DESIGN OF A 250 MeV, X-BAND PHOTOINJECTOR LINAC FOR A PRECISION COMPTON-SCATTERING BASED GAMMA-RAY SOURCE*

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Abstract

We present a compact, X-band, high-brightness accelerator design suitable for driving a precision gamma-ray source. Future applications of gamma-rays generated by Compton-scattering of laser and relativistic electron beams place stringent demands on the brightness and stability of the incident electron beam. This design identifies the beam parameters required for gamma-ray production, including position, and pointing stability. The design uses an emittance compensated, 11.4 GHz photo-gun and linac to generate 400 pC, 1-2 mm-mrad electron bunches at up to 250 MeV and 120 Hz repetition rate. The effects of jitter in the RF power system are analyzed as well as structure and optic misalignments. Finally, strategies for the mitigation of on-axis Bremsstrahlung noise are discussed.

INTRODUCTION

Bright, narrow bandwidth gamma-ray sources based on Compton scattering of laser pulses with ultra-relativistic electron beams have recently been used to excite Nuclear Resonance Fluorescence (NRF) lines in various isotopes [1, 2]. Applications of isotope specific detection based on excitation of NRF by Compton sources are under investigation at LLNL, and include homeland security, waste identification, and material characterization.

Common to all of the proposed NRF applications is the need for high average photon flux at a specified energy (i.e., to maximize $N_\gamma/eV/sec$ at the NRF resonances line) while concurrently minimizing background noise from off-resonance radiation. For the Compton source, these requirements motivate the use of small laser and electron beam sizes, $\sigma_x$, at the interaction point (IP) to increase flux, yet maintain a small normalized beam divergence, $\gamma \sigma_{x'}/\lambda$, to decrease the bandwidth of the $\gamma$-rays.

The effect of electron beam divergence on source bandwidth can be seen through the expression for scattered photon energy in the Thomson limit (where $\gamma E_L \ll m_e c^2$),

$$E_\gamma \approx 2\gamma^2 E_L \frac{1 + \cos \phi}{1 + \gamma^2 \theta^2},$$

(1)

where $\phi$ is the angle between electron and incident photon, defined such that $\phi = 0$ for a head-on collision, and $\theta$ is the observation angle with respect to the electron direction. If we consider the head-on collision geometry, then the angles are defined with respect to the electron beam axis, and $\phi = \theta$ is the small angle made by an electron with respect to the beam axis due to non-zero emittance. Then Eq. 1 can be expanded to give

$$\frac{\Delta E_\gamma}{E_\gamma} \bigg|_{on-axis} = \frac{\Delta E_L}{E_L} + \frac{2\gamma}{\gamma - 1} \gamma^2 \theta^2.$$

(2)

In a more rigorous analysis [3], it has been shown that, in summing over the beam, the terms in Eq. 2 add in quadrature to give the $\gamma$-ray source bandwidth. The final term corresponds with the square of the normalized beam divergence, or $\varepsilon_n^2/\sigma_z^2$. Because this expression involves the normalized emittance, a high brightness beam is required to efficiently scatter photons while maintaining a narrow bandwidth. Tolerance to electron beam pointing jitter at the IP can also be evaluated using Eq. 2. Over multiple shots, errors in electron beam pointing will increase the effective beam divergence and therefore increase source bandwidth:

$$\Delta \theta_{eff}^2 = \sigma_{x'}^2 + \theta^2_{jitter, rms}$$

(3)

In the accelerator design described below, we choose as a goal $\theta_{jitter, rms} < 0.2 \sigma_{x'}$, to keep the effect of pointing jitter negligible. A similar constraint on position jitter is chosen to minimize growth of the effective spot size at the IP.

INJECTOR BEAM DYNAMICS

The 250 MeV linac design begins with a 5.5 cell X-band photo-gun to be built by a collaboration between LLNL and SLAC. The gun design is based on a previous SLAC gun [4] which was operated with 200 MV/m peak accelerating field, and generated 0.5 nC, 7 MeV bunches [5]. Beam parameters are chosen partially by scaling the design of the S-band, T-REX (Thomson-Radiated Extreme X-rays) photoinjection [6]. The ideal design scaling of lengths with $\lambda_{RF}$ and fields with $\lambda_{RF}^{-1}$ [7] would require 480 MV/m electric field on the photo-cathode. In the present case, the beam plasma wavenumber, $k_p = \sqrt{4\pi r_c n_b/\lambda^2}$, where $r_c$ is the classical electron radius and $n_b$ is the beam density, is scaled with the increase in anticipated field strength from the S-band system (a factor of 5/3). To maintain an RF curvature induced energy spread of a few times $10^{-3}$, the pulse length is set at 10 degrees of RF phase, scaled strictly with frequency. A bunch charge of 400 pC was selected with transverse size at the cathode chosen to produce the
desired $k_p$. Also scaling with $k_p$ is the drift distance from
gun to linac section, chosen in this case to be 80 cm.

A PARMELA [8] simulation of the injector is shown in
Fig. 1. The well developed emittance compensation tech-
nique [9] is employed to produce an emittance minimum
before injection into the first linac section where accel-
eration arrests the space-charge emittance oscillation at a
second emittance minimum of just under 1 $\mu$m, rms, nor-
malized. The accelerator uses 6 X-band traveling-wave
sections of type T53VG3 [10], developed by SLAC in a
program for International Linear Collider structure R&D.
These 60 cm, $2\pi/3$ phase advance per cell structures are
simulated with an accelerating gradient just below 80
MV/m, limited by anticipated RF power availability. Al-
though Fig. 1 shows the beam evolution through only three
sections, the emittance and spot sizes are essentially un-
changed by the following sections, and the simulated final
beam energy is 267 MeV.

