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Operating the LCLS gas attenuator and gas detector system with apertures of 6 mm diameter*

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Abstract

The possibility of increasing the apertures of the LCLS gas attenuator/gas detector system is considered. It is shown that increase of the apertures from 3 to 6 mm, together with 4-fold reduction of the operation pressure does not adversely affect the vacuum conditions upstream or downstream. No change of the pump speed and the lengths of the differential pumping cells is required. One minor modification is the use of 1.5 cm long tubular apertures in the end cells of the differential pumping system. Reduction of the pressure does not affect performance of the gas attenuator/gas detector system at the FEL energies below, roughly, 2 keV. Some minor performance degradation occurs at higher energies.

Disclaimer

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This report was prepared in a draft form in December 2007. At that time the diameter of the apertures of the gas attenuator/gas detector system was supposed to be 3 mm. The main objective of the note was to assess the feasibility of increasing the apertures to 6 mm and evaluate the effect of related trade-offs. Since then, decision was made to increase the apertures to 4 mm. Still, we have thought that a coherent discussion of possible further increase of the diameter (up to 6 mm) might remain useful, should the need of that increase appear at some point.

As a reference system we choose the one with apertures of 3 mm, as there exist detailed reports [1-4] describing gas attenuator and gas detector properties for this size of the apertures.

One can note that the diameter of 3 mm is more than sufficient to admit the whole FEL beam, whose diameter even in the low energy range will not exceed a fraction of a millimeter. The need of a substantial increase of the size of the apertures may arise at the commissioning phase of the LCLS facility, to allow for a possible uncertainty of the beam centroid at this early stage of operation and tuning. The increase of the size may also be desirable to admit a much larger fraction of the spontaneous radiation – to better understand the performance of a wiggler. In the course of operation, other (hard to foresee now) reasons may also appear.

Conceptually, the increase of the aperture is certainly possible without any change of assumed maximum pressures in either the gas attenuator (20 torr) or the gas detector 2 torr): one would "just" have to use higher-speed pumps. However, switching to higher-speed pumps would increase the cost of the system; in addition, space limitations may make a 4-fold increase of the pump speed a difficult task; finally, the working gas throughput would increase by a non-trivial factor of 4 (compared to the reference, 3-mm case).

So, we have chosen a different approach, in which we will not change the pumps or the lengths of various cells, but rather reduce the maximum operation pressure in both the gas attenuator and gas detector by a factor of 4 (i.e., to 5 torr in the gas attenuator and 0.5 torr in the gas detector). We will then assess an impact of this pressure reduction on the performance of the system, in particular, on the attainable attenuation and on the magnitude of the signal from the gas detector. Our conclusion is that, for a lower-energy range of the FEL, below roughly 1.5 keV, no noticeable performance degradation will occur. In the range of 2-3 keV, the attainable attenuation will be affected stronger, but will still be significant (factor of 2 at 2.5 keV, sufficient for, e.g., tests of the linearity of the gas detector). At still higher energies, the attenuation will be performed by a solid attenuator anyway, so that the lower pressure in the gas attenuator will have no significant effect on the attainable attenuation.

With regard to the gas detector, the lower maximum pressure in it will have no effect on its performance at lower FEL energies, below ~2 keV. At higher energies, there will be some reduction of the optical yield. However, as was shown by the modeling supported by direct experiments (Ref. [1]), even at 8 keV the signal for the nominal pulse energy of 2 mJ will be orders of magnitude higher than the noise level.

The overall design of the system will not change, except for introducing 1.5 cm long tubular apertures (instead of an orifice) at the windows of the last cell. As discussed below, the presence of these short tubes is compatible with a design constraint related to the possibility of removal of all the material windows and creating a 3-cm diameter clear aperture throughout the system (of course, without any gas throughput in this case). If introduction of the tubes proves to be not too complex, one may consider adding tubular apertures also to the gas detector cells: this would limit the flux to these cells in the regimes where the cell pressure is much smaller than that in the attenuator.

