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TECHNICAL NOTE

Coordinate Systems for the Beam Distribution Systems

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Contents

1 General definitions

The general orientation of coordinate systems at the European XFEL is shown in Figure 1. The +x direction is southbound, +y is up, and the propagation direction of the electron or photon beam is +z (westbound).

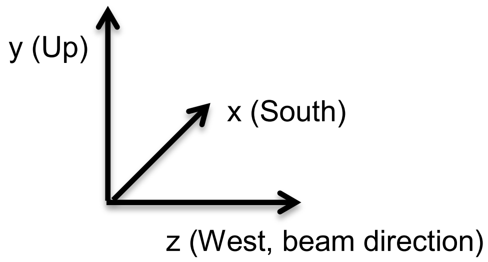

Figure 1: *General orientation of European XFEL coordinate systems*

Since the European XFEL facility is overall more than 3 km long, two coordinate systems have been defined to follow the curvature of the earth: The linear accelerator (LA) system is designed for the XTL tunnel, while the photon distribution (PD) system describes a line in the plane of the undulator and photon system along the SASE1 beam (Figure 2). The LA z-axis is horizontal in the middle of the XTL, and the PD z-axis is horizontal in the experiment hall.

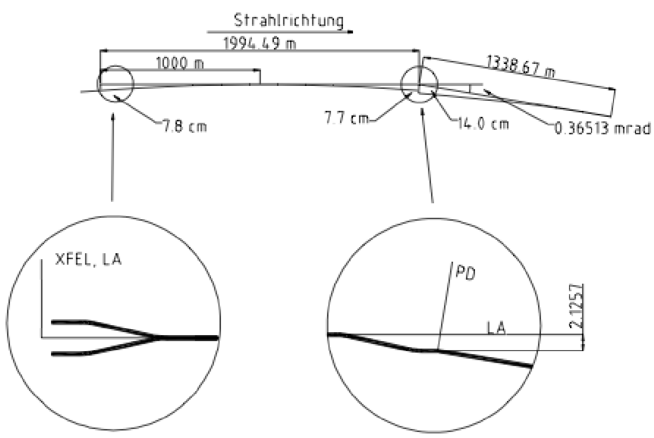

Figure 2: *Definition of LA and PD coordinate systems [1]*

2 Beam distribution system

After the linac, the electron beam is divided into two branches and guided through up to five undulators (Figure 3). The photon beam distribution system can direct the free-electron laser (FEL) radiation to one out of three experiments for each undulator.

