JLAB-TN-01-034
23 July 2001

Extending the IR Upgrade Driver to Support MegaWatt-Class FEL Performance

David Douglas

Abstract

Resolution of a blunder in the analysis of the IR FEL Upgrade Driver design suggests that both the IR Demo and IR Upgrade drivers possess momentum acceptances well in excess of the nominal design values of 5% and 10%, respectively. The extra available aperture may allow utilization of higher FEL extraction efficiencies, with commensurately increased output powers. Various possible extensions of the Upgrade parameter set are discussed; the more optimistic of these suggest that MW class performance may be achievable with appropriate injector and linac modifications.

An Entertaining Error

The "acid test" of a design during DIMAD analysis is the tracking of a phase space through critical portions of the machine. In JLab FEL driver design studies, this test traces the behavior of an initial distribution from the wiggler through the recirculator and linac during energy recovery. The distribution is created using the DIMAD "`generation of particles`" command, which randomly populates a phase space with a specified number of particles. The phase space is characterized by a previously defined "`beam matrix`" command; one of the "`gener`" inputs is the number of sigmas (as defined by "`beam`") over which the distribution is to extend.

Throughout the design process for both the IR Demo and the IR Upgrade, it was assumed that the "number of sigmas" input defined the *full* beam width in each of the phase space dimensions. A 6σ extent was therefore used. During Upgrade design studies, it was persistently noted however that the distributions (particularly after tracking of a moderate number – on the order of a few thousand – of particles through the lattice) were "fuzzier" than anticipated and that some particles were encountered outside the nominal 6σ full width after energy recovery. Concern that this was due to a nonlinear lattice effect led to a check of the initial and final phase space distributions. Test particles at displacements well beyond the expected $\pm 3\sigma$ limits were observed in both the initial and final loads when the phase space was heavily enough populated to sample the tails of the distribution (this typically required use of several thousand particles). A more detailed check of the initial distribution revealed that the sigma input of `gener` in fact defines the number of sigmas in the extent of the half-axes of the six dimensional phase ellipsoid that the code is populating – it is essentially a *radial* parameter and thus defines a half-width.

A consequence of this confusion is that both the Demo and the Upgrade were inadvertently designed to accept not 6σ, but rather "12 σ" distributions. Given the statistics imposed by the sample size (DIMAD is array-size limited to the use of 10000 or fewer particles) the actual volume of phase space being probed is probably closer to 8σ full width – so the ray-tracing simulations support in particular the conclusion that the Demo momentum acceptance is of order ±4% and the Upgrade momentum acceptance will likely be of order ±8%. We remark that the Demo is physical aperture limited (by a 20 cm wide vacuum chamber at a location with ~2 m dispersion) to a maximum full momentum spread of 10%, and has recovered beams with full momentum spread of order 6–8%. The Upgrade will be physical aperture limited (by a 25 cm wide vacuum chamber at a location with 1.7 m dispersion) to a maximum full momentum spread of 15%.

Amusingly, this is well beyond the Upgrade design specification of 10% [1]. To characterize the machine performance while utilizing the larger aperture, we simulated energy recovery from 145 MeV/c to 10 MeV/c with a nearly uniform initial momentum distribution (as suggested by Steve Benson [2]). Figure 1 shows sections of both the input and output phase spaces and Figure 2 the distributions for the 1000 particle load used in this test. The initial phase space (at the wiggler) was generated using ~30 mm-mrad normalized initial emittances in x and y (0.1 mm-mrad geometric) and an rms bunch length of 60 μm (corresponding to the design specification of 200 fsec rms). Three (radial) sigmas were used in the transverse dimensions and 2 in the bunch length for a full 6-sigma transverse phase space and a 4-sigma bunch length. The momentum distribution was, as implied above, made to appear non-Gaussian; the initial load was specified to subtend 0.075 sigmas of a distribution with an rms of 100%; this artificial (and rather unphysical) input had the effect of forcing the code to generate an essentially uniform momentum distribution across ±7.5%.

Figure 1a: Phase space input to simulation of energy recovery from 145 MeV/c to 10 MeV/c in the IR Upgrade with 15% initial energy spread. Units are meters and radians.

