CDR OF MCP BASED PHOTON DETECTOR

FOR THE EUROPEAN XFEL

Evgeny Syresin, Oleg Brovko, Michael Kapishin, Alexey Shabunov,

Joint Institute for Nuclear Research, Dubna, Russia

Mikhail Yurkov, DESY, Hamburg, Germany

Wolfgang Freund, Jan Grünert, Harald Sinn, European XFEL GmbH, Hamburg, Germany

Goal:

To provide successful operation of the SASE XFEL the radiation detectors should operate in a wide dynamic range from the level of spontaneous emission to the saturation level, in a wide wavelength range from 0.05 nm to 0.4 nm for SASE1-SASE2 and from 0.4 nm to 4.4 nm for SASE3 and at a high relative accuracy of measurements, which is crucial for detection of a signature of amplification and characterization of statistical properties of the radiation.

The XFEL radiation detector on the basis of micro-channel plates (MCP) satisfies these requirements. The photon detector is intended for measurements of the pulse radiation energy and the image of the photon beam.

The dynamic range of the photon pulse energy is between 1 nJ and 25 mJ. This applies to spontaneous and FEL radiation.

The relative accuracy of the pulse energy measurements is better than 1%.

The visualization of a single bunch in a train, or average image over the full train will be performed by the MCP imager at a spatial resolution of 30 μm.

XFEL MCP PHOTON DETECTOR

An important task of photon beam diagnostics at the European FEL is reliable measurements for the search for and fine tuning of the FEL process. The problem of finding SASE is crucial for the XFEL because of large

synchrotron radiation background. This requires a detector with a wide dynamic range, controllable tuning to the required wavelength range, and suppression of the unwanted radiation background.

Three different tasks can be fulfilled with the XFEL MCP-based photon detectors:

study of the initial stage of the SASE regime;

measurement of the photon pulse energy;

measurement of the photon beam image.

The MCP will allow operation at the XFEL pulse repetition rate, thus resolving each individual radiation pulse.

The following first harmonic wavelength ranges are to be covered by three MCP stations:

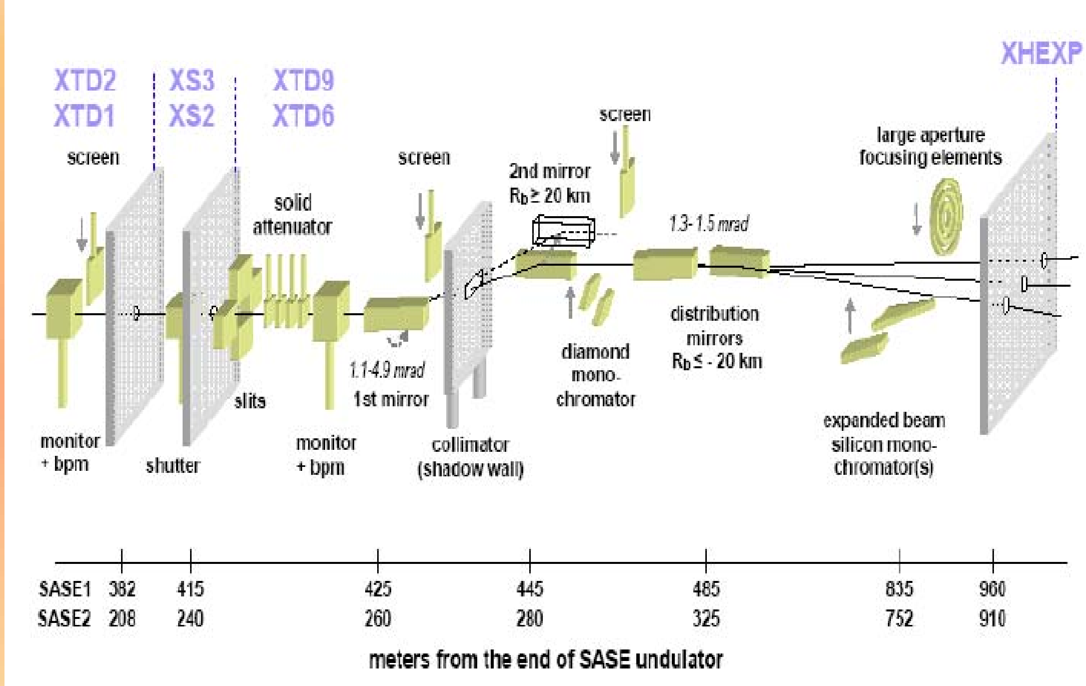
0.05-0.4 nm for MCP1 and MCP2,

0.4-4.43 nm for MCP3.

SASE1&SASE2 mirrors and attenuators applied for the MCP detectors

The SASE1&SASE2 systems associated with the MCP detectors consists of four main elements: the first XFEL C mirror 800 mm long with a variable incident angle of 1.1-3.6 mrad; the second XFEL C mirror placed at a distance of 10.4 m from the first one, which provides the large incident photon angles of 10-30 mrad; the diamond attenuator; the Ya screen installed in front of the first C mirror.

The C mirrors operate as an attenuator of the FEL radiation. The dynamic range of the C mirror attenuator and diamond plates is about 10^3-10^4. The dynamic range of the MCP monitor is 10^3-10^4. It detects XFEL radiation in the dynamic range of 10^7.



However, the C mirror considerably reduces the available horizontal space to 0.9-2.9 mm during the search of SASE1&SASE2 radiation.

Schematic view of the SASE1&SASE2 mirrors and attenuators for the MCP.

Three MCP operation regimes

The search for the SASE regime by the MCP is realized when the first mirror is displaced from the beam axis in the horizontal direction to increase the acceptance of the setup.

