AN OPTIMIZED X-BAND PHOTOINJECTOR FOR THE LLNL MEGA-RAY PROJECT*

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Abstract

We present an optimized 5+$\frac{1}{2}$ cell, X-band photoinjector designed to produce 7 MeV, 250 pC, sub-micron emittance electron bunches for the LLNL Mono-Energetic Gamma-ray (MEGa-ray) light source. This LLNL/SLAC collaboration modifies a design previously demonstrated to sustain 200 MV/m on-axis accelerating fields [1]. We present the photoinjector operating point, optimized by scaling beam dynamics from S-band photo-guns and by evaluation of the MEGa-Ray source requirements.

INTRODUCTION

The MEGa-ray project currently under construction at LLNL is a Compton scattering-based light source that collides a 250 MeV, high brightness electron beam with a Joule-class, 532 nm laser pulse to generate narrow bandwidth, high peak and average brilliance γ-rays. The facility will pursue nuclear photo-science applications based on Nuclear Resonance Fluorescence (NRF) such as isotope resolved, material detection, imaging, and assay. The γ-ray source figure of merit for many of the planned applications is number of photons per second within a given ~eV width NRF resonance. In addition, it is desirable to minimize the number of off-resonance photons to reduce experimental noise sources, total radiation dose, and enable advanced applications and detection methods.

The need for high flux, narrow bandwidth γ-rays places stringent requirements on the driving electron beam. For the Compton source, these requirements motivate the use of small laser and electron beam sizes, σ_x, at the interaction point (IP) to increase flux, yet maintain a small normalized beam divergence, $\gamma\sigma_{x'}$, to decrease the bandwidth of the γ-rays. Given the light source metric, $N_\gamma/eV/sec$, the average transverse brightness, $\frac{N_e f_{rep}}{\varepsilon_n^2}$, where f_{rep} is the pulse repetition frequency, should be maximized.

Here we investigate the beam dynamics of an X-band photoinjector, with the goal of maximizing the parameter Q/ε_n^2 for the single electron bunch. The optimization of an rf photoinjector design usually requires a time intensive search of a large parameter space. This involved process must include rf and magnet design calculations and multi-particle simulations. It is very convenient therefore, to begin a design by scaling either charge or rf frequency (or both) from a previously optimized design using the relevant transverse and longitudinal dynamics equations.

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BEAM DYNAMICS

Previous analysis of photoinjector scaling [3] has shown that a robust frequency scaling exists, in which the normalized rf vector potential, $\alpha = eE_0/2k_{rf}m_ec^2$, where E_0 is the peak accelerating electric field and k_{rf} the rf wavenumber, is held constant. This model scales the bunch charge, and all length dimensions linearly with rf wavelength, λ_{rf}, including the beam emittance. Thus, for a single bunch, the figure of merit Q/ε_n^2 scales as $1/\lambda_{rf}$.

For an X-band photoinjector, our design is forced by rf breakdown limitations to hold the peak accelerating field to approximately 200 MV/m, and therefore limit $\alpha \lesssim 1$. The design described here therefore has much in common with low-α, integrated injector type designs such as the LANL AFEL injector [4], or the UCLA plane-wave transformer [5]. On the other hand, this injector is a split design with a 7 MeV gun, emittance compensation in a drift section, and proper matching onto the invariant envelop in the first linac section. Strict wavelength scaling of an integrated design is therefore not applicable. Instead, we examine the consequences of decreasing α in the beam dynamics of a split injector, and scale beam parameters from the well developed 'LCLS working point' [6] ($E_0 = 120$ MV/m at S-band) to X-band, with $E_0 = 200$ MV/m. To simplify the analysis, we assume the wavelength dependence, $\alpha \propto \lambda_{rf}^{1/2}$, which approximately fits the two points of interest.

Longitudinal Motion

Following the analysis of Kim [7], at the photocathode ($\gamma_0 \approx 1$ and $\phi = \phi_0$), particles initially gain energy at a rate $d\gamma/dz \approx 2\alpha k_{rf}\sin(\phi_0)$ and slip significantly in phase while the particle is nonrelativistic. As energy increases, the phase slippage is arrested and an asymptotic value is reached. An approximate expression for this asymptote is found by Kim [7],

$$\phi_\infty = \frac{1}{2\alpha\sin\phi_0} + \phi_0. \quad (1)$$

As one might expect, the amount of phase slippage increases as α decreases. In addition, a transverse emittance is induced due to the phase dependence of the radial force applied by the rf fields. This *rf emittance*, ε_{rf}, is minimized when the structure exit phase is $\pi/2$, and away from the minimum increases as $\varepsilon_{rf} \propto |\cos\langle\phi\rangle|$.

