A COST ESTIMATION MODEL FOR HIGH POWER FELS*

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ABSTRACT

A cost estimation model for scaling high-power free-electron lasers has been developed for estimating the impact of system-level design choices in scaling high-average-power superconducting-accelerator-based FELs. The model consists of a number of modules which develop subsystem costs and derive as an economic criterion the cost per kilojoule of light produced. The model does not include design engineering or development costs, but represents the 2nd through *n*th device. Presented in the paper is the relative sensitivity of designs to power and linac frequency while allowing the operating temperature of the superconducting cavities to optimize.

INTRODUCTION

A spreadsheet-based cost estimation model for scaling high-power FELs has been developed motivated by a desire to uncover the elements with the highest cost leverage to guide a program to develop high-power FELs for industrial processing applications [1]. The point of comparison in this note is the cost per kilojoule of light delivered—the primary economic criterion industry will use to judge the advantage of an FEL for photon processing. There are, of course, other factors which will enter into any decision as to the applicability, practicality, or profitability of a high-power FEL system: reliability, unit power capability, pulse structure compatibility with the desired process, and ability to meet the desired output wavelength.

In this model we have assumed the FEL is an oscillator based on a continuous wave (CW) radio-frequency (RF) recirculating accelerator with energy recovery. The model includes both superconducting RF (SRF) cavities and normal conducting cavities for comparison. The FEL extraction efficiency is an input assumption. Beam average powers, subsystem losses, etc., are calculated self-consistently in the model. An adjunct calculation is performed to estimate the overall device electrical efficiency. The model can optimize cost per kilojoule of delivered light on the SRF operating temperature.

Table 1 shows a set of input machine parameters for a 200 nm output at 100 kW. The FEL single-pass efficiency has been taken as 1.2%, which results in a net FEL efficiency of 0.8% after allowing for mirror losses within the optical cavity. The fundamental limitation in achieving such efficiencies may be the beam transport considerations of the large FEL-induced energy spread.

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Table 1: Input parameters to the cost model for the cases shown in the results. Case 2 is used in Figs. 1 and 2.

Case	**1**	**2**	**3**	**4**	**5**
Power out (kW)	100	100	100	100	100
Wavelength (μm)	0.2	0.2	0.2	0.2	0.2
Energy (MeV)	250	250	250	250	250
Current (A)	0.05	0.05	0.05	0.05	0.05
Frequency (MHz)	**300**	**500**	**805**	**1100**	**1300**
Gradient (MV/m)	5	5	5	5	5
Temperature (K)	**4.5**	**4.2**	**2.9**	**2.5**	**2.3**
# of recirculations	2	2	2	2	2
Cells/cavity	5	5	5	5	5
# inj. cavities	2	2	2	2	2
Inj. energy (MV)	10	10	10	10	10
Availability (%)	.85	.85	.85	.85	.85

The subsections below discuss the cost estimating modules for each element.

<u>RF Model</u> We were guided by analyses in Reference 2 and CEBAF experience to estimate RF costs by summing two terms, one proportional to the RF power required (high voltage, regulation, mounting, klystrons, and circulators) and one proportional to the number of low-level controls. The low-level controls are frequency independent. Each system costs $65k connected in sets of eight, including procurement, calibration, and installation.

<u>Cryogenics Model</u> The cryogenics module is based on analyses due to C. Rode and D. Proch [3]. In that model, the heat loads consist of three elements: 1) the temperature-dependent surface resistance (BCS) losses, 2) temperature-independent residual losses due to surface resistance of impurities and defects, and 3) static loads which represent heat leakage through fundamental and higher-order-mode power couplers, tuners, and piping connections. The BCS losses in W/m are given by

$$P_{\mathrm{BCS}} = \frac{AE^2}{T}(f/500)^{1.1}\, e^{(-17.67/T)}$$

where $A = 2.6 \times 10^{-10}$ for the frequency f in MHz, gradient E in MV/m, and temperature T in K showing the exponential operating temperature dependence. The residual power dissipated is

$$P_{\mathrm{res}} = E^2/ZQ_{\mathrm{res}}$$

with a curve fit to existing cavities giving a shunt impedance $Z(\Omega/\mathrm{m}) = 380(f/500)^{0.9}$. Q_{res}, the residual quality factor, is taken as fixed at 3×10^9, although in many cases this has by now been exceeded using careful cleaning techniques at CEBAF. Static losses are given by

$$P_{\text{static}}\,(\text{W/m}) = 8/\sqrt{\text{f}/500}$$

to account for the smaller surface area per meter at higher frequencies. From the total loss at the assumed temperature and gradient the refrigerator power can be calculated. Refrigerators become more efficient and cost-effective as unit size increases. Capital costs scale as $P^{0.7}$ and inversely with T since such operation is less efficient and requires subatmospheric helium transport. Electricity and cryogens are included in the efficiency and operating cost calculations.

