WBS 3.0: Beam Physics Requirements for IR Upgrade Driver Accelerator

Keeper: D. Douglas, x7512, douglas@jlab.org
Revision: 1.0
Date: 31 May 2000

WBS 3.0 Overview

The IR Upgrade FEL will be driven by an 80-210 MeV, 10 mA energy-recovering, SRF-based CW linear accelerator. The machine, shown schematically in Figure 1, comprises a 10 MeV injector, a linac consisting of three high-gradient Jefferson Lab accelerator cryomodules, and a recirculator providing beam transport through, and phase space conditioning for the FEL and energy recovery. This concept directly supports the FEL design paradigm – a low-extraction-efficiency, low peak/high average power, high-repetition-rate light source. As the SRF linac driver operates natively in CW mode, it allows a high repetition rate and extremely high beam quality. This, in turn, provides the high peak-current and beam brightness required by the FEL with the use of only modest single bunch charge, reducing demands on the electron source. Energy recovery limits cost and technical risk by limiting demands on the RF system (RF power requirements in the driver accelerator, RF window power tolerances), improving system efficiency, and limiting radiation power in the expended beam (which is dumped below the neutron production threshold). Required and achieved machine parameters for both the IR Demo and the Upgrade are given in Table 1.

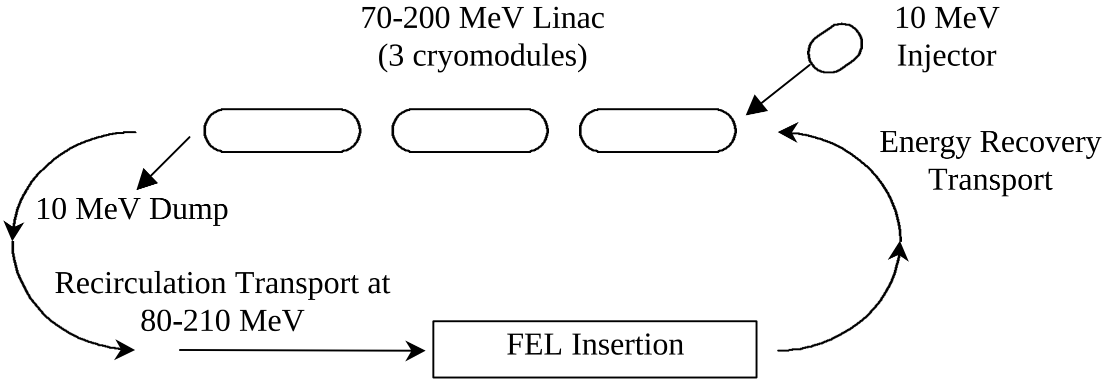

Figure 1: Machine Schematic.

The choice of design paradigm and system architecture determines completely the two primary driver performance requirements: 1) the driver accelerator must provide a phase space at the wiggler configured for the FEL interaction, and 2) it must subsequently energy-recover the electron beam following the FEL. In addition, various system integration issues impose requirements as well. These include specific features peculiar to the SRF environment, the potential for spatial and temporal interference with the existing IR Demo FEL, global machine issues, and the design and modeling of a driver linac operating in a nearly non-perturbative regime. The upgrade will, for example, utilize the first cryomodule based on Jefferson Lab 7-cell 1.5 GHz SRF cavities. The project must, in addition, be executed in a manner maximizing the remaining operation time available to the IR Demo and limiting interference with installed IR Demo hardware, while minimizing the time required for the Demo to Upgrade transition. Certain concerns, such as beam transport component specifications, commissioning, and so forth, span the full beam path through the machine and must be treated globally. Finally, the large acceptances required during energy recovery impose a significant burden on machine design and modeling tools, which are generally applied only to systems transporting smaller relative phase space volumes.

Detailed beam physics requirements and resulting features of the driver design follow as immediate consequences of the preceding top-level criteria. These have been discussed in numerous JLab Technical Notes [1] and are summarized in outline format below.

Table 1: System Parameters.

