PERFORMANCE AND MODELING OF THE JLAB IR FEL UPGRADE INJECTOR

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Abstract

The JLab IR Upgrade Injector has delivered up to 9.1 mA of CW electron beam current at 9 MeV. The injector is driven by a 350 kV DC Photocathode Gun. Injector behavior and beam-based measurements are in good agreement with PARMELA simulations. The injected beam envelopes were established by measuring beam spot sizes and comparing them with those predicted by a transport matrix based model. The emittances were measured by fitting an initial trial beam matrix to the measured data. The injected bunch length was established by measuring the energy spread downstream of the Linac while operating at either side of crest.

INTRODUCTION

The injector for the Jefferson Lab 10kW Upgrade IR FEL is very similar to the 1kW IR Demo FEL [1]. The IR Demo injector has been described elsewhere [2,3]. A block diagram of the injector is shown in Figure 1. It consists of a high-DC-voltage GaAs Photocathode Gun driven by a frequency-doubled, mode-locked Nd:YLF laser, two solenoidal lenses, a room temperature buncher cavity, a 10 MeV cryounit with two CEBAF-type 5-cell superconducting cavities, a matching section composed by four quadrupoles and a bunch compressor composed by three, 20°-bending-angle dipoles. Beam diagnostics in the injector include a ceramic viewer at the entrance of the cryounit, and three optical transition radiation (OTR) profile monitors.

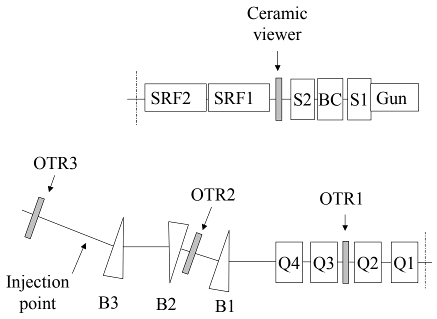

Figure 1: Block diagram of the Injector. S1 and S2 are solenoidal lenses. BC is the RF Buncher Cavity. SRF1 and SRF2 the superconducting RF cavities, Q1, Q2, Q3, and Q4 are quadrupoles, B1, B2, and B3 are dipoles.

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The 10kW Upgrade IR FEL DC Photocathode Gun is an upgrade version of the 1 kW IR Demo DC Photocathode Gun, which was operated at 320 kV and achieved 5 mA of CW beam at 37.425 MHz (fortieth sub-harmonic of the accelerator rf fundamental frequency, 1.497 GHz) with 135 pC per bunch [4]. With a new 600 kV DC HVPS the current capability in the Upgrade Gun has been increased from 5 mA to 10 mA at 74.85 MHz and 135 pC/bunch, as required by the 10kW Upgrade IR FEL [5]. The 10kW Upgrade IR FEL Injector has delivered up to 9.1 mA of recirculated CW beam at 9.1 MeV with the gun operating at 350 kV and 122 pC/bunch. Pulsed operation has also been demonstrated. 8 mA/pulse in 2-16 ms-long pulses have been achieved with the drive laser operating at 75 MHz (micro-pulse frequency) and 2 Hz repetition rate. The gun routinely delivers 350 kV, 5 mA pulsed and CW beam for FEL operations. The charge extracted from the photocathode between re-cesiations is on the order of 200 C. A typical day of operations draws between 30 and 40 Coulombs from the photocathode.

MODELING

The IR FEL Demo Injector has been modeled and studied previously as a function of gun voltage [6], bunch charge [7], and number of particles [8], using a modified version of the particle-pushing code PARMELA [9] implementing the CEBAF-type SRF cavities [10]. Further modifications to the code have been recently made to incorporate overlapping of the electric field of the gun with the magnetic field of the solenoid [11]. For the Upgrade Gun, the first solenoid (S1 in Figure 1) has been shifted upstream so that now the solenoid is right against the gun's anode plate and the fields overlap. In the IR Demo Gun, the solenoid was positioned so that the magnetic field started where the electric field ended.

The design beam parameters at injection for the 10kW Upgrade IR FEL are listed in Table 1 [12,13,14].

Table 1: Beam parameters specification at injection

Transverse	Longitudinal
$\varepsilon_{N\ x,y} = 10\ \pi$ mm-mrad	$\varepsilon_{N\ z} \leq 28\ \pi$ ps-keV
$\beta_{x,y} = 10$ m	$\sigma_E \leq 15$ keV
$\alpha_{x,y} = 0$	$1.5 \leq \sigma_z \leq 2.5$ ps

The design operating voltage of the IR Demo Photocathode Gun was 500 kV (10 MV/m at the cathode), but field emission from the electrode structures encountered during its commissioning led to a decrease in the gradient at the cathode achieved by lowering the operating voltage to 320kV and by increasing the cathode-anode gap (6 MV/m at 500 kV [15]). Simulations showed that operating the gun at lower gradient would still keep the transverse emittance within specifications [6], as measurements later proved [4].

