PHYSICS OF JLAB FEL INJECTOR*

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Abstract

Jefferson Laboratory is currently commissioning a high-power kW-level cw IR FEL which recently demonstrated impressive high-power capability with the linac operating in a nonrecirculating mode[1]. The injector, which provides a 10 MeV electron beam with high bunch charge (60-135 pC) to the linac, consists of a 350 kV dc photocathode gun and two 5-cell superconducting rf cavities, along with a buncher cavity. Due to the nonrelativistic nature of the electron beam at 350 keV there is some interesting physics involved in the $\beta = 1$ srf cavities during acceleration. This is discussed, as is the usual space-charge-originated emittance degradation at various injector components.

1 INTRODUCTION

Requirements at the wiggler for a high power kW-level cw IR-FEL at Jefferson Laboratory, which has been designed for a typical range of optical wavelengths between 3 μm and 6 μm, are quite stringent for a 42 MeV electron beam of 60 pC bunch charge. They are:

$$\varepsilon_{x,y} = 8.7\ \pi \text{ mm-mrad}$$
$$\varepsilon_z = 33\ \pi \text{ deg-keV}$$
$$\sigma_E/\sigma_z = 85 \text{ keV}/0.5 \text{ deg}$$

Space charge effects are significant throughout the injector beam line designed to deliver 10 MeV electron beam to the linac starting at photocathode. One must include them properly in a design study. For this purpose we have extensively used a version of PARMELA[2] which implemented a point by point space charge computational algorithm to simulate better 3-d beam.

2 NOMINAL INJECTOR PROPERTIES

A logical block sketch of JLAB FEL injector beam line is shown in Figure 1. Total beam line is 10.5 m long. Details can be found in several JLAB publications[3].

2.1 INJECTOR SETUP

Design study of JLAB FEL injector has been carried out with PARMELA supplemented by POISSON, MAFIA and DIMAD. Initial electron bunch produced at cathode by a laser spot of 6 mm in diameter is round with a uniformly distributed charge distribution transversely. Longitudinally, the bunch is 90 ps long with a Gaussian

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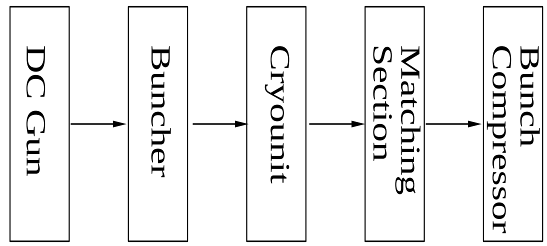

Figure 1: The beam line is also equipped with 3 viewers, 1 beam position monitor, 1 Happek device and 2 multi-slits.

distribution whose one σ value is taken to be 15 ps. A DC gun quickly accelerates electrons to 350 keV. After a 1497 MHz buncher at zero crossing electron beam gets a further acceleration to 10 MeV passing through 2 CEBAF 5-cell superconducting cavities. The 10 MeV beam is then transported to the entrance of a cryomodule via a matching section which consists of 4 quadrupoles and a bunch compressor. Alternatively, the beam can also be transported to a 10 MeV dump.

Optimized machine setups for various bunch charges ranging from 0 to 135 pC have been found. In this paper we list one for a 60 pC bunch charge in Table 1 as this is the most frequently used setup presently. For the sake of completeness, settings for the cryomodule cavities are included.

Table 1: 60 pC Machine Parameters

Element	Setting
1st Solenoid	260 G
Buncher	0.39 MV/m at zero crossing
2nd Solenoid	-205 G
Cryounit Cavities	
1st Cavity	11 MV/m and on crest
2nd Cavity	9 MV/m and –19.7 deg off crest
Cryomodule Cavities	
Gradient	8 MV/m for all
Phase	-7.5 deg off crest for all

2.2 BEAM PROPERTIES

Beam properties at various beam line locations in injector as expected from PARMELA simulations are summarised in Table 2.

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Table 2: Injector Performance

Location	$\varepsilon_x/\varepsilon_y$ (π mm-mrad)	ε_z (π deg-keV)	σ_E/σ_z (keV / deg)
Gun	1.3/1.2	2.2	0.7/8.7
Cryounit	3.9/3.8	7.1	15.5/0.9
Injector Exit	4.7/3.9	8.0	12.0/0.7

This optimized setup is fully capable of delivering an electron beam which meets all design beam specifications at the wiggler. PARMELA prediction of the beam quality at the wiggler is:

$\varepsilon_x/\varepsilon_y$ = 5.3 / 5.1 π mm-mrad

ε_z = 10 π deg-keV

σ_E/σ_z = 50 keV/0.2 deg

3 A DC PHOTOCATHODE GUN

In a DC gun there are no rf induced effects which degrade beam quality. However, one must quickly accelerate the beam to minimize space charge effects that become dominant in our bunch charge range between 60 to 135 pC. Presently, photocathode gun operates at 350 kV and the beam exits the gun after traveling a short distance of 14.4 cm. Longitudinal and transverse electric fields at 0.35 cm from the axis, which is just about at the beam edge, are shown in Figure 2.

