IR FEL Driver ERL Configuration for the DarkLight Aperture Test

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Abstract

This note documents requirements placed on the FEL driver ERL for use in the 2012 DarkLight aperture transmission test and describes the system configuration that was developed to meet these requirements.

Requirements

The DarkLight aperture transmission test [1] is intended to validate the use of an internal gas target in an ERL. It therefore has as its goals both the clean transmission at 100 MeV of as much current as possible through a small (2 mm) aperture and the characterization of beam loss and radiation background as a function of bunch charge and current. The beam characteristics should be consistent with those required during the DarkLight experiment; thus, the beam should be of modest emittance and small (<0.1% rms) momentum spread.

These basic objectives imply a number of subsidiary requirements. Given the small test aperture, the ERL must be configured and operated so as to deliver a very small beam spot at the test location. This is equivalent to the use of a “mini-beta” insertion, with Twiss envelopes of a few cm at the “interaction point” (IP). The machine configuration must provide adequate means of halo management so as to avoid excessive losses on the test aperture (and elsewhere), and must allow control of resistive wall heating in the test chamber, BBU, and other power deposition from wakes, stray fields, or interception of halo. The bunch length should be kept long (as it will be as a consequence of Liouville, given the required small momentum spread) so as to mitigate resistive wall heating in the test aperture and to avoid other wakefield/impedance effects and CSR-induced momentum spread or other degradation of beam quality.

Use of the ERL in this manner also introduces a number of operational issues. The machine configuration must provide some means – equivalent to the miniphase procedure – of recovering and tuning beam. This will allow checks of the longitudinal match, including use of the Happek device (which quantifies bunch length compression and provides a quick check of the transport system operating point, as well as providing a check on beam energy by maximizing the Golay cell output and generating CSR-driven enhancement of beam momentum spread) and verification of energy compression during energy recovery.

Finally, the test configuration must be observant of machine performance limits. In particular, operation must be restricted to currents of 5 mA or lower so as to protect the electron gun and injector booster, both of which are exposed to potential damage at higher current. In addition, field emission from the linac – when operated at maximum available gradient – is of concern and must be controlled. The 100 MeV beam energy is thus dictated not only by user energy requirements, but also by a need to limit field-emission-driven backgrounds at the
location of the test aperture in an effort to simulate background management at the experimental detector.

**Design Options**

Solutions for the machine configuration must define the features of three principle categories in the machine architecture: the injector, the longitudinal match, and the transverse match. Options for operational implementation in this study are to some extent constrained by machine performance issues.

**Injector** – The current limit – of 5 mA, needed to protect the front end – leads us to run a UV-like injector configuration, delivering 60 pC at 75 MHz, rather than running the full IR charge of 135 pC at 37.5 MHz. The reduced charge leads to better transverse emittance and notionally better halo, and avoids the use of an undesirable injector orbit gronk implemented in March 2012 [2] to allow operation at 135 pC despite the presence of finger stock damage – with associated obstruction in the beam aperture – in a bellows upstream of the injector cryounit. With this configuration, there will thus be no ghost-pulse train at a full-current repetition rate of 75 MHz, – further reducing the potential halo burden.

**Longitudinal Match** – As intended by the system design, there are numerous options for the longitudinal match. The phase set point could, in principle be run with conventional chirping as for normal FEL operation. This allows use of the standard miniphase procedure to set and check RF phases nad match the beam energy to the recirculator setpoint – but will result in an undesirably large momentum spread. To reduce the momentum spread, acceleration can be performed on crest, with recovery in trough. This was done in CEBAF-ER [3] and for streak camera measurements in the IR Upgrade [4]. It is a robust configuration capable of producing small momentum spread at both full energy and after recovery. Significantly, the small momentum spread at full energy prevents bunch length compression – so the bunch will be long at the test aperture, avoiding resistive wall heating. However, phasing the linac and verifying that the energy has reproduced is rather more involved than during FEL operation: the linac must be crested (rather than checking with cross-phasing) and the energy match checked by confirming the beam orbit is properly turned into the arc (rather than by checking bunch compression as during a miniphase).

