Design Principles for a Compact, High Average Power IR FEL

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This note outlines the reasoning and arrives at a specification of design parameters for a high average power IR FEL driven by a superconducting, energy recovering linac. The top level design requirements are: a) FEL output average power ~100 kW b) FEL wavelength ~1 μm c) Compact design d) High overall system efficiency. The need for high system efficiency motivates the use of a high average current energy recovering linac (ERL) as the driver accelerator. ERLs are very efficient devices, with their efficiency increasing as function of beam current [1].

We follow two design principles: First, is the use of as high an accelerating gradient as technologically available. Recent advances in superconducting rf technology have made accelerating gradients of >20 MV/m at $Q_0 \sim 10^{10}$ at the rf frequency of 1300 MHz routinely achievable. Higher gradients allow for a shorter linac and therefore for a more compact design. Furthermore, the cryogenic dynamic losses, which scale with the square of the gradient and can, in principle, present a limitation on the maximum gradient an accelerator may be designed or operated, are not a concern for any FEL application because of the small number of rf cavities involved.

The second principle is to arrive at the required average current by using the highest possible bunch repetition frequency and therefore the lowest possible charge per bunch. There are several benefits to this approach. Although the precise scaling of emittance with bunch charge is not entirely clear, it is generally agreed that lower bunch charge implies lower emittance at the source. Moreover, relatively low bunch charge, of order 100 pC in the case of a 100kW FEL, greatly alleviates single-bunch dynamics issues such as wakefield effects and CSR and the associated phase space degradation. Therefore lower bunch charge implies lower emittance at the wiggler as well. The HOM power dissipation in the superconducting rf (srf) cavities is a topic that becomes increasingly important with the shorter bunches required for maximum peak current in the undulator, and scales with the square of the charge per bunch but linearly with the bunch repetition frequency. Therefore, lower bunch charge and higher repetition frequency gives rise to lower HOM power load, compared to higher bunch charge and lower frequency, for the same average current.

The reasoning that determines the top level derived parameters of the 100 kW IR FEL is presented next. We assume that the operating rf frequency is 1300 MHz. The electron beam energy is determined by the required FEL wavelength, according to the resonance condition, and the requirement for compactness which motivates the use of a single, 8-cavity cryomodule in the linac, operating at ~20 MV/m.

The average current is determined by the FEL average power requirement together with the assumption of ~ 0.6% FEL extraction efficiency. The bunch repetition frequency is set equal to the rf frequency. The required small-signal gain together with longitudinal dynamics considerations in the driver accelerator, determine the bunch length at the wiggler. Additional considerations, which affect other system parameters, include the induced energy spread after the FEL interaction and the ability to recirculate, the power loading on the mirrors and the electron beam transverse and longitudinal emittance. The remaining FEL and accelerator parameters are determined using a one-dimensional model based on parametrizations from Dattoli [2]. Two additional scenarios, based on 805 MHz and 1500 MHz are examined and self-consistent design parameters are derived. Table 1 summarizes the design parameters for a compact 100 kW FEL under the three scenarios.

Several accelerator physics issues are important in these designs. Due to the recent interest in ERLs, most of these issues have been theoretically analyzed and some are being experimentally studied in the context of other ERL applications. The most important issues include the injector design, multibunch-multipass instabilities and the HOM power dissipation in the srf cavities. A more extensive discussion of the issues and possible cures is presented in [3].

In the recent years, much progress has been made in the development of srf cavities in general, and in the development of 1.3 GHz cavities in particular, primarily driven by the need for further optimization required for the TESLA linear collider project. It was recently reported [4] that quality factors of $Q_0 \sim 2x10^{11}$ have been demonstrated in 1.3 GHz cavities and further improvements of Q_0 are expected at cryogenic temperatures below 2K. Furthermore, 32 MV/m accelerating gradients have now been demonstrated at 1.3 GHz 9-cell cavities [5]. These specifications already exceed the parameters presented in Table 1; therefore no significant R&D towards higher gradients and higher Q_0 is required. R&D is still necessary for improved HOM extraction efficiency. An additional benefit of high gradient options is that fewer accelerating cavities are required, with fewer klystrons and fewer rf control systems, resulting in cost savings and operational simplicity. Furthermore, because the ratio of beam power to HOM power is proportional to the accelerating gradient, higher gradient designs imply better beam quality, because of the smaller relative energy spread induced by longitudinal wakefields, and greater system efficiency.

Finally, the progress made in srf technology together with the successful and reliable demonstration of energy recovery at the Jefferson Lab IR FEL have inspired much interest and action towards designs of synchrotron light sources based on ERLs. Several proposals for ERL-driven light sources are based on 1.3 GHz or 1.5 GHz technology [6,7, 8], largely due to the high gradients and high associated Q_0's demonstrated at these frequencies. It is one of the goals of this note to point out that these sources, presently under development, could be used very effectively to drive high average power FELs.

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References

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Parameter	Units	Scen1	Scen2	Scen3
e^- beam				
E_{inj}	MeV	10	10	10
E_{beam}	MeV	170	200	170
Q_{bunch}	pC	80	125	70
f_{rf}	MHz	1300	805	1500
f_{bunch}	MHz	1300	805	1500
I_{ave}	mA	104	100	100
$\sigma_z^{wiggler}$	psec	0.1	0.1	0.1
I_{peak}	A	320	500	280
ε_n	μm	6	7.5	5.6
ε_{long}	keV psec	50	62.5	46.6
$\Delta E/E_{out}$	%	5-6	5-6	5-6
FEL				
P_{FEL}	kW	100	110	100
$\eta_{ext}\ \eta_{opt}$	%	0.57	0.55	0.57
η_{opt}	%	80	80	80
K_w		1.6	1.64	1.6
λ_w	cm	6	8	6
g_w	cm	2.4	3.25	2.4
N_w		28	28	28
L_w	m	1.68	2.24	1.68
G_{ss}	%	76	103	68
$L_{opt\ cav}$	m	64	60	60
z_R	cm	60	80	60
$Q_{opt\ cav}$		5	4	5.56
$P_{mirror\ load}$	kW/cm^2	73	98	94
RF				
E_{acc}	MV/m	20	14	19
Q_0		1e10	1e10	1e10
L_{cav}	m	1.04	1.12	0.7
N_{cav}		8	12	12
N_{CM}		1	3	2
L_{CM}	m	~12	6.2	~10
R/Q/cavity	Ω	1000	~600	~700
P^{TOTAL}_{wall}		320	492	303
P^{TOTAL}_{HOM}	kW	1.3	2.4	1.7

Table 1. Design parameters for a 100 kW, IR FEL based on 1300 MHz (scenario 1), 805 MHz (scenario 2) and 1500 MHz (scenario 3).