SRF Cavities Model SRF represents a major fraction (40%–60%) of the system capital costs. Unfortunately there is a large uncertainty in this value as addressed in presentations at the 1990 TESLA Workshop [4], presumably due to different system designs as well as accounting structures between the laboratories. An expected dependency on frequency due to lower material costs at the higher frequencies does not emerge. For this note, we use $600k/m independent of frequency.

Normal Conducting Cavities Model If an NC accelerator is assumed, a different cavity module is used and the cryogenic system cost and power consumption are eliminated. No added cost for the cooling system required to maintain the cavities in tune has been applied.

Other Models The cost of the injector exclusive of RF power is assumed to vary as the (beam power)$^{0.7}$. A cost per pass of acceleration is taken as $1.2M for magnets, power supplies, alignment, and vacuum hardware.

Most wigglers to date have been "one off" so commercial costs include non-recoverable engineering. An exception is the 2.5 m wedge-pole hybrid design at APS, with a cost of ~$600k. Allowing for procurement, alignment, integration, and controls, we use $400k/m as the nominal cost. Caution is advisable since it is not obvious that wiggler costs should scale linearly with the length.

The model uses a rule of thumb that diagnostics and control should cost 10% of the systems they are controlling. An optical system cost of $2500k and a fixed dump cost of $200k were assumed.

Amortization In many companies capital costs are amortized by calculating present value and return on investment. In this model the capital is amortized at 13.3% per year, roughly corresponding to a 7% rate with an assumed ten-year life.

Operating Costs Operating costs include electricity, cryogens, supplies, and operating labor. Electric costs are assumed at a flat rate of 0.08 cents/kWh in the cited examples. It is assumed that FEL operation requires two people on shift. Maintenance is assumed handled by a separate contract at 1.5% of the system capital cost annually, consistent with CEBAF experience.

Figure 1 shows the relative capital cost contributions in Case 2. On the operating side amortization consumes 59% of the annual budget, followed by labor and electricity at 14% each, and maintenance and supplies at about 7% each.

Stability In addition to cost, the model estimates beam stability margins as a way to ensure some level of credit for changed accelerator performance. The calculations are based on some formulas by J. Bisognano [5]. Three relative margins are calculated: beam breakup (BBU) sensitivity, longitudinal wakefield effects, and transverse wakefield effects. Together they give guidance as to the possibility of operating at high average currents and thus high average powers.

Generally the most limiting effect is BBU, with the threshold current for instability taken to scale as

$$I_{\text{th}} \sim 1\Big/\left[\omega^2 \times L_{\text{acc}} \times \left(R/Q\right)_{\perp}\right]$$

where ω is the linac frequency, L_{acc} is the accelerator length, and $(R/Q)_{\perp}$, the transverse impedance, has no explicit frequency dependence. No judgment is made relative to the lattice, since such a choice could be made (in principle, at least) independent of the cavity parameters.

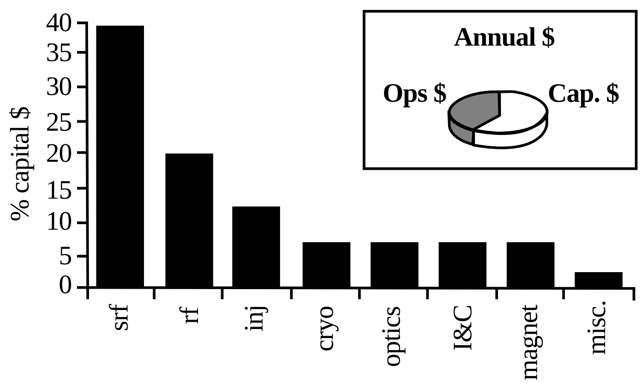

Figure 1. Cost factors. Relative capital cost contribution of each subsystem is shown with annual capital retirement vs. operating cost inset.