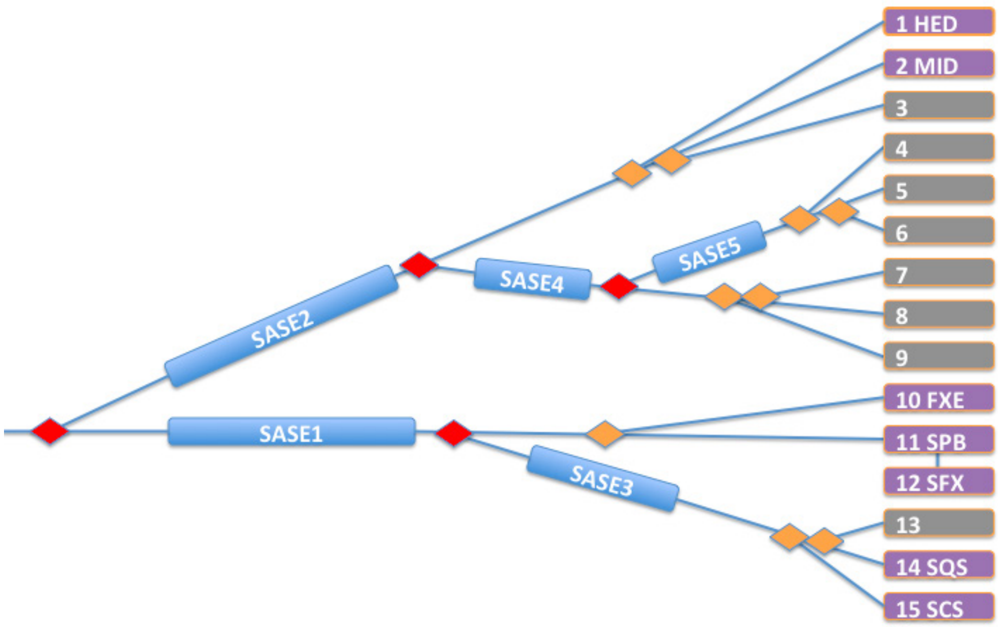

Figure 3: *Beam distribution system at the European XFEL. Deflection elements for electron beams are shown in red, for photon beams in orange.*

In the following chapters, coordinates systems are defined for each undulator beam and each beam reaching the currently planned experiments. The names of the coordinate systems are identical to the undulator names or experiment acronyms.

SASE1 is identical to the PD system, except that SASE1 z=0 starts in the middle of the first undulator module. SASE2 and SASE3 are the corresponding coordinate systems for the other two undulators rotated according to the electron beam deflections and with z=0 in the *middle of the* *first undulator segment*. These coordinate systems can be used for installation of the undulators.

For the photon beam coordinate systems—Single Particles, Clusters, and Biomolecules (SPB), Femtosecond X-Ray Experiments (FXE), etc.—z=0 is selected in *the middle of the third last undulator segment for SASE1 and SASE2, and the second last undulator element for SASE3*, which is a rough approximation of the expected source point location. Also, the minimum offset at the distribution mirrors (25 mm for SASE1 and SASE2, and 35 mm for SASE3) is taken into account. The offset is chosen such that the first mirror deflects to the closer tunnel wall. In this way, the mechanics driving the mirror and, to some extent, also the downstream electronics, is protected better against Compton scattering arising in the first offset mirror. The variable offset [2] is not considered here. Therefore, the instrument coordinate systems represents the X-ray beam corresponding to the highest photon energy setting (minimal offset). The coordinate systems for the branch beamlines—FXE, Small Quantum Systems (SQS), etc.—are rotated at the corresponding distribution mirrors, but keep the z-coordinate as the source distance.

For the experiment hall, the coordinate system XHEXP1 from the XFEL CAD integration model is used [3, 4]. This coordinate system is initially not defined by any beam but by the building of the experiment hall. In particular, the zero point of XHEXP1 is the center of the SASE3 tunnel entrance to the experiment hall. However, by defining a fixed relation to the PD system, XHEXP1 becomes also a beam-based system and—due to building tolerances—its origin will deviate a few centimeters from the SASE3 tunnel center in the real building [5].

Note that the experiment hall is not aligned perpendicular to the SASE1 beam but to the middle of the SASE3 and SASE2 beams. A detailed explanation of geometries of electron beam distribution and buildings is given in [6].

3 Undulator coordinate systems

A rotation around the x-axis (in vertical plane) for a right-handed coordinate system can be expressed by

$$A(\propto) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\propto & -\sin a \\ 0 & \sin\propto & \cos\propto \end{bmatrix}$$

Correspondingly, a rotation around the y-axis (in horizontal plane) is

$$B(\beta) = \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix}$$

The transformation of a point in the LA system to the PD system is [1]

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{PD} = A(-0.02092\ deg)\left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{LA} - \begin{bmatrix} 0 \\ -2.4386 \\ 1994.492 \end{bmatrix}\right)$$

From the PD to the LA system:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{LA} = A(0.02092\ deg)\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{PD} + \begin{bmatrix} 0 \\ -2.4386 \\ 1994.492 \end{bmatrix}$$

From the PD to the SASE1 system:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{SASE1} = \left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{PD} - \begin{bmatrix} 0 \\ 0 \\ 244.0851 \end{bmatrix}\right)$$

From the PD to the SASE2 system:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{SASE2} = B(-2.28586\ deg)\left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{PD} - \begin{bmatrix} 5.8015 \\ 0 \\ 205.9712 \end{bmatrix}\right)$$