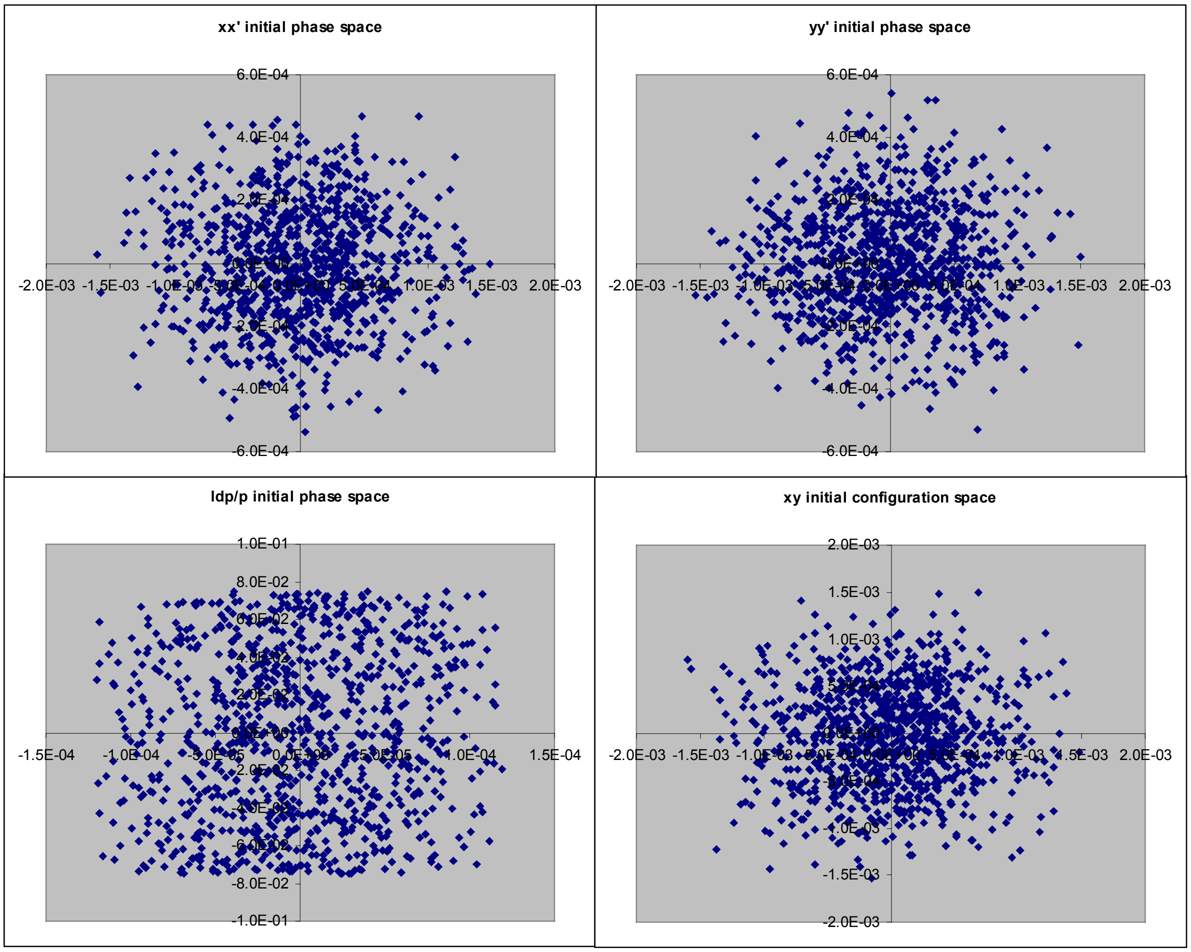
