Commissioning and Measurements of the Neptune Photo-injector


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Abstract. The photo-injector for the Neptune Advanced Accelerator Laboratory is introduced. Its component parts, including the radio frequency gun, photo-cathode drive laser system, booster linac, RF system, chicane compressor, beam diagnostics, and control system are described. The injector is designed to produce high brightness, short pulse electron beams. Measurements of the photo-injector beams including quantum efficiency, emittance, pulse length, and pulse compression are presented.

THE NEPTUNE PHOTO-INJECTOR

The Neptune Advanced Accelerator Laboratory consists of two main components, the RF photo-injector and the high power, short pulse, two frequency Mars CO$_2$ laser. [1] The main goal of the lab is to accelerate a high quality, relativistic electron beam injected into a plasma beat wave accelerator (PBWA) to over 100 MeV, while preserving the phase space density of the injected beam. [2] The PBWA experiment can take two different forms, one where a beam of moderate charge and emittance ($Q \approx 1$ nC, $\epsilon_n \approx 5$ mm mrad) covers more than one plasma wavelength, and the second where a shorter, low charge and emittance beam ($Q \approx 50$ pC, $\epsilon_n < 0.1$ mm mrad) is loaded into a single cycle of the PBWA.

Because of the range of injected beams required by the two phases of the PBWA experiment, the Neptune photo-injector is designed to produce an emittance compensated [3,4], optimized beam over an extent of different charges. This is done with a powerful method of charge scaling recently developed for photo-injectors. [5] This flexibility in the beam parameters the photo-injector can produce makes feasible many advanced accelerator experiments in the Neptune lab. These include free-electron laser (FEL) microbunching for injection into the PBWA, underdense plasma focusing [6-8], plasma wake-field acceleration (PWFA) [6,9], and inverse FEL acceleration [10]. In addition to these advanced acceleration experiments, studies of the high brightness beams themselves are underway at Neptune. These include the role of space-charge in emittance measurements, beam compressibility, and the process of emittance dilution in bends.
In the remainder of this section we describe the various component parts of the photo-injector and where applicable, their current performance. The components of the photo-injector include the RF gun, photo-cathode drive laser system, booster linac, rf system, chicane compressor, beam diagnostics, and control system. Figure 1 shows the layout of the photo-injector beamline.

**Accelerator Sections**

The photo-injector has a split accelerator design consisting of a photo-cathode gun, a drift space, and a booster linac. The gun is a 1.625 cell π-mode standing wave cavity produced by a BNL-SLAC-UCLA collaboration. [11] The gun has been conditioned up to an input power of 6.5 MW, which corresponds to an on-axis peak field of 100 MV/m. The current operating power in the gun is somewhat lower than this (due to limited total output power of the rf system) and the nominal peak accelerating field is 85 MV/m. The original cathode of this gun was simply the OFHC copper backplane of the half-cell. More recently however, this backplane was replaced with one including a 1 cm diameter, 1 mm thick disk of single crystal copper (Cu100). [12] The properties of the two cathodes will be discussed further in the measurements section below. The booster linac is a 7 and 2/2 cell π-mode standing wave structure. The linac design is that of a plane-wave transformer (PWT) which benefits from strong cell-to-cell coupling and large mode separation. [13] The linac has been conditioned up to 13 MW of input power and runs with a nominal peak accelerating field of 50 MV/m.

**RF System**

Low level RF starts with the 38.08 MHz output signal of the mode-locked laser oscillator (which is the first component of the photo-cathode drive laser). This signal is frequency multiplied by 75 to produce S-band RF. After passing through a phase
shifter, which allows us to control the laser injection phase, the signal is amplified to approximately 700 Watts by a pulsed amplifier. The kW level RF is then used as the input to a SLAC XK-5 klystron. The klystron is pulsed by a modulator with a pulse length of 4 μsec. The modulator was designed to produce a flat-top pulse impedance matched to the klystron at high voltage when fired by an SCR-triggered thyratron. The current klystron typically makes 20 MW of RF power.

The RF power distribution system consists of SF6 filled wave guide separating power manipulating elements. The first of these is a circulator, which protects the klystron from reflected power due to the impedance mismatch at the standing wave structures at the beginning and end of an RF pulse. The power is then split by a 4.77 dB divider sending one third to the gun. After the split high power attenuators control the power delivered to each accelerator. In addition the linac wave guide has a phase shifter to control the relative phase of the two structures. Figure 2 shows a schematic diagram of the Neptune RF system.