Finally, three MCP operation regimes are considered:

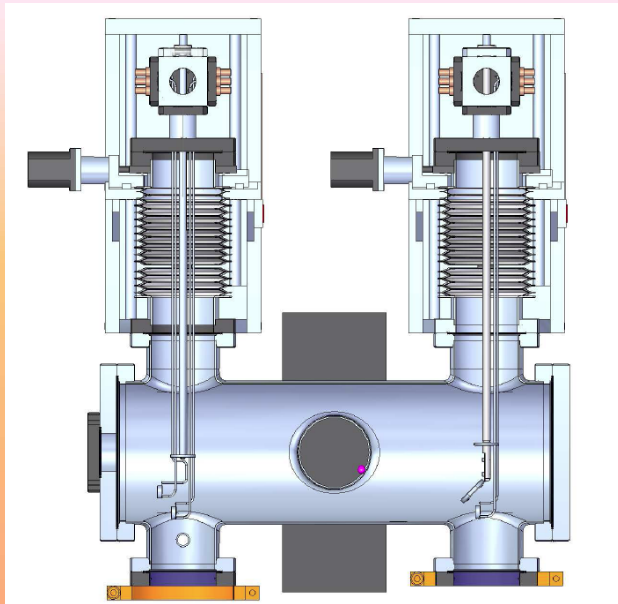
with both C mirrors removed at large horizontal acceptance to search for initial stages of SASE processes,

with only one C mirror installed to provide the attenuation factor $R=1^{-3} \cdot 10^{-2}$ and small horizontal acceptance,

with two C mirrors installed to produce the total attenuation factor $R=1\text{-}10^{-5}$.

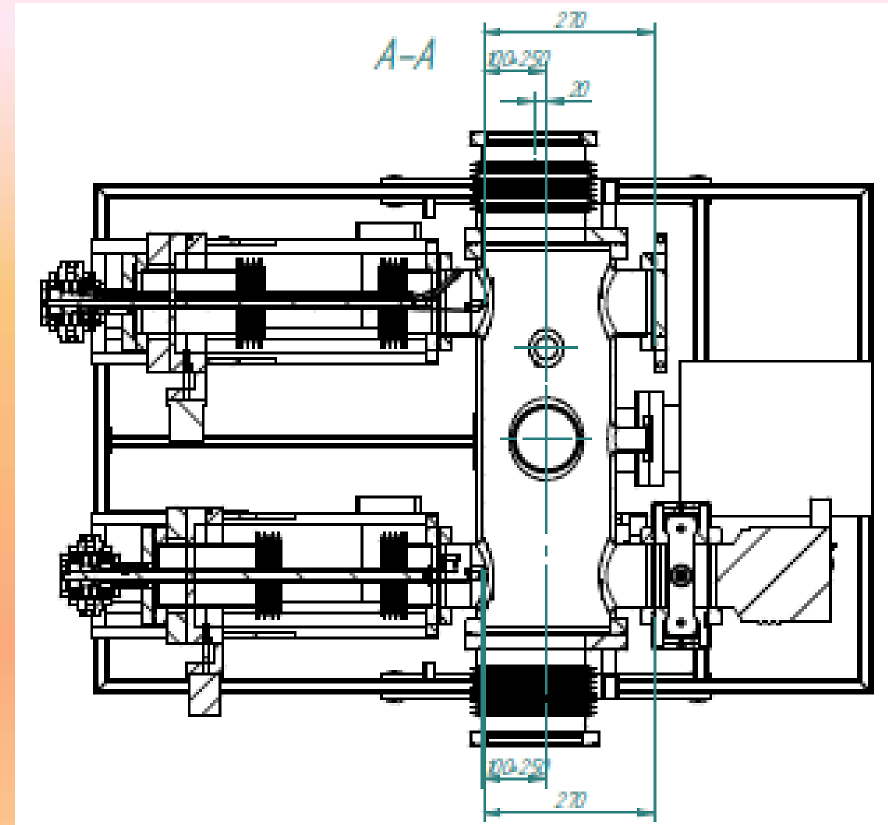
Design of of the SASE-1&SASE-2 MCP detector

An SASE1&SASE2 MCP detector consists of three MCPs equipped with anode as a pulse energy monitor and one MCP detector for imaging the photon beam.



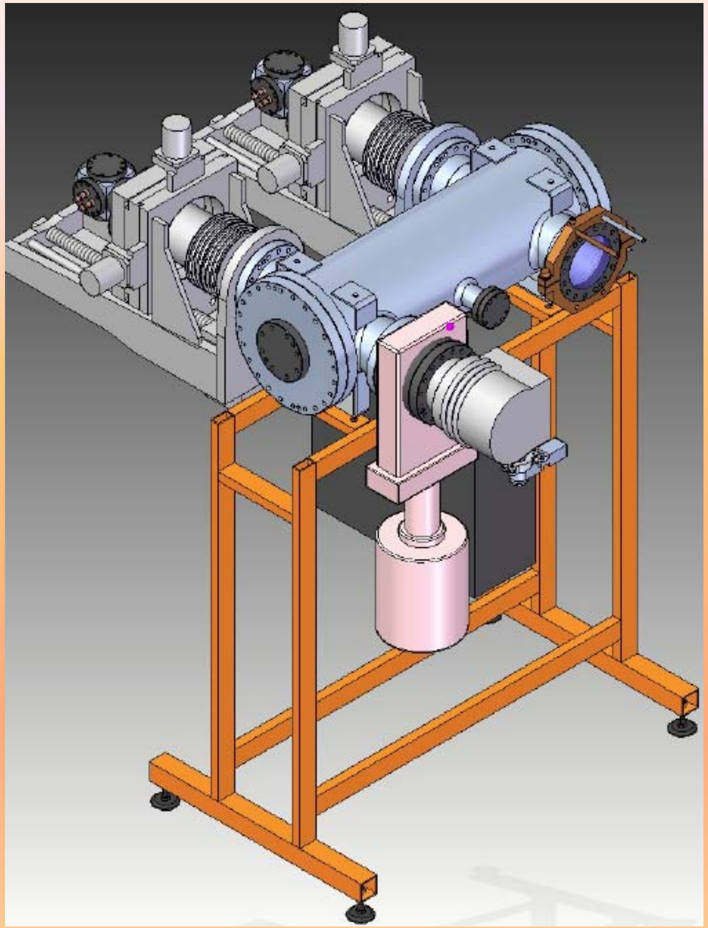
View of the SASE-1&SASE-2 MCP detector.