We therefore have chosen a third option for the longitudinal match: we will run the linac cross-phased, with the first and third modules on the rising side of the RF waveform and the second module on the falling side. This configuration is very close to that used in normal FEL operations and has been run during the CSR study. It does required slightly higher gradients in the linac than on-crest operation – but only by a factor of ~1/cos 10° – or just a few percent. This will not significantly aggravate field emission. By construction, such a match leads to a completely energy recovered beam, with equal energies at injection and at the dump. It is operationally convenient in that it allows use of a slightly modified version of the miniphase...
procedure to check RF phases and beam energy. Like on crest/in trough operation, the momentum spread is inherently small, with a commensurately long bunch.

In addition to choice of linac phase, we must also establish the recirculator momentum compaction schedule. All choices of phase require the recirculator be globally isochronous to insure robust energy recovery with small momentum spread at the dump. This can be achieved using either a doubly isochronous configuration (wherein the linac-to-observation point and observation point-to–reinjection transports are both isochronous) or by using a compressional configuration (wherein the linac-to-observation point compaction is of nonzero compaction, and the observation point-to reinjection compaction is nonzero of opposite sign). The former choice is notionally simple to check using a phase transfer function measurement; the latter is simple to use with cross-phasing and miniphasing to check machine setpoints. We therefore have chosen the compressional configuration; the linac-to-wiggler insertion compaction is \( \sim -0.2 \) m and the wiggler-to-reinjection compaction is \( \sim +0.2 \) m. By putting all three modules on the rising side of the RF waveform, CSR enhancement of energy spread can be conveniently used as a signature that the beam energy is properly matched to the recirculator setpoint.

**Transverse Match** – The modular design of the ERL allows convenient implementation of a test of the type under consideration here. The test aperture will be located in the geometric center of the driver 3F region, replacing the center skew quad of the 5-quad rotator. When appropriately reconfigured, the transport will allow matching to/from a “minibeta” value of \((\text{aperture length})/2 = 6.35 \, \text{cm at the center of the test aperture of length 5”}\). The test will thus constitute a conversion of the 3F region to a collider/ring-style “insertion”. We will unskew the rotator quads to provide additional degrees of freedom for the betatron match and to allow variations of phase advance to manage halo. Initial startup will proceed with the 3F tuned to a FODO configuration, and then migrate to the minibeta insertion solution.

**Design Concept**

Comparison of the various options suggests use of a UV injector configuration with a charge/time structure of 60 pC x 75 MHz. We have selected a longitudinal match based on cross-phasing of Zone 3 and “normal” (bunch length compressing) recirculator arc optics. This allows a quick check of cryomodule phases (by jumping them across crest), and provides a quick check of the beam energy, as the Golay cell output will be maximized for the “correct” energy when all three linac zones are chirped in the same sense (head of bunch at lower energy) by acceleration on the rising side of the RF waveform. This approach also provides the requisite small energy spread. Given the choice of compaction, there will therefore be essentially no bunch length compression at the test aperture, so that resistive wall heating will be mitigated.

The transverse matching scheme will use the 3F region as an “insertion” and keep the rest of the machine tuned to the same betatron match as used during FEL operations. This limits the retuning needed in the rest of the machine. This choice requires minor modifications to the 3F focusing structure; in particular, MQX3F06S will be removed to provide space for the test
aperture, and MQX3F05S and MQX3F07S will be rotated from skew to normal orientation to provide additional required focusing channels. The resulting transport line will allow a full transverse phase space match from the standard FEL transport solution at the front end of the 3F region to the test cube, and back to the conventional transport solution at the back end of 3F. It will also retain multiple quads as “free knobs” to control halo and BBU (via the choice of phase advance), as is done during FEL operation.

**Longitudinal Match**

The longitudinal match is specified by the beam energy, the linac accelerating phase profile, and the recirculator compactions. The beam energy will be 100 MeV to meet user specifications and to allow operation at reduced gradient, which will alleviate field emission and thus mitigate the radiation background at the location of the test aperture.

We have chosen a “cross-phased” linac solution using momentum compactions quite close to those employed during FEL operation. This provides a very small energy spread (Figure 1) and allows use of a minimally modified miniphase procedure (Appendix B) to set phases and energy, with the most obvious change being simply that Zone 3 is “left on the wrong side of crest” once finished.

![Synchrotron radiation image at dispersed location (center of first arc 180° dipole). Left – nominally chirped linac phasing; full momentum spread in excess of 2%. Right – zone 3 cross-phased; full momentum spread less than ¼%.

