Optimizing the Bunching Process in the FEL Photo-injector

P. Piot, G.A. Krafft, *Jefferson Lab*

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Abstract. This note describes recent achievement in setting up the longitudinal dynamics in the FEL injector. The method consists of measuring the so-called "M_{55}" transfer map pattern and comparing it with an ideal "M_{55}" pattern computed via numerical simulation. The results presented in this note are the most recent based on the 320 keV photo-emission gun for a charge per bunch of 60 pC.

I Introduction: Validity of Phase-Phase Correlation Measurement

The phase-phase correlation method consists of varying the photocathode drive laser phase and measuring, for each phase, the time-of-flight (TOF) at the location of a downstream 1.497 GHz pill-box pickup cavity. Each bunch is therefore emitted at a different phase and the TOF of its centroid is measured. In such measurement a bunch can be considered as a macroparticle and single particle beam dynamics is applied to its centroid. Hence such TOF measurement potentially provides information on the phase-phase transfer function between the photocathode and the pickup cavity. Unfortunately in the case of the FEL injector, the pickup cavity is located in a dispersive region which renders the TOF dependent on other parameters [1], in particular to RF-induced steering which depends on the injection phase of the bunches in the cryounit accelerating section. Hence at the cavity location, the phase of arrival of the bunch centroid emitted at the photocathode surface with initial phase ϕ_i with respect to the "zero-crossing" bunch (i.e. the bunch for which the TOF is zero by definition) is:

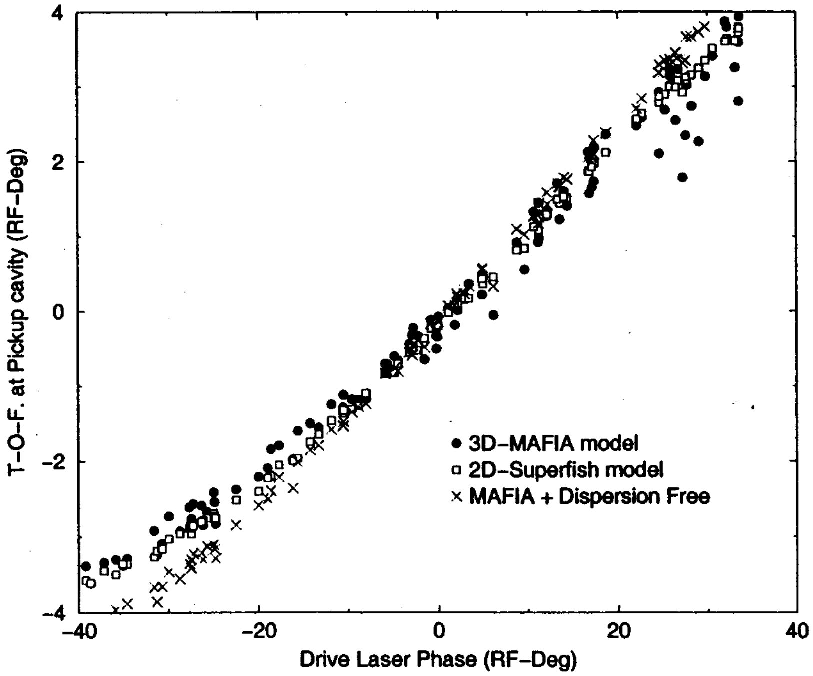

Figure 1: "M_{55}" transfer map generated with PARMELA for (1) different cavity model (3D mafia and 2D superfish) at the pickup cavity located in the injection chicane and (2) for the case where the pickup cavity is located downstream the cryounit after a drift in a dispersion-free region.

$$\phi_f = \phi_{RF} + M_{55}^{i \to f} \phi_i + M_{56}^{i \to f} \delta_i \tag{1}$$

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[1] This was brought to our attention by D. Douglas, see also Ref [3] p. 3.

