THE NPS-FEL INJECTOR UPGRADE*

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Abstract

The Naval Postgraduate School (NPS) has begun the design and assembly of the NPS Free-Electron Laser (NPS-FEL). As part of this effort, the original DC gun-based injector system from the Stanford Superconducting Accelerator has been moved to NPS and is being refurbished and upgraded to operate as a photoinjector. Design work has begun on a new, SRF, quarter-wave resonator based cavity that can serve as either an energy booster or photocathode gun.

The overall NPS-FEL design parameters are for 40-MeV beam energy, 1 nC bunch charge, and 1 mA average beam current, built as an energy-recovery linac in its final configuration [1]. As we move towards this goal, the injector system will be incrementally upgraded to add photocathode capability, have a higher final beam energy, and improve the beam brightness, to meet the needs of the overall experimental program.

OVERVIEW

The NPS-FEL is based around key components from the Stanford Superconducting Accelerator (SCA). These include:

- two, Stanford/Rossendorf cryomodules, each of which contains two, TESLA-type 9-cell 1.3-GHz cavities;
- four, 10-kW 1.3-GHz CW klystrons;
- a 240-kV gridded DC thermionic injector, with subharmonic buncher;
- the FIREFLY electromagnetic undulator; and
- assorted power supplies and magnets.

At present, the 240-kV SCA injector has been moved to NPS and is being prepared for beam in a temporary facility. This will serve as a platform for initial experiments while the main NPS-FEL vault is being constructed.

The nominal voltage gain in the TESLA structures is 10 MV per structure. The structures are matched for β~1, so injecting a 240-kV beam (β~0.73) results in significant phase slip and consequent reduction of maximum beam energy, as was observed at the SCA [2]. An injection voltage of 1.5 MV (β~0.97) will significantly reduce the phase slip during injection into the first linac structure, increasing final voltage and probably also helping to preserve beam quality. Higher injection beam energies are also desirable from the standpoint of constructing ERL return-loop beam merges.

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Also, while reliable and robust, the gridded DC injector places limits on both the charge per bunch that can be extracted, and on the quality of the beam produced.

For these reasons, we intend to gradually upgrade the NPS-FEL injector system, including diagnostics, from the original 240-kV DC gun to a superconducting RF photoinjector capable of generating nC bunches at 1.5 MeV (kinetic), with good transverse beam quality.

The incremental upgrade process will also allow us to continually perform experiments of interest in low-energy beam transport and cathode characterization.

DC GUN

The original SCA injector beam source is a 2-stage, 240-kV DC gun with a Pierce-type geometry and gridded cathode, shown schematically in Figure 1.

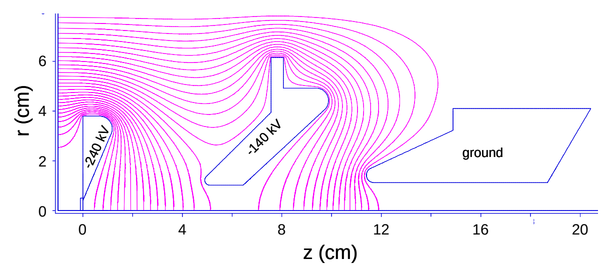

Figure 1: SCA DC-gun electrode geometry and equipotentials.

In the nominal configuration, with a potential difference of 100 kV between the cathode and first anode, the gradient at the cathode center is ~ 1.4 MV/m. The maximum radius of the cathode is 4mm, defined by the inner radius of the Pierce-type electrode ring.

Initial Configuration

As installed in the SCA, the gun was followed by a 260-MHz prebuncher and series of focusing solenoids, with approximately 3m from the cathode to the entrance of the first TESLA-type cavity. To configure the line as a photoinjector, the first solenoid lens and prebuncher will be moved downstream by approximately 13 cm (5”) to install a laser injection port. For the initial series of experiments, the prebuncher will be removed and replaced with diagnostics, such as screens and slits for emittance measurement.

The first drive laser will be a Continuum Minilite-II Q-switched Nd:YAG laser [3]. This laser has a maximum repetition rate of 15 Hz, and a relatively long (relative to the RF period of the linac) pulse duration of ~ 5 ns (FWHM). The laser is appropriate for an initial series of experiments to study photothermal cathodes, and will allow us to refine our laser injection system, operational procedures, safety protocols, etc., before installation of a higher-power, higher-repetition-rate drive laser system. Based on other studies making use of this type of laser, we expect bunch charges of up to 5 nC per pulse [4].

