XFEL.EU TR-2012-004

CONCEPTUAL DESIGN REPORT

Imaging Stations for Invasive Photon Diagnostics

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at the European XFEL

Stakeholders

Table 1: List of external stakeholders

Stakeholder (WP or Coordination)	**Fields of concern**
TC-PBS: Technical Coordination, Photon Beam Systems Tobias Haas	Technical infrastructure, radiation shielding Coordination between WPs (e.g. tunnel integration and installation sequencing, MPS)
MLC: Machine Layout Coordination Winfried Decking and Torsten Limberg in cooperation with: ■ WP15: Bunch Compression ■ WP17/WP18: e-Beam Diagnostics ■ WP28: Accelerator Control Systems	Location of instrument Bunch compressor parameters e-beam diagnostics: e-BPMs for (bunch resolved) energy measurements, electron energy scan Timing system
WP19: Warm Vacuum S. Lederer	Interface to vacuum system for devices close downstream of the e-beam separation point
WP32: Survey and Alignment Johannes Prenting	Mechanical survey and alignment during installation and commissioning of devices
WP71: Undulator Systems Joachim Pflüger	Requirements for undulator commissioning
WP72: Simulation of Photon Fields Gianluca Geloni	Calculation of spontaneous radiation and anticipated intensities on detector Programming of for online comparison of theoretical and experimental data
WP73: X-Ray Optics and Transport Harald Sinn	Interface to vacuum system, Position of the instruments, attenuators, collimator, requirements for optics alignment procedure
WP76: DAQ and Control Systems Chris Youngman	Control program and special software issues Readout and control of the cameras, screen movers, and timing module Low-level stepper motors motion control
WP36: General Safety Andreas Hoppe	Safety aspects Technical risk analysis
External reviewers (DESY) Rolf Treusch, Markus Degenhardt, and Micheal Sprung	N/A
Martin Staark	Technical Interface to Machine Protection System

Contents

Introduction

This conceptual design report describes the concepts and proposed main components of the European X-Ray Free-Electron Laser (European XFEL) imaging stations for invasive photon diagnostics and their connections to the other beamline components.

Due to interfacing with other work packages (presented in the list of stakeholders), some basic design decisions on the imaging stations have to be taken and the devices have to be prepared based on the technical design report of European XFEL [1], the photon beam properties [2], and the X-ray beam transport layout [3].

The scope of this conceptual design report includes the imaging stations for photon beam diagnostics located between the electron beam separation and the experiment hall for the three undulator beamlines: SASE1, SASE2, and SASE3.

1 Types of imaging stations

Imaging of spontaneous radiation (SR) and free-electron laser (FEL) radiation has proven to be extremely valuable in helping to establish, diagnose, and optimize the lasing process as well as in aligning various optical elements at FEL sources, such as the original Linac Coherent Light Source (LCLS-I) at the SLAC National Accelerator Laboratory in the USA, the SPring-8 Angstrom Compact Free-Electron Laser (SACLA) in Japan, and the Free-Electron Laser in Hamburg (FLASH) in Germany. These imagers are based on optical imaging of an X-ray scintillation material impinged on by the photon beam. For the European XFEL, the same design principle will be used with the aim of high spatial resolution and simultaneous operation of multiple devices at hard X-ray energies (3–25keV).

The imaging stations are intended to reliably measure the beam profiles for both the spontaneous radiation and the FEL beam. The images should allow measuring the beam profile while extracting some basic statistics, such as beam spot size and centre, total pulse energy, and beam pointing with sufficient accuracy for undulator commissioning, optical alignment, and performance optimization.

To measure and optimize the beam conditions, the European XFEL photon diagnostic system supplies five to seven imaging stations at different locations for SASE1 and SASE2, and five for SASE3. Although screens are widely regarded as standard diagnostics equipment, the number of the imaging stations is subject to change, depending on changes in the beam transportation system requirements, user requirements, or both for the European XFEL.

There will be three types of screen stations at each undulator beamline at the European XFEL. These devices, their purpose, and the minimum requirements are listed below, according to relevance.

1.1 2D-imager

The 2D-imager will be located downstream from the *K*-monochromator. It has a twofold function: 1) aid in commissioning of the undulators and 2) visualization of the initial lasing after first time of establishing self-amplified spontaneous emission (SASE). The design is composed of two imaging cameras, one for each type of radiation: SR and FEL. The beam profile on the fluorescent screen is imaged with a commercially available camera—a charge coupled device (CCD) or a complementary metal oxide semiconductor (CMOS) sensor—located outside the vacuum chamber. The targeted position accuracy is 5% of the expected beam size sigma or better; to observe beam jitter from shot-to-shot and the expected daily drift of the beam. Different types of screens may be switched with a translation stage in order to cover a wide range of intensities. For details, see Chapter 5, "Scintillation screens", on page 24.

For the 2D-imager at SASE3, the field-of-view (FOV) and resolution aimed for are different since, at that undulator, the energies are very low and the beam size large compared to the hard X-ray beamlines.

Requirements from this device are as follows:

- Must be able to function at the bunch repetition rate of 10Hz (limitation of current technology), with high sensitivity, large dynamic range, low noise, and sufficient pixel count. The choice of pixel size is a compromise between resolution and full well capacity. At low intensities, a large dynamic range is required, but large pixels are acceptable. Resolution and FOV determine the required pixel format.
- Possibility of image and data storage
- Statistics about the photon beam required from the acquired images: center-of-mass, intensity, and width for a region-of-interest
- Two types of scintillators: one for SR and one for the FEL case.
- Two types of imagers: low-light-level capability for SR versus high dynamic range for FEL detection. For visualization of the FEL beam, the imager has a rather straightforward mission. As for the commissioning of

the undulators, a rather more complex methodology is involved. This is explained in Section 2.1, “Commissioning of the undulators”, on page 12.

1.2 Pop-in monitors

Pop-in monitors are considered only for the initial alignment and some re-adjustments (e.g. during maintenance periods) of optical elements (due to drifts), in single bunch mode (10 Hz), in accordance with the requirements of X-Ray Optics and Beam Transport (WP73). The last of the pop-in monitor devices in SASE3, will be used in combination with the VLS monochromator grating as a shot-to-shot spectrometer, able to separate spectral modes.

Device requirements are:

- Must be able to function at the bunch repetition rate of 10 Hz
- Possibility of image and data storage
- Statistics required from the images acquired: centre of mass, intensity, width for a region of interest
- Flexibility in horizontal motion since, for the offset, mirrors cause beam displacements and should be able to cover any beam offsetting due to the monochromators

The minimum diameter of the scintillator screens should be larger than the alignment tolerance. The design of these monitors is not a single design replicated throughout the undulator beamlines. The intended scintillator, mirror, optics, and camera layout remains unchanged.

However, these monitors must accommodate different scenarios, given below:

1. **Offset mirrors for all beamlines**

   Those monitors located after the offset mirrors have to account for the beam displacement as the beam is at different horizontal locations due to the beam energy and the alignment of the offset mirrors, as shown in Figure 1. Since this displacement also has an energy dependent behavior (due to grazing incidence of the mirrors), the monitor has to accommodate for this shift in the beam that is expected to be 25–59 mm for SASE1 and SASE2, and 35–125 mm for SASE3 [3-5]. The imagers are not attached to the mirror chambers as these chambers do not move hence; it will not be possible to tracke the motion of the beam.