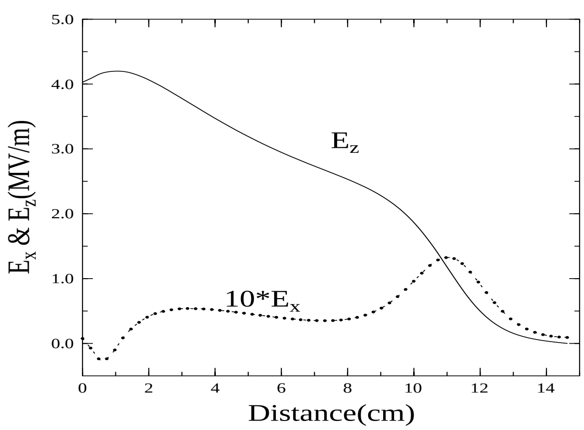

Figure 2: Electric fields at r = 0.35 cm. E_x has been multiplied by 10 to fit in the scale together with E_z

The fields are cylindrically symmetric. Longitudinal electric field within a volume occupied by the beam is independent of radial offset r to a good approximation, even though its dependence on z is quite complicated.
Consequently transverse fields depend linearly on r and emittance degradation due to DC fields is minimal. Emittance degradation due to space charge is substantial as shown in Figure 3. Energy spread increases also exhibiting a typical S-shape. In order to minimize these degrading effects the gun voltage should be kept as high as possible. Original design calls for a 500 kV DC gun.

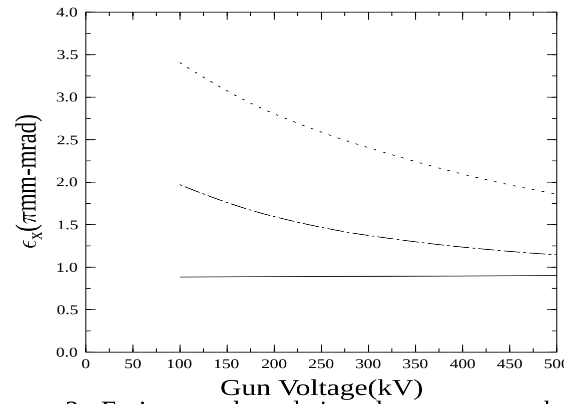

Figure 3: Emittance degradation due to space charge effects is shown as a function of a DC gun voltage. Dotted (dot-dashed) line is for a 135 pC (60 pC respectively) bunch charge. Solid line for the case without space charge.

4 ACCELERATION IN CRYOUNIT

A 350 keV electron beam enters a pair of CEBAF 5-cell superconducting cavities separated by 2.25 wavelengths - an arrangement known as cryounit - for a further bunching and an acceleration. The first cavity which the beam encounters is powered at 11 MV/m gradient and the second one at 9 MV/m gradient as shown in Table 1. Electron beam becomes more or less relativistic at 10 MeV with β very close to 1 after the completion of acceleration through the cryounit. However, at an initial 350 keV energy, β for the beam entering the cryounit is only 0.8. As a result, electron acceleration in these cavities, which are designed for β = 1 particles, turns out to exhibit a few interesting features. We find the following to be noteworthy:

1) Upper limit of an energy gain.
Presently, in the FEL injector the first superconducting cavity the beam sees is powered at 11 MV/m gradient. If we keep increasing the gradient of this cavity, the beam energy gain peaks at a gradient of about 40 MV/m.

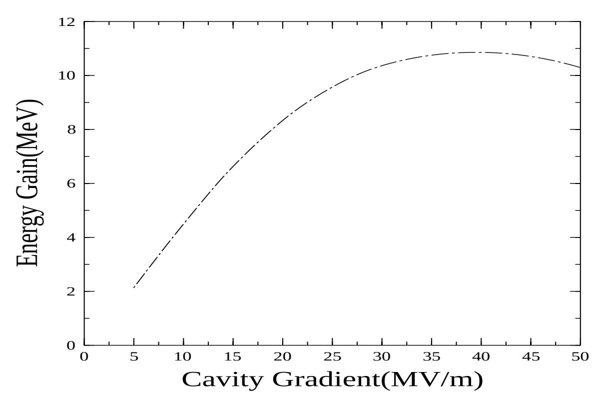

Figure 4: Maximum energy gain by a 350 keV electron beam traversing a 5-cell CEBAF cavity.

