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# Beam Transport Out of the FEL Injector

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## Introduction

In response to multiple inquiries (well, to be precise, *three* inquiries) regarding the use of the FEL injector (for nefarious, unnamed, nuclear physics purposes [1] and as a driver for a THz source [2, 3]) we have investigated various options for the transport and utilization of the low energy electron beam at the front end of the machine.

## Requirements

Requirements for either class of user are at present unclear (and, by the way, the reader should not construe any value judgment about the "class" of the user from the order stated in the Introduction…), and therefore by default trivial to meet. The somewhat close-mouthed earthly agent [see reference 1] of the sole apparent potential nuclear physics user has provided no information to the author other than "can [an individual who will remain nameless so as to protect his reputation by not ever linking him in the mind of the public with the disreputable characters at the JLab FEL facility] use the injector beam?" In this situation, we will thus assume only three requirements are imposed:

1. we need to get the beam out of the machine to some target (presumably in the vault)
2. we need to control the transverse beam size at the target (and thus manage dispersion and make provision for betatron matching), and
3. we must dump the beam after interaction with the target.

THz addicts have, however, been somewhat more informative, instructing us [4] that two scenarios might be used for the production of narrowband THz radiation. The first, which we think of as the "yeah, we can do that" [ywcdt] scenario, would simply take the long bunch that is now produced by the injector and put it through the W80 wiggler embedded in an optical cavity. The major constraints imposed in this case include:

1. getting the beam out of the driver to some FEL station,
2. preservation, more or less, of the longitudinal phase space features presently available, which we construe as "managing the momentum compaction somehow",
3. provision for appropriate betatron matching to the wiggler, and
4. disposal of the beam after the wiggler,

all to be done within a footprint allowing use of an appropriate optical cavity.

The second scenario – which we term the "well, maybe, if we can figure out how to run the injector differently" [wmiwcfohtrtid] scheme – assumes a more interventionist approach wherein the bunch length is compressed before transport through the wiggler,

resulting in the superradiant production of absolutely frightening amounts of coherent THz. Given that normal operation of the injector produces a long, low momentum spread bunch, there is little we can do with subsequent magnetic transport to provide the desired compression. But the wmiwcfohtrtid scenario *could* be implemented if appropriate manipulations of the injector RF (say, for example, we run cavity 1-3 way off crest) could be used to impose an appropriate phase-energy slew on the bunch, whereupon magnetic compression would be effective. In this case, the requirements are analogous to, but dissimilar in detail from, those of the ywcdt scenario:

1. getting the beam out of the driver to some FEL station,
2. generation of appropriate momentum compaction for bunch length compression,
3. provision for appropriate betatron matching to the wiggler, and
4. disposal of the beam after the wiggler.

No optical cavity constraints are present in this case.

Common to either scenario are betatron matching requirements, kindly provided by Steve Benson [3, 4] as

1. assume a vertical wiggler field (horizontal bending, vertical focusing) with k~1
2. match into the wiggler as a drift in the bending plane, as usual (which we read as $\beta_x$~2 m, $\alpha_x$~1 at the front of the wiggler), and a matched beta of around 10 cm in the nonbending plane (so $\beta_y$~0.1 m, $\alpha_y$~0).

We assume that if the transport system can provide this level of beam envelope control, the nuclear science users can be served as well.

In all cases, the waste beam must be managed: we note that this can be done by reinstalling the old high power injector dump, nominally rated to 50 kW but probably perfectly tolerant of higher powers (as it is the same as the energy recovery dump that received 9.1 mA at 9.2 MeV CW during previous high power runs).

In all cases, we will make use of the installed "x-chamber", which – rather than producing mutant superheroes with unusual powers – was deliberately with malice and aforethought designed to allow for the very exercise under consideration by allowing extraction of the low energy beam from the driver by switching off the final injection line dipole.