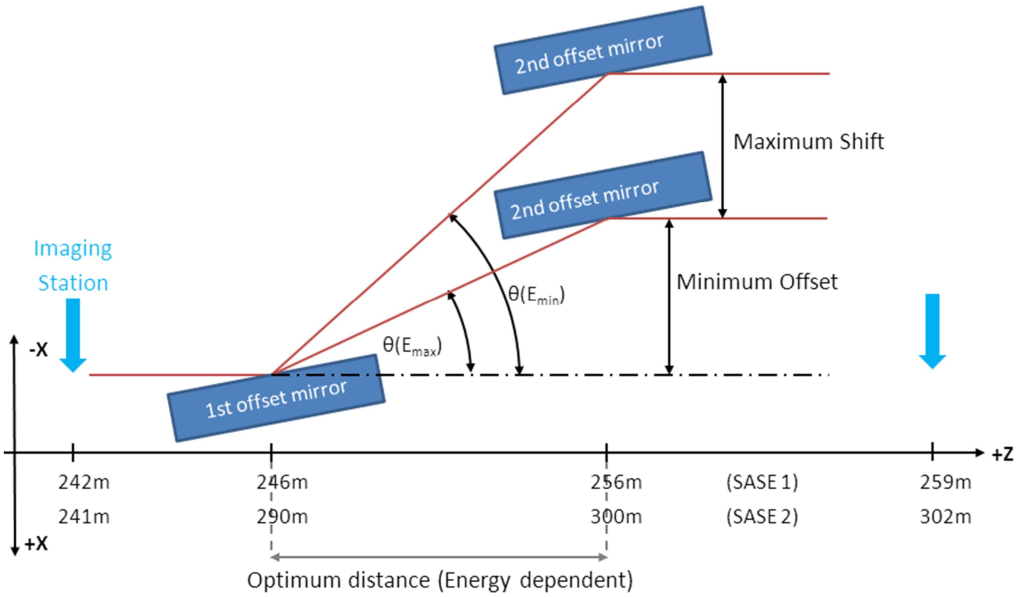

Figure 1: *Schematic of offset mirror shift range for the energy limits of SASE1 and SASE2 [5]. The blue arrows indicate the approximate location of the imaging stations.*

For this reason, the vacuum chamber of the device shall have to be placed on adjustment stages that allow two degrees of freedom: perpendicular to the direction of the beam (*x*) and height (*y*). The *x*-motion must be synchronized with the motion of the offset mirrors at low beam intensity to ensure that the chamber will not be misaligned with respect to the beam, which would cause significant damage at full power operation.

2 Distribution mirrors

The monitors located before the distribution mirrors (Figure 2) also have to account for a beam shift of 0.8 of the shift after the offset mirrors. The location of these mirrors may be shifted immediately downstream of the distribution mirrors.

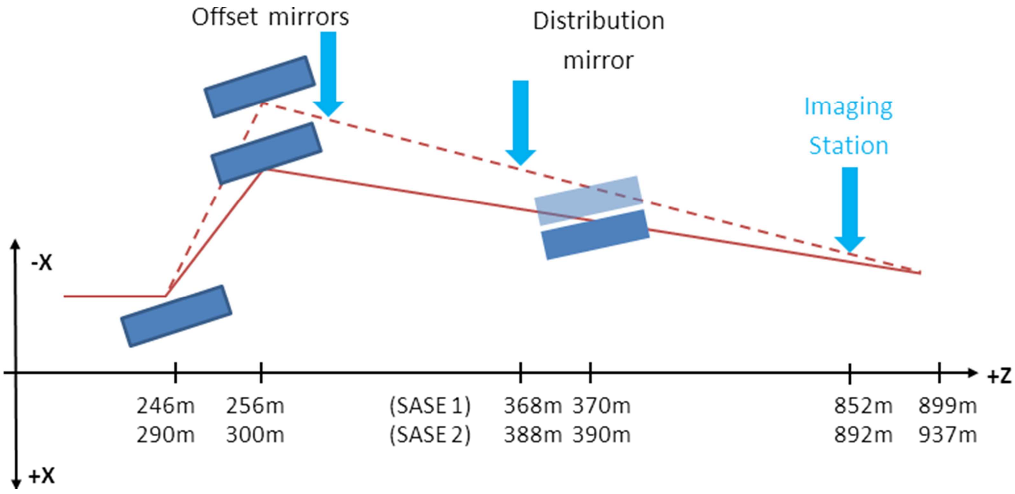

Figure 2: *Schematic of mirror distances between offset and distribution mirrors in SASE1 and SASE2 [5].The imaging station right before the Distribution mirror may also be placed downstream of it.*

3 After hard X-ray monochromator (SASE1 and SASE2)

The maximum beam size at 3 keV, at 850 m (location of monochromator, distances are given in Figure 3) from the source point (middle of the third last undulator segment), is 5.7 mm FWHM. With a Bragg angle (41^{o} at 3 keV), the minimum vertical offset would be 9.7 mm. For the whole energy range, the offset would vary from 9.7 mm (3 keV) to 19.3 mm (24 keV) in the worst possible case for the Si(111) channel-cut crystal monochromator. These calculations have been taken from [3].

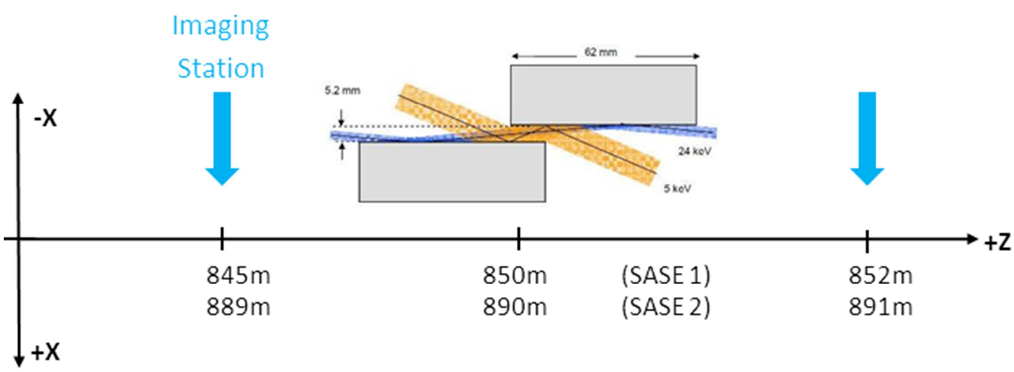

Figure 3: *Conceptual design of Si-(111) channel cut for 5–24 keV [3].*

4 SASE3 exit slits (shot-to-shot spectrometer)

The monitor placed after the exit slit at the SASE3 beamline will serve the purpose of allowing spectroscopic measurement (i.e. photon energy per shot, in single bunch mode) with the aid of the VLS grating monochromator, with the same principle as in [3]. The resolution restriction on this monochromator imager is more severe since it should be able to resolve the beam enough to spatially resolve the spectral modes.

1.3 Transmissive imager

The transmissive imager will be located before all devices in the photon beam transport system. The aim is to have an “expendable” imager (i.e. low-cost camera) and a very thin, radiation-hard scintillator to visualize both the SR and FEL before it reaches the 2D-imager. The correlation of beam images with a second imager downstream can be used to give the beam pointing.

This imager will not be transmissive in the SASE3 energy range. For this reason, its sole purpose will be to look at the SR and the first FEL beam from the SASE3 undulators.

Minimal device requirements:

- Must operate at the bunch repetition rate of 10Hz
- Possibility of image and data storage
- Statistics required from the images acquired: centre of mass, intensity, width for a region of interest
- Blocking of background due to visible light with appropriate foil
- Scintillator is radiation hard; may have to be cooled
- Camera and optics are shielded to avoid radiation damage; any electronics that may be decoupled from the device shall be placed at a distance to reduce radiation damage. Camera will be a low-cost device to make it easily replaceable.

2 Purpose of operation

Photon diagnostics will be needed both in the commissioning phase and in the operating phase of the European XFEL. Its main purpose is the characterization of the FEL radiation properties. These properties depend strongly on electron beam parameters that are often not measurable directly. Photon diagnostics is thus an indispensable tool to optimize the FEL for user needs. The more parameters are accessible with the best possible resolution, the better the control of the FEL will be. This section summarizes the requirements to the imaging stations, as part photon diagnostics, that are derived from undulator commissioning.

2.1 Commissioning of the undulators

There are two types of radiation that are imperative to commissioning of the Undulators: spontaneous radiation (SR) and self-amplified spontaneous emission (SASE) radiation.

2.1.1 Spontaneous radiation

The main purpose of SR diagnostics is the photon-beam-based alignment (pBBA) of undulator gap adjustment and phase tuning. It can also be used in the commissioning to characterize some properties of the electron beam (trajectory alignment) that are otherwise not possible with the e-beam-based alignment (eBBA). The details of these methods have been described in [6-9].

SR diagnostics includes the following:

- **Beam pointing in each undulator segment**

  The photon beam pointing of each undulator segment can be measured by detecting the center of the spontaneous radiation on a screen and deriving the electron beam pointing. This information can also be used for cross correlation with the electron beam position monitors (eBPMs).

- **Gap tuning**

  The absolute electron energy can be derived from the spontaneous undulator spectrum. Electron-based methods allow an accuracy of about 10^{-3}. Measurements of each undulator segment are to be done one by one and pairwise. The accuracy has to be in the same order of magnitude, and the absolute scale can at least be cross correlated. This is accomplished by simultaneously using the undulator commissioning monochromator (*K*-monochromator) and the 2D-imager.

