RADIOACTIVITY AND DAMAGE STUDIES FOR NEXT GENERATION COLLIDERS*

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Abstract

Optimization of the average, generalized luminosity per unit cost of a linear collider requires a detailed study of this Figure-of-Merit. We consider what might be called a triangle inequality between damage, efficiency and cost. Examples over the length of an LC, starting at the source and ending at the dump, suggest that both costs (capital and operating) and environmental issues can be improved in a compatible way. Thus, a RoHS by any other name (WEES or OSHA) need not present thorny problems requiring unexpected R&D but a push to leverage the most recent advances in materials and technology. Further, the true amortized cost may be seriously underestimated by ignoring such issues. As example, the entire, interior surface of a laser driven RF gun involves materials science where the space requires continuous UHV to sustain stable, acceptable quantum efficiency as well as avoid RF breakdown damage in an environment that is also subject to radiation damage. All of these can seriously reduce the gun's output and an LC's luminosity. Dealing with them provides opportunities to innovate that can justify the costs.

INTRODUCTION AND BACKGROUND

Among the many aspects in the design of linear colliders (detectors, accelerators, beam delivery/disposal systems) as well as advanced accelerator techniques to reduce size and cost, ES&H issues become peripheral due to the immense size and complexity of the problem. Also, there are value oriented questions and efficiencies that do not seem to be related to either cost or luminosity. We try to show that a better understanding of materials issues provide ways to minimize radioactivity, damage, improve capital and operating costs and leverage developments in other fields.

To justify any FoM for a system implies a reasonable value for it on completion that is commensurate with its cost. If the reason for it goes away or is achieved by other means before completion then its value goes down unless it is useful for other things. This is one basis for a general linear collider[1] capable of producing luminosity in multiple incident channels[2]. If the initial cost is considered too high to incorporate all of these, they should still remain viable for upgrades in a cost effective way. Whereas radioactivity, damage and remediation costs are important concerns here, it is first necessary to reconsider the overall FoM because the ideas apply repeatedly for the various components to be discussed.

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Figure-of-Merit

First, optimizing the *average, generalized* luminosity $\bar{\mathcal{L}}$, for a fixed, wall-plug power P_{AC}, implies that $\mathcal{L}$ must be available and preferably with short switching times. Also, for P_{AC} as cost function, $\bar{\mathcal{L}}/P_{AC}$ is reasonable for the FoM but far too simple even if one recycles and aggressively minimizes all power usage and includes original capital equipment expenditures. Efficiency, reliability and damage are all correlated in ways that couple $\bar{\mathcal{L}}$ and costs.

Higher efficiency can increase component lifetimes and decrease both energy costs and environmental impacts but may not optimize $\bar{\mathcal{L}}$ without considering the related demands of reliability and damage. Clearly, there are always additional ways to increase energy efficiency such as recycling spent beam power at the klystrons or linacs either by operating them as oscillators by feeding back power from an output cavity or using other high Q cavities at lower frequencies or recycling the output beams themselves in other ways such as fixed target experiments. None of these are planned for reasons of cost even though the term "value" is being used in costing estimates.

Here we focus on other aspects of the ILC problem that might be characterized as the triangle inequality – damage/reliability, efficiency and cost because of developing concerns in these areas. More specifically, examples are given over the full length of an ILC that attempt to support the hypothesis that a broader, greener perspective and increased flexibility is both good and not as difficult as it seems. We begin by considering the sources of radioactivity in a collider followed by examples running from the source to the dump:

- The Source (or Gun)
- Hybrid Magnets/Power Systems
- Detector and Luminosity Monitoring
- The Disposal or Dump System
- Optimal Control in Hostile Environments

Radioactivity and Radiation Resistance (RR)

While studies of damage due to to radiation effects are done because damage limits system performance, one sees few discussions of the residual induced radioactivity and how that should inform the design process. For magnets, both permanent and superconducting, although they can save energy, they are less well understood since they are still being developed with better primary properties. Even so, these may differ wildly in their residual radioactivity and RR with little apparent justification[3].