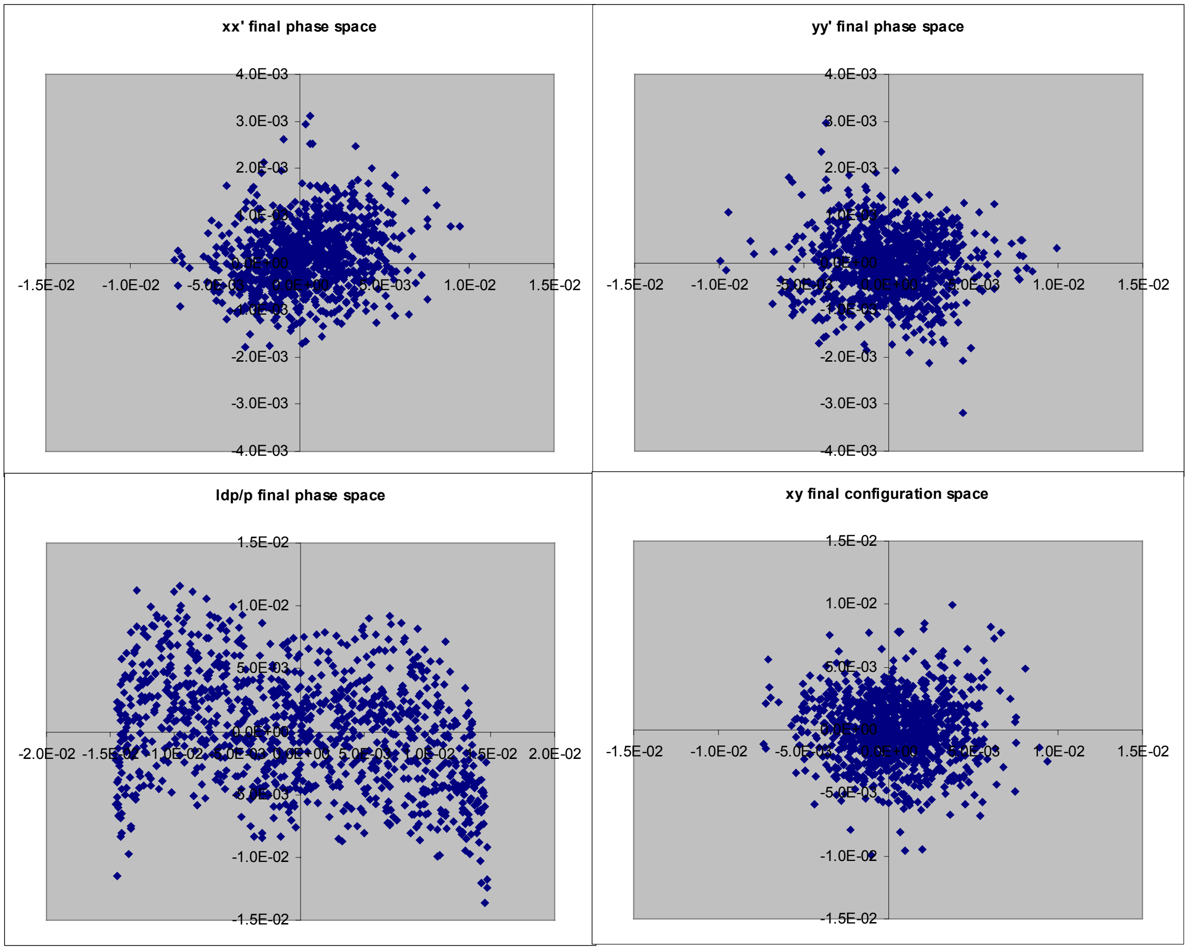