From the PD to the SASE3 system:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{SASE3} = B(1.318245\ deg)\left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{PD} - \begin{bmatrix} -4.8082 \\ 0 \\ 809.0289 \end{bmatrix}\right)$$

From the PD to the XHEXP1 system (x, y = 0 at the center of the SASE3 tunnel):

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{XHEXP1} = B(-0.483808\ deg)\left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{PD} - \begin{bmatrix} -17.5 \\ -0.11 \\ 1338.8180 \end{bmatrix}\right)$$

In addition to the three coordinate systems SASE1, SASE2, and SASE3 dedicated for undulator installation, we define three further coordinate systems for the installation of X-ray optical components of the beam transport (subscript "BT") in the tunnels. The origin is shifted with respect to the undulator systems from the middle of the first undulator to the middle of the third or second last undulator, which is the expected source location of the SASE process. It is

SASE1 to SASE1_BT system:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{SASE1\_BT} = \left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{SASE1} - \begin{bmatrix} 0 \\ 0 \\ 195.2 \end{bmatrix}\right)$$

SASE2 to SASE2_BT system:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{SASE2\_BT} = \left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{SASE2} - \begin{bmatrix} 0 \\ 0 \\ 195.2 \end{bmatrix}\right)$$

SASE3 to SASE3_BT system:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{SASE3\_BT} = \left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{SASE3} - \begin{bmatrix} 0 \\ 0 \\ 115.9 \end{bmatrix}\right)$$

4 Photon beam system

The parameters for the photon beam coordinate systems are defined in the technical design report of the X-Ray Optics and Beam Transport group [7] and are shown below as well as in the mathematical transformations.

SPB: With respect to SASE1, offset in x + 25 mm (south), source point at U33 (total 35 undulators): z = z + 32*6.1.

MID: SASE2 -25 mm (north) and source U33 + 32*6.1 in z.

SQS: SASE3 +35 mm (south), source U20 (21 total) + 19*6.1 in z.

FXE: Based on SPB. Distribution mirror at 370 m from source, deflection angle 2*1.35 mrad = 2.7 *0.180/pi = 0.15469860°.

HED: Based on Materials Imaging and Dynamics (MID). Distribution mirror at 390 m from source, deflection angle 2*1.3 mrad = 2.6*0.180/pi = 0.14896902°.

NNN: Based on MID. Distribution mirror at 395 m from source, deflection angle 2*-1.3 mrad = 2.6*0.180/pi = -0.14896902°.

SCS: Based on SQS. Distribution mirror at 339 m from source, deflection angle 2*-9 mrad = 18*0.180/pi = -0.10313240°.

SQS2: Based on SQS. Distribution mirror at 344.5 m from source, deflection angle 2*9 mrad = 18*0.180/pi = 0.10313240°.

SASE1 to SPB system:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{SPB} = \left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{SASE1} - \begin{bmatrix} 0.025 \\ 0 \\ 195.2 \end{bmatrix} \right)$$

SPB to FXE system:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{FXE} = B(-2.7\,mrad)\left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{SPB} - \begin{bmatrix} 0 \\ 0 \\ 370 \end{bmatrix}\right) + \begin{bmatrix} 0 \\ 0 \\ 370 \end{bmatrix}$$

Zero point of FXE coordinate system with respect to SPB:

$$\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}_{FXE} = \begin{bmatrix} -0.9990 \\ 0 \\ 0.0013 \end{bmatrix}_{SPB}$$, angle to SPB system: +2.7 mrad

SASE2 to MID system:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{MID} = \left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{SASE2} - \begin{bmatrix} -0.025 \\ 0 \\ 195.2 \end{bmatrix}\right)$$

MID to High Energy Density Physics (HED) matter experiments system:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{HED} = B(-2.6\,mrad)\left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{MID} - \begin{bmatrix} 0 \\ 0 \\ 390 \end{bmatrix}\right) + \begin{bmatrix} 0 \\ 0 \\ 390 \end{bmatrix}$$