Figure 1: Synchrotron radiation image at dispersed location (center of first arc 180° dipole). Left – nominally chirped linac phasing; full momentum spread in excess of 2%. Right – zone 3 cross-phased; full momentum spread less than ¼%.

A second – more subtle – operational modification is driven by the circumstance that the energy at the dump is essentially the same as the injection energy, and is phase insensitive (having at lowest order a quadratic phase dependence). This is a consequence of the fact that zones 2 and 4 are on the opposite side of crest and trough from zone 3 – so if the reinjection phase shifts either way, the energy variation due to the phase change in zones 2 and 4 is offset by
the energy shift due to the phase offset in zone 3. The energy spread at the dump is thus minimized – and the energy is at a minimum – for the “correct” phasing, and thus serves as a signature that the recirculator path length is properly set (Figure 2).

![Figure 2](image)

Figure 2: Longitudinal phase space at dump as a function of recirculator path length. Left – recirculator 1 mm short of nominal length; center – recirculator at nominal length; right – recirculator 1 mm longer than nominal. Recovered momentum spread minimized at nominal path length.

Given the small momentum spread at full energy and the modest recirculator momentum compaction values the bunch is “long” throughout the system, resulting in minimal resistive wall heating and avoiding other potential collective effects. A simulation of the match is shown in Figure 3. At 100 MeV with roughly uniform gradients (chosen to suppress field emission), the bunch is fully dechirped when zone 2, 3, and 4 are gang-phased, respectively, to -10°, +14°, and -10° (ϕ<0 for acceleration on the rising side of the RF waveform, i.e., ahead of crest). The energy at the dump equals that at injection, providing essentially complete energy recovery and energy compression with cross-phasing when the path length is properly set.

Note that this “compressional” solution will – with proper choice of compactions – accommodate energy spread and loss in a target via energy compression during energy recovery. The resulting energy shift from scattering is analogous to coupling power out of the beam using an FEL. This is not the case with doubly isochronous solutions, wherein scattering-induced energy spread will not be compressed during recovery and loss will lead to an energy down-shift at the dump. In either case, however, degradation of energy spread due to interaction with the target can (because the bunch is long) potentially lead to large growth of longitudinal emittance (as is always the case when inducing momentum spread at a point of low beam divergence/large beam size). The details of the match must therefore be reviewed as understanding of the expected beam/target interaction evolves.

The bunch length compresses fully at the Happek device when Zone 3 is normally chirped – that is, set to -14° (on the rising side of the RF waveform). This requires linac-to-Happek compactions of $M_{56}=-0.172$ m and $T_{566}=-2.25$ m. Full compression produces the usual CSR signature (momentum spread enhancement), certifying that the energy is correct (by
insuring the orbit is centered in the sextupoles). The bunch energy fully compresses at the dump when Zone 3 is cross-phased – that is, set to +14° (on the falling side of the RF waveform, after crest). The simulation assumed both transport arcs were set to the 100 MeV nominal energy, and used Happek-to-linac compactions of $M_{56} = +0.172$ m and $T_{566} = +2.25$ m, though the results for the nominally cross-phased beam are somewhat insensitive to these settings (due to the small momentum spread). These values do, however, produce energy compression during recovery when Zone 3 is set at -14° to check the energy setpoint. This is not surprising – as it renders the recirculator isochronous from linac back to reinjection – and provides guidance for the initial machine longitudinal setup (Appendix A).

Small momentum spreads are apparent at full energy and at the dump. As discussed above and shown in Figure 2, the dump energy spread is minimized (and the dumped energy equals the injection energy) when the reinjection phase results in complete energy recovery. This gives guidance for setting the path length, and forms a part of a modified miniphase procedure used to set/check the machine tuning (Appendix B).

**Transverse Match**

Transverse optics for the DarkLight aperture test are based on a conversion of the 3F region (Figure 4) to a modular insertion, with essentially no change to the upstream or downstream ERL configuration. The 5-quad rotator will be rearranged by replacing the center skew quad with the test cube and turning off the first and last quads. The second and fourth skew...
quads will be rotated to a normal configuration. The resulting installation can be run as a FODO (the original design mode for 3F) and with various arrangements of singlets, doublets, and triplets. This allows for use of any of a variety of solutions and thus gives flexibility in the choice of phase advances for the control of both halo and BBU. Figure 5 shows the nominal focusing configuration.