- **Phase tuning**

  It should be possible to optimize the phase between segments [8, 9] using an imager to look at the angular profiles at different phase shifts, with the K-monochromator fixed at the fundamental photon energy.

2.1.2 SASE radiation

The onset of SASE radiation has to be measured. The SASE photon spot can be measured on a scintillation screen. In order to prevent these screens from damage due to an intense beam, only single or at best few tens of pulses per bunch may hit the screen material. Resolution and the possibility of damage are the driving factors behind the choice of the scintillation screens. Detectors with a wide dynamic range are required.

2.2 Alignment of the SASE beamlines

Once lasing is achieved from the undulators, the next step will be to transport the beam all the way down to the experiment hall (XHEXP1) and to the scientific instruments: FXE, SPB, MID, HED, SCS, SQS1, and SQS2.

The task of the X-ray beam transport systems is to deliver X-ray radiation from undulators to experiments. Located in underground tunnels up to 1 km long, the X-ray transport systems have to separate the XFEL beam from its high energetic radiation background, bring it to a usable size, and—for some of the experiments—limit its bandwidth by monochromators [3]. To align these optical elements, some imaging stations will be needed to locate and study the beam profile. Detailed requirements according to the locations of these imaging stations are provided in the subsequent chapters.

3 Description of the main components

The conceptual design of a typical imaging station is shown schematically in Figure 4.

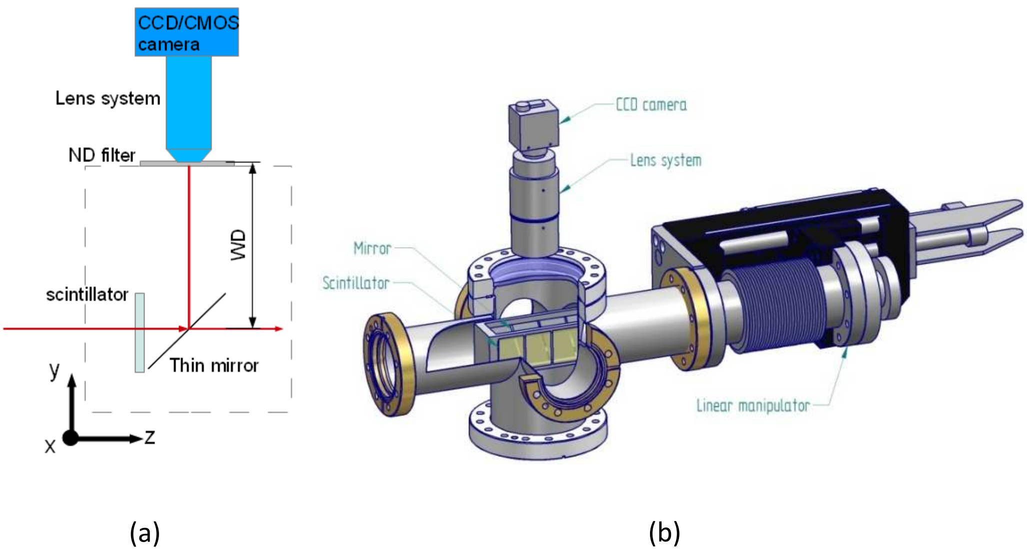

Figure 4: *Conceptual design of an imaging station: (a) optical imaging system at fixed working distance (WD) from the mirror and (b) mechanical model.*

The imaging stations for the European XFEL undulator beamlines consists of two major parts:

- Vacuum chamber for the screen unit (moveable) with a vacuum compatible exit window for visible light and a camera system situated outside the chamber, but rigidly connected to it.
- The photon beam will produce a beam spot on the scintillator screen, emitting visible light. Using an optical setup, it is possible to measure with sufficient precision in order to retrieve the desired X-ray beam size and profile information.

The optical assembly consists of:

- X-ray scintillation screen with its normal parallel to the beam. Size is dependent on the thickness of the material, which in turn affects resolution.
- Optically reflecting mirror that is partially transparent to X-rays rotated by 45^{o}.
- Optical camera (CCD or CMOS) capable of operating at least at the bunch train repetition rate (currently, 10 frames per second; this requirement is subject to change)
- Optical lens system

Both the scintillation screen and mirror are retractable to permit user beam delivery. The camera and optics will be placed outside of the vacuum which facilitates maintenance of the cameras.

3.1 Scintillators

Concerning the beam size and profile measurement itself, two general types of scintillator screen operations are planned:

1. **On-axis screens**

   Imaging stations at different locations along each SASE beamline are used to set up the beam, look at the beam, and measure the beam size at locations of interest. The screen will be well-aligned to the optical axis of the beam pipe. These stations will be used in single or few bunch operations only. In the case of the 2D-imager, there will be separate screens for imaging the spontaneous radiation and the FEL beam.

2. **Calibration screens**

   There will be one calibration screen in each imaging station. This will have a cross-hair pattern of a known size to cross check the optical imaging quality and allow very quick visual feedback about effects such as beam drift.

The screens require precise moving mechanisms allowing for adjustable screen positions. The overall size of the screens determines the stroke of the mover. In any given screen station, there may also be screens of different scintillation materials, such as cerium doped yttrium aluminum garnet (Ce:YAG), polycrystalline Chemical Vapor Deposited (pc-CVD) Diamond, etc. There will also be a redundant screen in case of damage. The choice of the scintillator depends on many parameters, such as light yield, effect on spatial resolution, emission wavelength, and radiation hardness.

It is intended that different types of screens are exchanged with a translation stage, in order to cover a wide range of intensities, and carry one redundancy screen, in the event that a screen is damaged. For instance, a Ce:YAG screen is intended for detecting the low intensities, while a B-doped CVD diamond screen is used for monitoring intense FEL radiation. The latter is expected to have a high damage threshold for XFEL radiation. Its linearity has been proven for high average flux at a SPring-8 beamline [10]. Figure 5 shows a close-up view of a possible scintillator and mirror insertion assembly.

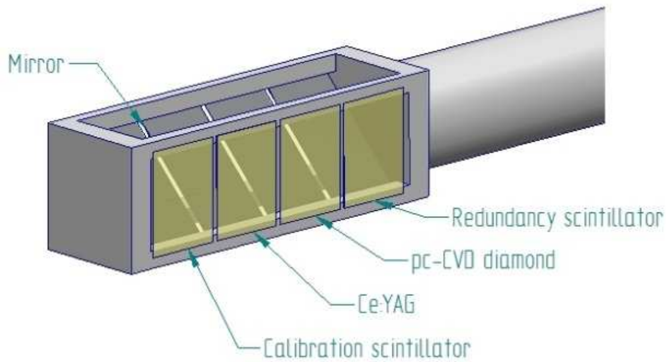

Figure 5: *Detailed view of scintillator and mirror holder housing a calibration screen with crosshairs; a Ce:YAG, pc-CVD Diamond scintillator; and a redundancy scintillator.*

3.2 Mirror

The mirror parameters are as follows:

- Quality: optical grade
- Reflectivity: > 95% @ 45º incidence, in the wavelength range of 475–650 nm
- Broadband, permitting visual inspection using white light

- Viewing aperture matches size of scintillator screen
- Thickness: suitable for > 50% transmission for X-ray energies > 5 keV

In the case of SASE3 photon energies, the X-rays will be all absorbed in the scintillator hence; mirror damage (e.g. a 2µm SiN wafer, covered by a 270 nm Aluminum layer) is not an issue. However, this may not be the case for SASE1 and SASE2. For this reason, for the setup at SASE1 and SASE2, to place the scintillator at 45º incidence instead of a mirror, is considered.

The mechanical stability of a thin mirror is an additional a concern that shall have to be tested via mounting it on an imaging station prototype (to be built).

3.3 Imaging system

The field of view (FOV) for the optics of the imaging stations depends on the maximum beam size expected and the area in which the beam is expected to be located.

The spatial resolution is an important parameter, in the imaging of the FEL beam spot. It is useful to study

- the wavefront of the beam at several locations throughout the tunnel,
- observe the shot-to-shot beam jitter and other possible beam drifts:
  - long-term drifts due to tunnel ground settling or mirror performance
  - short-term drift in the event that the mirrors drift or are damaged

The upper and lower limits on the beam sizes in each undulator beamline, at the locations of interest, were extracted from Table 1 in [3] at the extremes of the energy ranges.

