A Design Framework for Transforming MADMAN to REALITI

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Introduction

A previous note describes a concept for a small ERL intended to drive sources of high power coherent radiation [1]. In this note, we discuss issues to be resolved during the evolution of this concept into the “next step” FEL driver. This machine – intended as a follow-on to the IR Demo and the IR Upgrade – will have as its design goal the acceleration, recirculation, and energy recovery of a 100 MeV/100 mA CW electron beam for the purpose of driving a 100 kW IR FEL. We therefore refer to it as REALITI: a Recirculated Electron Accelerator for Logarithmically Integrated Tests of Intensity.

Overview

The design process for an accelerator system typically comprises 1) detail of user requirements, 2) enumeration of relevant phenomena and evaluation of subsidiary constraints, 3) development of rationale for design decisions, and 4) generation of potential system concepts [2]. In the case of REALITI, the machine will not be a unique system, but rather will simply be the third step in an ongoing process intended to take FEL performance from the 1kW level of the IR Demo to 1 MW levels [3, 4]. The procedure for establishing system requirements is therefore identical to that used for the IR Demo [Ref. 2] and the IR Upgrade [5].

We will thus proceed under the assumption that REALITI will be – as are all prior JLab systems – a SRF-ERL driver for a high repetition-rate cavity-resonator-based modest peak/high-average-power FEL. The basic system parameters (bunch charge, current/rep rate, beam energy, bunch length, extraction efficiency)) are dictated by the FEL and will be stated in comparison to requirements for the legacy systems and contrasted with performance as achieved to date. Subsidiary requirements and relevant phenomena are in many ways similar to those attending the legacy systems. The substance of this note resides in a review of these issues and the enumeration of various issues to be resolved during the design process.

FEL-Driven Requirements

The primary requirements remain 1) delivery to the wiggler of a drive electron beam with a properly configured phase space and 2) recovery of energy from the drive electron beam after the FEL. These requirements impose as a consequence a number of familiar constraints, which will be discussed below. Table 1 provides a summary of IR Demo and Upgrade objective beam properties, and quotes achieved properties.
Table 1: System Parameter Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IR Demo</th>
<th>IR Upgrade</th>
<th>Achieved</th>
<th>100 kW FEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy (MeV)</td>
<td>35-48</td>
<td>80-210</td>
<td>80-165</td>
<td>100</td>
</tr>
<tr>
<td>average CW current (mA)</td>
<td>5</td>
<td>10</td>
<td>9.1</td>
<td>100</td>
</tr>
<tr>
<td>charge/bunch (pC)</td>
<td>60</td>
<td>135</td>
<td>135</td>
<td>135</td>
</tr>
<tr>
<td>FEL repetition rate (MHz)</td>
<td>18.75-75</td>
<td>4.6875-75</td>
<td>0.586**-75</td>
<td>9.375**-750</td>
</tr>
<tr>
<td>RMS bunch length (psec)</td>
<td>½</td>
<td>¼</td>
<td>0.125</td>
<td>0.2</td>
</tr>
<tr>
<td>peak current (A)</td>
<td>60</td>
<td>250</td>
<td>500</td>
<td>250</td>
</tr>
<tr>
<td>RMS δp/p (%)</td>
<td>½</td>
<td>½</td>
<td>½</td>
<td>½</td>
</tr>
<tr>
<td>εN (mm-mrad)</td>
<td>&lt;13</td>
<td>&lt;30</td>
<td>8-10</td>
<td>5</td>
</tr>
<tr>
<td>FEL extraction eff. (%)</td>
<td>½</td>
<td>1</td>
<td>2.5</td>
<td>&lt;3</td>
</tr>
<tr>
<td>full energy spread after lasing (%)</td>
<td>5</td>
<td>10</td>
<td>&gt;12</td>
<td>&lt;20</td>
</tr>
<tr>
<td>FEL design output power (kW)</td>
<td>1</td>
<td>10</td>
<td>&lt;120</td>
<td>&lt;100</td>
</tr>
<tr>
<td>FEL achieved output power (kW)</td>
<td>2.3</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Footprint (m x m)</td>
<td>5 ½ x 40</td>
<td>5 ½ x 65</td>
<td>-</td>
<td>&lt; 2 x 15</td>
</tr>
</tbody>
</table>

