OPTIMAL SCALED PHOTOINJECTOR DESIGNS FOR FEL APPLICATIONS*

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Abstract

Much of the research and development surrounding the effort to create X-ray FELs based on the SASE process has centered on the creation of ultra-high brightness electron beam sources. The sources for existing short wavelength FEL designs, which employ RF photoinjector technology, have all been specified to contain 1 nC of charge. We show, by scaling existing designs, that this constraint causes the maximum beam brightness to be found when the rf wavelength is shortened to X-band. If, instead of holding the charge constant, we assume a certain RF wavelength device and then scale the charge, notable improvements in the beam brightness, and thus the FEL performance, are found. Charge scaling assumes that the density and aspect ratio of the beam stays constant as the charge is changed. If we relax the requirement of a constant aspect ratio in order to maximize the beam current and brightness by shortening the beam pulse, we find that the pulse lengthening due to space charge eventually brings this effort to a stop. The results of this investigation and their impact on SASE FEL design is discussed.

1 PHOTOINJECTOR SCALING LAWS

The optimization of rf photoinjector performance can be can be understood most straightforwardly by the scaling, in frequency, and in charge, of the beam dynamics – beams are simply brighter when produced in the short rf wavelength, high field environment. A strict scaling of photoinjector design parameters has been developed by Rosenzweig and Colby[1], allowing the understanding of systematic variations of both charge and wavelength. The scaling laws for maintaining optimum operation of an rf photoinjector while changing the rf wavelength λ in the design are summarized as follows:

1) The accelerating and focusing field amplitudes must scale as the inverse of the wavelength,

$$E_0 \propto \lambda^{-1},\ B_0 \propto \lambda^{-1}. \qquad (1)$$

2) In this change, the natural scaling of the beam parameters is then

$$\sigma_i \propto \lambda,\ Q \propto \lambda. \qquad (2)$$

This scaling rigorously produces (including all space-charge, rf, chromatic and thermal effects), an emittance which scales as

$$\varepsilon_n \propto \lambda. \qquad (3)$$

Note that this "natural" wavelength scaling implies that at shorter wavelength, the charge and the bunch length both scale downward as λ, yielding a design current which is independent of λ. Thus the beam brightness scales naturally as

$$B \equiv \frac{2I}{\varepsilon_n^2} \propto \lambda^{-2}. \qquad (4)$$

If one constrains the charge Q needed for a given application, however, one may not use natural scaling alone, one must rescale the charge to re-obtain theinitial charge after first scaling naturally in wavelength. This is accomplished by keeping the beam density (proportional to the beam plasma frequency squared) constant,

$$\sigma_i \propto Q^{1/3}. \qquad (5)$$

Under these circumstances, current scales as $I \propto Q^{2/3}$, the space charge contribution to the emittance follows $\varepsilon_{sc} \propto Q^{2/3}$, while the rf/chromatic contribution scales as $\varepsilon_{rf} \propto Q^{4/3}$. Assuming these two sources of emittance are independent (which is approximately valid), the full emittance then scales in charge as

$$\varepsilon_n = \sqrt{aQ^{4/3} + bQ^{8/3}}. \qquad (6)$$

2 SCALING OF SPECIFIC DEVICES

The coefficients a and b in Eq. 6 are properties of a given type of device. At UCLA[2], we have developed two types of high-brightness rf photoinjectors, a split photoinjector consisting of a high-gradient 1.6 cell gun[3] followed by a drift and a low gradient plane-wave transformer (PWT) post-acceleration linac[4], and an integrated, low gradient device, the 10+2/2 cell PWT photoinjector[5]. A direct comparison of the advantages and disadvantages of these designs is given in Ref. 6.

As scaling to short rf wavelength implies high fields (according to Eqs. 1), the high gradient gun and its focusing scheme cannot easily be scaled. Thus we

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concentrate on the PWT photoinjector in this paper, which is now proposed as a serious candidate for development at short rf wavelength.

The characteristics of the PWT photoinjector have investigated by computer simulation scans of charge[6]. It is found that for this 2856 MHz ($\lambda = 10.49$ cm) device

$$\varepsilon_n = \sqrt{1.34 \cdot \tilde{Q}^{4/3} + 0.11 \cdot \tilde{Q}^{8/3}}\,, \qquad (7)$$

with charge $\tilde{Q}$ in nC and rms normalized emittance in mm-mrad. To obtain a full scaling of the expected performance for arbitrary charge and rf wavelength, therefore, we write the emittance as

