FEL Upgrade Scenarios

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Abstract

We present scenarios for upgrading the IR FEL Demo to higher power and shorter wavelength.

Introduction

The ongoing success of the IR FEL Demo [1] has stimulated speculation on machine upgrades to higher IR power and shorter (UV) wavelength [2]. Guidance for such a discussion is provided by the “green-field” high power/short wavelength design generated in 1994-5 [3]; recent advances in SRF technology suggest however that a simpler machine geometry based on higher RF gradients may be feasible. In this note, we summarize achieved IR Demo machine performance, review the performance objectives of the Industrial IR/UV Demonstration FEL, and relate the two configurations via various upgrade scenarios, each of which may best suited to particular funding profiles and patterns of end-user demand.

Present and Upgraded Machine Performance Goals

The IR FEL Demo has produced kW level performance at ~5 μm using an electron beam of energy of ~38 MeV and current up to 4 mA. IR powers in excess of 200 W have also been achieved at ~3 μm using a drive beam energy of 48 MeV at currents of ~4¾ mA. Near term upgrades are intended to extend the power reach of the system to ~20 kW at 6 – 25 μm and to push the wavelength reach to give order 1 kW at ~200 nm. Top level requirements imposed by these goals are presented in Table I.

Table I: Upgraded FEL Top-Level Performance Goals

Parameter	*Today*	*Goal*
FEL Power	~1 kW IR	20 kW IR\1 kW UV
Derived top level requirements		
Energy	~50 MeV	200 MeV\200 MeV
Current	~5 mA	10 mA\5 mA
Extraction Efficiency	½%	1%\0.1%
Normalized Emittance	10 mm-mrad	30 mm-mrad\11 mm-mrad
Charge/bunch	60 pC	135 pC\135pC

Figure 1 presents a machine schematic meeting the upgraded performance goals [4]. It is based on a two pass ("one up, one down") linac consisting of three high-gradient Jefferson Lab cryomodules providing a total energy of ~200 MeV. The electron beam can be used to drive various FELs in a "wiggler garden" [5] to provide a range of output wavelengths.

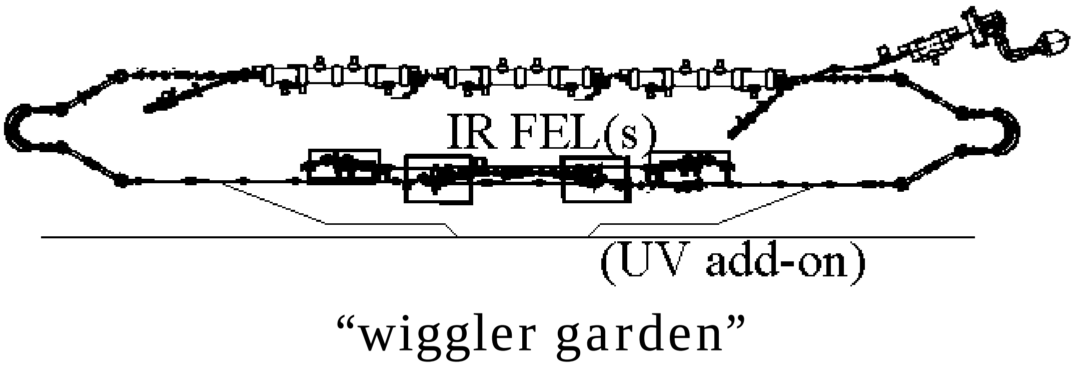

Figure 1: Schematic of Upgraded FEL System

System Level Requirements

The top-level goals presented in Table I impose numerous subsidiary constraints on individual accelerator systems. In particular, performance of the source, injector, acceleration, and beam transport systems must be improved to support upgraded FEL operation. Some implications of the enhanced system level requirements are presented in Table II. As each top-level system parameter is pushed to higher performance, rework or replacement of existing IR Demo systems will be needed.