Injector setup

The Injector modeling starts at the photocathode. Transversely, the distribution is a Gaussian truncated at $2\sigma_r$, with σ_r=2 mm. Longitudinally the distribution is Gaussian as well with σ_t =23 ps and truncated at $3\sigma_t$. The first solenoidal lens (S1 in Figure 1) strength is adjusted to focus the highly divergent electron beam following the $3\sigma_{x,y}$=beampipe-radius criterion. The buncher (BC) is a 1.497 GHz copper cavity operated at zero-crossing phase. Its gradient is set to minimize the longitudinal emittance at injection by finding the minimum energy spread at OTR2 (see Figure 1). A second solenoidal lens (S2) matches the beam transversely into the cryounit.

The cryounit accelerates the 350 keV beam to 9.1 MeV. Ideally, the solenoid (S2) strength is adjusted to position the beam waist at the middle of the first cell of the upstream (SRF1) cavity. However, this is not possible for this particular geometry due to transverse space charge effects, so the solenoid strength is set to position the beam waist as close as possible to the entrance of the SRF1 cavity. The upstream cavity (SRF1) is operated on crest, while the downstream (SRF2) cavity is operated at 20° ahead of crest for proper longitudinal beam match to the achromatic compression chicane (B1, B2, and B3). Downstream of the cryounit, four quadrupoles (Q1, Q2, Q3, and Q4) transversely match the beam to the injection point, located 1.0 m upstream of the first accelerator cryomodule (see Figure 1).

There are only two parameters that can be set in the injector and be stated as accurate, the gun voltage and the drive laser pulse length. All the rest have to be set and verified using beam-based measurements in concert with modeling results.

Code calibration

Dependencies of downstream beam parameters on a given parameter can be used to calibrate just about all the parameters. Beam-based measurements have been used to calibrate almost all of the injector parameters.

To calibrate S1, the field that produced a waist at the ceramic viewer (see Figure 1) was found by running PARMELA with the space charge option turned off. Then the same procedure was followed in the actual injector and the two field setpoints compared. It was found that the actual solenoid field is 2.24% larger than that predicted by the model.

It is difficult to calibrate the gradient value for the SRF cavities in the model against the actual setpoints, since even in EPICS there is an uncertainty of about 10%. However, the gradient ratio SRF1/SRF2 was measured by operating both cavities on crest [16]. The model was then adjusted to match the measured ratio.

There is a big discrepancy in the buncher gradient between model and the actual value reported in EPICS. The buncher setting for smallest energy spread at OTR2 corresponds in PARMELA to 0.41 MV/m, while for the actual injector is 2.5 MV/m. Therefore, the buncher gradient is set in both, model and machine, to produce the smallest energy spread at OTR2. Variations from this setpoint in the machine are translated to the model by taking the percentile increase or decrease. A careful measurement of the actual buncher gradient will be conducted later.

INJECTOR PERFORMANCE AND MODEL PREDICTIONS

Continuous feedback between PARMELA modeling and machine behavior observations proved to be an important tool during the FEL commissioning.

Longitudinal dynamics

The longitudinal match is achieved with the buncher cavity (BC), the downstream cryounit cavity (SRF2), and the downstream solenoid (S2). The buncher gradient is adjusted to minimize the energy spread at injection. The injected bunch length is adjusted with the off-crest phase on the downstream cryounit cavity (the injected bunch length is also controlled with the buncher gradient, but the energy spread grows if the buncher is not at the optimum for smallest energy spread). The downstream solenoid controls the longitudinal space charge force at the entrance of the cryounit by adjusting the beam spot size. Figure 2 shows the normalized longitudinal emittance from the cathode to the injection point.

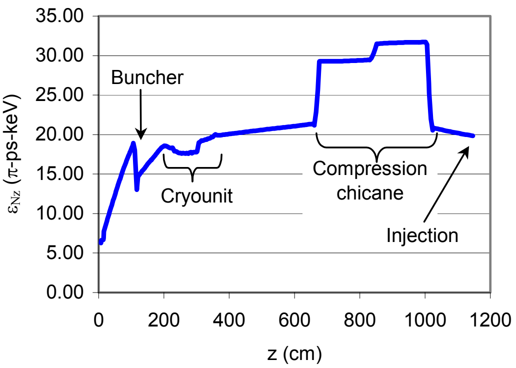

Figure 2: Normalized longitudinal emittance as a function of distance from the cathode to the injection point.

The IR Upgrade design requires an injector setup with the smallest injector energy spread. The energy spread is set using the buncher gradient, which in turn determines the injected bunch length. According to PARMELA, such a setup provides the smallest longitudinal emittance at injection (buncher gradient at 2.5 MV/m). Although the FEL lased with those settings (with the linac operating at 15° off crest), it lased better with a lower buncher gradient (2.0 MV/m) that minimized the injected bunch length.

Furthermore, the maximum Happek signal was not produced for the design buncher gradient. The optimum was a compromise between producing a small injected energy spread and a long injected bunch.

PARMELA predicts that this configuration occurs for a buncher setting 20% lower than the one that minimized the energy spread at injection. In fact this is what was observed. Measurements of the full-energy momentum spread after acceleration can be back propagated to evaluate the bunch length at injection [17]. A comparison of longitudinal phase space parameters predicted by PARMELA and those inferred *via* back-propagation is shown in Table 2.