*The IR Upgrade has lased at the 8th subharmonic of the 32 m optical cavity 4.6875 MHz fundamental.
**Assumes 16 m optical cavity; other subharmonics of 75 MHz fundamental will give different low end repetition rates

We note that “achieved” parameters should not necessarily be construed as simultaneously achieved. The IR Upgrade typically runs 135 pC up to 37.5 MHz/5 mA; above 5 mA, we have to date run less than full bunch charge (hence the 9.1 mA). Energy spread, bunch length, and emittance have been simultaneously provided but may not be coincident with best FEL performance. The IR Upgrade has at present reached a maximum extraction efficiency of 2.5% with somewhere over 12% exhaust energy spread, but at low CW current. The 10 kW result for the IR Upgrade was in 1 second pulses every 4 seconds, limited by mirror heating; to date full CW operation has achieved 8.4 kW at 5 microns, 6.7 kW at 2.8 microns, and 4.2 kW at 1.6 microns.

The 100 kW FEL requirements are, for single bunch parameters, not dissimilar from those already achieved save for the emittance. The requirement for smaller emittance is driven by a desire for higher gain so as to allow smaller optical cavity Q [6]. The order-of-magnitude increase in FEL output is achieved solely by upping the peak repetition rate from 75 MHz to 750 MHz.

Attendant with these parametric requirements are the system constraints familiar from discussions of earlier designs. The delivery to the wiggler of a drive electron beam with a properly configured phase space implies a) some type of longitudinal matching to provide bunch compression and b) betatron matching to values dependent on the details of the wiggler (number of periods, k, and period length). It also implies that beam quality be adequately preserved in the presence of a witches’ brew of collective effects. These will be discussed below.
The recovery of energy from the electron beam following the wiggler implies provision will be made for a) longitudinal matching adequate to the task of energy compression during energy recovery, b) adequate transverse control of the beam, and c) appropriate management of the various chromatic aberrations that can, in principle, couple to the large exhaust momentum spread. In our discussions, we will assume – as we have in prior, successful, designs – that the exhaust momentum spread is the superposition of the beam momentum spread on that imposed by the FEL, taken to be 5.5 times the extraction efficiency.

**Relevant Phenomena & Subsidiary Requirements**

REALITI will be subject to numerous effects that may impose potential performance limitations. Many of these have been encountered in previous FEL driver implementations and may be addressed using legacy solutions; others are newly troublesome because of the decade increase in current. We now briefly discuss each ingredient of the witches’ brew.

**CSR** – As a single bunch effect, this can be addressed using legacy methods of appropriate recirculator design. Given the desired small driver footprint, careful evaluation of CSR effects in compact arc geometries is essential, despite retention of the relatively low single bunch current used in the IR Demo and IR Upgrade FEL designs.

**Space Charge** – As a single bunch effect, this can be addressed using legacy methods of appropriate choice of injection parameters. The retention of 135 pC single bunch charge allows us to avoid transverse and longitudinal effects provided a) the required emittances do not decrease too dramatically, b) similar transverse and longitudinal matching requirements can be applied at injection, c) the injection/merge geometry is not excessively extreme, and d) the injection energy is not pathologically low. We note that direct off-axis injection [7] as proposed for MADMAN will shorten the injection line and avoid beam-quality-degrading injection line bending. This may help achieve lower emittance and avoid some space-charge driven effects. Careful study of space charge effects will, however, be required to certify the viability of direct injection.