where ϕ_{RF} is the TOF contribution due to the RF-induced steering: $\phi_{RF} = M_{51}^{c\to f} x_c + M_{52}^{c\to f} x'_c$; c, i, and f are respectively the location of the cryounit exit, the photocathode surface, and the pickup cavity.
The RF steering is due to (1) the RF transverse equation of motion in an accelerating cavity, and (2) the forward power and high order mode coupler induced kicks. First we have compared phase-phase correlations generated via numerical simulation using PARMELA with two distinct models of the CEBAF cavity: a 3D MAFIA model (which includes the couplers effects) and a 2D-cylindrical symmetric SUPERFISH model. The results are presented in figure 1, which shows that there is not significant difference between the generated transfer map except some broadening in the case the of the map generated using the 3D MAFIA model which incorporates the RF-kick due to couplers. In the same figure we also compare the phase-phase correlation pattern generated if the cavity was located downstream the cryounit after a drift of similar length to its present location in the injector chicane; since the calculation corresponds to a a dispersion free drift, this transfer map give insights on the effects of the ϕ_{RF} in the above equation. We can clearly observe that this effect does not wash out the TOF variation due to energy changes; a small effect is observable for large drive laser phase.
Because there might be some effect of the ϕ_{RF} term in the Eqn.(1), performing non-linear fit of the phase-phase correlation pattern might provide erroneous numbers for the compression efficiency except if one takes time to study and deconvolve RF-induced steering. In fact, we can use a similar technique to the one already in use in the CEBAF accelerator [1] that consists of comparing the phase-phase pattern experimentally measured with one numerically generated for the optimum setup.

The PARMELA model developed is phenomenological since no time was allocated for properly calibrating the buncher and accelerating cavities in the injector. Therefore devising a "good" bunching is a 3 parameters problem with one possible "measurement": the phase-phase correlation pattern. The three unknowns are the buncher, cavity #4, and cavity #3 gradients. Assuming the RF-module and software coefficients are the same for the two cryounit cavities, the ratio of gradient values for the current operating point (cav #4 at 12.4 and cav #3 at 9.55) is $\simeq$1.3. Using the PARMELA code we have varied the gradient of the two cryounit cavities, assuming cavity #4 is operated at a gradient 1.3 times higher than cavity #3 until the simulated energy at the injection point matched the experimentally estimated kinetic energy of 9.56 MeV (inferred from the strength of the injection chicane dipoles: 11080 G.m); during the simulations the cavity #4 was set to operate on crest while the cavity #3 was -20 deg off-crest. The buncher was operated at a gradient of 0.32 MV/m [2]. The so-generated model is henceforth termed as "ideal" injector.

II Measurements

Measurements performed on May 19th
We have investigated the buncher effect on the 320 kV gun setup after the injector RF-phases were properly set [2]. The optimized phase are gathered in Table 1. The buncher gradient was initially set at 1.6, and we investigated the effect on the "M_{55}" transfer map pattern by systematically varying the buncher gradient. The recorded patterns are presented in figure 2 along with the pattern generated with PARMELA for the ideal injector. From this figure we decided to operate the buncher at 1.8 since it provides a pattern very close to the simulated one.

Elements	Phase	MEDM Phase	MEDM Gradient
Laser	reference phase	85 deg	N/A
Buncher	zero-crossing	-46 deg	1.60 (a.u.)
Cavity #4	-10 deg off-crest	-51.5 deg	12.4 MV/m
Cavity #3	-20 deg off-crest	-104 deg	9.55 MV/m

Table 1: Nominal injector settings before the measurement. (All save `Wed May 19 23:52:38 1999`).

We also measured the rms transverse beam size on an OTR viewer located close to the pickup cavity

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[2] These values were recommended by B. Yunn, and are now the "GOLD" values for the 320 kV gun.

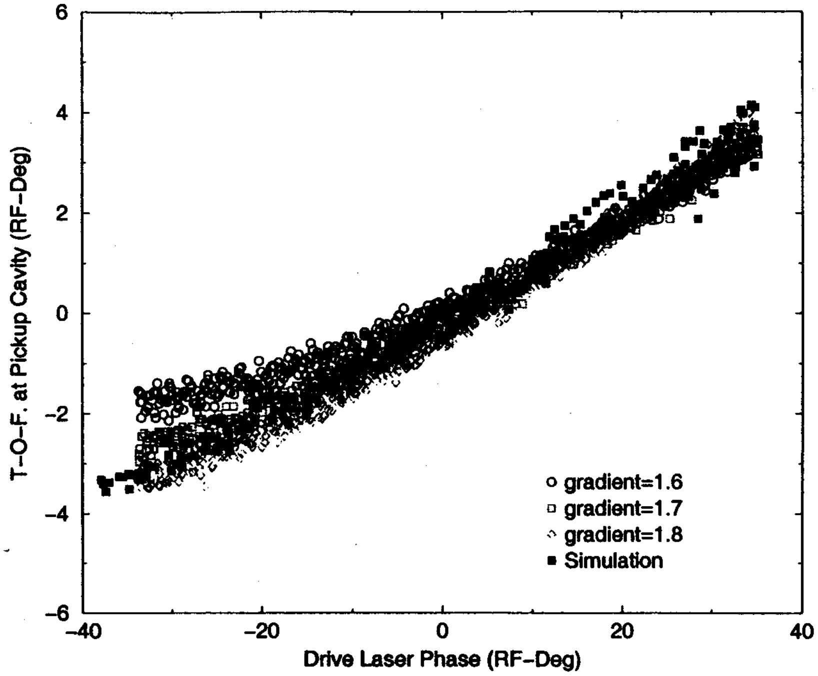

Figure 2: "M_{55}" transfer map for different experimental operating point of the buncher gradient. The measurement are also compared with the "ideal" injector devised from numerical simulations. (May 19th setup)

