The European XFEL
Toroid and Toroid Protection System

Conceptual Design Report

XFEL, WP-17

Part 4: Conceptual Design Description

Change History starting from CDR Comments

Date	Who	Comment
28.02.2011	D.Nölle	Substantial changes marked in red xTCA changed into µTCA Controls interface: Transmission display based on middlelayer server Possibility to provide charge data for the photon systems included, also a section in the interface chapter on a fast digital link for bunch to bunch charge information.
1.03.2011	D. Nölle	Work on comments by P. Göttlicher. Remark on the position of FE electronics, that will not be in a shielded area. We do it based on FLASH experience. Mistake on calibration and test pulser corrected. Cal

		pulse has to be installed. Test pulse is available from all installations. Warning to take care on noise introduced by neighbours in the crate included. Comment included, that the concepts of the timing system are not finalized. Remark on alternative topology included

1 Conceptual Design Description

The XFEL charge measurement or toroid system will be based on the systems in use in all accelerators at DESY for many years. Depending on the machine they are called AC monitors or toroids. The pickup consists of a transformer that is mounted over a ceramic gap. The integral of the induced voltage is proportional to the charge that has passed the device. This signal is amplified by a local amplifier, then digitized and the values are provided to the control system. Since the pulse shape is determined by the read out filter, evaluation of the maximum voltage with respect to the baseline is sufficient. Due to the AC coupling of the transformer, there is a base line shift in case of bunch trains. This is the reason why the actual baseline value needs to be recorded and subtracted.

The instruments used for XFEL will be very close to that developed and used at FLASH. Main difference will be on the readout side. XFEL will make use of fast ADCs a digital processing in a FPGA and digital signal transmission from toroid to toriod. Moreover, the sensitivity will be increased by modifications of the front end electronics to cope with small bunch charges.

For FLASH pairs of toroids have been used to monitor the transmission of the charge and to provide a fast interlock in case of poor transmission. This feature will again be implemented for XFEL in a modified manner, and will provide information to the machine protection system. At FLASH analogue signals from toroids close to the gun and to the dump have been transmitted via long cables to a central place, and have been evaluated by a special electronics [ref Hamdi]. For a machine of the size and complexity of E-XFEL this principle does not work any more. For XFEL it is planned to use a chain like topology using digital fibre transmission lines (Fig. 1) evaluating how much of the charge, measured by an upstream toroid, has reached the next charge monitor(s). This distributed design allows including the branching of the beamlines and the fast switching in a consistent manner.

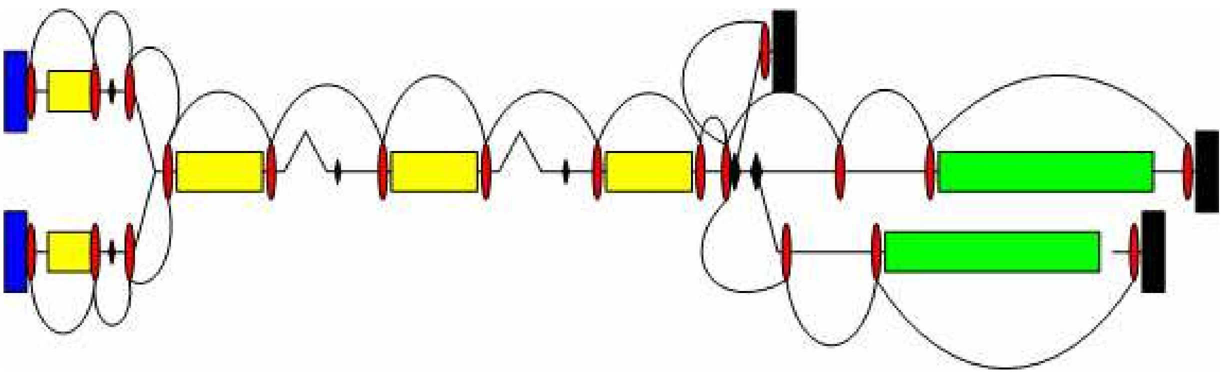


Fig. 1: simplified topology of the XFEL including the components relevant for the toroid and TPS system. Blue: Guns; Yellow: LINAC sections; Green: Undulators; Black rectangle Dumps; Black diamond: Kicker magnets; Red: Toroids. The curved lines indicate the communication lines between the toroids.

Currently 38 devices are planned for the XFEL. There will be two types with 40.5 and 100 mm diameter, according to the requirements on beam pipe diameter. The 40.5 mm type will be available with different vacuum chamber, a shielded and an unshielded one, taking care of the particle cleanliness requirements close to the superconducting accelerator and impedance optimisation in the sections with ultrashort electron bunches.

2 Specification of the charge measurement

The following table summarizes the specification of the charge readout.

Table 1: Specification of the performance of the charge measurement

Parameter	Unit	Value	Comment
XFEL Operation[1] Range	nC	0.02 – 1	Nominal operation charge regime of the XFEL
Measurement [2]Range	nC	< 1.5	ADC Readout will allow maximum charge of 1.5 nC before going into an overflow. Two measurement ranges: 0… 0.30 nC 0… 1.50 nC With remote switchable amplifier gain
RMS Noise Floor of the Charge Measurement	pC	< 2	RMS noise level of the signal. This corresponds also to the statistical error of the charge measurement. This value is valid under optimum “lab” conditions. Since toroids cannot be shielded from environmental electronic noise or spurious currents on the beam pipe, the EMI aspects of their neighbourhood have to be investigated carefully.
Accuracy of Charge measurement @ 1nC	%	< 3	All toroids will be calibrated with the same test pulse following a well defined calibration process, used for all toroids in the DESY accelerators.
Calibration Accuracy between different toroids	%	1	RMS error of the toroid calibration, following the procedure described before.
Max. Bunch Repetition Rate	MHz	4.5	Arbitrary bunch pattern with a minimum spacing of 222 ns has to be possible.
Macropulse Repetition Rate	Hz	≤ 30 Hz	
Number of Bunches per train		<= 2700	Arbitrary bunch pattern possible.

In order to measure the charge and monitor the transmission, toroids are located in general at the beginning and at the end of each warm section. Furthermore, they are located at the interfaces between sections and especially at branches in the machine. The following table shows the distribution of the toroids in the accelerator. The third column indicates the fast connections between the toroids to exchange the charge information that allows an online calculation of the transmission.

[1] The concept of the toroid system, like the other diagnostic systems was already in an advanced state. The reduction of the minimum charge to 0.02 nC was not known in time. Nevertheless the system will be capable to measure to such low charges, but limitations of the performance have to be expected. A noise level of 2 pC is included in the spec. Improvements are investigated but cannot be guaranteed.

[2] Extension of the charge range for higher charges has to be done manually if necessary, using attenuators to be installed in the signal chain.

Table 2: Overview over the different types of toroids planned for XFEL

Short Name	Beam pipe [mm]	Number	Length	Flange	IDEAS number	Remark
TORA Unshielded	40,5	10	215 mm (incl. Bellow)	CF50 Fixed/Fixed	130_01_63_65 With RF shielding: 130_01_63_69	The bellow unit is 58 mm long, with rigid fixing to the girder it might be not necessary.
Shielded		21				
TORB	34	1	To be defined	Welded to neighbour components		This type will be used only for the gun. The design will be cloned from FLASH.
TORC	100	6	250 mm (incl. Bellow)	CF100 Fixed/Fixed	130_01_63_67	The bellow unit is 100mm long. It is necassary only if external forces can act on the ceramic chamber.

Table 3: Scheduled distribution of the toroid in the XFEL

SECTION	CADRoom	MDI	MPS Connection to	NAME1	TYPE	Pipe Diameter[mm]	RF-Shielding	S	Z	Comment
I1	XTIN_000	1		TORB.24.I1	TORB	34,00	no	0,91460000	24,11460000	Gun, 44 mm in a 34 mm pipe
I1	XTIN_000	2	1	TORA.47.I1	TORA	40,50	no	23,89470000	47,09470000	after first module
I1	XTIN_000	3	2	TORA.61.I1	TORA	40,50	no	38,49000000	61,68770000	Before dogleg to LINAC
I1D	XTIN_000	4	3	TORC.64.I1D	TORC	100,00	no	41,73080000	64,59290000	Injector dump
I1	XTL_001	5	3	TORA.94.I1	TORA	40,50	no	71,08600000	94,02780000	End of the dogleg
I1	XTL_001	6	5	TORA.117.I1	TORA	40,50	no	94,53290000	117,45290000	Entry L1
B1	XTL_002	7		TORA.175.B1	TORA	40,50	no	152,53970000	175,45970000	Entry B1
B1	XTL_003	8	6	TORA.203.B1	TORA	40,50	no	180,48840000	203,35970000	After B1 Chicane
B1	XTL_003	9	8	TORA.233.B1	TORA		no	210,83840000	233,70970000	End of B1