**FIGURE 2. The Neptune RF System**

**Photo-cathode Drive Laser**

The drive laser system begins with a 1064 nm mode-locked Nd:YAG laser oscillator which is matched into a 500 m long fiber to lengthen the pulse and yield a frequency chirp. The chirped pulse is then sent to a regenerative amplifier that increases the signal by a factor of one million. The chirp correlation is then removed and the pulse compressed by a grating pair. Adjustments to the grating pair allow control over the pulse length which is currently set at 6 psec (FWHM). At this point the pulse is frequency doubled by a BBO doubling crystal. The green laser light is then transported approximately 40 meters to the next BBO crystal which frequency doubles again to produce 266 nm light. The pulse energy in UV has been measured at
FIGURE 3. The Neptune Photo-cathode Drive Laser

130 µJ. Under nominal run conditions 100 µJ of UV energy is delivered to the cathode. Below is a schematic of the laser system.

Due to the long transport length, a vacuum transport system has been constructed to hold beam optics and to combat fluctuations in transverse position. To handle long time scale (> 10 sec) beam drift, a feedback system consisting of motorized mirror mounts and segmented photodiodes functions in the transport system. This system is computer automated by iteratively reading the position of a beacon laser with the photodiodes (beam position monitors) and adjusting the motorized mirrors accordingly.

Chicane Compressor

The compressor installed at Neptune was designed in part by scaling an L-band compressor designed for the TESLA Test Facility (TTF). [14] As shown in figure 4, it consists of four dipole magnets which can be configured either as a compressor or a spectrometer. In compressor mode a negative correlation in longitudinal phase space caused by running off-crest in the PWT is removed by the difference in path length of particles of different momentum. The problem of excessive vertical focusing in the chicane has been addressed by adjusting the initial and final edge angles to approximately equalize horizontal and vertical focusing in the device. By switching off the first two dipoles, the second two are used as a spectrometer. The chicane in spectrometer mode is used to measure the beam energy and energy spread. The typical beam energy at Neptune is 12 MeV with an energy spread of about 0.2%. The chicane is also being used to compress the beam and these measurements will be discussed in more detail below.
An important beam diagnosing tool is the pop-in view screen. At Neptune view screens are used for beam transport, spot size and profile measurement, and as an aid in the emittance compensation process. For this device phosphor is deposited on the downstream side of an aluminum foil mounted normal to the incident beam. A 45° mirror then directs light produced by the phosphor out to a CCD camera. From there the video data is digitized by a computer and analysis is performed on the image. In addition to phosphor, pop-in screens using YAG crystals, which offer higher resolution and better vacuum properties, are active at Neptune. The resolution limits of YAG crystals [15] are not a concern at Neptune because of the relatively low beam energy (12 MeV) and because in the photo-injector itself, the beam is never focused to a small spot.

Beam charge is measured primarily with an integrating current transformer (ICT). The ICT allows single shot, non-destructive charge measurements and has been used at Neptune to measure charges from 10 pC to over 1 nC. A charge of 600 pC is readily produced in the optimal accelerating phase of the RF gun. Measurements of charge and quantum efficiency (QE) will be detailed further below. At the end of the photo-injector beamline the beam is dumped into a Faraday cup, which was used to do initial charge measurements.

Additionally, beam diagnostics include a slit based emittance measurement system [16], and a bunch length measurement technique using coherent transition radiation (CTR). [17] Both of these will be discussed in greater detail below.
Control System

The photo-injector control system begins with an Apple Macintosh computer. The computer has a video digitizing card which allows real time analysis such as dark current subtraction, spot size calculation, and emittance slit image analysis. Also, the computer is equipped with a GPIB interface which is used to import oscilloscope traces, and communicate with a GPIB controlled CAMAC crate. The CAMAC crate contains modules responsible for pop-in screen insertion, steering and quadrupole magnet control and read-back, chicane control, and rf attenuators and phase shifters.

BEAM MEASUREMENTS

In this section we discuss measurements made on the basic properties of the high brightness beams produced by the Neptune photo-injector. In particular, measurements of quantum efficiency, emittance, and pulse length are presented.