	Demo	Upgrade	Achieved
energy (MeV)	35-48	80-210	20-48
average current (mA)	5	10	5
charge/bunch (pC)	60	135	135
FEL repetition rate (MHz)	18.75-75	4.6875-75	18.75-75
RMS bunch length (psec)	1/2	1/4	<1/2 (60 pC) ? (135 pC)
peak current (A)	60 A	250 A	>60 A (60 pC) ? (135 pC)
RMS $\delta p/p$ (%)	1/2	1/2	1/4 (60 pC) 1/4 (? 135 pC)
ε_N (mm-mrad)	<13	<30	5-10 (60 pC) ~25 (135 pC)
FEL extraction eff. (%)	1/2	1	>1
full energy spread after lasing (%)	5	10	>6-8

WBS 3.1 Driver Performance Requirements

WBS 3.1.1 Delivery of appropriately configured electron beam phase space to wiggler

The delivery of an appropriate configured electron beam phase space to the wiggler entails the production, acceleration, transport and conditioning of the beam for lasing (with preservation of beam quality).

WBS 3.1.1.1 *Generation of appropriate source beam* – the gun and injector must produce an electron beam with the following characteristics

- up to 135 pC/bunch
- transverse emittance adequate to ensure, in the presence of downstream dilution effect such as space charge, coherent synchrotron radiation, and wakefields, a normalized emittance below 30 mm-mrad at the wiggler
- longitudinal emittance adequate to ensure, in the presence of downstream dilution effects such as space charge, coherent synchrotron radiation, and wakefields, an rms momentum spread under ½% at the wiggler with FWHM bunch length at the wiggler of ½ psec

The injector linac should in addition meet the following requirements:

- photocathode and wafer lifetime should allow delivery of >500 C between cesiations and 2 kC between wafer replacements; this in turn will allow two shifts of full current (10 mA) operations (~14 hours) between cesiations ~1 week (4 days, 2 shifts/day) between wafer changes. At 10 kW output laser power, this provides an IR output of ~2 GJ/wafer.
- The injected phase space should support the production of the bunch length and momentum spread at the wiggler using a “off crest acceleration/magnetic compression” scheme of the type presently implemented in the IR Demo. The present IR Demo injector will, during Demo operations, be fully characterized to determine the dependence of beam emittances (transverse and longitudinal), lattice functions and beam envelopes, bunch lengths and momentum spreads on system hardware parameters. This will indicate how to alter the present 60 pC injected phase space (which gives 1 psec FWHM bunch length and ¼% rms momentum spread at the wiggler) to provide the phase space required at 135 pC for 10 kW operation (bunch length of ½ psec FWHM with rms relative momentum spread of ½% [2]).
- the Upgrade injector must be reproducibly operable by Jefferson Lab operations staff using documented manual and automated setup and recovery procedures.

WBS 3.1.1.2 *Acceleration, transport and conditioning of electron beam for* lasing – the driver linac must accelerate the 10 MeV injected beam to 80-210 MeV and transport it to the wiggler. It must provide conditioning of the beam to ensure an appropriately configured phase space is available at the wiggler for lasing. This will require:

- transverse matching into the wiggler, to be provided by one or more quadrupole telescopes. This matching should be variable over a factor of 3 range of initial, and a factor of 2 range in final, conditions so as to compensate for
  1) changes in the electron beam due to any undiagnosed alterations or irreproducibility in the injector and linac – such as variations in beam envelopes at the end of the linac from changes in RF focussing due to differences in energy gain,

