NPS PROTOTYPE SUPERCONDUCTING 500 MHz QUARTER-WAVE GUN UPDATE*

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Abstract

The Naval Postgraduate School (NPS) Beam Physics Laboratory, Niowave, Inc., and The Boeing Company have completed construction of a superconducting 500 MHz quarter-wave gun and photocathode drive laser system. This prototype gun went from conception to initial operation in just under one calendar year. Such rapid progress is due in part to the decision to develop the gun as a prototype, deliberately omitting some features, such as tuners and a cathode loadlock, desired for a linac beam source. This will enable validation of the basic concept for the gun, including high-charge bunch dynamics, as rapidly as possible, with lessons learned applied to the next generation gun. This paper presents results from initial testing of the gun, technical challenges of the prototype design, and improvements that would enhance capabilities in future versions of this novel design.

GUN CONCEPT

In keeping with the NPS Beam Physics Lab desire to be a test bed for linear accelerator and free electron laser (FEL) components, we desired to explore the use of a superconducting radiofrequency (SRF) gun as part of the injector for the future NPS FEL [1, 2]. Borrowing the quarter-wave geometry from the heavy ion community and changing the transit path to axial rather than radial, we are able to operate at lower frequency and will have the ability to swap cathodes, enabling testing of novel cathode concepts in a realistic gun geometry. The current gun configuration installed in the test beam line is shown in Figure 1. The gun has been pursued as a rapid prototype, building a working cavity for physical testing to develop improvements for future generations of a common gun design. First beam for the NPS SRF gun occurred less than 24 months after initial concept development.

MANUFACTURE

Manufacture of the cavity was performed at Niowave, Inc. facilities in Lansing, MI. The nose cone and end plates were machined from bulk, large-grain, niobium. The side wall of the cavity is formed from sheet material. Standard electron beam welding processes were used for joining. Surface preparation of the cavity through standard buffered chemical polish (BCP) etching removed approximately 150 μm of material. High pressure rinse with ultra-pure water (17.5 MΩ-cm) was used to remove any remaining acid and particulates in the cavity. Standard vacuum vessel construction was used to complete the cryomodule, including a mu-metal shield surrounding a liquid nitrogen heat shield and the liquid helium dewar. A NbTi superconducting solenoid is outside the helium dewar and attached via two copper bus bars for conductive cooling. During assembly, multiple temperature sensors were installed throughout the cryomodule to monitor component temperatures during operation.

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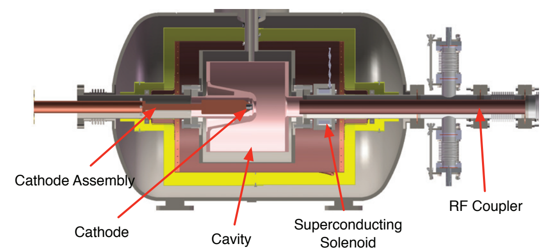

Figure 1: The NPS 500 MHz SRF gun, including the cathode assembly and coaxial RF coupler.

COLD CAVITY AND RF TESTING

Initial cold testing and RF testing/processing was accomplished in September and October, 2009. During this testing, our ability to process to full fields was limited x-ray emission associated with field emission at available RF power levels (100 W). First cooling to 4 K was successful, demonstrating no leaks and successful superconducting transition of the cavity. Unfortunately, the solenoid at the cavity exit is not cooled enough by the copper bus bars attaching it to the liquid helium dewar to reach superconducting temperatures.

RF testing and processing of the cavity without the cathode assembly proceeded without major incident, reaching a maximum gap voltage of approximately 750 kV which is below the design value of 1.2 MV. Cavity Q_0 was measured at 8×10^8. Helium processing [3, 4] was performed onsite at Niowave and demonstrated improvement of about 25% from the Q vs. E curve shown in Figure 2. During RF testing and processing, no quench events were encountered. In the booster configuration, the cavity is field emission limited.