$$\varepsilon_n = \tilde{\lambda}\sqrt{1.34 \cdot \left(\frac{\tilde{Q}}{\tilde{\lambda}}\right)^{4/3} + 0.11 \cdot \left(\frac{\tilde{Q}}{\tilde{\lambda}}\right)^{8/3}} \qquad (8)$$

where $\tilde{Q}$ is again in nC and $\tilde{\lambda} = \lambda(\mathrm{cm})/10.49$. This expression implies that the emittance is optimized for a certain charge at a given rf wavelength, as at very short wavelength, the rf emittance asserts itself very strongly, and the advantages of running at high accelerating gradient are lost. Differentiation of this expression with respect to λ

$$\frac{\partial \varepsilon_n}{\partial \tilde{\lambda}} = 0 \rightarrow \tilde{\lambda} = 0.286\,, \qquad (8)$$

gives an optimum PWT operating wavelength of 9.97 GHz for 1 nC operation, which is the benchmark charge for SASE FEL designs.

The simulations also give the scaling of the bunch length with charge at S-band,

$$\sigma_z = 0.69 \cdot \tilde{Q}^{1/3}\ (\mathrm{mm}), \quad \text{or} \quad \sigma_t = 2.3 \cdot \tilde{Q}^{1/3}\ (\mathrm{psec}). \quad (9)$$

We thus can arrive at a final expression for the brightness

$$B\left(\mathrm{A/m^2}\right) = \frac{347 \cdot \tilde{Q}^{2/3}}{\tilde{\lambda}^2\left(1.34 \cdot \left(\frac{\tilde{Q}}{\tilde{\lambda}}\right)^{4/3} + 0.11 \cdot \left(\frac{\tilde{Q}}{\tilde{\lambda}}\right)^{8/3}\right)}. \quad (10)$$

Since the current is not an explicit function of the wavelength, the brightness for a constant charge is optimized at the same point as the emittance.

3 X-BAND INJECTOR OPTIMIZATION

The PWT photoinjector was first proposed as a good candidate for a scalable type of high-brightness source several years ago[7]. In the intervening time, a UCLA/DULY Research/LLNL-UCD collaboration has been investigating the physics and engineering issues associated with this scaling. One of the issues surrounding this project is the choice of rf frequency between 3 and 4 times the S-band PWT (8.56 and 11.42 GHz), set by the availability of high power rf sources. Note that the brightness is optimized, according to Eq. 9, at a frequency is directly between the two X-band frequencies we have considered for development.

In order to illuminate the possible differences between the two choices of λ, as well as the superiority of short versus long wavelength operation, we plot of these dependences are shown for 2.856 GHz, 8.6 GHz, and 11.4 GHz operation below. The emittances and brightnesses shown in Figs. 1 and 2 also include a small contribution of emittance growth due to multipole field errors in the PWT (due to cooling/disk-support rods)[8].

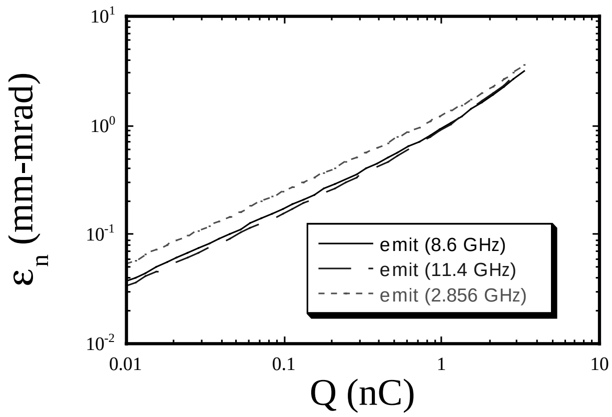

Figure 1. Emittances for scaled PWT photoinjectors as a function of charge.

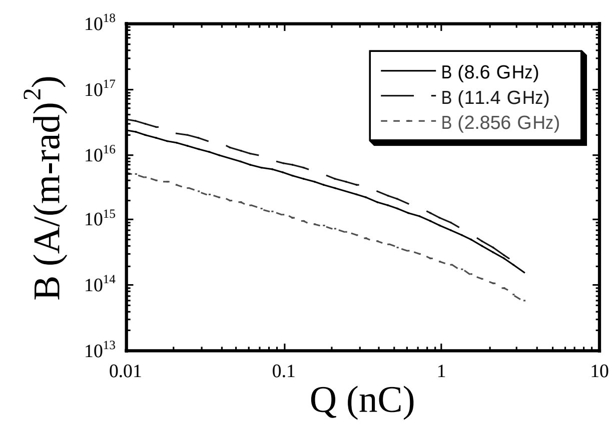

Figure 2. Beam brightness for scaled PWT photoinjectors as a function of charge.

