PARMELA VS MEASUREMENTS FOR GTF AND DUVFEL

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Abstract

The particle-pushing PARMELA was used to design the photo-injector beamline of the Linac Coherent Light Source (LCLS) to be built at SLAC in 2005. PARMELA predicts that projected emittances smaller than 1.2 mm.mrad and slice emittance smaller than 1.0 mm.mrad will be achievable for 1nC, 10ps electron bunches with an S-band RF gun and an emittance compensating system. To benchmark PARMELA, comparisons between simulations and measurements for two photo-injector test facilities, the Gun Test Facility (GTF) at SLAC and the Deep Ultra Violet FEL (DUVFEL) at BNL, have been performed. Aspects of the modeling of fields and initial distributions are discussed. The agreement between measured and simulated beam parameters (projected and slice emittance, Twiss parameters) is satisfying. Accordingly, it gives credibility to the extrapolation made for studying the LCLS case. PARMELA also indicates possible improvements in the tuning of those facilities to achieve the LCLS required beam properties.

1 INTRODUCTION

The GTF and DUVFEL photo-injector beamlines are based on a 1.6 cell S-band gun with a copper photocathode, an emittance compensating solenoid and an S-band linac section located approximately 90 cm from the photocathode.

2 MODELING

2.1 Geometry and fields

Solenoid field maps used in the PARMELA simulations were deduced from measurements of B_z along z. The radial component was computed from the $B_r = -r/2 \, dB_z/dz$. The fields of the RF gun and of the traveling wave accelerating section were computed with Superfish.

The energy at the exit of the gun, the first quantity to be compared to match simulations to experiments, depends on injection phase, gun field and gun field balance. The injection phase is known within a few degrees from the zero-crossing determination of charge vs phase measurements. The field balance is measured in cold tests using a network analyzer. The calibration of solenoid field and energy at the exit of the gun can be performed by combining the two measurements :

- beam displacement in the presence of steering coil (requires good calibration of screen and coil)
- rotation of beam restricted to an L-shaped transverse profile by means of a laser mask when reversing polarity of solenoid field

2.2 Pulse

The GTF drive laser is a Nd:glass and delivers Gaussian pulses. The DUVFEL drive laser is a Ti-Saphire which delivers flatter pulses with shorter rise times. The laser profile is measured using a cross-correlator at the DUVFEL and is systematically input in PARMELA for all the DUVFEL simulations. The laser profile is measured with a streak camera at the GTF. As profiles were Gaussian and the streak camera not always available Gaussian distributions were used for the GTF simulations. The transverse profiles were uniform disks unless otherwise specified.

2.3 Thermal emittance

Thermal emittance measurements at the GTF give a 0.3 mm.mrad per mm radius [1]. The DUVFEL measurement gives a 0.6 mm.mrad per mm radius. The measurement technique consists in measuring beam sizes vs solenoid current and is described in [2]. The thermal emittance model used in the simulation consists of Gaussian distributions for the transverse velocities in the two transverse planes.
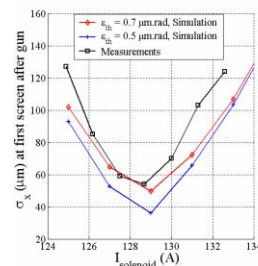

Figure 1. Beam spot sizes vs solenoid current, r_{spot} = 0.75 mm; the simulated curve with a thermal emittance of 0.5 mm.mrad has the curvature of the measured one.

3 GTF

3.1 Experimental conditions

Two series of measurements were performed with 2ps and 4ps FWHM Gaussian pulses. Normalized projected emittances at the location of the first quadrupole are given

in Figure 2 for two different values of thermal emittance (0, 0.4 mm.mrad). The projected emittance shown for the simulations is for the optimum solenoid current.
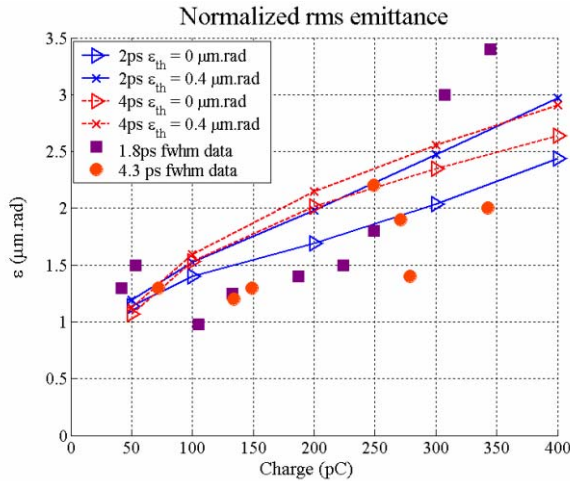