Table 2: Model predictions at injection for two buncher settings compared to measurements inferred *via* back-propagation of energy spread measured at 80 MeV to injected energy of 9.2 MeV.

	Buncher at 2.5 MV/m	Buncher at 2.0 MV/m
PARMELA	σ_z =1.85 ps σ_E =13.2 keV ε_z =22.4 ps-keV	σ_z =0.74 ps σ_E =50 keV ε_z=36.5 ps-keV
Inferred *via* back-propagation	σ_z =1.65 ps	σ_z =0.55 ps

Note that the longitudinal emittance is much larger for the lower buncher gradient setup. The predicted longitudinal distributions at injection for the buncher gradient settings listed in Table 2 are shown in Figure 2. The energy distribution becomes the temporal distribution at the FEL and the phase distribution becomes the energy distribution. Note the large energy spread seen on the PARMELA distribution for the lower buncher gradient. This may be one of the causes for the lower FEL gain at the lower buncher setting [18].

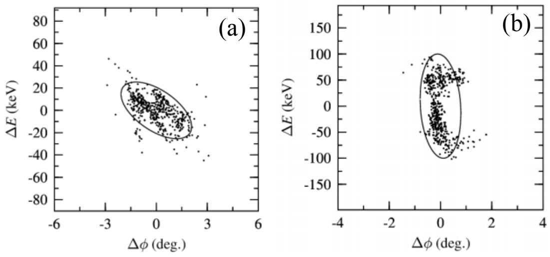

Figure 2: PARMELA longitudinal phase space at injection for: a) Buncher gradient (2.5 MV/m) optimized for smallest energy spread, and b) buncher gradient (2.0 MV/m) optimized for shortest bunch length.

For the lower buncher setting, the injected energy spread is too large and the bunch is too short. Although the injector setting with the buncher gradient that minimized the energy spread provided the design phase space at injection -a long bunch with small energy spread, it was not the best setup for lasing.

While modeling in search for an alternative injector setting, an asymmetry in the energy spread vs. linac phase and its apparent relation to bunch length were observed during the FEL commissioning. To confirm those observations, the PARMELA model was extended through the first accelerator module. The simulations confirmed the observations, indicating that the longitudinal space charge will induce what appears to be a phase-dependent asymmetry in the beam momentum spread during and after acceleration [19].

To alleviate the longitudinal space charge problem, a new injector setup was modeled to produce a longer bunch while maintaining a small energy spread. This is achieved by running the cryounit downstream cavity (SRF2) closer to crest, at 10° ahead of crest instead of the design value (20° ahead of crest). PARMELA predicts for this configuration (with the buncher gradient optimized for minimum injected energy spread) σ_z=2.4 ps, σ_E=10 keV, and ε_z =19.5 ps-keV. When the new injector configuration was implemented the injected rms bunch length inferred via back-propagation was 2.3 ps, in excellent agreement with PARMELA. Laser gain with this configuration was about as strong as the previous configuration but the peak efficiency in the detuning curve was much higher (1.25%).

Transverse Dynamics

To meet the design transverse beam envelopes at injection (see Table 1), the quadrupoles (see Figure 1) are adjusted in the model. Once a solution is found, the quadrupoles in the injector are set to the value specified by PARMELA. Then the beam transverse spot size is measured at each OTR monitor and compared to values predicted by PARMELA. The quadrupoles have not been calibrated yet against the model, but it was found that beam spots in all three OTR monitors agree with those predicted by PARMELA within 10% if the field for each quadrupole is shifted by –10 Gauss with respect to the PARMELA setpoint.

However, there is a discrepancy between the injected beam envelopes predicted by PARMELA and those established in the injector. The injected beam envelopes were established by measuring beam spot sizes after acceleration and comparing them with those predicted by a transport matrix based model. The transverse beam emittance, however agrees well with the model and it is within design specifications. The transverse emittances were measured by fitting an initial trial beam matrix to the measured data. Table 3 shows PARMELA and measured transverse beam parameters at injection with the buncher gradient set for minimum injected energy spread.

Table 3: Transverse beam parameters at injection with SRF2 cavity operating at –10 degrees off crest, buncher gradient at 2.6 MV/m, Q1=-30.5, Q2=-5, Q3=240,Q4=-248 Gauss.

	PARMELA	Established at injection
$\varepsilon_{N\ x}/\varepsilon_{N\ x}$ π mm-mrad	11.2 / 7.6	10.0 / 10.0
β_x/β_y m	14.1 / 8.4	10.7 / 6.1
α_x/α_y	-3.7 / 0.3	-0.3 / 0.4

CONCLUSIONS

The 10 kW Upgrade IR FEL Injector has demonstrated operation at 9.1 mA CW, 9.2 MeV and 122 pC/bunch. Routinely the injector delivers 5 mA pulsed and CW at 135 pC/bunch for FEL operations. In general there is good agreement between PARMELA predictions and machine behavior. The measured performance matches de model in detail.

The operational experience gained during the injector commissioning process and the constant feedback between model and machine will be very valuable for modeling and operation of future 100 mA class injectors.

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