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Aperture Considerations for the FEL Upgrade

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Abstract

We discuss aperture requirements for the FEL upgrade and make recommendations based on previous experience and preliminary design work.

Aperture Selection as a Part of Machine Design

Aperture specification during accelerator design typically proceeds as follows:

1) Generate an accelerator physics design – this provides beam spot size (σ) information (*via* beam envelope, β, and emittance, ε),
2) Estimate beam handling requirement (W) – this estimate can be developed once the beam and lattice properties are known from 1), and
3) Set the machine aperture as $A=N\sigma+W$.

Typically N is 4 to 6; the “working aperture” W is usually very system specific. For example, the IR Demo has $A= 6\sigma+(4\text{ cm})$ through most of the machine. This has proven to be an operationally robust choice.

Other restrictions may apply during the aperture selection process. For FEL drivers, the laser itself may impose constraints. For example, in the FEL Upgrade, the IR optical mode is much larger than in the IR Demo. As a result, machine regions common to both electron beam and optical mode will have to be sized to accommodate the optical mode.

In the case of the FEL upgrade, programmatic considerations force a fast-tracked schedule, which in turn causes us to deviate from accepted practice. As a result, risk will escalate. This, however, can be limited by using *all* available information, such as that provided by previous design studies and experience with the IR Demo [1]. In the following discussion, we attempt to draw on this information to make reasonable and quantitatively justified estimates of the aperture requirements in the upgraded FEL driver *absent* a detailed accelerator system design.

What Is Presently Known?

At this time there is no detailed design, though a preliminary concept exists and studies are underway [2]. Thus, beam envelopes are not available to serve as a basis for spot size and working aperture estimate. Moreover, the existing FEL injector is not fully understood. Component calibrations, particularly for RF components, are not firmly established and, despite significant progress, detailed agreement between modeled and observed performance is therefore not available. In particular, there is not a confirmed projection of the source normalized emittance at the elevated bunch charge (135 pC) required in the upgraded system. Hence, spot sizes are known to be unknown.

It is known that the high power IR FEL optical mode will be larger than in the present system. As a consequence, 3” vacuum chamber will be required if the electron beam shares a common environment with the optical mode over essentially the entire optical cavity. Smaller electron beam component apertures can be used only if the electron beam transport is “compressed” into a short length around the wiggler or otherwise spatially displaced from the optical mode.

What Can Be Reasonably Surmised?

Certain features of the upgraded driver and its performance can be assumed as a consequence of reasonable conjectures. First, it is likely the normalized source emittance (at 135 pC) will increase over that in the IR Demo (which runs at 60 pC), due to the action of space charge. Secondly, it is likely that beam envelopes in the upgraded driver will be larger than those in the IR Demo, as a consequence of the increased machine size.

We note that this assumption presupposes some design choices. Typically, a larger machine has either more quadrupoles than a smaller one, or has larger beam envelopes (or, most likely, both). In this case, more quadrupoles (and especially more quadrupoles per unit length) is undesirable inasmuch as it will have not only a higher cost, but also increased chromatic insult. This in turn represents a limit on the large momentum acceptance (10%) required in the upgraded driver. “More quads” is therefore not the preferred approach. A first iteration of the linac optics has been completed [3], and has significantly larger beam envelopes than those in the IR Demo. Figure 1 displays a preliminary linac optics solution. We note that the “in-module” beam envelopes are about the same in this solution as they were in the IR Demo design [4]. This implies that the 2” aperture available in the existing 5-cell FEL modules may be adequate (as it was, more or less, in the IR Demo), provided space-charge driven emittance growth is not significant. However, the beam envelopes in the upgraded driver *warm* regions are a factor of two larger than in the regions of the IR Demo adjacent to the module. This is a consequence of the use of triplet focussing, which is needed to manage beam behavior in the longer linac with higher RF gradients (and associated greater RF focussing).

As spot sizes and beam response to steering scale with the square root of beam envelopes, assuming essentially similar emittances suggests the upgraded driver will need $\sqrt{2}$ times larger aperture than did the IR demo. We therefore turn our attention to a comparison of the emittances in the two systems.