RESULTS

As expected, the cost per watt decreases monotonically with increasing power, as is shown in **Figure 2** for both the superconducting design at 500 MHz and the 180 MHz normal conducting design. The range shown for the superconducting design covers a nominal system cost down to what might be achieved using an aggressive approach to cost reduction to get photon costs down to $0.002/kJ. The room temperature system suffers in comparison from the much higher RF power required due to wall losses, the cavity costs to achieve the same energy (due to low gradients), and the higher electrical costs to power the RF. At 180 MHz and a 2.8 MV/m gradient, the NC system has a BBU threshold which is twice a 500 MHz, 5 MV/m SC system but only 60% of a similar 350 MHz SC linac. Each of these systems could transport in excess of 100 mA (provided a suitable lattice is adopted) which should be sufficient to produce on the order of 100 kW of FEL output.

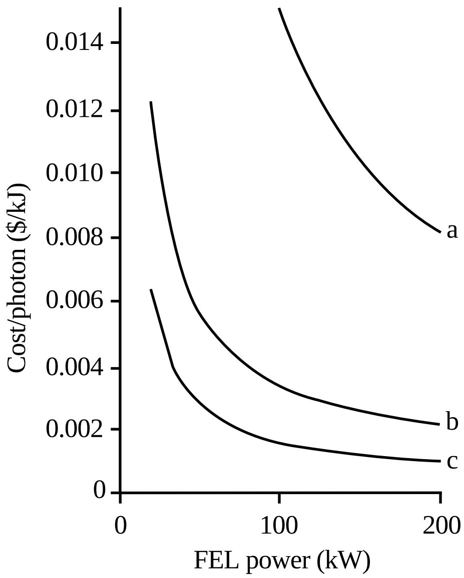

Figure 2. Photon cost versus power. The costs are calculated for a) 180 MHz normal conducting cavities, b) 500 MHz superconducting cavities using nominal values for the element costs, and c) 500 MHz superconducting cavities assuming an aggressive program to minimize costs: SRF cavities reduced to 67% nominal, RF reduced 47%, similar reduction factors for other elements.

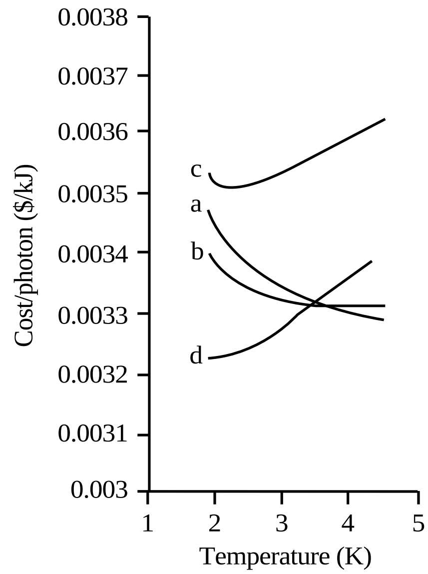

Figure 3. Photon cost as a function of temperature. The output power is assumed to be 100 kW. Costs are shown for: a) 300 MHz at 5 MV/m, b) 500 MHz at 5 MV/m, c) 1300 MHz at 5 MV/m, d) 1300 MHz at 7 MV/m. The lower-frequency cavities optimize around 4 K, and high-frequency cavities around 2 K. These curves all lie within the error bars of the cost model. The high gradient is shown for the 1300 MHz cavity because it is easier to achieve high-gradient operation in higher-frequency cavities due to the reduced surface area, which reduces the possibility for gradient-limiting imperfections.

For a given gradient and frequency the operating temperature can be optimized. Higher-frequency cavities want a lower operating temperature. Due to the competing factors of lower losses but lower refrigerator efficiency at lower temperature, the net frequency dependence of capital and operating cost is quite weak, lying within a 10% band. Uncertainties in the cost algorithm surely exceed this variance. For example, in **Figure 3** the cost per photon is plotted versus temperature The lower-frequency systems are seen to be the least expensive at 5 MV/m and around 4.5 K. If credit is taken for the higher gradients achievable at higher frequencies, the situation reverses and higher frequency cavities yield a less expensive system, as shown in curve d. It thus appears that the operating frequency should be chosen on the basis of issues such as transport robustness, maturity of the technology, and reliability of the equipment. For RF and cryogenics, this clearly favors operation below approximately 800 MHz in the technically mature commercial UHF band and at around 4.5 K for ~1 atm liquid helium transfer pressure leading to simplified and more reliable cryogenics. The conclusion of more extensive parameter variations not presented here is that significant effort should focus on the SRF cavities' capital cost followed by the RF systems. If electron transport to as many as four passes with energy recovery can be technically achieved then benefits accrue. High availability and low operating costs are also important.

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