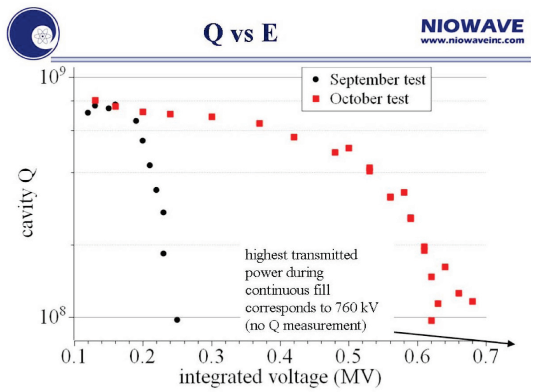

Figure 2: Two separate curves from initial cold testing (September) and conditioning (October) experiments. Cavity Q_0 values were found to be in the 8×10^8 range and the cavity demonstrates promise of continued conditioning improvement as RF power and radiation levels can be increased.

CATHODE INSTALLATION

After obtaining reasonable cavity gradient values, the cavity vacuum was broken in order to install a cathode stalk. The cathode stalk, shown in Figure 3, is non-resonant at the cavity fundamental with impedance mismatches in order to reduce RF power coupling from the cavity. Two capacitively coupled antennae are installed at the shorted end of the stalk to measure RF field strength or to apply an RF signal to reduce multipacting in the cathode assembly tube. The cathode itself is a machined niobium button prepared using BCP and press fit into the copper receptacle for conductive contact.

The cathode position is adjustable from approximately -14 mm to +1.5 mm along the axis of the cavity relative to the cavity nose cone. Altering the cathode position relative to the nose cone allows for changing the surface accelerating field and focusing fields. Assuming the cavity is at design gradient, retracting the cathode 6.5 mm provides significant focusing fields ($E_r \approx$ -1.5 MV/m) in the nose cone region while maintaining an accelerating gradient sufficient for diamond field emission cathode turn-on gradients ($E_z \approx 17$ MV/m) [5].

Due to the cathode surface not being shorted to the cavity, it is possible to operate room-temperature cathodes in the quarter-wave gun without a large conductive thermal load on the cryogenics. However, we have observed decreased Q_0 and the associated accelerating fields after cathode installation. Insertion of the cathode further into the cavity results in further depression of Q_0 and the observation of increased field emission. At full retraction, the Q_0 was measured at 5×10^8, decreasing a further order of magnitude as the cathode was inserted to 9 mm retraction. RF processing and helium processing have reduced field emission, however a cathode-to-cavity RF joint may be necessary in future designs to minimize the impact of the cathode stalk on the cavity Q_0.

BEAM TESTING

To facilitate diagnostic testing of the NPS 500 MHz SRF gun and other electron sources, an instrumented beam line, shown in Figure 4, was developed and installed at Niowave's facilities. The beam line consists of multiple window frame correctors for beam steering, a normal conducting solenoid, three quadrupoles, a spectrometer leg for beam energy and energy spread measurements, two beam position monitors and multiple diagnostic stations. Each diagnostic station contains an electrically isolated plate that can be used as a faraday cup and a cerium doped YAG crystal for beam imaging. The first diagnostic station has two pin holes drilled in two of the plate positions acting as pepper pots for emittance measurements, and was later modified to include slits for emittance measurements.

The UV drive laser, provided by Boeing, is a modified Coherent Elite DUO delivering approximately 1 mJ per 40 ps pulse at repetition rates from 1 Hz to 1 kHz. The gun solenoid currently limits the system to a repetition rate of 1 Hz due to the necessity of operating the solenoid in pulsed mode to decrease heating and compliance issues associated with insufficient cooling to reach superconducting temperatures. Laser performance has been exceptional for a new drive laser, providing stable operation throughout all experiments to date. Spot size and laser steering is accomplished via a moveable aperture, allowing for almost complete coverage of the cathode surface for quantum efficiency mapping.

First beam with the NPS 500 MHz gun was achieved 09 June 2010, establishing the NPS gun as the first operational SRF electron gun in the United States. Initial bunch charge measured was 30 pC. As experience with the gun increased, at optimal phase and transport settings, bunch charges as high as 110 pC have been obtained. Quantum efficiency estimates of approximately 3×10^{-6} correlate well with measurements made on a separate niobium cathode test stand using the same laser system. Commissioning of the rest of the diagnostic beam line proceeded rapidly and successful transport had been established to all diagnostics and beam controls less than 8 hours after first beam. Electron beam energies were estimated at 250 - 300 keV based on RF calculations and beam deflection measurements at both the spectrometer dipole and using the window frame correctors.