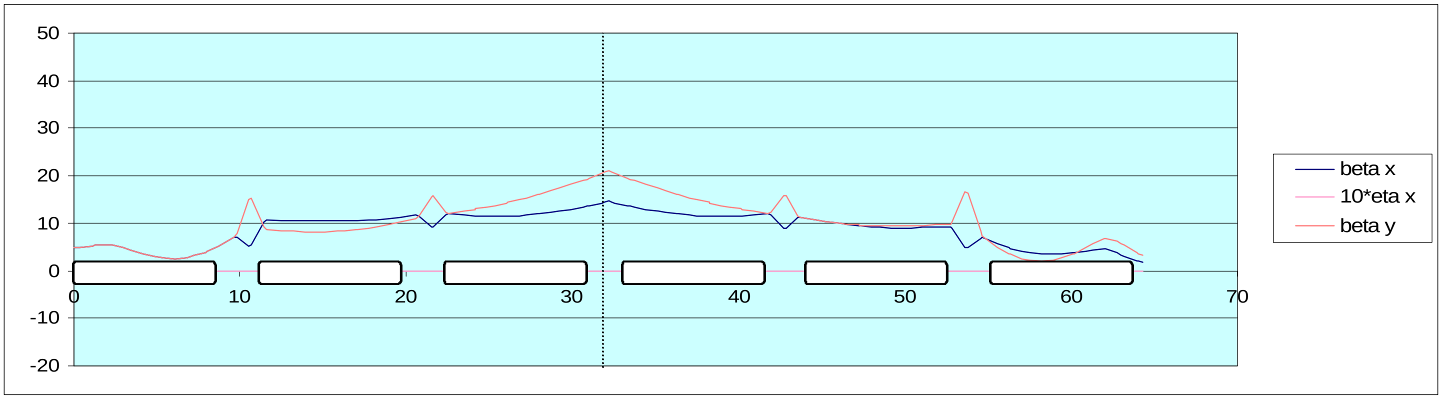
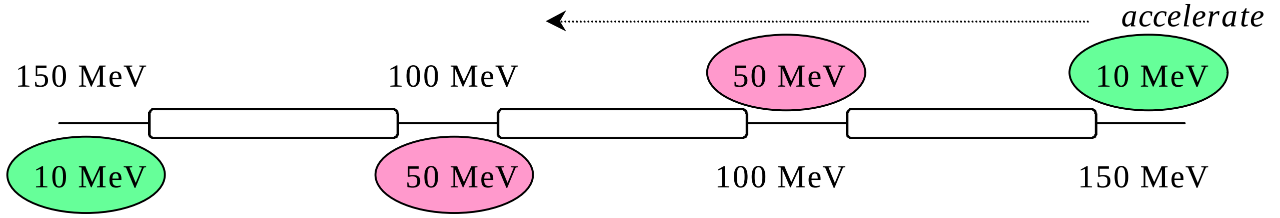


Figure 1: Preliminary beam envelope solution for upgraded driver linac.

Geometric Emittance Comparison to Demo

Figure 2 presents a comparison of geometric emittances in the upgraded driver to those in the IR Demo. The highlighted warm regions are positions along the upgraded machine at which the geometric emittance is likely to match (if space charge does not affect the normalized source emittance) or exceed (if space charge does effect the normalized source emittance) that at equivalent locations/energies in the IR Demo driver.

We note that $\varepsilon^N_{135\ pC} > \varepsilon^N_{60\ pC}$ is likely and, from Figure 1, $\beta^{upgrade} > \beta^{demo}$ is certain. Moreover, recent injector setups used during high FEL gain operation in support of tapered wiggler tests were limited to 1.5 mA by BLM trips [5]– suggesting that the present 2” injector aperture may be inadequate even at 60 pC when a high FEL gain configuration is required.



🟣 $\beta^{upgrade} > \beta^{demo}$ with $\varepsilon^{upgrade}_{geometric} > \varepsilon^{demo}_{geometric} \Rightarrow$ larger spots certain
🟢 $\varepsilon^{upgrade}_{geometric} > \varepsilon^{demo}_{geometric}$ with $\beta^{upgrade} \sim \beta^{demo} \Rightarrow$ larger spots likely

Figure 2: Emittance/envelope comparison – Upgrade to Demo

Conclusion #1: Though 2" aperture is possibly (probably?) adequate in the modules the peak b's in the upgrade are in warm regions and will drive an increase in aperture there.