As noted above, there is a requirement for a factor of ~2 smaller transverse emittance. This might possibly be achieved simply through use of a) higher gun voltage and b) a shorter injection line based on the direct-injection geometry. Careful analysis will be required.

**HOM Effects** – BBU will be a major issue for REALITI insofar as it is intended to run very high currents. This will be addressed a) through careful cavity design of b) lower frequency cavities and c) through the use of phase space reflectors, rotators, and/or betatron phase control as appropriate. Careful simulation will be vital to establish that thresholds lie above the anticipated operating current, and active damping of HOMs and/or feed-forward/back may prove necessary.

Propagating HOM effects may prove interesting – or even pose challenges – given the considerably higher currents to be run and the larger cavity/beam pipe apertures anticipated in REALITI. Analysis will be required as cavity designs progress and
appropriate responses – such as damping or trapping such modes – may required should they lead to unacceptable beam disruption or heating.

**Halo** – Given experience with the IR Upgrade, halo will certainly be a cause for concern. The smaller machine footprint likely precludes any use of collimation on the one hand, but allows on the other hand designs with smaller beam envelopes. Use of larger apertures will assist in this regard, as will the stronger focusing associated with tighter recirculation geometries and shorter matching regions.

**THz Effects** – In addition to beam quality degradation, THz-induced mirror heating (or, possibly, even vacuum chamber heating) will become eventually become a serious for high current FEL drivers – possibly even at the 100 mA level. Use of at least a THz suppression chicane is prudent, with bending as soon as possible after the wiggler and as far as possible from downstream mirrors. Use of outcoupling on the upstream end of the optical cavity is advisable as this will position the high reflector – with its higher available cooling throughput – at the location with higher loads. Cryogenic mirrors may prove necessary to achieve the desired FEL performance.

**Enviromental Impedances** – As in the previous systems, an appropriate impedance policy is required. Given use of legacy single bunch charges and legacy longitudinal beam property requirements at the FEL, one might blithely assume that legacy impedance budgets will prove acceptable. Given the order-of-magnitude higher current, however, careful review of these budgets is in order, as is an empirical check of effects in the existing 10 mA driver. The importance of this issue has been recently underscored by observations in the IR Upgrade FEL, wherein significant heating of the wiggler vacuum chamber (possibly attributable to resistive wall effects [8]) and downstream OCMMS [9] have proven excessively instructive.

In addition to constraints implied by these fundamental physical processes, the REALITI design exercise will require numerous interconnected choices, each with potentially significant impact. A brief discussion of several of these follows

**Injection Energy and Injection Line/Merge Geometry** – The choice of injection energy has traditionally been coupled to the injection line geometry and its impact on space-charge effects. Use of direct injection [10] may relax injection energy requirements and allow use of significantly lower injection energies than previously anticipated [11], at least from the perspective of the single particle beam dynamical transverse and longitudinal matching requirements. Investigation of this question – including collective effects – is vitally important, inasmuch as it allows significant cost reduction (injector RF power savings), dramatic improvement in wall-plug-power conversion efficiency, and simplification of beam disposal requirements after energy recovery.

The use of direct injection also has significant implications on HOM/BBU effects, and may rise or fall on its sensitivity to RF phase [12]. These issues absolutely must be evaluated
Use of Complete vs. Incomplete Energy Recovery – Ideally, high power FEL drivers would employ complete energy recovery, as this would balance the accelerated and decelerated beam RF phase vectors and simplify the RF drive system. In this case, the FEL power has as its source the injector RF and the exhaust (recovered) beam is at lower energy than the injected beam. Given, however, the high power draw of a 100 kW FEL and the potential for use of a low injection energy, this may not be ideal. In addition, the use of extremely high extraction efficiency - with the attendant large exhaust energy spread – may lead to the dangerous “incompressible high energy tail”, even if the machine is operated quite far off crest. We therefore must carefully consider the use of incomplete energy recovery and the implications of this choice on the RF drive system.