Zero point of HED coordinate system with respect to MID:

$$\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}_{HED} = \begin{bmatrix} -1.0140 \\ 0 \\ 0.0013 \end{bmatrix}_{MID}$$, angle to SPB system: +2.6 mrad

MID to NNN system:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{NNN} = B(2.6\,mrad)\left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{MID} - \begin{bmatrix} 0 \\ 0 \\ 395 \end{bmatrix}\right) + \begin{bmatrix} 0 \\ 0 \\ 395 \end{bmatrix}$$

Zero point of NNN coordinate system with respect to MID:

$$\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}_{NNN} = \begin{bmatrix} 1.0270 \\ 0 \\ 0.0013 \end{bmatrix}_{MID}$$, angle to SPB system: -2.6 mrad

SASE3 to SQS system:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{SQS} = \left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{SASE3} - \begin{bmatrix} 0.035 \\ 0 \\ 115.9 \end{bmatrix} \right)$$

SQS to SCS system:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{SCS} = B(18\,mrad) \left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{SQS} - \begin{bmatrix} 0 \\ 0 \\ 339 \end{bmatrix} \right) + \begin{bmatrix} 0 \\ 0 \\ 339 \end{bmatrix}$$

Zero point of SCS coordinate system with respect to SQS:

$\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}_{SCS} = \begin{bmatrix} 6.1017 \\ 0 \\ 0.0549 \end{bmatrix}_{SQS}$, angle to SPB system: -18 mrad

SQS to SQS2 system:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{SQS2} = B(-18\,mrad) \left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{SQS} - \begin{bmatrix} 0 \\ 0 \\ 344.5 \end{bmatrix} \right) + \begin{bmatrix} 0 \\ 0 \\ 344.5 \end{bmatrix}$$

Zero point of SQS2 coordinate system with respect to SQS:

$\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}_{SQS2} = \begin{bmatrix} -6.2007 \\ 0 \\ 0.0558 \end{bmatrix}_{SQS}$, angle to SPB system: 18 mrad

5 Reference tables

The tables in this chapter are meant as references that could be used to debug software tools for calculating coordinate transformations and to help the design of shielding hutches in the experiment hall. Table 1 shows in each line the same point in different coordinate systems. The points were chosen such that they can be easily identified (for example, the middle of the first and the last undulator segment) in the component list of the electron beam dynamics group (WP16) [8].

Table 2 shows the x-coordinates of each of the photon beams in the coordinate system XHEXP1 of the experiment hall. These points were obtained by setting the x-coordinate to zero in each individual coordinate system and choosing the z-coordinate such that it agrees with the displayed coordinates in the XHEXP1 system.

Table 3 shows the z-coordinates (approximate distances to the source) for each beam location in Table 2. Combining the information from Tables 2 and 3, one can obtain the full set of coordinates for a photon beam coordinate and the corresponding XHEXP1 coordinates. For example:

(0, -0.11, 414.0787)_SCS = (-0.8165, 0, 0)_XHEXP1

Figure 4 shows a top view of the beams in the experiment hall with reference to the z=0 line of the XHEXP1 coordinate system.

Excel tables for calculations of transformations between coordinate systems in this technical note can be found in [9].