It can be seen that the 8.6 and 11.4 GHz results are nearly identical for 1 nC operation. Also, the beam brightness in both X-band cases is better than that achieved at S-band by roughly an order of magnitude. Since the engineering problems (scaling of the solenoid field, cooling rods, rf power needs, dark current intensity at large accelerating fields, etc.) associated with operation at 8.6 GHz are smaller than those at 11.4 GHz[9], the

UCLA/DULY/LLNL development collaboration has decided to proceed with work at 8.6 GHz.

It should be duly noted that the operation of the device is better in X-band all cases regardless of charge for any high brightness beam case. It would perhaps be better to run very high charge, low emittance beams (*e.g.* for wake-field accelerator drivers) at long rf wavelength, meaning S- or even L-band. This is in fact the case for the facilities which demand this type of beam (ANL at L-band, CLIC at S-band). For high brightness, lower charge (<2 nC) beams, however, these scaling studies have pointed towards X-band as the most promising direction.

4 X-BAND INJECTOR DEVELOPMENT

The UCLA/DULY/LLNL collaboration has completed a Phase I SBIR project, which has analyzed the feasibility of constructing an ultra-high brightness 8.6 GHz photo-injector based on the PWT design principle. In this study[9], the problems of scaling the magnetic field (solved by use of a permanent magnet design) and the cooling rod geometry (the effects of induced multipole fields were understood) were addressed. In addition, the cold testing of an 11.424 GHz, 10+2/2 cell device was undertaken to show the robustness of the cavity design (the mode separation between the π–mode and the $10\pi/11$–mode was shown to be 18 MHz), and good comparison to the results of the 3D EM field simulation program GdfidL was demonstrated. In the PWT design, in order to solve the problem of reflected power from the standing wave structure during filling, a split structure which allows cancellation of reflected power has been proposed. For more information on this program, see Ref. 9.

In addition, UCLA and SLAC has been exploring a hybrid design based on a standing wave 1.5 cell gun “married” to a travelling-wave section, with external coupling accomplished through the joining cell. This design would eliminate both the cooling rods (and their associated engineering problems) as well as the reflected power associated with a pure standing wave structure.

With these possible methods of scaling integrated photoinjector technology to X-band operation, it seems likely that beam brightnesses which are significantly higher than those foound in today’s sources can be achieved. The X-band photoinjector would be an important component of the proposed[10] ultra-short wavelength SASE FELs currently under development[11].

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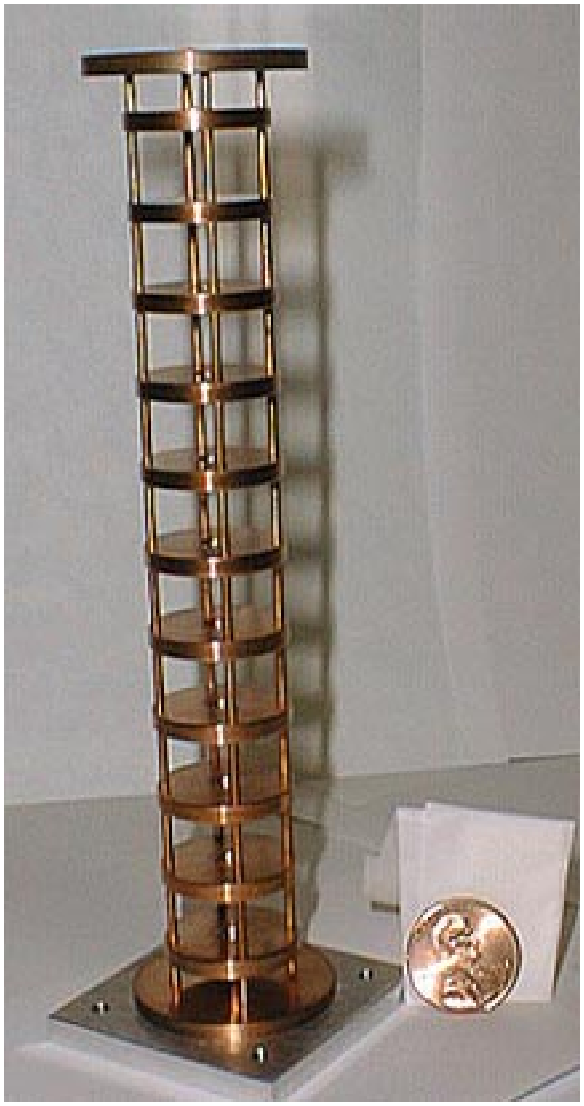

Figure 3. Cold test model (with outer wall removed) of 11.424 GHz, 10+2/2 cell PWT photoinjector.

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