![Nominal FODO configuration for 3F region; Bottom – nominal phase space exchange configuration.](image1)

![DarkLight configuration; “normalize” two skew quads, replace one skew quad with test cube containing test apertures, and rearrange focusing solution](image2)

The quads upstream of the test aperture will be used to match the beam exiting the 2F region to the “optimal” match for the aperture: $\beta_{\text{in}} = L_{\text{aperture}}$, $\alpha_{\text{in}} = 1$; $\beta_{\text{center}} = L_{\text{aperture}}/2$, $\alpha_{\text{center}} = 0$ in both transverse planes. Given that $L_{\text{aperture}} = 5'' = 12.7$ cm, we must have $\beta_{\text{center}} = 6.35$ cm. With a nominal 60 pC normalized emittance of 10 mm-mrad and an energy of 100 MeV, this will result in a spot size of ~60 $\mu$m at the center of the aperture.

The small spot and Twiss amplitude parameter is associated with a large beam divergence, and leads to large beam envelopes in the adjacent quadrupoles. Given given that there are eight quads up- and downstream of the test aperture, we can optimize the match to limit $\beta_{\text{max}} \sim 100$ m or less by limiting the strength of the quads immediately adjacent to the test cube. As noted, we treat the entire 3F region as a modular insertion, matching the beam/lattice from the
nominal ERL configuration in 2F to a nominal beam/lattice configuration in 4F (with minor adjustments to compensate for small changes in the longitudinal match).

The system is underconstrained by the matching requirements at the test aperture; eight quads are available to meet four constraints: $\beta_x, \alpha_x, \beta_y$, and $\alpha_y$, to (or from) the test aperture; the redundant families can be used to limit excursions in the beam envelopes (limiting the maximum size, as noted above), and for control of phase advance for BBU and halo management as during normal FEL operations without the rotator.

The small envelopes and relatively tight quad spacing results in relatively strong focusing; this in turn leads to high chromaticity. This is not inherently dangerous inasmuch as the intrinsic beam energy spread is very small. It does, however, create potential (and observed [5]) operational delicacy in that small changes in energy setpoint can (and do) lead to significant changes in phase advance. The BBU threshold thus becomes very energy-dependent, and energy drifts can push the beam to a tune that leads to instability. Some care must therefore be taken to hold the energy sufficiently close to the nominal set point during long beam runs.

**Design Process**

Requirements were met and concepts implemented using a design process that has become a standard method for devising new system configurations. We evaluated the longitudinal match (presented above) using a spreadsheet model [6]. Initial analysis of the full system was then performed using DIMAD [7]. Once an initial solution meeting transverse matching requirements was established, a performance analysis was conducted (results below).

Operational tunings were set up using a spreadsheet-based machine model [8]. This allowed rapid fine-tuning to get a small spot size at the test apertures and to exercise a method for halo and BBU control, which consisted of:

- varying MQX3F01 to modify the phase advance to the aperture
- rematching to the aperture
- varying quads downstream of the test aperture to modify phase advance to the wiggler while holding the match at the wiggler fixed (note that the wiggler jaws were locked fully open to reduce dose to the PM material)
- adjusting the energy recovery match (typically with MQX4F11 and the 5F reinjection telescope) to vary phase advance while managing core beam envelopes so as to manage halo and BBU

Details of the operational implementation of the design solution will be provided in a subsequent technical note [9].

**Performance Analysis**

DIMAD was used to evaluate several figures of merit. We checked beam envelopes to verify that 3F could be operated as a modular insertion with the rest of the machine unchanged
(save for those adjustments needed to manage phase advance for halo and BBU control). We verified that spot sizes were of order 50 μm at the test aperture, 200 μm at the wiggler, and sub-millimeter elsewhere, and that beam envelopes could be kept under 100 m maximum.

Momentum scans were performed to verify that lattice and beam parameters did not change significantly over the required momentum acceptance. We note that this configuration uses a far smaller momentum bite than FEL operations, as the user requires small momentum spread. Thus, momentum acceptances of a few parts per thousand – rather than 10% - are needed. Momentum scans also detail chromatic behavior, in particular the high chromaticity associated with the strong focusing used to produce a small spot size at the test aperture. It is therefore necessary to ascertain the variations of phase advance and phase space across the full bandwidth of momentum acceptance.