## Design Options

There are two basic geometries that admit the use of simple, symmetric, easily operated transport systems based on components of types already in use: direct the beam parallel to the injector axis (which is how it emerges from the installed x-chamber), or direct the beam parallel to the linac axis. Other geometries are possible but will likely invoke operationally complex manipulations (like involved dispersion modulation schemes) and/or use components of types not presently in the inventory (such as dipoles bending at angles not presently in use).

If we pursue the obvious options, at least three basic layouts become immediately apparent:

1. Reflect the injection line around the injection point (Figure 1); in its simplest incarnation, this would be done with complete symmetry and would trivially maintain dispersion suppression (Figure 1a). Note that this layout is simple a staircase translation of the beam path after the cryounit. If interferences occur, all requirements can still be met if exact symmetry is mildly violated and some mechanism for perturbing the dispersion is provided (Figure 1b). Further increase in the complexity of the dispersion management scheme could allow for variation of the compaction (at the expense of added operational burden).
2. Extend the basic injection line geometry past the injection point (Figure 2). This solution would require some dispersion management to preserve achromaticity, and compaction management would likely not be possible.
3. Extend the injection line geometry past the injection point by viewing the final injection line dipole – which is turned off in this application – as a "virtual" first bend of a staircase translation (Figure 3).

Each of these can be readily modeled and performance comparisons made. Results of this analysis follow.

Figure 1: "Simple" staircase geometry (Figure 1a) and perturbed staircase (Figure 1b).

Figure 1a: Simple staircase; beamline and Cavity 2-7 and 2-8 waveguides interfere.

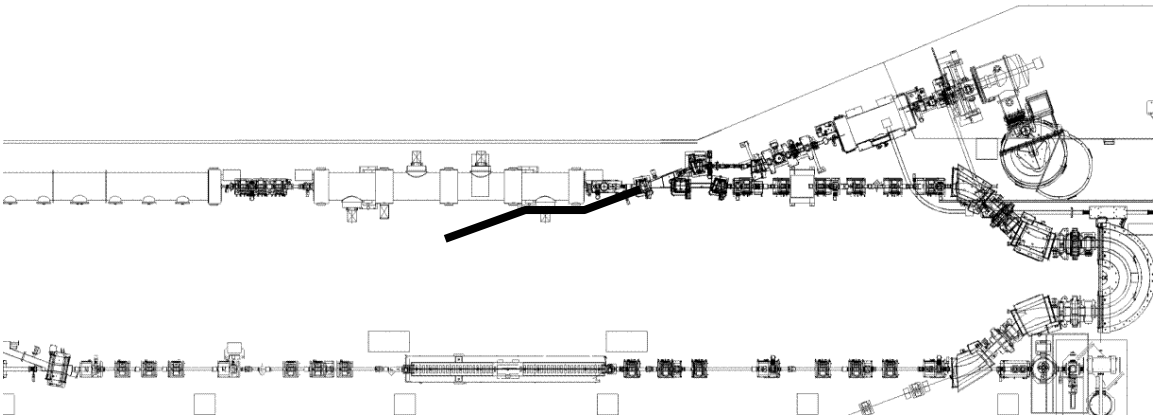


Figure 1b: Perturbed staircase; additional pair of quads needed as indicated.