Simulation Studies

The transverse placement of the laser injection mirror is critical: too close to the beam axis and the mirror will cause wakefield effects on the beam and, potentially, intercept a portion of the beam; too far from the axis and the laser beam will be clipped.

To address this, a series of simulations was conducted using General Particle Tracer (GPT) v2.8. Beam charges of 0.5, 1.0 and 1.5 nC were assumed, with uniform transverse and either uniform or quadratic longitudinal distributions. The laser spot radius was varied between 1 and 4 mm, and the bunch duration between 0.1 and 1.5 ns. These simulations were used to find the maximum radius of the electron beam 30 cm from the cathode, the nominal mirror location.

Given a maximum laser beam radius of 4 mm, and a clear aperture radius of 1.1 cm at the exit anode 18.8 cm from the cathode, the laser injection angle can be a maximum of approximately 2 deg. At 30 cm, this corresponds to a distance from the inner edge of the mirror to the beam axis of 6 mm (for a 4 mm laser spot radius). The results of the simulations are shown in Figure 2 for 0.5-nC bunch charge, and a quadratic temporal profile.

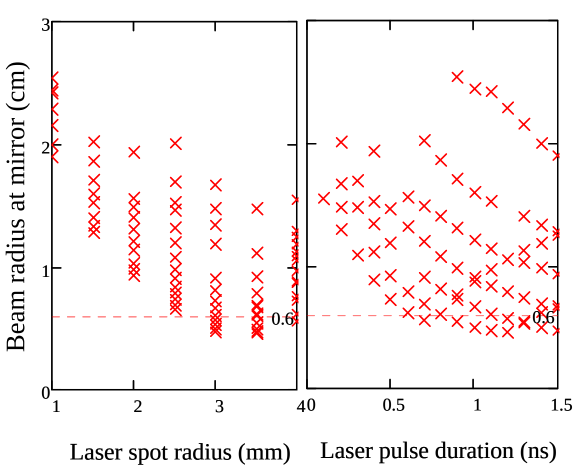

Figure 2: Electron beam radius at mirror location, as a function of laser spot radius (left plot) and pulse duration (right plot) at cathode for a quadratic temporal profile.

Similar results are obtained for 1.0 and 1.5 nC simulations. Generally speaking the mirror clearance is less at these charges, but beam should not be intercepted at the longer laser pulses and spot radii. Depending on experimental results, we will consider adding additional focusing coils near the gun to help contain the beam during initial transport.

The emittance of the beam was also calculated at the mirror position, and is shown in Figure 3.

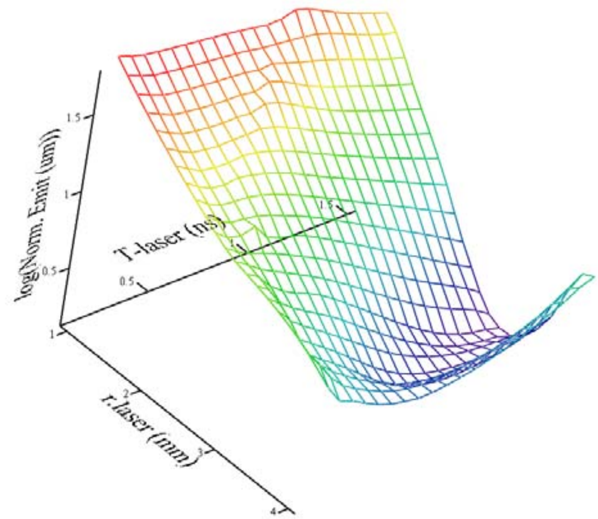

Figure 3: Normalized emittance at the mirror location as a function of laser spot size and pulse duration at the cathode. The emittance axis is plotted on a log scale and is normalized to 1 μm.

The GPT simulations indicate that, theoretically, normalized emittances on the order of 2 μm are possible (not including thermal emittance). Simulations with the particle-in-cell code **spiffe** [6] show similar results.

QUARTERWAVE GUN

There has been increasing interest in the use of reentrant-type structures for high-brightness, high-current CW injectors [7]. Compared to pillbox-type structures, these geometries offer a number of advantages, including more efficient use of RF power and smaller outer wall radii for a given frequency.

For the NPS-FEL, we have selected a quarter-wave superconducting resonator geometry with a nominal instantaneous gap voltage of 1.5 MV, and an operating frequency of 500 MHz. This allows for a maximum injection rate of 100 MHz into the 1.3-GHz linac cavities. With a nominal beam current of 1 mA, this injection frequency would correspond to a bunch charge of 10 pC, sufficient to be of interest for several studies. The structure will be designed to have a removable cathode insert, allowing the resonator to be used as both a beam source in its own right (which application we focus on below), and as an energy booster for an external beam source such as the DC injector. Given a small transit-time factor (or ratio of realizable to instantaneous voltage), phase slip effects can be minimized in this application.