						40,50				
B1D	XTL_003	10	9	TORC.236.B1D	TORC	100,00	no	213,97330000	236,69020000	B1 Dump
B2	XTL_006	11	9	TORA.386.B2	TORA	40,50	no	364,01880000	386,89010000	Entry B2
B2	XTL_007	12		TORA.414.B2	TORA	40,50	no	391,65070000	414,51010000	After B2 Chicane
B2	XTL_008	13	11	TORA.471.B2	TORA	40,50	no	449,13070000	471,99010000	End of B2
B2D	XTL_008	14	13	TORC.478.B2D	TORC	100,00	no	455,39820000	478,10440000	B2 Dump
L3	XTL_023	15	13	TORA.1262.L3	TORA	40,50	no	1240,00350000	1262,86290000	End of L3, Beginning of Temp beamline
CL	XTL_031	16	15	TORA.1652.CL	TORA	40,50	yes	1629,96220000	1652,82160000	Entry Collimator
CL	XTL_033	17	16	TORA.1764.CL	TORA	40,50	yes	1741,59720000	1764,44640000	Symmetry Point Collimator
CL	XTL_035	18	17	TORA.1862.CL	TORA	40,50	yes	1839,22720000	1862,06640000	End Collimator, Start Distribution
TLD	XTL_037	19	18	TORA.1995.TLD	TORA	40,50	yes	1972,46730000	1995,30390000	Entry beamline to TLDump, After separation
TLD	XS1_000	20	19	TORC.2127.TLD	TORC	100,00	no	2105,85840000	2127,96550000	Toroid before TLDump
TL	XTL_038	21	18	TORA.2011.TL	TORA	40,50	yes	1988,64230000	2011,48140000	Distribution, straight line, After first separation
T2	XTD2_001	22	21	TORA.2164.T2	TORA	40,50	yes	2141,34740000	2164,18650000	Before SASE1
T4	XTD2_005	23	22	TORA.2373.T4	TORA	40,50	yes	2350,85240000	2373,69150000	After SASE1
T4	XTD4_001	24	23	TORA.2790.T4	TORA	40,50	yes	2767,56580000	2790,35450000	Before SASE3
T4D	XTD4_003	25	24	TORA.2932.T4D	TORA	40,50	yes	2910,16580000	2932,91670000	After SASE3
T4D	XTD4_006	26	25	TORA.3065.T4D	TORA	40,50	yes	3043,25080000	3065,96650000	Entering the Dump Line T4D
T4D	XDU2_000	27	26	TORC.3103.T4D	TORC	100,00	no	3081,40600000	3103,77250000	Main dump in T4D
T1	XTL_038	28	21	TORA.2038.T1	TORA	40,50	yes	2015,71730000	2038,55470000	Entry beamline to TD1 (SASE2), After separation
T1	XTD1_001	29	28	TORA.2164.T1	TORA	40,50	yes	2141,33730000	2164,10000000	Before SASE2
T3	XTD1_006	30	29	TORA.2428.T3	TORA	40,50	yes	2405,77430000	2428,32660000	After SASE 2
T3	XTD3_001	31	30	TORA.2682.T3	TORA	40,50	yes	2660,27440000	2682,72890000	Before UND1
T5	XTD3_002	32	31	TORA.2744.T5	TORA	40,50	yes	2722,46540000	2744,91950000	After UND1

T5	XTD5_001	33	32	TORA.2977.T5	TORA	40,50	yes	2955,38040000	2977,77090000	Before UND2
T5D	XTD5_002	34	33	TORA.3040.T5D	TORA	40,50	yes	3017,91370000	3040,27590000	After UND2
T5D	XTD5_005	35	34	TORA.3149.T5D	TORA	40,50	yes	3127,39370000	3149,70660000	Entering the Dump Line T5D
T5D	XDU1_000	36	35	TORC.3187.T5D	TORC	100,00	no	3165,32290000	3187,27980000	Main dump in T5D

3 System Description

A single toroid can be described by the following block diagram:

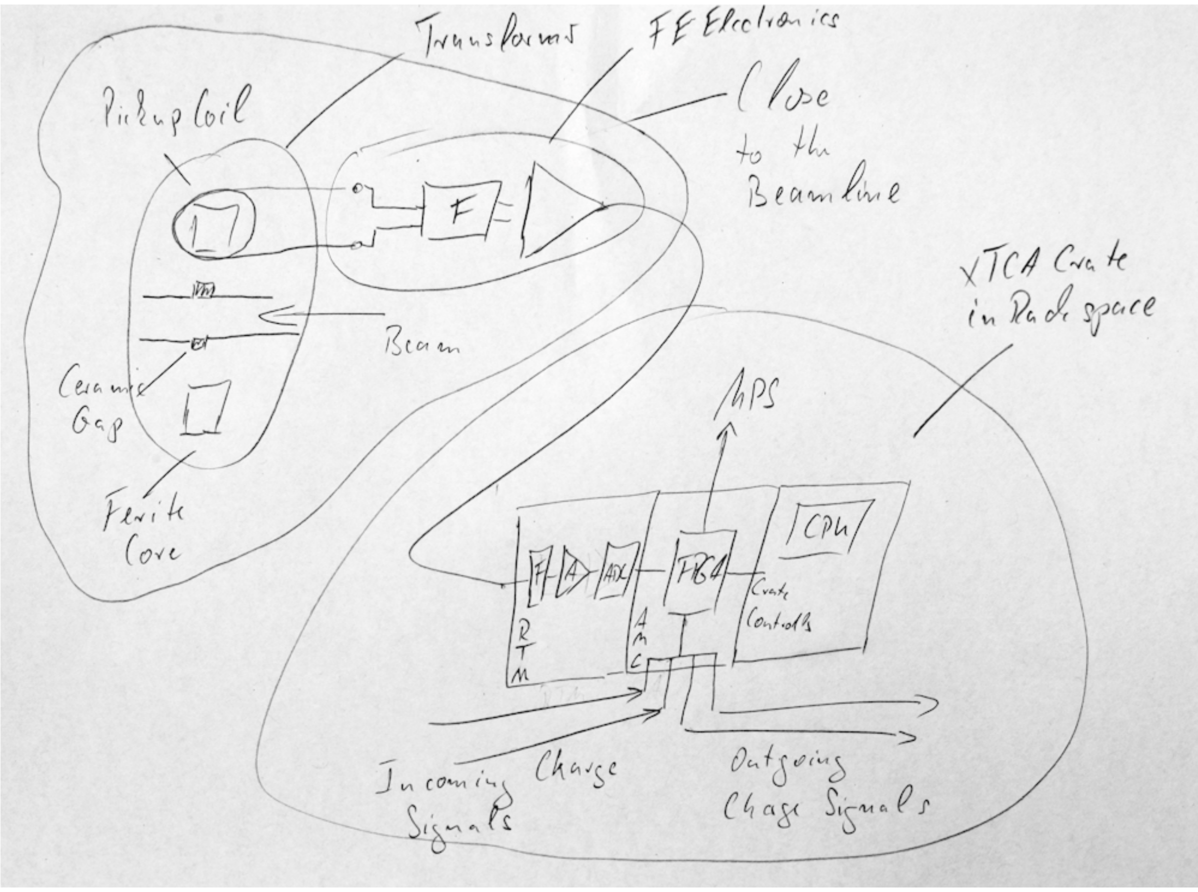


Fig. 2: Schematic drawing of a toroid station

The system consists of the vacuum chamber with the ceramic gap. The gap allows that the electromagnetic fields of the beam induce some flux in the toroidal ferrite core of the monitor. The flux is picked up by 4 coils (only one shown in the picture), added up to a single signal. This signal is filtered and amplified. This front-end part of the electronics is very close to the beamline[3].

The amplified signal is then transmitted by a cable to the electronics rack. Here some further filtering and amplification is done before digitizing the signal, and processing it in the FPGA.

[3] Radiation levels are expected similar to FLASH. There we have a similar setup, with electronics close to the beam, and no real problems up to now. We intend to have the FE electronics below the girder, thus shielded by some iron. It will have no perfect shielding.

The charge information is then provided to the CPU of the front end computer and delivered to the control system.
In addition to the readout via the control system, 4 fast optical links are available. They will be used as fast communication links controlled by the FPGA firmware.

Further actions performed in the FPGA are:

- Receiving charge data from the next downstream toroids via a fast optical link. Up to three links are foreseen, due to the branching of the beamlines.
- These signals are synchronized to the data of this toroid, such that charge comparison for each single bunch is possible. Based on this synchronized data the transmission to the next charge monitor stations can be calculated. In case of poor transmission an interlock is released on a dedicated interface to the machine protection system.
- In order to provide the next toroid in upstream direction with data, the measured charge is sent out on a fast optical link.
- At special locations near to the RF stations, another optical link is provided to send out low latency charge information to the LLRF system, to be used for beam based feedbacks.

In the following the components of a toroid station will be described in detail.

3.1 Vacuum Chamber of the Toroids

The vacuum chamber of the toroids has a length of 215 mm and CF50 flanges for a 40.5 mm beam pipe and 250 mm length and CF100 for a 100 mm beampipe. The length includes the chamber with a ceramic gap in the centre surrounded by two very short bellows and an additional short bellow unit (see Fig. 5 and Fig. 6). This unit is required to take potential stress from the ceramic gap, and thus is a safety measure. In case of rigid and precise alignment of the main toroid chamber, the bellow unit might be not necessary.

An exception will be the toroid at the gun. This monitor will be based on the FLASH design, since the design of the entire section will copy FLASH.