Schematic of the system is shown in Fig. 1. [More details can be found in Refs. 1-4.] Only the part directed towards the accelerator is actually shown; there is a symmetric part pointing in the direction of experimental halls. The lengths of the cells are not to scale in Fig. 1. Cell #0 is the gas attenuator, whereas cell # 3 is the gas detector. The tubular apertures have to be introduced in cell #5. In a rough sketch of Fig.1, all apertures are shown as simple orifices. The schematic of the tubular aperture is shown in the inset.

The plot of log$A$, with A being the attenuation coefficient, vs the energy of X-ray quanta for the energies below 3 keV is shown in Fig. 2, for the pressures in the attenuator of 20, 5 and 1 torr. One sees that, for the pressure of 5 torr, the achievable attenuation exceeds ~100 for the energies below ~ 1.5 keV. Attenuation is significant (higher than 2) even for the energies as high as 2.5 keV. The solid attenuator can be used at the energies exceeding ~ 2.5 keV.

The performance of the gas detector at lower energies will also be unaffected. Indeed, from the condition that the detector itself should not reduce the beam intensity by more than 5%, it follows that, at the energies below, roughly, 1.4 keV the operational pressure of the gas detector would have to be lower than 0.5 torr, anyway. At somewhat higher energies, up to ~ 2.5 keV, the pressure would still have to be kept lower than 0.5 torr because of non-linearities produced by space-charge effect [3].

The energies affected by the lowering of the pressure in the gas detector are those exceeding 2.5 keV. Here we have some loss of signal related to the lower pressure. On the other hand, both experimental results and modeling [1] show that the signals from the 8 keV beam would be detectable even for the pulse energy as low as a few microjoules.

So, we conclude that reduction of the operational pressure by a factor of 4 has only very minor effect on the performance of the system at the energies below, roughly, 2 keV. At higher energies, there is a modest impact: a need in a stronger emphasis on the use of the solid attenuator, and some reduction of the signals from the gas detector.

Consider now in more detail the impact of the larger apertures on the vacuum system. Reduction of the pressure by a factor of 4 allows us to exclude any adverse effect on the performance of the pump in the cell 1, adjacent to the gas attenuator. In the case of a reference values of the aperture diameter (3 mm) and the pressure in the attenuation cell (20 torr), the pressure in cell 1 would be ~ 0.5 torr. The pump in this cell operates near its capacity and would not be able to properly work at the pressure higher than that [2]. This means that the increase of the surface area of the aperture by a factor of 4 must be accompanied by reduction of the operational pressure also by a factor of 4, as we implied in the discussion above. The flow even at this reduced pressure will be a hydrodynamical flow, as the mean free path will still be couple of orders of magnitude smaller than the size of the orifice (see Ref. [4]). The total gas throughput will then scale as a product of the pressure and the surface area of the aperture, i.e., will not change. This, in turn, means that, for a given pump speed, the pressure in the cell 1 will not change, and the pump in this cell will not be strained any more than in the reference case.

As the pressure in cell 1 remains unchanged, the gas flow from cell 1 to cell 2 will increase by a factor of 4. If we do not change the pump in cell 2, the pressure there will also increase by a factor of 4. It will still be quite low, below 10 mtorr, and the mean free path will be larger than the diameter of the aperture (6 mm). So, the flow from cell 2 to the gas detector, if the latter is pumped to a low pressure, will be molecular. One can easily keep the pressure in the gas detector below 0.01 mtorr, if so desired.

At the pressure of 0.5 torr in the gas detector, the pressure in cell 2 will be the same as in the case of a 3-mm apertures and 2 torr in the gas detector. This again shows that the conditions for the pumping of cell 2 do not become more strenuous than in the baseline design.

Consider now the situation in cells 4 and 5. The pressure in cell 4 will be below 0.005 torr. This pressure corresponds to a mean-free-path of more than 1 cm. Accordingly, the gas flow between cells 4 and 5 will be molecular, and one can apply Eq. (15) from Ref. [4]. One then finds that for the disc apertures the pressure in cell 5 will be by a factor of 4-5 higher than in a baseline case. This leads to an increased outflow to the undulator. Specifically, using Eq. (15) of Ref. [4], we find that the outflow will now be 2×10^{-5} *torr*×*l/s.* On the other hand, as was evaluated by P. Stefan, in order not to have an adverse effect on the longevity of the ion pumps situated upstream and downstream of the gas attenuator/gas detector system, the outflow should not exceed 10^{-5} *torr*×*l/s* .

