SURVEY OF SRF GUNS*

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Abstract

Developing Superconducting RF (SRF) electron guns is an active field with several laboratories working on different gun designs. While the first guns were based on elliptic cavity geometries, Quarter Wave Resonator (QWR) option is gaining popularity. QWRs are especially well suited for producing beams with high charge per bunch. In this talk we will describe recent progress in developing both types of SRF guns.

INTRODUCTION

Superconducting RF has become the technology of choice for accelerating systems of many high-intensity particle accelerators. As the technology has matured, it is now finding applications other than just accelerating structures. One of such applications is photocathode RF guns. SRF has advantage over other electron gun technologies in CW mode of operation, where it potentially can provide higher rate of acceleration, generating high-charge bunches and high average beam currents.

SRF guns are complex devices merging several technologies: high Quantum Efficiency (QE) photocathodes, superconducting RF, high repetition rate synchronizable lasers. Among the challenges imposed by these technologies are maintaining UHV environment for the cathodes, maintaining cleanliness of the cavity RF surfaces while allowing operation and replacement of the cathodes, designing low RF loss and low heat leak interface between the cold cavities and warmer cathodes, synchronizing high repetition rate lasers with RF.

While SRF guns made excellent progress since previous SRF Conference [1], many issues still have to be addressed. Some of those are outline below. To produce **low emittance** beams, SRF guns have to have high acceleration rate, RF focusing near the cathode, first solenoid as close to the cavity as possible, precise synchronization of a laser with RF, and proper transverse and temporal bunch shaping. For **high bunch charge at high repetition rate** we must develop high QE photocathode with long life time, high average power, high repetition rate lasers. The semiconductor (and other high QE) photocathodes have to be able to operate in the SRF cavity environment. At least one type of photocathodes, Cs_2Te, has demonstrated to have long lifetime in an SRF gun, but more studies needed for other cathode types. **Preparation of cavities** for SRF guns proved to be difficult so far. The cavities either have very small opening to insert a cathode or no opening at all in case of superconducting cathodes. This makes chemical etching and cleaning of cavities challenging. Also, effect of the NC cathodes on SRF performance is still unclear. Finally, SRF guns have to **demonstrate stable operation in accelerators**. This includes handling of high average RF power, managing parasitic kicks from input power couplers, and effective damping of higher-order modes.

This paper is focused on reporting recent progress in the field. A more comprehensive description of the SRF guns can be found in [1].

TYPES OF SRF GUNS AND PHOTOCATHODES

In [1], SRF guns are classified by cavity/cathode type. The first SRF guns were based on elliptic cavity geometries – conventional shapes of high-β SRF cavities. While guns to be installed in accelerators use normal-conducting photocathodes, small R&D guns utilize superconducting (Nb or Pb) photocathodes. Quarter Wave Resonator (QWR) option is gaining popularity. QWRs are especially well suited for producing beams with high charge per bunch. QWRs can be made sufficiently compact even at low RF frequencies (long wavelengths). The long wavelength allows to produce long electron bunches, thus minimizing space charge effects and enabling high bunch charge. Also, such guns should be suitable for experiments requiring high average current electron beams. More details on QWRs can be found in [2]. One more type is a hybrid DC-SRF gun.

Semiconductor photocathodes are the preferred option for many projects. They can provide very high QE, up to 0.1 or even higher. However, these cathodes are very sensitive and require very good vacuum. The most developed semiconductor materials are GaAs(Cs), Cs_2Te, and CsK_2Sb. Gallium arsenide is the only photocathodes suitable for producing polarized electrons, but is more sensitive to ion back-bombardment than others, requires extremely good vacuum and has short lifetime. Cesium telluride is the most robust of the three, but requires UV lasers, which makes it more difficult to use for high bunch charge: more laser power needed for the same QE than at longer wavelength, optics and pulse shaping is more difficult as well. Cesium potassium antimonide can be used with green lasers and is the most preferred at present. Metal cathodes, while much more robust, have low QE and suitable only for use in the initial phases of SRF gun development. However, special coating of metals can increase QE up to 7×10^{-3} [3]. Finally, diamond can be used to boost current by a factor of ~100 and is very promising for high charge applications. We refer the readers for more details to the recently published review of photocathode R&D for future light sources [3].