Figure 1b: Phase space output from simulation of energy recovery. Units as above.



The system performance with 15% initial momentum spread is surprisingly good. The spot at the extraction point (1 m after the final module, just upstream of the extraction dipole) is of order 1 cm in radius; this should readily transmit through the beam pipe (which is 2 – 3" in diameter in this region). Using a compaction management scheme with 2 quad and sextupole families and 1 octupole family, the initial 15% full energy spread at 145 MeV (~20 MeV) is compressed at 10 MeV to <3% full spread (300 keV). Figures 1 and 2 illustrate another previously documented feature of JLab FEL driver longitudinal phase space management [3]. The initial longitudinal distribution is small and roughly Gaussian in phase (path length) and large and uniform in momentum, while the final distribution is large and uniform in phase (path length) but small and Gaussian in momentum spread. This is because the energy compression during energy recovery is accomplished by performing a 1/4-synchrotron oscillation phase space rotation. What fun!

A slightly more detailed analysis of the distributions is available through the DIMAD "`particle distribution analysis`" command, which computes the moments of a phase space distribution and thereby provides sigma matrix elements and beam emittances. Table 1 gives the output of "`part`" for the initial and final distributions using a load of 10000 particles. The data is in the DIMAD "beam matrix output" format

[4], wherein the displayed diagonal elements $\Sigma_{ii}=\sqrt{\sigma_{ii}}$ and off-diagonal elements are the correlation cosines $\Sigma_{ij}=r_{ij}\equiv\sigma_{ij}\big/\sqrt{\sigma_{ii}\sigma_{jj}}$, with σ_{ij} denoting the i-j element of the usual beam sigma matrix. Horizontal beam matrix elements, projected horizontal emittance and horizontal beam envelope functions are then related as follows [5]; similar relations hold for the vertical.

$$\begin{aligned}\varepsilon_x &= \Sigma_{11}\Sigma_{22}\sqrt{1-\Sigma_{12}^2}\\ \beta_x &= \Sigma_{11}^2\big/\varepsilon_x\\ \alpha_x &= -\Sigma_{12}\Sigma_{11}\Sigma_{22}\big/\varepsilon_x\end{aligned}$$

Table 2 compares nominal beam envelopes and emittances at the dump (again assuming design envelopes and 0.1 mm-mrad geometric = ~30 mm-mrad normalized emittance at the wiggler with the initial "uniform" 15% momentum spread) to those derived from tracking data using "`part`". The agreement is good, with tracking results matching linear prognostications to ~20%. Even with large momentum spread, near-ideal performance can thus be expected; little degradation of the phase space is anticipated.

Figure 2a: Distributions of initial 1000 particle load.