Table 1: *Reference points for the undulator systems in PD and LA coordinates*

Comment	PD_x	PD_y	PD_z	LA_x	LA_y	LA_z	SASE1_x	SASE1_z	SASE2_x	SASA2_z	SASE3_x	SASE3_z
S1 first	0.000	0.000	244.085	0.000	-2.528	2238.577	0.000	0.000	-7.317	37.852	-8.190	-564.905
S1 last	0.000	0.000	451.485	0.000	-2.603	2445.977	0.000	207.400	-15.589	245.087	-3.419	-357.560
S2 first	5.802	0.000	205.971	5.802	-2.514	2200.463	5.802	-38.114	0.000	0.000	-3.267	-603.142
S2 last	14.073	0.000	413.206	14.073	-2.589	2407.698	14.073	169.121	0.000	207.400	9.770	-396.152
S3 first	-4.808	0.000	809.029	-4.808	-2.734	2803.521	-4.808	564.944	-34.654	602.155	0.000	0.000
S3 last	-7.615	0.000	930.997	-7.615	-2.779	2925.489	-7.615	686.912	-42.324	723.914	0.000	122.000
Hall start	0.000	0.000	1338.660	0.000	-2.927	3333.152	0.000	1094.575	-50.974	1131.556	16.991	529.380
Hall end	0.422	0.000	1388.658	0.422	-2.946	3383.150	0.422	1144.573	-52.547	1181.531	18.564	579.355

Table 2: *X-coordinates of photon beams in XHEXP1 system*

XHEXP1_z	SCS	SQS	SQS2	SPB	FXE	NNN	MID	HED
0.00	-0.8165	0.5355	1.7870	17.5256	18.9550	67.0633	68.4757	69.9012
10.00	-1.3114	0.2209	1.6525	17.4412	18.8975	67.3519	68.7903	70.2418
20.00	-1.8063	-0.0937	1.5180	17.3567	18.8401	67.6405	69.1049	70.5825
30.00	-2.3012	-0.4083	1.3834	17.2723	18.7827	67.9291	69.4195	70.9231
40.00	-2.7961	-0.7229	1.2489	17.1879	18.7252	68.2177	69.7341	71.2638
50.00	-3.2911	-1.0376	1.1144	17.1034	18.6678	68.5063	70.0488	71.6044

Table 3: *Z-coordinates of instrument coordinate systems corresponding to Table 2. The y-coordinates are +0.11 (y-offsets and beam angles for monochromatic beams are not taken into account).*

XHEXP1_z	SCS_z	SQS_z	SQS2_z	SPB_z	FXE_z	NNN_z	MID_z	HED_z
0.00	414.0787	414.0240	413.9959	899.3849	899.3748	937.9267	937.9693	938.0160
10.00	424.0909	424.0290	423.9968	909.3853	909.3749	947.9309	947.9742	948.0218
20.00	434.1031	434.0339	433.9977	919.3856	919.3751	957.9350	957.9792	958.0275
30.00	444.1154	444.0388	443.9986	929.3860	929.3752	967.9392	967.9841	968.0334
40.00	454.1276	454.0438	453.9995	939.3863	939.3754	977.9433	977.9891	978.0392
50.00	464.1399	464.0488	464.0005	949.3867	949.3756	987.9475	987.9940	988.0450