<u>Recommendation(s) #1</u>

- Make an effort to understand the injector quantitatively – and run 5 mA CW at 135 pC. This will help define if the present 2" injector chamber will allow reliable operation at higher single bunch charges, and will serve to characterize the normalized emittance at elevated charge.
- Use a 3" aperture in the linac warm regions.

Linac-to-FEL Transport at 100-200 MeV

Consideration of Figure 2 forces one to allow that it may be possible for $\varepsilon^{geometric}_{upgrade} < \varepsilon^{geometric}_{demo}$ in the module to FEL transport even with space-charge-driven degradation of the normalized emittance. This is a simple consequence of the higher final energy. Thus, the larger upgrade beam envelopes are offset by the smaller geometric emittance to give comparable spot sizes in the two machines. Apertures in the full energy transport therefore can, from the spot size perspective, be similar.

The enlarged beam envelopes imply an increased sensitivity to steering and error effects. This suggests that either an increase in beam handling allowance should be considered, or the system should be designed to allow more robust orbit correction and matching. We have chosen the latter approach for this design. In the IR Demo, space considerations (short optical cavity, smaller machine) forced us to interleave the FEL optical cavity with the beam transport. Optical cavity chicanes were therefore embedded in matching telescopes, leading to some operational difficulty in both steering and matching. In the upgraded system, the much longer high-power IR FEL optical cavity must be located in the machine backleg. This allows space for the separation of matching modules from electron beam handling near the FEL, with a consequential reduction in system operational complexity. This advantage should, in turn, offset any need to increase the beam handling allowance due to larger beam envelopes.

We note that at the *same* energy (mid-linac in the upgrade, full-energy ends of the linac in the demo), spot sizes will almost certainly be larger in the upgrade. This is the substance of the above Conclusion #1 and Recommendation #1. Moreover, at the low end of the final energy range (~100 MeV), spots may again be larger in the upgrade than in the demo, due to increased normalized emittance and larger beam envelopes. Low energy performance (both in terms of minimum achievable energy and maximum achievable current) are therefore somewhat at risk unless large apertures are available. Given however the intention of running the machine at energies of 150 MeV or higher, we reach

Conclusion #2: 2" aperture may be adequate for full *energy beam from the end of the linac to the start of the FEL insertion.*

<u>Recommendation #2</u>

- Utilize apertures as indicated in Figure 3.