The MCP imager and two MCP pulse energy monitor are removed in horizontal direction, so it provides completely empty aperture of MCP vacuum chamber at diameter of 201 mm.

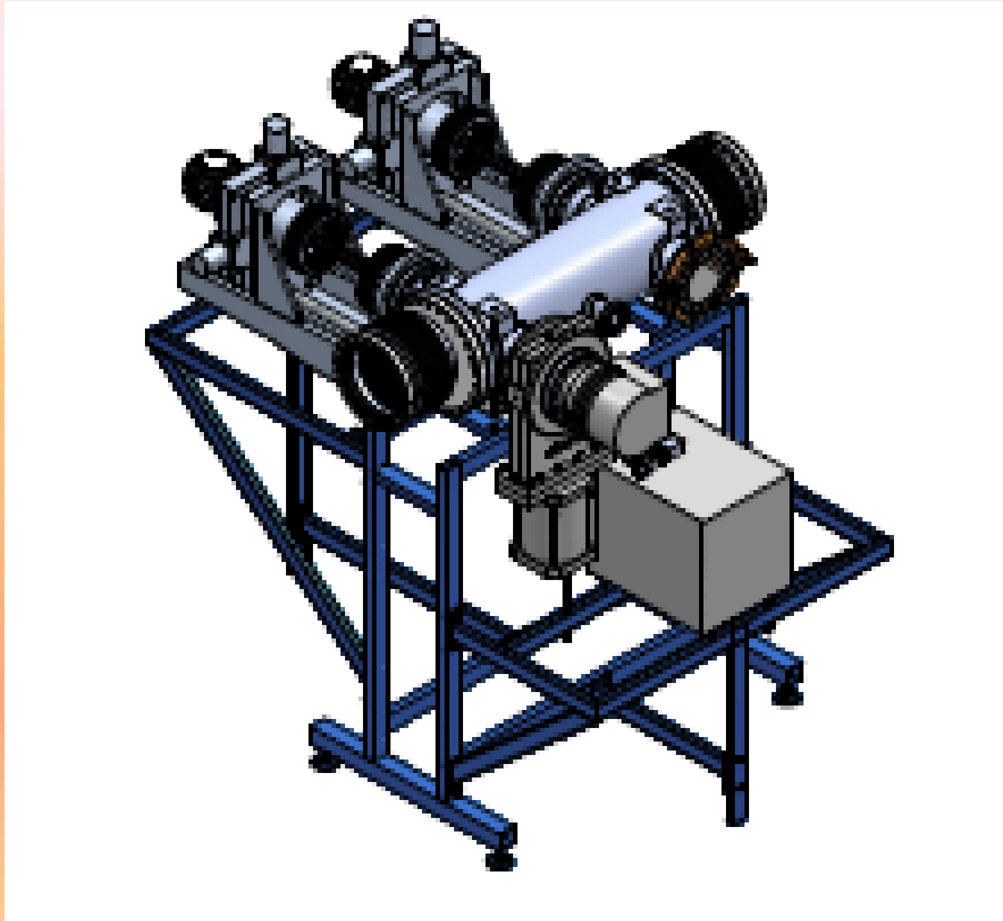


SASE-1&SASE-2 MCP detector with bellow sections for connection with mirror chamber and XFEL chamber.

3 D design of SASE1 and SASE 2 MCP detectors



SASE-1&SASE-2 MCP detector



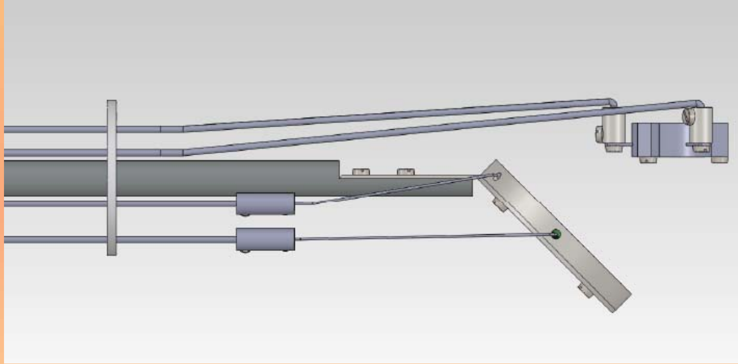
SASE-1&SASE-2 MCP detector with bellow sections

Equipment of MCP detector

The first MCP detector port houses two F4655 Hamamatsu MCPs 18 mm in diameter, which are used for measuring the pulse energy and used searching for the initial stage of the SASE regime.

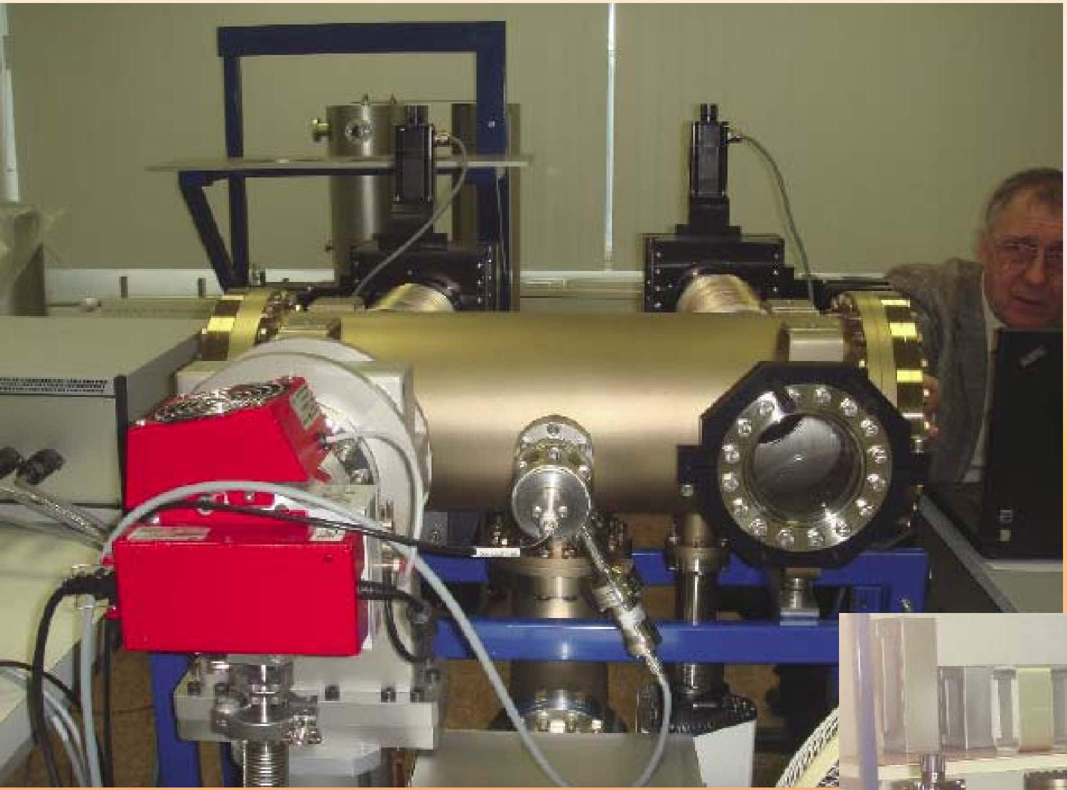
The PM 100-250 3D vacuum manipulator displays these MCPs in the horizontal direction at a distance of 203 mm. The MCPs have vertical displacement at a distance of ±2.5 cm relative to the beam axis. It permits a considerable increase in the vertical size of the SASE regime search area (20.3×6.4 cm) in comparison with the MCP diameter.

