COST ESTIMATION OF AN ENERGY RECOVERY LINAC LIGHT SOURCE

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Abstract

A cost estimation model for scaling energy-recovery linacs (ERLs) has been developed for estimating the impact of system-level design choices in scaling superconducting accelerator facilities. The model consists of a number of modules which develop subsystem costs and derive as a budgetary criterion. The model does not include design engineering or development costs. Presented in the paper is the relative sensitivity of designs to the accelerators and the refrigerators while allowing the accelerating field to optimize.

INTRODUCTION

Light source has become an integral part of the experiment in most science concerned with the structure of matter on the atomic scale. This impact is felt over a broad range of science from protein crystallography in the biological science to studies of atomic and electronic structure in systems ranging from high temperature superconductors to tonic elements in soil. The impact of this research has grown exponentially as the sources have evolved. Although synchrotron radiation is produced by about 70 storage-ring based facilities in the world, the performance is nearly at its ultimate level. Superconducting ERLs can be extremely efficient accelerators for free-electron lasers, synchrotron radiation light sources. In an ERL, a beam is accelerated to the energy required for the application, and returned to the linac 180 degrees out of phase with respect to the accelerated electrons. In this way the returning high-energy electrons are decelerated, and they recycle their energy to the rf field to provide most of the power necessary to accelerate the entering electrons. Besides the high efficiency, ERLs offer crucial advantages for a new user-oriented light sources, including very high brightness, a large degree of spatial coherence, and ultra-fast temporal structure.

A spreadsheet-based cost estimation model for ERLs has been developed motivated by a desire to uncover the element of the highest cost and to determine the ERL parameters with which the construction and running costs become reasonable. The point of comparison in the present paper is the total cost – the primary budgetary criterion used to judge the advantage of an ERL.

PARAMETERS FOR COST ESTIMATION

In the present model we have assumed the ERL is based on a continuous wave (CW) rf superconducting accelerator (SCA), the final energy of 6GeV, the current of 0.1A and 40 sections of light sources. The injector installed before the recirculating SCA is not included in the cost because the design of the injector has not examined in detail yet. The cost of the site is not included neither because the cost widely changes with the choice of the site. The model can optimize cost on the accelerating field of SCA.

The subsections below discuss the cost estimating modules for each element. We use the exchange rate to \$1=1Euro=130JPY.

SCA Cavities Model

SCA cavities represent a major fraction (16%-34%) of the system capital costs. Fortunately we can refer to the TESLA design [1,2]. We assume to use the TESLA-type cavities and cryo modules. The TESLA module is 12.2m long including 1.3GHz eight 9-cell cavities. The unloaded Q value is 1×10^{10}. The cost of the SCA module is evaluated to \$1M including a cavity assemble and a cryo vessel.

Refrigerator System Model

Required cooling power of the refrigerator system is estimated from static heat leak, dynamic heat leak and rf wall loss. Since cost of the refrigerator system depends on number and capability of the refrigerators, we assume the cost of refrigerator system is proportional to the cooling power for 2K and 4.5K. It is assumed to cost \$3.4k/W for refrigerator operating at 2K and \$1.7k/W at 4.5K in accordance with the Very Large Hadron Collider (VLHC) [3]. The electrical power consumption of 1W refrigerator is assumed to 600W at 2K and 245W at 4.5K in accordance with the TESLA cryogenic system [4].

RF Power Source Model

The rf power is small owing to energy recovery, but it is necessary to supply rf power for compensating the beam power loss due to light generation and correcting the amplitude and phase errors. Required rf power is estimated from the parameters such as beam current, cavity shunt impedance, unloaded Q value, accelerating field, current error and phase error [5]. Since the cost and the efficiency depend on a type of the rf source, the cost is assumed to be proportional to the rf power with the factor of \$1.15/W and the efficiency from AC power to rf power to 0.5 for calculation of the power consumption.

Magnetic System Model

ERL optics is designed to suppress the beam breakup (BBU) instability by obtaining small pass-to-pass matrix elements of R12 and R34. Required magnetic parameters depend on accelerator design. We assume that a

quadrupole triplet magnet of 25T/m is installed between adjacent SCA modules. The middle magnet of the triplet has length of 50cm and the others of 25cm. The back-straight beam line has half the number of triplets in the accelerator line.

