A Photon Beam Diffuser for the ATHOS Beamlines at SwissFEL

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Abstract. SwissFEL is a free electron laser at the Paul Scherrer Institut in Switzerland, which became operational by the end of 2017. Initially, it will host two undulators ARAMIS and ATHOS. The former is operational and generating tender to hard x-rays (2 to 12 keV), whilst the latter is in the process of being installed and will provide soft x-rays ranging from 0.2 to 2 keV. Each undulator will eventually serve three different endstations.

Recent Genesis [1] simulations have shown that the ATHOS branch can operate in a high-power mode, which will increase the photon pulse energy by one order of magnitude to 8.1 mJ at 250 eV. This will lead to peak beam intensities inside the frontend, which will damage any normal incidence absorber. To overcome this issue a photon beam diffuser is proposed in this paper. At the core of this instrument is a bent rod, which is positioned at a grazing angle relative to the incident beam, so that it acts like a defocussing mirror, reflecting most of the incident power and increasing the divergence of the reflected beam. Due to the increased divergence, the beam diameter is increased by a factor of 10 after propagating over a few meters, thus reducing the peak intensity by a factor of 100 to a level, which can be safely absorbed by a normal incidence absorber.

INTRODUCTION

Figure 1. Operational Modes of the ATHOS Beamline

The ATHOS beamline will use a series of 16 AppleX undulators [2] with a period of 38 mm and a single device length of 2 m. These are ex-vacuum devices with k values ranging from 0.9 to 3.6, permitting to continuously vary the polarisation between linear and circular. The linear accelerator can generate electron bunch energies between 2.9 and 3.15 GeV with a bunch charge of up to 200 pc. In combination with the undulator this will cover a photon-beam energy range from 200 to 2000 keV. In addition to this the machine can run in several different modes like high-bandwith, high-power or two-colour (see Table 1). Concerning damage on components exposed to the x-ray pulse, the high power mode at low energies is the most critical mode. It is most likely to inflict damage onto the exposed component, due to the very limited penetration depth of the x-ray beam, hence depositing most energy in a very thin surface.
sheet. Recent Genesis [1] simulations have shown that in high power mode a pulse energy of 8.1 mJ at 200 eV can be reached. In this paper we will discuss how to mitigate the impact of this most demanding mode onto the front-end photon beam absorbers.

**Damage threshold for normal incidence photon beam absorbers**

A beam stopper as shown in Figure 2(a) has to stop any radiation generated inside the machine from entering the downstream hutch through the beam port, when the machine is running and access to the hutch is required. Therefore it is part of the personal safety system. At a storage ring such a device is typically implemented by using a several ten centimetre thick block of Tungsten, with a cooled grazing incidence copper surface in front of it to absorb the heatload associated with the x-ray beam. For a free electron laser like SwissFEL, which operates at a maximum repetition-rate of 100 Hz, the impinging heatload will be less than 1 W for pulses with 8.1 mJ. Assuming that this heatload is fully absorbed by a 50 mm × 50 mm in-vacuum metal plate, which is considered to be thermally insulated as a worst case scenario, then only radiative cooling is possible. In this case Stefan-Boltzmanns law requires that the plate will be ≈30 °C (considering two surfaces) above ambient temperature to ensure a heatflow of at least 1 W. Hence heatload effects are negligible in contrast to the high peak-power of the x-ray beam, which drills a hole into most materials. To prevent this, a material with a low absorption coefficient like B$_4$C is required, so that the pulse energy is deposited over a larger volume. Therefore a 30 mm thick B$_4$C plate is installed in front of the tungsten block to absorb the x-ray pulse. As an additional safety feature, there is a nitrogen filled chamber, called a burn through monitor, between the B$_4$C plate and the tungsten block. Should the x-ray laser beam ever drill trough the B$_4$C, then the gas from this chamber will leak into the machine vacuum and lead to a pressure increase, which in turn will trigger the machine protection system, such switching off the machine immediately, before the x-ray laser beam can inflict significant damage on the tungsten absorber. If the photon energy is reduced the absorption length reduces and thus the energy absorbed per volume B$_4$C increases again. With a pulse energy of 8.1 mJ at 250 eV the damage threshold is once more surpassed (see Figure 2(b)) and the x-ray laser pulses would drill through the B$_4$C plate at a rate of 1 mm in 14 sec, using the dose to melt approximation to estimate the burn through speed. To enable the safe operation of the machine at these energies with the beam stopper intercepting the beam, additional measures have to be considered as detailed in the next sections.