    2) differences in the required electron beam/optical mode overlap conditions between multiple optical cavities (broadband and high power) and operational modes – such as undulator mode vs. optical klystron mode, and
    3) variation in the optical mode due to mechanical variability in the the optical cavities (such as mirror replacements, *etc*.)
- longitudinal matching making use of momentum compactions provided by recirculation arc and/or magnetic chicanes used to interleave the electron beam and optical mode. This matching should
    1) provide variable linear and nonlinear (quadratic) momentum compactions (to complement the slope and curvature of the RF waveform and wakefields)
    2) be available through "orthogonal" knobs (using trim quads and sextupoles),
    3) be based on both machine modeling and beam based bunch length and longitudinal transfer function measurements at the wiggler
- beam quality preservation during acceleration, transport and conditioning. The beam at the FEL must meet the aforementioned phase space requirements; the driver accelerator must therefore conform to an error budget that precluded violation of beam quality requirements. Issues to be addressed are:
    1) management of collective effects, including
        a) space charge
        b) coherent synchrotron radiation, and
        c) wakefields (*via* impedance stewardship)
    2) Other emittance dilution effects, including
        a) lattice aberrations (chromatic/geometric effects)
        b) accelerator error sensitivities, including
            i) alignment
            ii) field quality
            iii) excitation errors
        c) RF related effects, such as
            i) RF phase errors
            ii) fundamental power coupler/head-tail driven emittance dilution
            iii) correction of higher order mode coupler generated skew quad driven coupling

WBS 3.1.2 Energy recovery of electron beam following FEL interaction

Following the FEL insertion, the driver accelerator must energy-recover the electron beam. As previously noted, implementation of energy recovery technology reduces both cost and technical risk by limiting demands on the RF system, improving system efficiency, and assisting in the radiation control of the dumped beam.

WBS 3.1.2.1 *Capture, transport, conditioning and deceleration of electron beam after the FEL* – which will entail the capture, transport, conditioning (transverse and longitudinal matching), and deceleration and energy compression of a large phase space volume, inasmuch as the 1% extraction efficiency of the FEL will induce a beam momentum spread of up to 10%. Requirements are:

- large transport system acceptance for loss-less energy recovery of the large phase space volume, particularly the 10% relative momentum spread; the system must therefore control beam transport lattice aberrations (both chromatic and geometric)
- transverse matching from the wiggler into the linac for energy recovery, which will probably require at least one variable quadrupole telescope
    1) to accommodate optical cavity change-driven variations of the electron beam out of the wiggler, and
    2) provide compensation for undiagnosed changes in the deceleration cycle beam envelopes,
    3) provide phase advance control for the management of BBU instabilities (see below)
- longitudinal matching to the linac for energy recovery and energy compression to order 1% full relative momentum spread at the dump, making use of momentum compactions provided by the recirculation arc. This matching should
    1) provide variable linear, quadratic, and cubic momentum compactions (to complement the corresponding dependencies of the RF waveform),
    2) be available through "orthogonal" knobs (using trim quads, sextupoles, and octupoles), and
    3) be based on machine modeling and beam based bunch length and longitudinal transfer function measurements before and after the recirculation arc and momentum spread measurements at the energy recovery dump
- management of accelerator error induced beam quality degradation. The design must conform to an error budget ensuring errors such as
    1) alignment errors,
    2) field quality errors, and
    3) excitation errors
    4) RF phase errors

  do not degrade beam quality to the point that lossless transport during energy recovery becomes difficult or unachievable.
- management of collective and nonlinear effects, such as
    1) space charge,
    2) beam break up (in particular, phase advance control should be available to modify threshold currents as needed – see above)
    3) the FEL/RF interaction
- management of higher order mode coupler generated skew quad driven coupling during energy recovery. As the error source is RF driven, the first pass correction of this error (see WBS 3.1.1.2 will impose a *doubled* coupling burden on the phase space during energy recovery. The design must either be insensitive to this effect or provide compensation for it through the use of a nonlocal decoupling scheme or local RF skew quadrupoles.

WBS 3.2 Integration Requirements

WBS 3.2.1 SRF Issues

The low energy and high currents utilized in the IR Upgrade may lead to unanticipated RF/SRF interactions with the beam, resulting in degradation of driver performance. WBS 3 activities must support preservation of beam quality in this SRF environment. Allusion to this is made under WBS 3.1.1.2 ("wakefields/impedance stewardship") but the interface between RF, SRF and beam physics must be explicitly noted.