Table 1: Beam sizes at the limits of the respective undulator beamline energy ranges, at the ring collimator (6σ), and in the experiment hall (4σ) [3]. The beam sizes at the monochromators (6σ) were calculated using the divergence and distances quoted in [3].

Undulator beamline	Location	Energy [keV]	Largest FEL beam size [mm]
SASE1	Ring collimator	3	4.10
	Before Si monochromator (850 m)	3	13.4
	Experiment hall	3 24	5.57–3.10 1.17–0.53
SASE2	Ring collimator	3	4.10
	Before Si monochromator (850 m)	3	13.4
	Experiment hall	3 24	5.81–3.23 1.22–0.55
SASE3	Ring collimator	0.26	14.50
	Before VLS grating	0.26	21.2
	Experiment hall	0.26 3	16.3–11.6 2.61–1.45

An optical camera having more than 1 megapixel (Mpx), 10-bit grey levels, and frame rate matching the pulse train repetition rate (currently, 10 Hz), will be used along with a zoom lens. The optical design will allow the imaging station to resolve down to the order of few microns to few tens of microns.

4 Locations

There are a total of three different types of imaging stations. The location of each device is crucial to its function.

The locations of the three imagers in relation to other devices are:

- Transmissive imager upstream of the 30 mm aperture
- 2D-imager right downstream the *K*-monochromator
- Pop-in monitors:
  - Downstream from the MCP-based detector (intended for SASE search) to look at the beam after the offset mirrors
  - Upstream or downstream of the distribution mirror
  - Upstream of the Si monochromator for the FXE instrument and a corresponding one for SPB at the same distance from the source in case of SASE1; to look at the beam profile after the distribution mirror
  - Downstream of the Si monochromator for the FXE instrument
  - For the same reasons, up and downstream of the Si monochromator for the MID instrument and a corresponding one for HED at the same distance from the source, for the SASE2 beamline
  - One immediately downstream of the exit slit in SASE3, before the entry to the experiment hall, that will act as part of a spectrometer, in addition to alignment purposes

The locations of the imaging devices for all SASE beamlines are shown in Table 2 by giving the tunnel names locations and approximate distances to the XFEL source point[1].

Table 2: Planned imaging stations with their approximate tunnel locations and distances from the source point [4]. Locations of some of the imaging stations are yet

[1] For the definition of distances as used here, the XFEL source point is assumed to be located in the centre of the third-last undulator segment.

*to be determined. *indicates the pop-in monitors that may be shifted downstream of the distribution mirrors.*

	Tunnel	Device	Source Distance [m]
SASE1	XTD2	Transmissive imager	176–185 (to be determined)
		2D-imager	242
		Pop-in monitor	261.36
	XTD9	Pop-in monitor*	368
		Pop-in monitor	848.25 (FXE)
		Pop-in monitor	848.25 (SPB)
		Pop-in monitor	851.75 (FXE)
SASE2	XTD1	Transmissive imager	176–185 (to be determined)
		2D-imager	241.56
		Pop-in monitor	304.86
	XTD6	Pop-in monitor*	388.5
		Pop-in monitor	888.25 (MID)
		Pop-in monitor	888.25 (HED)
		Pop-in monitor	891.75 (MID)
SASE3	XTD10	Transmissive imager	174–182 (to be determined)
		2D-imager	276.57
		Pop-in monitor	287.37
		Pop-in monitor	351.25
		Pop-in monitor	413.25

5 Scintillation screens

The scintillation screens are intended to provide an immediate image of the beam spot and, quantitative data about the beam spot dimension and its profile.

On-axis screens will be used to investigate single or few bunches, hitting the screen “on” axis (naming in concurrence with the e-beam imaging stations). Therefore, the view field needs to cover the centre of the chamber and some few millimeters around it only. The holder will carry a screen, a redundancy screen, and a calibration screen. The sizes and types of screens used depend on the energy range of the undulator beamline and the location of the imaging stations.

It is intended to place the scintillation screen positioned with its surface normal to the FEL beam for obtaining high resolution. For short wavelength photons, a thickness of about a few tens of microns is optimal for high resolution with sufficient florescence yield. In the case of imaging spontaneous radiation for undulator commissioning, the scintillator will have to be thicker (~ 100 µm). The larger a scintillator is required to be, the thicker it must be for structural stability; however, there is a trade-off between thickness and resolution.

The mirror is oriented at 45°, and is made of an al uminized thin Si or SiN membrane that is partially transmissive to hard X-rays to permit simultaneous operation with multiple imaging systems or other beam diagnostics, at the risk of some loss in transmission.

The peak energy concentration in all X-ray optics discussed here has to stay significantly below the melting threshold. A rough estimate for the melting threshold W_{melt} per atom can be obtained by [3],

$$W_{melt} = 3k_B T_{melt} \quad (1)$$

The absorbed dose and melt threshold calculated for some scintillators are shown in Table 3 for certain photon and pulse energies. The absorbed dose per atom is calculated based on the XFEL beam divergence, total energy, and assumed location of 200 m from the source. Absorption dose, *D*, is estimated by

$$D = \frac{4\log(2)\mu W_{pulse} A}{\pi\sigma_L^2 \rho N_A} \qquad (2)$$

Where W_{pulse} is the energy of a single FEL pulse μ is the absorption coefficient, σ_L is the rms beam size at the sample position, distance *L* from the source, *E* is the photon energy, *A* is the average atomic weight, *ρ* is the average density, and N_A is Avogadro's number.

A material is considered damaged when the absorbed dose reaches the melt threshold [3]. The calculated values for the absorbed dose required to reach the melt threshold for various scintillator candidates is given in Table 3, for the the following beam parameters: bunch charge of 1 nC, 200m away from source point, with a lower limit beam divergence [3] of,

$$\theta_{fwhm} = \frac{8.76}{E^{0.85}}[\mu rad] \qquad (3)$$

Table 3: The absorbed dose for some scintillation screen candidates at specific photon and pulse energies and the calculated melt thresholds. The beam sizes at the above mentioned energies were calculated using eq. (3), for 1nC bunch charge.

	Material properties				**Absorbed dose (mJ/atom) to reach W_{melt}, 200 m from source point**			
	Heat Capacity (J/g/K)	Thermal Conduct. (W/cm/K)	Melting Point (C)	W_{melt} (eV/atom)	3 keV	7.75 keV	12.4 keV	20.7 keV
Diamond	0.502	15	3550	0.988	520.5	1756	3300	4666
YAG	0.59	0.13	1950	0.575	11.4	25.8	44.3	12.9
LYSO	0.31	0.036	2047	0.6	0.72	1.48	0.58	0.87
LuAG	0.411	0.096	2020	0.593	4.22	8.65	3.4	5.38
BGO	0.0404	0.02	1050	0.342	1.33	2.98	3.1	1.68

At 1 nC bunch charge the pulse energies at different photon energies can be found using [3],

$$W_{pulse}[mJ] = \frac{19 \cdot Q[nC]}{E} \qquad (4)$$

Using the pulse energy values from eq. (4) the number of pulses a material is expected to survive within a bunch train are given in Table 4. Heat removal from a single pulse is not considered here.

Table 4: Number of pulses different types scintillators are expected to survive in a pulse train of 1nC bunch charge, 200 m downstream from the source point at various energies.

Beam Properties @ 1 nC		**N_{max} (200m away)**				
Energy (keV)	**Pulse Energy (mJ)**	**Diamond**	**YAG**	**LYSO**	**LuAG**	**BGO**
3 keV	6.33	82	1	0	0	0
7.75 keV	2.45	716	10	0	3	1
12.4 keV	1.53	2156	16	0	2	2
20.7 keV	0.92	5071	14	0	5	1

From the calculations in Table 4, it can be seen that even Diamond is not expected to survive the full train at 12.4 keV. YAG is the next durable candidates that can survive on the order of ten pulses (> 3 keV beam energy). These calculations have been done assuming the closest distance of 200 m. For larger distances, the number of pulses a material can survive will be larger. However, the results in Table 4 show that all imaging measurements with the imaging stations will have to be restricted to single or few bunches per train only.

5.1 Light yield

The light yield from the screens has to be sufficient to guarantee a well-exposed image. Therefore, the material and thickness of each scintillator has to be such that enough light is produced via the radiation mechanism. An added concern to the choice of scintillators is their emission wavelength. The wavelength at which the fluorescence yield is highest should match well with the quantum efficiency curve of a typical (commercial) optical camera.

