

EMITTANCE MEASUREMENTS OF THE ADVANCED PHOTON SOURCE PHOTOCATHODE RF GUN*

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Abstract

The Advanced Photon Source (APS) photocathode rf gun is the primary beam source for the APS Low-Energy Undulator Test Line (LEUTL) free-electron laser (FEL) experiment. In the current operating regime of LEUTL, peak current has been the dominant factor in determining FEL performance. As LEUTL's operational wavelength is reduced, however, the beam emittance will play an increasingly important role. Thus, efforts are underway to more completely characterize, control, and predict photocathode gun performance. This paper reports the results of recent emittance measurements using the APS photocathode gun, and comparison of these measurements with simulation.

1 INTRODUCTION

The APS photocathode rf gun (PCgun) has been the primary beam source for a series of self-amplified spontaneous emission free-electron laser (SASE-FEL) experiments at the APS. The APS SASE-FEL experiment has reached its initial goals, by achieving saturated optical power output first in the visible (at 530 nm) and then in the near-UV (at 385 nm) regimes.

To date, the APS SASE-FEL has operated in regimes where the performance is more readily improved by increasing the peak current, rather than by reducing the beam emittance. This has been achieved via the APS linac bunch compressor, which, if the beam is not taken to full compression, does not seriously degrade the beam emittance due to coherent synchrotron radiation (CSR) effects [1].

Future plans for the APS SASE-FEL include pressing to shorter wavelengths and supporting user experiments. In

these projected regimes, it becomes more efficient to raise our figure of merit by decreasing our electron beam transverse emittance. To that end, we are beginning to focus more on detailed measurement of our PCgun performance and performing finer comparisons with simulation.

2 APS LINAC LAYOUT

The APS PCgun itself is a standard SLAC/BNL/UCLA-style gun, consisting of a 1.6-cell rf cavity oscillating in a π -mode, and with an external focusing solenoid following the cavity. We are currently using a copper cathode.

A block diagram of the APS linac is shown in Fig. 1. The APS linac operates at 2856-MHz S-band, and all linac sections are disk-loaded traveling-wave (TW) SLAC-type structures 3 m long. Linac sectors L2, L4, and L5 are powered with a single klystron equipped with a SLED. Linac section L1 (the PCgun capture section) and the PCgun are each powered by a single klystron.

The three-screen emittance measurement areas provide two functions. First, they permit the rapid measurement of the beam emittance and Twiss parameters without requiring any change to the magnetic lattice. Second, via the use of matching quadrupoles immediately upstream of the three-screen measurement areas (not shown in Fig. 1), they can be used to obtain the desired match for the downstream portion of the accelerator.

The bunch compression is adjusted by changing the phase of the L2 linac sector to provide a correlated energy spread on the electron beam; the L2 sector rf power is also adjusted to keep the beam energy constant at the bunch compressor.

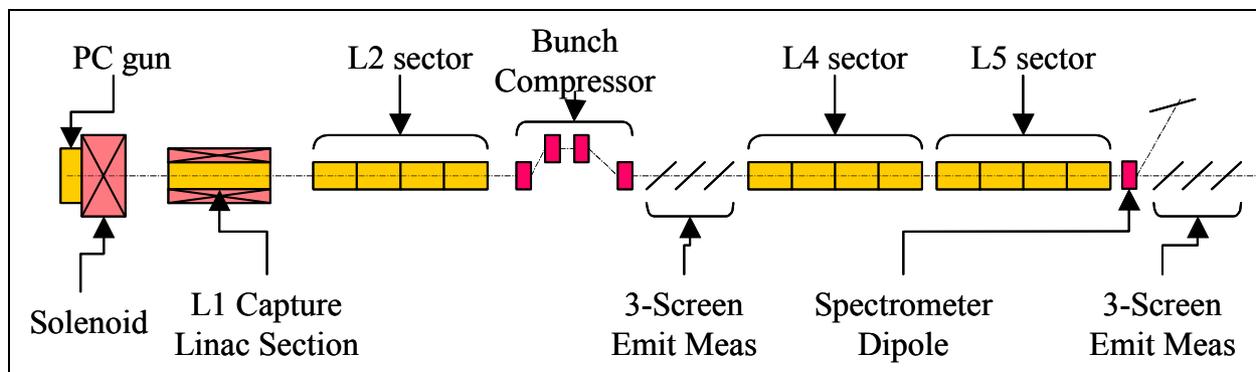


Figure 1: A block layout of the APS linac. Many details have been omitted for clarity.

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3 MEASUREMENTS AND CALCULATIONS

3.1 Measurement Setup

The APS linac was tuned in the following fashion for the measurements presented in this paper.