The special imaging MCP (model BOS-40-IDA-CH/P-47) 40 mm in diameter with a phosphorus screen and energy measurement (MCP F4655), installed in the second detector port inside the vacuum chamber. These MCPs are also displaced in the horizontal direction at a distance of 203 mm and in the vertical direction at a distance of ±2.5 cm relative to photon beam axis. To provide imaging through the glass window in the CCD, the incident photon angle to MCP surface is about 45^0.



F4655 MCP and imaging MCP (model BOS-40-IDA-CH/P-47)

SASE1&SASE 2 MCP Prototype Construction and Tests



Tests of SASE1&SASE2 MCP Prototype
(February 2012)

SASE 1 and SASE2 MCP detector component specification

Pos.	Quan pcs	Item
1	2	Model BOS-40-IDA-CH/P-47, Internal Imaging Assembly, P-47 Phosphor screen, Dual MCP
2	4	MCPF4655
3	1	Dual controller 1 ion pump negative, RS 232 9297012
4	2	UHV Manipulator, Z-travel 250 mm X,Y-trave l±25 mm, Motor drive in all axesIncl. Motor controller 3-axis and PC-controller program , PM 100-250
5	1	Ion pump Valcon Plus 150 StarCell with heaters, 9191542 flange DN100CF-F, 125 l/s for N_2<10^{-11} mbar
6	1	HV cable, length 4 m 9290705
7	5	Ceramic spacer of Macor, 12 pins, Ø35 mm, 3,2 mm thick
8	6	Beryllium bronze tube connector for MCP wires and holder connections
9	1	CFL 100-A Elbow. Flanges DN100CF 103038
10	4	Blank flange DN40CF of 316L stainless steel
11	1	Blank flange DN63CF of 316L stainless steel
12	5	Blank flange DN100CF of 316L stainless steel
13	1	Blank flange DN200CF of 304 L stainless steel
14	1	Zero length Reducer DN200CF-DN160CFof 304 L stainless steel
15	2	E-CU-150-6 Cubes DN40CF 408008
16	2	E-CTS 100-40 Reducer DN100/40CF, length 75 mm, 1115037
17	1	CVP-100 Glass 7058 viewport, flange DN100CF, 1219993
18	1	VP-UV-C63 Fused silica viewport, flange DN63CF
19	4	Flange DN40Cf with four SHV-5 coaxial recessed feed troughs, max 5kV Dc, 5A
20	1	CVP-100 Glass 7056 viewport, flange DN100CF, Part Nr. 1210003
21	1	MCP detector holder 1 on the flange DN40CF
22	1	MCP detector holder 2 on the flange DN40CF
23	1	Frame stand
24	1	Camera holder
25	1	UHV chamber at diameter 200 mm of 316 L st. steel with flanges 2×CF200, 5CF100, 2 CF-40

XFEL SASE-1-SASE 2 -MCP detectors concept validation

PETRA III Door for MCP Prototype SR tests in 2012

Proposed beam lines are P0-P03, P05-P06, P08-P10. The bunch charge is 20 nC, the bunch repetition rate corresponds to 192 nc, the photon flux is of 10^{10} -10^{12} ph/s. The photon energy range corresponds to 5.4 -29.4 keV. The photon beam size (FWHM) at the MCP can be less or around 30 μm.

The planned program of MCP measurements:

1.*Calibration experiments at hard X-ray radiation*

1.1 MCP gain versus MCP voltage at different photon energies at range 5.4 -29.4 keV

1.2 Measurements of MCP photon conversion efficiency in range of 5.4 -29.4 keV

2.*Absolute measurement of photon pulse energy*

2.1 Absolute measurements of photon pulse energies between 0.2 nJ and 20 nJ.

2.2 Measurements of photon pulse energy fluctuations at a level 0.3%.

2.3 Pulse to pulse photon energy measurements with 192 ns repetition intervals

3. *Image measurements*

3.1 Visualization, with the MCP imager of SR beam size at a spatial resolution of the MCP imager 30 μm

3.2 Pulse to pulse photon size measurements at 192 ns repetition intervals.

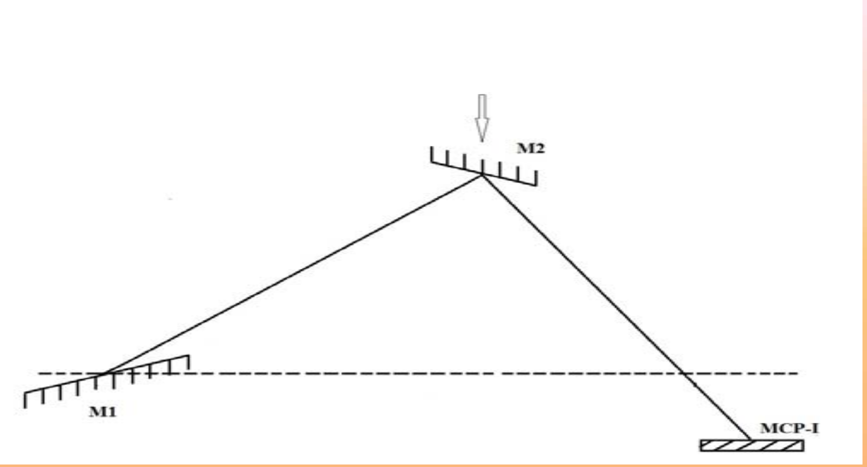
4. *Influence of breamsstrahlung produced aet electron energy of 6 GeV on MCP operation.*