Different materials are being investigated. Table 5 lists the probable scintillator materials and their properties, including light yield. There is not enough information on pc-CVD diamond scintillators.

Table 5: Scintillator material candidates and their propriety for both SR and FEL. The light yields quoted vary from producer to producer. Ce:YAG and Ce:LuAG were quoted from Crytur Ltd [11], LYSO is quoted from Saint Gobain [12], and pc-CVD Diamond is quoted from Diamond Materials [13].

Scintillator candidates	Density [g/cm^3]	Emission wavelength [nm]	Decay time [ns]	Index of refraction	Light yield [ph/KeV]	Intended use
Ce:YAG	4.55	550	70	1.82	35	SR, FEL
Ce:LuAG	6.73	535	70	1.84	28	SR
LYSO	7.30	375	41	1.81	32	-
BGO	7.13	480	300	2.15	8-10	-
pc-CVD Diamond	3.515	550–700	-	2.41	-[2]	FEL

The optical properties of scintillating materials, such as the light yield, are affected by the temperature of the beam target. The light yield decreases with temperature as a result of thermal quenching of the luminescent centers and thermally induced ionization of excited electrons, in which the electrons escape to the conduction band, rather than emitting scintillation photons [15]. The investigation of different screen materials to be utilized for the standard screen stations will take such effects into account.

5.2 Effect of scintillation material on spatial resolution

Simulation studies are being carried out currently into the effect of different scintillators and observation geometry on spatial resolution using Zemax [16] and SLitrani [17]. Experimental studies at a synchrotron source have been initiated[3]. Measurements at an FEL source are planned for the near future.

Studies on high-energy and high-intensity electron beams have been and are being carried out by [18-19]. Their work so far has proven that different scintillation materials, thicknesses, and even observation geometries have a

[2] No data by producers. Measurements carried out using pc-CVD Diamond at PITZ (electron beam) have shown that it scintillates about five times less than Ce:YAG [14].

[3] Thanks to colleagues at the Swiss Light Source (PSI, Switzerland).

noticeable effect on the achievable spatial resolution. Bearing in mind that these studies were done for the electron beam and reduction of the coherent optical transition radiation (COTR) effect, this may not always be the case for X-rays. However, their work shows that scintillators with a higher index of refraction have a better spatial resolution. A comparison between the spatial resolution obtained from images of illuminating BGO, YAG, LYSO, and PWO with an electron beam at MAMI [19] showed that YAG (despite being thinner than the other scintillators) displayed the worst resolution, while LYSO yielded the best results (independent of beam current).

Naturally, there is a tradeoff between scintillator thickness and achievable spatial resolution hence, the choice of the FEL screen will be that of a thin scintillator to improve resolution.

Taking the melt threshold, light yield, and emission wavelength into account, the intended default screens are Cerium-doped Yttrium Aluminum Garnet (Ce:YAG) and pc-CVD Diamond. A Ce:YAG single crystal is used as the main X-ray scintillating material that has been shown to exhibit characteristics suitable for imaging X-ray sources like the FEL, and is currently in use at other XFEL facilities (LCLS, SACLA). YAG has a high melting temperature and thermal conductivity higher than most scintillators (ref. Table 3), and has proven its capability of sustaining an unfocused FEL beam at normal incidence even at low X-ray photon energies. It is a fast scintillator (decay time constant 70ns) with its maximum luminescence yield (550 nm) that matches well with the quantum efficiency curve of a typical optical camera.

Although the resolution results, from the electron beam studies, suggest that Ce:YAG and Diamond are not the best of scintillators, their proven performance and emission wavelength of these scintillators becomes a dominant factor in their applicability to imaging the FEL beam.

5.3 Screens for the 2D-imager

There are two scintillator screens for this device, depending on what type of radiation is to be imaged. In the case of spontaneous radiation, a 50-100 µm thick Ce:YAG or LuAG crystal is to be used as a scintillator; since the SR is expected to be weak, there is a need for a good light yield to detect single photons reaching the screen during undulator commissioning (250–450 m away from source point). A thin foil (e.g. Beryllium) may be used to block out any stray visible light to reduce background on the detector.

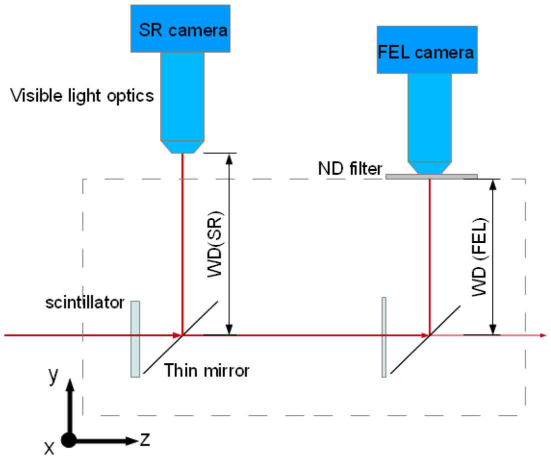

Figure 6: *Schematic diagram of the 2D-imager with the two cameras and optics systems (two working distances (WD), field-of-views) back-to-back.*

For the FEL case, due to the intensity of a single pulse, the scintillator thickness can be reduced to 50–75 µm to avoid blooming effects on the imaging camera. A pc-CVD diamond is also a choice for FEL imaging, as it naturally scintillates less than YAG [14]. The latter is expected to have a high damage threshold.

The largest FEL beam size (6σ) was calculated as 4.1 mm for SASE1 and SASE2, and 14.5 mm for SASE3 at the ring collimator, situated right after the 2D-imager [3]. During undulator commissioning with the *K*-monochromator, the SR beam spot is expected to be 12 mm (at 1 A, 240 m away from the source point) and is expected to move 20 mm vertically [6], when inserting one channel-cut crystal. The same shift is valid also for SASE3, as the higher harmonics will be used for commissioning.

Table 6: Scintillator screen types and sizes for 2D-imager per radiation type (SR vs. FEL).

Radiation type	**On-axis scintillator candidates**	**Scintillator active area [mm^2]**
SR	Ce:LuAG	35 x 35
FEL	Ce:YAG, pc-CVD Diamond	35 x 35

5.4 Screens for the pop-in monitors

Since there are pop-in monitors for various purposes, the screen sizes will have to be large enough to host the beam deviations accordingly. All calibration screens will be Ce:YAG with laser-engraved cross-hairs on it. Due to the high intensity of the single FEL pulse, a scintillator with good light yield is not a concern. A good spatial resolution is, however, required.

Table 7 gives the calculated beam deviations and the screen types, sizes, and thickness, according to the pop-in monitors in all undulator beamlines.

Table 7: Scintillator screen sizes according to location. The screens for the exit slit pop-in monitors have not yet been decided as the expected vertical deflections are not yet known.

Location	On-axis scintillator candidates	Expected beam deflections in Horizontal (H) or vertical (V) [mm]	Scintillator active area [mm^2]
SASE1 and SASE2			
After offset mirrors	Ce:YAG/Diamond	H: 25–57	20 x 20
After distribution mirror	Ce:YAG/Diamond	H: 20–46	20 x 20
Before hard X-ray monochromator for FXE Same location for SPB	Ce:YAG/Diamond	H: 3–4 H: 2–7	20 x 20
After hard X-ray monochromator	Ce:YAG/Diamond	V: 9.7–19.3	20 x 20
SASE3			
After offset mirrors	Ce:YAG/Diamond	H: 35–125	35 x 35
Before reflecting mirror and VLS grating	Ce:YAG/Diamond	H: 28-100	35 x 35
After exit slits	Diamond	V: TBD	TBD

5.5 Screens for the transmissive imagers

The screens for the transmissive imagers have to be as thin as possible to allow most of the beam through, while providing enough light. It should be optical grade to avoid any distortion on the wavefront in case of using it simultaneously with the 2D-imager for beam pointing measurements. The scintillator will consequently have a high melt threshold; hence, the most suitable candidate is considered to be pc-CVD Diamond. At this point in the tunnel, the average heat-load from the spontaneous radiation background is expected to be high: of the order of 400 W at 15 000 bunches/s with 33 undulators segments closed [20]. For this reason, the scintillator holder may have to be water-cooled.

In the case of SASE3 energy range, the scintillator cannot be thin enough (minimum permissible for diamond is 20 µm at 10x10 mm^2 [21]) to be transparent. Hence, this imager cannot be used for any reason other than looking at the SR from the SASE3 undulators.