A key tradeoff in this geometry is the gap length, or distance between cathode (or input beamport) and exit aperture. By decreasing the gap, the transit time factor and peak field at the cathode are both increased; this is good in terms of emittance preservation and minimization of the beam energy spread, but bad in terms of peak surface fields, field emission, etc.

Using MathCAD to perform 1-d particle tracking, we calculated the transit time factor, peak cathode field, and beam launch phase for maximum energy gain, for a variety of cathode-to-exit port distances, given a nominal instantaneous voltage of 1.5 MV.

Another parameter of interest is the launch window, defined here as the spread in phase over which a particle gains at least 99% of the maximum possible voltage. The results are summarized in Table 1. A plot of exit beam energy as a function of launch phase is shown in Figure 4.

Table 1: 1-d Tracking Results for Various Cathode-Beamport Gaps

Gap [cm]	Cathode gradient [MV/m]	Transit-time factor	KE_{max} phase [deg]	Launch window [deg]
2	63	0.993	78	16.2
4	37	0.985	70	16.4
6	27	0.973	62	16.9
7	24	0.965	59	17.1
8	22	0.957	56	17.3

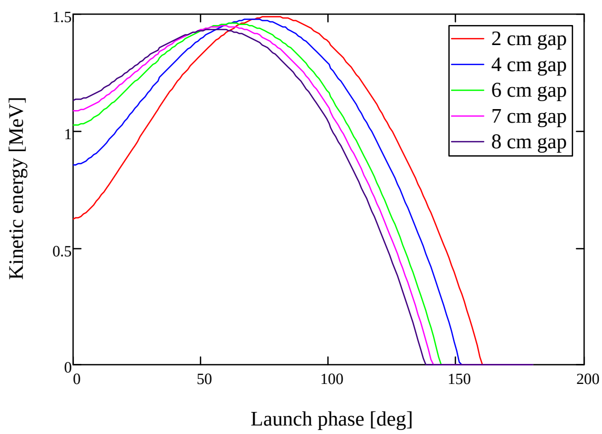

Figure 4: Kinetic energy as a function of launch phase, for various cathode-to-beamport gaps.

The free-space wavelength corresponding to 500 MHz is 0.6 m. A typical RF gun design has a cathode cell length on the order of $\lambda/4$; the cell lengths examined above thus correspond to $\lambda/30$ – $2\lambda/15$, or less than half the length of a typical cathode cell. This is the principal reason the transit-time factor is so high, along with the relatively wide launch windows for low energy spreads. In effect, the quarter-wave resonator "looks" more like a DC gun than an RF gun, for the time the beam is in the gap.

A first-cut design of a quarter-wave resonator geometry for the NPS injector upgrade is shown in Figure 5.

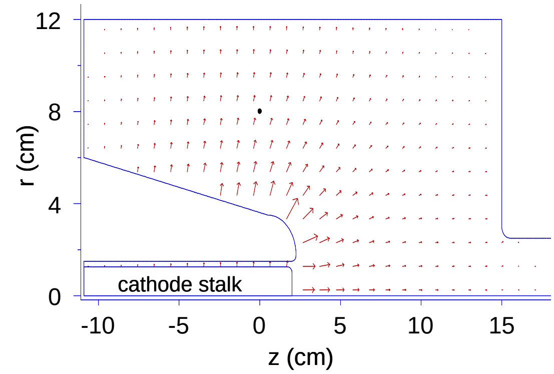

Figure 5: First-cut design for the NPS QW cavity.

We are still in the process of optimizing the gap and nosecone shape to obtain a good balance between peak surface electric and magnetic fields, transit-time factor, and gap. Detailed beam simulations will be conducted following the cavity parameter optimization, both in "injector" mode and "booster" mode.

CONCLUSIONS

The NPS-FEL project has formally begun with the installation of the SCA DC-gun injector line at NPS. The line is now under vacuum, and we are preparing to modify the gun for photocathode operation.

The quarter-wave resonator design process has also begun. Initial calculations indicate that cathode-to-beamport gaps of 8 – 10 cm may provide a good balance between peak fields and transit-time factors. Detailed beam dynamics calculations will begin shortly, when the cavity design has been further refined to balance these factors. The calculations will study the anticipated performance of the quarter-wave cavity as both an energy booster and as a stand-alone photoinjector.

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