# Chapter 4

# Electron beam

The performance of the photon source is dependent upon the parameters of the electron beam in several important areas. The most important parameters are listed in Table 4.1. The first column of numbers gives the set of parameters that have been adopted as the design goals for the source. These are the values that have been taken as input in calculating the characteristics of the coherent bremsstrahlung source. The second column of numbers was obtained from a concrete design of the HALL D beam line that was carried out by members of the Jefferson Lab Accelerator Division [13]. The exact choice of the final parameters has not yet been made, but the preliminary design exceeds the design goals for the most important parameters. In the original design goals the minimum stable current desired was 100 pA. These low current operation is needed only for calibration measurements using a total absorption counter. The presently listed minimum current of 1 nA is determined by the minimum current in the machine for the stable operation of the beam position and beam current monitors. For short runs a lower current should be possible which is sufficient for calibration purposes. The other parameters which does not meet the design goals are the dispersion in x and y. The dispersion effects the beam size through the following equation

$$\sigma(\mathrm{s}) = \sqrt{\varepsilon(\mathrm{s}) \times \beta(\mathrm{s})} + \mathrm{D}(\mathrm{s})\frac{\Delta \mathrm{p}}{\mathrm{p}} \tag{4.1}$$

where $\sigma$, $\varepsilon$, $\beta$, D, and p are the beam size, the emittance, the beta function, the dispersion, and the momentum respectively. A 400mm dispersion then increases the beam spot size by about 0.08 mm which is small contribution to total spot size at the radiator of 0.8 and 0.36 mm in x and y respectively. The reduction of the radiator-collimator distance from 80 $m$ to 76 $m$, which was decided in 2002, did not significantly affect the performance of the source.

| parameter | design goals | 2008 design |
|---|---|---|
| energy | 12 $GeV$ | 12 $GeV$ |
| electron polarization | not required | available |
| minimum stable current | 100 pA | 1 nA |
| maximum useful current | 3 $\mu$A | 5 $\mu$A |
| r.m.s. energy spread | $< 10$ $MeV$ | 2.5 $MeV$ |
| transverse $x$ emittance | 10 $mm{\cdot}\mu$r | 3 $mm{\cdot}\mu$r |
| transverse $y$ emittance | 2.5 $mm{\cdot}\mu$r | 0.9 $mm{\cdot}\mu$r |
| x-dispersion at radiator | $<2$ cm | 40 cm |
| y-dispersion at radiator | 0 | 40 cm |
| $x$ spot size at radiator | 1.7 $mm$ r.m.s. | 0.82 $mm$ r.m.s. |
| $y$ spot size at radiator | 0.7 $mm$ r.m.s. | 0.36 $mm$ r.m.s. |
| $x$ image size at collimator | 0.5 $mm$ r.m.s. | 0.3 $mm$ r.m.s. |
| $y$ image size at collimator | 0.5 $mm$ r.m.s. | 0.25 $mm$ r.m.s. |
| distance radiator to collimator | 80 m | 76 m |
| position stability | $\pm 200$ $\mu m$ | |
| beam halo* | $< 1 \times 10^{-5}$ | none |

*Halo ≡ fraction of particles >5 mm from beam axis

Table 4.1: Electron beam properties that were asked for (column 2) and obtained (column 3) in the 2008 optics design for the transport line connecting the accelerator to the HALL D photon source.

Finally in Table 4.1 there is no quoted stability for the photon beam spot on the collimator. The reason for this is that the machine simulations do not give an estimate for this parameter. It will be described in later sections how the beam position is measured and stabilized.

The most important parameter in Table 4.1 is the electron beam energy. The electron beam energy defines the maximum photon beam energy and thus the range of meson masses which can be detected. With a 12 GeV beam the diamond can be oriented so that the peak in the coherent bremsstrahlung beam is at 9 GeV with an average linear polarization of 40%. This gives a sensitivity to mesons with masses up to about 3 GeV/c$^2$. If the beam energy were to decrease then either the photon beam energy would have to be decreased or the resulting polarization would decrease. Because of this the beam energy is seen as critical to the photon source and all simulations are based on a beam of this energy. For a fixed beam energy the beam emittance then determined how well one can use collimation to separate the coherent and incoherent bremsstrahlung components to the photon beam and also the energy width under the coherent peak. The emittance of the beam will be discussed in the next section followed by a beam polarization discussion.

The other way in which the electron bean can impact the performance of the photon source is through the generation of background in the tagging spectrometer detectors. The three main sources of electron beam generated background are from the beam halo, background from the electron beam dump, and showers generated by electrons striking the downstream end of the tagger vacuum chamber. The effect of beam halo and vacuum chamber background will be discussed with the design of the vacuum chamber and the beam dump background will be discussed when the electron dump is described.