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Sources of Radioactivity in an LC All relevant nuclei have multipole states that are strongly excited by γs in the 10-25 MeV range e.g. the giant dipole resonance absorption of photons. The lowest resonances have been characterized by excitation energies $\approx 70 A^{-\frac{1}{3}}$ depending on whether the collective excitations are isoscalar or isovector where the interaction between nucleons in the nucleus is attractive or repulsive. Because the threshold for the (γ,n) reaction opens up slightly below this region and roughly tracks the mass dependence of such resonances, neutrons can be expected to be a problem induced by bremsstrahlung (Bethe-Heitler processes). Since the bremsstrahlung spectrum varies inversely with energy, any reduction in the atomic mass number of the materials used should reduce radioactivity due to cascades - other considerations equal. We show this in the examples. Notice that the (γ,p) process is reduced by the Coulomb barrier and the fact that there are always more neutrons in higher shells. Further, even though multi-nucleon decays occur, their thresholds are higher and the (γ,np) and (γ,2n) channels are favored. Also, because the protons are charged they tend to stop nearer to where they are produced losing energy through the more benign ionization processes until they can no longer interact with nuclei to produce radioactivity. Then, both types of nucleons end as hydrogen which does its own solid- state materials damage as discussed elsewhere.

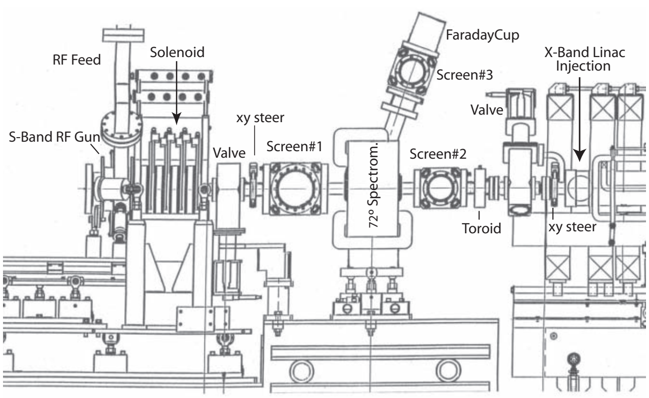

Figure 1: Layout of the SLAC NLCTA RF photoinjector.

EXAMPLES

One question is whether a "green" collider necessarily increases costs? Recent studies have yielded a number of conclusions that support a broader view of the total design process including various cost factors and green issues that suggest examples where the best system is greener and less expensive to implement and operate. These run from the source, that shares features with the detector, and proceed through the entire complex to the dump including the underlying control systems. Because initial conditions are so important, emphasis is on the photoinjector (Fig. 1).

RF Photoinjector The ILC requires a high-energy, highly-polarized beam with low emittance and high charge. For SLC, photocathodes were made of gallium arsenide, a Group III-V, direct band gap semiconductor crystal. For the correct photon energy and polarization, unstrained GaAs provides 50% polarization. To date, almost 90 % has been obtained by using alternating layers of gallium arsenide with gallium arsenide phosphide in the top 100 nanometers of the cathode surface[4]. A major question is what frequency RF can be used with this and how to increase it, while maintaining polarization, through use of improved materials? Superconducting options present a number of complications including lower fields in what may easily turn into an elaborate cold trap.

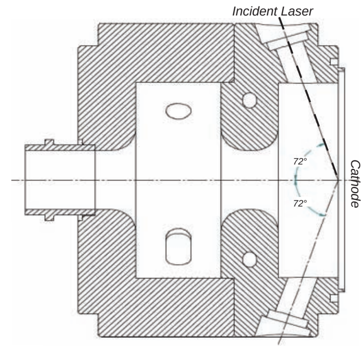

Figure 2: Schematic, cross-sectional view of a 1.6-cell, laser-driven RF gun. The internal, unshaded areas are to be maintained continuously at very high vacuum to sustain a stable and acceptable quantum efficiency as well as avoid RF breakdown damage. L or S-Band RF cells set the scale.

In addition to increasing polarization, layering improves GaAs quality and increases electron production efficiency (QE typically 1%) by a factor of 2-3 times that for single strained GaAs. While the current ILC design is based on a DC gun like the SLC, it requires a subharmonic buncher. Improvements would include an RF gun as well as a flat beam off the cathode both of which require R&D but could prove to be cost efficient. Figures 1-2 show a typical RF gun setup. Regardless of the specific requirements, the photocathode's material, surface and handling are very important and subject to many kinds of damage but so is every other surface of this gun as well as the volume of the laser windows. Dispenser cathodes that require frequent handling or windows that darken in the required wavelength range or nearby detectors all benefit from reduced radiation. Work functions, fabrication methods, ease of handling, crystal orientation and low atomic numbers all impact the merit function.