ESRF for MCP Prototype SR tests in 2012

Proposed beam lines are ID01-ID03, ID09B, ID10A, ID10B, ID10C, ID13, ID14-4, ID 21. The bunch charge is 20 nC, the bunch repetition rate is about 200 nc, the photon flux is of 1010 -1012 ph/s. The photon energy range is placed in a range between 3 keV and 30 keV. The photon beam size (FWHM) at the MCP can be less or around 50 μm.

Spot horizontal position in MCP detector

The SASE1& SASE2 MCP is placed at the distance L_2= 1.75 m from the middle of the second mirror. The distance between the middle points of the first and second mirrors is L_1=10.4 m.



Sketch of SASE1 & SASE2 MCP and two reflection mirrors

When two mirrors are used, the horizontal position of the X-ray spot displacement in the MCP relative to the undulator axis is determined by the photon incident angles θ1 and θ2 on the first and second mirrors.

The horizontal X-ray spot displacement is

$$\delta x=2L_1\theta_1-2L_2(\theta_2-\theta_1).$$

When only the first mirror is used, the horizontal light spot displacement in the MCP is

$$\delta x=2(L_1+L_2)\,\theta_1.$$

The system with two mirrors easily provides the attenuation factor $R=10^{-3}$ at all wavelengths in the range of 0.1-0.4 nm on the first undulator harmonic. The operation with one mirror permits implementation of the scheme for hard radiation at a wavelength of 0.05-0.1 nm and attenuation factor $R=10^{-2}$-10^{-3}.

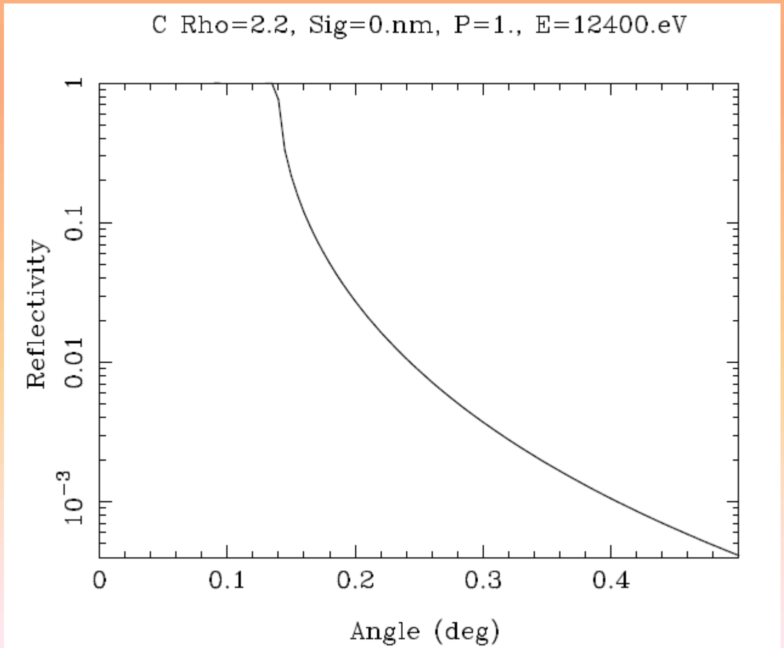
ATTENUATION OF XFEL RADIATION

Mirror attenuation

C mirror in the SASE-1 and SASE-2 MCPs is used as an attenuator. Attenuation of the photon radiation signal is effected by a plane C mirror in combination with a diamond attenuator. The C mirror reflectivity is reduced by the factor R when the incident angle is

$$\theta_R(\text{mrad})=25.5\times \lg(R^{-1})\times\lambda(\text{nm}).$$

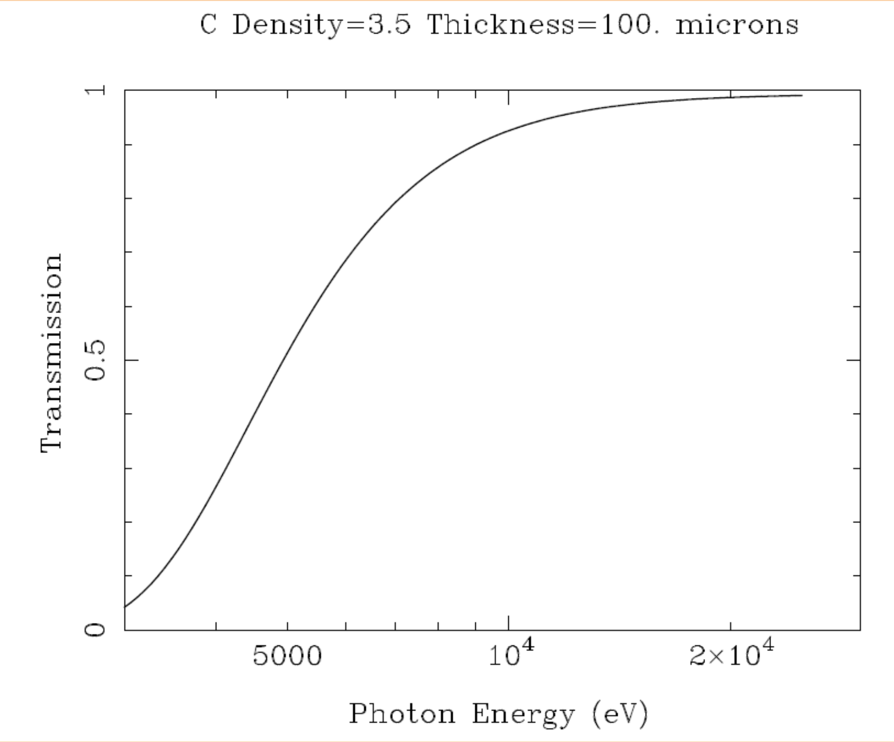
At the wavelength of 0.1 nm the reflectivity is close to 100% at the incident angle of 0.15^0 (2.6 mrad). The maximum incident angle for the first mirror is 3.6 mrad (0.206^0). The attenuation of the reflectivity is reduced to 3×10-2 at this angle. The use of two mirrors for photon beam attenuation permits the intensity reduction more than 2.5×10^{-5}. At the FWHM photon beam diameter of 0.5 mm the FWHM spot size on the C mirror is about 20 cm.