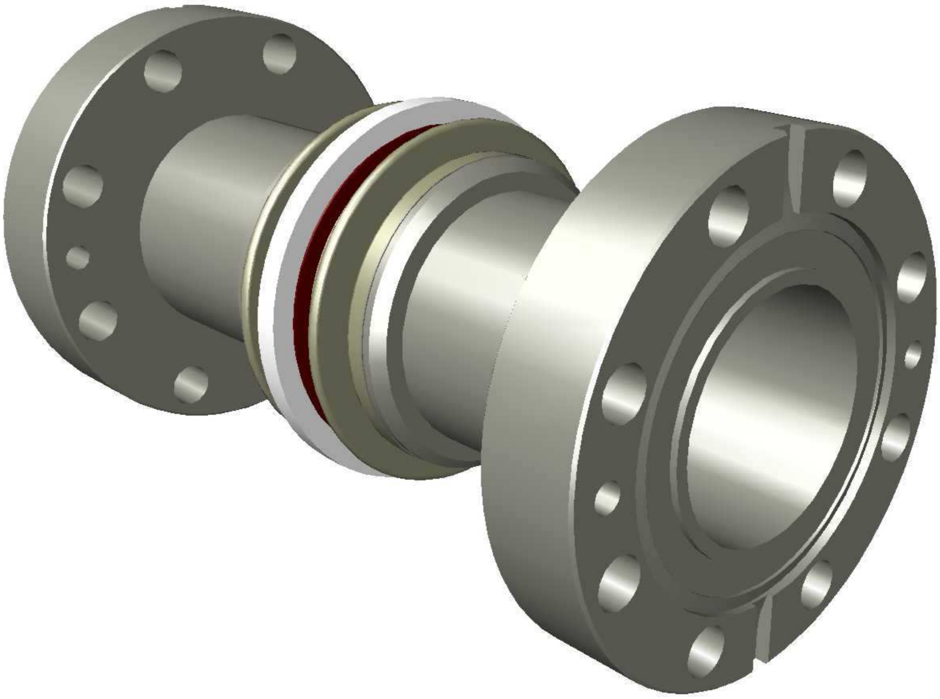


Fig. 3: 3D picture of the ceramic chamber for the toroids.

In the operational setup this chamber is not visible, since it is inside the housing of the transformer. The flanges are used to support the housing of the toroid and are also part of the electromagnetic shielding for the gap. A good electrical connection between the flanges and the toroid housing is provided by the use of RF springs between the two components[4].

Due to the ceramic gap, the chamber must be rigidly fixed to the support structures, so that no forces can act on the ceramics.

The toroid housing will be assembled after cleaning and installation into the vacuum string. To protect the ceramics during before installation of the housing special connection bars between the two flanges will be provided by WP17. The housing will cover the entire chamber and will connect to the flanges of the ceramic chamber. **Therefore the supports for the toroids have to be fixed at the flanges of the neighbour components.**

Maintenance might require the removal of the housing in the tunnel and temporarily mounting of the safety bars of the ceramic chamber.

[4] These RF springs are outside of the vacuum system. They are different from the RF shielding to minimize wakefield effects. These shieldings are inside the vacuum chamber and are used in non particle clean beamlines only.

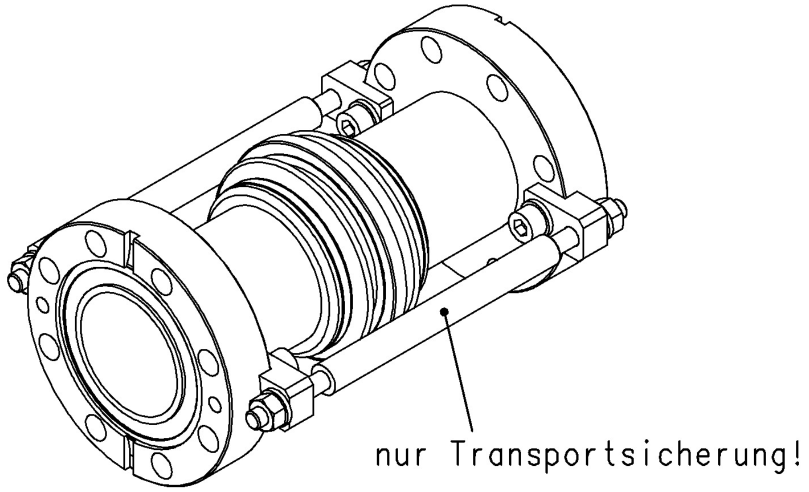


Fig. 4: Safety bars serving as the transportation and assembly locks mounted on the ceramics chamber

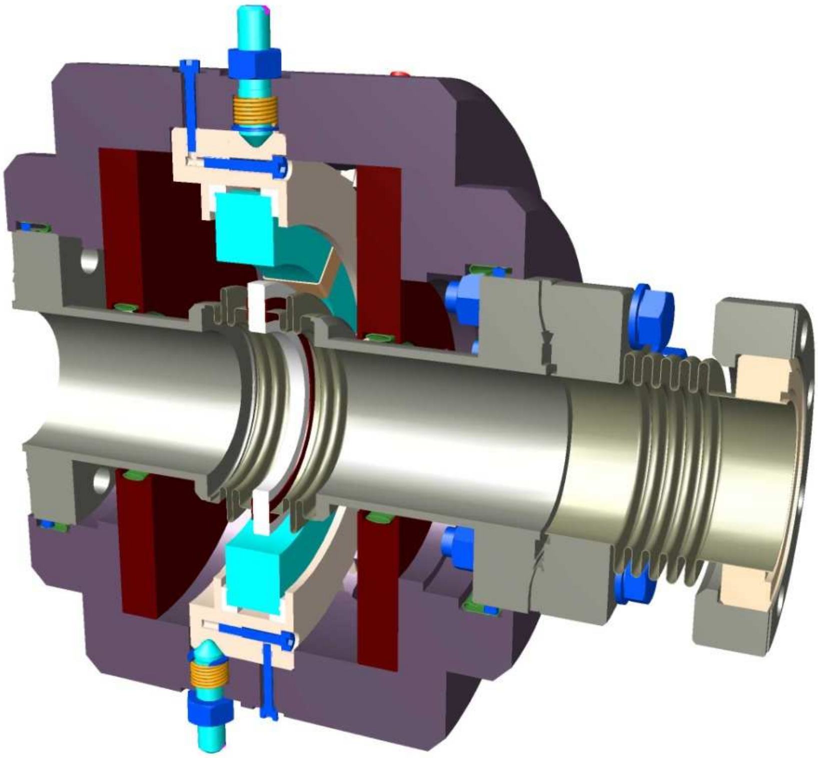


Fig. 5: Cut through a 3D picture of a completely assembled toroid. From left to right one can see the bellow unit and the ceramic gap (without RF shielding) with the housing of the transformer. Furthermore, one can see that the toroid housing is supported by the flanges of the ceramic chamber.

There are two versions of ceramic chambers, one with and one without RF shielding. The influence on the impedance budget was evaluated and agreed by beam dynamics group. The first 10 toroids in the beamline will have no RF shielding. The one in the remaining part of the machine will get RF shielding. Independent on particle cleanliness requirements toroids to be used in the different dump sections will get no RF shielding.

3.1.1 Sections requiring Particle Cleanliness

For sections requiring particle cleanliness the vacuum chamber will get an open design, i.e. without RF shielding of the ceramic gap. These chambers will be used before the main LINAC and in the last particle free section after the main LINAC. Leaving out the shielding allows for a simpler wet cleaning process.

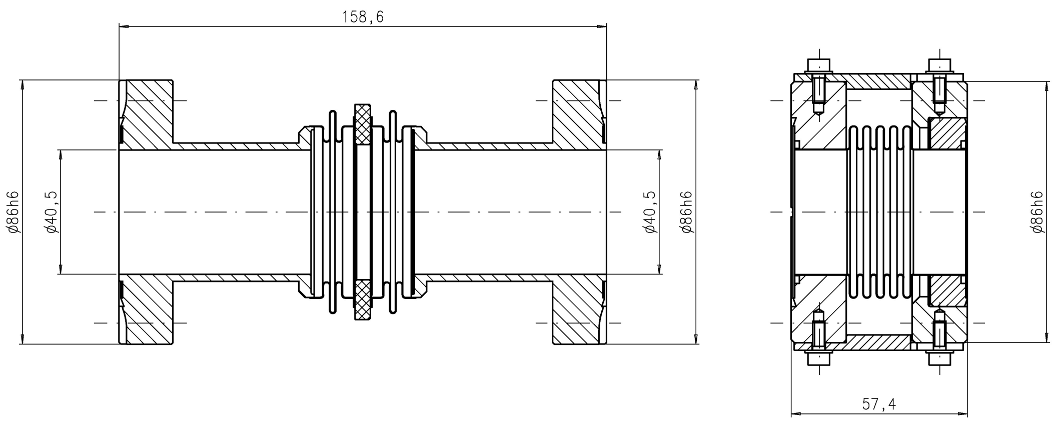


Fig. 6: 2D drawing of the toroid chamber and the bellow unit. This picture shows the unshielded version for the low energy part of the machine, where particle cleanliness is required.