Given the changes in lattice configuration, we checked geometric aberrations to verify that stronger focusing, changes in the evolution of the phase advances, and details of the new operating point do not introduce significant amplitude dependences. Finally, we performed ray-tracing checks to assess the effects of the cross-terms amongst multiple elements and higher order aberrations and to confirm the absence of formation of obvious nonlinear tails on the beam.

**Beam Envelopes** – Evaluation of beam envelopes indicates that it is possible to keep their values near nominal through most of the machine, that maximum values can be kept under 100 m, and that the desired β* of 6.35 cm can be obtained at the center of the test aperture. Figure 6 presents the DIMAD design solution for this configuration. Figure 7 presents nominal and DarkLight configurations as evaluated with the spreadsheet-based machine model. In Figure 7a, the generic (rotator off) lasing optics are shown; DarkLight test optics are shown in Figure 7b. They are fairly similar to one another and to the DIMAD model outside the 3F region; the DarkLight operational and DIMAD design models agree well in the 3F region. Peak envelopes are well under the 100 m goal.

![Figure 6: DIMAD results for DarkLight beam envelopes.](image)

Figure 8 provides a zoomed-in view of 3F test insertion for the solution of Figure 7b. Peak envelopes have been kept under 75 m by limiting the strengths of the quadrupoles immediately adjacent to the test aperture (location shown by black bar).
Spot Sizes – The DarkLight test will run 60 pC to mitigate halo and allow operation at full (75 MHz) repetition rate while providing some degree of protection to the injector by limiting the gun current to 5 mA. This will significantly reduce the probability of cryounit waveguide trips that can result in damage to the cathode if running high (~6+ mA) current. It will also provide “better” core emittance than operation at the IR standard charge of 135 pC; UV operation at 6 pC typically assumes 5 mm-mrad normalized emittance while IR operation at 135 pC assumes ~10 mm-mrad.

The use of 60 pC bunch charge also allows use of the standard UV injector setup. This is advantageous for the DarkLight test as scheduled; at the scheduled time the IR injector tuning
requires use of a severe orbit “gronk” in the very front end so as to alleviate beam interception on finger stock protruding from a damaged bellows shield between the buncher and the cryounit. This work-around is not necessary at the lower charge, and avoids potential degradation of beam quality associated with strong steering and large offsets in the second solenoid.

The design under discussion assumes 10 mm-mrad injected normalized transverse emittance and 50 keV-psec longitudinal emittance. This provides additional transverse safety margin. Beam operations included emittance measurements; results of these will be discussed in a follow-on technical note [10].

Figure 9 presents beam envelopes as evaluated by DIMAD for the design configuration. Figure 9a is on a linear scale, and shows a number of useful features of the solution. Firstly, the evolution of the momentum spread shows the impact of linac cross-phasing during acceleration and recovery, and indicated the full-energy momentum spread is quite small. Secondly, the bunch length is nearly constant throughout the acceleration/transport/recovery cycle. Finally, spot sizes remain modest throughout the system. Figure 9b is on a log scale, and is included to provide additional resolution for the size of the small spot at the test aperture (which is at about 60 to 65 m path length).

Figure 9a: RMS beam sizes through ERL for 10 mm-mrad normalized transverse emittance and 50 keV-psec longitudinal emittance.

Figure 9b: Log-scale plot of beam sizes showing details of small full-energy momentum spread and small spot (10s of μm) at test insertion (~60 to 65 m in path length from start of ERL).

Figure 10 provides spot sizes generated for rotator-off lasing optics (Figure 10a) and for the DarkLight tuning (Figure 10b) using the operational model. Results are consistent with
experience and with the DIMAD results. RMS spot sizes are modest throughout the system –
even at the points of maximum beam envelope and/or at low energies (where the geometric
emittances are large). Spot sizes are quite small at the location of the test apertures.

Figure 10a: Operational model evaluation of spot sizes in generic (rotator off) lasing optics with
10 mm-mrad normalized emittance.

(DarkLight_07-10-2012-allsave-4108.xls at 10 mm-mrad)

Figure 10b: Operational model evaluation of spot sizes in DarkLight test optics with 10 mm-
mrad normalized emittance; test aperture spots ~60 μm.