Table II: System Level Requirements Imposed By Upgrade Top-Level Goals

Parameter	**Value**	**Implications**
Energy	50 MeV	*achieved*
	100 MeV	need 2nd module/new recirculator
	200 MeV	need 3rd module (and a miracle)
Current	5 mA	*achieved*
	10 mA	need additional injector RF, "improved" gun
Emittance	10 mm-mrad	*achieved (at 60 pC)*
	11 mm-mrad	need new gun (at 135 pC)
Extraction efficiency	½%	*achieved*
	1%	need new wiggler/optical cavity, recirculator transport system with larger momentum acceptance
Gun availability	33%	*achieved*
	80%	need "improved" gun

Approach

The preferred approach to achieving the stated goals is that of an incremental upgrade, from the present 1 kW IR capability to a 20 kW IR capability and thence to a system providing 1 kW in the UV. The UV is thus viewed as an “add-on” to a high-power IR system. This philosophy will enable us to meet objectives of maintaining a user program, providing the highest available FEL performance at any point during the upgrade project, and providing a cost-optimum path to the goal of high IR/UV power. It is, moreover, conducive to support from multiple sponsors using phased funding.

Certain constraints are imposed on this approach. These are due to lead time on several critical systems, and are as follows:

- *IR/UV optics* – which have a 12-18 month lead time from start of design to beam,
- *High power klystrons* for the injector, which have an 18 month lead time
- *Beam line magnets*, which will require from 18 to 24 months for design, procurement, installation, and pre-beam commissioning, and
- *Electron gun* – which will require 24 to 30 months from start of design to first beam.

Several scenarios can be envisioned within the context of this staged upgrade philosophy. In the following we will consider two of these. The first, aptly called “Scenario I”, is a staged incremental upgrade from the present 50 MeV IR system to a 100 MeV IR system at intermediate (few kW) power. A subsequent move to 200 MeV and high (~20 kW) IR power is followed by the implementation of a UV capability at 1 kW. This multi-stage process is best suited to a situation using a protracted funding profile, and provides numerous opportunities to accommodate long-lead time systems or developmental issues. The second scenario, “Scenario II”, is a direct upgrade from the IR Demo to a 200 MeV high power IR system, with a UV follow-on. This approach is better suited to a compressed funding profile in which the project is front-end loaded with long lead-time procurements.

Scenario I

This scenario moves from the IR Demo to an “intermediate” configuration, initially upgrading from 50 to 100 MeV by adding a second cryomodule. The basic Scenario I intermediate machine is shown in Figure 2. It has a new, large-acceptance beam transport system in “final” locations, but retains the existing “Engwall” gun, albeit with improvements to enhance performance. The basic driver performance parameters are 100 MeV\5 mA\135 pC/bunch. This is adequate to drive the Northrop-Grumman wiggler and an optical cavity (assumed to be in the backleg) using metal optics to lase in the 6-25 μm range. The resulting IR power will be order 3 kW in ~24 months from project start, with a minimal upgrade work (primarily, the addition of a third module) required to achieve 10 kW at 30 months. The subsequent move to the UV will require a new gun, with the final system as shown in Figure 1.

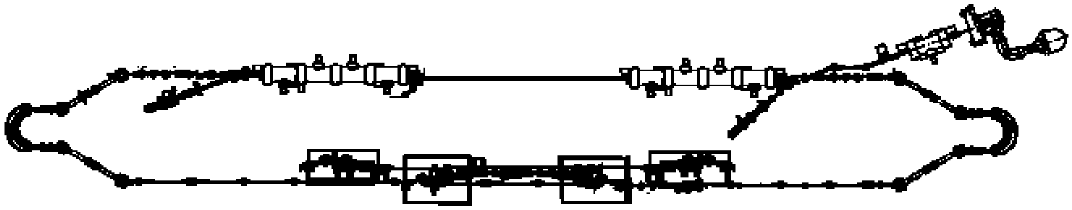

Figure 2: Intermediate "Scenario I" configuration.