The PCgun was tuned to have the beam leave the cathode at 40° following the field zero-crossing in the gun. The drive laser beam duration is approximately 1.5 ps (rms) in the UV, and the transverse spot size is a strongly clipped Gaussian with a transverse cutoff at approximately 1.8 mm and a sigma of 1.5 mm.

The above transverse parameters are estimated from the appearance of the beam on a virtual photocathode. It is also possible to use the PCgun solenoid lens to image the cathode plane to a viewscreen located between the gun and capture linac section. When this was done, we observed a dark spot in the center of the electron beam; this dark spot disappears when the drive laser is steered off-center in the gun. The width of this “dead spot” on the cathode is difficult to quantify; however, we estimate its size to be on the order of 1/6 the beam spot width (to the edge), or about 0.3 mm in radius.

The beam energy at the exit of the PCgun is measured by kicking the beam with a steering corrector located within the focusing solenoid and measuring the deflection of the beam on a screen between the solenoid and capture linac section. The measured beam energy under the conditions at which we performed the measurements was 5.2 ± 0.2 MeV. With this gradient and at this launch phase, the bunch charge was 70 pC. Due to the large dark charge of 500 pC, this measurement has a bad signal-to-noise ratio and is accurate to ± 5 pC at best.

The capture linac section acceleration gradient was 7 MV/m, and phased to obtain maximum energy gain through the structure. The L2 linac sector was phased to obtain minimum energy spread at the high-dispersion point in the chicane compressor. (Due to longitudinal wakefield effects, this is several degrees different from the phase required for maximum energy gain.) The beam energy at the exit of the L2 linac sector was 150 MeV.

The beam emittance was measured as a function of PCgun solenoid strength, under the conditions listed above. To perform the emittance measurement the beam was first matched at the bunch compressor 3-screen emittance measurement area, at a given solenoid setting. The beam mismatch parameter is defined as

$$M = \frac{1}{2}(\beta_o \gamma_m - 2\alpha_o \alpha_m + \beta_m \gamma_o), \quad (1)$$

where β , α , and γ are the beam Twiss parameters, and the subscripts “o” and “m” refer to the design and measured values, respectively. For a perfect match, $M=1$ [2].

Once a good match was obtained (defined by having the beam mismatch parameter < 1.05) a final measurement was made of the beam emittance. Then the solenoid was changed to the next setting and the process repeated. We chose the mismatch parameter cutoff at 1.05, because if the beam is mismatched too severely the

measured beam parameters, including emittance, are not measured properly. We empirically find that a mismatch of < 1.05 provides a sufficiently good match for a reliable emittance measurement.

The emittance measurement uses the entire image, summed across (rows, columns) to obtain the true integrated (vertical, horizontal) spot sizes. Ten images are taken at each screen, with background subtraction; bad images (e.g., those with anomalous peak intensities or large size changes) are discarded by the analysis routine. A Monte Carlo simulation is used to generate the error bars shown; as mentioned, sequential measurements typically generate repeatable measurements to within 10% (hard-edge).

3.2 Simulation Setup

The simulation code PARMELA [3] version 2 was used for all particle simulations. The rf fields for the gun were generated via a model of the photocathode rf gun derived from the mechanical as-built drawings of the gun and were calculated using the Poisson/Superfish group of codes [4]. The PCgun solenoid was modeled by both a series of current coils set to closely approximate the on-axis solenoid field, and a Poisson model of the actual solenoid; the final results are almost identical. The TW linac model includes 85 cells plus a half-cell input coupler. Details of the linac model were provided by M. Hernandez of Stanford and SSRL [5]

According to simulation, for a perfectly balanced gun field (i.e. peak on-axis field strengths are the same in the cathode and the full cells) an average on-axis gradient of 45 MV/m yields a beam energy of approximately 5.2 MeV when the beam centroid launch phase is 40 degrees. This corresponds to a peak on-axis field of about 110 MV/m. The beam charge was set to 70 pC and the PARMELA 2-D space charge model was enabled for the simulations. Our solenoid has a measured on-axis maximum field of 14.89 gauss/amp; this ratio was used to set the equivalent solenoid strength in the simulation. The linac gradient was set to 7 MV/m, and the phase was set for maximum centroid energy gain.

The least certain parameters in this simulation relate to the electron beam generation. The drive laser beam has some visible structure, and, as mentioned, the cathode has known regions of poor quantum efficiency. The emission model used for these simulations is uniformly populated azimuthally and has a Gaussian longitudinal density distribution, with sigma of 1.5 degrees and a cutoff of ± 7.5 degrees. The radial distribution is approximated by a lowest-order Gaussian mode with a sigma of 1.5 mm and radial cutoff at 1.8 mm, and no particles with radius < 0.32 mm. This is not the same as a higher-order Gaussian mode distribution.