Hybrid Magnets/Power Systems These systems run the length of the collider and are expensive to build, run and control. They are most vulnerable when cycling or switching power. Superconducting systems are the most vulnerable because they store the most switchable energy even though they are not necessarily the strongest magnets[5] as shown in Fig. 3. This argues for minimal apertures and the smallest favor permanent magnets (PMs) that require no cooling fluids or direct power. Another argument for PMs comes from analyzing $\mathcal{L}/P_{AC}$.

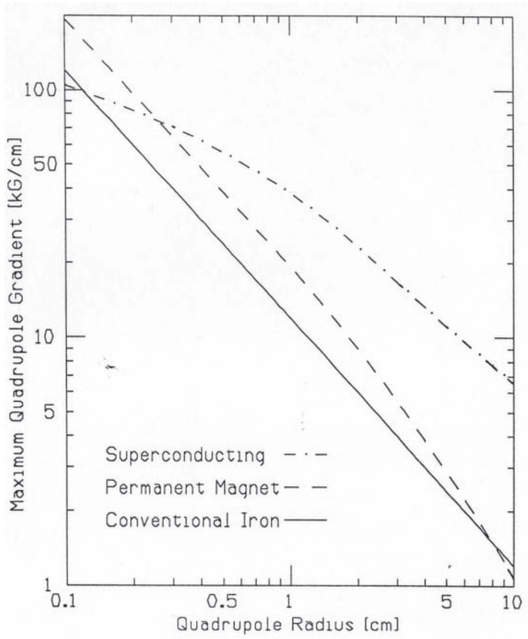

Figure 3: Strengths obtainable for different quads types[5]: iron pole-tip fields B_p=12 kG, remanent fields B_r=11.5 kG for PMs and NbTi wire with J_c=2 kA/mm^2 at 5T & 4.2°.

It follows that $N_B/\sigma_x\sigma_y$ must increase as the cube of the beam energy γ_b^3. While decreasing bunch sizes give the best gains, it also implies changes to N_B[7]. SmCo PM multipoles have been in use in the SLAC damping rings and their injection and extraction lines since 1985[5] because NdFeB was not available. First tests of this newer, stronger material were done in 1987[6]. Even though it develops very little radioactivity[3], its use has been avoided except where small scales are unavoidable as for undulators.

The Disposal or Dump System(s) While multiple dumps should be used to deal with various outgoing beam components, one genre for the primary that minimizes radionuclide production is a "swimming pool" structure – reentrant through shaped aluminum window(s). It could be loaded with remotely controlled irradiation, isotope production or other experiment chambers. Their location and exposure depend on the beam energy, flux distribution (and its measurement) and the experiments. It could be used like a reactor but with several significant differences. It doesn't produce actinides but might be used to convert them to more benign elements. It could provide a very different spectrum and makeup of particles and should be easier to use and interact with. The dimensions of the pool would be sized to contain/moderate the shower to minimize radioactivity in the walls. Continuous filtration can capture and separate the various isotopes produced e.g. hydrogen for use although tritium is benign and will be produced in other water systems as well. The first pass on this was much more conventional without a spoiler[8]. The wall material is one of the interesting aspects that needs simulation. Failure modes do not seem serious if pressure vents and double windows are used and monitored.

Controls There has been a natural convergence to a new class of controller – the Programmable Automation Controller (PAC) based on PLCs using COTS hardware and PCs incorporating real-time systems. These improve both efficiency and costs when wireless is added if ruggedized and radiation resistant (RR). There are many examples where RR is important and costs could be reduced through R&D and closer ties to aerospace.

Another good example is bright illumination across the entire visible spectrum (depending on phosphor and dye concentrations in acrylic resins) based on phosphorescence after exposure to white light that consumes no electricity. Because many of these last for more than an hour after illumination, they are ideal for safety signage requirements in work areas and require no wiring or emergency power.

CONCLUDING REMARKS

Valid questions are being raised concerning whether congress should enact a single compliance standard for RoHS while California just enacted a RoHS-like law. A European RoHS directive became effective last year eliminating lead, mercury, cadmium, hexavalent chromium and the polybrominated biphenyls (PBB)and their ethers (PBDE) in *commercial* electrical and electronic equipment. Where there are no substitutes, exemptions may be made. They may modify their list to avoid impeding scientific and technical progress. Is this wise or otherwise and why?

For accelerators and HEP facilities, further regulations apply and there are the added questions of direct radiation and induced radioactivity that increase the dimensionality of the problem. A major question is what the performance limiting factors are and how to avoid or overcome them. In very many cases, answers can come from materials science and technology if Adam Smith's "invisible hand" is not cut off by the funder *or* fundee.

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