Advantages of this approach are apparent. In this plan, all driver accelerator components are in final location and at final performance when beam operations commence. An upgrade to 200 MeV/10 mA/20 kW can be accomplished through the installation of a third cryomodule, a new or further improved gun, and additional injector RF capacity. This configuration allows immediate utilization of high FEL extraction efficiencies, which are allowed by the availability of improved beam transport. It also will allow the present user program at ~3 µm to continue uninterrupted until upgrade installation is initiated.

Certain drawbacks are associated with this plan. This scenario represents a very invasive first step, inasmuch as it requires the removal of most of the existing IR Demo driver. It also has the highest phased up-front cost. Once implemented, it will have significant impact on the present near-IR (under 6 µm) user program. Finally, it will, in light of the aforementioned long lead-time items, be difficult to complete in 24 months. Beam transport design and procurements in particular lie on the critical path and tend to pace the project as a whole.

Scenario I "Lite" – A lower cost, shorter lead-time approach to higher (few-kiloWatt class) IR power is provided by a modification of the above scenario. A schematic is shown in Figure 3. This "lite" version of Scenario I will upgrade the present Engwall gun for improved reliability and replace the present optical cavity with a second cryomodule, but leave the existing end-loop transport in place. The magnets will be pushed to operate somewhat beyond their nominal 79 MeV design upper limit to accommodate a beam energy anticipated to be ~100 MeV. The Northrop-Grumman wiggler will, as in the full Scenario I, be embedded in the backleg and use metal optics to produce 6-25 mm light. Key operating parameters will be 100 MeV\5 mA\135 pC/bunch. This approach is expected to provide 3 kW within 12 to 18 months of project start, but will require extensive rework of the driver accelerator (particularly the beam transport system) to achieve 10 kW some 30 months after project start.

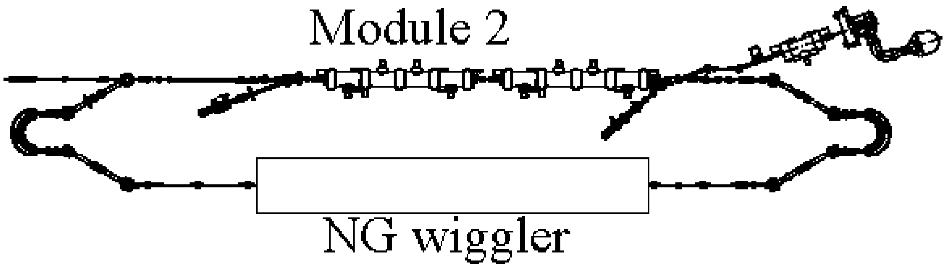

Figure 3: Schematic of “lite” version of Scenario I.

This “quick-start” plan will provide opportunities to rapidly test critical FEL features such as optics, scaleable optical cavity, and high extraction efficiencies. It provides a fast track to higher IR power at a low up-front cost, and represents an evolutionary approach to the upgrade process. It allows for early characterization of limits on energy recovery – and thus provides input for the high-power IR design, with attendant reduction in risk to the final project goals. This approach also provides for early tests on the second FEL cryomodule, and allows early demonstration of progress within a multi-year funding profile.

This reduced scenario is, however, at best a “scenic” route to the final machine. It requires significantly more installation and commissioning effort than the preceding scenario, and (as with that scenario) it is not conducive to the near-IR user program inasmuch as it provides light only in the 6-25 µm range. The “extensive rework” for 10 kW at 30 months represents a significant modification of the machine as a whole, including all the upgrade work of the full Scenario I as well as the installation and commissioning of a 200 MeV-capable recirculator.

Scenario I “Ice” – The deficiencies of the “lite” scenario can be remedied in part by adding a capacity for near-IR user service through the reinstallation of the present STI wiggler-based FEL. This somewhat more colorful “lite” scenario, dubbed (as with beer) “ice”, is shown in Figure 4. It is essentially the same as Scenario I Lite, except that it has an additional “bypass” to house the wiggler and optical cavity from the present IR Demo. This is possible since the present FEL has a lower extraction efficiency than that anticipated for the upgrade, and thus requires less momentum acceptance than the Northrop-Grumman wiggler based system. The additional FEL extends the wavelength reach from 0.8 to 25 µm, supporting an ongoing near-IR user program. Key operating parameters remain 100 MeV\5 mA\135 pC/bunch;

the machine again requires significant modification to achieve 10 kW in a 30 month time frame.