**Damage threshold and ray-tracing calculations for a reflecting grazing incidence rod**

The most obvious solution to the issue described in the previous section is to use a grazing incidence surface, so that the x-ray beam is spread out over a much larger area. But reducing the angle of incidence, also reduces the penetration depth of the x-rays normal to the surface and thus the amount of energy absorbed per unit volume is not significantly reduced. This only changes, once the incident angle goes below the angle of total reflection $\sqrt{2}\delta$.
whereby $\delta$ corresponds to the refractive index decrement [3], and thence most of the energy is reflected. In Figure 3 the absorbed dose per atom is shown versus the incident angle for $B_4C$ and silicon for various photon beam energies. The associated pulse energies and beam parameters are based on the values calculated for the ATHOS undulator operating in high power mode at a location 39.5 m downstream of the last undulator, which is where we anticipate to install a photon-beam diffusor. These dose to melt calculations show, that for low Z materials one does not surpass the damage threshold (dashed black line) and thus can safely reflect the photon beam.

Since the beam reflected by the grazing incidence surface is only insignificantly weaker than the initial beam, it will still damage any absorber, unless its energy density is considerably reduced. This can be achieved by using a grazing incidence rod, which will behave like a sagittally defocussing mirror and thus expand the beam diameter over a relatively short propagation distance, which consequently reduces the peak intensity of the beam. The performance of the diffusing rod can be improved even more by also adding a convex meridional bend to the rod, so that it has a torodial shape and is defocussing in two directions. In Figure 4 ray-tracing simulations using XRT [4] are shown to demonstrate the feasibility of the scheme. Subfigure (a) shows the footprint of the beam on the absorber, whilst Subfigure (b) shows the beam diameter at an absorber 7.5 m further downstream. At this position the beam size is increased from less than 1 mm to over 10 mm, thus reducing the peak-intensity by more than hundredfold. Subfigure (c) shows that the diffusor is still working, even if a significant missalignment of 45 $\mu$rad in the diagonal direction is added to the incident beam and an even smaller diameter rod at a lower grazing angle is used.
Parameter | Specification
---|---
Angle of incidence | 13 – 15 mrad
Length | 800 mm
Diameter (2×Sag. Curv.) | ≤20 mm
Meridional Radius of Curvature | convex: 80 – 120 m
Angular Point | ≤1 mm
Material | Si, Al
Slope-error surface | ≤10 urad
Micro-roughness surface | 1 nm(rms)
Coating | 100 nm of B$_4$C
Reflectivity | >90 %
Photon-Beam Size | 1.3 mm(FWHM)
Beam Footprint on Rod | 86 mm(FWHM)

**FIGURE 5.** Schematic sketch of the photon beam diffusor and a typical set of design parameters for the diffusor rod. It is important to note that the sketch is not to scale, namely, in reality, the deflection angle is much smaller than drawn and the normal incidence absorber is located significantly further downstream (i.e. 7.5 m from the rod).

**Proposed design for the photon beam diffusor**

In Figure 5 a schematic sketch of the photon-beam diffusor is shown in conjunction with typical design parameters for the toroidally shaped rod reflecting the beam and thus increasing its divergence. To increase the damage threshold of the rod, we suggest to consider coating it with an approximately 100 nm thick layer of B$_4$C. The upstream end of the rod is connected to a pivot bearing, whilst the downstream end is connected to a pusher, which can be implemented via a pneumatic motion and rotates the rod into the beam until it touches an arrester. The latter should be equipped with a limit switch signalling that the rod is in its correct in-position. During normal operation, the photon-beam diffusor will be flipped into the beam, before the beam stopper is moved in. It is important to note that the diffusor is not a part of the personal safety system, but rather a device, which ensures the integrity of the machine, and thus helps to guarantee uninterrupted machine operation. The radiation safety is implemented via the burn through monitor: If the diffusor rod fails to move in and that is not signalled to the machine protection system via the in-position limit switch, the photon-beam will hit the B$_4$C plate in front of the beam stopper. Once the beam drilled a hole through the plate, gas will leak into the machine vacuum and the increased pressure will trigger an emergency shutdown of the machine.

**Summary**

In this paper we have shown via dose to melt calculations and ray-tracing simulations, how to overcome damage threshold limitations for beam-stoppers required for soft x-ray beams with a high peak power, like the ATHOS beamline at SwissFEL. To achieve this goal we use a convex toroidally shaped rod, which is exposed to the incident beam under such a small grazing incident angle, that its mirror-like surface will reflect most of the beam energy and due to its convex shape the peak beam intensity is reduced by two orders of magnitude after a short propagation distance. We have concluded the paper by proposing a practical implementation of such a device.

**REFERENCES**