The scintillator will have to be large enough to accommodate the largest SR beam size (FWHM) of about 6.4 mm for SASE1 and SASE2, and 21.6 mm for SASE3, at a distance from the first undulator segment (about 383 m). Depending on the wavelength at which the commissioning of the undulators is finalized, the scintillator size may become smaller. To reduce background on the detector a thin Beryllium foil will be used to block out visible light from the bending magnet (for electron beam deflections) after the Undulators.

Table 8: Scintillator screen types and sizes for Transmissive imager according to radiation type (SR and FEL).

Radiation type	**On-axis scintillator candidates**	**Scintillator active area [mm^2]**
SR: SASE1 and SASE2 SASE3	pc-CVD Diamond (preferred due to radiation hardness) Ce:LuAG	 35 x 35 35 x 35
FEL:	pc-CVD Diamond	20 x 20

6 Imaging system

The imaging system of an imaging station consists of the lens (possibly, with variable focus and zoom), the actual imaging camera, and, in some cases, neutral density filters. The imaging system will always be located outside of the vacuum chamber of each imaging station to be installed in each undulator tunnel.

6.1 Lens system

A large format lens design, able to give an extended depth-of-field (wave optical imaging depth) is to be used. The lens is vital in fulfilling the spatial resolution requirements.

The crucial parameters for the correct derivation of absolute beam spot dimensions are:

- Working distance (WD) and depth-of-field
  - Resolution generally would increase when going to smaller focal length (thus shorter WD) for a given optics diameter; preferable to use a lens system that has shorter WD if the requirements for the field-of-view (FOV) can be met
  - Light collection efficiency is higher at short WD
  - Depth-of-field decreases with WD
- Another resolution effect that must be considered is parallax distortion: when the object is extended in the direction of the optical axis and smears the resolution by appearing in the image space being tilted away from the axis.
  - Thinner scintillator screen

In the following sections, the resolution required from the various imaging stations are listed as 5% of beam size sigma—for the lowest bunch charge—

in order to realistically resolve position jitter and drift of the beam (7.6–110 µm/day) throughout the beamlines [3].

6.1.1 2D-imager

For SR visualization the required field-of-view (FOV) on the scintillator screen should be 30 x 30 mm^2 for all undulator beamlines. With a large sensor format with 2 500 x 2 200 pixels, 6.5 µm, and a view field at a 1:1 magnification, this would be about 16.25 x 14.3 mm^2, the spatial resolution has to be 12–19 µm [6]. With a magnification of 1:2, the sensor area will be sufficient.

For FEL visualization, a better spatial resolution is required. Therefore, a camera with high dynamic range capability and a variable zoom lens system will have to be mounted. The minimum expected spatial resolution is given in Table 9.

*Table 9: Required spatial resolution and corresponding lens parameters . * indicates the minimum required by the undulator commissioning [6]. The FEL resolution is calculated as the expected beam size at the position of the imaging station, using the upper bound divergence eq. (1) from [2].*

	FOV [mm^2]	**Minimum required resolution [µm]**	**Lens parameters (preferred)**			
			Type	**Mag.**	**WD [mm]**	**Sensor/pixel size**
SASE1 and SASE2						
SR case	30 x 30	12–19*	Fixed	0.5	160	2500 x 2200 7.4 µm
FEL (at 24 keV)	10 x 10	7	Variable focus and zoom	0.18–4.2	165	1600 x 1200 5.5 µm
SASE3						
SR case	30 x 30	12–19*	Fixed	0.5	160	2500 x 2200 7.4 µm
FEL (at 3 keV)	30 x 30	32	Variable focus and zoom	0.88–1.48	108	1600x1200 7.4 µm

6.1.2 Pop-in monitors

The required spatial resolution for the pop-in monitors, their respective lens parameters and the minimum required resolution at imaging station distance are given in Table 10.

Table 10: Lens parameters for the pop-in monitors in different locations.

Location	FOV [mm^2]	Minimum required resolution [µm]	Lens parameters			Corresponding sensor/pixel resolution
			Type	Mag.	WD [mm]	
SASE1 and SASE2						
After offset mirror	10 x 10	7	Variable focus and zoom	0.8–1	86	1600 x 1200 5.5 µm
Before dist. mirrors	10 x 10	10	Variable focus and zoom	0.57–1	86	1600 x 1200 5.5 µm
Before monochromator	20 x 20	24	Variable focus and zoom	0.23–1.2	165	1600 x 1200 7.4 µm
After monochromator	20 x 20	15	Variable focus and zoom	0.25–1	86	1600 x 1200 7.4 µm
SASE3						
After offset mirror	20 x 20	38	Variable focus and zoom	0.4–4.6	165	1600 x 1200 7.4 µm
Before reflecting mirror and grating	25 x 25	46	Variable focus and zoom	0.4–4.6	165	1600 x 1200 7.4 µm
After exit slits	TBD	TBD	Variable focus and zoom	TBD	TBD	TBD

6.1.3 Transmissive imager

Wide field-of-view is acceptable, as the intention is to observe the first light. A spatial resolution on the order of 10–20 µm is adequate, as this resolution is also on par with the SR resolution for the 2D-imager for measuring beam pointing. In this case, the lens system will be fixed (no focus or zoom adjustments). Another reason for the fixed optics system is to avoid having electronics in part of the beam pipe where radiation protection from higher harmonic rejection by the mirrors is not afforded.

The resolution, FOV, lens parameters and corresponding sensor size are given in Table 11 for SASE1, SASE2 and SASE3.

Table 11: Required spatial resolution and corresponding lens parameters to obtain required resolution.

Location	Minimum resolution [µm]	FOV [mm^2]	Lens parameters (desired)			Corresponding sensor/pixel resolution
			Type	Mag.	WD	
SASE1 and SASE2	10–20	30 x 30	Fixed	0.44	160 mm	2300 x 1800 7.4 µm
SASE3	10–20	30 x 30	Fixed	0.33-0.42	160 mm	2300 x 1800 7.4 µm

As it can be seen from sections 6.1.1-3, each imaging station requires a camera with a certain sensor size, FOV and lens parameters that are different from one and other. For ease of integration into the DAQ and Control Systems and maintenance, we will endeavor to keep the cameras such that they are from the same producer and production series, with the exception of the sensor size to accommodate the required FOV. For ease of maintenance a standardization of the optics is also considered. To achieve this, a minimum resolution for the FEL detection is to be fixed at 7 µm and the FOV for SASE1 and SASE2 to be 20x20mm^2 and for SASE3 to be 30x30mm^2.

6.2 Neutral density filters

To avoid saturation effects on the camera sensors, neutral density filters will be mounted into a filter wheel to allow the option of additional attenuation of the visible light from the different scintillators present in each device. The remote-controlled wheel will accommodate five 50 mm diameter filters, with the following values: 0 (clear), 0.5, 1.0, 1.5, and 2.0. Currently, ND filters are foreseen to be mounted in the transmissive and 2D-imagers.

6.3 Illuminator

A remote-controlled LED is intended to be mounted, outside the chamber but between the viewport and the lens system, for camera “live” check, visual inspection, and possible alignment of the scintillators. The exact placement of this LED is not yet decided.

6.4 Camera

The cameras to be mounted in the imaging stations will all be commercial products based on visible light CCD or CMOS sensors. All signals coming from the camera will be routed to the DAQ and control system developed by WP76.

Before mounting the final imaging stations into the tunnel, each device will have to undergo a preliminary form of spatial and intensity calibration. The camera and the relevant optics, mounted outside of the vacuum, will always sit perfectly aligned to the optical axis.

The camera has to allow a sufficient integration, and the sensing area itself has to be large enough, to assure a complete recording of the screen image. For instance, a large image sensor will be required for the 2D-imager (5 Mpx). Cameras have to deliver images at a frame rate of 10 Hz minimum with high sensitivity, large dynamic range, low noise, and sufficient pixel count. Compatibility with the DAQ and control system is required. Resolution and FOV determine the required pixel format. The camera sensor has to have a high granularity to guarantee the highest required resolution. The camera parameters for all imaging stations are summarized in Table 12.

Table 12: Requirements of imaging cameras for the three types of imaging stations. High dynamic range here is considered to be > 65 dB.

