EMITTANCE AND ENERGY SPREAD STUDIES IN THE JEFFERSON LAB FREE-ELECTRON LASER

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Abstract

Preserving emittance and energy spread in a free-electron laser (FEL) driver-accelerator is a major concern to minimize FEL-gain reduction due to non-perfect overlap of the electron beam with the considered optical mode and/or due to slippage effects. In the Jefferson Lab FEL-oscillator, careful measurements of transverse emittance and energy spread have been conducted at different locations along the beamline for a variety of beam initial conditions. We present some of the these measurements, and review the different mechanisms that could (or could not) provide explanation for our observations.

1 INTRODUCTION

Generation of laser light driven by free-electron imposes stringent requirements on the electron beam parameters, especially concerning transverse emittance, bunch length and energy spread. In the Jefferson Lab FEL, the IR-Demo (for a description of the machine see Reference [1]), typical requirements for these parameters are $\tilde{\varepsilon} \leq 8$ mm-mr, $\langle\delta^2\rangle^{1/2} \leq 0.0022$, and $\langle\sigma_z^2\rangle^{1/2} \leq 300\,\mu$m respectively, for a charge per bunch of 60 pC. While achieving the required bunch length is not a concern [2], the two other parameters can easily deteriorate and reach values out of specifications if no care is taken. There are several effects that can leads to energy spread growth and/or emittance dilution: (1) optics-related (e.g., chromaticity, head tail effects,...) and (2) collective effects (e.g., wakefields, coherent synchrotron radiation,...). At the time of the IR-demo design, CSR theory was not yet well-established; we therefore decided to install the wiggler in the straight line immediately downstream the superconducting radio-frequency (SRF) linac (W1 in Fig. 1) and not, as initially planned, in the recirculation loop (W2 in Fig. 1). The series of energy spread and emittance measurements conducted during the summer 99 were performed to establish if there was significant emittance degradation downstream arc #1. During our measurements, the machine was not fully optimized, this accounts for the larger values of emittance reported hereafter compared to the 8 mm-mr aforementioned. All measurements presented in this paper are averaged measurements over macropulses of 250 μsec with a microbunch frequency of 18.6 MHz, such averaging is not problematic since the beam dynamics is dominated by single bunch effects because of the large ($\simeq$8.06 m) microbunch separation.

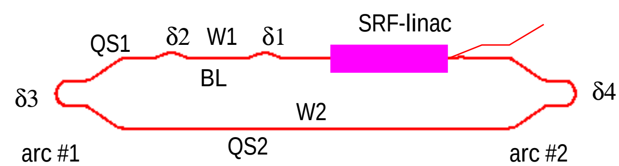

Figure 1: Locations of the emittance (QS1, QS2), bunch length (BL) and energy spread (δ) measurement stations in the IR-Demo. W1 and W2 are the two options for the wiggler locations.

2 ENERGY SPREAD MEASUREMENTS

2.1 Setup

The rms energy spread, $\langle\delta^2\rangle^{1/2}$ was measured in the midpoints of the two 4-bends by-pass chicanes, and the 180 deg end-loop arc; during the measurements, the upstream optics was tuned to insure the betatron contribution to the beam spot size, $\beta\tilde{\varepsilon}$, was unsignificant compared to the dispersive contribution $\eta\langle\delta^2\rangle^{1/2}$. The beam profile/width measurement utilizes optical transition radiation (OTR) emitted in the backward direction as the beam crosses thin aluminum foils.

2.2 Energy spread versus charge

The energy spread in the two by-pass chicanes was measured as a function of the charge. The result is presented in Fig. 2: we observe an energy spread generation between the two measurement stations $\delta 1$ and $\delta 2$ which is increasing with the charge per bunch.

2.3 Energy spread versus SRF-linac phase

The energy spread is a strong function of the linac phase, so that the phase dependence of a potential energy spread dilution might be difficult to discern. Nevertheless some energy profiles measured for different SRF-linac operating phases, ϕ, are gathered in Fig. 3. At the time of the measurement, the "maximum compression" phase was $\phi_{MC} \simeq 11.5$ deg approximately. It is interesting to note that as ϕ approaches ϕ_{MC}, the energy profile starts to show some fine structure; such effect was systematically reproduced and we could not attribute it to some accelerator subsystem problems (e.g. the photocathode drive-laser autocorrelation was monitored during all measurement and