To reduce the outflow to an acceptable level, one can replace a disc aperture separating cells 4 and 5 by a tubular aperture, 6 mm diameter and 1.5 cm long. As analysis performed by M. Roeben has shown, installing such a tube is compatible with the currently used valves. This tube will have a conductance at least 3 times less than the disc aperture (Cf. Ref. [5]). Therefore, the pressure in cell 5 will drop by a factor of 3, and the leak to the external system will go down to an admissible level of 7×10^{-6} *torr*×*l/s.* If further reduction by another factor of 3 is desirable, one can install tubular apertures also at the exit from the cell 5.

Finally, we evaluate the effect of beaming. Eq. (14) of Ref. [4] can be used for this purpose. The use of tubular apertures does not introduce any significant reduction of the beam component, because the length of the cell is much greater than the length of the aperture. Applying Eq. (14), we find that the beam component of the leak will be 3×10^{-6} *torr×l/s.*

In conclusion: Increase of the apertures from 3 to 6 mm is compatible with the current design of the vacuum system, provided the maximum pressures in the gas attenuator and gas detector would be reduced to 5 torr and 0.5 torr, respectively. The pressure reduction will have no effect on the performance of the system for the FEL energy below approximately 1.5 keV. It will cause a modest reduction of the performance of the attenuator at the energies up to ~ 2.5 keV. At higher energies, the solid attenuator will have to be used. The output of the gas detector in the high energy range will be reduced, but will still remain sufficient for the reliable detection even for pulse energies of ~ 1% of the design value. The use of one or two tubular apertures on each side of the system would keep the leak to the rest of accelerator at an acceptable level.

Various trade-offs are possible, e.g., reducing the diameter of the aperture to, say, 4.5 mm and using the maximum pressures as high as 10 torr and 1 torr, respectively. Another option is to slightly reduce the aperture (from 6 to, say, 5 mm), without increasing the pressure. The leak to the accelerator volume will then decrease by at least a factor of 3 (if it is of a concern), and there will be no need in using the tubular apertures.

References.

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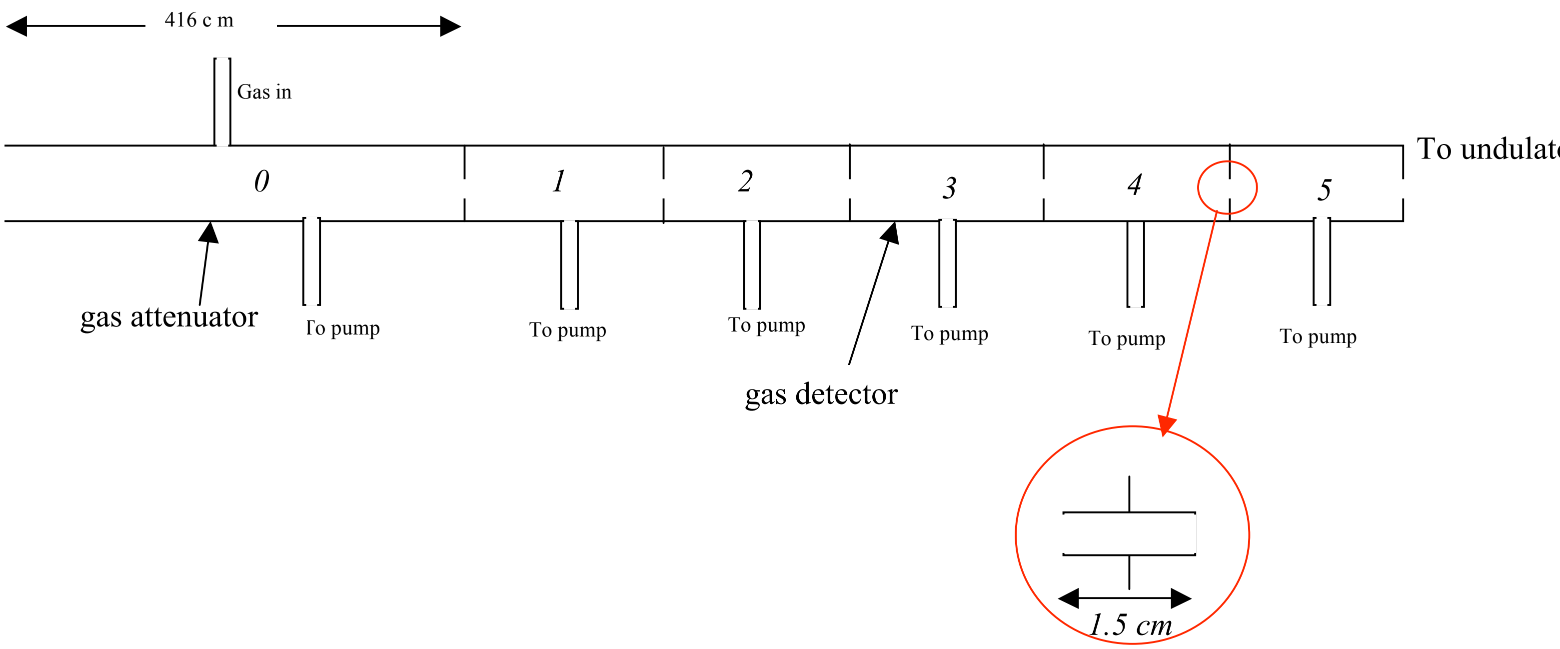