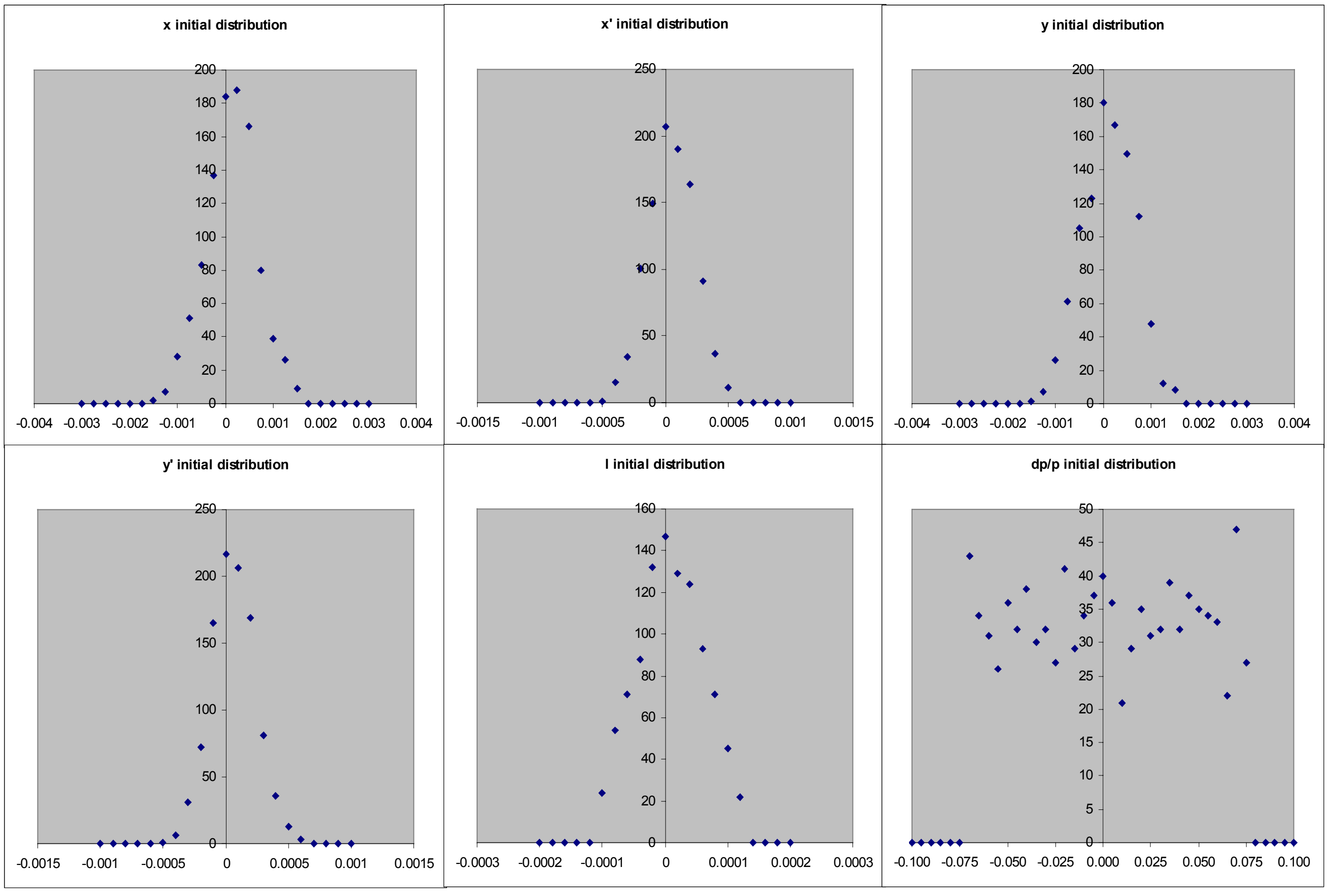


Figure 2b: Distributions after energy recovery.