At the very least, this choice implies the availability of tens of kW of forward RF power put through each linac cavity and the capability of the RF system to stably control the beam and hold the final energy constant as the FEL turns on, the beam energy drops, the phase of the energy recovered beam shifts accordingly, and the recovered RF power decreases.

Use of phase space rotator/reflector and or provision for feed-forward/back – Results from SRF cavity design efforts may indicate that insufficient HOM damping is available to guarantee adequately high BBU threshold currents. In this case, various interventions may be required to deal with this instability. At a minimum, the lattice design should admit the possible use of a phase space rotator/reflector and ideally will additionally allow at least some control of betatron phase advances. It would also be advantageous if provision could be made for implementation of some type of active beam stabilization. Given the small machine footprint, it is unlikely that fast traditional bunch-by-bunch feedback can be used, but some active stabilization by mode damping, feed-forward or imposition of appropriately configured drive signals on the electron beam may be possible.

Mirror loading/performance – Mirror performance has been identified as a major issue, with resonator FEL fans proclaiming victory and amplifier FEL fans shrieking for a pound of optician flesh. The outcome of ongoing 10 kW FEL testing will inform this “discussion”, but at a minimum it is very important to provide a proof-of-principle of the viability of cryogenic mirror system. Given recent IR Upgrade experience, considerable thought should go into the management of THz loading, stray laser and bending magnet synchrotron light, and other effects that may burden mirror cooling budgets. Consideration of alternatives to transmissive outcoupling should occur, as should the possible use of “upstream” outcoupling, reserving the downstream position for a potentially heavily cooled high reflector.

Additional design issues and decisions are implied by the FEL requirements and major design choices discussed above. These drive ancillary or subsidiary requirements, which we will now discuss.

Degree of operational flexibility – This requirement is, roughly, a “tuning knob count”. Sorry, you’re out of luck. This is supposed to be a compact, simple, robust machine. You
don’t get to tune. At present, we anticipate “tuning” by altering magnetic field integrals through shimming or shaving magnet pole faces. We expect most beam properties will be locked to the orbit and magnet geometry, and the only readily available tuning parameters will be RF phases and gradients and machine path length, with the latter perhaps available only by mechanical motion of one or both arcs.

Significant orbit “correction” capability is not anticipated. It should be underscored by this discussion that extremely precise control of magnetic fields must be achieved during magnet fabrication, testing, and commissioning; “matchathon” tune-fests are not planned.

Of greater potential impact is any requirement to provide for multiple matches to a wiggler. If significantly different wavelengths are needed - there is an implied need for a more or less tunable betatron match. This will increase the complexity (and the tunability) of the transport system.

**Transverse/longitudinal matching scenarios** – given the desire for extreme compactness and operational robustness, we will adopt particular matching requirements at the design stage and lock them in hardware.

All matching requirements will be dictated by the FEL. Transversely, the required beam envelopes are dictated by the wiggler k and the period length; the detailed match point is defined through the number of periods. A recent notional FEL parameter set uses a wiggler with 30 periods of 4 cm length with \( k_{\text{max}} \) of 1.5; this implies a matched \( \beta \) of 0.74 m for 1 micron operation, or 0.55 cm for 1.6 microns [13]. Note well that the present MADMAN concept does not admit tuning the matched \( \beta \); this implies you must not only pick your wiggler and optical cavity parameters, you must also pick your wavelength. Alterations might be accommodated by moving the few quadrupoles to change the match into the wiggler (there are only three, so it is not possible to rematch by simply changing quad excitations) – but there is no provision to alter the energy recovery match. One must determine if the acceptance is adequate to accommodate a range of mismatch; if it is not, you will be moving dipoles (after cutting or shimming their poles). We note that the beam envelopes and required emittances are consistent with spot sizes of order ¼ mm. Were one to believe that “beam sigma counts” meant anything, this would imply that a 5 mm aperture (consistent with the anticipated 8 mm wiggler gap in the strawman FEL concept) would accept up to 20\( \sigma \) of beam. Hmm. Well, we did say halo was a likely problem. You were warned.