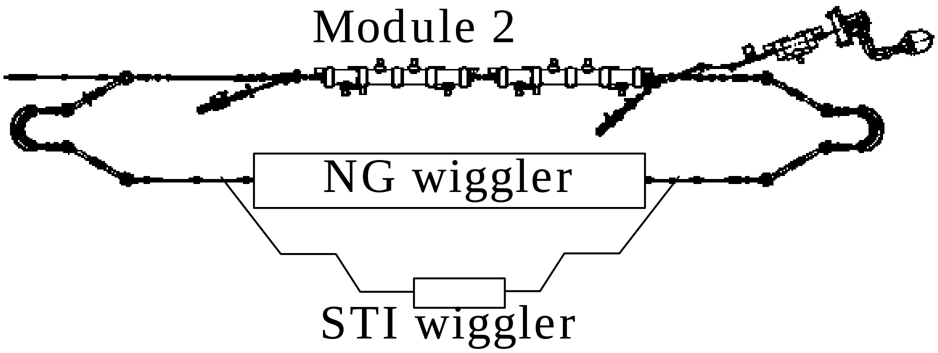

Figure 4: Scenario I "Ice", which provides extended output bandwidth over the 0.8 to 25 µm range.

This scenario provides the same advantages as those given by Scenario I Lite. Moreover, broadband light made available through this scheme extends the present user program to include work down to ~1 µm. It is less invasive than other scenarios providing this wavelength reach, and will provide early experience running multiple FELs (or, in other words, in the cultivation of a "wiggler garden"). The drawbacks are the same as those of Scenario I Lite as well. It also entails some risk beyond that in the present IR Demo, in that the repositioning of the short IR wavelength FEL may lead to a possible reduction in power at ~3 µm due to degradation of the recirculator momentum acceptance by the bypass. The bypass itself introduces a minor cost increase, though with proper design it may be reused for a UV follow-on.

Scenario I "Dry" – The wavelength reach of the "ice" scenario can be provided by an alternative concept, which will have the desired far IR performance and will in addition retain the near IR performance provided by the STI wiggler based FEL. This configuration (the "dry", which is similar to, but not the same as, the "ice") is shown in Figure 5. In this configuration, the present FEL is moved into the slot for the third cryomodule while the far IR FEL, based on the Northrop-Grumman wiggler, is installed in the backleg. The transport system could be either a reinstallation of the existing recirculator or could be a 200 MeV capable recirculator intended for service in the final full machine.

In the event that the existing recirculator is reused, the machine would perform as in the "ice" scenario, with exactly the same advantages. In addition, the risk of degraded near IR performance is reduced, inasmuch as the STI wiggler based FEL is retained intact in the present configuration (albeit at a slightly different location). Moreover, a preliminary design study of a similar configuration is already available, having been performed at the time of the IR Demo design [6]. In this case, we would expect to have ~3 kW in ~18 months from project start, with a significant rework of the machine required for 10 kW in ~30 months. In the event that the recirculator is replaced by a 200 MeV capable system, the initial time invested to FEL beam operations at ~3 kW would be more similar to the nominal Scenario I time of 24 months, but the overhead to move to high IR powers would be reduced. This evolution would then principally consist of removing the near IR system, rearranging the linac back-end focussing and energy recovery dump, and installing a third cryomodule.