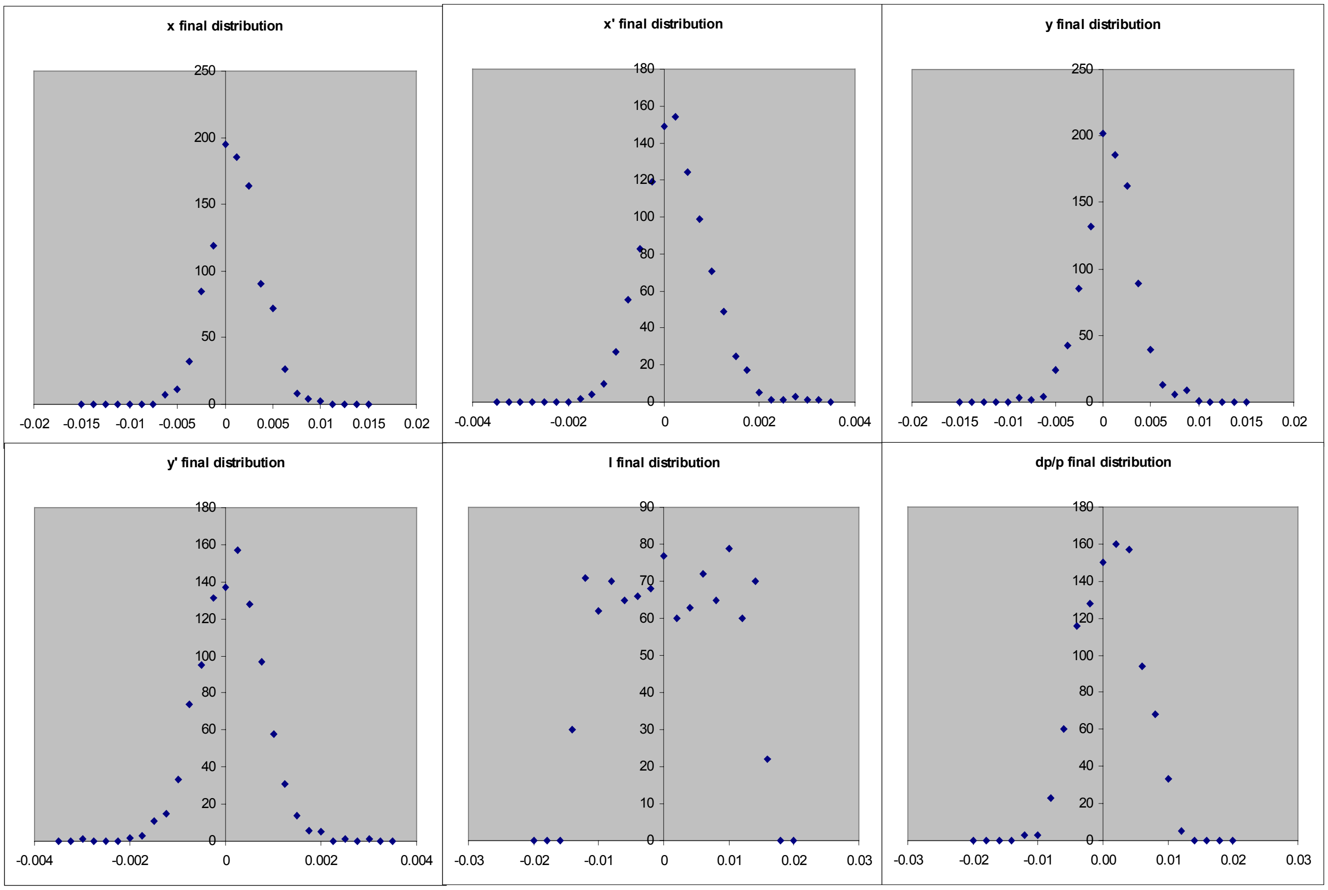


Table 1: Input and final results for a 10000-particle load with initial (145 MeV/c) geometric emittance of 0.1 mm-mrad with tracking to 10 MeV/c.

Initial Data:

```
PARTICLE DISTRIBUTION ANALYSIS FOR THE MASSES
3,

AVERAGES FOR X,XP,Y,YP,L,DELTA ARE
-.50066E-05   .14487E-06   .49500E-05   .12131E-05  -.24459E-06  -.63000E-03

STDDEV FOR X,XP,Y,YP,L,DELTA ARE
 .53970E-03   .18009E-03   .53916E-03   .17960E-03   .53328E-04   .43164E-01

THE FULL BEAM MATRIX IS :
    .5397E-03  -.9005E-02  -.7107E-02   .1396E-01   .3911E-02   .1042E-01
                .1801E-03   .3029E-02  -.1395E-01  -.8781E-02   .4140E-02
                            .5392E-03  -.4991E-03  -.1223E-01   .6511E-02
                                        .1796E-03   .5682E-02  -.6074E-02
                                                    .5333E-04   .2488E-01
                                                                .4316E-01

  epsxproj = 9.718829189758786E-08
  epsyproj = 9.683389443752839E-08
  epslproj = 2.301131659769257E-06

  DETERMINANT OF FULL BEAM MATRIX * 1.0E 8 IS :  .4686E-31
```

Final Data:

```
PARTICLE DISTRIBUTION ANALYSIS FOR THE MASSES
3;

AVERAGES FOR X,XP,Y,YP,L,DELTA ARE
 .33582E-03   .11163E-03   .20765E-04  -.10888E-04  -.11603E-03   .10104E-03

STDDEV FOR X,XP,Y,YP,L,DELTA ARE
 .26115E-02   .67222E-03   .26209E-02   .69485E-03   .84307E-02   .44544E-02

THE FULL BEAM MATRIX IS :
    .2612E-02   .1942E+00  -.1425E-01  -.1837E-01  -.5224E-01   .1491E-01
                .6722E-03  -.8886E-02   .8588E-02  -.3097E+00   .9089E-02
                            .2621E-02  -.2212E-01   .9268E-02  -.5166E-02
                                        .6949E-03  -.2304E-01  -.1704E-02
                                                    .8431E-02  -.3022E+00
                                                                .4454E-02
  epsxproj = 1.722104455878732E-06
  epsyproj = 1.820692766726796E-06
  epslproj = 3.579784735216374E-05

  DETERMINANT OF FULL BEAM MATRIX * 1.0E 0 IS :  .1127E-31
```

Table 2: Comparison of “ideal” and simulated final phase spaces

Parameter	Initial Value		Final Value	
	Ideal	Simulated	Ideal	Simulated
Momentum (MeV/c)	145	145	10	10
β_x (m)	3.0000	2.9967	3.355	3.967
α_x	0.0000	0.0009	-0.1712	-0.1982
ε_x (m-rad)	0.1000	0.0972	1.45	1.72
β_y (m)	3.0000	3.0035	3.458	3.775
α_y	0.0000	0.0005	-0.2380	0.0221
ε_y (m-rad)	0.1000	0.0968	1.45	1.82

