EXPERIMENTAL RESULTS FROM AN INJECTOR FOR AN IR FEL

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Abstract

An electron injector capable of delivering the high brightness electron beam necessary for an infrared free-electron laser (FEL) is described. The injector is composed of a high-DC-voltage GaAs photocathode gun coupled with a normal-conducting rf buncher and two superconducting rf cavities operating at 1.497 GHz. The gun pulse structure is mode locked to the fourtieth subharmonic of the rf fundamental using a Nd:YLF drive laser. The gun provides 50 picosecond FWHM bunches at 60 pC per bunch with a normalized RMS transverse emittance less than 6 mm-mrad at 9.5 MeV/c and an average current of 1.1 mA. Experimental measurements of the transverse and longitudinal beam properties of the injector are described. The results are compared with PARMELA . Operational issues for the injector are also presented.

1 INTRODUCTION

Jefferson Lab is currently commissioning a high average power infrared free-electron laser [1]. This user-oriented facility is also devoted to the study of beam dynamics phenomena and technologies associated with the realization of a high-average-power free-electron lasers. The driver accelerator comprises a 10 MeV injector followed by a 38 MeV energy recovering superconducting RF linac that allows high average current operation with modest klystron power [2]. The accelerator in its "first light configuration", i.e. without the energy recovery scheme being used, is currently in commissioning. The requirements on beam quality at the wiggler location to lase with a 100 W average power using 60 pC bunches are: (1) the transverse emittance is to be less than 9 mm-mrad, (2) the bunch length should be less than 1 ps, (3) and the energy spread should be below 0.2%. The photoemission injector, whose block diagram is shown in Figure 1, is a key element in achieving the required beam quality. It principally consists in a 350 keV line coupled with a high gradient RF structure consisting of two CEBAF-type superconducting cavities that can accelerate the beam up to approximately 10 MeV. The accelerating section is followed by a 10 MeV injection line. The whole injector (from the electron generation to the injection point) has been designed [3] and extensively studied using the PARMELA [4] "particle pushing" code. The optimized transverse and longitudinal beam envelope are presented in Figure 2.

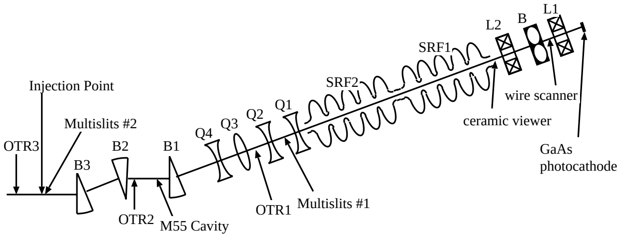

Figure 1: Block diagram of the injector. L1 and L2 are solenoidal lenses, B the buncher, SRF1 and SRF2 the RF cavities, Q1, Q2, Q3, Q4 are quadrupoles and B1, B2, B3 are dipoles.

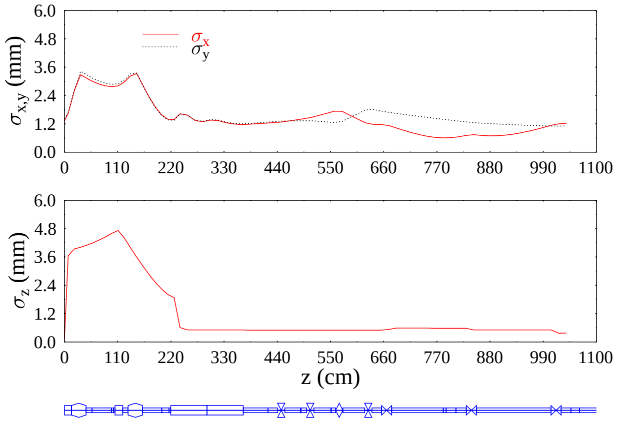

Figure 2: Simulated transverse and longitudinal rms beam envelopes along the injector beamline.