One section of the arc, where an insertion device is installed, is assumed to have three bending magnets, four quadrupole triplet magnets, two quadrupole doublet magnets and an undulator.

Since it is difficult to estimate the cost of magnets precisely without beam optics design, we roughly estimate the magnet cost to be proportional to the weight of magnet. Referring to the magnet cost of several accelerator facilities such as the JAERI-FEL, the Spring-8 and the TESLA, we assume the cost to \$60/kg for quadrupole and bending magnets.

The cost of the DC power supply is assumed to be proportional to the DC power with the factor of \$1410/kW. The conversion ratio from AC to DC of the DC power supply is typically 0.85.

The cost of an undulator is assumed to \$230k in accordance with the JAERI-FEL undulator.

Building Model

The straight parts of the SCA modules and back-straight beam line including the auxiliary components are assumed to be installed in the tunnel same as that of the TESLA. The parts of the light sources are installed in the buildings along the arc with concrete wall of 1m thickness to shield the radiation caused by beam loss of 1×10^{-5}. The tunnel cost is estimated to \$9k/m and the arc building \$55k/m. The arc building includes the experimental rooms.

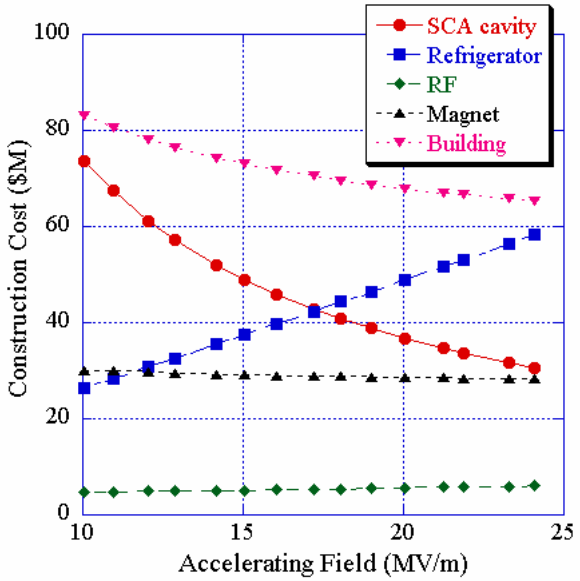

Figure 1: Construction cost of each model as a function of the accelerating field

RESULT

Two types of costs are discussed below. The first is a construction cost. Figure 1 shows the each cost of models as a function of the accelerating field. As expected, the costs of the SCAs and building decrease monotonically with increasing the accelerating field. The high accelerating field decreases number of the SCA modules and the length of the tunnels. On the other hand the cost of the refrigerators increases with the accelerating field since the number of the SCAs decrease inverse-proportionally and the heat load, dynamic heat leak and rf wall loss, increases square-proportionally with the accelerating field. The costs of the magnets and rf system vary slightly enough to be considered to be constant. Since the major parts of ERL, SCAs and refrigerators, vary inversely, the optimum accelerating field exists as shown in Figure 2. The construction cost at the accelerating filed of 21MV/m is minimum and the increase over 20MV/m is very small.

The second is a running cost. Figure 3 shows the electrical power consumption of the refrigerator system, the rf power source and the magnet system. The power consumption of the refrigerator and the rf power source increases with the accelerating field. Typical electric charge is about \$9k/MW per month for maximum power of the facility and \$75/MWh for electrical power consumption at a typical rate of Japanese electric companies. The running cost increases monotonically with the accelerating field as shown in Figure 4.

If the running cost includes a depreciation expense of the construction cost as the 10-year useful life of the ERL machine, the running cost has optimum accelerating field near 13MV/m as shown in Figure 5. This means that the ERL does not require as high gradient cavities as a linac for nuclear physics. The higher unloaded Q value is expected at the low accelerating field than at the high field. The high Q value can reduce the required cooling power of the refrigerator and the running cost as shown in Figure 6. The optimum accelerating field increases with the Q value for dominant of the construction cost over the running cost. The ERL requires the SCAs with high Q value than with high accelerating filed.