3.1.2 Sections without Requirements on Particle Cleanliness

The vacuum chambers in the high energy part of the XFEL, except the first one, do not have to fulfil requirements on particle cleanliness. For these toroids there will be an RF shield included. From the point of view of impedance the shield was checked and approved by the beam dynamics group.

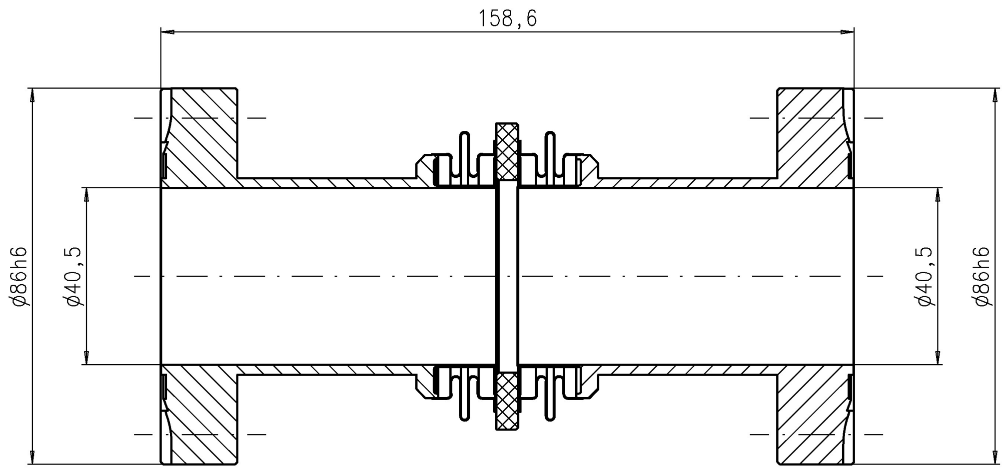


Fig. 7: Version of the toroid chamber for the high energy part of the XFEL without requirements on particle cleanliness. For these cases the chamber has an inner shielding of the short bellow units close to the ceramic gap. The shielding minimizes wake field effects.

3.1.3 Toroids for the Main Dumps

As mentioned before, the toroids for the main dumps will have an inner aperture of 100 mm, CF 100 (fixed/movable) flanges and an overall length of 250 mm (including bellow unit.) A sketch of the chamber is shown below.

The dump chambers will have no RF shielding. Therefore the same design can be used for section with or without particle cleanliness requirements.

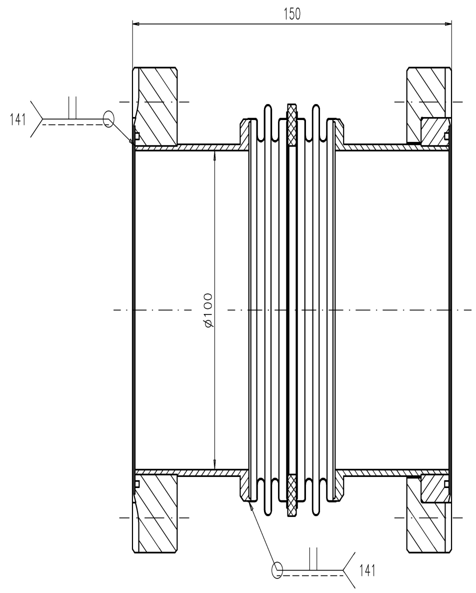


Fig. 8: Sketch of the vacuum units for the dump sections.

3.2 Read-out Electronics

The toroids are read out by an electronics system that can be divided into two parts (see Fig. 2), a front-end part and a back-end part. The front-end part provides the signal conditioning and amplification. This part should be as close as possible to the beamline. The back-end part prepares the signal for the ADC and performs the digitization that is followed by digital signal processing in an FPGA. The latter will provide all algorithms for the processing of the charge, the interlock functionality and the communication to the control system.

3.2.1 Front-end Electronics

(Author: Neumann, Wentowski)

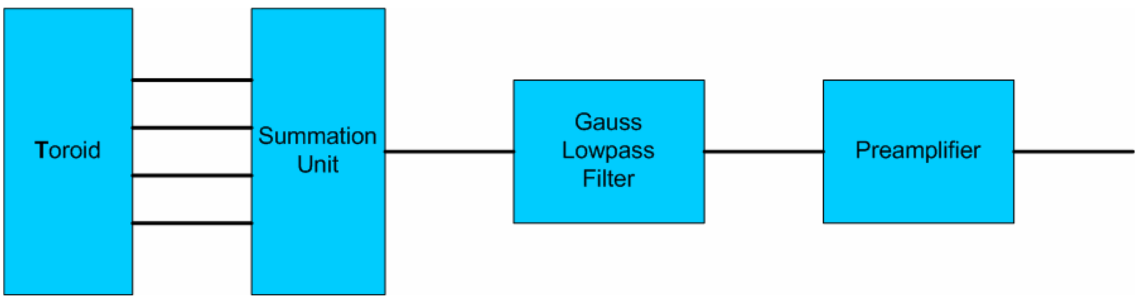


Fig. 9: Block circuit of the signal chain for the toroid read out.

The front-end electronics consists of the transformer pickup. After the transformer the summation unit is used to sum up the four signals to one single signal. This signal is then filtered and amplified. This front-end electronics is very close to the beamline.

3.2.1.1 Transformer Unit

The pickup consists of the vacuum chamber with the ceramic gap. The gap allows that the electromagnetic fields of the beam induce some flux in the toroidal ferrite core of the transformer. The flux is picked up by 4 coils. The signals of these coils are matched to the cable impedance by RF transformers and passed to connectors at the transformer housing.

The toroidal ferrite core together with the pickup coils and the following RF transformers is located in an aluminium housing which is fixed with RF tight connections to the beampipe. This housing (shown in Fig. 5 and Fig. 10) provides the mechanical support and the electric shielding to the outside world. Special to the DESY toroids is that the ferrite core and also the housing are split into two parts. This allows assembly of the transformers after the assembly of the vacuum chamber and also makes maintenance much easier.

In addition to the 4 pickup coils mentioned before, each toroid has two additional test coils on the ferrite core. One of these coils is used to induce calibration signals to the ferrite core, and thus to the pickup coils. This coil will be called test loop later in this document.

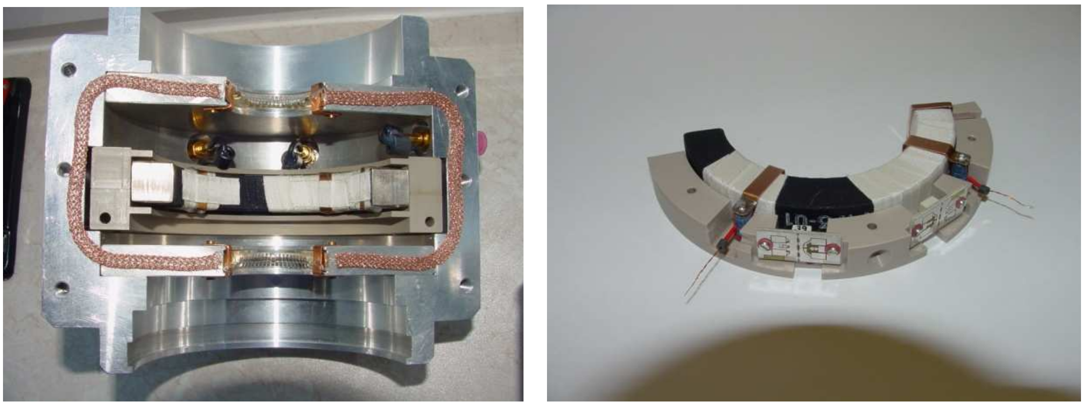


Fig. 10: View to the transformer inside the toroid housing

3.2.1.2 Summation Unit

(Author: Neumann, Wentowski)

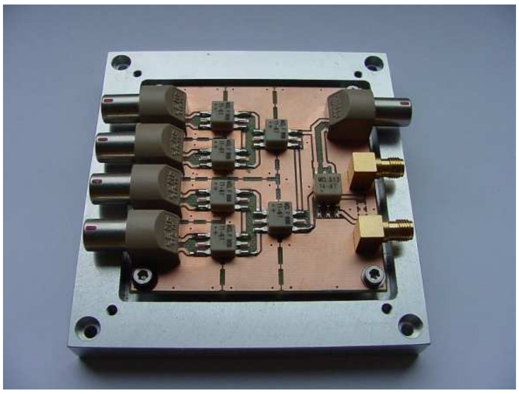


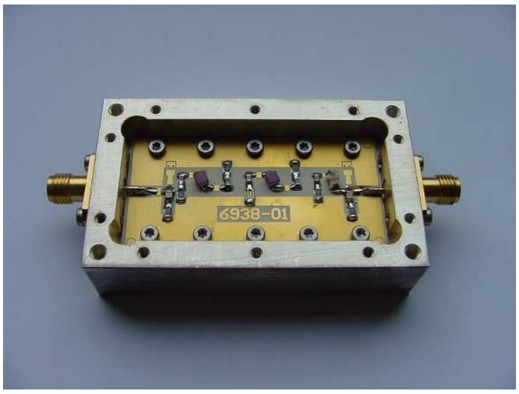
Fig. 11: Picture of the summation circuit prototype

The summation unit (Fig. 11) adds the signals of the 4 transformer coils in the pickup to a single signal. This is done to be independent of the electron beam position. The transmission of the signal from the toroid to the summation circuit is done using a symmetric scheme and twisted pair cables[5]. This scheme provides less noise; especially common mode noise is suppressed. The transmission to the filter and amplifier unit is possible either in an asymmetric or symmetric mode; also the polarity of the signal can be adjusted. The distance to the back-end electronics should be less than 20 m.