The cavity demonstrates a wide acceptance of launch phases with the greatest transport near the upper phase cut-

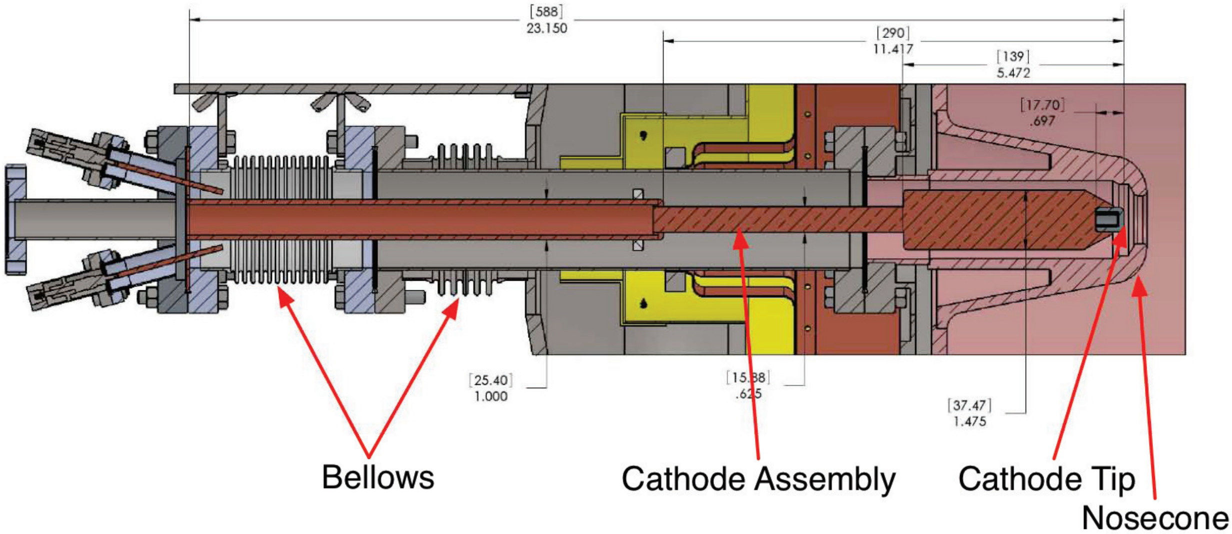

Figure 3: The cathode at the end of the stalk assembly is cantilevered into the high field region. The stalk radius changes act as impedance mismatches to minimize coupling of the stalk with the RF fields in the cavity. Not shown is a teflon spider to provide support located near the end of the hollow copper section of the stalk.

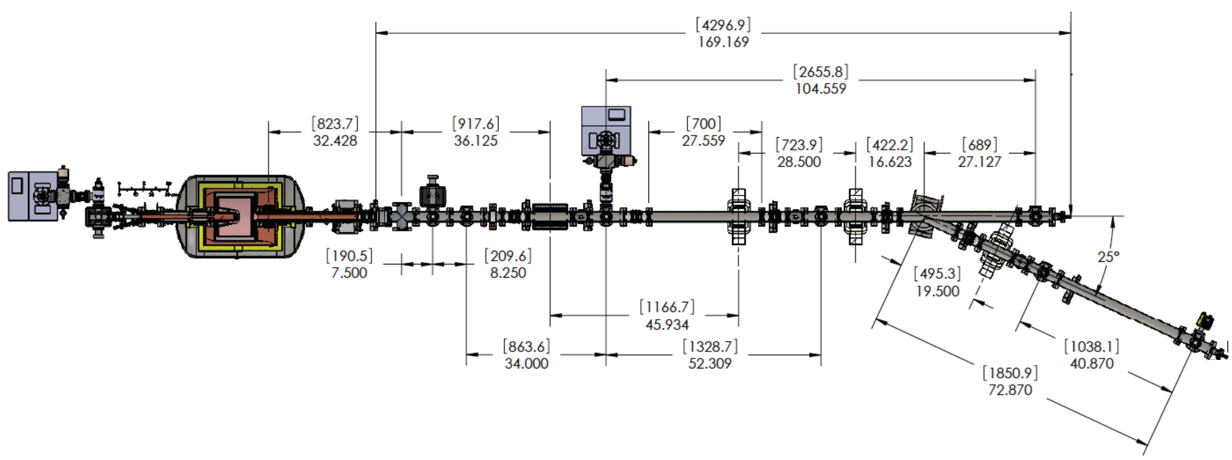

Figure 4: Diagnostic beam line developed in collaboration with Dr. W. S. Graves of MIT. Dimensions are in inches [mm].

off, as seen in Figure 5. We determined the acceptance by measuring the voltage across a resistor in series with the faraday cup in the second instrument station (FC2) while changing the RF phase relative to the laser pulse by adjusting a manual phase shifter. The acceptance window for the gun appears to increase as the cavity fields are increased, which agrees with observations made from simulations.