2 THE 350 KEV LINE

The low-energy line consists of a high-voltage DC photoemission gun for electron generation, a room-temperature buncher cavity and two solenoidal lenses (see figure 1). The gun uses a GaAs photocathode driven by a Nd:YLF laser [5]. The drive laser is mode locked to 37.425 MHz corresponding to the fourtieth subharmonic of the rf fundamental frequency (1497 MHz) of the RF system. It can provide 23 ps (rms) micropulses with a variable repetition rate ranging from 0.245 to 37.425 MHz. The gun voltage can reach 500 kV but is currently operated at 350 kV without significant loss of beam quality as a source for the IRFEL. At the gun exit, a solenoidal lens provides focussing for the

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	measured	PARMELA	required
$\tilde{\varepsilon}_x$ (mm-mrad)	2.4±0.3	2.20	≤3
$\tilde{\varepsilon}_z$ (deg-keV)	–	7.6	≤12
ΔE (keV)	9.4	7.4	≤20

Table 1: Typical beam parameters measured at the exit of the high gradient structure with 60 pC and a gun voltage of 350 kV.

strongly diverging beam and insures the beam is transmitted without loss to the buncher which compresses the bunch down to 15 ps. Then a second solenoidal lens matches the electrons at the entrance of the cryounit. Because of the influence of space charge, the 350 keV line was designed to be as short as possible, thereby preventing the installation of a lot of diagnostics. Indeed, prior to its installation the gun with the first solenoidal lens was characterized in a series of parametric studies whose results were previously reported [6, 7]. For the 60 pC charge used in the first-light scenario, the measured beam parameters are shown in Table 1

3 THE 10 MEV LINE

The 350 keV electrons are then injected in a high gradient structure which consists of two CEBAF-type SRF cavities. By design the first cavity is operated on crest at 11 MV/m and longitudinally “freezes” the phase space, while the second one is operated -19.6 deg off-crest at a gradient of 9 MV/m. The overall effect is to provide a suitable longitudinal-phase-space slope to match the M_{56} $(= \partial\phi/\partial(\Delta E/E))$ of the downstream achromatic chicane in order to optimize the bunch compression. Between the cryounit and the injection chicane a telescope, composed of four quadrupoles, is used to transversely match the beam into the main linac.

3.1 Transverse Dynamics

The injection line is instrumented [8] with three optical transition radiation (OTR) profile monitors that are routinely used to measure the beam 2D transverse density and profiles. Figure 3 compares typical beam spot measured at the accelerating section exit (OTR2 on Figure 1) with a PARMELA simulation. The code clearly reproduces the beam structure which consists in a core with a surrounding halo and gives within a few percent the same beam size as the one experimentally measured.

Because of the significant space-charge contribution to the beam envelope, transverse emittance measurement using the standard envelope fitting technique is not possible. Hence we use two multislit masks [9] to perform such measurements: the beam is sampled by the mask into emittance-dominated beamlets which drift to an OTR screen where they are analyzed with an on-line program. Typical normalized rms transverse emittance results are given in Table 2. Despite the fact that the results are about 80% larger than the PARMELA numbers, they are within the specified values for the FEL. The discrepancies with the PARMELA generated values are still not understood.

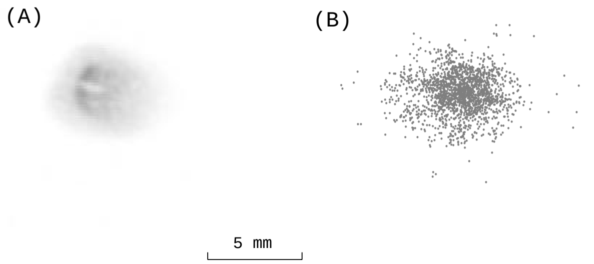

Figure 3: Comparison of experimentally measured beam density (A) with PARMELA generated one (B).

	measured	PARMELA	required
$\tilde{\varepsilon}_x$ (mm-mrad)	5.3	3.87	≤ 6
α_x	0.60	-1.109	–
β_x (m)	3.70	9.018	–
$\tilde{\varepsilon}_y$ (mm-mrad)	5.7	3.89	≤ 6
α_y	-0.19	-1.306	–
β_y (m)	2.41	9.847	–

Table 2: Transverse beam parameters measured at the exit of the high gradient RF-structure.