[5] The use of high quality network cables (CAT7) is currently evaluated.

3.2.1.3 Filter and Preamplifier

(Author: Neumann, Wentowski, Werner)



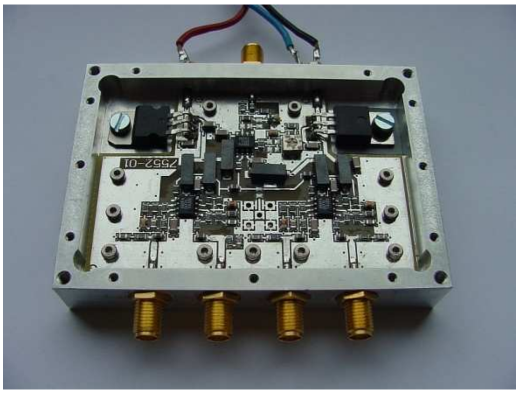


Fig. 12: Pictures of the prototypes of the low pass filter (left) and the preamplifier (right). The preamplifier has several outputs, to allow for using the analogue signal for different purpose. One of the additional channels is always reserved for an oscilloscope for maintenance purpose.

The next unit after the summation consist of a filter and a preamplifier. A Gaussian-low-pass filter is used to shape the analogue signal. The parameters of the filter are chosen such, that there is no leaking of the signal into the signal of the next electron bunch. On the other hand, the shape has to be flat enough to ensure precise sampling of the peak value. But the pulse must not be flattened too much, to keep a good signal to noise ratio.

The preamplifier is an improved version of the amplifier already used at FLASH. The amplifier provides lower noise and is optimised to the XFEL operation concerning bandwidth and amplification. The amplifier will allow for two remote controlled switchable amplification levels, so that the bunch charge can be matched to the ADC range. This will improve the dynamic range, especially useful for low charge operation.

In order to avoid ground loops all active elements of the frontend electronics will be powered by a power line coming from the back end electronics (RTM)

3.2.1.4 Calibration of the Toroids

The calibration of the toroids will be done in several steps.

- Basic Calibration in the lab

  All transformers will be calibrated on a test bench in the lab. Using the same calibration pulser and test setup guaranties comparable calibration results of each two transformers within about 1% RMS. Two steps are applied, one using an antenna in the centre of the transformer to simulate the beam, the other using the built-in test loop of the transformer. The measurements are used to determine the calibration constants of the individual transformer. The measurement using the antenna is the best method, but it cannot be applied in the machine. Therefore also the measurement with the test loop is done, and the systematic shift of its result is documented.

- Beam based calibration tuning

If the lab calibration is not sufficient, the calibration constant can be tuned beam based. With an optimum setting and all beam loss monitors below any threshold, one can make the hypothesis that all charge is transmitted between two toroid locations. In this case the reading of two consecutive toroids must be equal, and thus the calibration constants can be adjusted. This method was used at FLASH for quite some time, to tune the toroid system for sensitive transmission measurements. The use of average modes of the TPS might require such fine tuning. But one has to be aware of the risk that such a method can spoil the initial calibration and might hide some undetected losses. Therefore, the changes of the calibration constants due to this method must be small.

- Optional Recalibration in the machine tunnel

The calibration of a toroid can be checked in situ in the machine tunnel. Using the test loop the signal of the calibration pulser can be feed into the system and the entire signal chain can be checked and calibrated. For this option a special trigger output on the RTM will be foreseen. The existing calibration pulser must be replaced by a device that can be triggered. For these measurements the corrections from the "antenna measurements" have to be applied.[6]

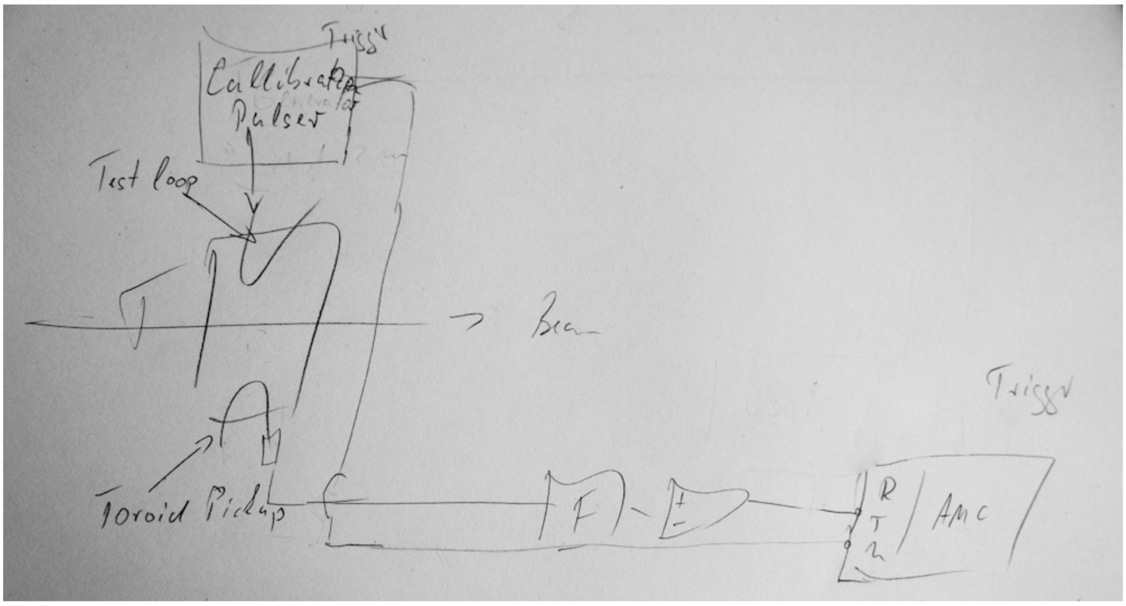


Fig. 13: Schematic of the calibration of the toroids in the tunnel. A calibration pulser is connected to the test loop of a toroid. The pulser will be triggered by the toroid electronics. Then the complete signal path from the pickup to the display in the control system can be calibrated.

There are no permanent calibration signals foreseen for the toroid, since the effort would be rather high. In terms of calibration the precision requirements of such an installation would be very high, and all calibration devices would have to be cross-calibrated to each other. In order to provide a possibility for a remote system check, the front-end electronics will include a simple pulse generator. The signal, which can be triggered from the control system, will be fed into the test loop. This allows checking the overall signal chain and some consistency checks, but no calibration.

The repair of a system failure in any case requires access to the tunnel.

[6] Since the toroid housings are made of two halves, the transformer can also be dismounted without opening the vacuum system and recalibrated in the lab using the antenna method.

3.2.2 Back end Electronics

(Author: Werner/Nölle)

The back end electronics will consist of a double sized AMC module plus rear transition module (RTM). For the AMC module the DESY AMC02 (DAMC02) board is foreseen. This design enables easy integration into the control and timing systems of the XFEL. Therefore no special crates are foreseen for the toroids; they can be integrated in µTCA crates provided by the control system group. This concept will allow using “the next µTCA crate” and thus rather short analogue cables (less than 20 m).

The DAMC02 board will provide all required interfaces to the control system via the µTCA backplane, the processing power of the FPGA for charge, transmission and interlock processing as well as 4 fast communication lines to other toroid electronics boards or the LLRF system (as described in chapter “System Topology”).

The electronics special to the toroid readout and the TPS functionality will be located on the RTM, specially designed for this application.

3.2.2.1 The Rear Transition Module

(Author: Werner)

The electronics of the Rear Transition Module (RTM) consists of a filter, an amplification unit and two ADCs for the signal path. The clock path contains a low bandwidth jitter attenuator and individually variable delays for the ADC clocks. The clock is derived from the TCLKA signal on the backplane (108.333 MHz) to avoid extra cabling between timing system components and the RTM.

A synchronous sampling scheme was chosen, which provides good signal-to-noise ratio (SNR), compatibility to various pulse shapes and low processing latency.

It is foreseen to calculate the timing offset and to use it for a sampling phase feedback loop and for digital amplitude correction.

The two ADCs will provide a reliable timing and pulse shape calibration during commissioning and an improved SNR during standard operation.

The LTC2255 (14 bits, 125 Msps) was selected as ADC because of its low latency and power dissipation while providing the necessary SNR.