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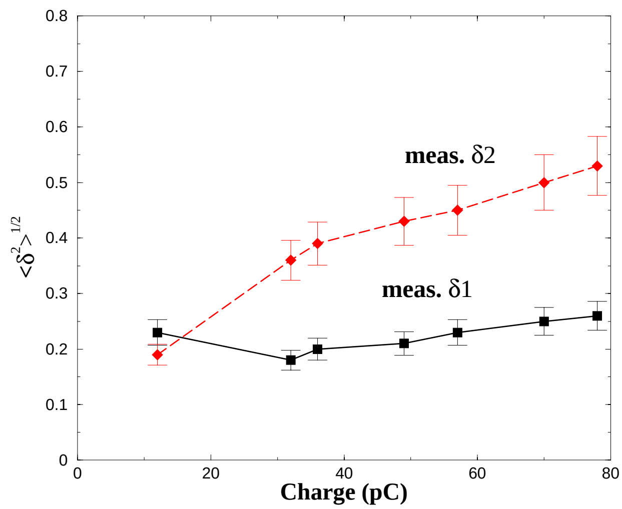

Figure 2: rms relative energy spread (in %) measured in the two by-pass chicanes versus the bunch charge.

did not show any fine-structure). Moreover, we observed, in consistence with the results presented Fig. 2, that these “fine structures” were enhanced as the charge per bunch was increased.

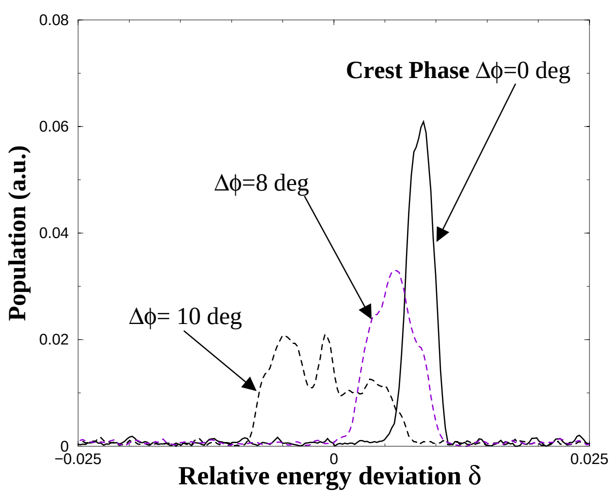

Figure 3: Energy spread profile at the station $\delta 2$ for different operating phase of the SRF-linac.

3 EMITTANCE MEASUREMENTS

3.1 Setup

The emittance measurements were performed with the quadrupole scan technique (indicated as QS1 and QS2 in Fig. 1), by properly tuning the upstream optics, systematics errors were reduced to the 10% level and each measurement was performed at least three times to estimate the statistical errors, which in most of the case were also below the 10% level. In the recirculation transport we also measured emittance using four profiles monitors separated by a betatron phase advance of 60 deg: the measurements yielded similar values compared to the quadrupole scan technique. As in the case of energy spread measurement the profile monitors consist of OTR viewers. Because all the emittance measurements take place downstream achromatic chicanes or arcs operated in achromatic mode, we carried out dispersion studies at the location QS1 and QS2. The maximum amplitude of spurious dispersion was found to be $\eta \simeq 2\,\mathrm{cm}$ approximately, this latter result combined together with a maximum $\langle\delta^2\rangle^{1/2}$ of 1%, gives a ratio $(\eta\langle\delta^2\rangle^{1/2})/(\beta\tilde{\varepsilon}) \simeq 1\times10^{-3} \ll 1$ (for typical values of emittance and β-functions). Thus spurious dispersion does not significantly impact the emittance measurement.

3.2 Emittance versus SRF-linac phase

We varied the SRF-linac phase between the same limits as during the energy spread measurement. For each phase settings the total coherent transition radiation (CTR) power (at BL in Fig. 1) was recorded. Such power gives some insight on the bunch length, e.g. when the bunch length is minimum the CTR power is maximized. Figure 4 presents the emittance measured versus the SRF-linac phase. Firstly, we observe that the emittance after the arc #1 is not significantly altered under the nominal operation setup which corresponds to a minimum bunch length (i.e. $\phi \simeq 11.5$ deg) at the wiggler location (W1 or BL). On the other hand, the emittance increases as the energy-phase correlation is changed to shift the longitudinal waist toward the arc #1 entrance.

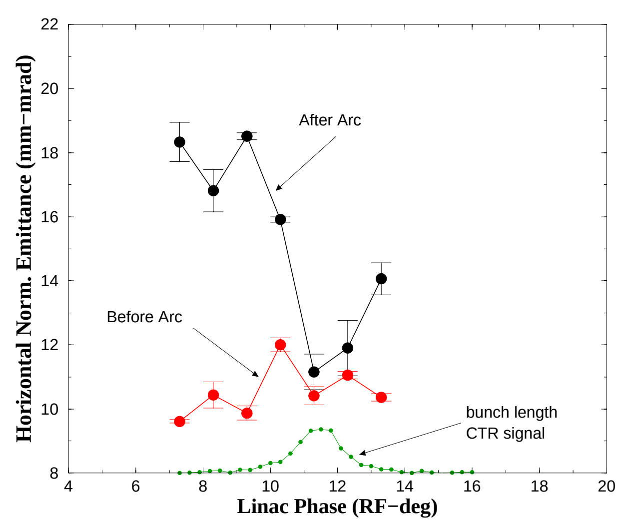

Figure 4: Transverse horizontal emittance at QS1 (before arc #1) and QS2 (after arc #1) versus SRF-linac phase. The bunch length CTR signal is measured at station BL.

