Deflecting structures development for XFEL and PITZ TDS

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on behalf joint group

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TDS purpose

To achieve and maintain stable operation of the European X-Ray Free-Electron Laser (XFEL), three dedicated diagnostic sections are foreseen for the characterization of the electron beam. The diagnostic sections will be located in the injector and downstream of the two bunch compressor sections BC1 and BC2.

For the measurement of the longitudinal beam profile, the slice energy spread and the slice emittance, transverse deflecting structures (TDS) will be installed in all three diagnostic sections.

The slice emittance measurement will be accomplished by using the TDS in combination with fast kickers that deflect individual bunches onto 4 off-axis optical transition radiation (OTR) screens. The aim is to achieve a temporal resolution of 1/10th of the nominal rms bunch length (1/5th for BC2). The resolution is determined by the TDS deflecting voltage and beam size at the location of the TDS.

Location	Beam Energy, MeV	rms Bunch Length, μm	Required Temporal Resolution fs	Deflecting Voltage MV /filling time, ns
Injector	130	2000	220	1.7/120
BC1	500	110	20	15/360
BC2	2000	25	14	27/360

TDS should be constructed in Russia (INR is responsible) in frames of Russian contribution to XFEL Project.

TDS requirements

1. *Single bunch* ***operation with bunch repetition rate 4.5 MHz (Injector) – short filling time.***
2. ***The remaining bunches in the bunch train*** *must not be affected* ***by RF field of the TDS.***
3. *A conservative, proven design is favored* ***compared to a technically challenging design which requires substantial R&D. Also powerful RF hardware for deflecting system (DS) must be commercially available.***
4. *The impact of the TDS installation on regular beam operation regarding must be minimized.* ***The structures have to be designed to balance performance and wakefields, both longitudinal and transversal effects, as well as short range and long range (multi-bunch) effects.***

PITZ TDS is a direct analog for XFEL TDS Injector in main solutions and parameters. Together with own purpose for PITZ beams measurements (more flexibility is desirable), it has the goal to test solutions and parameters for XFEL TDS.

The operating TDS frequency and operating mode

Arguments for TDS operating frequency and operating mode definition.

Frequency range	Operating TW mode	Operating SW mode
L-band	Increased filling time and extra high required RF power. Relaxed impedance problem. Enlarged dimensions with relaxed tolerances.	Relaxed impedance problem. Enlarged dimensions with relaxed tolerances. Not acceptable rise time.
S-band	Tolerable filling time and required RF power. Tolerable impedance problem. Reasonable dimensions with realistic tolerances.	Tolerable impedance problem. Reasonable dimensions with realistic tolerances. Not acceptable rise time. Additional R&D is required.
C-band	Shorter filling time and lower required RF power. Smaller dimensions with more severe tolerances. Strong rise in the impedance problem. Combination problem starts.	Still long rise time. Smaller dimensions with more severe tolerances. Strong rise in the impedance problem. Additional R&D is required. Combination problem starts.
X-band	Not acceptable rise in the impedance problem.	Not acceptable rise in the impedance problem.

Consideration shows S-band TW operation for XFEL-TDS structure as the most reasonable, realistic and well balanced choice.

TDS main RF parameters

1. *Filling time τ_t =L /(c β_g);*
2. *RF efficiency, shunt impedance is not of primary importance;*
3. *Primary important are b_g and E_d;*
4. *Contradiction between filling time and efficiency;*
5. *Attenuation is not so important, $\alpha = \pi f / (c\ \beta_g\ Q)$, total attenuation* $\alpha L < 0.3$;

$$\frac{E_d \lambda}{\sqrt{P}} = \sqrt{\frac{2\pi\lambda r_{sh}}{\beta_g Q}} \qquad V_d = \int_0^L E_d e^{-\alpha z} dz = \frac{E_d \left(1 - e^{-\alpha L}\right)}{\alpha}$$

frequency independent

Constant impedance TW option for XFEL TDS is chosen.

Disk Loaded Waveguide (DLW) based structures fit with requirements.