Dependence of the C mirror reflectivity on the incident photon angle.

Diamond plate attenuation

Diamond plates are used as the solid attenuator of FEL radiation. Dependence of the photon transmission through a diamond plate 100 μm thick on the photon energy is shown in Fig. The attenuation coefficients at λ=0.4 nm are T=0.1 at 81 μm, T=10-2 at 162 μm, and T=10-3 at 243 μm.

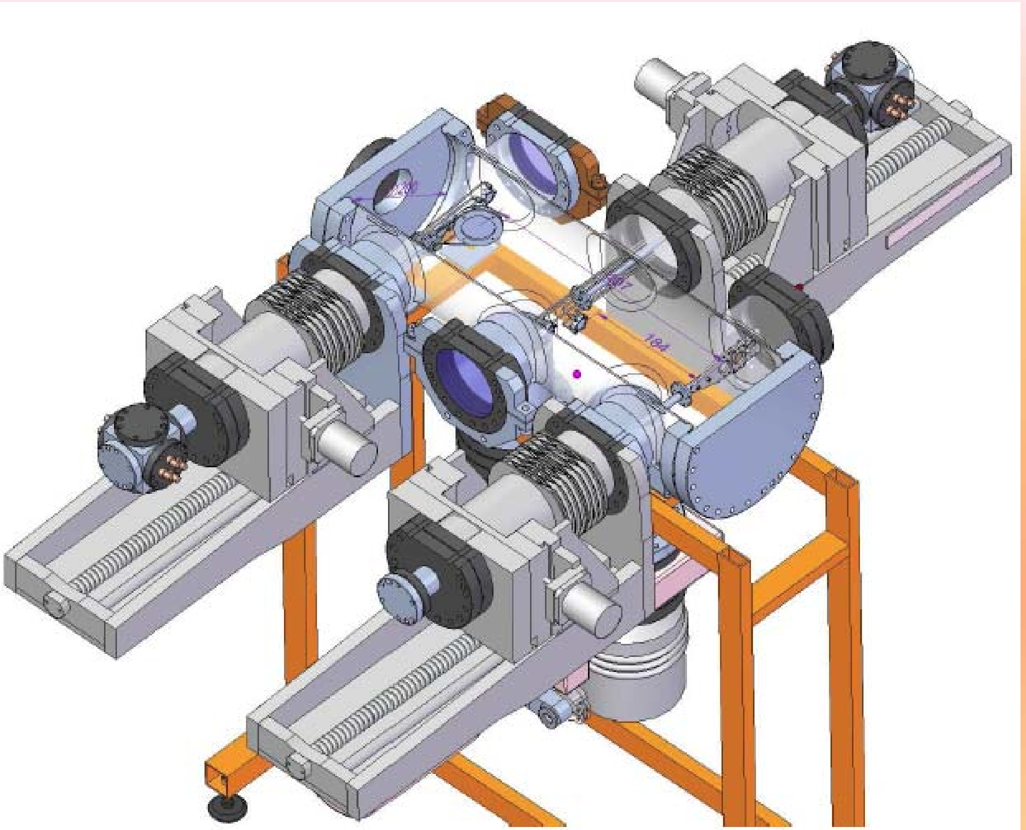


Dependence of the photon transmission through a diamond plate 0.1 mm thick on the photon energy.

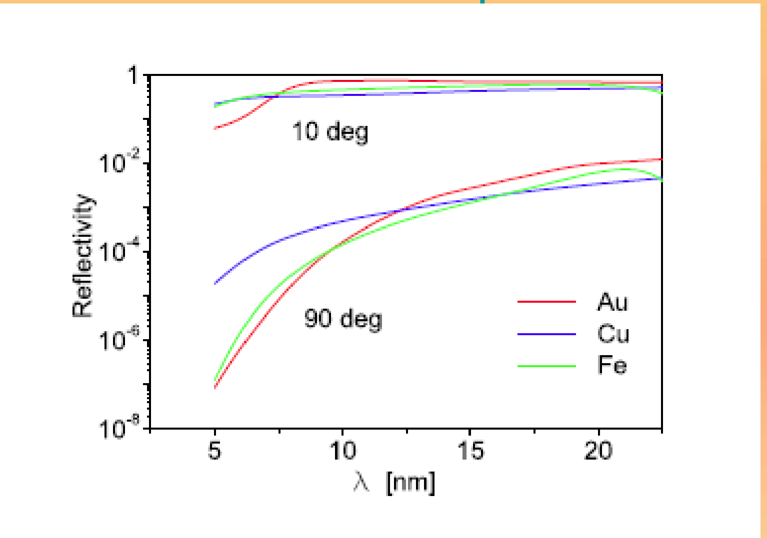
At λ=0.1 nm the diamond plate permits the following attenuation coefficients T to be reached at the zero photon scattering angle depending on the plate thickness: T=0.1 at 0.5 cm and T=10^{-2} at 1 cm. The attenuation coefficient in the plate is dictated by the photoeffect. The fraction of Compton- scattered photons is 27%, and the fraction of coherently scattered photons is 24 % at the attenuation of 10^{-1}.