Longitudinal matching is expected to be as in the legacy FELs. The machine must deliver a ½% rms momentum spread, 200 fsec rms length bunch of 135 pC to the wiggler. Preliminary results [11] suggest this is possible from the injected beam performance achieved with the IR Upgrade FEL Driver, though this must be evaluated in light of our desire to go to direct injection with much lower injection energy. The longitudinal matching scenario assumed at this time uses the IR Upgrade achieved longitudinal phase space at injection, accelerated 20° ahead of crest and magnetically bunched during transport to the wiggler using the hardware-wired transport compaction schedule. Minor tuning range is available by mismatching the arc excitation to the beam energy, thereby moving the beam around in the equivalent sextupole and feeding down \( T_{566} \) to alter the linear compaction and change the bunch rotation. Minor linac phase variations can also add to or buck this.
Energy recovery tuning is available using a similar mechanism. The final energy after recovery is set using path length; energy compression is controlled by varying the excitation of the downstream arc relative to the FEL exhaust beam energy to vary the compaction by moving in sextupole and octupole order field variations. It is necessary to compute these carefully and to fabricate them with considerable control as no tuning knobs are available; magnet shim and shave is the only alternative.

**FEL Extraction Efficiency** – will dictate the exhaust energy spread and the choice of energy recovery transport compaction. Preliminary results [11] suggest that proper selection of path length and compaction schedule will result in an energy fixed point after energy recovery. As noted above, this is at the expense of significant phase variation during FEL turn on and extraction ramp-up; as noted above, the RF drive system will have to accommodate this (or die trying). The beam will be incompletely energy recovered; the energy of the beam at extraction influences the tolerable extraction efficiency. It appears that extracting at a 2 MeV injection (kinetic) with acceleration 20° off crest will allow up to perhaps 3% extraction efficiency. At that point, the usual incompressible high energy tail starts to become unmanageable, though the meaning of “unmanageable” is not completely clear given a design assumption of “direct extraction” (in analogy to direct injection). The beam may tolerate considerably large final energy spread in linear transport to the dump than it does when the beam is bent into the dump in the manner used in the IR Demo and IR Upgrade.

Going even farther out of trough appears in principle to allow compression of even larger FEL exhaust momentum spreads, though things get pretty dicey if you go too far beyond 3% extraction efficiency. Again, “dicey” makes assumptions about how bad things are when you bend to a dump, which we hope to avoid in this design.

The assumed (implemented) extraction efficiency also dictates the required energy acceptance of the energy recovery transport. In our considerations we have and will continue to assume a superposition of (injected full energy spread) on 5.5 times the extraction efficiency. Some preliminary designs seem to suggest the 3% extraction efficiency might be managed from a beam transport perspective. Then again, some people thing a multi-GeV SRF linac is a good idea, too. They even talk about energy recovery in such a context. And then there are those that think Jeffersonian Democracy can be imposed thorough military action. Go figure.

**Issues**

From the discussion above, we can derive a relatively short list of issues, milestones on the critical paths, 800 pound gorillas, whatever. These are primarily either tests of enabling technology or workarounds for problems already apparent at the 10 kW level.

1. Test of low injection energy: we must develop a reasonable design and verify in simulation that it is not unduly susceptible to space charge effects and/or does not excessively degrade sensitivity to BBU. We should also test suppressed injection energy in the IR Upgrade (as was done – to the 5 MeV/3.5 mA CW level – in the IR Demo).
2. The implications of off-axis injection should be investigated. In particular, the potential for significant BBU coupling and the possibility of RF head/tail driven emittance dilution must be addressed.

3. Tests to establish viable high power mirror technologies. We must test a cryo mirror system in the near term, and should prepare for testing of downstream high reflector with particularly robust cooling.