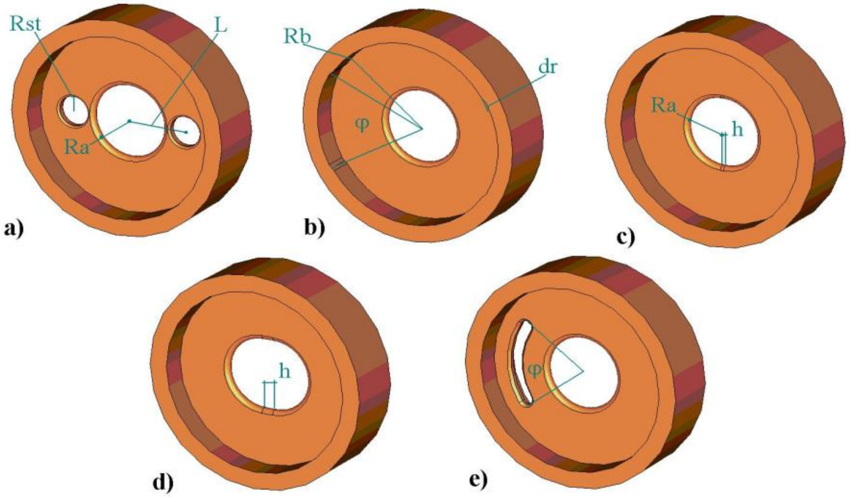
DLW was investigated again. Mostly reasonable choice is phase advance $2\pi/3$ with negative dispersion, near inversion point. Old masters already done this choice!

Another structures?

Considered structures.

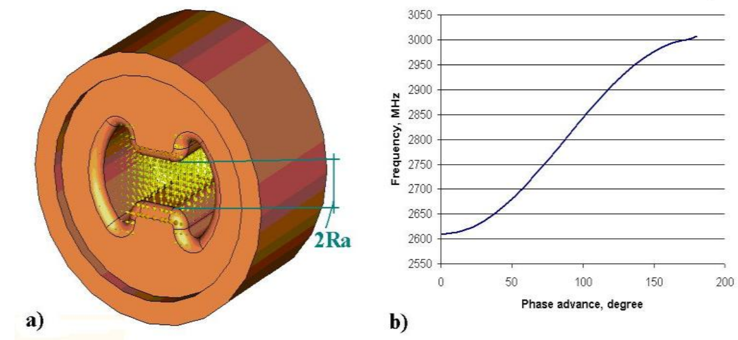
DLW based, deflecting plane is vertical.

H-type

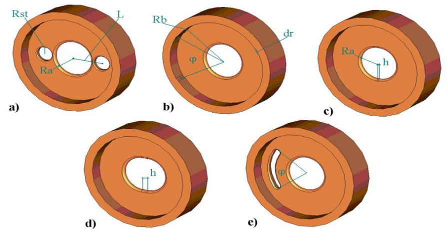


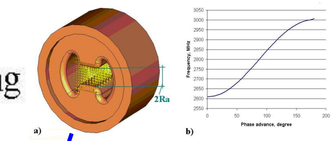
Structures, considered for TDS application. a) - the structure with two stabilizing holes, b) - the structure with two peripheral recesses, c),d) - the structures with smaller (c) and bigger (d) oval aperture, e) – the structure with resonant slot. ***Difference** is in the **solution for deflecting plane stabilization**.*

The hybrid HE11 mode in the cylindrical disk loaded deflectors is twice degenerated. To ensure operational performance and stabilize the position for the plane of deflection, the dispersion curve for modes with Perpendicular Field Polarization (PFP) must be shifted in frequency with respect to the curve for modes with operating Deflecting Field Polarization (DFP).



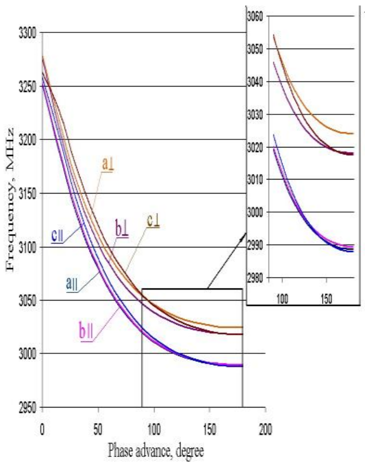
Deflecting field distribution (a) and dispersion curve (b) for the adopted L-band (originally) deflector. This structure has essential differences from DLW.





The dimensions and RF parameters for the structures at operating frequency 3 GHz, considered for TDS, $\Theta=2\pi/3$.

