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Revision History

Revision	Date Released	Description of Change
R0	7/21/2014	Original Release.

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1 Introduction

These requirements form a basis for design to insure the properties of the electron beam are not adversely affected by residual gas in the beamline and to protect the permanent-magnet undulators from excessive radiation damage. They also insure the beam halo is contained and attenuated by the collimation system so that excessive radiation is not produced in sensitive areas.

2 Scope and Limitations

The scope of these requirements includes the vacuum enclosures for all LCLS-II electron beam lines, including existing beam lines down-beam of the merge magnet BXSP1H, which will experience higher average current when LCLS-II is operating than during LCLS operation. It does not cover x-ray beam lines or other electron beam lines at SLAC. These are default requirements to protect beam properties. Special equipment, such as SRF cavities or electron guns, may have need of more restrictive vacuum requirements to insure the proper function of such equipment [1]. Such requirements are not part of this document.

3 Requirements

3.1 Residual Gas Pressure Limits

During normal operation average residual gas pressure must be kept below the limits in Table 1. The average is to be taken over a period of 1 day and over a distance of roughly 100 m. That is, in any given 100 m section of beamline the daily average pressure must be below the stated limits.

The pressure requirements are expressed in terms of an effective pressure P_{eff} defined below. Different residual gas profiles will have the same effect on the beam if they have the same effective

Table 1: Limits on the effective pressure P_{eff}.

From	To	P_{eff} [torr]
Gun $z = 0$	BSY $z = 3000$	10^{-6}
BSY $z = 3000$	PCMUON $z = 3568$	10^{-8}
PCMUON $z = 3568$	BYD $z = 3744$	10^{-7}
BYD $z = 3744$	DUMP$z = 3775$	10^{-6}

pressure. The effective pressure is defined as:

$$P_{eff} = \sum_{i,j} P_j \left(\frac{Z_{ij}}{Z_0}\right)^{5/3}$$

where the sum is taken over j molecular species and the i atoms of each species, P_j is the partial pressure of the jth species, Z_{ij} is the atomic number of the ith atom on the jth species, and $Z_0 = 7$. For a residual gas composed entirely of CO, the effective pressure will be approximately the same as the measured pressure. On the other hand a gas composed mostly of hydrogen, because of the low atomic number, will have an effective pressure that is less than 4% of its measured pressure. Pressure rather than density is quoted for convenience. If the residual gas is not at room temperature, for example the residual gas inside the superconducting cavities, a factor of $300/T$ should be applied to the right hand side, where T is the absolute temperature in kelvins.

3.2 Beam Stay-Clear

Stay-clear distances are given in Table 2 as a function of distance along the machine. The entries correspond to black plotted lines in Figure 1 and by design are outside the apertures defined by the collimation system. Between points given in Table 2 the stay-clear requirements may be interpolated with a straight line. No material should intrude on this stay-clear boundary except movable components such as collimator jaws or insertable diagnostics. Vacuum components (and magnets) must have adequate internal dimensions, taking into account reasonable alignment tolerances.

4 Basis of Requirements

For reference, this section provides some of the considerations used to derive the requirements given above. There are two fundamental needs:

- The properties of the electron beam should not be adversely affected by the presence of background gas.
- Electrons scattered by background gas do not cause an unacceptably high level of background radiation, particularly in the undulator.

Beam-gas scattering will cause a certain amount of emittance growth and energy spread. The electron beam has to maintain a very low slice emittance and slice energy spread in order to generate FEL radiation. These requirements were derived so that the emittance growth due to beam-gas scattering is at the level of 1% of nominal slice emittance, 0.45 μm [2], or lower.

Table 2: Table of stay-clear distance from beam center

Z coordinate [m]	horizontal [+/− mm]
19.8	14.3
136.3	14.3
139.8	21.0
146.8	21.0
146.9	14.3
379.8	14.3
379.8	35.0
403.2	35.0
403.4	10.0
3617.7	10.0
3617.8	4.0
3727.7	4.0
3728.5	14.3
3775.6	14.3

Z coordinate [m]	vertical [+/− mm]
19.8	14.3
403.2	14.3
403.4	10.0
3617.7	10.0
3617.8	1.5
3727.7	1.5
3728.5	21.0
3775.6	21.0