Design of of the SASE-3 MCP detector

The MCP detector for SASE3 has an additional port with movable semitransparent mesh and wire targets for production of scattering FEL radiation similar to those used at FLASH.



The SASE3 MCP is placed at the distance L_2= 1.5 m from the middle of the second mirror. The distance between the middle points of the first and second mirrors is L_1=3.89 m.



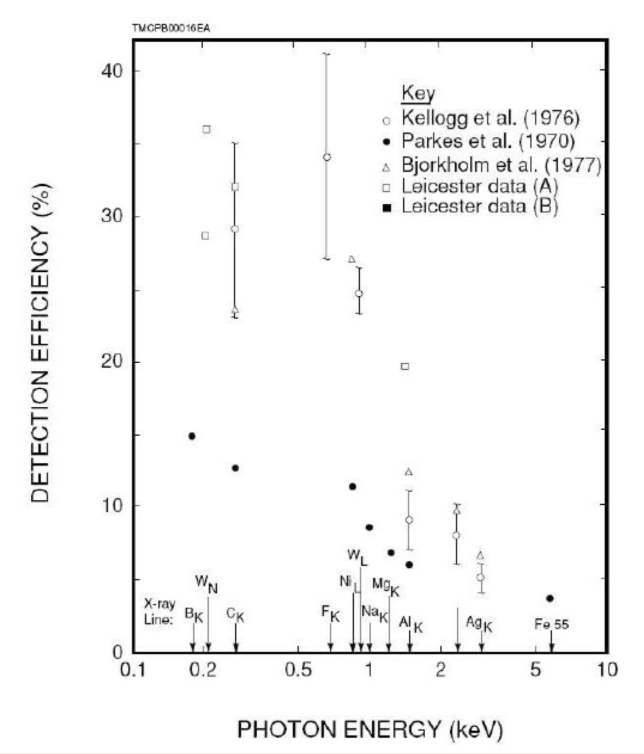
View of the SASE-3 MCP detector.

The special movable Fe and Cu targets are installed in SASE 3 MCP vacuum chamber before MCP detector, to provide large variation of SASE 3 signals at different observation angles of scattered radiation.

Comments to Review of Dr. T. Tschenscher from 13.02.12 and 15.02.12

The requirement described in the abstract are pretty good and it would be very good to achieve them in order to easily achieve an efficient SASE search. However, I'm still of the firm opinion that MCP detectors are not the proper choice. This is true definitely for the hard x-ray branches at SASE 1 & 2, but possible even for SASE 3.

The commissioners and operators of FLASH have a very distinctly different view on this and requested such devices as mandatory for commissioning and SASE optimization. Their everyday experience is also for later operation phase, that they use these detectors extensively during wavelength tuning and subsequent SASE optimization.



Dependence of MCP detection efficiency on photon energy

Before even continuing with this work one should get to see experimental data observed e.g. from synchrotron radiation to prove the response function of the MCPs (photon energy range, efficiency, saturation and dead time effects). Once this is successfully achieved one could continue in the design.

A MCP prototype for hard Xray tests (e.g. at PETRA III or ESRF tests) was currently constructed and these tests are planed in summer 2012 and must address the response function in question as you mentioned them (efficiency etc.). Concerning the MCP response to X-rays, there is literature data provided in the CDR.

Either I missed this or the issue of damage (both to foils used for coating the MCPs and of the MCPs themselves) is neglected. This should be included and experimental data would be helpful.

M. Yurkov comments

Currently we use direct exposure of MCP at FLASH when searching SASE at short wave lengths below10nm. Typical SASE pulse energies when we finish search procedure is about a few uJ, Fwhm photon beam size on MCP is 2-5 mm. Number of pulses is up to 30 per train. Up to now we did not detect degradation of MCP. May be, these experimental observations can be scaled to the case of EXFEL.

MCP material is lead-silicate glass(20-40% weight PbO). Electrode material is Inconel (Ni-Cr alloy, a few microns layer). When estimating damage one should take into account shallow angle (about 8 degrees) of MCP channels with respect to incident photon beam.

E.Syresin comment

We also plan to study effects of MCP degradation at SR tests on PERTA III or ESRF.

The document describes not only the MCPs but a combined operation of mirrors and MCP to reach the proposed goal. This makes the whole operation highly complex and the risk of failure extremely high. I would definitely not use such a complex and little determined system for the commissioning phase of the European XFEL. Keep in mind that neither the reflectivity of the mirrors is known, nor the cut-off region can be well described by theory. It will be pure try-and-error to find settings giving you an absorption needed for the MCPs to survive. Not even considering that this is a regime in which one would not want to operate the mirrors due to the enhance absorption.

The combination with the offset mirrors was extensively discussed in early 2011 between Sinn, Yurkov, Syresin, Molodtsov, Geloni, Gruenert, Freund, and others. It was decided that this application of the offset mirrors is feasible and the most reasonable configuration, and should be used. Also, the option to use 0, 1, or 2 mirrors was highlighted and supported in the design layout.

For any regimes with 0, 1 and 2 mirrors the MCP monitors can be displaced in horizontal direction, so it provides completely empty aperture of MCP vacuum chamber at diameter of 201 mm. Finally, we should provide clearance in horizontal direction from -80 mm to +25 mm relatively to axis. We provide horizontal gap from -100.5 mm to +100.5 mm at displaced MCP.

During initial SASE search the configuration without mirrors will be used, and the beamline attenuators also are available. Only when SASE is found and intensity is increased for gain curve studies and SASE optimization, the mirrors are applied as attenuators. Detailed calculations about using the different mirrors for this purpose are included in the CDR.

T. Tschentscher conclusion from 13.02.12:

a) First test MCPs with x-rays and measure response function(s).

Tests of this kind with a prototype chamber are foreseen in 2012.

b) Develop a new concept without offset mirrors. A possibility would be to concentrate really on the regime with very little SASE gain and use build-in or beamline solid absorbers.

This is described in the CDR as the initial operation with beamline absorber use, without use of mirrors. A new concept is not required.

c) In the present version I consider the MCP system as a high risk item, which will draw a lot of resources and poses a considerable risk to start of operation.