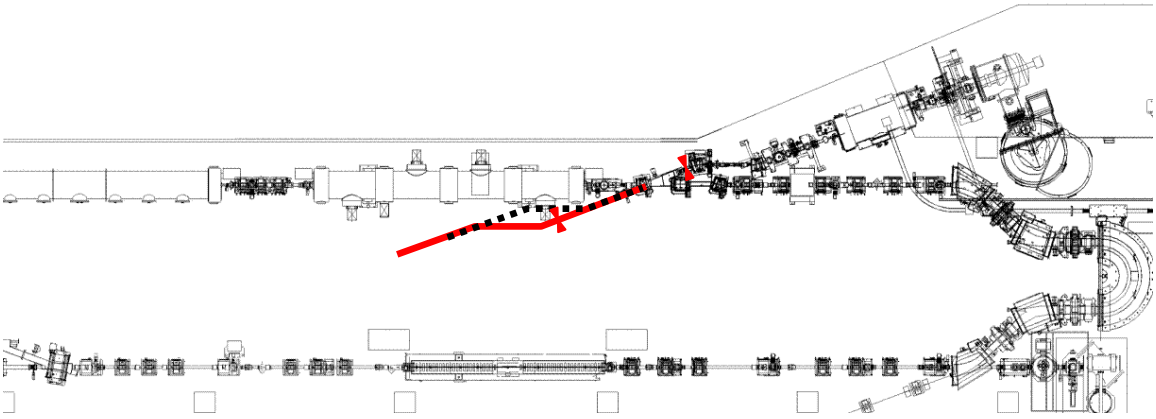


Figure 2: Extended injection line; additional quads are needed as indicated for dispersion suppression and betatron control.

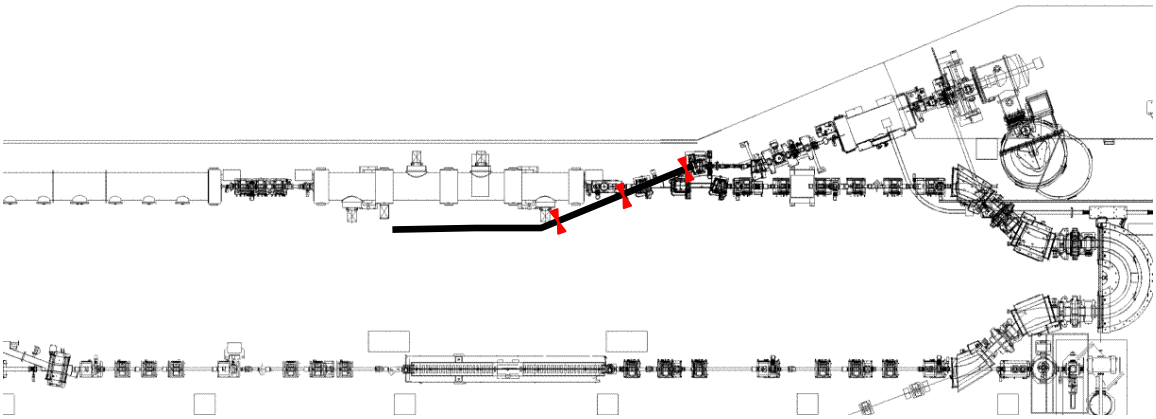
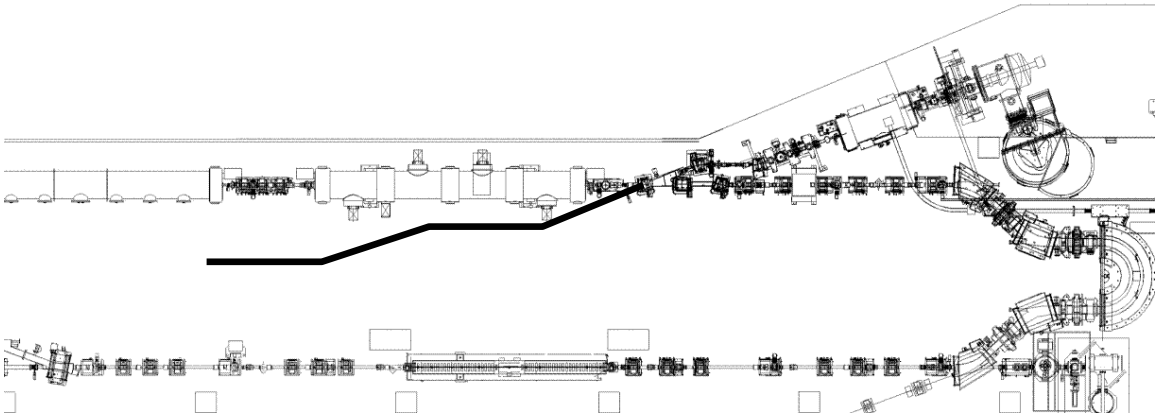


Figure 3: Full staircase initiated by "virtual" dipole at nominal injection point.