An optimized design should therefore seek $\phi_\infty = \pi/2$. Substitution in Eq. 1 shows the condition the initial launch phase should meet,

$$\alpha = \frac{1}{(\pi - 2\phi_0)\sin\phi_0}. \tag{2}$$

Thus, we should expect the optimal launch phase to decrease as α decreases, and in fact there is a minimum ($\alpha \approx 0.89$) below which there is too much phase slippage to produce $\phi_\infty = \pi/2$ and minimize the rf emittance. This effect is seen in PARMELA simulations varying the

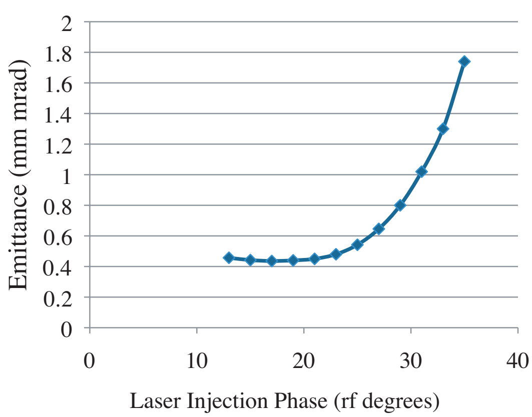

Figure 1: Simulated normalized emittance of the beam transported from the photo-gun through the drift and first travelling wave section versus launch phase. The optimum is significantly lower than high-α designs.

beam launch phase in the X-band photoinjector, as shown in Fig. 1. Here the best emittance is produced by injecting at roughly 18° ahead of the rf zero crossing, significantly lower than the optimum for high-α S-band guns (typically $\sim 30°$).

In considering an electron bunch as opposed to single particles, it is clear that the RMS bunch length, σ_z, must scale with λ_{rf} in order to maintain a constant bunch length as measured in rf degrees, σ_ϕ, and in turn, constant rf curvature induced energy spread acquired in the linac. Because the Compton source performance is very sensitive to energy spread, we enforce the scaling, $\sigma_z \propto \lambda_{rf}$, regardless of the chosen field strength scaling. Given this bunch length scaling and constant injector exit energy, we can ensure that undesired bunch lengthening effects due to longitudinal space-charge forces are not present by preserving the peak beam current, $I = \text{constant}$, and therefore, $Q \propto \lambda_{rf}$.

Transverse Motion

The scaling of the transverse beam dynamics can be deduced by examining the RMS transverse envelope equation,

$$\sigma_r'' + \frac{\gamma'}{\gamma}\sigma_r' + k_\beta^2\sigma_r = \frac{I}{\gamma^3 I_0 \sigma_r}. \tag{3}$$

The transverse dynamics are preserved by equal scaling of the space-charge defocusing (imaginary) wave number, given by

$$\kappa_{SC}^2 = \frac{I}{\gamma^3 I_0 \sigma_r^2} = \frac{c}{\gamma^3 I_0} \cdot \left(\frac{Q}{\sigma_z \sigma_r^2}\right), \tag{4}$$

with the external focusing wave number, k_β^2. For rf focusing, we have

$$k_\beta^2 \propto \frac{F_{rf}}{r} = \frac{e}{2}\frac{dE_z}{dz} \propto \frac{E_0}{\lambda_{rf}}. \tag{5}$$

Since we wish to consider the scaling, $E_0 \propto f^{1/2}$, we see from Eq. 5 that

$$k_\beta^2 \propto \frac{1}{\lambda_{rf}^{3/2}}, \tag{6}$$

and therefore, the transverse spot size must scale as

$$\sigma_r \propto \lambda_{rf}^{3/4}. \tag{7}$$

The starting point for optimization of the X-band working parameters uses a 1.6 cell, S-band photo-gun and SLAC-type traveling wave accelerator sections to produce the electron beam. The parameters of the S-band design are loosely based on the LCLS working point, and produce a final simulated emittance of 0.6 mm mrad (rms, normalized) for 1 nC of beam charge.

PHOTOINJECTOR DESIGN

The X-band photoinjector is based on a 5.5 cell design developed by A. Vlieks at SLAC [1, 2]. Improvements to the original rf design include increased mode separation, elliptical irises, a dual-feed racetrack coupler and optimized coupling β [8]. The 7 MeV beam exiting the gun is injected into a T53 type X-band traveling wave structure, which was developed and extensively tested at SLAC for high gradient operation with low breakdown rates [9].The gun, drift section, and T53 accelerator layout is shown in Fig 2.