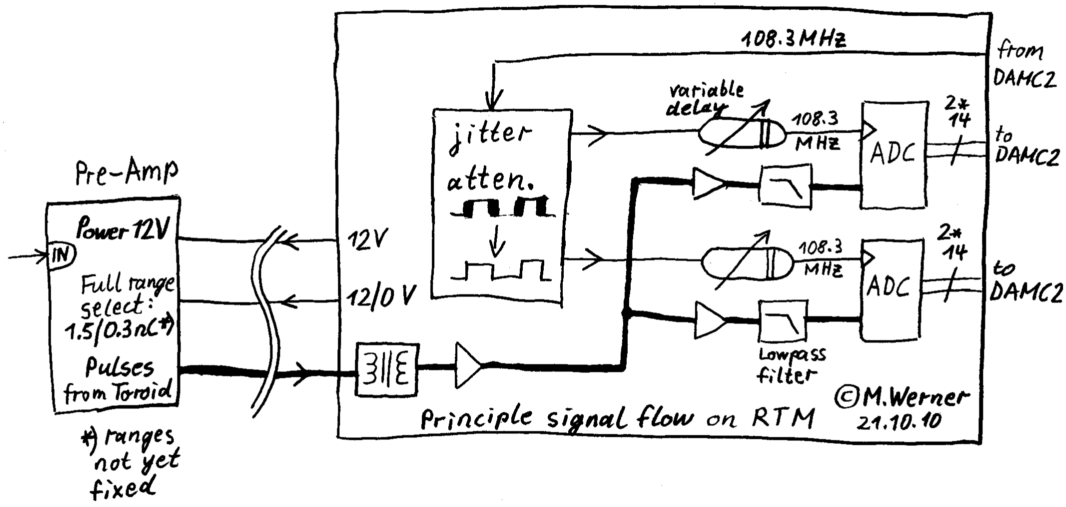


Fig. 14: Principle signal flow in the RTM and connections to the preamplifier and the DAMC2 module

3.2.2.2 Functionality of the Toroid System

(Author: Neumann/Werner/Nölle)

The toroid system shall provide the following functionality

- Measure the charge of each single bunch in the bunch train
- Deliver the charge data to the control system. The data is accessible after the end of the bunch train. Readout for up to 30 bunch trains per second is possible. The interface to the control system is given by the PCI Express interface of the DAMC02 board.
- Deliver charge data on a fast digital link to the LLRF systems. Four toroids close to the LINAC systems will provide fast bunch by bunch data. The distribution of the signals to the LLRF stations is not provided by WP17. These connections have to be implemented by WP02.
- Calculate the transmission and interlock on beam transmission failures. The toroids system includes a transmission interlock feature, named toroid protection system (TPS) for historical reasons. This systems checks the transmission from one location of a toroid in the machine to the next ones (including branches) and makes sure that all charge registered at one location is also seen at the next location(s) within the specified tolerance limits. This system acts on a bunch by bunch basis. If the transmission is worse than required, the system releases an alarm to the machine protection system. The TPS is a second beam based interlock source in addition to the beam loss monitors.

3.2.2.3 Charge Readout to the Control System

(Author: Neumann/Nölle)

The charge data calculated by the toroid electronics will be stored as bunch by bunch data for the entire bunch train on the AMC board (DAMC02). It is made available for read out by the control system server after the RF Pulse. A maximum bunch train repetition rate of 30 Hz for the readout is foreseen.

The server and client software has to be provided by the controls work package (WP-28):

- The server software for the toroids has to allow accessing the charge data, as well as ADC raw data. All registers of the digital hardware must be accessible using this server.
- Readout and display of the charge information of individual toroids in the control room. This has to include the display of the entire charge vector, as well as history data.
- Readout and display of the transmission of charge along the accelerator. The transmission display shall display the charge reading, as well as the percentage of transmission of the charge, started at the gun, and reaching the location of the toroid. This display hast to be customized in a way, that either single bunch data of bunch #n is displayed, or an average over the bunch train.
- Access to the registers of the toroid electronics in the DAMC02 board. This allows full parameterisation of the system. Save/restore tools must allow saving a status after optimisation or recovering a status after problems.
- WP-28 supports WP-17 in creating a GUI for the administration of the toroid server programs.

3.2.2.4 Charge Signal for the LLRF System

(Author: Werner/Nölle)

The toroid system is suited to provide fast access to charge data. This means that the toroid data is processed online, and bunch by bunch data is provided with a latency of about 1 µs over a fast digital link[7]. This link is foreseen mainly for the LLRF systems for compensation of the beam loading and beam based feedbacks.

Data will be transmitted over a fibre optics link (Single Mode Fibre) with a raw data rate of 1.083333 Gb/s (1.3 * 10 / 12 Gb/s) with 8b/10b encoding, corresponding to a payload data rate of 108.333 MByte/s. Charge and status information has to be transmitted, a return channel is not foreseen. It should be investigated if the LLRF system can receive the data optionally with double that speed (2.166666 Gb/s).

WP-17 provides for each LINAC: INJ, L1, L2, L3 either at the position of the toroid electronics or at one location specified by the LLRF. WP-02 is in charge of the distribution of the data along the RF stations.

3.2.2.5 Charge Signal for other Systems e.g. the Photon Systems

The fast digital interface described in the section before is available at all toroids. Therefore, it can be used also be other systems, e.g. the photon systems. WP-17 will provide the signal at the location of the toroid electronics. The signal transfer to other systems has to be provided by the requesting system.

3.2.3 Toroid Protection Functionality

(Author: Werner/Nölle)

[7] The latency estimate does not include the latency due to transmission to the RF systems via long fibres.

As already mentioned before, the system provides the functionality to control and to interlock on the transmission of charge through the accelerator.

3.2.3.1 System Topology

(Author: Werner/Nölle)

The TPS has to cope with the requirement that the bunch train can be distributed into several beamlines. Therefore a different topology is required as in case of FLASH, where the TPS "simply" does a comparison of charge measurements close to the gun and close to the dump.

The idea of the TPS is to make sure that any charge, that has passed toroid T_n is measured again in one of the following toroids $T_{n+1,\,i}$[8]. Therefore the toroids $T_{n+1,\,i}$ next to the toroid T_n transmit their charge measurements to T_n via fast digital fibre links. The electronics of toroid T_n synchronizes the data, so that bunch by bunch comparison is possible. Using the additional bunch pattern information provided by the timing system (see next section "Bunch Pattern Definition"), the TPS knows which bunch has to appear at which of the possible toroid stations. The transmission check is now based on the principle, that the charge at T_n must arrive at the expected following toroid $T_{n+1,\,i}$ within the given loss thresholds. Following the same principle the toroid T_n transmits its data to T_{n-1}, and the T_{n+1} toroids receive data from their further downstream neighbours.

The basic idea of the topology is shown in Fig. 15.

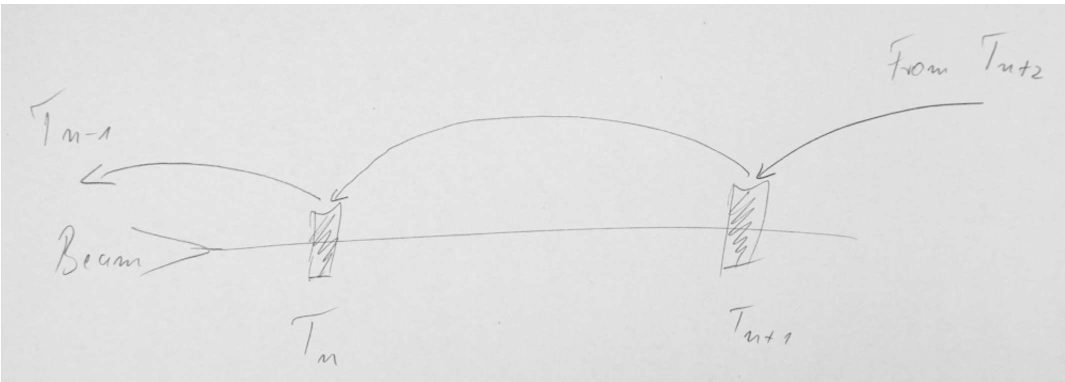


Fig. 15: Basic idea of the topology of the TPS shown in the simple case of a straight beamline. Charge information is transmitted backwards from Toroid T_{n+1} to Toroid T_n. At this location the upstream data is compared with the charge measured at position of T_n.

The maximum number of branches is given for the beam distribution section, where the bunch train can be split up into the two SASE lines and the beamline to the dump. This situation is shown in the figure below.

[8] $T_{n+1,\,i}$. The "n+1" indicates the next toroid downstream and "i" is an indication of the possibility of a branching into two beamlines.