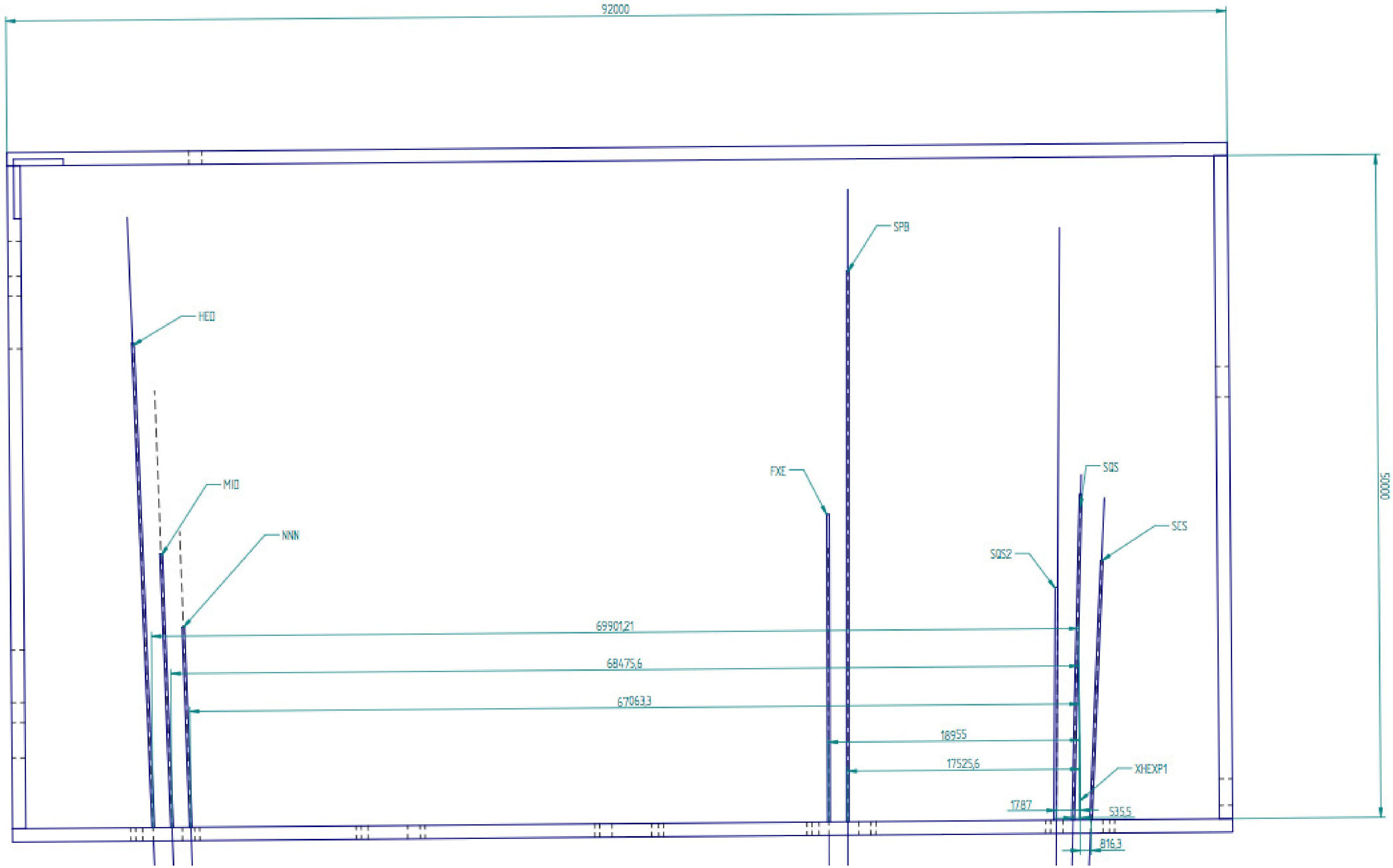

Figure 4: *Beams in the experiment hall implemented in Solid Edge (from Nadja Reimers)*

A References

[1] W. Graeff: "LA and PD coordinate systems for XFEL" (EDMS D*497635)

[2] H. Sinn et al.: "Conceptual Design Report: X-Ray Optics and Beam Transport", XFEL.EU TR-2011-002 (2011) (doi:10.3204/XFEL.EU/TR-2011-002)

[3] "BO-Liste" with coordinate systems for CAD rooms (EDMS D*496900)

[4] Extendet "BO-Liste", including coordinates for civil construction (EDMS D*1322191)

[5] According to recent (November 2013) measurements from the DESY survey and alignment group, XTD tunnels and the experiment hall seem to be shifted about 4 cm to the south, compared to the XTL and the LA/PD systems, which is, however, within the building tolerances of 10 cm. No change of beam geometries and coordinate systems was therefore considered to be necessary. Measurements can be found at geo.desy.de.

[6] W. Graeff: "XFEL-3D-Coordinates, first phase design", XFEL.EU TN-2007-001 (2007)

[7] H. Sinn et al.: "Technical Design Report: X-Ray Optics and Beam Transport", XFEL.EU TR-2012-006 (2012)

[8] Component list of FEL beam dynamics group (www.desy.de/xfel-beam)

[9] Excel tables for transformations between coordinate systems: Coordinates.xlsx (general table) and Coordinates_ref.xlsx (tables with values from this note)

Acknowledgements

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