(DarkLight_07-10-2012-allsave-4108-3F-edge-to-edge-compress-size.xls at 10 mm-mrad)

**Momentum Scans** – Analysis of off-momentum behavior is needed in the DarkLight
configuration because of the extremely strong focusing involved in producing the small spot size
at the test aperture. We must verify that the beam is not unduly distorted by chromatic errors –
despite its small momentum spread. We must also insure that momentum tails will propagate
cleanly, and must evaluate chromatic aberrations so as to establish transport sensitivities to
energy drift and jitter. The analysis must characterize potential betatron mismatch and phase
advance shifts resulting from the high chromaticity associated with strong focusing.
Chromatic aberrations have potential implications for BBU; if the chromaticity is high enough (and it is...) momentum shifts can (and do) drift the beam onto tunes that lower the BBU threshold and induce instability. Care must be (and has been) taken in setting and holding energy stable during operation. A discussion will be provided in a follow-on note [11].

The nominal beam rms momentum spread is of the order of a few $10^{-4}$. We conducted the analysis over $\pm 1/2\%$ – several tens of $\sigma_{dp/p}$ – to characterize effects over several beam widths and several times typical energy drift or jitter. Orbit and Twiss parameter response to momentum shifts are evaluated at multiple critical apertures: the test assembly in 3F, the IR wiggler in 4F, and the 5F reinjection point. Results follow; behavior is acceptable but the chromaticity is quite high. Figure 11 shows the Twiss $\beta$ and $\alpha$ at the start, center, and end of the test aperture. Figure 12 presents the momentum dependence of the orbit and the linac-to-test aperture phase advances. The large phase advance across the aperture (from small $\beta$) and high chromaticity is obvious.

Figure 13 provides the same information at the wiggler center, and Figure 14 characterizes the performance at the reinjection point. Behavior is good, but evolution of nonlinear chromatic effects and high chromaticity is apparent.

Figure 11: Horizontal and vertical Twiss parameters at start, center, and end of test aperture.
Figure 12: Linac-to-test aperture phase advances and orbit as a function of momentum.

Figure 13: Results of momentum scan for figures of merit describing linac-to-wiggler transport.
Geometric Aberrations – Amplitude dependences in the transport system can lead to orbit-dependent optics and, if sufficiently severe, phase space distortion and/or amplitude-dependent phase advance, which could in turn result in instability issues. We therefore explored the impact of geometric aberrations in the recirculator, evaluating phase space distortion and amplitude dependences of phase advance and beam envelopes to determine if sensitivities arise during the transition from the FEL setup to the aperture test.

This was done using the DIMAD “line geometric aberration analysis”, in which phase ellipses of various (large) emittance are tracked at various momentum offsets through the lattice and the beam parameters of, and degree of distortion in, the image phase spaces are evaluated. Given the radial aperture constraint of \( r = 0.001 \) m at a point with beam envelope of \( \beta = 0.0635 \) m, we are interested in behavior out to emittance \( \varepsilon = \frac{r^2}{\beta} \sim 16 \) mm-mrad. This is some 320 times the nominal geometric emittance of 0.05 mm-mrad (for 10 mm-mrad normalized at 100 MeV). We therefore set initial ellipses at 1, 2, 4, 8, 12, and 16 mm-mrad (20, 40, 80, 160, 240, and 320 times nominal beam emittance) for each of three momentum offsets \( \delta p/p = \pm 0.001, 0 \) (±3–4 times the rms beam momentum spread and on momentum).

Results of the linac-to-IP and linac-to-reinjection ellipse tracking are shown in Figures 15 and 16. The image phase spaces are well-described by the linear emittance and beam envelope parameter values out to the physical aperture when “best fit” ellipses describing the image phase spaces are evaluated. Some distortion is, however, apparent. The degree of distortion is characterized in DIMAD by evaluating the emittances associated with individual test rays lying...
off the fitted linear ellipse – assuming fitted ellipse beam parameters – and comparing them to the emittance of the best-fit ellipse describing the collection of image rays as a whole. The ratio of the difference between maximum and minimum ray emittance to the fitted ellipse emittance is shown in Figure 17; the values are reasonably well-controlled given that the test rays in question sample the full physical aperture of the machine.