* Work is supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. DOE.
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3½ CELL DC-SRF PHOTOINJECTOR AT PEKING UNIVERSITY

This unique design combines a compact 100-kV Pierce DC gun with a 3½ cell 1300 MHz superconducting RF cavity. This simplifies the cavity design and somewhat decouples it from the photocathode. The cryomodule design is shown in Figure 1. The gun is designed to produce 5 MeV beam with the bunch charge of 100 pC, rms emittance of 1.2 μm, and repetition rate of 81.25 MHz.

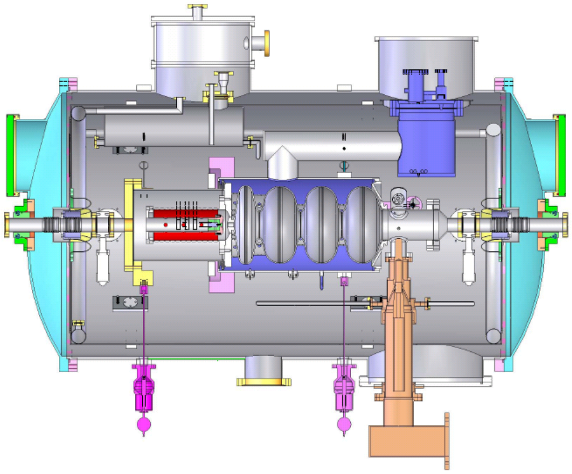

Figure 1: DC-SRF gun at Peking University.

The gun cavity demonstrated good performance during vertical test reaching quality factor of $>10^{10}$ at the accelerating gradient of 23 MV/m. During horizontal cold test the field was up to 11.5 MV/m (limited by available RF power) at $Q_{ext} = 6\times10^6$. The beam test of this gun is in progress [4].

ELLIPTICAL CAVITY SRF GUNS

ELBE Linac at HZDR

This 3½ cell 1300 MHz gun (Figure 2) is the first SRF gun in the world to inject beam into an accelerator. After installation and commissioning a special dogleg beam line, it provided ELBE with CW and pulsed beams. Maximum bunch charge injected into the linac is 120 pC at the repetition rate of 50 kHz with some beam losses, and 60 pC at 125 kHz with 100% beam transmission. The kinetic energy is limited to 3 MeV due to field emission in the SRF cavity in CW mode. Pulsed mode operation allows increase of the energy to 4 MeV. The Cs_2Te photocathode demonstrated lifetime of ~1 year.

Several upgrades are planned for this gun [5,6]. The new laser will have repetition rate of 13 MHz and better stability of the optical pulse amplitude. Two new cavities have been constructed, one from RRR300 fine grain niobium, and one from the large grain Nb. The first cavity was recently tested at Jefferson Lab, achieving accelerating gradient of 13 MV/m. If this performance is preserved, it will allow to reach the kinetic energy of 6.5 MeV.

BERLinPro at HZB

BERLinPro at HZB is an ERL designed to provide 100 mA beam with 1.3 GHz repletion rate (77 pC per bunch). To achieve these rather demanding parameters, a three-stage program to develop an SRF gun was initiated. At the first stage, a 1½ cell gun with a superconducting lead cathode is used as a beam demonstrator [7]. A thin film of Pb, deposited on the back wall of the cavity, is used to take advantage of an order of magnitude better QE of lead over niobium.

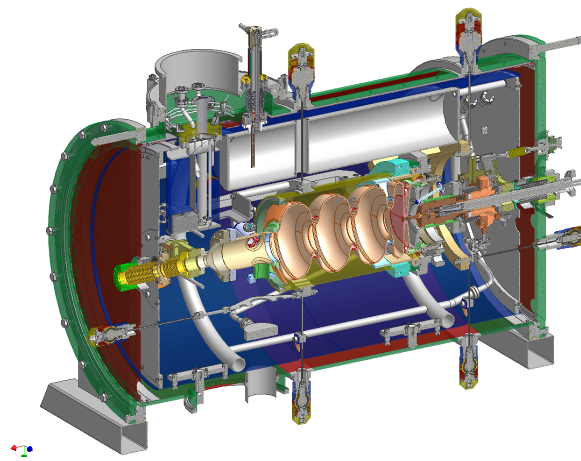

Figure 2: SRF gun for ELBE.

After cavity preparation and successful testing at Jefferson Lab (Figure 3), it was brought to HZB for testing in HoBiCaT. A diagnostic beam line was designed, installed and commissioned and the first beam was generated on April 21st of 2011. The beam measurements are in progress.