This device will lower the risk to be stuck without lasing, therefore it will improve the probability of timely start of operation. Also the MCP monitors can be displaced in horizontal direction, so it provides completely empty aperture of MCP vacuum chamber

In my view the CDR needs to be correspondingly rewritten and resubmitted.

Not mentioned so far: apart from its use for later FEL-beam imaging, the MCP-imager will allow to trouble-shoot in a commissioning situation when there is only low intensity radiation and the need to understand the background (e.g. dipole radiation or even radiation originating from upstream of the undulator) which might fool other (transversely integrating) systems. This is a lesson learnt from more recent studies at FLASH.

1. MCPs are not suitable detectors for hard x-rays. This was mentioned several times in the past and is demonstrated by the 1000s of hard x-ray

There are other SR instruments that have used MCP detectors for direct X-ray detection, see e.g. FEL09 contribution TUPC23 [4] by Kazuyuki Sakaue, Waseda University, Japan (kazuyuki.sakaue@aoni.waseda.jp). They upgraded from a prior setup [3] with LYSO sciintillator and PMT detector to the later version using direct X-ray detection with MCPs. Concerning fast enough time response: in above case, the rep-rate was even much higher than at XFEL.EU: 100 X-ray pulses in 280ns (typical SR multibunch mode).

The MCP producer ARRADIANCE provided more detailed hard X-ray efficiency data, where it is roughly 1% < QE < 12% in the range 1 – 10 keV, and ~1% up to the 25 keV.

One reason why MCPs might not be so interesting for SRs is that the dynamic range requirement at SR is more relaxed compared to the XFEL-requirement when spontaneous radiation and FEL light shall be detected on the same detector.

M. Yurkov comments

1.My conclusion is that present concept and design of MCP detector for the European XFEL is sufficient to reach goal for searching and tuning SASE in the whole wavelength range and whole range of FEL intensities. As we already demonstrated at FLASH, measurement with MCP detector of full bunch train is possible with individual resolution of the pulse energies of each pulse in the train. MCP Tool software developed at FLASH can be used as a starting for development of relevant software for the European XFEL MCP Tool.

2. These are detectors serving needs of SR users with diferent goals. Currently we have only LCLS and SACLA FELs. Situation with detectors there is not a bible, and there are lot of problems there. I can not add more arguments in addition to those expressed in CDR and my review note attached here. Present design is based on working prototypes. There is no extra physical or technical problems when moving from 4 nm to 0.1 nm - just moderate reduction of the efficiency. An order of magnitude of efficiency reduction is easily compensated by tuning HV of MCP by 100 V.

As I suggested one should not proceed until the x-ray tests using similar/comparable conditions with the MCPs of choice have been performed successfully.
In case you did not understand: This critics is not about the method of tuning used at FLASH, but about using MCPs for hard x-rays. You should not compare the situation at FLASH since for hard xrays there exist a multitude of single photon sensitive x-ray detectors and using absorbers a dynamic range of 10^5-10^6 should be no miracle. If I remember correctly, the SASE gain compared to spont. rad. is something like 10^4. Why not use a standard x-ray detector coupled to an absorber ?

The SASE gain compared to the spontaneous radiation is 10^6 to 10^7 depending on wavelength (the specs for the MCP detector take this into account). The HV of the MCP can tune the MCP sensitivity over ~10^3, and the beamline absorbers can provide max. 10^2 attenuation, so that for full FEL intensity additional attenuation by the mirrors is advisable.
Calibrated PtSi photodiodes (we require 1% rel. accuracy!) saturate at 100-500 nJ, and the destruction level is ~10mJ/cm^2.
In first versions of MCP detectors for TTF FE:/FLASH semiconductor detectors were installed, but they never have shown predicted behaviour. The problem was high local power density and ultrashort (femtosecond) pulses resulted in early and strong local saturation effects of the signal.

2. The use of the mirror cut-off regime I still consider highly speculative. Well understood: for commissioning! Once everything is well characterized one surely can operate the mirrors in this regime and can make statements about the reflectivity, but not during the commissioning phase. I'll ask Harald about that past meeting, but I had up to now the impression that he was critical too. I personally consider this idea as high risk operation not suitable for the commissioning. I would like to see how it compares to the use of solid absorbers instead the mirrors.

a) for the first, initial commissioning when there is only SR light, it is planned to directly illuminate the MCP without any mirrors
b) in that situation, there will be also photo diodes as part of the K-Mono / 2D-imager setup, but the MCP detector has a larger dynamic range
c) for that phase the solid/gas attenuators of the beamline will be important and applied for attenuation
d) AFTER first lasing, when SASE is established, at increased intensity, diodes will saturate, and then it is planned to additionally attenuate with the mirrors before hitting the MCP
e) The application of the beamline mirrors for attenuation was suggested by and developed together with Harald in many meetings (not just one...), and as he repeated below, this is technically feasible.
f) The main advantages of attenuation by mirrors:
i. high-energy radiation (SR, Bremsstrahlung from Dipole, etc.) is cut off effectively which reduces thermal load, and improves S/N
ii. higher harmonics of the FEL are effectively suppressed which is important for the gain curve characterization and harmonic content determination. This is not possible with absorbers.
iii. Solid absorbers offer only more or less discrete attenuation, whereas the attenuation by mirrors can be continuously tuned with the angle.

Imaging using MCPs. Whether this device is superior to a fluorescence screen needs to be shown. Yet I'm not convinced.

The MCP imager also contains a phosphor screen, however it offers additional “gain knobs” compared to a pure fluorescence screen. The performance of this component was estimated in simulations (Litrani code), and will be evaluated in experimental tests. Additionally, the MCP-HV could be.

In summary I fully maintain my conclusions. Of course we need a technique for the commissioning period. But your proposal is too risky.

The configuration of the MCP detector using the beamline mirrors as attenuators is not foreseen for the initial commissioning until first lasing. In this first phase the conventional combination of direct illumination and using beamline absorbers is planned. One special feature of the MCP detector design, the large transverse scanning range of the MCPs, reduces the risk to spatially miss the SASE beam.