**BEAM TRANSPORT**

The key issues addressed in the design of the beam trans-
port lattice from the exit of the linac to the Compton-
scattering IP are emittance preservation, mitigation of on-
axis Bremsstrahlung, and incorporation of the interaction
laser into the final-focus optical system. In previous Com-
ton source development work at LLNL, unwanted back-
ground radiation limited the utility of many of the $\gamma$-ray
beam diagnostics employed. This radiation was observed
to be effectively on-axis (i.e., only partially removed by
collimation), unchanged by absence of photo-beam, and
eliminated by removing RF power in the photo-gun. Spe-
ctral measurements were performed using a high-purity Ger-
nium detector, which showed the radiation to be broad-
band, and extending upwards of 8 MeV (detector range
limited). From this evidence, the noise source is deter-
mained to be Bremsstrahlung produced by dark current elec-
trons generated in the gun and striking the walls of the ac-
celerator and vacuum system downstream.

The increase in photo-cathode peak field in the planned
machine, and its associated increase in dark current, makes
the removal of the anticipated on-axis Bremsstrahlung an
important lattice design consideration. The dog-leg and
chicane geometries are examined here. We investigate the
designs shown in Fig. 2. Both the dog-leg and chicane
beamlines offer methods to shield radiation on the linac
axis, while terminating dispersion-free ($\eta = \eta' = 0$). While
the dog-leg design offsets the $\gamma$-ray beam from the
linac axis, and offers better potential for shielding, it is less
compact, requires strong focusing, and is operationally less
robust than the chicane. The chicane also has the advantage
that it can be disabled to allow straight through operation
if desired. While either lattice may be used for bunch com-
pression, this design focuses on emittance preservation.

To investigate the effect of coherent synchrotron radia-
tion (CSR) on emittance in these two cases, phase space
distributions were taken from PARMELA simulations of the
linac and fed into the code ELEGANT [11]. In the simul-
ation of both systems a quadrupole triplet is inserted after the
final linac section for proper matching into the bend lattice.
Two more sets of focusing triplets follow, the last providing
the final focus to the IP. The simulated beam sizes and final
focus configuration space is shown for the dog-leg geo-
metry in Fig. 3. The final bend plane ($x'$) emittance increases
slightly with inclusion of CSR in the simulation from 1.4
to 1.9 $\mu$m, rms. This growth can be seen as an asymmetric
tail in the configuration space.

Two different chicane geometries were simulated, the
first using 2 meter radius of curvature, 15° bends, and the
second using 3.09 meter radius and 7° bends. In each case
a 15 cm drift is set between the center magnets for insertion
of on-axis shielding material. The final focus configuration
space for each case is shown in Fig. 4. In the case with
larger bend angles there is significant CSR induced emitt-
ance growth to 3.2 $\mu$m, while for the smaller chicane, no
emittance growth is observed. The advantages of chicane
beamlines mentioned above and effective emittance pres-
ervation of the small chicane motivate use of this design over
the dog-leg.

**Figure 1:** PARMELA simulation showing the horizontal
emissance and rms beam size in the photo-gun and three
following traveling-wave sections.

**Figure 2:** Dog-leg and chicane geometries studied in ELE-
GANT simulations. Dimensions are in cm.
ALIGNMENT AND JITTER

As mentioned above, rms position and pointing jitter should not exceed roughly 20% of respective bunch dimensions at the IP to avoid appreciable decrease in the photon source brightness. In the cases considered here, the IP sizes are $\sigma_x = 20\mu m$, and $\sigma_x' = 0.2\mu rad$, indicating a desired jitter below $4\mu m$ and $40\mu rad$, respectively.

A series of ELEGANT simulations has been performed to determine the effect of various random errors on the beam first and second moments at the IP. Jitter in beam position and pointing at the lattice entrance, ground motion induced jitter in magnet position, and magnet misalignments were all simulated in batch runs of 400 to give 5% statistics on the resulting jitter figures, summarized in Table 1. The simulations show that beam pointing stability from the accelerator is required to be on the order of 1$\mu rad$. This can be accomplished with $10^{-3}$ linac energy jitter and steering due to misaligned elements kept on the order of 1 mrad.

<table>
<thead>
<tr>
<th>Varied Input Parameter</th>
<th>IP Jitter</th>
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<tbody>
<tr>
<td>$\sigma(x) = 12\mu m$</td>
<td>$\sigma(x) = 3\mu m$</td>
</tr>
<tr>
<td>$\sigma(x') = 1.5\mu rad$</td>
<td>$\sigma(x') = 6\mu rad$</td>
</tr>
<tr>
<td>1$\mu$m magnet offsets</td>
<td>$\sigma(x) = 3.6\mu m$</td>
</tr>
<tr>
<td></td>
<td>$\sigma(x') = 2.4\mu rad$</td>
</tr>
<tr>
<td>250$\mu$m magnet misalignment</td>
<td>negligible $\varepsilon$ increase</td>
</tr>
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REFERENCES