Leveraging the Epiphany

Given a conclusion that the Upgrade may accept 15% momentum spread, what are the performance implications? Recall that FEL throughput is the product of electron beam power and FEL efficiency: $P_{\mathrm{FEL}} = E_{\mathrm{e\text{-}beam}} \times I_{\mathrm{e\text{-}beam}} \times \eta_{\mathrm{FEL}}$. The performance-limiting factor of this relation is the FEL efficiency as it relates to the driver accelerator acceptance. Higher efficiency produces larger exhaust momentum spread, with associated increasingly severe constraints on driver performance. If the acceptance of the driver increases, higher FEL efficiency can be tolerated and greater FEL power generated.

Experience with the IR Demo [6] and simulation-based prognostication of Upgrade performance [7] suggest that the induced exhaust momentum spread is a factor of five to six times the extraction efficiency. The extraction efficiency allowed by a driver with acceptance A providing a beam with initial momentum spread $(\Delta p/p)_0$ can then be conservatively estimated as follows:

$$6\eta_{\text{FEL}} + \left(\frac{\Delta p}{p}\right)_0 \le A$$

or

$$\eta_{\text{FEL}} \le \frac{1}{6}\left[A - \left(\frac{\Delta p}{p}\right)_0\right]$$

In the IR Demo, with a perceived 8% acceptance and initial momentum spread of 1%, this suggests a tolerable extraction efficiency of something over 1%. This has been frequently achieved [8], and in fact the Demo recently produced ~2.25 kW beam power while running ~4.8 mA at ~48 MeV [9]. In the Upgrade, with the conjectured 15% acceptance and a similar initial momentum spread (1%, probably a generous allowance at the higher energy, even with a design bunch length only half that in the Demo) this predicts a tolerable extraction efficiency of order 2.5%. At turn-on, with 10 mA of current/145 MeV energy (two five-cell and one seven-cell module), this will yield ~35 kW. With a full complement of three seven-cell modules giving 210 MeV, this could give in excess of 50 kW.

We can, moreover, fantasize about even more insanely high powers. The values under discussion here will be achieved at a gun/drive laser-limited micropulse repetition rate of 75 MHz. Given specified single bunch performance, FEL power can be further increased by increasing the electron beam current with higher repetition rate. Table 3 presents various 100 kW and MW-class scenarios based on a direct extension of Upgrade performance solely through increases of injected current. Isn't energy recovery a *great*?

Table 3: A path to MW-class performance [10]

	IR Demo (achieved)	IR Upgrade (turn-on)	IR Upgrade (complete)	IR Upgrade (extended[1])
Energy (MeV)	48	~145	210[1]	210
Q/f/I (pC/MHz/mA)	60 / 75 / 5	135 / 75 / 10	135 / 75 / 10	135 / 750 / 100
P_{beam} (kW)	240	1500	2100	21000
η_{FEL} (%)	~1%[1]	1 (design) / 2.5 (?)	1+ (design) / 2.5 (?)	2.5 (as at left)
P_{FEL} (kW)	2.25	15 (design) / 35 (?)	21 + (design) / 50+ (?)[2]	500[2]
$(\Delta E/E)_{\text{exhaust}}$ (%)	6-8	8-10 (design[1]) / 15 (?)	8-10 (design[3]) / 15 (?)	15
Caveats	[1] Can go to ~2% with taper but can't losslessly energy recover	[1] NPS simulations suggest 1% extraction efficiency gives 5.5% energy spread	[1]using 3 7-cell modules [2]power increase due to beam power increase from higher energy [3]see note 1 at left	[1]assumes new injector at 750 MHz to alleviate RF window issues, BBU, HOM power deposition) [2]MW class; see "Caveats" section of text

The right-most column of Table 3 describes a scenario with a 100 mA injector (probably at lower frequency than the present 1.5 GHz system), and ignores all other technical problems (BBU, HOM power deposition, etc). Given a means to avoid these issues, MW class performance will be accessible using an unmodified Upgrade Driver accelerator at nominal Upgrade single-bunch parameters. If the charge/bunch can be raised to 270 pC, 1 MW output may be achieved.