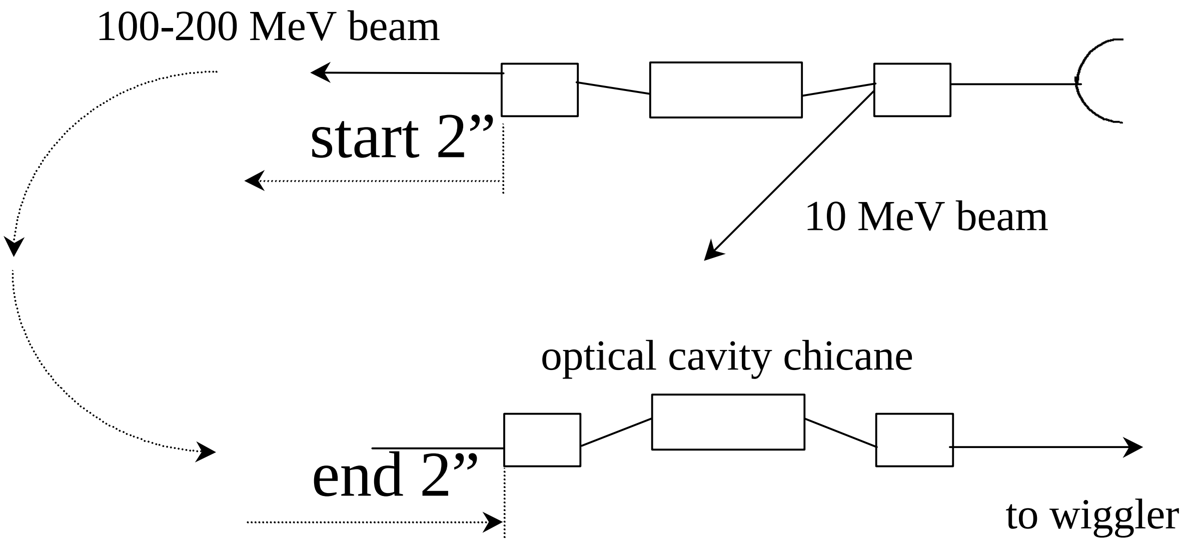


Figure 3: Aperture recommendation for linac to FEL transport

Component Reuse

Since this is nominally an "upgrade" project, one must address the reuse of existing components. We note that the machine, beam and performance properties of the upgraded system are significantly beyond those specified for the IR Demo. In particular, *larger aperture requirements limit component reuse to regions such as the linac-to-FEL transport*. Guidelines follow:

- Diagnostics (viewers, BPMs, BCMs) are reusable without modification.
- QB quadrupoles are probably reusable without modification. We note that at 48 MeV, the IR Demo QB maximum operation current is ~2 A. QBs are spec'd to 10 A (with cooling water), suggesting that they can be used at 200 MeV with 20% headroom for matching.
- Correctors may prove useful under similar analysis; a review of corrector excitations must be performed and conclusions drawn.

FEL Insertion Region

It is here that "other restrictions may apply". Specifically, the IR upgrade optical mode will require 3" apertures – so either the electron beam transport uses 3" aperture components, or the FEL interaction region must be configured to minimize common length of the two systems. The most straightforward means of doing the latter is to limit the length of the quad telescopes matching the electron beam to the wiggler – in this case, the lengths would have to be limited to ~5 m [6].

Ongoing work has produced a preliminary design for the upgrade energy recovery arc that seems to meet stated performance goals [7]. This design manages aberrations at ±5% momentum offsets by adjusting phase advances amongst quad telescope and endloop components, thereby causing destructive interference of chromatic effects. Preliminary results seem to indicate that a 10 m long matching telescope after the wiggler is needed to achieve this control.

We recall that the accumulated phase advance $\psi \sim \int ds/\beta$. If the telescope length is to be reduced, β must also get smaller. This is better for small apertures, *but* it implies that the focussing must get stronger. Stronger focussing means, in turn, that chromatic aberrations get larger. Roughly speaking, the focussing is linear in the quad strength, but the higher order chromatic effects of interest will be quadratic in quadrupole strength – so halving the telescope length with double the quad excitation, and fourfold the aberrations. Reduction of the matching telescope length will therefore have a serious negative impact on the chromatic performance. This in turn suggests that 2” aperture, with associated short matching regions around the wiggler, is not a credible scenario.

Conclusion #3: Insofar as the “strawman” 10 m match “meets spec”, a 5 m match will be “4 x out of spec”. We must therefore allow for long matching telescopes, in which the electron beam and optical mode share a common 3” chamber.

<u>Recommendation(s) #3</u>

- Configure the FEL insertion region as illustrated in Figure 4.
- Recall that the basic optimization for the matching telescope must balance keeping β small – for good performance and acceptance – with keeping L large – to limit quad strength. Design for a match length of ~10 m in this machine.