$f_0 = f_{\mathrm{def}2\pi/3} = 3$ GHz, $\Delta f_1 = |f_0 - f_{per2\pi/3}|$, $\Delta f_2 = |f_0 - f_{def\pi}|$, $\Delta f_3 = |f_0 - f_{per\pi}|$



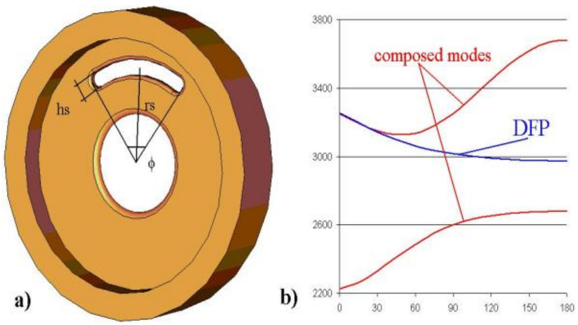
Parameter	Structure option					
	Fig.1.1a	Fig.1.1b	Fig.1.1c	Fig.1.1d	Fig.1.1e	Fig.1.5
L, mm	34.65	-	-	-	-	-
R_{st}, mm	9.0	-	-	-	-	-
h, mm	-	-	1.7	6.5	-	-
φ, degree	-	65	-	-	74	-
dr, mm	-	1	-	-	-	-
R_a, mm	21.55	21.5	20.5	21.5	21.7	8.0
R_b, mm	55.27	55.03	55.49	53.45	55.43	38.93
α, 1/m	0.153	0.144	0.125	0.121	0.145	0.189
β_g	–0.0174	–0.0178	–0.0204	0.0200	-0.0178	0.023
r_{sh}, MOhm/m	17.15	17.21	19.34	17.71	17.76	36.68
Q	11840	12400	12360	12530	12200	7270
Δf_1, MHz	30	28	30	147	153/200	-
Δf_2, MHz	11	11	13	16	14	9
Δf_3, MHz	-24	-18	17	157	154/500	-
$E_d\lambda/\sqrt{P}$, Ohm$^{1/2}$	229	223	220	221	227	372

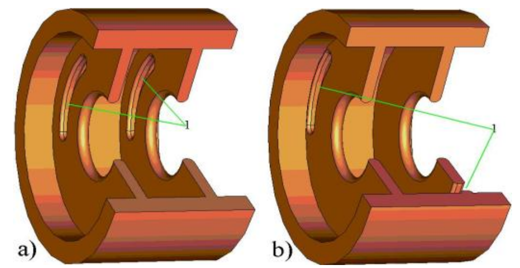
Very effective in RF, no mode mixing problem, but not fits with impedance requirements.

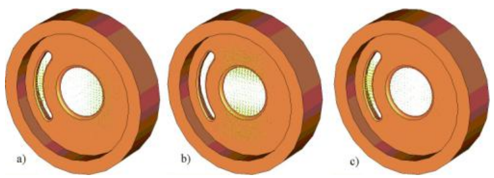
Structures a, b, c, d, e are practically identical in efficiency. Structures a, b, c are similar in frequency separation.

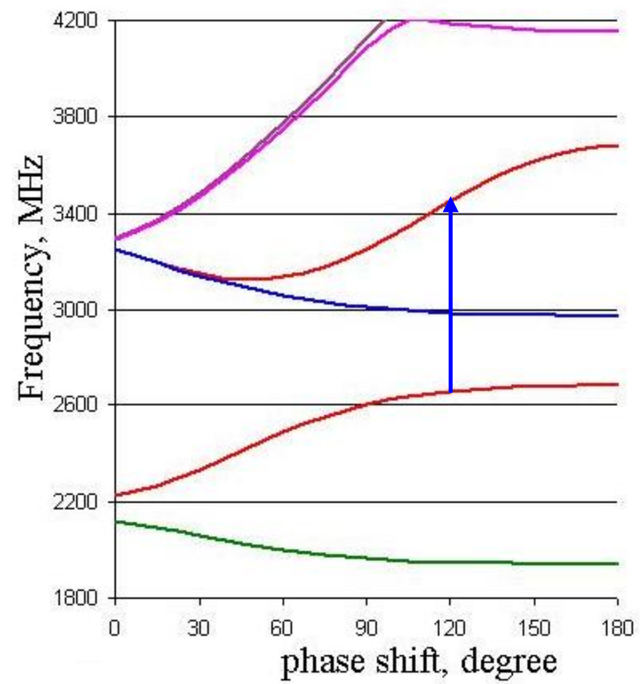
H-type structure not fits with impedance requirements and has exotic phase advance – 172.5^{o} .

Structure with resonant slot.









