WISCONSIN SRF ELECTRON GUN COMMISSIONING*

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Abstract

The University of Wisconsin-Madison has completed installation of a superconducting electron gun. Its concept was optimized to be the source for a CW free electron laser facility with multiple megahertz repetition rate end stations. This VHF superconducting configuration holds the promise of the highest performance for CW injectors. Initial commissioning efforts show that the cavity can achieve gradients of 35 MV/m at the cathode position. With the cathode inserted CW operation has been achieved at 20 MV/m with good control of microphonics, negligible dark current, and $Q_0 > 3\times10^9$ at 4 K. Bunch charges of ~100 pC have been delivered, and first simple beam measurements made. These preliminary results are very encouraging for production of 100s pC bunches with millimeter-milliradian or smaller normalized emittances.

MOTIVATION

An FEL complex operating at high repetition rates and delivering intense, ultra-short, fully-coherent, variably-polarized beams to multiple experiments enables transformational research in diverse science disciplines. The Wisconsin SRF electron gun program is a response to the demand for a very bright electron source that can be used for these next generation light sources. SRF guns hold the promise to produce very bright, CW beams because of the correlation between high electric field on the cathode and brightness [1].

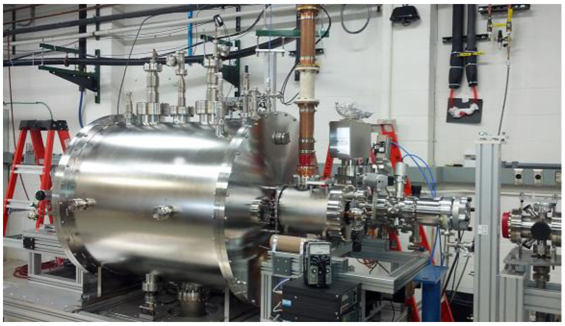

Figure 1: Electron gun installed in vault.

FACILITY OVERVIEW

The design uses a 199.6 MHz, quarter wave resonator geometry at a peak gradient up to 45 MV/m. Details of the superconducting cavity design, fabrication, and modeling have been presented in earlier publications [2]. The lower frequency design allows operation at 4 K and close to spatially constant electric field while the electron transits the accelerating gap. Thus, beam properties are expected to be superior to CW L-band guns, and relative to DC electron guns, should offer better performance with higher cathode fields. A copper photocathode was installed for initial testing with repetition rates limited to 1 kilohertz by the drive laser. Figure 1 shows the overall installation, and Table 1 contains key parameters for the gun.

Table 1: SRF Electron Gun Design Parameters

Max beam kinetic energy	4.0 MeV
Bunch charge	10–200 pC
Normalized trans. emittance	0.2–1 μm
Ultimate average beam current	1.0 mA
Peak current	50 A
Driving laser wavelength	266 nm

SUBSYSTEMS

RF System

The RF system utilizes a commercial, 30 kW, solid state transmitter driving coaxial waveguide through a circulator to the RF coupler. The low level RF controller (LLRF) [3] allows self-excited cavity operation and incorporates cavity fault and tuner control. It is based on the JLab upgrade design.

Magnets

The emittance compensation solenoid is of high temperature superconductor design. Nominal operating parameters are an integrated field of 3.1 T^2-mm at 38.45 A excitation at about 25-30 K (i.e., intermediate between LHe and LN_2 temperatures). An 18 bit AD7608 ADC is used to measure voltages at both ends and at the center of the solenoid for quench protection. The voltage difference between the two halves of the coil are compared and differences as small as 1 millivolt can be used to trigger a quench trip. There are two octupoles in the beamline. On each octupole the poles are independently powered with excitations mixed in software to produce normal and skew dipole and quadrupole correctors.

Cryostat

The cryostat consists of the helium vessel, internal tuner mechanism, cathode stalk, beam pipe, LN_2 cooled thermal radiation shield, magnetic shield, cryogenic plumbing and external vacuum vessel. The cavity is

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immersed in 100 liters of batch fed LHe within the helium vessel. Minimizing static heat loss is critical since the LHe bath is not a closed loop system and the cryostat consumes LHe all the time that the cavity is held at 4.2 K. Calorimetric measurements using a heater in the helium vessel resulted in a static loss measurement of 6 W which agrees favorably with earlier calculated predictions of 7.5 W. Future plans include the addition of a LHe refrigerator, and the existing cryostat can be configured to run closed loop. The required modifications will most likely result in an increase in static thermal loss of approximately 2 W.