## Optical Solutions

DIMAD models have been constructed for the first two geometries. The third has not been treated for reasons discussed below. In each case (in the absence of input from potential nuclear physics users) only an optimization for production of coherent THz radiation was performed. The attendant computation of betatron matching to the wiggler was performed, as noted above, assuming a vertical wiggler field with horizontal bending and vertical focusing. At the start of the wiggler the beam is therefore matched to a drift-like condition $\beta_x \sim 2$ m $\alpha_x \sim 1$ in the horizontal plane (coming to a 1 m waist in the center of a 2 m-ish wiggler); in the vertical plane, the beam envelope is matched (at the wiggler entrance) to a waist at the wiggler matched beta value, which yields as stated above the conditions $\beta_y \sim 0.1$ m, $\alpha_y = 0$.

## Discussion

*First Geometry* – A completely symmetric implementation of the first geometry leads immediately to a recognition that the beamline will interfere with the waveguides on the first cryomodule. This interference is apparent in Figure 1a. A perturbed version of this solution is therefore required. A solution is easily obtained by stretching the drift from GV0F06 through the nominal injection point to the first dipole of the extended transport system. A pair of defocusing quadrupoles adjacent to these dipoles (as shown in Figure 1b) modulates the dispersion so as to preserve dispersion suppression. We have inspected the installed beam line and it appears that there is room just downstream of GV0F06 to retrofit the required quad without extensive vacuum chamber modification.

The resulting beam envelopes are, as shown in Figure 4, reasonable in magnitude. The momentum compaction of this geometry is twice that of the usual injection line, or almost -0.4 m. Further analysis is required to determine if this supports operation of a THz source in either of the two postulated modes.

We have not investigated layouts of the first type with more involved dispersion and compaction management. This analysis can be performed should future injector studies suggest that significantly different compaction values would be beneficial for one or the other of the presently envisioned operating scenarios.

*Second Geometry* – The second geometry leads to focusing solutions that can have locally large (several tens of m) beam envelope values (see Figure 4b). Though indicative of possible error sensitivity and halo issues, the observed values are not necessarily excessive. This layout has, however, a significant advantage over the others in that the associated $M_{56}$ is *identical* to that of the usual injection line. It would therefore be of considerable use in a system based on an optical cavity calling for a beam with the nominal injection properties (i.e., a beam with relatively long bunch and low momentum spread). We further note that this layout will require – in an operational implementation – somewhat more active dispersion management than the first geometry. Though not a conceptual difficulty, it will in practice require a well instrumented beamline with good quadrupole field control and reproducibility.

*Third Geometry* – A DIMAD solution using the third geometry has not been developed; this layout presents no particularly obvious transverse optical problems, but will have quite a large $M_{56}$ inasmuch as it has three dipoles (the second, third, and fourth) with sizable dispersion. The resulting compaction will likely therefore be of order three times the value of that of the baseline injection line. This may be of use should future analysis of injector beam dynamics reveal a means of compressing the bunch length so as to use the superradiant operational mode – i.e., the "wmiwcfohtrtid" scenario. The compaction associated with this layout is, however, extremely large and may interfere with use of beam with the nominal injected properties in the optical cavity based "ywcdt" scheme. This layout will therefore be revisited if injector beam dynamics analyses suggest the enlarged compaction would be of benefit.

All three geometries appear to admit solutions that would allow use of an 8 m optical cavity for the production of THz radiation. Figure 5 presents the layout of the nominal injection line, the perturbed version of the first geometry, and the second geometry. The latter two layouts are those used when computing the beam envelopes shown in Figure 4.

