Abstract:
Closest approach of the CEBAF beam to material walls (apart from target windows, of course) in the as-built 4 GeV accelerator occurs in the extraction regions. In these regions, an RF separator “forks” the beam bunches along two distinct paths straddling a material septum. We compare the existing septum clearances and the beam sizes to provide updated guidance for beam center to first wall spacings in upcoming work. Supporting evidence from the G0 experiment is also considered. We conclude that the existing spacing guideline of 5.6 mm from first wall should remain sufficient for 12 GeV operation, but that the first wall on the opposing side of the beam pipe in septum areas should be placed more than 7.5 mm from the beam center. This recommendation allows for increased septum clearance if ultimately required, so that the outer walls do not immediately become the new scraping location. We further note that all “risk” factors for 12 GeV operation would remain unchanged with respect to 4 GeV practice were one simply to add approximately 1.0 mm to the stand-offs presently in use.

The Hall A and C apertures of the Lambertson magnet and the differential pump apertures in the linacs are adequately large apertures, and therefore should require no alteration of bore dimension for 12 GeV application. The calculations below result in a 4.5 mm minimum stand-off as applied to the Hall B Lambertson magnet aperture (just over 10 mm in diameter). We deem this appropriate because with the small current delivered to Hall B, there is also small risk of hardware damage. The beam position at the Hall B Lambertson is difficult to monitor, but a nano-Amp BPM could be located there if needed as a supplement. It does not appear to be required.

Beam to Wall Stand-Off:
The beam pulse train from the injector contains three interleaved 500 MHz beams. These are separated by RF separators into individual pulse trains. Given the small separation available from RF devices, the beams must be further coaxed apart. Septum magnets are used for this purpose. They must remain intact and functional between two high-power pulse trains which the external focusing of the lattice is trying to merge back into a single beam. The term “stand-off” may more clearly indicate the distance from the center of the beam to the first wall, but unless specifically stated otherwise we will use the term “clearance” interchangeably. We do not intend for either term to denote the space between the first wall and any loosely defined “edge of the beam.”

In the CEBAF accelerator, both beam line damage and scraping-induced parity asymmetries must be considered. The parity asymmetry concern is commonly the tighter constraint, and it will remain for Halls A/B/C in the 12 GeV operational period. One must provide sufficient separation of the beam from a first wall to keep the edges of the beam from scraping on the material.

The typical first septum in the CEBAF accelerator has been the YA magnet. This will continue for the 12 GeV system. That septum thickness from beam wall to beam wall is about 5.3 mm (from standard mechanical drawings; see Figure 1). The standard beam-to-beam separation of the CEBAF beams of 16.5 mm at the YA septum leaves 5.6 mm available stand-off from both extracted and recirculating beam centers to the vacuum wall. This stand-off has been adequate for CEBAF operation so far. Mitigation for these septa includes specifically sited Beam Loss Monitors (BLMs) to protect against otherwise unnoticed drifts in beam position and against irregularities in the RF separator power. Both sources have caused interruptions in beam transport. The spacing includes an allowance for beam size, an allowance for normal steering variations, and an ultimate “safety margin.” We estimate the allocations for such a budget and compare it against the prior septum clearances to understand where margin may possibly be reclaimed.
Beam Scraping Limitations:

PParity experiments require equality of beam currents for both polarizations. The scale of beam motion between spin states is 10 microns [private communication, R. Suleiman, JLAB]. With 10 micron variation in beam position and RMS beam sizes $\sigma_{\text{beam}}$ of a few hundred microns, current equality between alternate polarizations at the part per million level is expected to be violated if scraping occurs at less than about 5 RMS widths from the beam core. We'll use $5 \cdot \sigma_{\text{beam}}$ as a slightly conservative outer radius for the beam for this purpose. The part per billion level charge symmetry requires that any scraping occurs closer to $6 \cdot \sigma_{\text{beam}}$.

Steady-State Beam Position Control:

The target beam position performance for CEBAF is now to maintain an RMS variance from the design orbit of $\sigma_{\text{orbit}}$ of 0.6 mm. Maintaining the $5 \cdot \sigma_{\text{beam}}$ scraping condition (more stringent than a machine protection beam loss limit) requires allowing for...
variations of the beam position of up to about $3\cdot\sigma_{\text{orbit}}$ or 1.8 mm over and above the beam size allowance.

Beam Position Fluctuations:

In addition to slow drifts, the beam position also suffers momentary fluctuations. The largest common fluctuations in beam position in the CEBAF accelerator result from fluctuations in the RF acceleration cavities. The transient energy fluctuations are transformed into beam position excursions in the dispersive areas of the beam transport. We wish for the tightest limitations energy aperture to remain within arcs 1A and 2A (6 meter peak dispersion), which tolerate approximately $1.5\cdot10^{-3}$ relative energy fluctuation with respect to centered beam. Operational experience with the existing CEBAF accelerator shows that optical drifts result in occasional leakage dispersions as high as 1 meter. In the case of a $1.5\cdot10^{-3}$ relative energy fluctuation, a 1 meter dispersion would result in a 1.5 mm transient beam offset. This “safety margin” should be added to the other two contributions to provide confidence that the accelerator will continue operation through such events, meeting requirements with minimal interruption to beam delivery due to beam transport.

