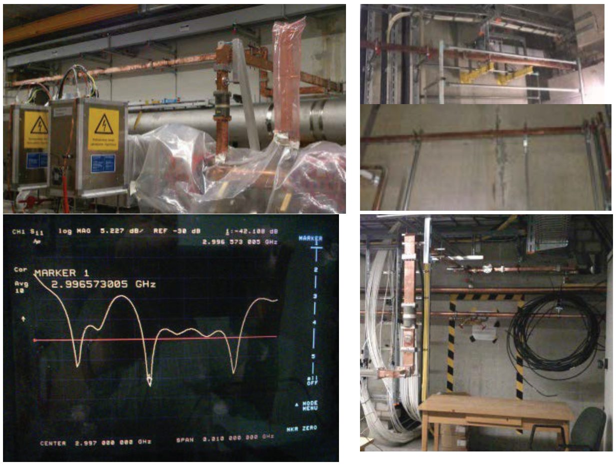

Figure 11: 55 m long waveguide system of the XFEL TDS INJ.

The whole TDS Systems BC1 and BC2 are located in local space in the accelerator tunnel. 3D design of the TDS System BC1 is shown in Figure 14.

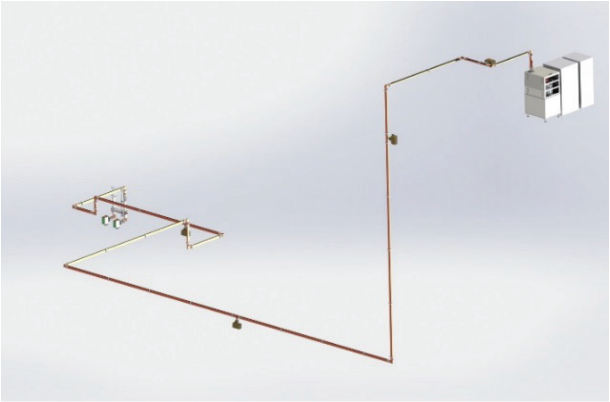

Figure 12: 3D design of the TDS INJ.

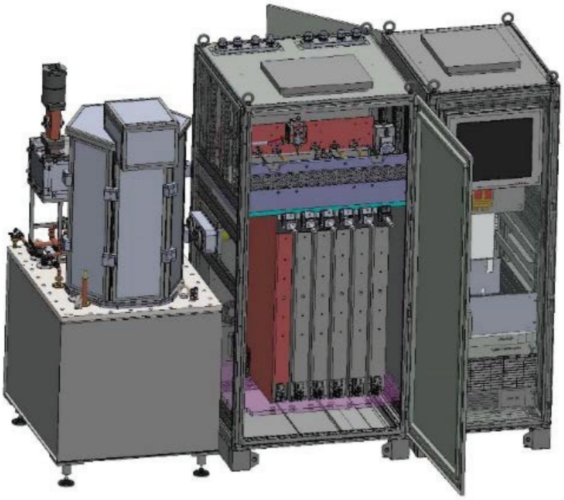

Figure 13: 3D design of the TDS HPRF INJ: RF generator, modulator and control cabinet.

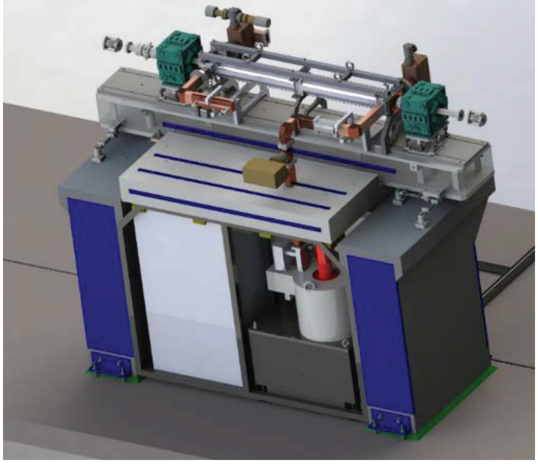

Figure 14: 3D design of the TDS BC1.

ASSEMBLING AND COMMISSIONING

The TDS System INJ has been assembled, tuned and tested. Figure 15 shows operating HPRF INJ and TDS structure INJ.

The TDS Deflector BC2 including two deflecting structures has been installed in the XFEL tunnel (Figure 16).

DESY has successfully concluded tests of the first section of the particle accelerator for the European XFEL. The TDS based diagnostic system produces elongated images of individual electron bunches and allows analysing them in slices. Measured images of individual electron bunches are shown in Figure 17 [7].

Figure 15: HPRF INJ and TDS structure INJ.

Figure 16: Two TDS structures BC2 in XFEL tunnel.

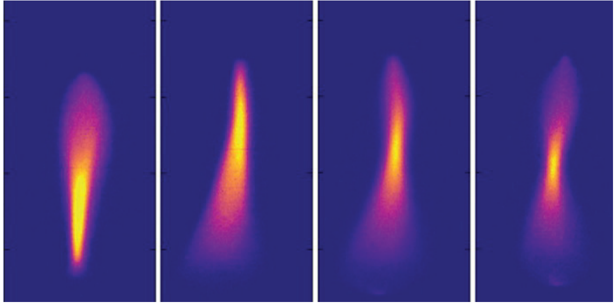

Figure 17: Bunch images produced by TDS System.

CONCLUSION

1. TDS System INJ has been tuned and installed at XFEL. It operates for the beam diagnostics.
2. TDS Structures and waveguide systems for XFEL TDS BC1 and XFEL TDS BC2 have been manufactured, tuned and supplied to DESY.
3. TDS Structure BC1 will be assembled on the girder in the XFEL tunnel in accordance with XFEL schedule.
4. The modulator for XFEL TDS BC1 is under production. It will be supplied to DESY, tested at the test stand and installed in the XFEL tunnel then.
5. Two TDS Structures BC2 have been assembled on the girder in the XFEL tunnel.

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