Caveats

The reader should harbor certain reservations regarding the preceding conjectures. Firstly, DIMAD is a 2^{nd}-order matrix based speed of light code. Can we really believe it at ±7.5% momentum offset? Secondly, photon optics at enormous powers remains a delicate subject. Thirdly, such discussions of transport of 100 mA currents in Upgrade Driver-class machines blithely ignore the rather murky but extremely entertaining issues of halo generation and propagation [11]. Finally, what with all the fashionable blather about "energy recovery" and "reduced RF power requirements" and whatnot, the reader should really ask herself/himself, "If we recover all the RF power used to accelerate the beam, where does the power produced by the FEL come from?" This is readily glossed over in low power devices such as the present 2 kW JLab IR Demo, but does involve folding-money levels of hardware at 1 MW. This topic will therefore be considered in a forthcoming note [12].

Acknowledgements

Thanks to all FEL team members in general, and Steve Benson & George Neil in particular, for useful discussions related to this topic.

References & Notes

[1] D. Douglas, "WBS 3.0: Beam Physics Requirements for IR Upgrade Driver Accelerator", JLAB-TN-00-012, 31 May 2000.

[2] Noting that the momentum distribution after lasing is more uniform than it is Gaussian, Steve Benson suggested trying to trick DIMAD into "flattening" the initial momentum load. This was readily done by requiring the code to generate 0.075 sigmas of a 100% rms momentum spread, thereby generating a nearly flat distribution with a ±7.5% width.

[3] D. Douglas *et al.*, "Analytic Modeling and Lattice Scaling Relations for IR FEL Driver Accelerators", CEBAF-TN-95-015, 21 March 1995; D. Douglas, "Lattice Issues Affecting Longitudinal Phase Space Management During Energy Recovery, Or, `Why the FEL Needs Sextupoles'", JLAB-TN-98-025, 9 July 1998; D. Douglas, "Modeling of Longitudinal Phase Space Dynamics In Energy-Recovering FEL Drivers", JLAB-TN-99-002, 14 January 1999; D. Douglas *et al.*, "The Jefferson Lab 1 kW IR FEL", Proc. LINAC2000, Monterey, August, 2000; D. Douglas, "Longitudinal Phase Space Management in the IR Upgrade FEL Driver", JLAB-TN-00-020, 13 September 2000; D. Douglas *et al.*, "Driver

Accelerator Design for the 10 kW Upgrade of the Jefferson Lab IR FEL", Proc. LINAC2000, Monterey, August, 2000; D. Douglas *et al.*, "A 10 kW IR FEL Design for Jefferson Lab", PAC2001, Chicago, June 2001 (available online at http://www.cebaf.gov/~douglas/FELupgrade/talks/PAC2001.ppt).

[4] R. Servranckx *et al.*, "User's Guide to the Program DIMAD", SLAC Report SLAC-285, UC-28 (A), May 1985.

[5] K. L. Brown, "A First- and Second-Order Matrix Theory for the Design of Beam Transport Systems and Charged Particle Spectrometers", SLAC-75 (Revision 2) August 1971; K. L. Brown *et al.*, "TRANSPORT A Computer Program for Designing Charged Particle Beam Transport Systems", SLAC-91, UC-28 (I/A), May 1977.

[6] S. Benson, privately communicated folklore

[7] J. Blau, NPS simulations of JLab IR Upgrade performance, as presented at an Upgrade semi-annual review (March, 2001).

[8] S. Benson, various communications and papers.

[9] The high power was achieved on a lark (*i.e.*, "gee I wonder what happens if we turn up all the knobs…?) following machine studies July 2-3, 2001; D. Douglas *et al.*, "Three Pass Operation of the IR Demo FEL Driver", JLAB-TN in preparation.

[10] This table is drawn from a talk presented by the author at the Naval SuperUltraMegaDeathRay Workshop (Newport News, June 5-6, 2001; (available at http://www.cebaf.gov/~douglas/FELupgrade/talks/NSUMDRW2001.ppt).

[11] D. Douglas, "Design Considerations for Recirculating and Energy-Recovering Linacs", JLAB-TN-00-027, 13 November 2000.

[12] D. Douglas, "Energy Recovery" *vs*. "Power Recovery" – Acceptance Implications of Energy Conservation in FEL Drivers", JLAB-TN in preparation.