Resonant elements – slots, coupled only with PFP modes, are placed in the disks. Two branches of dispersion curve for composed slot - structure modes are generated and placed symmetrically with respect to the non perturbed dispersion curve for DFP modes. In the plane stabilization it provides qualitative advantage with respect a simple frequency shift, because cancels, in the first order, the influence of PFP modes on the plane of deflection.

At present time has no proven experience.

The choice of the structure

Basing on:
- fulfillment of TDS requirements with well balanced parameters combination;
- level of development both for the structure itself and for all steps in the TDS construction and tuning;
- proven experience, including high RF power operation,

we chose the structure with two stabilizing holes (LOLA structure) for realization in XFEL TDS.

Cell dimensions choise

Safety margins:

1- the klystron regular operation at the output RF power level 0.95 from the specified one by customer.

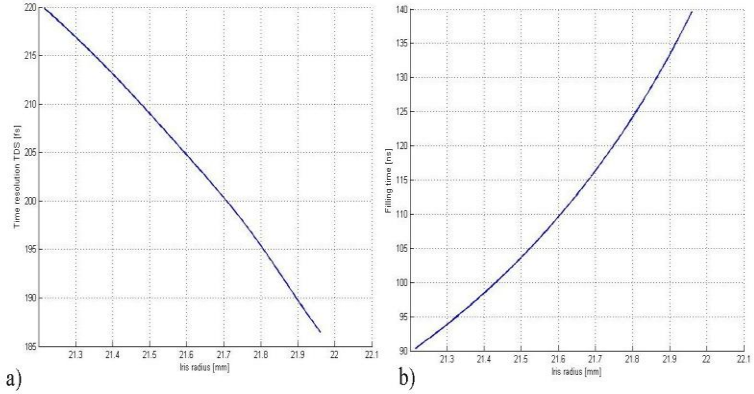
2- the attenuation in the waveguide is 0.021 dB/m.

3- the practical Q value for TDS 0.8 from the calculated one for regular cells.

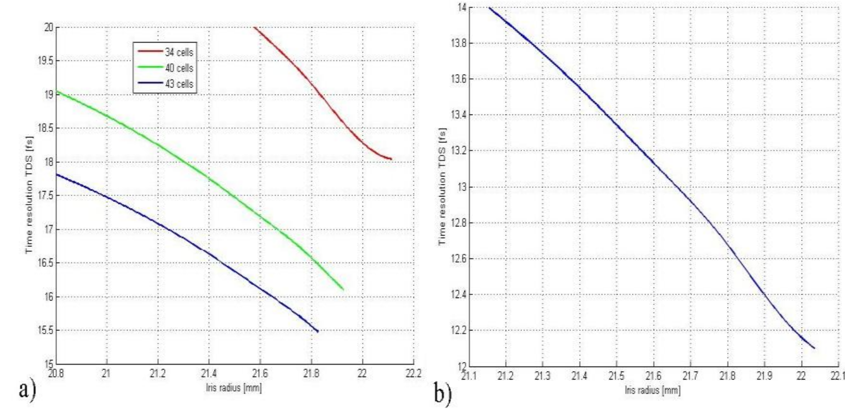
4- one cell should be added - RF coupler cells have reduced efficiency for particle deflection.

Calculated TDS RF parameters for different aperture radius R_a at operating frequency 2997.2 MHz.

R_a, mm, aperture radius	R_b, mm, cell radius	β_g	α, 1/m	$E_d\lambda/\sqrt{P}$, $Ohm^{1/2}$	Esm/Ed	Esm/Hsm Ohm
19.8	55.90	-0.02949	0.08929	188.52	3.829	256
20.0	55.83	-0.02838	0.09290	190.73	3.857	256
20.2	55.76	-0.02718	0.09739	193.41	3.920	258
20.4	55.69	-0.02589	0.10249	196.67	3.984	261
20.6	55.62	-0.02450	0.10828	200.57	4.048	263
20.8	55.55	-0.02302	0.11544	205.30	4.081	263
21.0	55.49	-0.02147	0.12426	210.85	4.114	263
21.2	55.43	-0.01982	0.13483	217.63	4.200	267
21.4	55.37	-0.01808	0.14762	225.98	4.270	270
21.6	55.31	-0.01624	0.16425	236.43	4.342	273
21.8	55.26	-0.01433	0.18638	249.42	4.362	272
22.0	55.21	-0.01234	0.21602	266.47	4.437	275
22.2	55.16	-0.01025	0.26067	276.85	4.482	277