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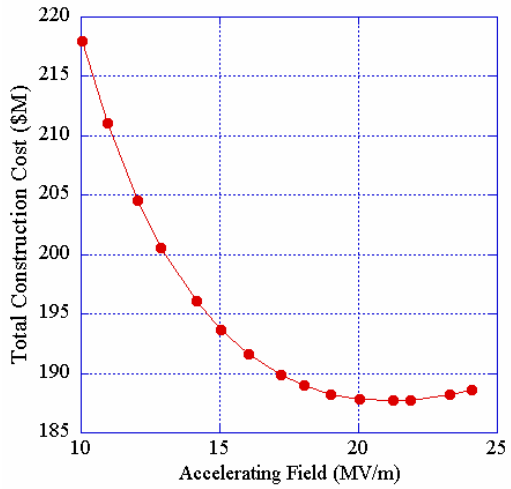

Figure 2: Total construction cost

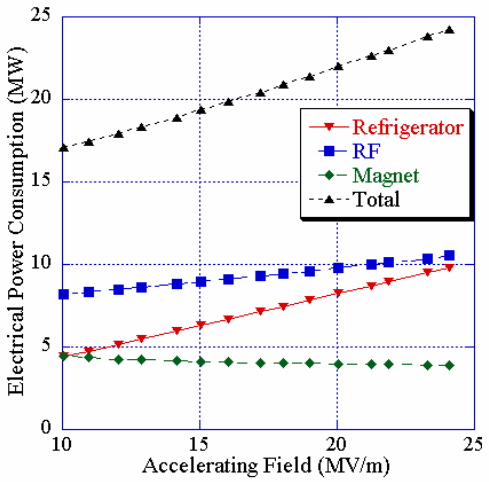

Figure 3: Electrical power consumption

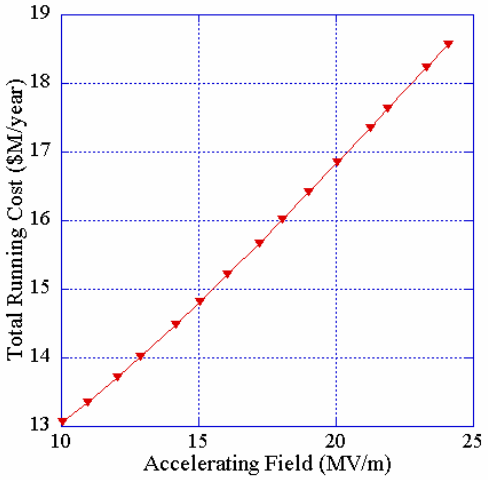

Figure 4: Running cost

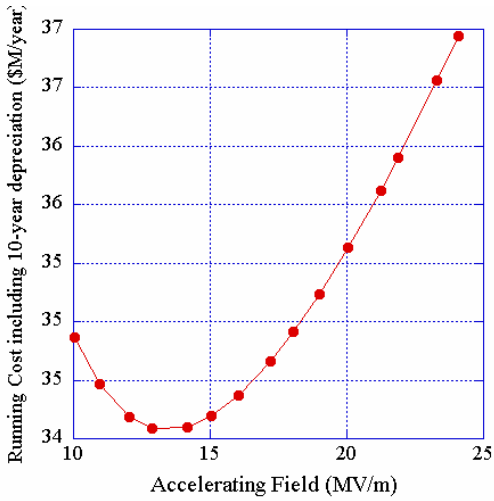

Figure 5: Running cost including a depreciation expense of the construction cost as 10-year useful life

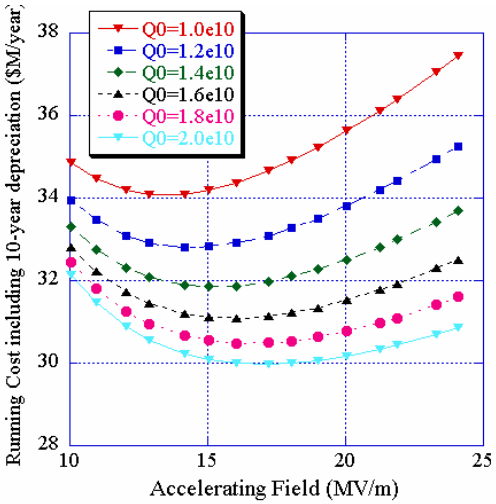

Figure 6: Running cost including a depreciation expense of the construction cost as 10-year useful life for various Q values