

# A NEW LOW EMITTANCE INJECTOR FOR FUTURE FEL UPGRADES

Byung C. Yunn  
JLAB-TN-01-009  
February 6, 2001

## *Abstract*

We study a new injector design based on a photo-cathode dc gun. The injector is capable of producing an excellent quality of electron beam suitable for Jlab FEL upgrades (and for some of future high power high brightness machines). It can operate with the bunch charge at least between 100 pico Coulomb(pC) and 300 pC.

Jefferson Lab IRFEL[1] is based on a photo-cathode dc gun operating at 320 kV. A 10 kW IRFEL upgrade under construction will probably be using the same 320 kV dc gun. A doubling of beam current from 5 to 10 mA by increasing the bunch charge from the present value of 60 pC to 135 pC, and accelerating the beam to a higher energy by about a factor of 5 at the same time will suffice for generation of about 10 kW light. The anticipated beam quality from the injector in our optimized setup is shown in Table 1 (note that values for emittances and bunch length mentioned throughout the paper are all for rms quantities.).

Table 1: Performance of the IRFEL injector

Bunch Charge	60 pC	135 pC
$\epsilon_x(\text{mm-mrad})$	5	10
$\epsilon_z(\text{deg-keV})$	10	14
$\sigma_E / \sigma_z (\text{keV} / \text{deg})$	12/0.7	21/0.8

The IRFEL injector will deliver electron beam that meets the beam quality specification set for the upgrade with a sufficient margin.

However, it became clear that an improved design must be found before a photo-cathode dc gun based injector to be competitive as the electron beam source for much more demanding machines under study at the Jefferson Lab and other places[2]. It is in this context that we have searched for an injector design that does a better job in preserving a good beam quality started at the gun.

Electron bunch produced at a dc gun tends to be very long due to a low beam energy of only a few hundreds keV. The rms bunch length is typically about 20 to 30 ps long. A

chopping later can make a bunch shorter but is not recommended because of resulting beam power loss. In most situations a chopping is not required in an injector with a photo-cathode dc gun. For a high charged bunch (roughly from 10 pC upward) space charge force effects must be included in the calculation of beam dynamics. The beam quality can degrade rather quickly and the bunch shape can change significantly during the beam transportation as a result of the relatively low beam energy after the gun. It is generally accepted that the acceleration of the bunch should take place at the earliest possible opportunity in order to minimize the distance the beam being transported at the low energy. For a high charged bunch one often finds that the emittance at the gun exit already has grown so much leaving little room for an additional increase at a subsequent beam line which is inevitable even in an ideal machine. There is a physical mechanism that makes a substantial reduction of space charge induced emittance degradation possible. The emittance compensation scheme[3] has been successfully applied in the design of a photo-cathode rf gun based injector. The beam characteristics from rf gun is quite different. The beam energy at the gun exit is typically an order of magnitude higher and the bunch is short enough for no further bunching necessary. One of the underlying requirements for the scheme to work well is that the bunch should not suffer from a wild change in its shape, which is difficult to maintain in transporting the beam from a dc gun. In spite of such difficulty the beam line should be laid out to achieve the maximum emittance compensation as in a design of a rf gun injector.

Starting from a 500 kV dc gun with the original Jlab configuration which fixed the anode-cathode distance equal to 5 cm with the resulting electric field at the cathode surface close to 10 MV/m, we have designed a 10 MeV injector employing only 1497 MHz cavities in order to benefit from Jefferson Lab's vast experience with the CEBAF accelerator. Emittance compensation at the every step in the design of beam line is the key and the design has resulted in a 10 MeV emittance that is even lower than the value the beam has acquired immediately after the gun exit. For all cases studied we have assumed a longitudinally Gaussian shaped bunch with the rms bunch length of 20 ps. The bunch was cut off at  $+2\sigma_{\text{rms}}$ . It also turns out that in this design a shorter bunch length at the start is not necessarily good for the beam even though the technology to produce a shorter bunch is worth to pursue. Depending on the bunch charge the transverse optimum spot (assumed to be round) size at the cathode needs to be carefully adjusted to keep bunch shape distortions under control while the beam is still in the gun.

Cavity gradients can simply be taken from the current IRFEL operating parameters. Therefore, no further improvement is needed even though the availability of higher gradients could only help.

There is no need to change the order of elements in the new design and the beam line is similarly compact. An injection chicane, which can be used for a further beam bunching at the same time when needed, is required for the beam insertion to the main linac. Since the existing IRFEL chicane is perfectly suitable, there is no need to redesign the current one at this point.

Beam emittance obtained is summarized in Table 2.

Table 2: Emittances at 10 MeV

<b>Bunch Charge</b>	<b>135 pC</b>	<b>270 pC</b>
$\epsilon_x(\text{mm-mrad})$	1.6	3.5
$\epsilon_z(\text{deg-keV})$	15	26

The results are at a location just before the entrance to the chicane. An extensive study with Jefferson Lab version PARMELA during the design stage of the current IRFEL injector has shown that a properly matched beam can be transported through the chicane without suffering any noticeable emittance degradation for the bunch charge up to 135 pC. We don't expect any significant space charge related problem at the injection chicane with the bunch charge ranging between 100 pC and 300 pC. But, the problem requires a further study to be certain.

It can be argued that a photo-cathode dc gun developed and operating at Jlab is equally competitive as an electron source for many low emittance machine projects. A dc gun typically produces a lower emittance beam at the cathode than an rf gun and is more suitable for a cw operation. The Jlab IRFEL injector has been in operation reliably delivering 5 mA average current 10 MeV beam. Experience and research at Jefferson Lab have demonstrated that the type of 500 kV dc gun assumed for this work should be available in a not too distant future. Besides the new gun the most rewarding improvement would be to develop a coupler kick free power coupler to replace the current wave guide FPC for the CEBAF cavity.

A compact injector based on a photo-cathode dc gun combined with the super-conducting rf cavity is definitely capable of producing a high brightness and high power bunched beam for a variety of future high brightness machines being studied here and elsewhere.

The evaluation of design has been carried out with PARMELA[4] and POISSON-SUPERFISH[5] codes provided by Los Alamos National Laboratory.

## REFERENCES

- [1] G. R. Neil et al., "Sustained Kilowatt Lasing in a Free-Electron Laser with Same-Cell Energy Recovery", *Phys. Rev. Lett.*, **84**, 662 (2000).
- [2] M. Tigner, Cornell University (2000); D. Douglas, private communication (2000).
- [3] B. Carsten, "New Photoelectric Injector Design for the Los Alamos National Laboratory XUV FEL Accelerator", *Proceedings of the 10<sup>th</sup> International FEL Conf.*, Jerusalem (1988).
- [4] K. Crandall, Los Alamos National Laboratory (1980).
- [5] K. Halbach and R. F. Holsinger, "SUPERFISH - A Computer Program for Evaluation of RF Cavities with Cylindrical Symmetry", *Particle Accelerators* **7** (1976).