To model the electron beam from the photo-cathode through the linac the code PARMELA has been used. The results have been benchmarked against the codes GPT and ASTRA with good agreement found between the codes. The initial set of parameters established using the scaling results was optimized in simulations incorporating the field maps for the Mark 1 photo-gun, solenoid, and T-53 section. The optimized input parameters are given in Table 1. The peak accelerating field used in the photo-gun was based on the performance of the Mark 0 gun. The T-53 accelerating gradient was set based on the expected amount of rf power

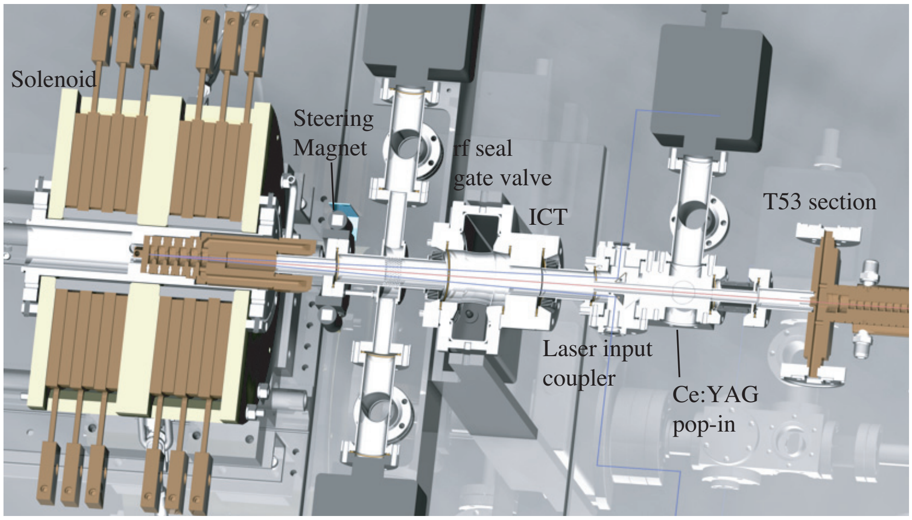

Figure 2: CAD Rendering of photoinjector beamline.

Table 1: Working Point Parameters for the X-band Photoinjector

Parameter	Value
Gun peak field	200 MV/m
T-53 gradient	70 MV/m
Cathode to T-53 distance	80 cm
Charge	250 pC
Laser temporal	8x 200 fs FWHM, 275 fs spacing
Laser spatial	$\sigma_r = 0.55$ mm, $r_{cut} = 0.46$ mm
Injection Phase	20°
Intrinsic emittance	0.9 μm per mm
Final emittance	0.35 μm, rms, norm.

delivered to each section. The simulations assume a cathode laser consisting of a train of 8 Gaussian pulses with temporal duration of 200 fs FWHM spaced by 275 fs. The resulting temporal profile is approximately 2 ps in duration. The laser pulses are Gaussian spatially with $\sigma_r = 0.55$ mm, but with a hard cut on the distrbution at $r = 0.46$ mm.

The simulated evolution of the horizontal rms size and emittance through the linac for the parameters in Table 1 are shown in Fig. 3. In this simulation there is a thermal distribution of velocities of the particles emitted from the cathode that corresponds to an intrinsic emittance of 0.9 μm, rms per mm of laser spot radius. As the figure shows, the horizontal emittance reaches a minimum value after roughly 2 T-53 sections of 0.35 μm, rms.

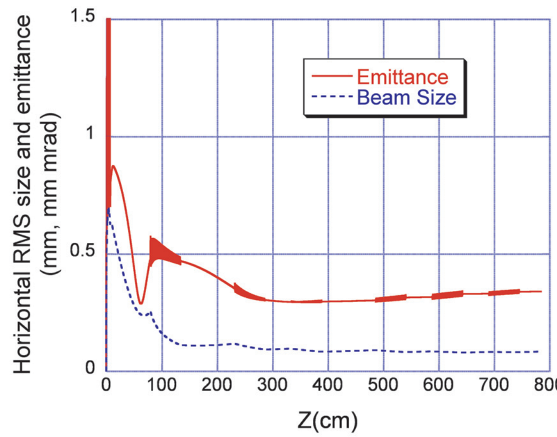

Figure 3: PARMELA simulation of the rms horizontal beam size and emittance in the photoinjector and linac

REFERENCES

[1] A. Vlieks, in High Energy Density and High Power RF: 5th Workshop,Vol. CP625, AIP, 2002, p. 107.

[2] A. Vlieks, in High Energy Density and High Power RF: 6th Workshop,Vol. CP625, AIP, 2003, p. 358.

[3] J. Rosenzweig and E. Colby, in Advanced Accelerator Concepts: 6th Workshop, Vol. 335, AIP Conference Proceedings, 1995, p. 724.

[4] R. Wood, *et. al.*, Nucl. Instrum. Meth. Sec. B, Vol. 79, p. 800 (1993).

[5] X. Ding, *et. al.*, in Proceedings of the 1999 Particle Accelerator Conference, 1999, p. 2021.

[6] M. Ferrario, *et. al.*, in Proceedings of the ICFA Advanced Accelerator Workshop on the Physics of High Brightness Beams, Los Angeles, 2000, p. 534.

[7] K. J. Kim, Nucl. Instrum. Methods Phys. Res., Sect. A 275 (1989) 201.

[8] R. A. Marsh, *et. al.*, TUP023, *these proceedings*.

[9] C. Adolphsen, in Proceedings of the 2003 Particle Accelerator Conference, IEEE, 2003, p. 668.