Figure 4: Beam envelopes for perturbed symmetrical (Figure 1b) and extended nominal (Figure 2) injection lines.

Figure 4a: Betatron functions for perturbed version of first geometry (Figure 1b).

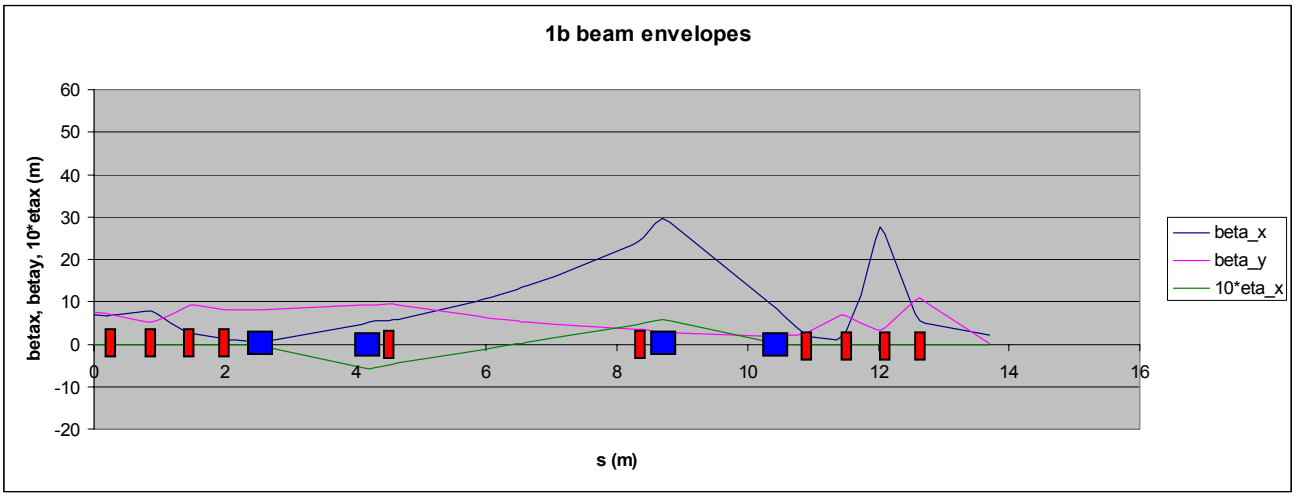



Figure 4b: Betatron functions for extended version of nominal geometry (Figure 2).