Photocathode Laser

The drive laser system consists of a Spectra Physics Tsunami titanium-sapphire oscillator seeding a Spitfire Pro Ultrafast Amplifier. It operates at 1 kHz and is synchronized to an external 80 MHz signal which is phase locked to the RF master oscillator. A Minioptic TPH tripler provides the frequency doubled and tripled beams at 400 nm and 266 nm respectively. The 800 nm light is used for laser diagnostics while the 266 nm light passes through an adjustable aperture optical transport system before being directed onto the photocathode.

The laser transport optical system consists of two nested Schiefspiegler telescopes with a 0.4 net magnification. A laser pulse length of 120 fs has been achieved.

Controls

The control system is based on EPICS utilizing several soft-IOCs running on a Scientific Linux server. Koyo DL205 PLCs are used to interface most of the beamline hardware. Additional soft-IOCs were written for cryogenic thermocouples, Faraday cup picoammeters, and motorized laser mirror mounts. Cameras are used to capture the YAG:Ce screen images. New capture software was written based on existing diagnostic cameras that implemented Gaussian fitting and automatic exposure control.

COMMISSIONING

Cooldown

Without a helium refrigerator, a two-step cool-down procedure has been utilized with vendor delivered LN_2 and LHe. The procedure takes two consecutive days. The first step, cooling down by LN_2, is performed on the first day followed by filling the cavity cryostat with liquid helium to complete the cool-down procedure on the second day. The first cool-down step also includes pre-cooling of the cavity cryostat by liquid nitrogen in a manual mode. Right before the liquid helium filling step (on the next day of the cool-down procedure) the cavity cryostat is purged by dry (boil-off) nitrogen until there is complete evaporation of the liquid nitrogen. Then, the gaseous nitrogen in the cryostat is purged by helium gas. Cooldown is about 29 hours to the most poorly cooled points. However, RF input can begin after about 10 hours.

Cathode Positioning

The cathode longitudinal position can be adjusted to ensure it is flush with the cavity surface. Although the cathode can be viewed axially through the cavity, the longitudinal positioning of the cathode face is complicated by the cryogenic contraction and flexure of the structure under vacuum load. Dead reckoning from warm measurements results in a ±2 mm error, which exceeds tolerances.

Our technique for positioning involves measurements of cavity resonant frequency versus cathode insertion. Comparable geometry runs were made in SuperFish [4]. The technique begins with frequency computations and measurements with the cathode withdrawn. From SuperFish one has the frequency shift expected with the cathode flush with the cavity's cathode snout; in this case it is nearly -3000 Hz. The cathode is then physically adjusted to achieve this frequency shift.

Microphonics

Generator Driven Resonator mode is an operating mode where the RF frequency is fixed and the cavity's mechanical tuner is used to keep the cavity frequency within a few hertz of the reference frequency. The field control chassis has the capability to send data on the phase difference between forward and transmitted power to a DAC output. The rms value of the frequency shift was 0.35 Hz and the peak-to-peak value was 2.7 Hz. The largest frequency component was a cavity frequency excursion of 0.14 Hz rms at a vibrational mode of 1.8 Hz The loaded Q of the cavity is 10^7. The microphonics are within the cavity bandwidth, and are well controlled by the LLRF system.

Plasma Processing and Q_0 Improvement

During the initial cold tests at Niowave, the cavity showed a low field Q_0 of 3×10^9 at 4 K. However, the cavity exhibited relatively severe field emission which limited operation to approximately 5 MV/m peak field at the cathode. To improve the anticipated initial performance, a novel surface preparation technique, plasma processing [5, 6], was used [7].

Figure 2 shows the Q_0 data plotted with the data from cold test at Niowave. Data show the cavity has a Q_0 of 3×10^9 at 4 K at a peak cathode gradient of 26 MV/m.