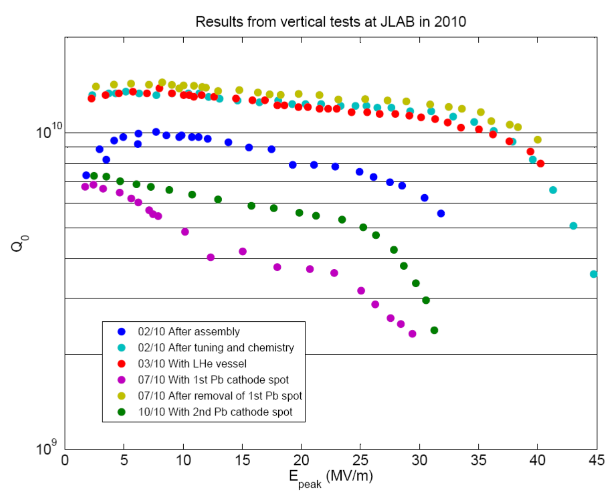

Figure 3: Results of 1½ cell gun cavity vertical testing at Jefferson Lab.

At the second stage, a new gun cavity will be developed, followed by design and engineering of the cathode insert, cold mass and cryomodule. In parallel, there will be studies of photocathodes, beam dynamics simulations, new drive laser, etc. Starting from this stage, a CsK_2Sb photocathode will be used. The tests will be performed in a new gun test area. Finally, at the third stage, the gun will have to be upgraded for high average RF power.

704 MHz gun for ERL at BNL

The 704 half-cell SRF gun (Figure 4) has two RF input power couplers allowing to deliver 1 MW of RF power to 0.5 A electron beam. HOM damping is provided by an external beamline ferrite load with a ceramic break. The gun and its cryomodule were designed and fabricated by AES. Input couplers are manufactures by CPI/Beverly. The gun cavity was tested in a vertical cryostat last year. The input power coupler test is complete with max power of 125 kW CW in full standing wave mode [8]. The cavity has been cleaned and the cavity string assembled at JLab. Assembly of the cryomodule at BNL will begin in August. The plan is to finish the cryomodule assembly in September of 2011, following by the gun installation in ERL and cold test. First beam will be generated with a metal cathode, following by experiments with CsK_2Sb.

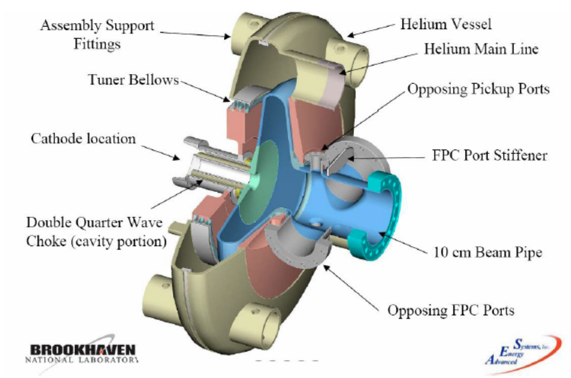

Figure 4: 704 MHz elliptical SRF gun.

QWR SRF GUNS

112 MHz SRF gun at BNL

Superconducting 112 MHz QWR was developed for electron gun experiments by collaborative efforts of BNL and Niowave, Inc. [9] The low frequency was chosen for this gun to take full advantage of QWR benefits, among which are: ability to generate long bunches would reduce space charge effects; short accelerating gap (relative to the wavelength) makes transit time factor close to unity and the gap filed practically constant; the center conductor geometry naturally accommodates choke joint and allows mechanical decoupling of the cathode assembly from the niobium cavity. This gun was designed for bunch charges of several nonocoulombs with emittance of ~3 μm at 2.7 MeV.

The gun cryomodule features (Figure 5): stainless steel helium vessel, superinsulation, LN2 thermal shield, magnetic shield, low carbon steel vacuum vessel. The first cold test was successfully performed at Niowave, Inc. in December of 2010 [9]. This gun is now a baseline option electron gun for the Coherent electron Cooling Proof-of-Principle (CeC PoP) experiment at BNL [10]. In addition, it will be used in studies of different photocathode types. The gun cryomodule will undergo some hardware modifications: the low carbon steel vacuum vessel will be replaced with the stainless steel one to satisfy the pressure vessel code requirements; a low RF loss, low heat load stalks for multi-alkali and diamond-amplified photocathodes will be designed and fabricated; a load lock system for multi-alkali photocathodes will be built; the cryomodule will be equipped with a combine function FPC/tuner assembly [11]. The design of these upgrades/modifications is in progress. The beam experiments are expected to begin in early 2012.