3.2 Longitudinal Dynamics

The beam energy achieved at the injector front-end is 9.53 MeV as measured with a standard spectrometer technique. The energy spread is estimated using an OTR profile monitor (OTR2 in Figure 1) located at a high-dispersion point ($\eta = 0.54$ m) assuming the betatron contribution is insignificant. The routinely measured rms energy spread is dp/p=0.11%. A corresponding energy profile is presented in Figure 4.

The bunch compression is quantified by measuring the M_{55} (i.e $\partial\phi_{in}/\partial\phi_{out}$) transfer function. The measurement is performed by modulating the RF phase of the drive laser and measuring the time-of-flight with a pickup cavity [10]. A typical measurement with the injector with nominal settings is shown in Figure 5 along with a PARMELA simulation. Both the measurement and simulation give a pattern with slope in good agreement. We conclude that the bunch compression at this stage is being performed as predicted by the code, although one can see the pattern itself does not reproduce very well: the PARMELA transfer function is wider than the measured one.

The bunch length is inferred from an autocorrelation measurement of the coherent transition radiation (in the submillimeter regime) emitted as the bunches cross the 1.5 μm

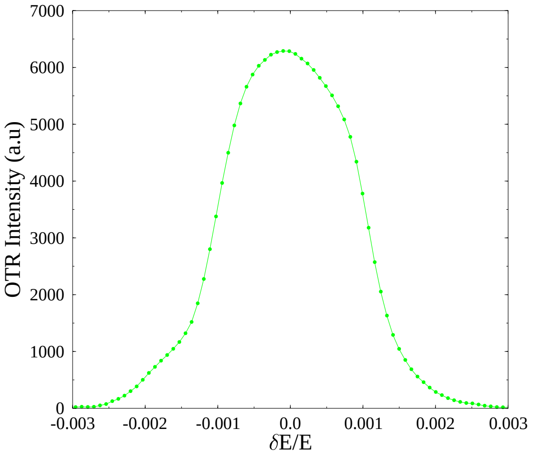

Figure 4: Example of beam profile measured at a high dispersion point to deduce the energy distribution.

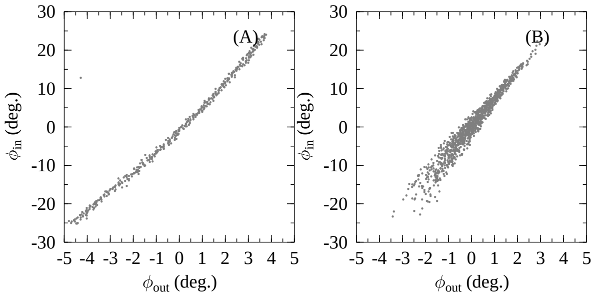

Figure 5: Comparison of measured M_{55} transfer map (A) with the PARMELA generated (B).

aluminum foil also used as an OTR profile monitor [12]. The autocorrelation is performed by means of a polarizing Michelson interferometer [11]. Up to now we have only measured the bunch length in the main linac since the injector bunch length monitor is not yet operational. Preliminary measurements, performed close to the wiggler location, indicate the injector is capable of achieving short enough bunches that the bunch length measured at the wiggler is within the specification of 1 ps.

4 OPERATION

We routinely devote shifts to production runs intended to exercise the injector (and the driver accelerator) at the required current for lasing with 60 pC per bunch. The desired CW average current of 1.1 mA has been achieved without any problem. These runs were also used to study the photocathode lifetime whose half life tends to be several hours.

5 CONCLUSION

The beam parameters of the Jefferson Lab IR FEL injector seem to meet the required beam quality for first lasing at low power using 60 pC bunches. However, there are still discrepancies between measurement and numerical simulation of the beam dynamics in the injector. Some of these discrepancies are probably due to a not yet fully optimized injector setup. These descrepancies are still under investigation. There is no doubt we will learn more as we continue our commissioning activities.

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