Figure 15: Geometric aberration analysis, linac to “IP” for emittances reaching out to 1mm radial limit of test aperture. Contours at 1, 2, 4, 8, 12, 16 mm-mrad geometric (20, 40, …, 320X nominal of 10 mm-mrad normalized ~ 0.05 mm-mrad geometric at 100 MeV).

Figure 16: Geometric aberration analysis, linac to reinjection for emittances reaching out to 1mm radial limit of test aperture. Contours at 1, 2, 4, 8, 12, 16 mm-mrad geometric (20, 40, …, 320X nominal of 10 mm-mrad normalized ~ 0.05 mm-mrad geometric at 100 MeV).
Figure 17: Relative emittance distortion as function of emittance for various momentum offsets.

Amplitude (and chromatic) dependence of phase advance can be characterized by a similar same tracking method. Rather than using several tens of particles at each emittance, we trace only four rays, with initial conditions at the RMS spot size and divergence (on the axes of the transverse phase subspaces) at the test emittances for each momentum of interest. For completely linear transport, the data will lie on straight lines; amplitude-dependent phase advance will manifest itself as curvature in the image data. Chromaticity (also an issue here) will be manifested as changes in slope of the image curves. Results are shown in Figures 18; minor amplitude dependent detuning is present; chromaticity is clearly visible.

Raytracing — The “acid test” of the configuration is provided by ray-trace simulation from injection to dump with adequately detailed physics models to give assurance that the behavior of problematic phenomena will be capture. Previous experience with the IR driver ERL, and the large number of unconstrained parameters available as tuning knobs, suggests that this configuration can avoid deleterious effects of collective phenomena by appropriate care in setup and operation. We therefore have used DIMAD’s relatively rudimentary modeling capability to vet the design with respect to lattice and tuning issues.

A 1000-particle injection-to-dump simulation was therefore used to check the phase space at the test aperture, reinjection, and at the back end of the linac after recovery. Figure 19 provides scatter plots of the test distribution at injection. Figure 20 shows the distribution as delivered to the test cube; Figure 21 shows it at reinjection; Figure 22 shows it after energy recovery. In each location the behavior is as expected and acceptable.
Figure 18: Amplitude and chromatic dependence of phase advance for horizontal (left) and vertical (right) phase space from linac to IP (top) and linac to reinjection (bottom).

Figure 19: Test raytracing distribution (1000 particles) at injection.
Figure 20: Test distribution at test cube after acceleration and transport.

Figure 21: Test distribution at reinjection.
Summary and Conclusions

We have described a machine configuration for the DarkLight internal target validation test. Minor modifications of 3F region beamline hardware in the existing system will allow operation in a simulated “mini-beta” mode and provide some degree of control over halo. Standard analysis of the proposed configuration indicates performance should be acceptable. Outlines of procedures for setting the (modified) longitudinal match and miniphasing that match are given in appendices.

Notes and References


Appendix A: Machine Longitudinal Setup Procedure

The major steps in initial setup of the longitudinal match are as follows.

1. Set linac to ~100 MeV gain, and set extraction dipole string to match injection string.
2. Phase linac
   a. Set zone gang phases to -10°, -14°, -10°
3. Set energy to 100 MeV with precision
   a. Steer carefully into arc
   b. Turn 1st corner by setting energy (center in trim quad)
4. Refine orbit to Happek
5. Compress bunch length with 1st arc trims quad and sextupoles
6. Recover beam to dump (set path length; when complete $E_{\text{dump}} = E_{\text{injection}}$)
7. Refine orbit
8. Compress recovered energy spread with 2nd arc trim quads, sextupoles, and octupoles
9. Cross-phase zone 3 (set phase to +14°)
10. Adjust path length to minimize energy spread at dump
Appendix B: Modified Miniphase Procedure

The major steps in miniphasing while operating cross-phased are as follows.

1. Phase injector as usual
2. Verify linac phases of -10°, -14°, -10° using usual method
3. Set vernier cavity gradient to maximize Golay cell readback
   a. Verify presence of CSR enhancement of momentum spread in 2nd arc
4. Verify beam is to dump
5. Cross phase zone 3 (go to +14° => falling side of waveform)
6. Adjust path length to minimize energy spread at dump