For these initial series of simulations, the beam was propagated only to 1 m past the exit of the capture linac section. We generally use an alternate simulation code, **elephant** [6], to propagate the beam after the capture linac simulation because of limitations imposed by PARMELA

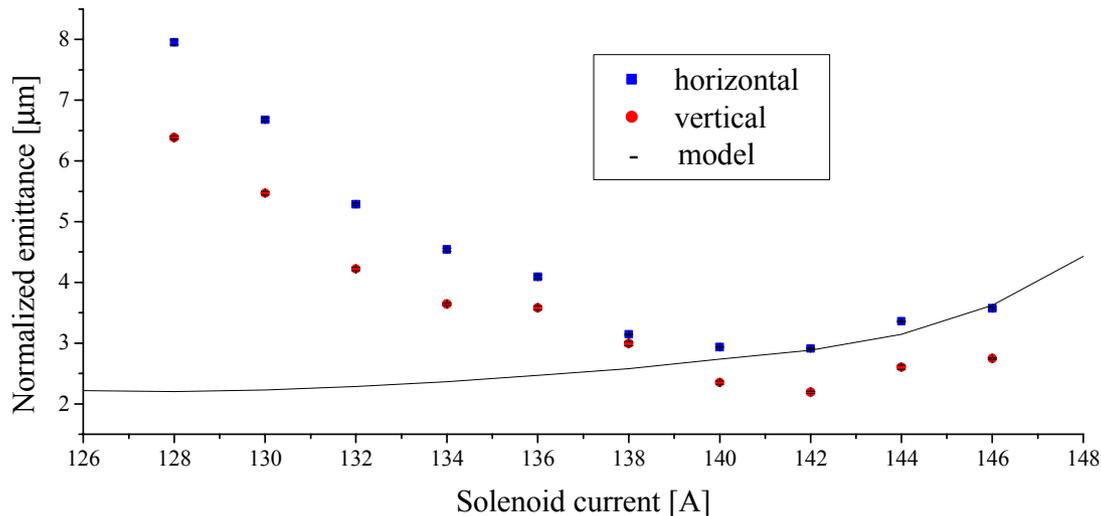


Figure 2: Measured and simulated emittance as a function of PCgun solenoid current. See text for explanation.

(e.g., automatic phasing and optimization are not possible). **legant** is not space-charge capable, however, so we limit our presentation of results to those generated by PARMELA.

4 DISCUSSION OF RESULTS

Fig. 2 is a plot of the measured and simulated beam emittances vs. solenoid current. The measurements were made at the three-screen area immediately following the chicane bunch compressor.

The measured horizontal emittance is consistently greater than the measured vertical emittance. There are several possible reasons for this. First, it may be due to structure on the drive laser beam. Other causes include small solenoid field errors, effects of the rf structure input couplers, and transverse wakefield effects. The discrepancy may be due in small part to CSR effects, as the measurement is performed after the bunch compressor and the bends of the compressor are in the horizontal plane. The camera calibrations have been verified by several different methods, therefore we do not believe camera issues account for the discrepancy.

The comparison between the measured and calculated emittance values is very interesting. The calculated lowest emittance is equal to the (y-plane) lowest emittance to within experimental error, and simulated and actual solenoid settings for minimum emittance differ by only 10%. The solenoid offset may be due to a slightly low estimate of beam charge. The dependence of the emittance upon solenoid current is found to be much stronger in experiment than in simulation, however.

The emittance minimum depends upon the details of the distribution of the beam as it is emitted from the cathode. To first order, simply scaling all dimensions of our launch distribution merely scales the emittance vs. solenoid curve height; the shape of the curve and location of the minimum are not strongly influenced if the initial transverse distribution is scaled, even for as nonideal a beam as this. The much stronger dependence of

emittance upon solenoid in the experiment, then, is almost certainly due to the additional effects of transport through the APS linac. Even at 70 pC, the beam has not fully ceased its emittance oscillations upon exiting the first linac section, and the presence of quadrupoles between the capture linac section and the L2 sector may influence the emittance growth. The alpha and beta Twiss parameters at the end of the capture linac section vary rapidly with solenoid current, so unless we are operating at or close to the minimum emittance point, the beam will be mismatched into its focusing channel.

5 CONCLUSIONS

Our simulations and measurements indicate that, even with a strongly nonideal beam and limited transport model, the results of PARMELA simulations are well-matched to the measured experimental minimum emittance and solenoid setting for the same. There is a strong discrepancy between the measured and calculated change of emittance with solenoid; however, this is most likely due to a very limited transport model in PARMELA and will be addressed in future work.

6 REFERENCES

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