Initial energy estimates were obtained via bending angle calculated from both window frame steering corrector magnetic fields and comparison with the magnetic fields necessary to bend the beam into the spectrometer leg. Both an impulse calculation and comparison with simulation using appropriate field maps were used and compared with estimates of the beam energy based on RF calculations. Energy estimates using the correctors have tended to be higher than those estimated using RF methods, so all reported energies are based on the lower estimate. As we refine transport through the diagnostic line, energy estimates from beam dynamics should converge with other calculations.

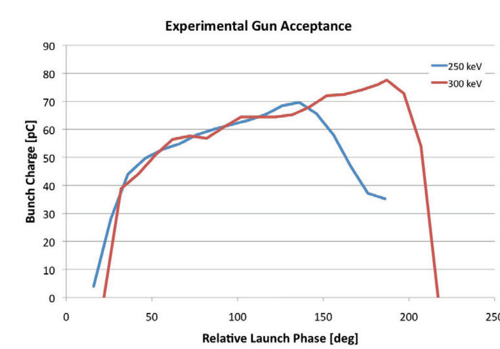

Figure 5: Cavity acceptance curves for two beam energies: 250 keV and 300 keV.

Subsequent experimental runs have allowed us to further refine beam transport as well as generate the first emittance estimate for the beam. By varying the gun solenoid current to obtain a near waist at the first diagnostic station in the system, we can measure the emittance using standard slit techniques [6]

$$\epsilon_{rms} = \sqrt{\langle x^2 \rangle \langle x'^{\,2} \rangle - \langle xx' \rangle^2}\,. \tag{1}$$

We find by using slotted screens in both axis that our initial estimate of beam emittance is $\epsilon_{rms} \approx 4$ mm-mrad in both planes for a beam with $\sim$40 pC bunch charge and $\sim$330 keV energy.

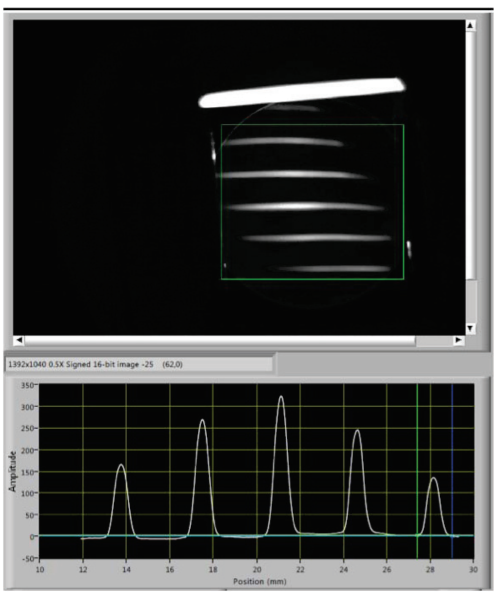

Figure 6: Electron beam image from diagnostic station 2 showing beamlets (upper panel). The lower panel shows the projected intensity along the axis (white line). Each beamlet is windowed individually and combined to obtain the final emittance value.

CONCLUSION

The NPS Beam Physics Lab and its Boeing and Niowave collaborators have achieved first beam in the first purpose built SRF electron gun in the United States. The cavity has demonstrated acceptable beam parameters in terms of bunch charge and emittance and shows promise in progressing to the full design gradient. The team successfully demonstrated operation of a new gun design only 24 months after concept, a remarkably short development period in electron gun development processes. Further work with the gun will proceed for the time being at the Niowave facilities, investigating cathode laser processing techniques and working to increase cavity fields. We intend to bring the gun and beam line to NPS near the end of this calendar year to begin assembly of the initial linear accelerator and free electron laser systems.

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