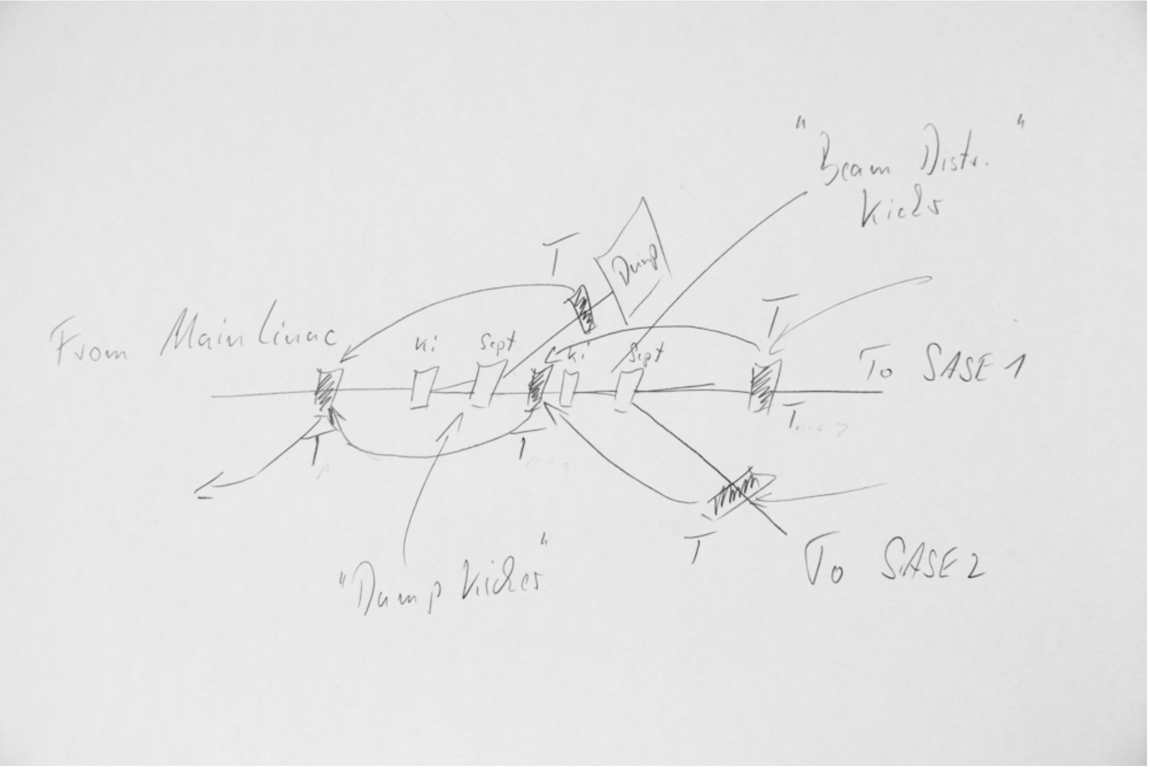


Fig. 16: Sketch of the topology of the toroid protection system.

In addition to branching also intentional loss of a bunch has to be covered by the system. This is possible using the bunch pattern information. This information tells the TPS beforehand, how far a bunch can get in the machine. In this case the TPS will issue a failure, if a bunch, which should be dumped by a kicker magnet or other destructive device, is reaching a toroid, where it should not appear.

An alternative topology to the single chain, shown in Fig. 15, providing higher redundancy is currently also under discussion. It is shown in Fig xx. In the double chain the sections surveyed get longer, but due to the fact that always two toroid pairs cover one section, one system might fail, without causing a break in the full TPS chain.

The installation of the optical fibres for the toroid system should be done such that at least two fibres for the TPS are in one bundle and are installed on a patch panel. This would allow switching topology from the simple chain to a double chain by simple rerouting the fibres by means of bridges.

3.2.3.2 Transmission Detection Schemes

(Author: Werner/Nölle)

The TPS will check the transmission for the following failure conditions:

- Bunch by bunch transmission failure:
  If the charge values of an individual bunch measured at neighbour toroids differ by more than a given threshold, an alarm is sent to the MPS. The threshold can be set individually for each toroid system.
- Total charge loss per bunch train:

If the total charge lost between neighbour toroids exceeds a given threshold within one macropulse, an alarm is sent to the MPS. The threshold can be set individually in each toroid system.

- Moving average transmission failure:
  The charge lost between neighbour toroids is averaged over a given number of consecutive bunches within one macropulse, using a moving average. If this threshold is exceeded, an alarm is sent to the MPS. The threshold and the number of bunches to be averaged can be set individually in each toroid electronics.
- Bunch pattern failure:
  The TPS compares the bunch pattern recognized at its location with the one announced in advance by the timing/control system. If there is a difference, an alarm will be issued.

The thresholds mentioned will be given in terms of charge, thus as absolute values and not as relative values. The reason to use absolute values is, that the damage thresholds and also the systems sensitivity depend on charge and not on relative losses.

The TPS will provide these alarms on the interface to the machine protection system with a latency of about 1 µs[9]. For the TPS the MPS interface will consist of 4 independent RS422 lines. The protocol of this interface (e.g. length of the alarm pulse) has to be specified by the machine protection system. Each of these alarms can be masked individually inside the MPS via a control system interface.

3.2.3.3 Bunch Pattern Definition

Since the TPS will compare the expected bunch pattern with the actual bunch pattern in the machine, the expected bunch pattern for each toroid location has to be known beforehand. This information has to be provided by the control system. This information is not only required by the TPS, but also by other systems like kickers, the MPS or the photon beamlines. The information should also be used to generate the pulse pattern of the injector laser. The pattern should be accessible as readable properties of the timing modules. The actual pattern must be available at each location with high reliability in advance to the next bunch train. Therefore, it is proposed to transmit the data in the data stream of the timing system.

The bunch pattern at a given location depends on the distribution of bunches onto the two main SASE lines and the dump line in XSE. In addition the pattern depends also on the setting of diagnostic systems like the kicker system of the TDS diagnostics in the bunch compressors.

[9] The latency does not include additional delay due to cable length.

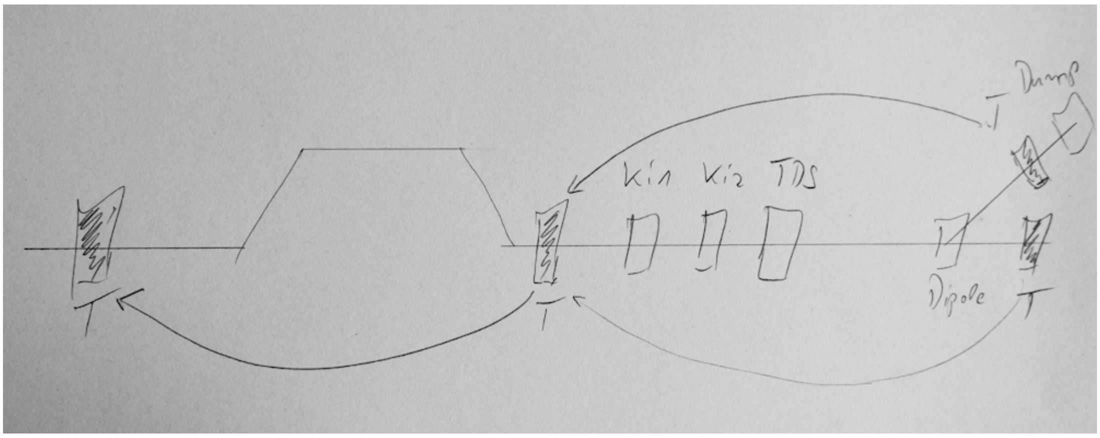


Fig. 17: Typical warm section in the low energy part of the machine. The structure with 2 kicker magnets and a transverse mode structure repeat in the injector and both bunch compressors. Each kicker and the TDS is an "intentional loss point" in this section. In addition these sections have a dump, where the entire beam can be stopped.

To make this information available beforehand it is proposed to distribute a vector consisting of 2700 elements corresponding to the maximum number of bunches, and containing 1 byte per bunch. This byte contains a code of the location and the device where the bunch should be kicked or dumped. This information can be used to trigger devices like abort or distribution kickers, as well as TDS kickers. From this information the toroid electronics can derive the required bunch pattern at its location. Furthermore this information can be used for setting the MPS masks individually for each bunch in the train according to the operation mode. For each possible loss point a code has to be defined. According to Fig. 17, four codes each have to be defined for the injector, bunch compressor 1 and bunch compressor 2, taking care of

- The two kickers of the TDS system
- The TDS system itself, and
- The branching dipole into the commissioning or diagnostics dump.

Two codes are needed for dump and distribution kickers in the XSE. The system should provide some "space" for future codes, like the XFEL extension by further beamlines and a second experimental hall. The second injector foreseen for XFEL would be a "second source of electrons" in the system. A special bit to signal the "active injector" allows integrating of two electron sources into this system. Nevertheless one data byte per bunch (7 bit used for coding for the "loss actuators" and 1 bit to code the electron source) should provide enough possibilities.

If one of the "intentional loss actuators" fails, the dump kicker of the distribution system should send all bunches with an end location other than the dumps T4D and T5D onto the dump in the distribution system.

A more precise definition of the bunch pattern definition should be a part of the detailed technical specification of the timing system.

4 Interfaces

4.1 Vacuum System

(Nölle/Siemens)
(Check: Lilje)

The specification of the vacuum requirements for the entire XFEL is published by the vacuum work packages:

- http://edmsdirect.desy.de/edmsdirect/baseline.jsp?edmsid=*1383041

- Vakuum 005/2008, General DESY UHV Guidelines for Vacuum Components
- N. Mildner et al., Specifications for the Vacuum Sections of the European X FEL, D00000001975641 on EDMS
- MVS und ZM, Qualitätssicherung bei der Entwicklung und Fertigung von Vakuumkammern, 11/2009

The toroid vacuum vessels have to be built compliant to these documents.

All vacuum components need to pass a review by the vacuum group in charge. This review is part of the PPR. Details of cleaning, handling and the hand over procedures for installation will be fixed during the PRR process.

4.1.1 Particle Free Sections

(Nölle/Siemens)
(Check: Lederer)

This chapter applies to the sections from the gun to the main LINAC plus 30 m after the LINAC. For all other parts there are no requirements concerning particle cleanliness.

The toroid chambers in these sections have to be particle clean according to ISO 5 (clean room class 100).