4. We should establish the longitudinal & transverse matching scenarios for the machine; these will be particularly at issue if very low injection energy is to be used, as this imposes RF gradient limits on the first and final cavities and/or requires the use of unique (e.g. single or double cell) structures in these locations. We note that the matching constraints will be direct consequences of FEL characteristics. In particular, the transverse matching and the degree of flexibility required therein will be dictated by the desired FEL spectrum. The machine will become significantly more complex if multiple output wavelengths are needed.

5. SRF concepts and designs should be solidified. In particular, HOM effects – both trapped and propagating – must be known early on so as to allow the use (or preclusion) of a rotator and/or skew-quad based betatron matching.

Initial Design Decision(s)

Parsing of at least one of the alternatives can be readily done. We expect to use an RF frequency of 748.5 MHz. This frequency can be leveraged with installed infrastructure (JLab facilities and cryomodule designs). It provides improved BBU performance over higher frequency and allows increased aperture (with attendant potential use of off-axis injection and advantages for halo management). For a specific peak current and charge per bunch, it allows lower intra-bunch charge density for the same full-energy momentum spread. For example, the bunch can be temporally twice as long (but subtend the same RF phase) at injection and produce the same full energy energy spread as provided by a 1497 MHz system; for fixed bunch charge the bunch line charge density is thus lower at 748.5 MHz, with attendant better collective behavior. The lower frequency will thus provide better linearity in the longitudinal transport.

Other choices – particularly involving flexibility and operability – are better left as collective decisions, as the impact is broader (and people haven’t already decide what to do!).

Conclusions

I really don’t have any. We have simply identified a set of top level parameters that can, in principle, allow generation of 100 kW of light. We have enumerated a list of things that will interfere with doing so, indicated which of these may be the most serious impediments, and suggested actions that would help clarify appropriate levels of concern. I’d love to say “use this framework, design and build a machine, and it’ll work”, but I can’t. With some conviction, however, I will assure you that ignoring these issues will lead to some sorrow. In fact, it probably already has.
I guess I do have one conclusion. I conclude that this note is the kind of thing that happens if you leave me alone in an airport for 8 hours after a DOE programmatic review waiting for a red-eye flight home.

Acknowledgments
Thanks to Steve Benson, George Biallas, Carlos Hernandez-Garcia, Kevin Jordan, George Neil, Tom Powers, and Michelle Shinn for various reality checks on the topics discussed here. Thanks even more to them for their patience even though I invariably chose to ignore their counsel, but they should know by know I never listen to anyone but Dick Walker and Jim Boyce. Thanks to Fred Dylla for paying the piper, even though others almost always called the tune. Thanks to Gwyn and Jennifer Williams for throwing a great party on Memorial Day weekend. It was really fun.

References
[9] The OCMMS upstream of the wiggler is heated with a charge/bunch length/current dependence consistent with THz heating (heating cares about bunch length and bunch charge – i.e. peak current). The downstream OCMMS heats with a behavior consistent with RF heating: it is sensitive primarily to average, not peak, current.
[12] The steering of the beam depends on the phase of the RF field, so the beam will experience a spread in steering – around the centroid – along the bunch length. This is analogous to the head-tail effect in the FPC. If it is too large, the emittance can be irrecoverably degraded. Preliminary examination suggests that the RF focusing doesn’t “change a lot” over the bunch – the variation of M21(t) over the temporal duration of the bunch is of order 2% or so. This means that the beam
experiences a transverse “smear” of 2% in the imposed $x'$, with an attendant smear – along the duration of the bunch in downstream position of order 1% of the final offset of the beam. Given that the final positional offset is (from the MADMAN study, see reference [1]) of order 5 cm, this implies the “smear” is about 1 mm – or about 10% of the order 1 cm beam spot size. This may be a tolerable emittance degradation, but the calculation should be done carefully. Thanks to Steve Benson for emphasizing this point.