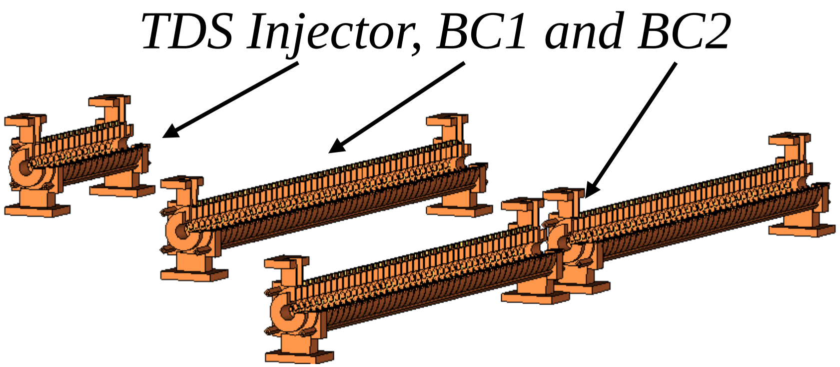
The temporal resolution (a) and filling time (b) of the TDS Injector, Nc =16 for different iris radius Ra



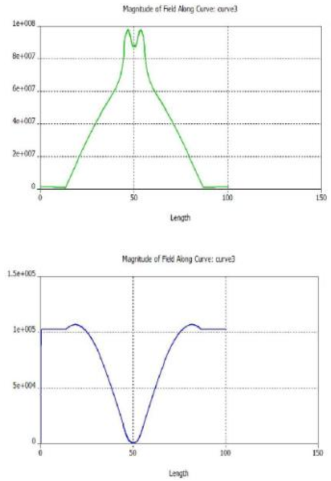
The temporal resolution of the TDS BC1 for Nc =34, Nc =40 and Nc =43 (a) and TDS BC2, Nc =43 (b), assuming 45 MW klystron.

As the result of mutual consideration, the aperture radius Ra is chosen the same for all TDS sections.

For construction costs reduction, XFEL TDS section have the high level of unification.



Maximal fields and heating



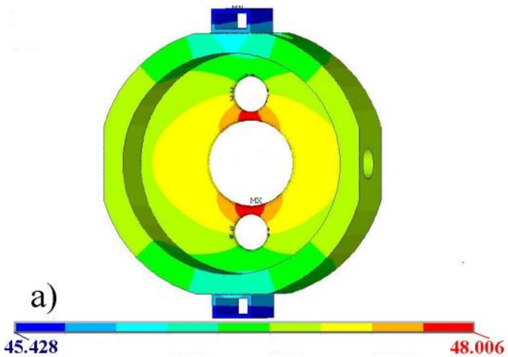
Maximal fields are in BC1 input cells.

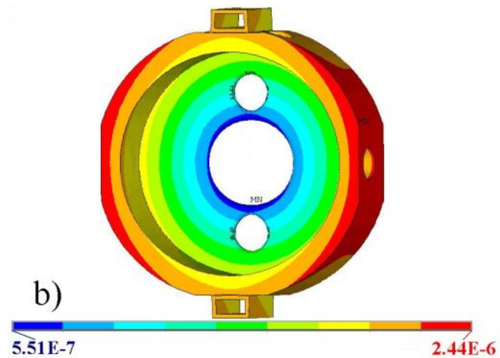
E_{smax} ~ 58 MV/m (1.1 Ek)

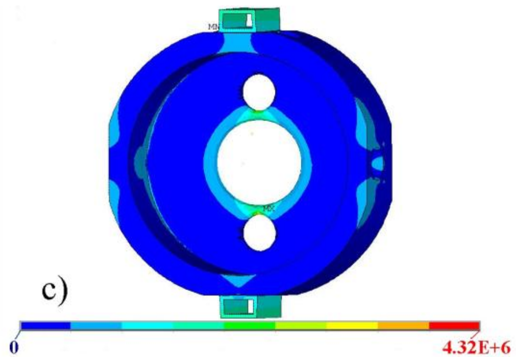
H_{smax} ~ 220 kA/m

Visible RF pulsed heating with Ts ~ 17 C^o for 3.1 μs pulse.