As a summary of all our above considerations, the main requirement for stand-off values can be expressed (in mm) as

$$R_{\text{stand-off}} = n_{\text{beam}} \sigma_{\text{beam}} + n_{\text{steering}} \sigma_{\text{steering}} + 1.5$$

where $\sigma_{\text{beam}}$ is an RMS beam size, $n_{\text{beam}}$ is the beam size factor which has been chosen equal to 5 to help maintain charge symmetry during parity violation experiments, $\sigma_{\text{steering}}$ is a beam steering accuracy equal to 0.6 mm, $n_{\text{steering}}$ is a steering accuracy factor, which is equal to 3, and finally 1.5 mm as a “safety margin” for transient beam fluctuations.

Stand-Off Comparison with Current Practice

We take the 5.6 mm center to first edge spacing of the 4 GeV CEBAF layout as acceptable, given the long time frame over which it has been successful. The approximate RMS beam size at the various septa is $\sqrt{\beta\epsilon}$ where $\beta$ is the envelope function for the beam and $\epsilon$ is the usual (geometric) emittance. For the CEBAF extraction septa, $\beta$ is approximately 60 meters and the peak value of the emittance is thought to be approximately $0.4\cdot10^9$ meter (radian). Measurements of the beam
emittance are not well substantiated, but values extracted from the JLAB electronic logbook have been catalogued by Benesch [TN-05-074].

The RMS beam size is corresponding to the peak emittance values and with beta values close to 60 meters is estimated to be about 0.15 mm. Allowing $5 \cdot \sigma_{\text{beam}}$ for the spatial beam edge, or about 0.75 mm, approximately 4.8 mm is left for the combination of normal beam position variation (steering allowance) and a residual hardware safety margin. This is somewhat greater than required by the above analysis, which resulted in an estimate of 3.3 mm (sum of orbit drift and “safety margin”) for the stand-off allowance beyond the beam size. It may be possible to recover some of the 1.5 mm difference between these numbers to use for the increased beam size in 12 GeV operation.

We do not want for the beam to impinge upon the material of the septum or beam pipe very often, but occasional events are protected against by the Fast Shut-Down system, or FSD. This system reacts to trigger events within tens of microseconds, terminating the beam. We want for these last-ditch protection systems to be triggered only rarely, not multiple times per hour. This is the experience we have in running the CEBAF accelerator to date, except in the case of failing components like RF separators or dipole power supply controls (e.g., shunt modules).

Beam Size near Extraction and Recirculation Septa – 4/6 GeV vs. 12 GeV

For the 12 GeV upgrade beam, the largest geometric emittance is expected to be about $2 \cdot 10^{-9}$ meter with the same 60 meter beta functions at the extraction septa. The resulting RMS beam size is $\sqrt{5}$ times as large as at 4 GeV. This results in an increase in the $5 \cdot \sigma_{\text{beam}}$ beam size allowance of about 0.9 mm, which appears to “use up” only 60% of the 1.5 mm “excess” safety margin estimated above. Alternatively, it would reduce risk to preserve the hardware safety margin by adding another 0.9 mm to the 5.6 mm stand-off and specifying a 6.5 mm stand-off from the beam center to the first wall.

The other septum regions of concern are at the recirculation septa, where the design values of the beam envelope function $\beta \sim 300$ meters are much larger than 60 meters. These are regions to which orbit locks have not yet been applied because they are upstream from the first available spreader region correctors. These septa are vertically oriented, and the vertical beam emittance is expected to be no more than half of the horizontal emittance ($\epsilon < 1 \cdot 10^{-9}$ meter). The beam RMS size of 0.55 mm results in a
direct beam size contribution of 2.7 mm to the stand-off. The above analysis results in a minimum required stand-off of 6.0 mm. In these regions, following the YA septum pattern given above, one would expect a 12 GeV beam stand-off of 7.5 mm to provide the same standard of protection as in the 6 GeV machine.

We also comment that the 3 GeV experience with the G0 experiment supports this conclusion. For the G0 experiment it was possible to maintain its transport through the very narrow 6 mm diameter halo target fielded by G0. The scraping induced background rates were much too high for G0 with this target in place, but the beam envelope function was comparable to that in the extraction region. The beam was rastered across the experimental target to prevent its being damaged, with the raster sweep at the halo target being approximately 2 mm. The halo target itself was not damaged. This appears to confirm that recoverable margin at the mm level is included in the specification of 5.6 mm beam centroid to first wall spacing.