Device	Sensor size	Other requirements	Total
Transmissive imager (SASE1 and SASE2) Transmissive imager (SASE3)	2300 x 1800	High dynamic range, cooling, low cost	3
2D-imager (SR) 2D-imager (FEL)	2500 x 2200 1600 x 1200	Low readout noise, high dynamic range, cooling High dynamic range, low cost	3 3
Pop-in monitors (SASE1 and SASE2) Pop-in monitors (SASE3)	1600 x 1200 1600 x 1200	High dynamic range, low cost	10 3

Cameras tested at PITZ [22] and the European XFEL are being compared in performances for imaging of the spontaneous radiation (low-light level suitability).

In some cases, it would be useful to have a camera with a cooling system as this will help stabilize its performance in lengthy procedures such as undulator commissioning and pBBA. For those cameras that do not have built-in cooling systems, heat-exchangers will be mounted on the camera and a fan will be used to remove the heat via forced convection.

Currently, the preferred choice of technology for SR imaging is the scientific CMOS (sCMOS) [23] technology due to its low readout noise and high frame rates. The specifications of this detector – from one of the possible vendors - are given in Table 13. The readout specifications may change from one vendor to another.

Table 13: Parameters of the sCMOS [23] -- candidate camera for the SR imaging for the 2D-imager.

Sensor type	Front Illuminated Scientific CMOS
Active pixels (W x H)	2560 x 2160 (5.5 Mpx)
Sensor size	16.6 x 14.0 mm, 21.8 mm diagonal
Pixel size (W x H)	6.5 µm
Pixel readout rate (MHz)	560 (280 MHz x 2 sensor halves)
	400 (200 MHz x 2 sensor halves)
	200 (100 MHz x 2 sensor halves)
Read noise (e-):	1 @ 200 MHz
	1.2 @ 400 MHz
	1.4 @ 560 MHz
Min. temperature air cooled	-30ºC
Min. temperature coolant	-40ºC
Dark current, e-/pixel/sec	0.07 @ -30℃
	0.03 @ -40℃
Data range	11 bit & 16 bit
Maximum QE	57%
Readout modes	Rolling Shutter and Global Shutter
Internal memory buffer size	4 GB
Maximum frame rates	100 fps Rolling Shutter, 50 fps Global Shutter @ full frame
	1688 fps Rolling Shutter, 844 fps Global Shutter 144 x 128 ROI
Pixel well depth (e-)	25 000
Camera Readout	CameraLink

The search for a suitable camera for the transmissive imager is ongoing. Due to high possibility of radiation damage, the sensor will have to be low-cost which comes at degraded performance. Another option is to decoupled the readout electronics, which are then mounted in the possibly shielded racks at a distance from the beampipe. Despite the decoupling, the imaging unit will have to be lead shielded.

6.4.1 Hardware and software requirements

It is required that the camera have a hardware and software interface, which is in accordance with the control software for the European XFEL (in accordance with WP76).

It is recommended by WP76 that the cameras be equipped with a GigE-compliant interface. The high bandwidth (1000 Mbps) allows large uncompressed images to be transferred quickly in real time over large distances over standard low cost IP network infrastructure (RJ45 patch cable and switch LWL uplinks), thus allowing the camera servers to be located outside the accelerator tunnel. Ethernet is easily implemented into the server structure for the camera systems of the European XFEL imaging stations. This is not the case with every imaging station. Each 2D imager will be equipped with two cameras, one of which will have a CameraLink interface. To carry the signals to servers located outside the tunnel, a CameraLink to fiberoptic extender will be used. Integration of a CameraLink camera (sCMOS) to the DAQ and control system has been tested and approved by WP76.

6.4.2 Trigger and exposure time

Correct operation of the camera image acquisition system requires that image exposure is synchronized precisely with bunch delivery. All cameras allow use of an external electrical input signal to trigger exposure and this will be used. Synchronizing a single exposure to a bunch train requires a repetition rate of 10 Hz, but additional external trigger patterns can and should be foreseen. Note that not all cameras allow the exposure period to be derived from the length of the external trigger high signal and, consequently, the exposure time has to be controlled by software configuration and is fixed per bunch train [24, 25].

Each camera will be connected to an image server located outside of the tunnel, either via Gigabit Ethernet or CameraLink. Each camera will be connected to a camera control device (for software control and configuration) and all control devices will be connected to the image server for image processing and distribution. Cameras can be grouped to a single control device. The software is modular for handling image distribution.

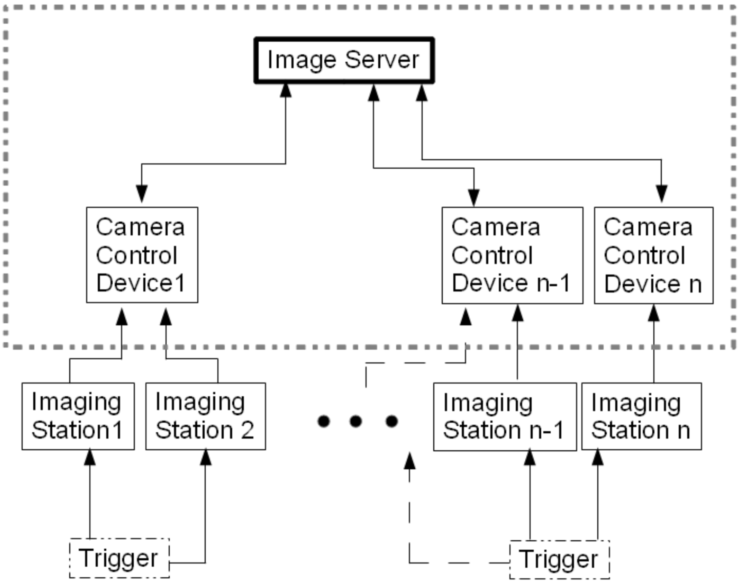

Figure 7: *Schematic of camera link to control system.*

6.5 Device electronics

The electronics that need to be integrated and controlled are the stepper motor drivers for the chamber motion and the screen mover, the ND filter wheel, the optics (where necessary), the illuminator (LED), and the external fan for cooling the camera. The stepper motor electronics is based on industry standard bus terminal controller and field bus components by Beckhoff that will be widely used within the European XFEL project.

Camera and device signals are low power and low duty cycle. The manipulation of the imaging stations will be supplied by WP76 control system interface.

Table 14: Summary of electronics parameters

Functionality	**Expected implementation**
Motor controller	Beckhoff controller
Camera / sensor	Gigabit Ethernet, CameraLink
Power Supply, LED	via Beckhoff
Trigger	External trigger hardware driven by XFEL timing system

7 DAQ and control system integration

All cameras, regardless of the imaging station to which they belong, will be integrated into the data acquisition supplied by WP76. All related operations will be carried out via graphical user interfaces supplied with the control system.

7.1 General functions

The control system monitors the movement and position of the scintillator mover, the focus position of the camera, and the image situation (validation and transportation), etc.

The following tasks are part of the control for the imaging stations:

- Camera read out and control
  - Camera preamplifier gain setting, trigger, exposure time, image integration
  - ROI on sensor, re-binning
  - Camera reset (an initialization file to save the last configuration and restart at the known configuration)
  - Standard image processing features (dark image subtraction, *x* and *y* profiles, intensity distribution, centroid and FWHM calculation, etc.)
  - Special image processing (scintillator screen orientation correction, commissioning phase calculations)
- Scintillator screen movement (± 0.05 mm) and screen position: any two imaging stations (in a single beamline) can have their scintillators inserted into the beam path simultaneously
- Imaging station chamber motion for alignment with respect to other elements in the beam pipe

- Operation of camera
  - Focus and / or working distance adjustment
  - Neutral density filter wheel
- Possible interface to WP73 for the pop-in monitors, WP71 and WP16 and WP17 for the commissioning phase, and the FEL beam profile with the 2D-imager
- Tagging bunch ID and other relevant information, such as positions of movers of nearby optics, beam energy, pulse energy, etc. to the images

7.2 Expected data rate and storage

The largest image is expected to come from the largest sensor, which has 5 MP. This means that a single image is a maximum of 10 MB. Since the cameras are expected to work at best 10 fps, the expected data rate from a single camera—worst case scenario—will be 100 MB per second per device. It is not expected that all of the imaging devices will actively take images at the same time. It is very likely that there may be more than one device imaging at any one time; however, no more than two are expected to be active simultaneously.

Storage of data is dependent on the operator. All acquired images are not necessarily to be stored. An option for short-term storage (of the order of 1–2 days) for debugging the system and analysing the data is deemed appropriate. Data that is considered worthy will be archived. This option will be available to the operator at all times [26].