## 4.1 Beam emittance

The values for the electron beam emittances shown in Table 4.1 are estimates based upon detailed calculations taking the $12GeV$accelerator lattice as input and using both the optim and elegant machine simulation codes [13]. The definition of emittance used here is the product of the r.m.s. widths of the beam in transverse position and divergence angle. Because synchrotron radiation inside the accelerator occurs mainly in the horizontal plane, the emittance values in $x$ are generally larger than those for $y$. This is reflected in the larger $x$ emittance for the design goals and the 2008 design. The CEBAF accelerator division has produced an excellent beam transport design for the HALL Dbeam which results in an expected emittance which is more than a factor of 2 better than our original design goals.

The longitudinal emittance of the beam is important as it is the limiting factor in determining the ultimate energy resolution of the tagger. The design goal of 0.1% photon energy resolution is well matched to the energy spread expected for the CEBAF beam at $12GeV$of 2.5 MeV.

The place where transverse emittance plays a critical role is at the photon collimator. For optimum effectiveness in collimation it is important that the virtual electron beam spot at the collimator position be as small as possible. The electron beam does not actually reach the photon collimator, being bent into the dump by the tagger magnet shortly after the radiator. But considering the optics of the electron beam as if the tagger dipole were switched off, the electron beam at the radiator can be projected forward to form a virtual image on the collimator entrance plane. The position and size of this virtual spot determines the definition of the 0° emission angle for the photons. If this spot is small compared to the collimator aperture and is correctly centered then the bremsstrahlung photons of a given emission angle $\alpha$ intersect the entrance plane of the collimator in a well-defined ring of radius $D\alpha$ concentric with the collimator aperture, where $D$ is the distance between the radiator and the collimator entrance plane. In this way a collimator of diameter $d$ passes only those photons of emission angle $\alpha \leq d/2D$. If however the size of the virtual spot is comparable to or larger than the collimator aperture then the ring image of photons of a given emission angle $\alpha$ is smeared out, so that the effect of collimation is simply to reduce the intensity of the beam but not to enhance the coherent component.

Note that this analysis does not place any specific limits on the size of the beam at the radiator. The beam spot can and should be larger there to increase the lifetime of the crystal between spot moves. For the SLAC coherent bremsstrahlung source the beam spot at the radiator was about 2 *mm* r.m.s. focused down to a 1 *mm* r.m.s. virtual spot at the primary collimator positioned 91 *m* downstream of the radiator.

The superior emittance characteristics of the CEBAF beam allow the transverse dimensions to be much smaller than this for the HALL D source, more so in the vertical than the horizontal dimension. Previous experiments have reported significant changes in the performance of diamond radiators when the charge which passed through the crystal exceeded 0.25 C/mm$^2$. This corresponds to roughly 2 weeks of continuous running at maximum luminosity for GLUEX with existing size diamonds. With CEBAF's excellent emittance the spot size on the crystal can be varied to make the most efficient use of the diamond crystals. The beam can be tailored to the size of the uniform areas of the crystals and to adjust the time between spot moves.

The difference between the horizontal and vertical emittance of the CEBAF beam implies that making the spot round at the radiator implies an elliptical virtual spot at the collimator, and *vice versa*. It is difficult to construct a collimator with an elliptical aperture, so the choice was made to make the virtual spot round. This is why the beam spot on the radiator is asymmetric.

Figure 4.1 shows how the collimated photon spectrum depends upon the transverse emittance of the electron beam. To generate this plot the increases in emittance were simply translated into an increased virtual spot size on the collimator. This was done because it was assumed that the spot size of the electron beam on the radiator, already close to 2 *mm* r.m.s., cannot be further inflated and stay contained within the limits of the crystal. When the virtual spot size becomes comparable with the collimator aperture then the collimation is rendered ineffective, and the photon spectrum and polarization revert to their uncollimated values. There is another connection between focal spot size and beam emittance that is connected with the requirement that