Recommendation and Conclusion:

We note that the beam position in the 12 GeV upgrade is planned to be more tightly controlled than it is in the 4/6 GeV accelerator systems. It appears to be justifiable for the 12 GeV design to use the existing CEBAF operational guideline of 5.6 mm spacing from the beam centroid to the first wall in the extraction septum regions. The Lambertson magnet and the differential pump apertures in the linacs are larger apertures, and therefore should require no alteration of bore dimension for 12 GeV application. For the Hall B Lambertson, the sum of beam size, steering allowance, and safety margin is 4.25 mm. Because of low Hall B beam current and low risk of hardware damage, we adopt 4.25 mm as the Hall B stand-off requirement. The available physical aperture of 10 mm diameter need not be changed. The increased beam size for the 12 GeV extraction and recirculation septum regions can be expected to use some of the margin built into the 4 GeV design, but still remain operable.

While the beam position stability is expected for other reasons to be better in the upgrade, it is not guaranteed that no additional noise sources will be added with (e.g.) the addition of high gradient acceleration modules. It should be borne in mind that if the beam clearance at tight apertures (the septa are the tightest clearances) has been too optimistically specified, it may be necessary to increase the RF separation by approximately the 1.0 mm estimated above for the increased “radius” of the beam at 12 GeV. Implementing this for both of the separated beams requires only a 12% increase in RF deflection. With this in mind, the outer beam pipe in the extraction regions should be
at least 7.5 mm from the beam center, sufficiently far from the beam that adding an extra millimeter of spacing from the septum would not cause the beam to scrape on the first wall on the side opposite the septum.

The recirculation septa for the highest passes may have envelope function values up to 300 meters. For these areas, estimating the vertical emittance as $\epsilon \sim 1 \cdot 10^{-9}$ meter, the minimum required stand-off distance is 6.0 mm. Provision of 7.5 mm of stand-off would retain protection equivalent to that used in the 4-6 GeV CEBAF accelerator.

Appendix 1.

Beam sizes at the most critical locations (septum magnets) of the beam extraction area. OPTIM beam extraction deck design files are provided by Y. Roblin and J. Benesch.

Figure A1_1. MYA2T01 location. Extracted beam.
Figure A1_2. MYA2T01 location. Recirculated beam.

Figure A2_1. MYB2T02 location. Extracted beam.
Figure A2_2. MYB2T02 location. Recirculated beam.

Figure A3_1. MYA4T02 location. Extracted beam.
Figure A3_1. MYA4T02 location. Recirculated beam.
Figure A5_1. MYA6T01 location. Extracted beam.

Figure A5_2. MYA6T01 location. Recirculated beam.

Figure A6_1. MYR6T02 location. Extracted beam.
Figure A6_2. MYR6T02 location. Recirculated beam.
Figure A7_1. MYA8T01 location. Extracted beam.

Figure A7_2. MYA8T01 location. Recirculated beam.
Figure A8_1. MYR8T02 location. Extracted beam.

Figure A8_2. MYR8T02 location. Recirculated beam.
Figure A9_1. MYAAT01-MYAAT01A location. Extracted beam.

Figure A9_1. MYAAT01-MYAAT01A location. Recirculated beam.
Figure A10_1. MYRAT02 location. Extracted beam.

Figure A10_2. MYRAT02 location. Recirculated beam.
Figure A10_3. Lambertson location. 5-th pass. All three beam paths (A/B/C) will have comparable emittances and beta functions in the Lambertson magnet. The horizontal radius is shown in red, and the vertical in green.
Appendix 2. Summary tables for the estimated absolute minimum beam clearances at septum magnets and Lambertson magnet. These values are smaller than the requirement stated above and represent the smallest values deemed reasonable to attempt with judicious selection of mitigation measures and without undue risk. Reduction of the clearance/stand-off from the global requirements given may be possible on a case-by-case basis and with due regard to mitigations. Tables provided for reference in case a driving need is found.

Table 1: beam parameters used in calculations of stand-off (clearance) at various locations
Table 2: Beam parameters used in calculations of stand-off (clearance) at various locations

<table>
<thead>
<tr>
<th>ELEMENT NAME</th>
<th>pipe size (mm)</th>
<th>beam position</th>
<th>beam size (o) mm</th>
<th>steering accuracy</th>
<th>&quot;safety&quot; value</th>
<th>beam size factor</th>
<th>NB<em>0+riser</em>stands</th>
<th>BEAM CLEARANCE [X,Y] mm</th>
<th>NATURAL beam clearance [X,Y] mm</th>
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* NB*0+riser*stands = NB*0+risers*stands

Note: The table provides a detailed list of beam parameters calculated for stand-off (clearance) at various locations, including element names, pipe sizes, beam positions, steering accuracy, safety values, beam size factors, and calculated clearance values.