Average heating is rather small, BC1 df ~ 48 kHz

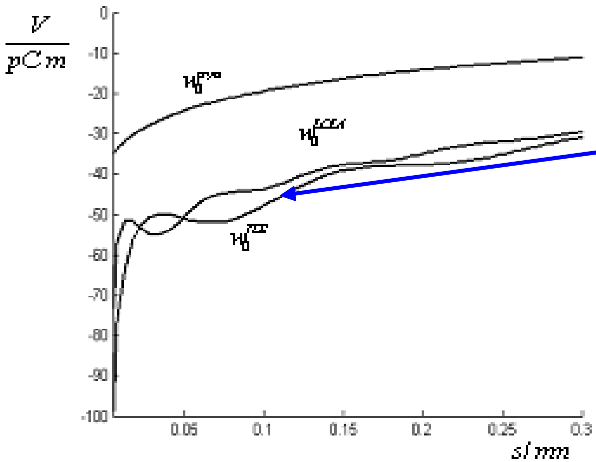




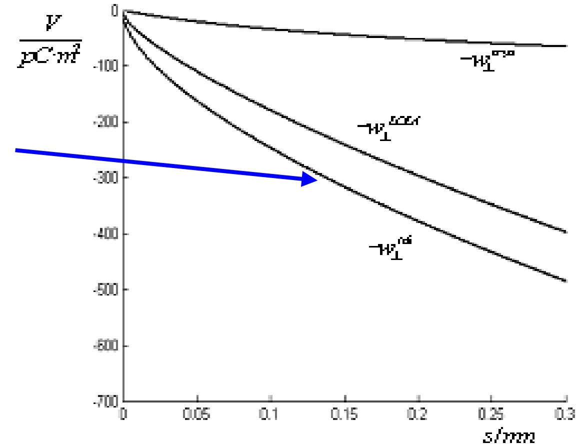


Temperature, displacements and stress distribution, first BC1 cell.

Short range wakefields



Longitudinal and transverse wakefunctions for TDS. Total effect is negligible.



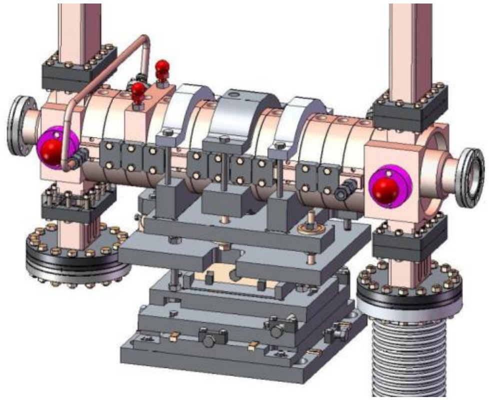
Induced correlated energy spread due to longitudinal wakefields in TDS.

Location	RMS bunch length, mm	RMS spread, kV	Relative RMS spread, %
Injector	2	6.8	8e-4
BC1	0.11	29.1	
BC2	0.025	104	
Total		139.9	

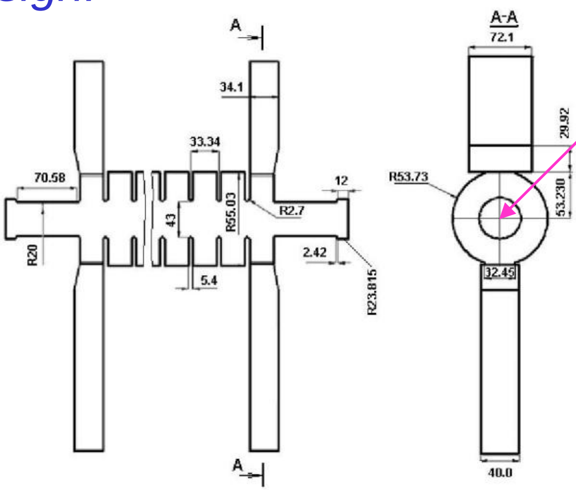
Emittance growth due to transverse wakefields in TDS.