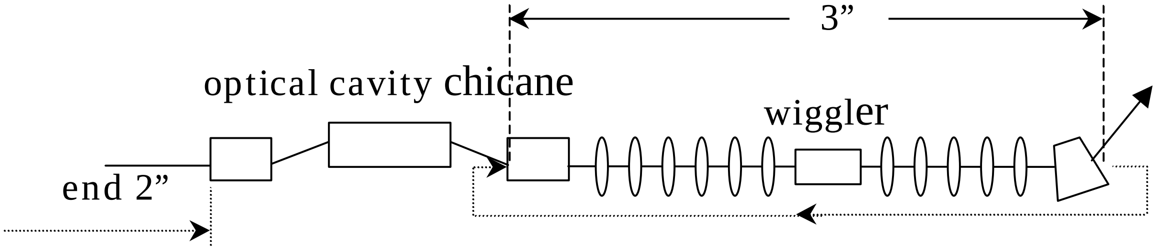
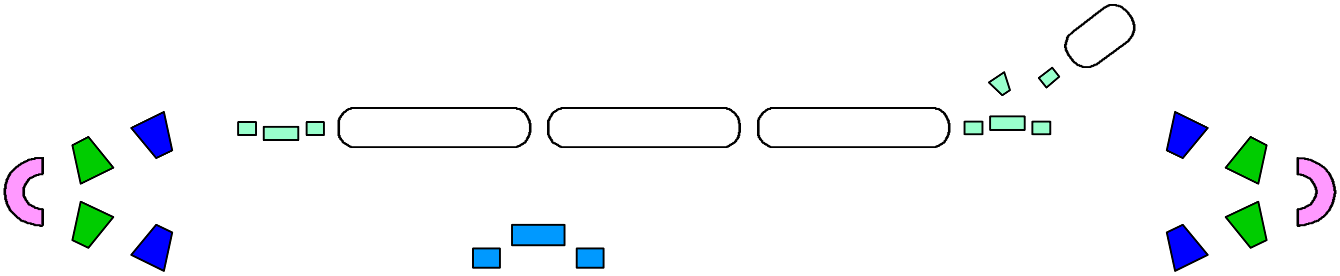


Figure 4: Recommended apertures for FEL insertion region.

- Choose magnet families to keep construction simple. Match magnet gaps within a family and across “similar” families. For example, in the Figure 4 optical cavity chicane, only the final dipole is compelled to be 3” gap – but it is simpler to make all three identically. Inasmuch as the fringe field models employed in optics codes were developed for large spectrometer magnets, a 3” gap is not “large”, so modeling predictive capability is likely okay. Figure 5 presents a color-coded guide to recommended gaps. Families in blue “must” be 3”. The green family “should” be 3” (as it is “similar” to the other, blue, reverse bend family and therefore will be easier to match across families by using 3”). The pink p-bends will probably tolerate a 2” gap because β (and η) are “smaller” there. This is advantageous from a DC power perspective as well; power requirements are dominated by the p-bends (they provide 180^o out of 300^o bending per end loop) so a reduced gap in these magnets represents a significant power savings. We note that the IR Demo demonstrated successful matching within and across magnet families [8]; we should anticipate similar results in the upgrade.



🟦 Blue families – 3” a “must”
🟩 Green family – 3” a “should”
🟪 Pink family – 3” a “like” (2” probably okay)

Figure 5: Magnet family assignments and gap recommendations.

Conclusion(s) #4: *To avoid undue risk must make FEL insertion 3”*

There is “little” incremental cost imposed by making all reverse bends 3”

Comments: The latter conclusion is supported by the following observations.

- Making all reverse bends 3” increases DC power, but only fractionally (most DC power is drawn by the π-bends).
- There is no overhead in “lost” magnets – none of the present dipoles (or trim magnets) can achieve the desired field levels, and new trim quads, sextupoles, and octupoles must be developed to provide the additional aperture necessary for the required 10% momentum acceptance. Essentially all end-loop magnets must be replaced (or at least extensively modified).
- Matching gaps amongst similar magnet families (“blue” and “green” reverse bends in Figure 5) simplifies magnet design and eases field integral matching across families.
- Use of 3” gaps provides significant risk reduction, especially for lower energy operation at higher space charge. This region of the machine would be able to tolerate about double the emittance and/or increased distortion of the phase space at larger momentum offsets than those occurring in the IR Demo.

Injection/Reinjection Regions – 2” or 3”?

We note the following comparisons:

- $\beta^{upgrade} \sim 2$ or 3 times β^{demo} at reinjection
- $\varepsilon^{N}_{upgrade} > \varepsilon^{N}_{demo}$ (due to space charge)
- $\varepsilon^{geometric}_{upgrade} > \sim 1/2$ to $1/3\ \varepsilon^{geometric}_{demo}$ (due to additional adiabatic damping).