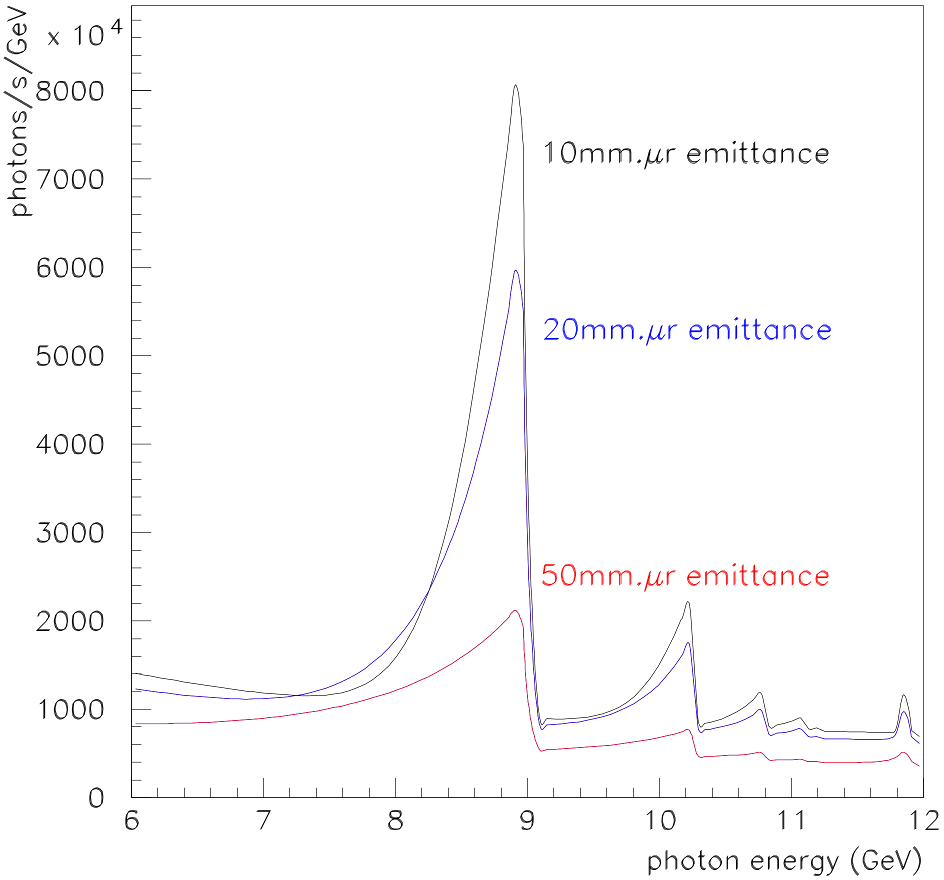

Figure 4.1: Coherent photon spectrum for three different values of the electron beam transverse emittance. The horizontal (shown on the plot) and vertical emittances are assumed to scale together. A 3.4 *mm* collimator located 80 *m* from the radiator was used for this calculation.

all electrons enter the radiator at the same incidence angle with respect to the planes of the crystal. Practically, the divergence does not broaden the coherent peak provided that it is kept below the mosaic spread of the crystal. A conservative value for the allowable angular divergence $\delta$ in the electron beam at the radiator would then be 20 $\mu r$ . Taken together with a 500 $\mu m$ r.m.s. spot size at the focus, this leads to an emittance of 10 $mm{\cdot}\mu r$ at $12GeV$. This corresponds to the upper curve in Fig. 4.1.

Fig. 4.2 shows the horizontal and vertical r.m.s. beam size from the 2008 beam optics. The size of the beam is shown from 100 m upstream of the diamond radiator and projected to 100 m downstream. The design of the upstream elements allows the ratio of the spot sizes at the radiator and collimator to be adjusted over about an order of magnitude simply by changing the current in the beam line elements. In this way it will be possible to optimize the optics for a given size of crystal and collimator after beams are delivered to the hall, and more precise values for the emittances are in hand.

## 4.2 Beam polarization

It has already been stated that to generate bremsstrahlung photons with linear polarization it is necessary to use an oriented crystal radiator. However photons with circular polarization are produced by ordinary incoherent bremsstrahlung any time the incident electrons are longitudinally polarized. In fact for $9GeV$ photons produced by $12GeV$ electrons, the transfer from electron beam longitudinal polarization to photon beam circular polarization is greater than 80%. This raises the question of what happens when one has longitudinally-polarized electrons incident on an oriented crystal radiator. What happens in this case is that the photon beam is elliptically polarized; it carries both circular and linear polarization. There is a sum rule that limits the sum of the squares of the linear plus circular polarizations to be no greater than 1. Hence one sees the linear polarization in coherent bremsstrahlung going to zero as one approaches the end-point energy (see Fig. 3.5) while at the same time the circular polarization goes to 1 at the end-point (assuming electrons of 100% longitudinal polarization).

The statement in Table 4.1 that electron beam polarization is not required for the GlueX experiment in Hall D is correct, but it is not correct to assume that the photon source is independent of the state of polarization of the electron beam. The presence of a non-zero circular polarization in the Hall D photon beam will, in principle, produce observable effects in the angular distributions measured in photoproduction reactions. This means