Of course, the cavity stops being efficient way before. Indeed, beyond about 20 MV/m gradient it is no more economical as Figure 4 shows.
In addition we also note a strong dependence of the cavity crest phase on the gradient. Particularly we point out a linear dependence starting at a gradient of about 11 MV/m up to a reasonably useable higher gradient.

2) Dependence of Crest Phase on Buncher Phase.
If buncher is not at zero crossing, electron beam gets accelerated or decelerated depending on phases, however small they may be. This in turn has a consequence in relative phasing between two cavities in the cryounit in addition to changing overall time of arrival at the unit. Fortunately, the effect appears to be small. For a 10 deg off zero crossing at the buncher relative crest phase change is about a half degree.

3) Time of Flight through CEBAF Cavity.
Time of flight for an electron to pass through a CEBAF 5-cell cavity depends strongly on initial rf phase of the cavity as a result of the electron not being relativistic at 350 keV at the cavity entrance. In Figure 5, difference of flight time (relative to the one for an electron gaining maximum energy) is shown as a function of rf phase when cavity gradient is 11 MV/m. Note that the flight time is a function of gradient, too.

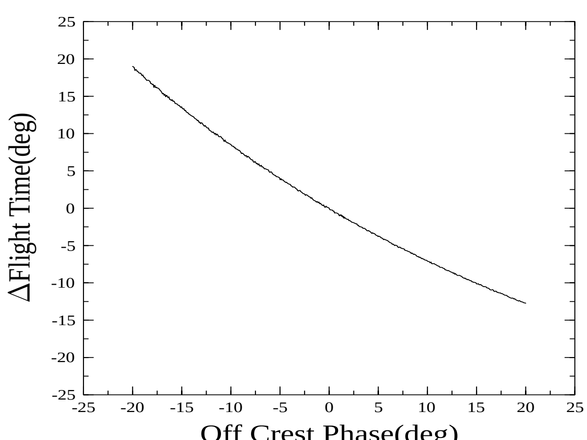

Figure 5: Time of flight difference as a function of cavity phase. The case of cavity gradient at 11 MV/m is shown here.

This 'M_{55}' property of the first cavity in the cryounit along with the fact that electron beam becomes fairly relativistic at the exit suggests a practical method of phasing cavities in the unit accurate to a few degrees.
Namely, first find a crest phase of the 2nd cavity at an initial phase of the 1st cavity, and then locate maximum energy point by sliding phases of two cavities with a fixed relative phase (note that order of executing these steps can be reversed).

5 MATCHING AND BUNCH COMPRESSION

Matching section is a 235 cm long straight beam line consisting of four 15 cm quadrupoles separated by 60 cm from the center to the center. An electron bunch is compressed by passing through a bunch compressor consisting of three 20 degree bending magnets arranged in a right-left-right horizontal bend pattern. The dipoles are 175 cm apart from each other. The quads are set to minimize emittance degradation in the bunch compressor, and in the following linac. At same time transverse phase space at the linac exit must satisfy a few requirements to facilitate beam matching into the wiggler subsequently. Space charge effects are not substantial for a 60 pC bunch at 10 MeV in the matching section as evidenced by a following comparison between DIMAD and PARMELA computations. Emittance degradation is less than 5%.

Table 3: Twiss Parameters at the Matching Section Exit

	β_x/α_x	β_y/α_y
Space Charge On	7.97 m/ 0.33	13.63 m/3.02
Space Charge Off	7.09 m/0.59	12.37 m/3.03
DIMAD	7.05 m/0.58	12.32 m/3.01

Bunch compressor is achromatic when space charge force is neglected, and has an M_{56} of -19.25 cm that enables to rotate bunch longitudinally. M_{56} behaves as a negative drift in the longitudinal phase space. Space charge effects observed in the compressor include 20% degradation of the horizontal emittance and 20% change in energy spread, up to 50% change in the bunch length, 20 to 70% change in βs along with a drastic change in αs. All these for a 60 pC bunch. Consequently, PARMELA has been an essential tool for a proper matching through the bunch compressor to generate a desired beam phase space before entering the cryomodule.

6 CONCLUSION

1 kW IR FEL is still in the middle of commissioning and we have been successful so far in achieving 700 watts of IR power with a little less than 4 mA electron beam recirculating and energy recovering. Even though injector setup is still in need of finalization, JLAB FEL injector is providing a quality beam which set many records in the operation of cw IR FEL.

7 REFERENCES

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