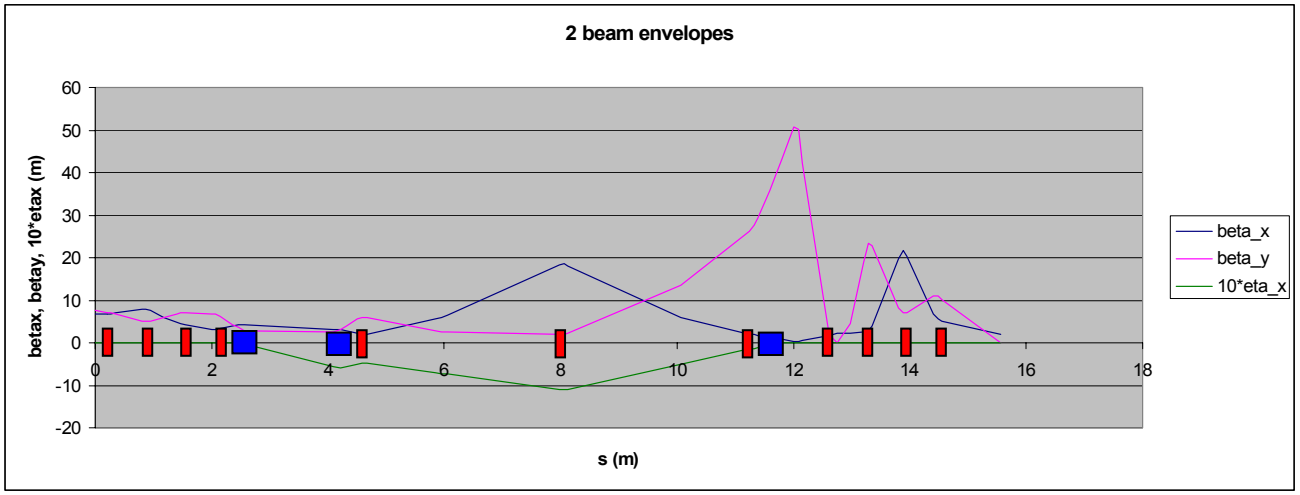
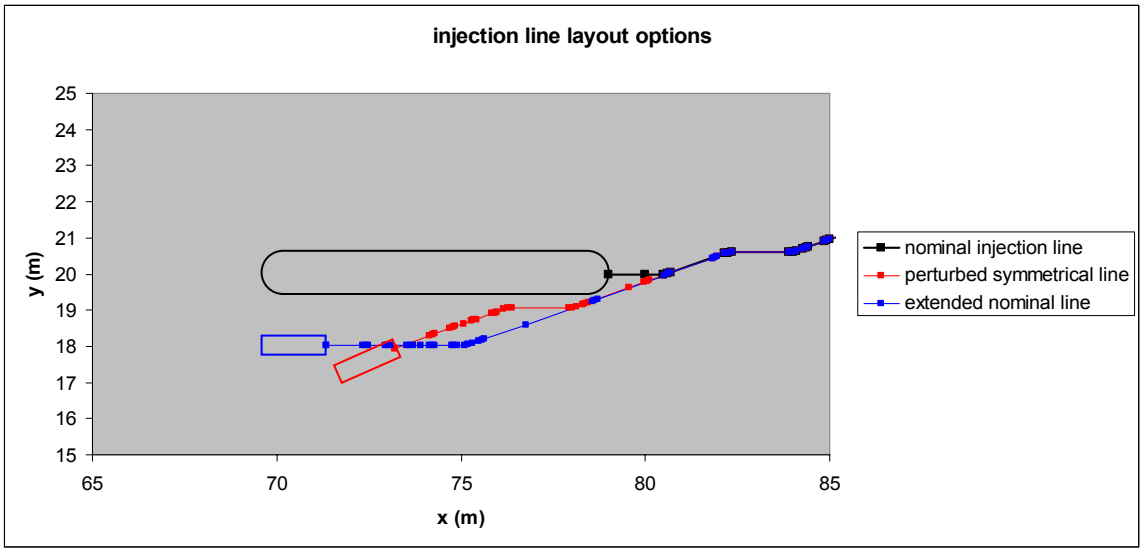


Figure 5: Layouts of nominal injection line, perturbed geometry (Figure 1b), and extended nominal geometry (Figure 2).




## Conclusion

We have investigated use of the FEL injector as a source for nuclear physics studies and the production of coherent THz radiation. It appears that beam can be transported out of the injector without significant modification to the existing installation using either of two geometries based on the existing injection line. Both appear to have acceptable transverse properties. One layout has longitudinal properties identical to that of the nominal injection path, the other has a larger (and, with some modification, potentially variable) momentum compaction. Either employs one or two dipoles of specification similar to those in use already, and would make use of order 6 to 8 quadrupoles (similar to the QJ or QI designs) in addition to the quartet already installed in the 0F region.

These solutions should be further investigated to determine their expected performance in the presence of space charge and to reconcile their compaction properties with the longitudinal matching required for THz production.

## Notes and References

[1] J. Boyce, *private communication*.
[2] G. Neil, *private communication*.
[3] S. Benson, *private communication*.

Hmmmm. A pattern of secretive behavior emerges…

[4] S. Benson, *op. cit.* (though isn't it a bit bogus to cite a *conversation* as previously referenced "opus"? And, besides, shouldn't I have used "*ibid*" here?)