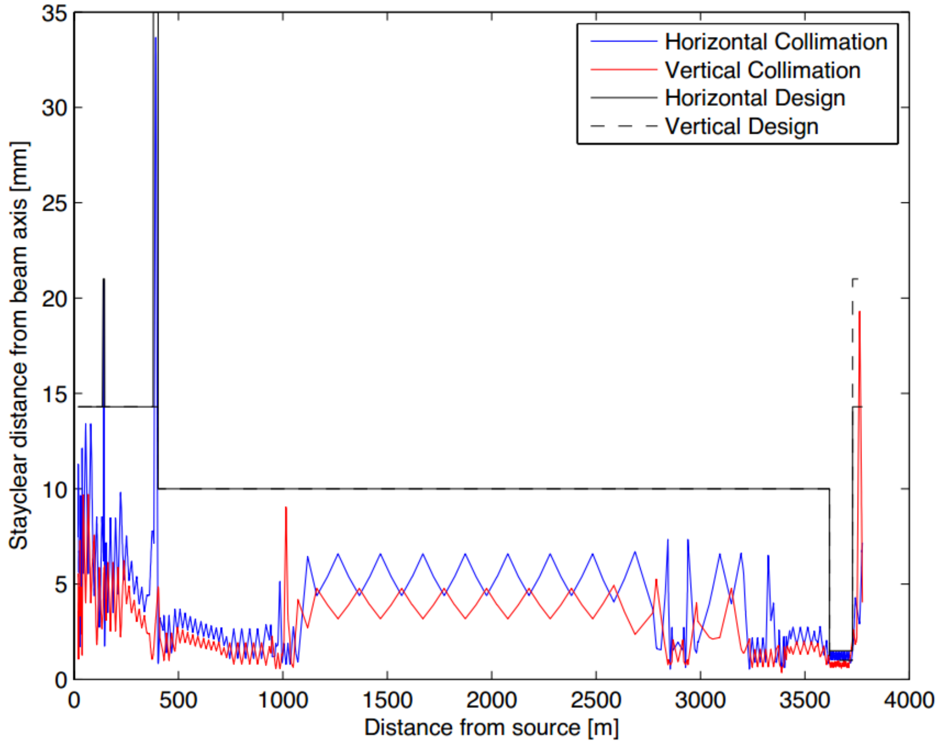

Figure 1: Stay-clear requirements as a function of distance along the accelerator starting at the gun.

The nominal slice energy spread is 500 keV rms. These requirements insure that beam-gas generated energy spread is well below 100 keV rms. For good lifetime of the high precision permanent magnets in the undulator, beam loss in the undulator section must be limited to below 3 pA (see Section 4.1). These requirements should keep the beam-gas generated beam loss below 1 pA even in the worst cases.

4.1 Elastic scattering by atoms

For LCLS-II, the most important process related to the beam-gas interaction is elastic scattering of high energy electrons by atoms. In this process beam electrons interact with the combined potential of the nucleus and the atomic electrons, and screening of the Coulomb field of the nuclei by the electrons of the atom is very important. The differential cross section in cgs units for this process is [3]:

$$\frac{d\sigma}{d\Omega} \approx \left(\frac{2Ze^2}{E}\right)^2 \cdot \frac{1}{\left(\theta^2 + \theta_{min}^2\right)^2}$$

where Z is the atomic number, e the electron charge, E the energy of the incident electron, θ is the scattering angle, and θ_{min} is the cutoff angle. For typical background gases where Z is not too high

$$\theta_{min} \approx \frac{Z^{1/3}}{192\gamma}$$

where γ is the Lorentz factor for the incident electron.

The differential cross section can be integrated over all scattering angles to yield

$$\sigma \approx \pi a^2 \left(\frac{2Ze^2}{\hbar c}\right)^2$$

where a is the Bohr radius of the atom. For $Z \sim 7$ (or less), typical of LCLS-II background gases, since $e^2/\hbar c \approx 1/137$, one can see that the total cross section is only a small fraction of the atomic area πa^2.

It is worth noting that for typical LCLS-II parameters, most electrons do not interact with the background gas at all, a few scatter only once, and very few undergo multiple scattering. This behavior differs from that at storage rings where beam particles persist for a relatively long period of time and multiple scattering is important. As an example, if we assume a background of pure CO at 1×10^{-6} torr (considerably higher than typical) over a distance of 3000 m the probability of a single scatter is about 1% per beam electron. Clearly the slice emittance will not be adversely affected if only 1% of the beam is scattered — even if scattered to high angles and lost. This example is the basis of the required pressures upstream of the bend magnets in the BSY, where beam-gas generated halo is highly attenuated by the collimator system, and emittance preservation is the main concern.