WBS 3.2.1.1 *Interface with/support for WBS 5 (SRF) and 6 (RF)* – in which interface issues involving beam physics and the impact of RF and SRF systems on beam performance are addressed, including

- theoretical and empirical characterization of beam dynamics effects in 5 and 7 cell SRF cavities (5 and 7 cell; steering, focussing effects such as RF focussing, FPC steering, HOM driven skew quad coupling)
  1) steering (such as FPC steering)
  2) focussing (such as RF focussing and HOM driven skew quad coupling)
  3) HOM effects
- theoretical and empirical haracterization of RF drive system specifications and performance, such as
  1) performance of CEBAF 5 cell cavity control module with 20 mA in structure and with 7 cell cavities
  2) specification of Qext for 7 cell cavities
  3) support for JLab 7 cell control module design and production

WBS 3.2.2 Installation and interface with IR Demo operations

The Upgrade will be designed and built during the operations lifetime of the IR Demo. The Upgrade design should therefore be sensitive to the following interface issues:

WBS 3.2.2.1 *Physical interface* – the upgraded driver must

- fit into the existing vault and
- be installed around the IR Demo with the smallest reasonable interference.

WBS 3.2.2.2 *Schedule interface* – the upgraded driver design should support installation as a work-around during IR Demo operations and be configured so as to maximize the IR Demo

- support installation as a work-around during IR Demo operations and
- be configured so as to
  1) maximize the IR Demo operations lifetime,
  2) minimize changeover time from the IR Demo to the Upgrade, and
  3) minimize Upgrade commissioning time and effort.

WBS 3.2.3 Global issues

WBS 3 must provide support for upgrade construction and commissioning through beam optics design, analysis, and specification, and operations-related beam physics studies on the IR Demo and, when installed, the IR Upgrade.

WBS 3.2.3.1 *Beam transport interface* – WBS 3 provides support to WBS 7 (Beam Transport) through beam optics design and analysis. Under this category falls

- beam transport system design, which must
  1) meet driver performance requirements detailed under WBS 3.1 and
  2) ensure system-wide loss free and error insensitive transport through standard techniques for large acceptance lattices, such as
     a) limiting beam envelope functions (for a machine of this size, ~25 m maximum), dispersions, and transfer matrix elements (both linear and nonlinear)
     b) utilizing beam transport system components of adequate acceptance (3", round, at nondispersed locations, 10"x3" rectangular at dispersed locations)
     c) using magnets of modest strength so as to provide gentle bending (radii ~1 m or greater) and focussing (quad focal lengths > ~1 m, sextupoles of field curvature ~**) so as to avoid untoward chromatic and geometric effects
     d) designing to limit error sensitivities so IR Demo component specifications are adequate to provide the required system performance
- support for engineering design and construction through, for example, magnetic system performance integration

WBS 3.2.3.2 *Commissioning* – WBS 3 provides beam physics support to Upgrade commissioning.

WBS 3.2.4 Design and Modeling tools

The upgrade will, during energy recovery, operate in a nearly nonperturbative regime, with relative momentum spreads as large at 10% and bunch lengths as large as tens of RF degrees. Details of RF acceleration, deceleration, and focussing are required to properly predict beam behavior throughout the system. Existing accelerator design and simulation codes are typically monoenergetic and/or low order perturbative and thus may not provide sufficient detail. The applicability of these models to the Upgrade must be confirmed; if the available tools are inadequate, new ones must be developed.

Acknowledgments

Thanks to Steve Benson, Geoffrey Krafft, George Neil, and Richard Walker for reading and commenting on this document. I would like thank Steve in particular for pointing out the gigajoule of energy delivered by full power operation over a 2 kC wafer lifetime.

References

[1] A partial list of beam physics related technical notes is available at http://www.jlab.org/~douglas/FELupgrade/masterindex.html

[2] At present, it appears that the required modification of the phase space at injection into the linac is a reduction of the injected rms momentum spread by a factor of two and a doubling of the injected bunch length.