Quantum Efficiency

The number of electrons freed from the cathode surface per incident photon (the QE) is an important quantity for photo-injectors, both in the demands it puts on the drive laser and in its effect on the output beam quality (QE variations over the emitting surface of the cathode lead to variations in the beam density and can cause emittance growth [18]). For that reason, a number of studies of quantum efficiency and uniformity of emission of different materials are planned at Neptune. We present here the QE found for a single crystal copper (Cu_{100}) cathode. [12]

The procedure used to measure the QE is straightforward. As mentioned above, an ICT was used to measure the beam charge. The ICT response was calibrated using a fast pulser and that calibration was in agreement with the factory specifications. The ICT signal was then fed into a fast, integrating ADC CAMAC module, which could be read by the computer. Knowing the calibrations of the ICT and the CAMAC module allowed the calculation of the charge on a single shot basis. As a further check, the ICT and Faraday cup signals were compared and found in agreement. UV energy was measured with a power meter placed behind a mirror. Because the amount of light transmitted through the mirror was very small, the power meter signal was amplified before being sent to a GPIB connected oscilloscope. The calibration between this signal and the UV energy was performed by measuring the energy directly with a second power meter. The relatively slow repetition rate of the photo-injector (1 Hz) allowed the computer to record both the charge and UV energy between shots and calculate the QE single-shot. The QE was obtained by varying the laser energy delivered to the cathode as shown in figure 5 below.
We found the QE with a peak accelerating field of 85 MV/m and an injection phase of 45°, (corresponding to an electric field of about 60 MV/m at injection) to be $5 \times 10^{-5}$. This is a promising result because it is roughly twice the value found for an OFHC copper cathode operating under the same conditions. Measurements of the uniformity of emission, cathode cleaning with kV electrons [19], and the QE of different materials are planned for the near future.

**Emittance**

The space charge dominated behavior of the high brightness beams produced at Neptune can be seen through examination of the RMS envelope equation for a beam in a drift.

$$
\sigma_x'' = \frac{\varepsilon_n^2}{\gamma^2 \sigma_x^2} + \frac{4I}{\gamma^2 I_0 (\sigma_x + \sigma_y)}
$$

(1)

Here the ratio of the space charge to emittance terms determines the character of the electron beam.

$$
R = \frac{2I\sigma_n^2}{I_0 \varepsilon_n^2}
$$

(2)

For typical Neptune parameters $R \approx 20$, indicating a space charge dominated beam. Thus, any emittance measurement scheme based on beam propagation in a drift must take this ratio into account.
The slit based emittance measurement system is illustrated by figure 6. In this system the beam is collimated into narrow beamlets by a set of slits inserted into the beam path. The beamlets are then allowed to drift a given distance to a pop-in view screen. By integrating the digitized image over the vertical dimension (for horizontal emittance) an intensity profile is produced. This intensity profile is analyzed to determine the position, momentum, and momentum spread of each beamlet and thus, the emittance.

In addition, a crucial function of the slits is to produce emittance dominated beamlets. The ratio of space charge to emittance in the envelope equation for a beamlet is:

\[
R_{\text{beamlet}} = \frac{2}{3\pi} \frac{1}{\mathcal{J}_0} \left( \frac{d}{\varepsilon_n} \right)^2
\]  

where \( d \) is the width of the slit. For the slits installed at Neptune, \( d = 50 \) \( \mu \)m and \( R_{\text{beamlet}} \approx 0.04 \). There are other issues that were considered in the design of the slit system including angular acceptance and interaction between beamlets. [16]

The single-shot nature of the slit emittance measurements allows real time calculation of the emittance via the analysis of the image intensity profile. This is done at Neptune with the computer running LabVIEW programs. An example of the computer program calculating emittance is shown in figure 7 below.

The horizontal, normalized emittance of the photo-injector has been measured using the slit system. We found typical normalize, RMS emittances of 5 mm mrad with a charge of 600 pC and pulse length of 3.6 ps (RMS). The complete set of nominal Neptune beam parameters is given in table 1 at the end of this report.

Planned beam dynamics studies using this technique are an examination of the emittance compensation process, and emittance growth in the compressor.
FIGURE 7. Emittance calculation software allows the measurement of emittance and other beam parameters such as charge in the same shot. The top image is a picture of the beam passing through the slits. The bottom image is the program calculating the emittance of the beam.