Performance Summary

Conditioning of the cavity and especially the cathode stalk has not been completed. The RF circulator failed at higher average powers and is currently under repair at the vendor, and further conditioning has been postponed. Following are performance limits achieved to date, but further improvements can be expected:

Highest CW gradient: 29 MV/m, cathode out
Highest CW gradient: 20 MV/m, cathode in
Highest pulsed gradient: 35 MV/m, cathode out
Highest pulsed gradient: 29 MV/m, cathode in
Dark current: < 1 pA at 20 MV/m CW

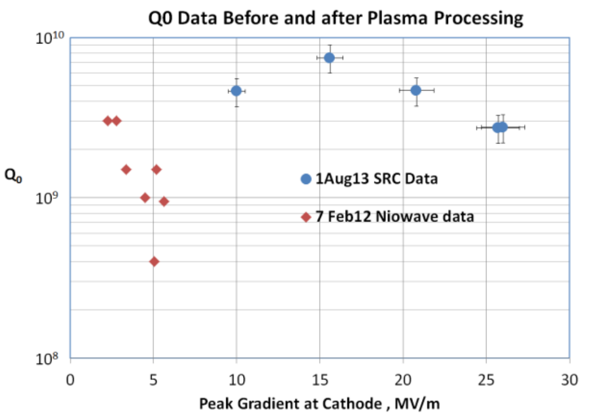

Figure 2: Calorimetric Q_0 data for cavity.

BEAM MEASUREMENTS

The gun and diagnostic beamline are shown in Figure 3. The transverse profile of the beam can be measured at three locations using 0.1 mm thick YAG:Ce screens. Two of the viewers, the first of which also contains a slit array, are located on the straight-ahead beamline, for use in transverse emittance measurements. The third viewer is located on the 30° branch line, and is used to measure beam energy and energy spread. The beam is deflected down the branch line by an H-frame dipole. Both the straight-ahead line and the branch line are terminated with a Faraday cup/beam dump read by a picoammeter.

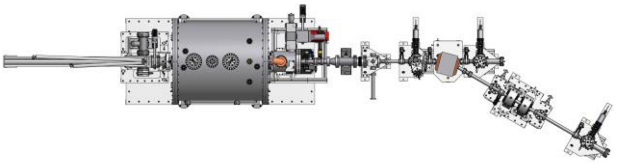

Figure 3: Layout of the gun and diagnostic beamline.

First beam measurements were made in mid-2013 although multipactor conditioning of the cathode stalk to higher gradients was still moving forward. To minimize cryogenic load during debugging of the diagnostics, first data were taken at 12 MV/m.

Initially there was 60 Hz motion of the beam that was traced to an AC solenoid on a vacuum valve. Additionally, it was found that the synchronization of the drive laser and the RF system was not stable. In particular, the 1 kHz repetition frequency from the drive laser is not well phase locked to the 200 MHz cavity fundamental, which results in an erratic bunch repetition rate and possible phase wandering. A laser upgrade is being provided by the vendor to correct this problem.

The electron energy was measured by centering the beam on the first beam viewer and the viewer on the 30° branch line. Based on the dipole calibration, the energy at 12 MV/m was 1.1 MeV. This is consistent what would be expected based on the accelerating gradient. The width of the beam spot on the 30° line viewer gave a projected energy spread of 2 % full width. The average bunch charge was measured to be roughly 100 pC.

Only one shift was devoted to transverse beam measurements before the RF circulator failure and only very limited data were acquired. We have initially used the quad-scan technique [8] for emittance measurement. To take space charge into account, ASTRA [9] simulations were compared to the measurements, and plausible emittances extracted. The estimated value for the normalized projected emittance is 1.5 mm-mrad. Given that laser/RF synchronization problem was present and that no systematic optimization was possible before the circulator failure, this result is surprisingly good and already near baseline goals. Since higher gradients can be obtained and optimization of phase tuning, cathode positioning, laser spot size, and emittance compensation has yet to be performed, considerable performance improvements can be expected.

FUTURE PLANS

A plan for a three year Phase II program is in place. We will work to fully characterize gun operation including exploration of tuning configurations (charge, peak current, RF phase, laser pulse length and spot size, emittance compensation, cavity gradient, etc.). The self-expanding blowout mode [10] and lower charge configurations for reduced emittance will be thoroughly investigated. A high repetition photocathode laser will be added together with a cathode preparation chamber for high quantum efficiency photocathode materials. Ultimately, exotic cathode materials for lowest emittance will be introduced. These improvements will allow operation at an average current of 1 mA at repetition rates up to 40 MHz.

SUMMARY

All together, the preliminary results are very encouraging for production of 100s pC bunches with millimeter-milliradian or smaller normalized emittances.

ACKNOWLEDGMENTS

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