Figure 2. Projected emittance vs bunch charge as measured at GTF for Gaussian pulses, and PARMELA simulation results for the same parameters.

3.2 Results

Figure 2 shows that measurements and simulations are in relatively good agreement. Measured values are slightly below PARMELA results. However, by performing a quadrupole scan with PARMELA, and truncating the tails of the Gaussian at a 5% level for the projected distributions, it was demonstrated with simulations that the emittance fitted from beam sizes is 20% smaller than the rms emittance.

A counterintuitive observation to be made both for the measurements and the simulations is that emittances are in the same range for the 2ps and 4ps pulse cases. The emittance is even smaller for the 2ps case than for the 4ps case when no thermal emittance was included. The stronger bunch lengthening relatively for the 2ps bunch case compared to the 4ps case cannot explain this effect. In figure 3, the simulated slice emittances along the bunch and matching parameters are given for the two bunch lengths of 2 and 4 ps fwhm. The matching parameter ξ is computed from the Twiss parameters (α,β,γ) of individual slices and those of the whole bunch $(\alpha_o,\beta_o,\gamma_o)$. The first column corresponds to the nominal linac gradient of 8.5 MV/m as used in figure2. The second column corresponds to a reduced gradient of 4.5 MV/m. The initial distributions include a thermal emittance of 0.4 mm.mrad. The slice emittances are larger for the 2ps cases however, for the gradient of 8.5 MV/m, the mismatch is much worse for the 4ps resulting in a projected emittance larger for 4ps than for 2ps. With a 4.5 MV/m linac gradient the mismatch of the core of the bunch is improved for both cases. With the slice emittance remaining unchanged the projected emittance is better for the 4ps case.
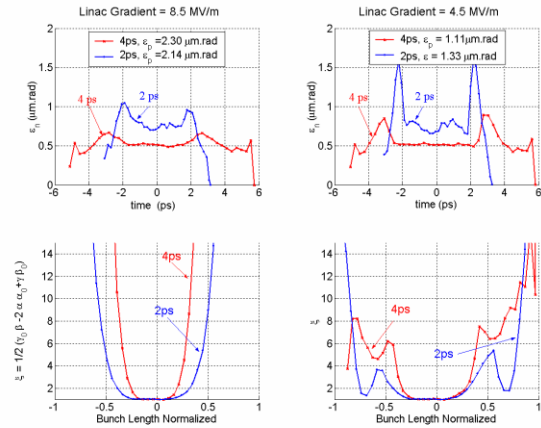

Figure 3. Slice emittance and matching parameters.

3.3 Improvements in emittance

With Gaussian bunches, projected emittances close to the LCLS specifications of 1.2 mm.mrad for 100A beams, can be measured at the GTF. Reducing the linac gradient from 8.5MV/m to 4.5MV/m the projected emittance should be close to 1.3 mm.mrad at 200pC, according to PARMELA. Simulations indicate the emittance is very sensitive to the solenoid field and the emittance measurement becomes sensitive to space charge effects. Parmela also indicates that keeping the gradient at 8.5MV/m but reducing the injection phase from 37 degrees down to 25 degrees the projected emittance should be of 1.46 mm.mrad.

The pulse stacker now installed at the GTF [4] will produce flat top, 8ps fwhm, with 0.85 ps rise time distributions. With flat top distributions, the projected emittance will be closer to the slice emittance value shown in figure 3.

4 DUVFEL

4.1 Experimental conditions

Achieving slice emittances smaller than 1 mm.mrad is an important milestone for demonstrating the feasibility of the LCLS photo-injector characteristics. A SLAC/BNL collaborating team has initiated this effort. The DUVFEL facility is described in [2,5]. The slice emittance measurement is done by inducing an energy chirp (energy–time correlation) using the zero-crossing voltage from the 4th linac section of the DUVFEL beamline. The time profile is then projected horizontally by means of a bend magnet. A quadrupole scan is done on the vertical beam size. More details are given in [5].