These imply spot sizes, error sensitivities, and consequential machine performance are not likely to get better in the upgrade. The present performance therefore provides a basis for comparison and making recommendations. At the present time, module cavity 8 tunes a fair bit, suggesting beam losses do occur at reinjection. ILM0F062 trips have, historically, been a performance limitation, and, as noted above, ILM0F06 driven trips were a limit when the injector was recently run so as to provide high wiggler gain. We therefore draw the following conclusion.

Conclusion #5: *3” aperture in the injection and reinjection regions provides prudent risk reduction at modest incremental cost.*

Comments: The latter conclusion is supported by the following observations.

- New injection/extraction dipoles will be needed to increase the available dynamic range of injected to final energy. These will be “small” magnets, rather like the DU/DV bends; an increase of gap to 3” will therefore have only a minor power impact.
- QJ injector quadrupoles and their associated correctors support 3” aperture and thus may be reused.
- The present machine does not have enough high field quadrupoles to provide for the upgraded reinjection telescope. In particular, there are not enough QBs to populate the reinjection region. At the very least, several additional QGs would have to be modified. As an alternative, additional FEL interaction region quadrupoles could be procured to provide for the reinjection match. Their cost would be partially recovered by not reprocessing the QGs.

References and Notes

[1] Design studies of interest include the UV Industrial Demo design (Laser Processing Consortium, “Free-Electron Lasers For Industry, Vol. 2 UV Demo Conceptual Design”, May 1995) and various descriptions of the IR Demo (see, for example, D. Douglas, “Lattice

Design for a High-Power Infrared FEL", Proc. 1997 I.E.E.E. Part. Accel. Conf., Vancouver, May 1997). Experience with the IR Demo is documented in several locations, including C. L. Bohn *et al.*, "Performance of the Accelerator Driver of Jefferson Laboratory's Free-Electron Laser", Proc. 1999 I. E. E. E. Part. Accel. Conf., New York, March 29 – April 2, 1999; the online Jefferson Lab FEL Logbook at http://felweb.acc.jlab.org/internal/fel/flog/html/logdir.html (internal only) and in various Jefferson Lab technical notes, such as D. Douglas, "Beam Transport Issues in the Fall/Winter 1998 FEL Run", JLAB-TN-99-007, 9 April 1999, and D. Douglas "Beam Transport Issues in the Winter/Spring 1999 FEL Run", JLAB-TN-99-008, 9 April 1999.

[2] D. Douglas, "A Driver Accelerator for an FEL Upgrade", JLAB-TN-99-019, 21 July 1999; D. Douglas *et al.*, "FEL Upgrade Scenarios", JLAB-TN-99-020, 2 July 1999; D. Douglas, "A 75% Solution for the FEL Upgrade", JLAB-TN-99-040, 30 November 1999; D. Douglas, "IR/UV Upgrade Project Accelerator Physics Plan", JLAB-TN-99-041, 2 December 1999.

[3] See D. Douglas, "A Driver Accelerator for an FEL Upgrade", *op. cit.* Actually, this is something of a second iteration of the optics – the first being presented in Laser Processing Consortium, *op. cit.*

[4] D. Douglas, "Lattice Design for a High-Power Infrared FEL", *op. cit.*

[5] See, for example Benson *et al.*, FLOG entries 7295 and 7316, 22 November 1999, and 7327, 23 November 1999; the injector current limit was related to me by S. Benson (private communication).

[6] This number pointed out by S. Benson, in "Talking points for 2" vs. 3" chambers", unpublished note.

[7] This design is based on the concept presented in D. Douglas, "A Driver Accelerator for an FEL Upgrade", *op. cit.* It does not necessarily fit in the existing vault and as yet has not been studied in detail. It is however an "existence proof" for a paper design of a simple system with 10% momentum acceptance.

[8] G. Biallas *et al.*, "Making Dipoles to Spectrometer Quality Using Adjustments During Measurement", Proc. 1999 I. E. E. E. Part. Accel. Conf., New York, March 29 – April 2, 1999; K. Tremblay *et al.*, "Magnetic Measurements of the Pi Bend Dipole Magnets for the IR-FEL at the Thomas Jefferson National Accelerator Facilty", Proc. 1999 I. E. E. E. Part. Accel. Conf., New York, March 29 – April 2, 1999.