7.3 Image processing

Upon acquisition, the images go through a series of processing routines. The first processing of images can be done for calibration purposes (explained in Section 7.3.1, "Calibration" on page 40). The image would then be analysed for beam properties, such as beam width and centre, and displayed at the Control Room console.

The processing software will be flexible to adapt to the beam changes, and its performance must guarantee the acquisition and analysis of the images at the linac repetition rate. Pipelining of analysis algorithms to process data is required.

Graphical user interfaces and script-level user interfaces should allow the command of the camera operation. The graphical panel should allow interaction with the device server API (attributes and commands) and visualize the beam image at a selectable refresh rate. It will be possible to save a snapshot (TIFF, etc.) and store the image raw data.

An option of integrating multiple images of the same exposure time should be possible to avoid changing the trigger pattern.

7.3.1 Calibration

Acquired images must go through some image calibration and correction procedure.

The purpose of these procedures is to:

- Convert image coordinates to positional coordinates in the plane transverse to the beam.
- Possibly correct for geometric distortions in the images if the scintillator is placed at 45^{o} orientation with respect to the beam and other optical effects.

The calibration procedures that are <u>not</u> currently foreseen are:

- Perform a pixel-by-pixel intensity calibration to correct for pixel to pixel variability and changes due to radiation damage.
- For scintillation targets operating under high beam currents, adjust the pixel intensity to account for temperature-dependent light yield of scintillators.
- Adjust pixel intensity to account for the position dependency of the optics to collect light emitted from different locations on the beam targets.

7.3.2 Online image processing

After the necessary calibration, the image processing will be according to one of the following scenarios:

- **Standard scenario**

  Dark-field images will be acquired with the camera (i.e. no beam interaction with scintillator), averaged, and then subtracted from each acquired image. This will ensure subtraction of any background effects and account for pixel non-uniformity in the camera and damaged pixels. Dark images will be acquired before starting acquisition of any image at all and then using the same dark image to subtract from subsequent measurements. The frequency of acquiring dark images will depend on the performance stability of the camera.

  The bunch repetition rate of the linac sets the time frame (100 ms) within which to acquire, process, and display each image. For this reason, it may be convenient to analyze only the portion of image containing the beam profile.

  The image processing is divided into four steps:

  1. Dark image subtraction
  2. Automatic ROI detection
  3. Calculation of the beam profile moments
  4. Data storing with precise shot ID and other device parameters (device temperature, surrounding optics positions in the case of pop-in monitors, photon wavelength, pulse energy, scintillator position/type, imaging station chamber position, etc.)

- **Undulator commissioning scenario**

  The camera acquisition system is one of the most important diagnostics tools for the commissioning. The capability to acquire beam images and correlate them with the other machine parameters on a shot-to-shot basis will contribute significantly to the success of the commissioning operations.

  During commissioning, the beam shape will vary, depending on the undulator commissioning method utilized. The parameters to be extracted will be more than the standard beam profile moments and will require different algorithms to extract information relevant for Undulator commissioning. These algorithms will be developed in-house, in collaboration with WP76 [27] and WP72.

8 Mechanical setup

The vacuum vessels of the imaging stations are either five- or six-way crosses, sizes depending on the SASE beam-pipe diameter. All connections with movable parts for the screens to be positioned inside the beam pipe are flanged to the vessels via bellows. The imaging system (camera, lens, and neutral density filters) will be mounted in front of an optical window, outside of the chamber to ease access to the imaging system for maintenance. The imaging system must be precisely mounted so as not to lose accuracy with respect to the screen. The working distance will have to be maintained.

So far, there are two options foreseen as solutions to accommodating for the expected beam deflections:

a The whole vacuum chamber sits on linear adjustment stages that shall allow for adjustments in two directions: horizontally and vertically perpendicular to the beam direction.

b For horizontal motion, moving the imaging system over a large viewport, with the beam. This option has to be studied considering the flatness of a viewport that is suitable for a DN150 chamber or larger (especially in the case of SASE3).
As for the horizontal deflection, the chamber will have to be moved vertically for accommodation.

8.1 Optical window

A vacuum-approved, fused silica window of optical quality is to be used to observe the screen light at the camera. Windows must at least transmit light in the spectral band from 400 nm to 600 nm. The vacuum windows and the camera lenses will need to be operated such that no external light is introduced into the chamber or camera during operation. The intended lead shielding (see Chapter 11, “Radiation protection” on page 482) shall cover the camera and optics region up to the view port. In this way, any external light will be blocked.

8.2 Movers and screen holder

The mover system for the screens is based on stepper motors, allowing the insertion of screens with different sections at the corresponding positions, and to vary these positions according to choice of screen and fine adjustment in case of some damage of the screen.

The design of the insertion assembly is to provide enough motion to completely remove the scintillators, and any support hardware, from the beam path. The system must accurately position the scintillators along the *x*-axis within 0.05 mm and be repeatable to 0.005 mm.

The vacuum flight path must be sized to exclude the possibility of it being struck by the X-ray FEL beam. All components that are exposed to the X-ray beam inside the chamber are to be fabricated of Aluminium. The frame is to be designed to support up to four scintillators (sizes will vary according to location), and it must cover the outer edges of each scintillator plate, which emit significant amounts of visible light through light-guiding internal reflections. The surface normal to the plane containing the scintillators and resolution test chart lies in the *y*-*z* plane. It either makes a 45° angle to both the positive *y*-axis and negative *z*-axis, or hosts a mirror at 45° angle. In locations where the mirror is not to be mounted, the scintillator will be mounted at the 45° angle.

The mover has to move the scintillator into the beam path such that the beam is well positioned to hit the screen. The beam spot has to coincide with the field of view of the optics, attached to the vessel. Thus, optics, vessel, and screen have to be well-aligned to each other.

Where necessary, the imaging station will also be mounted on adjustment stages that will help adjust the whole device in the vertical direction and the direction perpendicular to the beam. The expected beam deflection and the travel ranges of the device manipulators is summarized in Table 16.

Table 16: *Summary of device movement range*

Device	Location	Maximum expected beam movement [mm]	Expected device travel range [mm]
Transmissive imager	SASE1,2,3	-	-
2D-imager	SASE1,2,3	20 (Vertical)	50
Pop-in monitor after offset mirrors	SASE1 and SASE2 SASE 3	25-70 (Horizontal) 35-130 (Horizontal)	100 150-200
Pop-in monitor after offset hard x-ray monochromator	SASE1 and SASE2	20 (Vertical)	50
Pop-in monitor before VLS grating	SASE3	78 (Vertical)	100
Pop-in monitor after exit slits	SASE3	TBD	TBD

The repeatability of these stages should be on the order of 0.005 mm. Limit switches and an absolute positioning encoder will be required for all movers. The transmissive imagers are not foreseen to be mounted on linear stages and can be attached to the beampipe without the aid of bellows.

8.3 Vacuum conformity

The design of the vacuum chamber of these screen stations, in terms of geometry, materials, and manufacturing, has to compatible with the UHV requirements for X-ray beam transport systems (WP73). Details on the vacuum requirements are given in [28].

9 Survey and alignment

For the optical alignment of the camera system of the imaging stations, it is crucial that the beam axis is well defined on the superstructure level (girders, concrete blocks, etc.).

WP32 will develop a “linear straightness alignment system”, which will be a large laser beam in a vacuum pipe. This system will cover the undulator region and the beamlines up to the Bremsstahlung collimator. This system will improve the accuracy of the survey net in this area to 300 µm. The rest of the beamlines will have the regular survey network, based on retro-reflectors and trackers. This will give, at worst, probably 2–5 mm deviations [4]. There will have to be placements to mount holders for the retro-reflectors on the imaging stations, for easy integration into the survey system. The tranmissive imager and the 2D-imager can make use of the survey and alignment system setup by WP32, whereas the pop-in monitors will have to depend on the trackers.

10 Machine protection system

When operated, the screen systems are inserted into the beam and may require an interface to the machine protection system (MPS). Technical details on the interface will be agreed on with the stakeholders and the MPS team. The simplest implementation would require limit switches to be integrated. Using this interface, the MPS could check whether a screen is inserted or is out. Depending on this information, the operation mode of the machine would be set.

11 Radiation protection

Since calculations of expected radiation fields inside the tunnel around the beam pipes do not currently exist, it is hard to predict if all imagers will have to be shielded. For this reason, it is currently foreseen that the detection unit (camera, optics, and ND filters) of at least all imaging stations in the tunnels shared with the electron beam are to be completely shielded within 3 mm lead sheets.

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