For regions where collimators do not attenuate the beam-gas generated halo, such as within an undulator or after the last collimator, the differential cross section is integrated to estimate the number of electrons that will be lost in the undulator. The estimate of such loss was done using conservative values for the beam energy, 2 GeV, the undulator beta functions, 30 m, and the effective aperture of the undulator, 1.5 mm. A limit of 1 pA of beam current loss from the maximum current of 30 µA was then used to set the background gas requirements. The value of 0.1 mW/m, which is equivalent to 3 pA loss in the undulator, is estimated to result in a roughly 10 year period of time before the undulator segments will demagnetize at the level of 1×10^{-4} and may have to be retuned [4]. Specific simulations of gas-bremsstrahlung beam losses were performed in [5].

4.2 Inelastic scattering

Though the process causes an increase in energy spread and electrons to be lost, inelastic scattering, whereby an electron loses some of its energy when scattering off beam-gas nuclei or atomic electrons, is less important in LCLS-II than elastic scattering. Inelastic scattering cross sections are generally considerable smaller than those of elastic scattering, so fewer of the beam electrons are involved. The undulator is largely transparent to energy (wide band-pass of the weak FODO-cell focusing), so off-energy electrons are usually within the transverse acceptance of the undulator and are not lost there. Inelastic scattering in the dispersive regions will generate some beam-gas halo, but such scattered electrons will usually be attenuated by downstream collimators. For these and other reasons, the elastic scattering process determines the net requirements on the limits for background gas.

Reference [6] gives expressions for total cross sections that involve energy loss by the beam electrons scattering off nuclei or atomic electrons. For example, the cross section for high energy electron to lose δ_{max} of relative energy or more by bremstrahlung scattering off unshielded nuclei of atomic number Z is

$$e_{inelastic\ nuclei} = \frac{4r_e^2 Z^2}{137}\frac{4}{3}\ln\frac{183}{Z^{1/3}}\left(\ln\frac{1}{\delta_{max}} - \frac{5}{8}\right)$$

where r_e is the classical radius of an electron. The corresponding cross section for energy loss from scattering off electrons in an atom with atomic number Z is

$$\sigma_{inelastic\ atomic\ electrons} = \frac{2\pi r_e^2 Z}{\gamma}\frac{1}{\delta_{max}}.$$

We are interested in scattering events where the energy loss is as low as 100 keV, as these could contribute to the energy spread at the 10% level. Evaluating the expressions for $Z = 6$ and energy loss of 2.5×10^{-6} (= 100 keV/4 GeV) yields cross sections about two orders of magnitude smaller than the elastic scattering cross section. Given the example worked out in Section 4.1, this implies such inelastic scatters will only occur to less than 0.01% of the beam electrons and will not significantly affect the energy spread.

5 References

[1] “Vacuum Engineering Specifications”, LCLSII-1.1-ES-0231-R0

[2] “LCLS-II Parameters”, Physics Requirement Document, LCLSII-1.1-PR-0133-R0, released 4/8/14.

[3] “Classical Electrondyamics, 3rd edition”, J.D. Jackson, p 640f.

[4] M. Santana, S. Mao, “Undulator damage for halo losses beams in LCLS-I // LCLS-II”, talk given March 2014.

[5] M. Santana, RP-14-0Y

[6] J. LeDuff, “Current and Current Density Limitations in Existing Storage Rings”, Nuclear Instruments and Methods in Physics Research A239 (1985) 83-101, http://www.sciencedirect.com/science/article/pii/0168900285907028

Wong, Theresa

From: Ross, Marc C.
Sent: Sunday, July 06, 2014 3:37 PM
To: Wong, Theresa
Subject: Residual_Gas_Beam_Stay-Clear.pdf
Attachments: Residual_Gas_Beam_Stay-Clear.pdf

Theresa -

I approve. No changes or corrections.

Thanks,
Marc

Annotations in the attached document can be seen with Acrobat Reader on the computer. To view annotations on the iPad, use compatible app like PDF Expert.