4 MECHANISMS THAT COULD / COULD NOT EXPLAIN THE OBSERVATIONS

Chromatic effects: The technique we used to study the chromatic aberration at the emittance measurement stations consists of raytracing few points on the initial beam ellipse in the transverse phase space at the cryomodule exit. This raytracing is performed for a variety of energy spread within an energy span of $\pm 1\%$. The tracking is done with the arbitrary order code TLIE[3] using Taylor expansion of the transfer map up to the third order. The resulting phase space ellipse distortions, for the two different locations where emittances are measured, are presented in Figure 5. This chromatic distortion is very small; to further quantify this statement we have computed the emittance growth due to this effect: for an rms relative energy spread of 1% (which can be reached depending on the SRF-linac operating phase) the expected growth is less than 4%.

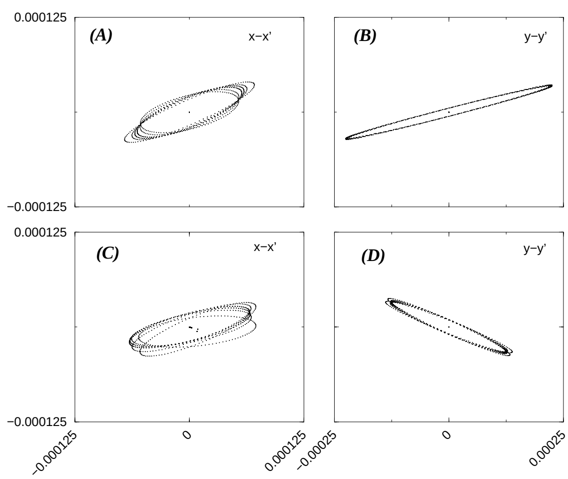

Figure 5: Distortion of phase space ellipse at QS1 (A) and (B) and QS2 (C) and (D) locations. Units are meters and radians for the horizontal and vertical axis respectively.

Head-Tail RF-effects: Another optical effects that can results in an increase of emittance comes from the so-called head-tail effects: because of the non-zero bunch length and the time-dependence of the RF-field in the accelerating structure, different slices along the bunch do not see exactly the same field. In regions such as input/HOM couplers or in case of cavity misalignment this will results in a differential transverse kick along the bunch which in turn impacts the transverse emittance. To quantify this effect we used a modified version of PARMELA [4] to track the beam in a 3D field map of the SRF-linac. The tracking was performed for different SRF-linac phase and the beam parameters did not change significantly: $\Delta\sigma_{x,y}/\sigma_{x,y} < 10\%$ (due to RF-focusing), and $\Delta\tilde{\varepsilon}_{x,y}/\tilde{\varepsilon}_{x,y}$ <1%.

Short-range wakefield: A longitudinal and transverse wakefield study of the whole beamline was performed using an impedance analysis [5]. From this study we inferred the total transverse and longitudinal impedance between $\delta 1$ and $\delta 2$ measurement stations to be $k_{\parallel} \simeq 70\,\mathrm{V/pC}$ and $k_{\perp} \simeq 157\,\mathrm{V/pC}$, such values results in unsignificant energy spread dilution compared to the beam nominal energy spread $\simeq 50\,\mathrm{keV}$ approximately. This result is also confirmed by simulations using ABCI [6]. Hence wakefield cannot account for the observations presented in Figure 2.

Long-range wakefield: Another effect that could yield emittance growth comes from potential bunch to bunch interaction via long-range wakefields. We have investigated this effect using the TDBBU code [7] with the measured external quality factor of the high order mode (HOM) fields in the CEBAF-cavities [8] that compose the SRF-linac. The results show not increase at all of the projected emittance even over a macropulse of $250\,\mu\mathrm{m}$.

Coherent Synchrotron Radiation Effects At the time the experiment was performed, a self consistent simulation tool was being developed [9], and generally the simulations, that used gaussian phase-space density, seemed to underestimate our observations. Recently it was found that including non-gaussian phase space density (e.g. by taking into account RF-induced curvature) could lead to much stronger CSR-induced degradation [10] than for the gaussian case.

5 CONCLUSION

From the measurements campaign carried out during summer 99, we can draw the following conclusions: (1) we have observed that there was some potential energy spread and emittance dilution in the IRFEL-Demo, (2) however for the nominal setup, it was found that the emittance after arc #1 is not altered thereby supporting the relocation of the wiggler downstream this arc, (3) among the potential explanations for our observations, CSR seems the most probable.

6 REFERENCES

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