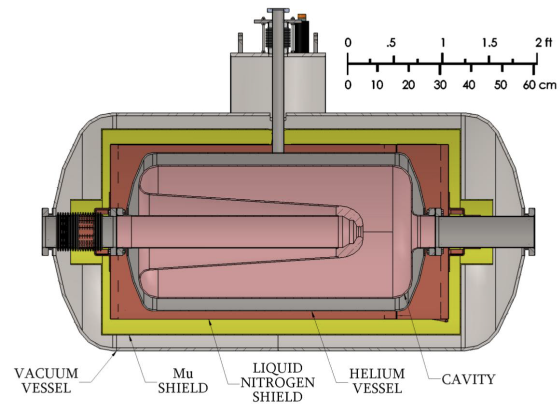

Figure 5: 112 MHz electron gun cryomodule.

500 MHz NPS SRF gun

This gun, built and beam tested recently [12], shown in Figure 6. A niobium cathode on a copper stalk was used. In the initial test the following beam parameters were achieved: beam energy of >460 keV, bunch charge of 70 pC, rms emittance of 5 μm. NPS is working on a new, 700 MHz, gun design, which will incorporate a number of improvements, enhancements, and problem fixes over the 500 MHz gun design.

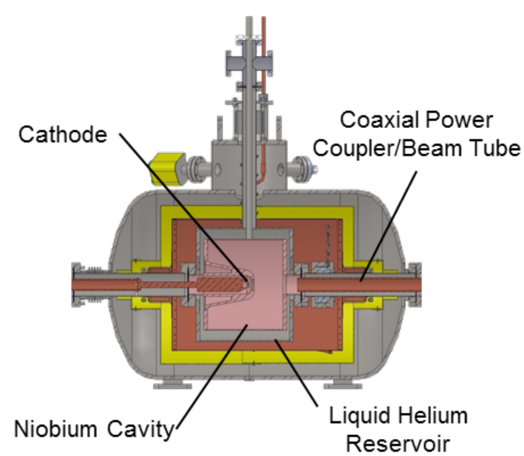

Figure 6: 500 MHz NPS QWR gun.

200 MHz SRF gun at University of Wisconsin

The goal for this R&D SRF gun [13] is to demonstrate single bunch beam dynamics and operation of SRF gun. It will be used with a low repetition rate drive laser, which allows option of using doubled or tripled Ti:Sapphire laser. A copper cathode will be used for initial operation: little chance of cavity contamination from evaporated cathode material; cathode will not degrade over time like semiconductor; no cathode preparation chamber needed. Later on, a load lock will be used for high QE photocathodes. The gun (Figure 7) is in fabrication at Niowave, Inc.

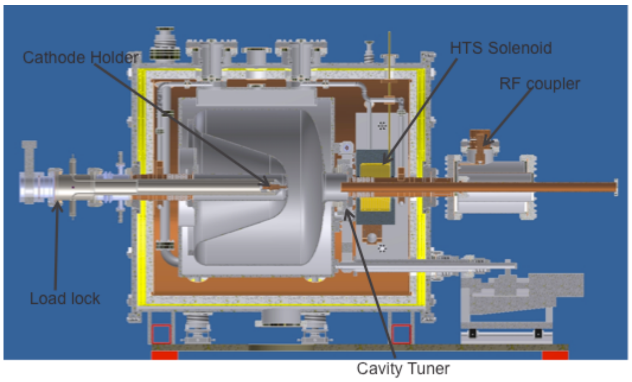

Figure 7: 200 MHz WiFEL SRF gun.

SUMMARY

SRF guns made excellent progress in the last two years. Several guns generated beams and one, at HZDR, injected beam into an accelerator. By accomplishing this, HZDR/ELBE gun demonstrated feasibility of the SRF gun concept with a normal-conducting Cs_2Te cathode. The cathode demonstrated very good performance with the lifetime of ~1 year. However, for high average current/high bunch charge operation CsK_2Sb is preferred as it needs green lasers, unlike UV laser for the Cs_2Te, which makes it easier to build laser/optics systems. Other high QE photocathodes are being developed for SRF guns, most notably diamond-amplified photocathode. Several QWR guns are under development with one producing beam already. They are very promising for high bunch charge operation. The field is very active and we should expect more good results soon.

ACKNOWLEDGEMENTS

I would like to thank the following colleagues, who provided materials on their projects for this paper: John Harris and John Lewellen (NPS), Kexin Liu (Peking University), Thorsten Kamps (HZB), Jochen Teichert (HZDR), Robert Legg (JLab).

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