Fig. 1 Schematic of the gas attenuator/gas detector system. The length of the attenuator is 416 cm, the lengths of the subsequent cells are 31 cm (cell 1), 41 cm (cell 2), 48 cm (cell 3, gas detector), 39 cm (cell 4) and 39 cm (cell 5). An inset shows a schematic of a tubular aperture. Such an aperture can also be used at the other end of cell 5, if one would need to reduce the gas flow to the undulator by another factor ~ 2.

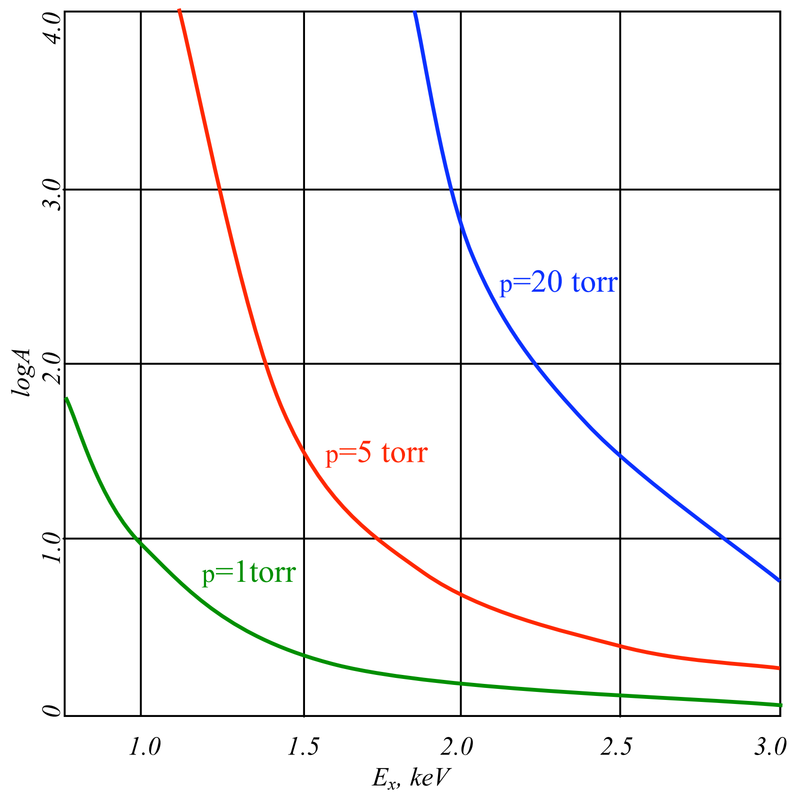

Fig. 2 Logarithm of attenuation A *vs.* the X-ray energy for three attenuator pressures, 1, 5 and 20 torr (nitrogen, attenuator length 4.16 m). Based on B.L. hence, E.M. Gullikson, J.C. Davis, http://www-cxro.lbl.gov/optical_constants/.