WP-17 will provide the ceramic chambers to WP-19 for cleaning in the DESY clean room facilities (MVS). Cleaning will be done by WP-19.

Details of cleaning, handling and the hand over procedures for installation will be fixed during the PRR process.

4.1.2 Supports

(Author: Nölle/Siemens)
(Check: Prenting/Meyners/Lilje)

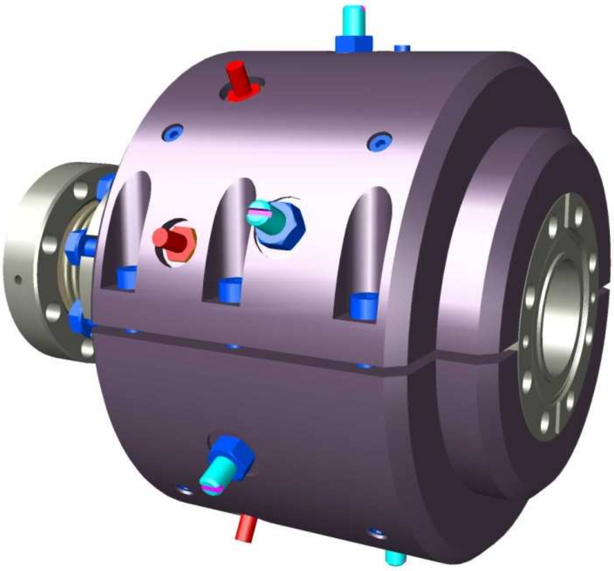


Fig. 18: Toroid transformer completely with housing. One can see that the housing is supported by the flanges of the vacuum chamber.

For the XFEL the alignment tolerances of the vacuum system are determined by the impedance budget, putting requirements on the gap and displacement of the flanges. There are no further alignment requirements from the toroids. Therefore, there will be no alignment marks on the toroids.

The toroids require a stable support of the neighbour components that prevents forces to act on the ceramic gap. In case the support is not stable enough, or provides individual degrees of freedom for later adjustment, the additional bellow unit has to be used.

The optimum design would be to fix the flanges of the neighbour components rigidly. Supporting the flanges of the toroid ceramic chamber is not possible, because they serve as the interface for the transformer housing. Therefore, the neighbour components or flanges have to be used for the supporting of the toroids.

4.2 Control System

4.2.1 Control System Hardware

(Author: Nölle)

The toroid and TPS electronics is based on the DAMC02 board. This AMC board is planned to be hosted by the µTCA system next to the location of the toroid. The distance should be less than 20 m. These µTCA systems are supplied by the controls group within the framework of WP-28.

The timing signals have to be supplied by WP-28, details on the required signals are given in the timing subsection.

WP17 will provide the necessary funding for a slot within such a crate. There is currently no restriction known for the use of the other slots in the µTCA crate by other applications.[10]

4.2.2 Control System Software

(Author: Nölle)

WP-28 provides the required software to access the toroid data. This includes the toroid server with the interface to the AMC board and some basic software to read the charge data from this board. Furthermore basic client software is needed to display the data of a single charge monitor. A middle layer server is requested for collecting the transmission data along the machine. Date from this server shall be used to display the transmission along the machine. For the technical and beam commissioning, the XFEL control system has to provide all functionality and infrastructure required to perform the relevant commissioning and basic operational tasks, including:

- Synchronized readout, and archiving of all relevant charge, ADC and relevant diagnostics data for each bunch train
- Visualisation of the charge information, either as
  - Charge of the bunches along the bunch train
  - Charge of bunch n along the machine (n to be chosen by the operator)
  - Transmission display of the “averaged charge” of one bunch train
- Read/write access to all relevant toroid system parameters and settings
- DOOCS also provides an API to access toroid data and system parameters by MATLAB or C code.

4.2.2.1.1

4.2.3 Timing System[11]

(Author: Werner/Nölle)

The design of the toroid and especially the toroid protection system requires detailed knowledge of the XFEL timing system.

The following features have to be available and precisely defined:

All µTCA crates, at least the ones containing modules for toroids or wire-scanners, shall provide the following signals on the backplane:

- Clock of 108.3333333 MHz on the dedicated “TCKLA” clock line,
- Accelerator data on one of the differential bus lines,
- A pre-trigger on one of the differential bus lines.

The desired properties of these signals are explained in the following:

Clock of 108.3333333 MHz (TCLKA):
This shall be an **un-modulated clock without phase jumps**. The phase relation between the positive edges of TCLKA and bunch 1 between the gun and the first bunch compressor shall

[10] But there are no placement restrictions for EMI-sensitive and EMI-disturbers. Especially magnetic emitters (DC/DC, relays, and bad layouts) will be hard to shield. That is a point to be watched, be aware off, when assembling into a crate with random neighbors.
[11] The details on the concept of timing system still need to be fixed with WP28. Therefore, some changes on the concept cannot be excluded.

be a fixed value. This phase relation shall be re-established even after power down in the timing system, the master oscillator or the injection laser. If the timing of the injection laser changes due to modifications in the electrical or optical path, this shall be compensated by electrical phase shifters. A beam arrival monitor (BAM) should be used to check the phase relation between the master oscillator (MO) and bunch 1 continuously.
The jitter of the TCLKA signal should be below 50ps RMS. As agreed with the control group, this value will be achieved by routing the low jitter signal from the timing slave (approx. 10ps RMS) through a dedicated low jitter clock distribution chip or clock multiplexer in the MCH to the µTCA slots.

Accelerator data:
Data on bunch patterns (see chapter on this topic in this document), a timestamp, an ID of the actual macro pulse and other data (still to be defined) shall be available on the backplane before arrival of the macro pulse. The format will be fixed by the control group in agreement with the users, and the control group will provide an “IP core” (a piece of FPGA code) which allows decoding of the information inside the FPGA. It is recommended to send this information as early as possible before the following macro pulse to avoid corruption of the timing precision during the macro pulse due to modulating of the optical fibre signals within the timing system.

Pre-trigger (Mainly required for the wire-scanner partly using the same hardware):
The pre-trigger shall take place 30ms before bunch 1 of every macro pulse, this large time is necessary for the wire-scanner. A time of 30ms corresponds to 3 250 000 cycles of TCLKA (108.3333333 MHz). It is recommended to fix this value, so that always 3 250 000 TCLKA cycles are between the pre-trigger and the bunch 1 trigger for all crates containing toroids or wire-scanners. The individual pre-triggers for each application can then be derived from this pre-trigger by counting the TCLKA clocks inside the FPGA.
The pre-trigger will be used to select a certain positive edge of the TCLKA clock; therefore it has to meet the setup- and hold-times required by the FPGA. A pulse width of approx. one TCLKA period (9.2 ns) is recommended; the timing uncertainty is not critical and can be 2 ns for example, as long as the setup- and hold-times with respect to TCLKA are met.

4.2.4 Machine Protection System

The toroid electronics provides an interface to the machine protection system MPS. On the RTM 4 RS422 lines will be provided to signal different alarms to the MPS. The use of more than one interlock line enables the MPS to react differently on the four interlock conditions of the TPS.

The MPS will take care of masking the interface lines, in case of customizing the alarms to a dedicated machine operation.

Technical details on the interface will be agreed by WP17 and the MPS team.

4.2.5 Fast interface to Bunch by Bunch Charge Data

The toroid electronics provides a fast digital interface providing bunch by bunch charge data. Data will be transmitted over a fibre optics link (Single Mode Fibre) with a raw data rate of 1.083333 Gb/s (1.3 * 10 / 12 Gb/s) with 8b/10b encoding, corresponding to a payload data rate of 108.333 MByte/s. Charge and status information has to be transmitted, a return channel is not foreseen. Users of this connection have to provide the connectivity to their systems.

5 Failure of the Toroid Systems

(Author Nölle)

Since the toroid system belongs to the basic diagnostic systems and the TPS is an essential sensor of the machine protection system, the aspect of system failures will be described shortly. A failure of a toroid system means, that a system delivers no or wrong charge data. This includes failures of the measurement itself as well as communication failures to the control system and neighbour toroid systems.

- Single, Short Bunch Mode; the machine is operated with bunch train durations shorter than the overall reaction time of the machine protections system[12].
  If a toroid system fails, there will be no charge signal from this system. Since also the BPMs will provide charge information, the situation for this operation mode is uncritical. Operation can be continued, without major restrictions.
- Operation with long bunch trains
  If a toroid system fails in case of long bunch operation, the charge display can also be taken over by neighbour BPMs. But the chain of the TPS system gets broken. This will affect the TPS functionality from the broken toroid system to the next one downstream, and to the previous one upstream. The preferable action in such a case is instantaneous repair, meaning tunnel access. Operation might be continued by masking the corresponding alarms in the MPS, but this will result in a lower security level of the MPS system. A more complicated and more expensive network topology of the optical fibre connections of the toroids would give more redundancy. But the topology described here is communicated and agreed by the PM (MLC).

[12] This time is defined by the reaction time of the MPS sensors, the MPS electronics and the involved cable lengths. An estimate of this time is between 10 and 20 µs. This time also defines the number of bunches that might hit machine components in case of failure, and thus defines a requirement on robustness for components, that can be hit in case of failure.