ITV0F06). At that location the beam size can well be approximated as the product of the dispersion ($\eta \simeq$42 cm) with the rms energy spread. It is seen from the figure 3 that the "best" buncher gradient devised by matching the experimental phase-phase pattern with the simulated one occurs for a buncher gradient of approximately 1.8; such a gradient DOES NOT correspond to the minimum energy spread on ITV0F06; this fact is also verified with numerical simulation as showed in figure 4. Therefore a current practice that consists of setting the buncher to achieve minimum energy spread on the OTR viewer ITV0F06 is incorrect.

Measurements performed on May 20th

A second measurement was performed after the FEL photon beam was optimized for 60 pC/bunch [4]. The value for the phases and gradients recorded before the our measurement are gathered in table 2. The phase-phase pattern measured is compared in figure 5 with the "ideal" one obtained by numerical simulations. The agreement between the measurement and simulation is excellent.

Elements	Phase	MEDM Phase	MEDM Gradient
Laser	reference phase	79 deg	N/A
Buncher	zero-crossing	-48 deg	1.85 (a.u.)
Cavity #4	-10 deg off-crest	-51.5 deg	12.4 MV/m
Cavity #3	-20 deg off-crest	-104 deg	9.55 MV/m

Table 2: Nominal injector settings before the measurement. (All save from `Thu May 20 00:15:49 1999`).

III Conclusion

The technique presented in this note seems to be a good "starting" point to make the longitudinal dynamics manipulation in the FEL injector perform as close as possible to the one devised via numerical simulation. In order to achieve design parameters in the FEL injector, the order that should be followed is to first work

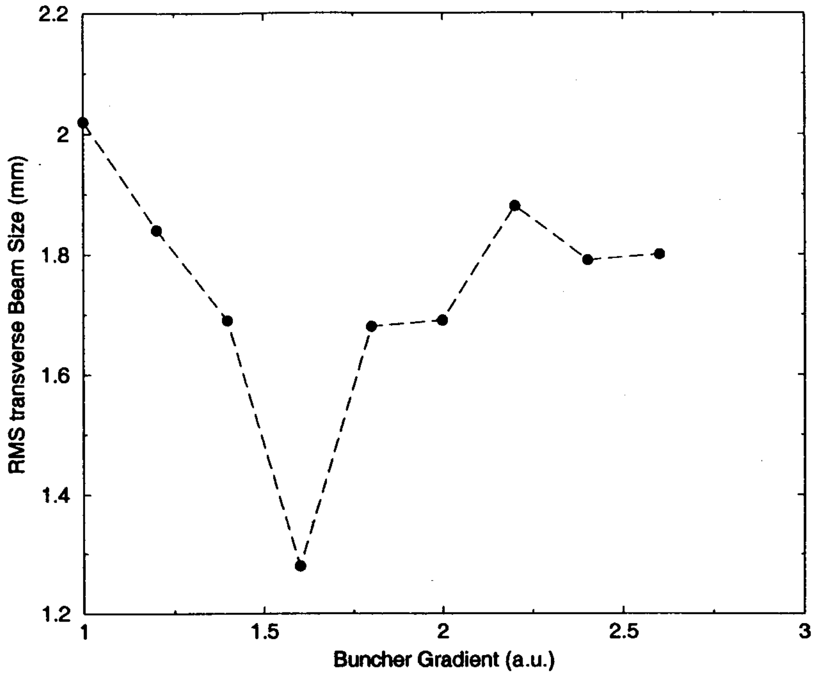

Figure 3: Experimentally measured beam size on the OTR viewer ITV0F06 versus buncher gradient using May 19th setup.

on the longitudinal dynamics only: (1) adjust phase-phase correlation in the injector, (2) adjust the phase of the whole linac to minimize the bunch length at the undulator location, and (3) verify the phase-phase correlation pattern at the linac exit. Then the transverse dynamics should be set (without changing anymore the longitudinal settings).

This order is simply deduced from the coupled rms envelope equations for bunched electron beams not yet in the emittance dominated regime: the longitudinal envelope affects the transverse envelope via space charge force, but the longitudinal envelope is less significantly affected by the transverse envelope.