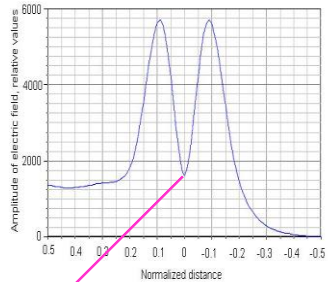
Location	RMS bunch length, mm	Bunch Energy, MeV	RMS kick, kV/mm	Emittance growth, %/mm
Injector	2	120	71.5	0.2
BC1	0.11	400	35.4	0.01
BC2	0.025	2000	45.6	0.005
Total			152.5	0.215

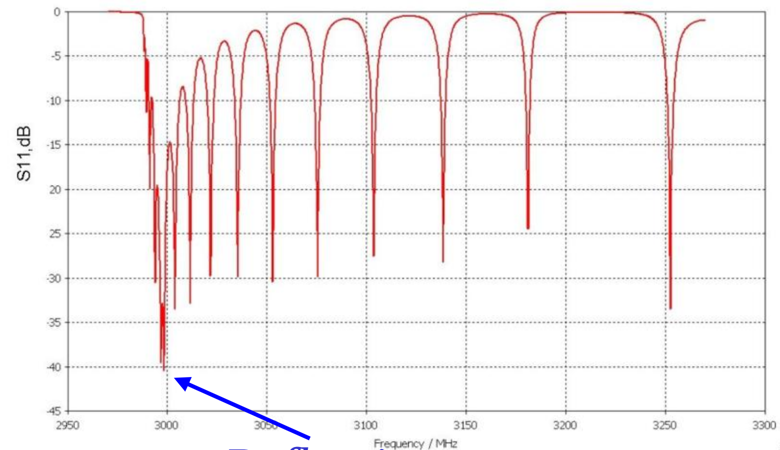
RF couplers



TDS Injector (PITZ) deflector design.

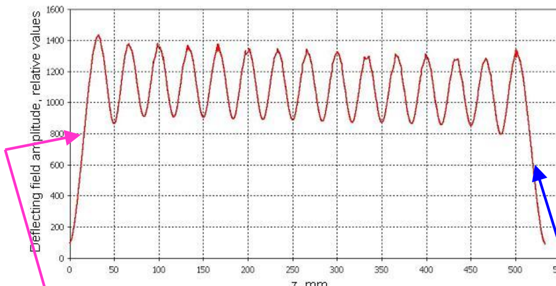






Reflection

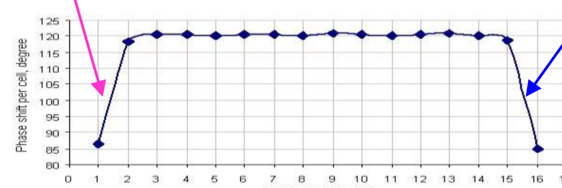
RF input cell



beam

Amplitude

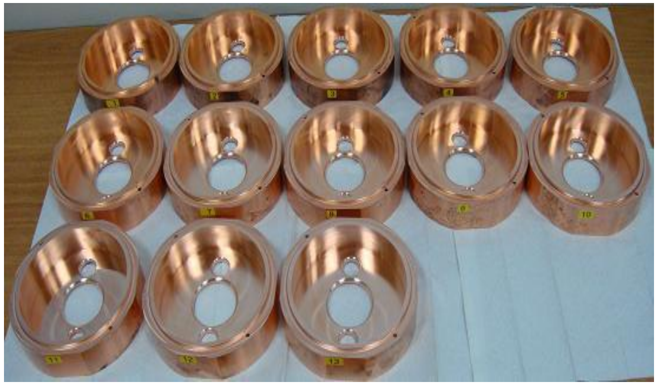
RF output cell



Phase advance

Quasisymmetrical RF coupler design, input and output RF couplers are identical, couplers should be the same for all TDS.

Cells RF measurements



The frequencies of the manufactured cups have been checked using the 3-cell copper test model. The frequency deviation is –0.159…+0.117 MHz (peak to peak). It is equivalent peak to peak deviations in the cell radius +3.2 μm ....-2.4 μm.

The frequency, measured in the 12-cell structure is f =2997.078 MHz. Required frequency is . 2997.077 MHz at the same environmental conditions.

Measured unloaded Q-factor is Q=11044, which is 94% of calculated value.

The deflector tuning after brazing is foreseen in the range ±2 MHz by using thin wall bending.

Summary

1. ***TDS structure fulfill XFEL TDS requirements with well balanced parameters combination.***
2. ***Well developed and proven solution (LOLA type) is chosen for deflecting structure.***
3. ***Cost effective design with high degree of unification is developed for XFEL TDS deflecting sections.***
4. ***Together with own value for PITZ beams diagnostic, the PITZ TDS is direct prototype of the XFEL TDS Injector and has the goal to test again all solutions in total.***
5. ***Present RF measurements of cells for PITZ TDS show quite sufficient level of manufacturing.***