The beam emittance and Twiss parameters are reconstituted at the scanned quadrupole location and transported back to the end of the 2nd linac section where they are compared to PARMELA results.

4.2 Results

Measurements and PARMELA simulation results are are compared for a 200pC, 3ps fwhm pulse. The

transverse distribution used in the simulations is a uniform disk with diameter 1.5 mm containing 9500 particles on top of which a uniform disk of radius 0.15 mm containing 500 particles centered on the axis is superimposed. This additional disk was introduced to model a high emission region (hot spot) present when the experiment was performed. A small 0.3 mm.mrad thermal emittance was used in the simulations. Results are very similar when using a 0.5 mm.mrad value for the cases studied.

In figure 4, the beam transverse parameters are given for three solenoid settings. The Twiss parameters are in fairly good agreement. The slice emittances are in good agreement for the second solenoid case. The data analysis was made difficult by the presence of the hot spot which generated a two–stream beam at the spectrometer screen. A truncation of 10% above noise level was applied. More details on data analysis are given in [5].
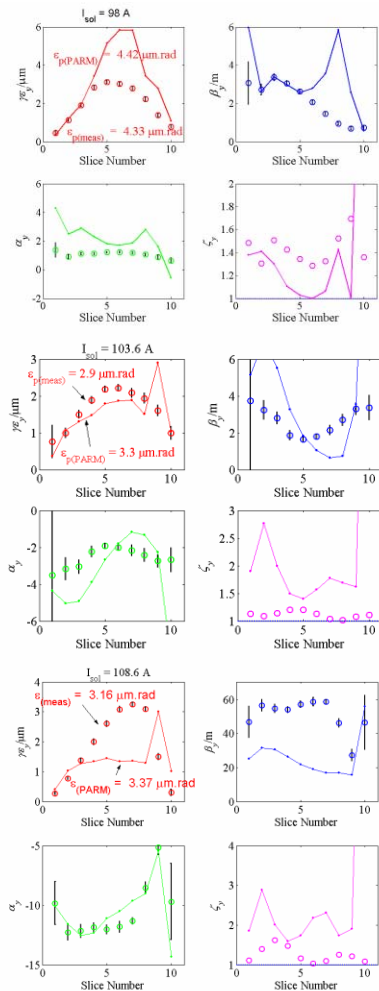

Figure 4. Slice emittance, Twiss parameters and matching parameters for a 200pC, 3 ps fwhm bunch for 3 different solenoid values; experiment (circles) and Parmela (lines), both for 10 slices.

4.3 Analysis

Non-uniform emission from the cathode produced the large slice emittances observed in the experiment. Various emission profiles were used in PARMELA simulations and are presented in figure 5. During the experiment, an attempt was made to remove the hot spot with a shadowing mask inserted into the laser beam. Only a modest improvement in projected and slice emittances was obtained. PARMELA simulation confirms this effect. Preliminary work has been done to specify requirements on emission spot uniformity, experimentally [6] and with simulations [3].
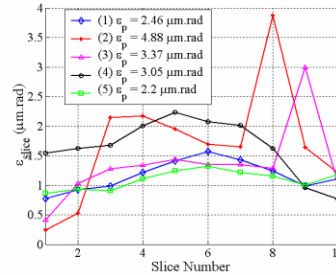

Figure 5. Slice emittance from PARMELA with different distribution for the 1.5 mm diameter emission spot and I_{sol} = 104 A; (1) uniform disk, (2) high emission region r=0.15mm, 10% out of 10k particles, (3) same as (2) with 5%, (4) hole of r =0.15 mm in uniform disk, (5) same as (1) but I_{sol} = 116 A.

5 CONCLUSION

Progress has been made in simulating photo-injectors with PARMELA and fairly good agreement has been obtained. Such comparisons are very valuable to improve the tuning of the photo-injector facilities and to understand possible error in the measurements. The results presented in this paper are very promising and the effort will be pursued.

6 REFERENCES

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