IV References

[1] G. A. Krafft, "Correcting M56 and T556 to obtain very short bunches at CEBAF", AIP conf. proc. **367**, pp. 46-55 (1995)
[2] S. Benson and T. Siggins, FEL electronic logbook, entry #5073 (May 19th, 1999)
[3] D. R. Douglas, "Beam transport issues in the winter/spring 1999 FEL run", **JLAB-TN-99-008**
[4] S. Benson and T. Siggins, FEL electronic logbook, entry #5107 (May 19th, 1999)

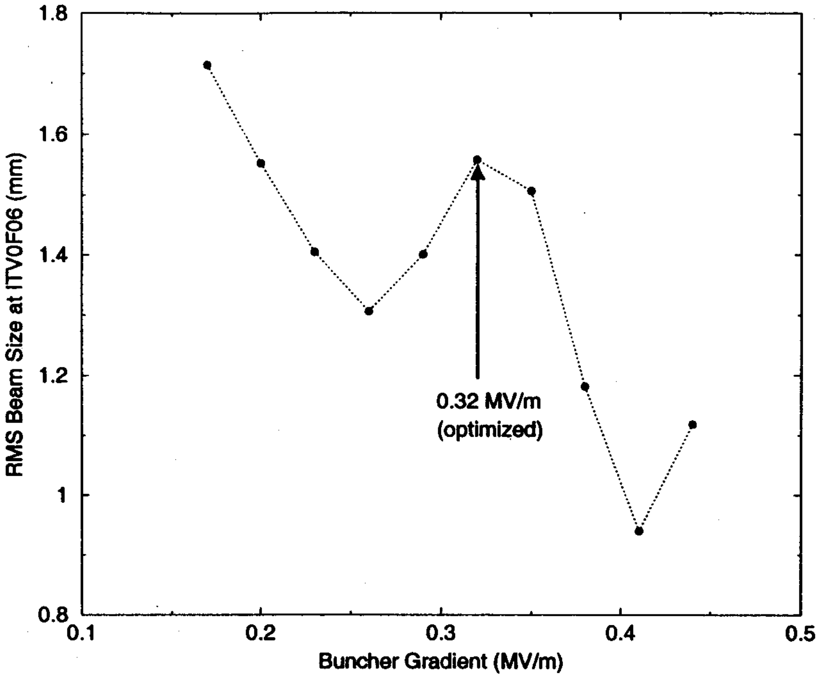

Figure 4: Numerical simulation of the beam size on the OTR viewer ITV0F06 versus the buncher gradient using the "ideal" injector.

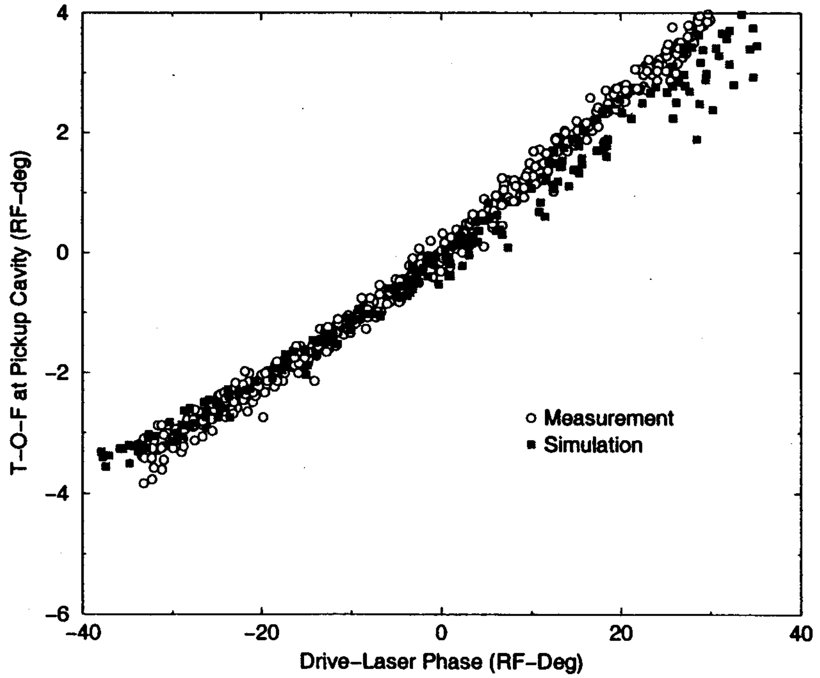

Figure 5: Comparison of the measured M_{55} pattern after the FEL was optimized with the "ideal" M_{55} pattern generated with PARMELA (using May 20th setup).