Pulse Length

Direct measurement of the pulse length of the electron beam is made with a device developed by Uwe Happek at the University of Georgia. [20] This device uses coherent transition radiation (CTR) to find the bunch longitudinal profile. The CTR is created by colliding the beam with a 45° foil. The radiation is directed out through a window into the device shown in figure 8. The device is a polarizing transmission (wire grating) Michelson interferometer.
Since the CTR created at the foil has the same temporal profile as the electron beam, the signal at the interferometer detector should be proportional to the autocorrelation of the beam density profile. [17] Thus, if the beam is gaussian longitudinally, the detector signal should also be a simple gaussian. The data, as shown in figure 9, does not show a simple form, but rather has multiple hills and valleys. This pattern was found in all cases the measurement was performed.

FIGURE 9. Raw data taken with the CTR interferometer.
The reason the raw data does not look like a simple autocorrelation of the beam profile is because the longer wavelength components of the CTR are lost in the device due to diffraction and finite apertures of the optics. Therefore, the data is the autocorrelation of the filtered beam distribution. The analysis of the time domain signal produced by the interferometer including this filtering effect was performed previously in reference 17. The key ideas of that analysis are presented now in order to obtain a pulse length from the measurements performed at Neptune.

The missing low frequency information in the autocorrelation can be modeled in the frequency domain by multiplying by a filtering function.

\[ \hat{\rho}_m(\omega) = \hat{\rho}(\omega)g(\omega) \]  

We chose \( g(\omega) \) to be

\[ g(\omega) = 1 - e^{-\xi^2 \omega^2} \]  

This choice of filter function eases further analysis and is physically motivated. It is obtained by the aperturing of a diffraction-limited transverse Gaussian-mode photon beam of uniform initial frequency spectrum in the far field. With the filter function applied, the spectrum of the measured signal is

\[ \tilde{s}(\omega) = \left| \hat{\rho}_m(\omega) \right|^2 = \left| \hat{\rho}(\omega) \right|^2 \left[ 1 - 2e^{-\xi^2 \omega^2} + e^{-2\xi^2 \omega^2} \right] \]  

By assuming a Gaussian beam profile we obtain an analytical expression for the signal in the time domain.

\[
    s(t) \propto \left[ e^{-\frac{(t-\tau_0)^2}{4\sigma^2}} - \frac{2\sigma}{\sqrt{\sigma^2 + \xi^2}} e^{-\frac{(t-\tau_0)^2}{4(\sigma^2 + \xi^2)}} + \frac{\sigma}{\sqrt{\sigma^2 + 2\xi^2}} e^{-\frac{(t-\tau_0)^2}{4(\sigma^2 + 2\xi^2)}} \right]
\]

Figure 10 shows the autocorrelation data for different compressor settings with this time domain fit function applied in each case. We see that the agreement between the time domain fit function and the data is good and that the compressor set to its design bend angle compresses the beam to a pulse length of 1.0 ps RMS (the uncompress pulse length was found to be 4 ps RMS).

The pulse length measurement scheme, in combination with the compressor and emittance slits, allows us to investigate the phenomenon of emittance growth in bends. Experiments in this area are planned for the near future and will be complimented by simulations using a three-dimensional code based on Lienard-Wiechart potentials. [21]
**FIGURE 10.** Interferometer data for two different compressor settings. In the first case the compressor magnets were set for the design bend angle of 22.5°. The pulse length calculated from the time domain fit is 1 ps (RMS). In the second case the bend angle was set to 11° and the calculated pulse length is 2.7 ps (RMS).

**CONCLUSION**

The photo-injector in the Neptune Advanced Accelerator Laboratory has been commissioned and the various properties of the beam have been measured. Table 1 summarizes the beam parameters. In addition to the PBWA experiment, the photo-injector will be utilized in a variety of advanced accelerator experiments as well as high brightness beam studies such as the process of emittance growth in bends.
TABLE 1. Neptune Photo-injector Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun Power</td>
<td>6 MV</td>
</tr>
<tr>
<td>Gun Peak Field ($E_z$)</td>
<td>85 MV/m</td>
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<tr>
<td>PWT Power</td>
<td>12 MV</td>
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<tr>
<td>PWT Peak Field ($E_z$)</td>
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<tr>
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<tr>
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<td>Energy Spread (RMS)</td>
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<tr>
<td>Pulse Length (RMS)</td>
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<tr>
<td></td>
<td>1 ps compressed</td>
</tr>
<tr>
<td>Charge</td>
<td>600 pC typical</td>
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<tr>
<td></td>
<td>up to 1 nC</td>
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<tr>
<td>Quantum Efficiency</td>
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<tr>
<td>Emittance (normalized, RMS)</td>
<td>5 mm mrad at 600 pC</td>
</tr>
</tbody>
</table>

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REFERENCES

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