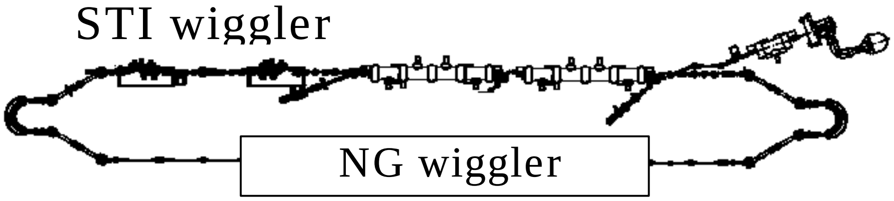

Figure 5: Alternative scenario retaining near-IR wavelength reach.

This configuration possesses most of the drawbacks of the previous scenario (with the exception of concerns about near IR performance). It does, however, possess a significant disadvantage absent in all previous scenarios – the STI wiggler is in an awkward location for high power running of the far IR system. The vacuum chamber acceptance is only 9 mm, which may lead to beam transmission problems and has been observed to generate wakefield effects [7]. These difficulties can be circumvented by removing the STI wiggler and vacuum chamber for high power far IR running, but such an operational scenario precludes the rapid switching between near and far IR programs provided, at least in principle, by the previous alternative.

Scenario II

As an alternate to the phased or staged upgrade scenarios discussed above, we can consider a direct upgrade to a machine providing ~20 kW by running 200 MeV at 10 mA. In this scheme, component design and fabrication would proceed in parallel with operation of the present IR Demo FEL for the first 18 months of the project. From 18 to 30 months, the IR Demo would be decommissioned and dismantled, and an entirely new machine, that shown in Figure 1, installed in its place. This project timeline assumes either a 2 to 3 year funding profile, or one-year funding with 1st year commitments paid out in years 2 and 3.

This scenario maintains a good near-IR user program until installation time. It engenders minimum installation and commissioning costs. It does however entail greater risk than the more protracted incremental upgrade scenarios discussed above. As noted above, numerous critical system components are long lead-time and/or developmental items. These include a third cryomodule, magnets, and a high availability/10 mA gun. This would consequently make it difficult to accommodate a single year funding profile; simply put, the money could not be spent rapidly enough. In addition, this scenario provides no opportunity for early system tests. Thus, there would be no ongoing input to the design beyond that provided by the IR Demo, nor would there be opportunity for early demonstrations of scalable technologies. Finally, this approach, though completely reasonable, is non-incremental and completely nonevolutionary. It is essentially the construction of a new machine rather than an upgrade of an existing one. It thus entails greater risk, both technically and politically, than do any of the preceding incremental scenarios.

UV Follow-On

Given the ~20 kW IR-capable machine discussed above, a 1 kW UV-capable system [8] is an incremental add-on. The system would require three major components to conform to the configuration of Figure 1. These are as follows.

- A new gun will be needed to provide the smaller emittances (11 mm-mrad, normalized) at high charge/bunch (135 pC) required for UV operation (Table 1). This performance is presently not available from the Engwall gun, nor is it anticipated as a consequence of gun improvements intended to provide higher charge/bunch and greater reliability in support of the IR component of the upgrade project.
- Drive beam transport to a UV wiggler will be required. We note that the momentum spread imposed on the energy-recovered beam by the UV FEL will, as a consequence of the relatively low UV extraction efficiency (0.1%, Table 1), be small. This transport system will therefore likely be only an additional backleg beam line, not an entire recirculator upgrade.
- The system will, of course, need a UV wiggler, optical cavity, and optical transport system.

These systems could be readily retrofitted to an existing high power IR source at relatively low cost in several months, provided developmental work on each system proceeds in parallel to the design, construction and commissioning of the IR upgrade. The principle constraints would, as for the IR system, be imposed by procurement lead times on components. The resulting machine can be expected to produce ~1 kW at wavelengths of a few hundred nanometers.

Notes and References

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[3] Laser Processing Consortium, “Free-Electron Lasers for Industry, Vol. 2: UV Demo Conceptual Design”, May 1995.

[4] D. Douglas, *op. cit.*

[5] A small undulator farm…

[6] See, for example, the discussion at http://www.jlab.org/~douglas/FEL/guide/upgrade.html .

[7] S. Benson, private communication.

[8] Laser Processing Consortium, *op. cit.*